Meson production in ultra-peripheral heavy ion collisions

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Collaboration

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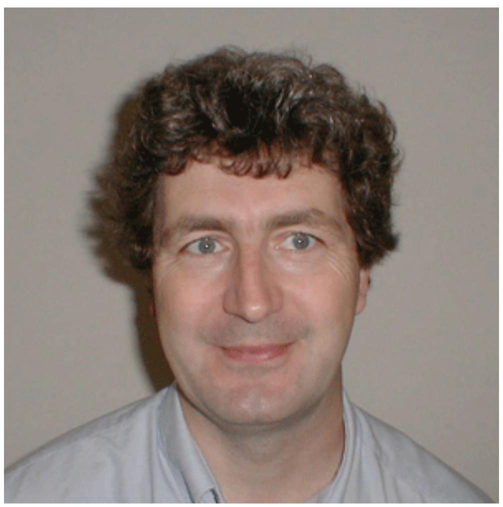

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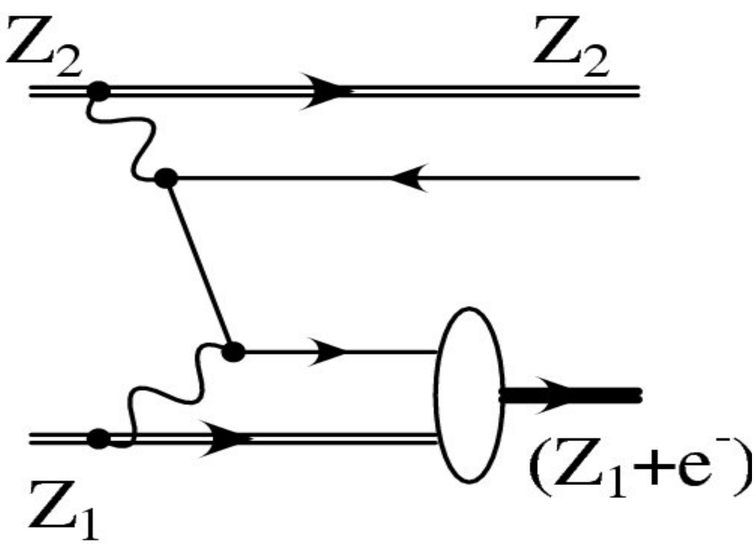
Texas A&M-Commerce

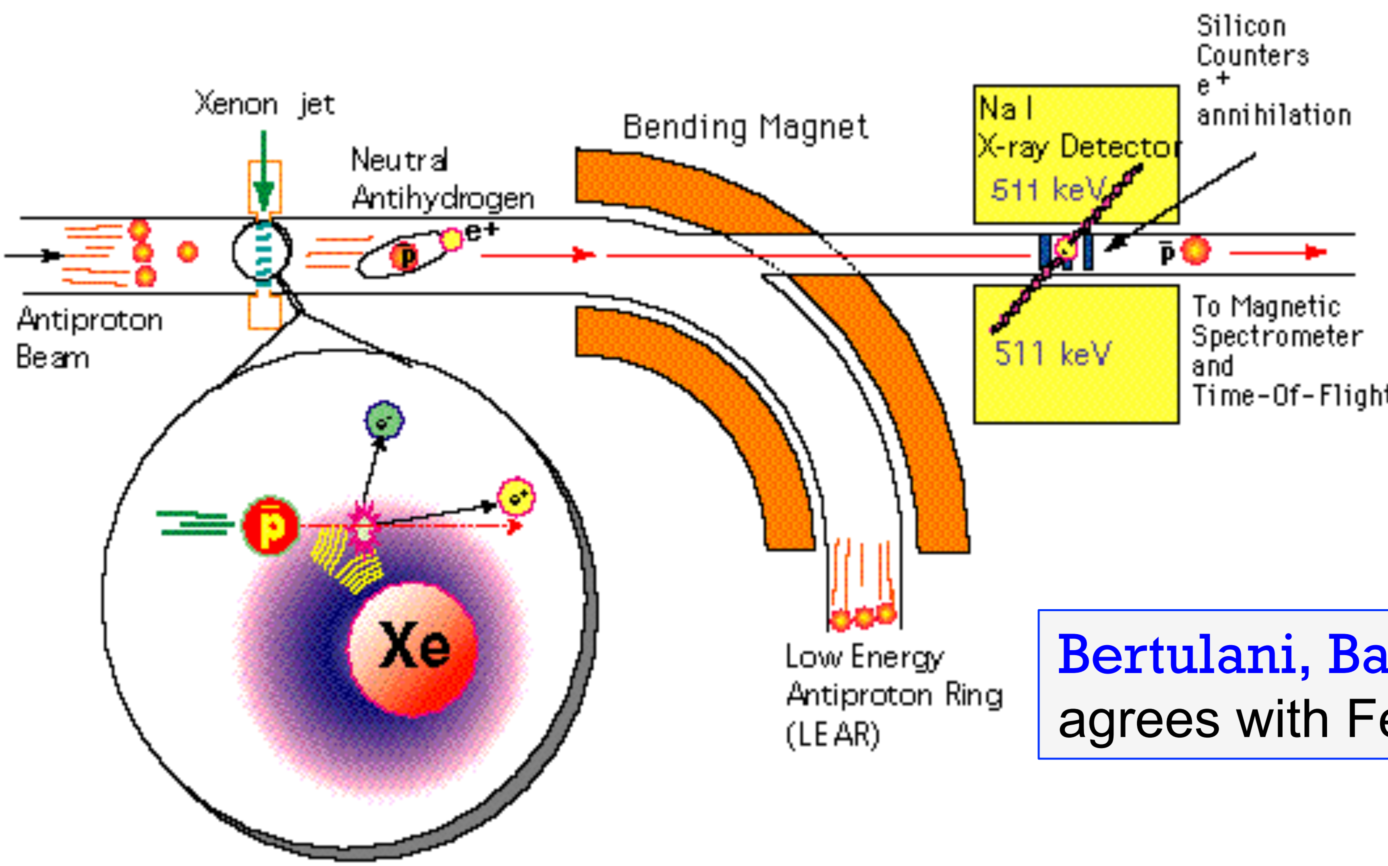
Pair Production with Capture



Bertulani, Baur, Phys. Rep. 163, 299 (1988)

$$\sigma \propto \frac{Z^8 \alpha^8}{m_e^2}\left[\ln\left(\frac{0.68\gamma}{2}\right) - \frac{5}{3}\right]$$

~ 300 b for Pb+Pb at LHC



Production of anti-H

CERN: Baur et al, PLB 368, 251 (1996)

Fermilab: Blanford et al, PRL 80, 3037 (1998)

Bertulani, Baur, PRD 58, 034005 (1998) agrees with Fermilab data.

The New York Times

WORLD | U.S. | N.Y. / REGION

Physicists Manage to Create The First Antimatter Atoms

By MALCOLM W. BROWNE
Published: January 5, 1996

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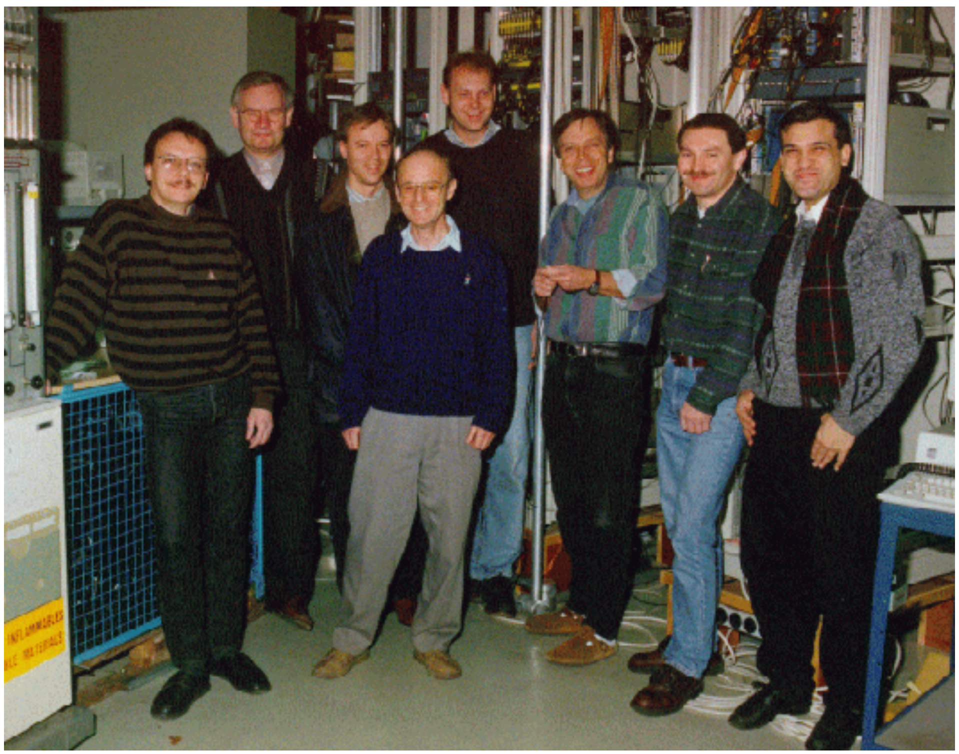
But the neutrality of antihydrogen, like that of ordinary hydrogen, renders it impossible to contain or manipulate using magnetic fields. Moreover, an antiatom cannot be contained in an ordinary vessel, since the slightest contact with the container's wall causes it to annihilate. Consequently, other groups are developing enormously sophisticated methods, including interacting lasers, to manipulate and secure antiparticles inside vacuum chambers.

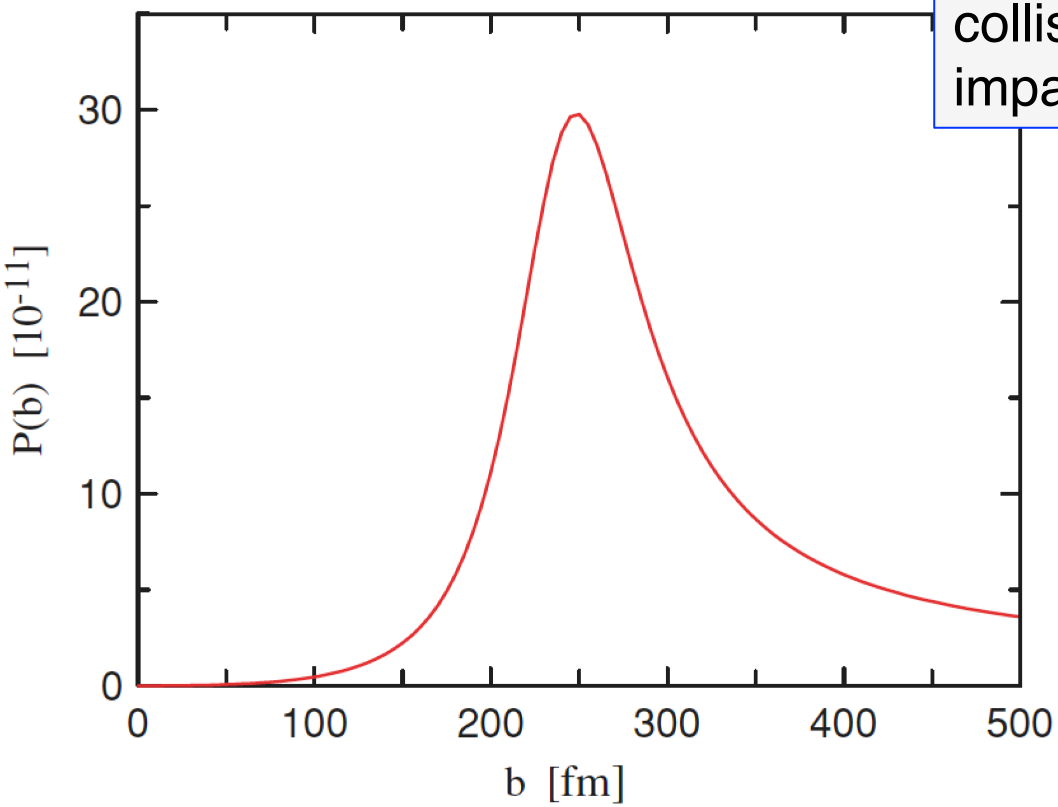


1996

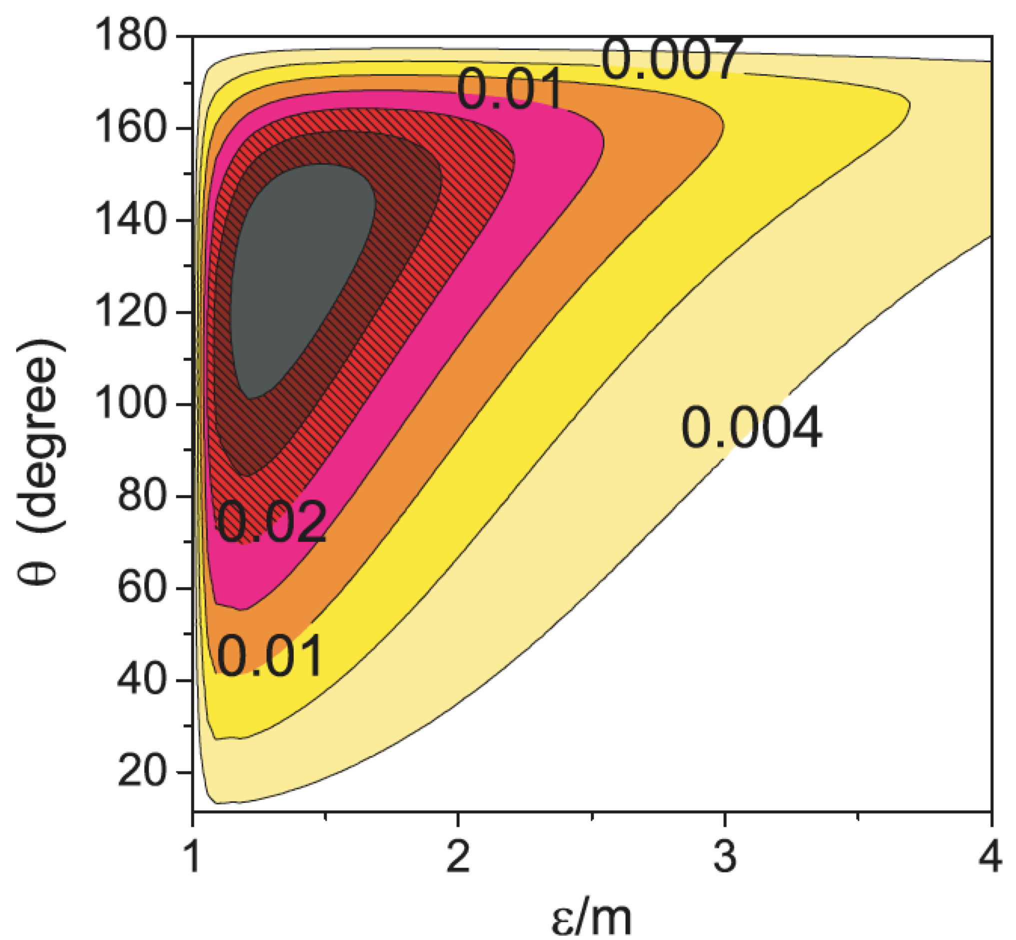
Virtual photons, antiatoms, and the public

Production of Exotic Atoms

Bertulani, Ellermann, PRC 81, 044910 (2010)



Probability of muonic atom production in pp collisions at the LHC as a function of the impact parameter.



Angular distribution of the positive muon when the negative muon is captured by a proton at the LHC, as a function of the angle that the free muon has with the direction of motion of the muonic atom.

Production of Exotic Atoms

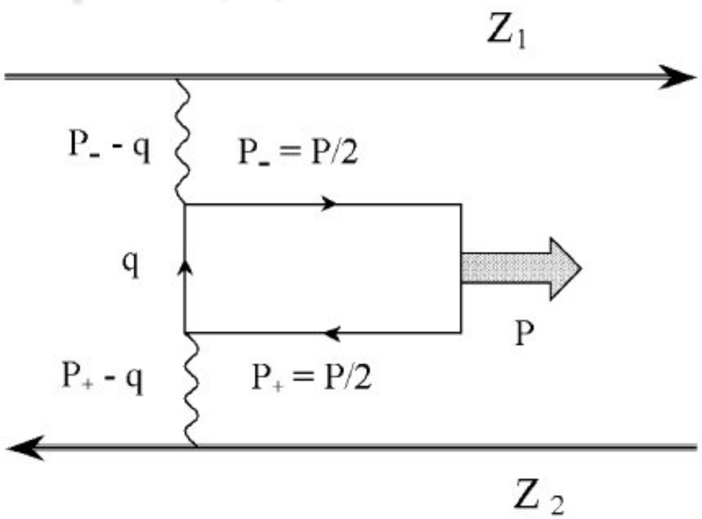
Bertulani, Ellermann, PRC 81, 044910 (2010)

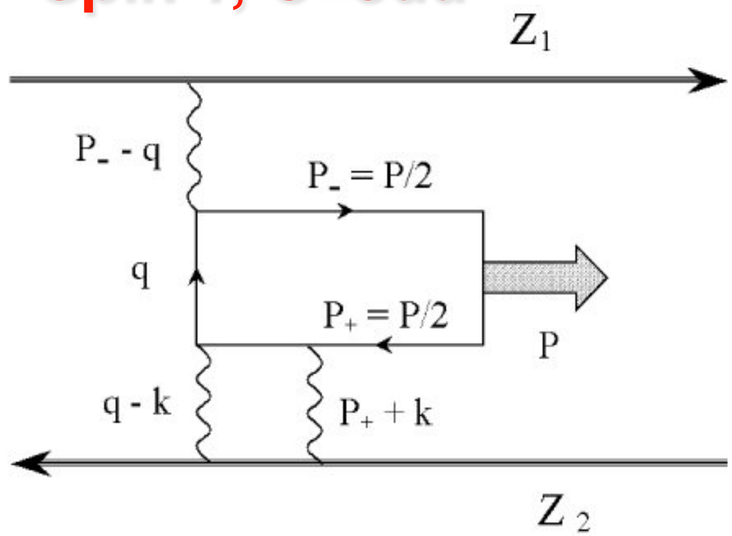
"Exotic" atom	pp	PbPb
Hydrogen	63.4	132 b
muonic	44.8×10^{-4}	0.16 mb
pionic	21.3×10^{-4}	0.09 mb
kaonic	1.3×10^{-4}	4.3 μb
ρ atom	0.51×10^{-4}	1.3 μb
protonium	0.09×10^{-4}	0.5 μb

Cross sections for production of exotic atoms in pp and PbPb collisions at the CERN Large Hadron Collider (LHC).

QFT with Bound states

Spin 0,2, C=even | **Spin 1, C=odd**





$$\mathcal{M} = -ie^2\bar{u}\left(\frac{P}{2}\right)\left[\int \frac{d^4q}{(2\pi)^4}\, \not{A}^{(1)}\left(\frac{P}{2}-q\right)\frac{\not{q}+m}{q^2-m^2} \times \not{A}^{(2)}\left(\frac{P}{2}+q\right) + \not{A}^{(1)}\left(\frac{P}{2}+q\right)\frac{\not{q}+m}{q^2-m^2}\,\not{A}^{(2)}\left(\frac{P}{2}-q\right)\right] v\left(\frac{P}{2}\right)$$

Bodwin, Yennie, Gregorio,
Rev. Mod. Phys. 57, 723 (1985)

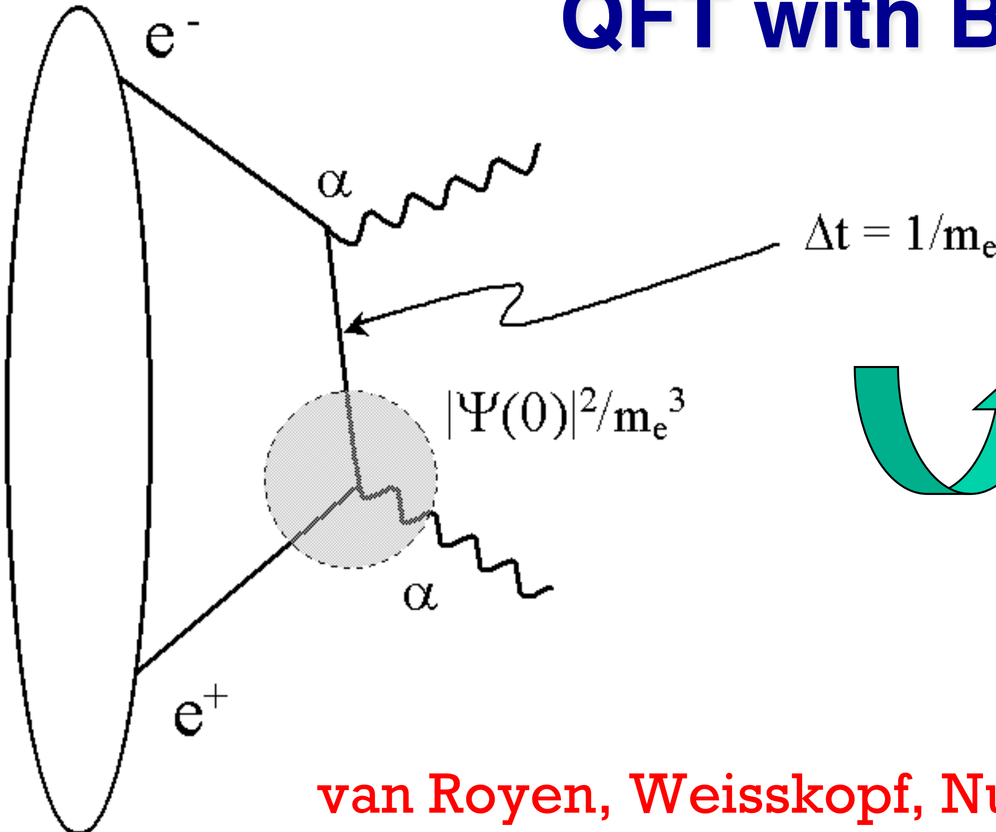
Bertulani, Navarra, NPA703 (2002) 861

Spin 0 $\quad \bar{u}Bv \longrightarrow \sqrt{2M}\ \mathrm{tr}\left(\frac{B}{\sqrt{2}}\right)\Psi(0)$

Spin 1 $\quad \bar{u}Bv \longrightarrow \sqrt{2M}\ \mathrm{tr}\left(\frac{\hat{\epsilon}.\boldsymbol{\sigma}}{\sqrt{2}}B\right)\Psi(0)$

Example: parapositronium (S = 0) and orthopositronium (S = 1)

QFT with Bound states



$$\Gamma \sim \alpha^2 |\Psi(0)|^2 / m_e^2$$

RECIPE for mesons:

- replace electrons by quarks
- get rid of $|\psi(0)|^2$

van Royen, Weisskopf, Nuovo Cim. A 50, 617 (1967)
Appelquist, Politzer, PRL 34, 365 (1975)

$$\Gamma_{\gamma\gamma}^{J=0} = \frac{48\pi\alpha^2}{M^2} |\Psi(0)|^2 \sum_i Q_i^4 \qquad \Gamma_{\gamma\gamma}^{(J=2)} = (2J+1)\Gamma_{\gamma\gamma}^{(J=0)} = 5\ \Gamma_{\gamma\gamma}^{(J=0)}.$$

Example: parapositronium (S = 0) at LHC (PbPb)

$$|\Psi(0)|^2 = (m_e\alpha)^3 / 8\pi n^3 \quad \longrightarrow \quad \sigma = 325\ \text{mb}$$

Study of positronium propagation in thin metals:
QFT for bound states

QFT with bound states

$$\sigma_X = \int d\omega_1\, d\omega_2\; n_\gamma(\omega_1)\, n_\gamma(\omega_2)\, \sigma_{\gamma\gamma}^X(\omega_1\omega_2 s)$$

$$n(\omega,b) = \frac{2Z^2\alpha\omega^2}{\pi\gamma^2}\int_0^\infty db\, b\left[K_1^2(\xi)+\frac{1}{\gamma^2}K_0^2(\xi)\right]\exp\left\{-\sigma_{NN}\int_{-\infty}^\infty dz'\int d^3r\,\rho(\mathbf{r})\rho(\mathbf{r'}-\mathbf{r})\right\}$$

$$\xi = \frac{\omega b}{\gamma_c}$$

No need for minimum impact parameter

$$\frac{dn}{d\omega} = 2\pi\int db\, b\int_0^R dr\, r\int_0^{2\pi} d\phi\,\frac{d^3n(\omega, b + r\cos\phi)}{d\omega d^2b}$$

Baur, Baron, NPA 561, 628 (1993)

For meson production at CERN use above in conjunction with

Low, Phys. Rev. 120, 582 (1960)

$$\sigma_{\gamma\gamma}^X(x_1x_2s) = 8\pi^2(2J+1)\frac{\Gamma_{m_X\to\gamma\gamma}}{m_X}\delta\left(x_1x_2s - m_X^2\right)$$

Testing widths of various mesons at LHC

Bertulani, PRC 79, 047901 (2009)

	J^{PC}	$\Gamma_{\gamma\gamma}^{th}$ (keV)	$\Gamma_{\gamma\gamma}^{exp}$ (keV)	Cross section (mb)
π_0	(0^{-+})	$3.4 – 6.4 \times 10^{-3}$	$8.4 \pm 0.6 \times 10^{-3}$	27 – 52
π (1300)	(0^{-+})	0.43 – 0.49	unknown	0.69 – 0.71
π (1880)		0.74 – 1.0	unknown	0.8 - 1.1
π_2 (1670)	(2^{-+})	0.11 – 0.27	< 0.072	0.41 – 1.1
π_2 (2130)	(2^{-+})	0.10 – 0.16	unknown	0.36 – 0.54
π_2 (2330)		0.21 – 1.6	unknown	0.04 – 0.31

→ Needs a dedicated experimental collaboration

Testing widths of various mesons at LHC

Bertulani, PRC 79, 047901 (2009)

Mesons	J^{PC}	$\Gamma^{th}_{\gamma\gamma}$ (keV)	$\Gamma^{exp}_{\gamma\gamma}$ (keV)	Obs.	$\sigma^{X}_{\gamma\gamma}$
$a_0^{K\bar{K}}$ (980)	(0^{++})	0.6	0.30 ± 0.10	$\longrightarrow K\bar{K} \longrightarrow \gamma\bar{\gamma}$	3.1mb
$a_0^{q\bar{q}}$ (980)		1.5		Hypothetical, NR q-model	8.6 mb
$a_0^{q\bar{q}}$ (980)		1.0		Hypothetical, R q-model	5.5 mb
$f_0^{K\bar{K}}$ (980)	(0^{++})	0.6	$0.29^{+0.07}_{-0.09}$	$\longrightarrow K\bar{K} \longrightarrow \gamma\bar{\gamma}$	3.1 mb
$f_0^{q\bar{q}}$ (980)		4.5		Hypothetical, NR q-model	25.8 mb
$f_0^{q\bar{q}}$ (980)		2.5		Hypothetical, R q-model	14.3 mb
f_0 (1200)		3.25–6.46	Unknown	For $m_q = 0.33$ to 0.22 GeV	9.6–21 mb
f_2(1274)	(2^{++})	1.75–4.04	2.6 ± 0.24	$\Gamma_{\gamma\gamma}(f_0) / \Gamma_{\gamma\gamma}(f_2) = 1.86$–1.60	21–49 mb
$f_2^{\lambda=2}$ (1274)		1.71–3.93		$(\lambda = 0) / (\lambda = 2) = 0.022$–0.029	20–44 mb
$f_2^{\lambda=0}$ (1274)		0.04–0.11			0.09–0.23 mb
f_0 (1800)		2.16–2.52	Unknown	2^3P_0 radial excitation	2.5–3.1 mb
f_2 (1800) $(\lambda = 2)$		1.53–2.44		2^3P_2 radial excitation	1.7–2.9 mb
f_2 (1800) $(\lambda = 0)$		0.08–0.16		"	0.08–14 mb
f_2 (1525)	(2^{++})	0.17	0.081 ± 0.009	$s\bar{s}$, $m_s = 0.55$ GeV fixed	0.86 mb
f_2' (1525) $(\lambda = 0)$		0.065		"	0.21 mb
f_2' (1525) $(\lambda = 2)$		0.9×10^{-3}		"	0.42 μb
f_4 (2050)		0.36–1.76	Unknown	$^3F_4$	0.03–0.14 mb
f_4 (2050) $(\lambda = 2)$		0.33–1.56		"	0.02–0.13 mb
f_4 (2050) $(\lambda = 0)$		0.03–0.20		"	2–12 μb
f_3 (2050)		0.50–2.49	Unknown	$^3F_3$	0.03–0.13 mb
f_2 (2050)		2.48–11.11	Unknown	$^3F_2$	0.12–0.53 mb
f_2 (2050) $(\lambda = 2)$		1.85–8.49		"	0.09–0.46 mb
f_2 (2050) $(\lambda = 0)$		0.63–2.62		"	0.01–0.07 mb
$f_0^{K^*K^*}$ ($\simeq$ 1750)		$\simeq$0.05–0.1	Unknown	Vector-vector molecule	0.19 mb

Testing widths of various mesons at CERN

Mesons	J^{PC}	$\Gamma^{th}_{\gamma\gamma}$ (keV)	$\Gamma^{exp}_{\gamma\gamma}$ (keV)	Obs.	$\sigma^{X}_{\gamma\gamma}$
η_c	(0^{-+})	3.4–4.8	$6.7^{+0.9}_{-0.8}$	$m_c = 1.4$–1.6 GeV	0.26–0.34 mb
$\eta_c(3790)$		1.85–8.49	1.3 ± 0.6	$m_c = 1.4$ GeV	0.06–0.1 mb
$\eta'_c(3790)$		3.7	Unknown	$m_c = 1.4$ GeV	0.11 mb
$\eta_c(4060)$		3.3	Unknown		0.09 mb
$\eta^{1D}_{c2}(3840)$		$20. \times 10^{-3}$	Unknown		0.15 μb
$\eta^{2D}_{c2}(4210)$		$35. \times 10^{-3}$	Unknown		0.14 μb
$\eta^{1G}_{c4}(4350)$		0.92×10^{-3}	Unknown		0.08 μb
χ_2	(2^{++})	0.56	0.258 ± 0.019	$(\lambda = 2) / (\lambda = 0) = 0.005$	82 μb
χ_0	(0^{++})	1.56	0.276 ± 0.033	$\Gamma_{\gamma\gamma}(\chi_0) / \Gamma_{\gamma\gamma}(\chi_2) = 2.79$	0.05 mb
χ'_2	(2^{++})	0.64	Unknown		0.09 mb
$h_{c2}(3840)$		20×10^{-3}	Unknown	$^1D_2$	82 μb
$\chi_2(4100)$		30×10^{-3}	Unknown	$^3F_2$	0.11 μb

Mesons	J^{PC}	$\Gamma^{th}_{\gamma\gamma}$ (keV)	$\Gamma^{exp}_{\gamma\gamma}$ (keV)	Obs.	$\sigma^{X}_{\gamma\gamma}$
$\eta^{1S}_b(9400)$		0.17×10^{-3}	Unknown		19 nb
$\eta^{2S}_b(9400)$		0.13×10^{-3}	Unknown		16 nb
$\eta^{3S}_b(9480)$		0.11×10^{-3}	Unknown		14 nb
$\eta^{1D}_{b2}(10150)$		$33. \times 10^{-6}$	Unknown		0.4 nb
$\eta^{2D}_{b2}(10450)$		$69. \times 10^{-6}$	Unknown		0.8 nb
$\eta^{1G}_{b4}(10150)$		$59. \times 10^{-6}$	Unknown		0.7 nb
$\eta_b(9366)$	(0^{-+})	0.17	Unknown		0.12 μb
η'_b		0.13	Unknown		0.17 μb
η''_b		0.11	Unknown	$s\bar{s}$, $m_s = 0.55$ GeV fixed	0.15 μb
$\chi_{b2}(9913)$	(2^{++})	3.7×10^{-3}	Unknown		0.09 μb
$\chi_{b0}(9860)$	(0^{++})	$13. \times 10^{-3}$	Unknown		0.08 μb

Parton Distribution Functions (PDFs)

- HERA: $W_{\gamma p} \sim 200\ \text{GeV}$ LHC: $W_{\gamma p} \sim 1\ \text{TeV}$

Gonçalves, Bertulani, PRC 65, 054905 (2002)

$$\sigma_{\gamma g \to q\bar{q}}(s) = \int_{2m_c}^{\sqrt{s}} dM_{q\bar{q}} \frac{d\sigma_{\gamma g \to q\bar{q}}}{dM_{q\bar{q}}} G_N\left(x, \sqrt{M_{q\bar{q}}}\right)$$

For heavy quarks the photoproduction can be described using perturbative QCD,

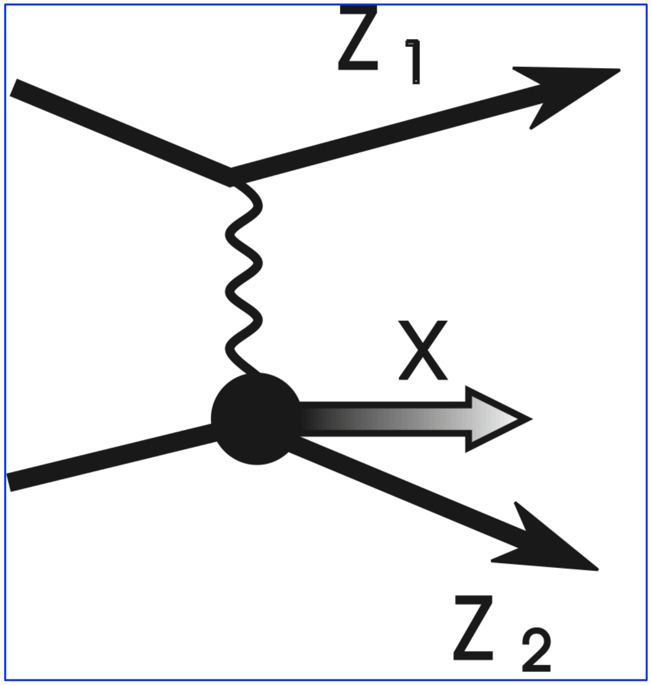
$$\frac{d\sigma_{\gamma g \to q\bar{q}}}{dM_{q\bar{q}}} = \frac{4\pi\alpha\alpha_s e_c^2}{M_{q\bar{q}}^2}\left[\left(1+\varepsilon-\frac{1}{2}\varepsilon^2\right)\ln\left(\frac{1+\sqrt{1-\varepsilon}}{1-\sqrt{1-\varepsilon}}\right)-(1+\varepsilon)\sqrt{1-\varepsilon}\right]$$

Glueck, Reya, Phys. Lett. 79, 453 (1978)

$$\varepsilon = \frac{4m_q^2}{M_{q\bar{q}}^2}$$

Parton Distribution Functions (PDFs)

$$\sigma\left(AA \rightarrow XXq\bar{q}\right) = \int \frac{d\omega}{\omega} n\left(\omega\right) \otimes \sigma_{\gamma g \rightarrow q\bar{q}} \otimes xG_A\left(x, Q^2\right)$$



$$\gamma_c = 2\gamma_{lab}^2 - 1$$

Bjorken $\quad x = \frac{M}{2p} e^{-y} << 1$

No medium corrections

$$xG_A\left(x, Q^2\right) = A \otimes xG_N\left(x, Q^2\right)$$

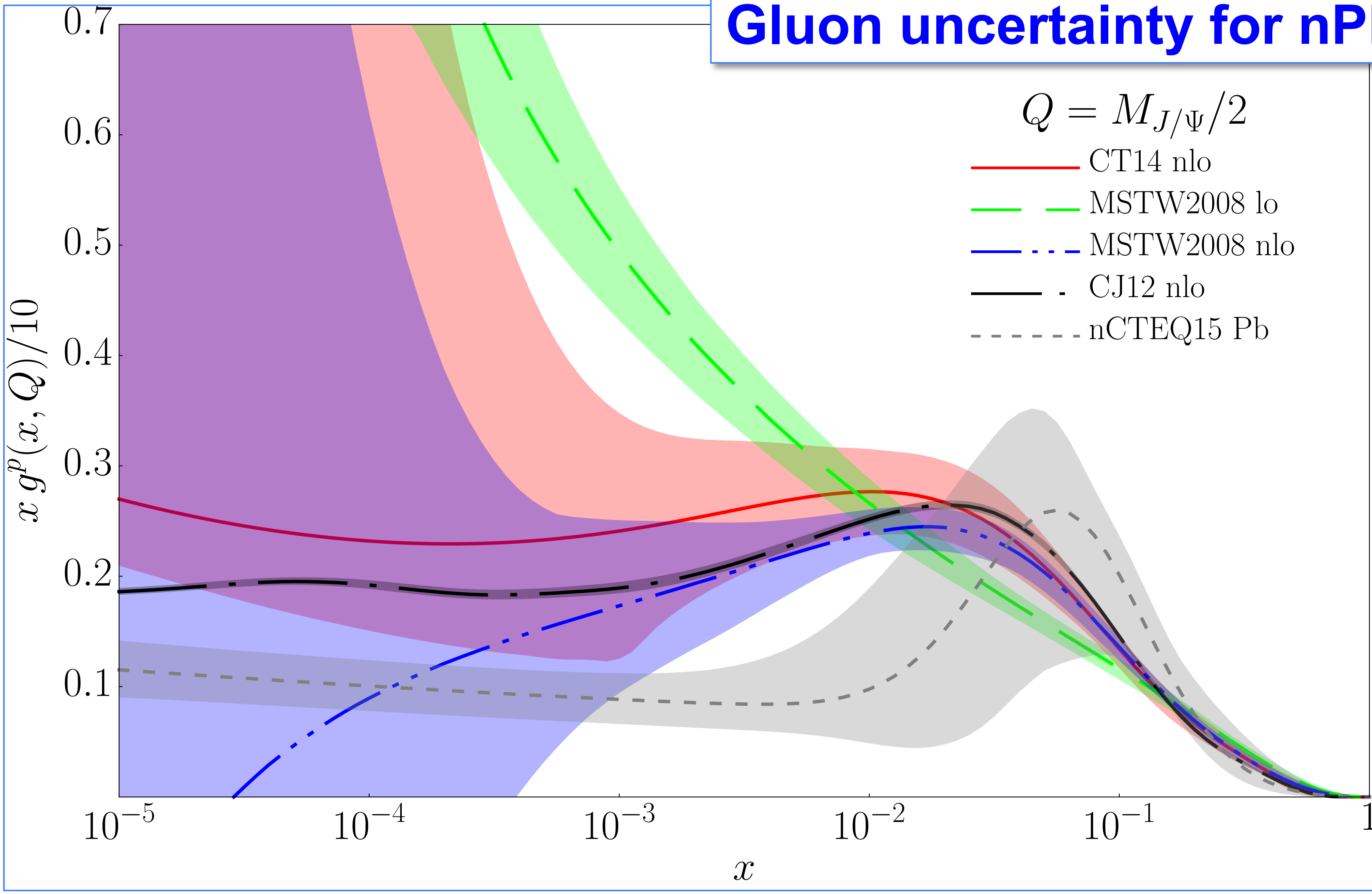
medium corrections

$$xG_A\left(x, Q^2\right) = R_G \otimes xG_N\left(x, Q^2\right)$$

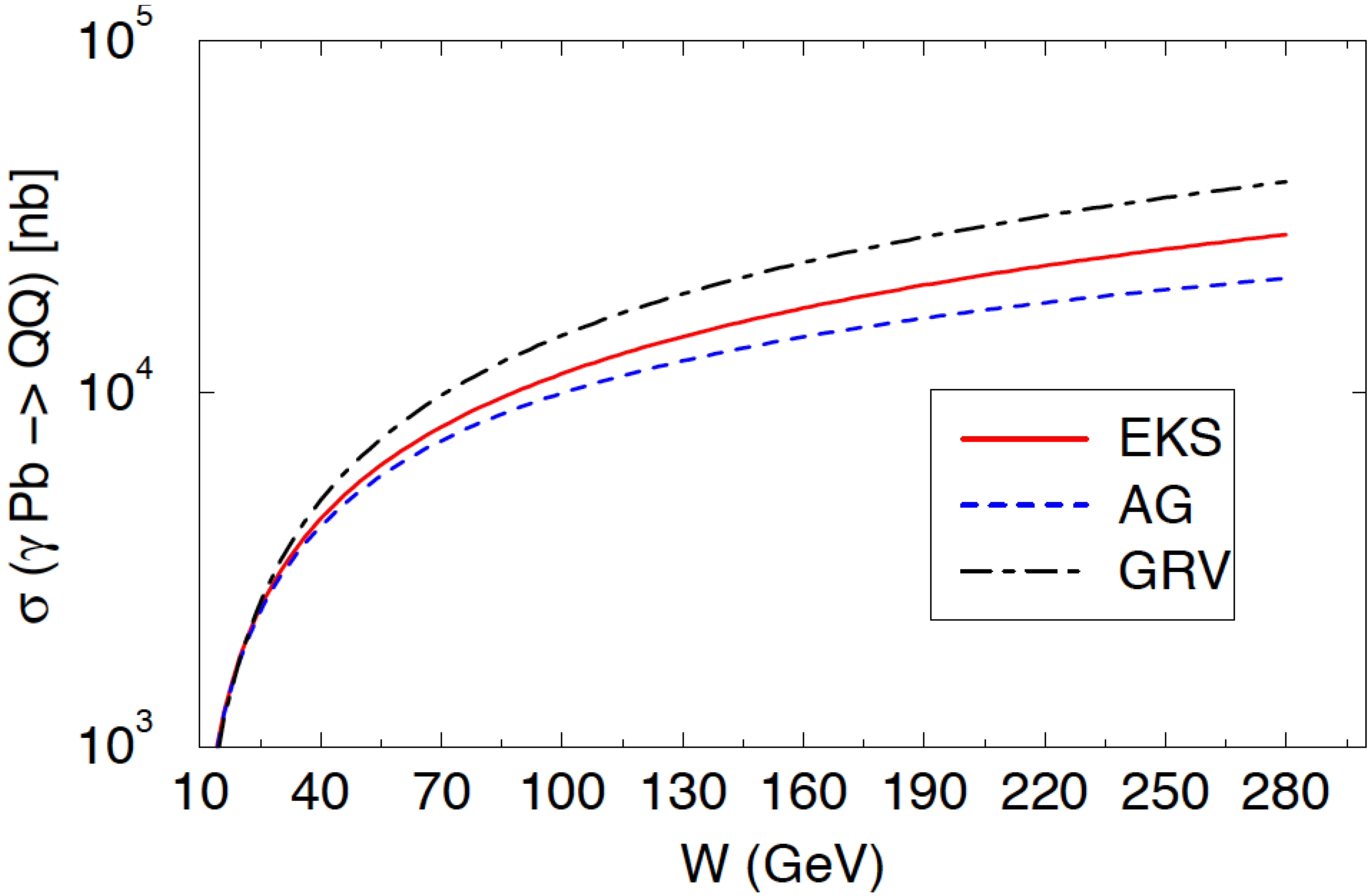
Uncertainties in PDFs

Thomas, Bertulani, Brady, Clark, Godat, Olness. ArXiv:1603.01919

Gluon uncertainty for nPDF



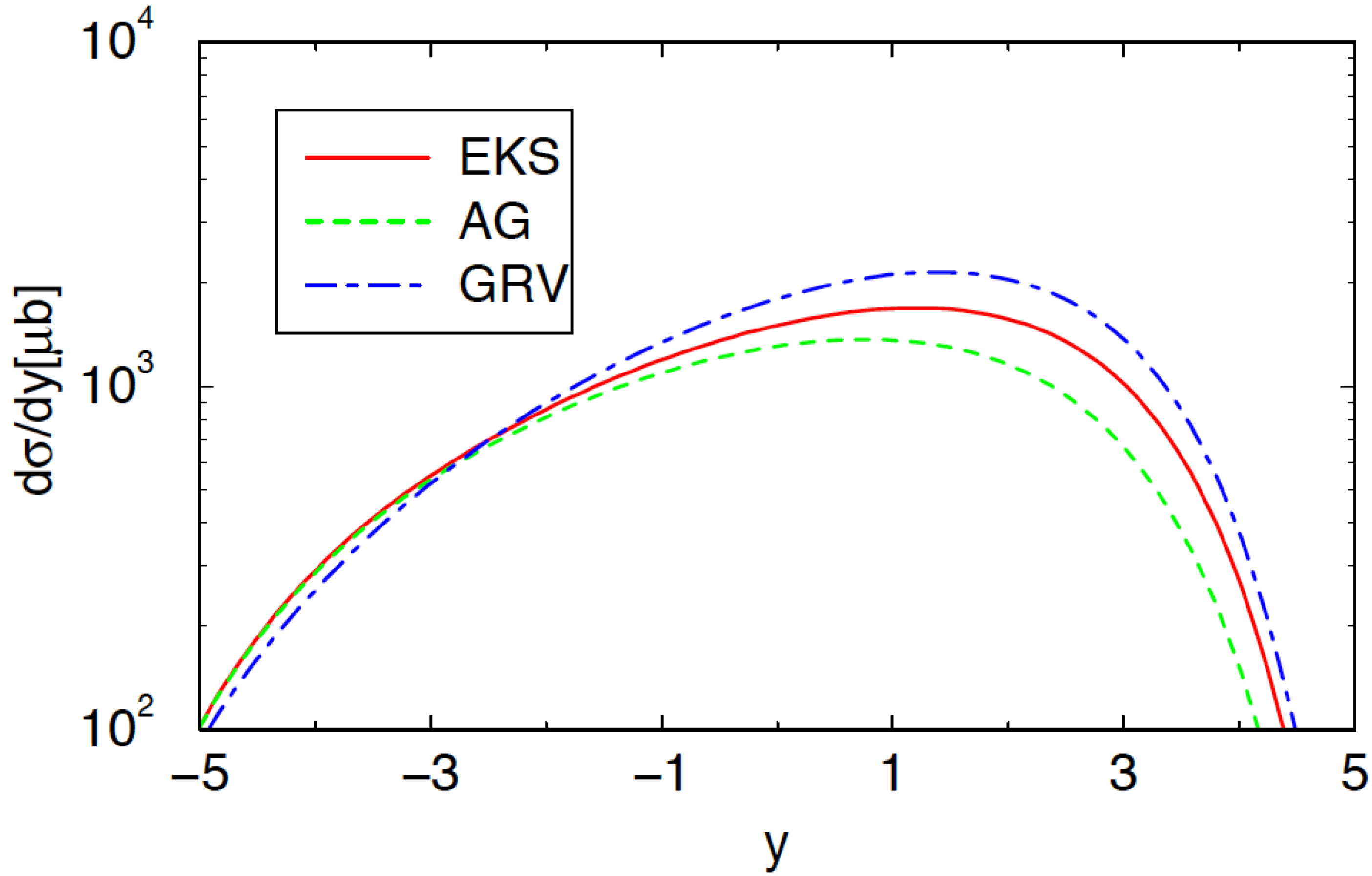
Parton Distribution Functions (PDFs)



Energy dependence of the photoproduction of heavy quarks for distinct nuclear gluon distributions (A = 208).

- EKS = Eskola, Kolhinen, Salgado, EPJ. C9, 61 (1999)
- AG = Ayala, Gonçalves, EPJ. C 20, 343 (2001)
- GRV = Glück, Reya, Vogt, Z. Phys. C67, 433 (1995)

Parton Distribution Functions at LHC

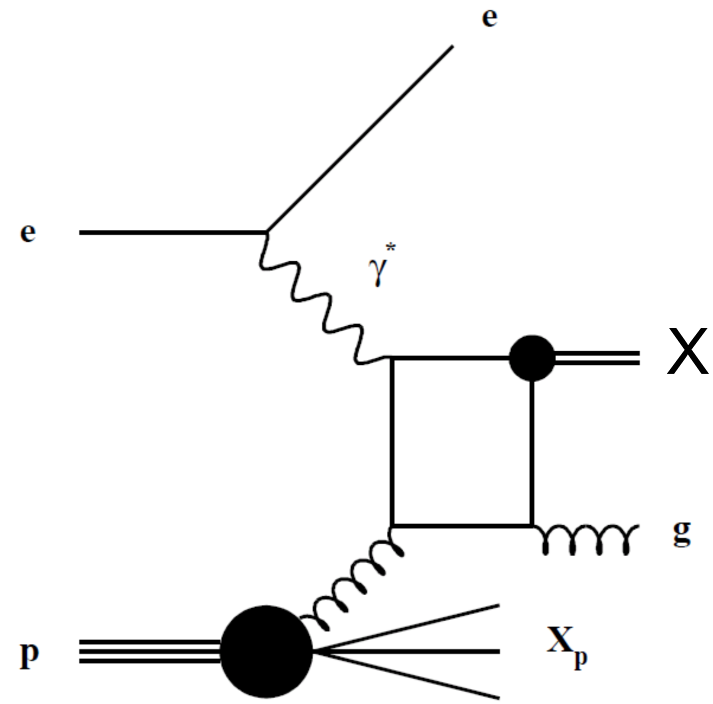


Rapidity distribution for the photoproduction of charm quarks in ^{208}Pb + ^{208}Pb collisions at the LHC.

- EKS = Eskola, Kolhinen, Salgado, EPJ. C9, 61 (1999)
- AG = Ayala, Gonçalves, EPJ. C 20, 343 (2001)
- GRV = Glück, Reya, Vogt, Z. Phys. C67, 433 (1995)

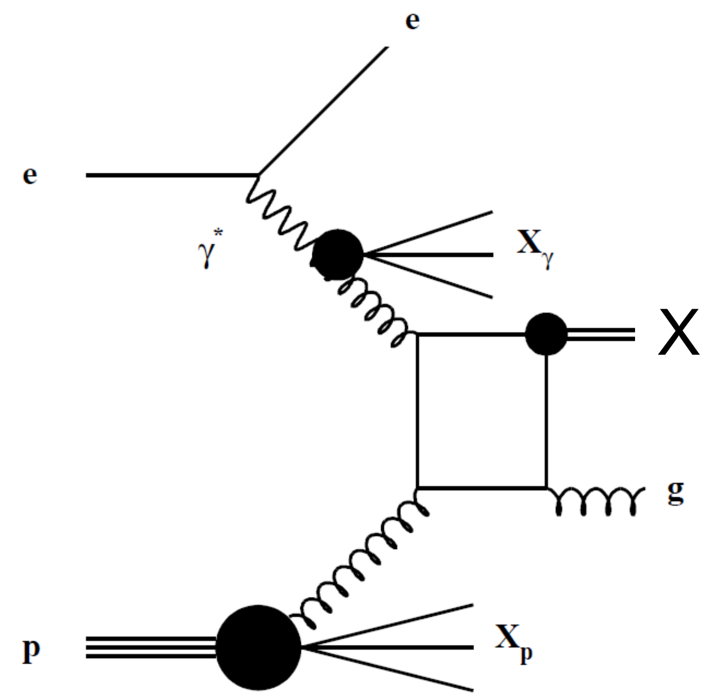
Resolved Photons

$$\sigma\left(AA \to XXq\bar{q}\right) = \int \frac{d\omega}{\omega} n(\omega) \otimes x_\gamma G_\gamma\left(x_\gamma, Q^2\right) \otimes \sigma_{gg\to q\bar{q}} \otimes xG_A\left(x, Q^2\right)$$

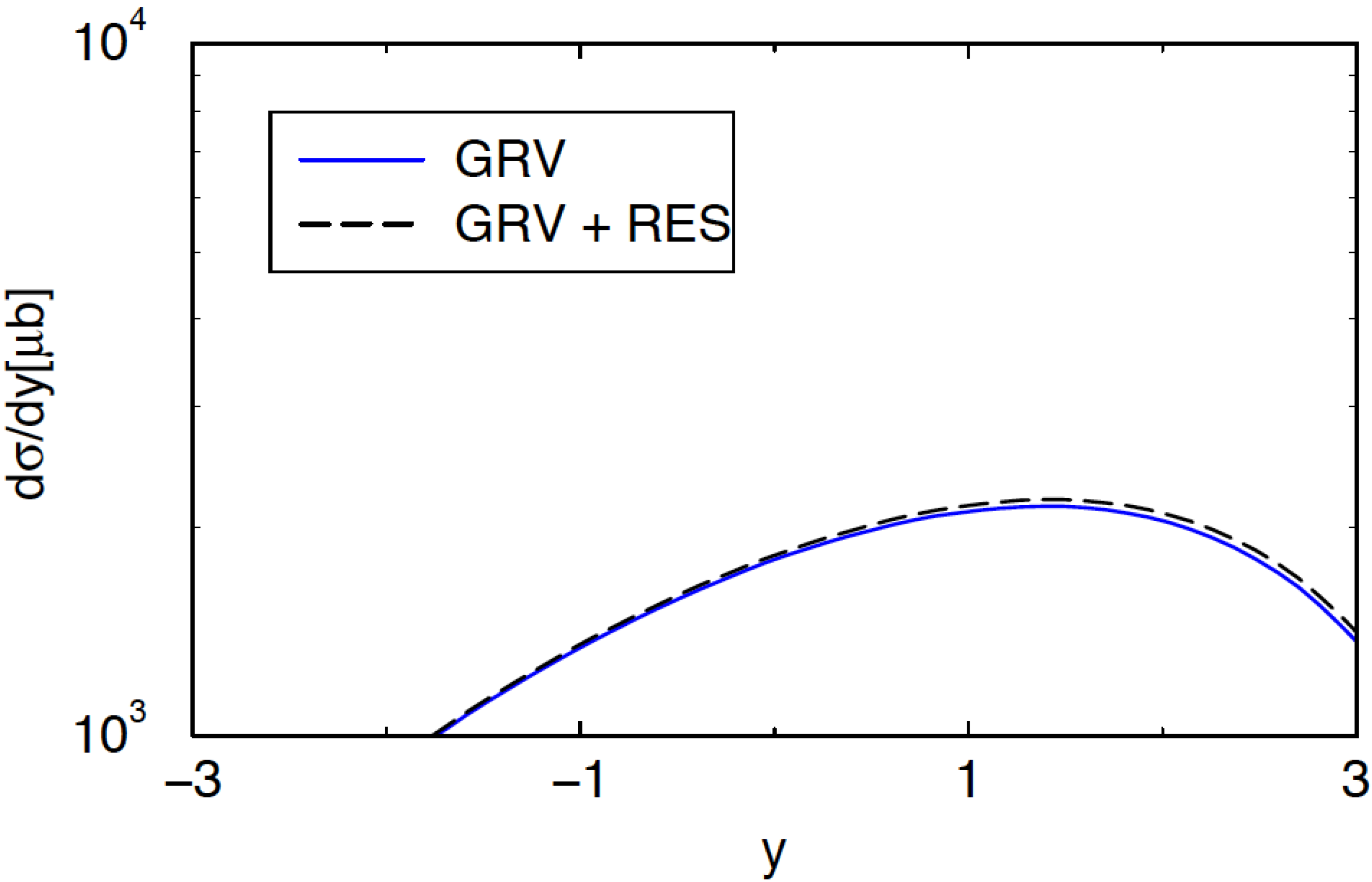


Glück, Owens, Reya, PRD 17, 2324 (1978)

$$\sigma_{gg\to q\bar{q}}(\hat{s}) = \frac{\pi\alpha_s^2\left(Q^2\right)}{3\hat{s}}\left[\left(1+\varepsilon+\frac{\varepsilon^2}{16}\right)\ln\left(\frac{1+\sqrt{1-\varepsilon}}{1-\sqrt{1-\varepsilon}}\right) - \left(\frac{7}{4}+\frac{31}{16}\varepsilon\right)\sqrt{1-\varepsilon}\right]$$



Resolving resolved photons



Rapidity distribution for the photoproduction of charm quarks in $^{208}Pb + ^{208}Pb$ collisions at LHC with (GRV+RES) and without (GRV) the inclusion of the resolved contribution.

J/ψ production at the LHC

color dipole approximation

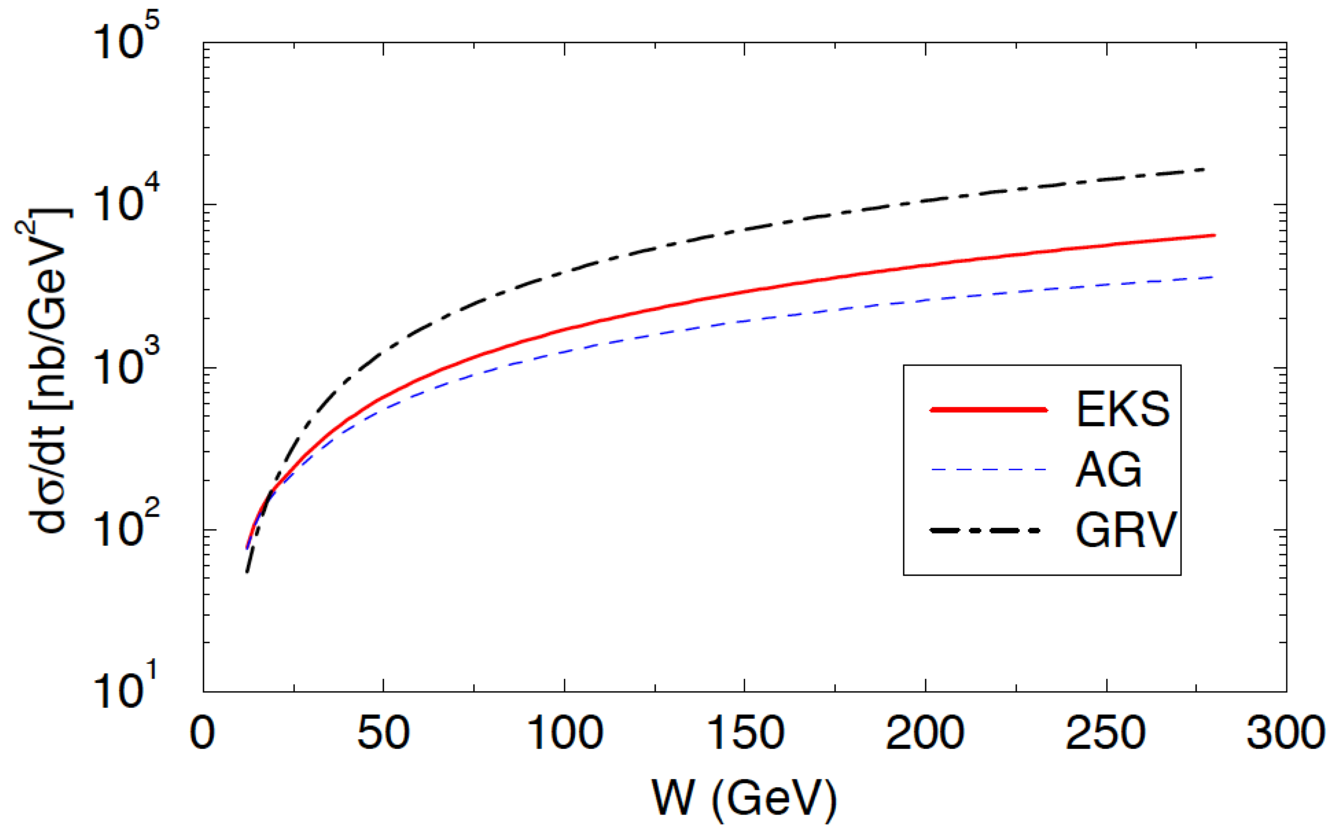
$$\left.\frac{d\sigma(\gamma A \to J/\psi)}{dt}\right|_{t=0} = \frac{\pi^3 \Gamma_{ee} M^3_{J/\psi}}{48\alpha} \frac{\alpha_s^2(\bar{Q}^2)}{\bar{Q}^8}\left[xG_A(x,\bar{Q}^2)\right]^2$$

Stronger dependence on G_A

$$\sigma(AA \to AAJ/\psi) = \int \frac{d\omega}{\omega} n(\omega) \int_{t_{min}}^{\infty} dt \left.\frac{d\sigma(\gamma A \to J/\psi)}{dt}\right|_{t=0} |F(t)|^2$$

$m_{J/\psi} = 3.097$ GeV

Gluon distribution	LHC
GRV	6.6 mb
EKS	2.5 mb
AG	0.9 mb



Energy dependence of the elastic photoproduction of J/ψ for distinct nuclear gluon distributions (A = 208).

Nuclear modification of PDFs

Adeluyi, Bertulani, PRC84, 024916 (2011)

$$\sigma\left(AA \to XXq\bar{q}\right) = \int \frac{dn}{d\omega}\left(\omega\right) \otimes \sigma_{\gamma g \to q\bar{q}} \otimes xG_A\left(x,Q^2\right)$$

$$xG_A\left(x,Q^2\right) = R_G \otimes xG_N\left(x,Q^2\right)$$

$x \leq 0.04, \quad R_G < 1$ shadowing

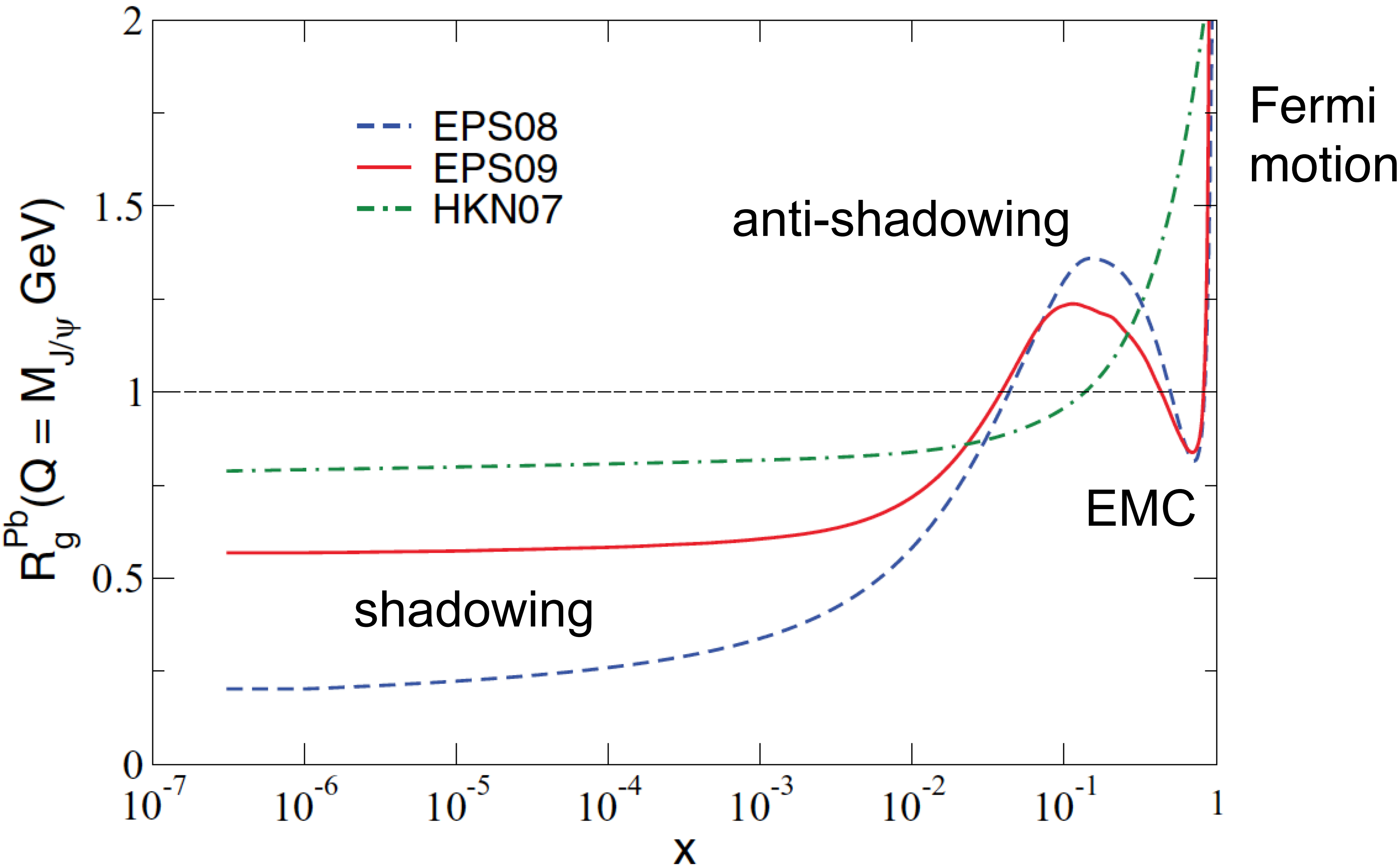
$0.04 \leq x \leq 0.3, \quad R_G > 1$ anti-shadowing

$0.3 \leq x \leq 0.8, \quad R_G < 1$ EMC effect

$x > 0.8, \quad R_G > 1$ Fermi motion

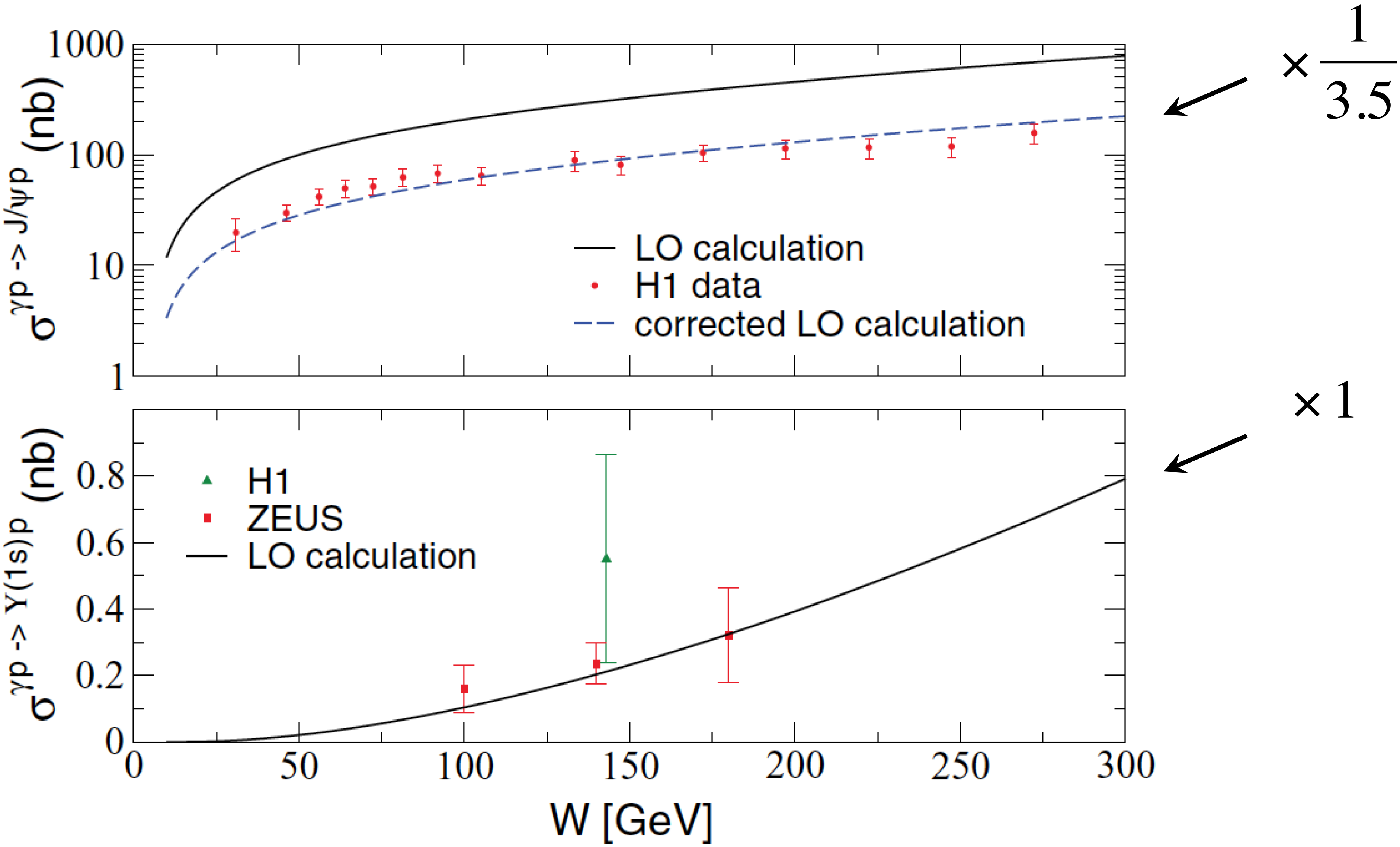
- EPS08 = Eskola, Paukunnen, Salgado, JHEP 07, 102 (2008)
- EPS09 = Eskola, Paukunnen, Salgado, JHEP 04, 065 (2009)
- MSTW08 = Martin, Stirling, Thorne, Watts, EPJ C 63, 189 (2009) ($R_G \sim 1$)
- HKN07 = Hirai, Kumano, Nagai, PRC 76, 065207 (2007)

Nuclear modification of PDFs



- EPS08 = Eskola, Paukunnen, Salgado, JHEP 07, 102 (2008)
- EPS09 = Eskola, Paukunnen, Salgado, JHEP 04, 065 (2009)
- HKN07 = Hirai, Kumano, Nagai, PRC 76, 065207 (2007)

Nuclear modification of PDFs

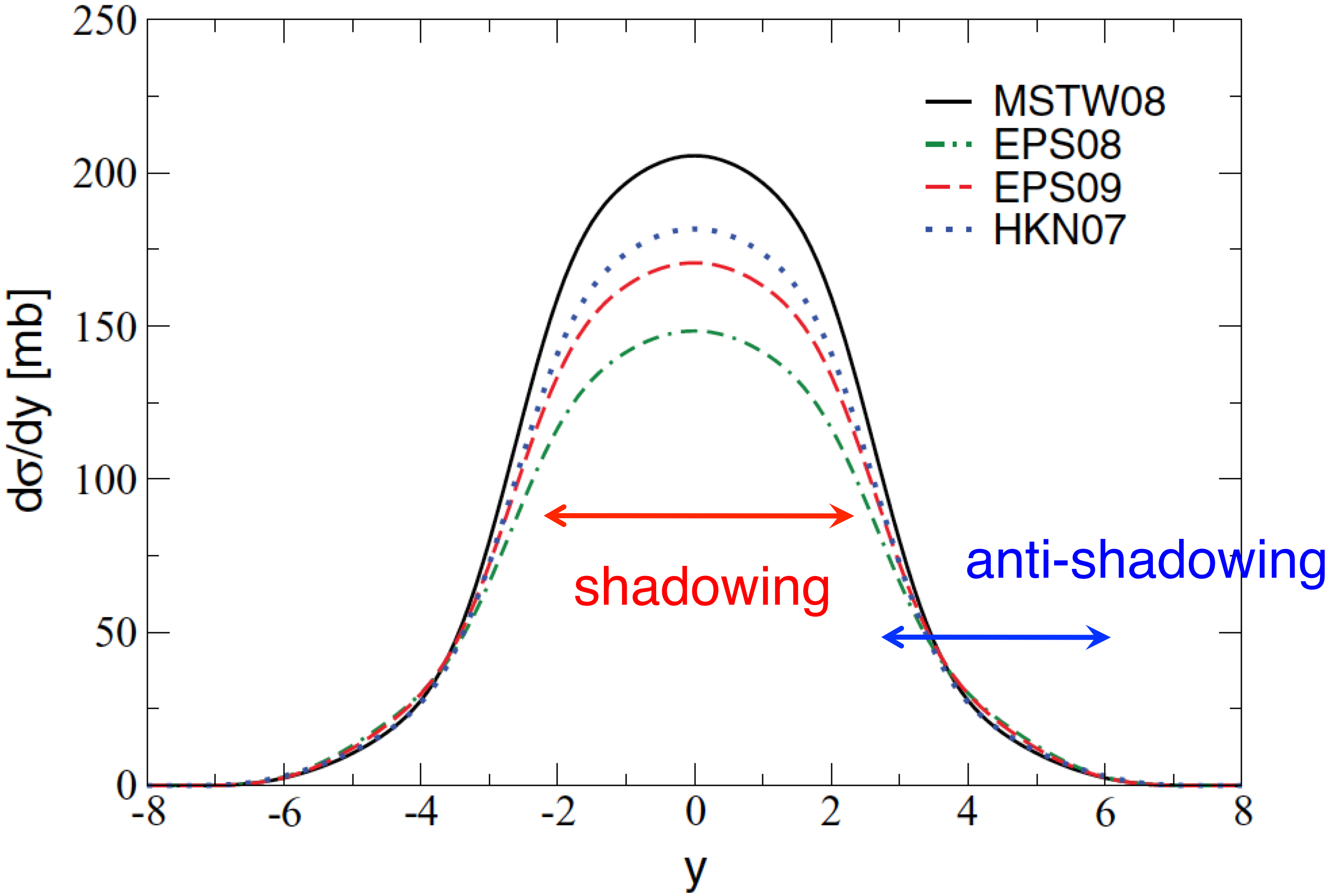


Cross section for photoproduction of J/ψ (ϒ) as a function of energy $W_{\gamma p}$.

$m_{J/\psi}$ = 3.097 GeV

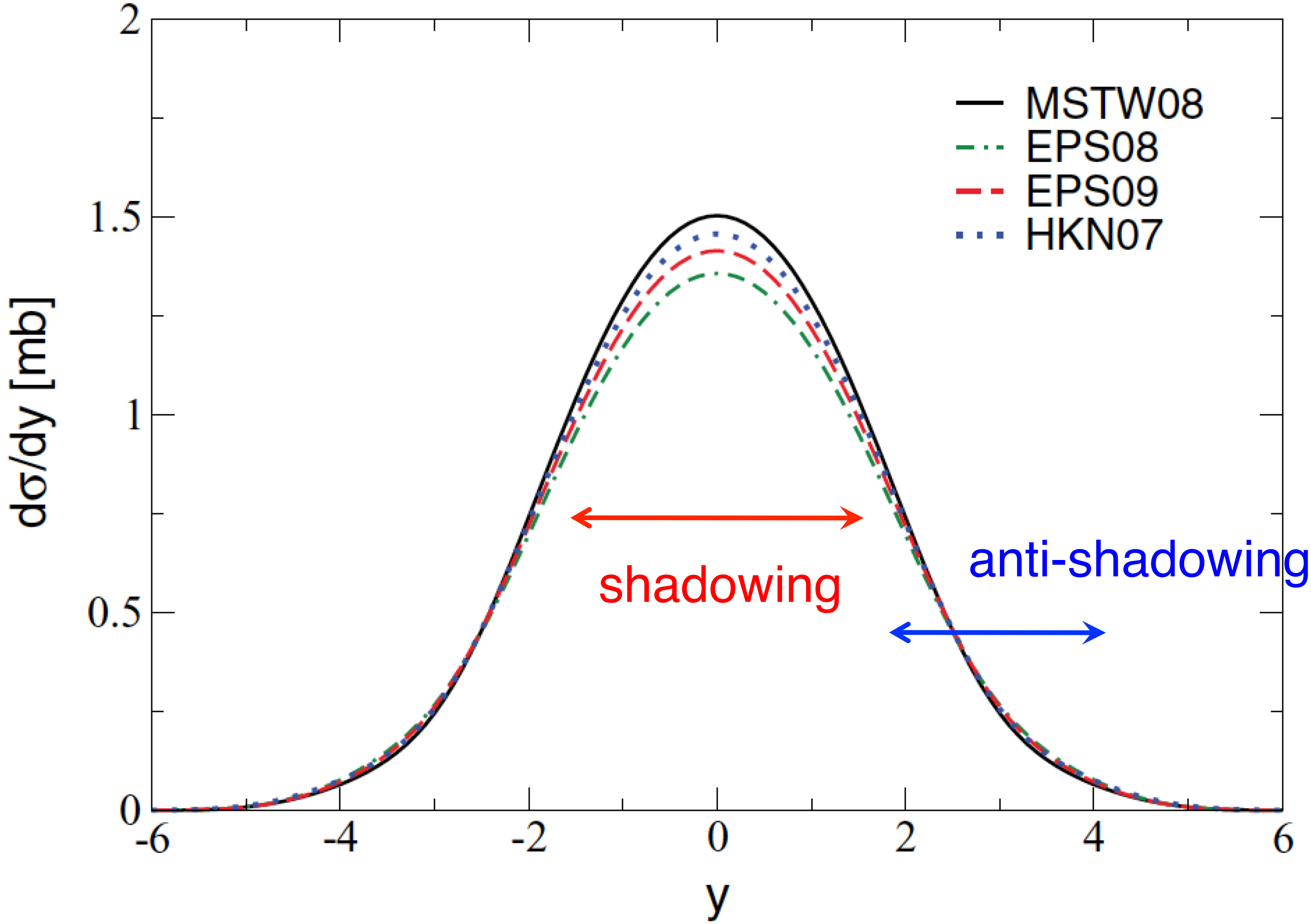
m_{Υ} = 9.46 GeV

Nuclear modification of PDFs in $c\underline{c}$ production



Total rapidity distributions of the photoproduction of $c\underline{c}$ in Pb-Pb collisions at the LHC.

Nuclear modification of PDFs in b$\underline{b}$ production



Total rapidity distributions of the photoproduction of b$\underline{b}$ in Pb-Pb collisions at the LHC.

Nuclear modification of PDFs in qq-bar prod.

Gluon distribution	$Q^2 = s$ (mb)	$Q^2 = 4m_c^2$ (mb)
MST08	1170	1090
EPS08	890	780
EPS09	1000	910
HKN07	1080	1000

Total cross sections for direct photoproduction of $c\underline{c}$ in ultraperipheral Pb-Pb collisions at the LHC.

Gluon distribution	$Q^2 = s$ (mb)	$Q^2 = 4m_b^2$ (mb)
MST08	6.2	7.0
EPS08	5.8	6.2
EPS09	6.0	6.6
HKN07	6.1	6.7

Total cross sections for direct photoproduction of $b\underline{b}$ in ultraperipheral Pb-Pb collisions at the LHC.

Nuclear modification of PDFs at the LHC

Gluon distribution	LO (mb)	Scaled LO (mb)
MST08	260	74
EPS08	36	10
EPS09	101	29
HKN07	173	49

Total cross sections for elastic photoproduction of J/ψ in ultraperipheral Pb-Pb collisions at the LHC.

Gluon distribution	Cross section (μb)
MST08	189
EPS08	99
EPS09	130
HKN07	146

Total cross sections for elastic photoproduction of $\Upsilon(1s)$ in ultraperipheral Pb-Pb collisions at the LHC.

pA versus AA collisions

Adeluyi, Bertulani, PRC85, 044904 (2012)

Adeluyi, Bertulani, Murray, PRC86, 047901 (2012)

$$\frac{dn}{d\omega} = \frac{\alpha}{2\pi\omega}\left[1+\left(1-\frac{2\omega}{\sqrt{s_{NN}}}\right)^2\right]\left(\ln D - \frac{11}{6} + \frac{3}{D} - \frac{3}{2D^2} + \frac{1}{3D^3}\right)$$

Drees, Zeppenfeld, PRD 39, 2536 (1989)

$$D = 1 + \frac{0.71\,\mathrm{GeV}^2}{Q^2_{min}}$$

$$Q^2_{min} = \frac{\omega^2}{\gamma^2\left(1-2\omega/\sqrt{s_{NN}}\right)}$$

$$\sigma^X = \int d\omega\left[\frac{dn^Z_\gamma}{d\omega}\sigma^{\gamma p\to X}(\omega) + \frac{dn^p_\gamma}{d\omega}\sigma^{\gamma A\to X}(\omega)\right]$$

$$\sigma_{q\bar{q}\to Q\bar{Q}}(\hat{s}) = \frac{8\pi\alpha_s^2(Q^2)}{27\hat{s}}\left[\left(1+\frac{\varepsilon}{2}\right)\sqrt{1-\varepsilon}\right]$$

$$\hat{s} = x_1 x_2 s$$

Combridge, Nucl. Phys. B 151, 429 (1979)

Photon PDFs for resolved interactions:

- GRV = Glück, Reya, Vogt, Phys. Rev. D 46, 1973 (1992)
- SaS1d = Schuler, Sjostrand, Z. Phys. C 68, 607 (1995)
- CJK2 = Cornet, Jankowski, Krawczyck, Acta Phys. Pol. B 35, 2215 (2004)

pA versus AA collisions

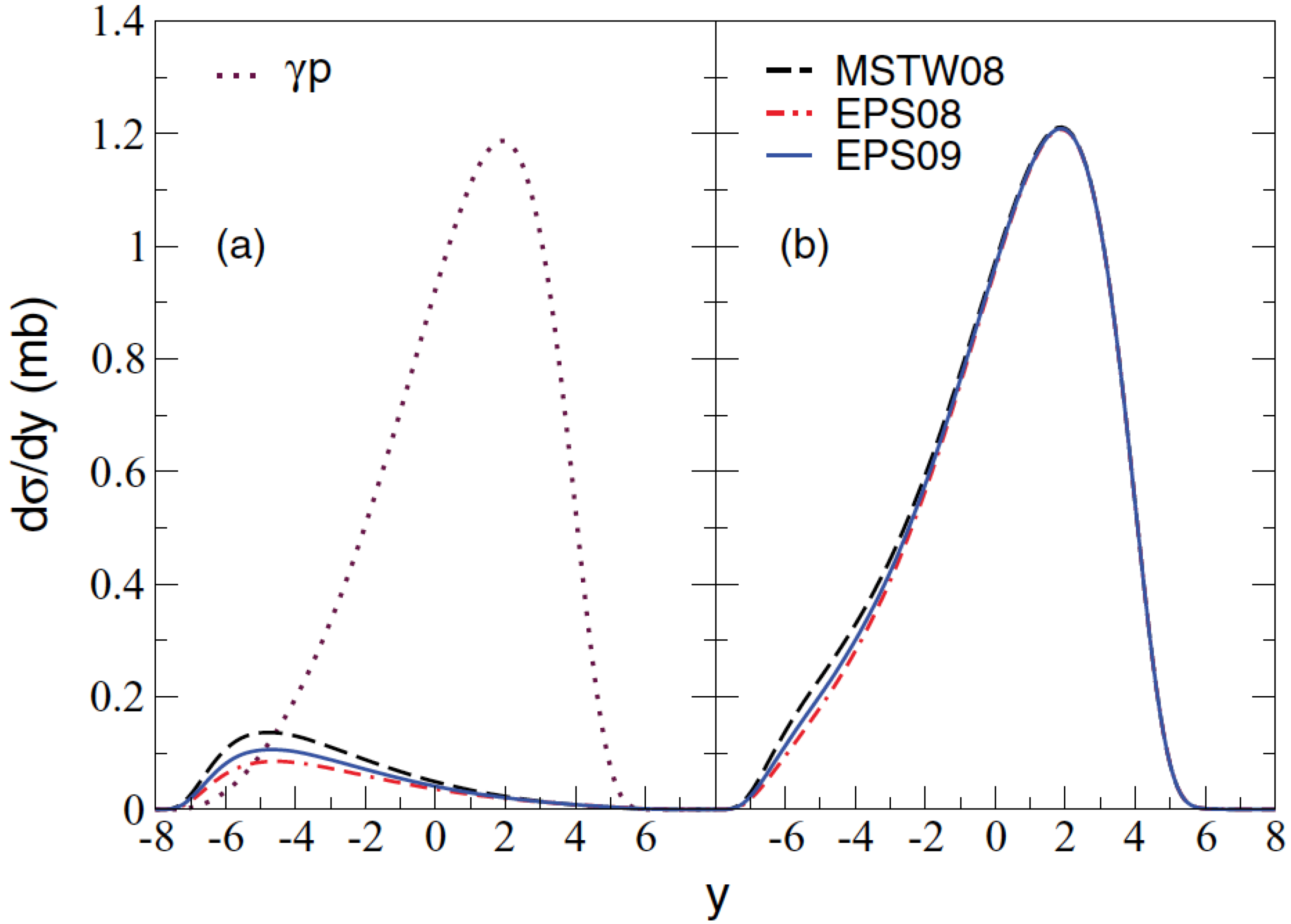
	PDF	direct		Resolved	
			SaS1d	GRV	CJK
γp	MSTW08	5570	692	1157	1418
	MSTW08	607	114	195	228
γA	EPS08	376	95	164	187
	EPS09	471	103	177	204

Cross sections for photoproduction of $c\underline{c}$ in ultraperipheral pPb collisions at the LHC. All cross sections are in **microbarns (μb)**.

PDF	direct		Resolved	
		SaS1d	GRV	CJK
MSTW08	1167	110	180	226
EPS08	890	104	172	213
EPS09	1002	106	176	219

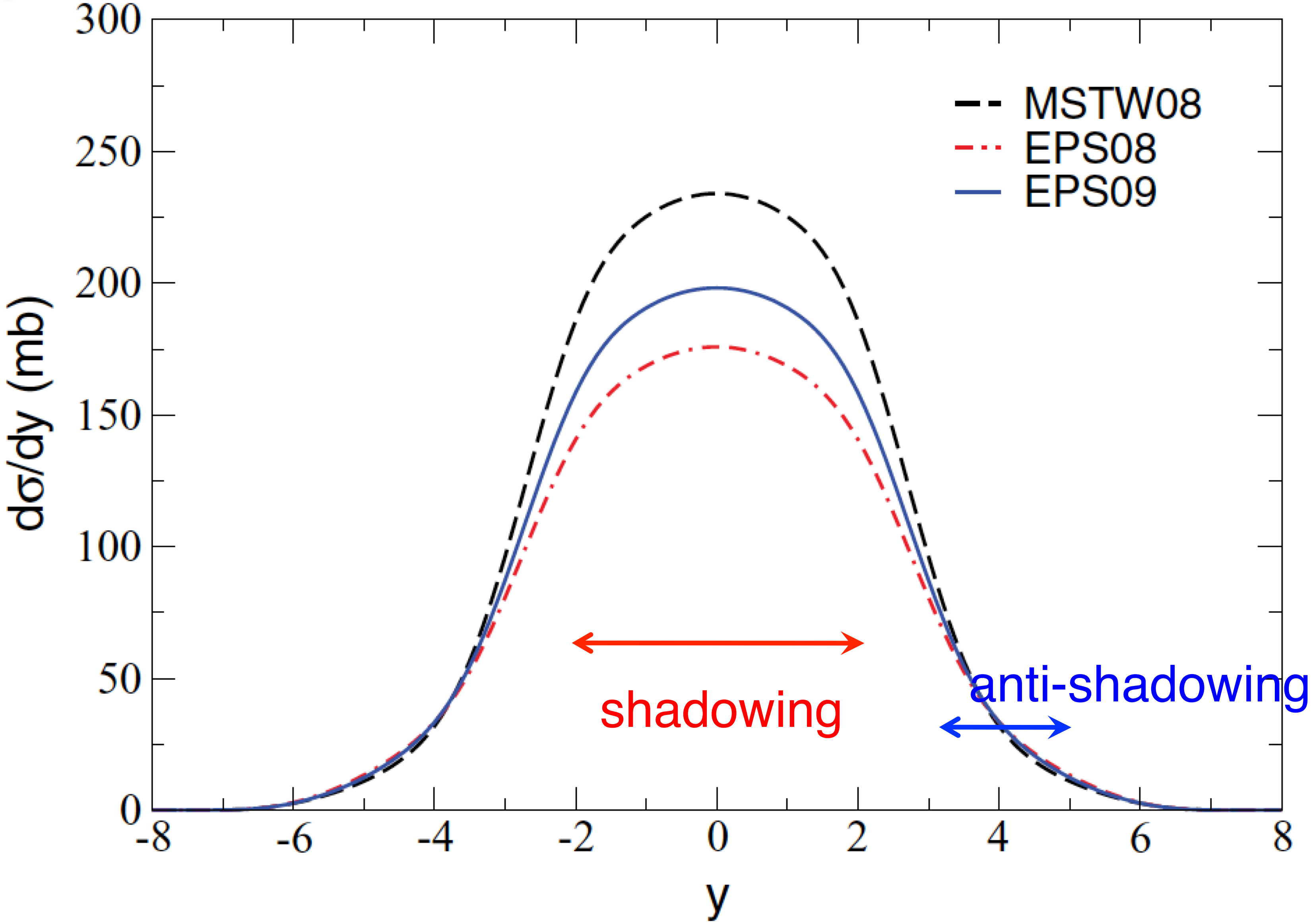
Cross sections for photoproduction of $c\underline{c}$ in ultraperipheral PbPb collisions at the LHC. All cross sections are in **millibarns (mb)**.

pA versus AA collisions



Rapidity distributions of c$\underline{c}$ photoproduction in pPb collisions at the LHC using the GRV photon parton distributions. (a) γp and γPb contributions to total rapidity distributions. Dotted line is the γp contribution, while the dashed (MSTW08), solid (EPS09), and dash-dotted (EPS08) lines correspond to γPb contributions. (b) Total rapidity distributions (sum of γp and γPb contributions).

pA versus AA collisions



Total rapidity distributions of the photoproduction of $c\underline{c}$ in PbPb collisions at the LHC using the GRV photon PDFs. Dashed line uses the MSTW08 gluon distribution. Solid and dash-dotted lines uses nuclear-modified gluon distributions from EPS09 and EPS08.

pA versus AA collisions

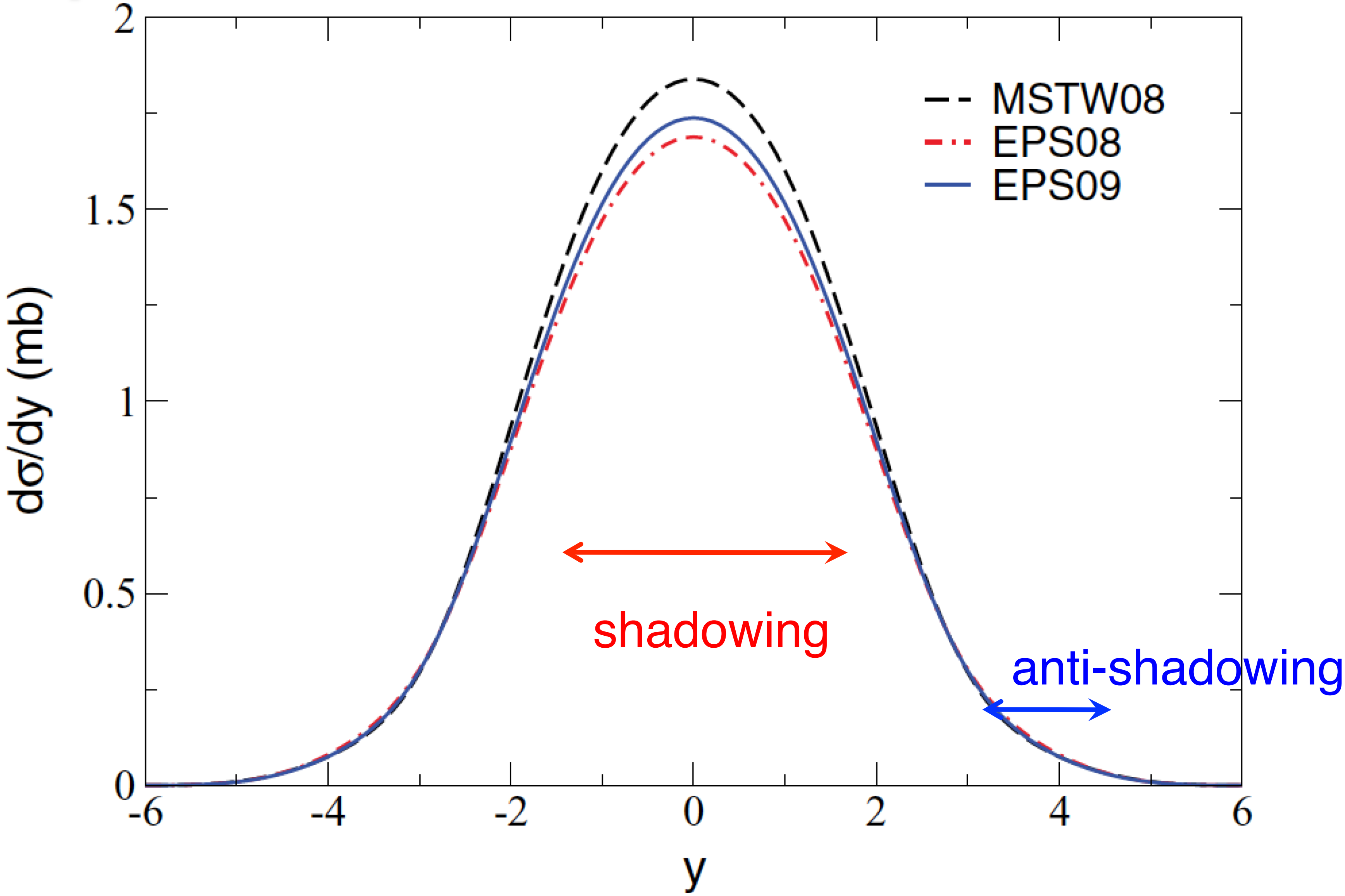
	PDF	direct	Resolved SaS1d	Resolved GRV	Resolved CJK
γp	MSTW08	36512	8641	112178	114977
	MSTW08	5084	2061	3032	3663
γA	EPS08	3972	1936	2872	3451
	EPS09	4409	1988	2942	3543

Cross sections for photoproduction of $b\underline{b}$ in ultraperipheral pPb collisions at the LHC. All cross sections are in **nanobarns (nb)**.

PDF	direct	Resolved SaS1d	Resolved GRV	Resolved CJK
MSTW08	6227	1076	1468	1800
EPS08	5812	1097	1516	1867
EPS09	5992	1085	1496	1842

Cross sections for photoproduction of $b\underline{b}$ in ultraperipheral PbPb collisions at the LHC. All cross sections are in **microbarns (μb)**.

pA versus AA collisions



Total rapidity distributions of b$\underline{b}$ photoproduction in PbPb collisions at the LHC using the GRV photon PDF. Dashed line uses the MSTW08 gluon distribution (no nuclear modifications). Solid and dash-dotted lines uses nuclear-modified distributions from EPS09 and EPS08.

pA versus AA collisions

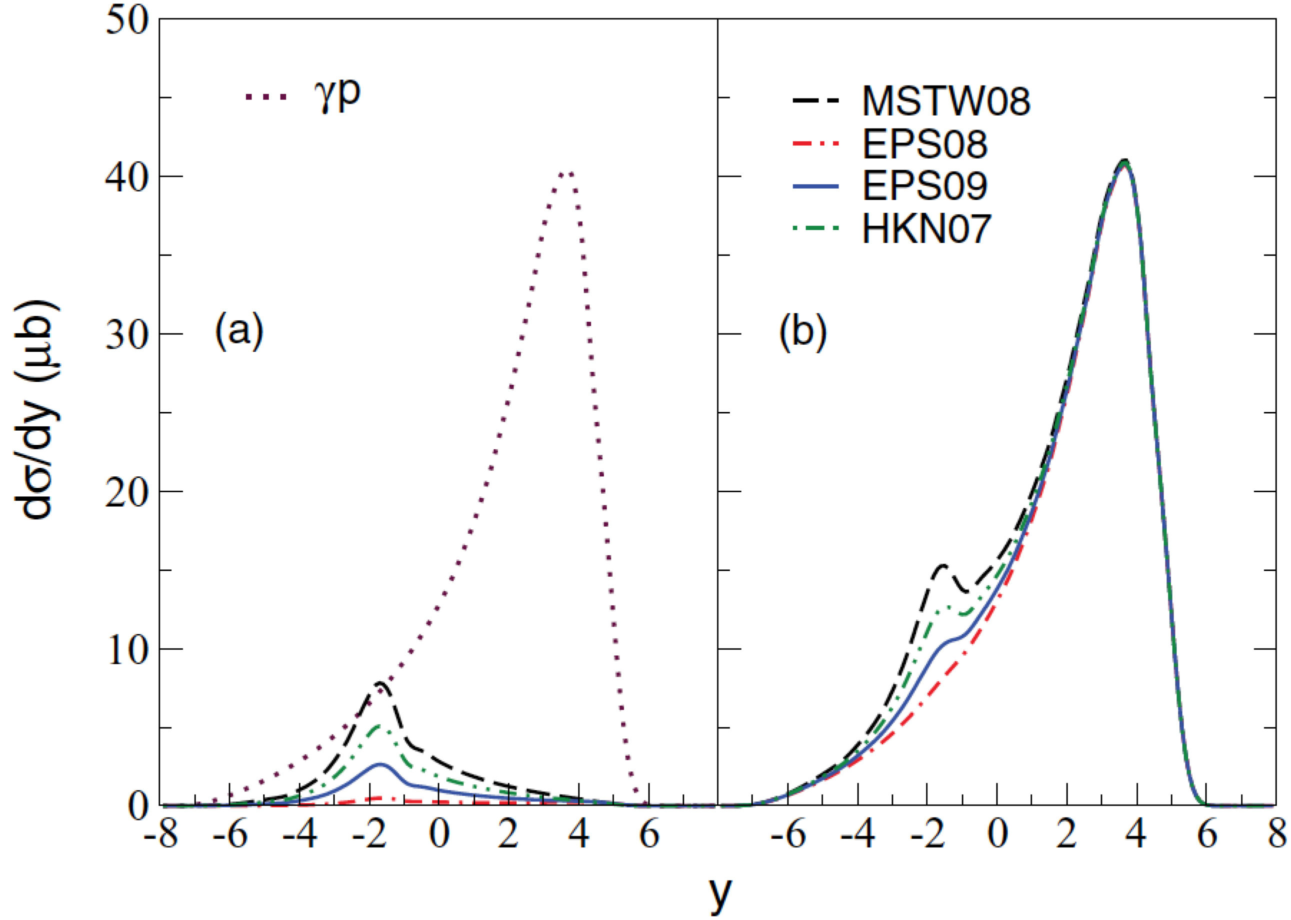
	γp	γA	total
MSTW08	167.3	23.6	190.9
EPS08		2.2	169.5
EPS09		8.5	175.8
HKN07		15.4	182.7

Cross sections **(in μb)** for elastic photoproduction of J/ψ in ultraperipheral pPb collisions at the LHC. Second and third columns are the contributions from γp and γPb. The sums of the two contributions are presented in the fourth column.

	Cross section (μb)
MSTW08	74
EPS08	10
EPS09	29
HKN07	49

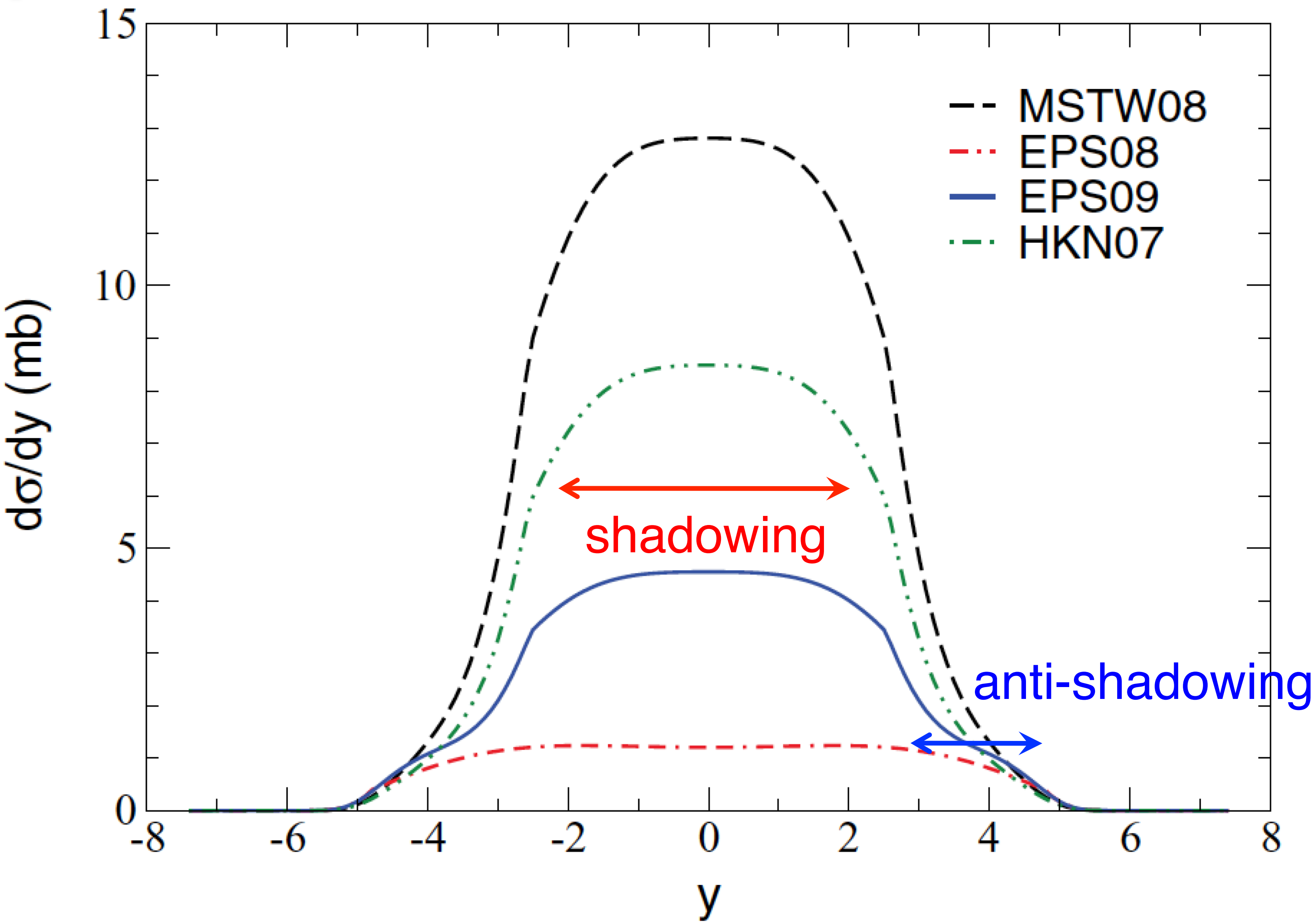
Total cross sections **(in mb)** for elastic photoproduction of J/ψ in ultraperipheral PbPb collisions at the LHC.

pA versus AA collisions



Rapidity distributions of exclusive photoproduction of J/ψ in pPb collisions at the LHC. (a) The γp and γPb contributions to total rapidity distributions. Dotted line depicts the γp contribution while the dashed (MSTW08), dash double- dotted (HKN07), solid (EPS09), and dash-dotted (EPS08) lines correspond to γPb contributions with no shadowing, weak shadowing, moderate shadowing, and strong shadowing, respectively. (b) Total rapidity distributions (sum of γp and γPb contributions).

pA versus AA collisions



Total rapidity distributions of exclusive photoproduction of J/ψ in PbPb collisions at the LHC. Dashed line uses the MSTW08 gluon distribution. Solid, dash-dotted, and dash-double-dotted lines are results from nuclear-modified gluon distributions from EPS09, EPS08, and HKN07.

pA versus AA collisions

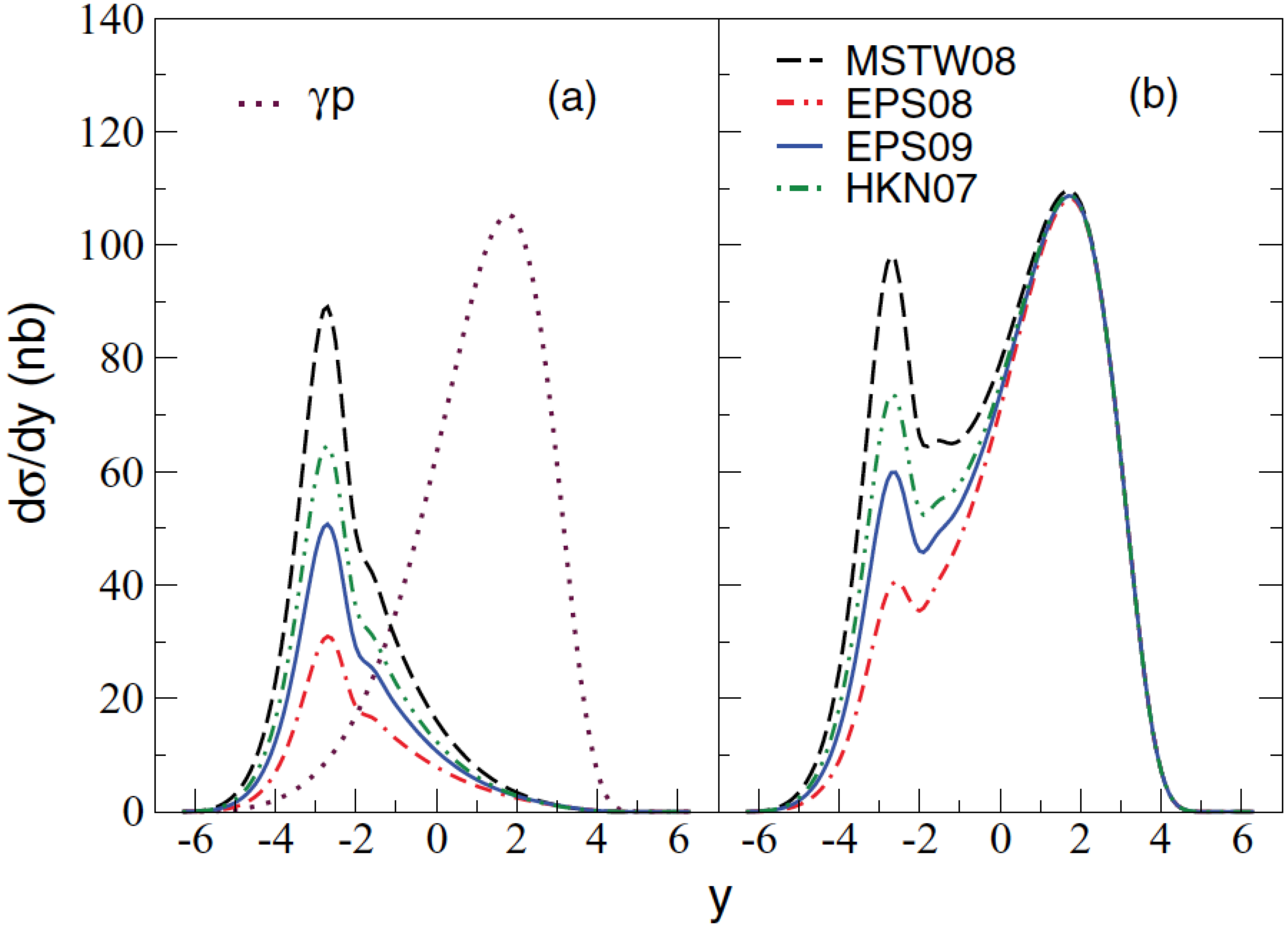
	γp	γA	Total nb
MSTW08	390	219	609
EPS08		84	474
EPS09		130	520
HKN07		161	551

Total cross sections **(in nb)** for elastic photoproduction of ϒ(1s) in ultraperipheral pPb collisions at the LHC. Second and third columns are the contributions from γp and γPb. The sums of the two contributions are presented in the fourth column.

	Cross section pb
MSTW08	189
EPS08	99
EPS09	130
HKN07	146

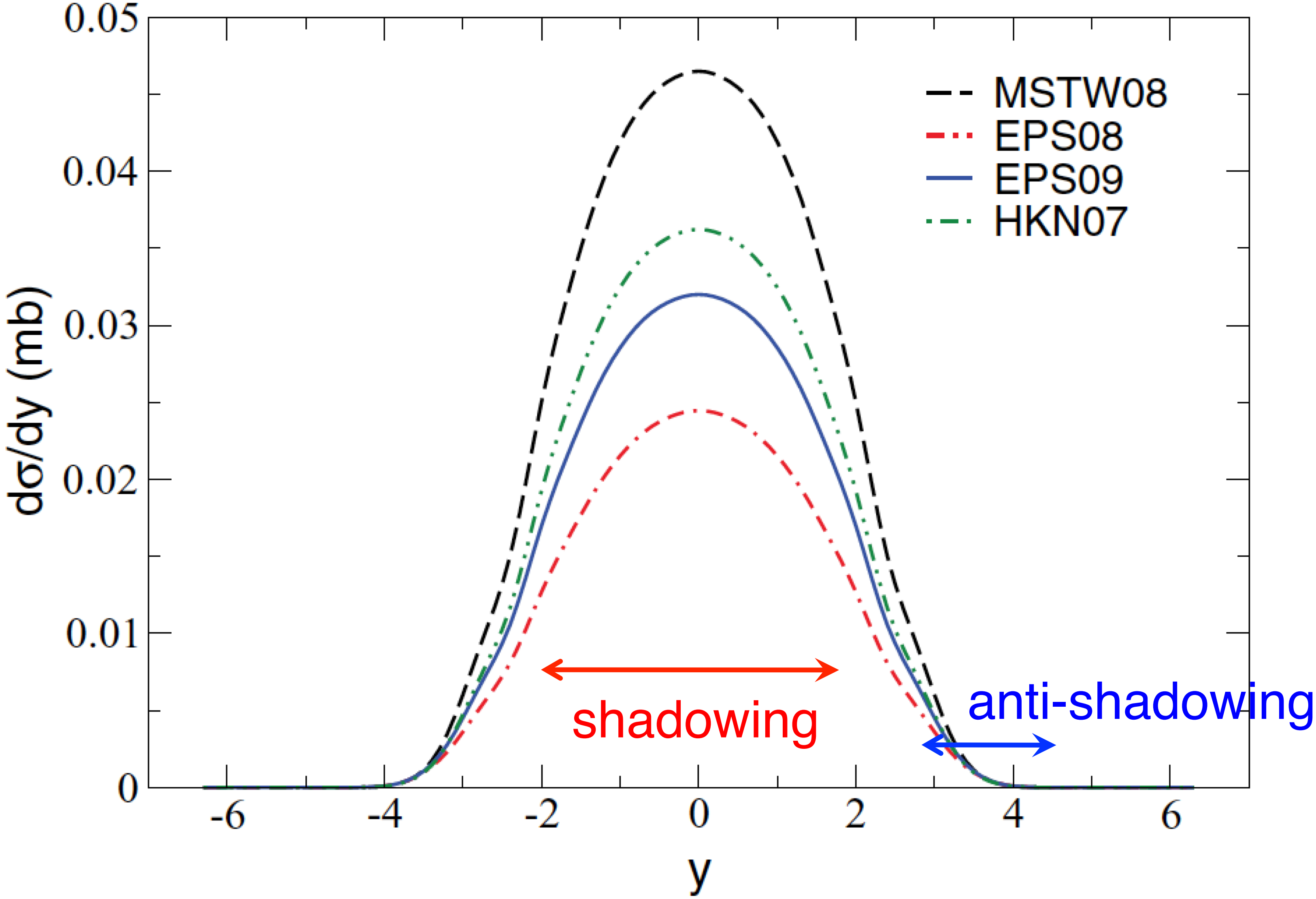
Total cross sections **(in μb)** for elastic photoproduction of ϒ(1s) in ultraperipheral PbPb collisions at the LHC.

pA versus AA collisions



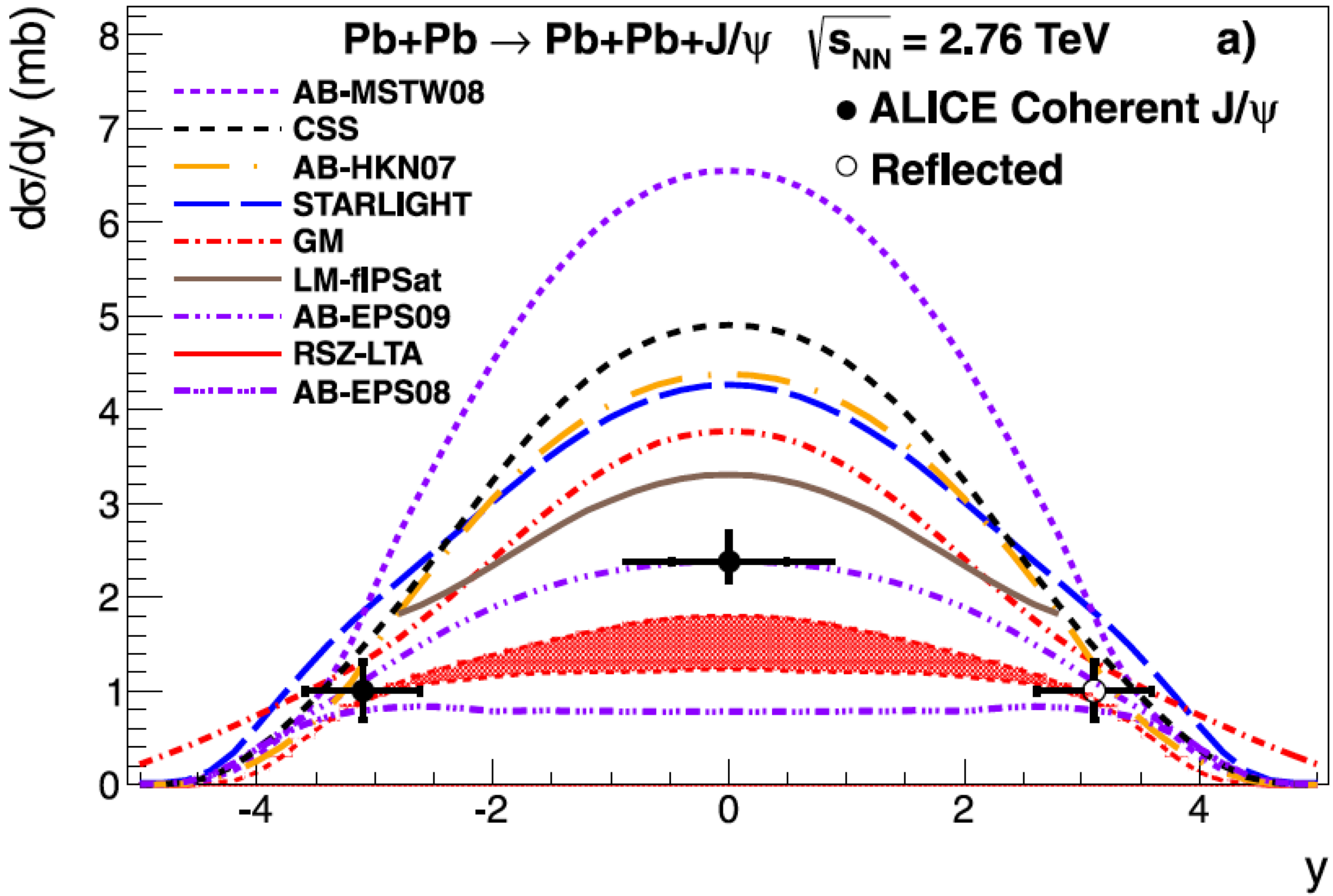
Rapidity distributions of exclusive photoproduction of ϒ(1s) in pPb collisions at the LHC. In (a) we show the γp and γPb contributions to total rapidity distributions. Dotted line depicts the γp contribution while the dashed (MSTW08), dash double-dotted (HKN07), solid (EPS09), and dash-dotted (EPS08) lines correspond to γPb contributions with no shadowing, weak shadowing, moderate shadowing, and strong shadowing, respectively. In (b) we present total rapidity distributions (sum of γp and γ Pb contributions).

pA versus AA collisions



Total rapidity distributions of exclusive photoproduction of Υ(1s) in PbPb collisions at the LHC in the modified hard sphere density distribution approximation. Dashed line uses the MSTW08 gluon distribution. Solid, dash-dotted, and dash-double-dotted lines uses nuclear-modified gluon distributions from EPS09, EPS08, and HKN0.

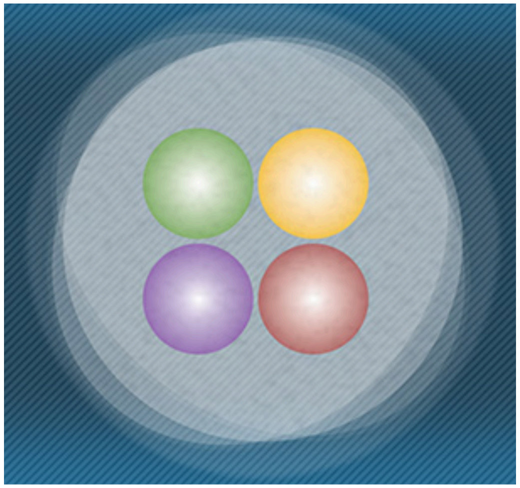
PDFs at the LHC

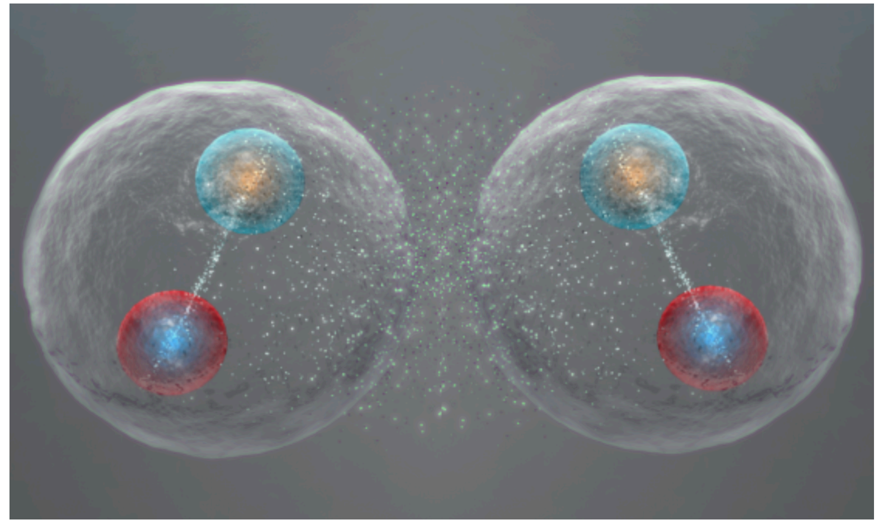


De Gruttola et al., NPA 926, 136 (2014)

Comparison among the published value of the cross section at forward rapidity, the result at central rapidities and several theoretical models. The error is the quadratic sum of the statistical and systematic errors.

Tetraquarks or meson molecule ?





X(3872) = c-cbar (97%) + D-$\underline{D}^*$ (3%)

Matheus, Navarra, Nielsen, Zanetti,
PRD 80, 056002 (2009)

Charmonium-molecule = χ'_{c1} + D-$\underline{D}^*$, with (28%–44%) $c\underline{c}$

Ce Meng, Hao Han, Kuang-Ta Chao,
PRD 96, 074014 (2017)

$$\Gamma_{\gamma\gamma} \sim \frac{2\pi\alpha^2}{M_R^2}\left|\psi(0)\right|^2 \quad \Rightarrow \quad \Gamma_{\gamma\gamma}^{\text{tetraquark}} >> \Gamma_{\gamma\gamma}^{\text{molecule}} \quad \Rightarrow \quad \sigma_{\gamma\gamma}^{\text{tetraquark}} \sim 10^2\, \sigma_{\gamma\gamma}^{\text{molecule}}$$

Moreira, Bertulani, Goncalves, Navarra, PRD 94, 094024 (2016)
Eur. Phys. J. 137, 06019 (2017)

Tetraquarks

Moreira, Bertulani,
Goncalves, Navarra,
PRD 94, 094024 (2016)
Eur. Phys. J. 137, 06019 (2017)

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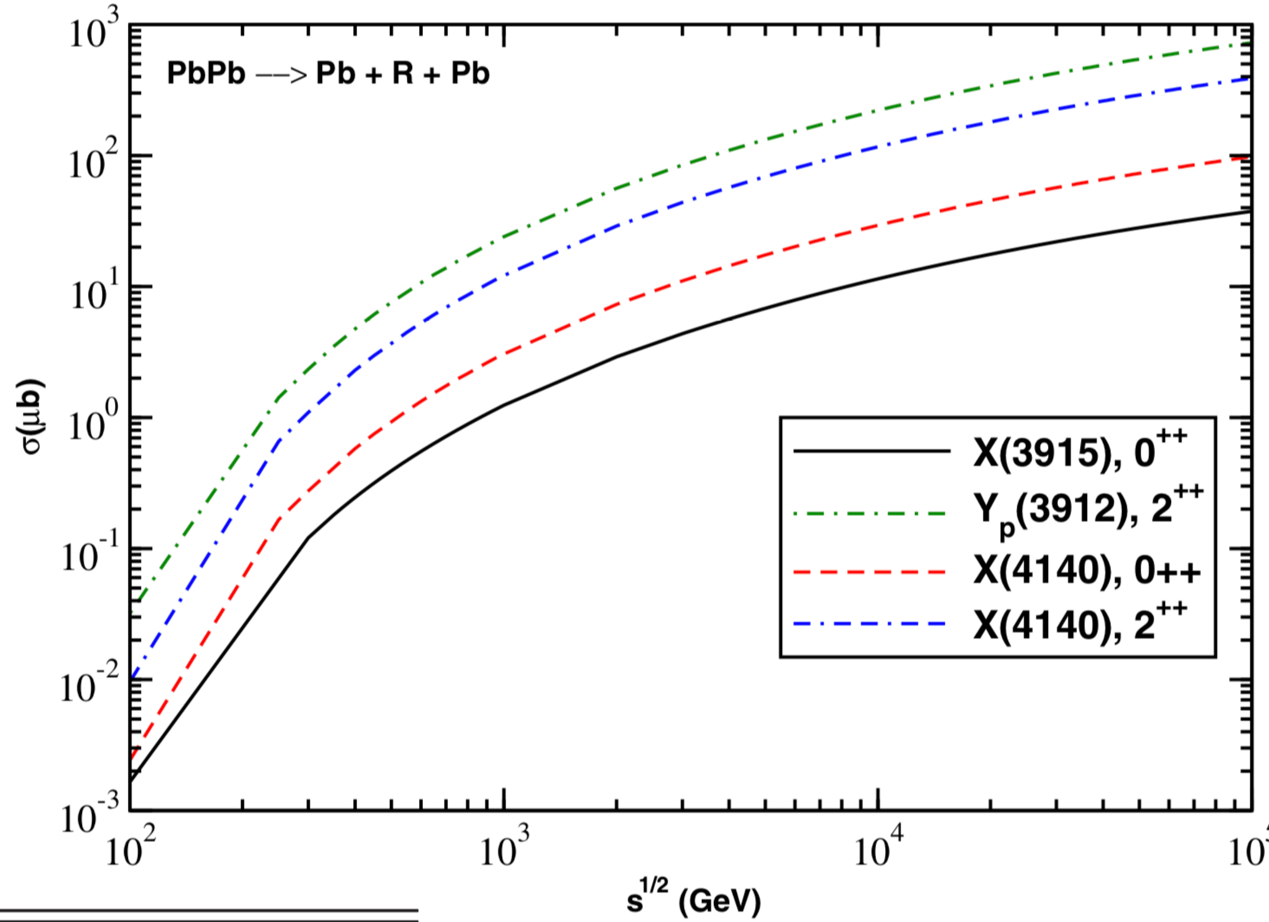
Measurement can help contrain which configuration (tetraquark or molecule) through $\Gamma_{\gamma\gamma}$



State	Mass	$\Gamma_{\gamma\gamma}^{\text{theor}}$ (keV)	σ_R (μb) 2.76 TeV	5.5 TeV	39 TeV
$X(3940)$, 0^{++}	3943	0.33	5.7	10.8	39.6
$X(3940)$, 2^{++}	3943	0.27	23.4	44.2	162.0
$X(4140)$, 0^{++}	4143	0.63	9.0	17.1	63.6
$X(4140)$, 2^{++}	4143	0.50	35.5	67.7	252.3
$Z(3930)$, 2^{++}	3922	0.083	7.4	13.9	50.5
$X(4160)$, 2^{++}	4169	0.363	25.2	48.1	178.7
$Y_p(3912)$, 2^{++}	3919	0.774	68.9	129.9	473.7
$X(3915)$, 0^{++}	3919	0.20	3.6	6.7	24.5

For pp at 7, 14, and 100 TeV

→

Cross sections drop to pb due to Z^4

Summary

- LHC looks for physics beyond the SM
- LHC can be very useful for complementary studies,

e.g. $\gamma^* + \Lambda \rightarrow \Sigma^0$ and Σ^0 lifetime

- **antihydrogen (CERN 1996)**

- **multiphonon giant resonances (RHIC, CERN)**

- **alternatives for nuclear astrophysics (everywhere but LHC)**

- **QFT of bound states (nowhere)**

- **PDFs (RHIC, LHC)**

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