Leptoproduction of vector meson from the small x to the valence region

Adrien Besse

Irfu - SPhN

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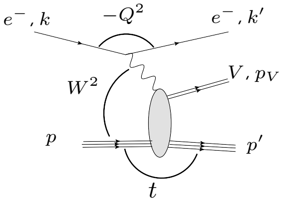
Outline



Hard exclusive vector meson leptoproduction
from small x to the valence region

- Important exclusive process for at least two communities :
  - Small$-x$ community (k_T-factorization, dipole models)
  - GPD community (Collinear factorization framework)
- Comparison between the two descriptions

The hard vector meson electroproduction

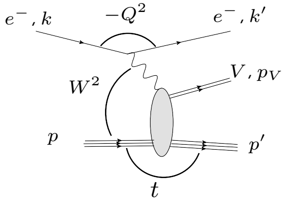
Probing the non-perturbative physics
of the nucleon and the meson

- Information on the nucleon Generalized Parton Distributions (GPDs) :
  - intrinsically non-forward amplitudes : $|t|_{\text{min}} \sim \frac{4\, m^2 \xi^2}{1-\xi^2}$
    $\Rightarrow$ Skewness effects
  - DVMP $\Rightarrow$ scan the flavor content of the nucleon
    (via quark diagram contributions)

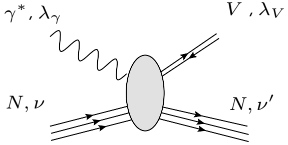
$$\rho = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \quad \phi = s\bar{s}, \quad \omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}), \cdots$$

- Small x : Information on the dipole cross-section $\hat{\sigma}(x, \underline{r})$:
  - Saturation effects and transverse distribution of gluons
  - Skewness factor (Shuvaev, Golec-Biernat, Martin, Ryskin, '99)
- Information on the wavefunction or the distribution amplitudes of the vector meson (VM)

Observables and kinematic ranges

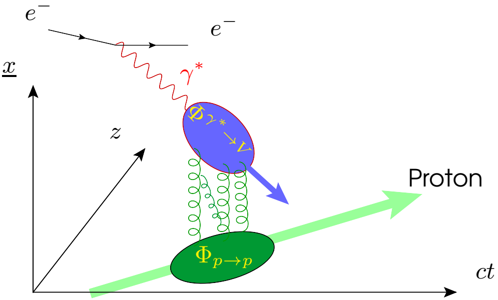


$\rightarrow \mathcal{M}_{V,\{\lambda_V \nu';\lambda_\gamma,\nu\}} =$



- Spin density matrix elements (SDME) linked to the helicity amplitudes : (Schilling Wolf, '73) & (Dielh, '07)
  - small x HERA (H1 and ZEUS)
  - mid-x region: COMPASS, HERMES, E665, NMC
  - valence region: CLAS

Part I : DVMP within k_T −factorization and dipole models



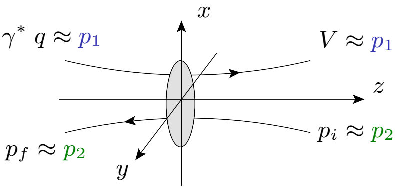
Sudakov Basis

- Light-cone vectors p_1 and p_2 :

$$p_1{}^2 = p_2{}^2 = 0$$

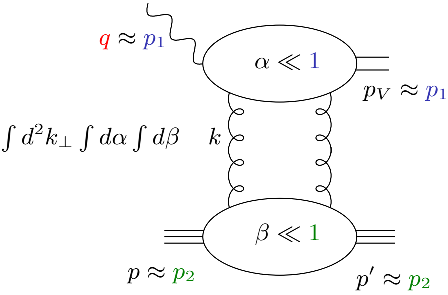
$$2\, p_1 \cdot p_2 = s$$

- We can choose:



- Euclidean notation : $\underline{k}^2 = -k_\perp^2$

- $k = \alpha p_1 + \beta p_2 + k_\perp$



- Writing $g_{\mu\nu} = \frac{p_{2\mu}p_{1\nu}+p_{1\mu}p_{2\nu}}{s/2} + g_{\perp\mu\nu}$
- Eikonal approximation :

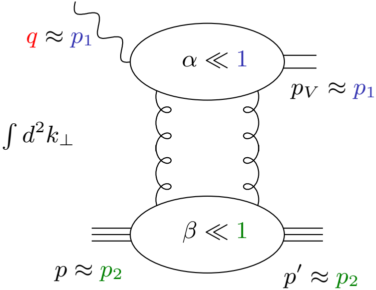
$$\gamma^\mu g_{\mu\nu} \rightarrow \frac{\not{p}_2}{p_1 \cdot p_2} p_{1\nu} + \cdots$$

- Next-to-Eikonal approximation at small-x in pA gluon production
  See talk (T. Altinoluk)

- Impact factor representation of the helicity amplitudes

$$\mathcal{M}_{\lambda_V \lambda_\gamma} = is \int \frac{d^2 \underline{k}}{(2\pi)^2 (\underline{k}^2)^2} \Phi^{\gamma^*(\lambda_\gamma) \rightarrow V(\lambda_V)}(\underline{k}) \; \Phi^{P \rightarrow P}(-\underline{k})$$

- $k = \alpha p_1 + \beta p_2 + k_\perp$



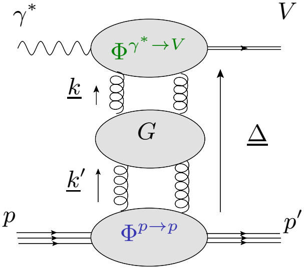
$$\Phi^{\gamma^* \to V}(\underline{k}^2) \propto \int d\beta \mathcal{M}^{\gamma^* g \to V g}(0, \beta, \underline{k})$$

$$\Phi^{P \to P}(\underline{k}^2) \propto \int d\alpha \mathcal{M}^{pg \to pg}(\alpha, 0, \underline{k})$$

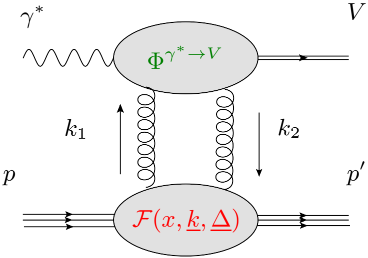
- Impact factor representation of the helicity amplitudes

$$\mathcal{M}_{\lambda_V \lambda_\gamma} = is \int \frac{d^2\,\underline{k}}{(2\pi)^2 (\underline{k}^2)^2} \Phi^{\gamma^*(\lambda_\gamma) \to V(\lambda_V)}(\underline{k})\ \Phi^{P \to P}(-\underline{k})$$

k_T−factorization



$\Rightarrow$



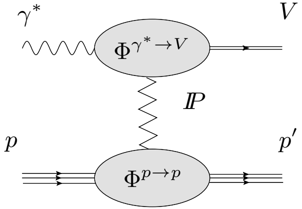
$$\mathcal{M}_{\lambda_V\lambda_\gamma}(s,t) = \frac{is}{(2\pi)^2}\int\frac{d^2\underline{k}}{\underline{k}^2}\Phi^{\gamma^*\to V}(\underline{k},\,\underline{\Delta}-\underline{k})\int\frac{d^2\underline{k}'}{\underline{k}'^2}\Phi^{p\to p}(-\underline{k}',\,-\underline{\Delta}+\underline{k}')$$

$$\times\int_{\delta-i\infty}^{\delta+i\infty}\frac{d\omega}{2\pi i}\left(\frac{s}{s_0}\right)^{\omega}G_\omega(\underline{k},\underline{k}',\underline{\Delta})$$

$$\equiv is\int\frac{d^2\underline{k}}{\underline{k}^2(\underline{\Delta}-\underline{k})^2}\Phi^{\gamma^*\to V}(\underline{k},\,\underline{\Delta}-\underline{k})\mathcal{F}(x,\underline{k},\underline{\Delta})$$

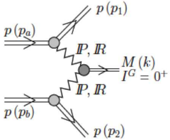
Regge theory point of view

- At high energy (low x)



- Pomeron $I\!P$ exchange in $t-$channel
- Pomeron contains the $s-$dependence
- Fits (Donnachie, Landshoff, '92) of experimental data $\Rightarrow$ Pomeron intercept $\alpha_P(0) = 1.08 \Leftrightarrow \sigma_{tot} \propto s^{0.08}$!

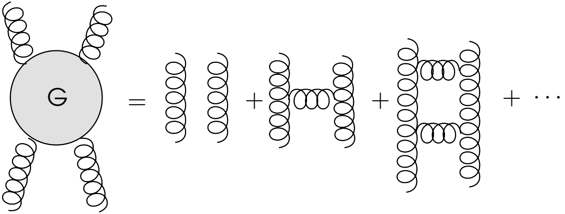
- Pomeron couplings to hadrons:



Double Pomeron exchange in central meson production
See talk (P. Lebiedowicz)

BFKL resummation

- Resummation in $\alpha_s \ln(s)$:

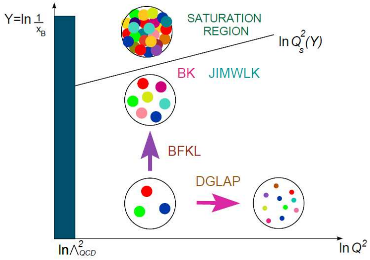


$$= \alpha_s \sum_n (\alpha_s \ln(s))^n$$

- BFKL equation Balitsky, Fadin, Kuraev, Lipatov, '77, '78
- LO BFKL solution = LLx Hard QCD Pomeron leads to $\sigma_{tot} \sim s^{\alpha_P - 1}$ with $\alpha_P > 1$ Pomeron intercept
- Probing BFKL dynamics in Mueller-Navelet jets
  See talks. (B. Ducloué), (R. Maciula), (G. Safronov)
- NLLx evolution $\Rightarrow$ NLLx impact factors :
  Heavy quark NLLx impact factors : See talk (M. Deak))

Saturation and pQCD evolution equations

- QCD evolution equations



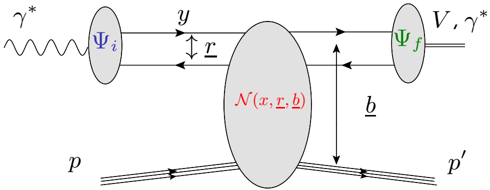
- Q^2 evolution driven by DGLAP equation Dokshitzer-Gribov-Lipatov-Altarelli-Parisi, '72, '77
- small x evolution driven by BFKL equation in the diluted regime and BK-JIMWLK equation in the dense regime (Balitsky-Kovchegov '96, Jalilian-Marian-Iancu-McLerran-Weigert-Leonidov-Kovner, 97', '99, '01) .

- Low-x evolution equations:
  See talks : (K. Kutak) (gluon evolution at strong coupling), (G. Beuf) (Improv. Kinematics), (Y. Mulian) (NLO JIMWLK)

- Dipole model approach, a convenient scheme to introduce saturation effects

Color dipole factorization scheme

- Impact parameter space representation of the amplitudes in the infinite momentum frame
  Nikolaev, Zakharov, '91, Mueller, '90



  - Initial Ψ_i and final Ψ_f states wave functions.
  - Universal dipole/target scattering amplitude $\mathcal{N}(x, \underline{r}, \underline{b})$:
    - DIS structure functions, DIS diffractive, exclusive processes ..
    - See talk (H. Mäntysaari): initial condition for the dipole scattering amplitude from DIS

- Amplitude for DVMP (Kowalski, Motyka, Watt, '06):

$$\mathcal{M}_{\lambda_V \lambda_\gamma}(Q^2, x, t) = is \int dy \int d\underline{r} \int d^2\underline{b}\, \Psi^*_{\lambda_V}(y, \underline{r})\, \Psi_{\lambda_\gamma}(y, \underline{r})\, e^{-i(\underline{b}-\bar{y}\underline{r})\cdot\Delta} \mathcal{N}(x, \underline{r}, \underline{b})$$

  Next talk: dipole models with $\underline{b}-$dependence (A. Rezaeian)

- In the limit $\underline{\Delta} = 0$, i.e. $|t| = |t|_{min}$,

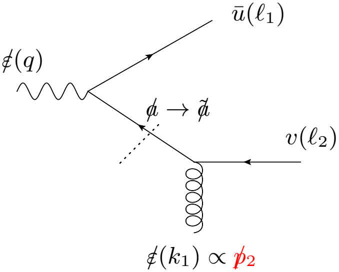
$$\mathcal{M}_{\lambda_V \lambda_\gamma}(Q^2, x) = is \int dy \int d\underline{r}\, \Psi^*_{\lambda_V}(y, \underline{r})\, \Psi_{\lambda_\gamma}(y, \underline{r})\, \hat{\sigma}(x, \underline{r})$$

- Dipole cross-section and unintegrated gluon density at Born level

$$\hat{\sigma}(x, \underline{r}) = \frac{N^2-1}{4} \frac{4\pi\alpha_s}{N} \int d^2\underline{k} \frac{1}{(\underline{k}^2)^2} \mathcal{F}(x, \underline{k}) \left(1 - e^{-i\underline{k}\cdot\underline{r}}\right) \left(1 - e^{i\underline{k}\cdot\underline{r}}\right)$$

- Skewness effects can be taken into account in dipole cross-section model (Shuvaev, Golec-Biernat, Martin, Ryskin, '99)

Factorization of the wavefunctions and models



- Eikonal approximation leads to (Anikin, Wüsthof, '99)

$$\not{a}\, \not{p}_2 \to \not{\tilde{a}}\, \not{p}_2 \propto v(\tilde{a})\bar{v}(\tilde{a})\, \not{p}_2\,, \text{ such that } \tilde{a}^2 = 0$$

- The wavefunction factorizes

$$\Psi_{\gamma^*}(y, \underline{\ell}) \propto \frac{\bar{u}(\ell_1)\not{\epsilon}(q)v(\tilde{a})}{a^2 + i\epsilon}\Big|_{\ell_1 = y p_1 + \ell_\perp + \frac{\underline{\ell}^2}{2ys} p_2}$$

- Vector meson wavefunction: need to be modeled
  See talk (M. Djuric) on nucleon and meson holographic wavefunctions in ADS

Dipole models

Models of dipole cross-section

- Small$-x$ evolution
  - Initial condition for the dipole cross-section at a given rapidity from DIS structure functions
  - Evolution with rc-BK equation (Balitsky, '07)

  See talk (H. Mäntysaari) for details

- DGLAP evolution (Bartels, Golec-Biernat, Kowalski, '02)

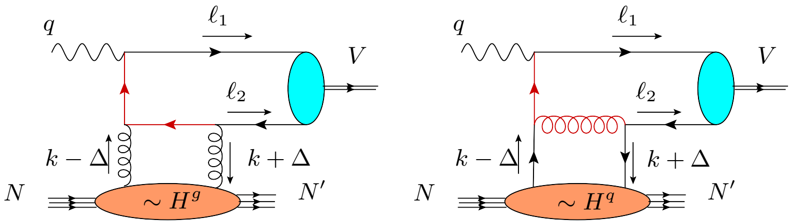
$$\hat{\sigma}(x, \underline{r}) = \sigma_0 \left(1 - \exp\left\{-\frac{\pi^2 \, \underline{r}^2 \, \alpha_s(\mu^2(\underline{r}^2)) \, xg(x, \mu^2(\underline{r}^2))}{3\sigma_0}\right\}\right)$$

  See talk (Kowalski) for details

Part II : Modified perturbative approach and connection to dipole models

Description of exclusive processes within
Collinear factorization approach

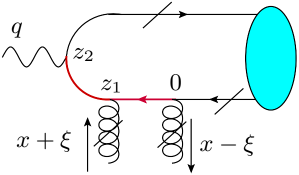
- Description of DVMP, DVCS, TCS, ... in the Bjorken limit
- Collinear factorization proven for LT amplitude $\mathcal{M}_{V,\{0+;0+\}}$
  (Collins, Frankfurt, Strikman, '97, Radyushkin, '97)
- Set of GPDs, $H(x,\xi,t)$, $E(x,\xi,t)$, $\tilde{H}(x,\xi,t)$, $\tilde{E}(x,\xi,t)$
- Quark and Gluon contributions:



Gluon contribution in MPA

$$\ell_q = y p_1 + \ell_\perp + \frac{\underline{\ell}^2}{2sy} p_2$$

$$\mathcal{M}_V^g = \int dx \int dy \int \frac{d^2 \underline{\ell}}{(2\pi)^2}$$

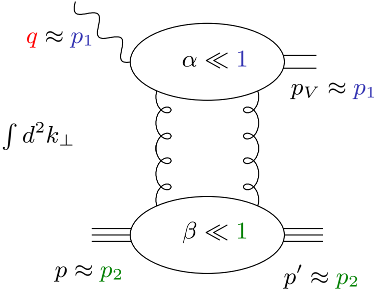


$$\langle V(p_1)|\, \bar{\psi}_i(z_2)\psi_j(0)\, |0\rangle \to \not{p}_{1,ij}\, \Psi_V(y, \ell_\perp)$$

$$\langle N(p')|\, \not{A}(z_1)\not{A}^*(0)\, |N(p)\rangle \to \sum_\lambda \not{\epsilon}_\perp^{(\lambda)} \not{\epsilon}_\perp^{(\lambda)*} \frac{H^g(x,\xi,t)}{x^2-(\xi-i\epsilon)^2}$$

- Neglect then $\frac{\ell_\perp^2}{y\bar{y}Q^2}$ terms in numerator in the MPA spirit
- Fourier transform in transverse space → impact parameter space
- Sudakov form factor (Sterman, Li ,'92)
  (Resums soft gluon emmisions from the quark-antiquark dipole)

- $k = \alpha p_1 + \beta p_2 + k_\perp$



$$\Phi^{\gamma^* \to V}(\underline{k}^2) \propto \int d\beta \mathcal{M}^{\gamma^* g \to V g}(0, \beta, \underline{k})$$

$$\Phi^{P \to P}(\underline{k}^2) \propto \int d\alpha \mathcal{M}^{pg \to pg}(\alpha, 0, \underline{k})$$

- Impact factor representation of the helicity amplitudes

$$\mathcal{M}_{\lambda_V \lambda_\gamma} = is \int \frac{d^2 \underline{k}}{(2\pi)^2 (\underline{k}^2)^2} \Phi^{\gamma^*(\lambda_\gamma) \to V(\lambda_V)}(\underline{k}) \; \Phi^{P \to P}(-\underline{k})$$

Dipole model vs MPA results

Results in the two different approaches in the limit $t \sim 0$

- MPA result for the helicity amplitude $\gamma_L^* \, N(p) \to V_L \, N(p')$ (A.B. in preparation):

$$\mathcal{I}m \, \mathcal{M}^g_{V,\{0+,0+\}} = -\int_0^1 dy \int d^2\underline{r} \sum_f C_V^f \left(\hat{\Psi}_V(y,-\underline{r}) \hat{\Psi}^f_{\gamma_L^*}(y,\underline{r}) \right) \times \left(\frac{\pi\sqrt{2\pi}}{N_c \, y\bar{y}} \alpha_s \frac{H^g(\xi,\xi,0)}{2\xi} \right)$$

- k_T-factorization result for the helicity amplitude $\gamma_L^* \, N(p) \to V_L \, N(p')$: (A.B., Szymanowski, Wallon, '13)

$$\mathcal{I}m \, \mathcal{M}^g_{V,\{0+,0+\}} = -\int dy \int d^2\underline{r} \sum_f C_V^f \left(\hat{\Psi}_V(y,-\underline{r}) \hat{\Psi}^f_{\gamma_L^*}(y,\underline{r}) \right) \times \left(\frac{s \, \hat{\sigma}(x,\underline{r})}{2\sqrt{2\pi}} \right)$$

- At small$-x$: $\xi \approx x/2$

Interpretation

- Forward dipole cross-section (Frankfurt, Radyushkin, Strikman, '97) :

$$\hat{\sigma}(x, \underline{r}) = \frac{\pi^2}{N_c} \underline{r}^2 \, \alpha_s \, xg(x) \qquad \text{(color transparency)}$$

- Comparing the results for DVMP:

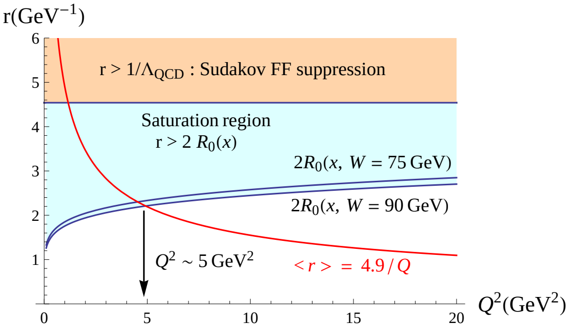
$$\hat{\sigma}(x, \underline{r}) \leftrightarrow \frac{\pi^2}{N_c} \left(\frac{4}{y\bar{y}Q^2} \right) \alpha_s H^g(\xi, \xi, 0) = \frac{\pi^2}{N_c} \underline{r}_0^2 \, \alpha_s H^g(\xi, \xi, 0)$$

with $\underline{r}_0^2 = \frac{4}{y\bar{y}Q^2}$

- Evaluating the average $<\underline{r}_0^2>$ over the amplitude $\Rightarrow\ \sqrt{<\underline{r}_0^2>} \sim \frac{4.9}{Q}$
- When does the average size of dipole $<r_0^2>$ enter the saturation region ?

$$\hat{\sigma}(x,\underline{r}) = \sigma_0 \left(1 - e^{-\frac{\underline{r}^2}{4R_0^2(x)}}\right)$$

, saturation for $|\underline{r}| > 2R_0(x)$
(Golec-Biernat,Wüsthof, '98)



- $<r_0^2>\sim$ independent on the normalization of the wavefunctions.

Beyond the imaginary part of gluon contribution in MPA

Contribution from gluons and quarks

- Within MPA : real and imaginary parts of gluon and quark contributions
- Replacement
  (extracting the flavor dependence of the overlap of wavefunction):

$$\sum_f e_f C_V^f \; \hat{\sigma}(x, \underline{r})$$

$$\longleftrightarrow \sum_f e_f C_V^f \; \frac{\pi^2}{N_c} \left(\frac{4}{y\bar{y}Q^2}\right) \alpha_s \left\{ \int_0^1 dx \frac{2\xi H^g(\xi,\xi,t) + 2\,x\,C_F\,\xi H^f_{\text{singlet}}(\xi,\xi,t)}{(x-\xi+i\epsilon)(x+\xi-i\epsilon)} \right\}$$

- Same $\underline{r}_0^2 = \frac{4}{y\bar{y}Q^2}$ for quark and gluon contribution.

Model dependences

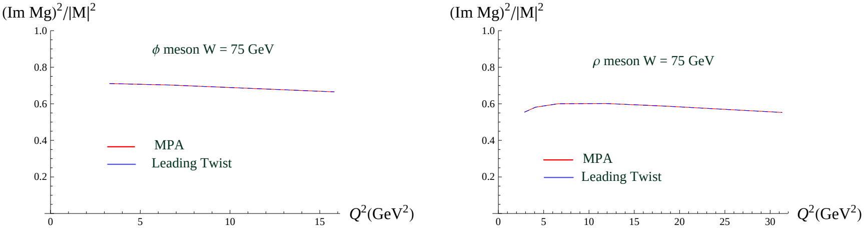
- Models and parameters from (Kroll, Goloskokov, '08) for :
  - GPDs with evolution approximated by the DGLAP evolution
  - Wavefunctions model (Gaussian ansatz)

$$\hat{\Psi}_V(y, \underline{r}) \propto \text{ Leading twist DA } \times \exp\left(-\frac{\underline{r}^2}{4a_V^2} y\bar{y}\right)$$

- Kroll&Goloskokov GPD model based on double distribution ansatz (Musatov, Radyushkin, '00)

$$H(x,\xi) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta + \xi\alpha - x)\, f(\beta, \alpha, t')$$

Contributions of other amplitudes

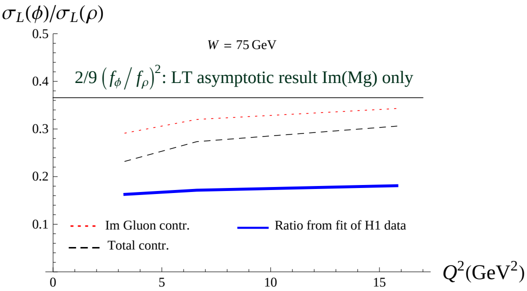


$(\mathcal{I}m\,\mathcal{M}_V^g)^2 \,/\, |\mathcal{M}_V|^2 \sim 70\%$ $\qquad$ $(\mathcal{I}m\,\mathcal{M}_V^g)^2 \,/\, |\mathcal{M}_V|^2 \sim 60\%$

- Sea quark contribution (via interference term) not negligeable in MPA approach with GK GPDs based on (CTEQ6M, '02) fits ($10^{-4} < x < 0.5$ and $4 < Q^2 < 40$ GeV^2)

Ratio ϕ over ρ

Ratio $\sigma_L(\phi)/\sigma_L(\rho)$



Data fitted from H1 (Aaron et al., '10)

- Red curve : $\sim |\mathcal{I}m\,\mathcal{M}^g_\phi|^2/|\mathcal{I}m\,\mathcal{M}^g_\rho|^2$
- Black curve : $\sim |\mathcal{M}^g_\phi|^2/|\mathcal{M}^g_\rho|^2$
- No additional factor from the normalization of the ϕ and ρ wavefunctions
- Quark GPD contributions $\Rightarrow$ decreases the ratio of $\sigma_L(\phi)/\sigma_L(\rho)$

Summary

From small x region to valence region

- Results for $\mathcal{M}_{V,\{0,+;0+\}}$ in MPA exhibits the factorization of the overlap of the wavefunctions as in the dipole model picture allowing to link the MPA result to the dipole cross-section.
- Perspectives:
  - Other Helicity amplitudes : $\mathcal{M}_{V,\{++,++\}}$, ...
  - PARTONS (PARtonic Tomography Of Nucleon Software) project (collaborations between CPhT, IPN, Irfu, LPT):
    - Software to extract of GPDs from observables with uncertainties on parameters
    - with systematic comparison between theoretical GPD related predictions and data
    - experimental results and theoretical predictions databases
  - Preliminary work on the DVMP observables
    - Descriptions of other helicity amplitudes with Natural (N) and Unatural parity exchange (U) ⇒ Sensitivity to other GPDs such as $\mathcal{M}^U_{V,\{++,++\}} \sim \tilde{H}$,

$$\mathcal{M}^N_{V,\{\mu+,\mu+\}} \sim H(x,\xi,t') \qquad \mathcal{M}^U_{V,\{++,++\}} \sim \tilde{H}(x,\xi,t')$$
$$\mathcal{M}^N_{V,\{\mu-,\mu+\}} \sim E(x,\xi,t') \qquad \mathcal{M}^U_{V,\{+-,++\}} \sim \tilde{E}(x,\xi,t')$$

      related to SDME and spin asymmetries.
    - Implementation of NLO GPD evolutions

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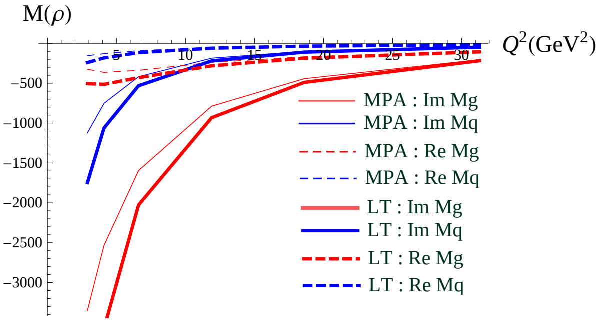
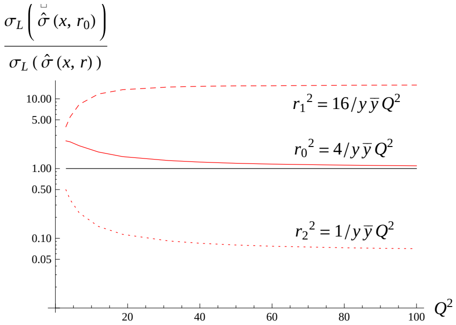
L. Szymanowski
S. Wallon

Contributions of other amplitudes



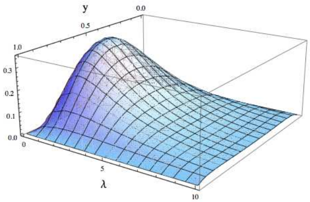
Large Q^2 limit check

- $\sigma_L \propto \left| \int dy \int d^2\underline{r}\, (\Psi_V^* \Psi_\gamma)\, (y, \underline{r})\, \hat{\sigma}(x, r) \right|^2$
- Expect to find same numerical values at large Q^2 using :
  - a dipole cross-section model (here GBW model, (Golec-Biernat, Wüsthof, '98)): $\hat{\sigma}(x, r) = \sigma_0 (1 - e^{-r^2/(4R_0(x)^2)})$
  - a dipole cross-section model with $\underline{r}^2 \to \underline{r}_0^2 = \frac{4}{y\bar{y}Q^2}$



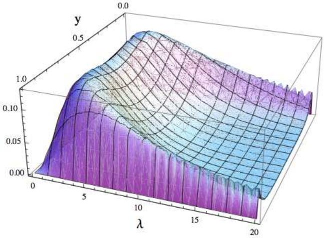
Transversely polarized cross-section

- Helicity amplitude $\mathcal{M}_{V,\{++,++\}}$ within MPA .. under study
- The overlap of wavefunctions appearing within k_T-factorization $\Psi_V^*(y,\underline{r})\Psi_{\gamma^*}(y,\underline{r})$:



$\lambda_\gamma = \lambda_V = 0$

Leading twist DA



$\lambda_\gamma = \lambda_V = \pm$

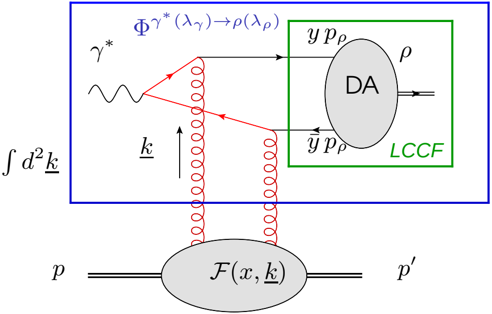
Twist 3 combination of DAs

(in Wandzura-Wilczek approx.)

(A.B., Szymanowski, Wallon, '13)

- Expected to be sensitive to the Sudakov form factor suppression

Factorization of helicity amplitudes



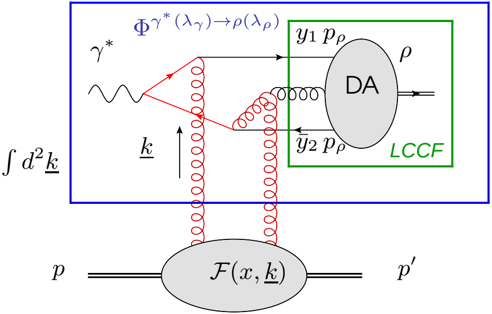
- Twist 2:
  - $\gamma_L^* \to \rho_L \; (\equiv T_{00})$
  - $\gamma_T^* \to \rho_L \; (\equiv T_{01})$

  Ginzburg, Panfil, Serbo, '85

- Twist 3, in the limit $t \sim 0$:
  - $\gamma_T^* \to \rho_T \; (\equiv T_{11})$

  Anikin, Ivanov, Pire, Szymanowski, Wallon, '10

Factorization of helicity amplitudes



- Twist 2:
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  Anikin, Ivanov, Pire, Szymanowski, Wallon, '10