Drell-Yan physics at the LHC

from theory to phenomenology

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“...our original crude fit did not even remotely resemble the data. Sid and I went ahead to publish our paper because of the model’s simplicity ... It is gratifying to see that ... the QCD improved version has been confirmed by the experiments carried out in the last 28 years.”

T-M Yan, at Drell Fest, July 31, 1998, SLAC

Drell Yan Physics Workshop, Trento
May 22th, 2012
Outline

Drell–Yan as an important tool for precision physics at the LHC

• motivation for DY studies at the LHC
• sources of uncertainties and theoretical challenges
• precision SM tests and the potential New Physics searches in DY–like processes

DY theory implications specific for the LHC physics

• QCD–improved Parton Model at small–x and uncertainties
• issues of the forward DY and saturation phenomenon
• TMD (kt) factorisation implications at the LHC (cursory, many talks here)
• EW/QCD corrections, large EW (Sudakov) logs, tools development
• color dipole approach for DY (pedagogical overview)
• Semi–inclusive/diffractive DY and Regge factorisation breaking
• still open issues…

Latest results from the LHC measurements

• ATLAS, CMS (cursory, next talk by I. Belotelov), LHCb
• Future prospects

Summary and Outlook
First di-muon measurements at ATLAS

Vast area of Drell–Yan physics has been opened up at the LHC!

+ photon-initiated DY continuum…
Physics motivation for DY studies at the LHC

At the LHC, both CC/NC DY reactions are of major importance for:

• extraction of PDFs in extended kinematics regions (high sensitivity to PDFs)
• best access to antiquark sea PDFs
• luminosity monitoring
• calibration of detectors (as “standard candles” for both Tevatron/LHC)
• the most precise ever definition of the W mass/width (CC from transverse mass)
• high precision SM tests (e.g. for Higgs physics)
• potential source of (or background for) many New Physics contributions (e.g. contact, 4–fermion interactions, extra W` and Z`, “unparticles” etc)
• we need unpolarised DY measurements from the LHC to use their results in later polarised DY experiments (e.g. will be useful for RHIC spin physics)

Why?

- rather large cross sections (statistics) expected
  - \( \sigma(W) = 30 \text{ nb} \), i.e. \( 3 \times 10^8 \) events with \( \mathcal{L} = 10 \text{ fb}^{-1} \)
  - \( \sigma(Z) = 3.5 \text{ nb} \), i.e. \( 3.5 \times 10^7 \) events with \( \mathcal{L} = 10 \text{ fb}^{-1} \)
- clear experimental signature (efficient for high \( p_{\perp} \) leptons pair or lepton+missing \( p_{\perp} \) typically looking for \( p_{\perp} > 25 \text{ GeV} \) in the central detector)
- no uncertainties from fragmentation functions
Overview of theoretical uncertainties

Are we ready to provide an adequately accurate theoretical description of Drell-Yan processes at LHC?

Experimental accuracy aimed at the LHC for inclusive DY observables is 1%.

In order to provide a reliable accuracy for LHC data analysis, theoretical models have to reach at most 0.3% of accuracy → a serious challenge for theory!

Sources for theoretical uncertainties in DY processes (dependent on kinematics!):

- QCD contributions in LO, NLO and NNLO (at small x/scales);
- parton shower and hadronisation effects (e.g. by PYTHIA or HERWIG);
- one-loop (or higher) EW corrections;
- resumed major higher order contributions;
- an interplay of QCD and EW corrections (HO matching issue);
- saturation effects (due to non-linear dynamics in gluon field evolution);
- partonic energy loss in cold nuclear matter (DY in pA collisions);
- couplings, hadronic vacuum polarisation, PDFs and other tuned inputs.
DY results from collinear factorisation

DY reaction is among a few hadron–hadron processes in which the collinear factorisation theorem has been rigorously proven (basics by Collins, Soper, Sterman’82–88)

Result known up to NNLO!

**Matrix element**

**LO**

\[ \gamma^*, W^\pm, Z \]

**NLO (very important at high qT)**

**Parton Model results**

\[
\frac{d^2 \sigma^{LO}}{dM^2 \, dx_F} = \frac{4\pi \alpha^2_{em}}{3N_c M^4} \frac{x_1 x_2}{x_1 + x_2} \sum_f c_f^2 \left\{ q_f(x_1, M^2) \overline{q}_f(x_2, M^2) + \overline{q}_f(x_1, M^2) q_f(x_2, M^2) \right\}
\]

**in LO**

\[
(x_1 p + x_2 \overline{p})^2 = M^2 \]

\[
x_1 = \frac{1}{2} \left( \sqrt{x_F^2 + 4\tau} + x_F \right), \quad x_2 = \frac{1}{2} \left( \sqrt{x_F^2 + 4\tau} - x_F \right), \quad x_F = x_1 - x_2
\]

**the hard scale**

\[
\mu^2 = M^2
\]

\[
\frac{d^2 \sigma^{NLO}}{dM^2 \, dx_F} = \frac{4\pi \alpha^2_{em}}{3N_c M^4} \frac{\alpha_s(M^2)}{2\pi} \int_{z_{min}}^1 dz \frac{x_1 x_2}{x_1 + x_2} \sum_f c_f^2 \left\{ q_f(x_1, M^2) \overline{q}_f(x_2, M^2) D_q(z) + g(x_1, M^2) \left[ q_f(x_2, M^2) + \overline{q}_f(x_2, M^2) \right] D_g(z) + (x_1 \leftrightarrow x_2) \right\}
\]

**in NLO**

\[
x_1 = \frac{1}{2} \left( \sqrt{x_F^2 + 4(\tau/z)} + x_F \right), \quad x_2 = \frac{1}{2} \left( \sqrt{x_F^2 + 4(\tau/z)} - x_F \right), \quad z > z_{min} = \frac{\tau}{(1 - x_F)}
\]

**Of special importance at the LHC (small-x)!**

**e.g.** Altarelli et al ’78–79
Role of the HO QCD corrections to NC DY at the LHC

For more details, see Roeck, Thorne "Structure Functions", arXiv:1103.0555
**Importance of EW corrections and QED-Improved PDFs**

Jet-production ($|\eta| < 2.5$)

$$\delta \equiv \frac{\text{NLO-LO}}{\text{LO}}$$

**NLO EW effect**

\[ \sqrt{s} = 14000 \text{ GeV (LO)} \]

- solid: CTEQ6L1
- dashed: CTEQ6L
- dotted: CTEQ6M

**Moretti'06**

At high scales $\alpha \sim \alpha_S^2$

EW corrections can be as large as NNLO QCD ones!

Large EW logs may affect the extraction of PDFs, so they must be carefully treated!

**photons-induced Drell-Yan:**

The simplest way: QED-improved DGLAP evolution, e.g. at LO

\[
\frac{\partial q_i(x, \mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{qq}(y) \ q_i\left(\frac{x}{y}, \mu^2\right) + P_{qg}(y, \alpha_S) \ g\left(\frac{x}{y}, \mu^2\right) \right\}
\]

\[
+ \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left\{ \tilde{P}_{qq}(y) \ e_i^2 q_i\left(\frac{x}{y}, \mu^2\right) + P_{T\gamma}(y) \ e_i^2 \gamma\left(\frac{x}{y}, \mu^2\right) \right\}
\]

\[
\frac{\partial \gamma(x, \mu^2)}{\partial \log \mu^2} = \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{\gamma q}(y) \ \sum_i e_i^2 q_i\left(\frac{x}{y}, \mu^2\right) + P_{\gamma\gamma}(y) \ \gamma\left(\frac{x}{y}, \mu^2\right) \right\}
\]

\[
\int_0^1 dx \ x \left\{ \sum_i q_i(x, \mu^2) + g(x, \mu^2) + \gamma(x, \mu^2) \right\} = 1
\]

Real/virtual contributions of the all gauge bosons to the initial/final states is necessary at the LHC!
Sensitivity of predictions for the LHC to PDFs

NLO W and Z cross sections at the LHC ($\sqrt{s} = 7 \text{ TeV}$)

- Plots by G. Watt, PDF4LHC benchmark meeting, CERN 2010

- Probing valence at small-$x$

- Probing intrinsic charm

- Ubiali et al'10

PDF4LHC benchmarks - LHC 7 TeV

- CTEQ6.6
- NNPDF2.0
- MSTW08

$\alpha_s = 0.118$  $\alpha_s = 0.119$  $\alpha_s = 0.119$  $\alpha_s = 0.120$
ATLAS DY data vs theory: total DY CS in electron channel

Predictions reflect PDF uncertainties only!

Uncertainty from luminosity is neglected!

Plots by J. Hartert, CERN-THESIS-2011-186
ATLAS DY data vs theory: electron rapidity distributions

Plots by J. Hartert, CERN-THESIS-2011-186

Allow to make a preliminary discrimination of PDF models

W charge asymmetry
ATLAS DY combined muon/electron data

\[ \sigma / \Delta \eta | L [pb] \]

\[ W^+ \]

66 < m_{ll} < 116 GeV

\[ \sigma_{Z} \times Br(\gamma^{*} \rightarrow ll) [nb] \]

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

arXiv: 1109.5141

MSTW2008 NNLO

68\% CL PDF uncertainty

arXiv: 1109.5141

Data 2010 (\(\sqrt{s} = 7\) TeV)

Data 2010 (\(\sqrt{s} = 7\) TeV)

arXiv: 1109.5141
qT distribution of DY leptons at the LHC: the neutral current

The DY cross section at fixed-order PT can be reliable only for $q_T \sim M_\nu$

However, at $q_T \to 0$, $\alpha^n_S \log^m(M^2/q_T^2) \gg 1$
the resummation of large logs is necessary!

Methods developed in many papers so far!

See e.g. Bozzi, Catani, de Florian, Ferrera, Grazzini, arXiv: 1007.2351 and refs. therein

more details and references in the talk by Giancarlo Ferrera at Moriond 2012
qT distribution of DY leptons at the LHC: the charged current

Based on qT–resummation with leptonic variables dependence

**DYNNLO code**

Ref. Catani, Cieri, de Florian, Ferrera, Grazzini’09

**Simulations for the LHC!**

Lepton transverse momentum spectrum from $W^+$ decay (very important for precision $W$-mass Measurement at the LHC!)

**ATLAS data vs. NNLL+NLO predictions!**

**NNLL+NLO vs. NNLO predictions!**

more details and references in the talk by Giancarlo Ferrera at Moriond 2012
Forward DY physics at LHCb: first results

New DY kinematics coverage (low x, large Q)!

$\rho_T > 10$ GeV muon
- 2010 dataset
  - 37.7 pb$^{-1}$
  - $\sqrt{s} = 7$ TeV
- 2011 dataset
  - 1.0 fb$^{-1}$
  - $\sqrt{s} = 7$ TeV
- 2012 dataset
  - 1.5 fb$^{-1}$
  - $\sqrt{s} = 8$ TeV

Good agreement with NNLO predictions so far!

huge uncertainties in the forward!

more details e.g. in the talk by Philip Ilten, at Phenomenology 2012, Pittsburgh
EWSB tests with DY: latest $W'$ exclusion limits

Takes into account a possible Interference $W'$ and SM $W$!

CMS Collaboration,
CERN-PH-EP/2012-103
2012/04/24
Why to go beyond collinear factorisation?

- **Transverse spin physics:**
  present understanding requires spin-correlated transverse momentum in distribution functions (Sivers effect) and fragmentation functions (Collins effect). Most important motivation for polarized fixed-target experiments with LHC beams (see Brodsky et al’12)
  Many talks about spin physics here!

- **Small-x physics:**
  the gluon density cannot continue its growth as $x \rightarrow 0$ (unitarity violation). Small-x physics is the major focus of the LHC DY. One can probe the universality of TMDs at small-x and non-linear effects (e.g. gluon recombination/saturation phenomena). Semi-inclusive and diffractive Drell-Yan are the most sensitive to these phenomena observables!

Linear/non-linear BK evolution is likely to be tested at the LHC!

\[ \tau = \ln(1/x) \]

Iancu, Venugopalan
hep-ph/0303204
Color dipole framework for forward (small-\(x_2\)) DY

Proposed and initially developed by


Motivation:

- best for forward dilepton rapidities
- access to large-\(x\) valence/sea antiquark distributions
- incorporates higher-twist effects due to multiple scattering of a dipole off target
- at high energies, one of the incoming partons has very small \(x\) probing dense gluonic fields in the target (difficult or impossible to incorporate in QCD parton evolution)

Higher-powers \(Q_s(x)^2/M^2\) (HT) become important (for not very large \(M\))

At LHC \(x\) can be as low as \(10^{-6}\) for low mass DY

One of the main interest for the QCD studies at the LHC!

The dipole approach is a promising attempt to account for saturation

Note: LHCb has unique opportunities for tests of higher twist effects!

1. High purities/efficiencies down to \(M_{\mu\mu}=2.5\text{GeV}\)
2. High rapidities coverage \(2.5 < \eta < 4.9\)
The color dipole approach for DY: pedagogical overview

In this frame, in the high energy limit, the DY cross section can be given in terms of the dipole cross section (similarly to DIS)

Cross section of the dilepton production in quark–target scattering:

\[ d^8 \sigma(qN \rightarrow q\ell^+\ell^- X) = \sum_X \sum_{\lambda\lambda'} \varepsilon^{*}_\lambda(\lambda)\varepsilon_\nu(\lambda')M^{\mu\nu} \frac{d\alpha d^2q_\perp d^2p_{f\perp}}{(2\pi)^5 8(p_i^0)^2\alpha(1-\alpha)} \]

\[ \times \alpha_{em} \varepsilon_\lambda(\lambda)\varepsilon^{*}_\rho(\lambda')L^{\rho\kappa} \frac{dM^2d\Omega}{16\pi^2M^4} \]

\[ \lambda \in \{\pm 1, 0\} \]

Spin–color averaged ME squared (hadronic part):

\[ \overline{M}^{\mu\nu} = \frac{1}{2} \sum_{\sigma_f \sigma_i} \frac{1}{N_c} \sum_{c_f c_i} (M^{\mu}_s + M^{\mu}_u)(M^{*\nu}_s + M^{*\nu}_u) \]

Leptonic tensor:

\[ L^{\mu\nu} = 4(p^{\mu}_l+p^{\nu}_l-\gamma^{\mu}_p p^{\nu}_l - g^{\mu\nu} p_l p_l^-) \]

Solid angle of the leptonic pair can be integrated out

\[ d\Omega = d\phi d(\cos \theta) \]

\[ \frac{d^4 \sigma(qN \rightarrow \ell^+\ell^- X)}{d\ln \alpha dM^2 d^2q_\perp} = \frac{\alpha_{em}}{3\pi M^2} \left\{ \frac{d^3 \sigma_T(qN \rightarrow \gamma^* X)}{d \ln \alpha d^2q_\perp} + \frac{d^3 \sigma_L(qN \rightarrow \gamma^* X)}{d \ln \alpha d^2q_\perp} \right\} \]
Wave function of the forward photon radiation

Photon polarisations contributions

\[ \frac{d^3\sigma_T(qN \rightarrow \gamma^* X)}{d\ln\alpha d^2q_{\perp}} = \int d^2p_f \sum_x \sum_{\lambda \in \{\pm 1\}} \frac{\epsilon^*_\mu(\lambda)\epsilon_\nu(\lambda)\mathcal{M}^{\mu\nu}}{(2\pi)^5 8(p_f^0)^2 (1 - \alpha)} \]

\[ \frac{d^3\sigma_T(qN \rightarrow \gamma^* X)}{d\ln\alpha d^2q_{\perp}} = \int d^2p_f \sum_x \frac{\epsilon^*_\mu(\lambda = 0)\epsilon_\nu(\lambda = 0)\mathcal{M}^{\mu\nu}}{(2\pi)^5 8(p_f^0)^2 (1 - \alpha)} \]

Can be dropped in the high energy limit!

The s-channel amplitude:

\[ i\mathcal{M}_s^\mu = e \sum_\sigma \frac{\bar{u}_{\sigma_f}(p_f)\gamma^\mu u_\sigma(p_f + q)}{(p_f + q)^2 - m_f^2} \] 

\[ t_{q,\sigma_\sigma_i}((p_f^0 + q^0), \vec{k}_{\perp}) = \bar{u}_\sigma(p_f + q)\gamma^0 V_q(\vec{k}_{\perp}) u_{\sigma_i}(p_i) \approx 2p_i^0 \delta_{\sigma,\sigma_i} V_q(\vec{k}_{\perp}) \]

where the quark-nucleon scattering amplitude is

In impact parameter space, we get

\[ \tilde{\mathcal{M}}_s^\mu(\vec{b}, \vec{\rho}) = \int \frac{d^2l_{\perp} d^2k_{\perp}}{(2\pi)^4} e^{-i\vec{l}_{\perp} \cdot \alpha \vec{\rho} - i\vec{k}_{\perp} \cdot \vec{b}} \mathcal{M}_s^\mu(\vec{l}_{\perp}, \vec{k}_{\perp}) \]

\[ \tilde{\mathcal{M}}_s^\mu(\vec{b}, \vec{\rho}) = -i\sqrt{\frac{4\pi}{\alpha^2}} \Psi_{\gamma^* q}(\alpha, \vec{\rho}) 2p_i^0 \tilde{V}_q(\vec{b}), \quad \tilde{V}_q(\vec{b}) = \int \frac{d^2k_{\perp}}{(2\pi)^2} e^{-i\vec{k}_{\perp} \cdot \vec{b}} V_q(\vec{k}_{\perp}) \]

The LC wave-function of gamma radiation!

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The LC wave-function of gamma radiation!
DY in quark-target scattering

The propagators can be transformed as

\[
\frac{1}{(p_f + q)^2 - m_f^2} = \frac{\alpha(1 - \alpha)}{\alpha^2 l_\perp^2 + \eta^2} \quad \frac{1}{(p_i - q)^2 - m_i^2} = -\frac{\alpha}{\alpha^2 (l_\perp + k_\perp)^2 + \eta^2}
\]

\[
\eta^2 = (1 - \alpha) M^2 + \alpha^2 m_f^2
\]

The DY cross section in quark-hadron scattering then is

\[
\frac{d^3 \sigma_{T,L}(qN \rightarrow \gamma^* X)}{d \ln \alpha d^2 q_\perp} = \frac{1}{(2\pi)^2} \int d^2 \rho_1 d^2 \rho_2 e^{i \vec{q} \cdot (\vec{p}_1 - \vec{p}_2)} \Psi_{\gamma^*_q}^T, L(\alpha, \vec{p}_1) \Psi_{\gamma^*_q}^{T, L}(\alpha, \vec{p}_2)
\]

\[
\times \frac{1}{2} \left\{ \sigma_{qq}^N(\alpha \rho_1) + \sigma_{qq}^N(\alpha \rho_2) - \sigma_{qq}^N(\alpha (\vec{p}_1 - \vec{p}_2)) \right\}.
\]

... or integrated over photon momentum

in terms of the LC wave functions

\[
\Psi_{\gamma^*_q}^T(\alpha, \vec{p}_1) \Psi_{\gamma^*_q}^{* T}(\alpha, \vec{p}_2) = \sum_{\lambda=\pm 1} \frac{1}{2} \sum_{\sigma_f \sigma_i} \epsilon^*_\mu(\lambda) \Psi_{\gamma^*_q}^{\mu}(\alpha, \vec{p}_1) \epsilon_{\mu}(\lambda) \Psi_{\gamma^*_q}^{\mu}(\alpha, \vec{p}_2)
\]

\[
= \frac{\alpha_{em}}{2\pi^2} \left\{ \frac{m_f^2}{\pi^2} \alpha^4 K_0(\eta \rho_1) K_0(\eta \rho_2) + [1 + (1 - \alpha)^2] \eta^2 \frac{\vec{p}_1 \cdot \vec{p}_2}{\rho_1 \rho_2} K_1(\eta \rho_1) K_1(\eta \rho_2) \right\},
\]

\[
\Psi_{\gamma^*_q}^L(\alpha, \vec{p}_1) \Psi_{\gamma^*_q}^{* L}(\alpha, \vec{p}_2) = \frac{1}{2} \sum_{\sigma_f \sigma_i} \epsilon_{\mu}(\lambda = 0) \Psi_{\gamma^*_q}^{\lambda=0}(\alpha, \vec{p}_1) \epsilon_{\mu}(\lambda = 0) \Psi_{\gamma^*_q}^{\lambda=0}(\alpha, \vec{p}_2)
\]

\[
= \frac{\alpha_{em}}{\pi^2} M^2 (1 - \alpha)^2 K_0(\eta \rho_1) K_0(\eta \rho_2).
\]

Dipole properties:
• cannot be excited
• experience only elastic scattering
• have no definite mass, but only separation
• universal – elastic amplitude can be extracted in one process and used in another

Fitted to data!

and the universal dipole cross section:

\[
\sigma_{qq}(\alpha \rho) = \sum_X \frac{1}{N_c} \sum_{c_f c_i} \int d^2 b \left| \tilde{V}_q(b) - \tilde{V}_q(b + \alpha \vec{p}) \right|^2.
\]
The universal dipole CS

\[
\frac{d\sigma^\gamma(pp \to \gamma X)}{dx_Fd^2p_T} = \frac{1}{x_1 + x_2} \int_{x_1}^1 \frac{d\alpha}{\alpha} F_2^p(\frac{x_1}{\alpha}, Q) \frac{d\sigma^{qN}(q \to q\gamma)}{d(ln\alpha)d^2p_T}
\]

probing proton structure function in DY at large \(x\)!

In Regge phenomenology, the dipole approach accounts for only Pomeron part of the cross section; the dipole CS is governed by gluon interactions and applicable at small \(-x\) only!

To the LO (two-gluon exchange + resumed \(\log(1/x)\)), in the Weizsacker-Williams approximation

color transparency!

\[
\sigma_{qq}(x_2, \rho) = \frac{4\pi}{3} \alpha_s \rho^2 \int \frac{d^2 k_\perp}{k_\perp^2} \left( 1 - \exp(i\vec{k}_\perp \cdot \vec{\rho}) \right) \frac{\partial G(x_2, k_\perp^2)}{\partial \ln(k_\perp^2)}
\]

cancellation of IR divergences!

UGDF at small \(x\)

GBW model (fitted to DIS only):

\[
\sigma_{qq}^N(\rho, x) = \sigma_0 \left[ 1 - \exp \left( -\frac{\rho^2 Q_s^2(x)}{4} \right) \right]
\]

\(Q_s^2(x) = 1 \text{ GeV}^2 \left( \frac{0.0003}{x} \right)^{0.288} \)

GBW-DGLAP preserves success of the GBW model while modifying large-\(Q\) behavior by evolution

Not good at large-\(x\) and large \(Q\)!

GBW-DGLAP model (with LO DGLAP evolution):

\[
\sigma_{qq}(x, \vec{r}) = \sigma_0 \left( 1 - \exp \left( -\frac{\pi^2 r^2 \alpha_s(\mu^2) x g(x, \mu^2)}{3\sigma_0} \right) \right)
\]

Bartels et al '02

\(F_2 \sim x^{-\lambda(Q^2)}\)
Parton Model versus Dipole Approach

Saturation at work (can change the DY CS at the LHC by a factor of 3)!

Large-\(x\) corrected dipole:

\[ Q_s^2(x) \rightarrow Q_s^2(x)(1 - x)^5 \]

\( M = 6, 8, 10 \) GeV

Golec-Biernat et al '10

CGC model gives similar results as GBW!

Leading twist is OK at the LHC if \( M > 6 \) GeV, below – resummation of higher twists is important!
Motivation for diffractive Drell-Yan at the LHC

- Diffraction cannot be accessed in collinear factorisation (transverse (TMD) evolution is crucial)
- Strongly sensitive to the soft physics – small $x$ and small transverse momenta!
- Excellent probe for QCD factorisation breaking effects!

Driven by Pomeron exchange (rightmost singularity in the complex angular momentum plane)

Topology of diffractive final states

- Non-diffractive
- Single-diffractive
- Double-diffractive
- Double-Pomeron exchange

$\Sigma_X^2 = \begin{align*}
p \to p, G^* & \rightarrow l, X & \rightarrow p, p, IP, IR + p, p, IP, IR \\
p \to p, G^* & \rightarrow l, X \rightarrow p, p, IP, IR & + p, p, IP, IR
\end{align*}$

Higgs, dijets, $\gamma \gamma, \chi_c$
Diffractive factorisation-based approach to DDY

e.g. by A. Szczurek et al, Phys.Rev.D84:014005,2011

Ingelman-Schein mechanism $\rightarrow$ QCD/Regge factorisation

Diffractive quark density

$$q_f^D(x, \mu^2) = \int_{x_{IP}}^{1} \frac{dx_{IP}}{x_{IP}} f_{IP}(x_{IP}) q_f/IP \left( \frac{x}{x_{IP}}, \mu^2 \right)$$

DY with gap and the leading proton

Raising with energy/dumping with scale!

Regge factorization vs absorptive corrections

**Eikonal part**

Diffractive Z,W / Inclusive Z,W \( \sim 30 \% \)

Noticeable growth with energy!

*A. Szczurek et al, Phys.Rev.D84:014005,2011*

**“Enhanced” part breaks the factorisation!**

Effect is largely unknown! Different models...

Open issue...

What can the dipole approach offer us in this situation?
Is forward Drell-Yan off a quark or off a dipole?

The standard DY contribution from Abelian Bremsstrahlung off a quark disappears!

**Landau-Pomeranchuk principle:** non-accelerated charge does not radiate!

\[ \alpha = x_\gamma / x_{q_1} \]

\[ \sigma_{qq}(\vec{r}_1 - \vec{r}_2) \]

\[ \sigma_{qq}(\vec{r}_1 - \vec{r}_2 + \alpha \vec{r}) \]

By optical theorem

Amplitude of DDY in the dipole-target scattering

\[ M_{qq}^{(1)}(\vec{b}, \vec{r}_p, \vec{r}, \alpha) = -2i p_i^0 \sqrt{4\pi} \frac{\sqrt{1 - \alpha}}{\alpha^2} \Psi_{\gamma*q}^\mu(\alpha, \vec{r}) \left[ 2 \text{Im} f_{el}(\vec{b}, \vec{r}_p) - 2 \text{Im} f_{el}(\vec{b}, \vec{r}_p + \alpha \vec{r}) \right] \]
DY off a hadron: probing large distances in the proton


GBW dipole

\[ \sigma(r) = \sigma_0 \left( 1 - e^{-r^2/R_0^2} \right) \]

Amplitude

\[ \sim \sigma(\vec{R}) - \sigma(\vec{R} - \alpha \vec{r}) = \frac{2\alpha \sigma_0}{R_0^2(x_2)} e^{-R^2/R_0^2(x_2)} (\vec{r} \cdot \vec{R}) + O(r^2) \]

Interplay between hard and soft scales

Diffractive DIS \( \sim r^4 \)

...of the higher twist nature!

QCD factorization holds!

Diffractive gauge bosons production

\( \sim r^2 \)

...of the leading twist nature!

diffractive factorization is broken!
Diffractive DDY: probing proton structure at large x

The general result:

\[
\frac{d^{5}\sigma_{\lambda_{G}}(pp \rightarrow pG^{*}X)}{d^{2}q_{\perp} d \ln \alpha d^{2}\delta_{\perp}} = \frac{1}{(2\pi)^{2}} \frac{1}{64\pi^{2}} \sum_{q} \int d^{2}r_{1}d^{2}r_{2}d^{2}r_{3} d^{2}r' d^{2}b d^{2}b' \ dx_{q_{1}}dx_{q_{2}}dx_{q_{3}} \\
\times \Psi^{\lambda_{G}}_{V-A}(\vec{r}, \alpha, M)\Psi^{\lambda_{G}^{*}}_{V-A}(\vec{r}', \alpha, M) |\Psi_{i}(\vec{r}_{1}, \vec{r}_{2}, \vec{r}_{3}; x_{q_{1}}, x_{q_{2}}, x_{q_{3}})|^{2} \\
\times \Delta(\vec{r}_{1}, \vec{r}_{2}, \vec{r}_{3}; \vec{b}; \vec{r}, \alpha)\Delta(\vec{r}_{1}, \vec{r}_{2}, \vec{r}_{3}; \vec{b}'; \vec{r}', \alpha) e^{i\delta_{||}(\vec{b} - \vec{b}')} e^{i\vec{b}_{||} \cdot \alpha(\vec{r} - \vec{r}')} \\
\Delta = -2\text{Im} f_{el}(\vec{b}, \vec{r}_{1} - \vec{r}_{2}) + 2\text{Im} f_{el}(\vec{b}, \vec{r}_{1} - \vec{r}_{2} + \alpha\vec{r}) \\
-2\text{Im} f_{el}(\vec{b}, \vec{r}_{1} - \vec{r}_{3}) + 2\text{Im} f_{el}(\vec{b}, \vec{r}_{1} - \vec{r}_{3} + \alpha\vec{r})
\]

Proton wave function

\[|\Psi_{i}(\vec{r}_{1}, \vec{r}_{2}, \vec{r}_{3}; x_{q}, x_{q_{2}}, x_{q_{3}})|^{2} = \frac{3a^{2}}{\pi^{2}} e^{-a(r_{1}^{2}+r_{2}^{2}+r_{3}^{2})} \rho(x_{q}, x_{q_{2}}, x_{q_{3}}) \times \delta(\vec{r}_{1} + \vec{r}_{2} + \vec{r}_{3})\delta(1 - x_{q} - x_{q_{2}} - x_{q_{3}})\]

Valence quark distribution

\[
\int dx_{q_{2}}dx_{q_{3}} \delta(1 - x_{q} - x_{q_{2}} - x_{q_{3}}) \rho(x_{q}, x_{q_{2}}, x_{q_{3}}) = \rho_{q}(x_{q}) \\
\sum_{a} Z_{q}^{2} [\rho_{q}(x_{q}) + \rho_{\bar{q}}(x_{q})] = \frac{1}{x_{q}} F_{2}(x_{q})
\]

In DDY we get an immediate access to the proton structure function at large x!
Diffractive DY production cross sections at the LHC

Pasechnik et al’12
Diffractive vs inclusive Drell-Yan: probing small x physics

In the hard limit:

\[
\frac{1}{2} \left\{ \sigma(\alpha r) + \sigma(\alpha r') - \sigma(\alpha |\vec{r} - \vec{r}'|) \right\} \approx \frac{\alpha^2 \bar{\sigma}_0}{R_0^2(x)} (\vec{r} \cdot \vec{r}')
\]

Inclusive production CS:

\[
\frac{d^4 \sigma_{\lambda G}(pp \rightarrow G^* X)}{d^2 q_\perp \, dx_{bos1}} = \frac{1}{(2\pi)^2} \frac{\bar{\sigma}_0}{R_0^2(x)} \sum_q \int_{x_{bos1}}^1 d\alpha \left[ \rho_q \left( \frac{x_{bos1}}{\alpha} \right) + \rho_{\bar{q}} \left( \frac{x_{bos1}}{\alpha} \right) \right] \times
\]

\[
\int d^2 r d^2 r' (\vec{r} \cdot \vec{r}') \, \Psi^{\lambda G}_{V-A}(\vec{r}, \alpha, M) \Psi^{\lambda G*}_{V-A}(\vec{r}', \alpha, M) \, e^{i q \perp \cdot (\vec{r} - \vec{r}')}.
\]

with naive GBW parametrization:

\[
\bar{\sigma}_0 = 23.03 \text{ mb} , \quad R_0 \equiv R_0(x) = 0.4 \text{ fm} \times (x/x_0)^{0.144} , \quad x_0 = 3.04 \times 10^{-4} ,
\]

So, the diffraction-to-inclusive ratio:

\[
\frac{d\sigma^{sd}_{\lambda G}}{d^2 q_\perp \, dx_{bos1} \, dM^2}/d\sigma^{incl}_{\lambda G} = \frac{a^2}{6\pi} \frac{\bar{R}_0^2(M^2_{1}/x_{bos1} s)}{B_{sd}(s) \bar{\sigma}_0} \frac{\sigma_0^2(s)}{R_0^4(s)} \frac{1}{A_2} \left[ \frac{2}{(A_2 - 4A_1)^2} + \frac{A_2^2}{(A_2^2 - 4A_3^2)^2} \right]
\]

\[
M^2_{1} \equiv M^2 + |q_{\perp}|^2 = x_{bos1} \, x \, s
\]

universal quantity for probing soft/multiple interactions and saturation physics at the LHC!
Diffractive vs inclusive DY: drops with energy!?

Energy/scale behavior is opposite from predicted by QCD factorisation-based approaches.

Agrees well with the Tevatron data!

A good probe for QCD diffractive mechanism and soft interactions!

\[
\frac{d\sigma_{DDY}}{d\gamma_1 dM^2} \quad \frac{d\sigma_{DY}}{d\gamma_1 dM^2}
\]
Regge factorization breaking at the LHC

Absorptive effects destroy diffractive factorization in hadron-hadron scattering!

without the factorisation breaking: Diffractive Z,W / Inclusive Z,W $\sim 30\%$

with the factorisation breaking: Diffractive Z,W / Inclusive Z,W $< 1\%$

as predicted by the color dipole approach!
Summary and Outlook

The Standard Model works quite well so far!

- Theoretical work in “cleaning up” of the QCD theory uncertainties (NLO, NNLO, resummation) in DY for the LHC is going very well!

- Existing LHC data allow to discriminate and constrain PDFs in much wider kinematics than ever before (much more to come)

- Forward (small-x and diffractive) Drell-Yan data from the LHC offers a lot of opportunities to constrain saturation physics at small-x and the proton structure function at large-x