

PROJECT LBL: LIGHT-BY-LIGHT SCATTERING IN ST.MODEL

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with

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Jeremy Green (Mercator)
DESY Zeuthen

Kristof Schmieden
JGU Mainz

Matthias Schott
University of Bonn

“

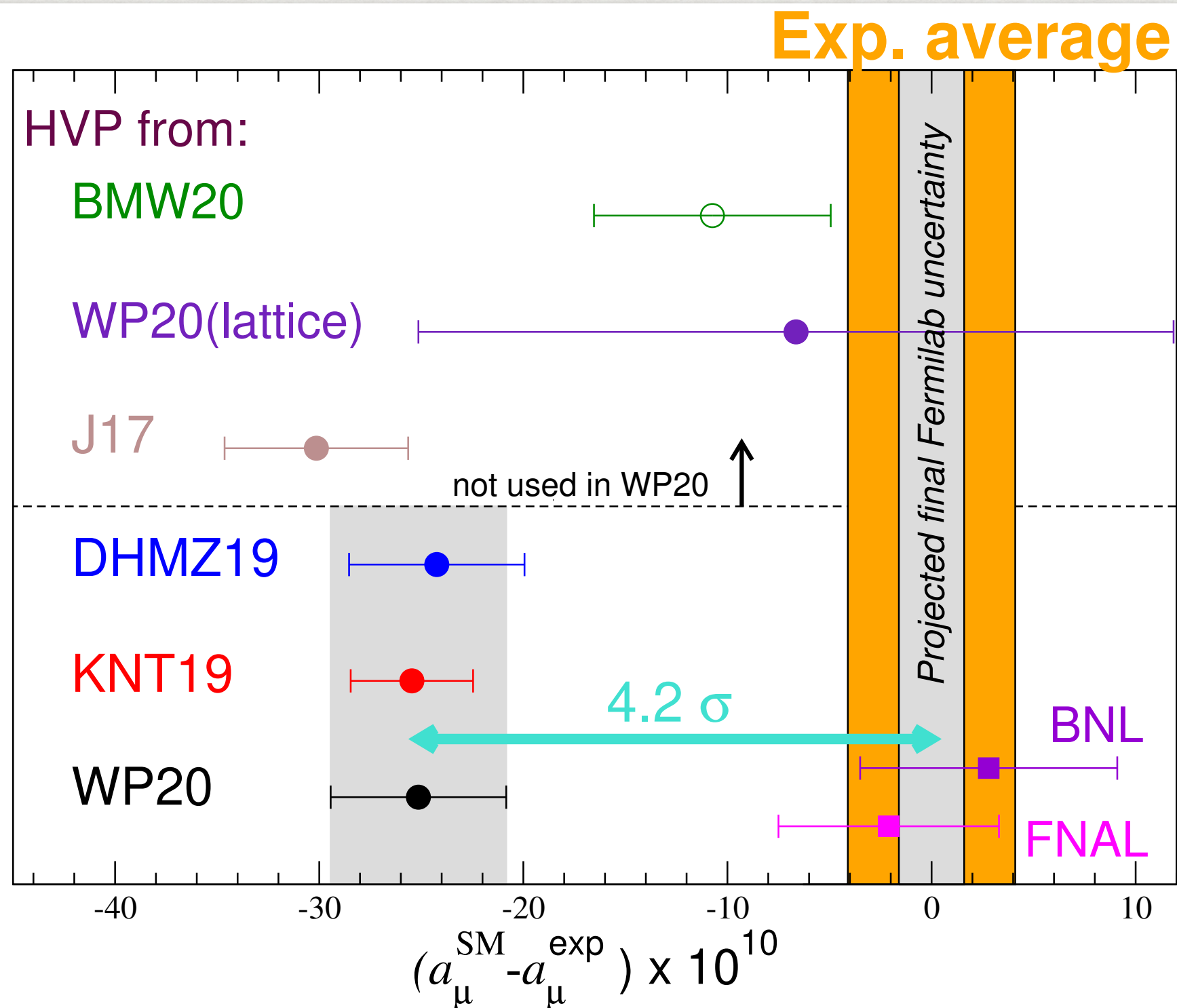
IT IS THE THEORY THAT DECIDES
WHAT WE CAN OBSERVE.

— *Albert Einstein*

”

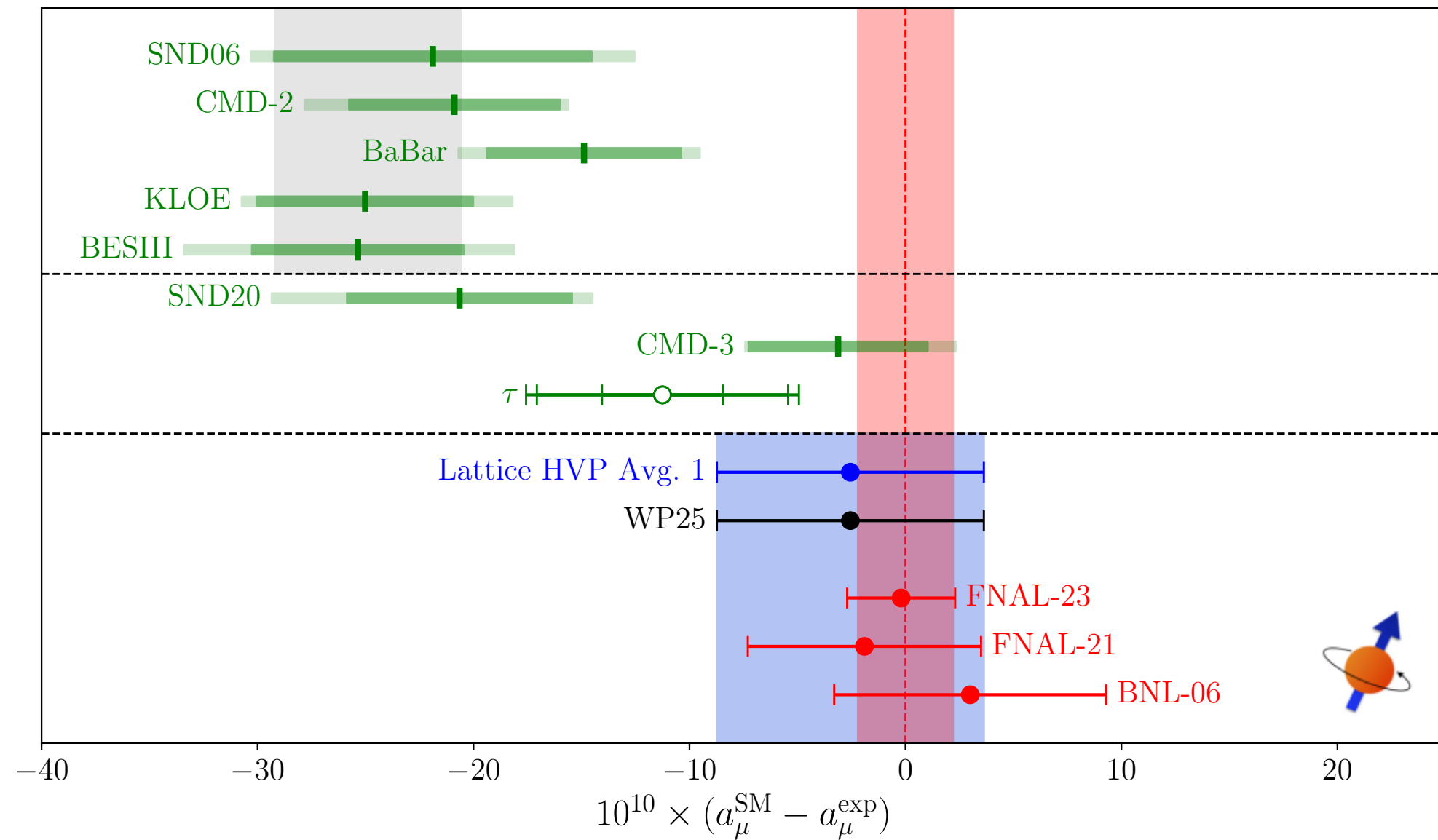
MUON ANOMALY

"THEORY INITIATIVE" WP 2020 VS 2025



MUON ANOMALY

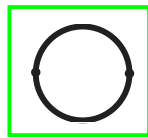
“THEORY INITIATIVE” WP 2020 VS 2025



The different contributions

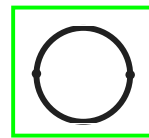
Figure from Borsanyi et al. Nature 2021

Isospin-symmetric



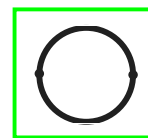
Connected light

$633.7(2.1)_{\text{stat}}(4.2)_{\text{syst}}$



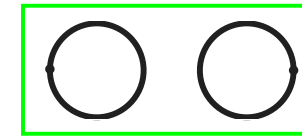
Connected strange

$53.393(89)_{\text{stat}}(68)_{\text{syst}}$



Connected charm

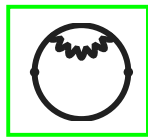
$14.6(0)_{\text{stat}}(1)_{\text{syst}}$



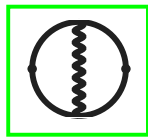
Disconnected

$-13.36(1.18)_{\text{stat}}(1.36)_{\text{syst}}$

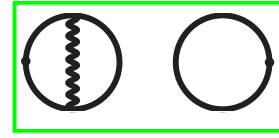
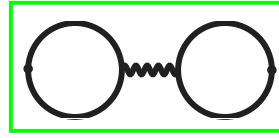
QED isospin breaking: valence



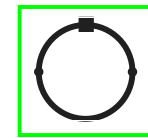
Connected $-1.23(40)_{\text{stat}}(31)_{\text{syst}}$



Disconnected $-0.55(15)_{\text{stat}}(10)_{\text{syst}}$

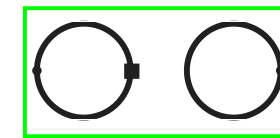


Strong-isospin breaking



Connected

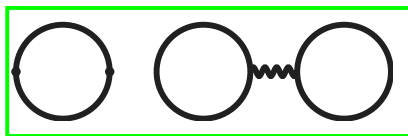
$6.60(63)_{\text{stat}}(53)_{\text{syst}}$



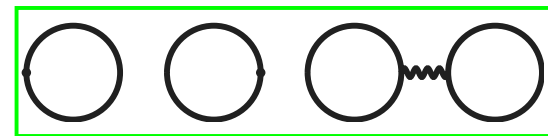
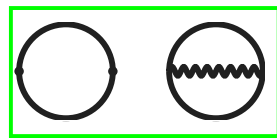
Disconnected

$-4.67(54)_{\text{stat}}(69)_{\text{syst}}$

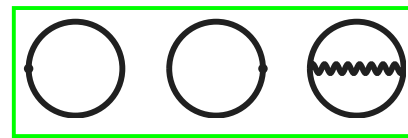
QED isospin breaking: sea



Connected $0.37(21)_{\text{stat}}(24)_{\text{syst}}$



Disconnected $-0.040(33)_{\text{stat}}(21)_{\text{syst}}$

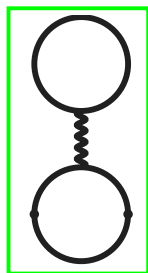


Other

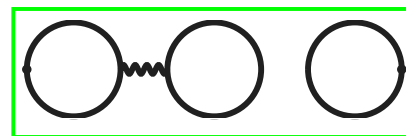
Bottom; higher-order;
perturbative

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Finite-size effects

Isospin-symmetric

$18.7(2.5)_{\text{tot}}$

Isospin-breaking

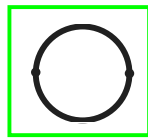
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The different contributions

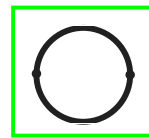
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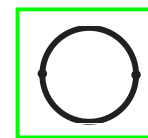
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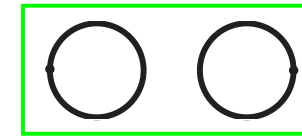
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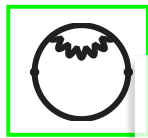
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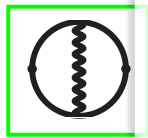
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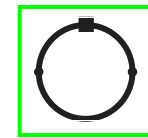
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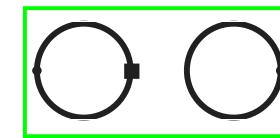
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Strong-isospin breaking



Connected

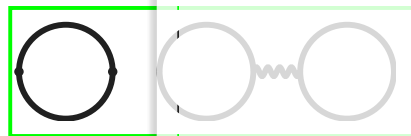
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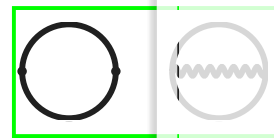
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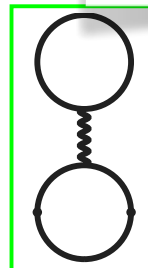
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Bottom; higher-order;
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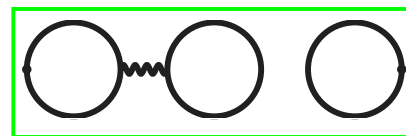
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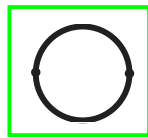
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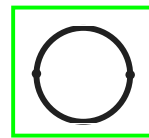
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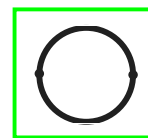
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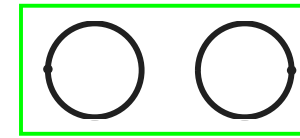
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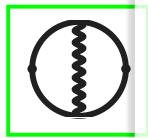
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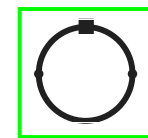
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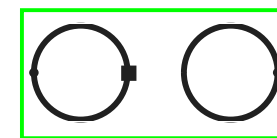
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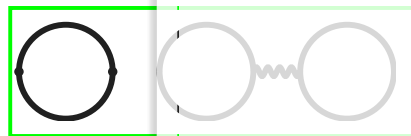
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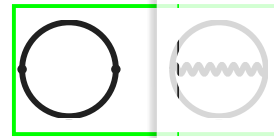
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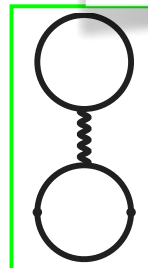
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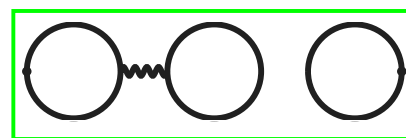
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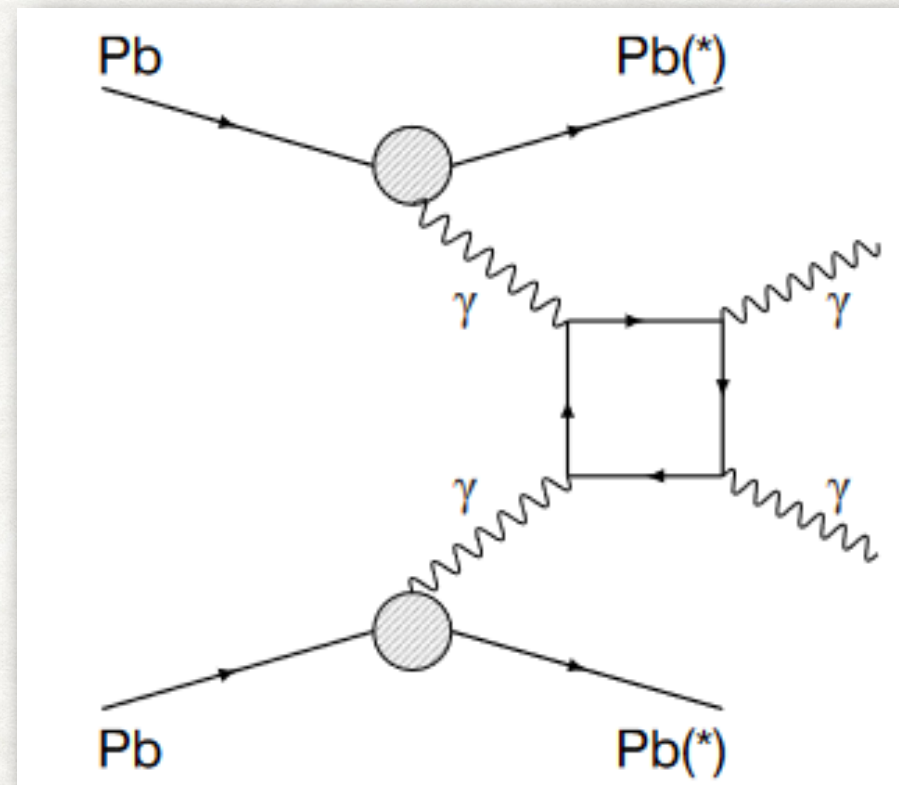
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QUASI-REAL LIGHT-BY-LIGHT SCATTERING AT THE LHC

IN ULTRA-PERIPHERAL COLLISIONS (ATLAS, CMS)

Large s, t, u

$$(s + t + u = 0)$$



$$\begin{aligned}\sigma_{\gamma\gamma\rightarrow\gamma\gamma}^{\text{excl}} &= \sigma(AB \xrightarrow{\gamma\gamma} A\gamma\gamma B) \\ &= \int d\omega_1 d\omega_2 \underbrace{\frac{f_{\gamma/A}(\omega_1)}{\omega_1} \frac{f_{\gamma/B}(\omega_2)}{\omega_2}}_{\text{Photon fluxes in equivalent photon approximation}} \sigma_{\gamma\gamma\rightarrow\gamma\gamma}(\sqrt{s_{\gamma\gamma}})\end{aligned}$$

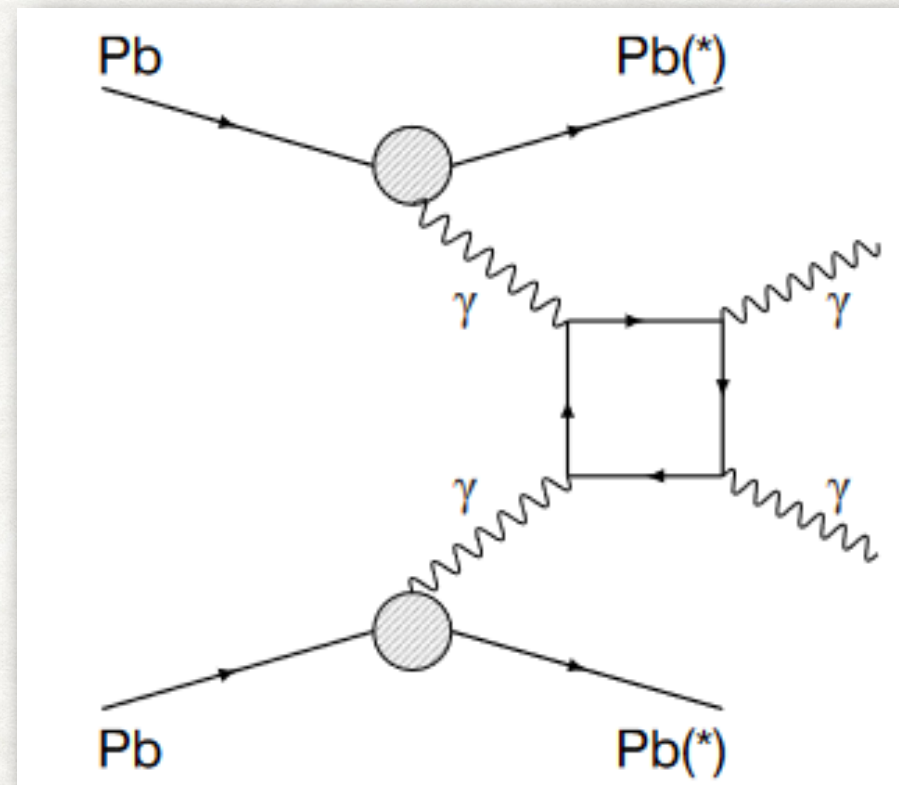
Photon fluxes in equivalent
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LBL-1
THEORY

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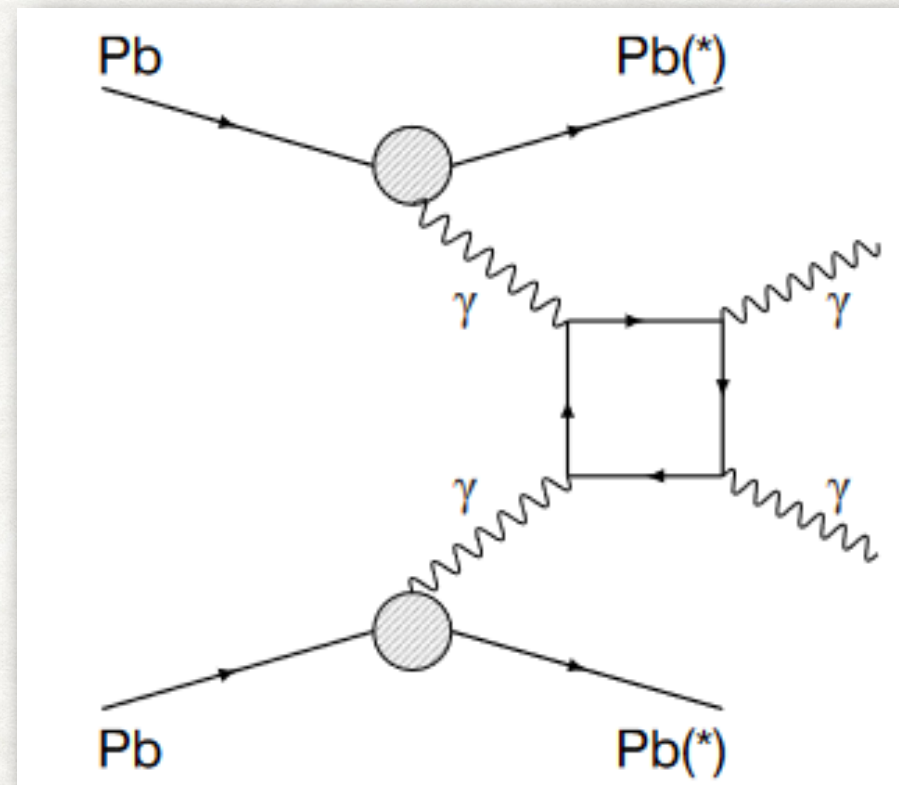
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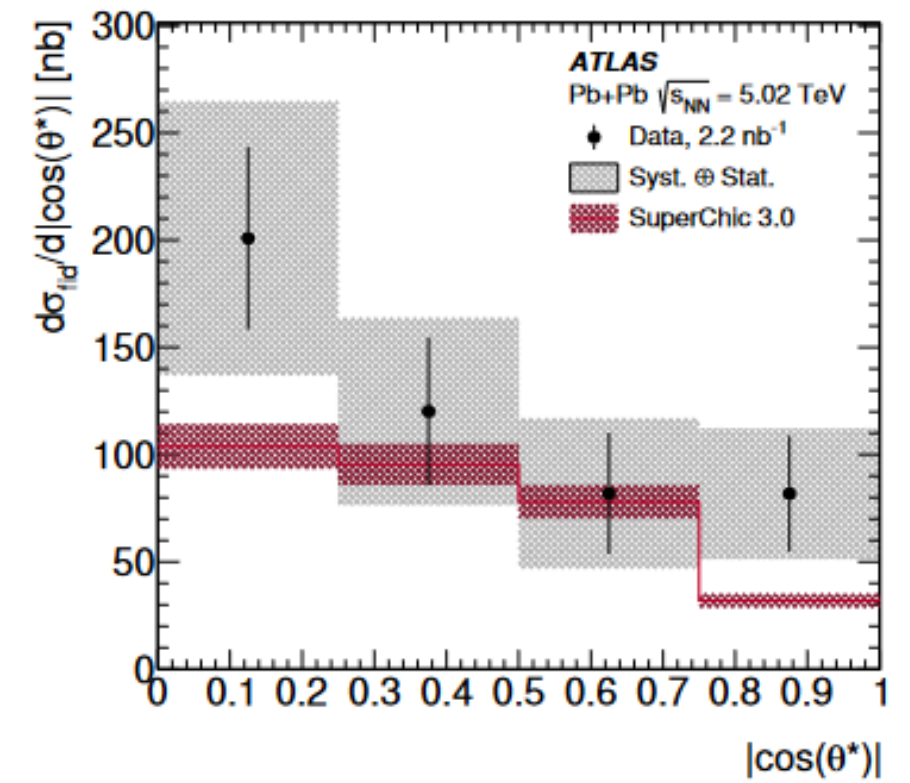
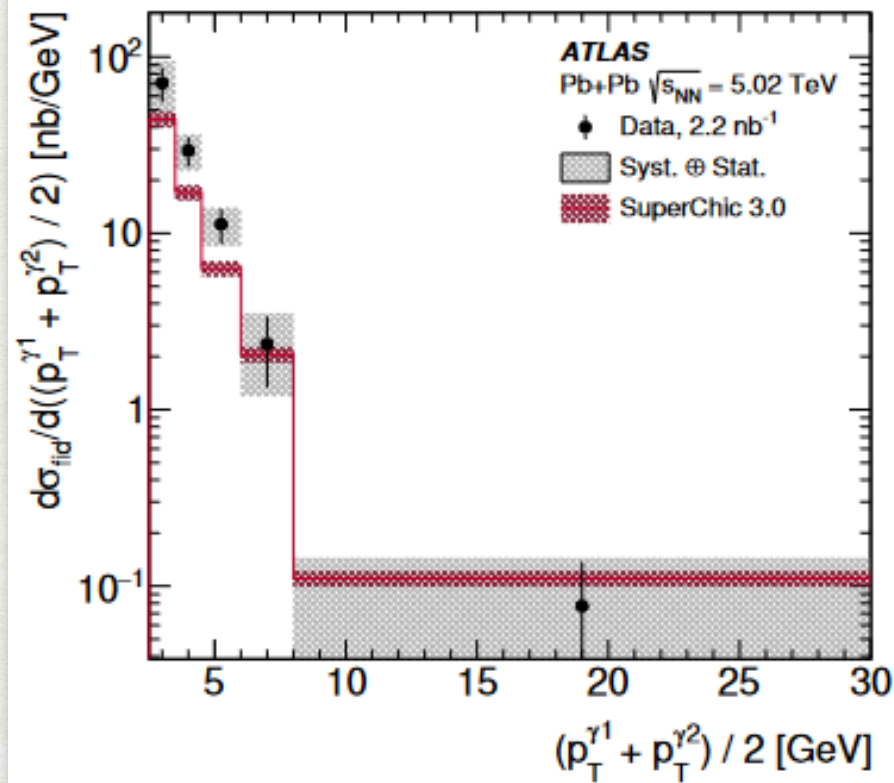
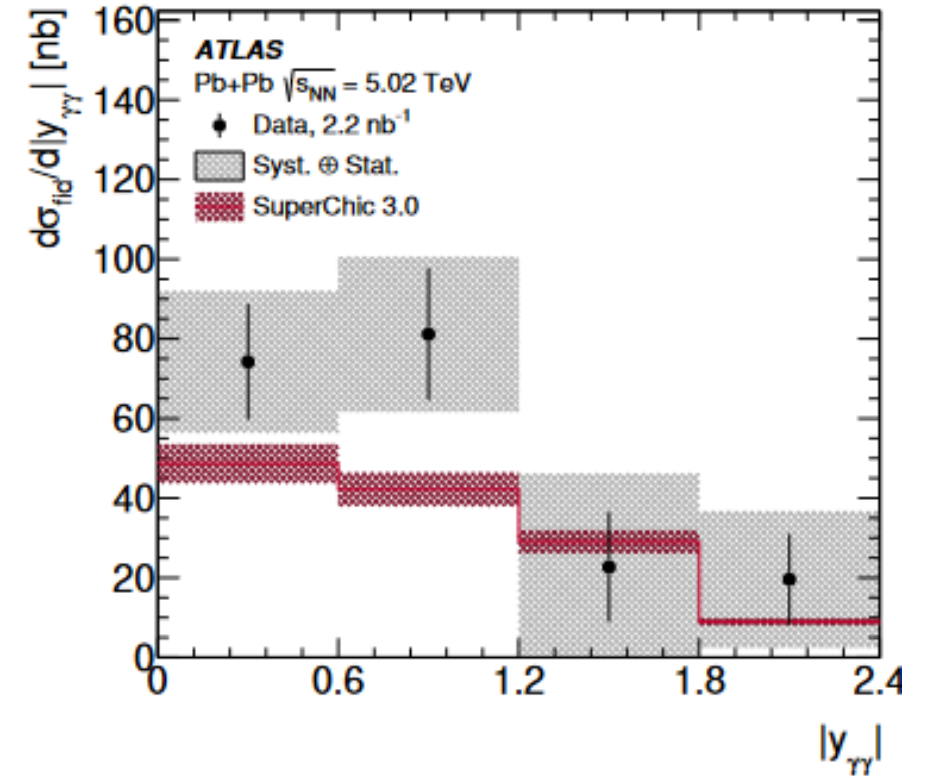
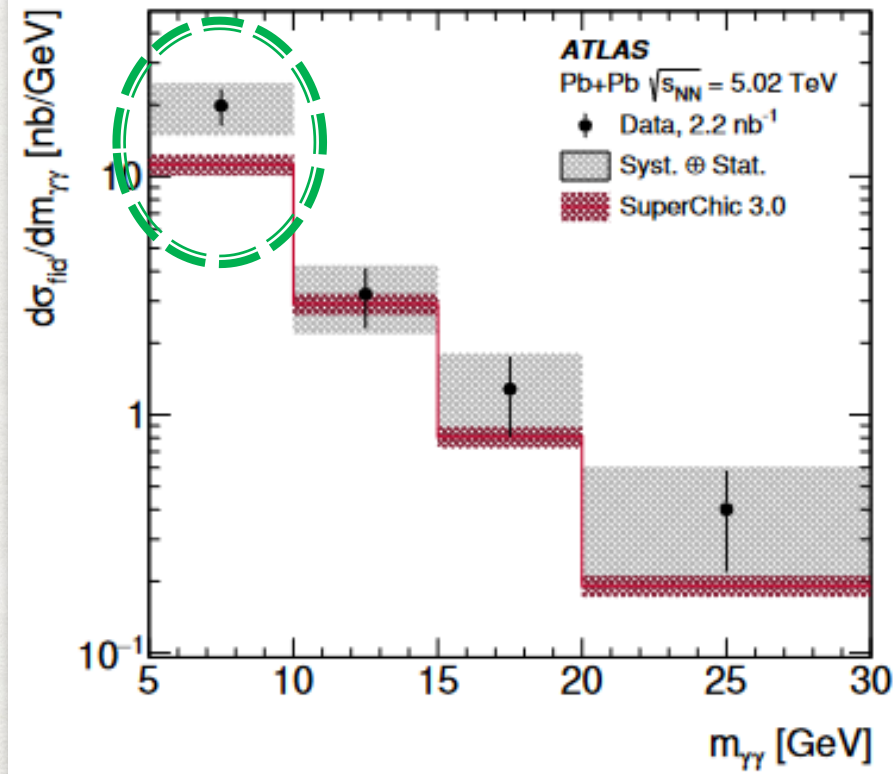
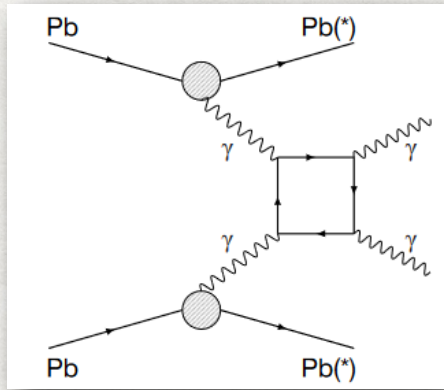


LBL-1
THEORY

LBL-2
EXPERIMENT

$$\begin{aligned}\sigma_{\gamma\gamma\rightarrow\gamma\gamma}^{\text{excl}} &= \sigma(AB \xrightarrow{\gamma\gamma} A\gamma\gamma B) \\ &= \int d\omega_1 d\omega_2 \underbrace{\frac{f_{\gamma/A}(\omega_1)}{\omega_1} \frac{f_{\gamma/B}(\omega_2)}{\omega_2}} \sigma_{\gamma\gamma\rightarrow\gamma\gamma}(\sqrt{s_{\gamma\gamma}})\end{aligned}$$

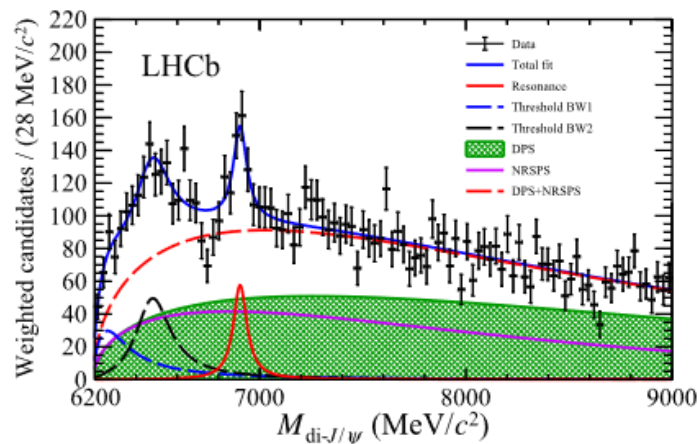
Photon fluxes in equivalent
photon approximation



NEW STATE X(6900)

[LHCb collaboration, 2020]

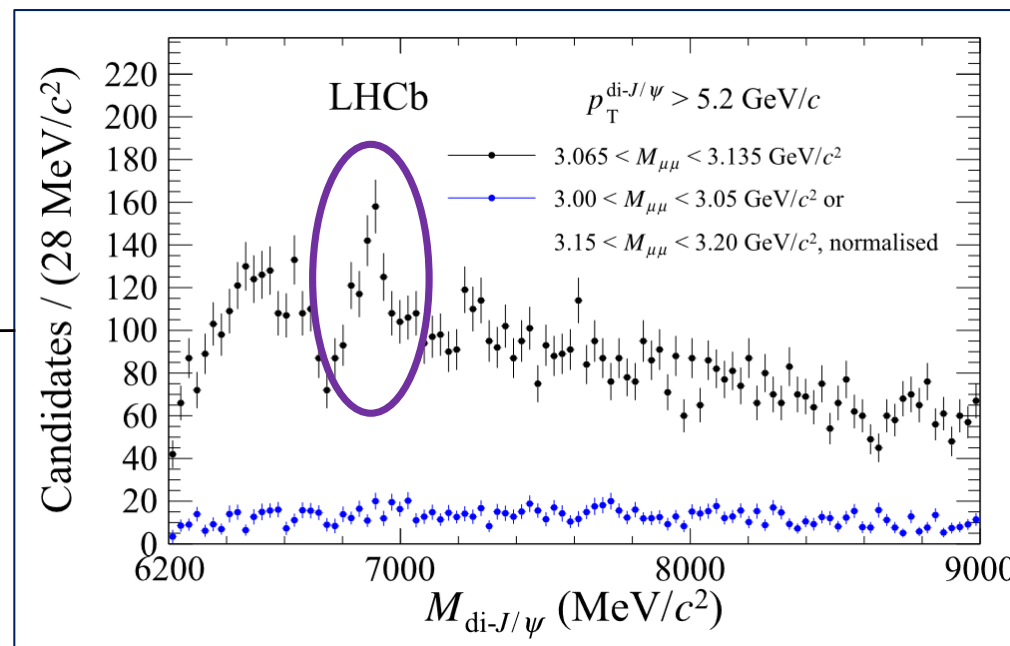
No-interference
fitting scenario



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

and

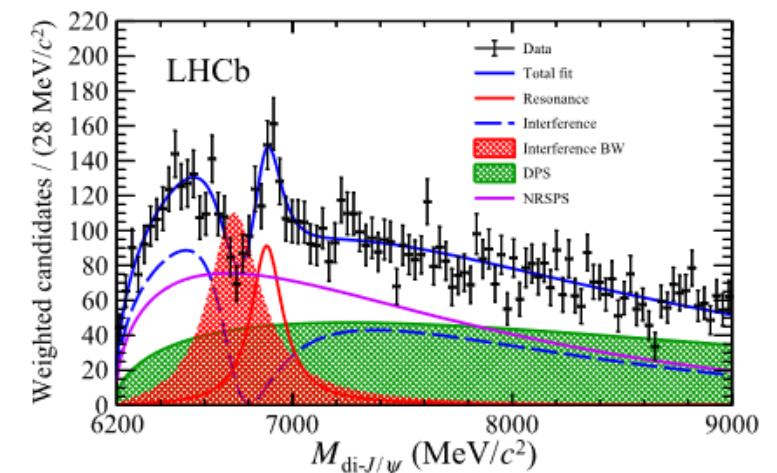
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33 \text{ MeV},$$



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

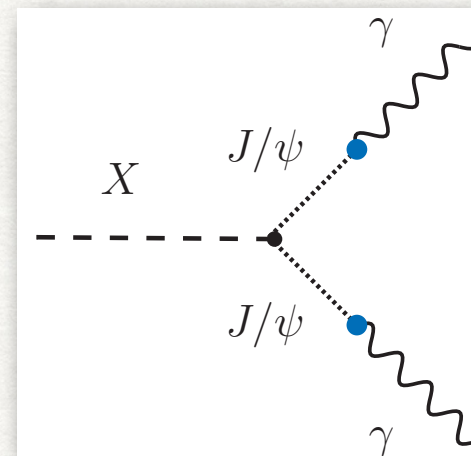
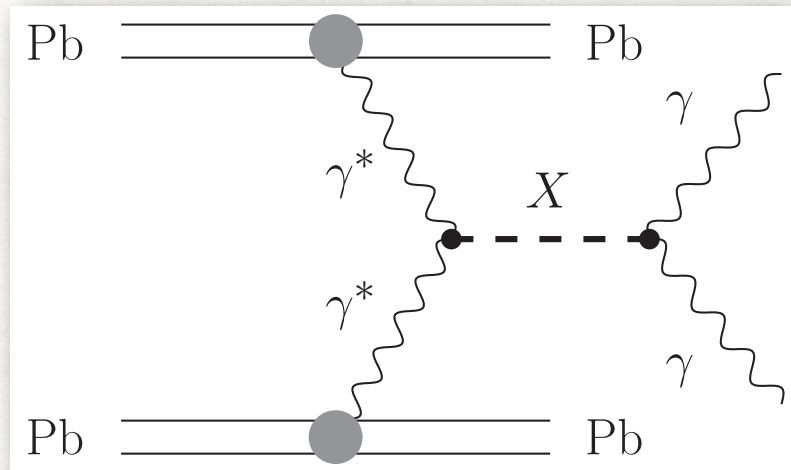


$$m[X(6900)] = 6886 \pm 11 \pm 11 \text{ MeV}/c^2$$

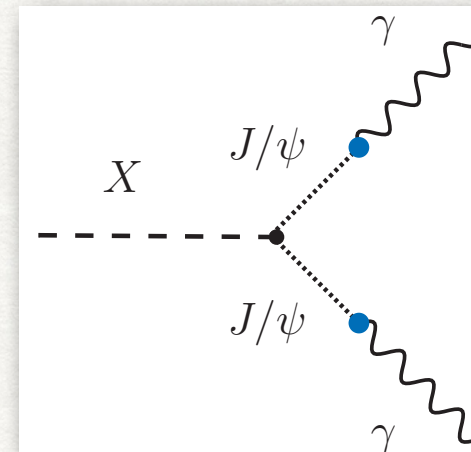
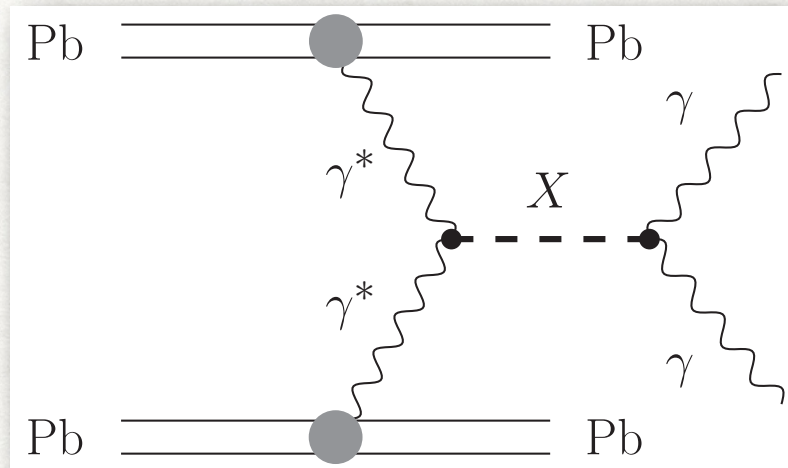
and

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

LBL-1



LBL-1



PHYSICAL REVIEW D **106**, L111902 (2022)

Letter

Two-photon decay of $X(6900)$ from light-by-light scattering at the LHC

Volodymyr Biloshytskyi^{[ID](#)} and Vladimir Pascalutsa^{[ID](#)}

Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany

Lucian Harland-Lang

Rudolf Peierls Centre, Beecroft Building, Parks Road, Oxford OX1 3PU, United Kingdom

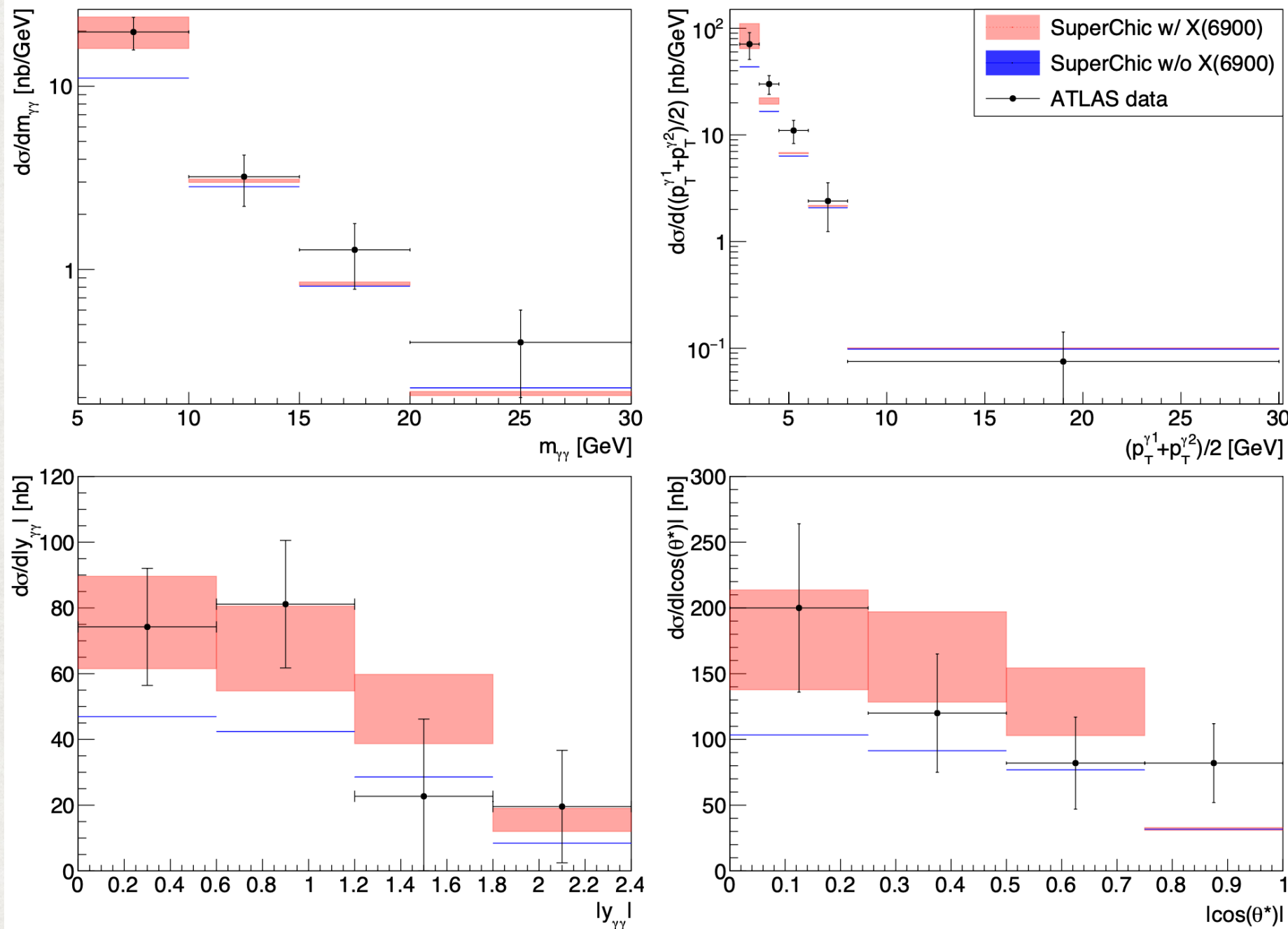
Bogdan Malaescu^{[ID](#)}

LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, 75252 Paris, France

Kristof Schmieden and Matthias Schott

Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany

The X(6900) state with LHCb parameters is fitted to the ATLAS data for LbL scattering



- X(6900) was embedded into SuperChic v3.5 at the level of helicity amplitude as a scalar (pseudoscalar) exchange
- Background: QED, pQCD and bottomonium exchanges
- Fit of the diphoton invariant mass spectrum

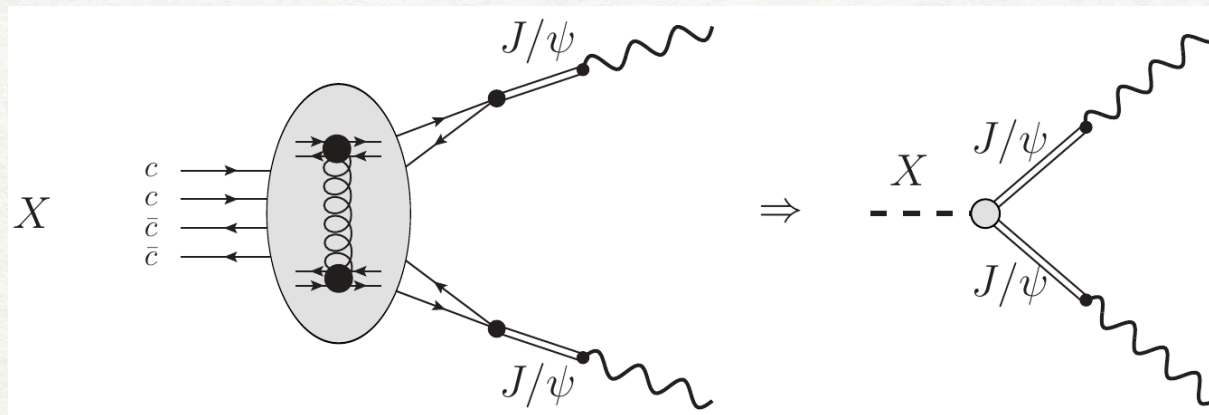
$$\chi^2/N_{\text{d.o.f.}} \approx 0.6$$

$$\Gamma_{X \rightarrow \gamma\gamma} = \begin{cases} 67_{-19}^{+15} \text{ [keV]}, & \text{model I} \\ 45_{-14}^{+11} \text{ [keV]}, & \text{model II} \end{cases}$$

$$\Gamma_{X \rightarrow \gamma\gamma} = \begin{cases} 67^{+15}_{-19} \text{ [keV]}, & \text{model I} \\ 45^{+11}_{-14} \text{ [keV]}, & \text{model II} \end{cases}$$

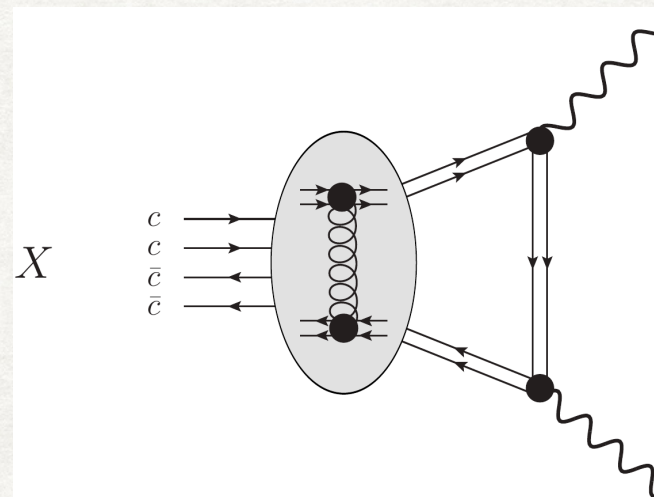
Two-photon decay width estimates

- Charmonium molecule structure \rightarrow vector-meson dominance



$$\Gamma_{X \rightarrow \gamma\gamma} \sim 0.1 \dots 1 \text{ keV}$$

- Decay of diquark-antidiquark state



$$\Gamma_{X \rightarrow \gamma\gamma} \sim 10 \text{ keV}$$

UPDATED FOR MORE NEW STATES

- CMS Collaboration (2022), di- J/ψ
 - ✓ X(6600) 6.5σ
 - ✓ X(6900) 9.4σ
 - ✓ X(7200) 4.1σ
- ATLAS Collaboration (2022), di- J/ψ , $J/\psi \psi(2S)$

di- J/ψ	$J/\psi \psi(2S)$
✓ X(6900) $>5\sigma$	✓ X(7200) 3.2σ

Two-photon decay of fully-charmed tetraquarks from light-by-light scattering at the LHC

Volodymyr Biloshytskyi^{1,*}, *Lucian Harland-Lang*², *Bogdan Malaescu*³, *Vladimir Pascalutsa*¹, *Kristof Schmieden*⁴, and *Matthias Schott*⁴,

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XVth Quark Confinement and the Hadron Spectrum

X-state nature	$\Gamma_{X(6600) \rightarrow \gamma\gamma}$ [keV]	$\Gamma_{X(6900) \rightarrow \gamma\gamma}$ [keV]	$\Gamma_{X(7300) \rightarrow \gamma\gamma}$ [keV]
scalar	1.6 ± 1.1	0.57 ± 0.18	0.23 ± 0.11
pseudoscalar	5.1 ± 3.4	1.4 ± 0.4	0.43 ± 0.21

LBL TIMELINE

Project	2022	2023	2024	2025	2026	2027	2028	2029
LBL-1	Real LbL theory, resonances				Possible improvements of theory and Superchic, anticipating the Run-4 at the LHC			
	Development and upgrade of Superchic (MC generator)				X(6900) and new states in Run 3 and 4 at the LHC			
	X(6900) in existing data							
LBL-2	ATLAS data taking (Run-3)				Preparation and Run-4			
	Analysis of LbL observables using updated Superchic							
LBL-3	Lattice QCD calculation of forward LbL amplitudes in (2+1)-flavour QCD				Lattice QCD calculation of LbL including the charm-quark valence contribution			
	Data-driven dispersive evaluation, interpretation of lattice results, connection with experimental data				Complementary dispersive evaluation, interpretation			

LBL-3

IN CONJUNCTION WITH JRP-3



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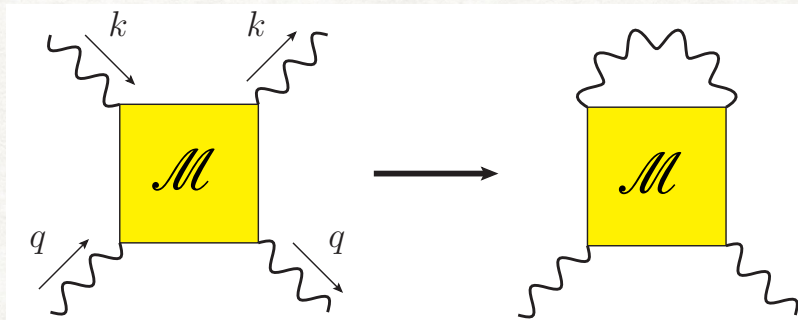
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Forward light-by-light scattering and electromagnetic correction to hadronic vacuum polarization

Volodymyr Biloshytskyi,^a En-Hung Chao,^a Antoine Gérardin,^e Jeremy R. Green,^b
Franziska Hagelstein,^{a,c} Harvey B. Meyer,^{a,d} Julian Parrino^a and Vladimir Pascalutsa^a

- Electromagnetic correction to the vacuum polarization via the Cottingham-like formula involving the forward doubly-virtual light-by-light amplitude \mathcal{M}



$$\Pi_{4\text{pt}}(q^2, \Lambda) = \frac{1}{3} g_{\mu\nu} \Pi_{4\text{pt}}^{\mu\nu}(q) = \frac{1}{6q^2} \int \frac{d^4k}{(2\pi)^4} \left[\frac{-i}{k^2 + i0^+} \right]_{\Lambda} \mathcal{M}(k, q)$$

$$\mathcal{M}(\nu, K^2, Q^2) \equiv g_{\mu\nu} g_{\sigma\rho} \mathcal{M}^{\mu\nu\sigma\rho}(\nu, K^2, Q^2) \quad \nu = k \cdot q, \quad k^2 = -K^2, \quad q^2 = -Q^2, \quad X = \nu^2 - K^2 Q^2$$

The advantage in lattice calculations:

photon propagator splitting: $\frac{1}{k^2} = \left(\frac{1}{k^2} - \frac{1}{k^2 + \Lambda^2} \right) + \frac{1}{k^2 + \Lambda^2}$ $\Lambda \approx 400 \text{ MeV}$ - separation scale

long-distance part

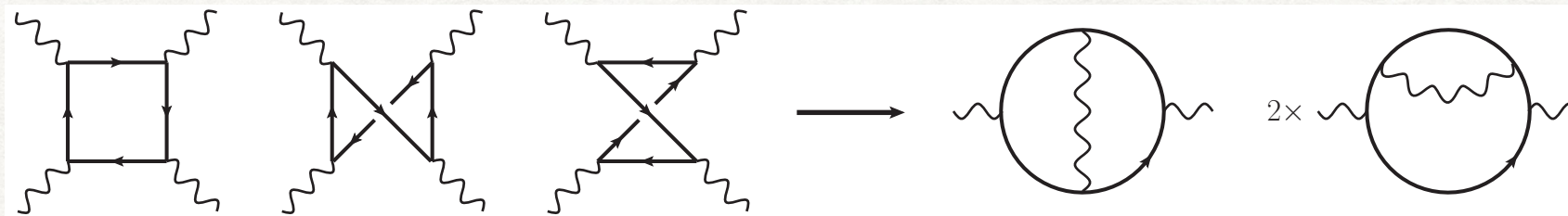
- treated by coordinate-space methods

short-distance part

- regulated by the lattice

COTTINGHAM-LIKE FORMULA VERIFICATION IN QED

✓ Verified in QED; compared with lattice QCD w/o gluons



[Källén and Sabry, Dan. Mat. Pys. Medd. (1955)]
... many others

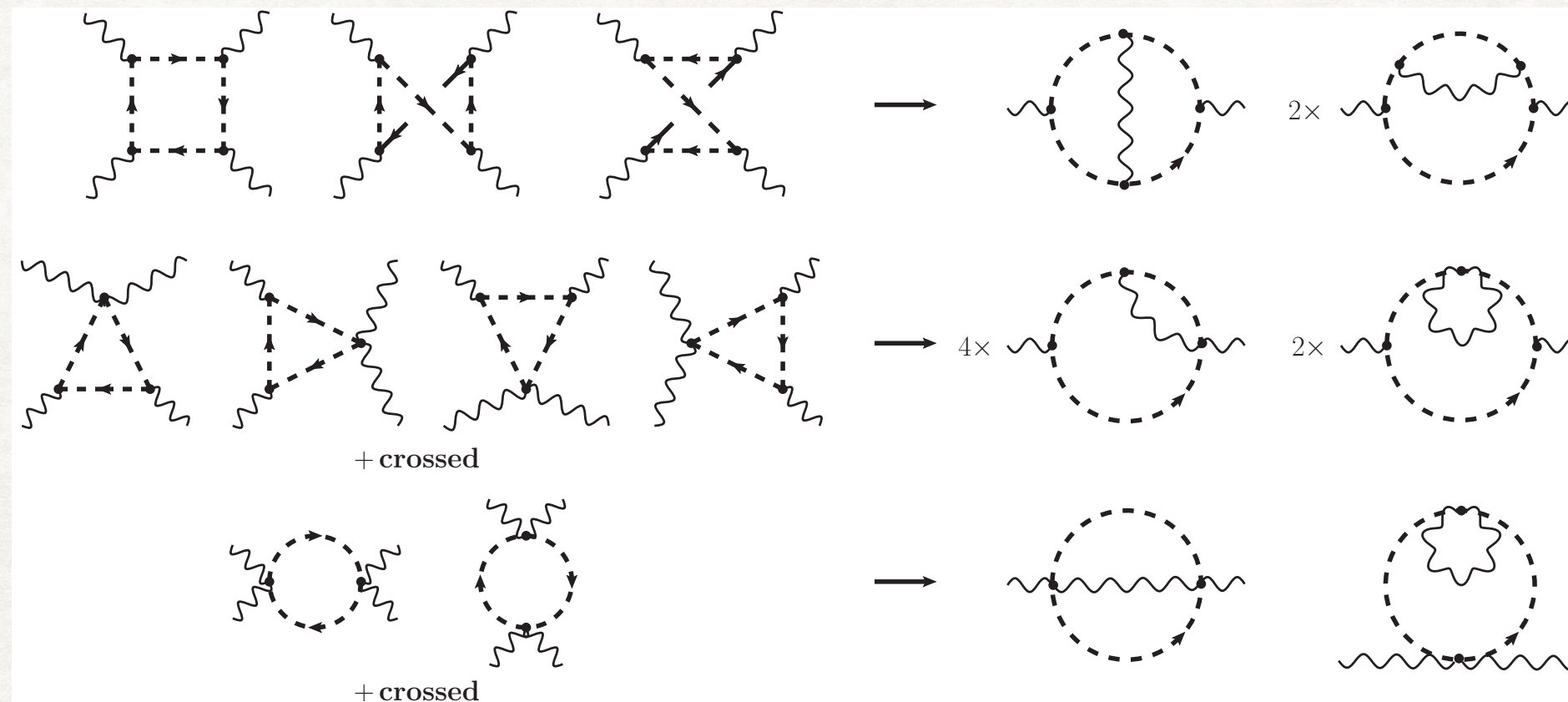
✓ The necessary counterterms, needed for renormalization, were quantified via OPE and confirmed in perturbative calculation

QED:

The diagram shows four Feynman diagrams representing the renormalization of a fermion self-energy loop. The first three diagrams show the loop with a photon insertion at different points. The fourth diagram shows the loop with a photon insertion at a point marked with a cross. This is followed by an equivalence symbol and the expression $\Sigma(m) \times \frac{d}{dm}$, which is then multiplied by a diagram of a fermion self-energy loop.

$$\equiv \Sigma(m) \times \frac{d}{dm} \text{ (fermion self-energy loop) }$$

✓ Verified in scalar QED; used for phenomenological model for charged pion loop contribution



[Schwinger, "Particles, sources and fields" (1998)]

[Bijnens et al., PRD (2019)]

✓ Various important benchmark points were provided for the cross check with lattice

- Lattice results are reported in the publications of Julian Parrino and Dominik Erb.

LBL TIMELINE

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LBL-3								