Small-x gluon from exclusive J/ψ production

$\sigma(\gamma p \to p + J/\psi)$ & $\mathrm{d}\sigma/\mathrm{d}y(pp \to p + J/\psi + p)$

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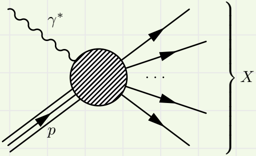
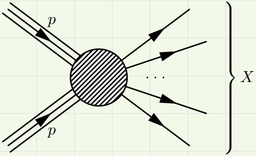
H1 Collaboration Meeting
12th September

Forward physics: Exclusive & Diffractive Processes

Inclusive Processes - Included in global analyses

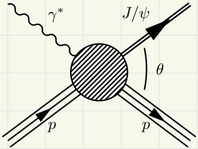


DIS

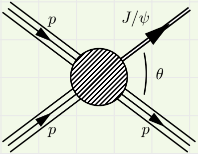


Inclusive pp Scattering

Exclusive & Diffractive Processes



Exclusive HVM Electroproduction



Ultraperipheral HVM production

Outline

Motivation

- Inclusive DIS poorly constrains $xg(x, \mu^2)$ at low scales ($\mu^2 < 6\ \mathrm{GeV}^2$) and small-$x$ ($\sim 10^{-4}$)
- Exclusive processes such as exclusive HVM production are a sensitive probe of the gluon in this domain

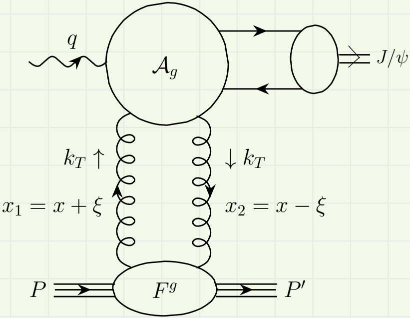
Contents

- Review of elastic J/ψ photo(electro)-production
- Extracting the gluon density at low μ^2, small-x
- Photoproduction data from LHCb events $(pp \to p + J/\psi + p)$
- Results & predictions
- Future theory improvements

Based on work with:

Alan Martin, Misha Ryskin and Thomas Teubner [arXiv:1307.7099[hep-ph]]

J/ψ Photo(electro)-production



- $Q^2 = -q^2$ photon virtuality
- W CM energy of $\gamma^* p$

General Setup & Assumptions

- Factorises: $\phi^{\gamma}_{c\bar{c}} \otimes T_{c\bar{c}+p} \otimes \phi^{J/\psi}_{c\bar{c}}$
- Non-relativistic J/ψ wave function $\propto \Gamma_{ee}$
- Γ_{ee}, $M_{J/\psi}$ from experiment
- Relativistic corrections $\mathcal{O}(4\%)$
- At LO: $k_T^2 \ll \bar{Q}^2$, leading log approximation (LLA)
- Scale: $\bar{Q}^2 = (Q^2 + M^2_{J/\psi})/4$

J/ψ Photo(electro)-production at LO

Amplitude (k_T Factorisation)

$$A \propto \int \frac{\mathrm{d}k_T^2}{2k_T^4} \left(\frac{1}{\bar{Q}^2} - \frac{1}{\bar{Q}^2 + k_T^2} \right) \alpha_s(k_T^2) f(x, k_T^2) \xrightarrow{\text{LLA}} \frac{\alpha_s(\bar{Q}^2) x g(x, \bar{Q}^2)}{2\bar{Q}^4}$$

Result (LLA, Im Part)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p \to J/\psi p)\bigg|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \frac{\alpha_S(\bar{Q}^2)^2}{\bar{Q}^8} \left[x g(x, \bar{Q}^2) \right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2} \right)$$

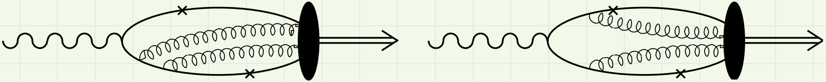
[Ryskin 1993]

- $x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2)$
- Can restore t dependence assuming form $\exp(-bt)$
- $b = b_0 + 4\alpha' \ln(W/W_0)$ is the *slope* parameter
- Proton-pomeron intercept (b_0) and pomeron slope (α') fitted from experiment

Non-relativistic J/ψ Formation (Theory Uncertainty)

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

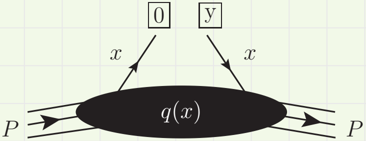
- Correction factor due to Fermi motion ≈ 0.96 (for cross-section)
- Our study neglects these corrections

Skewing (Theory Uncertainty)

GPDs

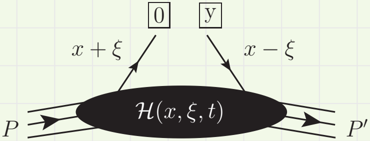
- Strictly, process does not couple to diagonal gluon but to non-diagonal Generalised PDF (GPDs)

PDF



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

GPD



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

Shuvaev Transform

- In small-x and ξ limit GPDs are related to PDFs via Shuvaev transform [Shuvaev et. al 1999]

Shuvaev Transform

Outline

- Anomalous dimensions of Gegenbauer moments, G_N of $H(x,\xi)$, are equal to anomalous dimensions of conventional Mellin moments, $M_N = \int_0^1 x^N H(x,0)\mathrm{d}x$
- Polynomiality: $G_N = \sum_{n=0}^{N} c_n^N \xi^{2n}$, allows all Gegenbauer moments to be determined $\mathcal{O}(\xi^2)$ from conventional PDFs $(c_0^N = M_N)$ [1]

Regge-based assumption

- No singularities in the right half plane $(j > 1)$ in the space-like $(\xi < |x|)$ domain of diagonal small-x input distributions

[1] reduces to $\mathcal{O}(\xi)$ at NLO

Shuvaev Transform (II)

- Shuvaev transform is an inverse (integral) transformation which determines x dependence of $H(x, \xi)$ for a given small ξ from diagonal $H(x, 0)$

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

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

- Computationally expensive to compute for realistic input distributions
- GPD grids obtained from PDFs via Shuvaev transform available [Martin et al. 2009]

Skewing & Real Part

- We use 'maximal skewing' limit ($\xi = x$), pure power PDF ($xg \sim x^{-\lambda}$) in transform which gives skewing factor

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

- $\mathcal{O}(20 - 30\%)$ error on cross section compared to full transform [Harland-Lang 2013]
- $\mathcal{O}(10 - 15\%)$ on gluon parameters

Real Part

- Real contribution included via dispersion relation assuming in the low x region $A \propto x^{-\lambda} + (-x)^{-\lambda}$

$$\frac{\mathrm{Re}A}{\mathrm{Im}A} \simeq \frac{\pi}{2}\lambda$$

Beyond LO Approach

- 'Unintegrated' PDF

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

- T is a Sudakov Factor representing the probability that no additional gluons emitted in DGLAP evolution from k_T^2 to μ^2 destroy the rapidity gap

$$T(k_T^2, \mu^2) = \exp\left[\frac{-C_A \alpha_s(\mu^2)}{4\pi} \ln^2\left(\frac{\mu^2}{k_T^2}\right)\right]$$

- Above some IR scale Q_0^2 up to kinematic upper bound perform explicit k_T^2 integration in the last step of the evolution

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

IR Part and Scale Choices

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
- $Q_0^2 = 1\ {\rm GeV}^2$ (fit relatively insensitive to this)
- Electroproduction typically contributes at higher scale

Fitting Procedure

- Try two different ansätze for small-x gluon

LO Approach

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

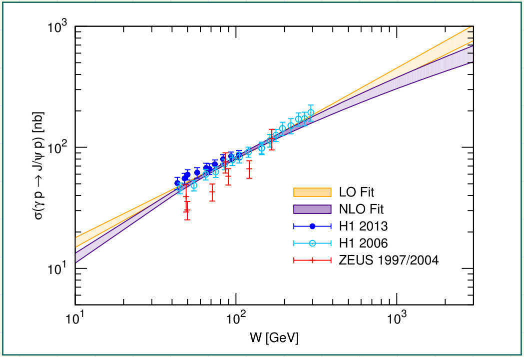
Beyond 'LO' Approach

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

Fitting Procedure

- Non-linear χ^2 fit to H1 and ZEUS exclusive data
- Compute full $\sigma(\gamma^* p \to J/\psi + p)$ vs N, a, b
- Minimise χ^2 iteratively
- Obtain best fit N, a, b and full covariance matrix for error estimate

HERA $(\gamma^* p \to J/\psi + p)$



Parameters

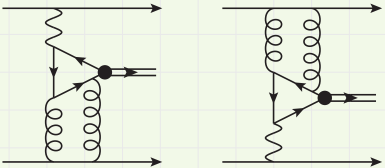
	LO	'NLO'
N	1.24	0.26
a	0.05	-0.10
b	0.08	-0.15
$\chi^2_{d.o.f}$	1.2	1.3

- Update to MNRT fit
  [Martin et al. 2008]

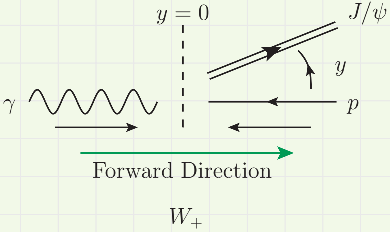
- Probes gluon for $10^{-4} \lesssim x \lesssim 10^{-2}$
- Note: Electroproduction data included in fit (not shown here)

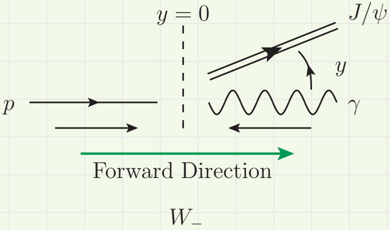
LHCb Data

- Measured $\mathrm{d}\sigma(pp \to p + J/\psi + p)/\mathrm{d}y$ vs y



- Aliasing problem extracting $\sigma(\gamma p \to J/\psi + p)$

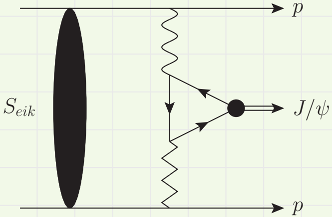




- $(W_\pm)^2 = M_{J/\psi}\sqrt{s}\exp(\pm|y|)$

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:
  - σ_{tot} - Total cross section ($\sigma_{\mathrm{el}} + \sigma_{\mathrm{inel}}$)
  - $\mathrm{d}\sigma/\mathrm{d}t$ - Elastic cross section
  - $\sigma^{\mathrm{D}}_{\mathrm{lowM}}$ - 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)

- Strictly, 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.

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

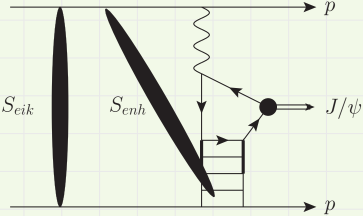
- Each GW eigenstate $|\phi_i\rangle$ independently parametrised by a form factor

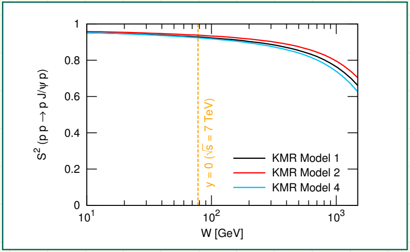
$$F_i(t) = \exp\left[-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}\right]$$

- 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 $S_{\rm enh}$ (see later)

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

$(\gamma p \to J/\psi + p)$ from $(pp \to p + J/\psi + p)$

$$\frac{\mathrm{d}\sigma(pp)}{\mathrm{d}y} = S^2(W_+)\left(k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\right)\sigma_+(\gamma p) + S^2(W_-)\left(k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\right)\sigma_-(\gamma p)$$

- Contribution from W_+ and W_- due to $\gamma p/p\gamma$ ambiguity
- Absorptive corrections $S^2(W)$, depends on W
- Cancellation between photon flux in cross section and denominator of S^2

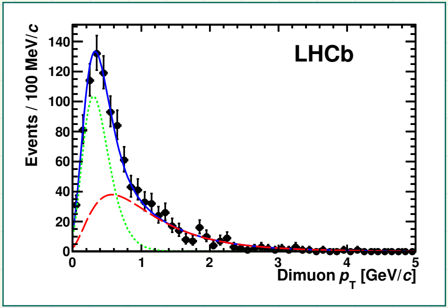
Fit Accuracy

- Directly fit to $\mathrm{d}\sigma(pp)/\mathrm{d}y$ data
- Undesirable dependence on $\sigma_-(\gamma p)$ unavoidable (Pb-p may improve this)

LHCb & CDF

LHCb

- Non-exclusive background from fitting p_T of events with 3–8 forward tracks and linearly extrapolating to 2
- Background higher p_T component may contain significant part of odderon contribution

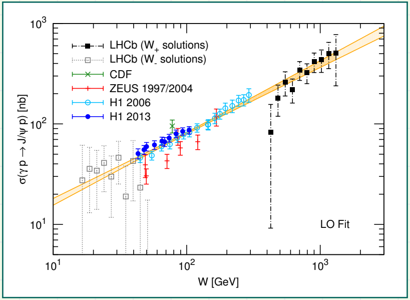


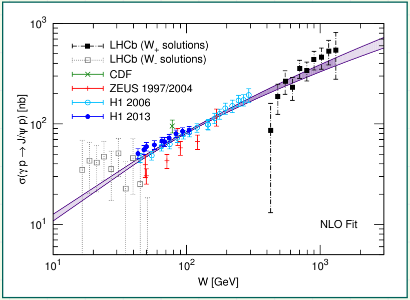
- LHCb provide 10 points for rapidities $2 < y < 4.5$ [LHCb 2013]

CDF

- CDF provide 1 point for $y = 0$ (no $W_\pm$ ambiguity) [CDF 2009]
- May include odderon contribution (point not included in our fit)

HERA & LHCb ($\gamma^* p \to J/\psi + p$)

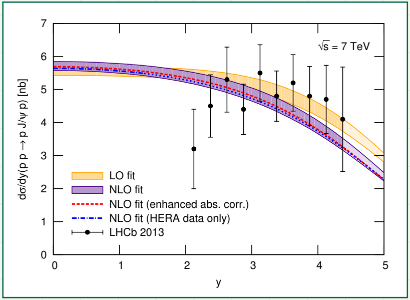


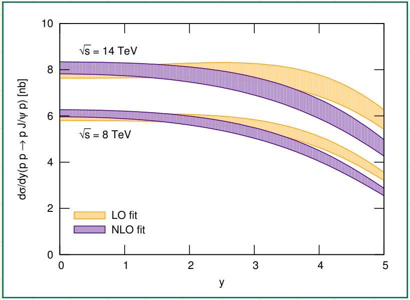


- Extends to $x \sim 10^{-6}$
- LHCb $W_\pm$ points calculated with our S^2, $\mathrm{d}n/\mathrm{d}k$, $\sigma_-(\gamma p)$
- Recall: LO and 'NLO' parameters have different meaning

	LO	'NLO'
N	1.27	0.25
a	0.05	-0.10
b	0.08	-0.15
$\chi^2_{d.o.f}$	1.1	1.2

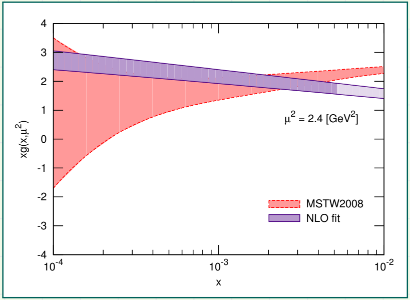
HERA & LHCb ($pp \to p + J/\psi + p$)

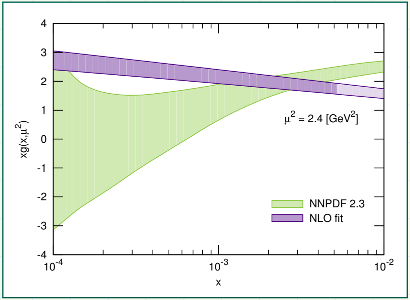




- Can use fitted gluon for $\mathrm{d}\sigma(pp)/\mathrm{d}y$ prediction (stable at 14 TeV)
- W_- component accounts for $\mathcal{O}(30-40\%)$ of $\mathrm{d}\sigma(pp)/\mathrm{d}y$
- Including ‘enhanced rescattering’ has small effect on prediction
- HERA fit is consistent with LHCb data (LHCb not constraining)
- New LHCb data will soon reduce errors and provide stronger constraints

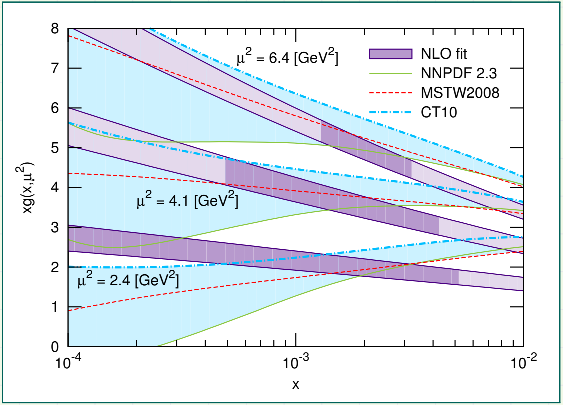
Gluon Fit





- Fitted gluons below global partons for higher $x \sim 10^{-2}$
- LHCb data provides support for fit down to $x \sim 10^{-6}$
- 14 TeV data will probe even lower x

Gluon Fit (II)

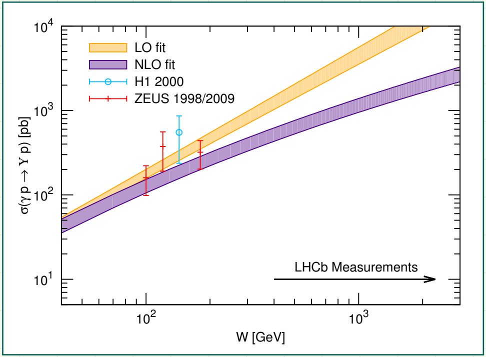


- Scale dependence from k_T^2 integral and HERA electroproduction data

- J/ψ data diminish the huge uncertainty on global gluons at low scale & small-x

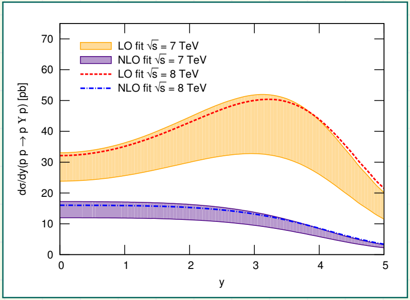
Υ Postdiction ($\gamma p \rightarrow \Upsilon + p$)

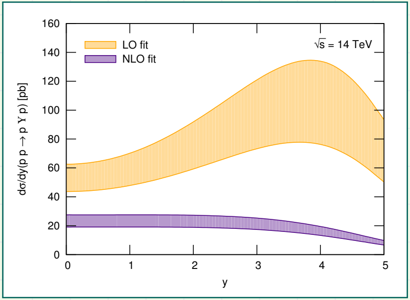
- Can use gluon fit extracted from J/ψ data to make Υ prediction
- $\sigma(\gamma p)$ and $\mathrm{d}\sigma(pp)/\mathrm{d}y$ as for J/ψ
- S^2 for Υ used



- Very little data available for comparison
- Need high energy Υ to determine scale dependence
- Huge discrepancy between extrapolated LO and ‘NLO’ fits
- LHCb data to come...

Υ Prediction $(pp \to p + \Upsilon + p)$





- 'NLO' gluon parametrisation grows $1/x$ and $\ln(\mu^2)$ less steep than $xg \propto x^{-\lambda}$
- Large discrepancy between LO and 'NLO' due to poor high energy constraints on scale behaviour
- Large real and skewing corrections when W_- is small
- But: W_- component only $\mathcal{O}(15 - 20\%)$ of $\mathrm{d}\sigma(pp)/\mathrm{d}y$

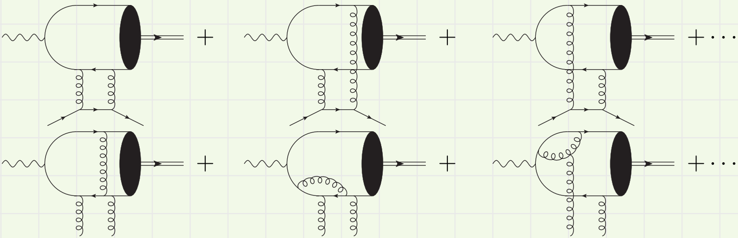
Scale Uncertainty

Observations from MNRT Study

- Varying μ from $\mu/2$ to 2μ in Sudakov factor (T) gives small effect
    - Inclusion of T at all only slightly alters the behaviour of the gluon
    - Reason: T mostly contributes in k_T^2 integral where derivative is taken
- Varying μ in α_s causes strong scale dependence
- Varying scale in both α_s and T simultaneously from $\mu/2$ to 2μ gives large effect $\pm 20\%$
    - Even including scale variation still obtain better gluon certainty than global partons!
    - Most scale variation is absorbed into the normalisation of the gluon
    - x-behaviour reasonably stable

Full NLO Contribution

- Currently working on full NLO matrix element in collinear factorisation [Ivanov et al. 2004]
- Quark contribution starts & many more gluon diagrams



- Better estimation of scale & check of scale variation
- Clear scheme choice ($\overline{\mathrm{MS}}$)
- Possibility to extend NRQCD treatment (e.g... 1-loop QCD)

Conclusion

Summary

- Updated MNRT gluon fit to include recent LHCb data [Martin et al. 2008]
- Provided predictions for J/ψ photoproduction @ 8 & 14 TeV
- Provided predictions for Υ photoproduction @ 7, 8 & 14 TeV

Issues

- Considerable scale uncertainty remains
- Not a complete NLO analysis (but main kinematic effects included)
- Can not directly identify extracted gluon with e.g. $\overline{\mathrm{MS}}$ partons

Future

- Work under way to include NLO gluon diagrams and quark coupling [Ivanov et al. 2004]
- More $pp \to p + J/\psi + p$ data on the way from LHCb (and others?)
- Pb-p data, reduced W_- component
- $pp \to p + \Upsilon + p$ data will have strong ability to constrain scale dependence
- Excellent opportunity to utilise new exclusive data to constrain small-x PDFs

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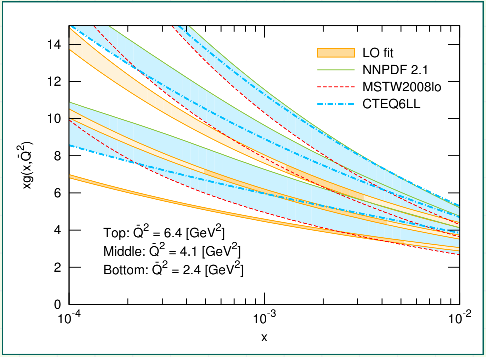
Extra

LO Gluon Fit



- Decreased uncertainty
- Steeply rising behaviour as for global partons
- Receive sizeable correction when including NLO effects (Like global partons)