

Small- x gluon from exclusive J/ψ production

$\sigma(\gamma p \rightarrow p + J/\psi)$ & $d\sigma/dy(pp \rightarrow p + J/\psi + p)$

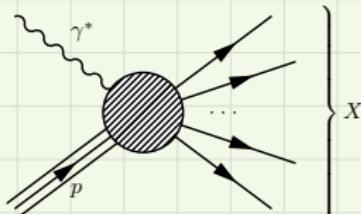


Stephen Jones

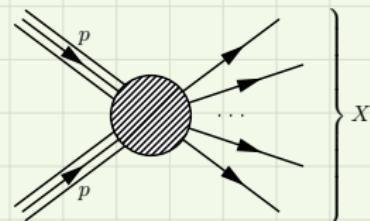
QCD@LHC2013
4th September

Forward physics: Exclusive & Diffractive Processes

Inclusive Processes - Included in global analyses

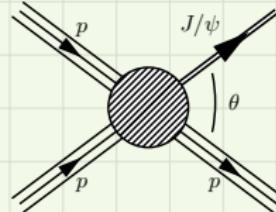
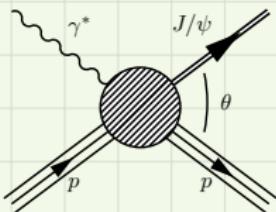


DIS



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 ($\mu^2 < 6 \text{ GeV}^2$) and small- x ($\sim 10^{-4}$)
- Exclusive processes such as exclusive HVM production are a sensitive probe of the gluon in this domain
- Can such processes constrain the gluon?

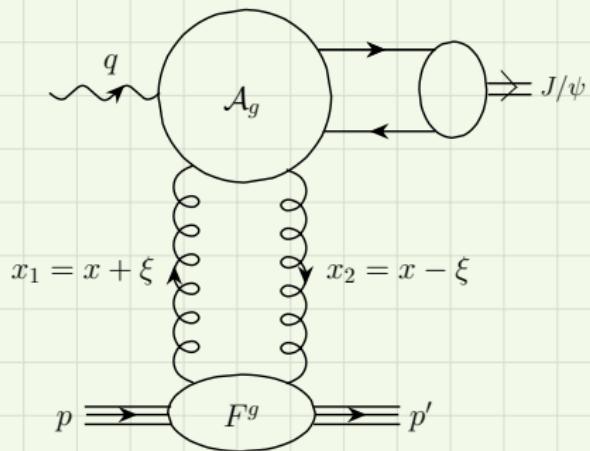
Contents

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

Based on work with:

Alan Martin, Misha Ryskin and Thomas Teubner [[arXiv:1307.7099 \[hep-ph\]](https://arxiv.org/abs/1307.7099)]

J/ψ photo(electro)-production



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

General Setup & Assumptions

- Factorises: $\phi_{c\bar{c}}^\gamma \otimes T_{c\bar{c}+p} \otimes \phi_{c\bar{c}}^{J/\psi}$
- Non-relativistic J/ψ wave function $\propto \Gamma_{ee}$
- Γ_{ee} , $M_{J/\psi}$ from experiment
- Relativistic corrections $\sim \mathcal{O}(4\%)$ [Hoodbhoy 1997]
- At LO: $k_T^2 \ll \bar{Q}^2$, leading log approximation (LLA)
- Scale: $\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4$

J/ψ photo(electro)-production at LO

Result (Im part only)

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

[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

Skewing & Real Part

GPDs

- Strictly, does not couple to diagonal gluon but to non-diagonal Generalised PDFs (GPDs): $H(x, \xi; \mu^2, t)$
- In small- x and ξ limit GPDs are related to PDFs via Shuvaev transform [Shuvaev et. al 1999]
- 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 ($\mathcal{O}(10 - 15\%)$ on gluon parameters) compared to full transform [Harland-Lang 2013]

Real Part

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

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

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

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

IR Part and Scale Choices

IR Part

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

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

- Gives IR Part:

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

Scale Choice

- Scale choice ambiguity remains (is extracted gluon e.g. $\overline{\text{MS}}$?)
- Choose $\mu = \max(k_T^2, \bar{Q}^2)$ and $\mu_{\text{IR}} = \max(Q_0^2, \bar{Q}^2)$
- Scale in IR Part matches lowest scale in integral
- $Q_0^2 = 1 \text{ GeV}^2$ (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 $\lambda = a + b \ln(\mu^2/0.45\text{GeV}^2)$

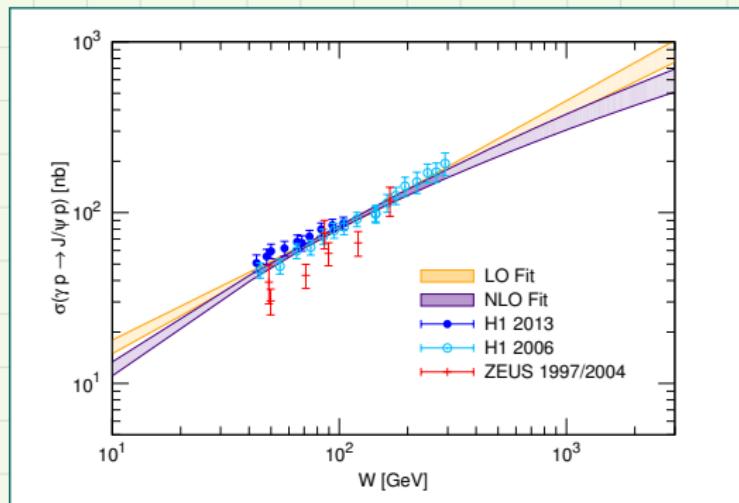
Beyond 'LO' Approach

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

Fitting Procedure

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

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



Parameters

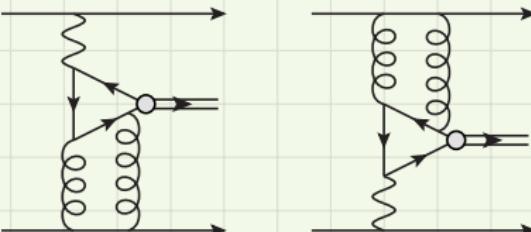
	LO	'NLO'
N	1.24	0.26
a	0.05	-0.10
b	0.08	-0.15
$\chi^2_{d.o.f}$	1.2	1.3

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

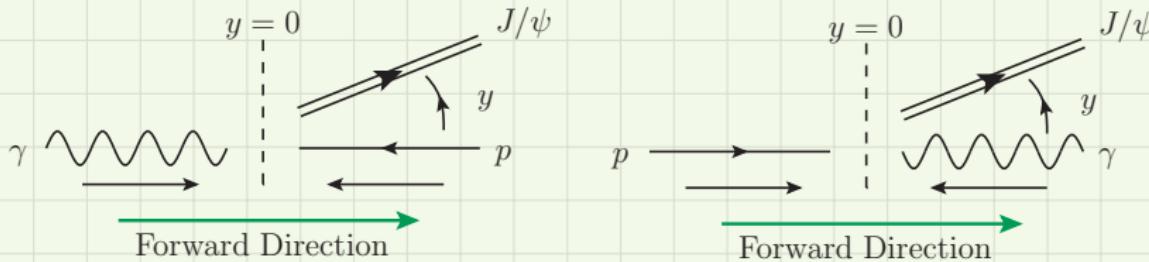
- Probes gluon for $10^{-4} \lesssim x \lesssim 10^{-2}$
- Note: Electroproduction data included in fit (not shown here)

LHCb Data

- Measured $d\sigma(pp \rightarrow p + J/\psi + p)/dy$ vs y



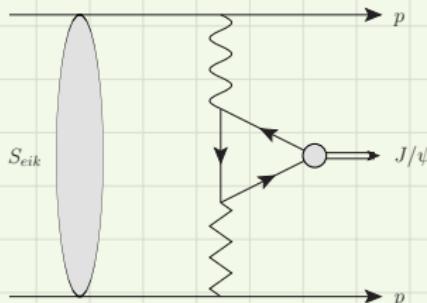
- Aliasing problem extracting $\sigma(\gamma p \rightarrow J/\psi + p)$



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

Survival factors

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



KMR Model

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

- \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 ($\sigma_{\text{el}} + \sigma_{\text{inel}}$)
 - $d\sigma/dt$ - Elastic cross section
 - σ_{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 $i = 1, 2$

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.

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

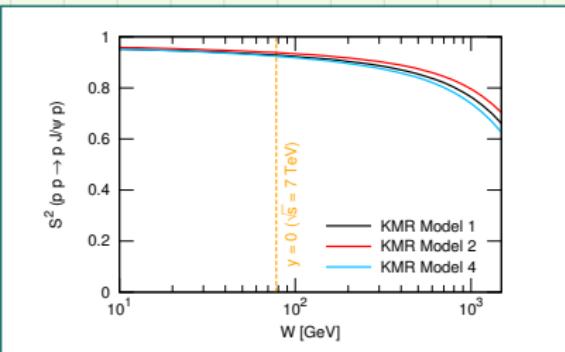
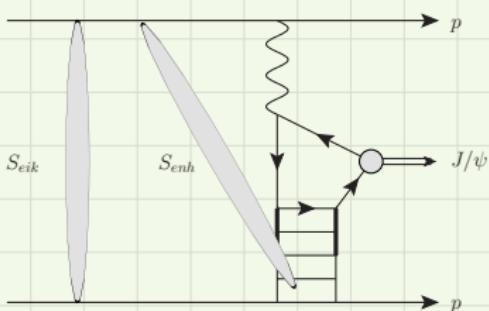
- Each GW eigenstate $|\phi_i\rangle$ independently parametrised by a form factor

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

- 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} (see later)

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

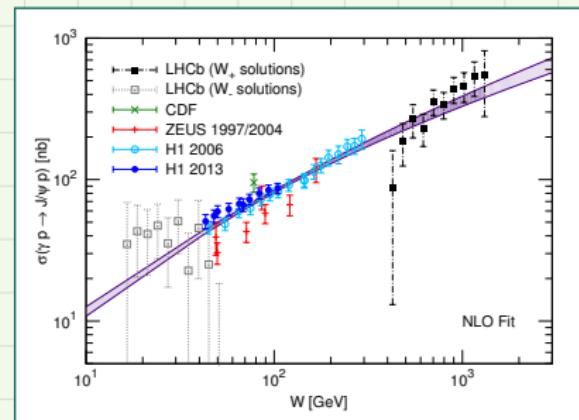
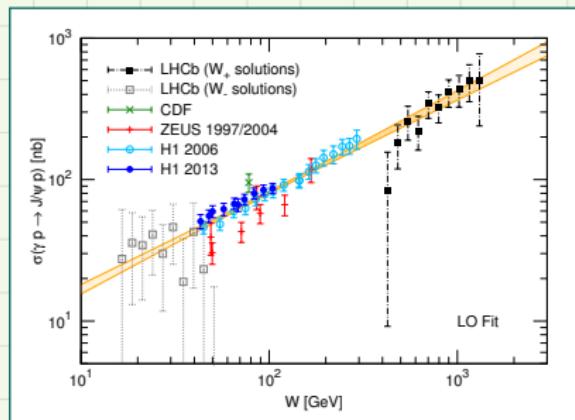
$$\frac{d\sigma(pp)}{dy} = S^2(W_+) \left(k_+ \frac{dn}{dk_+} \right) \sigma_+(\gamma p) + S^2(W_-) \left(k_- \frac{dn}{dk_-} \right) \sigma_-(\gamma p)$$

- 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 $d\sigma(pp)/dy$ data
- Undesirable dependence on $\sigma_-(\gamma p)$ unavoidable (Pb-p may improve this)

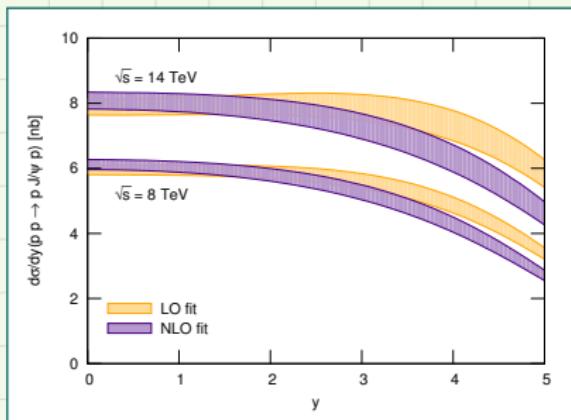
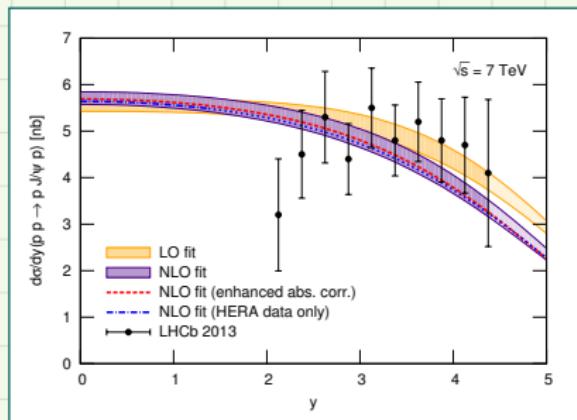
HERA & LHCb ($\gamma^* p \rightarrow J/\psi + p$)



- Extends to $x \sim 10^{-6}$
- LHCb W_{\pm} points calculated with our S^2 , dn/dk , $\sigma_-(\gamma p)$
- Recall:** LO and ‘NLO’ parameters have different meaning

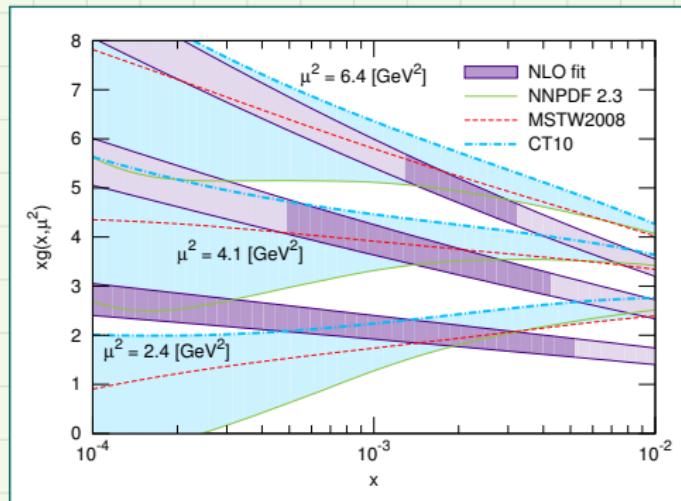
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N	1.27	0.25
a	0.05	-0.10
b	0.08	-0.15
$\chi^2_{d.o.f}$	1.1	1.2

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



- Can use fitted gluon for $d\sigma(pp)/dy$ prediction (stable at 14 TeV)
- W_- component accounts for $\mathcal{O}(30 - 40\%)$ of $d\sigma(pp)/dy$
- 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

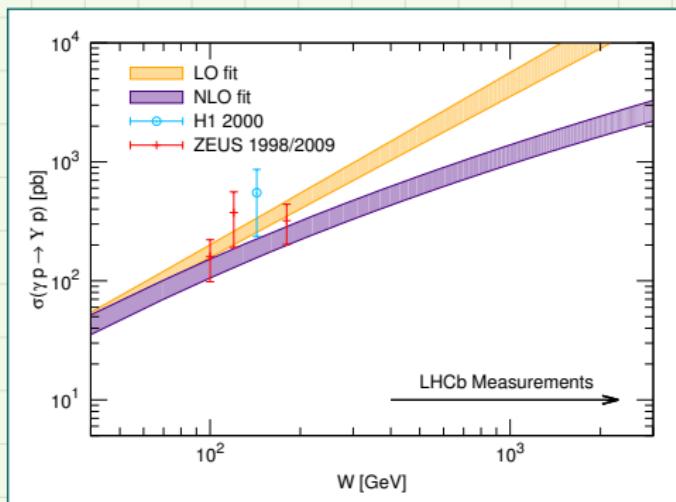


- Scale dependence from k_T^2 integral and HERA electroproduction data
- LHCb data provides support for fit down to $x \sim 10^{-6}$
- 14 TeV data will probe even lower x

- Fitted gluons below global partons for higher $x \sim 10^{-2}$
- J/ψ data diminish the huge uncertainty on global gluons at low scale & small- x

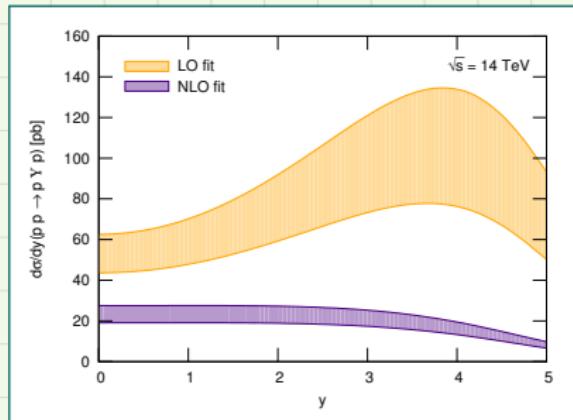
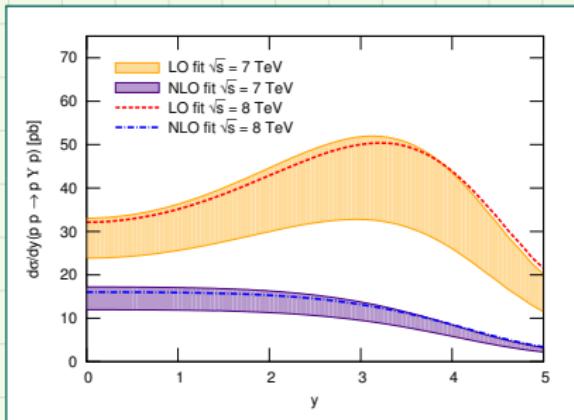
Υ Postdiction ($\gamma p \rightarrow \Upsilon + p$)

- Can use gluon fit extracted from J/ψ data to make Υ prediction
- $\sigma(\gamma p)$ and $d\sigma(pp)/dy$ 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 ($pp \rightarrow p + \Upsilon + p$)



- ‘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 $d\sigma(pp)/dy$

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. $\overline{\text{MS}}$ partons

Future

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

References

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Extra

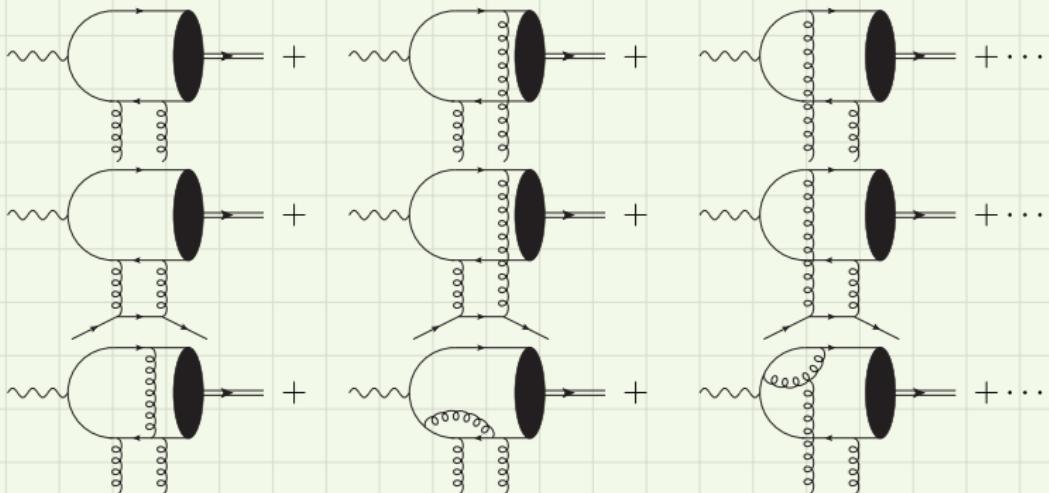
Scale Uncertainty

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

NLO Contribution

- Quark contribution starts & many more gluon diagrams

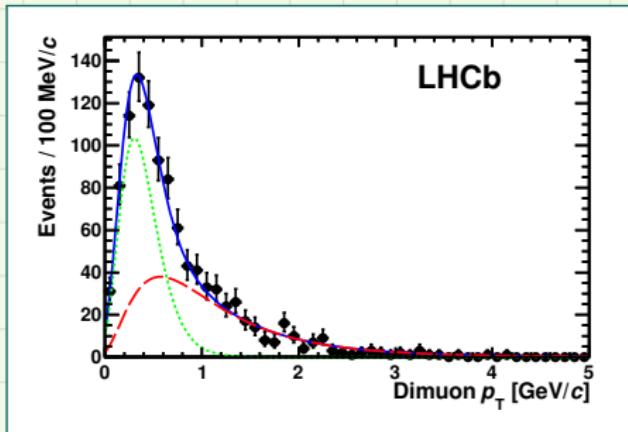


$$\mathcal{M} \propto \int_{-1}^1 dx [T_g(x, \xi) F^g(x, \xi) + T_q(x, \xi) F^q(x, \xi)]$$

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)

Photon Flux

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

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

- Proton form factor:

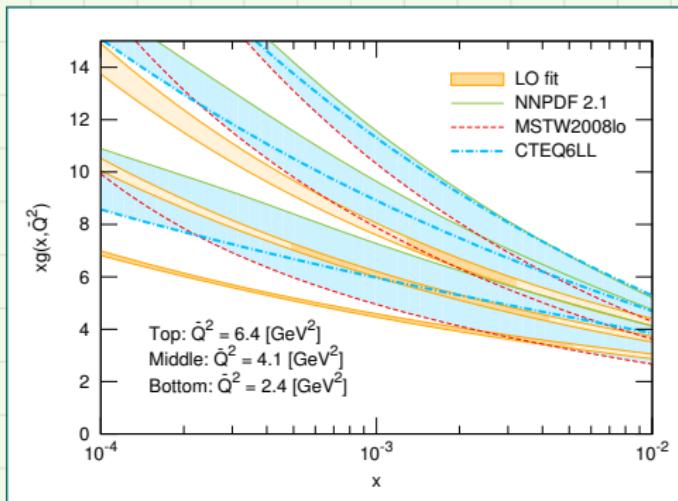
$$F_p(q_T^2) = \left(1 + \frac{t_{\min} + q_T^2}{0.71 \text{ GeV}^2}\right)^{-2}, \quad t_{\min} \approx \frac{(x_\gamma m_p)^2}{1 - x_\gamma}$$

- 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 $q_T^2 \rightarrow 0$
- Contributions from $q_T \sim 1/R_p$ are concentrated at small b_t , suppressed by large opacities

LO Gluon Fit



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

Shuvaev Transform

- Anomalous dimensions describing evolution of Gegenbauer moments G_N of $H(x, \xi)$ are equal to anomalous dimensions of conventional Mellin moments,
$$M_N = \int_0^1 x^N H(x, 0) dx$$
- 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 ($c_0^N = M_N$)
- LO conformal invariance of evolution equations broken at NLO, accuracy of transform reduced to $\mathcal{O}(\xi)$
- To get x distribution from G_N need analytical continuation to complex N , require no singularities in the input distribution in the right-half plane
- Additionally assume Regge-based form of diagonal small- x input distributions with no singularities in the right half plane ($j > 1$) in the space-like ($\xi < |x|$) domain.
- Shuvaev transform is inverse (integral) transformation which determines x dependence of $H(x, \xi)$ for a given small ξ from diagonal $H(x, 0)$

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

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

- PV- \int s can be solved numerically (slow)