

Probing the Low x Gluon With Exclusive J/ψ Production



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JPG 44 (2017) 03LT01, arXiv:1611.03711 [hep-ph]

EPJC 76 (2016) 633, arXiv:1610.02272 [hep-ph]

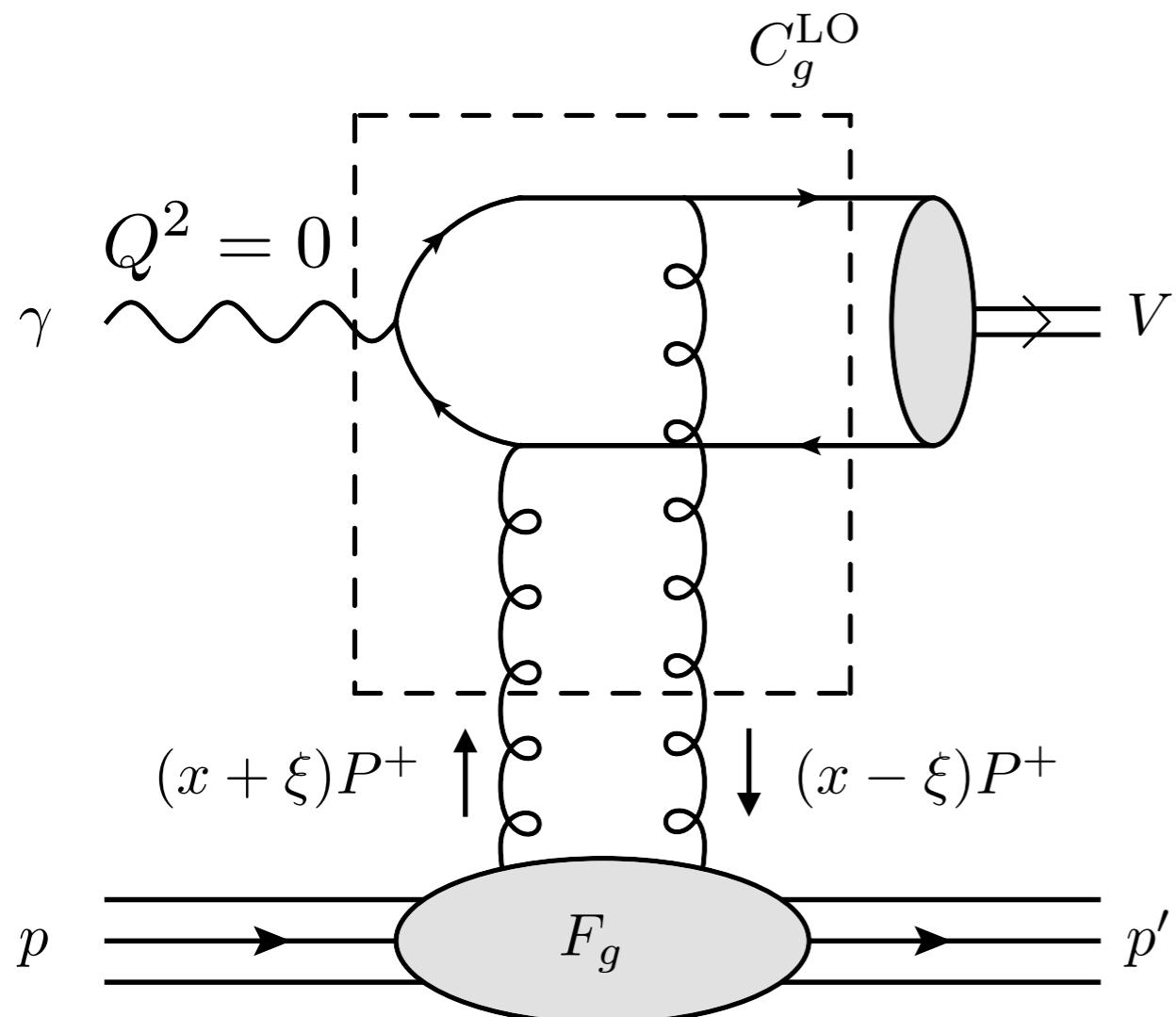
JPG 43 (2016) 035002, arXiv:1507.06942 [hep-ph]



MAX-PLANCK-GESELLSCHAFT



General Setup & Assumptions



Setup follows:

Ivanov, Schäfer, Szymanowski, Krasnikov, 04

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 $\bar{Q}^2 \sim 2.4 \text{ GeV}^2$ gluon

- Assume process factorises:

$$F_{q/g} \otimes C_{q/g} \otimes \phi_{Q\bar{Q}}^V$$

- 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

$$F_g(x, \xi, 0) = \sqrt{1 - \xi^2} \mathcal{H}_g(x, \xi, 0)$$

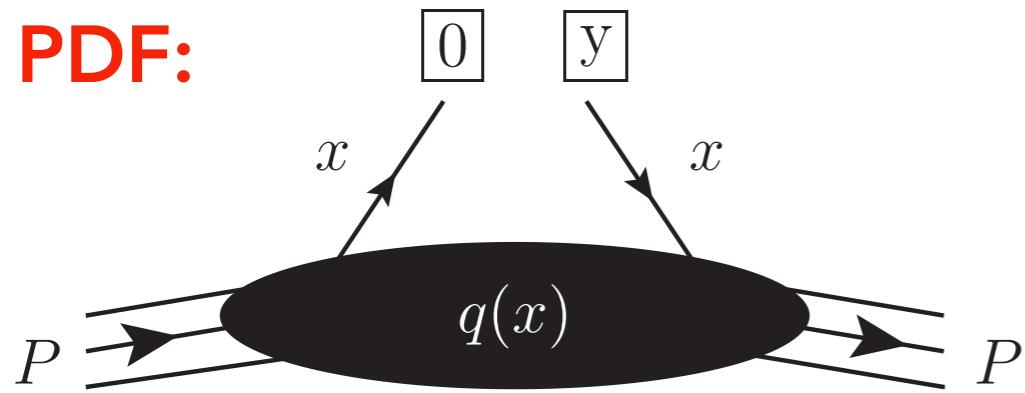
Contributes at NLO



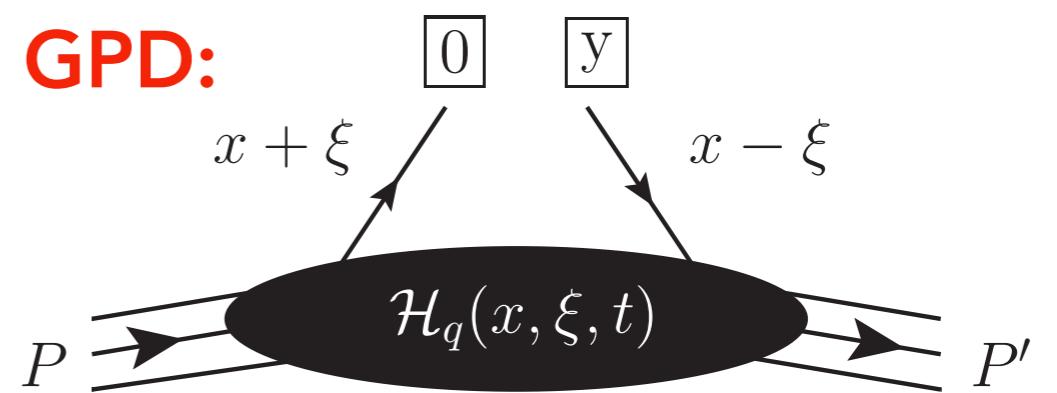
$$\sum_{q=u,d,s} C_q(x, \xi) F_q(x, \xi)$$

Shuvaev Transform

PDF:



GPD:



- Limit $\xi = 0, t = 0$ GPDs are equal to PDFs
- Can directly extract GPDs [Kumerički et al. 16; Berthou et al. 15; Guidal et al. 13;](#)

(Conjecture) Shuvaev Transform:

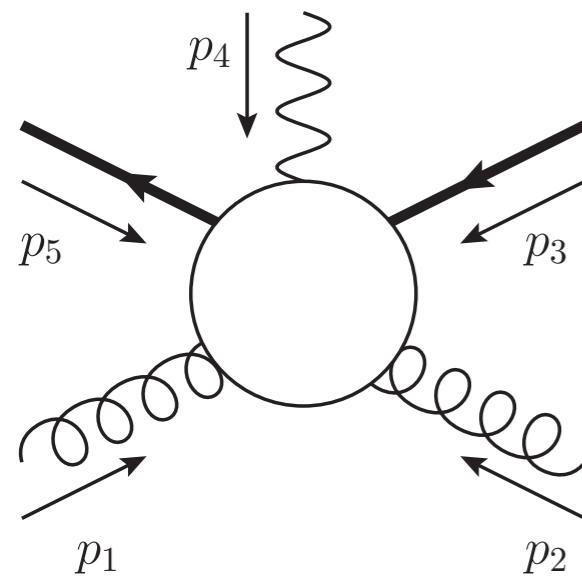
- In small- x and ξ limit GPDs are related to PDFs ($\mathcal{O}(\xi)$ corr. at NLO) by double-integral transform [Shuvaev 99](#)

Note:

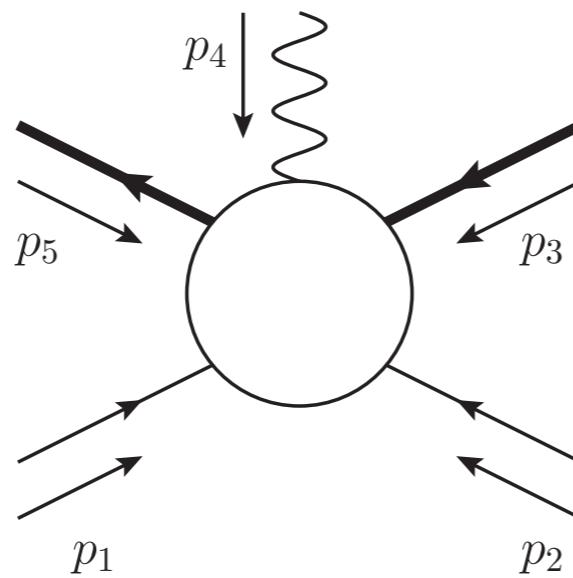
- (Regge-based) Must assume no singularities in right half N-plane of input distributions [Martin et al. 09](#)
- Transform is not valid for $|x| < \xi$ (time-like) region
- Further GPDs $\mathcal{E}_g, \mathcal{E}_q$ which vanish for $P = P'$ not known from PDFs

NLO Calculation

Gluon



Quark



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** → **REDUZE** → **FORM**

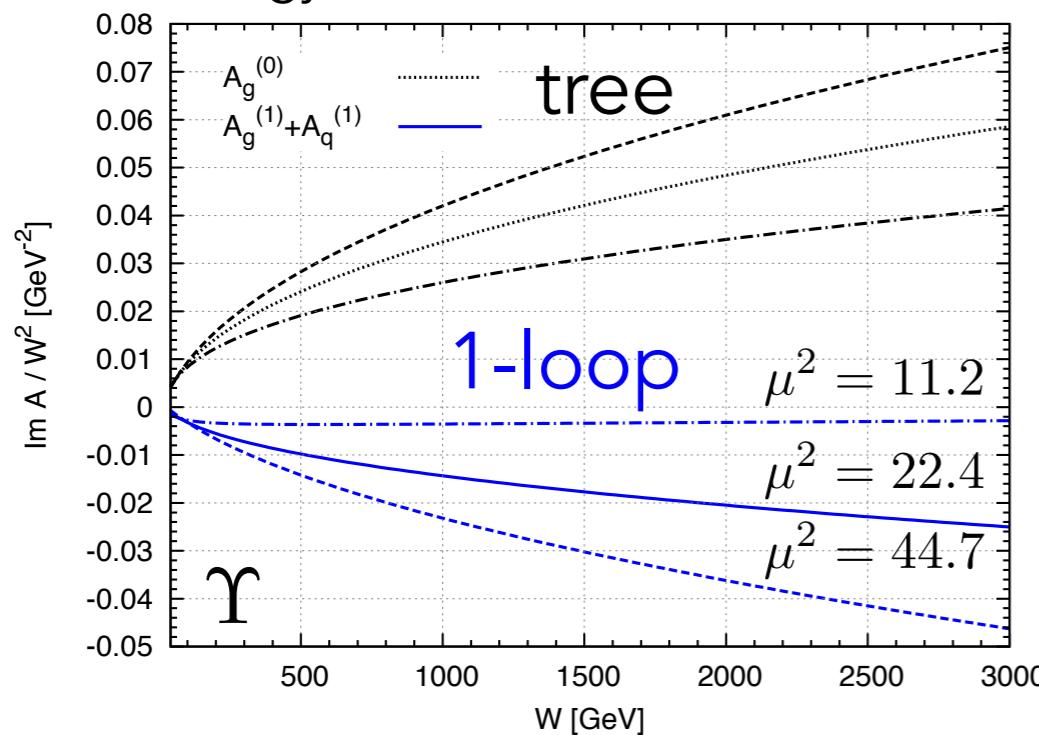
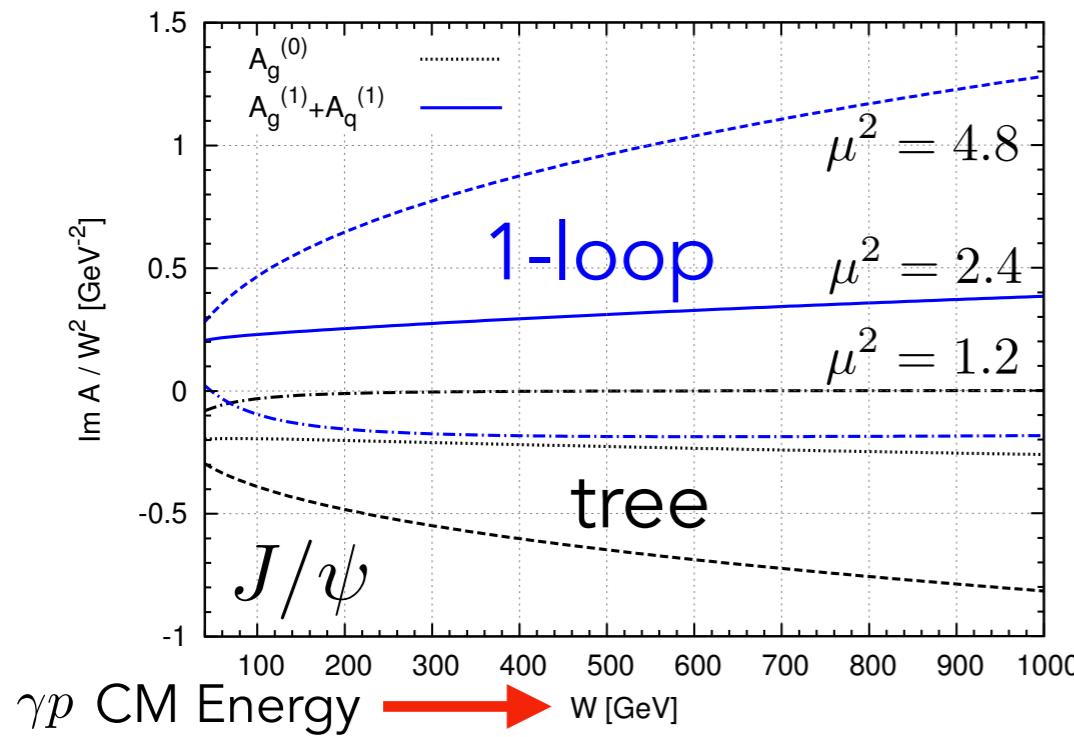
Nogueira 93; Vermaseren et al. 12; von Manteuffel, Studerus 12

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

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 $\mu^2 = \mu_R^2 = \mu_F^2 = (m^2/2, m^2, 2m^2)$
- Υ 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 LO Gluon Coefficient Function

$$A^{(1)} \approx -i\alpha_s(\mu_R) C_g^{(0)} \ln\left(\frac{m^2}{\mu_F^2}\right)$$
$$\left[C_A \int_{\xi}^1 \frac{dx}{x} F_g(x, \xi, \mu_F) + C_F \int_{\xi}^1 dx (F_S(x, \xi, \mu_F) - F_S(-x, \xi, \mu_F)) \right]$$

\uparrow \uparrow
~const **~ $1/x$**

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

SJ, Martin, Ryskin,
Teubner 16

Note: at this order in α_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:

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

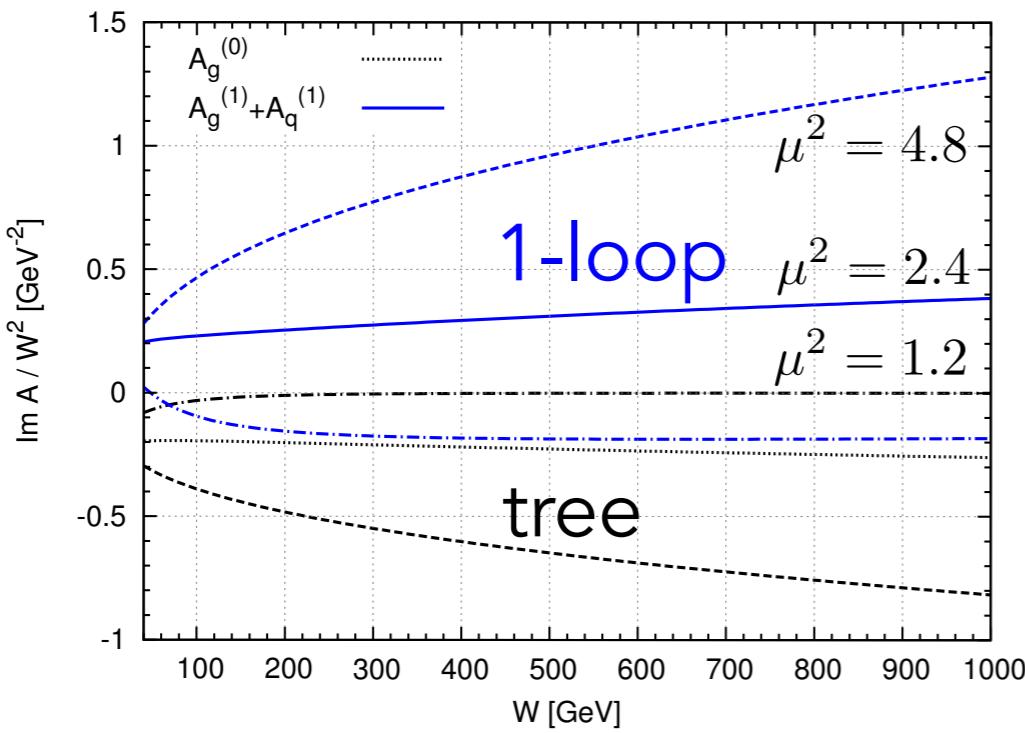
Others are working on resumming these logarithms,
will be very interesting to see their impact

Ivanov 07;
Ivanov, Pire, Szymanowski,
Wagner 15,16;

Scale fixing (J/ψ and γ)

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

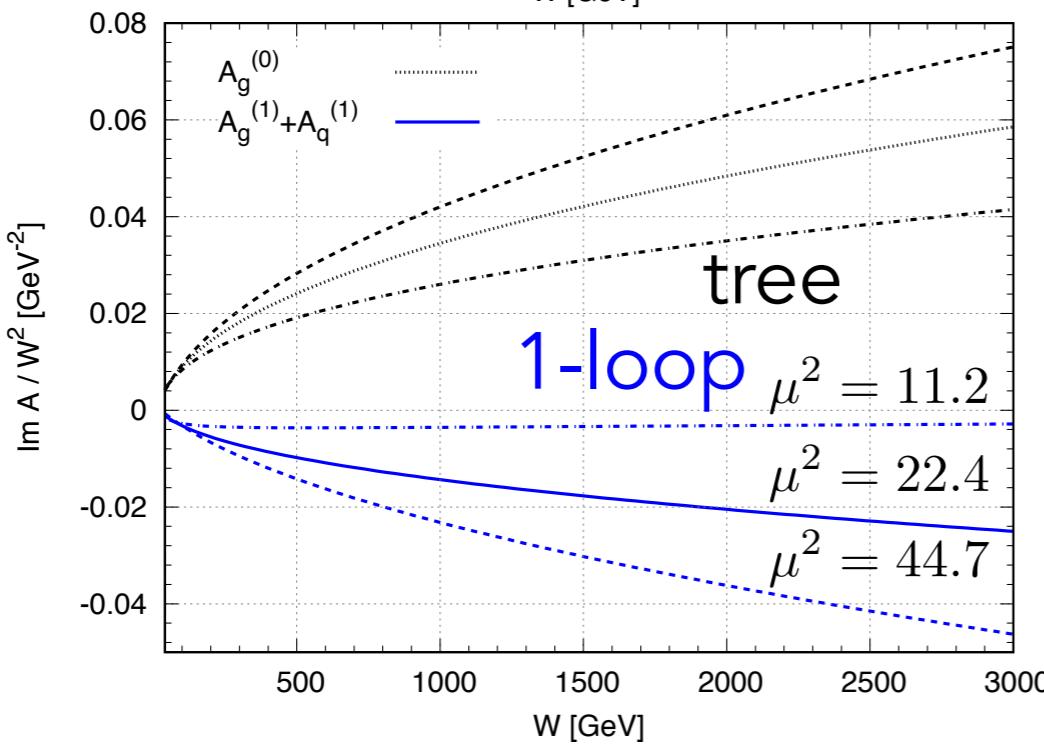
$J/\psi:$



Scale
Fixing



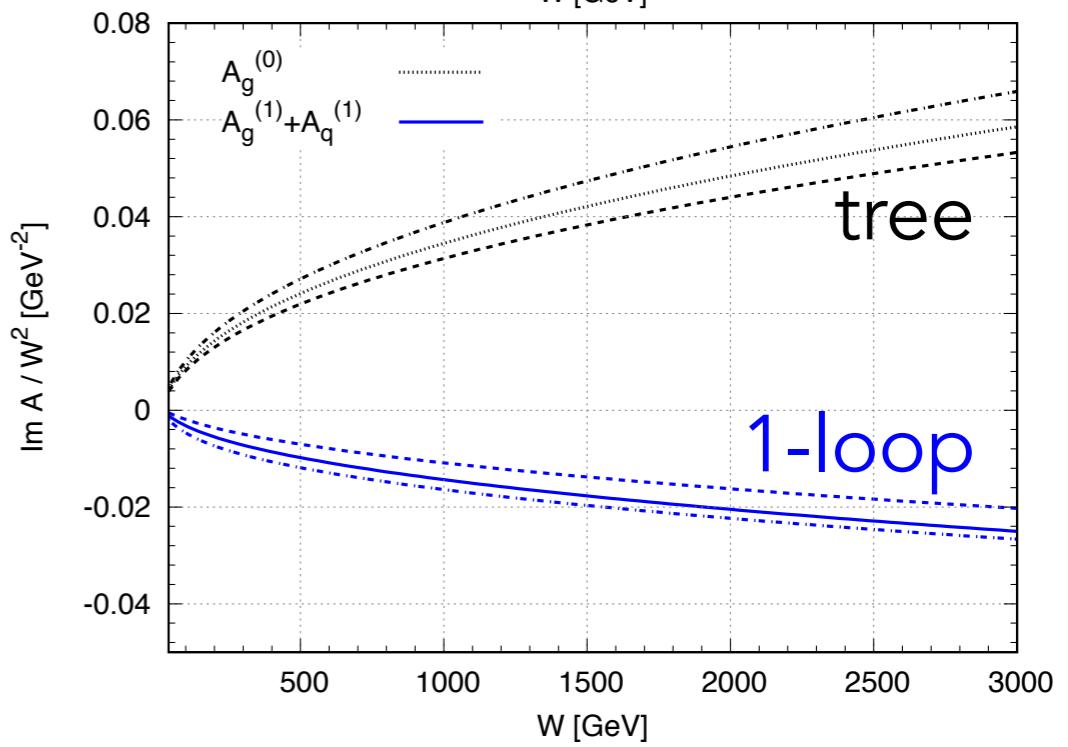
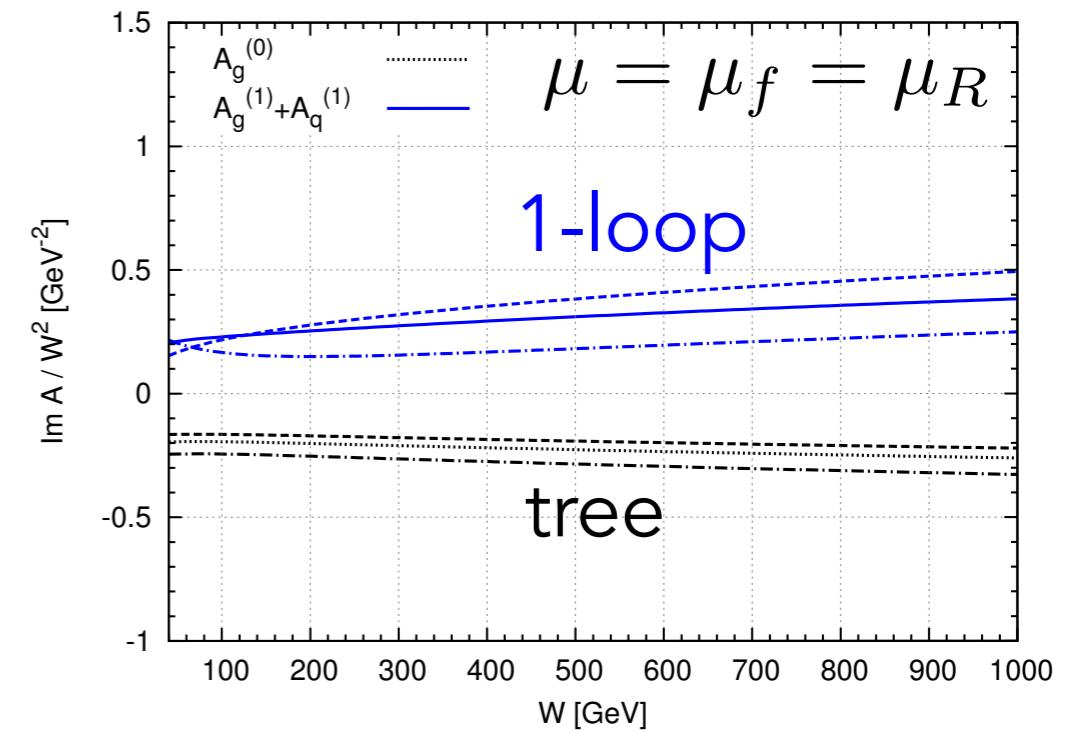
$\gamma:$



Scale
Fixing



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



Q_0 cut

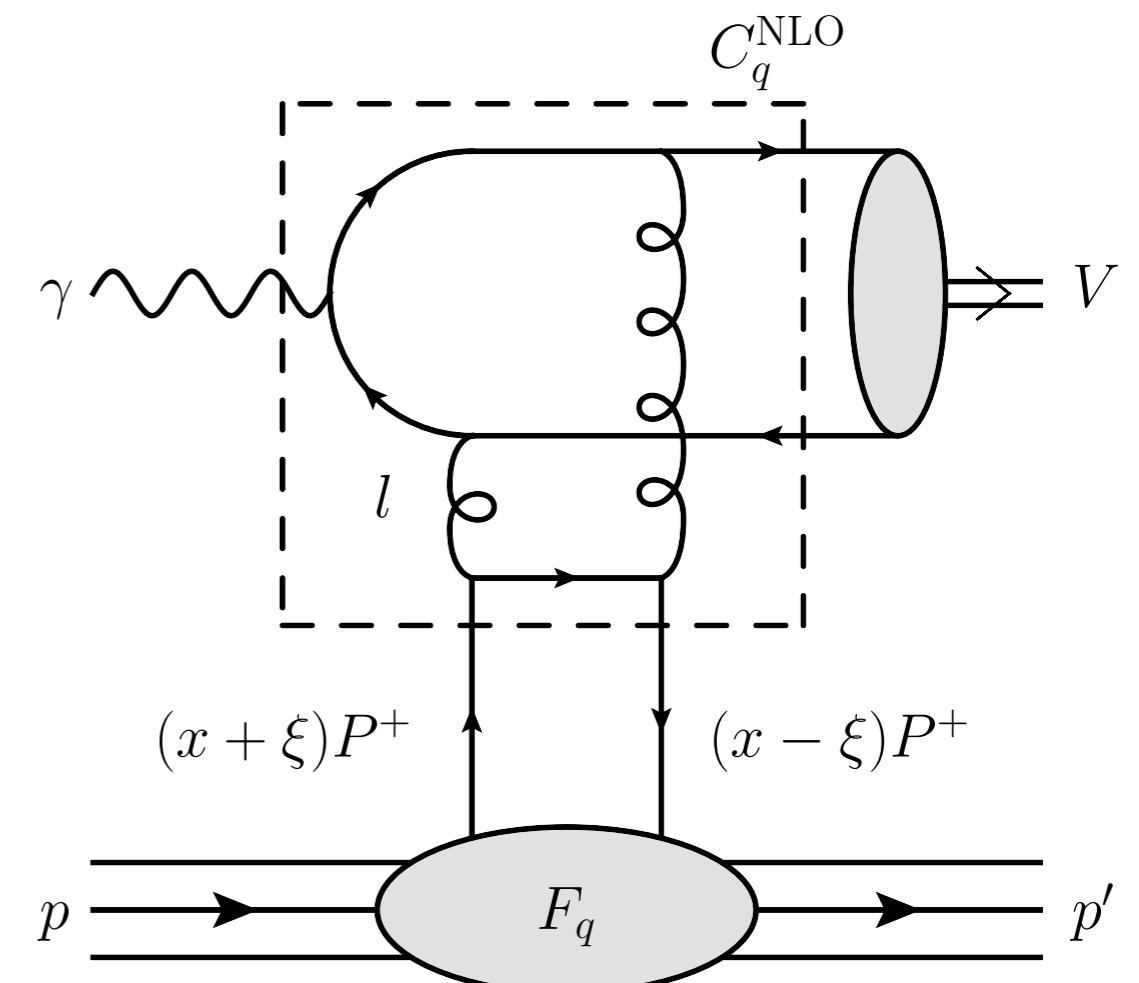
For low scale processes $\mathcal{O}(Q_0^2/M_{J/\psi}^2)$ contributions could be important

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

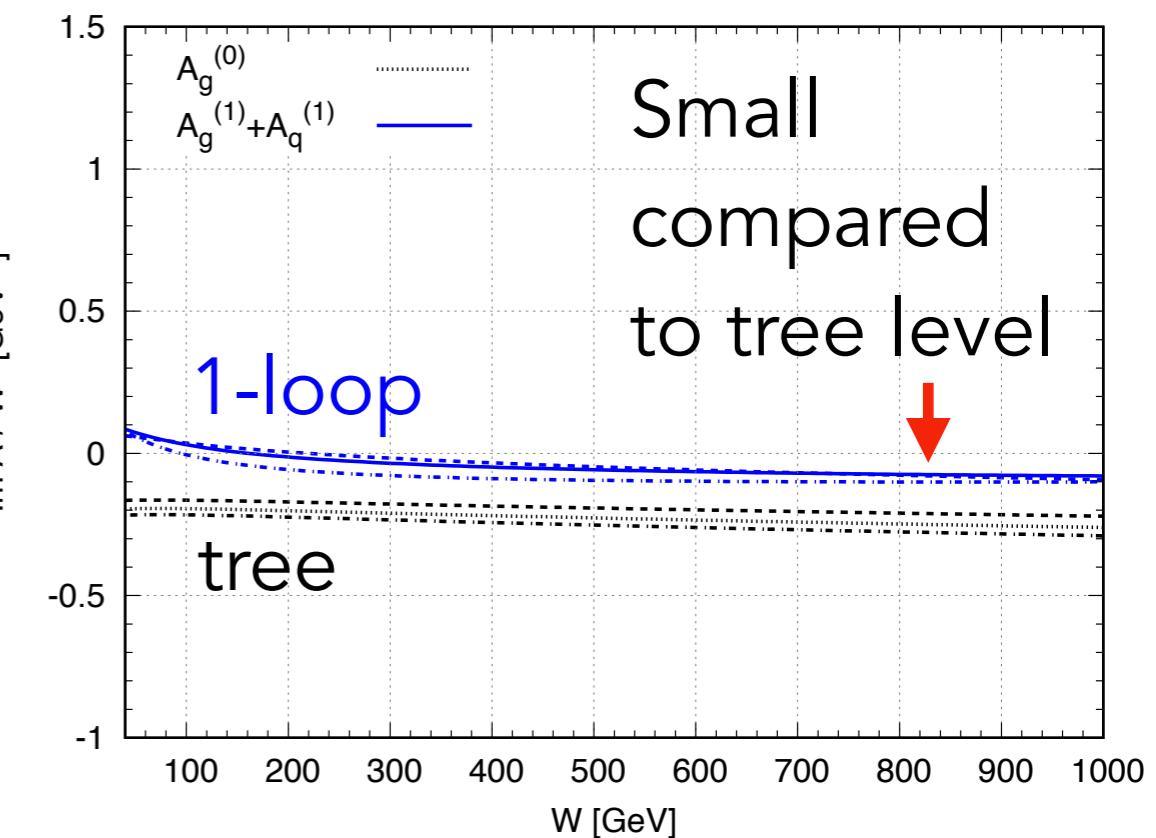
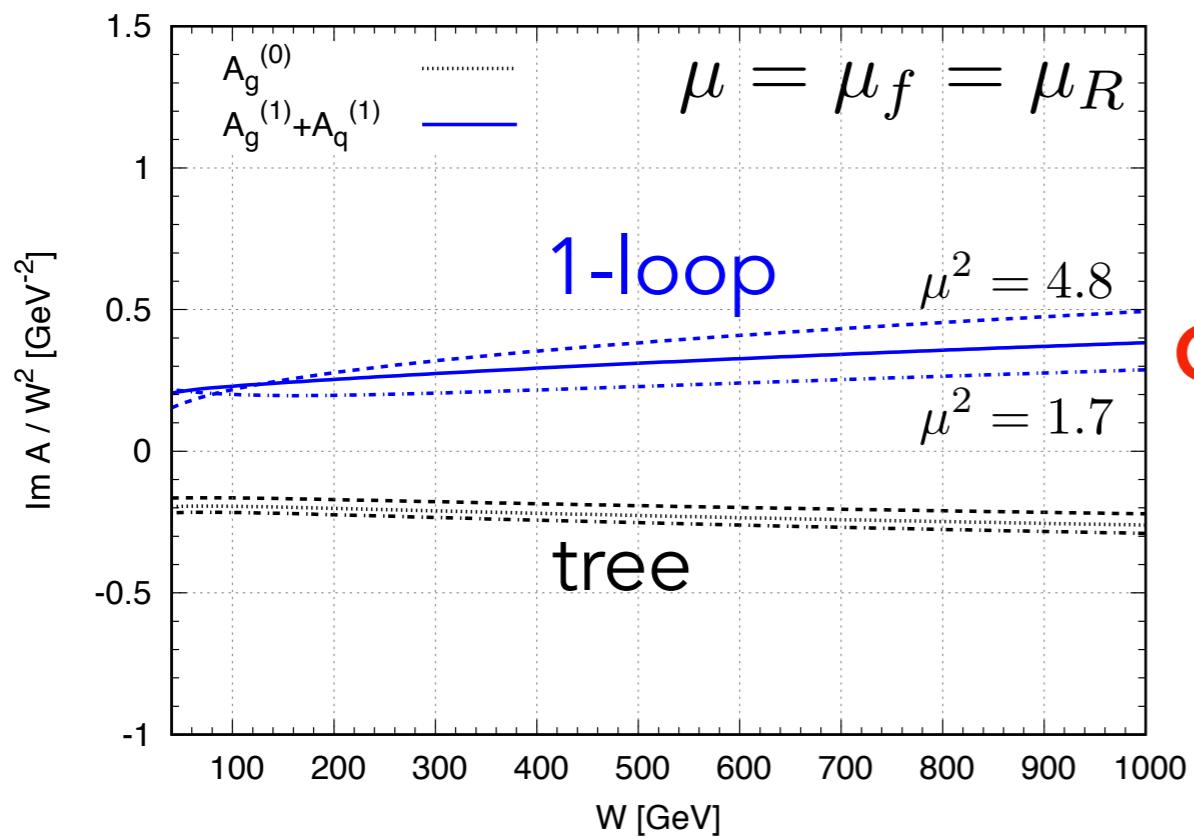
Idea: Subtract this contribution from coefficient function

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



Q_0 cut (J/Ψ)

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



1-loop correction now smaller than LO

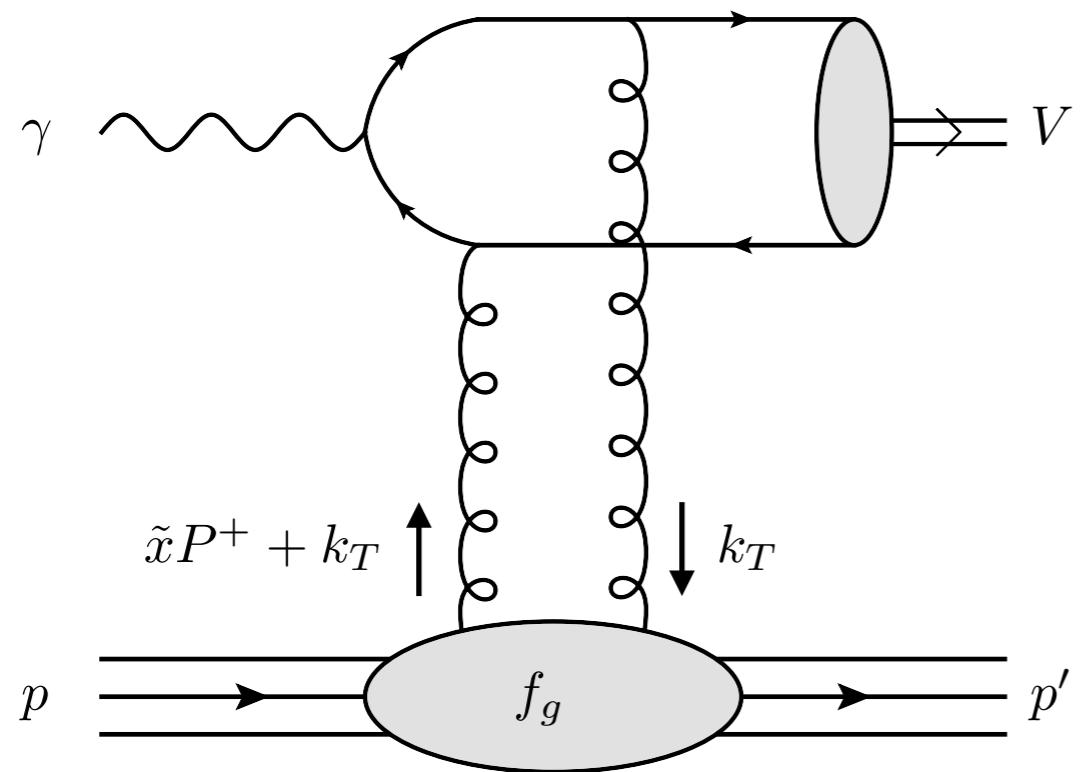
SJ, Martin, Ryskin, Teubner 16

Next step: try in the context of a global analysis (try using xFitter?)

Scale fixing and Q_0 cut optional

k_T Factorisation

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



Use LO calculation only

Use high energy 'maximal skew' approximation $x = \xi \approx \tilde{x}/2$
 σ_{tot} can be off by $\sim 20\%$
(compared to full transform)
Harland-Lang 13

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)

Small-x Gluon Parametrisation

Try two ansätze:

Model 1: simple parametrisation

Power law:

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

Model 2: improved parametrisation

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

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

Double LLA:

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

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

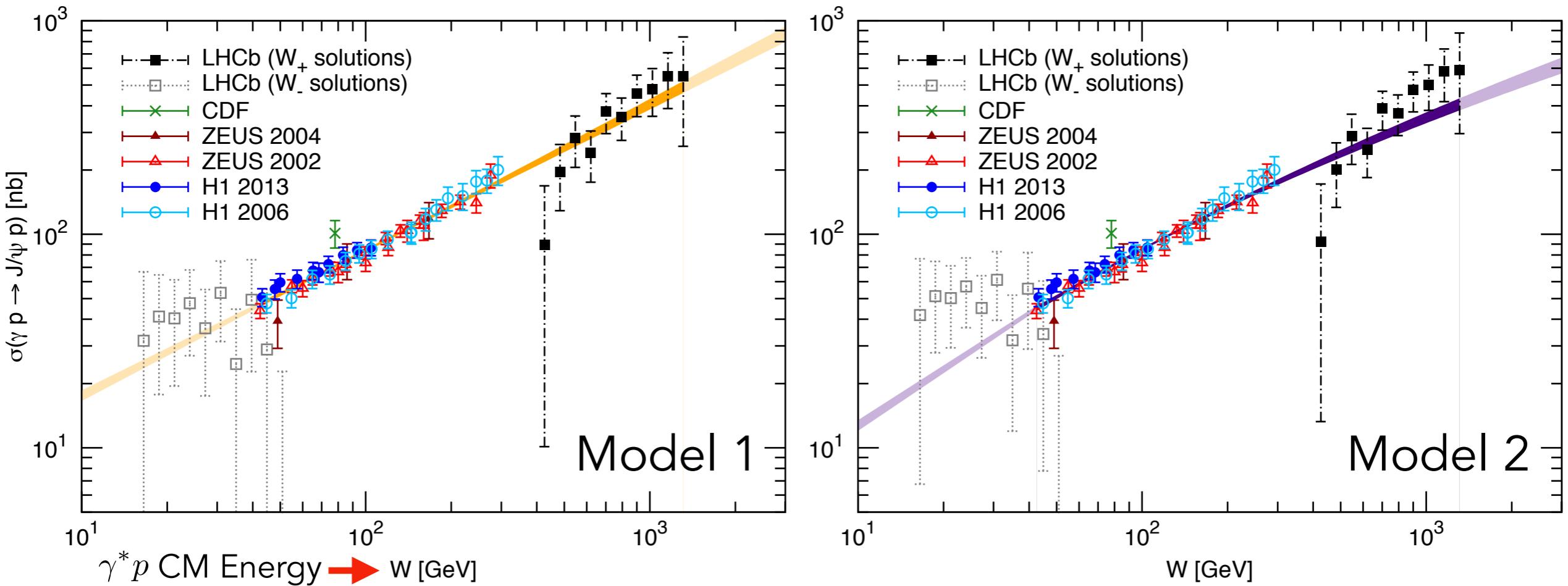
New fit:

- 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

Data Set	Data	Error Treatment
ZEUS 2002	19	6.5% Normalisation
ZEUS 2004	16	6.5% Normalisation
H1 2006	28	5% Normalisation
H1 2013	10	Covariance Matrix
LHCb 2013	Superceded	-
LHCb 2014	10	7% Normalisation
LHCb 2016	10	7% Normalisation

Previous Fit (2013)

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

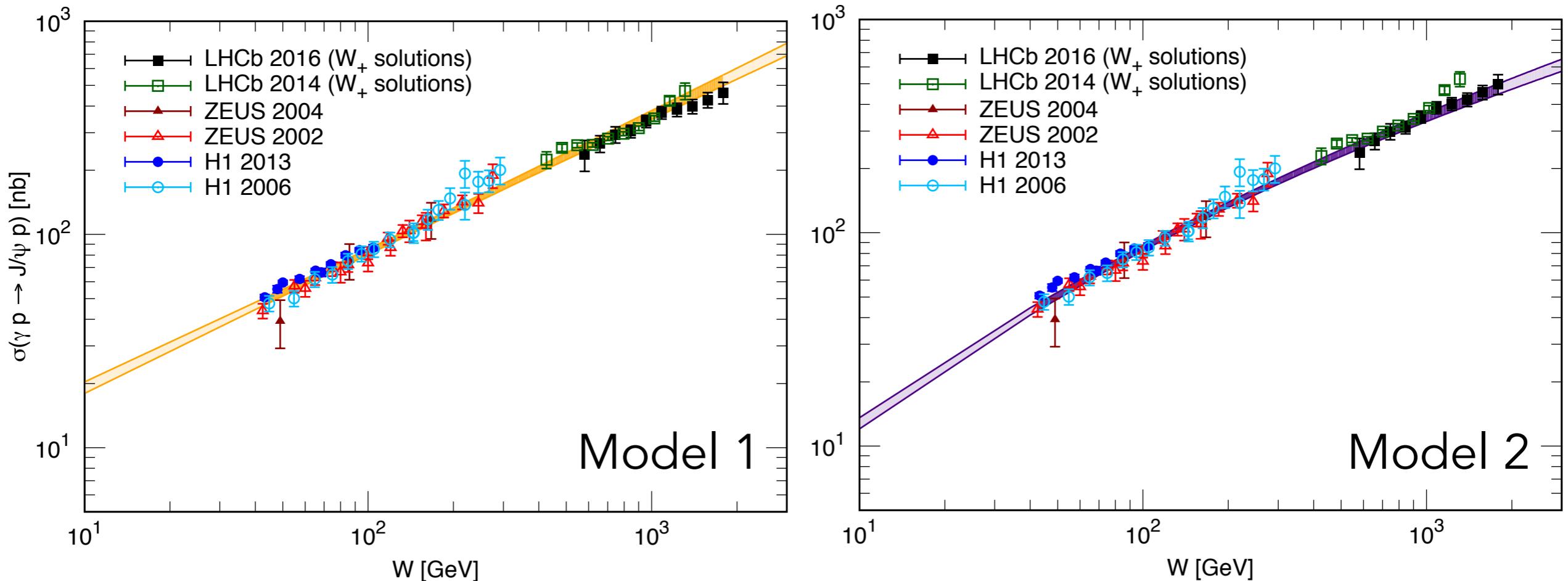


Fit	N	a	b	$\chi^2/d.o.f$
Model 1	1.20 ± 0.06	0.05 ± 0.01	0.079 ± 0.004	$41/79 \approx 0.5$
Model 2	0.29 ± 0.04	-0.10 ± 0.01	-0.20 ± 0.06	$50/79 \approx 0.6$

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

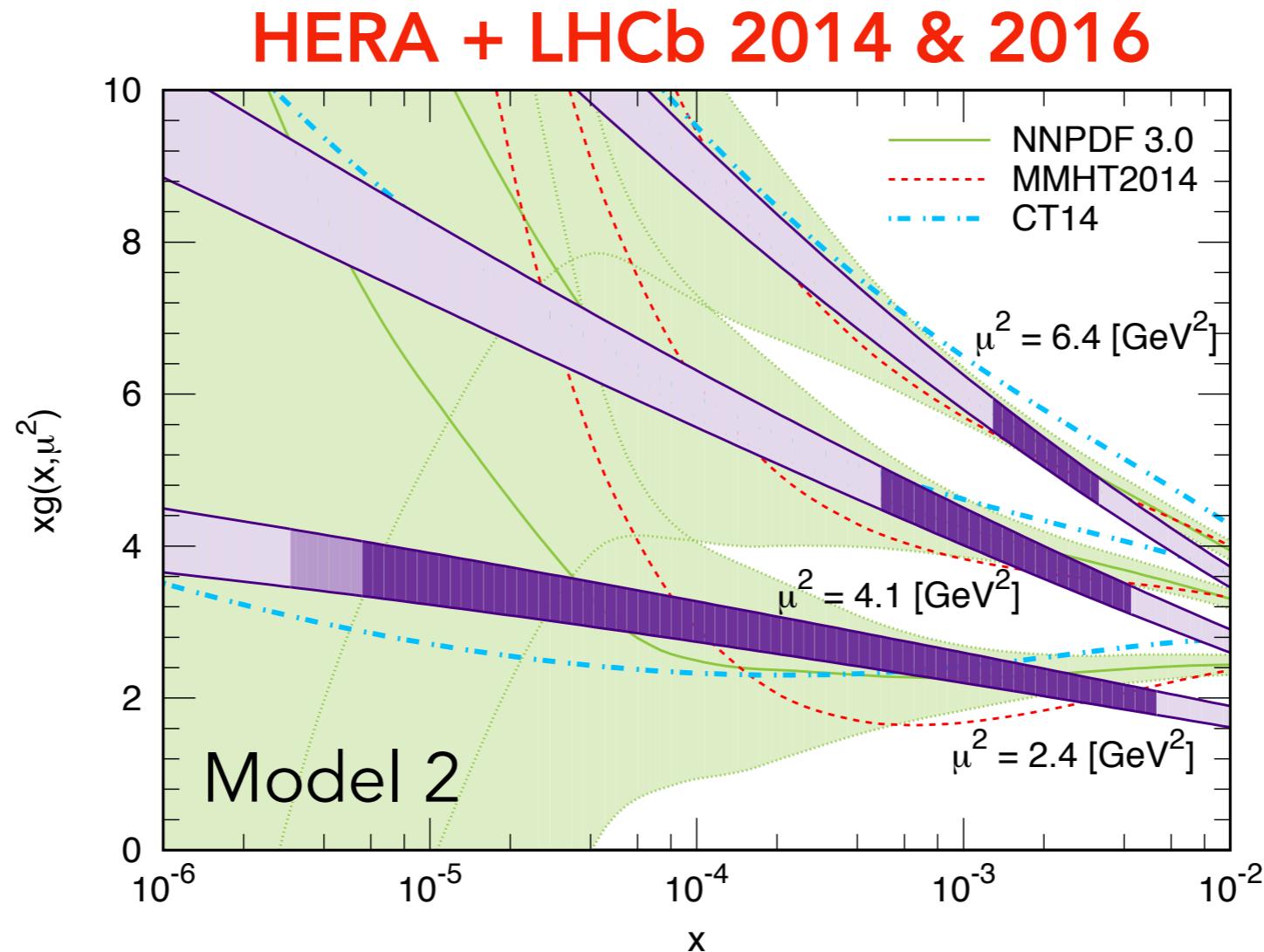
New Fit (2017)

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



Fit	N	a	b	$\chi^2/d.o.f$
Model 1	1.31 ± 0.06	0.04 ± 0.01	0.079 ± 0.005	$79/90 \approx 0.9$
Model 2 (w/o 2016)	0.29 ± 0.02	-0.10 ± 0.01	-0.20 ± 0.02	$74/80 \approx 0.9$
Model 2	0.29 ± 0.03	-0.10 ± 0.01	-0.20 ± 0.05	$76/90 \approx 0.8$

New Extracted Gluons (2017)



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 $\overline{\text{MS}}$ scheme and are in k_T factorisation framework - plot just gives a qualitative indication of what we can expect from a full extraction

Exclusive J/ψ vs Forward Charm

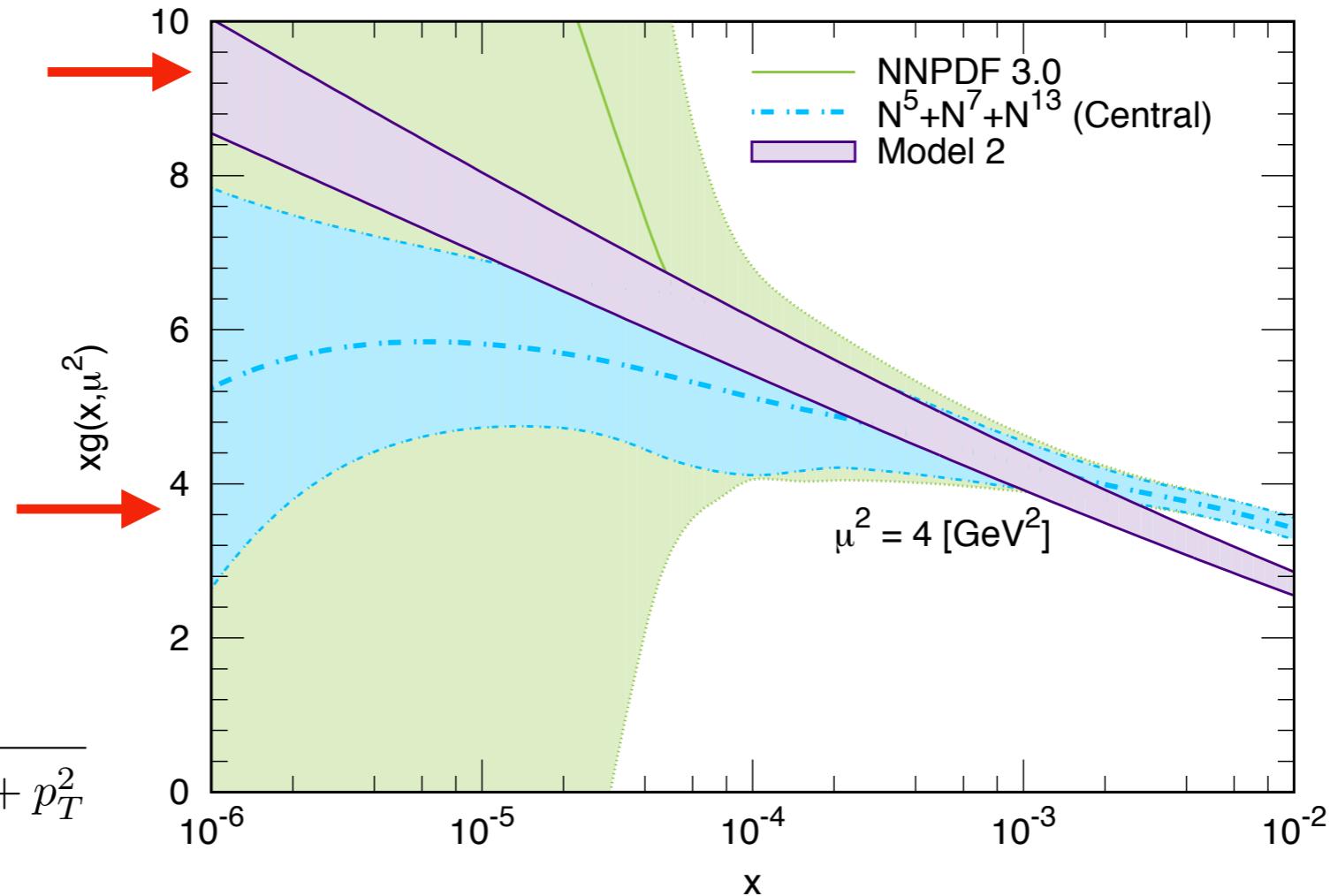
Exclusive
J/ψ

Forward
Charm

Gauld, Rojo 16

$$m_c = 1.5 \text{ GeV}$$

$$\mu = \mu_R = \mu_F = \sqrt{m_c^2 + p_T^2}$$



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)

Conclusion

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/ ψ 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

Thank you for listening!

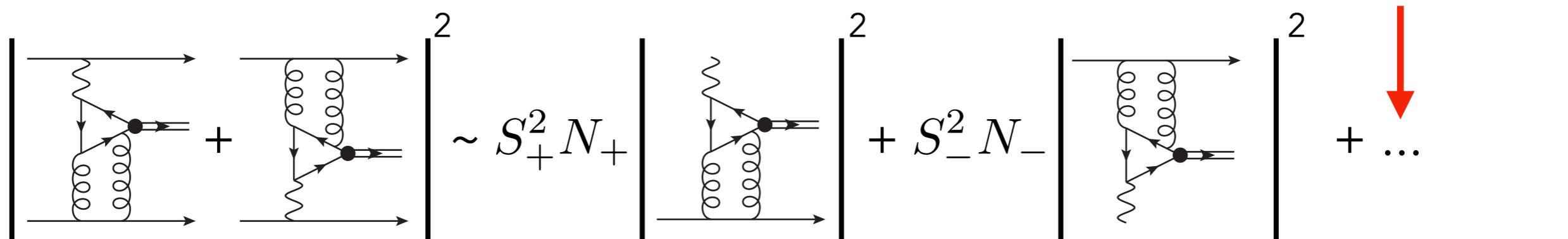
Backup

Ultraperipheral Production

Can create a model in terms of photoproduction cross-section
ultraperipheral cross-section vs rapidity y receives contributions from
two γp energies: $(W_{\pm})^2 = M_{J/\psi} \sqrt{s} \exp(\pm|y|)$

See e.g: Schäfer, Szczerba 07

(Very) Schematically:



Result:

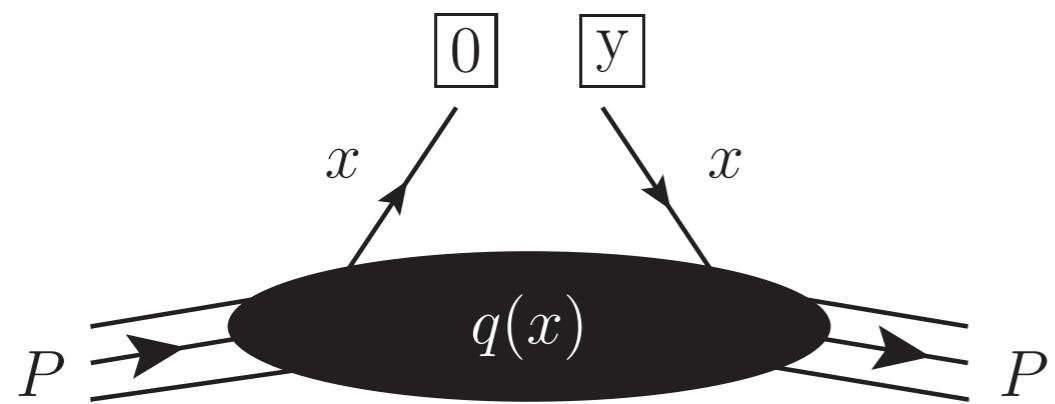
$$\frac{d\sigma(pp)}{dy} = S_+^2 N_+ \sigma_+(\gamma p) + S_-^2 N_- \sigma_-(\gamma p) + \dots$$

Photon flux **Gap survival factor**

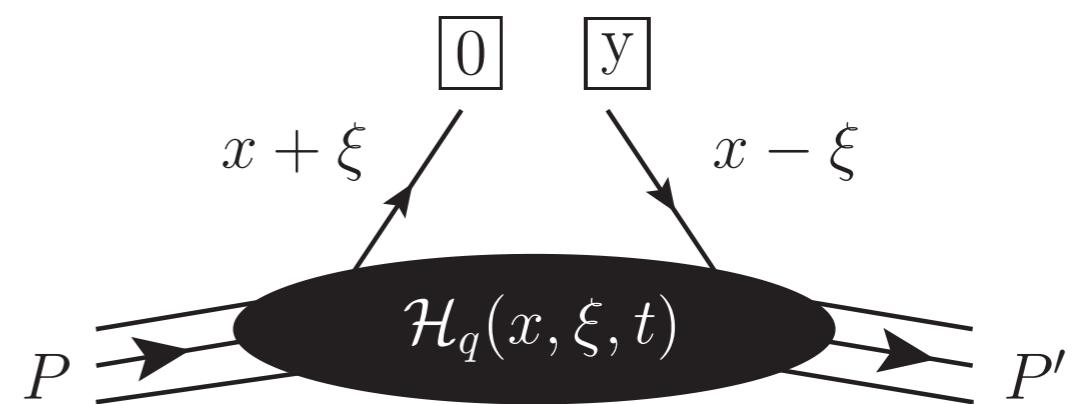
Note: We allow the survival factors to depend on energy

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

Shuvaev Transform

(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

Shuvaev Transform

Full Transform:

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

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

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

J/ ψ Formation

Formation of the J/ψ is $\propto \Gamma [J/\psi \rightarrow e^+e^-]$ ← **Measured by experiment**
Simplest picture: $c\bar{c}$ pair with equal momenta

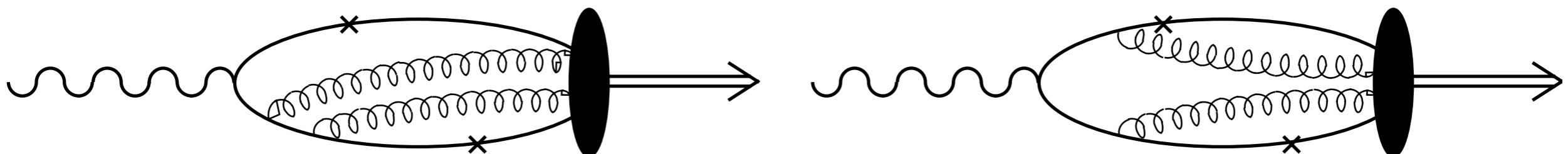
Pair can also have some non-zero relative momenta

Approach 1: Model J/ψ 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 ≈ 0.94 for cross-section

Hodbhoy 97



Here we neglect the relativistic corrections/ Fermi motion

Cross-section

Model 1: simple LO approach

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

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

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)

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

Assume gluon $\sim k_T^2$



Gluon Distribution

'Unintegrated' PDF:

$$f_g(x, k_T^2, \mu^2) = \frac{\partial[R_g x g(x, k_T^2) \sqrt{T(k_T^2, \mu^2)}]}{\partial \ln k_T^2} \quad x = \frac{Q^2 + M_{J/\psi}^2}{W^2 + Q^2}$$

Sudakov Factor: $T(k_T^2, \mu)$ gluon emitted during evolution from $k_T^2 \rightarrow \mu^2$ 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)

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

Shuvaev 99; Shuvaev et al. 99

Note: This R_g approximation is quite poor, σ_{tot} can be off by $\sim 20\%$
(Probably) now our dominant approximation error

Harland-Lang 13

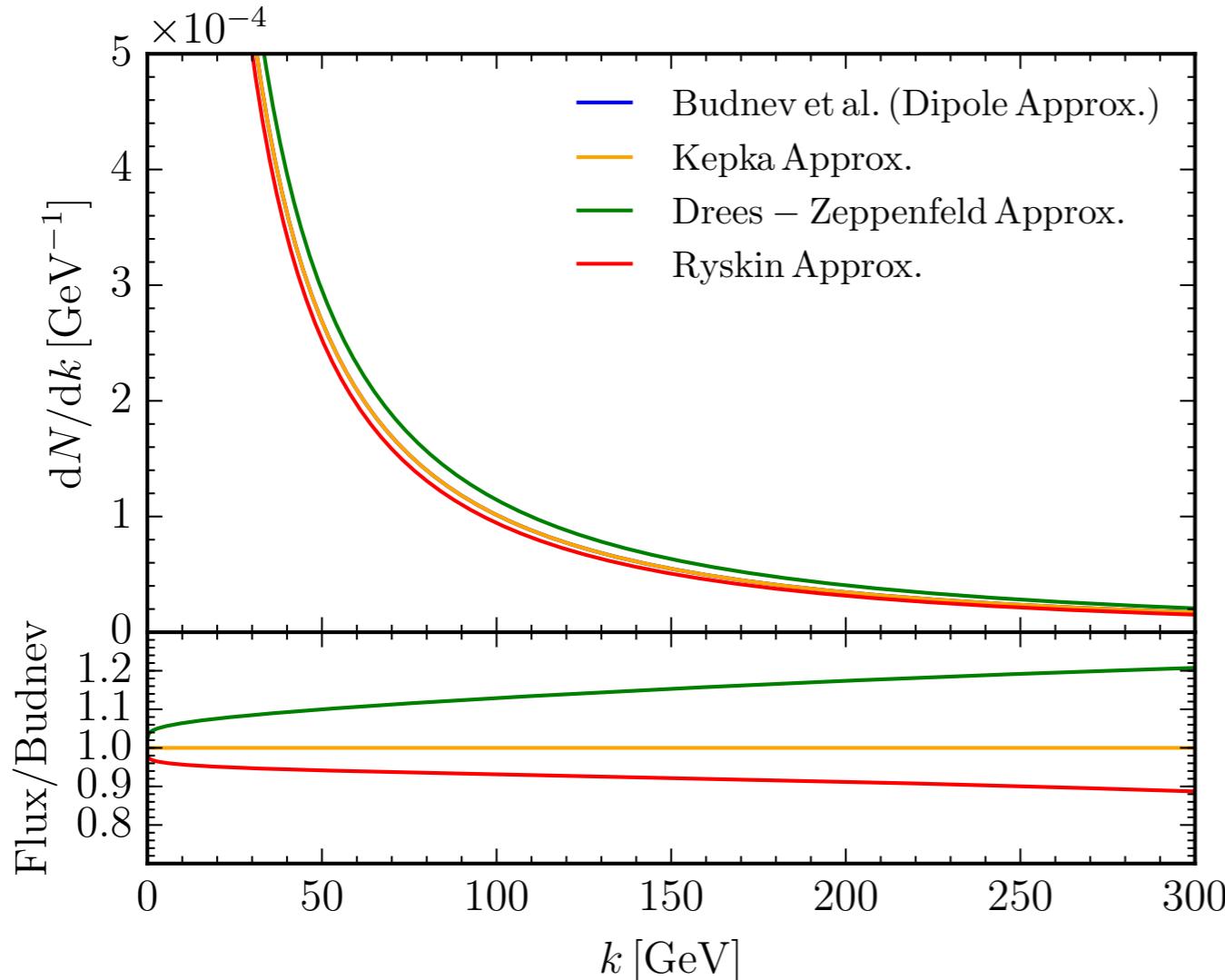
Refinement: Photon Flux

Equivalent Photon Approximation (EPA):

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

Budnev, Ginzburg, Meledin, Serbo 75

Proton Electric/Magnetic Form Factors

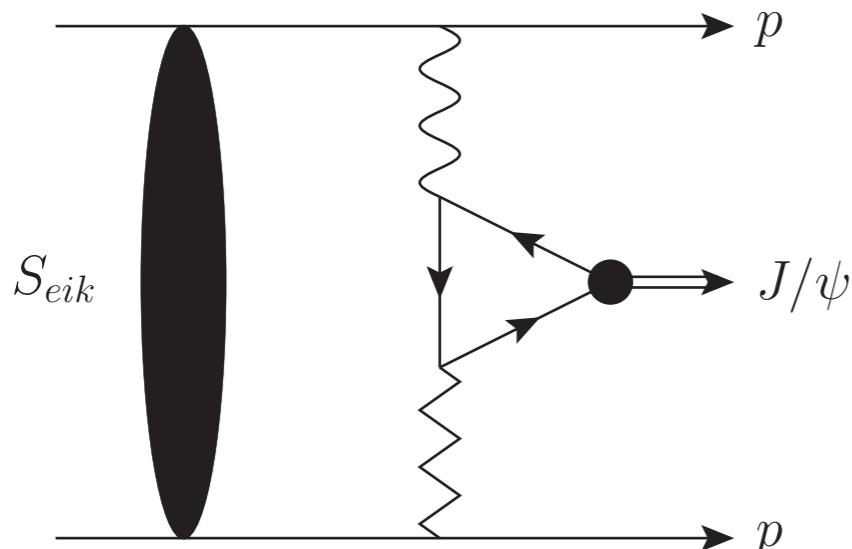


- Various approximations to the (cumbersome) Budnev et al. flux exist
- Previously used "Ryskin Approx." (neglects various subdominant terms) ~ 5-10% too small

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

Khoze et al. 02, 13, 14

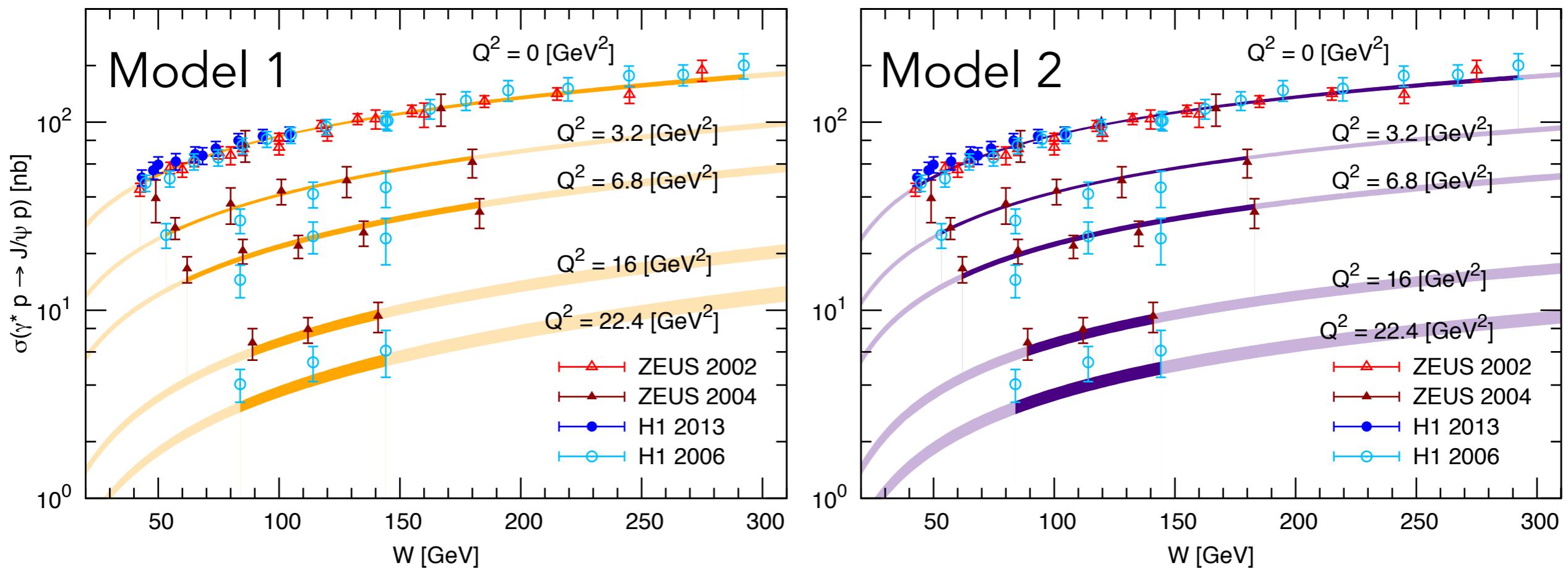
b_t^2 - impact parameter, \mathcal{M}_i - process dependent matrix elements,
 Ω_i - "universal" proton opacities **← Fit to data**

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

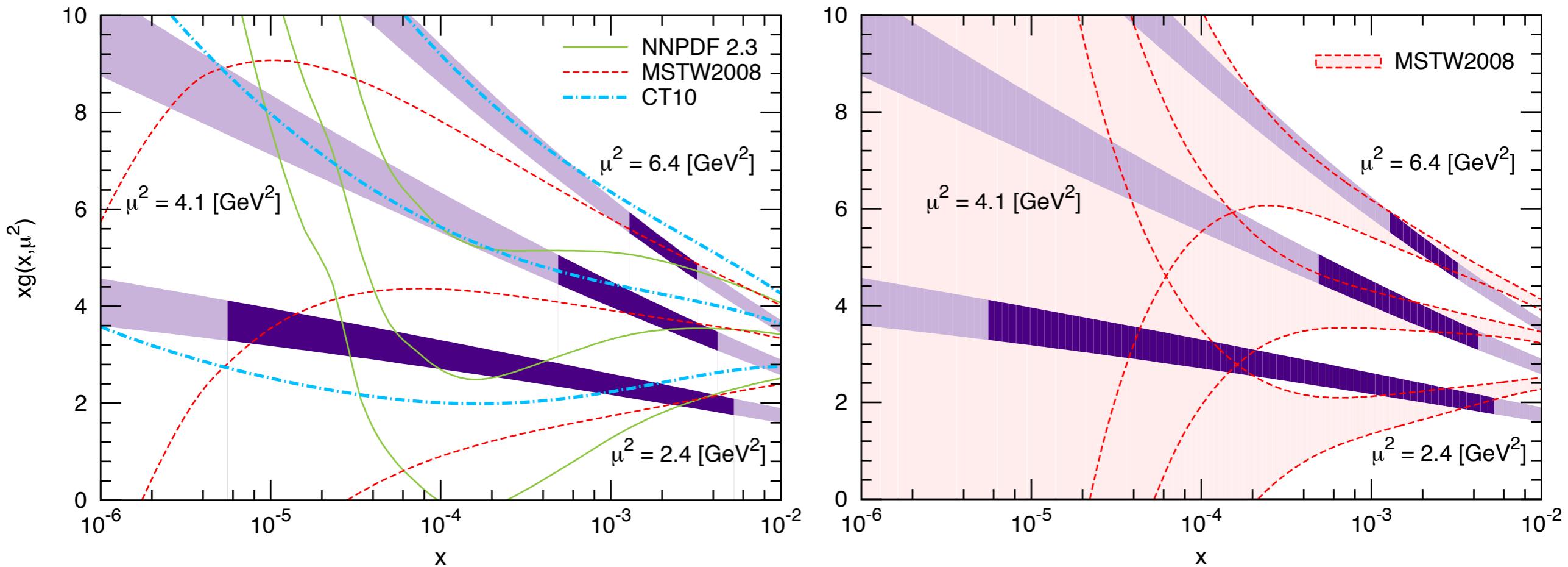
Previous Fit (2013)

Fit to HERA data only:



- Scale dependence from k_T^2 integral and HERA electoproduction data
- Fit describes both photoproduction and electroproduction data

Previous Extracted Gluons (2013)

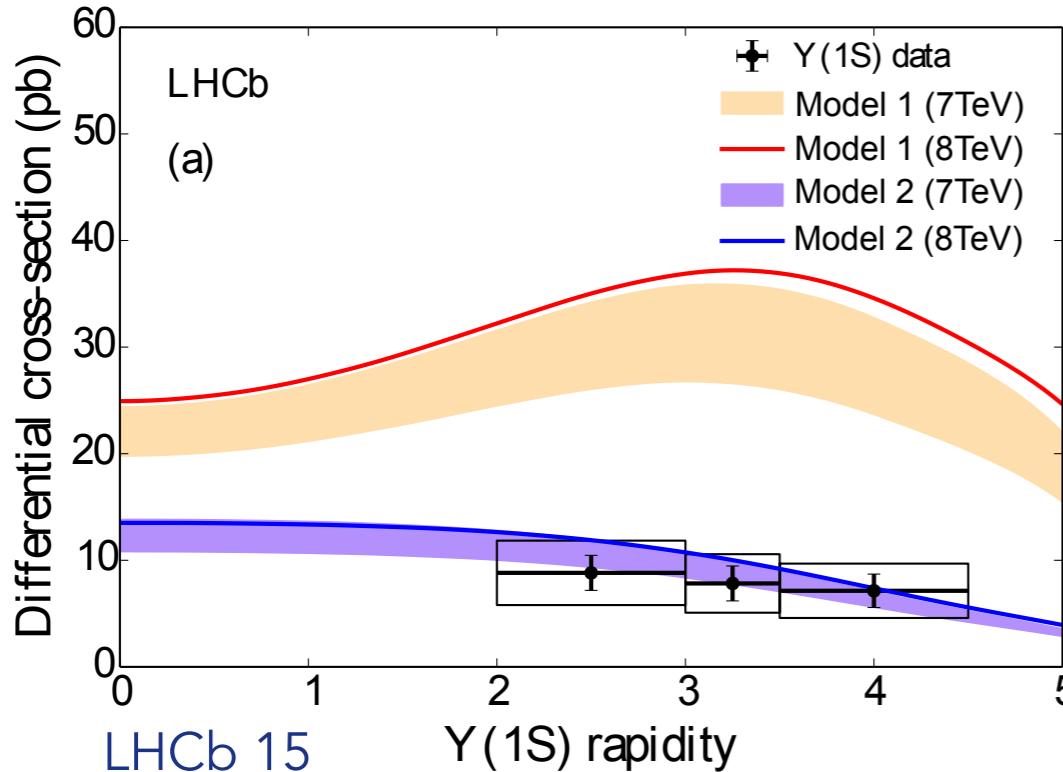
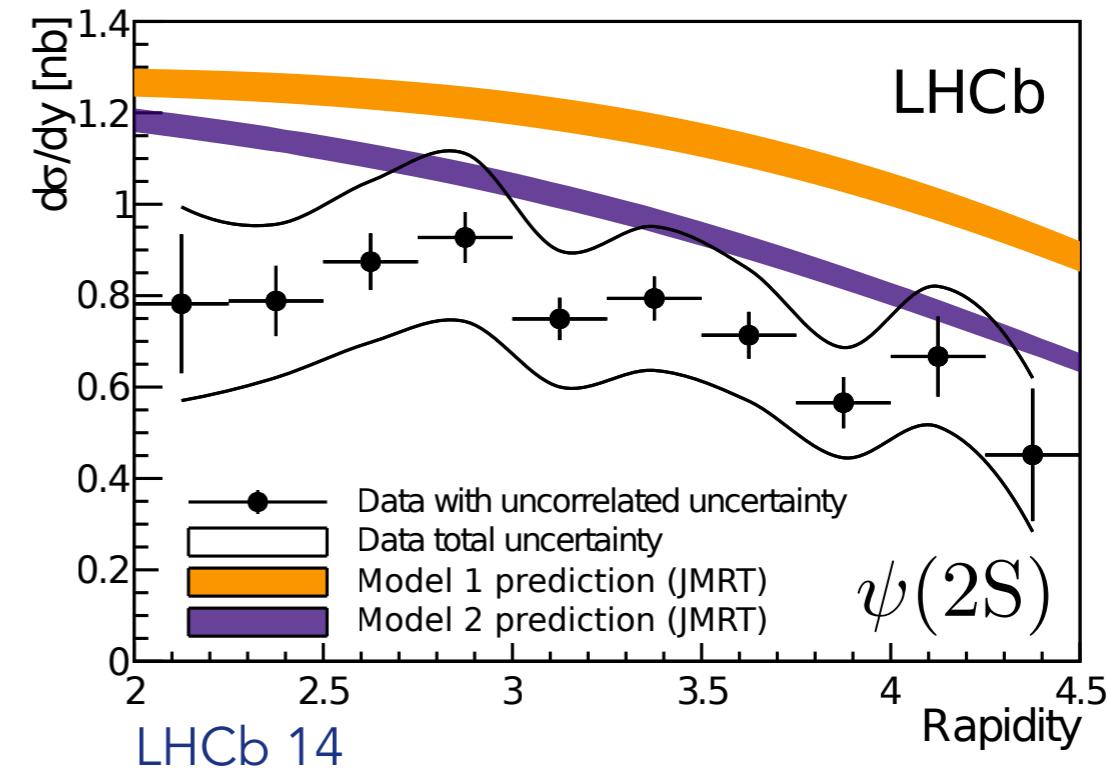
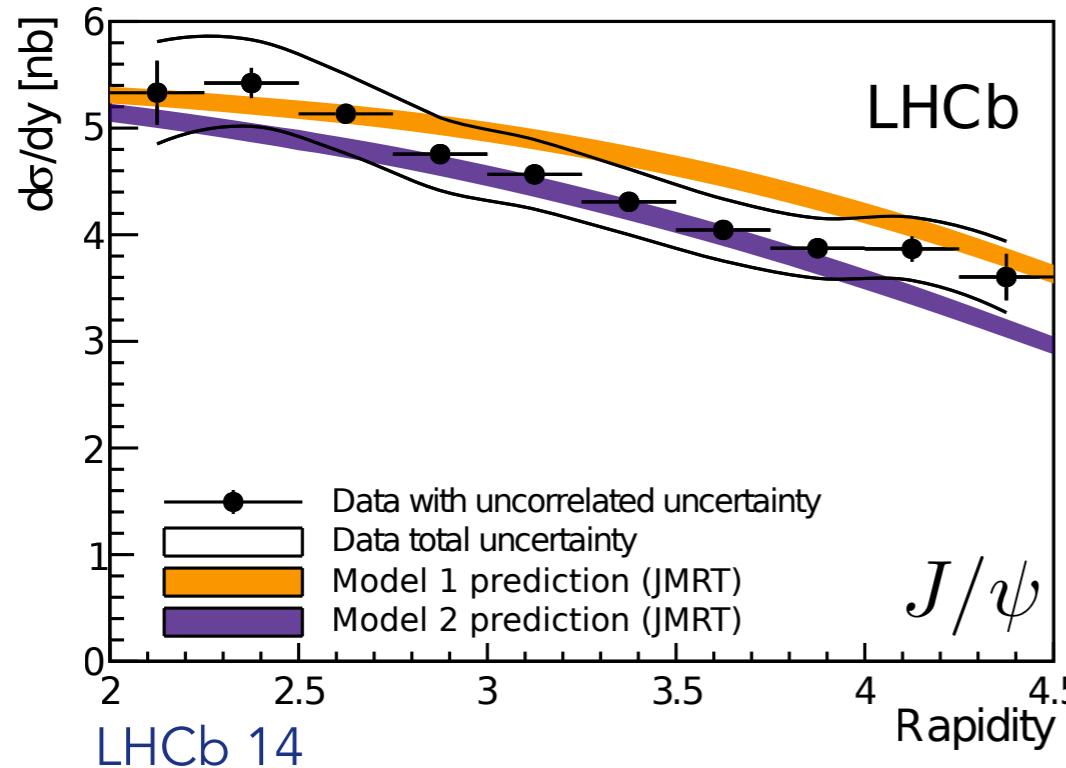


- Fitted gluons below global partons for higher $x_B \sim 10^{-2}$
- LHCb data provides support for the fit down to $x_B \sim 10^{-6}$

Not included here...

LHCb 2014, LHCb2016 J/ ψ , $\psi(2S)$ data & LHCb 2015 Υ data

Predictions vs 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!

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 \Rightarrow Relations between propagators N_i

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

Example:

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

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 :

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

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

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

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

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

Photon Flux (2013)

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

- 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

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)

- 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.

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

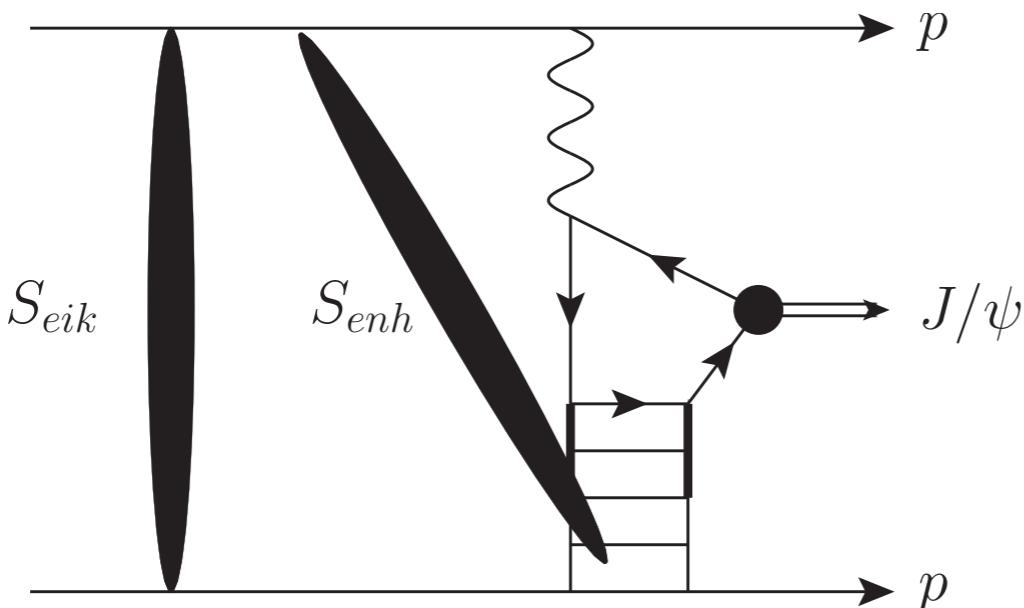
- Each GW eigenstate $|\phi_i\rangle$ independently parametrised by a form factor

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

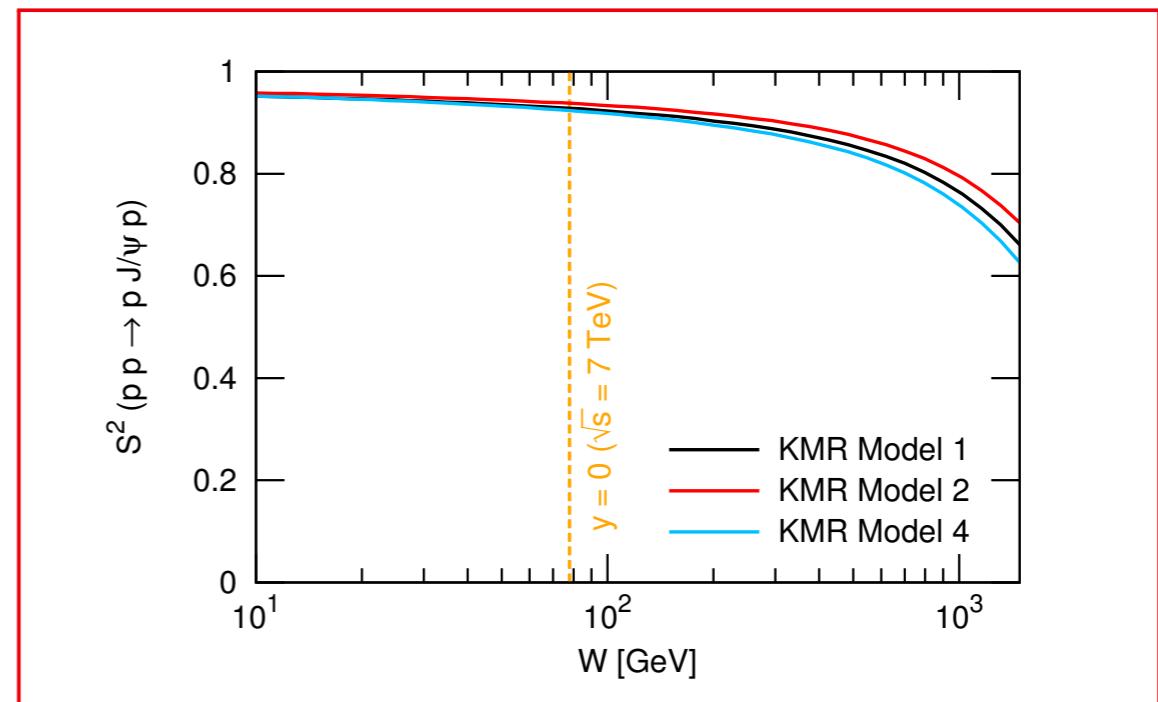
- 3 parameters per eigenstate + 1 relative weighting
- ‘Effective’ pomeron has energy dependent coupling to eigenstates
- 6 pomeron trajectory parameters: intercept (Δ), slope (α') and couplings (gives $b_0 = 4.9$, $\alpha' = 0.06$ for b slope)

KMR Model (III)

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



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



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