ELECTROWEAK PROBES OF THE INITIAL STATE

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QUARK MATTER 2017 STUDENT LECTURE
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DISCLAIMERS

• This is a student lecture, not a review
  • It’s tempting I know, but I resisted (and ran out of time!)

• Limited scope, to help students understand why we are making some of these (somewhat tricky measurements)

• Emphasis on LHC EM/electroweak, so only a passing mention of EM probes at RHIC
  • Direct photons
  • Low-mass dileptons
ACT I: WHY COLLIDE PROTONS
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- To discover new particles
  - Large masses, so only rarely produced

- At colliders, proton is used as a source of "partons"
  - Generic term for "quark and gluon" constituents
  - Structure mapped out by HERA in exquisite detail

"x" is fraction of proton momentum, as probed at scale 1/μ: most partons take a very small fraction!
PROTON-PROTON COLLISIONS AT THE LHC: A TYPICAL EVENT

Collision Event at 7 TeV

Soft particles with low $p_T < 2$ GeV

ATLAS EXPERIMENT

2010-03-30, 12:58 CEST
Run 152166, Event 316199

PROTON-PROTON COLLISIONS
AT THE LHC: A RARE EVENT

e.g. a Higgs boson candidate

Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST
A TYPICAL EVENT

diagrammatic view of a “soft” interaction between the proton constituents
“hard” interaction between the proton constituents:
large momentum exchange,
high multiplicity, complex topology.

RARE!
A single heavy ion collision event from ALICE

Pb+Pb @ \sqrt{s} = 2.76 \text{ ATeV}

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
To first order, A+A is just O(A) p+p collisions at the same time: but huge variations event-to-event
"Glauber model"

1. Generate two colliding nuclei with 3D nucleon positions chosen from measured density distributions (e$^-$ scattering)

\[
\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r - R}{a}\right)}
\]

2. Nucleons interact when transverse distance satisfies

\[
d < \sqrt{\frac{\sigma_{NN}}{\pi}}
\]

typically using the inelastic pp cross section for NN
“CENTRALITY”

Energy measured at forward angles

Convolve Glauber calculations with simple particle production models to estimate fraction of total AA cross section observed by each experiment.

Data is then divided into percentile bins:
Using only monotonicity, model allows extraction of $\langle N_{\text{part}} \rangle$, $\langle N_{\text{coll}} \rangle$, $\langle T_{AA} \rangle$ for each bin!

Miller et al, 2007

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INTERMEZZO:
HARD PROCESS RATES IN PP & AA

Rate of $X$ in pp

$$R^{pp}_X = L_{pp} \times \sigma^{pp}_X$$

Rate of $X$ in AA

$$R^{AA}_X = L_{AA} \times \sigma^{AA}_{tot} \times \langle N_{coll} \rangle \times \frac{\sigma^{pp}_X}{\sigma^{tot}_{AA}}$$

$$= L_{AA} \times \sigma^{pp}_X \times \langle N_{coll} \rangle \times \frac{\sigma^{tot}_{AA}}{\sigma^{tot}_{AA}}$$

$$= L_{AA} \times \sigma^{tot}_{AA} \times \sigma^{pp}_X \times \frac{\langle N_{coll} \rangle}{\sigma^{tot}_{AA}} = <T_{AA}>$$

"partonic luminosity"

"mean nuclear thickness"
INTERMEZZO:
THE "MASTER EQUATION" FOR AA

\[ N_X = N_{AA} \times \sigma_X^{pp} \langle T_{AA} \rangle \]

which defines "nuclear modification factor"

\[ R_{AA}^{X} = \frac{N_X}{N_{AA} \sigma_X^{pp} \langle T_{AA} \rangle} \]

Cross sections in pp, yields in AA, and thickness from calculations
(NB: if we could, we’d use $NN$ instead of $pp$ data! And we can do NN MC)
STANDARD MODEL (SM)

Still here, despite all attempts to #resist it 😎
INTERACTIONS IN THE SM

While quarks and gluons can emit $W/Z/\gamma$, they are typically unaffected by the QCD plasma: penetrating probes of the QGP!
ACT III:
ELECTROWEAK CALCULATIONS

- The standard model allows exquisitely precise calculations involving electroweak bosons, using the Feynman diagrams in the SM

- Of course, the diagrams I just showed you are only leading order
  - Quark from one proton (or neutron) & anti-quark from the other annihilate into a W, Z or photon

- Of course, life is never that easy...
The QCD corrections get complicated quickly.
**ONE MORE (CRITICAL) PIECE: PDFS**

- We mentioned before that nucleons are sources of partons: quarks and gluons

DIS measurements provide input into PDF fits (with errors!)

Lots of groups: CTEQ, MRST, GRV, NNPDF

THEY ARE ALL DIFFERENT, AND CHANGE ALL THE TIME
QCD FACTORIZATION

- One then uses the fact that QCD calculations can be written in a factorized form, where the non-perturbative physics in the structure functions is separated from the hard process cross section

\[ \sigma_{\text{hadronic}} = \sum_{ij} \int dx_1 \, dx_2 \, f_i(x_1) \, f_j(x_2) \, d\sigma_{\text{partonic}} \]

The key thing to remember: as we scan in rapidity and \( p_T \), we are changing \( x_1 \) and \( x_2 \), and exploring different regions of the PDFs!
While broad rapidity shape of Z and W production is captured by LO calculations, cross sections are underpredicted vs. NLO, and very sensitive to renormalization scale. NLO is much more stable (precise) NNLO is a noticeable change vs. NLO, but similar in magnitude (<10%): In LHC era, precision of experiment already outstrips NLO precision.
WHAT ABOUT NUCLEI?

from H. Paukkunen

DIS cross sections on nuclei do not scale w/ number of nucleons!
Various effects in different regions of Bjorken x:
(anti) shadowing & EMC effect are experimental facts:
Each non-student in this room thinks s/he understands them,
but many disagree with each other!
CHOICES OF NPDFS

- nPDFs are derived by fitting nuclear data (ratios to N or D)
  - EPS09 (most common), DSSV (more flexible), HKN07
  - These fits have their own error sets (added in quadrature to errors from PDF fits!)
- Can redo calculations including nPDF modifications to standard PDFs
  - Always ask yourself what the primary PDF is and which nPDF is modifying it!

Each modifies free nucleon structure differently: effectively different models, so important to compare them
ACT IV: EW MEASUREMENTS @ LHC

All experiments participating, including LHCb
This talk focuses on ATLAS & CMS, which are most similar
Partons lose energy traversing medium, due to:

1. **gluon radiation** (coherently if $t_{\text{form}} >$ m.f.p. $\Rightarrow L^2$)
2. **elastic scattering** (transfer of energy to medium)

Energy loss sensitive to density & coupling,
$\Rightarrow$ reduction in rate at fixed $p_T$
We are still picking out partons from the initial state, but the main products sail right through.
Collisions in Runs 1 & 2

$p+p$
- 900 GeV (2009)
- 2.76 TeV (2013)
- 5.02 TeV (2015)
- 7 TeV (2010-11)
- 8 TeV (2012)

$p+Pb$
- 5.02 TeV (2012-13)
- 8.16 TeV (2016)

$Pb+Pb$
- 2.76 TeV (2010-11)
- 5.02 TeV (2015)

Every Pb+Pb & P+Pb run has "reference" p+p run.
LHC AS A HEAVY ION COLLIDER

~0.3 µb\(^{-1}\)/day
\[ L_{\text{int}} = 2 \times 10^{25} / \text{cm}^2 \text{s} \]

~6 µb\(^{-1}\)/day
\[ L_{\text{int}} = 5 \times 10^{26} / \text{cm}^2 \text{s} \]

~30 µb\(^{-1}\)/day!
\[ L_{\text{int}} = 3 \times 10^{27} / \text{cm}^2 \text{s} \]

Huge improvements year-to-year, with a key limitation for future runs being **burn-off** from electromagnetic interactions

<table>
<thead>
<tr>
<th>RUN 1</th>
<th>RUN 2</th>
<th>RUN 3</th>
<th>RUN 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-11</td>
<td>2015-2018</td>
<td>2021-2023</td>
<td>2026-2029</td>
</tr>
<tr>
<td>0.15 nb(^{-1})</td>
<td>1 nb(^{-1})</td>
<td>10 nb(^{-1})</td>
<td>?</td>
</tr>
</tbody>
</table>
MEASUREMENTS IN ATLAS

The dashed tracks are invisible to the detector.
MEASUREMENTS IN CMS
ELECTROWEAK BOSONS FROM RUN 1

• Well measured in $p+p$
  • Among the first important standard model measurements

• Surprisingly accessible in Pb+Pb
  • Leptonic observables provide a clean channel
  • Sufficient statistics even in Run 1 for first measurements
  • Sufficient statistics/precision to see nPDF effects?

• In principle, $p+Pb$ provides an even more advantageous environment for nPDF effects
  • Asymmetric system provides opportunities
**GENERAL APPROACH FOR Z**

- **Accumulate dataset using a single- or di-lepton trigger**
  - Typically single leptons used in Pb+Pb, while dileptons used in p+p (larger rejection needed)

- **Measure opposite-sign dileptons**, with a specific kinematic selection on each muon (e.g. \( p_T > 20 \text{ GeV}, |\eta| < 2.4 \))
  - In some environments, an “isolation” criterion is imposed (track or energy flow) to reject leptons within jet.

- **Estimate backgrounds** contaminating signal region
  - Same sign leptons provide combinatoric contribution
  - MC estimates, or data-driven techniques provide other sources
  - Both are modest for Z

- **Correct for acceptance and efficiency**
  - Often performed in aggregate using a simple “bin-by-bin” correction
  - Appropriate when distributions vary slow

Then divide by \( <T_{AB}>N_{evt} \) and you can compare directly to the standard model!
p+Pb

Opposite sign backgrounds very modest, MC estimates give small contributions otherwise
Comparisons with calculations, scaled up by $\langle T_{AA} \rangle$ to data. **Pb+Pb** is not yet precise enough to decide on nPDFs. Compared to CT10 (NLO), w/ or w/o EPS09, some enhancement in the backwards direction of **p+Pb** (large $x_{pPb}$)...
CMS observes similar slight excess, also comparing to CT10 @ NLO
The same p+Pb with a new data reference (NNNNNNNNNLO?):
now the forward region (small $x_{Pb}$) looks suppressed, with some enhancement potentially remaining in backwards region
Not inconsistent w/ nPDF expectations:
a good warning be very careful with calculations!
Combined $\mu$ and e channels, fully corrected

Excess of $W^-$ in backwards hemisphere (Pb-going): well beyond EPS09. Requires weakening of assumed isospin symmetry?
Combined μ and e channels, fully corrected

NB, a noticeable discrepancy between μ and e, just in that region...
Scaling with $N_{\text{coll}}$ is equivalent to scaling with $\langle T_{AA} \rangle$: works for Z’s, works for W’s, works for photons

EW bosons provide an excellent cross check on centrality: some have even advocating using them to replace traditional centrality estimates!
Expect $Z$ yields in $p+Pb$ to scale with $<T_{ppb}>$: corrected yields do not do so (open circles)!

Two approaches to “fixing” this (if it needs it of course!)
1. Allow the NN cross section to fluctuate event by event (Alvioli et al)
2. Fix the bias accounting for the correlation of the forward ET with hard process yields

Both approaches seem to restore linearity: how to distinguish?
Run 1 statistics were good to get started, but are not enough: reasonable agreement with NLO calculations (CTEQ6.6 PDFs), but not enough precision to constrain presence of nPDFs. For photons the action in Run 2 will be in the forward region, where at least we might see isospin effects and/or EMC.
ENCORE: ULTRA-PERIPHERAL COLLISIONS

We have always assumed the two nuclei overlap.
ENCORE: ULTRA-PERIPHERAL COLLISIONS

But what if they miss?
ENCORE: ULTRA-PERIPHERAL COLLISIONS

Strong EM fields, highly contracted: quasi-real photons
**ULTRA-PERIPHERAL PHYSICS @ LHC**

**Photon-pomeron:**
production of vector mesons
(sensitivity to nPDF)

**Photo-nuclear:**
jet photoproduction
(probe nPDF directly)

**Photon-photon:**
dilepton production
(& other exclusive states)

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You are also working at a photon collider: use it!
Beautiful (challenging) data combined from ALICE and CMS: events with nothing else but a J/psi.
Also providing information on nuclear gluon distributions
EXCLUSIVE DIMUON EVENT

$M_{\mu\mu} = 173$ GeV

Run: 287038
Event: 71765109
2015-11-30 23:20:10 CST

Dimuons UPC Pb+Pb 5.02 TeV
STARLIGHT MC implements collisions of Weisacker-Williams quasi-real photons + QED $\mu^\pm$ production:
good agreement with ATLAS (Run 2) & ALICE (Run 1) data
Already helping to calibrate incoming photon flux for $\gamma+A$ and $Lb+L$
CONCLUSIONS

• EW probes produced by partonic interactions are a great tool for studying several aspects of HI collisions
  • Informing our understanding of the initial nPDFs
  • Validating Glauber geometric pictures
  • The LHC provides great variety and kinematic reach
  • Rich program at RHIC as well, at lower $p_T$ scales

• The nuclei themselves provide EM probes
  • Photon-pomeron, photon-photon, photon-nuclear
  • Pioneered at RHIC, but now getting more and more interest (including from HEP side)

ENJOY QM2017!
**PHOTON PURITY ESTIMATE ("ABCD")**

"Nontight" (failing one of 4 ID cuts)

Tight ID

R=0.3 isolation $E_T$

$$A = \frac{BC}{D}$$

Assumes axes are uncorrelated for background candidates

$$N_{\text{sig}} = N_A - R_{\text{bkg}} \frac{(N_B - c_B N_{\text{sig}})(N_C - c_C N_{\text{sig}})}{N_D - c_D N_{\text{sig}}}$$

$$P = 1 - \frac{N_{\text{sig}}}{N_A}$$

>95% @ $p_T=100$ GeV for pp

>80-85% for Pb+Pb
PHOTON ID IN ATLAS

ATLAS photon ID uses full capabilities of calorimeter:
1. Narrow cluster in EM cal. 2nd layer (most of energy)
2. No energy leakage behind EM section
3. Shower shape inconsistent with diphoton hadron decay

Calorimeter cells corrected for UE in Pb+Pb, including $v_2$
using algorithm similar to what is used for ATLAS jets
**PHOTON ISOLATION DISTRIBUTIONS**

Isolation criterion based on $E_T$ of cells in $R=0.3$ cone, after subtracting core region, and shower leakage correction. $E_T<6$ GeV in Pb+Pb (approx 1-sigma, due to UE fluctuations)
STARLIGHT calculations only include pure $\mu^+\mu^-$, w/ no final state QED. Clearly required in $e^+e^- \rightarrow \mu^+\mu^-$, e.g. from DESY. Not easily available in existing MC codes: exploring several avenues