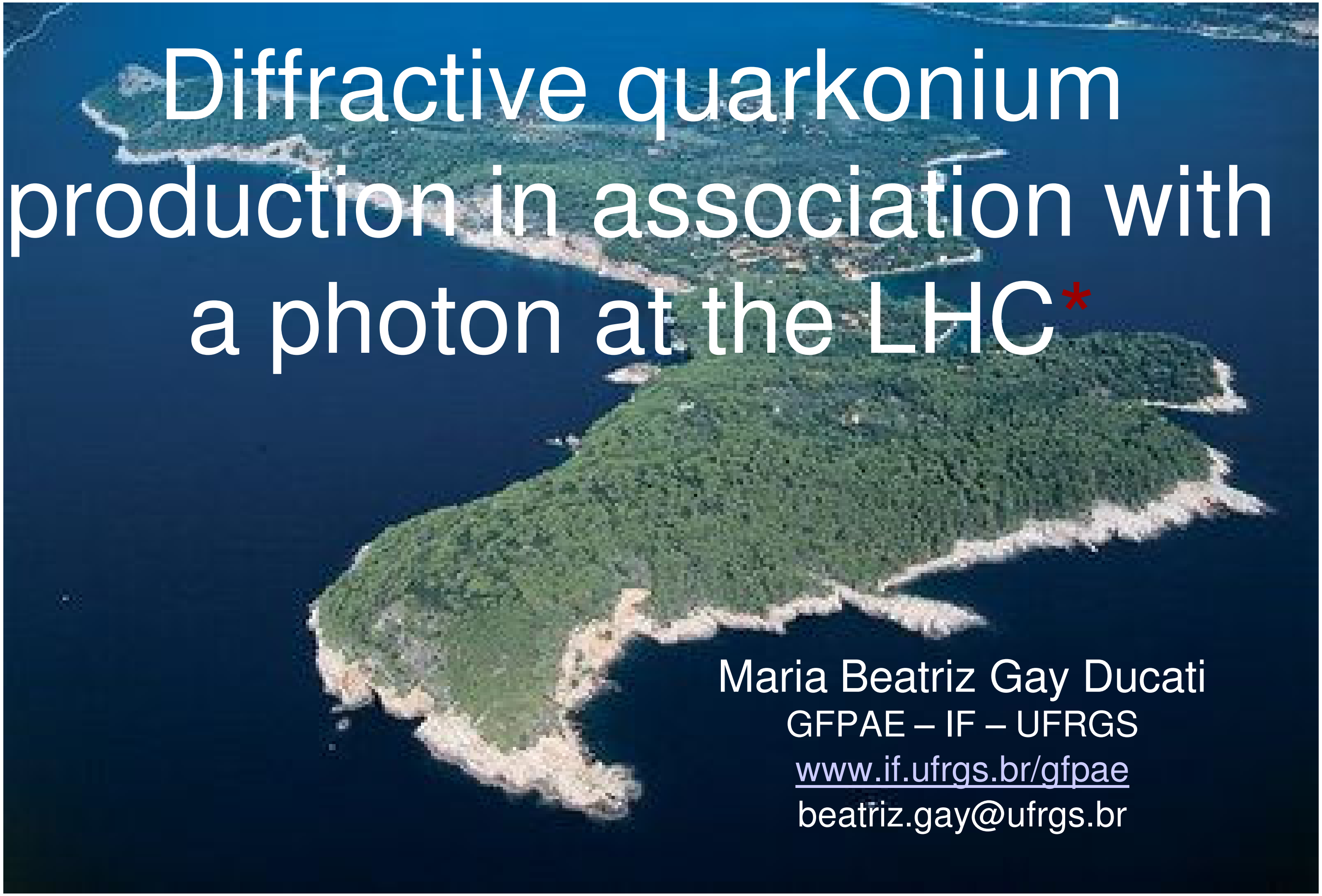

Diffractive quarkonium production in association with a photon at the LHC*

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* Refer to work: arXiv:hep/0908.0507

Low-x Meeting – Ischia Island, Italy – September 8 - 13 2009

Outlook

- Motivation
- Diffractive Physics
- Hadroproduction quarkonium + photon
- Pomeron Structure Function
- Multiple Pomeron Scattering
- Results
- Conclusions

GFPAE

Motivation

✓ Higher statistics of small-x and hard diffractive processes

→ intensive experimental study

✓ Has been used to improve the knowledge about QCD

✓ Several mechanisms for quarkonium production in hadron colliders

Color singlet model Color octet model[1] Color evaporation model

✓ Cross section for quarkonium production → gluon densities

✓ Pomeron with substructure → gluons

✓ Heavy quarkonium production → clean signature through leptonic decay modes

2 P. D. Collins, An Introduction to Regge Theory and High Energy Physics (1977)

Introduction

- Diffractive processes → overall cross sections
- Regge Theory → exchange of a Pomeron with vacuum quantum numbers
- Nature of the Pomeron and its reaction mechanisms[2] → not completely known
- Use of hard scattering → quark and gluon content in the Pomeron
- Observations of diffractive deep inelastic scattering (DDIS) at HERA (1994)
- Increased the knowledge about the QCD Pomeron
- Diffractive Distributions of singlet quarks and gluons in the Pomeron

Diffractive structure function

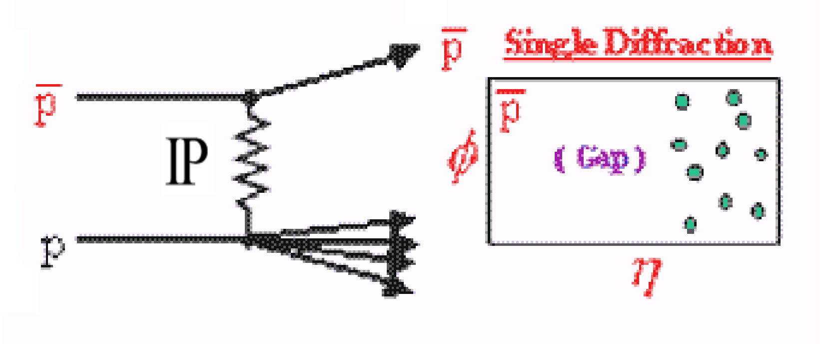
Diffractive events

- Both colliding hadrons remain intacts as they emit a Pomeron each

Central diffractive events

- Single diffraction in hadronic collisions

one of the colliding hadrons emits Pomeron that scatters off the other hadron



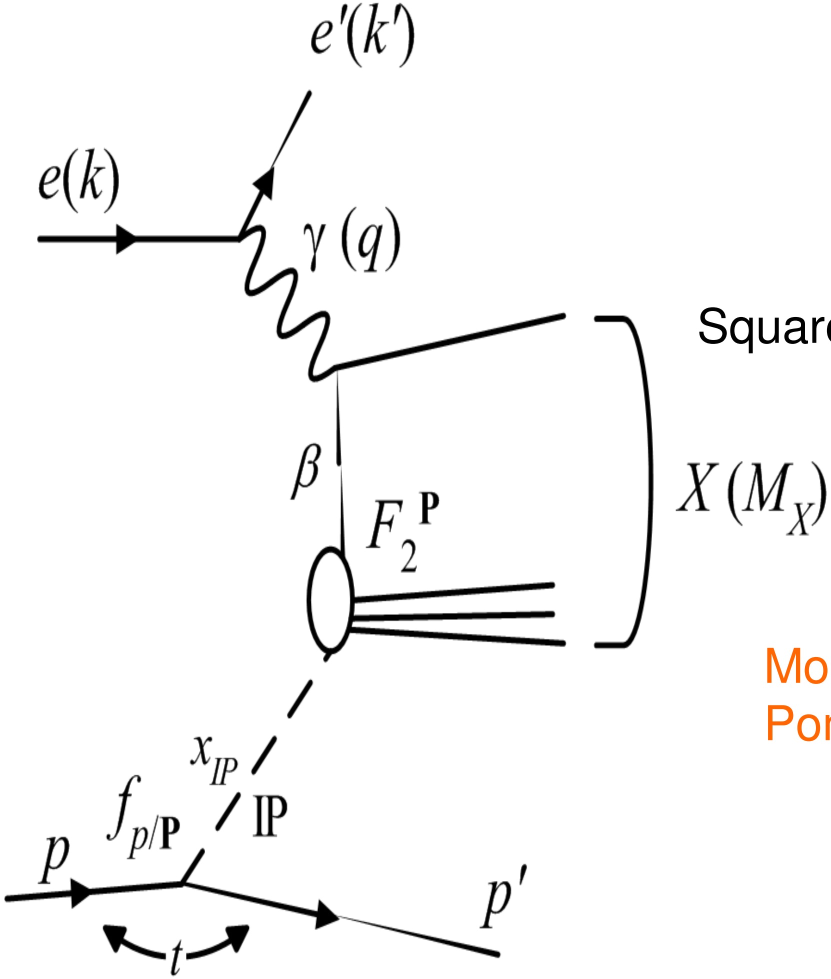
- Hard diffractive events with a large momentum transfer

Absence of hadronic energy in certain angular regions of the final state phase space

Rapidity gaps

[3] G. Ingelman and P. Schlein, Phys. Lett. 152B (1985) 256.

Diffractive Physics



Ingelman-Schlein Model [3]

$$t = (p - p')^2$$

Squared of the proton's four-momentum transfer

$$x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

Momentum fraction of the proton carried by the Pomeron

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t} = \frac{x}{x_{IP}}$$

Momentum fraction of partons inner the Pomeron

[4] J. P. Lansberg, arXiv:hep-ph/0901.4777

Diffractive hadroproduction

- o Focus on the following single diffractive processes

$$pp \to p + (J/\psi + \gamma) + X \qquad pp \to p + (Y + \gamma) + X$$

- o Diffractive ratios as a function of transverse momentum p_T of quarkonium state

- o Quarkonia produced with large p_T ➡ easy to detect

- o Singlet contribution

$$g + g \to \gamma + (c\bar{c})(^3S_1^{(1)})(\to J/\psi)$$

- o Octet contributions

$$g + g \to \gamma + (c\bar{c})(^1S_0^{(8)})(\to J/\psi),$$

$$g + g \to \gamma + (c\bar{c})(^3P_J^{(8)})(\to J/\psi),$$

- o Higher contribution on high p_T [4]

J/ψ+γ production

✓ Considering the Non-relativistic Quantum Chromodynamics (NRQCD)

✓ Gluons fusion dominates over quarks annihilation [4]

✓ Leading Order cross section → convolution of the partonic cross section with the PDF

✓ MRST 2001 LO → no relevant difference using MRST 2002 LO and MRST 2003 LO

✓ Non-perturbative aspects of quarkonium production

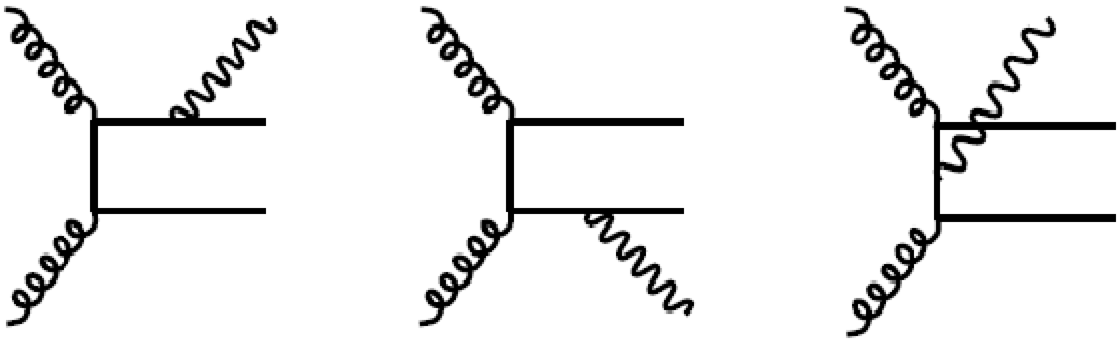
- Expansion in powers of v
  - v is the relative velocity of the quarks in the quarkonia

NLO expansions in α_s one virtual correction and three real corrections

[5] C. S. Kim, J. Lee and H. S. Song, Phys. Rev. D55 (1997) 5429

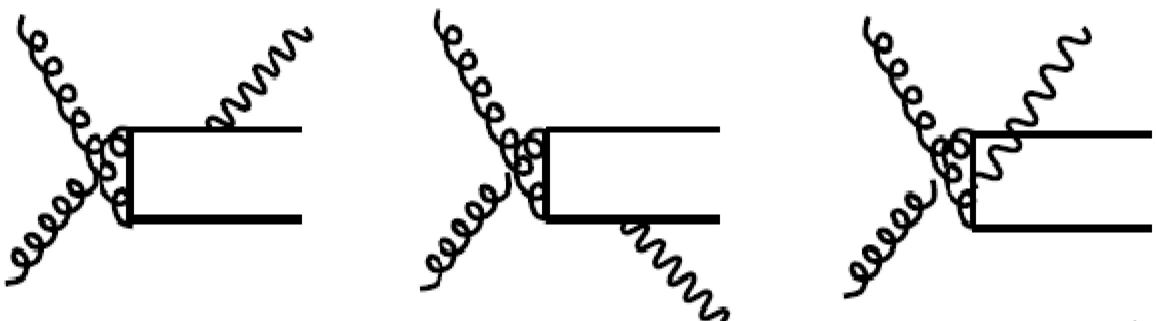
Quarkonium + photon production

Singlet subprocess [5]



No gluon interactions

$$g + g \to (c\bar{c})(^3S_1^{(1)}) + \gamma$$



Gluon interactions

$$g + g \to (c\bar{c})(^1S_0^{(8)},\, ^3P_J^{(8)}) + \gamma$$

Octet subprocess

[6] R. Li and J. X. Wang, Phys. Lett. B672 (2009) 51

NRQCD Factorization

$$g + g \;\rightarrow\; \gamma + (c\bar{c})\left[{}^3S_1^1, {}^3S_1^8\right]$$

$$g + g \;\rightarrow\; \gamma + (c\bar{c})\left[{}^1S_0^8, {}^3P_J^8\right]$$

- Negligible contribution of quarks annihilation at high energies[6]

$$\frac{d^2\sigma_{\rm inc}}{dy\,dp_T} = \int dx_1 g_p(x_1,\mu_F^2)\, g_p(x_2,\mu_F^2)\, \frac{4x_1x_2p_T}{2x_1 - \bar{x}_T e^{y}}\, \frac{d\hat{\sigma}}{d\hat{t}}$$

J/ψ rapidity

$$\bar{x}_T \;=\; 2m_T/\sqrt{s} \qquad\qquad m_T = \sqrt{p_T^2 + m_\psi^2}$$

9.2 GeV[2]

$\sqrt{s}$ is the center mass energy (LHC = 14 TeV)

NRQCD factorization

✓ x_1(x_2) is the momentum fraction of the proton carried by the gluon

$M^2/s \leq x_1 < 1$ M → invariant mass of J/ψ+γ system

$$x_2 = \frac{x_1 \bar{x}_T e^{-y} - 2\tau}{2x_1 - \bar{x}_T e^{y}} \qquad \tau = \frac{m_\psi^2}{s}$$

✓ Cross section written as

$$\sigma(H) = \sum_n c_n \langle 0 | O_n^H | 0 \rangle$$

Coefficients are computable in perturbation theory

Matrix elements of NRQCD operators

[7] T. Mehen, Phys. Rev. D55 (1997) 4338

Matrix elements

$$\langle 0|O_n^H|0\rangle = \sum_X \sum_\lambda \langle 0|\kappa_n^\dagger|H(\lambda)+X\rangle\langle H(\lambda)+X|\kappa_n|0\rangle$$

Bilinear in heavy quarks fields which create as a pair $Q\bar{Q}$

Quarkonium state [7]

$$\frac{d\sigma}{dt}(g+g\to J/\psi+\gamma) = \frac{\pi^2 e_c^2 \alpha \alpha_s^2 m_c}{s^2}\left[\frac{10}{9}\left(\frac{s^2 s_1^2 + t^2 t_1^2 + u^2 u_1^2}{s_1^2 t_1^2 u_1^2}\right)\langle O_8^{J/\psi}(^3S_1)\rangle \right.$$

$$+\frac{16}{27}\left(\frac{s^2 s_1^2 + t^2 t_1^2 - u^2 u_1^2}{s_1^2 t_1^2 u_1^2}\right)\langle O_1^{J/\psi}(^3S_1)\rangle + \frac{3}{2}\frac{tu}{s s_1^2 m_c^2}\langle O_8^{J/\psi}(^3S_1)\rangle$$

$$\left. + \frac{3}{2}\frac{1}{s s_1^2 m_c^4}\left(2s(2m_c)^2 + 3tu - \frac{4tu(2m_c)^2}{s_1}\right)\langle O_8^{J/\psi}(^1P_0)\rangle\right],$$

$$s_1 = s - 4m_c^2,\ t_1 = t - 4m_c^2,\ u_1 = u - 4m_c^2 \qquad e_c = \frac{2}{3}$$

α_s running

[8] E. Braaten, S. Fleming, A. K. Leibovich, Phys. Rev. D63 (2001) 094006
[9] F. Maltoni *et al.*, Phys. Lett. B638 (2006) 202

Matrix elements (GeV^3)[8, 9]

$\langle O_1^{J/\psi}(^3S_1)\rangle$	1.16	$\langle O_1^{\Upsilon}(^3S_1)\rangle$	10.9
$\langle O_8^{J/\psi}(^3S_1)\rangle$	1.19×10^{-2}	$\langle O_8^{\Upsilon}(^3S_1)\rangle$	0.02
$\langle O_8^{J/\psi}(^1S_0)\rangle$	0.01	$\langle O_8^{\Upsilon}(^1S_0)\rangle$	0.136
$\langle O_8^{J/\psi}(^1P_0)\rangle$	$0.01 \times m_c^2$	$\langle O_8^{\Upsilon}(^1P_0)\rangle$	0

$e_b = -\frac{1}{3}$

$m_b = 4.5$ GeV

$m_\Upsilon = 9.46$ GeV/c^2

Diffractive cross section

$$\frac{d^2\sigma_{\mathrm{SD}}}{dy\,dp_T} = \int_{x_{\mathbb{P}}^{min}}^{x_{\mathbb{P}}^{max}} dx_{\mathbb{P}} \int_{\frac{M^2}{s x_{\mathbb{P}}}}^{1} dx_1 \int_{-1}^{0} dt\, f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)$$

$$\times \quad g_{\mathbb{P}}(x_{\mathbb{P}}, \mu_F^2) g_p(x_2, \mu_F^2) \frac{4 x_1 x_{\mathbb{P}} x_2 p_T}{2 x_1 x_{\mathbb{P}} - \bar{x}_T e^y} \frac{d\hat{\sigma}}{d\hat{t}}$$

Momentum fraction carried by the Pomeron

Squared of the proton's four-momentum transfer

Pomeron flux factor $\quad f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \propto x_{\mathbb{P}}^{1-2\alpha(t)} F^2(t)$

$\alpha(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$ Pomeron trajectory

Variables to DDIS

Cuts for the integration over x_{IP}

$$x_{\mathbb{P}}^{min} \leq x_{\mathbb{P}} \leq 0.05 \qquad x_{\mathbb{P}}^{min} = \frac{\bar{x}_T e^{y} - 2\tau}{\bar{x}_T e^{-y} - 2}$$

Scales

$$Q_0^2 = 2.5\,GeV^2 \qquad \Lambda_{QCD} = 0.2 \qquad \mu_F^2 = \frac{\left(p_T^2 + m_\psi^2\right)}{4}$$

$$\begin{aligned} x_2 &= \frac{x_1 x_{\mathbb{P}} \bar{x}_T e^{-y} - 2\tau}{2 x_1 x_{\mathbb{P}} - \bar{x}_T e^{y}}, \\ \hat{s} &= x_1 x_2 x_{\mathbb{P}} s, \qquad \hat{t} = m_\psi^2 - x_2 \sqrt{s} m_T e^{y} \\ \hat{u} &= m_\psi^2 - x_1 x_{\mathbb{P}} \sqrt{s} m_T e^{-y}. \end{aligned}$$

10 H1 Coll. A. Aktas *et al*, Eur. J. Phys. J. C48 (2006) 715

Pomeron structure function

Parametrization of the pomeron flux factor and structure function → H1 Collaboration [10]

$$f_{\mathbb{P}/p}(x_{\mathbb{P},t}) = A_{\mathbb{P}} \frac{e^{B_{I\mathbb{P}}t}}{x_{\mathbb{P}}^{2\alpha_{\mathbb{P}}(t)-1}}$$

$$\alpha_{\mathbb{P}}(t) \; = \; \alpha \;\; (0) + \alpha'_{\mathbb{P}} t$$

$A_{\mathbb{P}}$ → Normalization parameter

$$|t_{min}| \;\approx\; m_p^2 x_{\mathbb{P}}^2/(1 - x_{\mathbb{P}})$$

m_p = proton mass

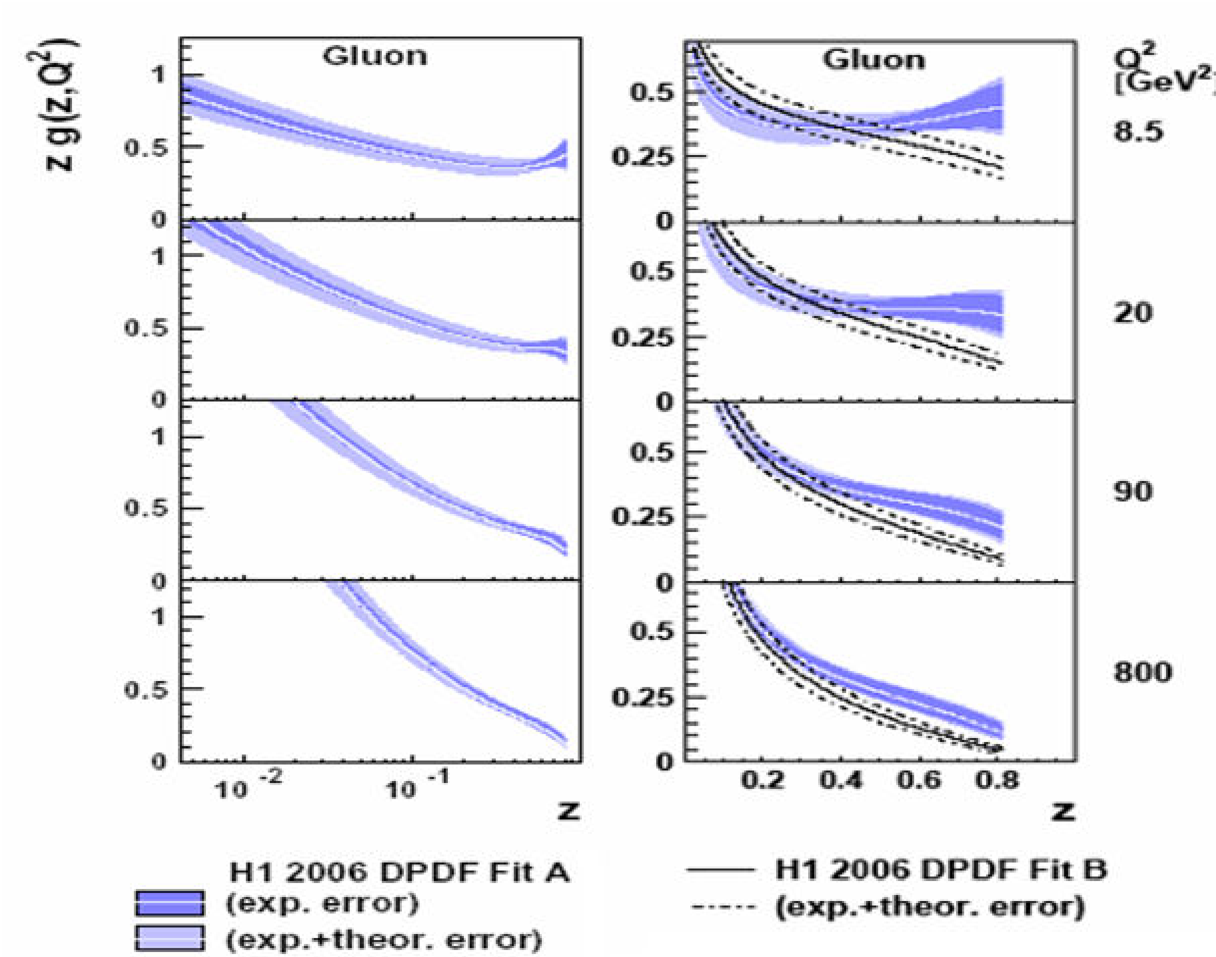
$$x_{\mathbb{P}} \int_{t_{cut}}^{t_{min}} f_{\mathbb{P}/p} dt \; = \; 1$$

Normalized for $x_{\mathbb{P}} \; = \; 0.003$

$$|t_{cut}| = 1.0 \text{ GeV}^2$$

Parameter	*Value*
α'_{IP}	$0.06^{+0.19}_{-0.06} GeV^{-2}$
B_{IP}	$5.5^{+2.0}_{-0.7} GeV^{-2}$
$\alpha_{IR}(0)$	0.50 ± 0.10
α'_{IR}	$0.3^{+0.6}_{-0.3} GeV^{-2}$
B_{IR}	$1.6^{+1.6}_{-0.4} GeV^{-2}$
m_c	$1.4 \pm 0.2 GeV$
m_b	$4,5 \pm 0.5 GeV$
$\alpha_8^{(5)}(M_Z^2)$	0.118 ± 0.002

Gluon distribution



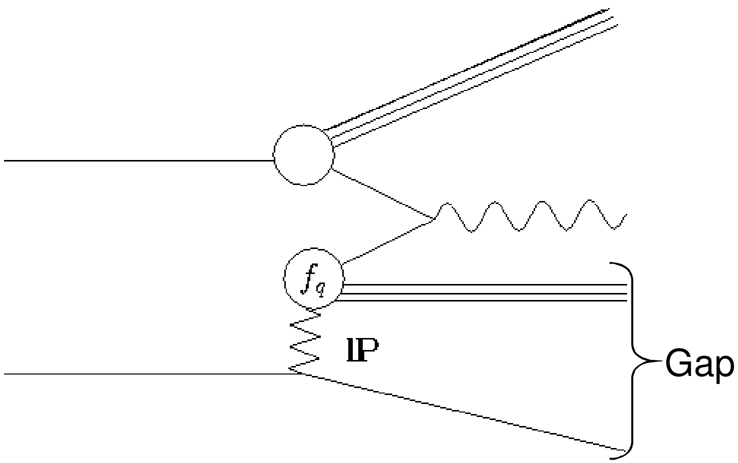
- Range 0.0043 < z < 0.8
- Same of experiment
- In this work we use FIT A.
- Similar results with FIT B

Fit A (and uncertainties) → color center line

Fit B (and uncertainties) → black line

[11] E. Gotsman, E. Levin, U. Maor and A. Prygarin, arXiv:hep-ph/0511060

Gap Survival Probability (GSP)



- Described in terms of screening or absortive corrections
- Multiple Pomeron effects → absorptive corrections
- $<|S|^2>$ → gap survival probability (GSP)
-

$$< |S|>^2 = \frac{\int d^2b \, |A(s,\, b)|^2 \; P^s(b,\; s)}{\int d^2b \, |A(s,\, b)|^2}$$ [11]

- *A(s,b)* → amplitude of the particular diffractive process of interest

- $P^S(s,b)$ → probability that no inelastic interactions occur between scattering hadrons

[11] E. Gotsman, E. Levin, U. Maor and A. Prygarin, arXiv:hep-ph/0511060

KKMR model

KKMR description to hadronic collisions embodies:[11]

- Pion-loop insertions in the bare Pomeron pole → nearest singularity generated by t-channel unitarity

- Two-channel eikonal → incorporates Pomeron cuts generated by elastic and quasi-elastic s-channel unitarity

- High-mass diffractive dissociation

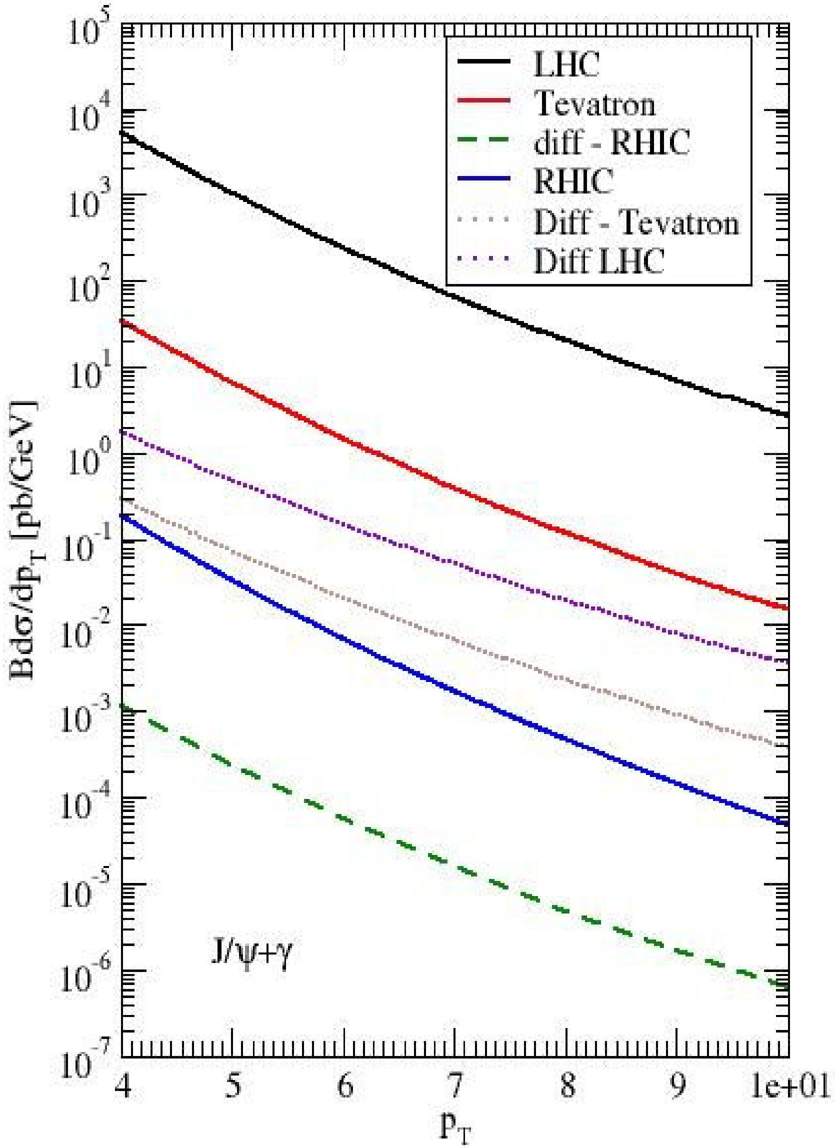
  Multiple Pomeron effects → absorptive corrections

- Good description of the data of the total and differential elastic cross section

- Value of $\langle|S|^2\rangle = 0.06$ at LHC single diffractive events

[5] C. S. Kim, J. Lee and H. S. Song, Phys. Rev. D55 (1997) 5429
[12] Renu Bala, XLVII International Winter Meeting on Nuclear Physics (2009)

Results to $J/\psi+\gamma$



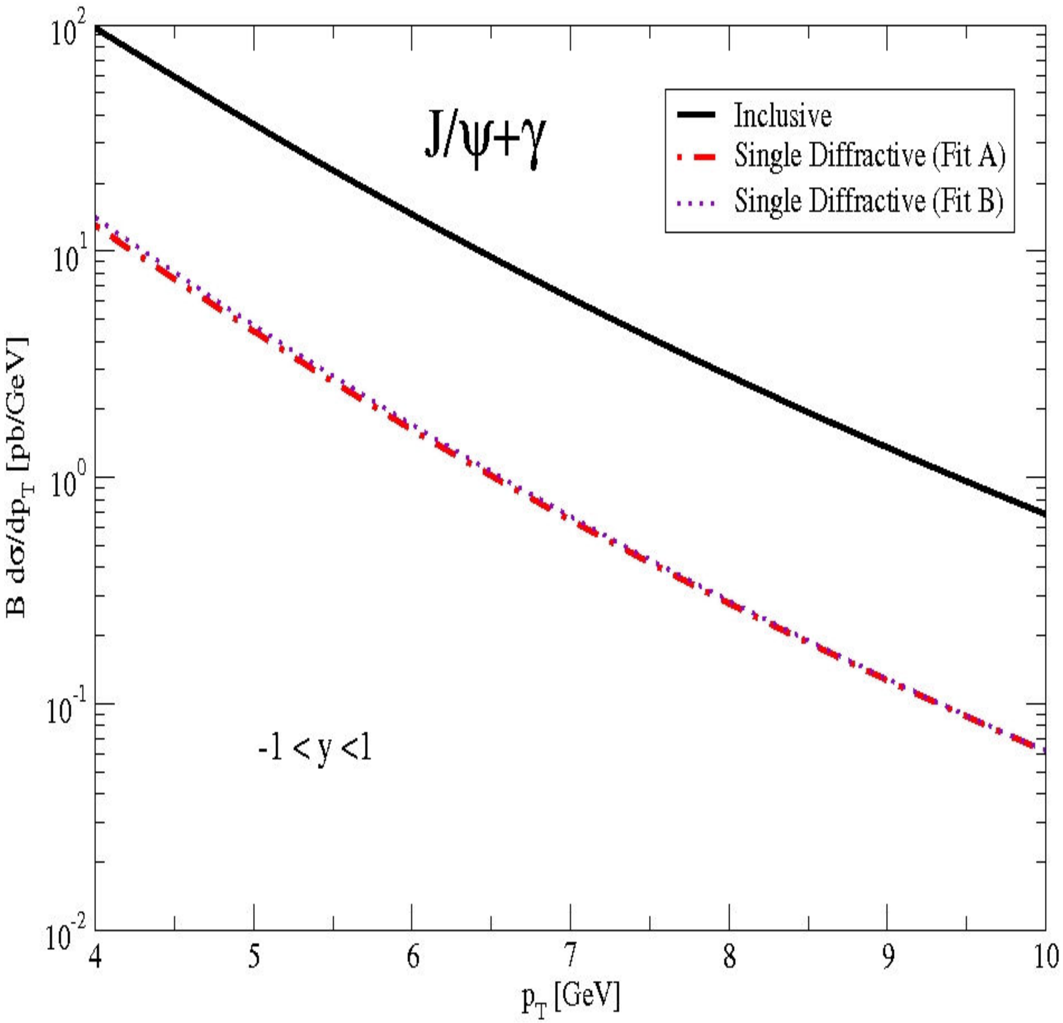
- Predictions for inclusive and diffractive cross sections
- RHIC, Tevatron and LHC
- Diffractive cross sections considering GSP ($<|S|^2>$)
- Reproduces descriptions of [5]

$$-1 < |y| < 1$$

- B = 0.0594 is the branching ratio into electrons

$1 \leq p_T \leq 20$ at LHC[12]

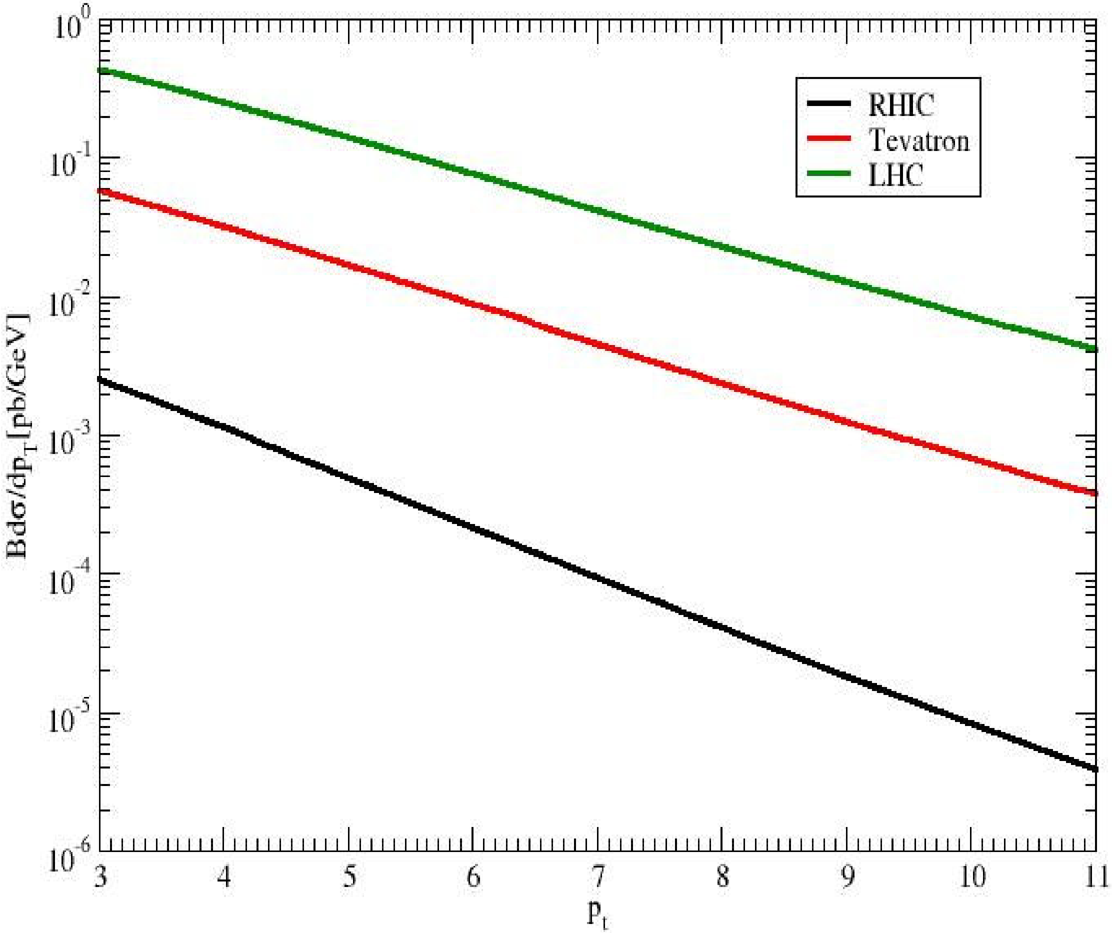
Results to J/ψ+γ at LHC



- B = 0.0594
- Absolute value of inclusive cross section strongly dependent
  - Quark mass
  - NRQCD matrix elements
  - Factorization scale
- Diffractive cross sections (DCS) without GSP
- Comparison between two different sets of diffractive gluon distribution (H1)
- Absolute value of DCS

weakly sensitive to the uncertainties of DPDF

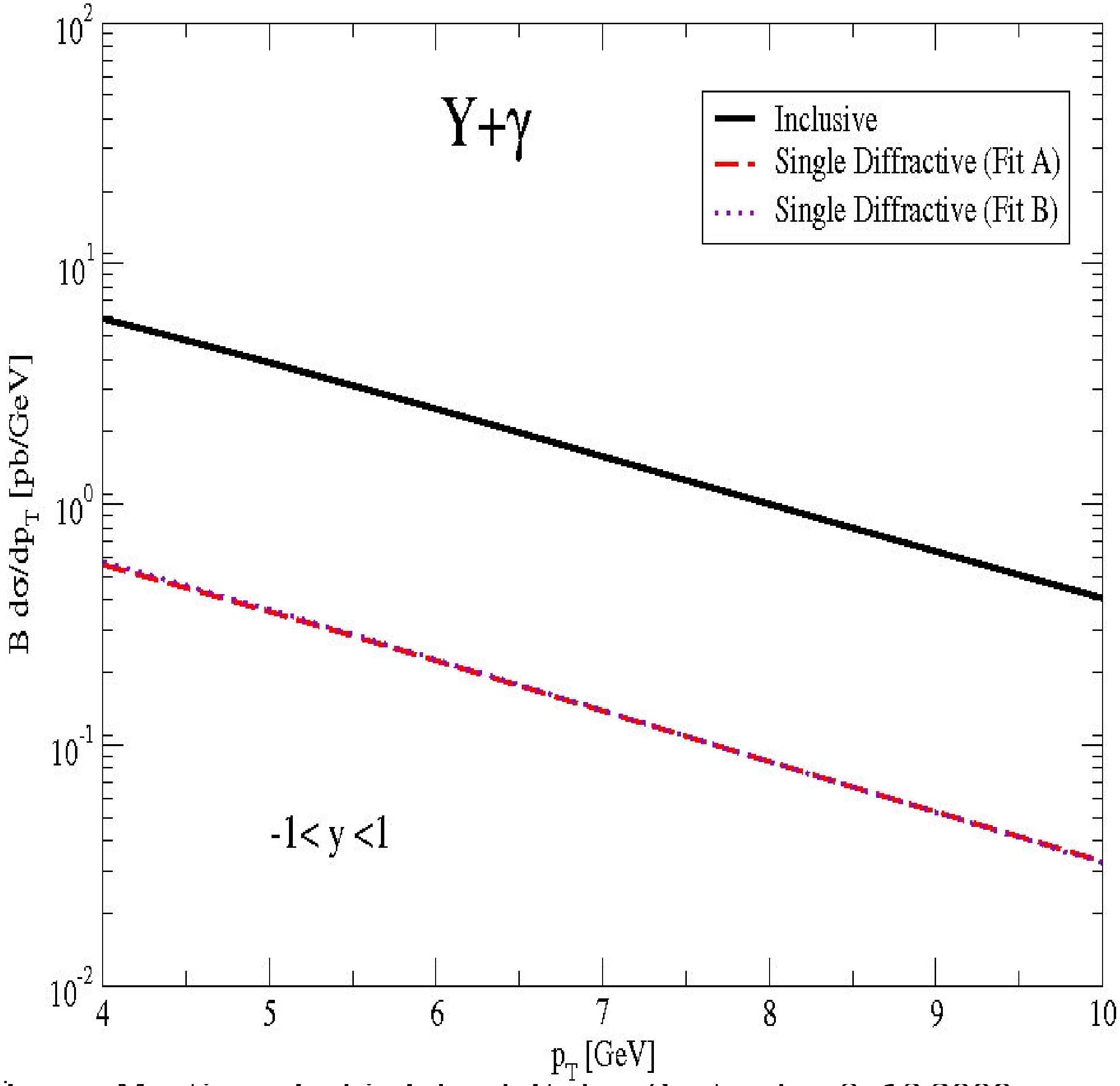
Results to $\Upsilon+\gamma$



- Predictions of inclusive cross section
- RHIC, Tevatron and LHC

  $-1 < |y| < 1$
- B = 0.0238 is the branching ratio into electrons

Results to Y+γ at LHC



- B = 0.0238
- Absolute value of inclusive cross section strongly dependent
  - Quark mass
  - NRQCD matrix elements
  - Factorization scale
- Diffractive cross sections (DCS) without GSP ($<|S|^2>$)
- Comparison between two different sets of diffractive gluon distribution (H1)
- Dependence of FITs are slight more pronounced in charmonium case

[5] C. S. Kim, J. Lee and H. S. Song, Phys. Rev. D55 (1997) 5429

Diffractive ratio

[σ] = pb

considering FIT A

p_T [GeV]	4	5	6	7	8	9	10
$\frac{d\sigma_{\rm inc}}{dp_T}$ (J/Ψ)	97.04	36.46	14.54	6.21	2.82	1.36	0.68
$\frac{d\sigma_{\rm SD}}{dp_T}$ (J/Ψ)	0.78	0.26	0.10	0.04	0.017	0.008	0.0036
$R_{\rm SD}$ [%] (J/Ψ)	0.8	0.71	0.69	0.64	0.6	0.59	0.53
$\frac{d\sigma_{\rm inc}}{dp_T}$ (Υ)	5.91	3.88	2.49	1.58	1.00	0.64	0.41
$\frac{d\sigma_{\rm SD}}{dp_T}$ (Υ)	0.036	0.022	0.013	0.008	0.0054	0.003	0.0018
$R_{\rm SD}$ [%] (Υ)	0.6	0.56	0.53	0.51	0.54	0.47	0.44

- Slight large diffractive ratio in comparison to [5]
- Could explain the p_T dependence in our results

This work	Ref 5
$\mu_F = \sqrt{\frac{(p_T^2 + m_\psi^2)}{4}}$	$\mu_F = E_T$
<|S|²>=0.06	Renormalized Pomeron flux
Evolution of Q^2 in gluon density	No evolution of Q^2

Conclusions

- Theoretical prediction for inclusive and single diffractive quarkonium + photon production at LHC energy in pp collisions
- Estimates for differential cross sections as a function of quarkonium transverse momentum
- Diffractive ratio is computed using hard diffractive factorization and absorptive corrections
- Ratios are less dependent on the heavy quarkonium production mechanism
- Quite sensitive to the absolute value of absorptive corrections
- Distribution on $4 \leq p_T \leq 10$ → $R^{(J/\psi)}_{SD} = 0{,}8 - 0{,}5\ \%$
  $R^{(\Upsilon)}_{SD} = 0{,}6 - 0{,}4\ \%$
- Next step → Next-to-Leading Order