Higher-order corrections in forward Drell–Yan production at the LHC

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in collaboration with
D. Gordo Gómez, **A. Sabio Vera**

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Phys. Lett. B786 (2018) 201-206   [arXiv:1808.09511]

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HAS QCD
HADRONIC STRUCTURE AND
QUANTUM CHROMODYNAMICS

INFN
Istituto Nazionale di Fisica Nucleare
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UNIVERSITÀ
DI PAVIA

Outline

Outline

1 Introductory remarks
- Motivation
- Parton densities: a brief overview

2 Theoretical setup
- Forward Drell–Yan in high-energy factorization
- Unintegrated gluon distribution
- LLA BFKL model in CDA

3 Results
- Numerical analysis

4 Conclusions and Outlook

Forward Drell–Yan production | **Introduction** | Theoretical setup | Results | Conclusions and Outlook | Backup
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Motivation

Drell–Yan process

Drell–Yan (DY) reaction: production of lepton pairs in the s-channel

- Excellent probe of **proton structure** in pp and $p\bar{p}$ collisions

- One of the few processes where the **collinear factorization** has been rigorously proven

- **Fixed-order** calculations up to NLO and NNLO

- **Lepton pair distributions** well measured over a wide range of kinematic parameters

    $\xrightarrow{\text{provide us}}$ useful data on DY **structure functions**

- High sensitivity to **low values** of parton κ_T

    $\xrightarrow{\text{serves as}}$ golden channel to access **TMD dynamics**

Drell–Yan process and small-x physics

- DY production in hadronic collisions as probe of the proton structure in the small-x limit

- Small-x regime $\rightarrow$ **BFKL approach**, the most effective tool to perform the all-order resummation of high-energy logs (LLA and NLA), allowing us to describe:

  ◇ hard scattering $\Rightarrow$ **semi-hard** sector (Mueller–Navelet jets, (di-)hadron(-jet) production, heavy-quark pair production,...)

  ◇ gluon evolution $\Rightarrow$ **high-energy factorization** (**HEF**)

- Previous studies based on the dipole formalism with saturation effects and LLA BFKL

[L. Motyka, M. Sadzikowski, T. Stebel, *JHEP* **05** (2015) 087]
[D. Brzemiński, L. Motyka, M. Sadzikowski, T. Stebel, *JHEP* **1701** (2017) 005]

Drell–Yan process at LO

Process: $\mathrm{hadron}(P_1) + \mathrm{hadron}(p_2) \rightarrow \mathrm{l}^+(l^+) + \mathrm{l}^-(l^-) + X$ ($l^{\pm}$ measured)
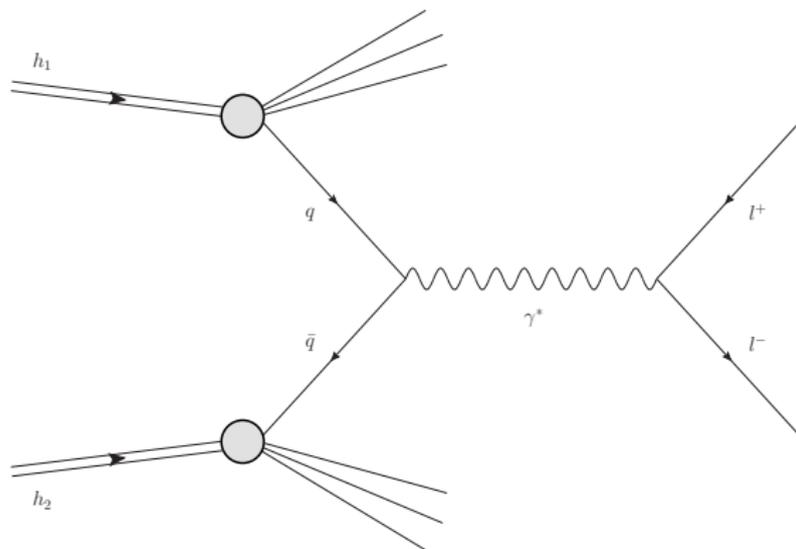
◇ LO QED and QCD (low-M region): $\mathrm{q}(p_1)\,\bar{\mathrm{q}}(p_2) \rightarrow \gamma^*(q) \rightarrow \mathrm{l}^+(l^+)\mathrm{l}^-(l^-)$

◇ NLO QCD: inclusion (anti-)quark–gluon fusion contributions

◇ at low κ_T $\rightarrow$ suitable channel for the **extraction** of TMD PDFs

Forward Drell–Yan process

- LHC, **forward region** $\rightarrow$ $(l^+ l^-)$ produced in the fragmentation region of h_2
  - ◇ Asymmetric configuration: $x_1 \gg x_2$, down to $x_2 \simeq 10^{-6}$
  - $\implies$ **possible small-x resummation effects expected!**

- **small-x** $\rightarrow$ evolution of sea $q\,(\bar{q})$ inside h_2 driven by gluon evolution
  - ◇ Dominance of sea $q\,(\bar{q})$ emerging in the last splitting (suppression of quark propagator at large rapidity)

- **high-energy factorization** $\rightarrow$ gluon exchange in the t-channel
  - ◇ collinear gluon PDF replaced by κ_T-UGD: $x\,g(x, \mu) \rightarrow \mathcal{F}(x, \kappa_T^2)$
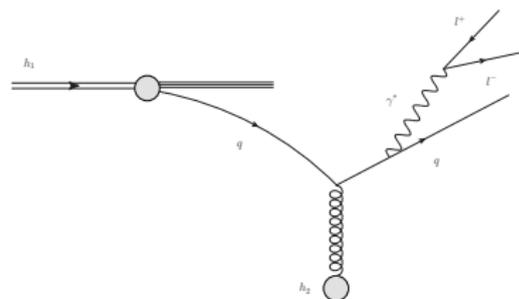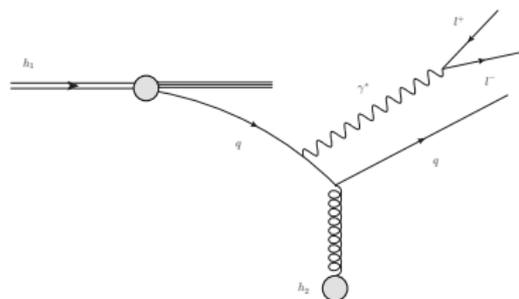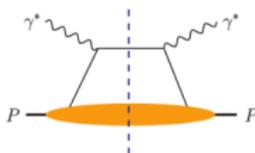
Parton densities: entrée

κ_T-integrated parton densities

► **Collinear PDF factorization**
- inclusive processes
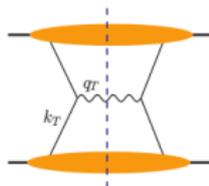- $\kappa_T \sim$ hardest scale

► **GPD factorization**
- exclusive processes
- skewness effects

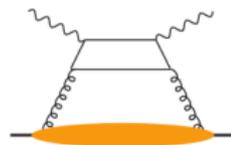κ_T-unintegrated parton densities

► **TMD factorization**
- (semi-)inclusive processes
- $\kappa_T \ll$ hardest scale

► **High-energy (small-x) factorization**
- inclusive or exclusive processes
- **Unintegrated gluon distribution**

Outline

DY: cross section and structure functions

- **Lepton** angular distribution given in terms of *4 independent* **helicity structure functions**, $\mathcal{W}_{[\lambda]}$ (projections of DY amplitudes on virtual photon polarizations)

- Differential cross section as factorization between the lepton pair angular phase space and the structure functions:

$$\frac{d\sigma}{dM\,d\Omega^*_l} \propto \left(1 - \cos^2\vartheta^*\right)\mathcal{W}_{\rm L} + \left(1 + \cos^2\vartheta^*\right)\mathcal{W}_{\rm T}$$

$$+ \left(\sin 2\vartheta^*\cos\varphi^*\right)\mathcal{W}_{\Delta} + \left(\sin^2\vartheta^*\cos 2\varphi^*\right)\mathcal{W}_{\Delta\Delta} \,,$$

$\xrightarrow{\text{where}}$ $d\vartheta^*\,d\varphi^* \equiv d\Omega^*_l$ $\xrightarrow{\text{with}}$ ϑ^* and φ^* the polar and azimuthal angles of the lepton momentum vector in the dilepton center-of-mass frame

[C.S. Lam, W.K. Tung, *Phys. Rev. D* **18** (1978) 2447]
[C.S. Lam, W.K. Tung, *Phys. Rev. D* **21** (1980) 2712]

Forward DY: cross section and structure functions
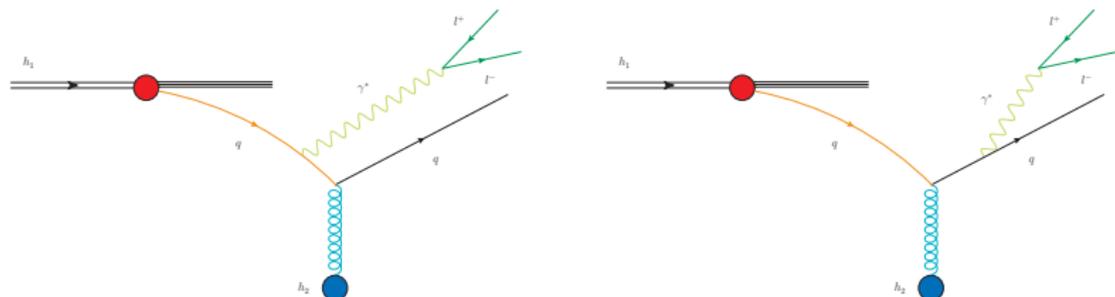
- Helicity structure functions in high-energy factorization:

$$\mathcal{W}_{[\lambda]} = \frac{2\pi M^2}{3} \int_{x_F}^{1} \frac{dz}{z^2} \sum_{r=q,\bar{q}} f_r\left(\frac{x_F}{z}, \mu_F\right) \int \frac{d\kappa_T \, d\phi_{\kappa_T}}{(\kappa_T^2)^2} \, \alpha_s(\mu_R) \, \mathcal{F}(x_g, \kappa_T^2) \, \Phi_{[\lambda]}(q_T, \vec{\kappa}_T, z)$$

- Forward DY **impact factors** known both in κ_T and in the Mellin representation

  (Mellin)   [L. Motyka, M. Sadzikowski, T. Stebel, *JHEP* **05** (2015) 087]

- Interesting channel to probe the **UGD**, $\mathcal{F}(x_g, \kappa_T^2)$, at very small values of x_g

  (Z^0 hadroproduction as a probe of parton κ_T)   [L. Motyka, M. Sadzikowski, T. Stebel, *Phys. Rev. D* **95** (2017) no.11, 114025]

Forward Drell–Yan production | Introduction ○○○○○○ | **Theoretical setup** ○○○●○○ | Results ○○○○○ | Conclusions and Outlook ○○ | Backup

Unintegrated gluon distribution

Hentschinski–Sabio Vera–Salas (HSS) model

▶ <u>Small-x</u> limit: **UGD** = [**BFKL gluon ladder**] ⊛ [**proton impact factor**]

  ◇ takes into account the resummation of high-energy logs

  ◇ describes the coupling of the gluon Green's function to the proton

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► Proton impact factor is non-perturbative $\implies$ UGD needs to be <u>modeled</u>!

◇ parametrization for the proton impact factor:

$$\Phi_{\mathrm{P}}(q, Q_0^2) \equiv \Phi_{\mathrm{P}}^{\mathrm{HSS}}(q, Q_0^2) = \frac{\mathcal{C}}{2\pi\Gamma(\delta)} \left(\frac{q^2}{Q_0^2}\right)^\delta e^{-\frac{q^2}{Q_0^2}}$$

◇ fit to the combined HERA data for the $F_2(x)$ proton structure function

$$Q_0 = 0.28\,\mathrm{GeV}, \qquad \delta = 8.4, \qquad \mathcal{C} = 1.5$$

[A. Sabio Vera, C. Salas, *Phys. Rev. Lett.* **110** (2003) no.4, 041601]

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▶ Former and current analyses:

    ◇ single bottom-quark production at the LHC

        [G. Chachamis, M. Deák, M. Hentschinski, G. Rodrigo, A. Sabio Vera, *JHEP* **1509** (2015) 123]

    ◇ J/Ψ and Υ photoproduction

        [I. Bautista, A. Fernandez Tellez, M. Hentschinski, *Phys. Rev. D* **94** (2016) no.5, 054002]

    ◇ exclusive ρ-meson leptoproduction at HERA   (talk by **A.D. Bolognino**)

        [A.D. Bolognino, F.G. C., D.Yu. Ivanov, A. Papa, arXiv:1808.02395, to appear in *Eur. Phys. J. C*]
        [A.D. Bolognino, F.G. C., D.Yu. Ivanov, A. Papa, in progress]

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Unintegrated gluon distribution

HSS UGD in the Mellin representation (γ-space)

▶ Take the projection onto the eigenfunctions of the LO BFKL kernel...

 ◇ Mellin representation of the proton impact factor:

$$\Pi_P^{\text{HSS}}(\gamma) \equiv \int \frac{d^2\vec{q}}{\pi} \, \Phi_P^{\text{HSS}}(q, Q_0^2) \, (q^2)^{-\gamma-1} = \mathcal{C} \frac{\Gamma(\delta - \gamma)}{2\pi \, \Gamma(\delta)} \, (Q_0^2)^{-\gamma}$$

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▶ ...to get the final expression of the UGD as convoluton in the γ-space:

$$\mathcal{F}(x, \kappa^2, M_h) = \int_{-\infty}^{\infty} \frac{d\nu}{2\pi^2} \, \mathcal{C} \, \frac{\Gamma(\delta - i\nu - \frac{1}{2})}{\Gamma(\delta)} \, \left(\frac{1}{x}\right)^{\chi\left(\frac{1}{2} + i\nu\right)} \left(\frac{\kappa^2}{Q_0^2}\right)^{\frac{1}{2} + i\nu}$$

$$\times \left\{ 1 + \frac{\bar{\alpha}_s^2 \beta_0 \chi_0 \left(\frac{1}{2} + i\nu\right)}{8 N_c} \log\left(\frac{1}{x}\right) \left[-\psi\left(\delta - \frac{1}{2} - i\nu\right) - \log\frac{\kappa^2}{M_h^2} \right] \right\}$$

◇ LO BFKL kernel eigenvalue:

$$\chi_0\left(\frac{1}{2} + i\nu \equiv \gamma\right) = 2\psi(1) - \psi(\gamma) - \psi(1 - \gamma)$$

◇ NLO BFKL kernel eigenvalue (**collinearly improved** and **BLM optimized**):

$$\chi(\gamma) = \bar{\alpha}_s \chi_0(\gamma) + \bar{\alpha}_s^2 \chi_1(\gamma) - \frac{1}{2} \bar{\alpha}_s^2 \chi_0'(\gamma) \chi_0(\gamma) + \chi_{RG}(\bar{\alpha}_s, \gamma)$$

◇ characteristic hard scale, M_h, set equal to the photon invariant mass, M

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LLA BFKL

Forward DY: LLA BFKL model in color dipole

- Factorized expression for the helicity structure functions:

$$
\mathcal{W}_{[\lambda]} = \int_{x_F}^{1} dz \sum_{r=q,\bar{q}} f_r\left(\frac{x_F}{z}, \mu_F\right) \int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \, \hat{\sigma}(\gamma) \left[\frac{z^2 \hat{Q}_0^2}{M^2(1-z)}\right]^{\gamma} \hat{\Phi}_{[\lambda]}(q_T, \gamma, z) \, ,
$$

$\xrightarrow{\text{with}}$ $\hat{Q}_0$ the **scale transform parameter**

- Forward DY **impact factors**, $\hat{\Phi}_{[\lambda]}$, in the Mellin representation (γ-space)

[L. Motyka, M. Sadzikowski, T. Stebel, *JHEP* **05** (2015) 087]

- LLA BFKL model for the **dipole cross section**, $\hat{\sigma}(\gamma)$:

$$
\hat{\sigma}(\gamma) \equiv \hat{\sigma}_{LL}(\gamma) = -\hat{\sigma}_0 \, \Gamma(-\gamma) \, e^{\bar{\alpha}_s \chi_0(\gamma) y} \, ,
$$

$\xrightarrow{\text{with}}$ **rapidity evolution:** $y = \log\left(\frac{x_A}{x_g}\right)$, $x_A = 0.1$ and $x_g = \frac{M^2(1-z)+q_T^2}{s\,x_F\,(1-z)}$

- Parameters fixed by a fit to DIS data (running-coupling effects neglected):

$$
\hat{Q}_0 = 0.51 \, \text{GeV}, \qquad \hat{\sigma}_0 = 17.04 \, \text{mb}, \qquad \bar{\alpha}_s = 0.087
$$

[L. Motyka, M. Sadzikowski, *Acta Phys. Polon. B* **45** (2014) no.11, 2079]

Outline

Forward DY: observables and kinematics

● **Observable:** differential cross section in the dilepton invariant mass, M,

$$\frac{\mathrm{d}\sigma(M)}{\mathrm{d}M} = \int \mathrm{d}\Omega_l^* \int \mathrm{d}x_F \int \mathrm{d}q_T \; \frac{\mathrm{d}\sigma}{\mathrm{d}M \, \mathrm{d}\Omega_l^* \, \mathrm{d}x_F \, \mathrm{d}q_T} \; , \quad \sqrt{s} = 7 \text{ TeV}$$

$\xrightarrow{\text{with}}$ Lorentz boost from the dilepton frame to the collision COM one

$\xrightarrow{\text{to impose}}$ kinematic cuts on dilepton momenta, $l^\pm, l_T^\pm$, and rapidities, $\eta^\pm$

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Numerical analysis

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- **_LHCb_ configuration:** forward-rapidity region, suited to HEF

$$2 < \eta^\pm < 4.5 \;, \quad l^\pm > 10 \text{ GeV} \;, \quad \begin{cases} l_T^\pm > 3 \text{ GeV} & \text{if} \quad M \leqslant 40 \text{ GeV} \\ l_T^\pm > 15 \text{ GeV} & \text{if} \quad M > 40 \text{ GeV} \end{cases}$$

$\xrightarrow{\text{with}}$ dilepton invariant mass in the range: $5.5 \text{ GeV} < M < 120 \text{ GeV}$

[LHCb Collaboration: LHCb-CONF-2012-013, CERN-LHCb-CONF-2012-013]

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- **ATLAS configuration:** central-rapidity region, less accuracy expected

$$|\eta^\pm| < 2.4 \, , \quad l_T^\pm > 6 \text{ GeV} \, , \quad l_T^+ > 9 \text{ GeV} \quad \text{or} \quad l_T^- > 9 \text{ GeV}$$

$\xrightarrow{\text{with}}$ dilepton invariant mass in the range: $12 \text{ GeV} < M < 66 \text{ GeV}$
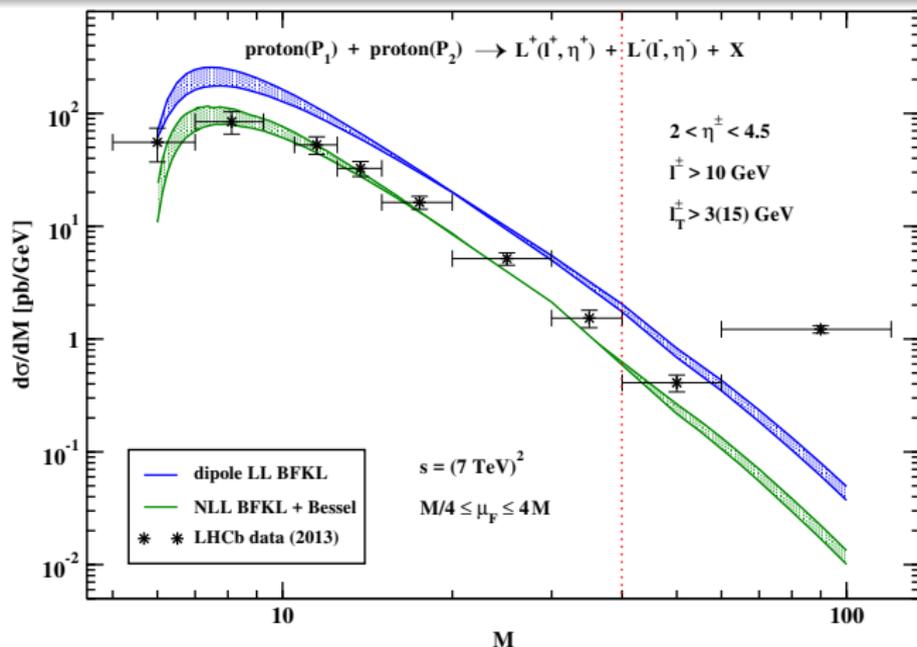
[E. Piccaro, PhD thesis, CERN-THESIS-2012-417]
[ATLAS Collaboration: G. Aad et al., *JHEP* **1406** (2014) 112]

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- ▶ **Technology**: $\mathfrak{Dynamis}$ (**HEP@WORK**, F2008) + LHAPDF + H@W UGD module

[under development]

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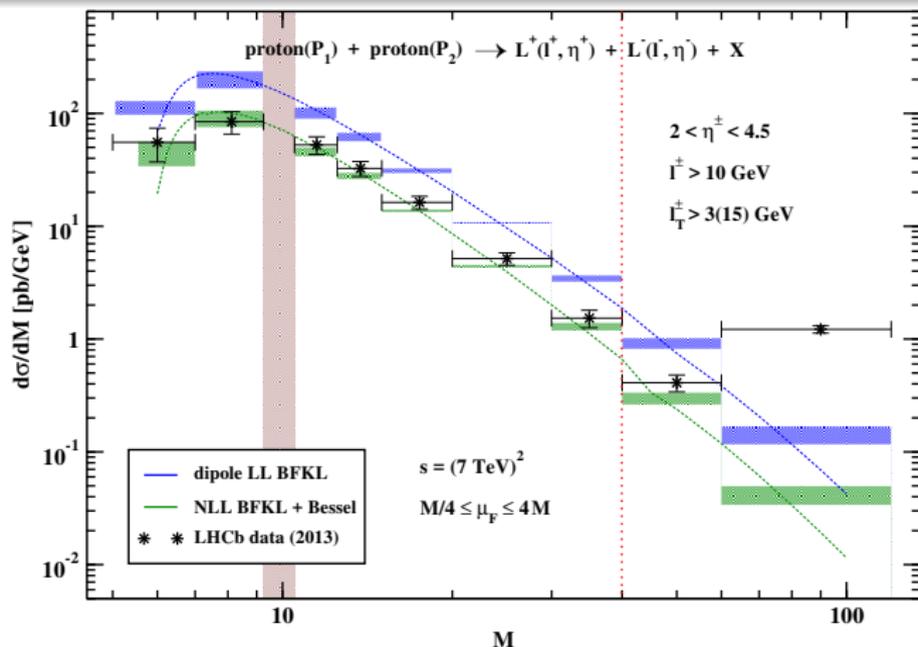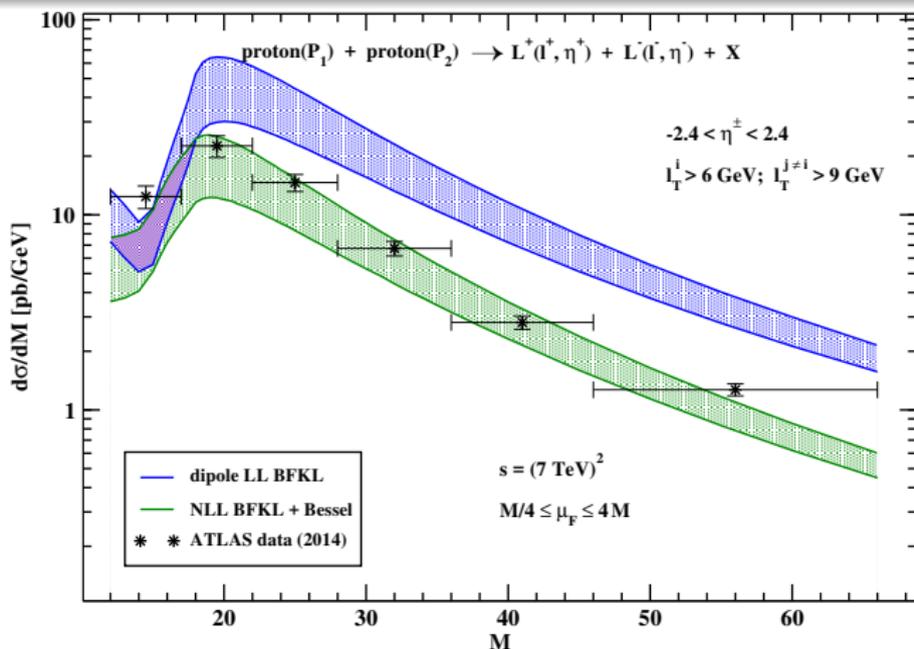# Forward DY: $d\sigma/dM$, **theory vs experiment** [*LHCb*]

[F.G. C., D. Gordo Gómez, A. Sabio Vera (2018)]

◇ LLA results from the BFKL model in the color dipole approach

[D. Brzemiński, L. Motyka, M. Sadzikowski, T. Stebel, *JHEP* **1701** (2017) 005]

◇ Uncertainty bands by allowing μ_F to be in the range: $M/4 \leqslant \mu_F \leqslant 4M$

Forward DY: σ averaged over M-bins [*LHCb*]

proton(P_1) + proton(P_2) $\longrightarrow$ $L^+(l^+, \eta^+)$ + $L^-(l^-, \eta^-)$ + X

$2 < \eta^\pm < 4.5$

$l^\pm > 10$ GeV

$l_T^\pm > 3(15)$ GeV

$s = (7$ TeV$)^2$

$M/4 \leqslant \mu_F \leqslant 4M$

— dipole LL BFKL
— NLL BFKL + Bessel
✳ ✳ LHCb data (2013)

[F.G. C., D. Gordo Gómez, A. Sabio Vera (2018)]

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[F.G. C., D. Gordo Gómez, A. Sabio Vera (2018)]

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Conclusions...

Forward Drell–Yan dilepton production in **high-energy factorization**:

- Good description of $d\sigma/dM$ @LHC in the **BFKL approach**

  $\xrightarrow{\text{with}}$ **UGD model** extracted from a fit to DIS HERA data

  $\xrightarrow{\text{accurately depicts}}$ **small-x evolution** of gluon density in the proton

- Future data for Drell–Yan production in forward directions

  $\xrightarrow{\text{peerless to}}$ gauge need for **high-energy resummation**

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- *Important remarks*:

  ! Same observable well described also by **fixed-order** calculations

  [LHCb Collaboration: LHCb-CONF-2012-013, CERN-LHCb-CONF-2012-013]
  [ATLAS Collaboration: G. Aad et al., *JHEP* **1406** (2014) 112]

  i! Recent studies on helicity amplitudes in ρ-meson leptoproduction

  $\xrightarrow{\text{have shown}}$ high sensitivity to **distinct UGD models** (talk by **A.D. Bolognino**)

  [A.D. Bolognino, F.G. C., D.Yu. Ivanov, A. Papa, arXiv:1808.02395, to appear in *Eur. Phys. J. C*]

Conclusions...

Forward Drell–Yan dilepton production in **high-energy factorization**:

- Good description of $d\sigma/dM$ @LHC in the **BFKL approach**

  $\xrightarrow{\text{with}}$ **UGD model** extracted from a fit to DIS HERA data

  $\xrightarrow{\text{accurately depicts}}$ **small-x evolution** of gluon density in the proton

- Future data for Drell–Yan production in forward directions

  $\xrightarrow{\text{peerless to}}$ gauge need for **high-energy resummation**

- *Important remarks*:

  ! Same observable well described also by **fixed-order** calculations

  [LHCb Collaboration: LHCb-CONF-2012-013, CERN-LHCb-CONF-2012-013]
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  ¡! Recent studies on helicity amplitudes in ρ-meson leptoproduction

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...Outlook

◇ Further channels to trace the path for **UGD extraction** from a **global fit**!

◇ Find and explore common ground between small-x and TMD gluon densities

[A. Bacchetta, F.G. C., P. Taels, in progress]

$\implies$ this is the *beginning* of the story...

dzięki! 😀

BACKUP slides

The unintegrated gluon distribution (UGD)

- ◇ DIS: conventionally described in terms of PDFs

- ◇ less inclusive processes: need to use distributions unintegrated over the parton κ_T

- • <u>example</u>: **virtual photoabsorption** in **high-energy factorization**

$$\sigma_{\text{tot}}(\gamma^* p \to X) \; \propto \; \mathcal{I}m_s\{\mathcal{A}(\gamma^* p \to \gamma^* p)\} \; \equiv \; \Phi_{\gamma^* \to \gamma^*} \; \circledast \; \mathcal{F}(x, \kappa^2)$$

- ◇ $\mathcal{F}(x, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton

- ▶ <u>small-x</u> limit: UGD = [BFKL gluon ladder] ⊛ [proton impact factor]

...UGD has to be modeled!
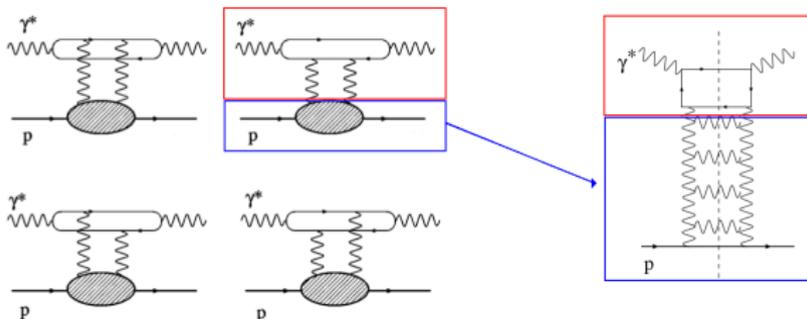
Forward Drell–Yan dilepton production

$$\Phi_L(q_T, \vec{\kappa}_T, z) = \frac{2M^2(1-z)^2 z^2 \left((z\vec{\kappa}_T - 2\vec{q}_T) \cdot \vec{\kappa}_T\right)^2}{[M^2(1-z) + q_T^2]^2 [M^2(1-z) + (\vec{q}_T - z\vec{\kappa}_T)^2]^2} \,,$$

$$\Phi_T(q_T, \vec{\kappa}_T, z) = \frac{1 + (1-z)^2}{2} \left[\frac{(q_T - z\kappa_x)^2 - z^2 \kappa_y^2}{[M^2(1-z) + (\vec{q}_T - z\vec{\kappa}_T)^2]^2} \right.$$
$$\left. + \frac{q_T^2}{[M^2(1-z) + q_T^2]^2} + \frac{2 q_T (z\kappa_x - q_T)}{[M^2(1-z) + q_T^2][M^2(1-z) + (\vec{q}_T - z\vec{\kappa}_T)^2]} \right] \,,$$

$$\Phi_\Delta(q_T, \vec{\kappa}_T, z) = \left(q_T(z\vec{\kappa}_T - 2\vec{q}_T) \cdot \vec{\kappa}_T + \kappa_x(M^2(1-z) + q_T^2) \right)$$
$$\times \frac{M(2-z)(1-z) z^2 (z\vec{\kappa}_T - 2\vec{q}_T) \cdot \vec{\kappa}_T}{[M^2(1-z) + q_T^2]^2 [M^2(1-z) + (\vec{q}_T - z\vec{\kappa}_T)^2]^2} \,,$$

$$\Phi_{\Delta\Delta}(q_T, \vec{\kappa}_T, z) = (z-1) \left[\frac{(q_T - z\kappa_x)^2 - z^2 \kappa_y^2}{[M^2(1-z) + (\vec{q}_T - z\vec{\kappa}_T)^2]^2} \right.$$
$$\left. + \frac{q_T^2}{[M^2(1-z) + q_T^2]^2} + \frac{2 q_T (z\kappa_x - q_T)}{[M^2(1-z) + q_T^2][M^2(1-z) + (\vec{q}_T - z\vec{\kappa}_T)^2]} \right] \,,$$

$\xrightarrow{\text{where}}$ $\kappa_x \equiv \kappa_T \cos\phi_{\kappa_T}$, $\kappa_y \equiv \kappa_T \sin\phi_{\kappa_T}$ and $\vec{q}_T \cdot \vec{\kappa}_T \equiv q_T \kappa_T \cos\phi_{\kappa_T}$

- **Boost parameters** to match kinematic cuts on dilepton phase space:

$$\gamma_B = \frac{x_F \sqrt{s}}{2M} \beta^+ \ , \quad \vec{v}_B = -\left(\frac{\vec{q}_T}{\gamma_B M}, \frac{\beta^-}{\beta^+} \right)_{x,y,z} \ , \quad \text{with} \quad \beta^\pm = 1 \pm \frac{M^2 + q_T^2}{s\, x_F^2}$$

- Expressions for **lepton momenta** and **rapidities** in the collision frame:

$$l^\pm \equiv |\vec{l}^\pm| = E^\pm = \frac{\gamma_B M}{2} \left(1 \mp \vec{v}_B \cdot \vec{u}_{\Omega_l^*} \right) \ ,$$

$$l^{z,\pm} = \frac{M}{2} \left[\pm \cos \theta^* + \gamma_B \frac{\beta^-}{\beta^+} \left(1 \mp \frac{\vec{v}_B \cdot \vec{u}_{\Omega_l^*}}{1 + \gamma_B^{-1}} \right) \right] \ ,$$

$$l_T^\pm \equiv |\vec{l}_T^\pm| = \left(l^\pm \right)^2 - \left(l^{z,\pm} \right)^2 \ , \quad \eta^\pm = \text{arctanh} \frac{l^{z,\pm}}{l^\pm} \ ,$$

$$\xrightarrow{\text{where}} \quad \vec{u}_{\Omega_l^*} \ \text{unit vector pointing in the } \Omega_l^* \text{ direction, and}$$

$$\vec{v}_B \cdot \vec{u}_{\Omega_l^*} = -\frac{\beta^-}{\beta^+} \cos \vartheta^* - \frac{q_T}{\gamma_B M} \sin \vartheta^* \cos \varphi^* \ .$$
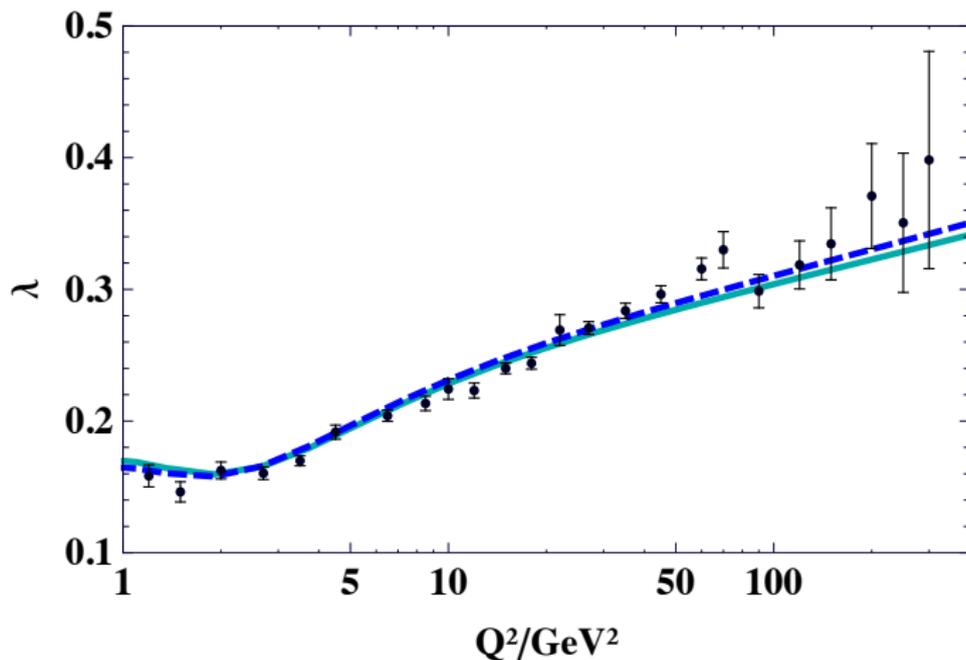
[A. Sabio Vera, C. Salas, *Phys. Rev. Lett.* **110** (2003) no.4, 041601]

◇ Fit of the effective intercept λ in the DIS structure $F_2 \simeq x^{-\lambda(Q^2)}$ for small-x HERA data
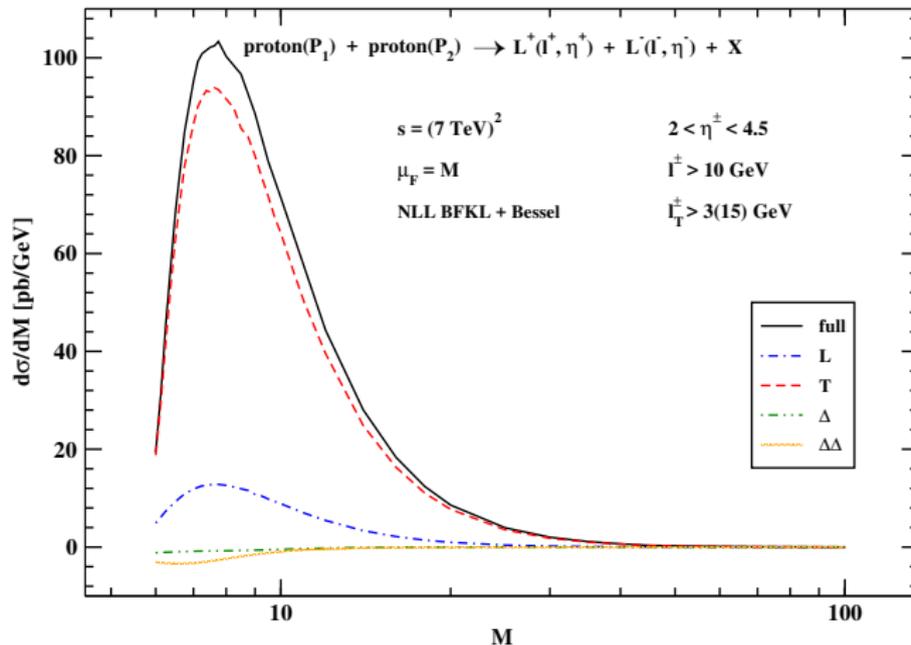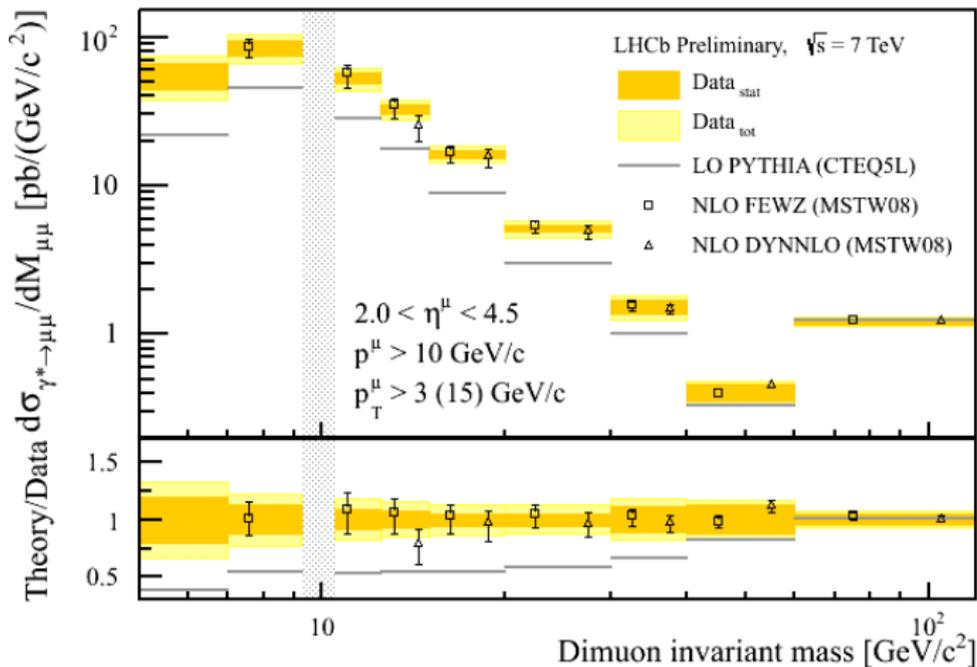
$\diamond$ Dominant contribution given by transversely polarized virtual photons

[LHCb Collaboration: LHCb-CONF-2012-013, CERN-LHCb-CONF-2012-013]
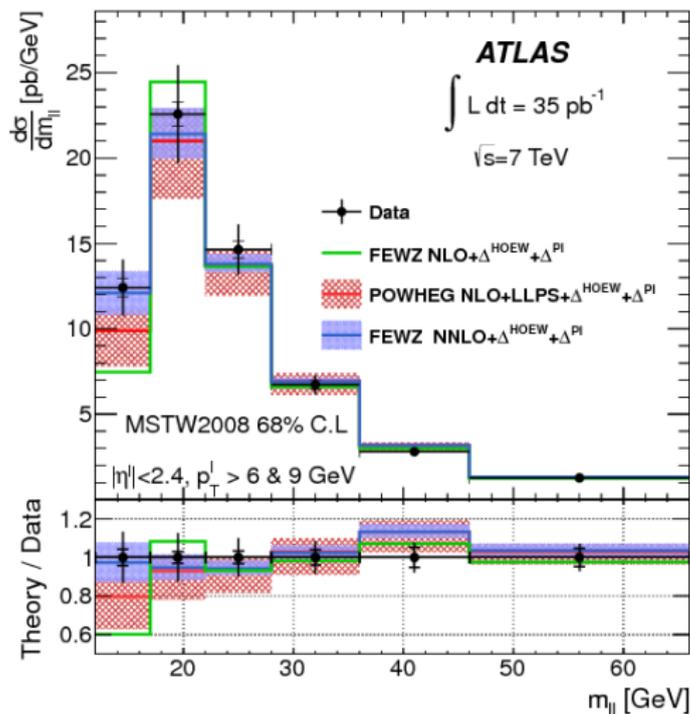
[ATLAS Collaboration: G. Aad et al., *JHEP* **1406** (2014) 112]

Leptoproduction of ρ mesons

Leptoproduction of ρ mesons at HERA

e-p collisions provide:

$$\gamma^* + \text{proton} \longrightarrow \rho + \text{proton} \qquad ...\underline{exclusive}\ process!$$
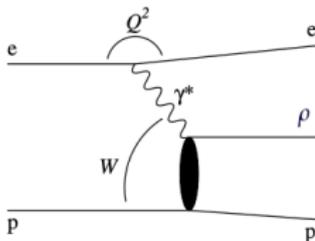
- High-energy regime:
  $$s \equiv W^2 \gg Q^2 \gg \Lambda_{\text{QCD}}^2 \implies \text{small } x = \frac{Q^2}{W^2}$$
- photon virtuality Q is the **hard scale** of the process

▶ **Process solved in helicity** $\implies$ so far **unexplored testfield** for UGD

$\implies$ constrain κ_T-dependence of UGD in the HERA energy range

$$2.5 \text{ GeV}^2 < Q^2 < 60 \text{ GeV}^2$$
$$35 \text{ GeV} < W < 180 \text{ GeV}$$

▶ Hierarchy of helicity amplitudes: $T_{00} \gg T_{11} \gg T_{10} \gg T_{01} \gg T_{1-1}$

[H1 collaboration: F.D. Aaron et al., *JHEP* **05** 032 (2010)]

▶ HERA data available for $\mathbf{T_{11}/T_{00}}$ [H1 collaboration: F.D. Aaron et al., *JHEP* **05** 032 (2010)]

▶ ρ-meson via **distribution amplitudes (DAs)**: $\varphi(y) = \varphi^{\text{WW}}(y) + \varphi^{\text{gen}}(y)$
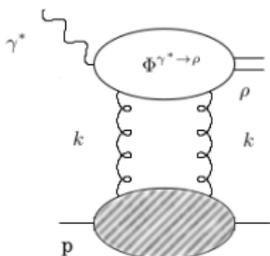
► Leading **helicity amplitudes** are known

Assumption:

- $\mathcal{I}m_s\{\mathcal{A}(\gamma^*p \to \rho\,p)\}$
- same W- and t-dependence for T_{11} and T_{00} $\implies$ high-energy factorization
  - $\to$ same physical mechanism, scattering of small transverse size of dipole on the proton target, at work $\Rightarrow$ high-energy factorization

$$T_{\lambda_\rho \lambda_\gamma}(s;Q^2) = is \int \frac{d^2\kappa}{(\kappa^2)^2} \Phi^{\gamma^*(\lambda_\gamma) \to \rho(\lambda_\rho)}(\kappa^2, Q^2)\, \mathcal{F}(x, \kappa^2), \quad x = \frac{Q^2}{s}$$
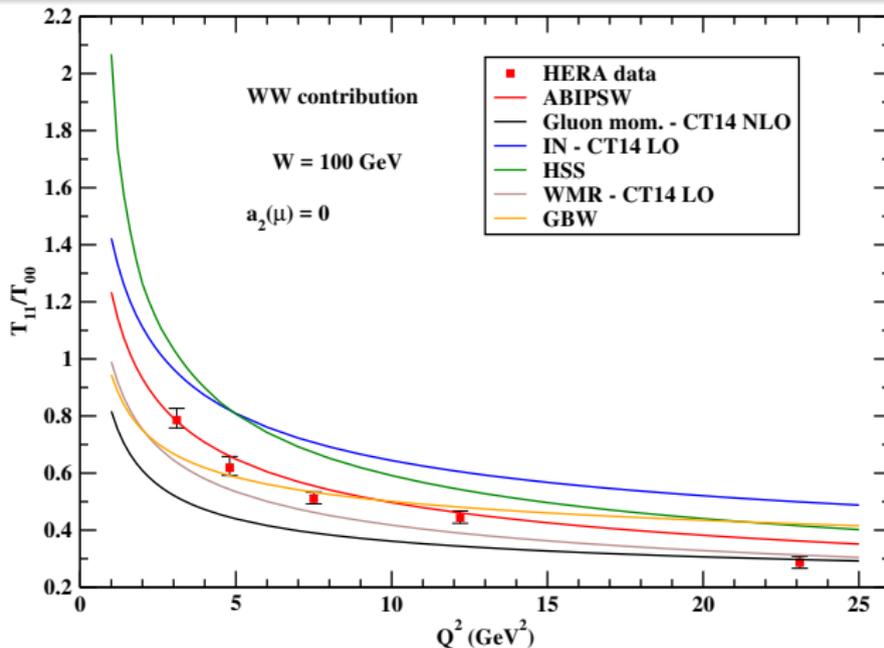

Interesting transitions:

- $\gamma_L^* \to \rho_L \xrightarrow{\text{encoded by}} \Phi^{\gamma_L^* \to \rho_L}$
- $\gamma_T^* \to \rho_T \xrightarrow{\text{encoded by}} \Phi^{\gamma_T^* \to \rho_T}$

$\implies$ **DAs** enter in $\Phi^{\gamma^* \to \rho}$

(preliminary analysis) [A.D. Bolognino, MD thesis (2017)]
[A.D. Bolognino, F.G. C., D.Yu. Ivanov, A. Papa (arXiv:1808.02395 [hep-ph])]

◇ None of the models is able to reproduce data over the entire Q^2-range

◇ x-independent ABIPSW and dipole GBW catch better intermediate-Q^2 data