Production of $p\bar{p}$ pairs in UPC at the LHC

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Plan

1) $\gamma\gamma \to p\bar{p}$ reaction

- non-resonant proton exchange contribution
- f_2 meson contribution
- hand-bag approach

2) results for $\gamma\gamma \to p\bar{p}$

- comparison with data from e^+e^- collisions

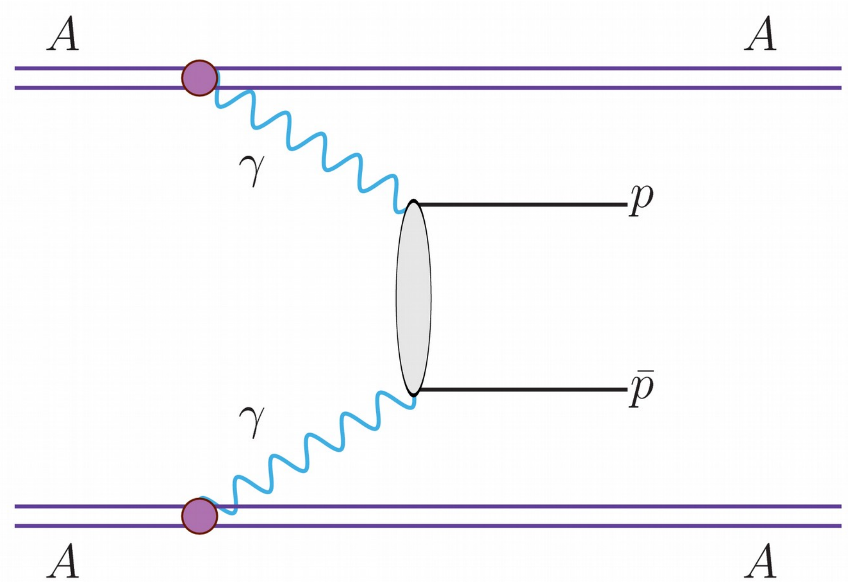
3) predictions for $Pb\, Pb \to Pb\, Pb\, p\bar{p}$

Based on:

M. Kłusek-Gawenda, P. Lebiedowicz, O. Nachtmann, and A. Szczurek,
From the $\gamma\gamma \to p\bar{p}$ reaction to the production of $p\bar{p}$ pairs in ultraperipheral ultrarelativistic heavy-ion collisions at the LHC, Phys. Rev. D96 (2017) 094029

Nuclear reaction

$$^{208}Pb + ^{208}Pb \to ^{208}Pb + ^{208}Pb + p + \bar{p}$$



$$\sigma_{AA \to AAp\bar{p}}(\sqrt{s_{AA}}) = \int \sigma_{\gamma\gamma \to p\bar{p}}(W_{\gamma\gamma}) N(\omega_1, \boldsymbol{b_1}) N(\omega_2, \boldsymbol{b_2}) S^2_{abs}(\boldsymbol{b}) \times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, d\mathrm{Y}_{p\bar{p}}\, d\bar{b}_x\, d\bar{b}_y\, 2\pi\, b\, db$$

$$W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$$

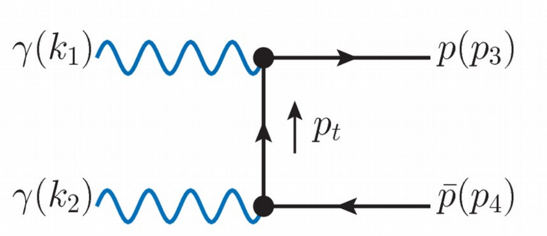
$$Y_{p\bar{p}} = \frac{1}{2}\sqrt{\mathrm{y}_p + \mathrm{y}_{\bar{p}}}$$

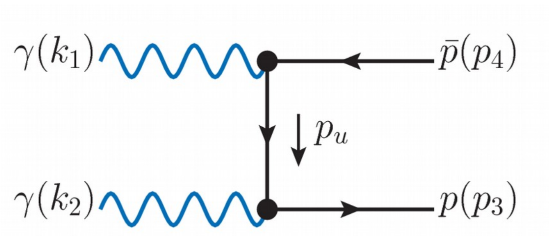
see talks by Antoni & Mariola

The quantities $\bar{b}_x$, $\bar{b}_y$ are the components of the $\boldsymbol{b_1}$ and $\boldsymbol{b_2}$ vectors which mark a point (distance from first and second nucleus) where photons collide and particles are produced.

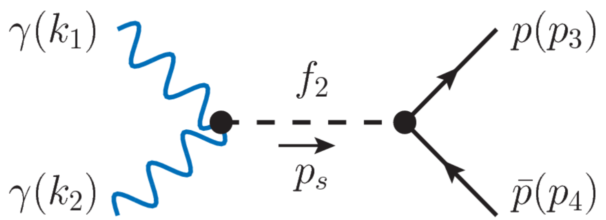
$\gamma\gamma \to p\bar{p}$ reaction

- nonresonant proton exchange

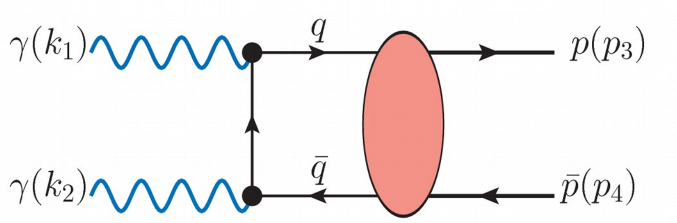




- s-channel tensor meson exchange – $f_2(1270)$ and $f_2(1950)$

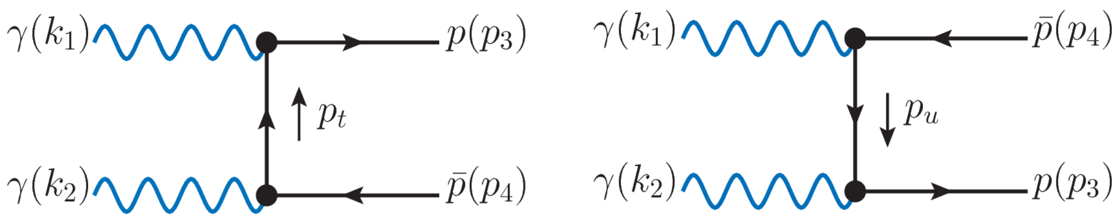


- hand-bag mechanism (M. Diehl, P. Kroll, C. Vogt, Eur. Phys. J. C26 (2003) 567)



\+ diagram with photon vertices interchanged

Proton exchange contribution



$$\mathcal{M}^{(p\ \mathrm{exchange})}_{\mathrm{bare}} = (-i)\,\epsilon_{1\mu}\epsilon_{2\nu}\,\bar{u}(p_3)\Big(i\Gamma^{(\gamma pp)\,\mu}(p_3,p_t)\frac{i(\not{p}_t+m_p)}{t-m_p^2+i\epsilon}i\Gamma^{(\gamma pp)\,\nu}(p_t,-p_4)$$
$$+i\Gamma^{(\gamma pp)\,\nu}(p_3,p_u)\frac{i(\not{p}_u+m_p)}{u-m_p^2+i\epsilon}i\Gamma^{(\gamma pp)\,\mu}(p_u,-p_4)\Big)v(p_4)$$

$$i\Gamma^{(\gamma pp)}_{\mu}(p',p) = -ie\left[\gamma_\mu F_1(q^2)+\frac{i}{2m_p}\sigma_{\mu\nu}q^\nu F_2(q^2)\right], \qquad q=p'-p$$

F_1 and F_2 are Dirac and Pauli form factors of proton, respectively;
for real photons: $F_1(0) = 1$ and $F_2(0) = \kappa_p = 1.7928$

- Virtual protons are off-shell. We take the off-shell dependences into account via multiplication of “bare” amplitude by an extra form factor

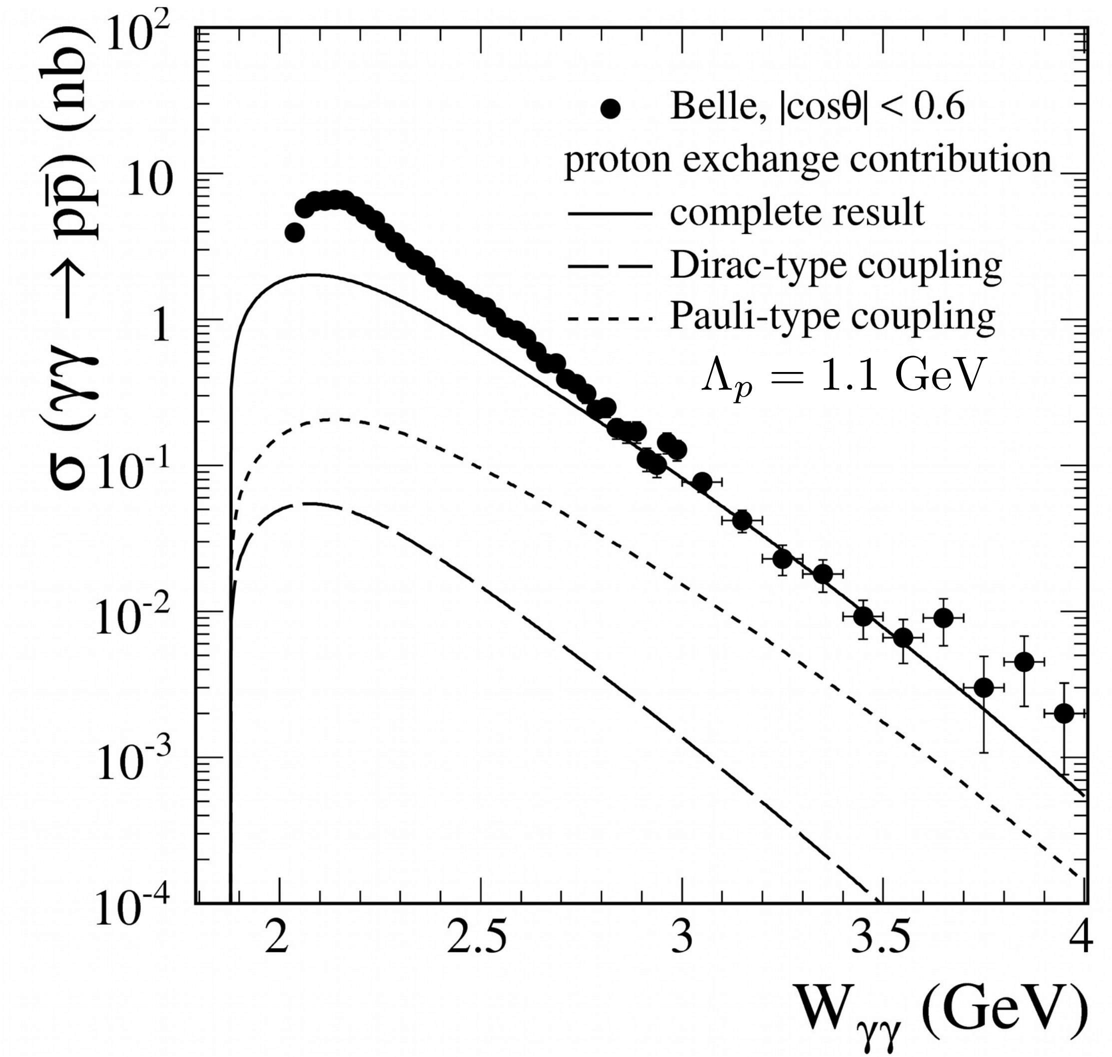
$$\mathcal{M}^{(p\ \mathrm{exchange})} = \mathcal{M}^{(p\ \mathrm{exchange})}_{\mathrm{bare}}\,F(t,u,s)\,; \qquad F(t,u,s) = \frac{[F(t)]^2+[F(u)]^2}{1+[\tilde{F}(s)]^2}$$

[M.Poppe, Int.J.Mod.Phys.A1 (1986) 545]

$$F(t) = \exp\left(\frac{t-m_p^2}{\Lambda_p^2}\right), \quad \tilde{F}(s) = \exp\left(\frac{-(s-4m_p^2)}{\Lambda_p^2}\right), \quad F(m_p^2,m_p^2,4m_p^2) = 1$$

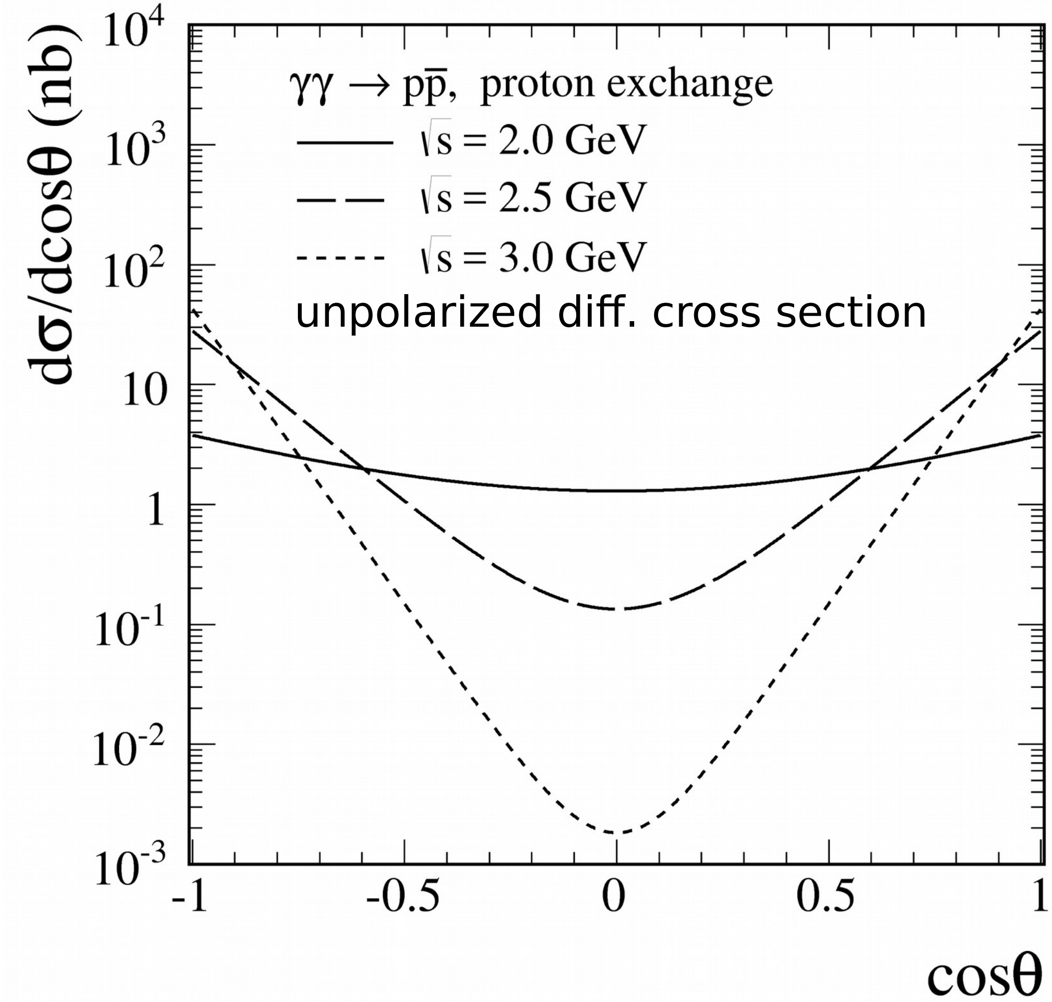
Our amplitude satisfied the gauge-invariance and the Bose-symmetry relations.

Comparison with Belle data

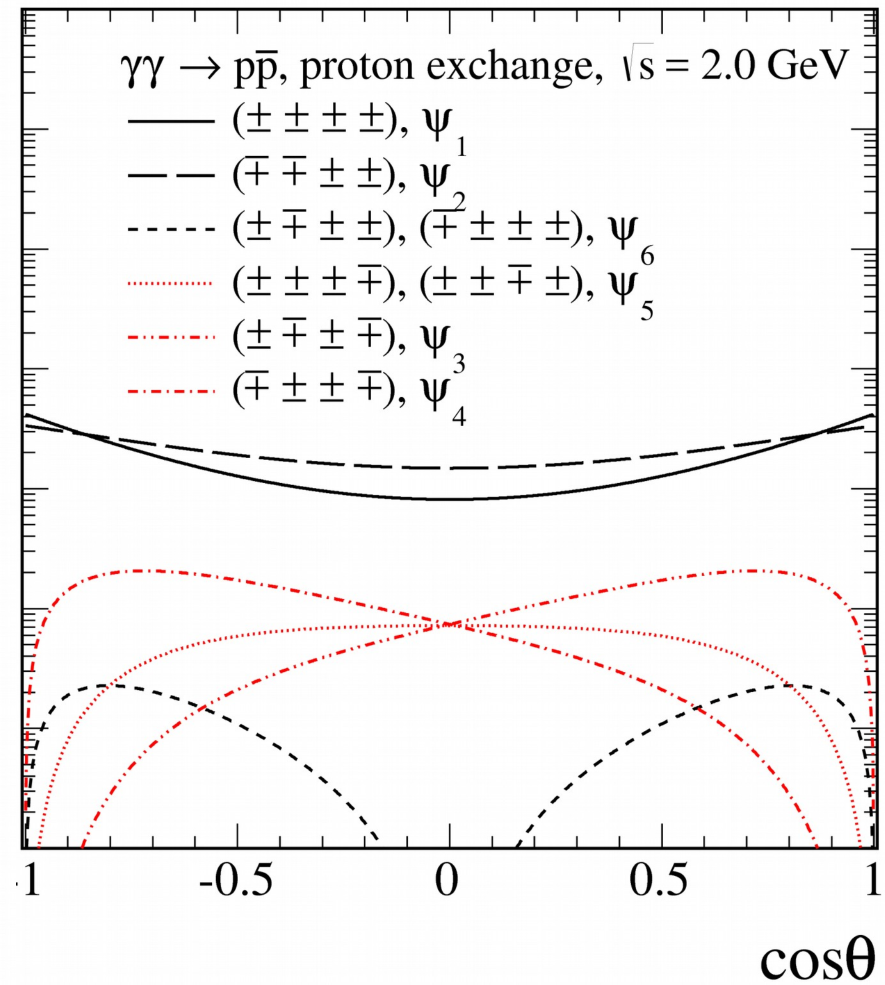


- Clearly, the proton exchange contribution is not sufficient to describe the Belle data [C.C.Kuo *et al.* (Belle Collaboration) Phys. Lett. B621 (2005) 41]
- Pauli-type coupling is very important, enhances the cross section considerably. Large interference effect of Dirac- and Pauli-type terms in the amplitude

Angular distributions

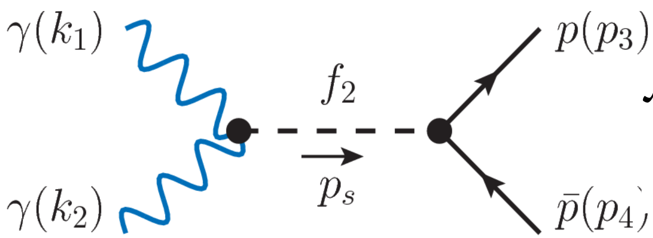


helicity terms ($2s_3$ $2s_4$ m_1 m_2)
for $< 2s_3\ 2s_4 \mid T \mid m_1\ m_2 >$



- Closer to the threshold energy the angular distributions become flatter and flatter
- We find dominance of the amplitudes ψ_1 and ψ_2. Contributions of ψ_3, ψ_4, ψ_5, and ψ_6, are suppressed in $\cos\theta = \pm 1$. This is clear from angular momentum conservation.

f_2 meson contribution



$$\mathcal{M}^{(f_2 \text{ exchange})} = (-i)\,\bar{u}(p_3) i\Gamma^{(f_2 p\bar{p})\,\alpha\beta}(p_3,p_4)\,v(p_4) \times i\Delta^{(f_2)}_{\alpha\beta,\kappa\lambda}(p_s)\, i\Gamma^{(f_2\gamma\gamma)\,\mu\nu\kappa\lambda}(k_1,k_2)\,\epsilon_{1\mu}\epsilon_{2\nu}$$

- $f_2\gamma\gamma$ vertex

$$i\Gamma^{(f_2\gamma\gamma)}_{\mu\nu\kappa\lambda}(k_1,k_2) = i\left[2a_{f_2\gamma\gamma}\,F_a^{(f_2\gamma\gamma)}(s)\,\Gamma^{(0)}_{\mu\nu\kappa\lambda}(k_1,k_2) - b_{f_2\gamma\gamma}\,F_b^{(f_2\gamma\gamma)}(s)\,\Gamma^{(2)}_{\mu\nu\kappa\lambda}(k_1,k_2)\right]$$

where *a* and *b* parametrise the so-called helicity 0 and helicity 2 $f_2 \to \gamma\gamma$ amplitudes
[C.Ewerz, M. Maniatis, O. Nachtmann, Annals Phys. 342 (2014) 31]

- $f_2 p\bar{p}$ vertex

$$i\Gamma^{(f_2p\bar{p})(1)}_{\kappa\lambda}(p_3,p_4) = -i\frac{g^{(1)}_{f_2pp}}{M_0}\left[\frac{1}{2}\gamma_\kappa(p_3-p_4)_\lambda + \frac{1}{2}\gamma_\lambda(p_3-p_4)_\kappa - \frac{1}{4}g_{\kappa\lambda}(\not{p}_3 - \not{p}_4)\right] F^{(f_2p\bar{p})(1)}(s)$$

$$i\Gamma^{(f_2p\bar{p})(2)}_{\kappa\lambda}(p_3,p_4) = -i\frac{g^{(2)}_{f_2pp}}{M_0^2}\left[(p_3-p_4)_\kappa(p_3-p_4)_\lambda - \frac{1}{4}g_{\kappa\lambda}(p_3-p_4)^2\right] F^{(f_2p\bar{p})(2)}(s)$$

Here $g^{(j)}_{f_2pp}$ $(j=1,2)$ are dimensionless coupling constants and $M_0 \equiv 1$ GeV.
The complete $f_2p\bar{p}$ vertex function is given by

$$i\Gamma^{(f_2p\bar{p})}_{\kappa\lambda}(p_3,p_4) = \sum_{j=1,2} i\Gamma^{(f_2p\bar{p})(j)}_{\kappa\lambda}(p_3,p_4)$$

- f_2 propagator

$$i\Delta^{(f_2)}_{\alpha\beta,\kappa\lambda}(p_s) = iP^{(2)}_{\alpha\beta,\kappa\lambda}(p_s)\,\Delta^{(2)}(p_s^2) = i\left[\frac{1}{2}(\hat{g}_{\alpha\kappa}\hat{g}_{\beta\lambda} + \hat{g}_{\alpha\lambda}\hat{g}_{\beta\kappa}) - \frac{1}{3}\hat{g}_{\alpha\beta}\hat{g}_{\kappa\lambda}\right]\frac{1}{p_s^2 - m_{f_2}^2 + im_{f_2}\Gamma_{f_2}}$$

Helicity amplitudes for $\gamma\gamma \to f_2 \to p\bar{p}$

$$\langle p(,s_3),\bar{p}(,s_4)|\mathcal{T}|\gamma(,m_1),\gamma(,m_2)\rangle \equiv \langle 2s_3,2s_4|\mathcal{T}|m_1,m_2\rangle\,,$$
$$2s_3,2s_4,m_1,m_2 \in \{+1,-1\}$$

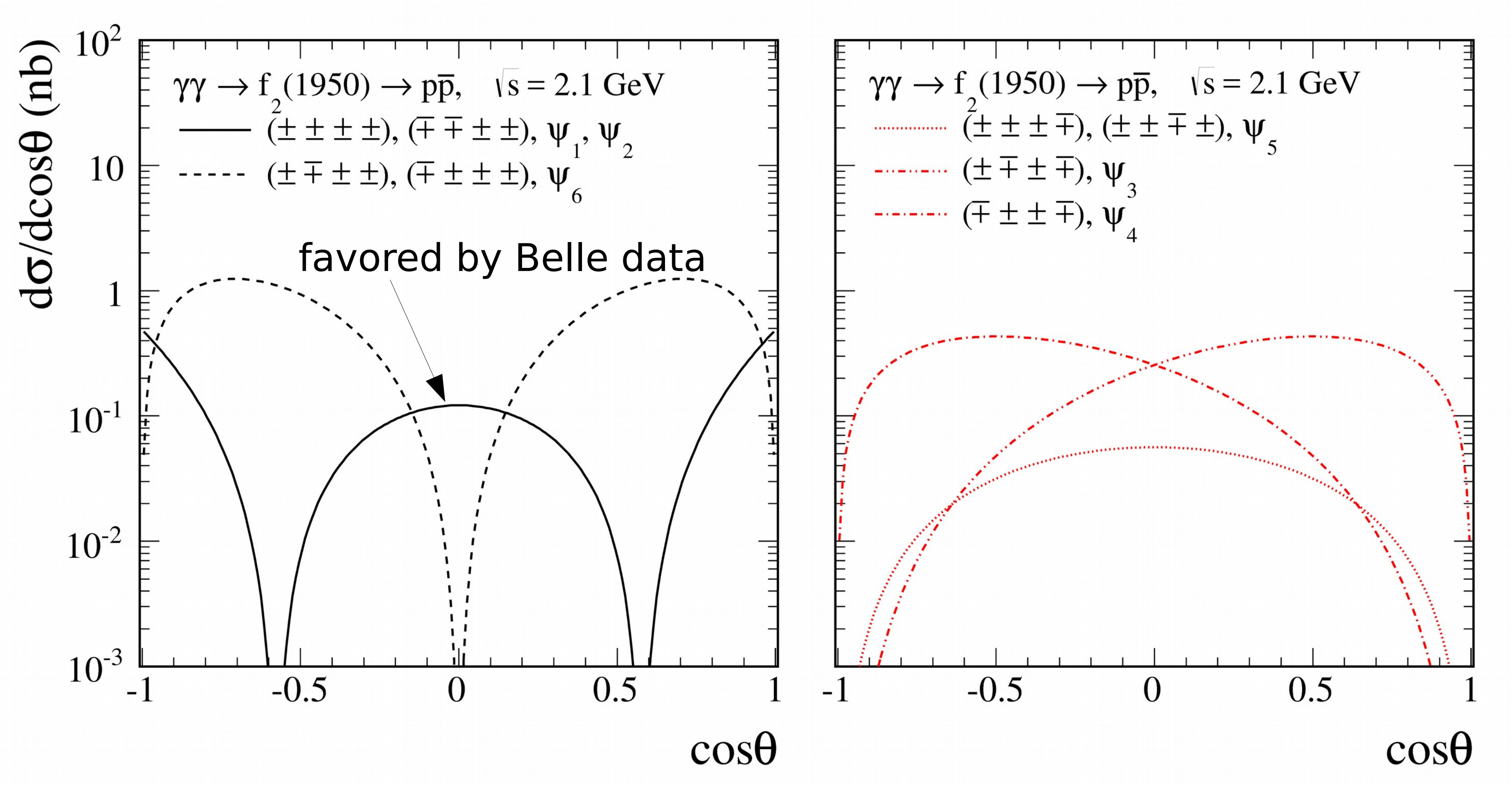
$$\langle 2s_3,2s_4|\mathcal{T}|+,+\rangle = \langle 2s_3,2s_4|\mathcal{T}|-,-\rangle$$
$$= -\frac{1}{2}s^2\sqrt{s-4m_p^2}\,\Delta^{(2)}(s)\,a_{f_2\gamma\gamma}\,F_a^{(f_2\gamma\gamma)}(s)$$
$$\times\left\{\frac{g^{(1)}_{f_2pp}}{M_0}F^{(f_2p\bar{p})(1)}(s)\left[-2m_p\left(\cos^2\theta-\frac{1}{3}\right)\delta_{s_3s_4}-\sqrt{s}\sin\theta\cos\theta\,\varepsilon_{s_3s_4}\right]\right.$$
$$\left.+\frac{g^{(2)}_{f_2pp}}{M_0^2}F^{(f_2p\bar{p})(2)}(s)\,(s-4m_p^2)\left(\cos^2\theta-\frac{1}{3}\right)\delta_{s_3s_4}\right\}$$

$$\varepsilon = (\varepsilon_{s_3s_4}) = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\langle 2s_3,2s_4|\mathcal{T}|\pm,\mp\rangle$$
$$= -\frac{1}{2}s\sqrt{s-4m_p^2}\,\Delta^{(2)}(s)\,b_{f_2\gamma\gamma}\,F_b^{(f_2\gamma\gamma)}(s)$$
$$\times\left\{\frac{g^{(1)}_{f_2pp}}{M_0}F^{(f_2p\bar{p})(1)}(s)\left[-2m_p\sin^2\theta\,\delta_{s_3s_4}+\sqrt{s}\sin\theta\cos\theta\,\varepsilon_{s_3s_4}\pm\sqrt{s}\sin\theta\,\delta_{s_3,-s_4}\right]\right.$$
$$\left.+\frac{g^{(2)}_{f_2pp}}{M_0^2}F^{(f_2p\bar{p})(2)}(s)\,(s-4m_p^2)\sin^2\theta\,\delta_{s_3s_4}\right\}$$

- We assume the same form for the form factors $F(s) = \frac{\Lambda^4_{f_2,pow}}{\Lambda^4_{f_2,pow}+(s-m_{f_2}^2)^2}$

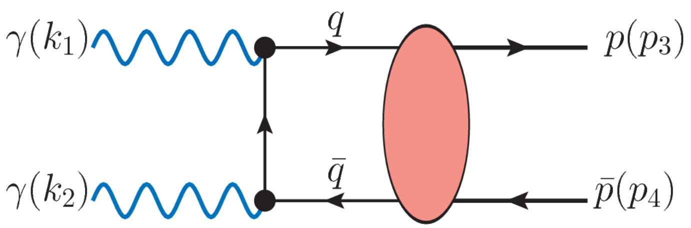
Angular distributions



Here the model parameters (form factors, coupling constants) are fixed arbitrarily.

Only the ψ_1 and ψ_2 amplitudes (solid line in left panel) are favored by the Belle data.

Hand-bag approach



The $\gamma\gamma \to p\bar{p}$ amplitude factorizes into a hard $\gamma\gamma \to q\bar{q}$ subprocess and a matrix element describing the soft $q\bar{q} \to p\bar{p}$ transition.
[M. Diehl, P. Kroll, C. Vogt, Eur. Phys. J. C26 (2003) 567]

$$\widetilde{\mathcal{M}}_{s_3 s_4, m_1 m_2} = \mathcal{A}_{s_3 s_4, m_1 m_2} + \frac{m_p}{\sqrt{s}}\Big[2s_3\mathcal{A}_{-s_3 s_4, m_1 m_2} + 2s_4\mathcal{A}_{s_3 -s_4, m_1 m_2}\Big] + \mathcal{O}(m_p^2/s)$$

$$\mathcal{A}_{s_3 s_4, +-} = -(-1)^{s_3 - s_4}\mathcal{A}_{-s_3 -s_4, -+} =$$
$$4\pi\alpha_{em}\frac{s}{\sqrt{tu}}\left\{\delta_{s_3,-s_4}\frac{t-u}{s}R_V(s) + 2s_3\delta_{s_3,-s_4}\Big[R_A(s)+R_P(s)\Big] - \frac{\sqrt{s}}{2m_p}\delta_{s_3 s_4}R_P(s)\right\}$$

The $q\bar{q} \to p\bar{p}$ transition form factors $R_V(s)$, $R_A(s)$ and $R_P(s)$ were determined phenomenologically. We neglect the term with $R_V(s)$ and assume $\frac{\sqrt{s}}{2m_p}\left|\frac{R_P(s)}{R_A(s)}\right| = 0.37.$
[formula (45) of DKV]

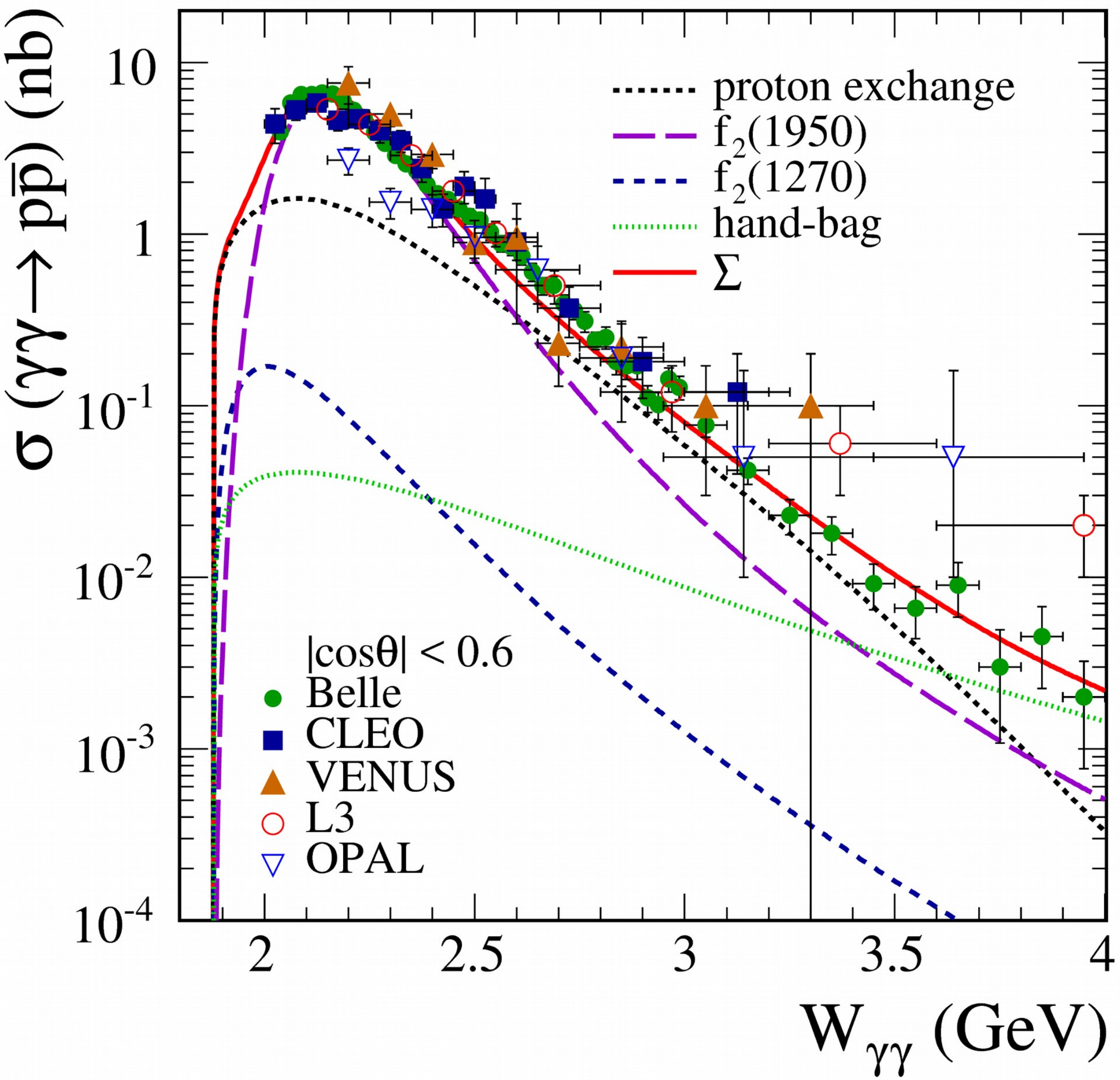
We parametrize $R_A(s) = C_A / s$ with C_A a parameter of dimension GeV^2 which we shall determine from a fit to the Belle data.

Due to different phase conventions we have: $\langle 2s_3, 2s_4|\mathcal{T}|\pm,\mp\rangle_{hb} = 2s_4\widetilde{\mathcal{M}}_{s_3 s_4,\pm\mp}$

We cut off the region of small |t| and |u| where the hand-bag approach does not apply.
We multiply the hand-bag amplitudes by a purely phenomenological factor:

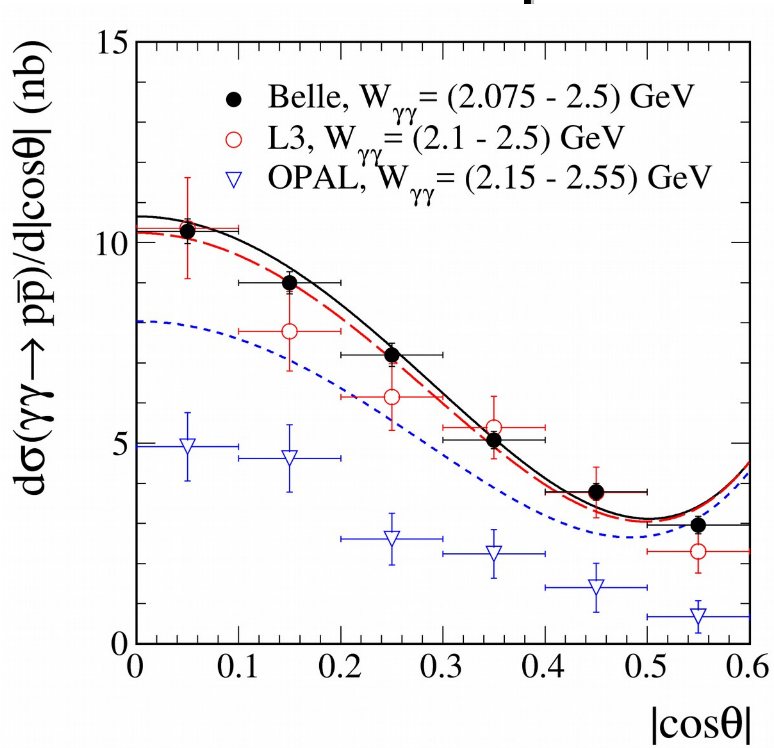
$$F_{corr}(t,u) = \left(1 - \exp\left(\frac{t}{\Lambda_{hb}^2}\right)\right)\left(1 - \exp\left(\frac{u}{\Lambda_{hb}^2}\right)\right)$$

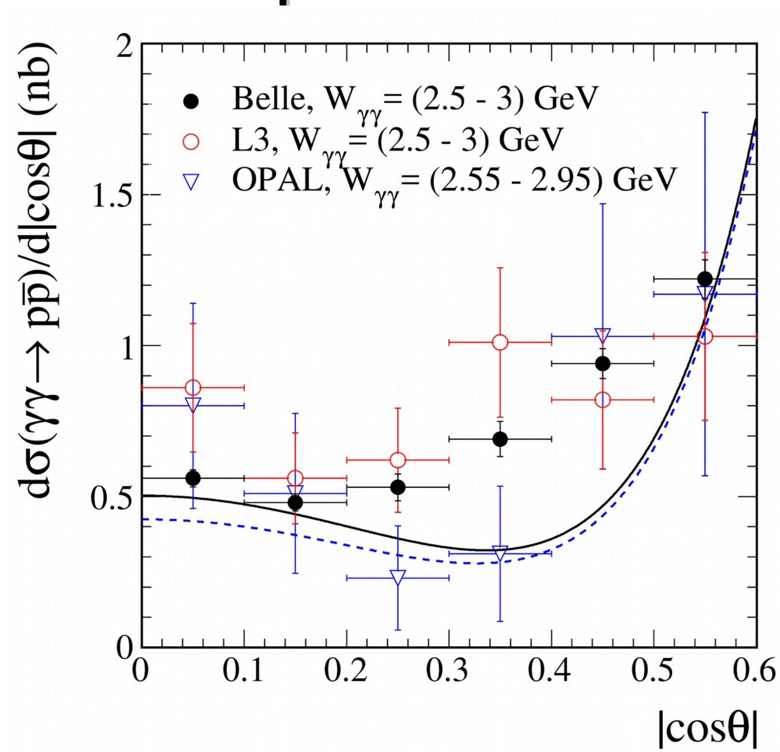
Comparison with experimental data

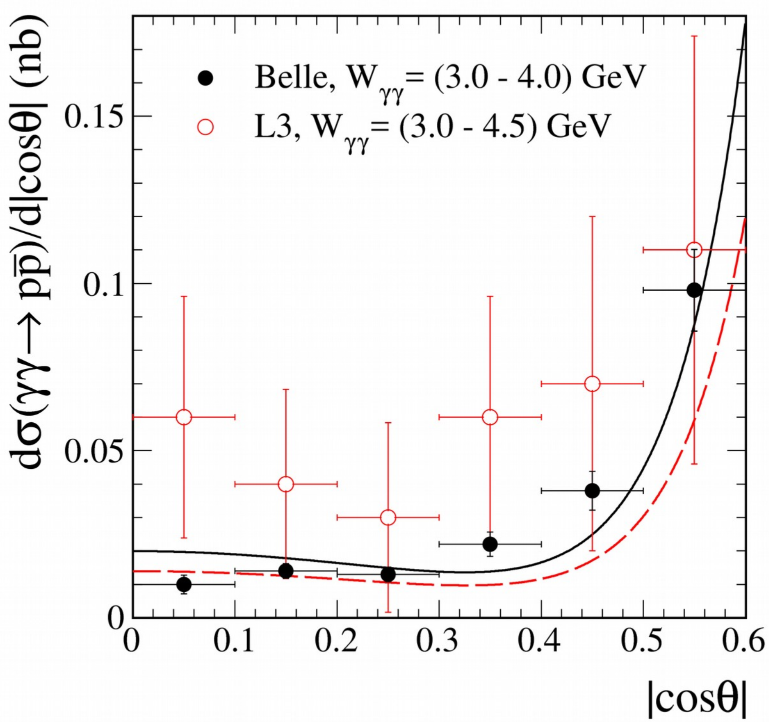


One can observe the dominance of the $f_2(1950)$ resonance term at low energies.
We slightly underestimate the Belle data around $W_{\gamma\gamma} = 2.6$ GeV.

Comparison with experimental data

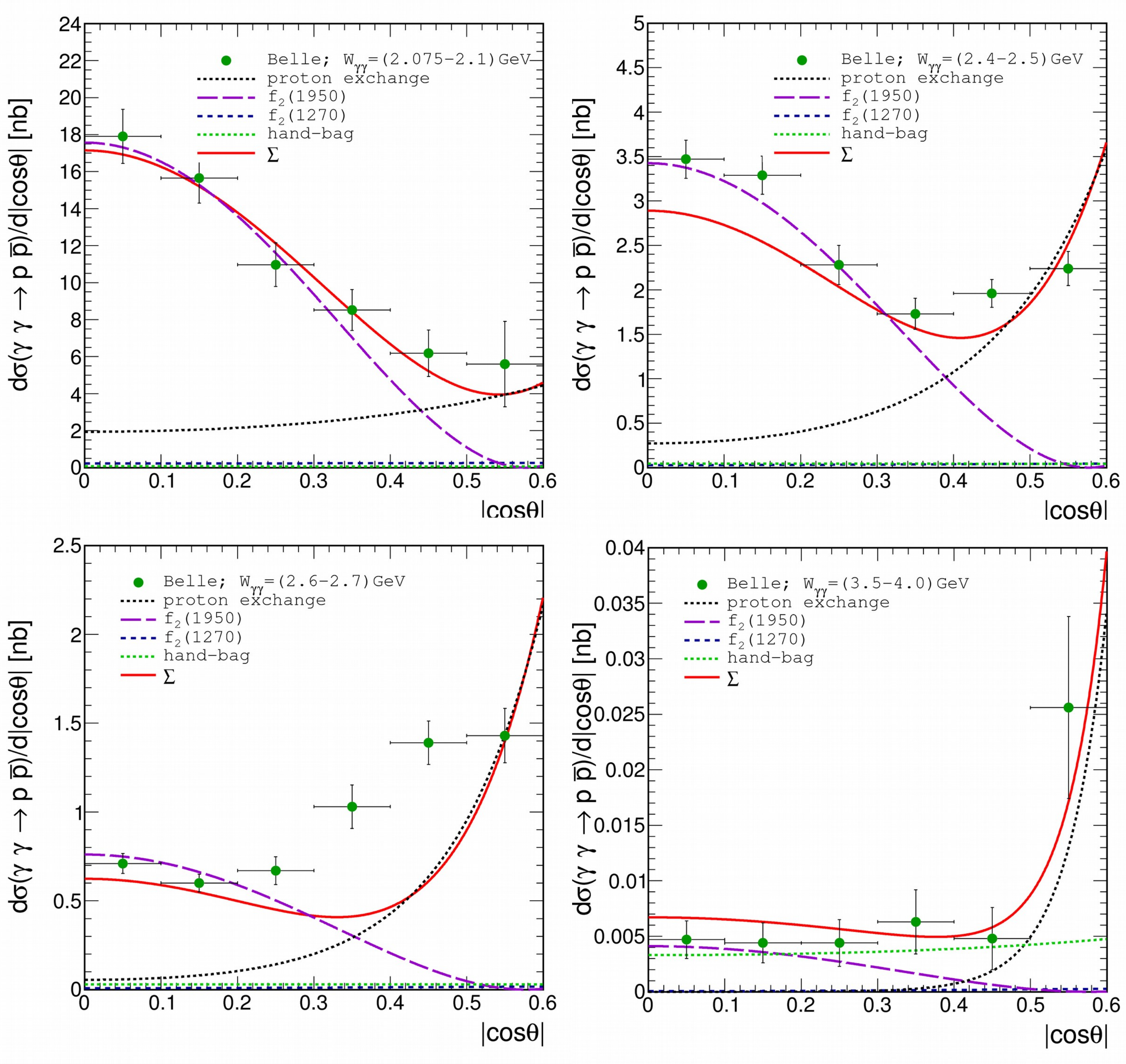




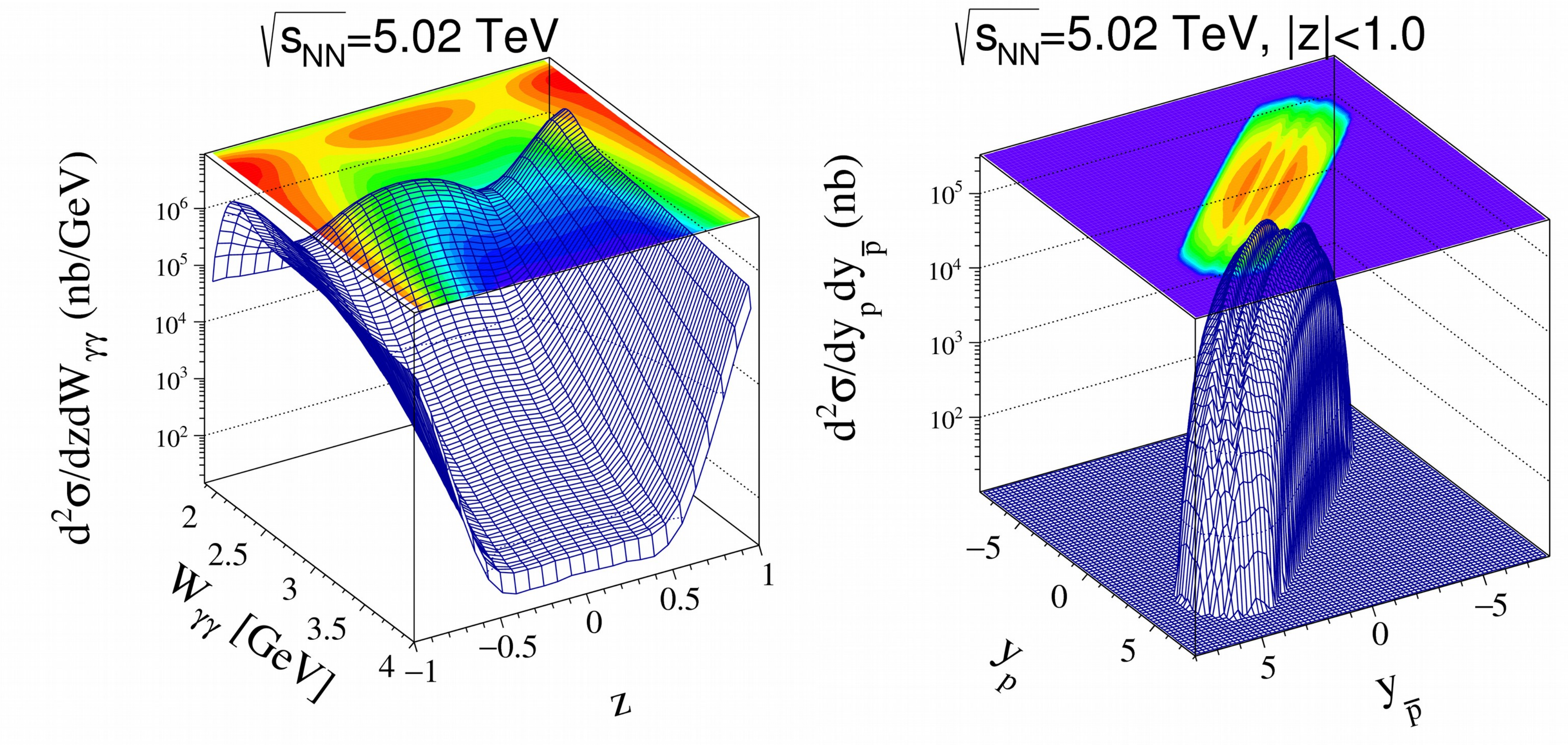


Due to the large error bars of the OPAL and L3 data only the comparison of the model results with the Belle data gives significant information.

Comparison with Belle data

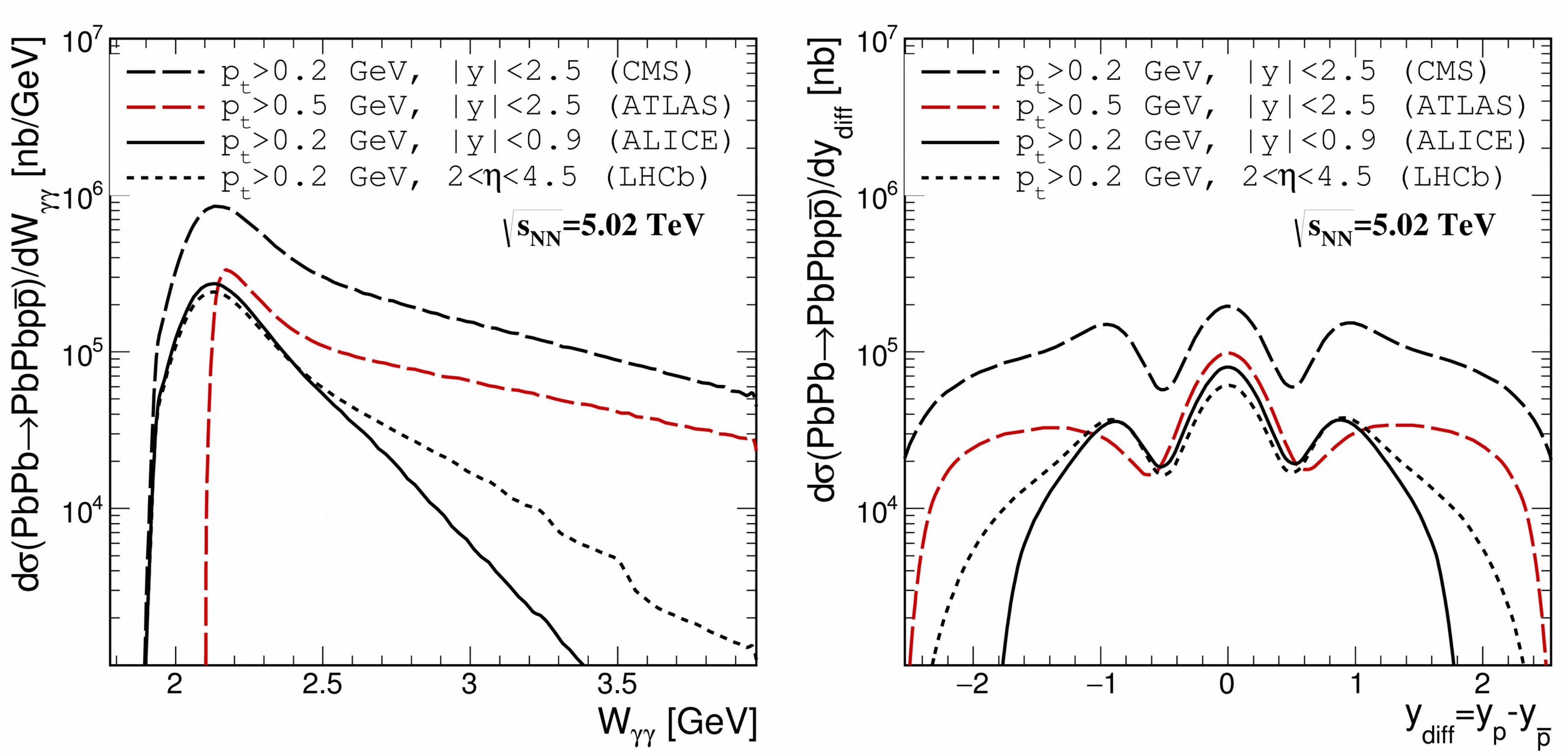


Predictions for nuclear reaction



- f_2(1950) contribution dominates at low $W_{\gamma\gamma} \equiv M_{p\bar{p}}$ and at z=0, ±1
- *p*-exchange contribution is concentrated mostly at larger $M_{p\bar{p}}$ and z= ±1
- cross section is concentrated at $y_p \simeq y_{\bar{p}}$

Predictions for nuclear reaction



σ = 500 μb (CMS cuts), 160 μb (ATLAS cuts), 100 μb (ALICE cuts), 104 μb (LHCb cuts)

We predict 46 events for $|y| < 0.9$, $p_t > 1$ GeV, and $L_{int} = 95\ \mu b^{-1}$ (ALICE)
→ important background for coherent $J/\psi \to p\bar{p}$ photoproduction

Conclusions

- To describe the dynamics of the $\gamma\gamma \to p\bar{p}$ process we take into account not only the non-resonant proton exchange contribution but also the *s*-channel tensor meson exchange contributions and the hand-bag mechanism.

- In our calculation of non-resonant contribution we have included both Dirac- and Pauli-type couplings of the photon to the nucleon and form factors for exchanged off-shell protons. We have found that the Pauli-type coupling is very important, enhances the cross section considerably, and cannot be neglected.

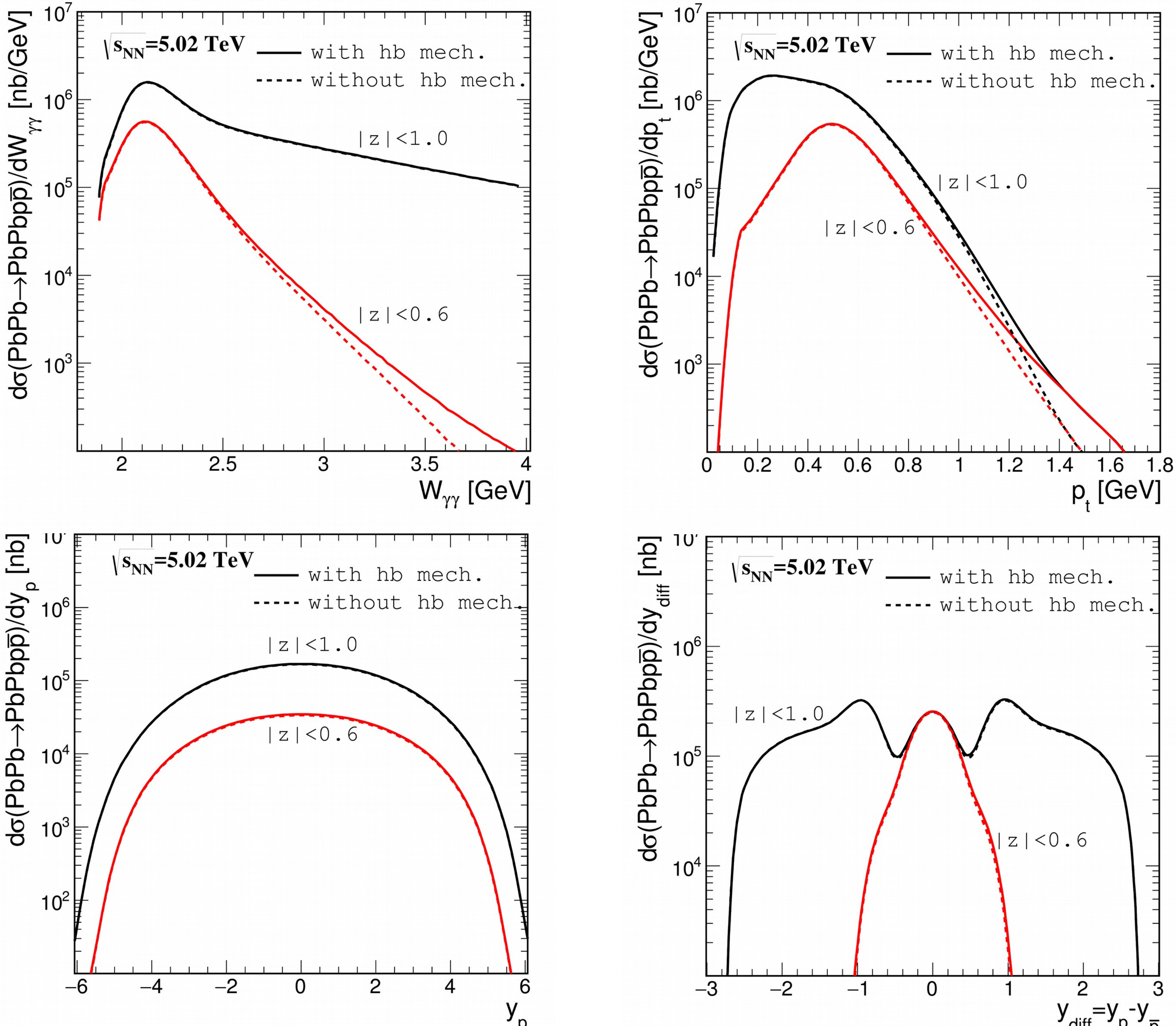
- We have shown that the Belle data for low $\gamma\gamma$ energies can be nicely described by including the $f_2(1950)$ resonance.

- Having described the angular distributions for the $\gamma\gamma \to p\bar{p}$ process we made predictions for Pb-Pb collisions. Both, the total cross section and several differential distributions including experimental cuts were presented.

- We predict large cross sections (e.g., 100 μb for ALICE cuts, 500 μb for CMS cuts).

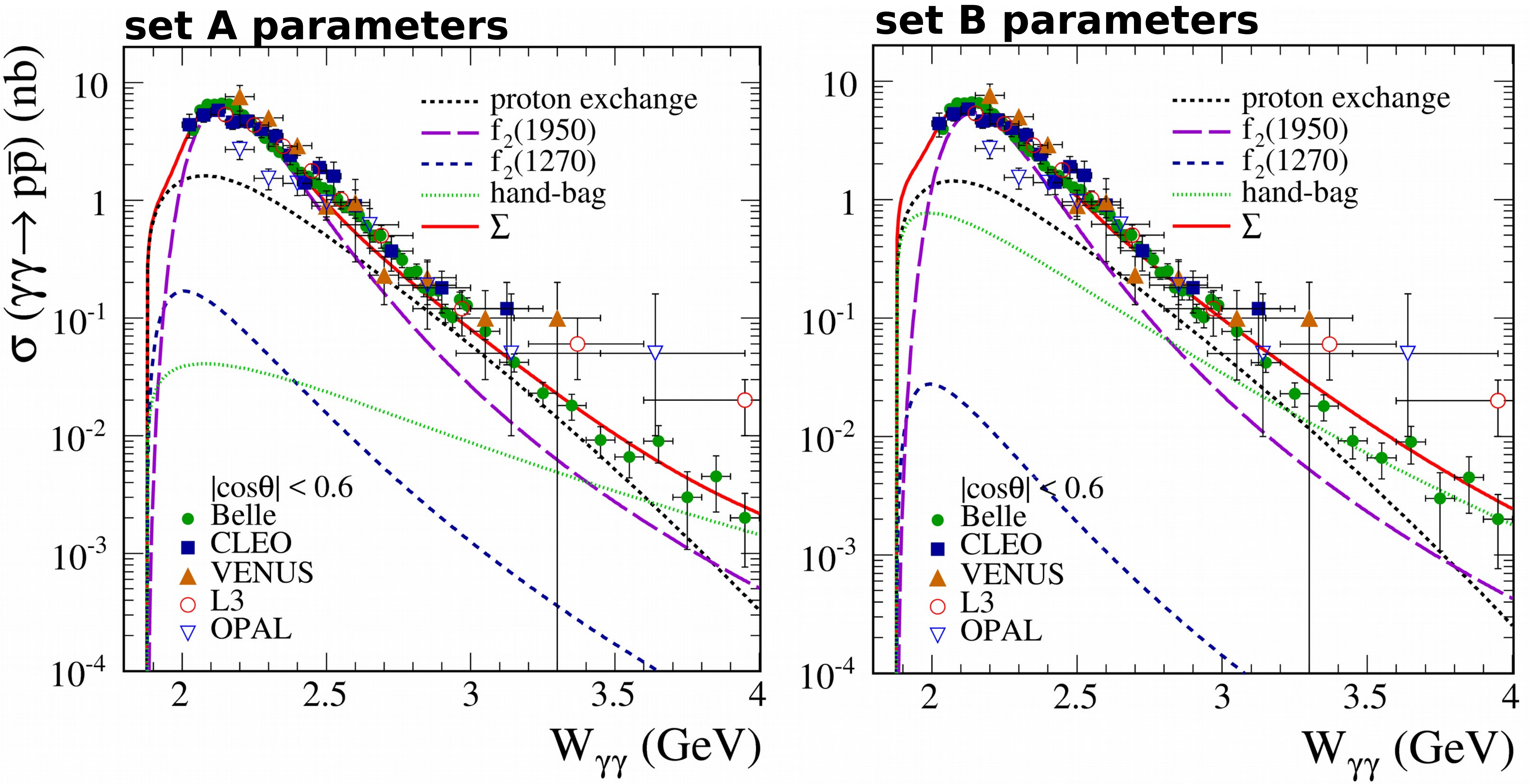
  This opens a possibility to study the $\gamma\gamma \to p\bar{p}$ process in UPC at the LHC and may provide new information compared to the presently available data from e^+e^- collisions, in particular, if structures of y_{diff} distribution can be observed.

Extra Slides



$\sqrt{s_{NN}}$=5.02 TeV
with hb mech.
without hb mech.
|z|<1.0
|z|<0.6
$d\sigma(PbPb \to PbPbp\bar{p})/dW_{\gamma\gamma}$ [nb/GeV]
$W_{\gamma\gamma}$ [GeV]
$d\sigma(PbPb \to PbPbp\bar{p})/dp_t$ [nb/GeV]
p_t [GeV]
$d\sigma(PbPb \to PbPbp\bar{p})/dy_p$ [nb]
y_p
$d\sigma(PbPb \to PbPbp\bar{p})/dy_{diff}$ [nb]
$y_{diff}=y_p-y_{\bar{p}}$

Comparison with experimental data



One can observe the dominance of the f_2(1950) resonance term at low energies.

We slightly underestimate the Belle data around $W_{\gamma\gamma}$ = 2.6 GeV.

Table 1: Model parameters and their numerical values used.

parameter for	eq.	value (set A)	value (set B)
non-resonant $p\bar{p}$			
κ_p		1.7928	1.7928
Λ_p		1.08 GeV	1.07 GeV
$f_2(1270)$			
$a_{f_2\gamma\gamma}$		$\frac{e^2}{4\pi}$ 1.45 GeV^{-3}	$\frac{e^2}{4\pi}$ 1.45 GeV^{-3}
$b_{f_2\gamma\gamma}$		$\frac{e^2}{4\pi}$ 2.49 GeV^{-1}	$\frac{e^2}{4\pi}$ 2.49 GeV^{-1}
M_0		1 GeV	1 GeV
$g^{(1)}_{f_2pp}$		11.04	11.04
$g^{(2)}_{f_2pp}$		0	0
$\Lambda_{f_2,pow}$		1.15 GeV	1 GeV
$f_2(1950)$			
$a_{f_2\gamma\gamma}g^{(2)}_{f_2pp}$		$\frac{e^2}{4\pi}$ 13.05 GeV^{-3}	$\frac{e^2}{4\pi}$ 12 GeV^{-3}
$b_{f_2\gamma\gamma}$		0	0
$g^{(1)}_{f_2pp}$		0	0
$\Lambda_{f_2,pow}$		1.15 GeV	1.15 GeV
hand-bag contribution			
C_A	$R_A(s) = C_A/s$	0.14 GeV^2	
$\tilde{C}_A$	$R_A(s) = \tilde{C}_A/s^2$		2.5 GeV^4
Λ_{hb}		0.85 GeV	0.85 GeV

Resonances that may contribute to $\gamma\gamma \to p\bar{p}$ reaction

Meson	m (MeV)	Γ (MeV)	$\Gamma_{p\bar{p}}/\Gamma$	$\Gamma_{\gamma\gamma}/\Gamma$
$f_2(1270)$	1275.5 ± 0.8	$186.7^{+2.2}_{-2.5}$		$(1.42 \pm 0.24) \times 10^{-5}$
$f_2(1950)$	1944 ± 12	472 ± 18	seen	seen
$\eta_c(1S)$	2983 ± 0.5	31.8 ± 0.8	$(1.50 \pm 0.16) \times 10^{-3}$	$(1.59 \pm 0.13) \times 10^{-4}$
$\chi_{c0}(1P)$	3414.75 ± 0.31	10.5 ± 0.6	$(2.25 \pm 0.09) \times 10^{-4}$	$(2.23 \pm 0.13) \times 10^{-4}$
$\chi_{c2}(1P)$	3556.20 ± 0.09	1.93 ± 0.11	$(7.5 \pm 0.4) \times 10^{-5}$	$(2.74 \pm 0.14) \times 10^{-4}$
$\eta_c(2S)$	3639.2 ± 1.2	$11.3^{+3.2}_{-2.9}$	$< 2 \times 10^{-3}$	$(1.9 \pm 1.3) \times 10^{-4}$

- Above we listed also the sub-threshold $f_2(1270)$ resonance
- The meson masses, their total widths and branching fractions are taken from PDG
- Our knowledge about the $f_2(1950)$ resonance comes from the BES and the CLEO analyses for $\psi(2S) \to \gamma f_2(1950) \to \gamma p\bar{p}$
- The tensor mesons were also needed to describe the Belle data for $\gamma\gamma \to \pi\pi$ processes [see e.g. M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. C87 (2013) 054908]
- The charmonium states (η_c, χ_{c0}) have small total widths thus they will appear as narrow peaks [see e.g. P. Lebiedowicz and A. Szczurek, Phys. Lett. B772 (2017) 330] for $\gamma\gamma \to \gamma\gamma$ reaction

Acknowledgements

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