What are Hard Probes?
What can we learn from Hard Probes?
How do we detect Hard Probes?
What did we learn from Hard Probes (2010-2015)
What remains to be learned?

a few thoughts by an experimentalist…
QCD (in vacuum) is hard

Complex multi-particle dynamics even in p+p

from Frank Krauss
QCD (in vacuum) is hard, but it factorizes

Universal, long-distance, low momentum, “soft” physics

Short-distance, high momentum, “hard” process

T=300MeV medium: 1/p ~ 0.2 fm

100 GeV Jet: 1/p_T ~ 0.002 fm
QCD (in vacuum) is hard, but it factorizes.

Nuclear PDFs

$\hat{\sigma}_{ij \rightarrow f+k}$

$D_{f \rightarrow h}^{vac}(z, \mu_f^2)$

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$\tilde{\rho}^{f/N}(x_1, Q^2)$

$\tilde{\rho}^{f/N}(x_2, Q^2)$

$\tilde{\rho}^{f/N}(x_1, Q^2)$
Hard Probes and Medium

Nuclear PDFs

$f_i/N(x_1, Q^2)$

$\hat{\sigma}_{ij\to f+k}$

$f_j/N(x_2, Q^2)$

$D_{f\to h}^\text{vac}(z, \mu_f^2)$

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Hard Probes and Medium

Nuclear PDFs

Unchanged
Separation of (time) scales

Presence of medium
changes evolution of probe

Here be new physics!
Hard Probes Gallery

**Vectorbosons**
- Colorless
- No medium effects
- Probe initial state (nPDFs, N_{coll})

**Quarkonia**
- Hidden color
- Dissociation in hot and cold medium
- Regeneration?

**Jets**
- Colored probe
- Induced radiation + elastic scattering
- Many observables: Jets ([u,d,s], g, c,b)
- Hadrons (u,d,s, D, B)
- Correlations

n.b. I’m going to be somewhat biased towards large Q^2
Typical collider detector
How do we assemble these detector objects to physical observables?
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Yesterday’s Nobel Prize….

Yield above background fit (or like-sign combinations) readily extracted. Efficiencies for resonances can be estimated using data ("Tag & Probe").
\( W \rightarrow \mu \nu \mu \): single high-\( p_T \) muon (>25 GeV) + “Missing \( E_T \)”
Phottons in Isolation

Leading order

Compton

Annihilation
• SumIso = uncorrected Track + ECAL + HCAL $E_T$ in $R < 0.4$
• GenIso = generator level particle energy in $R < 0.4$
• **Data:** Isolated prompt (non-decay) photons: SumIso < 5 GeV
• **pp MC:** Isolated photons: GenIso < 1 GeV
(High $p_T$) isolated photons in AA

1. Find a high ET ECAL cluster (photon candidate)
2. Subtract underlying event energy in iso cone
3. Apply isolation cut ($\text{SumIso} < 5 \text{ GeV}$)
4. Use 2nd variable (shower shape) to determine photon purity (1-fraction of decay photons) from data
Nuclear Modification Factor

\[ R_{AA} = \frac{d^2 N_{AA}}{dp_T d\eta} \langle T_{AA} \rangle \frac{d^2 \sigma_{pp}}{dp_T d\eta} \sim \frac{\text{"QCD Medium"}}{\text{"QCD Vacuum"}} \left\{ \begin{array}{ll} R_{AA} > 1 & \text{(enhancement)} \\ R_{AA} = 1 & \text{(no medium effect)} \\ R_{AA} < 1 & \text{(suppression)} \end{array} \right. \]

\[ \langle T_{AA} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{pp}^{inel}} \]

\( N_{coll} \): Number of binary nucleon-nucleon collisions within AA collision

**CMS (*preliminary)**

\[ \int L \, dt = 7-150 \mu b^{-1} \]

- **Z (0-100%)** \( p_T > 20 \text{ GeV/c} \)
- **W (0-100%)** \( p_T > 25 \text{ GeV/c} \)
- **Isolated photon (0-10%)**

**Au+Au, \( \sqrt{s_{NN}} = 200 \text{ GeV} \)**

We understand \( N_{coll} \) (from Glauber MC) to \( \sim 5\% \) in central AA (uncertainty larger for very peripheral collisions)
Beyond $N_{\text{coll}}$: nPDFs from pPb

Approaching sensitivity needed to see nuclear modifications of PDFs

Effects are small in kinematic region studied

Gunther Roland

Hard Probes of the Hot Medium
Hard Probes Gallery

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Gunther Roland

Hard Probes of the Hot Medium
Quarkonia as multi-scale QGP probes

from arXiv:1404.2246

from Yen-Jie Lee

ψ(2s)  Y(3s)  Y(2s)  J/ψ  Y(1s)

Gunther Roland  Hard Probes of the Hot Medium
Quarkonia as multi-scale QGP probes

from arXiv:1404.2246

Quarkonia as multi-scale QGP probes

from Yen-Jie Lee

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

Inclusive $\psi(2S)$ (6.5 < $p_T$ < 30 GeV/c, $|y| < 1.6$)

$\Upsilon(3S)$ ($|y| < 2.4$), 95% upper limit

$\Upsilon(2S)$ ($|y| < 2.4$)

prompt $J/\psi$ (6.5 < $p_T$ < 30 GeV/c, $|y| < 2.4$)

$\Upsilon(1S)$ ($|y| < 2.4$)

n.b.: high $p_T$ $J/\psi$

from Yen-Jie Lee

Gunther Roland
Hard Probes of the Hot Medium

QM’15 Student Day
One of the most striking LHC vs RHIC (SPS) results

$J/\psi$ not just created in initial hard collisions, but also during QGP evolution and/or hadronization
But surely $Y(ns)$ are fine, aren’t they?

Even at LHC, density of $b$ quarks is small.
Well, there is this in pPb...

Y(1s) shows “cold nuclear matter” effects (although one can now debate how “cold” p+Pb is)

Double ratio ($1 \equiv$ same effect for Y(1s), Y(2s), Y(3s)):

$$\left[ \frac{\mathcal{R}(nS)}{\mathcal{R}(1S)} \right]_{pp} = \frac{R_{pPb}(\mathcal{R}(nS))}{R_{pPb}(\mathcal{R}(1S))}$$

Initial state effects (nPDF) should $\sim$ drop out
But: Differential change seen vs binding energy!
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TOMOGRAPHY
a method of producing a three-dimensional image of the internal structures of a solid object by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures.

Jets probe (semi-) local medium properties
TOMOGRAPHY
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Use $p_T$, centrality, pathlength, $\sqrt{s}$ dependence, trigger biases, flavor tags, ... to isolate different processes in time, coordinate and momentum space.
Jet Transport Coefficients: $\hat{q}$ and $\hat{e}$

Jets as tools to **characterize** QGP

Medium effects on jets allow extraction of QGP transport coefficients:

- $\hat{q}$: transverse momentum diffusion (radiative energy loss)
  - induced gluon emission in medium

- $\hat{e}$: longitudinal drag (collisional energy loss)
  - collisions with medium patrons

Radiative energy loss suppressed for (slow) heavy quarks: *Dead Cone effect*

Changes relative importance of radiative vs elastic e-loss:
Use heavy flavor (c,b) vs light (g,uds) measurements to disentangle radiative vs collisional energy loss
What’s a jet?

Jet finding is easy...
High $p_T$ jets, pp collision

Jet 1
430GeV

Jet 2
420GeV
What’s a jet?

Jet finding is easy…
High $p_T$ jets, pp collision

…until it isn’t
Low $p_T$ jets, central heavy-ion collision UE
What’s a jet (in pp)?

Same pp collision event

Need to \textit{define} jet in experiment \textit{and} theory

from Gavin Salam
A jet is what Cacciari, Salam & Soyez say it is

2008: Fastjet revolution
Cacciari, Salam, Soyez, JHEP 0804 (2008) 063
“anti-kT” replaced zoo of prior algorithms:
• conceptually simple
• theoretically sound
  • infrared safe
  • collinear safe
• computationally efficient & robust
• part of Fastjet package

Anti-\(k_T\):
Sequential clustering of objects in event (calo towers, tracks etc) with a particular distance measure:
\[
d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},
\]
\[
d_{iB} = k_{ti}^{2p}, \quad p=-1
\]
Results in cone-shaped, approximately \(R\)-sized jets

Which jets are found depends on anti-\(k_T\) resolution parameter

from Yen-Jie Lee
Jets in heavy-ion collisions sit on top of large *underlying event (UE)*

Need to decide which particles are part of jet and which belong to UE:

**UE subtraction**

Current methods assume that local UE (under jet) is the same as elsewhere in the event

I.e., UE modification due to jet would manifest as modification of observed jet
Achieved good experimental control
- Reconstruction efficiency (close to 100%@50+ GeV)
- Jet energy scale (2-4% above 30 GeV)
- Resolution and UE fluctuations (~15%@100GeV)

This was not obvious a-priori; success enabled by nature of observed jet modifications

How do we avoid biasing measurement towards unmodified jets?

STAR, ALICE: Accept all jet candidates down to lowest $p_T$, remove “fake” jets statistically using mixed events

ATLAS, CMS: Study high $p_T$ jets such that efficiency, JES well controlled even for modified jets

For sufficiently high “trigger jet” $p_T$, all away-side jets found
Detecting Open Heavy Flavor (hadrons)

**non-photonic electrons**

- **c+b**
  - requires electron ID
  - limited info on kinematics
  - limited constraints on bkg's

**D mesons**

- **c**
  - requires VTX detector
  - hadron PID helps
  - full charm kinematics
  - clear mass peak
  - needs high statistics data (BR)

**B mesons**

- **b**
  - requires VTX detector
  - requires lepton ID
  - full bottom kinematics
  - clear mass peak
  - needs very high statistics, acceptance (BR)

**Displaced leptons**

- **c+b (c vs b)**
  - requires VTX detector
  - requires lepton ID
  - limited info on kinematics
  - limited constraints on bkg's

**non-prompt J/ψ**

- **b**
  - requires VTX detector
  - requires lepton ID
  - some bottom kinematics
  - some constraints on backgrounds
Heavy-flavor tagging
- Reconstruct jets as per usual
- Build taggers to discriminate light and b(c) jets
- Based on secondary vertex properties:
  - Flight distance significance
  - Secondary vertex mass
  - Secondary vertex track multiplicity
  - Track impact parameter at primary vertex
  - …
- Use orthogonal taggers to estimate efficiency, purity from data
- Extract b(c)-jet fraction vs $p_T$ etc by fitting MC derived templates
This is how it started in 2001

Today: High precision data from all RHIC and LHC experiments (out to 150 GeV)

- n.b.: A deceptively difficult measurement, as very high $p_T$ corrections (efficiency, fakes) rely on MC
- Calorimetric jet trigger can provide fake rejection
\( R_{AA} \) Mechanics

Shape and magnitude of \( R_{AA} \) depend on local “hardness” (slope) of spectrum

Harder spectrum \( \rightarrow R_{AA} \) closer to 1
My Opinion on Charged Hadron $R_{pPb}$

- NEVER skip taking high quality reference data for any physics topic you actually care about.

\[ R_{pPb} \]

- pPb jet spectra, hadron spectra and jet FF are internally consistent.

- Tension in interpolated “pp” references.
\( \hat{q} \) determined with about 35% uncertainty

Combined RHIC and LHC data:

- Test model consistency
- First hint of temperature dependence

Systematic multi-model, multi-experiment comparison: Need more!

Quantitative extraction of \( \hat{e} \) awaits more precise heavy flavor data
This is how it started in 2010

\[ A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

\( \langle A_J \rangle \) carries similar information as hadron \( R_{AA} \)

But: Wider range of theoretical tools for hadron \( R_{AA} \)

Jet quenching persists for \( p_T > 300 \text{GeV} \) jets

Many other measurements:
Jet \( R_{AA} \), Jet \( v_2 \),...
Jet Anatomy

Jets are extended objects with momentum and angular structure.

Most of momentum found close to jet axis in high $p_T$ particles ($p_T > O(10 \text{GeV})$)

Large angle component of jet contains small fraction of jet $p_T$ in soft particles ($p_T \sim O(1 \text{GeV})$)
Jet Anatomy: Many observables

Jet shapes

CMS PbPb, $\sqrt{s_{NN}} = 2.76$ TeV

$|\Delta R| = 0.2$ jets: $R = 0.3$

$|\Delta R| = 0.4$

$\Delta_{\text{Recoil}}(R=0.2)/\Delta_{\text{Recoil}}(R=0.4)$

Fragmentation functions wrt final state energy

$R_{AA}$ radius dependence

Narrowing/depletion at intermediate $r$, $p_T$

Broadening/excess at large $r$, low $p_T$

Little change at small $r$, high $p_T$

radius dependence

$\Delta_{\text{Recoil}}$ radius dependence

$\sum p_T^\text{Particle}/p_T^\text{jet}$

Radius $r$

$(\sim 2\%$ of jet energy)
Where is the “lost energy”? Use momentum-conservation to study momentum balance in the event: “Missing p$_T$”

\[ p_T^\parallel = \sum_{	ext{Tracks}} -p_T^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}}) \]

Subleading (“quenched”) jet

“lost energy” O(10GeV)

Leading jet

Distance $\Delta R$ from jet

background O(5000 GeV)

Sum over many events

Subtract this from this

background
“Lost energy” recovered at large angle, low $p_T$

Enhancement of low $p_T$ particles as a function of $\Delta R$

Larger imbalance in PbPb
Qualitative agreement with expectation:
• Mass ordering at low $p_T$
• $R_{AA}(b) \sim R_{AA}(\text{light})$ at high $p_T$

Much more to come this week from RHIC and LHC

$m_b \sim 5 \text{ GeV}$

$m_c \sim 1.5 \text{ GeV}$

n.b: s quarks are not “heavy” compared to typical QCD/QGP momentum scales

LHC Run 2: fully reconstructed B mesons

Buzatti, Gyulassy 2011
What will the future hold?
Recommendation #1:

The discoveries of the past decade have posed or sharpened questions that are central to understanding the nature, structure, and origin of the hottest liquid form of matter that the universe has ever seen. As our highest priority we recommend a program to complete the search for the critical point in the QCD phase diagram and to exploit the newly realized potential of exploring the QGP's structure at multiple length scales with jets at RHIC and LHC energies.

Part of the US nuclear physics long range planning process (btw, this might not be a bad read for new grad students)
Understanding the *nature* of QGP

QGP Microscopy

from Thomas Schaefer
Understanding the \textit{nature} of QGP

QGP Microscopy

\textit{pQCD kinetic plasma}

from Thomas Schaefer
Understanding the *nature* of QGP

QGP Microscopy

- pQCD kinetic plasma
- AdS/CFT low viscosity goo

from Thomas Schaefer
Jets as multi-scale probe

Angular and momentum structure of intra-jet parton cascade

Jets evolve in momentum and angular space

At different scales, evolution is dominated by different mechanisms:
- vacuum evolution
- (jet-constituent)-medium scattering
- in-medium cascade

Detailed understanding of jet modifications on all scales may allow to isolate interactions with “QGP quasiparticles”

Kurkela, Wiedemann, arXiv:1407.0293

Please forward detailed questions to this guy
Force Multiplier: Jets at RHIC and LHC

Future RHIC vs LHC Run 2:
- Probe different paths of QGP evolution
- Overlap in observables/kinematics

Isolate this
What could be done with **dijets in LHC Run 1** will be done with **photon-jet in LHC Run 2**
Indication of energy flow differences at RHIC vs LHC

Jets balanced when including $p_T > 0.2\text{GeV}$

Energy balance found outside of jet cone

Strong radius dependence of jet RAA

Weak radius dependence of jet RAA
Jet structure in pp and PbPb

Jesse Thaler, Boost 2014

Jet structure variables sensitive to (in-medium) shower evolution

**Critical** effort in pp highest sensitivity searches
(q/g and boosted object discrimination)

Stability vs pp pileup is major issue

Convergence of AA and pp needs

Quark/gluon discrimination in pp

Not directly applicable for g/q in AA (use $\gamma$ jet, Z+jet, b/c tag, 3-jet)

But: use QGL or similar to look jet-by-jet quenching
There is a *long* road ahead...

$$Z = \frac{p_{||}^{\text{Trk}}}{p_{\text{Jet}}}$$

- CMS-HIN-12-013
  - 0-10%/pp
  - $100 < p_T^{\text{jet}} < 300$ GeV/c
- ATLAS QM2014
  - 0-10%/60-80%
  - $p_T^{\text{jet}} > 100$ GeV/c

CMS: PRC 90 (2014) 024908
ATLAS: PLB 739 (2014) 320-342

Qualitative consistent results between CMS and ATLAS
But: Experiment-comparison suggests that we do NOT YET have sufficient control over systematics necessary for our decadal program

We’re not quite ready for detailed jet substructure data/MC comparisons

Two avenues:
- Better data and better MC
- Better observables
The importance of photon-jet correlations

Using isolated photons to tag away-side jets
- determines initial parton energy to $\approx 15\%$
- determines initial direction of the parton
- tags parton to be a light quark

Spectrum of PbPb jets is 
\textbf{suppressed} vs pp
\textit{Biased} jet selection

Sufficiently high $\gamma$ $p_T$ or sufficiently low jet $p_T$ yield \textbf{unbiased} selection of jets

\textbf{IMHO:} High stat. $\gamma$-jet data will provide qualitative breakthrough in understanding of jet modification and jet-medium interactions
Energy flow and medium response

Do we have a medium, if there’s no medium response?

Experimental and theoretical challenges:
• Strength and angular structure of medium response unknown
• Jets are correlated with the complex e-by-e flow fields through quenching
• How to distinguish medium-response from modified jet branching?

Fundamentally simpler for photon-jet events!

Ma, Wang PRL 2011

Neufeld, Vitev PRC 2012
Summary

- Rich harvest of results from RHIC and LHC
  - see much more in the next week!

- Entering the decade of Hard Probes
  - Results from STAR/PHENIX upgrades
  - Start of LHC Run 2
  - New RHIC detector (sPHENIX)

- Theory/experiment dialogue is essential
- Golden opportunity to change the field
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“Triangular flow” was invented (and named) by a grad student in late 2009 (450+ citations)
Enjoy!
(and close your g*ddamn laptops)