what motivates us?
what motivates us?
what motivates us?

low viscosity liquid
what motivates us?

why?

how does it work?

low viscosity liquid
"To understand the workings of the QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid."
what do we need to measure?

Long Range Plan: "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"
what do we need to measure?

Long Range Plan: "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."
what do we need to measure?

Long Range Plan: "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."
what do we need to measure?

- jets, upsilons and photons with high statistics over a wide kinematic and collision energy range
- jets from 20 GeV → 1 TeV
- collision energy from 200 GeV → 5.5 TeV
- luminosity for precision measurements at both facilities

Long Range Plan: "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."
why two facilities?
why two facilities?
why two facilities?

- the QGP itself is different at RHIC and the LHC
why two facilities?

- the QGP itself is different at RHIC and the LHC
- largest range of scales probed is from high energy jets at the LHC to low energy ones at RHIC
why two facilities?

• the QGP itself is different at RHIC and the LHC

• largest range of scales probed is from high energy jets at the LHC to low energy ones at RHIC

• the jets are differently sensitive to the medium through their virtuality evolution
why two facilities?

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goal

comprehensive set of hard probes observables at RHIC and the LHC along with theoretical models to constrain the microscopic interactions between jets and the QGP
goal

comprehensive set of hard probes observables at RHIC and the LHC along with theoretical models to constrain the microscopic interactions between jets and the QGP
what are we to measure about these jets?
what are we to measure about these jets?

- rate, balance, (sub)structure, correlations…
- how these depend on how we can classify the jets,
- how they look different than they do in pp collisions..
what are we to measure about these jets?

- rate, balance, (sub)structure, correlations...
- how these depend on how we can classify the jets,
- how they look different than they do in pp collisions..

we have a lot of measurements at the LHC & RHIC so our question is: what further improvements do we need for a quantitative understanding?
an evolving landscape

Figure 1.51: (Top) Statistical projections for the $R_{AA}$ of various hard probes vs $p_T$ in 0–20% Au+Au events with the sPHENIX detector after two years of data-taking, compared with a selection of current hard probes data from PHENIX. (Bottom) Kinematic reach of various jet quenching observables from previous and future RHIC and LHC data-taking. Adapted from slides by G. Roland at the QCD Town Meeting at Temple University.

**Legend:**
- RHIC Today
- RHIC Tomorrow
- LHC Today
- LHC Tomorrow

**X+Jet**
- Ensemble-based measurements
- $x$+hadron correlations
- add low $p_T$ reach

- $D$ Mesons
- $B$ Mesons
- $b$ Jets
- Dijets ($p_{T,1}$)
- $\gamma$+Jets ($p_T^\gamma$)
- $Z^0$+Jets ($p_T^{Z}$)
- Double b-Tag ($p_{T,1}$)
LHC Run 2/3 & sPHENIX

projections from CMS

<table>
<thead>
<tr>
<th>Event Type</th>
<th>2010–2011 2.76 TeV 160 μb⁻¹</th>
<th>HL-LHC 5.5 TeV 10 nb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet ( p_T ) reach (GeV/c)</td>
<td>(~300)</td>
<td>(~1000)</td>
</tr>
<tr>
<td>Dijet (( p_{T,1} &gt; 120 \text{ GeV/c} ))</td>
<td>(50k)</td>
<td>(~10M)</td>
</tr>
<tr>
<td>b-jet (( p_T &gt; 120 \text{ GeV/c} ))</td>
<td>(~500)</td>
<td>(~140k)</td>
</tr>
<tr>
<td>Isolated ( \gamma ) (( p_{T,1} &gt; 60 \text{ GeV/c} ))</td>
<td>(~1.5k)</td>
<td>(~300k)</td>
</tr>
<tr>
<td>Isolated ( \gamma ) (( p_{T} &gt; 120 \text{ GeV/c} ))</td>
<td>(~350)</td>
<td>(~70k)</td>
</tr>
<tr>
<td>W (( p_T^W &gt; 50 \text{ GeV/c} ))</td>
<td>(~35)</td>
<td>(~7k)</td>
</tr>
<tr>
<td>Z (( p_T^Z &gt; 50 \text{ GeV/c} ))</td>
<td>(~35)</td>
<td>(~7k)</td>
</tr>
</tbody>
</table>

current 5 TeV results:
\(~5\% of total expected Run 2 + 3 statistics

sPHENIX in 22 weeks AuAu
100 B MB events
rare triggers sample 600 B
LHC Run 2/3 & sPHENIX projections from CMS

<table>
<thead>
<tr>
<th>Jet $p_T$ reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dijet ($p_{T,1} &gt; 1$)</td>
</tr>
<tr>
<td>b-jet ($p_T &gt; 12$)</td>
</tr>
<tr>
<td>Isolated $\gamma$ ($p_T^\gamma &gt; 35$)</td>
</tr>
<tr>
<td>Isolated $\gamma$ ($p_T^\gamma &gt; 50$)</td>
</tr>
<tr>
<td>$W$ ($p_T^W &gt; 50$)</td>
</tr>
<tr>
<td>$Z$ ($p_T^Z &gt; 50$)</td>
</tr>
</tbody>
</table>

~5% of total

sPHENIX projections

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
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<tbody>
<tr>
<td>0-20% Au+Au events</td>
</tr>
</tbody>
</table>

Weeks AuAu events

Significant 600 B
LHC Run 2/3 & sPHENIX

projections from CMS

<table>
<thead>
<tr>
<th></th>
<th>2010–2011 2.76 TeV 160 µb⁻¹</th>
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</tr>
<tr>
<td>Isolated $\gamma$ $(p_T^\gamma &gt; 120$ GeV/c)</td>
<td>~ -</td>
<td>~ 10k</td>
</tr>
<tr>
<td>W $(p_T^W &gt; 50$ GeV/c)</td>
<td>~ 350</td>
<td>~ 70k</td>
</tr>
<tr>
<td>Z $(p_T^Z &gt; 50$ GeV/c)</td>
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<td>~ 7k</td>
</tr>
</tbody>
</table>

current 5 TeV results:
~5% of total expected Run 2 + 3 statistics

sPHENIX in 22 weeks AuAu
100 B MB events
rare triggers sample 600 B

what physics is delivered by this abundance of data?

sPHENIX projections

Figure 4.43: $R_{AA}$ projections from CMS for inclusive photons (green points, assuming
$\gamma$ + jet tagging efficiency of 50%, 10 weeks of $\gamma$ data)
and
$\gamma$ + jet tagging efficiency of 50%, 10 weeks of $\gamma$ data)
and
$\gamma$ + jet tagging efficiency of 50%, 10 weeks of $\gamma$ data)
jet-boson correlations
jet-boson correlations

now

**Figure:**

- **Left Panel:**
  - CMS Preliminary graph showing the difference in transverse momentum ($\Delta p_T$) distribution for different centrality bins in PbPb collisions compared to pp collisions.
  - The graph includes data points and error bars for various centrality bins.

- **Right Panel:**
  - ATLAS Preliminary graph showing the distribution of $(1/N)(dN/dx_J)$ for different $p_T$ bins in PbPb collisions.

- **Legend:**
  - Blue line: 0-10% Pb+Pb, 0.49 nb$^{-1}$
  - Yellow line: pp, 26 pb$^{-1}$
  - Yellow shaded area: PYTHIA 8 + Data Overlay

**Text:**

- **Overview of ATLAS results, Sept 23rd, 2016**
  - See Brian Cole's talk
jet-boson correlations

now

future

sPHENIX

precision, reaction plane dependence, RHIC, …
jet tagging: heavy quarks

b,c

b-jet balance

heavy flavor rates in sPHENIX

ALICE JHEP 1511 (2015) 205

\[ R_{AA}^{\pi^\pm} (\text{ALICE}) \text{ 8}<p_{T}^{\pi^\pm}<16 \text{ GeV/c, } |y|<0.8 \]

\[ \text{D mesons (ALICE) 8}<p_{T}^{\text{D}}<16 \text{ GeV/c, } |y|<0.5 \]

\[ \text{Non-prompt J}/\psi \text{ (CMS Preliminary) 6.5}<p_{T}<30 \text{ GeV/c, } |y|<1.2 \]

Counts Event with $P_{T}>P_{T}(0)$ (Au+Au 0-20%)

(empty) filled boxes: (un)correlated syst. uncert. (*) 50-100% for non-prompt J}/\psi

\[ 50-80\% \]

\[ 40-50\% \]

\[ 30-40\% \]

\[ 20-30\% \]

\[ 10-20\% \]

\[ 0-10\% \]

\[ \Delta E_{c} \approx \Delta E_{g} \text{ (?) or different parton } P_{T} \text{ distributions and fragmentation functions} \]

Charm hadronization through recombination in medium (?) — predicted in models

— hint of $R_{AA}^{\text{D}}<R_{AA}^{\text{D}}$ in data — to be confirmed with higher precision

measurements

ALICE JHEP 03 (2016) 082

JHEP 03 (2016) 081

ALICE JHEP 1511 (2015) 205

CMS-PAS-HIN-12-014

CMS-PAS-HIN-12-013

CMS-PAS-HIN-12-012

CMS-PAS-HIN-12-011

CMS-PAS-HIN-12-010

CMS-PAS-HIN-12-009

CMS-PAS-HIN-12-008

CMS-PAS-HIN-12-007

CMS-PAS-HIN-12-006

CMS-PAS-HIN-12-005
energy within the jets

potentially very discriminating, especially when combined with, e.g., photon tagging requires good control of JES and tracking in the cores of jets
correlations within and between jets

modification to the energy distribution between subjets inside a jet

different observations between CMS & STAR:
differences in jet reconstruction, underlying event, collision energy, triggering, jet $p_T$
important to minimize the differences to isolate the physics we're interested in

spectra of jets nearby to a "test" jet

obviously exciting and promising new class of discriminating observables!
quantitative measurements
Quantitative measurements

Extended kinematics and surface bias engineering

Physics Performance

Figure 4.21: The effect of smearing on $A_J$ for $R = 0.3$ jets. The left panel shows the effect of smearing on the ratio determined from jets reconstructed after embedding in Au+Au events. Although smeared, the reconstructed data still show a distinct difference between the quenched and unquenched results. The right panel shows the results of the "unfolding" procedure discussed in Section 4.3.2.

4.5 Extended kinematics and surface bias engineering

Thus far we have documented a range of jet energy, radius, and collision centralities over which inclusive jets dominate above backgrounds and provide clean measurements of $R_{AA}$ and $A_J$. One can significantly extend the jet radius to larger values and energies to lower values through various fake jet rejection methods including matching to track jets, identification of individual particle energies in the jet (e.g. tracks or clusters) and setting minimum energy thresholds, jet shape cuts, and more. As we demonstrate here, sPHENIX will have the full complement of these methods available (thus having complementary overlap with existing STAR jet observables). All of these rejection methods present a bias on the jet sample that often anti-correlates with the expected modification in the quark-gluon plasma medium.

Experiments have employed fake jet rejection cuts to substantially extend the high purity jet energy range accessible in central heavy ion collisions — for example see Refs. [11, 89]. With the sPHENIX detector we can utilize track + electromagnetic jets matched to fully calorimetric jets in a similar fashion. In addition to extending the measurable jet energy range to lower energies, for energies with high purity without any selection one can turn this method into a powerful tool to engineer the degree of jet surface emission. For example, in the sample of $10^5$ jets with $R = 0.4$ and $E_T > 40$ GeV, we can measure a high purity sample of reconstructed jets in central Au+Au collisions. We can then dial in the required track + electromagnetic cluster jet characteristics to achieve a particular...
quantitative measurements

sPHENIX simulation

w/ 2D Bayesian unfolding

Extended kinematics and surface bias engineering Physics Performance

w/ 2D Bayesian unfolding
quantitative measurements

sPHENIX simulation

w/ 2D Bayesian unfolding

unfolding necessary for quantitative comparisons between experiments and for theoretical comparisons!
The combinatorial background was studied by generating events with fake electrons due to misidentified pions with electrons. The results are summarized in Figure 4.45 (left), which shows the signal subtracting all like-sign pairs.

For the 0–10% most central Au+Au collisions a rejection factor of 90 is assumed. The pair efficiency is obtained by embedding electrons in HIJING events. The rejection and efficiency are still being studies of the electromagnetic calorimeter response to electrons and charged pions. The efficiencies due to misidentified pions is assumed here to be zero in a single electron track efficiency of 70% (giving a pair efficiency of 49%). The pair efficiency is

The systematic uncertainties are computed by varying the probability distribution function (PDF) describing the resolution obtained from both the Pb-Pb and pp results is taken as the systematic uncertainty. The quadratic sum of these three systematic uncertainties gives a relative scale calibration. The mass ratios between the states are left free, to accommodate a possible bias in the momentum resolution obtained from both the Pb-Pb and pp data. The solid lines show the result of the fit described in the text.

The separation of 1S, 2S & 3S states temperature dependence of screening is key! Requires excellent tracking & EM calorimetry for electron ID & mass resolution.

sPHENIX projection

PRL 107 052302
pA: crucially important

pA at the LHC & RHIC has been enormously successful & surprising; **necessary** for sPHENIX to measure full suite of pp/pA/AA
pA: crucially important

pA at the LHC & RHIC has been enormously successful & surprising; necessary for sPHENIX to measure full suite of pp/pA/AA

+ large vN, plus many other great measurements....
LHC upgrades

- ALICE inner tracking & TPC upgrades
  - motivated by low $p_T$ charm & bottom measurements
  - requires excellent tracking and PID
  - hard observables to trigger upgrade read out to 50kHZ
- ATLAS IBL installed during LS1
  - ATLAS & CMS trigger LS2
  - ATLAS ZDC development ongoing
what detector do we need?

Long Range Plan: "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."
what detector do we need?

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- high rate
- large uniform acceptance for jets, photons and upsilons
- excellent tracking and full hadronic and electromagnetic calorimetry
- first data: 2022
- 200 collaborators / 60 institutions
what detector do we need?

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- high rate
- large uniform acceptance for jets, photons and upsilons
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In order to perform the physics measurements outlined in Chapter 1, sPHENIX must satisfy a set of detector requirements. In this Chapter we discuss the physics-driven requirements on the performance of the sPHENIX detector. In addition, as outlined in the Executive Summary, this sPHENIX upgrade serves as the foundation for a future upgrade to a world class Electron-Ion Collider (EIC) detector built around the BaBar magnet and sPHENIX calorimetry, and those requirements are taken into account. The details of specific detector and simulations regarding the physics capability of the sPHENIX reference design are given in Chapter 4.

The sPHENIX physics program rests on several key measurements, and the requirements that drive any particular aspect of the detector performance come from a broad range of considerations related to those measurements. A consideration of the physics requirements has led to the development of the reference design shown in Figure 2.1 and this will be described in detail in Chapter 3.

sPHENIX: calorimeters

- steel / scintillator HCal
- WSciFi SPACAL
hadronic calorimeter

alternating steel scintillating plates

prototype assembled at BNL
sPHENIX EMCal

scintillating fibers embedded in tungsten powder

first 2D projective tungsten SPACALs being produced
sPHENIX tracking

- very successful tracker review in September 2016
- planned design:
  - 3 layers MAPS, using ALICE stave design
  - 4 layer intermediate silicon tracker
  - outer TPC
sPHENIX activity

- Babar magnet successful low power cold tests @ BNL
- FNAL EMCal/HCal test beam: April 2016 and January 2017

Project Scope

- Prototyping
- v1 Field Cage: Full sized, designed to be usable if successful.
- v1a/v1b modules: Investigations of segmentation, position linearity, IBF
- v2 Field Cage: Full sized, intended for use in sPHENIX.
- v2a/v2b/v2c modules: Design evolution toward final avalanche module, technology competition.
- Pre-production: Test both the design of final modules and quality of facilities.

Production

- Modules produced in parallel at 3 facilities: PNPI/ Vanderbilt/ Weizmann Institute

Electronics

- FEE: on board card carrying SAMPA chip and FPGA with “light duty” (initialization, elink)
- Data Aggregation Module (DAM): Collects 8 FEE and “clusters” across pads & time.
- Event Builder Data Compressor: Interface between DAM and (eventually RCF), reduces data via compression.

TPC work at Stony Brook

Illinois group at Fermilab
LHC Upgrades
Precision Era of Hard Probes in Heavy Ions

**RHIC / LHC Timeline**

- **LHC**
  - End of Long Shutdown 1: 2021
  - Long Shutdown 2: 7/18-12/19, 2020
  - Stochastic e-Cooling: 2020
  - LS2 Installation: 2021
  - sPHENIX Shutdown: 2021
  - Electron-Ion Collider (Notional BNL Plan): >2025

- **RHIC**
  - 1 Month Ion Running: 11/2015, 11/2016, 6/2018
  - 1 Month Ion Running: 11/2020, 11/2021, 12/2022
  - Installation Shutdown 2021
  - Install LEReC
  - Chiral Magnetic Effect Confirmation

**Projects**

- **2014-2017**
  - Heavy Flavor Probes of QGP
  - Origin of Proton Spin

- **2019-2020**
  - Beam Energy Scan II

- **2022-2025**
  - Precision jets and quarkonia

**Notes**

- sPHENIX & LHC Run 3 → era of precision hard probes!
an exciting future!

we have a unique opportunity to use hard probes to *understand* how the low viscosity liquid emerges from the microscopic interactions of quarks and gluons at high temperature!
an exciting future!

we have a unique opportunity to use hard probes to understand how the low viscosity liquid emerges from the microscopic interactions of quarks and gluons at high temperature!

• requires:
  • excellent detectors: sPHENIX & LHC upgrades
  • strong interactions with theory community vital to our success!
  • hard work of many people!
an exciting future!

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