Diffractive Production of Vector Mesons & the gluon at small x

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I. Why study $\gamma^* p \to V\, p$?

II. Theoretical Description in QCD (à la MRT using Parton Hadron Duality)

– unintegrated gluon $f(x, k_T^2)$ (k_T factorization)

– skewing corrections, IR regime, K factor

III. Results à la MRT for J/ψ:

– how relevant are the Skewing corrections?

– which scales; IR 'pollution'?

IV. Data vs TH: constraining $f(x, k_T^2)$ via diffr. VM production. Conclusions

I. Why study $\gamma^* p \to V\, p$

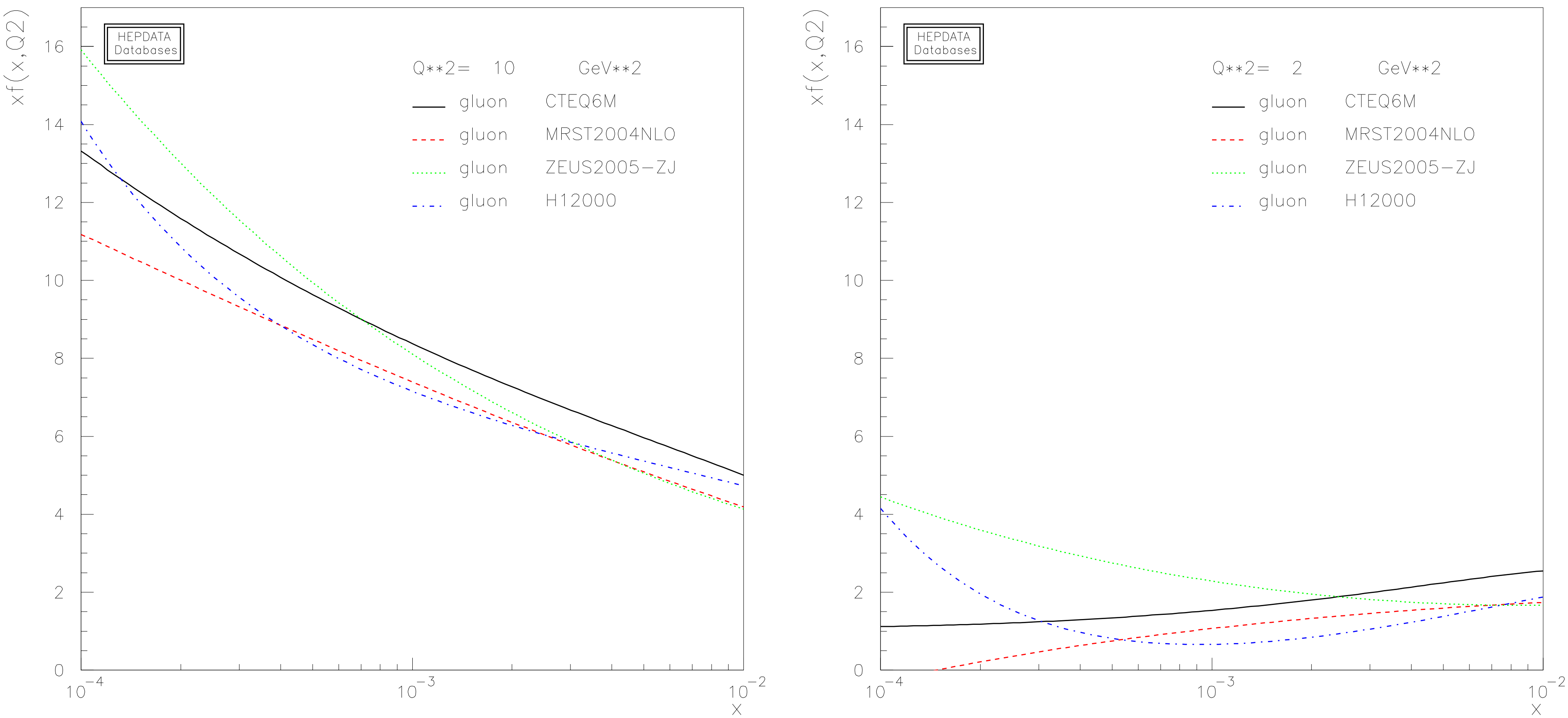
- Lots of data from HERA with increased accuracy and in a wider range of phase space (W, Q^2, M_V^2, t); diffraction at hadron colliders, ILC, ...
- Challenge to understand diffractive scattering *quantitatively*
- Chance to learn about *QCD dynamics in the semi-hard regime*
- $\sigma(\gamma^* p \stackrel{I\!P \sim 2g}{\longrightarrow} V\, p) \sim [xg(x, scale)]^2$: *constrain the gluon distribution* at small x and small-to-intermediate scales

  $\rightsquigarrow$ regime for diffractive Higgs at LHC!

  $\rightsquigarrow$ relevant for description of Underlying Events at LHC, ...

  $\longrightarrow$ Currently the (global) fits are only poorly constrained in this regime:

CTEQ6M, MRST2004, ZEUS-2005 and H1-2000 gluon fits:



→ Sizeable differences even at moderately small scales.

→ At small scales even the shapes are very different!

→ Negative gluon at small x ?!

II. Theoretical description of $\gamma^* p \to V\, p$ in QCD

- Recent TH-predictions go beyond the original LO formula

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p \to V p)\Big|_{t=0} = \frac{\Gamma_{ee}^V M_V^3 \pi^3}{48\alpha} \frac{\alpha_s(\overline{Q}^2)^2}{\overline{Q}^8} \left[x\, g(x, \overline{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_V^2}\right)$$

with the *effective scale* $\overline{Q}^2 = \left(Q^2 + M_V^2\right)/4$. (Non-relativistic limit.)

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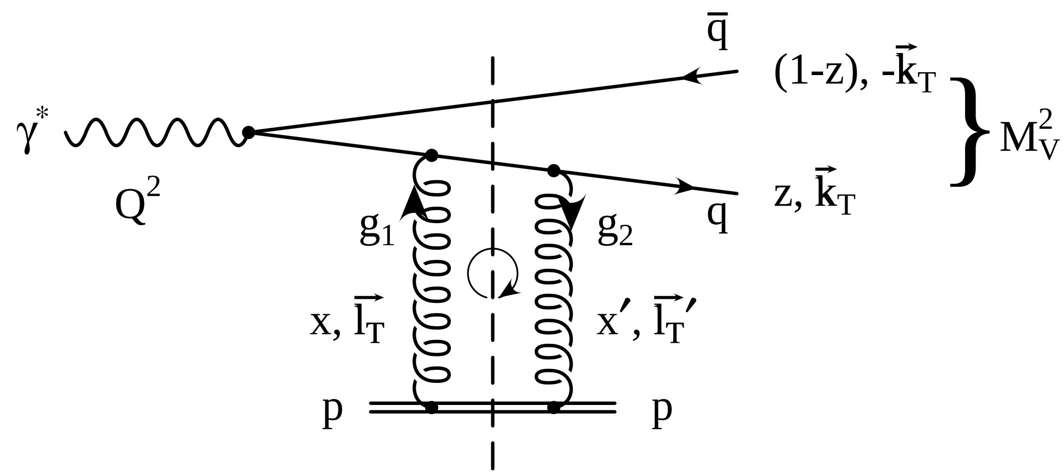
▶ Allow for transverse momentum $\boldsymbol{k_T}$ of $q,\bar{q}$, avoiding the non-rel. limit.

▶ Take into account $x \neq x'$ $\rightsquigarrow$ skewing effects (see below), $\mathcal{A} \sim$ generalized PDF.



▶ Allow for transverse momentum $\boldsymbol{\ell_T}$ of the gluons $\rightsquigarrow$ 'ℓ_T' factorization:

k_T (ℓ_T) factorization formula with unintegrated gluon:

$$\mathcal{A}(\gamma^*_{L,T}\,p \to q\bar{q}\,p) = \int_0^\infty \frac{\mathrm{d}\ell_T^2}{\ell_T^4}\,\alpha_s(\ell_T^2)\,f(x,x',\ell_T^2)\,\phi^{L,T}(Q^2,m^2,k_T^2,z,\ell_T^2)$$

- In the LLA formula the ℓ_T of the gluons is neglected ($\ell_T^2 \ll \bar{Q}^2 + k_T^2$):

$$\mathcal{A}^{LLA} \sim \frac{\alpha_s(K^2)}{K^2}\int^{K^2}\frac{\mathrm{d}\ell_T^2}{\ell_T^2}\,f(x,\ell_T^2) = \frac{\alpha_s(K^2)}{K^2}\,xg(x,K^2)$$

($K^2 = z(1-z)Q^2 + k_T^2 + m^2$)

$\longrightarrow$ Numerically this is a poor approximation!

k_T (ℓ_T) factorization formula with unintegrated gluon:

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- Unintegrated from integrated gluon: $f(x, \ell_T^2) = \left.\frac{\partial[xg(x,q_0^2)T(q_0^2,\mu^2)]}{\partial \ln q_0^2}\right|_{q_0^2=\ell_T^2}$

  [The *Sudakov* factor $T = \exp[\frac{-C_A \alpha_s(\mu^2)}{4\pi} \ln^2 \frac{\mu^2}{q_0^2}]$ resums virtual corrections; *probability for no gluon emission* in the interval $q_0^2 < q_T^2 < \mu^2 \sim (Q^2 + M^2)/4$.]

- At small $\ell_T^2 < \ell_0^2 \sim 2$ GeV^2 (IR regime) MRT use the 'linear' appr.:

$$\alpha_s(\ell_T^2) g(x, \ell_T^2) = (\ell_T^2/\ell_0^2)\alpha_s(\ell_0^2) g(x, \ell_0^2)$$

  Alternatively: neglect ℓ_T dep. in $\phi \rightsquigarrow$ similar IR contribution, see below.

Skewing (or off-diagonal) effects:

- Momentum fractions satisfy: $x \simeq \frac{Q^2+M^2}{W^2+Q^2} \gg x' \simeq \frac{\ell_T^2}{W^2+Q^2}$
- In this regime the skewed (integrated) gluon $H_g(x,x')$ is enhanced through the *off-diagonal evolution* by → Shuvaev et al.

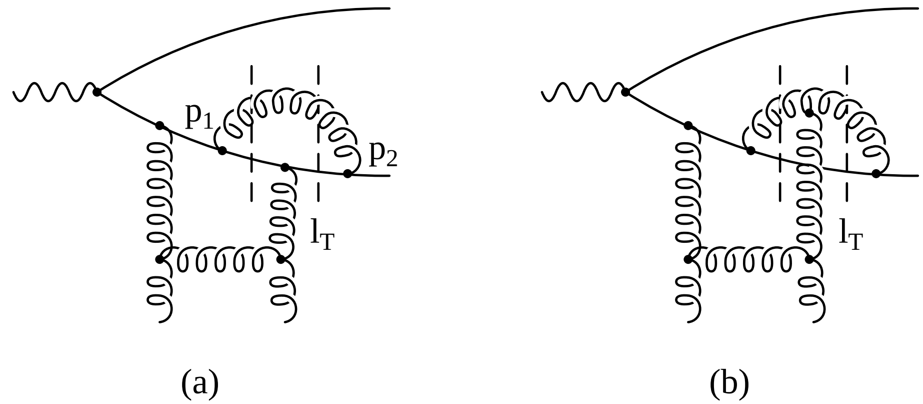
$$R_g = \frac{H_g(x, x' \ll x)}{H_g(x,x)} = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + \frac{5}{2})}{\Gamma(\lambda+4)}$$

- The *effective power* $\lambda(Q^2)$ of the gluon [assuming $xg \sim x^{-\lambda}$] is calculated numerically for all amplitudes $\mathcal{A}^{L,T}$: $\lambda = \frac{\partial \log \mathcal{A}^{L,T}}{\partial \log(1/x)}$.

→ Note: R_g is a leading $\ln Q^2$ effect and can be sizeable when the gluon is sampled at 'large' scales (for large Q^2 or M^2), e.g. $R_g^2 \sim 2$ for Υ photoproduction at HERA.

K factor:

Important missing ingredient for a full NLO prediction: One loop corrections to the $[(q\bar{q})(2g)]$ vertex



- Typically lead to a significant enhancement in the normalization of QCD processes $\longrightarrow$ K *factor* (may also be fitted from data)
- Up to now no full calculation within k_T factorization
- MRT estimate the K factor from π^2 enhanced terms, analogous to the well known corrections in Drell-Yan $\rightsquigarrow$ $\sigma = \sigma^0 \exp[\pi^2 C_F \alpha_s(..)/\pi]$.*
- First results for diagrammatic calculation for $\mathcal{A}^L$ by D.Yu. Ivanov et al..

* Exp. of the double logarithmic Sudakov form factor $\sim \ln^2(-M^2)$, $\ln(-M^2) = \ln M^2 + i\pi$

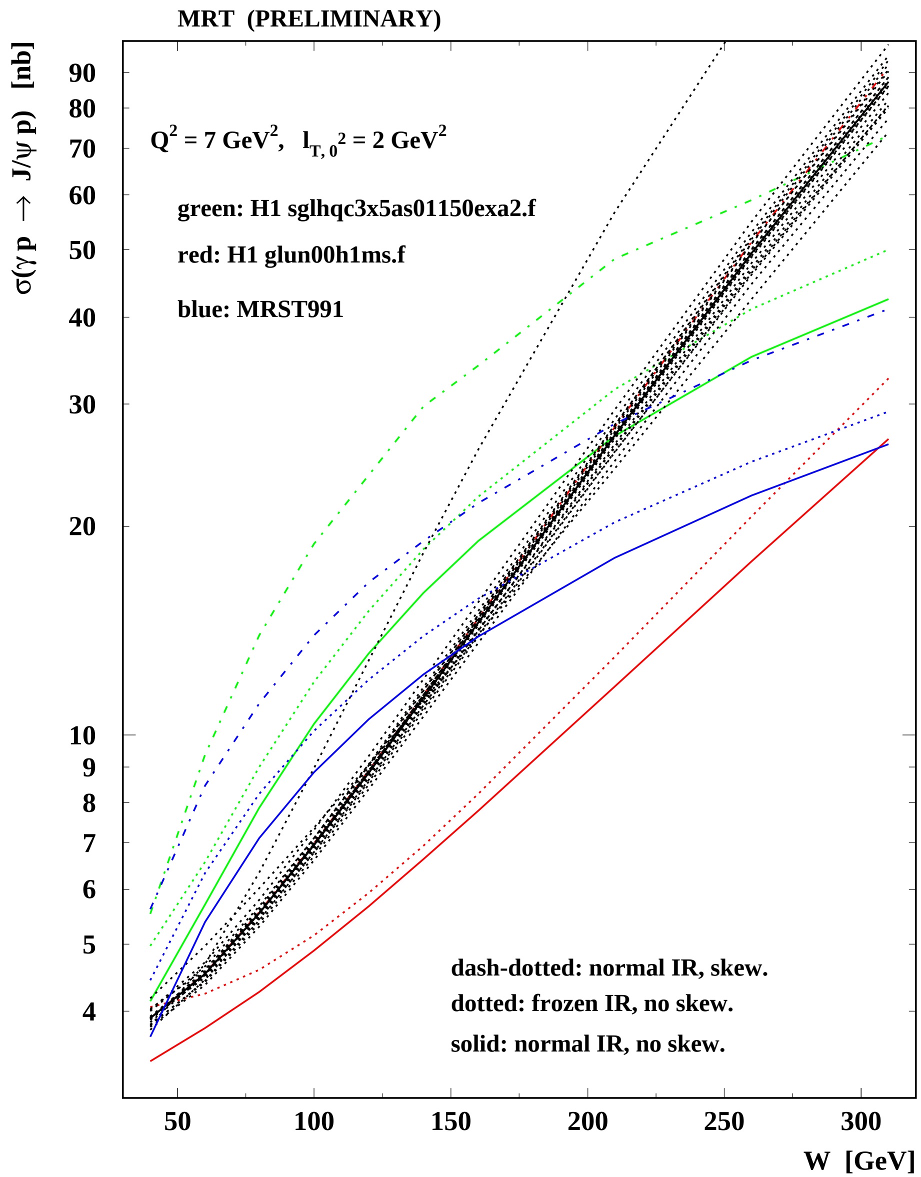
III. Results à la MRT for J/ψ

How well is the TH pred. under control? Quantify different contributions!

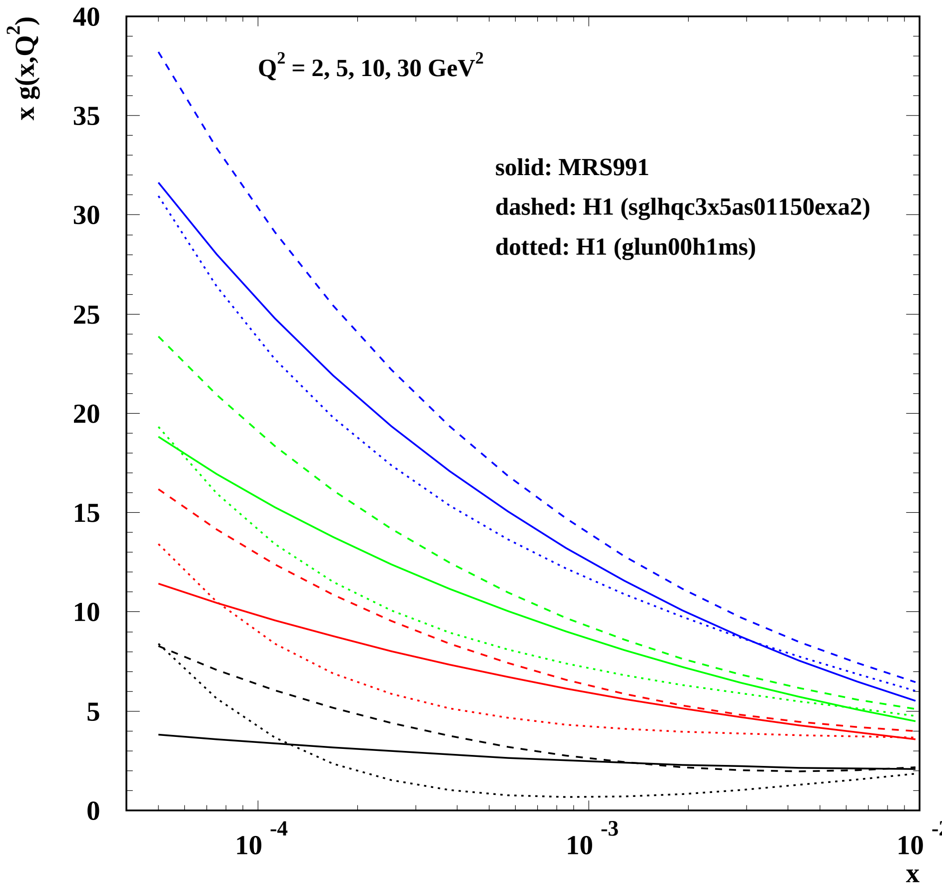
We'll see:

- Skewing corrections large but calculable.
- Uncertainty due to 'error band' of input gluon small compared to spread when using different fits.
- IR contribution non-negligible but under control.
- High sensitivity to input gluon where it is poorly contrained!

Skewing corr. PDF uncertainty.



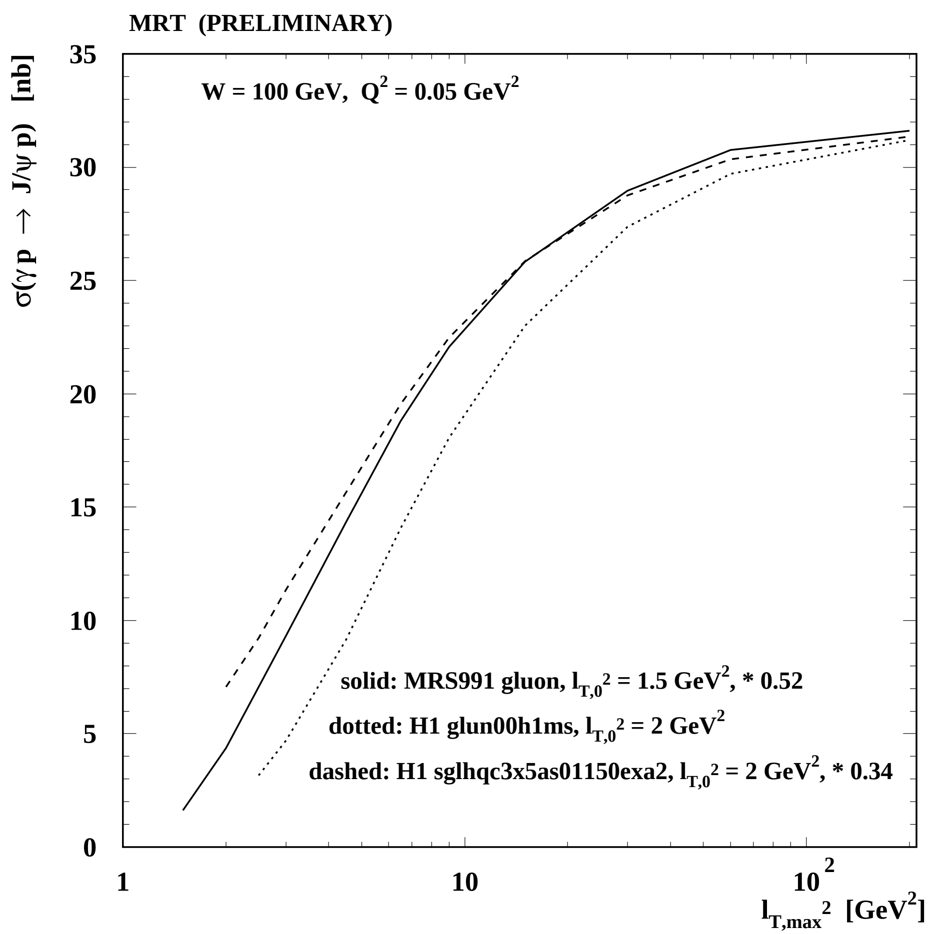
- Different energy dep. $\sigma(W)$ reflects different functional form of gluons. Effect enhanced through skewing corrections.
- 'Error band' from H1 gluon narrow compared to spread using different gluons.

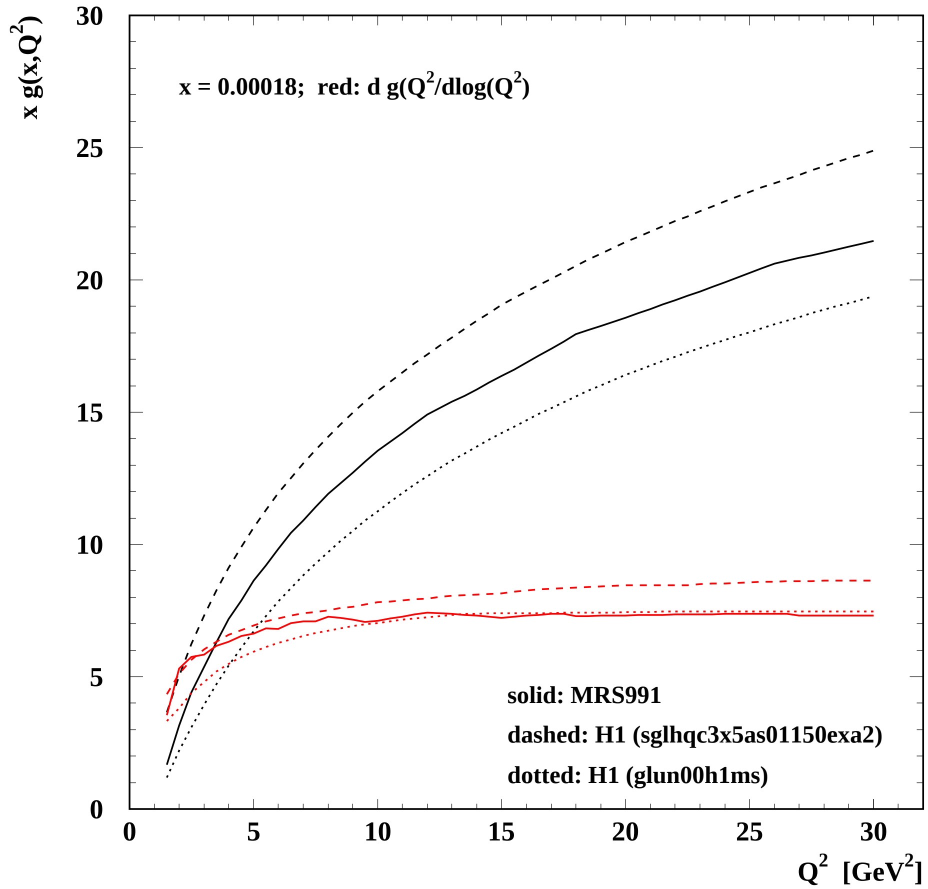


Which scales are relevant?

$$\mathcal{A} \sim xg(x, \ell_0^2) .. + \int_{\ell_0^2}^{\infty} \frac{d\ell_T^2}{\ell_T^4} f(x, x', \ell_T^2)\, \phi ..$$

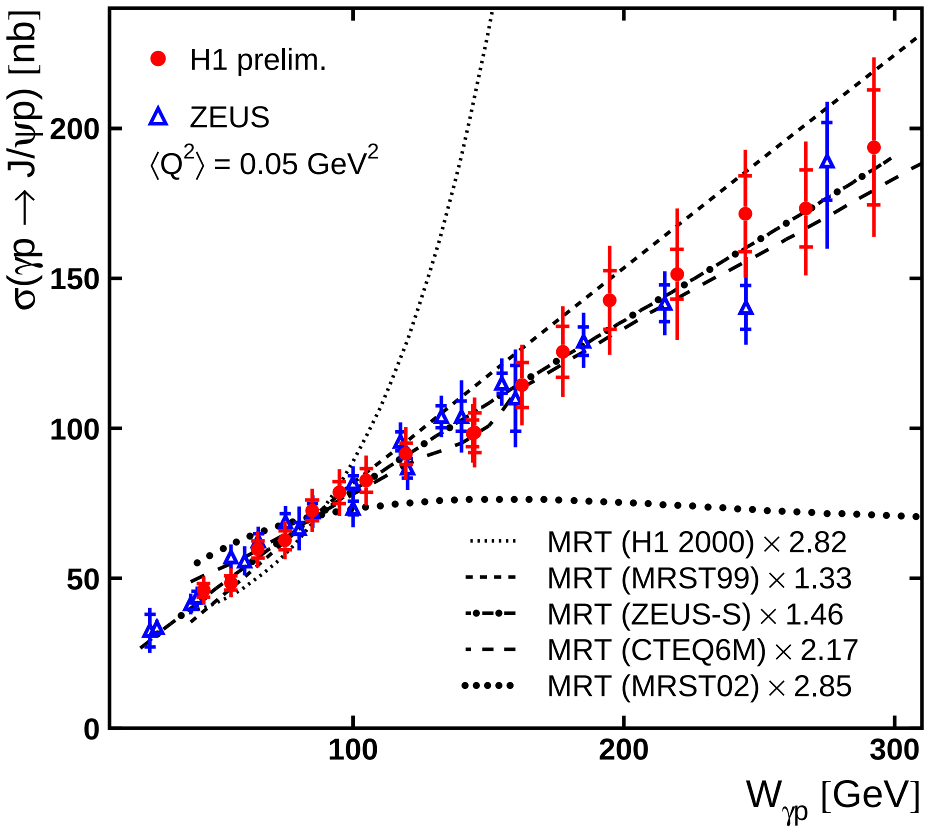
Distribution $\sigma(\ell_{max}^2)$ $[\mathcal{A} \sim \int_0^{\ell_{max}} \frac{d\ell_T^2}{\ell_T^4} \ldots]$ Input gluons, int. & unintegrated

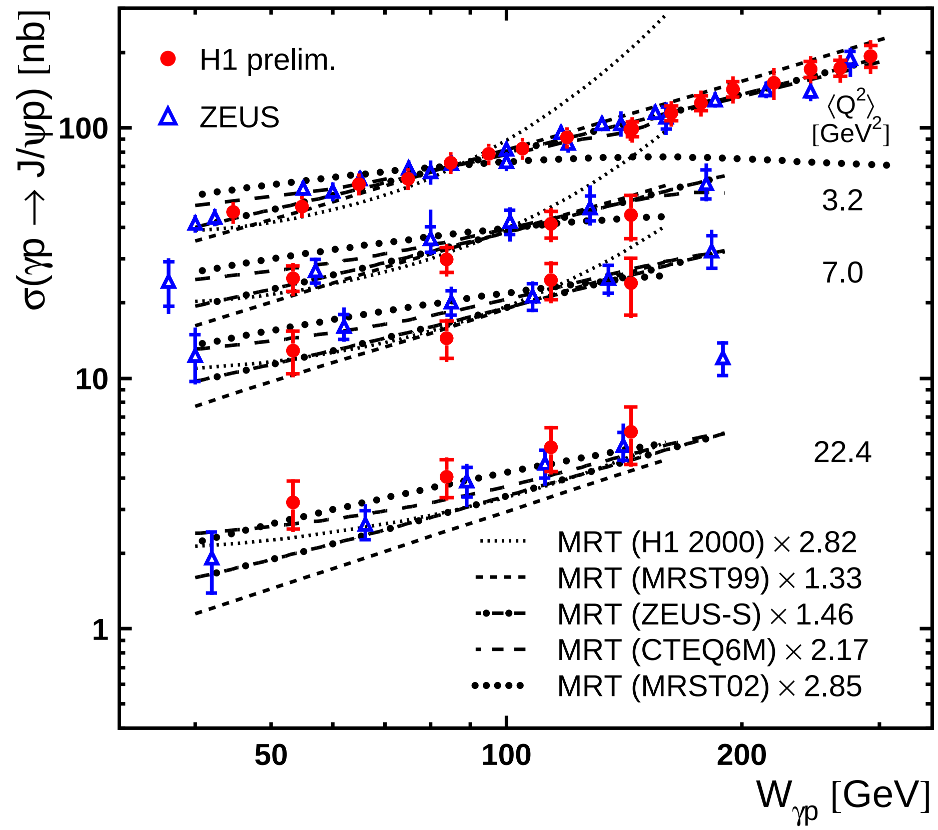




IV. Data vs TH: constraining $f(x, k_T^2)$ via diffr. VM production

Preliminary H1 and ZEUS data compared to MRT predictions:





Plots thanks to Philipp Fleischmann (H1)

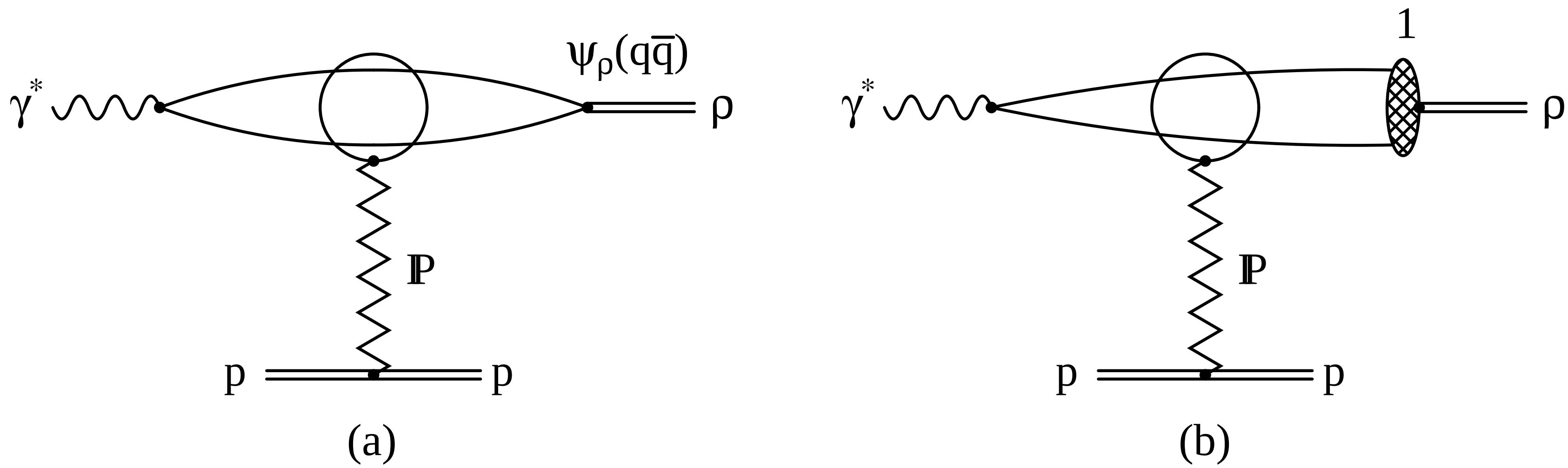
Conclusions

- Diffractive VM production tests QCD and the gluon in the important semi-hard high energy regime
- Theoretical QCD predictions indicate a very good sensitivity to the gluon and are able to describe most data
- Current PDF fits do not constrain the gluon sufficiently at small x and small to intermediate scales. Use diffr. VM data! For this:
- TH: better get QCD predictions under tighter control (generalized PDF, NLO impact factors, modelling of gluon in the IR)
- EXP: get VM data in the largest possible range (Q^2, W, L/T, M_V, t)

▶ Diffraction is getting understood quantitatively, and the exploitation of HERA data for the LHC is far from finished (EXP+TH)!

Some more details on the following pages

MRT avoid VM wave function: Use of Parton Hadron Duality:



Assumption: $\gamma^* \to q\bar{q} \to \pi^+\pi^-$ cross section in the region $M_{q\bar{q}} \sim M_\rho$ saturated by ρ

(up to $\sim 10\%$ for ω) when integrated over a *suitable* (universal?!) mass interval ΔM:

$$\sigma(\gamma^* p \to \rho p) \;\simeq\; 0.9 \sum_{q=u,d} \int_{M^2_{min}}^{M^2_{max}} \frac{d\sigma(\gamma^* p \to (q\bar{q})p)}{dM^2}\, dM^2$$

+ Projection of $q\bar{q}$ state on the correct VM Quantum Numbers $J^P = 1^-$.

($\rightsquigarrow$ Suppression of IR divergencies for contr. from transverse photon!)

Contributions from the real part of the amplitude:

- The basic amplitudes $\mathcal{A}^{L,T}$ are predominantly imaginary in the high energy (leading $\log 1/x$) limit. Analytical expressions are for $\mathrm{Im}\,\mathcal{A}$ only.
- Account for the contributions from the real parts through (crossing symmetry + power behaviour $\mathrm{Im}\,T \sim s^{\lambda}$):

$$\mathrm{Re}\,\mathcal{A} \;=\; \tan(\pi\lambda/2)\,\mathrm{Im}\,\mathcal{A}\,.$$

- $\lambda(Q^2) \;=\; \frac{\partial \log \mathcal{A}}{\partial \log(1/x)}$ calculated numerically on *amplitude level*.
- Martin-Ryskin-T, PRD62,2000: *'The inclusion of the real part enhances the cross section of ρ production by 14 to 19% in the range where we compare to data, J/ψ production by 18 to 25%, and Υ by about 30%, where the bigger effect always occurs at higher Q^2.'*

Structure of the MRT code:

Contributions to $\sigma(\gamma^*_{L,T}\, p \to V\, p)|_{t=0}$ from Re, Im for L, T, numerically

('straightforward', no iterative procedure for effective scales):

$$\textit{PHD:} \int \mathrm{d}M^2 \left[\textit{Projection:} \int \mathrm{d}k_T^2 \left(\textit{Skewed } \mathcal{A}\textit{'s w. } K \textit{ fact.; Re:} \int \mathrm{d}l_T^2 \right) \right]^2$$

Pro and Con's of the MRT approach

+ MRT not just one more *'model'* but an approximation of QCD in a certain regime of parameter space.

+ Not just another fit of the data $\rightsquigarrow$ predictive and can be improved.

+ Good description of basic observables: Q^2 and W dependence of σ, L/T.

+ Strong dependence on $g(x, Q^2)$.

– No prediction of t dependence (yet?)

– No q exchange needed for lower energies (could be added).

– PHD somewhat limiting: Details of VM wave-function in more exclusive measurements? Normalization not a good prediction.

– Full NLO still missing.