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The two-photon decay of X(6900) from light-by-light scattering at the LHC
(arXiv: 2207.13623)

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in collaboration with
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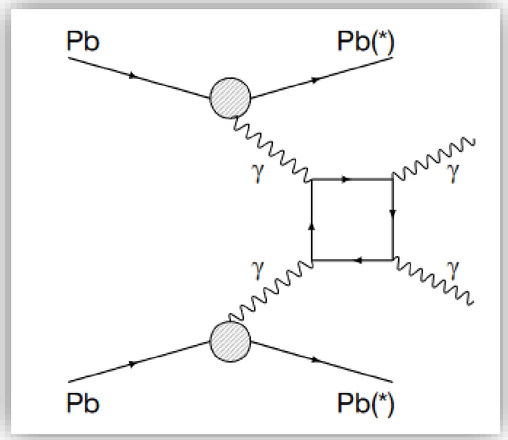
Outline

1. Introduction: two recent discoveries at the LHC
2. Fitting X(6900) into the light-by-light ($\gamma\gamma \to \gamma\gamma$) scattering data
3. Comparison to vector meson dominance estimate
4. Conclusions
5. Formalism of meson exchange in light by light scattering (backup)

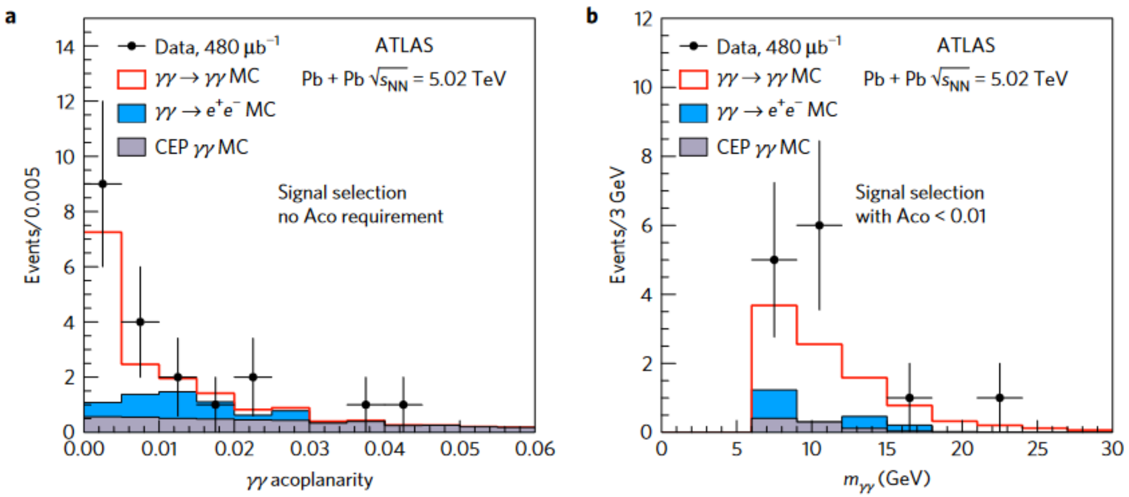
1) Introduction : two recent discoveries at the LHC

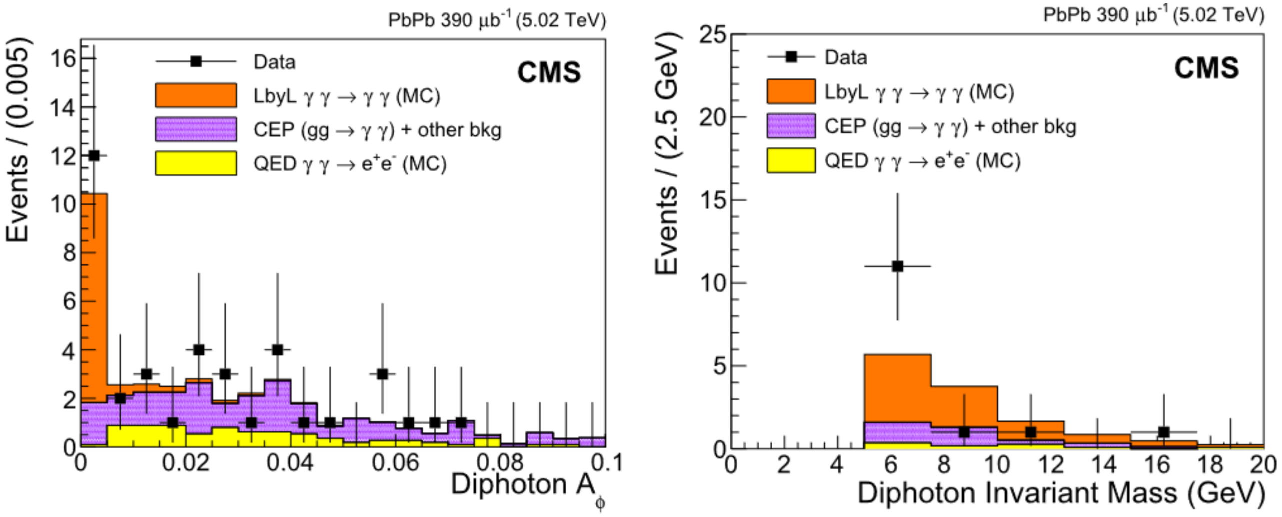
Light-by-light (LbL) scattering at the LHC: pilot experiments

[ATLAS collaboration, **2017**]



[CMS collaboration, **2019**]





$\sigma_{fid.} = 70 \pm 24(stat.) \pm 17(syst.)\ nb$

$\sigma_{fid.} = 120 \pm 46(stat.) \pm 28(syst.) \pm 12(lumi.)\ nb$

LbL scattering at the LHC: full Run-2 dataset

[ATLAS collaboration, 2021]

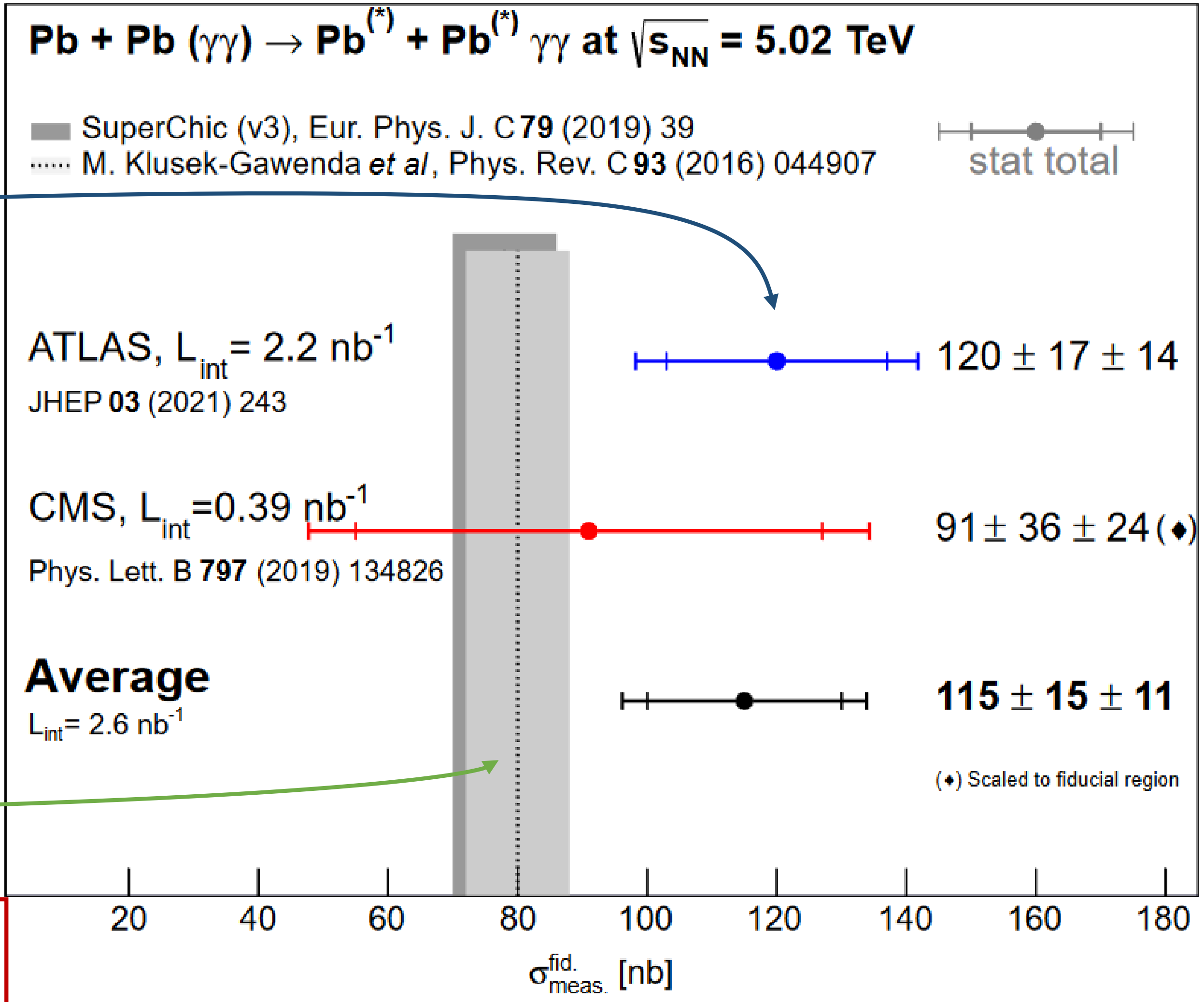
- provide full Run-2 dataset with improved statistics

$$\boxed{\sigma_{fid.} = 120 \pm 17(stat.) \pm 13(syst.) \pm 4(lumi.)\ nb}$$

$\sigma^{theor}_{K-G\ et\ al.} = 80 \pm 8\ nb$ $\sigma^{theor}_{SuperChic} = 78 \pm 8\ nb$

$Data/Theory = 1.50 \pm 0.32$ $Data/Theory = 1.54 \pm 0.32$

Theoretical estimations

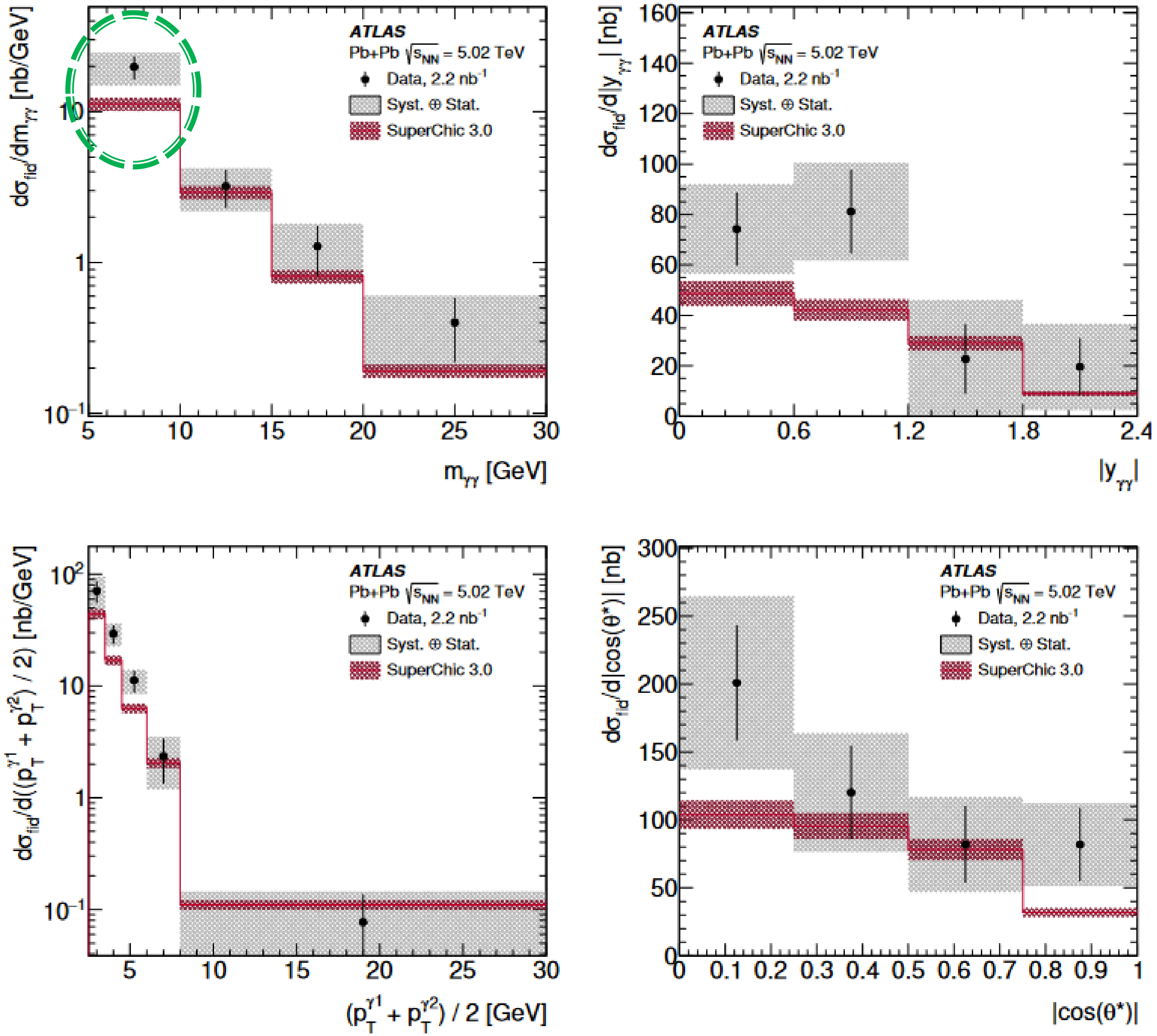


Results show ~2σ **discrepancy** between experimental observations and theoretical predictions

[Krintiras et al., arXiv:2204.02845]

LbL scattering at the LHC: full Run-2 dataset, differential cross sections

The excess is centered on the bin of 5-10 GeV of diphoton invariant mass

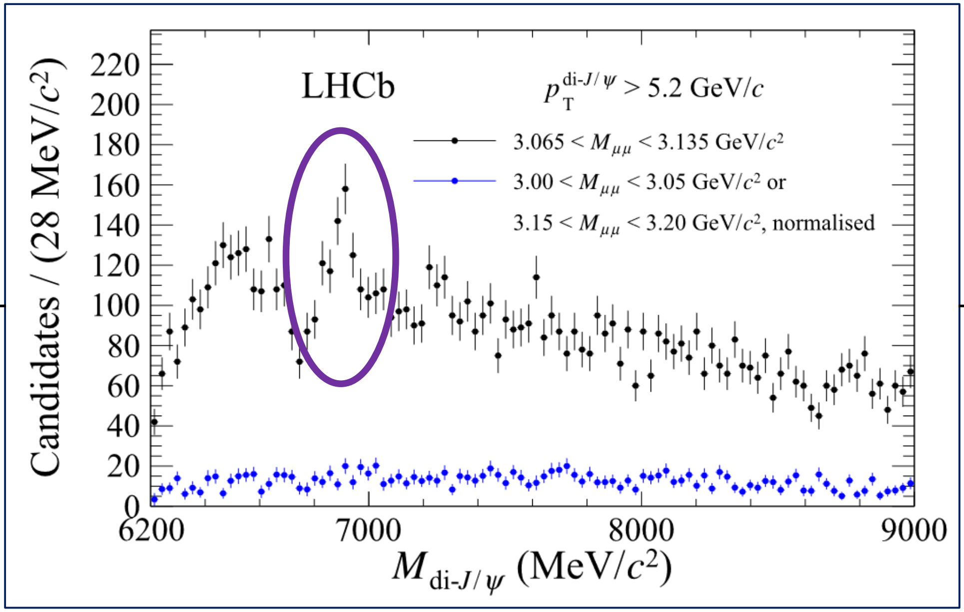


How can the observed mild excess be explained?

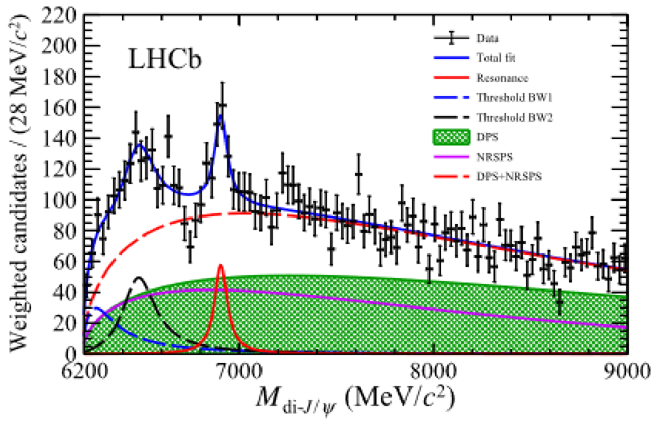
[ATLAS collaboration, 2021]

X(6900) at LHCb

[LHCb collaboration, **2020**]



No-interference fitting scenario



$m[X(6900)] = 6905 \pm 11 \pm 7$ MeV/c^2,

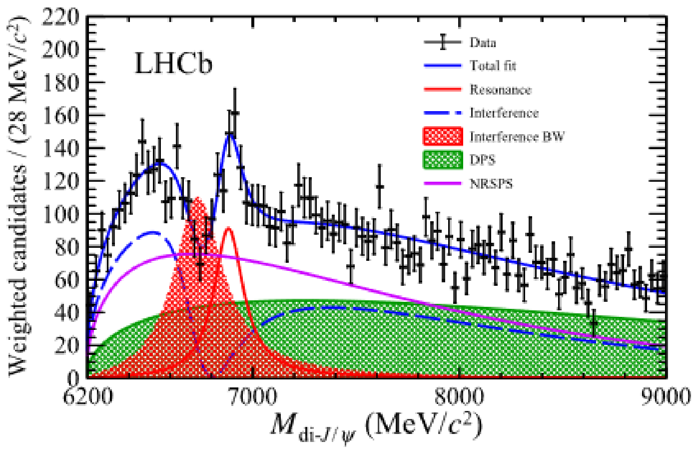
and

$\Gamma[X(6900)] = 80 \pm 19 \pm 33$ MeV,

This state is interpreted as possibly the lightest fully-charmed tetraquark state.

The following quantum numbers are considered for it in the literature on the tetraquark spectra:
$J^{PC} = 0^{++}, 0^{-+}, 1^{-+}, 2^{++}$.

Interference fitting scenario



$m[X(6900)] = 6886 \pm 11 \pm 11$ MeV/c^2

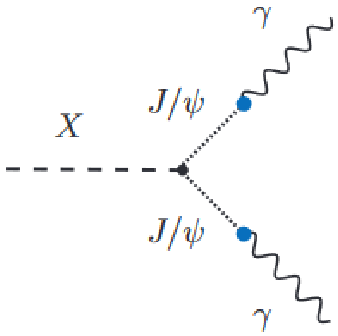
and

$\Gamma[X(6900)] = 168 \pm 33 \pm 69$ MeV.

Since X(6900) decays into 2 J/ψ, then it would likely couple to two photons and hence contribute to the LbL scattering.

- That could explain the discrepancy in light-by-light scattering!

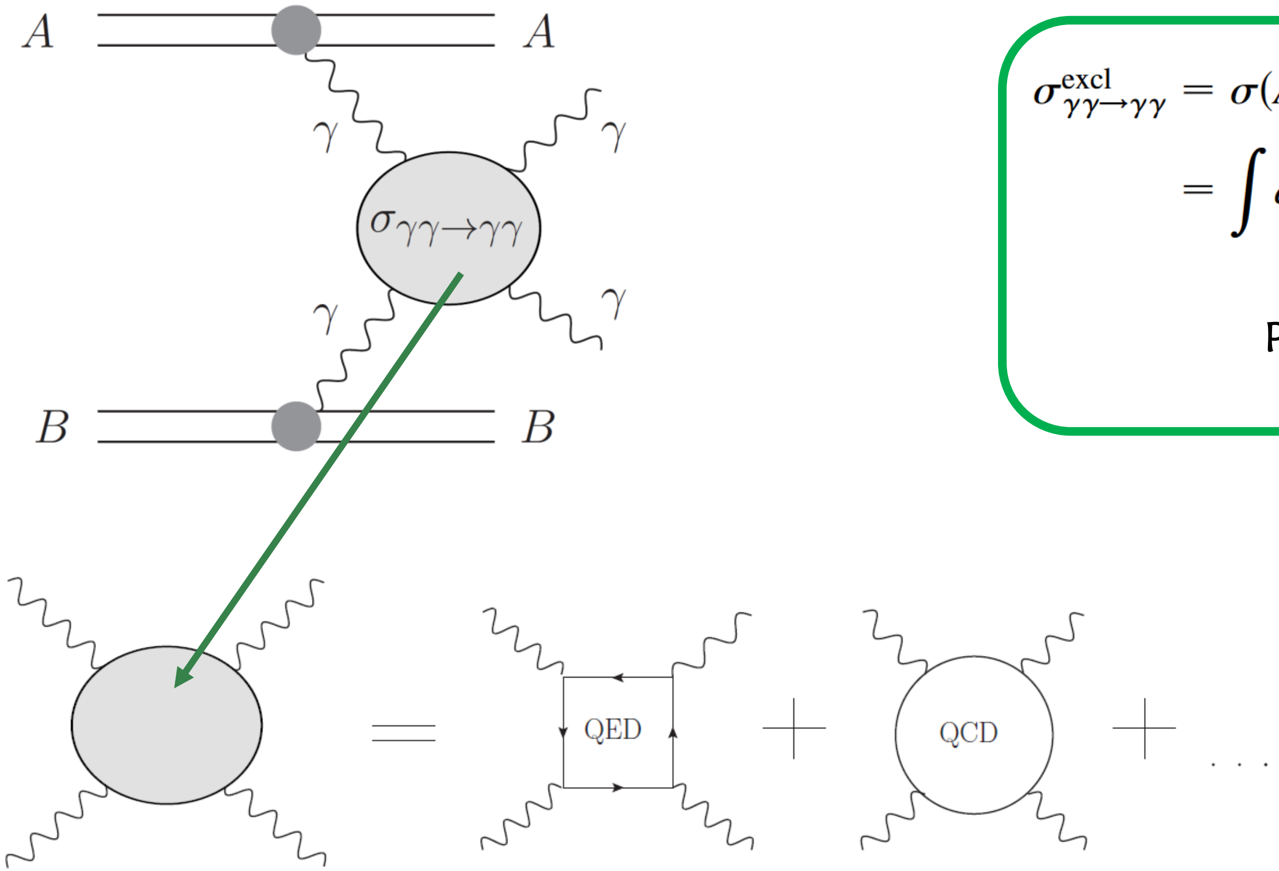
- Then one can extract the $X \to \gamma\gamma$ decay width of X(6900) exactly from the light-by-light data.



The $X(6900) \to \gamma\gamma$ decay via the VMD mechanism.

2) Fitting X(6900) into the light-by-light data

Theoretical approach to LbL scattering in HI collisions

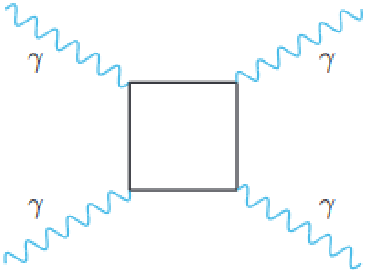


The problematic contributions

$$\sigma^{\mathrm{excl}}_{\gamma\gamma\to\gamma\gamma} = \sigma(AB \xrightarrow{\gamma\gamma} A\gamma\gamma B) = \int d\omega_1 d\omega_2 \underbrace{\frac{f_{\gamma/A}(\omega_1)}{\omega_1}\frac{f_{\gamma/B}(\omega_2)}{\omega_2}}_{\text{Photon fluxes in equivalent photon approximation}} \sigma_{\gamma\gamma\to\gamma\gamma}\left(\sqrt{s_{\gamma\gamma}}\right)$$

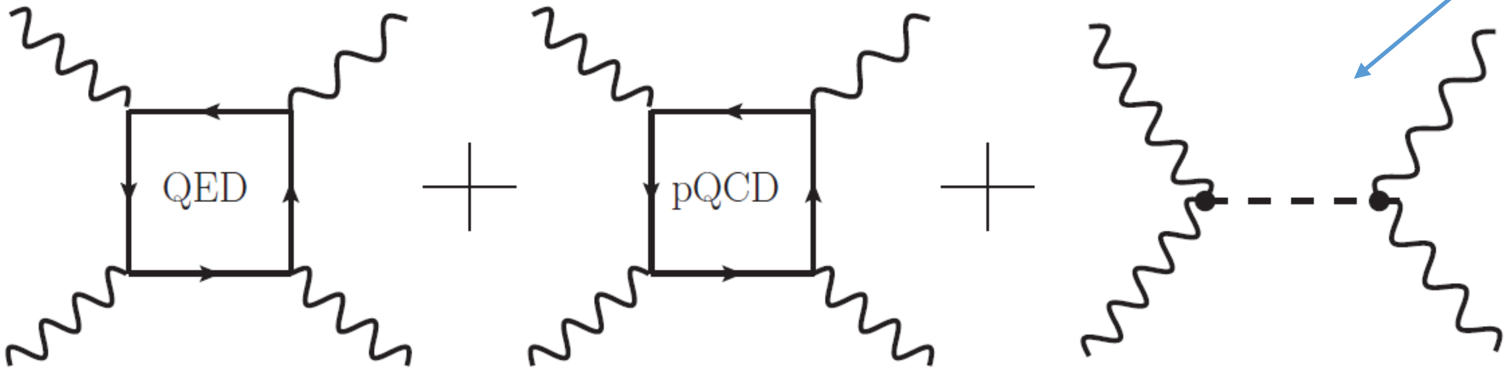
QCD contribution at high di-photon masses (above 5-10 GeV):

The approach, based on pQCD quark loops, described in many works (e.g. [D. d'Enterria and G.G. da Silveira, 2013]) and adopted in <u>SuperChic MC simulator [https://superchic.hepforge.org/] by L. Harland-Lang</u>



Fitting model

Basic SuperChic code



Bottomonium resonances included in the model:

Meson	J^{PC}	M, [MeV]	Γ_{tot}, [MeV]	$\Gamma_{\gamma\gamma}/\Gamma_{tot}$ [%]
$\eta_b(1S)$	0^{-+}	9399.0	17.9	5.87×10^{-3}
$\eta_b(2S)$	0^{-+}	9999.0	8.34	5.86×10^{-3}
$\chi_{b0}(1P)$	0^{++}	9859.44	3.39	5.87×10^{-3}
$\chi_{b0}(2P)$	0^{++}	10232.5	3.54	5.41×10^{-3}

QED loops | pQCD loops | Bottomonium and X(6900) exchanges

"background" | "signal"

- We have fitted the diphoton invariant mass spectrum

Fitting results

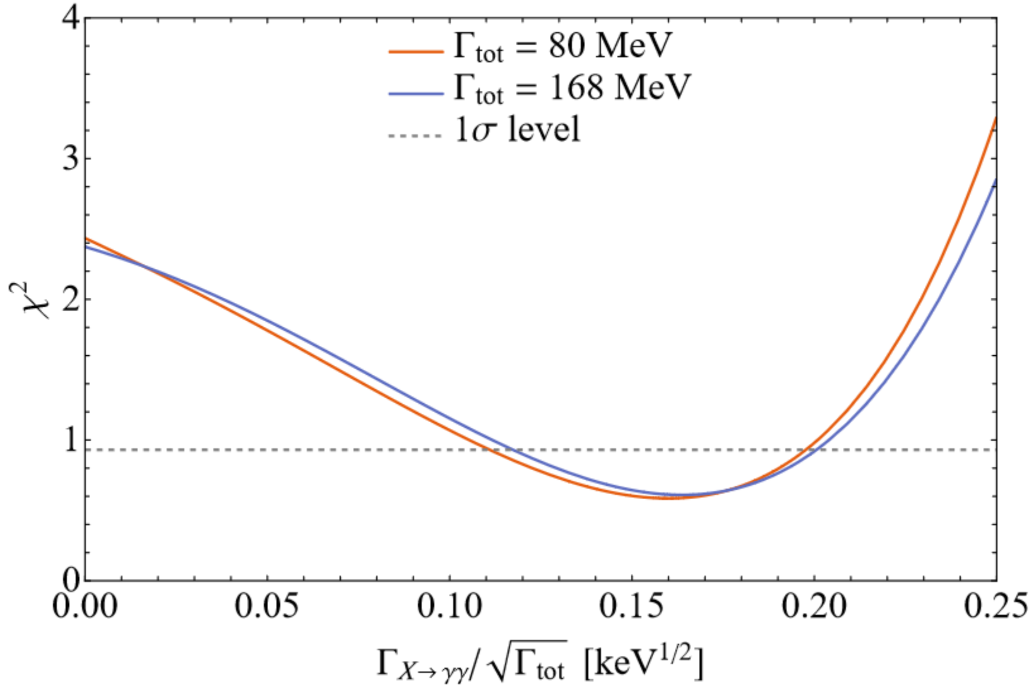


FIG. 1. The profile of χ^2 (divided by #d.o.f. = 3) for the values of Γ_{tot} used in the two LHCb scenarios. The gray dashed line cuts out the 1σ interval.

Numbers

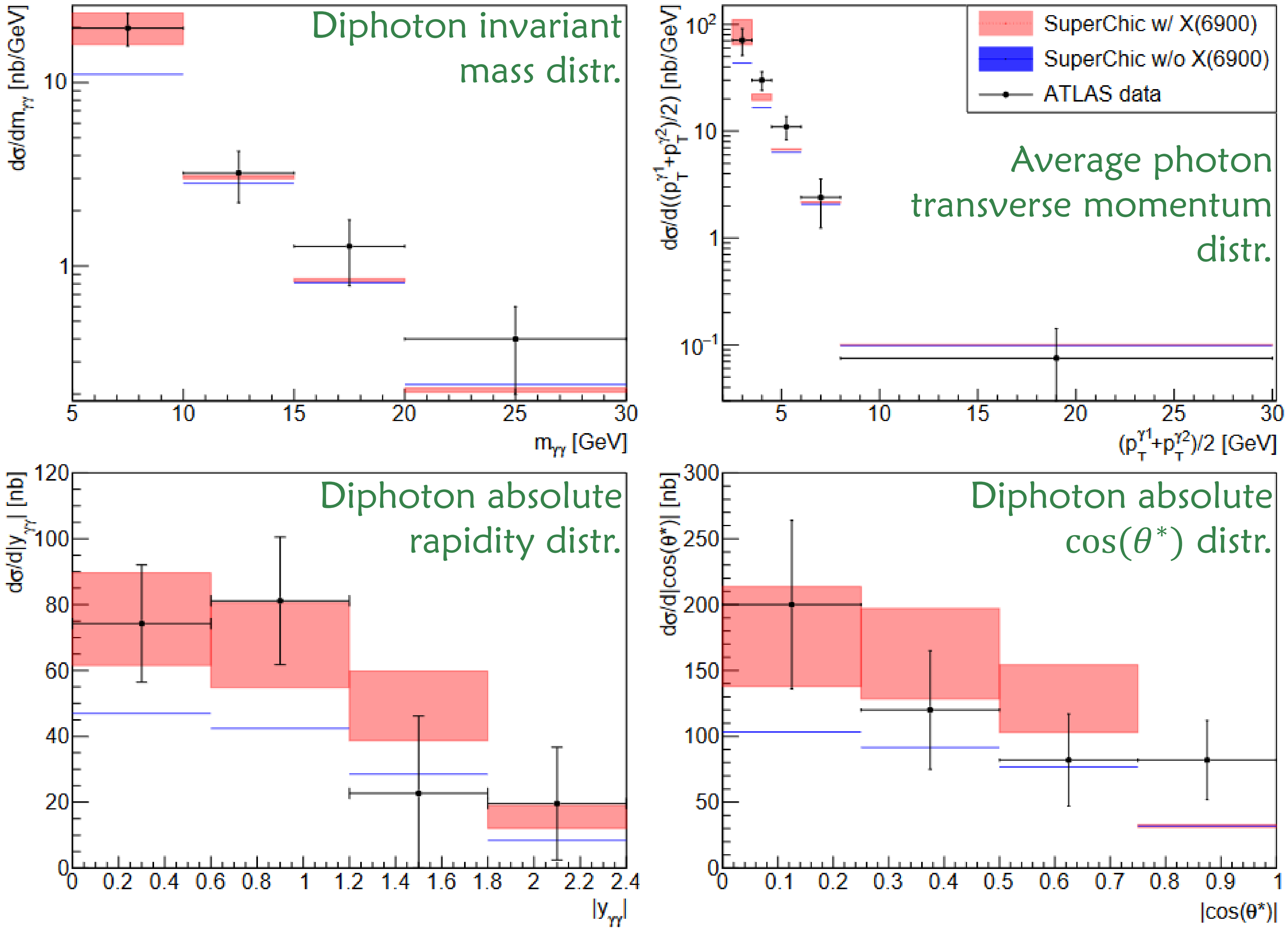
Branching ratio:

$$B(X \to \gamma\gamma) = \begin{cases} 5.6^{+1.3}_{-1.6} \times 10^{-4}, & \text{No-int. sc,} \\ 4.0^{+0.9}_{-1.1} \times 10^{-4}, & \text{Int. sc..} \end{cases}$$

$X \to \gamma\gamma$ decay width:

Parameter	Interference	No-interference
m_X [MeV]	$6886 \pm 11 \pm 11$	$6905 \pm 11 \pm 7$
$\Gamma_{X\to J/\psi J/\psi}$ [MeV]	$168 \pm 33 \pm 69$	$80 \pm 19 \pm 33$
$\Gamma_{X\to\gamma\gamma}$ [keV]	67^{+15}_{-19}	45^{+11}_{-14}

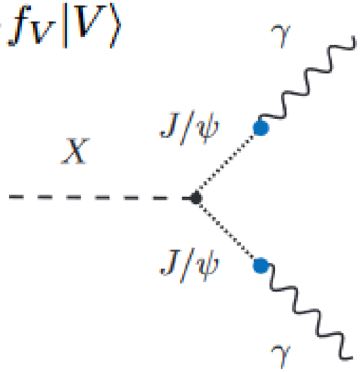
Fitting results



4) Comparison to VMD

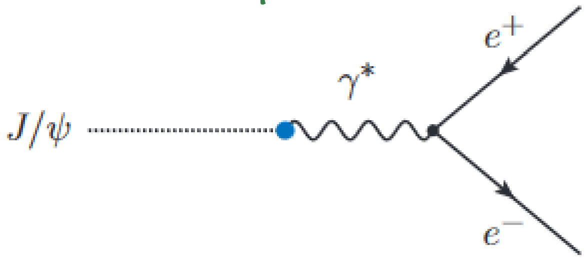
VMD estimate

$$|\gamma\rangle \to \frac{e}{M_V} f_V |V\rangle$$



The $X(6900) \to \gamma\gamma$ decay via the VMD mechanism.

Known from the experiment



$$\Gamma_{J/\psi \to e^+e^-} = \frac{4\pi\alpha^2 f_\psi^2}{3m_\psi}.$$

Here we also assume that the total decay width is dominated by the di-J/ψ width

Master formulae

$$\Gamma^S_{X\to\gamma\gamma} = \Gamma_{X\to J/\psi J/\psi} \left(\frac{ef_\psi}{m_\psi}\right)^4 \left\{\sqrt{1-\frac{4m_\psi^2}{m_X^2}}\left[\left(1-\frac{2m_\psi^2}{m_X^2}\right)^2 + 2\left(\frac{m_\psi}{m_X}\right)^4\right]\right\}^{-1},$$

$$\Gamma^{PS}_{X\to\gamma\gamma} = \Gamma_{X\to J/\psi J/\psi} \left(\frac{ef_\psi}{m_\psi}\right)^4 \left(1-\frac{4m_\psi^2}{m_X^2}\right)^{-\frac{3}{2}}.$$

Estimated branching ratios:

$$B^{\mathrm{S}}_{\mathrm{VMD}}(X \to \gamma\gamma) = (2.8 \pm 0.4) \times 10^{-6},$$
$$B^{\mathrm{PS}}_{\mathrm{VMD}}(X \to \gamma\gamma) = (6.4 \pm 0.8) \times 10^{-6}.$$

can be compared to those extracted from the fit:

$$B(X \to \gamma\gamma) = \begin{cases} 5.6^{+1.3}_{-1.6} \times 10^{-4}, & \text{No-int. sc,} \\ 4.0^{+0.9}_{-1.1} \times 10^{-4}, & \text{Int. sc..} \end{cases}$$

Fit vs. VMD: possible source of discrepancy

- Large uncertainties make the difference insignificant
- Other exotic states could contribute to the diphoton mass region of 5-10 GeV (e.g. at 6.4 GeV, 7.2GeV)

CMS recently detected new exotic states!

M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV	>5.7σ
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV	>9.4σ
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV	>4.1σ

[taken from Kai Yi's talk, CMS Collaboration, **ICHEP 2022**]

4) Conclusions

- ✓ The inclusion of X(6900) improves Standard Model prediction
- ✓ The decay parameters of X(6900) were extracted from LbL scattering data
- ✓ However, VMD estimate gives the number that is ∼2 order smaller.
- ✓ More light-by-light scattering statistics is needed to improve the analysis.
- ✓ The prospective double-differential (or even triple-differential) measurements at LHC may substantially improve the fit.
- ✓ Inclusion of the new states, recently detected by CMS, is in progress…

Thank you for attention!

BACKUP

5) Formalism of meson exchange in light-by-light scattering

Real LbL: preliminaries

16 helicity amplitudes, only 5 are independent:

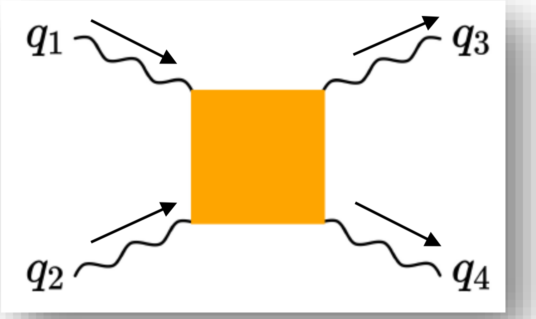
$$\boxed{\mathcal{M}_{++++}(s,t,u)} = \mathcal{M}_{----}(s,t,u),$$

$$\mathcal{M}_{+--+}(s,t,u) = \mathcal{M}_{-++-}(s,t,u) = \boxed{\mathcal{M}_{++++}(t,s,u)},$$

$$\mathcal{M}_{+-+-}(s,t,u) = \mathcal{M}_{-+-+}(s,t,u) = \boxed{\mathcal{M}_{++++}(u,t,s)},$$

$$\boxed{\mathcal{M}_{+++-}(s,t,u)} = \mathcal{M}_{-+--} = \mathcal{M}_{--+-} = \mathcal{M}_{---+}$$
$$= \mathcal{M}_{-+++} = \mathcal{M}_{+-++} = \mathcal{M}_{++-+} = \mathcal{M}_{+---}$$

$$\boxed{\mathcal{M}_{++--}(s,t,u)} = \mathcal{M}_{--++}.$$



$$s = (q_1 + q_2)^2$$
$$t = (q_1 - q_3)^2$$
$$u = (q_1 - q_4)^2$$

$$|\mathcal{M}(s,t,u)|^2 = 2\,|\mathcal{M}_{++++}(s,t,u)|^2 + 2\,|\mathcal{M}_{++++}(u,t,s)|^2 + 2\,|\mathcal{M}_{++++}(t,s,u)|^2 + 8\,|\mathcal{M}_{+++-}(s,t,u)|^2 + 2\,|\mathcal{M}_{++--}(s,t,u)|^2\,.$$

$$\sigma_{\mathrm{LbL}}^{\mathrm{total}}(s) = \frac{1}{256\pi s}\int_{-1}^{1} d\cos\theta\;|\mathcal{M}(s,\cos\theta)|^2$$

BACKUP

Real LbL sum rules

The set of exact LbL forward sum rules connects the LbL helicity amplitudes with the polarized photon absorption cross sections:

$$M_{++++}(s) + M_{+-+-}(s) = \frac{2s^2}{\pi}\int_0^\infty ds' \frac{\sigma_0(s') + \sigma_2(s')}{s'^2 - s^2 - i0^+},$$

$$M_{++++}(s) - M_{+-+-}(s) = \frac{2s}{\pi}\int_0^\infty ds' \frac{s'\left[\sigma_0(s') - \sigma_2(s')\right]}{s'^2 - s^2 - i0^+},$$

$$M_{++--}(s) = \frac{2s^2}{\pi}\int_0^\infty ds' \frac{\sigma_\parallel(s') - \sigma_\perp(s')}{s'^2 - s^2 - i0^+}.$$

[Budnev et al., 1975]

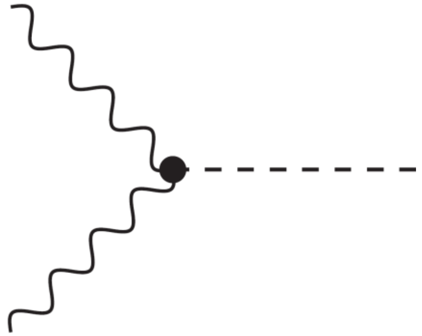
[Pascalutsa and Vanderhaeghen, 2010]

[Pascalutsa, Pauk, Vanderhaeghen, 2012]

In case of meson exchanges the cross sections has the following form:

$$\sigma_0(s) = 16\pi^2 \frac{\Gamma_{\gamma\gamma}}{m}\,\delta(s - m^2), \quad \sigma_2(s) = 0,$$

$$\begin{cases} \sigma_\parallel(s) = \sigma_0(s), & \sigma_\perp(s) = 0, \quad \text{for scalar,} \\ \sigma_\perp(s) = \sigma_0(s), & \sigma_\parallel(s) = 0, \quad \text{for pseudoscalar.} \end{cases}$$



BACKUP

Meson exchange helicity amplitudes

[arXiv: 2207.13623]

The effective interaction Lagrangian term

$$\mathcal{L}_{X\gamma\gamma} = -g_{X\gamma\gamma}\phi_X F^{\mu\nu}F_{\mu\nu}$$

(for the pseudoscalar interaction: $F^{\mu\nu} \to \widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$)

produces the following tree-level helicity amplitudes

Is it satisfies LbL sum rules?

$$\boxed{M^P_{++++}(s,t,u) = -\frac{16\pi s^2\Gamma_{\gamma\gamma}}{m^3\left(s-m^2\right)},}$$

the second sum rule is violated

$$M^P_{+++-}(s,t,u) = 0,$$

$$M^P_{++--}(s,t,u) = -P\frac{16\pi\Gamma_{\gamma\gamma}}{m}\left(\frac{s}{s-m^2}+\frac{t}{t-m^2}+\frac{u}{u-m^2}\right),$$

$$P = \pm 1$$

$$\boxed{M^P_{++++}(s,t,u) = -\frac{16\pi s\,\Gamma_{\gamma\gamma}}{m\left(s-m^2\right)}.}$$

BACKUP

Inclusion of the total decay width for X(6900)

[arXiv: 2207.13623]

We simply make the replacement in the denominators of the helicity amplitudes

$$1/(s-m^2) \longrightarrow 1/\left(s-m^2-\Pi(s)\right)$$

and neglect the real part of the self-energy, taking for its imaginary part the following expressions (**under an assumption that the di-J/ψ decay channel dominates**):

$$\mathrm{Im}\,\Pi_{J/\psi J/\psi}(s)=\frac{1}{16\pi}\sqrt{1-\frac{4m_\psi^2}{s}}\theta\left(s-4m_\psi^2\right)\times\begin{cases} g_{X\psi\psi}^2\left[\left(s-2m_\psi^2\right)^2+2m_\psi^4\right], & \text{for scalar}\\ \tilde{g}_{X\psi\psi}^2 s\left(s-4m_\psi^2\right). & \text{for pseudoscalar}\end{cases}$$

The interaction constants can be expressed exactly in terms of the di-J/ψ decay width