High-$p_T$ probes of excited nuclear medium in the LHC era

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LHC RUN I  2010-2013

\begin{align*}
p + p & \quad \sqrt{s} = 0.9, \ 2.76, \ 7.0, \ 8.0 \text{ TeV} \\
p + Pb & \quad \sqrt{s_{NN}} = 5.02 \text{ TeV} \\
Pb + Pb & \quad \sqrt{s_{NN}} = 2.76 \text{ TeV}
\end{align*}

- Circular tunnel 27 km in circumference (old LEP). 25 ns bunch spacing \( \Rightarrow \) 2835 bunches with \( 10^{11} \) p/bunch
- Design Luminosity: \( 10^{34} \text{ cm}^{-2}\text{s}^{-1} \Rightarrow 100 \text{ fb}^{-1}/\text{year} \), Stored energy/beam: 350 MJ, \( \sqrt{s} \) up to 14 TeV
1\textsuperscript{st} Rutherford scattering

High transverse momentum physics always played an important role when probing the structure of matter.

High-\(p_T\) actually invented in 1906 by Sir Rutherford. He studied the scattering of \(\alpha\) and \(\beta\) radiation on thin sheet of mica \textit{[Phil. Mag. 12, 134 (1906)]} and observed a rare but violent scattering of \(\alpha\) particles.

Rutherford remarked about this observation:

\textit{“It was as if one had fired a large naval shell at a piece of tissue paper and it had bounced back.”}

\textbullet\textsuperscript{\textup{Nuclear Physics.}}

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{Rutherford}} = \frac{\alpha^2}{4E^2 \sin^4 \left( \frac{\theta}{2} \right)}
\]

Note power \(n = 4\)
Limited transverse momentum

1971 CERN Intersecting Storage Rings (ISR), $\sqrt{s} \sim 20-60$ GeV

$p_T$ pseudorapidity $\eta$

Soft particle production - “longitudinal phase space” – dominant effect when increasing $\sqrt{s}$.


“Simple expressions for the fluxes of secondaries produced by protons colliding either with another proton beam (ISR) or with a proton at rest are derived using the general empirical properties of strong interactions."

$$\frac{df (p_T)}{dp_T} = \frac{p_T}{b^2} e^{-p_T/b} \quad \text{with} \quad b \sim 1/6 \quad \langle p_T \rangle = 2b \approx 0.33 \text{ GeV/c}$$
Early ISR era

The mean transverse momentum as a function of $\sqrt{s}$ scales.

\[ \langle p_T \rangle \text{ GeV/c} \]

\[ \sqrt{s} \text{ GeV} \]

The independency of $\langle p_T \rangle$ on $\sqrt{s}$ indicates the fundamental scale in the problem $\frac{\hbar c}{\langle p_T \rangle} \approx 0.6 \text{ fm}$, proton transverse size $\Rightarrow$

Landau: Hydrodynamical Model of Particle production

For an overview see: Phys.Rev., 1973, D8, 859-874
Why there were some people were studying “high-$p_T$” physics in the 1960’s?

They were looking for a ‘left handed’ intermediate boson $W^\pm$, the proposed carrier of the weak interaction [T. D. Lee and C.-N. Yang, PRL. 4, 307 (1960)]

The $W^\pm$ would be visible above the background as a peak at lepton transverse momentum

$$p_T^e \geq \frac{1}{2} M_W$$

Cocconi: $$\frac{dN}{dp_T} \approx e^{-p_T/b}$$

In the mean time: discovery of DIS at SLAC

Stanford Linear Accelerator Center (SLAC)  
electron beams up to 20 GeV.

First results in 1968 – discovery of DIS.

- Around \( q^2 \sim 1 \text{ GeV}/c \) elastic and inelastic  
cross sections are about equal.

- Above \( q^2 \sim 1 \text{ GeV}/c \)  \( \sigma_{el} \) drops  
significantly whereas  \( \sigma_{inel} \) remains  
approx const.

1) Mott, helicity cons.

\[
\left( \frac{d\sigma}{dQ^2} \right)_{\text{Mott}} = \frac{4\pi\alpha^2}{Q^4} \cos^2 \frac{\theta}{2}
\]

2) Inelastic, spin-\( \frac{1}{2} \), recoil  \( E'/E \) and magnetic term

\[
\frac{d^2\sigma}{dQ^2d\nu} = \frac{4\pi\alpha^2}{Q^4} \frac{E'}{E} \left[ W_2 \cos^2(\theta/2) + 2W_1 \sin^2(\theta/2) \right]
\]

2\textsuperscript{nd} : Discovery of Hard Scattering in p+p collisions

At the same time:
CERN-ISR breaking of $e^{-6 p_T}$

Discovery of high-$p_T$ production in p-p
  - Due to the point-like constituent (parton).
  - No scale (point-like) $\rightarrow$ conformal theory
  - Beginning of scaling era $\rightarrow$ QCD

\[ \text{Rutherford scatt.} \]

\[ \text{Power law:} \quad \frac{dN}{dp_T} \approx p_T^{-n} \]

\[ \text{Cocconi:} \quad \frac{dN}{dp_T} \approx e^{-p_T/b} \]


8/4/14
Birth of QCD

There were 4 key experimental observations that made the composite theory of hadrons believable

1. discovery of point-like constituents in DIS
2. complementary discovery of dilepton production in p+A collisions
   Drell-Yan annihilation \( q + \bar{q} \rightarrow \mu^+ + \mu^- \)
3. observation of enhanced particle production at large \( p_T \) in p-p collisions at ISR in experiments searching for single \( e^\pm \) from the \( W^\pm \) decays.
4. the observation of the \( J/\psi \) at BNL-AGS and SLAC.

These discoveries turned Gell-Mann and Zweig’s quarks from mere mathematical concepts to the fundamental constituents of matter \( \Rightarrow \) QCD.

High-\( p_T \) sector \( \Rightarrow \) pQCD
$p + p \rightarrow a + X$ kinematics is completely fixed by the two dimensional quantities $s$ and $p_T$ and two angles $\phi$ and $\vartheta$.

Dims of the invariant xsection

$[\sigma] = \text{GeV}^{-2}$ and $E \frac{d^3 \sigma}{d^3 p} = \text{GeV}^{-4}$

Any combination of $p_T$, $s$ or $x_T$ preserving dimensions yields

$$E \frac{d^3 \sigma}{d^3 p} = \frac{p_T^4}{s^4} g(x_T, \vartheta) = \frac{p_T^4}{256} \frac{x_T^8}{p_T^8} g(x_T, \vartheta) = \frac{1}{p_T^4} g(x_T, \vartheta)$$

Conformal limit $E \frac{d^3 \sigma}{d^3 p} \propto \frac{1}{p_T^4}$ or $\frac{1}{\sqrt{s}} g(x_T, \vartheta)$

LO QED-like vector boson exchange (glue, $\gamma$) ⇒ power low $p_T^{-n}$ with $n = 4$

$g(x_T, \vartheta)$ universal $\sqrt{s}$ independent function

$x_T \equiv 2p_T / \sqrt{s}$ rel. $p_T$ wrt. beam mom $\sqrt{s} / 2$

However

- Running $\alpha(Q^2)$
- PDF and FF scaling violation
- $k_T$ smearing and higher-twist phenom.

$n^{++} \rightarrow n \left(x_T, \sqrt{s} \right)$
Relativistic Heavy Ion Collider

RHIC – first Heavy Ion Collider
Brookhaven Nat. Lab

$\sqrt{s} = 500 \text{ GeV}$ p-p polarized

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

Low $p_T \sim e^{-a \cdot p_T}$ $a = 5.56 \pm 0.02 \text{ (GeV/c)}^{-1}$

High $p_T \sim p^{-n_T}$ $n = 8.10 \pm 0.05$ at $p_T > 4 \text{ GeV/c}$

Better than 30% agreement to NLO

PHENIX; Phys. Rev., 2007, C76, 034904
Inclusive charged distributions (INEL)

\[ n = 6.63 \pm 0.12 \pm 0.01 \]

Power low fit (3-10 GeV/c):

\[ \frac{1}{N_{\text{evt}}} \frac{1}{(2\pi p_T)} \left( \frac{d^2N_{\text{ch}}}{d\eta dp_T} \right) (\text{GeV/c})^2 \]

**Phys. Lett., 2010, B693, 53-68**


**ALICE**
High-$p_T$ region $\rightarrow x_T$ scaling

No scale $E \frac{d^3 \sigma}{d^3 p} \propto \frac{1}{\sqrt{s}^{n++}} g(x_T)$

The ratio of $E \frac{d^3 \sigma}{d^3 p}$ at two different $\sqrt{s_1}$ and $\sqrt{s_2}$

$g(x_T)$ cancels out

$$\left( \frac{\sqrt{s_1}}{\sqrt{s_2}} \right)^n (x_T, \sqrt{s}) = \frac{E \frac{d^3 \sigma}{d^3 p}(x_T, \sqrt{s_2})}{E \frac{d^3 \sigma}{d^3 p}(x_T, \sqrt{s_1})} \Rightarrow$$

$$\Rightarrow n_{\text{eff}}(x_T) = -\frac{\ln\left( d\sigma^{\text{inv}}(x_T, \sqrt{s_1}) / d\sigma^{\text{inv}}(x_T, \sqrt{s_2}) \right)}{\ln(\sqrt{s_1} / \sqrt{s_2})}$$

Prediction Arleo, Brodsky et. al. based on higher-twist dynamics. No room to discuss.


Nucl. Phys., 2011, A855, 461-464
$E \frac{d^3 \sigma}{d^3 p} \propto \frac{1}{\sqrt{s}} g(\frac{2p_T}{\sqrt{s}})$

$n = 4.9$ almost at conformal limit

"universal" $g(x_T)$

$g(x_T, \theta)$ scaled empirically $(\sqrt{s})^{4.9}$

Scaling holds in $\sqrt{s} = 0.2-7$ TeV!

Factor of 2 deviation from NLO

*JHEP, 2011, 1108, 086*
NLO doesn’t work at LHC?

\[ \pi^0 @ \sqrt{s} = 7 \text{ TeV} \]

\[ \pi^0 @ \sqrt{s} = 0.9 \text{ TeV} \]

\[ \eta @ \sqrt{s} = 7 \text{ TeV} \]

Identified particles even worse. NLO discrepancies factor >3!
RHIC better then 30%!
NLO doesn’t work at LHC?

Suspect: too-hard gluon-to-hadron FFs as the probable source of the problem,

Justify the need to refit the FFs using the available LHC and Tevatron data in a region of transverse momenta, $p_T > 10$ GeV/c,
Unitarity in pQCD

pQCD (mini)jet production x-section is larger than total inelastic $p$-$p$ x-section for $p_{T_{\text{min}}} \sim 5-7$ GeV at the LHC!


DGLAP PDF evolution

Possible solutions:

– Multi Parton Interaction
– Saturation - Color Glass Condensate – Larry MCLERRAN Thursday July 31st

$\sigma_{\text{hard}} > \sigma_{\text{inel}}$ at $p_T \sim 5-7$ GeV

[ H. Jung et al, arXiv:1209.6265]
high-$p_T$ spectrum components in $p$-$p$

**High-$p_T$ (hard) region**
- Power law exponent at LHC $h^\pm$
  - almost at the conformal limit $n=4.9$
- Old good $x_T$ scaling holds.
- $p$QCD NLO seems to have more difficulties with increasing $\sqrt{s}$?
- And violates the unitarity.

**Low-$p_T$ (soft) region**
- Exponential $\sim \exp(-6p_T)$ holds not only in $p$-$p$ but in DIS or $e^+e^-$ annihilation.
- Origin remains mysterious.

Maybe due to the: “effective event horizon introduced by the confining string, in analogy to the Hawking-Unruh effect”

[Kharzeev at. al. arXiv:1407.4087]
Relativistic Heavy Ion Collisions

- Two discoveries based on the analysis of the high-p_T tail already discussed.
- The next discovery came from the analysis of the high-p_T yield in A-A collisions.

\[ R_{AA}(p_T) = \frac{d^2N^{AA}}{dp_Td\eta} \langle N_{binary} \rangle d^2N^{pp} / dp_Td\eta \]
RHIC $\sqrt{s} = 200 \, \pi^0$ and $h^+ + h^-$ data

1. Strong suppression (x5) in central Au+Au coll.
2. No suppression in peripheral Au+Au coll.
3. No suppression (Cronin enhancement) in control d+Au exp.

Convincing evidence for the deconfined nuclear matter
The question at RHIC: is the $R_{AA}(p_T)$ const or rising with $p_T$?

The question at LHC: does $R_{AA}(p_T)$ grow saturates or turn down?
Dipole picture

Let me pick one:
And see Boris’s talk on Saturday Aug. 2nd

• Dipole survives even in a dense medium due to color transparency.
• However the dipole is expanding enhancing attenuation. At higher \( p_T \) expansion is Lorentz-delayed so transparency must rise with \( p_T \).
• According this picture the \( R_{AA} \) rises due to the color transparency.

Vacuum + induced energy loss

Solid lines includes an initial state interactions in nuclear collisions.

\[ R_{AA} \text{ rises due to the color transparency.} \]
39 to 2760 GeV from RHIC to LHC!


PhD of N. Novitzky.

$R_{AA}$ compared to
- pQCD MC
- GLV model
- Dipole model

Quantum Coherence in action?
Summary

High-\(p_T\) in proton-proton collisions

– Conformal limit \(n=4\) almost reached in \(h^\pm\) production at LHC.
– NLO pQCD has increasing difficulties with rising \(\sqrt{s}\).
– pQCD unitarity violation waiting for satisfactory resolution.

High-\(p_T\) in Heavy Ion collisions

– Deconfined nuclear medium clearly seen in the jet suppression.
– The features of \(R_{AA}\) at high-\(p_T\) very interesting program for LHC run-2.
– Color transparency and coherence in action?
backups
Large Transverse Momentum – Hard scattering

“Hard” means large momentum transfer, either

– a violent scatter or
– creation of a system of large mass

Hard scattering

– Exchange of colors
– Interaction of point-like constituents (q or g)

\[ M_{\text{inv}} = \sqrt{x_1 x_2 \sqrt{s}} \]

HS probes the virtual field
In 1971 the CERN Intersecting Storage Rings (ISR), being the first hadron-hadron collider, became operational. With $\sqrt{s} \sim 20$–$60$ GeV it was supposed to be a “next generation” as compared to the fixed target machine at Fermilab.
The physics aims of the LHC project are:

- to discover crucial missing elements of the Standard Model, namely the Higgs boson,
- search for possible new fundamental interactions,
- search for possible generations of quarks or leptons,
- search for particles responsible for the Dark Matter in the Universe
- explore the Quantum ChromoDynamics phases of matter in the Ultra-Relativistic Heavy Ion Collision (URHIC).

\[
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