DIS 2011
Small-x, Diffraction and Vector Mesons
Summary Review

David d’Enterria, Cyrille Marquet, Christina Mesropian
Summary of WG2

Small x, Diffraction and Vector Mesons

• 29 experimental talks
• 22 theory talks
• 3 joint sessions with
  - Structure functions
  - QCD and hadronic final states
  - Future of DIS
Theory Summary of WG2

Small x, Diffraction and Vector Mesons

• 22 theory talks
  – 13: Small x
  – 2: Diffraction
  – 2: Vector Mesons
  – 2: Central Exclusive Production
  – 2: Jets and Rapidity gaps
  – 1: AdS/CFT
Small $x$

\[ \sigma_{T,L}^{\gamma^*P}(x, Q^2) = \int_0^1 dz \int d^2 r \left| \Psi_{T,L}^{\gamma^* \rightarrow q\bar{q}}(z, Q, r) \right|^2 \sigma_{dip}^{(x,r)} \]

\[ \sigma_{dip}^{(x,r)} = 2 \int d^2 b \mathcal{N}(x, b, r) \rightarrow \text{Strong interactions and x-dependence are here} \]
Deviations from DGLAP

Juan Rojo

evidence for deviations from NLO DGLAP in inclusive HERA data
consistent with small-x resummations and non-linear dynamics not with NNLO corrections

general strategy
- cut out data in the “unsafe” region (small $x$ and $Q^2$)
- determine PDFs in the “safe” region (large $x$ and $Q^2$)
- evolve backwards and compare to data in causally connected region
- tension between data and back-evolution: deviations from NLO DGLAP

same analysis in e+A with pseudo-data
for a Pb nucleus, deviations from DGLAP would be identified within the $x$ range of the full-energy EIC
Alternative approaches at small-x

- Non-linear small-x QCD evolution  

- (first) pure BFKL description of the data, in particular of \( \lambda(Q^2), \ F_2 \sim (1/x)^{\lambda} \)
  
  Henri Kowalski
  
  - based on discreet Pomeron solution (DPS) of NLL-BFKL with running coupling
  
  \( \sim 150 \) eigenfunctions needed with 3 parameters each (the precision of new data allows to find a unique solution)

- N=4 SYM model of confinement, using the AdS/CFT correspondence

  \[
  F_2 = c \frac{Q}{Q'} \left( \frac{Q_0^2}{Q^2} \right)^{1-\rho} \frac{1}{x} \exp\left( -\frac{\log^2\left( \frac{Q}{Q'} \right)}{\rho \log\left( \frac{Q_0^2}{Q^2} \right)} \right)
  \]

  Chung-I Tan

  strong and fixed coupling, nevertheless a good data description is obtained

- small x resummations  

  Simone Marzani

  \( F_2 \) not discussed, extension of the formalism to compute rapidity distributions
Running-coupling BK analysis

⇒ x-dependence: translational invariant (no b-dependence) running coupling BK using Balitsky’s prescription the most advanced practical non-linear evolution

\[
\frac{\partial N(x, r)}{\partial \ln(x_0/x)} = \int d^2r_1 \ K^{Bal}(r, r_1, r_2) \left[ N(x, r_1) + N(x, r_2) - N(x, r) - N(x, r_1)N(x, r_2) \right]
\]

\[
K^{Bal}(r, r_1, r_2) = \frac{N_c \alpha_s(r^2)}{2\pi^2} \left[ \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_1^2} \left( \frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{1}{r_2^2} \left( \frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]
\]

Javier Albacete

fit parameters stable after the inclusion of the new data
The NLO photon impact factor

rcBK: first successful data description by the non-linear QCD evolution
- previous successful descriptions are based on parameterization of the $x$ dependence (dipole models)
- made possible by the running-coupling corrections (the most important corrections due to NLO evolution), but still using LO impact factors

• next step: full NLO calculation of $F_2$

non-linear evolution at NLO: already known (Balitsky-Chirilli)

Giovanni Chirilli

NLO impact factor:

$$f_{uuj}^{NLO}(x,y) = \frac{\alpha_s}{4\pi^2} \frac{\partial \Gamma^u}{\partial x^u} \frac{\partial \Gamma^d}{\partial y^d} \int \frac{dz_1}{z_{12}^2} U(z_1, z_2) R^2 \left\{ \frac{2}{\kappa^2} \left( g_{\alpha\beta} - 2 \frac{\kappa_{\alpha\beta}}{\kappa} \right) + \frac{C_1 C_2}{(\kappa \cdot \zeta_1)(\kappa \cdot \zeta_2)} \left[ 4 L_2(1 - R) - \frac{2\pi^2}{3} + \frac{2\ln R}{1 - R} + \ln R - \frac{4\ln R + 1}{2R} - 2 - 4C - \frac{2}{R} \right] \ight\}$$

no numerical implementation yet
About collinear resummations

(Linear) BFKL evolution suffers from spurious singularities. Collinear resummations are needed to get meaningful results.

Belief/hope: saturation cures the BFKL instabilities, no need for collinear resummations when non-linear effects are included.

This is wrong; resummations are needed and may have sizable effects.

Analytic understanding of this phenomena developed using the traveling wave method to solve the BK (and higher-order) equations.
BK evolution with impact parameter

the $b$ dependence in the small $x$ evolution is almost always neglected

- previous studies with LO BK
  - non-physical power-law tails at large $b$
  - non-trivial dynamics of large dipole sizes

- the $b$ dependence in the running coupling BK equation

  the IR regularization of the kernel becomes crucial

preliminary phenomenological analysis:
with Balitsky’s prescription one can get qualitative agreement with the data

however the agreement is perhaps accidental, due to the extreme sensitivity of the results to the regularization of

$$\alpha_s(x^2) = \frac{1}{b \ln \left( \frac{1}{x^2 + \mu^2} \right)}$$
Unintegrated gluon distributions

- the standard ugd, FT of the dipole amplitude

\[ x_g G^{(2)}(x_g, q_\perp) = \frac{q_i^2 N_c}{2\pi^2 \alpha_s} S_\perp \int \frac{d^2 r_\perp}{(2\pi)^2} e^{-i q_\perp \cdot r_\perp} S_{x_g}^{(2)}(0, r_\perp) \]

for instance used to calculate semi-inclusive DIS

- dijet production in DIS

\[ \frac{d\sigma^{\gamma^* \rightarrow q\bar{q}+X}}{dy_1 dy_2 d^2 P_\perp d^2 q_\perp} = \delta(x_{\gamma^*} - 1) x_g G^{(1)}(x_g, q_\perp) H_{\gamma^* g \rightarrow q\bar{q}} \]

no \( k_T \) or (TMD) factorization

- dijet production in pA

depends on both gluons distributions through appropriate convolutions

no “naive” \( k_T \) factorization but “effective” \( k_T \) factorization

Fabio Dominguez
Unintegrated sea quarks in CASCADE

implementation necessary to deal with processes such as Z production

idea: use the Catani-Hautmann $k_T$-dependent splitting function as the last step of the CCFM evolution

$$A_{\text{sea}}(x, q^2, \mu^2) := \frac{1}{q^2} \int_0^{1 \mu^2/x} dz \int_0^1 dk^2 P_{qg}^{\text{CH}}(z, k^2, q^2) A_{\text{CCFM}}^{\text{gluon}} \left( \frac{x}{z}, k^2, \mu^2 \right)$$

unintegrated quark distribution

comparison of $k_T$-factorized expression with full ME

agreement best for large $p_T$ region
The **DIPSY** event generator:
A BFKL-based dipole model in transverse space
(Christoffer Flensburg, Leif Lönnblad and Gösta Gustafson)

**The model**
- Based on LL BFKL
  - NLL corrections
  - Confinement
  - Saturation
- All fluctuations described!
- arXiv:1103:4321

**Applications**
- **pp**: tuned and published.
- **AA**: implemented and running
  - t=0 state can be fed to final state models (hydro, jet quenching, etc)
- **eA**: implemented, not tuned
- **DIS**: implemented, not tuned
Central Exclusive Production
Estimating Model Uncertainties

using the Forward Physics Monte-Carlo (FPMC) contains KMR and CHIDe model uncertainties coming from:
- gap survival probability
- unintegrated gluon distributions
- Suddakov form factor constrained by CDF data on diffractive di-jets ⇒ factor 10

Assume new measurement of exclusive jet production at the LHC: 100 pb-1, precision on jet energy scale assumed to be ~3% (conservative for JES but takes into account other possible systematics)
Meson pair production

novel QCD studies with the Khoze-Martin-Ryskin model

flavor non-singlet mesons

total amplitude given by convolution of parton level amplitude with non-perturbative wave functions

\[ M_{\lambda_1,\lambda_2}(s, t) = \int_0^1 dx dy \phi(x)\phi(y) T_{\lambda_1,\lambda_2}(x, y; s, t) \]

\( J_z = 0 \) rule

\( \pi^0\pi^0 \) BG to \( \gamma\gamma \) CEP is suppressed

flavor singlet mesons

new set of diagrams

\( J_z = 0 \) amplitude does not vanish

enhancement in \( \eta'/\eta' \) CEP rate and (through \( \eta-\eta' \) mixing), some enhancement to \( \eta\eta' \) rate. \( \eta\eta' \) CEP can also occur via this mechanism.
Vector Mesons and DVCS
A Regge-type model

Salvatore Fazio

using a logarithmic Regge trajectory and a very few parameters

good data description of $\sigma(Q^2)$ and $\frac{d\sigma}{dt}$ but room for improvement for $\sigma(W)$
at large $Q^2$, usual for soft Pomeron models

also presented an alternative to the Donnachie-Landshoff two-Pomeron model to describe $\sigma(W)$ in a large $Q^2$ domain
New constraints on rho WF and DA

Current data require qualitatively different light-cone wavefunctions for transverse and longitudinal polarisation.

\[ A = \rho \]

- \( r \): transverse dipole size
- \( z \): fraction of photon’s light-cone momentum carried by quark

At high energy \( s \gg t, Q^2, M^2 \), amplitude factorises

\[ \mathcal{A}_\lambda(s, t; Q^2) = \sum_{h, h'} \int d^2r dz \psi_h^{* \lambda, \rho} \psi_{h'}^{\lambda, \rho*} e^{-irz} \Delta N(x, r, \Delta) \]

A new distribution amplitude is also obtained

\[ |\Psi_T(0, \tilde{z})|^2 \]

Ruben Sandapen especially \( \sigma_L/\sigma_T \)

Agrees with QCD Sum Rules and lattice predictions
What I did not cover

• Misha Gorshteyn
  Asymptotic behavior of pion form factors

• Marat Siddikov
  Diffractive neutrino production of pions in the color dipole model

• Paolo Bolzoni
  Time-like small-x resummation for fragmentation functions
Thank you

Thanks to the speakers
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Christina Mesropian
Diffraction (ep, HERA)

\[ Q^2 = -q^2 = (k' - k)^2 \]
\[ x = \frac{Q^2}{2Pq} \]
\[ x_{IP} = \frac{q(P' - P)}{qP} = 1 - \frac{E'_p}{E_p} \]
\[ \beta = \frac{x}{x_{IP}} \]
\[ t = (P' - P)^2 \]

Diffractive DIS kinematics
Inclusive Diffraction (ep, HERA) 

H1 PRELIMINARY 

3 different detectors (2 different methods) 
very good agreement!
Forw. jets with leading $p$ in DDIS
- search for physics beyond DGLAP
  Selection of 1 cent.+ 1 forw.jet
  suppressing DGLAP phase space

Low $x$
Calculable in NLO (NLOJET++ with DPDF)
Good description by NLO QCD DGLAP predictions

VFPS –
  high accept. detector
  ↓
  high statistics

Good agreement
with NLO predictions

H1 VFPs Preliminary : $25.3 \pm 1.4$(stat.) $\pm 6.5$(syst.) pb
NLO DPDF Fit Jet 2007 : $19.9 \pm 7.4(4.4)$ $\pm 0.5$(had.) pb
Look for observables that would be sensitive to underlying parton dynamics

- The correlation in $\Delta \phi$ between scattered electron and the forward jet in DIS may be another signature of the BFKL dynamics

$x_{\text{jet}} = \frac{E_{\text{jet}}}{E_p} > 0.035$

enhancing phase space for BFKL

$0.5 < p_{t,je}^2/Q^2 < 6.0$

suppressing phase space for DGLAP evolution

- At lower $x$ forward jet is more decorrelated from the scattered electron

- Normalised shape distributions in $\Delta \phi$ don't discriminate between different QCD evolution schemes.
Diffraction (ppbar, Tevatron)

**Hard Diffraction - jets, W**

Fraction of diffractive W (measured with tagged pbar)

\[ R_W(0.03 < \xi < 0.10, |t|<1) = [0.97 \pm 0.05\text{(stat)} \pm 0.10\text{(syst)}]\%

consistent with Run I result (LRG)

**Central Exclusive Production**

\[ p \rightarrow e/\mu, \quad R_W(\xi < \xi^P) \leq 0.03 \text{ fb}^{-1} \]

\[ L = 0.6 \text{ fb}^{-1} \]

**Forward Jets with Rapidity Gap**

JJ - PRD 77, 052004 (2008)

\[ p \rightarrow e/\mu, \quad R_W(\xi < \xi^P) \leq 0.03 \text{ fb}^{-1} \]

\[ L = 0.6 \text{ fb}^{-1} \]

\[ \chi_c - PRL 242001 (2007) \]

\[ \gamma\gamma - PRL 99, 242002 (2007) \]

\[ \chi\chi - PRL 99, 242002 (2007) \]
Inelastic cross section (pp, LHC)

- ATLAS: Single-sided events
- CMS: Vertex counting in pileup evts:

\[ P(n_{\text{pileup}}) = \frac{(L \cdot \sigma)^{n_{\text{pileup}}}}{n_{\text{pileup}}!} \cdot e^{-(L \cdot \sigma)} \]

\[ \sigma_{\text{visible}} = 60.33 \pm 2.3 \text{ mb} \]
\[ \sigma_{\text{inel}} = 69.4 \pm 2.4 \pm 6.9 \text{ mb} \]
\[ \sigma_{\text{visible}} = 59.7 \pm 2.6 \text{ mb} \]
\[ \sigma_{\text{inel}} = 66.8 – 74.8 \text{ mb} \]

ATLAS (S. Tompkins)
CMS (M. Marone)
ATLAS: x-section as function of forward rapidity gap $\Delta \eta^F$

CMS: Observation in single-side trigger ($\Delta \eta \sim 2$ rap-gap, $\xi \sim E - p_z$)

- ATLAS Preliminary
- Data $L = 7.1 \mu b^{-1}$
  - Systematic unc.
  - MC Pythia6
  - MC Pythia8
  - MC Phojet

$\sqrt{s} = 7$ TeV
$p_T > 200$ MeV

CMS Preliminary 2010

$\sqrt{s} = 7$ TeV
$L = 20 \mu b^{-1}$

- $E_{\text{vis}} < 8$ GeV
- $p+p$ (BSC OR and Vertex)
- Energy scale $\pm 10\%$
- PYTHIA8 DBT
- PYTHIA8
- PHOJET
- PYTHIA8 DBT Non-diffractive
- PYTHIA8 Non-diffractive
- PHOJET Non-diffractive

- PYTHIA8 describes data best at low $\Delta \eta^F$
- PHOJET at high $\Delta \eta^F$
- Evidence of diffraction at high $\Delta \eta^F$
- Diffractive x-section $\sim 1\text{mb}$ per unit $\Delta \eta^F$ at high $\Delta \eta^F$

- No PYTHIA tune reproduces all data
- PHOJET ....
Forward hadrons (|\eta|=3-5, pp, LHC)

- Probe Underlying-Evt modeling (MPI, beam remnants) in MCs:
  - Data between HERWIG and PYTHIA
- Constraints for cosmic-rays MCs: Good agreement
Forward jets ($|y|=3-5$, pp, LHC)

- Probe PDFs down to $x \sim p_T/\sqrt{s} \sim 10^{-4}$
- DGLAP vs BFKL dynamics
- ATLAS data (±50% uncert) < parton-shower+POWHEG (NLO)
- CMS data (±30% uncert) agrees with TH predictions

ATLAS (D. Gillberg)
CMS (A. Massironi)
Forward-central jets (pp, LHC)

- Constrains multi-jets production & DGLAP vs BFKL dynamics
- **HERWIG** somehow better than **PYTHIA**.
- **POWHEG** (NLO) does not help.
- **HEJ** (BFKL-multijets) best agreement.

CMS (A. Massironi)
Small x Physics (RHIC)

Measuring correlations between two forward $\pi_0$ probes a limited, smaller x range

- Near-side peak is similar in p+p and d+Au
- Significant broadening from p+p to d+Au in the away side peak
- Agreement with CGC (?), MPI contributions (?)
Exclusive electroproduction of pions (ep, HERA)

Contribution of the three vector mesons $\rho^0$, $\rho^+$ and $\rho''$

compare their $Q^2$ dependence to QCD predictions

$0.4 < M_{\pi\pi} < 2.5$ GeV,
$2 < Q^2 < 80$ GeV$^2$,
$32 < W < 180$ GeV

$|t| \leq 0.6$ GeV$^2$
Exclusive VM production (ep, HERA)

$t|t| - dependence$

- Geometric picture -
- Transverse size: 
  \[ b = b_V + b_p \]

- Vector Meson: 
  \[ b_V \sim 1/(Q^2 + M_{VM}^2) \]

- Target (proton): 
  \[ b_p \approx 5 \text{GeV}^{-2} \]

- $b_p$ can be interpreted as
  \[ r_{\text{gluons}} \approx 0.6 \text{ fm} \]
  \[ r_{\text{em}} \approx 0.8 \text{ fm} \]

- New ZEUS measurement of $\Upsilon(1S)$ consistent with hard regime VM production.

ZEUS (G. Grzelak)
H1 (F. Huber)
**Exclusive photoproduction** $\gamma \gamma \rightarrow \mu \mu$ (pp, LHC)

- **CMS:** Rap-gap, $p_T(\mu) > 4$ GeV, $\eta(\mu) < 2.1$, $m(\mu\mu) > 11.5$ GeV

  Clear signal measured

  \[ \sigma(pp\rightarrow p\mu\mu p)_{\text{exp}} = 3.35\pm0.5\pm0.2 \text{ pb} \]

  Agreement with LPAIR:

  \[ \frac{\sigma_{\text{exp}}}{\sigma_{\text{QED}}} = 0.82\pm0.14\pm0.04 \]

  Uncertainties in inelastic contributions (proton taggers needed)

- **LHCb:**

  \[ m(\mu\mu) > 2.5 \text{ GeV} \text{ (not J/psi,psi') } \]

  Exclusivity: no backward tracks, no $\gamma$, $N>2$ forward tracks

  Agreement with LPAIR elastic

  \[ \sigma_{\text{exp}} = 67\pm19 \text{ pb}, \sigma_{\text{QED}} = 42 \text{ pb} \]
Central Exclusive IP+IP $\rightarrow$ X (pp, LHC)

- ALICE: IP+IP $\rightarrow f_0$, $f_2$ mesons.
  
  2-track events with gaps on both sides over events without gaps.

- LHCb: IP+IP $\rightarrow \chi_c$

$m(\mu\mu) = m(J/\psi) \pm 65$ MeV, $p_T(\mu\mu) < 900$ MeV, 1 $\gamma$

Exclusivity: no backward tracks, N>2 fwd tracks

$\sigma_{\text{chic0}} = 9.3 \pm 4.5$ pb ($\sigma_{\text{TH}} = 14$ pb)

$\sigma_{\text{chic1}} = 16.4 \pm 7.1$ pb ($\sigma_{\text{TH}} = 10$ pb)

$\sigma_{\text{chic2}} = 28 \pm 12.3$ pb ($\sigma_{\text{TH}} = 3$ pb)

Consistent with TH: SuperChic, Starlight

(but large TH/EXP uncertainties)

ChiC0:ChiC1:ChiC2 = 1:2.2$\pm$0.8:3.9$\pm$1.1
Exclusive photoproduction $\gamma$ IP $\rightarrow$ X (pp, LHC)

- LHCb: $\gamma$ IP $\rightarrow$ J/Psi, Psi'

\[ m(\mu\mu) = m(J/\psi) \pm 65 \text{ MeV}, \quad p_T(\mu\mu) < 900 \text{ MeV}, \quad \text{No } \gamma \]
Exclusivity: no backward tracks, N>2 fwd tracks

Consistent with Starlight/SuperChic (but large TH/EXP uncertainties)

- $\sigma_{J/\psi} = 474 \pm 103 \text{ pb (} \sigma_{TH} = 292-330 \text{ pb)}$
- $\sigma_{\psi'} = 12.2 \pm 3.2 \text{ pb (} \sigma_{TH} = 6.1 \text{ pb)}$
Vector Meson Production (PbPb, LHC)

- ALICE observed: PbPb → Pb+Pb+ ρ⁰

Centrality dependent J/ψ suppression observed at ATLAS
Vector Meson production (RHIC)

Motivation:
• More than 10% of bulk meson production in HI collisions.
• Lifetime comparable to QGP.
• Vector mesons (\(\rho\), \(\omega\), \(f\), \(J/\psi\), \(\psi'\), \(Y\)) have \(\rightarrow\) decay channels bring information about medium properties directly to the detector.

- Low mass vector mesons
  - PHENIX: Low mass e+e- pair enhancement in Au+Au
  - STAR: Similar analysis is ongoing. Stay tuned.
- \(Y\)
  - PHENIX, STAR: cross-section measured in p+p, dAu,AuAu
- \(J/\psi\)
  - PHENIX: High statistic measurement in p+p: spectra. \(\Psi'\) and \(\chi_c\) feed-down on p+p
  - High statistic measurement in d+Au
  - STAR: High statistic p+p data-sample is being analyzed.
Central Exclusive Production (pp, LHC)

1) **CED Higgs production in SM**
   - provides a moderate signal yields but it is attractive because
   - gives information about Hbb Yukawa coupling – which is difficult in standard searches

2) **CED Higgs production in MSSM**
   - the signal yields are greatly enhanced
   - it gives complementary information about Higgs sector
   - the Higgs width may be directly measured (for large \( \tan \beta \))

**Update of the 2007 analysis:**
   - background NLO CED \( gg \to bb \)
   - LEP/Tevatron exclusion regions (HiggsBounds)

   - improved theory calculations (as included in FeynHiggs)
   - new CDM benchmark planes (similar results as for \( M_{h_{\max}} \) and no-mixing benchmarks)

3) **CED Higgs production in 4th Generation Model**
   - LEP/Tevatron searches: \( 112 < M_H < 130 \) GeV allowed

(b,W,τ)
What I did not cover

• Vitaliy Dodonov
  Forward neutron $p_T$ distribution and forward photon spectra measured in H1 FNC

• Heiner Wollny
  Vector Meson & DVCS measurements in COMPASS

• Valery Kubarovsky
  Vector meson production & DVCS at J-Lab

• Anastasia Grebeniuk
  Transverse momentum spectra of charged particles at low $Q^2$
Thank you

Thanks to the speakers