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Exclusive J/ψ and ϒ photoproduction and the low x gluon

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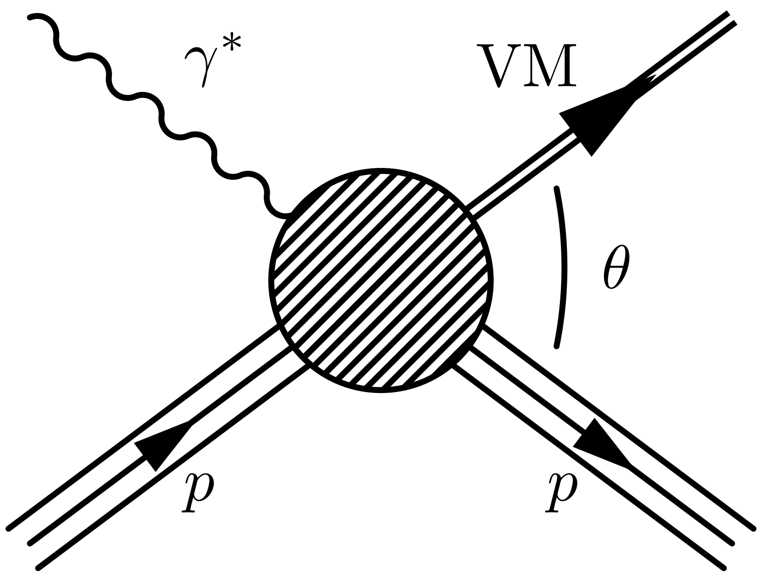
JHEP 1311 (2013) 085, arXiv:1307.7099 [hep-ph]

MAX-PLANCK-GESELLSCHAFT

higgstools

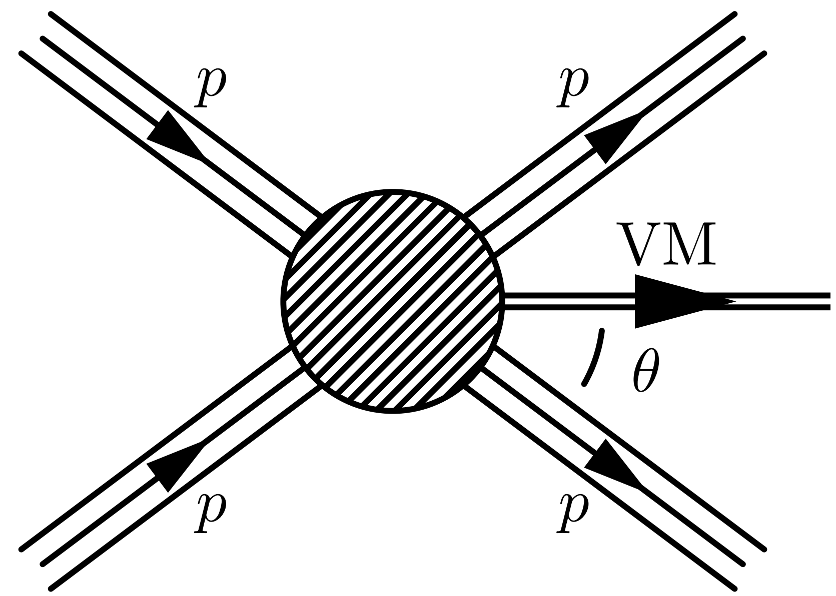
Exclusive HVM Production

Exclusive HVM Electroproduction



ZEUS 1998, 2002, 2004, 2009
H1 2000, 2006, 2013

Ultraperipheral HVM Production



CDF 2009
LHCb 2013, 2014, 2015…
ALICE (p-Pb) 2014
CMS (p-Pb)…

Wide variety of data already available, more coming soon…

Process sensitive to poorly constrained low $x_B \sim 10^{-5}$ gluon

Process Features

- Sensitive to Generalised Parton Distributions (GPDs)
  - Conjectured to be related to PDFs Shuvaev 99
- Must describe formation of HVM
  - Relativistic corrections unknown - could be large or small

Frankfurt, Koepf, Strikman 96, 98; Hoodbhoy 97

Also...

- J/ψ photoproduction ($Q^2 = 0$) has a low central scale

$$\bar{Q}^2 = (Q^2 + M_V^2)/4 > 2.4 \text{ GeV}^2$$

- For Ultraperipheral production typically use a model based on the Equivalent Photon approximation + (fitted) Survival Factors $S_\pm(y)$

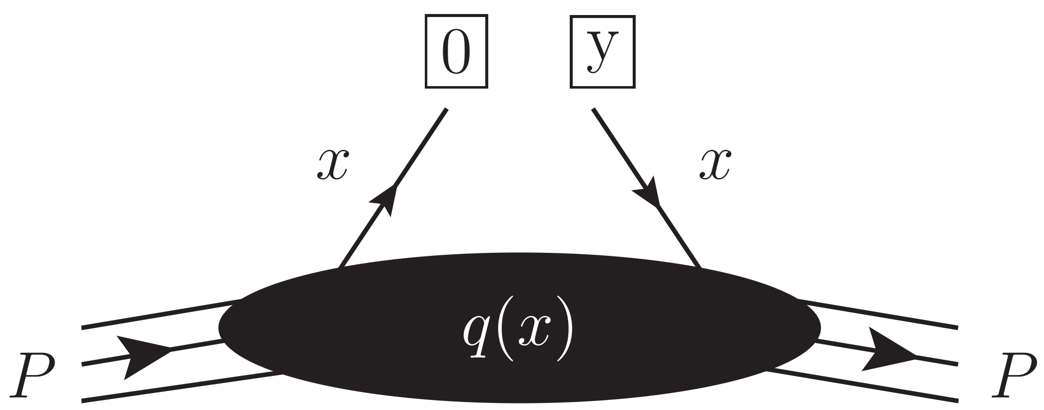
$$\mathrm{d}\sigma(pp)/\mathrm{d}y = S_+^2(y)N_+\sigma_+(\gamma p) + S_-^2(y)N_-\sigma_-(\gamma p) + \ldots$$

We use KMR model

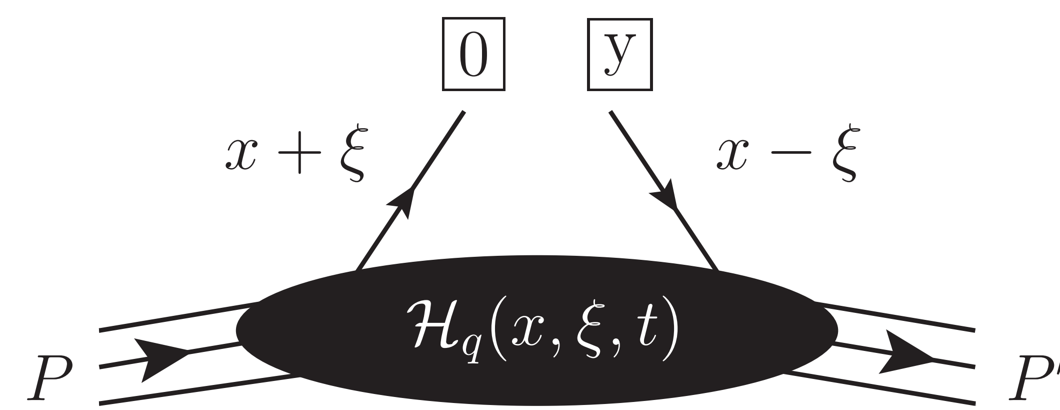
Khoze, Martin, Ryskin 02,13

Generalised Parton Distributions

GPDs generalise PDFs: outgoing/incoming partons carry different momentum fractions Müller 94; Radyushkin 97; Ji 97



$$\langle P|\,\overline{\psi}_q(y)\mathcal{P}\{\}\psi_q(0)\,|P\rangle$$



$$\langle P'|\,\overline{\psi}_q(y)\mathcal{P}\{\}\psi_q(0)\,|P\rangle$$

Forward Limit ($\xi = 0$):

$$\begin{aligned}
\mathcal{H}_q(x,0,0) =& q(x), \quad x > 0 \\
\mathcal{H}_q(x,0,0) =& -\bar{q}(-x), \quad x < 0 \\
\mathcal{H}_g(x,0,0) =& x g(x)
\end{aligned}$$

GPDs probed also in other hard exclusive processes, e.g. DVCS & TCS

Shuvaev Transform

- Can directly extract GPDs (data somewhat limited) Kumerički, Müller 16; Berthou et al. 15; Guidal et al. 13;

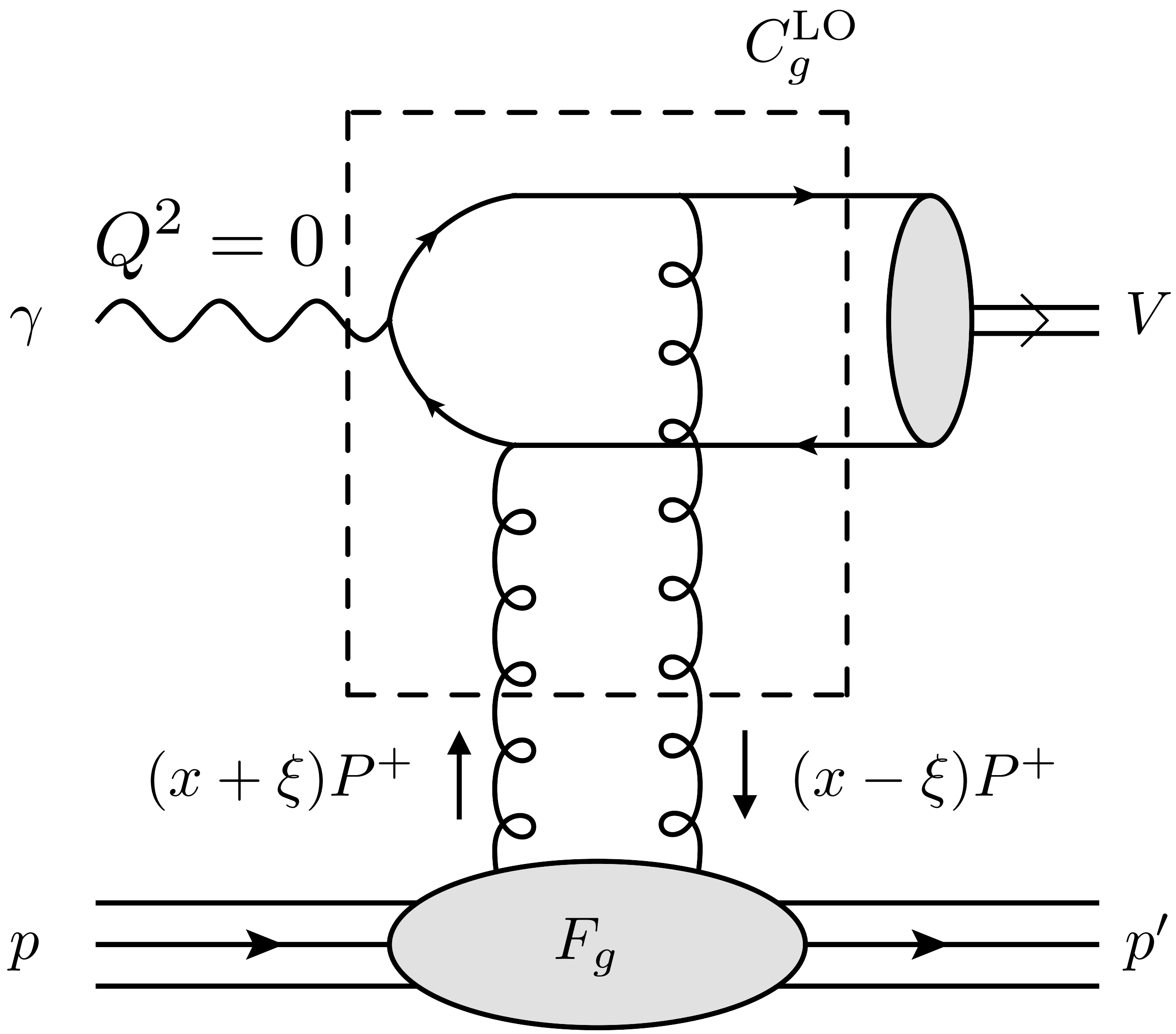
(Conjecture) Shuvaev Transform:

- In small-x and ξ limit GPDs are related to PDFs
- Anomalous dimensions of Gegenbauer Moments H_N of $\mathcal{H}(x,\xi)$ are equal to anomalous dimensions of conventional Mellin moments M_N
- Polynomiality: $H_N = \sum_{k=0}^{\lfloor (N+1)/2 \rfloor} c_k^N \xi^{2k}$ allows Gegenbauer moments to be determined from conventional PDFs $\mathcal{O}(\xi)$ at NLO

Note:

- (Regge-based) Must assume no singularities in right half N-plane of input distributions Martin et al. 09
- Transform is not valid for $|x| < \xi$ (time-like) region
- Further GPDs $\mathcal{E}_g, \mathcal{E}_q$ which vanish for $P = P'$ not known from PDFs

General Setup & Assumptions



- Assume process factorises:
  $$C_{g/q} \otimes F_{g/q} \otimes \phi_{c\bar{c}}^{J/\psi}$$
- HVM formation described in NRQCD, we take only the leading term: $\langle O_1 \rangle \propto \Gamma\left[V \to e^+ e^-\right]$
- Compute at (Mandelstam) $t = 0$, restore assuming $\sigma \sim \exp(-Bt)$
- Unpolarised, helicity non-flip
  $$F_g(x,\xi,0) = \sqrt{1-\xi^2}\mathcal{H}_g(x,\xi,0)$$

Amplitude:

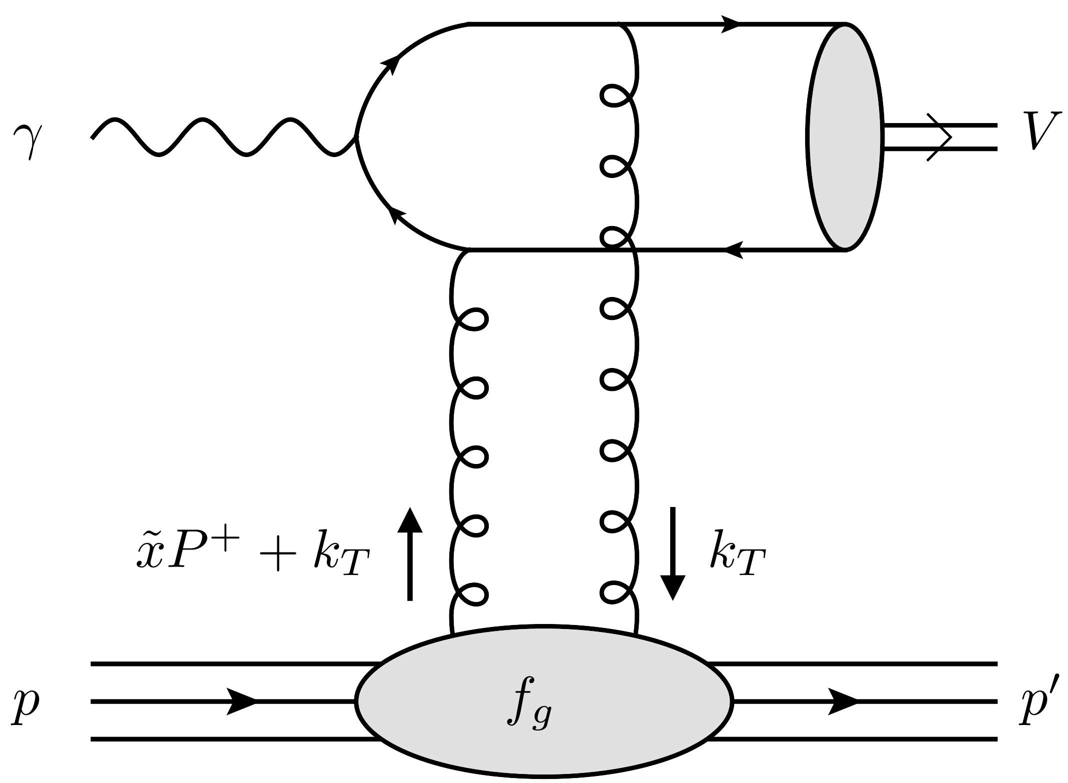
Contributes at NLO

$$T \propto \int_{-1}^{1} \mathrm{d}x \left[C_g(x,\xi)\, F_g(x,\xi) + \sum_{q=u,d,s} C_q(x,\xi)\, F_q(x,\xi) \right]$$

Setup follows: Ivanov, Schäfer, Szymanowski, Krasnikov, 2004

Previous Work

First: look at LO with a few simplifying assumptions…



- Consider only dominant Im part (Re part approx. restored via dispersion relation)
- High energy \`maximal skew' approximation $x = \xi \approx \tilde{x}/2$, Introduces $\mathcal{O}(20 - 30\%)$ on σ_{tot} (compared to full transform)

Harland-Lang 2013

And one generalisation…

k_T-fac.: gluons carry transverse momentum (\`unintegrated' PDFs)

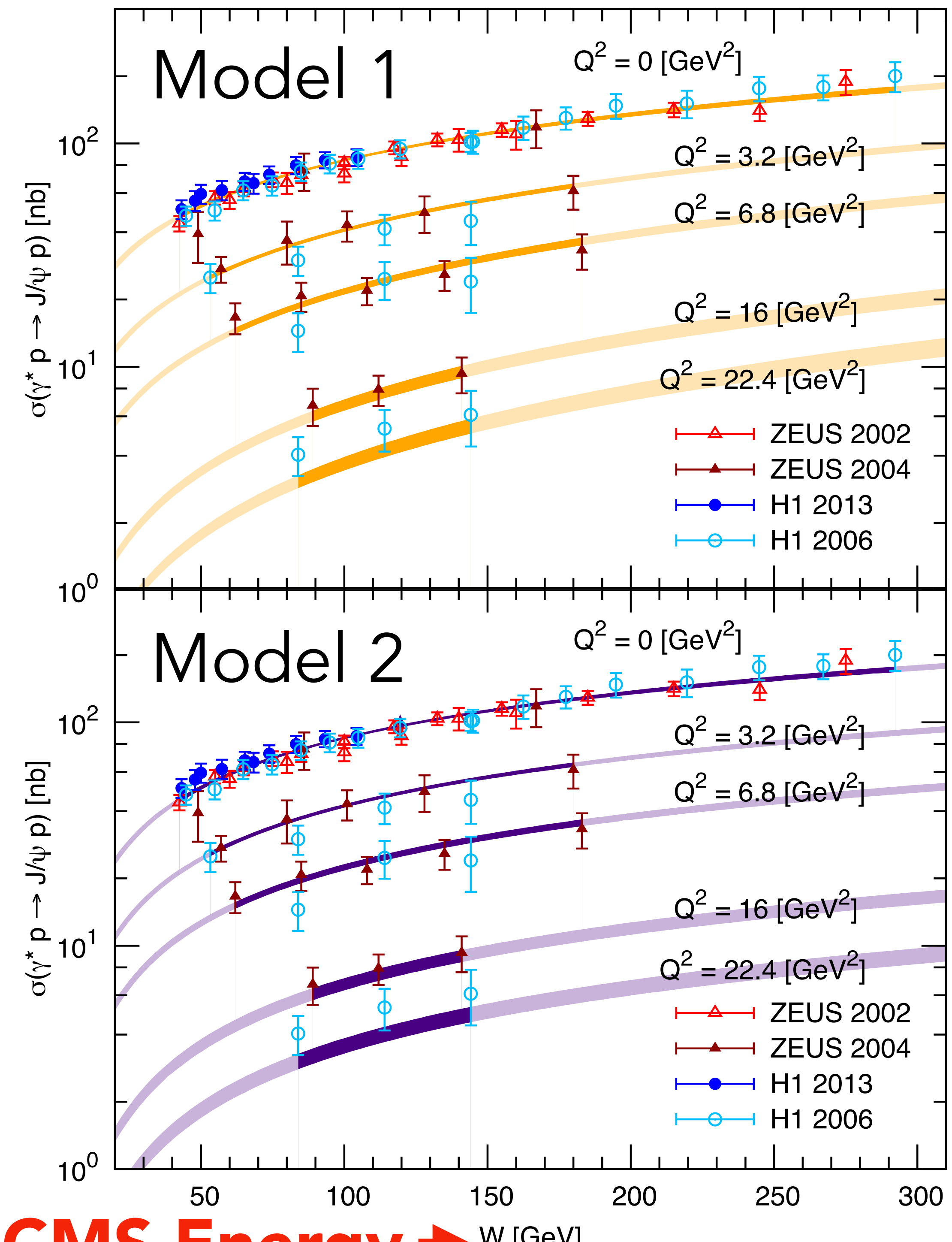
Fit (simplified) gluons to just exclusive J/ψ data:

Model 1: $k_T^2 \ll \bar{Q}^2$ equivalent to LO Collinear Factorisation

Model 2: Numerically compute k_T integral (this includes some NLO Collinear Factorisation Effects)

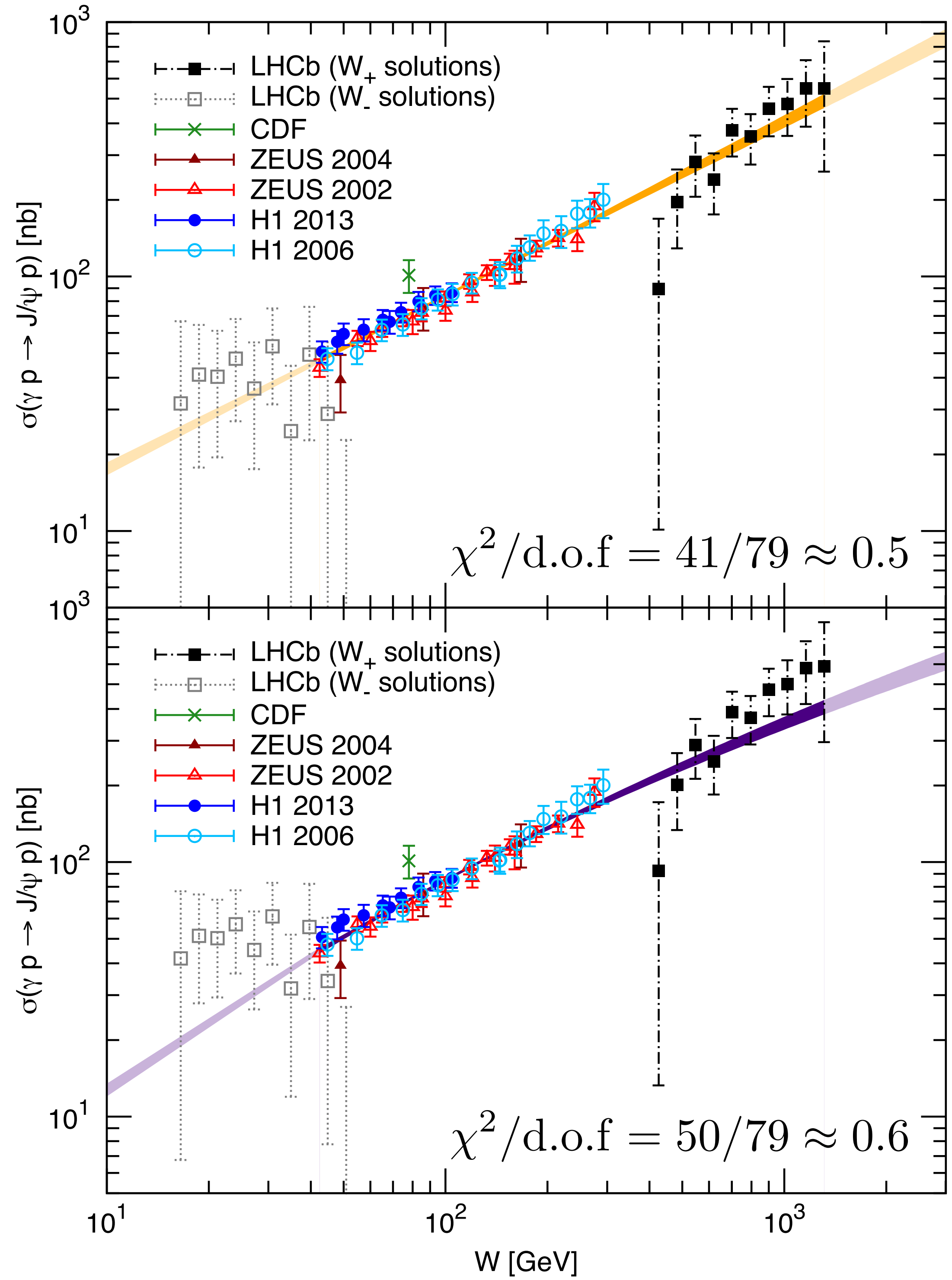
Fit: HERA, CDF, LHCb

Fit gluon to HERA:

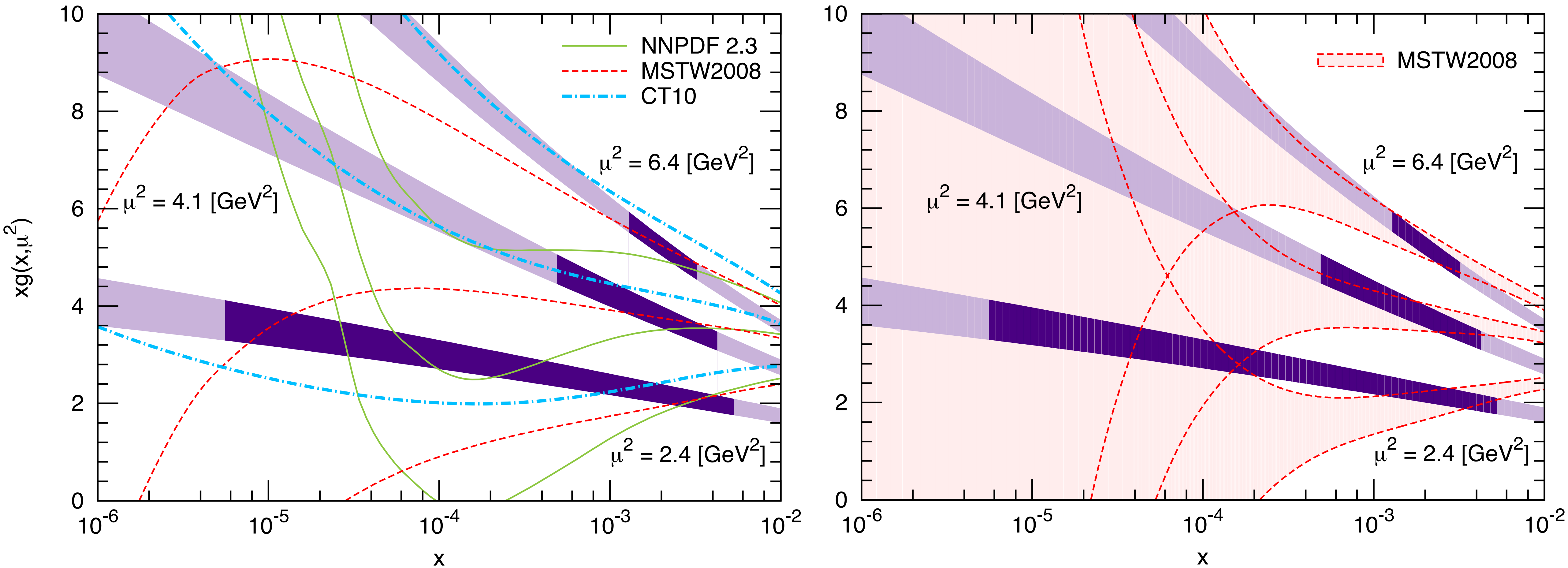


γp CMS Energy →

+ CDF, LHCb 2013 Data:



Extracted Gluons

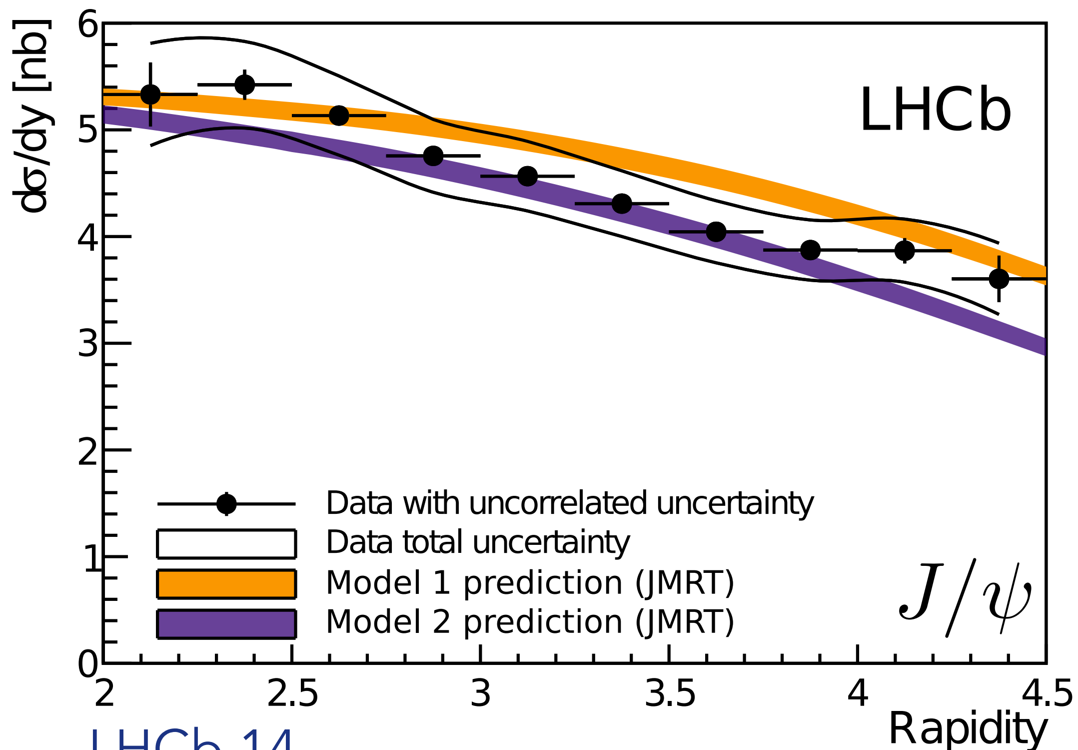


- Scale dependence from k_T^2 integral and HERA electoproduction data
- Fitted gluons below global partons for higher $x_B \sim 10^{-2}$
- LHCb data provides support for the fit down to $x_B \sim 10^{-6}$

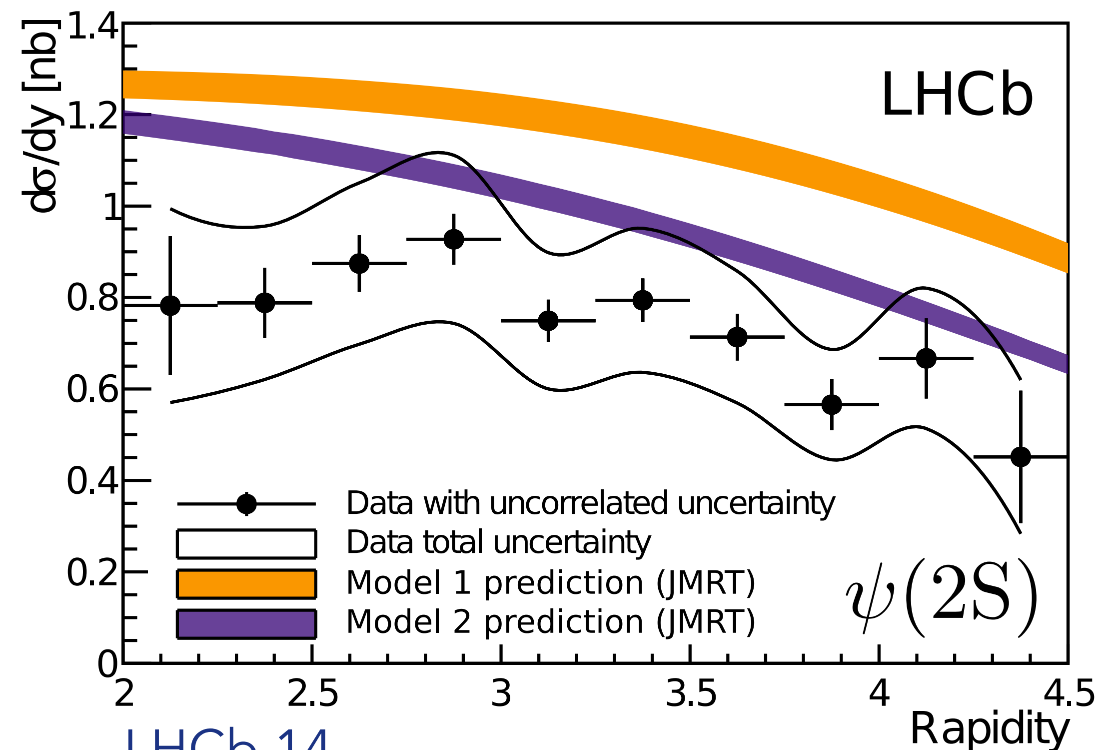
Not included here...

LHCb 2014 J/ψ, ψ(2S) data & LHCb 2015 ϒ data

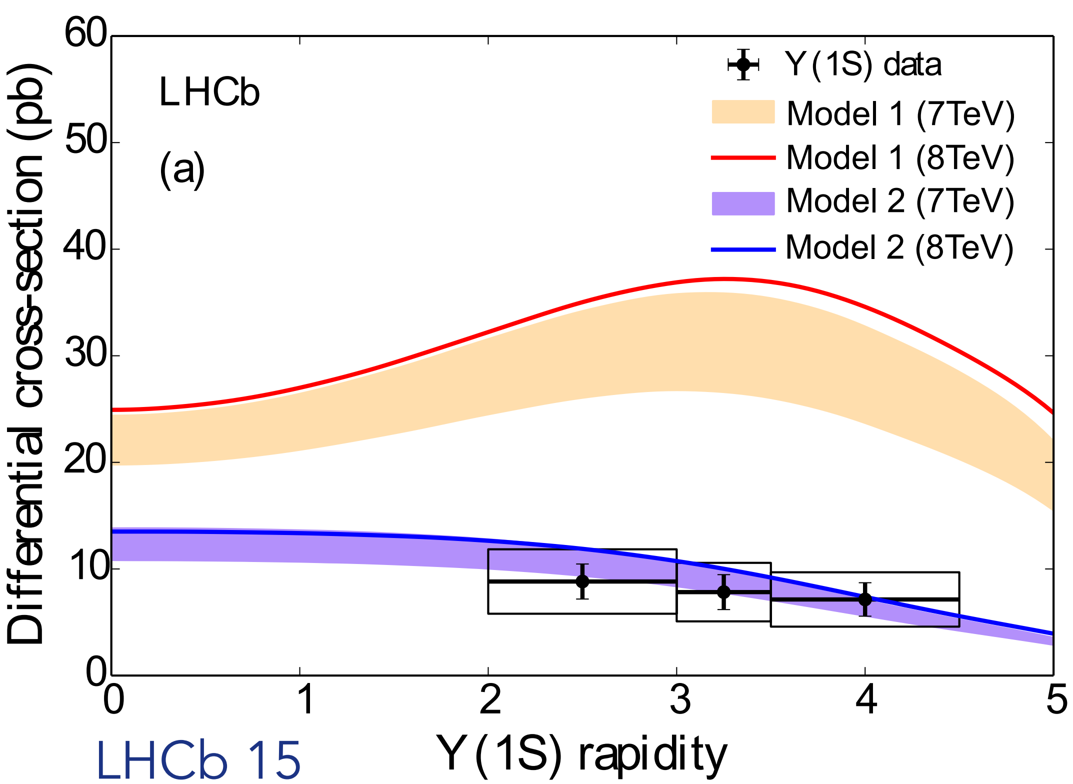
Predictions vs Data



LHCb 14



LHCb 14



LHCb 15

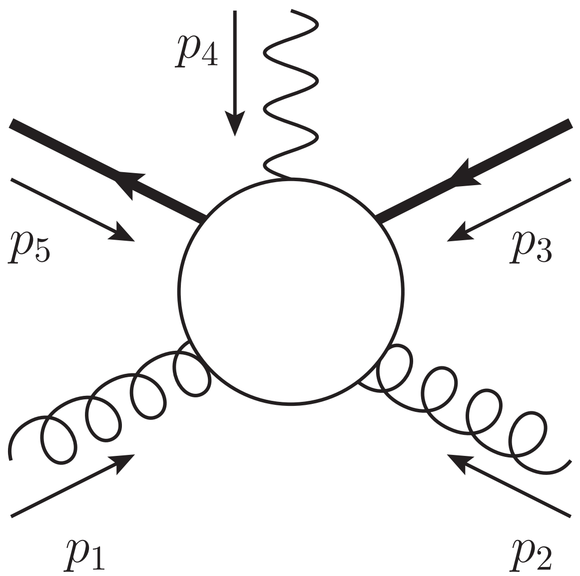
- ψ(2S): expect larger relativistic corrections
- ϒ(1S): Preference for Model 2 (which includes NLO effects)

NLO Calculation

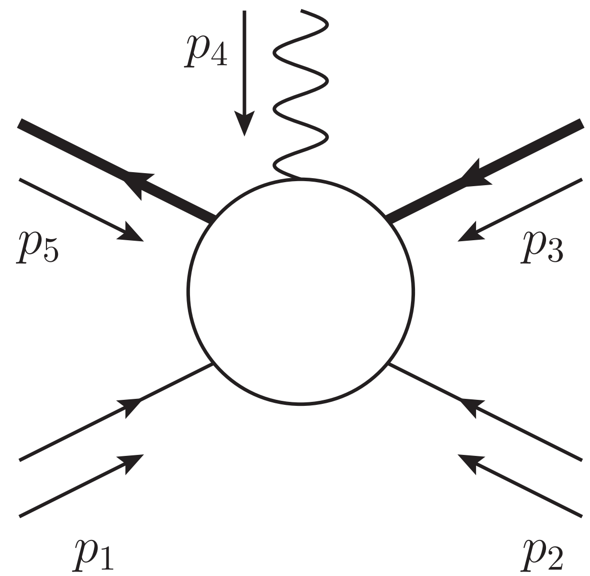
Now: Compute photoproduction at NLO in Collinear Factorisation

First computed in: Ivanov, Schäfer, Szymanowski, Krasnikov, 2004

Gluon



Quark



Loops	q Diagrams	g Diagrams
0	0	6
1	12	97

Compute in $d = 4 - 2\epsilon$ using Integral Reduction

`QGRAF` → `FORM` → `REDUZE` → `FORM`

Nogueira 93; Vermaseren et al. 12; von Manteuffel, Studerus 12

Original calculation used subtracted dispersion integrals

Our calculation corrected an error in treatment of gluon polarisations

NLO Calculation (II)

Kinematics

GPD $(t = 0) : p_1 \propto p_2$

NRQCD: $p_3 = p_5$

Collinear!

Vanishes due to kinematics

Must be careful with reduction but integrals simplify:

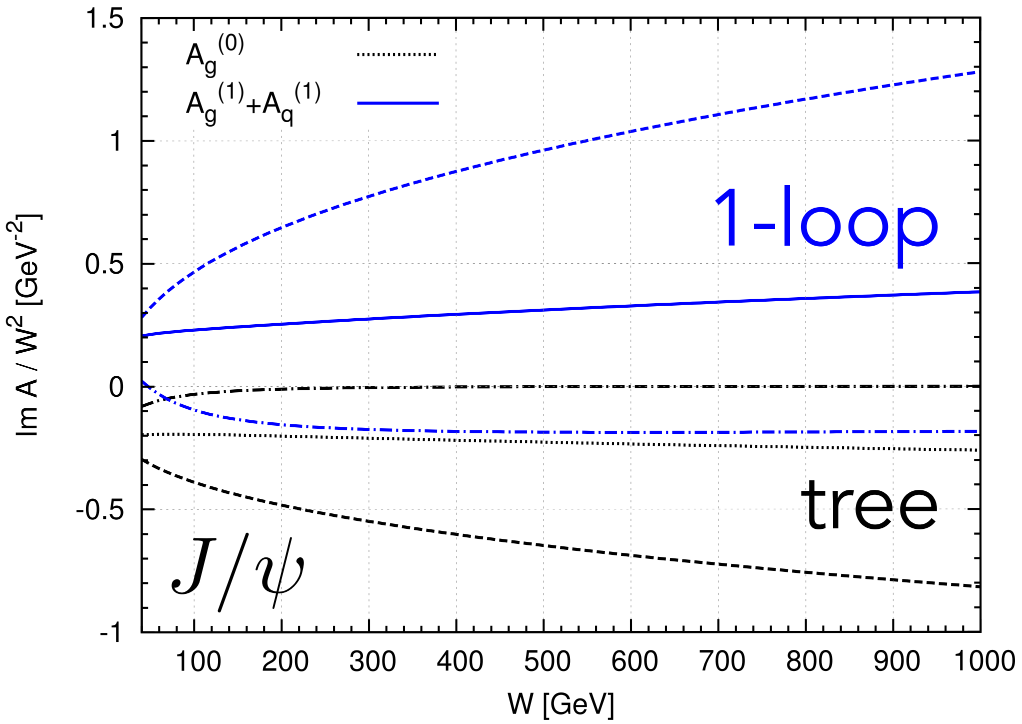
1. Perform Sudakov Decomposition: $p_i^\mu = (p_i \cdot n)p^\mu + (p_i \cdot p)n^\mu + p_{iT}^\mu$
2. Decompose integrals I in basis of Sudakov vectors p, n:
$$I^{\mu\nu} = \eta^{\mu\nu} I_{00} + p^\mu p^\nu I_{11} + p^\mu n^\nu I_{12} + n^\mu p^\nu I_{21} + n^\mu n^\nu I_{22}$$
3. Linearly dependent momenta ⇒ Relations between propagators N_i
4. Reduces N-point integrals to (N-1)-point integrals, retains the original basis of propagators

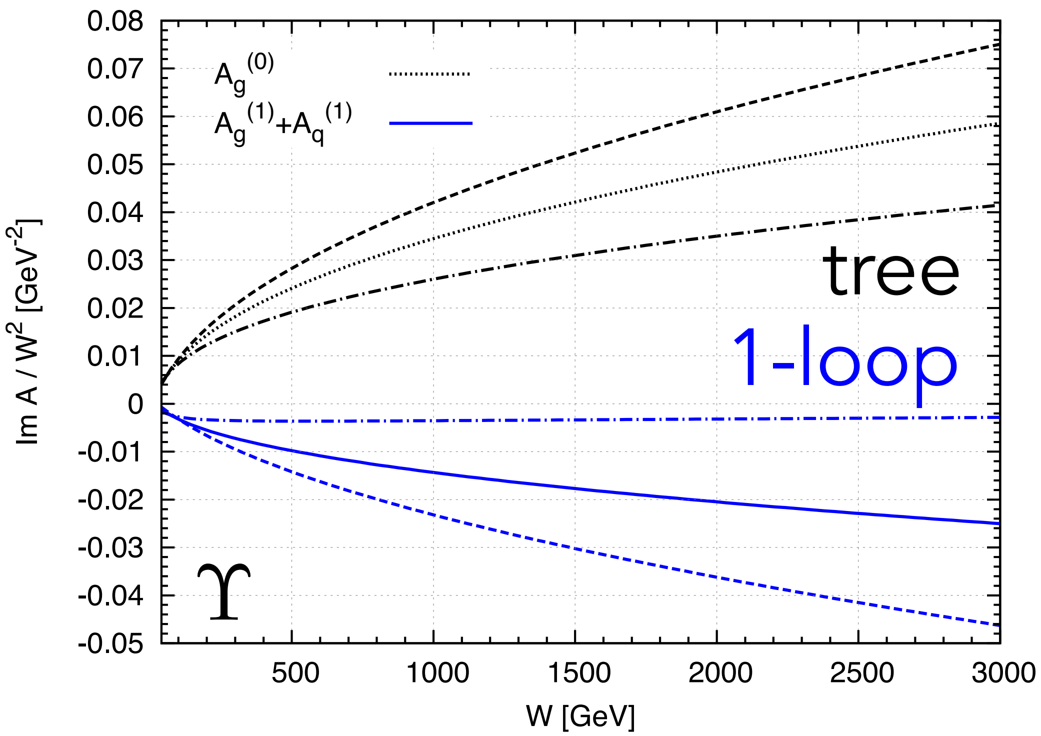
Example:

$$\sum_{i=0}^{2} a_i N_i = 1, \quad a_i \in \mathbb{R} \setminus \{0\} \implies \frac{N_2}{N_0 N_1} = \frac{1}{a_2}\frac{1}{N_0 N_1} - \frac{a_0}{a_2}\frac{1}{N_1} - \frac{a_1}{a_2}\frac{1}{N_0}$$

Photoproduction Amplitudes

GPDs obtained using full Shuvaev Transform from CTEQ66 Martin et al. 09





- J/ψ receives huge (opposite sign) loop corrections
- Loop corrections can dominate tree level contribution
- Very large variation with change of scale $\mu_R^2 = \mu_F^2 = (m^2/2, m^2, 2m^2)$

- ϒ still has sizeable (negative) loop corrections: NLO CS very suppressed compared to LO CS
- Tree level dominates loop corrections
- Variation with scale less dramatic

High-Energy Limit

At high energy $W^2 \gg M_V^2$ amplitude (in Collinear Factorisation):

$$T^{(1)} \approx -\,\mathrm{i}\pi\alpha_s(\mu_R) C_g^{(0)} \ln\left(\frac{m^2}{\mu_F^2}\right) \times$$

$$\left[\int_\xi^1 \frac{\mathrm{d}x}{x} \underset{\uparrow\ \sim\mathbf{const}}{F_g}(x,\xi,\mu_F) + \int_\xi^1 \mathrm{d}x \left(\underset{\uparrow\ \mathbf{1/x}}{F_S}(x,\xi,\mu_F) - F_S(-x,\xi,\mu_F)\right)\right]$$

- Large $\ln(1/\xi)$ can spoil perturbative convergence (at high-energy)
- Term originates from mass factorisation counter term

What can we do? Have a few options…

- \`Absorb' into LO (Scale fixing) SJ, Martin, Ryskin, Teubner 16
- Attempt to re-sum logs (à la BFKL) Ivanov 07; Ivanov, Pire, Szymanowski, Wagner 15,16;
- Impose a cut-off and transition to k_T-factorisation result (?)

Work ongoing…

Conclusion

In k_T Factorisation

- Gluon extracted from J/ψ data describes ψ(2S), ϒ(1S) data well
- Extracted gluon has considerably reduced uncertainty at small-x compared to global PDFs
- Cannot directly identify extracted gluon with $\overline{MS}$ partons

In Collinear Factorisation

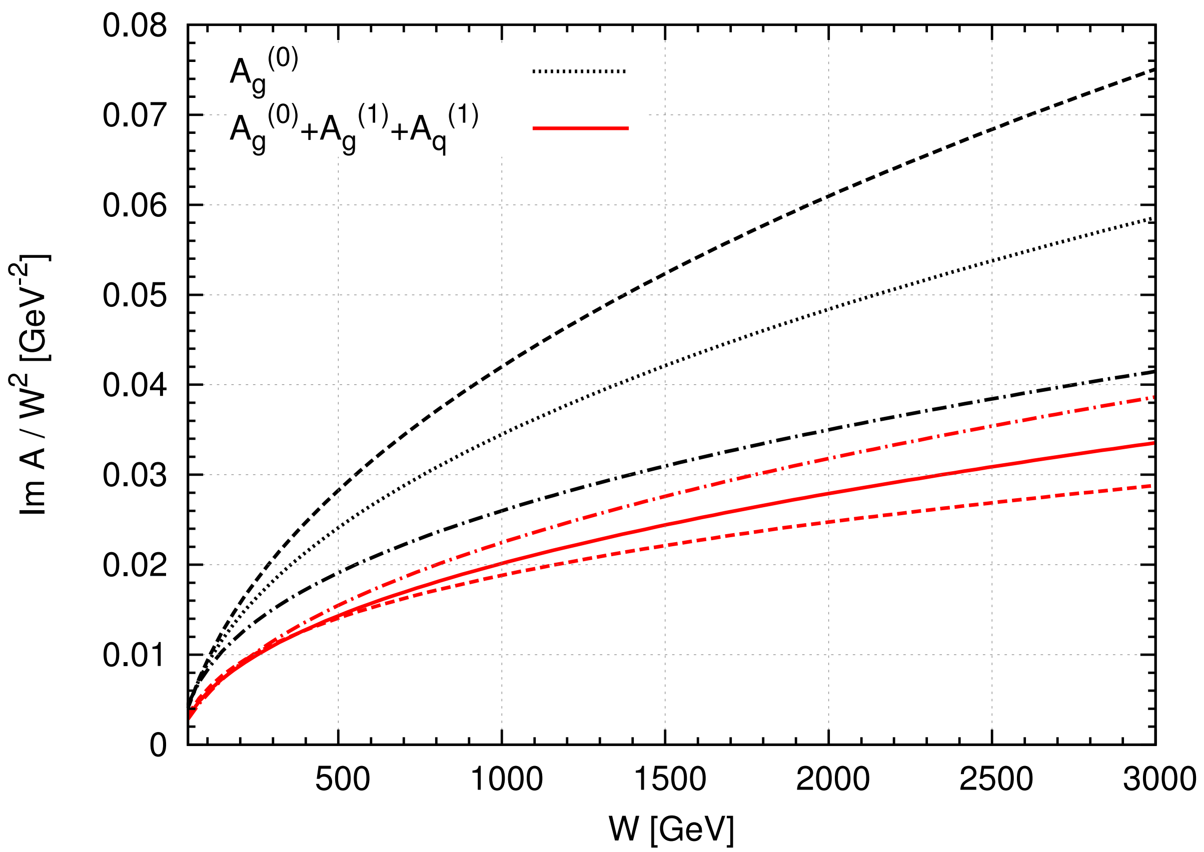
- Computed exclusive HVM production @ NLO w/ Integral Reduction (Independent cross-check of Ivanov, et al. 2004)
- Large (opposite sign) loop corrections and large $\ln(1/x_B)$ appear
- Several approaches to deal with large $\ln(1/x_B)$ proposed, work is ongoing…

Thank you for listening!

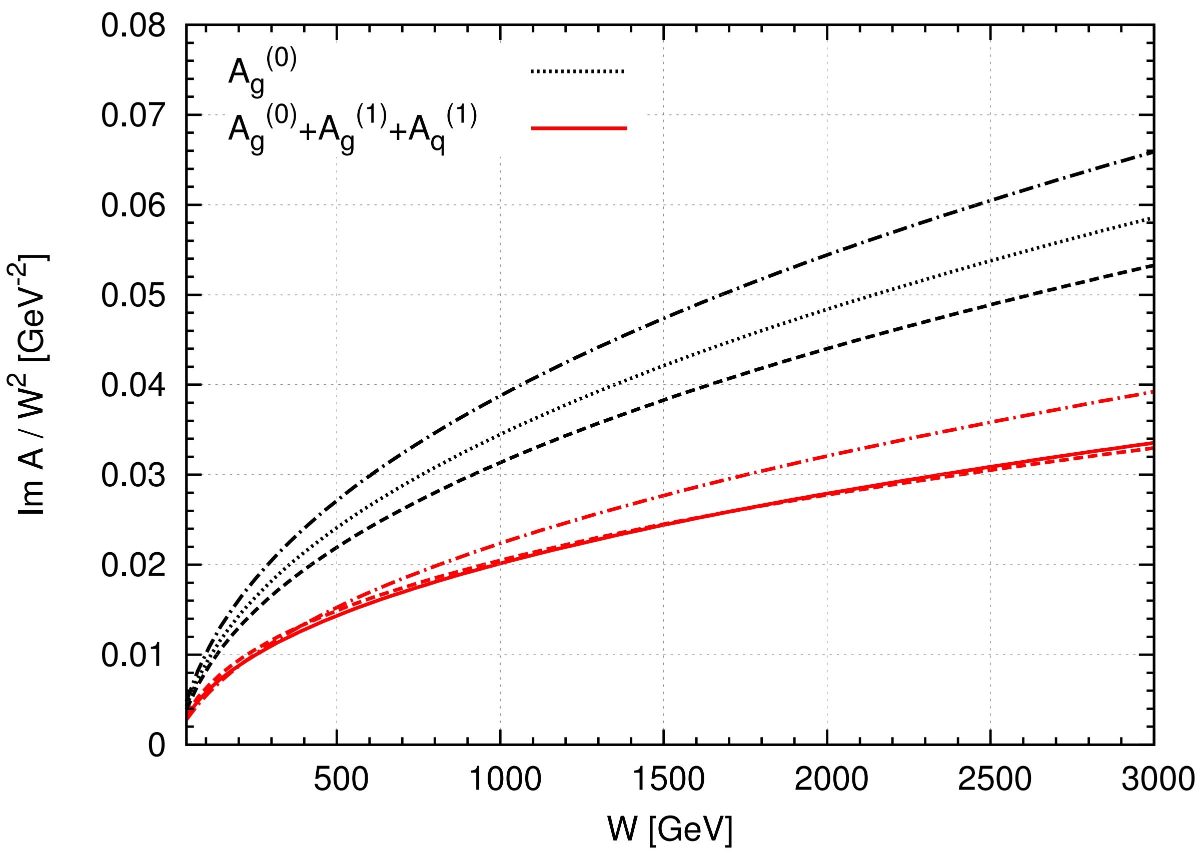
Backup

Scale fixing

$$T \sim C^{(0)} \otimes F(\mu_F) + \alpha_s(\mu_R) C^{(1)}_{\rm rem}(\mu_F) \otimes F(\mu_f)$$



$$\mu = \mu_F = \mu_f = \mu_R$$



$$\mu = \mu_f = \mu_R, \;\; \mu_F^2 = 22.4 \text{ GeV}^2$$

$$\mu^2 = 11.9, 22.4, 44.7 \text{ GeV}^2$$

SJ, Martin, Ryskin, Teubner 16

Extracting Small-x Gluon

Model 1

- Power law: $xg(x,\mu^2) = Nx^{-\lambda}$ with $\lambda = a + b\ln(\mu^2/0.45\mathrm{GeV}^2)$

Model 2

- Resum leading $(\alpha_s \ln(1/x)\ln\mu^2)^n$ contributions
- $xg(x,\mu^2) = Nx^{-a}(\mu^2)^b \exp\left[\sqrt{16N_c/\beta_0 \ln(1/x)\ln(G)}\right]$
- $G = \ln(\mu^2/\Lambda^2_{\mathrm{QCD}})/\ln(Q_0^2/\Lambda^2_{\mathrm{QCD}})$ with $\Lambda_{\mathrm{QCD}} = 200$ MeV

Fitting Procedure

- Non-linear χ^2 fit to data
- Obtain best fit N, a, b and full covariance matrix for error estimate

Model 2 (Integration)

- Above IR scale $Q_0^2 = 1\ \mathrm{GeV}^2$ up to kinematic upper bound perform explicit k_T^2 integration in the last step of the evolution

$$\mathrm{Im}A \sim \mathrm{IR\ Part} + \int_{Q_0^2}^{(W^2-M_{J/\psi}^2)/4} \frac{\mathrm{d}k_T^2}{k_T^2} \frac{\alpha_s(\mu^2)}{\bar{Q}^2(\bar{Q}^2+k_T^2)} f(x,k_T^2,\mu^2)$$

- Use 'Unintegrated' PDF

$$f(x,k_T^2,\mu^2) = \frac{\partial[R_g\, xg(x,k_T^2)\sqrt{T(k_T^2,\mu^2)}]}{\partial \ln k_T^2}$$

- T - Sudakov factor (hard gluon emits no additional partons)
- R_g - skewing factor [Shuvaev et. al 1999]

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+\frac{5}{2})}{\Gamma(\lambda+4)}$$

IR Part & Scale Choice

IR Part

- For $k_T < Q_0$ assume linear behaviour of gluon at small k_T^2

$$xg(x,k_T^2)\sqrt{T(k_T^2,\mu^2)} = xg(x,Q_0^2)\sqrt{T(Q_0^2,\mu_{\rm IR}^2)}k_T^2/Q_0^2$$

- Gives IR Part:

$$\ln\left(\frac{\bar{Q}^2+Q_0^2}{\bar{Q}^2}\right)\frac{\alpha_s(\mu_{\rm IR}^2)}{\bar{Q}^2 Q_0^2}xg(x,Q_0^2)\sqrt{T(Q_0^2,\mu_{\rm IR}^2)}$$

Scale Choice

- Scale choice ambiguity remains (is extracted gluon e.g. $\overline{\rm MS}$?)
- Choose $\mu^2 = \max(k_T^2,\bar{Q}^2)$ and $\mu_{\rm IR}^2 = \max(Q_0^2,\bar{Q}^2)$
- Scale in IR Part matches lowest scale in integral
- Electroproduction typically contributes at higher scale
- $Q_0^2 = 1\ {\rm GeV}^2$ (fit relatively insensitive to this)

NRQCD (HVM Formation)

- Effective field theory for production of heavy quarkonium [Bodwin et al. 1995]

$$\sigma_V = \sigma_{q\bar{q}} \cdot \langle O \rangle_V$$

- Relativistic corrections systematically computed by expanding matrix elements in powers of r:

$$\mathcal{M}[J/\psi] \propto (\mathcal{A}_\rho + \mathcal{B}_{\rho\sigma} r^\sigma + \mathcal{C}_{\rho\sigma\tau} r^\sigma r^\tau + \ldots)\epsilon^\rho_{J/\psi}$$

$\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$ - matrix elements $\epsilon^\rho_{J/\psi}$ - J/ψ polarization

- We will compute to leading order in relative quark velocity v, for J/ψ:

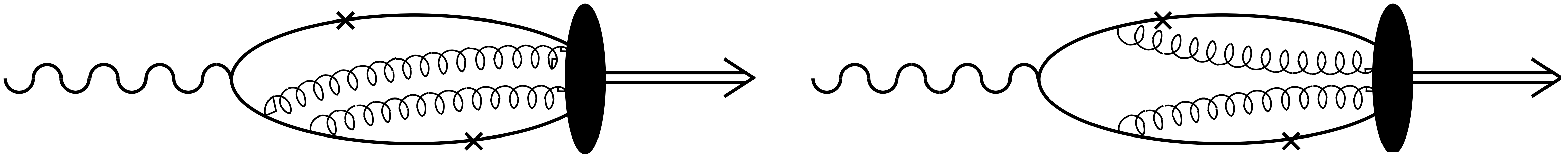
$$\mathcal{M}[J/\psi] = \left(\frac{\langle O_1 \rangle_{J/\psi}}{2N_c m_C}\right)^{\frac{1}{2}} \mathcal{A}_\rho \epsilon^\rho_{J/\psi}$$

- Compute $\Gamma_{ee} \propto \langle O_1 \rangle_{J/\psi}$
  - Extract $\langle O_1 \rangle_{J/\psi}$ from measurement of Γ_{ee}

Relativistic Effects (HVM Formation)

Hoodbhoy Study [Hoodbhoy 1997]

- Accounts for Fermi motion of the $c\bar{c}$ pair
  - Work in J/ψ rest frame using Coulomb gauge
  - Expand in powers of heavy quark relative velocity upto $\mathcal{O}(v^2)$
  - Necessary to include extra gluon fields to maintain gauge invariance
  - Procedure accounts for largest contribution from Fermi motion



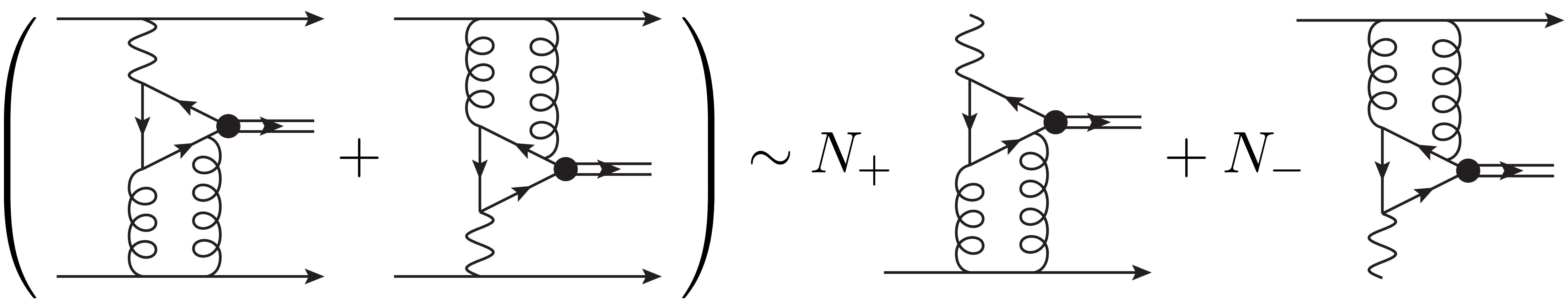
Result

- Correction factor due to Fermi motion ≈ 0.94 (for cross-section)

Ultraperipheral Production

- Ultraperipheral cross-section vs rapidity y receives contributions from two γp CM energies: $(W_\pm)^2 = M_{J/\psi}\sqrt{s}\,\exp\left(\pm|y|\right)$

$$\frac{\mathrm{d}\sigma(pp)}{\mathrm{d}y} = S_+^2 N_+ \sigma_+(\gamma p) + S_-^2 N_- \sigma_-(\gamma p)$$



- $N_\pm = k_\pm\,(\mathrm{d}n/\mathrm{d}k)_\pm$ - photon flux (EPA)
- $S_\pm^2$ - gap survival factors (KMR Model) [Khoze et al. 2002]

Photon Flux

$$\frac{\mathrm{d}n}{\mathrm{d}k} = \frac{\alpha}{\pi k} \int_0^{\infty} \mathrm{d}q_T^2 \frac{q_T^2 F_p^2(q_T^2)}{(t_{\min} + q_T^2)^2}$$

- k - photon energy
- q_T - photon trans. momentum
- $t_{\min}$ - kinematic q^2 cut-off

- Proton form factor:

$$F_p(q_T^2) = \left(1 + \frac{t_{\min} + q_T^2}{0.71\ \mathrm{GeV}^2}\right)^{-2}, \qquad t_{\min} \approx \frac{(x_\gamma m_p)^2}{1 - x_\gamma}$$

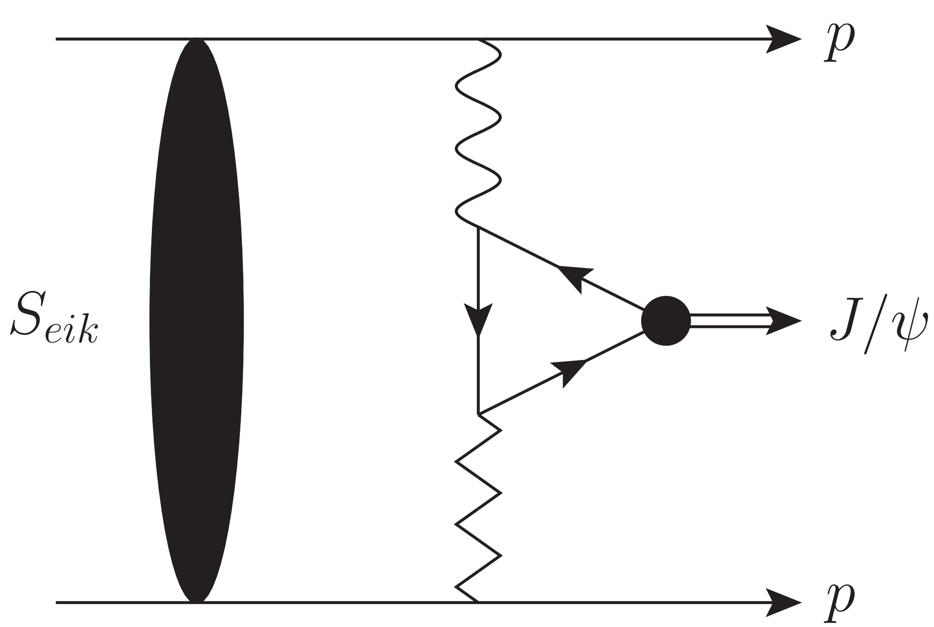
- Photon flux consistent with KMR model
  - Similar to equivalent photon approximation (EPA)
  - But: neglect terms $\propto$ anomalous magnetic moment of the proton

Accuracy

- Neglected terms $\propto q_T^2$ have no singularity at $q_T^2 \to 0$
- Contributions from $q_T \sim 1/R_p$ are concentrated at small b_t, suppressed by large opacities

Survival Factors

- For $pp \to p + J/\psi + p$ non-negligible interactions between spectator quarks
- Can populate rapidity gap
- Event not selected



KMR Model

$$S^2 = \langle S^2(b_t) \rangle = \frac{\int \sum_i |\mathcal{M}_i(s, b_t^2)|^2 \exp\left[-\Omega_i(s, b_t^2)\right] \mathrm{d}^2 b_t}{\int \sum_i |\mathcal{M}_i(s, b_t^2)|^2 \mathrm{d}^2 b_t}$$

- $\mathcal{M}_i$ - process dependent matrix elements
- b_t - impact parameter, Ω_i - 'universal' proton opacities

  [Khoze et al. 2002] [Khoze et al. 2013]

KMR Model

- Fitted to diffractive pp and $p\bar{p}$ data:
  - $\sigma_{\rm tot}$ - Total cross section ($\sigma_{\rm el} + \sigma_{\rm inel}$)
  - $\mathrm{d}\sigma/\mathrm{d}t$ - Elastic cross section
  - $\sigma^{\rm D}_{\rm lowM}$ - Low mass dissociation ($pp \to N^* + p$)
  - $\mathrm{d}\sigma/\mathrm{d}(\Delta\eta)$ - High mass dissociation
- Data from:
  - CERN ISR 1975–1980
  - CERN SPS 1982–1993
  - TEVATRON (CDF, DØ) 1990–2012
  - TOTEM 2011–2013
  - ATLAS 2012
- Two-channel eikonal model with one 'effective pomeron'
- Proton wave function written as superposition of two diffractive Good-Walker eigenstates $|p\rangle = \sum_i a_i|\phi_i\rangle$ with $i = 1, 2$

KMR Model (II)

- Use an opacity matrix Ω_{ik} corresponding to one-pomeron-exchange between states ϕ_i and ϕ_k
- Observables in terms of GW eigenstates depend on this opacity e.g.

$$\sigma_{\mathrm{inel}} = \int \mathrm{d}^2 b_t \sum_{i,k} |a_i|^2 |a_k|^2 (1 - \exp\left[-\Omega_{ik}(b_t)\right])$$

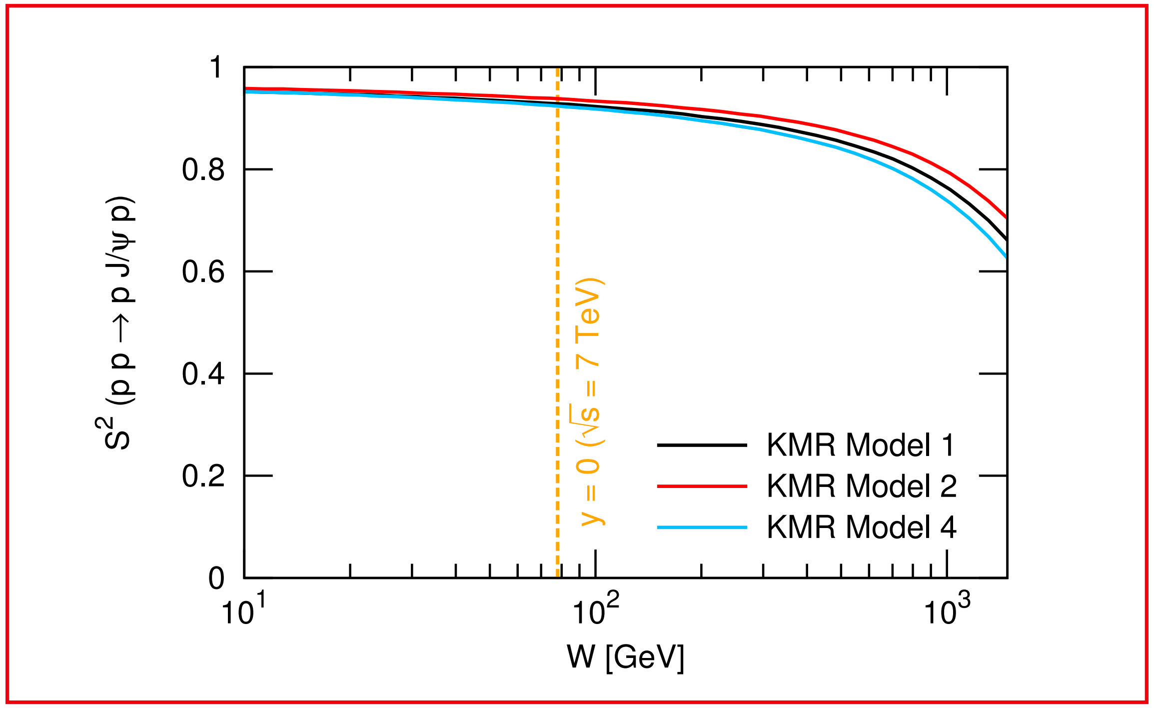
- Each GW eigenstate $|\phi_i\rangle$ independently parametrised by a form factor

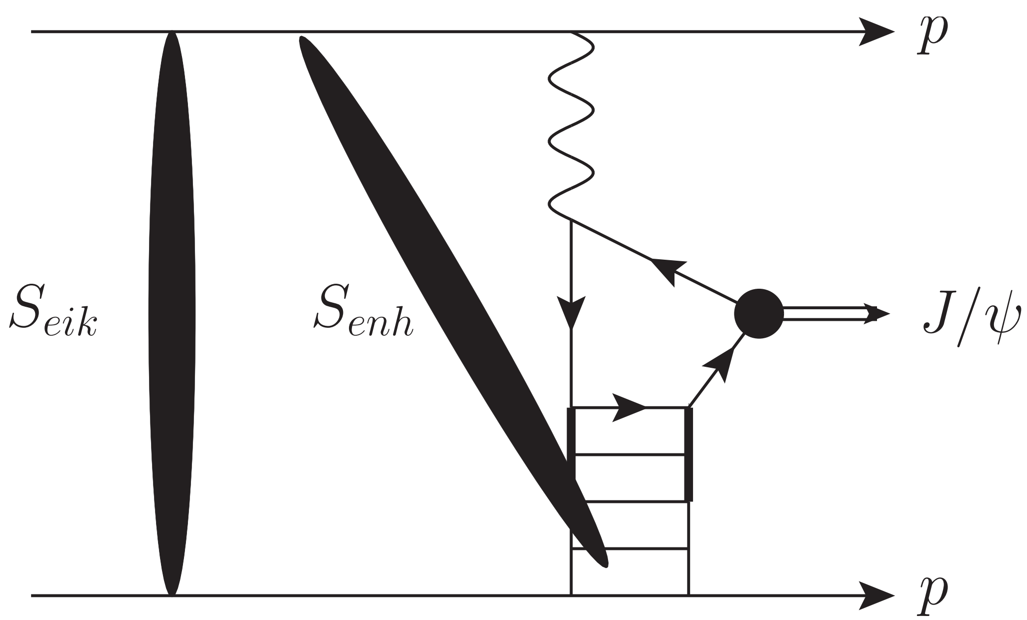
$$F_i(t) = \exp\left[-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}\right]$$

- 3 parameters per eigenstate + 1 relative weighting
- 'Effective' pomeron has energy dependent coupling to eigenstates
- 6 pomeron trajectory parameters: intercept (Δ), slope (α') and couplings (gives $b_0 = 4.9$, $\alpha' = 0.06$ for b slope)

KMR Model (III)

- Survival factors reasonably certain ($\mathcal{O}(5\%)$ difference between KMR models)
- Less certain for high rapidity





- Possibility of 'enhanced rescattering'
- Interaction between spectator quarks and parton in ladder

- Include this possibility using method of KMR [Ryskin et al. 2009]
- Find small effect from including S_{enh}

Shuvaev Transform

Full Transform:

$$\mathcal{H}_q(x,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{\mathrm{d}s}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'}\left(\frac{q(x')}{|x'|}\right),$$

$$\mathcal{H}_g(x,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{\mathrm{d}s(x+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'}\left(\frac{g(x')}{|x'|}\right),$$

$$y(s) = \frac{4s(1-s)}{x+\xi(1-2s)}.$$