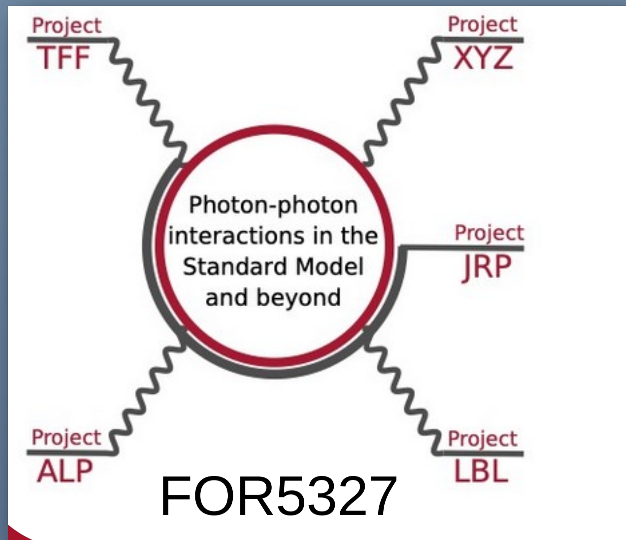


PROJECT LBL:

LIGHT-BY-LIGHT SCATTERING IN ST.MODEL

Vladimir Pascalutsa
JGU Mainz

with

Harvey Meyer
JGU Mainz

Volodymir Biloshytskyi
JGU Mainz —> Marseille

Jeremy Green (Mercator)
DESY Zeuthen

Kristof Schmieden
JGU Mainz

Matthias Schott
University of Bonn

DFG Deutsche Forschungsgemeinschaft
FOR5327

FOR5327 WORKSHOP
ST GOAR
JUNE 11—13, 2025

“

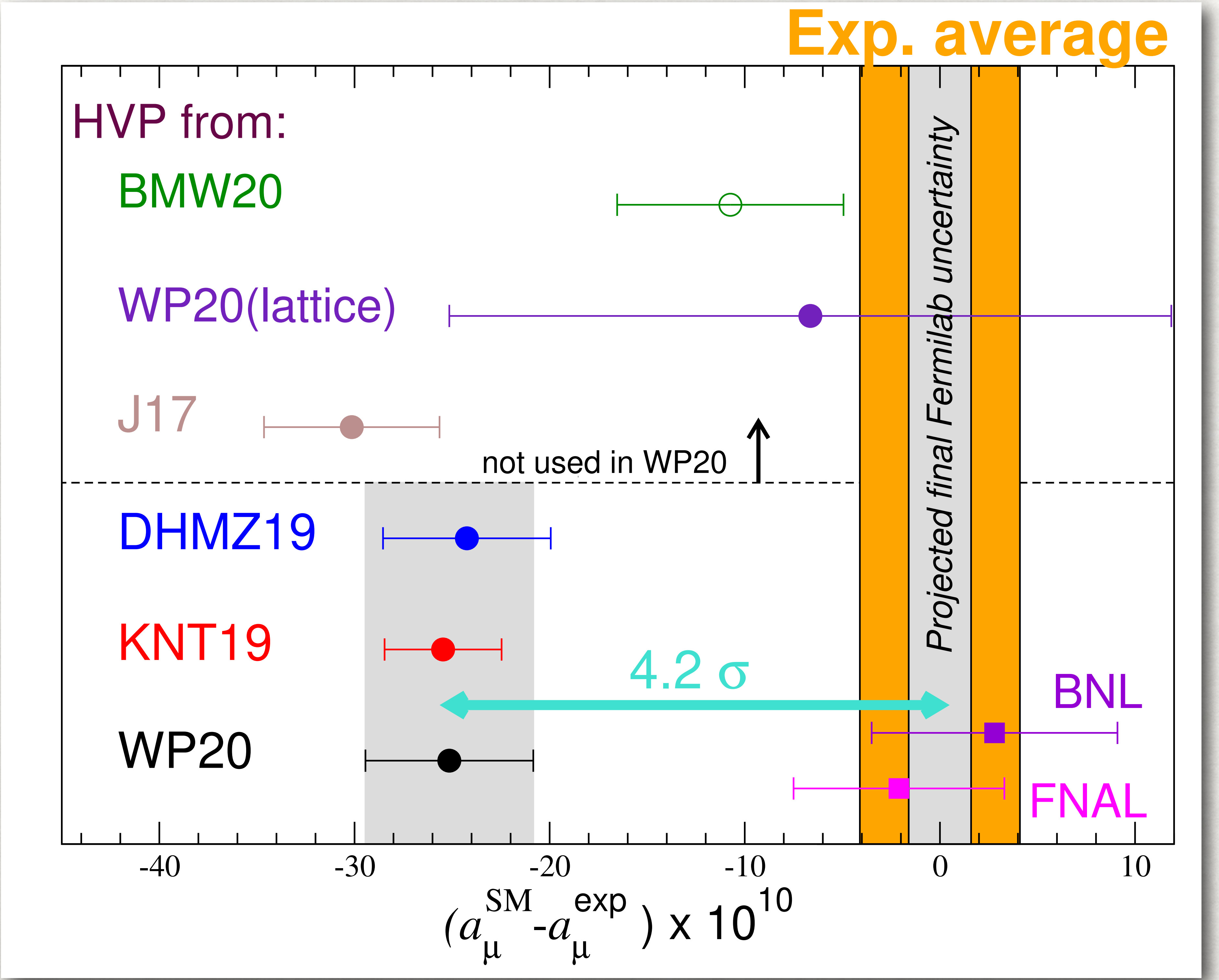
IT IS THE THEORY THAT DECIDES WHAT WE CAN OBSERVE.

— *Albert Einstein*

”

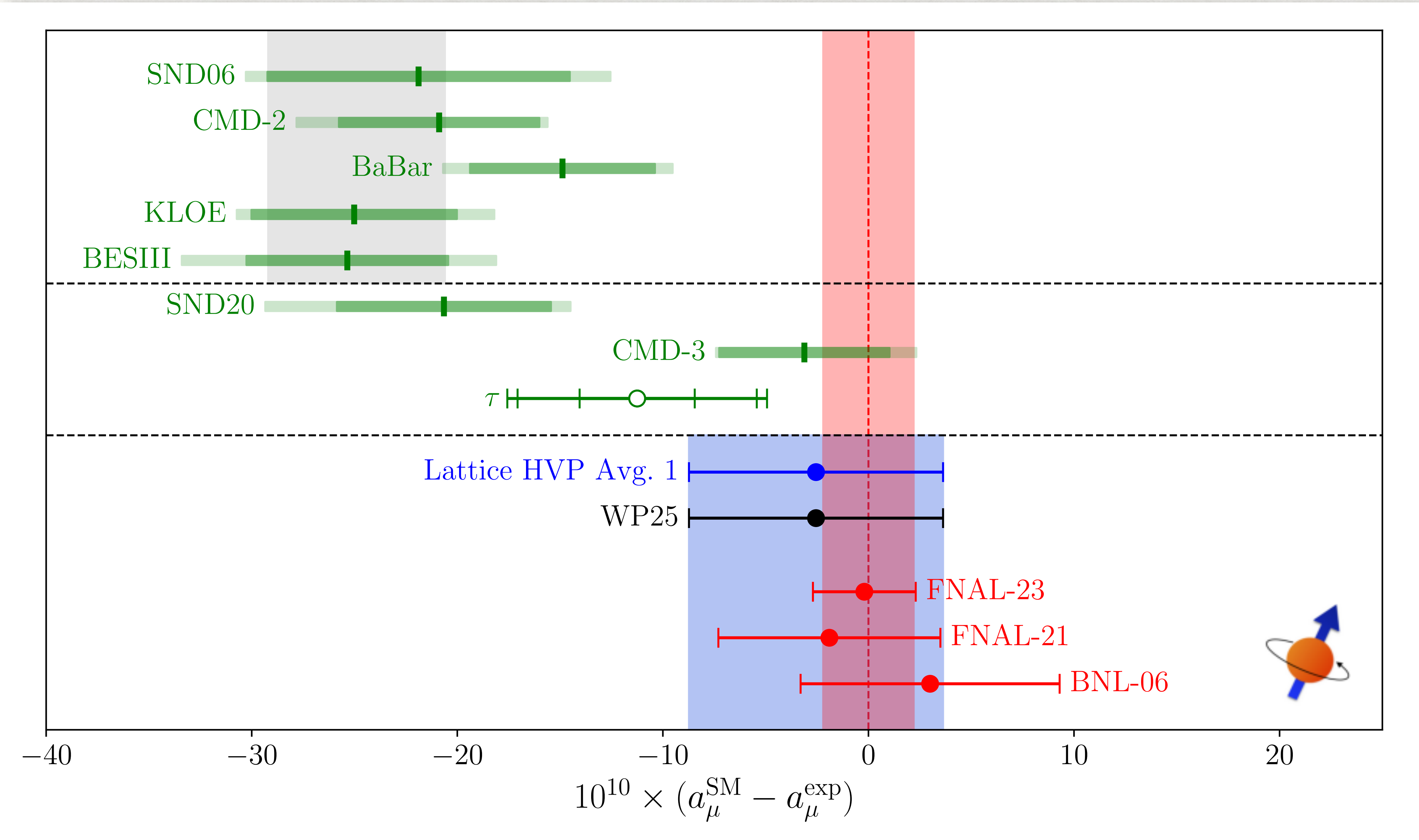
MUON ANOMALY

"THEORY INITIATIVE" WP 2020 VS 2025



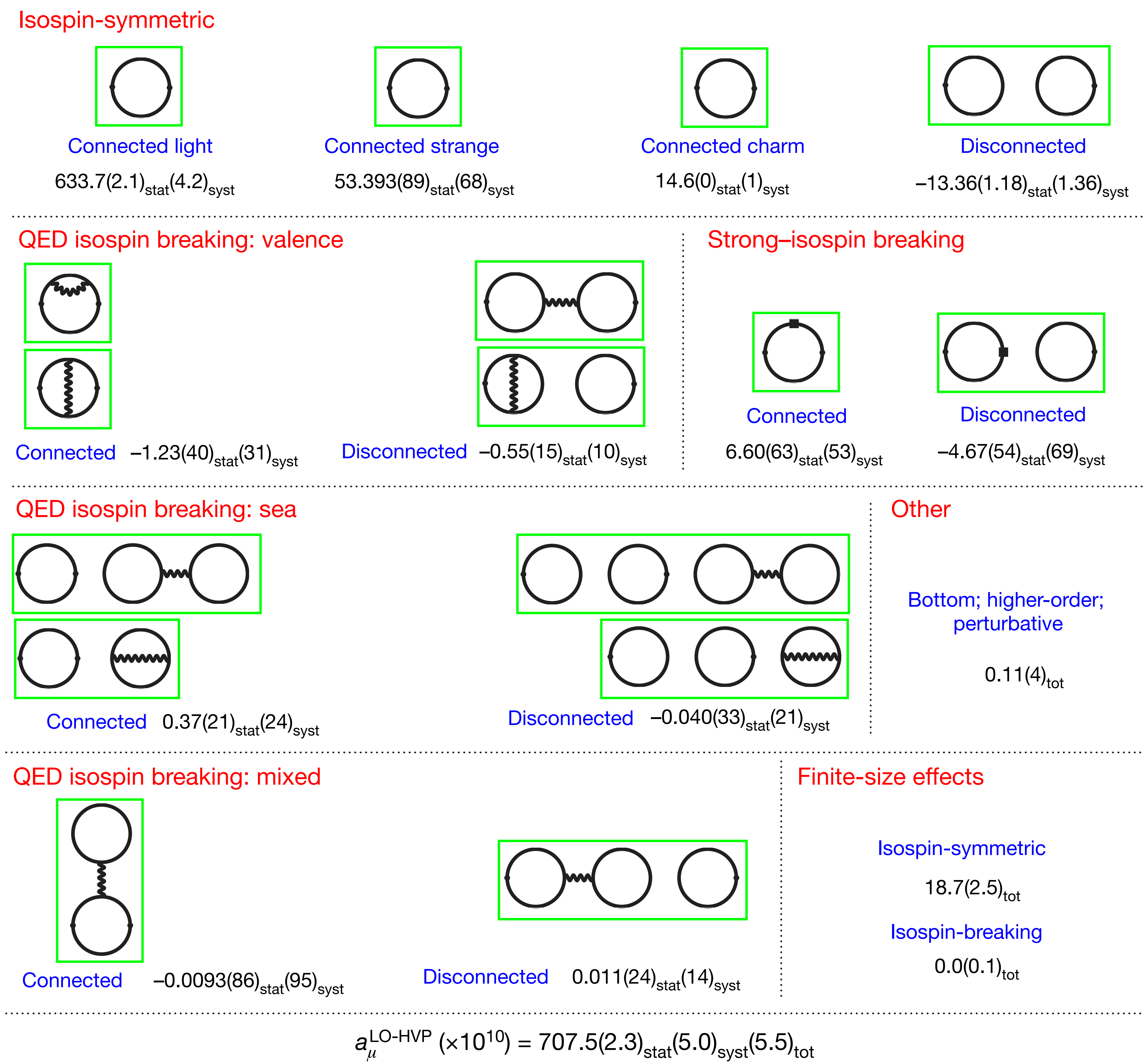
MUON ANOMALY

"THEORY INITIATIVE" WP 2020 VS 2025



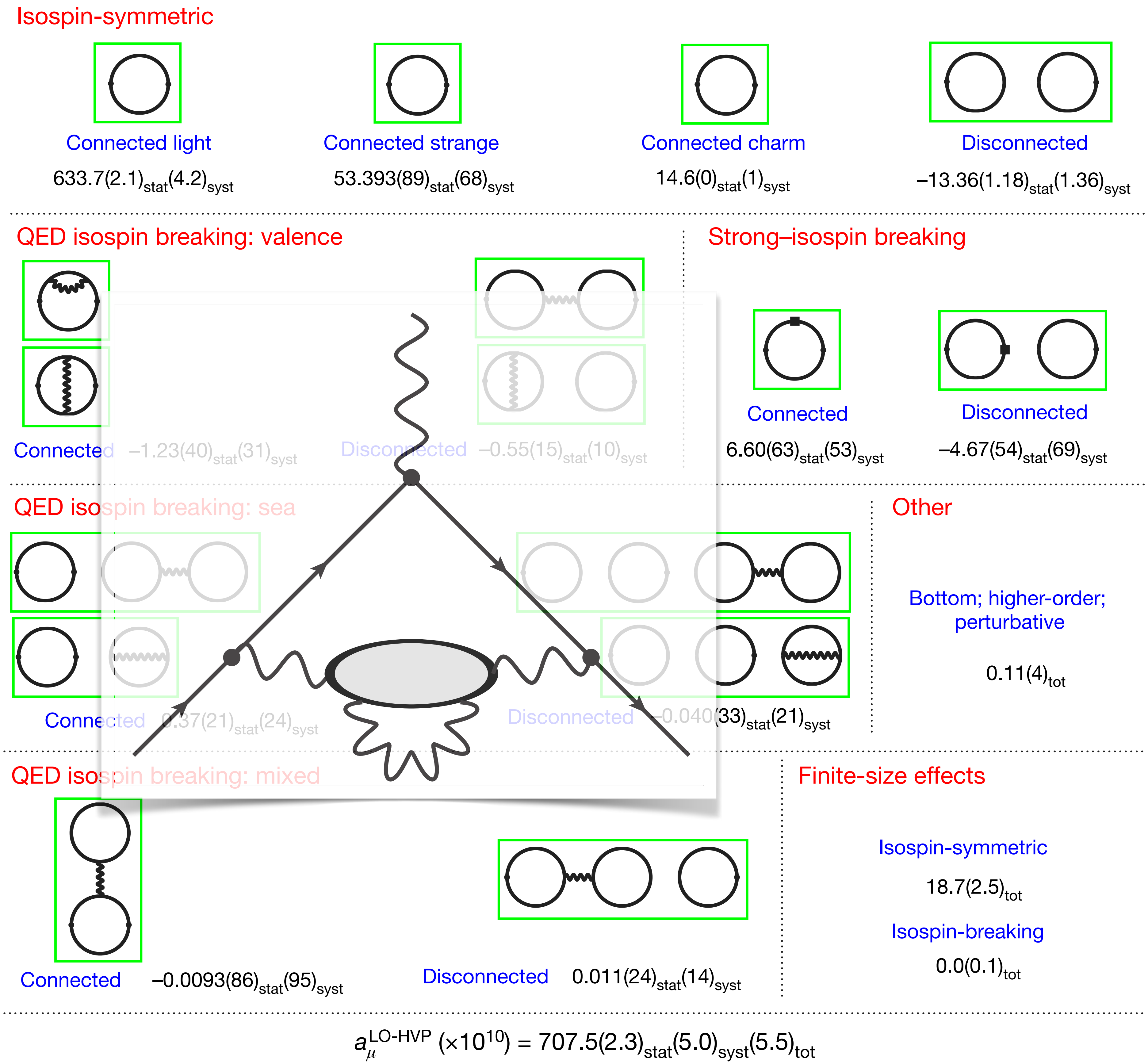
The different contributions

Figure from Borsanyi et al. Nature 2021



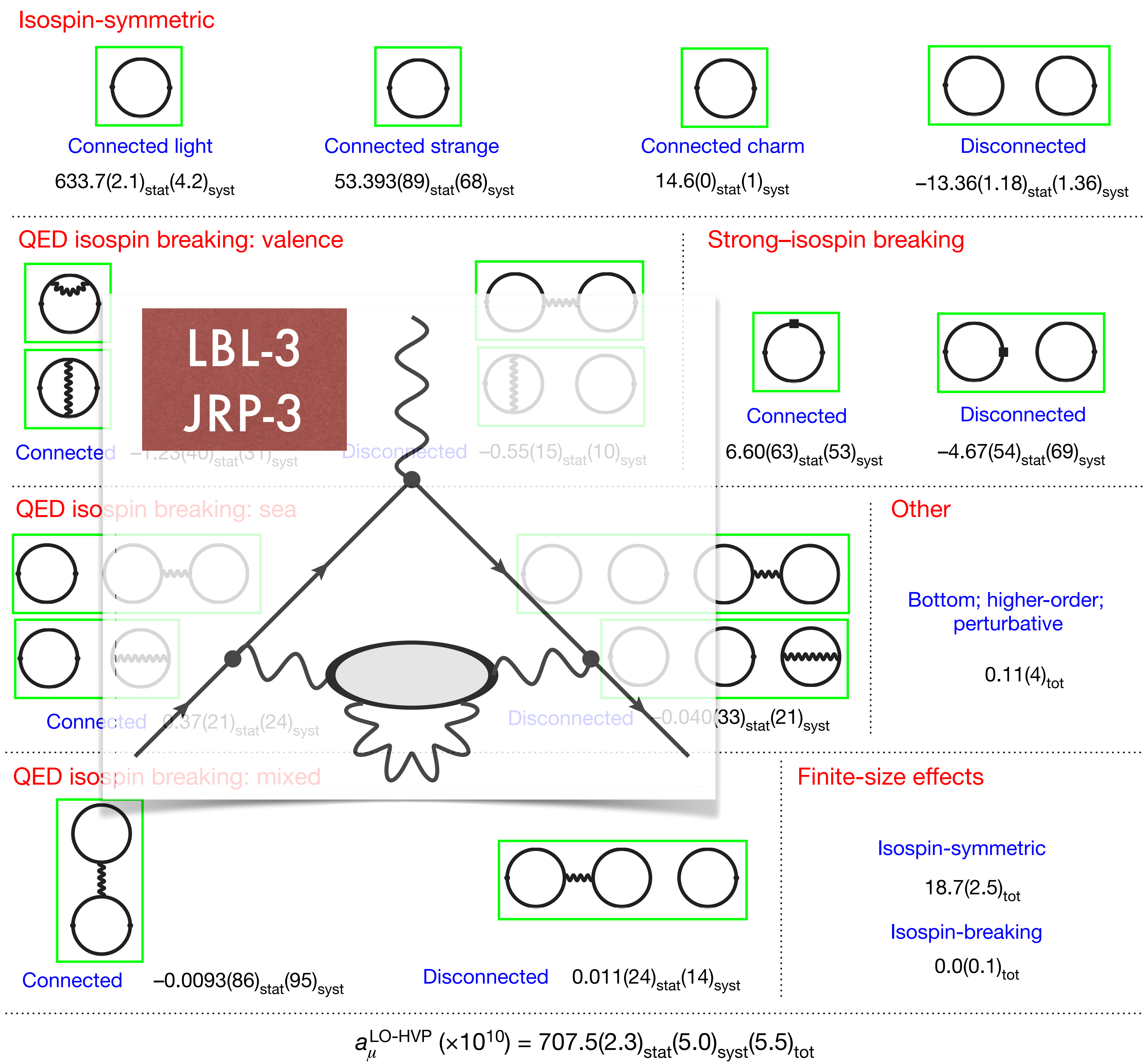
The different contributions

Figure from Borsanyi et al. Nature 2021



The different contributions

Figure from Borsanyi et al. Nature 2021

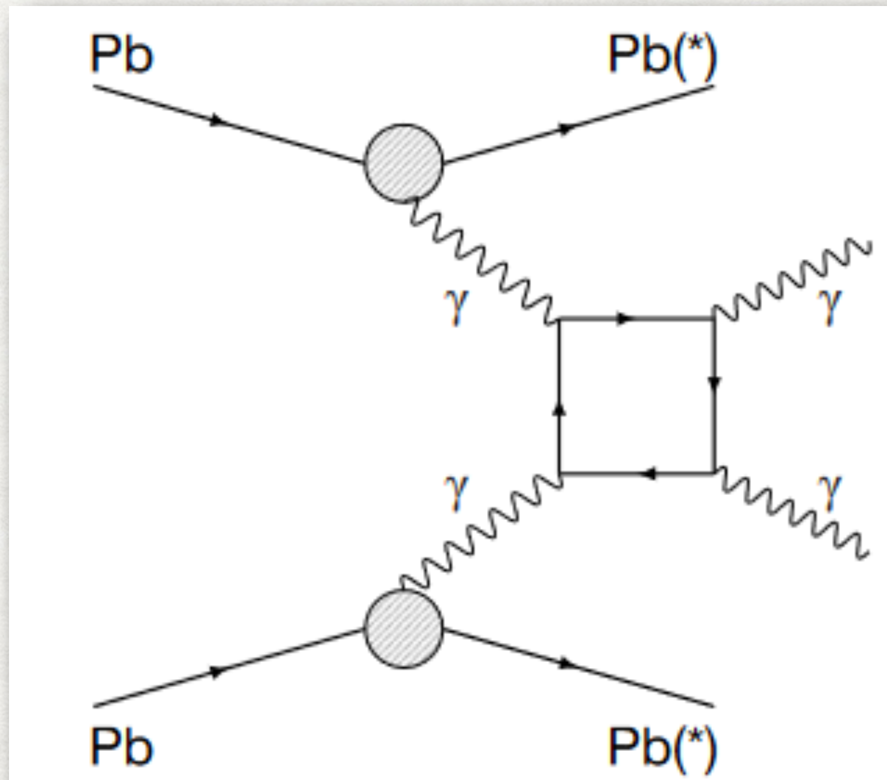


QUASI-REAL LIGHT-BY-LIGHT SCATTERING AT THE LHC

IN ULTRA-PERIPHERAL COLLISIONS (ATLAS, CMS)

Large s, t, u

$(s + t + u = 0)$



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

Photon fluxes in equivalent photon approximation

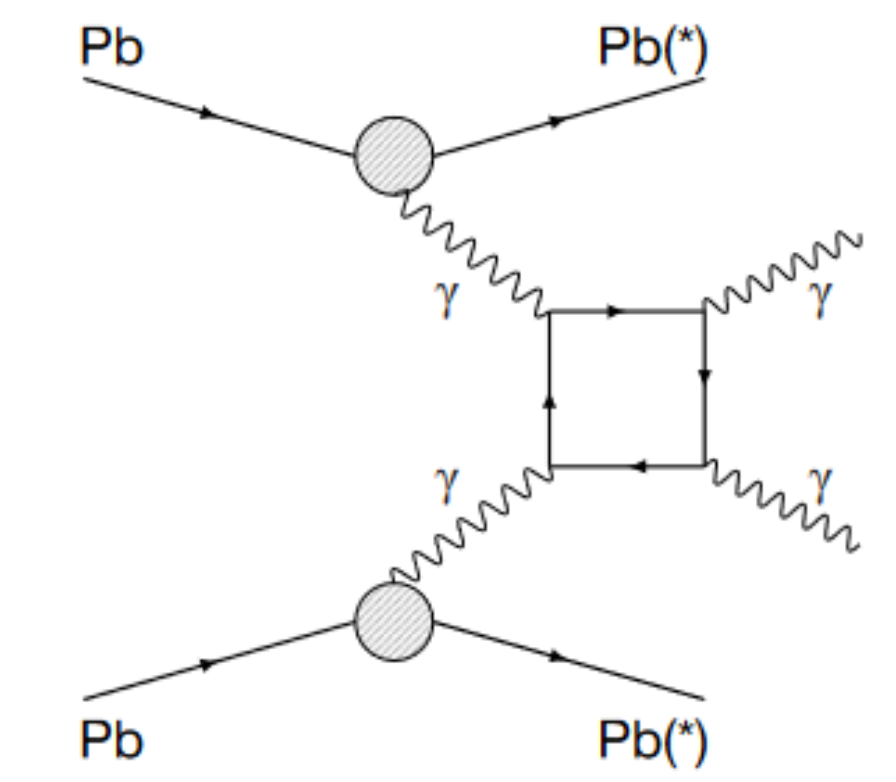
QUASI-REAL LIGHT-BY-LIGHT SCATTERING AT THE LHC

IN ULTRA-PERIPHERAL COLLISIONS (ATLAS, CMS)

LBL-1
THEORY

Large s, t, u

$(s + t + u = 0)$



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

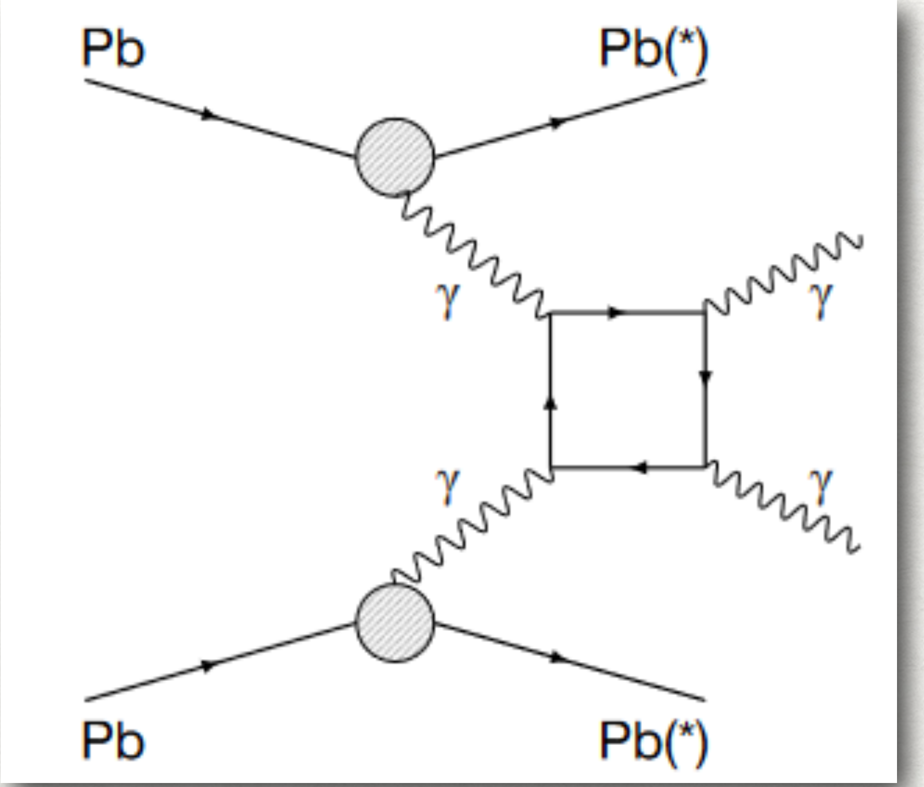
Photon fluxes in equivalent photon approximation

QUASI-REAL LIGHT-BY-LIGHT SCATTERING AT THE LHC

IN ULTRA-PERIPHERAL COLLISIONS (ATLAS, CMS)

Large s, t, u

$(s + t + u = 0)$



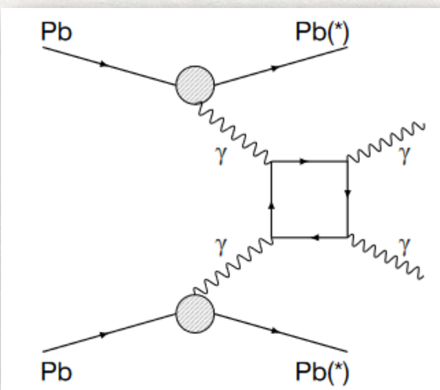
LBL-1
THEORY

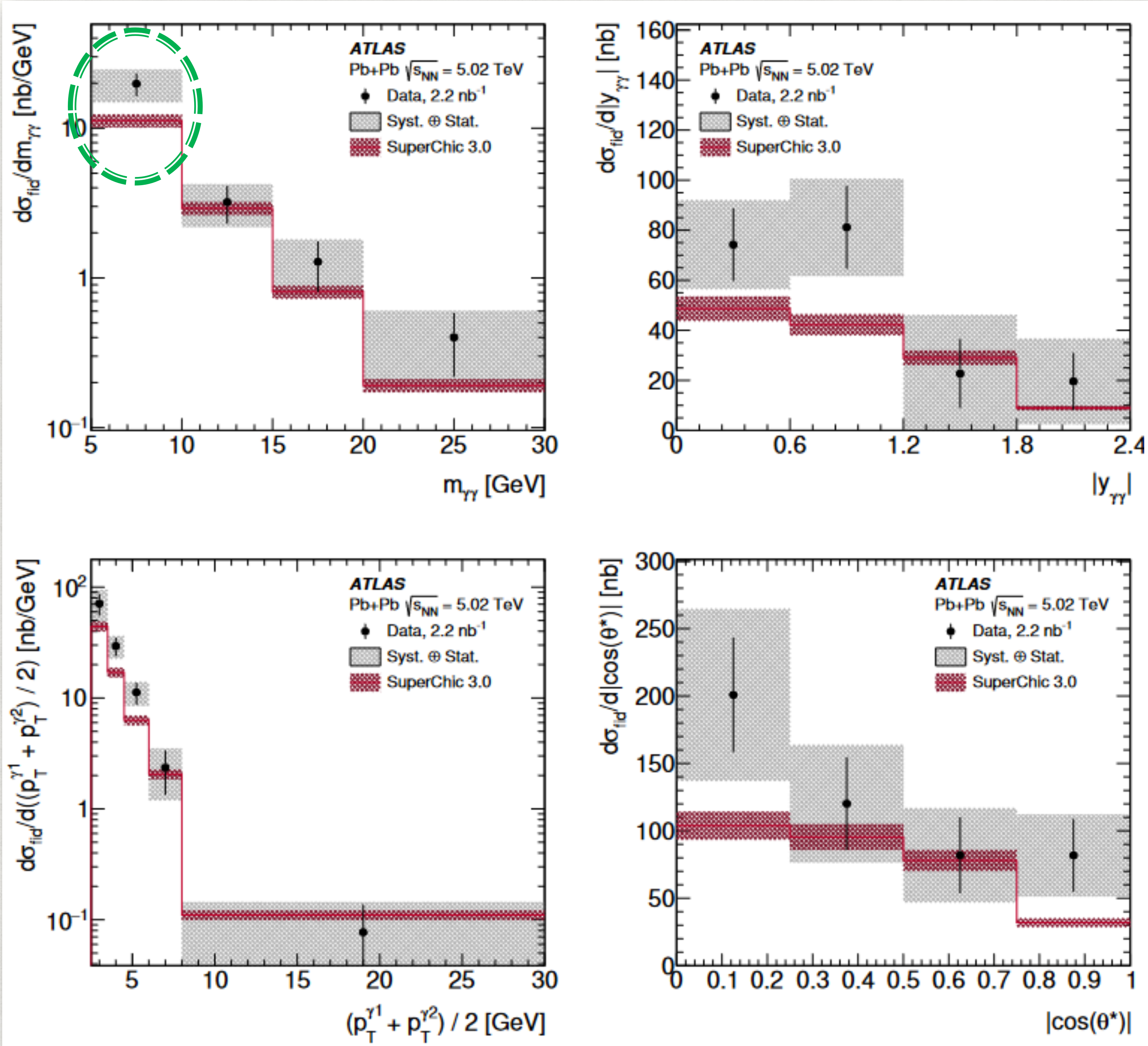
LBL-2
EXPERIMENT

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

Photon fluxes in equivalent photon approximation

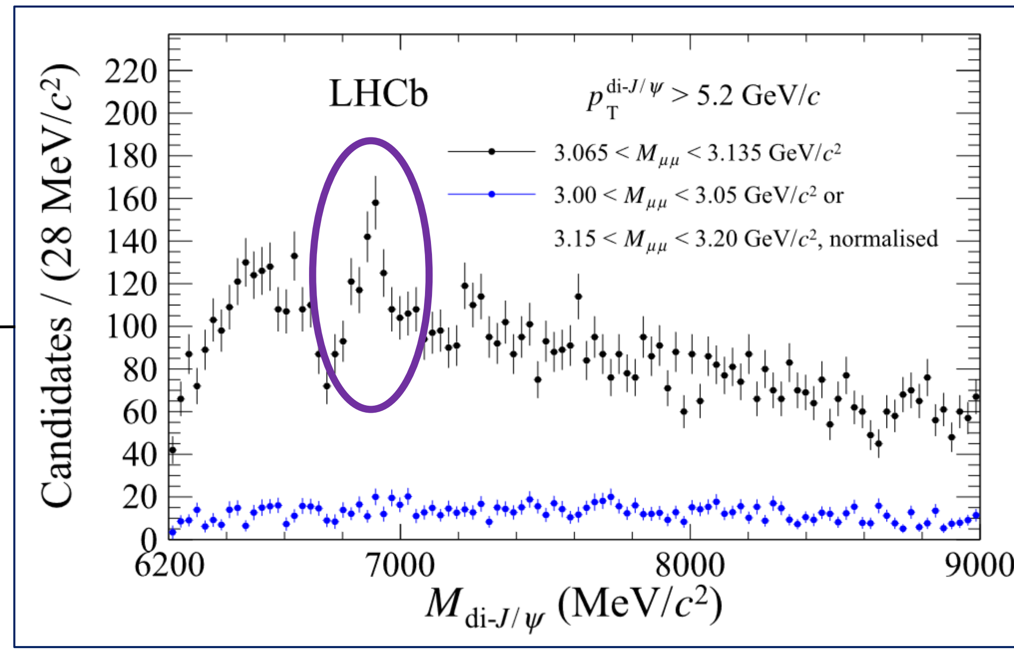
[ATLAS collaboration, 2021]



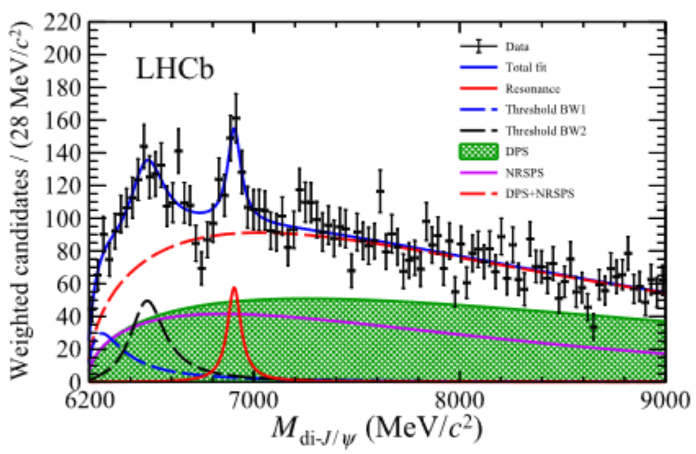


NEW STATE X(6900)

[LHCb collaboration, **2020**]



No-interference fitting scenario

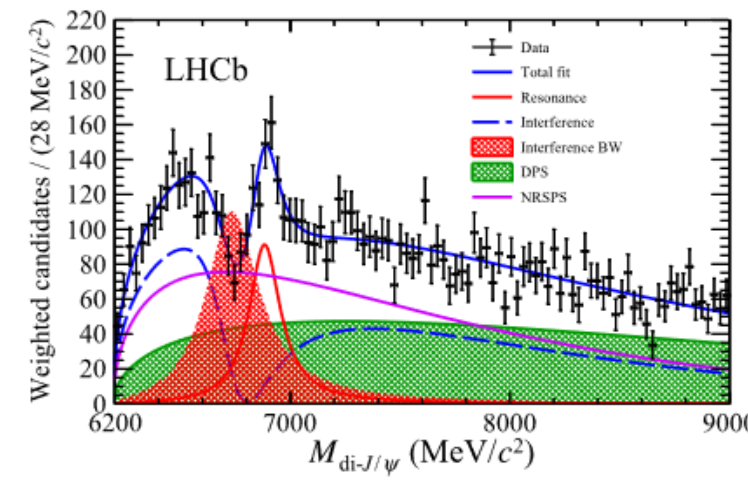


$m[X(6900)] = 6905 \pm 11 \pm 7$ MeV/c^2,

and

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

Interference fitting scenario



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

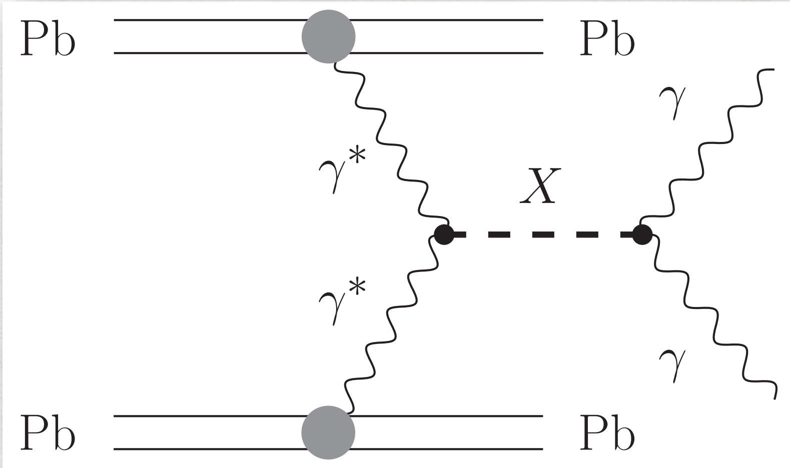
and

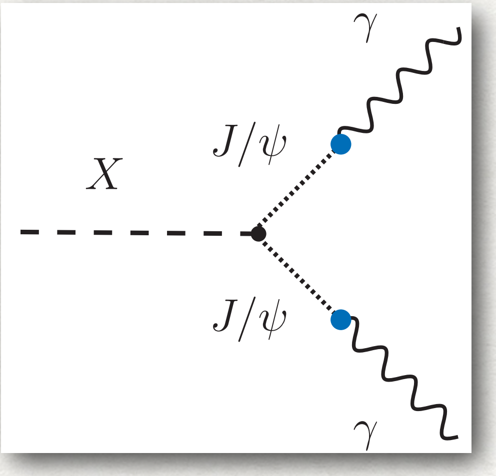
$\Gamma[X(6900)] = 168 \pm 33 \pm 69$ MeV.

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

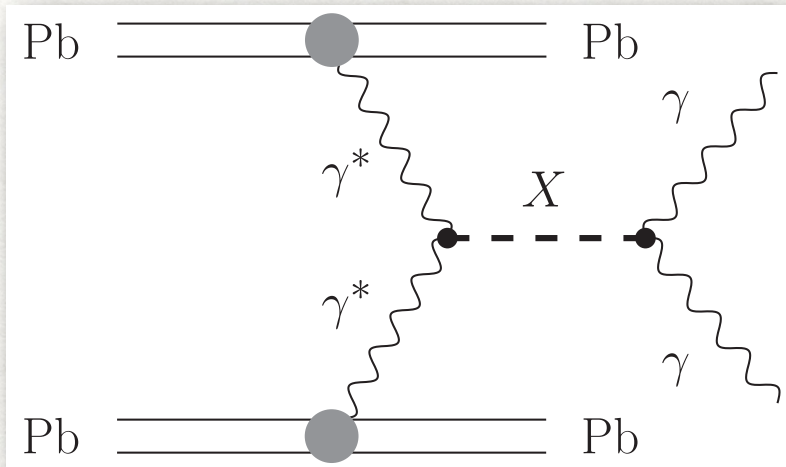
The following quantum numbers are considered for it in the literature on the tetraquark spectra:
$J^{PC} = 0^{++}, 0^{-+}, 1^{-+}, 2^{++}$.

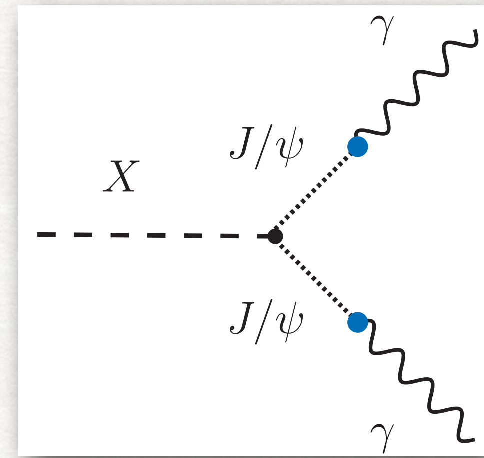
LBL-1





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 and Vladimir Pascalutsa
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

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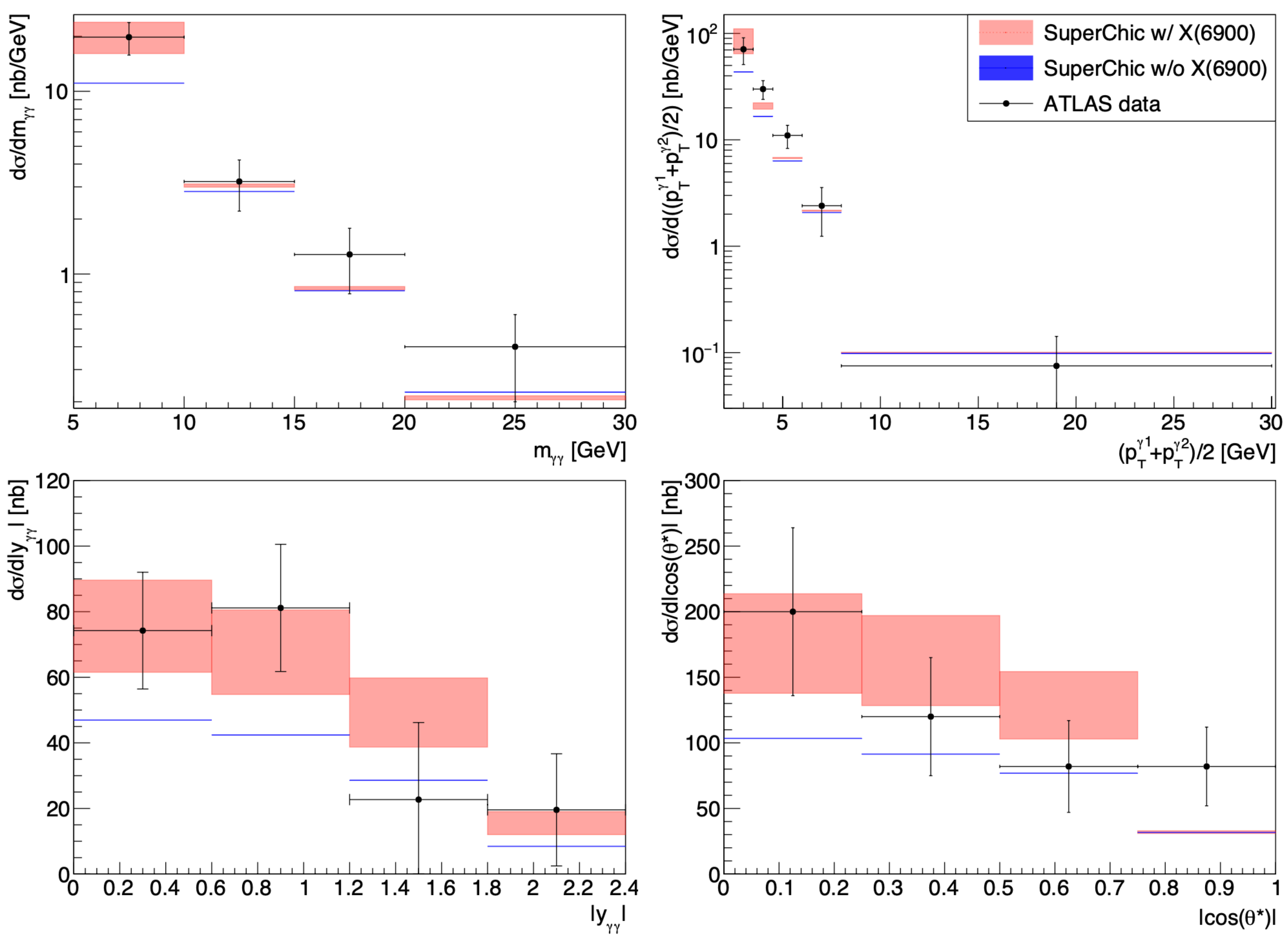
Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany

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

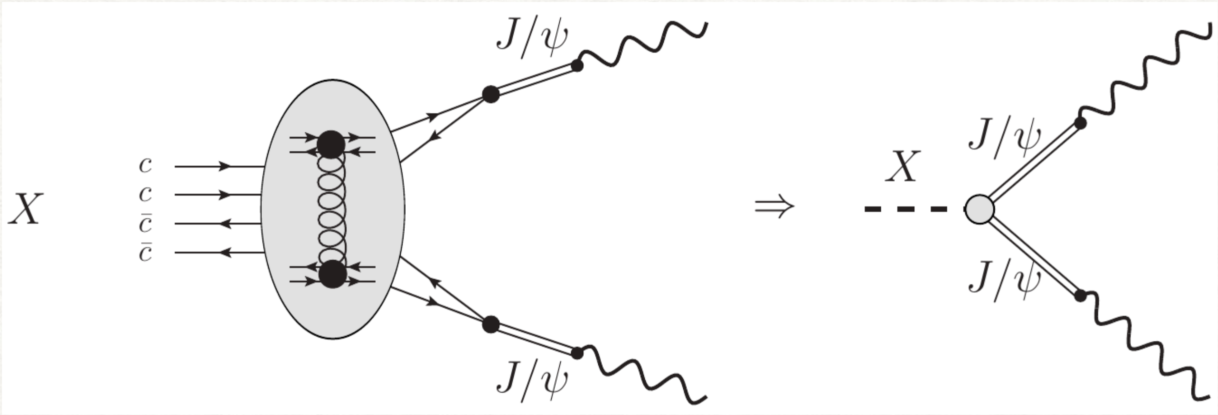
$$\chi^2/N_{\mathrm{d.o.f.}} \approx 0.6$$

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

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

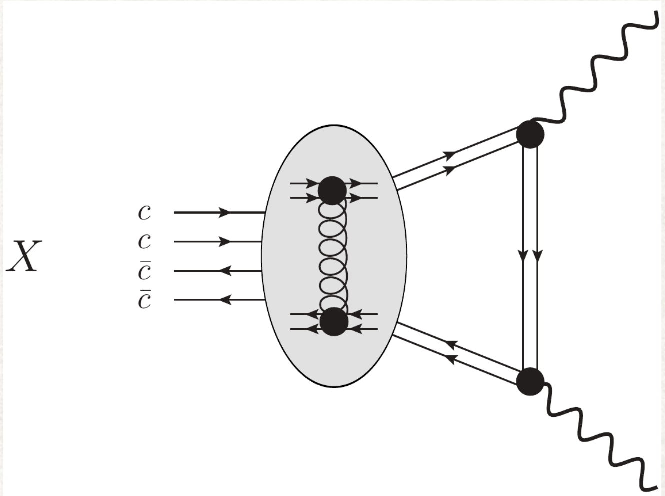
Two-photon decay width estimates

- Charmonium molecule structure → vector-meson dominance



$\Gamma_{X\to\gamma\gamma} \sim 0.1...1\,\text{keV}$

- Decay of diquark-antidiquark state



$\Gamma_{X\to\gamma\gamma} \sim 10\,\text{keV}$

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

✓ X(6900) >5σ

$J/\psi\ \psi(2S)$

✓ 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]

[1]Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany
[2]Rudolf Peierls Centre, Beecroft Building, Parks Road, Oxford, OX1 3PU, United Kingdom
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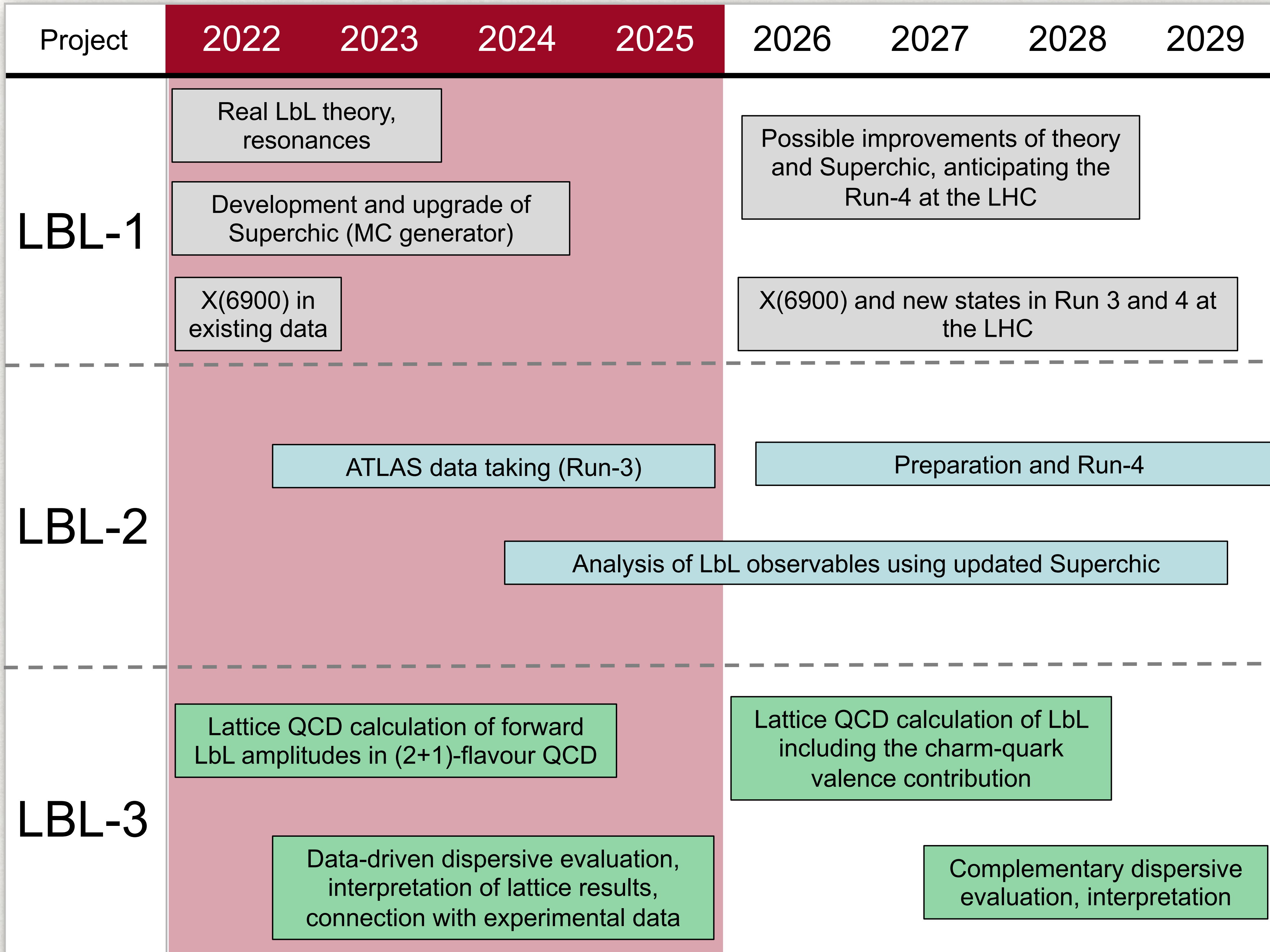
XVth Quark Confinement and the Hadron Spectrum

https://doi.org/10.1051/epjconf/202227406007

X-state nature	$\Gamma_{X(6600)\to\gamma\gamma}$ [keV]	$\Gamma_{X(6900)\to\gamma\gamma}$ [keV]	$\Gamma_{X(7300)\to\gamma\gamma}$ [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



LBL-3

IN CONJUNCTION WITH JRP-3

JHEP

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Accepted: *March 14, 2023*
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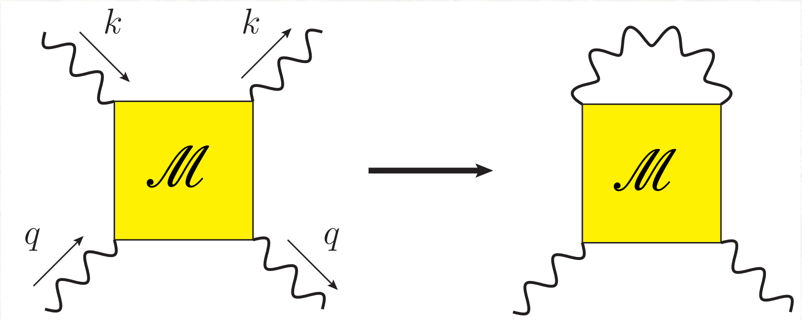
Forward light-by-light scattering and electromagnetic correction to hadronic vacuum polarization

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 $\mathscr{M}$



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

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

The advantage in lattice calculations:

photon propagator splitting: $\frac{1}{k^2} = \left(\frac{1}{k^2} - \frac{1}{k^2+\Lambda^2} \right) + \frac{1}{k^2+\Lambda^2}$

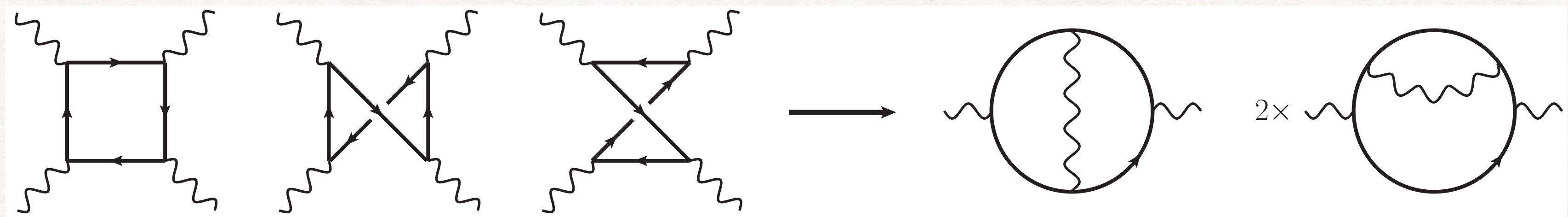
$\Lambda \approx 400$ MeV - separation scale

long-distance part
- treated by coordinate-space methods

short-distance part
- regulated by the lattice

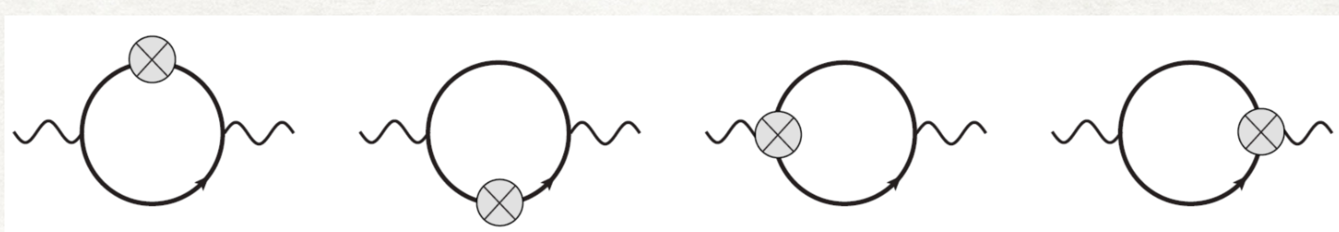
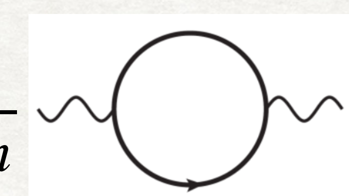
COTTINGHAM-LIKE FORMULA VERIFICATION IN QED

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

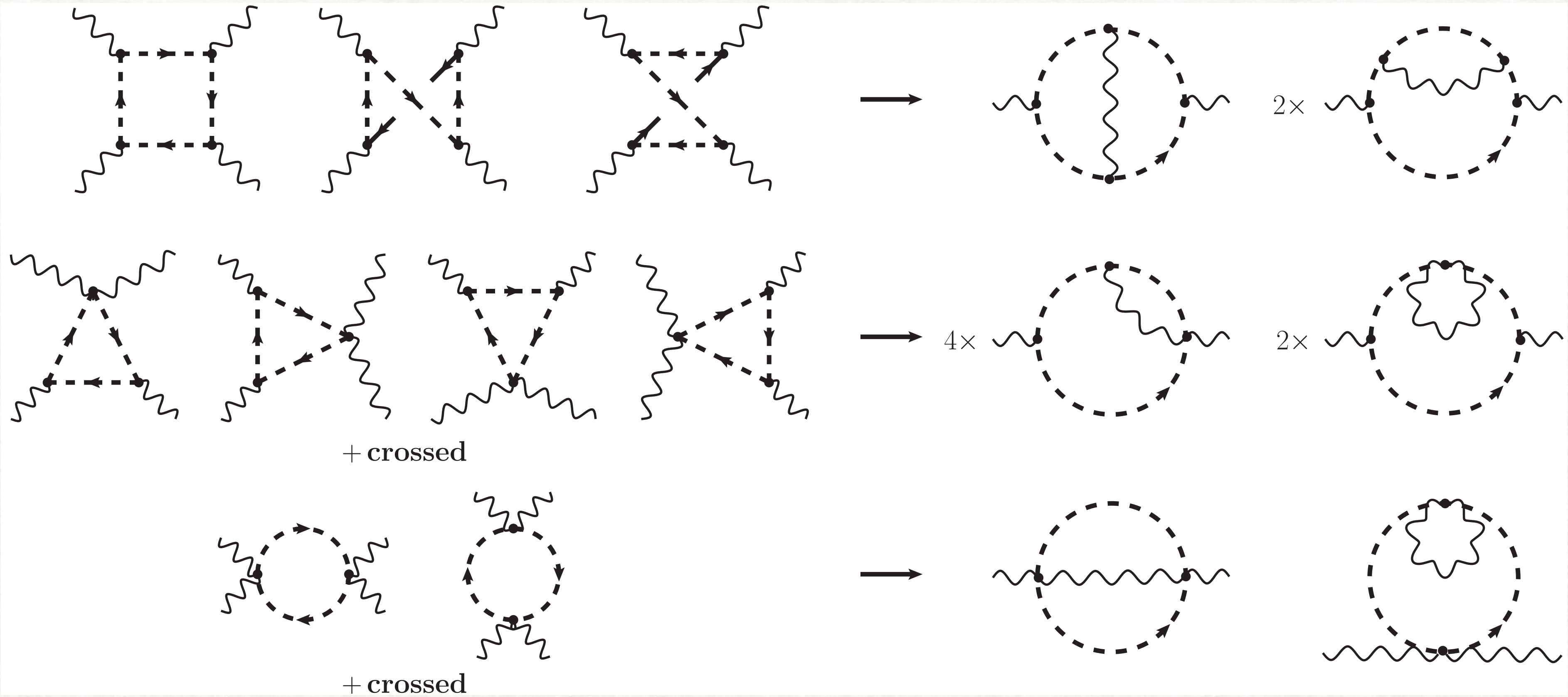


[Källén and Sabry, Dan. Mat. Pys. Medd. (1955)]
… many others

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

QED:  $\equiv \ \Sigma(m) \times \frac{d}{dm}$ 

✓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