Fits of the small x gluon from J/ψ data

UNIVERSITY OF LIVERPOOL

THOMAS TEUBNER

LIVERPOOL THEORETICAL PHYSICS

I. Introduction; the gluon at small x and low – medium scales

II. Exclusive J/ψ production in pQCD

III. Determining the small x gluon from exclusive HERA data

IV. Conclusions/Outlook

Ref/more details: Martin+Nockles+Ryskin+T, Phys. Lett. B 662 (2008) 252

I. Introduction; the gluon at small x

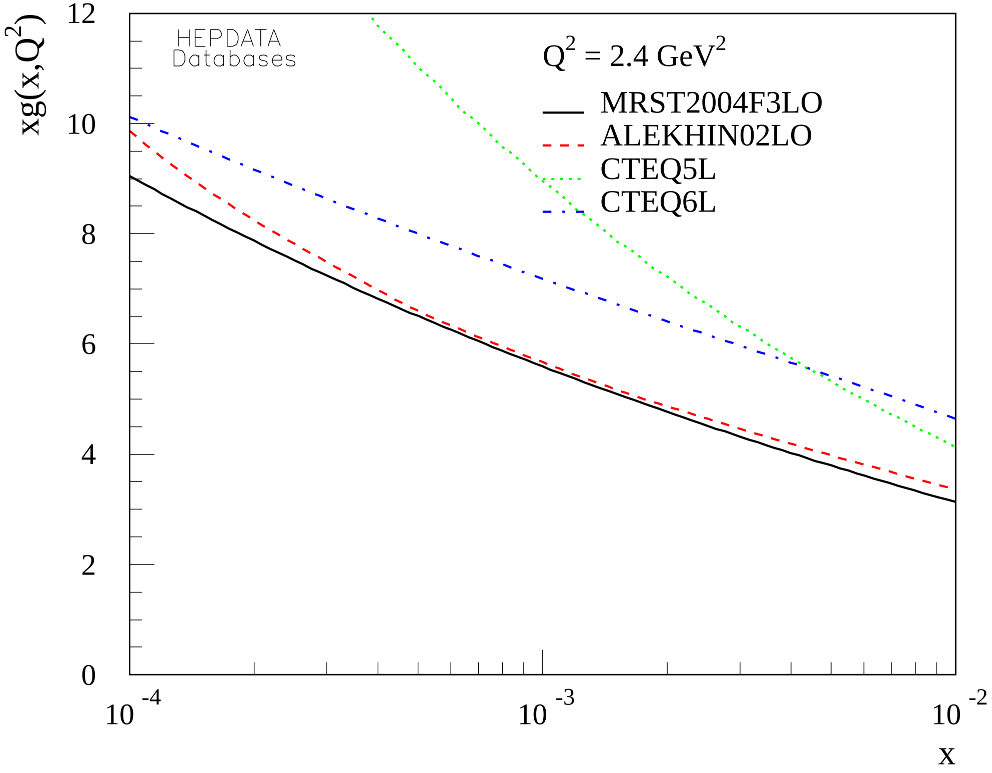
- Global fits constrain the gluon only poorly at small x:

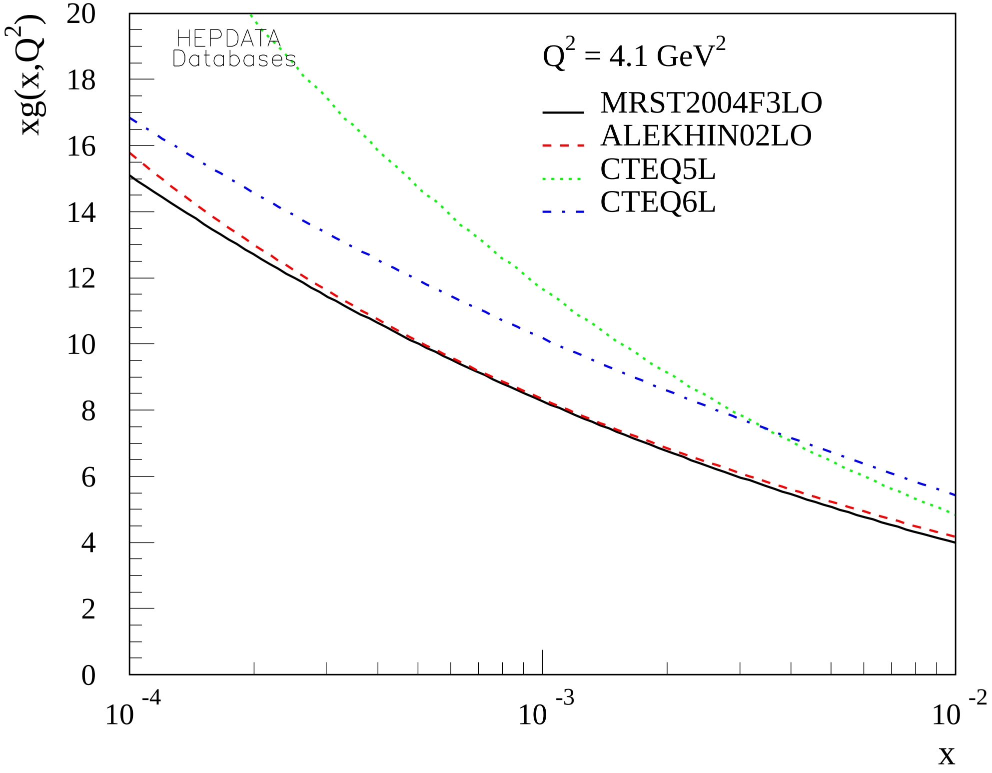
  $\longrightarrow$ lack of precise data + F_2 only limited sensitivity to gluon, but needed for

  $\rightsquigarrow$ description of semi-hard QCD / high energy scattering

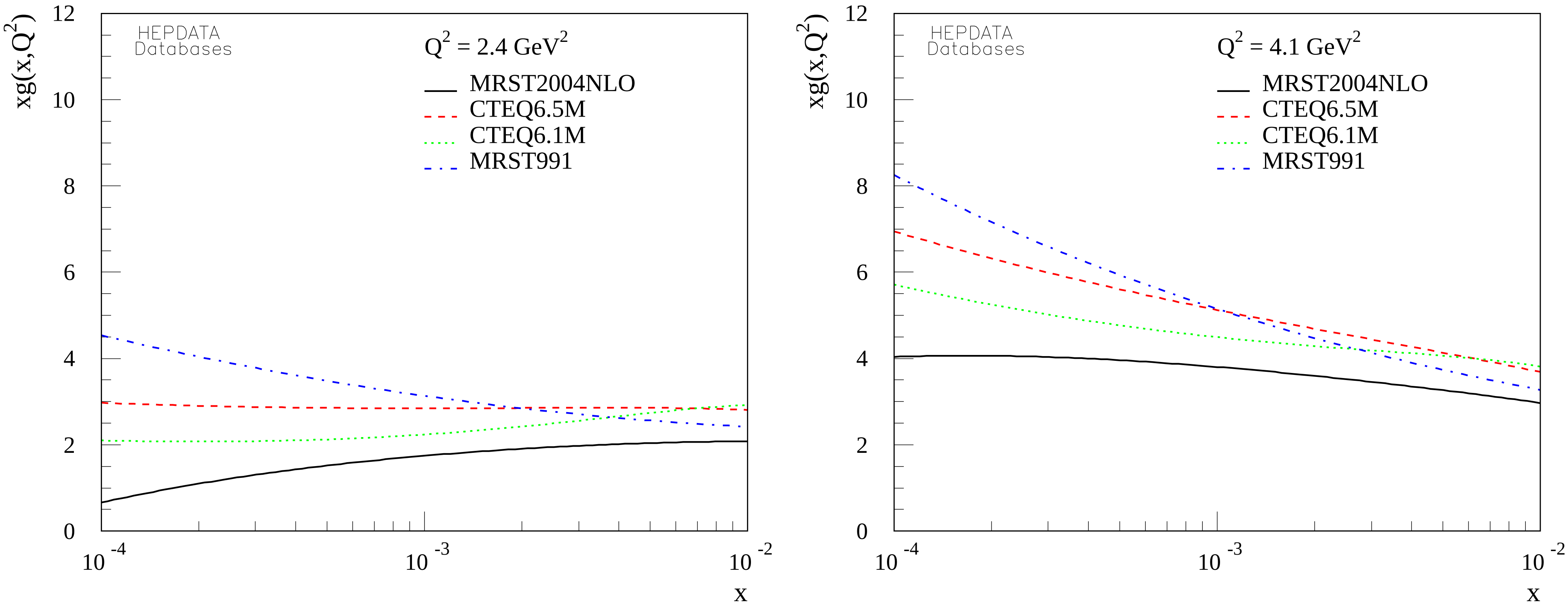
  $\rightsquigarrow$ Underlying Events, Multiple Interactions, exclusive Higgs at LHC ...

- Leading Order: (relevant for MC's)





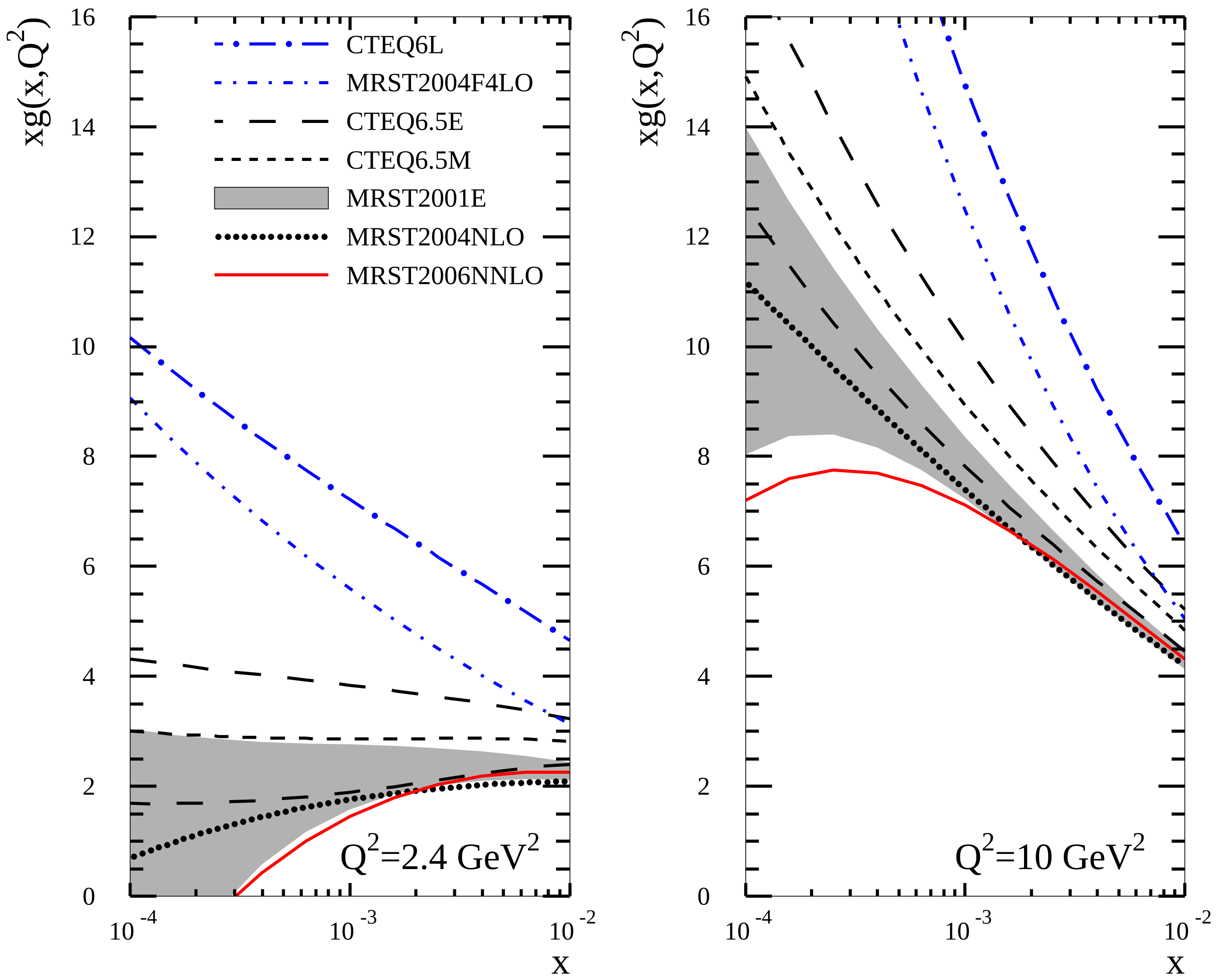
- Next-to-Leading-Order, again at 2.4, 4.1 GeV^2:



— Big differences between variants; also different shapes

— MRST99 the last 'physical' gluon at small x, used as default in MartinRyskinTeubner predictions for diffractive production of ρ, ϕ, J/ψ, Υ.

- Big differences between different fits at small x even at 10 GeV^2:



- Differences 'ok' within predicted errors,
- ... which are huge for small x.
- Large effects LO $\rightarrow$ NLO $\rightarrow$ NNLO.
- Unphysical NNLO gluon.

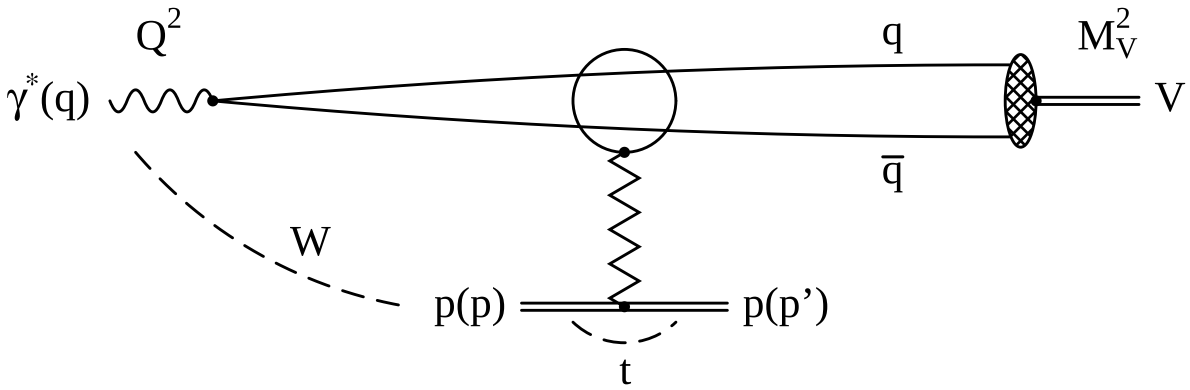
- This is the regime where we have a lot of diffractive data from HERA, in a wide range of the parameter space (W, Q^2, M^2, t), e.g. for diffractive Vector Meson production:

$$\sigma(\gamma^* p \stackrel{I\!P \sim 2g}{\longrightarrow} V\, p) \sim [xg(x, scale)]^2$$

$\longrightarrow$ *potential to directly constrain the gluon!*

- Light mesons: Large uncertainty from modelling of wave function and 'IR pollution' (only partly cured for electroproduction).
- Heavy mesons: can use non-relativistic approximation for J/ψ. [*Hoodbhoy*: rel. corrections incl. $c\bar{c}g$ component $\mathcal{O}(v^2)$ and 4% only.]
- Υ even better suited, unfortunately data much worse (see below).
- Our strategy: Use available J/ψ data to extract gluon in this regime. (No global fit, no inclusive data.)

II. Exclusive J/ψ production in pQCD



$$x = \frac{Q^2 + M_V^2}{Q^2 + W^2}$$
$$W^2 = (q+p)^2$$
$$t = (p-p')^2$$

- Factorization of amplitude: $\mathcal{A}(\gamma^* p \to Vp) = \psi_{q\bar{q}}^{\gamma} \otimes \mathcal{A}_{q\bar{q}+p} \otimes \psi_{q\bar{q}}^{V}$

  $\longrightarrow$ convol. with non-rel. VM wave function $\psi_{q\bar{q}}^{V}$ (alternatively: open $q\bar{q}$ + PHD)

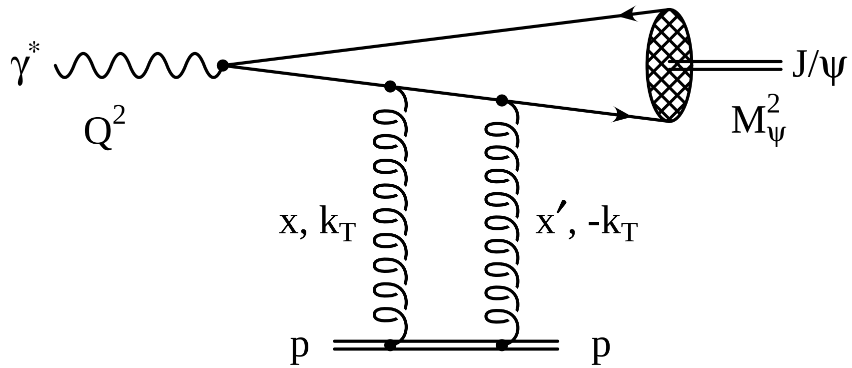
- 'Colourless' strong interaction in LO QCD: $\mathcal{A}_{q\bar{q}+p} \sim$ two gluon exchange:

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

with the *effective scale* $\overline{Q}^2 = \left(Q^2 + M_V^2\right)/4$ and the experimental Γ_{ee}^V.

Corrections beyond the leading $\ln 1/x$ limit:

- $x \neq x'$ $\rightsquigarrow$ skewing, $\mathcal{A} \sim$ general. PDF.



$\longrightarrow$ Correction factor à la Shuvaev:

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

with $\lambda(Q^2)$ the *effective power* of the gluon

$$xg \sim x^{-\lambda}.$$

- Contributions from the real part of the amplitude through

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

(Crossing symmetry + power behaviour $\mathrm{Im}\,\mathcal{A} \sim s^{\lambda}$.)

NLO corrections beyond the leading $\ln Q^2$ limit:

k_T factorization using unintegrated gluon $\boldsymbol{f(x, k_T^2)}$

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

$$\mathcal{A}^{\text{LLA}} \sim \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} \int^{\bar{Q}^2} \frac{\mathrm{d}k_T^2}{k_T^2} f(x, k_T^2) = \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x, \bar{Q}^2)$$

- Effect numerically important $\rightsquigarrow$ large corrections in DGLAP when going to (N)NLO
- Use k_T factorized amplitude:

$$\mathcal{A}^{\text{`NLO'}} \sim \frac{\alpha_s(Q_0^2)\, xg(x, Q_0^2)}{\bar{Q}^4} + \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^2} \int_{Q_0^2}^{(W^2-M^2)/4} \frac{\mathrm{d}k_T^2}{\bar{Q}^2 + k_T^2} \frac{\partial xg(x, k_T^2)}{\partial k_T^2}$$

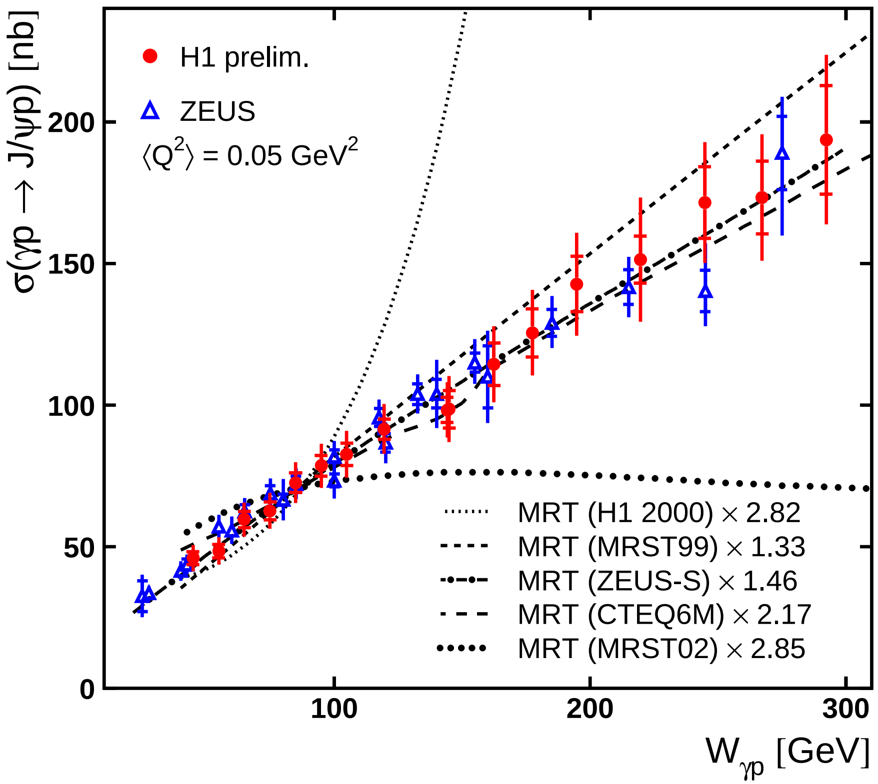
with small sensitivity on infrared transition parameter $Q_0^2 \sim 2$ GeV^2 in case of J/ψ.

- Small effect when including Sudakov supression: $f(x, k_T^2) = \left.\frac{\partial[xg(x,q_0^2)T(q_0^2,\mu^2)]}{\partial \ln q_0^2}\right|_{q_0^2=k_T^2}$

with *Sudakov* factor $T = \exp[\frac{-C_A \alpha_s(\mu^2)}{4\pi} \ln^2 \frac{\mu^2}{q_0^2}]$ resums virtual corrections $\sim$ probability for no gluon emission in the interval $q_0^2 \ldots \mu^2 \sim \bar{Q}^2$.

H1 and ZEUS data compared to MRT predictions; gluon fit strategy

Plot thanks to Philipp Fleischmann (H1)



- MRT predictions for VM production based on pQCD able to describe large body of data; however:

$\longrightarrow$ Huge uncertainty due to input gluon pdf!

$\longrightarrow$ And: Data much more precise now.

$\rightsquigarrow$ This study: use data to *determine* gluon at small x and low–medium scales via $\chi^2_{\rm min}$ *fit*.

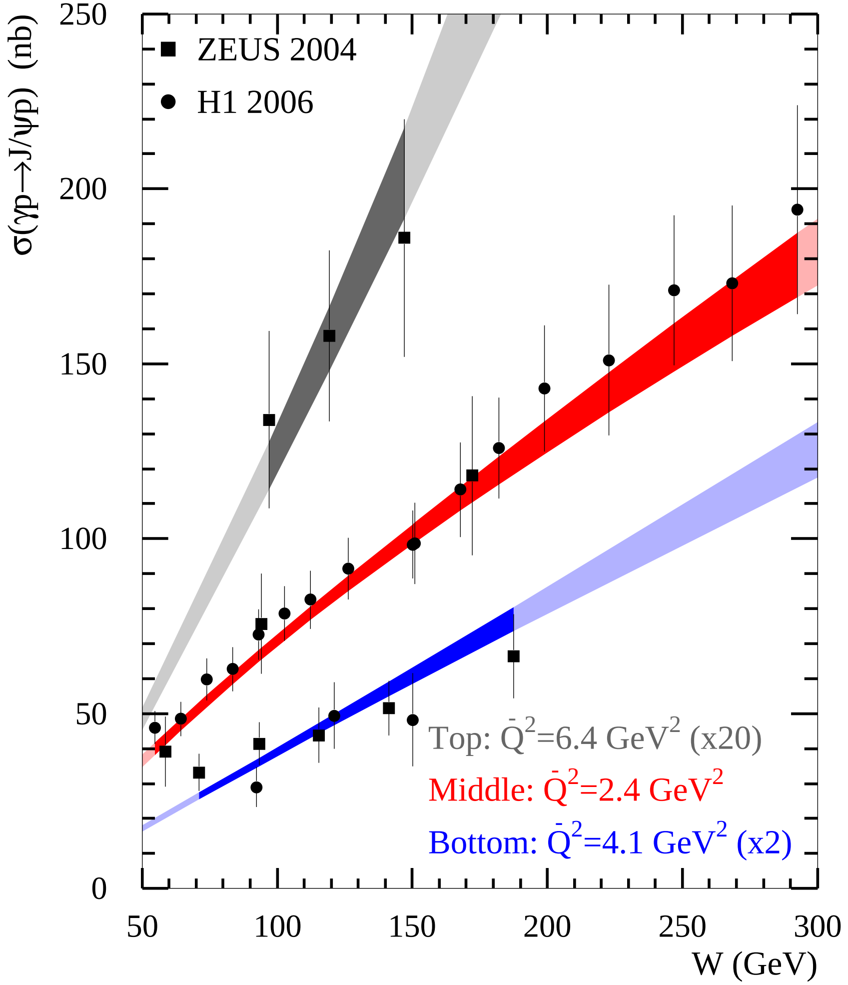
- Use of theory described above and a simple gluon ansatz with three free parameters:

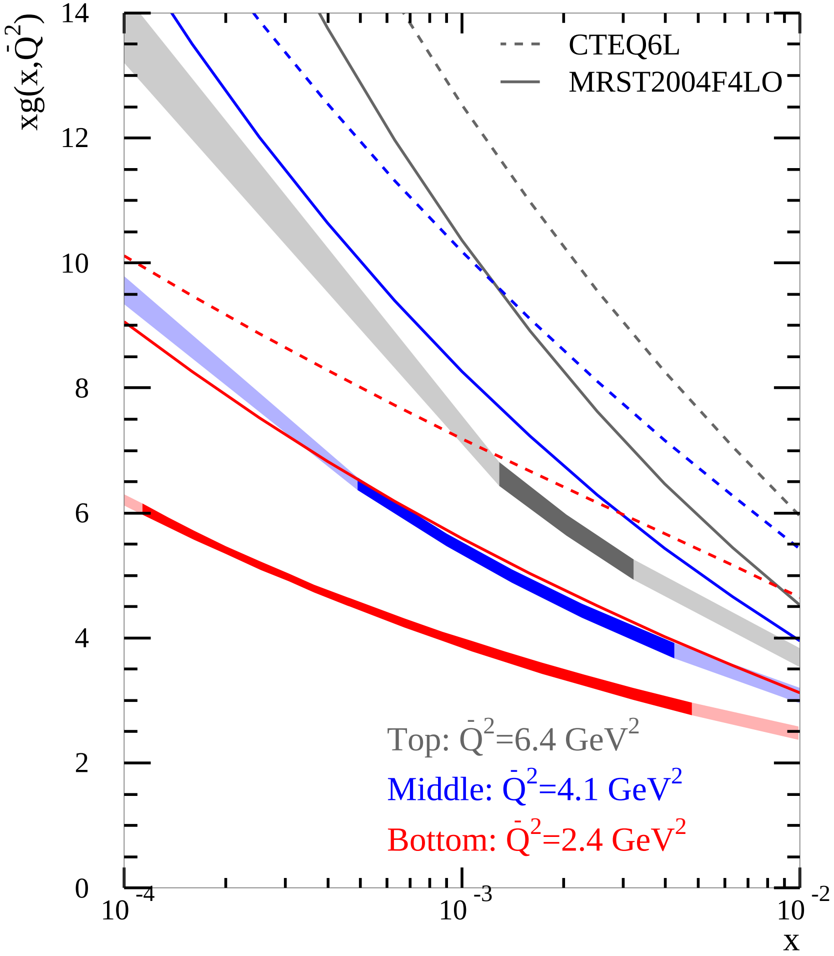
$\boldsymbol{xg(x,\mu^2) = N \cdot x^{-\lambda}}$, LO: $\lambda = a + b\ln\frac{\mu^2}{0.45\,{\rm GeV}^2}$, NLO: $\lambda = a + b\ln\ln\frac{\mu^2}{0.09\,{\rm GeV}^2}$

(form used successfully by Martin+Ryskin+Watt, EPJC37,285), ‘QCD anal. of diffr. DIS data’

III. Determining the small x gluon from diffractive HERA data

LO combined fit of H1 and ZEUS J/ψ data: (error bands including correlations)

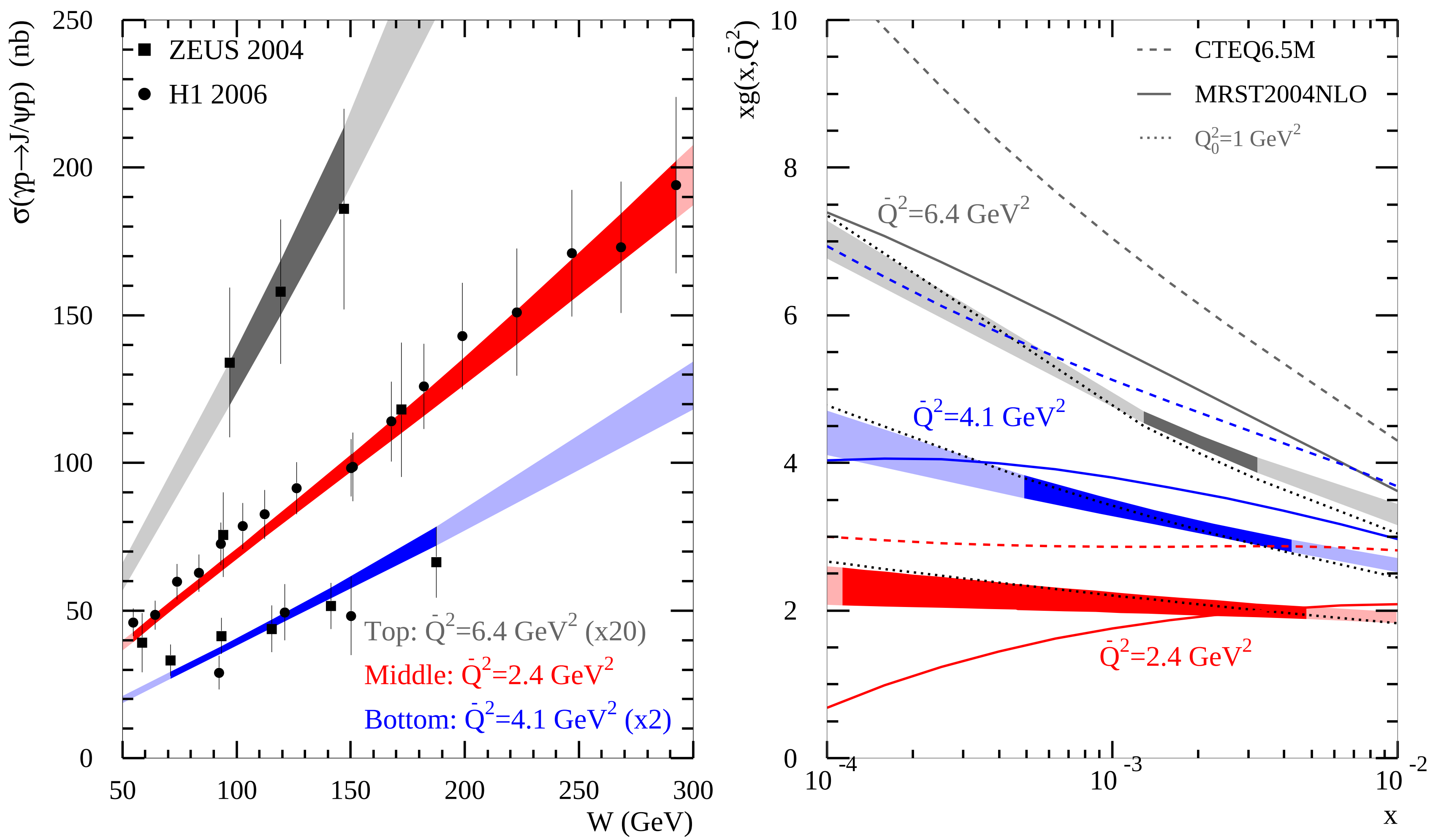




$\chi^2_{\rm min}/(d.o.f. = 48) \ = \ 0.9$

$N = 0.99 \pm 0.09, \quad a = 0.051 \pm 0.012, \quad b = 0.088 \pm 0.005$

NLO combined fit of H1 and ZEUS J/ψ data:



- Excellent overall fit to available J/ψ data: $\chi^2_{\text{min}}/(d.o.f. = 48) \;=\; 0.8$
  $N = 1.55 \pm 0.18, \quad a = -0.50 \pm 0.06, \quad b = 0.46 \pm 0.03\,.$
- Tendency for slightly too steep higher-Q^2 cross sections, but statistically less significant.

NLO combined fit of H1 and ZEUS J/ψ data:

- Quality of data sufficient to give strong constraint on gluon.
- Considerable less 'evolution' compared to MRST gluon, fair agreement with CTEQ; generally less steep at larger scales, but no unphysical 'turn-over' at low scales.
- k_T factorization using *unintegrated* gluon:

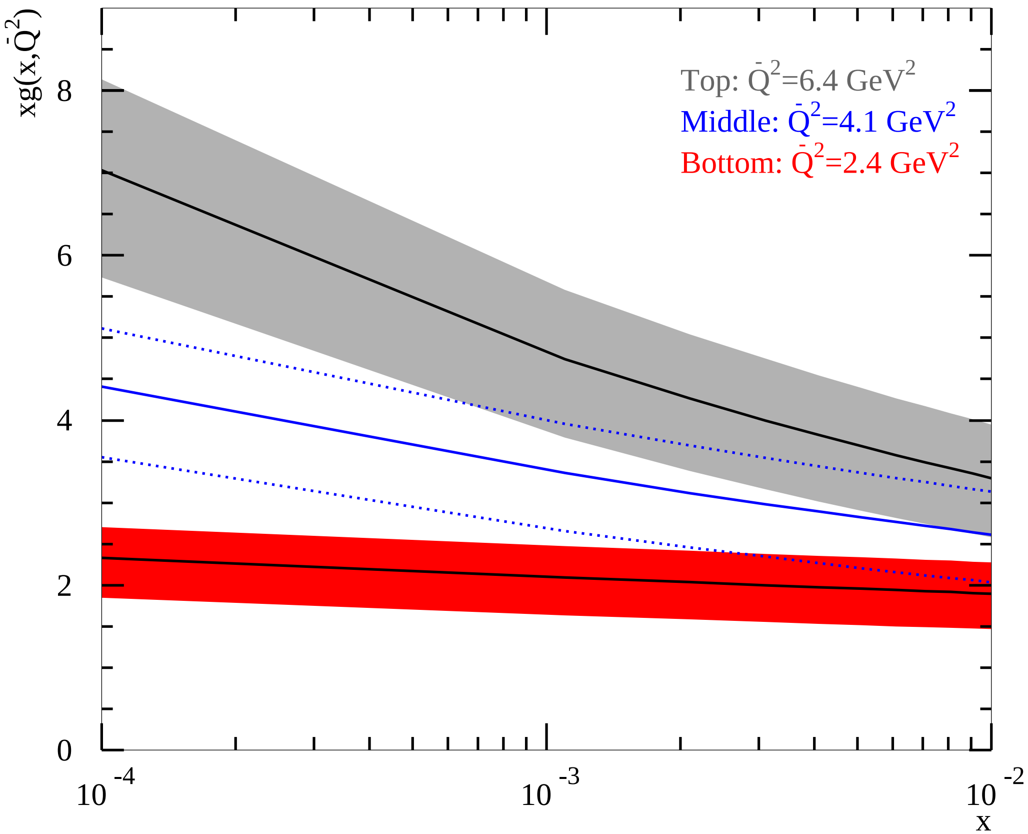
$$A \sim \int_{Q_0^2}^{(W^2-M^2)/4} \mathrm{d}k_T^2 \, \frac{f(x, k_T^2)}{\bar{Q}^2 + k_T^2}$$

⇝ significant large-scale constributions due to anomalous dimension rising with k_T^2, damped only by $\ln\ln$.

- In standard DGLAP fits based on collinear factorization we have strong k_T ordering
  ⇝ no such large scale contributions from the rising anomalous dimension, but
  ⇝ corrections captured order by order through coefficient function.
- q contributions absent, i.e. included in fitted gluon; possibly not negligible in collinear factorization; large skewing corrections.
- Our NLO gluon should be ideal for calculations based on k_T factorization.

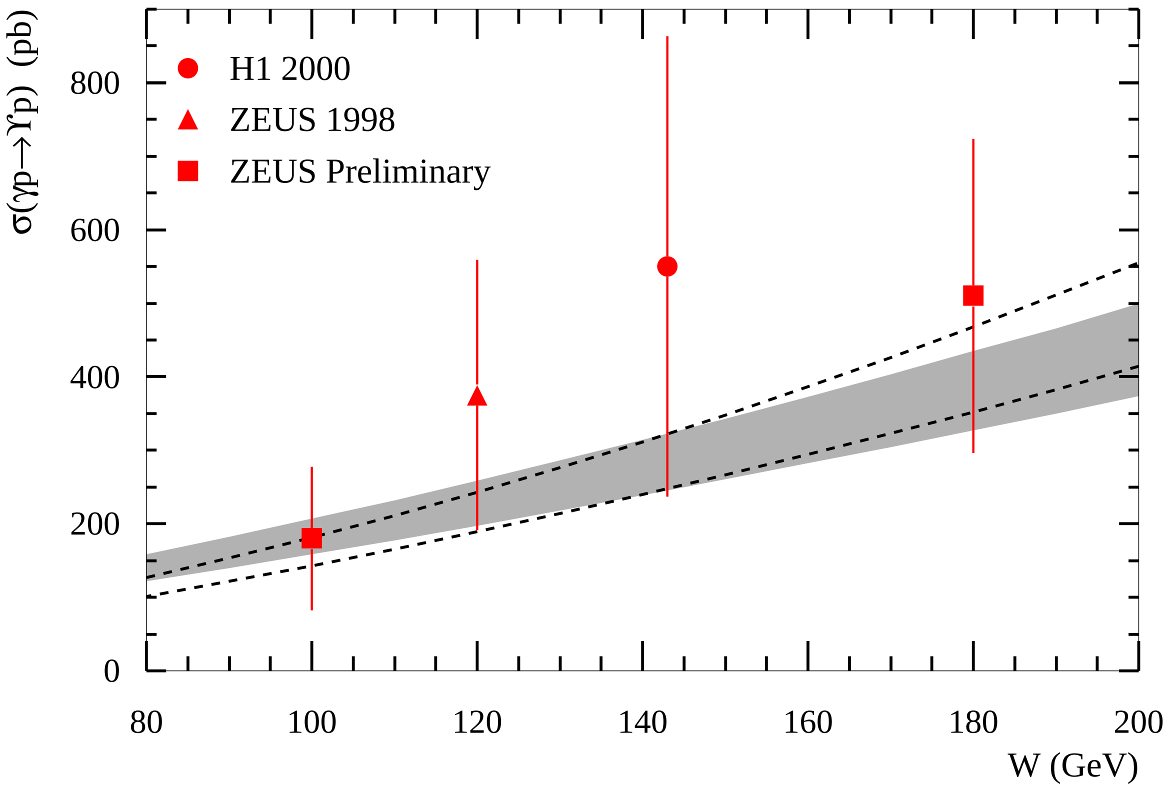
NLO Gluons; scale uncertainty

- Estimate of theoretical uncertainty via scale variation: $\mu^2/2 \ldots 2\mu^2$ in both α_s and the Sudakov factor results in an uncertainty of about $\pm 20\%$.
- Sizeable but conservative as cancellations expected and should be seen in comparison with large differences between global fit gluons.



Predictions for elastic Υ production

- Use of NLO gluon to predict Υ photoproduction in the same framework; applicability of pQCD and non-rel. approximation even better justified
- change of mass, electric charge, Γ_{ee}, but no other adjustments
- Comparison with HERA data: good description



IV. Conclusions/Outlook

- Current PDF fits do not constrain the gluon well at small x and low–medium scales.
- Diffractive Vector Meson production is very sensitive to the gluon in this regime.
- We have used the pQCD approach to determine the LO gluon pdf from exclusive J/ψ data from H1 and ZEUS.
  Our gluon fit is in fair agreement with MRST fits (undershooting CTEQ) at $x \sim 10^{-2}$ and shows a slightly flatter small x behaviour.
- Within k_T factorization a fit of a 'NLO' gluon turns out to have less evolution compared to DGLAP NLO global fits, as expected from the different framework.
- Further studies ongoing to quantify the correlation, incuding role of q contributions.
- Gluons applicable for predictions at LO, well suited for use of exclusive predictions within k_T factorization.

Other NLO corrections beyond the leading $\ln Q^2$ limit:

- Relativistic corrections $\mathcal{O}(v^2/c^2)$ from the wave function:

  If treated propery including higher Fock component $c\bar{c}g$ states of the J/ψ, and with use of experimentally measured Γ_{ee}, these corrections were shown to be small, $\mathcal{O}(4\%)$ [Hoodbhoy]

- q contributions suppressed for small x production of J/ψ:

$$\text{rough estimate: } \mathcal{A}_{\text{sea}} \sim \mathcal{A}_{\text{gluon}} \frac{1}{6} \frac{R_q}{R_g} \frac{\alpha_s}{4\pi}, \quad R_q/R_g \sim 2-3$$

- Genuine 'hard' NLO corrections to the $\gamma^* gg \to VM$ impact factor:

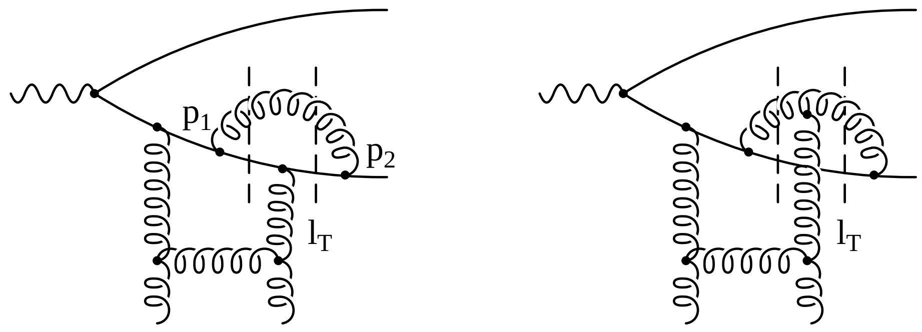
  Still not available $\rightsquigarrow$ additional K factor $\rightsquigarrow$ normalization uncertainty

  However: large logarithmic contributions captured with k_T factorization scheme and scale choice; quantitative study based on work of Ivanov et al. under way.

Some details of the original MRT approach:

K factor:

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

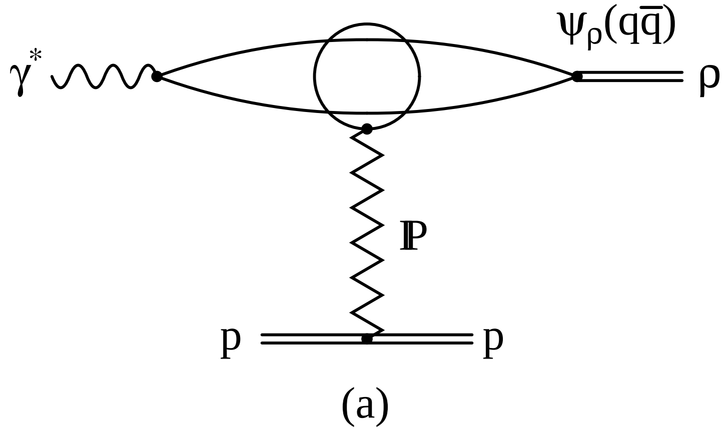


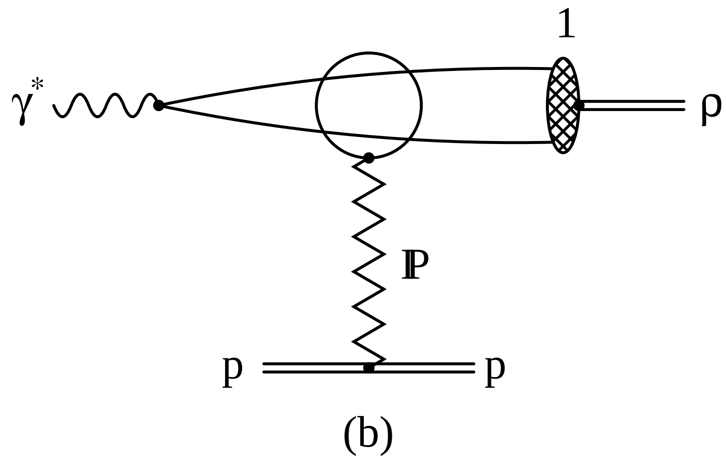
(a) (b)

- 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 $\sim \ln^2(-M^2)$, $\ln(-M^2) = \ln M^2 + i\pi$

Alternative to use of VM wave function: Parton Hadron Duality:





Assumption (case of ρ): $\gamma^* \to q\bar{q}$ 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!)

Structure of the calculation à la Martin+Ryskin+Teubner:

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):

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