Probing the Low x Gluon With Exclusive J/ψ Production

Stephen Jones

A. Martin, M. Ryskin, T. Teubner

• Assume process factorises:
  \[ F_{q/g} \otimes C_{q/g} \otimes \phi_Q^V \phi_{\bar{Q}} \]

• HVM formation described in NRQCD, we take only the leading term: \( \langle O_1 \rangle \propto \Gamma [V \rightarrow e^+ e^-] \)

• Compute at (Mandelstam) \( t = 0 \), restore assuming \( \sigma \sim \exp(-Bt) \)

• Unpolarised, helicity non-flip
  \[ F_g(x, \xi, 0) = \sqrt{1 - \xi^2} \mathcal{H}_g(x, \xi, 0) \]

**Contributes at NLO**

**Amplitude:**
\[ A \propto \int_{-1}^{1} dx \left[ C_g(x, \xi) F_g(x, \xi) + \sum_{q=u,d,s} C_q(x, \xi) F_q(x, \xi) \right] \]

Sensitive to poorly constrained low \( x_B \sim 10^{-5} \), low \( Q^2 \sim 2.4 \text{GeV}^2 \) gluon
Shuvaev Transform

- Limit $\xi = 0, t = 0$ GPDs are equal to PDFs
- Can directly extract GPDs

**Conjecture** Shuvaev Transform:
- In small-$x$ and $\xi$ limit GPDs are related to PDFs ($O(\xi)$ corr. at NLO) by double-integral transform

**Note:**
- (Regge-based) Must assume no singularities in right half N-plane of input distributions
- Transform is not valid for $|x| < \xi$ (time-like) region
- Further GPDs $E_g, E_q$ which vanish for $P = P'$ not known from PDFs
NLO Calculation

**Kinematics**
- GPD \((t = 0)\): \(p_1 \propto p_2\)
- NRQCD: \(p_3 = p_5\) **Collinear**

**Propagators contain linearly dependent momenta**

**Quark and Gluon coefficient functions known at NLO**
- Ivanov, Schäfer, Szymanowski, Krasnikov, 04

**Recomputed using integral reduction**
- SJ (Thesis) 15

**QGRAF → FORM → REDUCE → FORM**
- Nogueira 93; Vermaseren et al. 12; von Manteuffel, Studerus 12

**Small error in handling of gluon polarisation corrected**
- (alters behaviour of high-energy limit for quark channel)
- Nockles 09; Ivanov et al. 15 (Erratum); SJ, Martin, Ryskin, Teubner 15
GPDs obtained using full Shuvaev Transform from CTEQ66  

- \( J/\psi \) receives huge (opposite sign) loop corrections
- Loop corrections can dominate tree level contribution
- Very large variation with change of scale \( \mu^2 = \mu_R^2 = \mu_F^2 = (m^2/2, m^2, 2m^2) \)
- \( \Upsilon \) still has sizeable (negative) loop corrections: NLO very suppressed compared to LO
- Tree level dominates loop corrections
- Variation with scale less dramatic
High-Energy Limit

Origin of poor perturbative convergence clear from the high-energy limit $W^2 \gg M_V^2$ or $\xi \ll 1$ limit of amplitude:

1-loop amplitude

$$A^{(1)} \approx -i\alpha_s(\mu_R) C_g^{(0)} \ln \left( \frac{m^2}{\mu_F^2} \right)$$

$$\left[ C_A \int_{\xi}^{1} \frac{dx}{x} F_g(x, \xi, \mu_F) + C_F \int_{\xi}^{1} dx \left( F_S(x, \xi, \mu_F) - F_S(-x, \xi, \mu_F) \right) \right]$$

$\sim \text{const}$

$\sim 1/x$

Originates from mass factorisation counter term

Large $\ln(1/\xi)$ can spoil perturbative convergence

**Note:** After correcting handling of gluon polarisations quark channel also $\sim \ln(m^2/\mu_F^2) \ln(1/\xi)$
Scale fixing

One Option:

\[ A^{(1)} \sim C^{(0)} \otimes F(\mu_f) + \alpha_s(\mu_R)C^{(1)}(\mu_f) \otimes F(\mu_f) \]

\[ A^{(1)} \sim C^{(0)} \otimes F(\mu_F) + \alpha_s(\mu_R)C^{(1)}(\mu_F) \otimes F(\mu_f) \]

Fix Scale \( \mu_F = m \) to zero large double logarithms at NLO

**Note:** at this order in \( \alpha_s \) change in scale at tree level is compensated by change of scale in 1-loop part

What do we miss by doing this?

Could also be constants multiplying \( \ln(1/\xi) \) at higher orders:

\[ A \sim 1 + z \ln \left( \frac{m^2}{\mu_F^2} \right) + z^2 \left[ \frac{\pi^2}{6} + \frac{1}{2} \ln^2 \left( \frac{m^2}{\mu_F^2} \right) \right] + \ldots, \quad z^n \sim \alpha_s^n \ln^n(1/\xi) \]

Others are working on resumming these logarithms, will be very interesting to see their impact

SJ, Martin, Ryskin, Teubner 16

Ivanov 07; Ivanov, Pire, Szymanowski, Wagner 15,16;
Scale fixing (J/ψ and Υ)

\[ \mu = \mu_F = \mu_f = \mu_R \]

**J/ψ:**

1-loop\[ \mu^2 = 2.4 \]

Scale Fixing\[ \mu^2 = 4.8 \]

\[ \mu^2 = 1.2 \]

**Υ:**

1-loop\[ \mu^2 = 11.2 \]

Scale Fixing\[ \mu^2 = 22.4 \]

\[ \mu^2 = 44.7 \]

Fix: \[ \mu_F^2 = 2.4 \text{ GeV}^2 \]

SJ, Martin, Ryskin, Teubner 16
For low scale processes $\mathcal{O}(Q_0^2/M_{J/\psi}^2)$ contributions could be important.

**PDF Input Scale**

Contribution from $|l^2| < Q_0^2$ included both in PDF $\sim C^{(0)} \otimes P_{gq}$ (input distribution) and in coefficient function.

**Idea:** Subtract this contribution from coefficient function.

Compute leading part (ladder-diagrams) for $|l^2| < Q_0^2$ for both quark/gluon channels, subtract this from the full NLO coefficient functions.

*SJ, Martin, Ryskin, Teubner 16*
$Q_0$ cut ($J/\psi$)

Fix: $\mu_F^2 = 2.4 \text{ GeV}^2$

1-loop correction now smaller than LO

Small compared to tree level

Next step: try in the context of a global analysis (try using xFitter?)
Scale fixing and $Q_0$ cut optional
$k_T$-fac.: gluons carry transverse momentum (‘unintegrated’ PDFs)

- Use LO calculation only
- Use high energy ‘maximal skew’ approximation $x = \xi \approx \tilde{x}/2$
- $\sigma_{tot}$ can be off by $\sim 20\%$
  (compared to full transform)

Fit (simplified) gluons to just exclusive J/$\psi$ 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)
Small-x Gluon Parametrisation

Try two ansätze:

**Model 1: simple parametrisation**

Power law:

\[ xg(x, \mu^2) = N x^{-\lambda} \quad \text{with} \quad \lambda = a + b \ln(\mu^2/0.45\text{GeV}^2) \]

**Model 2: improved parametrisation**

Approximate \( P_{gg}(z) \propto 1/z \), resum leading \[ [\alpha_s \ln(1/x) \ln(\mu^2/\Lambda_{QCD}^2)]^n \]

Let \( G = \ln(\mu^2/\Lambda_{QCD}^2)/\ln(Q_0^2/\Lambda_{QCD}^2) \) and \( \Lambda_{QCD} = 200\text{MeV} \)

Double LLA:

\[ xg(x, \mu^2) = N x^{-a}(\mu^2)^b \exp \left[ \sqrt{16N_c/\beta_0} \ln(1/x) \ln(G) \right] \]

De Rújula, Glashow, Politzer, Treiman, Wilczek 74;

Here \( x^{-a}(\mu^2)^b \) allows approximately for single log contributions

**Note:** Including further singular terms \( \propto \delta(1 - z) \) would lead to the 'double scaling approximation' Ball, Forte 94
Update: Fitting & Data

New fit:

- Uncorrelated and bin-to-bin correlated errors within individual data sets (previous fit assumed errors uncorrelated)

- Budnev et al. (Dipole approx) for EPA photon flux  
  Budnev et al. 75; Kepka (Thesis) 10

- Updated gap survival factors for ultraperipheral production

- New LHCb data included

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Data</th>
<th>Error Treatment</th>
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</thead>
<tbody>
<tr>
<td>ZEUS 2002</td>
<td>19</td>
<td>6.5% Normalisation</td>
</tr>
<tr>
<td>ZEUS 2004</td>
<td>16</td>
<td>6.5% Normalisation</td>
</tr>
<tr>
<td>H1 2006</td>
<td>28</td>
<td>5% Normalisation</td>
</tr>
<tr>
<td>H1 2013</td>
<td>10</td>
<td>Covariance Matrix</td>
</tr>
<tr>
<td>LHCb 2013</td>
<td>Superceded</td>
<td>-</td>
</tr>
<tr>
<td>LHCb 2014</td>
<td>10</td>
<td>7% Normalisation</td>
</tr>
<tr>
<td>LHCb 2016</td>
<td>10</td>
<td>7% Normalisation</td>
</tr>
</tbody>
</table>
Previous Fit (2013)

Note: Here the LHCb points are extracted from \( \frac{d\sigma(pp)}{dy} \) data and depend on the fit.

### Model 1

<table>
<thead>
<tr>
<th>Fit</th>
<th>N</th>
<th>a</th>
<th>b</th>
<th>( \chi^2/d.o.f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>1.20 ± 0.06</td>
<td>0.05 ± 0.01</td>
<td>0.079 ± 0.004</td>
<td>41/79 \approx 0.5</td>
</tr>
<tr>
<td>Model 2</td>
<td>0.29 ± 0.04</td>
<td>-0.10 ± 0.01</td>
<td>-0.20 ± 0.06</td>
<td>50/79 \approx 0.6</td>
</tr>
</tbody>
</table>

Note: parameters of Model 1 can not be compared to Model 2 (different gluon parametrisation)
**New Fit (2017)**

**Note:** Here the LHCb points are extracted from $d\sigma(pp)/dy$ data and depend on the fit.

<table>
<thead>
<tr>
<th>Fit</th>
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<th>a</th>
<th>b</th>
<th>$\chi^2$/d.o.f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>1.31 ± 0.06</td>
<td>0.04 ± 0.01</td>
<td>0.079 ± 0.005</td>
<td>79/90 ≈ 0.9</td>
</tr>
<tr>
<td>Model 2 (w/o 2016)</td>
<td>0.29 ± 0.02</td>
<td>-0.10 ± 0.01</td>
<td>-0.20 ± 0.02</td>
<td>74/80 ≈ 0.9</td>
</tr>
<tr>
<td>Model 2</td>
<td>0.29 ± 0.03</td>
<td>-0.10 ± 0.01</td>
<td>-0.20 ± 0.05</td>
<td>76/90 ≈ 0.8</td>
</tr>
</tbody>
</table>
LHCb 2016 (Preliminary) data now probe $x_B \sim 10^{-6}$
Shape/uncertainty of fit largely unchanged by 2016 data

**Note:** Gluons we extract here are not in $\overline{MS}$ scheme and are in $k_T$ factorisation framework - plot just gives a qualitative indication of what we can expect from a full extraction
Can constrain small-x gluon also from forward charm production → talk Rhorry Gauld/Juan Rojo

Similar uncertainty, their fit prefers smaller gluon density at low-x

**Note:** Gluons here are not directly comparable (see previous slide)
Collinear Factorisation

- Described large scale uncertainty & large loop correction at NLO
- Suggested potential pragmatic solutions to allow use of NLO result
- **(Future)** Attempt to use NLO result (optionally with scale fixing and $Q_0$ cut) to extract PDF

$k_T$ Factorisation

- Updated fit with new J/$\psi$ data (LHCb 2014, 2016 Preliminary), survival factors & more accurate photon flux
- Extracted gluon has considerably reduced uncertainty at small-$x$ compared to global PDFs
- But: cannot directly identify extracted gluon with $\overline{\text{MS}}$ partons

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Thank you for listening!
Backup
Can create a model in terms of photoproduction cross-section ultraperipheral cross-section vs rapidity \( y \) receives contributions from two \( \gamma p \) energies: 

\[
(W_{\pm})^2 = M_{J/\psi} \sqrt{s} \exp(\pm |y|)
\]

(Very) Schematically:

\[
\begin{align*}
\left| \begin{array}{c}
\text{Photon flux} \\
\text{Gap survival factor}
\end{array} \right| \sim S_+^2 N_+ & \quad & \left| \begin{array}{c}
\text{Photon flux} \\
\text{Gap survival factor}
\end{array} \right| \sim S_-^2 N_-
\end{align*}
\]

Result:

\[
\frac{d\sigma(pp)}{dy} = S_+^2 N_+ \sigma_+(\gamma p) + S_-^2 N_- \sigma_-(\gamma p) + \ldots
\]

Note: We allow the survival factors to depend on energy

See e.g: Schäfer, Szczurek 07

Strongly suppressed interference (neglected)
Generalised Parton Distributions

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

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

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

Forward Limit ( $\xi = 0$):

$$\mathcal{H}_q(x, 0, 0) = q(x), \quad x > 0$$

$$\mathcal{H}_q(x, 0, 0) = -\bar{q}(-x), \quad x < 0$$

$$\mathcal{H}_g(x, 0, 0) = x g(x)$$

GPDs probed also in other hard exclusive processes, e.g. DVCS & TCS
(Conjecture) Shuvaev Transform:

- In small-\(x\) and \(\xi\) 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: \(H_N = \sum_{k=0}^{[(N+1)/2]} c_k^N \xi^{2k}\) allows Gegenbauer moments to be determined from conventional PDFs \(\mathcal{O}(\xi)\) at NLO
Shuvaev Transform

Full Transform:

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

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

\[
y(s) = \frac{4s(1 - s)}{x + \xi(1 - 2s)}.
\]
Formation of the $J/\psi$ is $\propto \Gamma [J/\psi \rightarrow e^+ e^-]$

Simplest picture: $c\bar{c}$ pair with equal momenta

Pair can also have some non-zero relative momenta

**Approach 1:** Model $J/\psi$ wave function, integrate over relative momenta - can give huge (order of magnitude) correction

Frankfurt, Koepf, Strikman 96, 98

**Approach 2:** (NRQCD based), expand in the relative velocity, include extra gluon fields (maintains gauge invariance) - correction factor $\approx 0.94$ for cross-section

Hoodbhoy 97

Here we neglect the relativistic corrections/ Fermi motion
Model 1: simple LO approach

Contribution of imaginary part of amplitude to differential cross-section in the LLA in $\bar{Q}^2$,

$$\frac{d\sigma}{dt}(\gamma^*p)\bigg|_{t=0} = \frac{\Gamma_{ee}^{J/\psi} M_{J/\psi}^3 \pi^3}{48\alpha_{em}} \left[ \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} R_g x g(x, \bar{Q}^2) \right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2} \right)$$

Ryskin 93

Model 2: improved, includes NLO effects

Above some IR scale $Q_0^2 = 1\text{GeV}^2$ perform explicit $k_T^2$ integral in last step of evolution (includes some effects that would appear at NLO in Collinear Factorisation)

$$\left[ \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} R_g x g(x, \bar{Q}^2) \right] \to \int_{Q_0^2}^{(W^2-M_{J/\psi}^2)/4} \frac{dk_T^2}{\bar{Q}^2(\bar{Q}^2 + k_T^2)} \frac{\alpha_s(\mu_R^2)}{\mu_F^2} \frac{f_g(x, k_T^2, \mu_F^2)}{IR}$$

Assume gluon $\sim k_T^2$
`Unintegrated' PDF:

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

Sudakov Factor: \( T(k_T^2, \mu) \) gluon emitted during evolution from
\( k_T^2 \to \mu^2 \) must not destroy rapidity gap

**Skewing:** Process depends on Generalised Parton Distributions \( H_g(x, \xi) \) related to PDFs via Shuvaev Transform \( \mathcal{O}(x) \) (conjecture)

\[
x = \frac{Q^2 + M^2_{J/\psi}}{W^2 + Q^2}
\]

Approx: \( R_g \equiv \frac{H_g(x/2, x/2)}{H_g(x, 0)} \approx \frac{2^{2\lambda_g+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda_g + 5/2)}{\Gamma(\lambda_g + 4)} \)

**Note:** This \( R_g \) approximation is quite poor, \( \sigma_{\text{tot}} \) can be off by \( \sim 20\% \)

(Probably) now our dominant approximation error

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Shuvaev 99; Shuvaev et al. 99

Harland-Lang 13
**Refinement: Photon Flux**

**Equivalent Photon Approximation (EPA):**

\[
\frac{dN}{dk} = \frac{\alpha_{em}}{\pi} \frac{1}{k} \frac{dQ^2}{Q^2} \left[ \left( 1 - \frac{k}{E} \right) \left( 1 - \frac{Q^2_{min}}{Q^2} \right) F_E + \frac{k^2}{2E^2} F_M \right]
\]

Budnev, Ginzburg, Meledin, Serbo 75

**Proton Electric/Magnetic Form Factors**

- Various approximations to the (cumbersome) Budnev et al. flux exist
- Previously used "Ryskin Approx." (neglects various subdominant terms) \(~5-10\%\) too small

**New Fit:** Use Kepka Approx.

Kepka (Thesis) 10
Update: Survival Factors

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

**KMR Model:**

$$S^2 \equiv \langle S^2(b_t^2) \rangle = \frac{\int \sum_{ij} \left| \mathcal{M}_j(s, \vec{b_t}^2) \right|^2 \exp \left[ -\Omega_i(s, \vec{b_t}^2) \right] d^2\vec{b_t}}{\int \sum_j \left| \mathcal{M}_j(s, \vec{b_t}^2) \right|^2 d^2\vec{b_t}}.$$  

$b_t^2$ - impact parameter, $\mathcal{M}_i$ - process dependent matrix elements, $\Omega_i$ - "universal" proton opacities  

**Note:** Photon flux appears in denominator of $S^2$, partly cancels that in ultraperipheral relation. Best to use same flux in both formulae.

**New Fit:** Survival Factors Updated + now use the Budnev (Kepka) Flux
Fit to HERA data only:

- Scale dependence from $k_T^2$ integral and HERA electoproduction data
- Fit describes both photoproduction and electroproduction 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, LHCb2016 J/$\psi$, $\psi(2S)$ data & LHCb 2015 $\Upsilon$ data
• $\psi$(2S): expect larger relativistic corrections
• $\Upsilon$(1S): Preference for Model 2 (which includes NLO effects)
NLO Calculation

Kinematics

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

NRQCD: \(p_3 = p_5\)

Collinear!

Must be careful with reduction but integrals simplify:

1. Perform Sudakov Decomposition: \(p_i^\mu = (p_i \cdot n)p^\mu + (p_i \cdot p)n^\mu + p_i^\mu_T\)

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 \(\Rightarrow\) Relations between propagators \(N_i\)

4. Reduces \(N\)-point integrals to \((N-1)\)-point integrals, retains the original basis of propagators

Example:

\[
\sum_{i=0}^{2} a_i N_i = 1, \quad a_i \in \mathbb{R} \setminus \{0\} \quad \Rightarrow \quad \frac{N_2}{N_0 N_1} = \frac{1}{a_2} \frac{1}{N_0 N_1} - \frac{a_0}{a_2} \frac{1}{N_1} - \frac{a_1}{a_2} \frac{1}{N_0}
\]
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 \( r \):

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

\( \mathcal{A}, \mathcal{B}, \mathcal{C} \) - matrix elements \( \epsilon_{J/\psi}^p \) - \( J/\psi \) polarization

• We will compute to leading order in relative quark velocity \( v \), for \( J/\psi \):

\[ \mathcal{M}[J/\psi] = \left( \frac{\langle O_1 \rangle_{J/\psi}}{2N_cm_C} \right)^{1/2} \mathcal{A}_\rho \epsilon_{J/\psi}^p \]

• Compute \( \Gamma_{ee} \propto \langle O_1 \rangle_{J/\psi} \)
  ○ Extract \( \langle O_1 \rangle_{J/\psi} \) from measurement of \( \Gamma_{ee} \)
Photon Flux (2013)

\[
\frac{dn}{dk} = \frac{\alpha}{\pi k} \int_0^\infty dq_T^2 \frac{q_T^2 F_p^2(q_T^2)}{(t_{\text{min}} + q_T^2)^2}
\]

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

- Proton form factor:
  \[
  F_p(q_T^2) = \left(1 + \frac{t_{\text{min}} + q_T^2}{0.71 \text{ GeV}^2}\right)^{-2}, \quad t_{\text{min}} \approx \frac{(x_\gamma m_p)^2}{1 - x_\gamma}
  \]

- 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
Fitted to diffractive $pp$ and $p\bar{p}$ data:
- $\sigma_{\text{tot}}$ - Total cross section ($\sigma_{\text{el}} + \sigma_{\text{inel}}$)
- $d\sigma/dt$ - Elastic cross section
- $\sigma_{\text{lowM}}^D$ - Low mass dissociation ($pp \rightarrow N^* + p$)
- $d\sigma/d(\Delta\eta)$ - 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 $i = 1, 2$
• Use an opacity matrix $\Omega_{ik}$ corresponding to one-pomeron-exchange between states $\phi_i$ and $\phi_k$

• Observables in terms of GW eigenstates depend on this opacity e.g.

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

• 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 ($\Delta$), slope ($\alpha'$) and couplings (gives $b_0 = 4.9$, $\alpha' = 0.06$ for $b$ slope)
• Survival factors reasonably certain \((\mathcal{O}(5\%))\) difference between KMR models
• Less certain for high rapidity

\[ S_{eik} \quad S_{enh} \quad J/\psi \]

• 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 \(S_{enh}\)