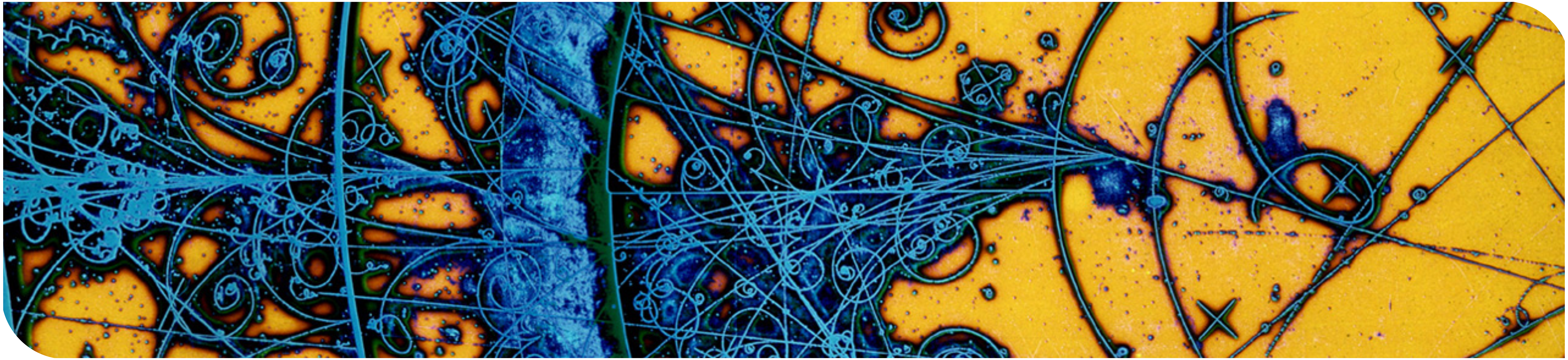
Karlsruhe Institute of Technology

Particle Physics 1
Lecture 21: Beyond the Standard Model (BSM)

Prof. Dr. Torben FERBER (torben.ferber@kit.edu, he/him), Institut für Experimentelle Teilchenphysik (ETP)
Wintersemester 2023/2024



Credit: CERN

CERN Trip 2024

DPG (Spring meetings of the German Physical Society)

Registration (free for KIT students): https://karlsruhe24.dpg-tagungen.de/registrierung/index.html?set_language=en

KCETA Colloquium

KCETA Colloquium

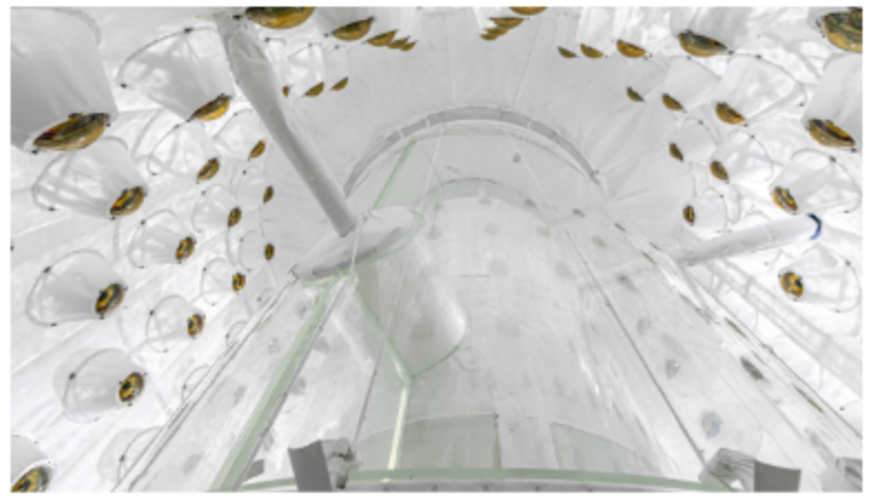
Recent results from the LZ experiment and future direct DM searches

Thursday, February 8, 2024
Kleiner Hörsaal A (CS) 15:45 - 17:00

Prof. Björn Penning
(University of Zürich)

The nature of dark matter (DM) is one of the most important questions in physics. The LUX-Zeplin (LZ) experiment is the most sensitive dark matter search experiment to date, located 1.6 km underground at the Sanford Underground Research Facility. The experiment utilizes a two-phase time projection chamber, containing seven active tonnes of liquid xenon to search for WIMPs. Auxiliary veto detectors, including a liquid scintillator outer detector, improve the rejection of unwanted background events in the central region of the detector. LZ has been designed to explore much of the parameter space available for WIMP models, with excellent sensitivity for WIMP masses between a few GeV and a few TeV.

In this talk, we will report the current status of the LZ experiment and recent results. We will also explore the prospects of two future experiments: Tesseract, a sub-GeV cryogenic dark matter search, and XLZD, a 3rd Generation experiment able to reach the neutrino floor, the ultimate frontier of standard DM searches.



Please note:
The colloquium will also be live-streamed to Seminarraum 224 in Bld. 402 (CN).

KIT Center Elementary Particle and Astroparticle Physics (KCETA)
www.kceta.kit.edu

Karlsruher Institut für Technologie

KCETA Colloquium

New results for searches of exotic particles with NA62 in beam-dump mode

Thursday, February 15, 2024
Kleiner Hörsaal A (CS) 15:45 - 17:00

Dr. Babette Döbrich
(MPI Munich)

We report on the search for visible decays of exotic mediators from data taken in "beam-dump" mode with the NA62 experiment. The NA62 experiment, conceived to measure the rare decay of a charged Kaon into a pion and two neutrinos, can be run as a "beam-dump experiment" by removing the Kaon production target and moving the upstream collimators into a "closed" position.
More than 10^{17} protons on target have been collected in this way during a week-long data-taking campaign by the NA62 experiment. We report on new results from analysis of this data, with a particular emphasis on Dark Photon and Axion-like particle models.
We also discuss future prospects of such physics searches with NA62 and its possible successor HIKE.

Please note:
The colloquium will also be live-streamed to Seminarraum 410 in Bld. 401 (CN).

KIT Center Elementary Particle and Astroparticle Physics (KCETA)
www.kceta.kit.edu

Karlsruher Institut für Technologie

Questions from past lectures

Learning goals

- Why are we looking for physics beyond the SM?
- How are we looking for physics beyond the SM?
- What are existing anomalies and unexplained effects of the SM

How many free parameters does the standard model have?

- 19 free parameters (different choices possible)
  - 3 running couplings constants (g, g', g_s) or ($\alpha_{QED}(0)$, $\alpha_S(m_Z)$, G_F)
  - m_Z and W mass (or Higgs vacuum expectation value)
  - 12 Quark and 3 charged lepton masses
  - Higgs mass
  - 3 rotation angles and one CP violating phase (CKM matrix)
- plus 7 parameters ~~if~~ because neutrinos are massive
  - 3 neutrino masses
  - Neutrino 3 rotation angles and one CP violating phase (PMNS matrix), maybe two more CP violating Majorana phases

The Standard Model: Particles and interactions

QCD

interactions between bosons (W, Z, H)

weak force

Higgs ghosts

weak ghosts

1

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] +$$

4

$$\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$

5

$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Source: Symmetry Magazine

(there is at least one sign mistake in this equation…)

Why do we look for physics beyond the Standard Model?

- **Unexplained phenomena**, aka “SM (or experiments) gets it very wrong”: measured effects unpredicted by theory
  - Dark Matter
  - Dark Energy
  - Matter/Antimatter Asymmetry of the universe
  - Gravity
  - Neutrino masses
- **Observed Anomalies** (or unexplained experimental results), aka “SM (or experiments) gets it somehow wrong”
  - Flavour anomalies: R(D*), g-2, P5’, until last year R(K) and R(K*)
  - W mass
  - Sterile neutrinos
- **Theory shortcoming**
  - adhoc assumptions
  - large number of free parameters
  - theta parameter in QCD
  - …

Theory problem example: CP violation in QCD

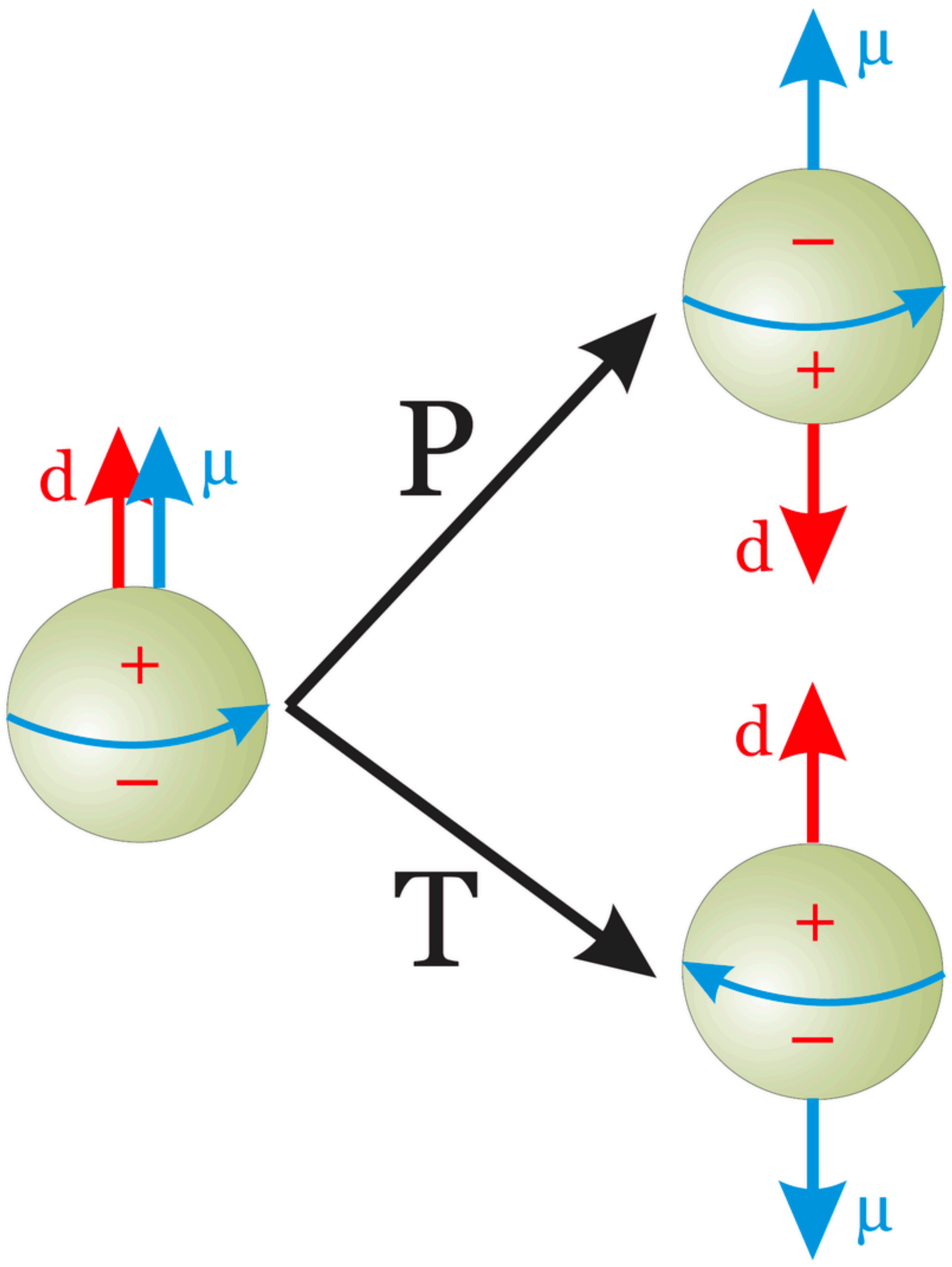
- The Standard Model in principle allows CP violating terms (here for two quarks, see [1]):

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{e\theta'\gamma_5})\psi$$

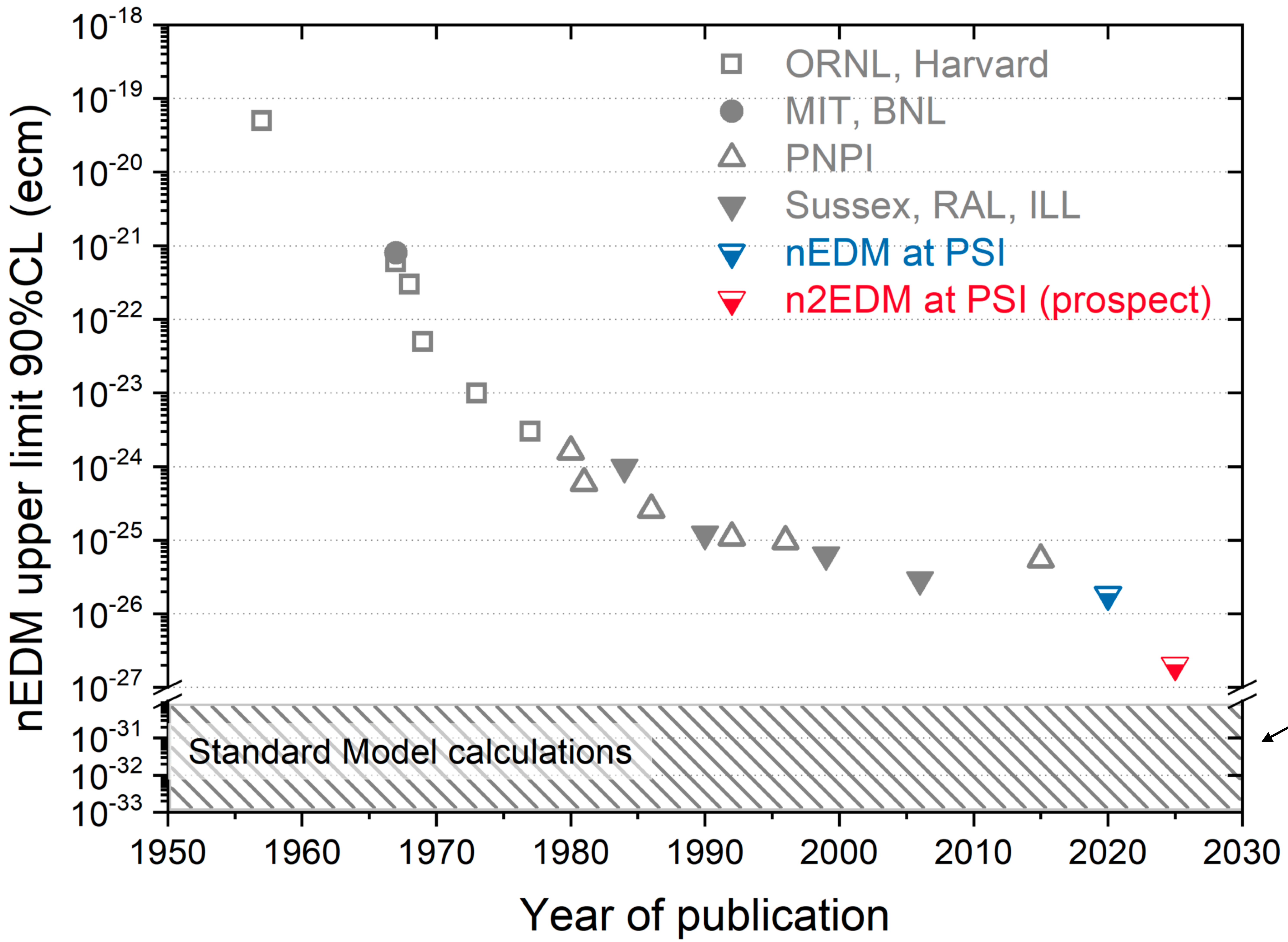
[1]: https://www.osti.gov/servlets/purl/6260191

Theory problem example: CP violation in QCD

- Neutrons are electrically neutral, but they could have a non-zero electric dipole moment (EDM): Positive and negative charges separated in spin direction.
- A non-zero electric dipole moment of the neutron (nEDM) violates both **parity** (spin unchanged, charge distribution reversed) and **time-reversal** (spin changed, charge distribution unchanged).
- If CPT is still conserved, T-violation directly indicates CP violation.



Theory problem example: CP violation in QCD



SM assuming θ=0

Picture: https://www.psi.ch/de/ltp-ucn-physics/n2edm

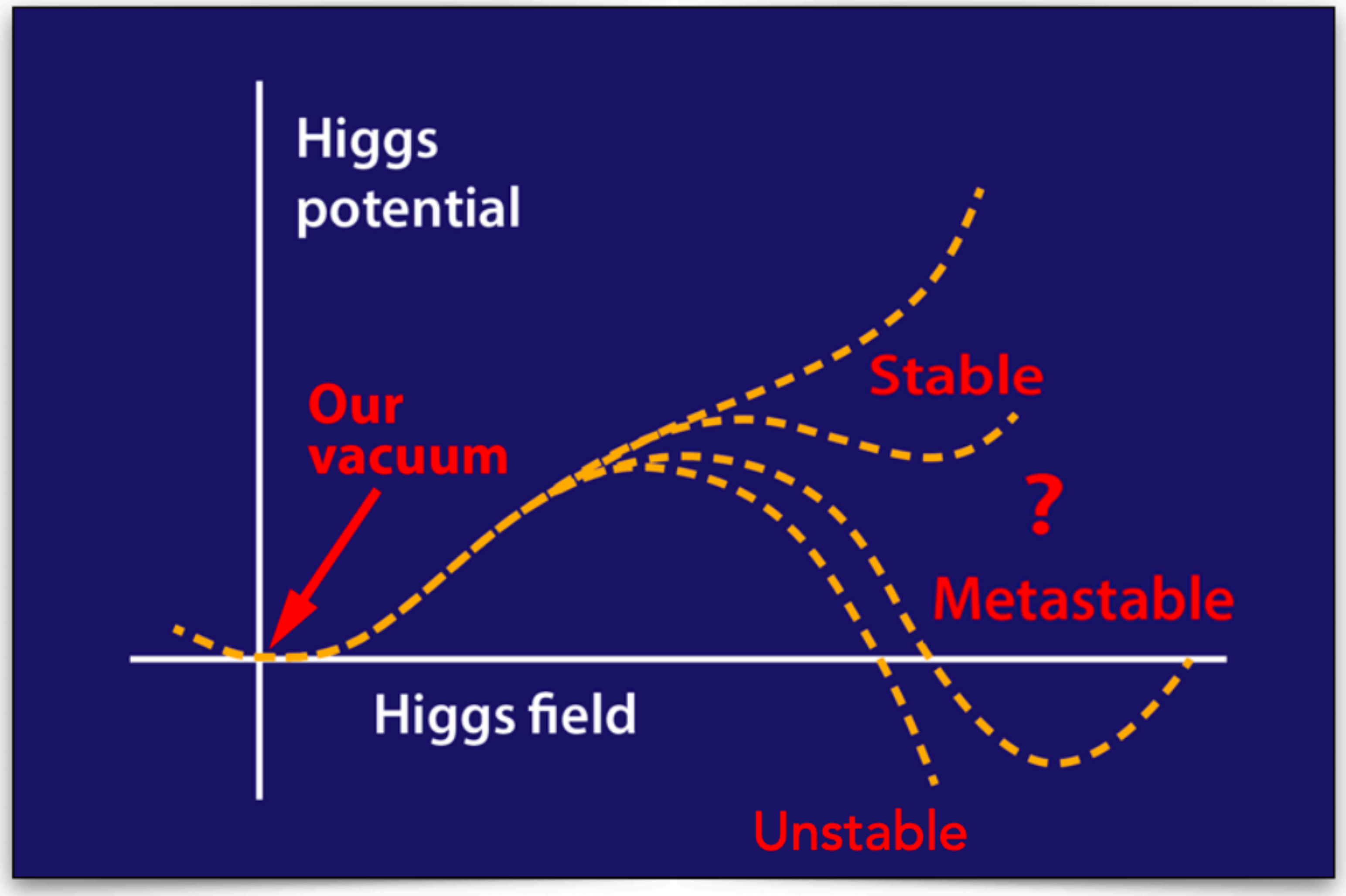
Theory: Fine-tuning Problem

- The Higgs mass can both be measured (as input to the theory), but it can also be predicted by the Standard Model

- The Higgs field depends on fluctuations of the Higgs field, the top field, the W field, … and all fields we dont know yet.

- The VEV and the Higgs mass are very small (== the Higgs field is rather flat around the minimum), despite many individual contributions to the Higgs field being large

  → This requires a very precise cancellation of various, partially unknown, effects (“unnatural”?)

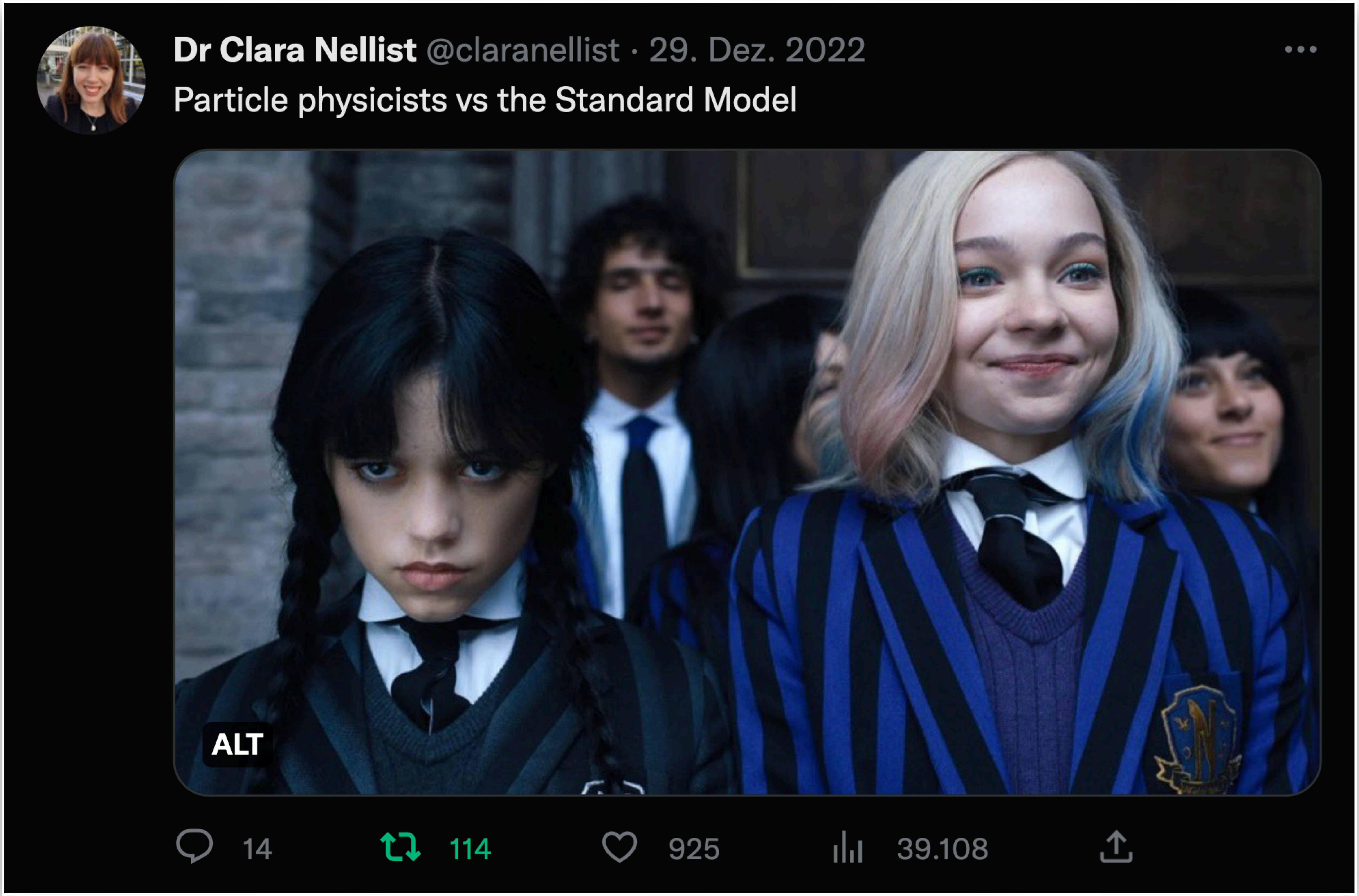


Source: https://physics.aps.org/articles/v8/108

How do we look for physics beyond the Standard Model?

- Resources are always limited, what is your best chance?
  - Processes where you can achieve very high experimental sensitivity, often because of technological breakthroughs give access to new parameter space (e.g. LHC, very fast readout, quantum sensors, …)
  - Processes where you have very small theory uncertainties
  - Processes where you already have indications of SM breaking (“anomalies”)
  - Processes where you have symmetry arguments for the existence of greater unified theories
  - Processes that would solve one of the open theory questions
  - Processes that are predicted by a new theory (confirm hypothesis or falsify theory)
  - …ideally several of the above!

Why is it so hard to find new physics?

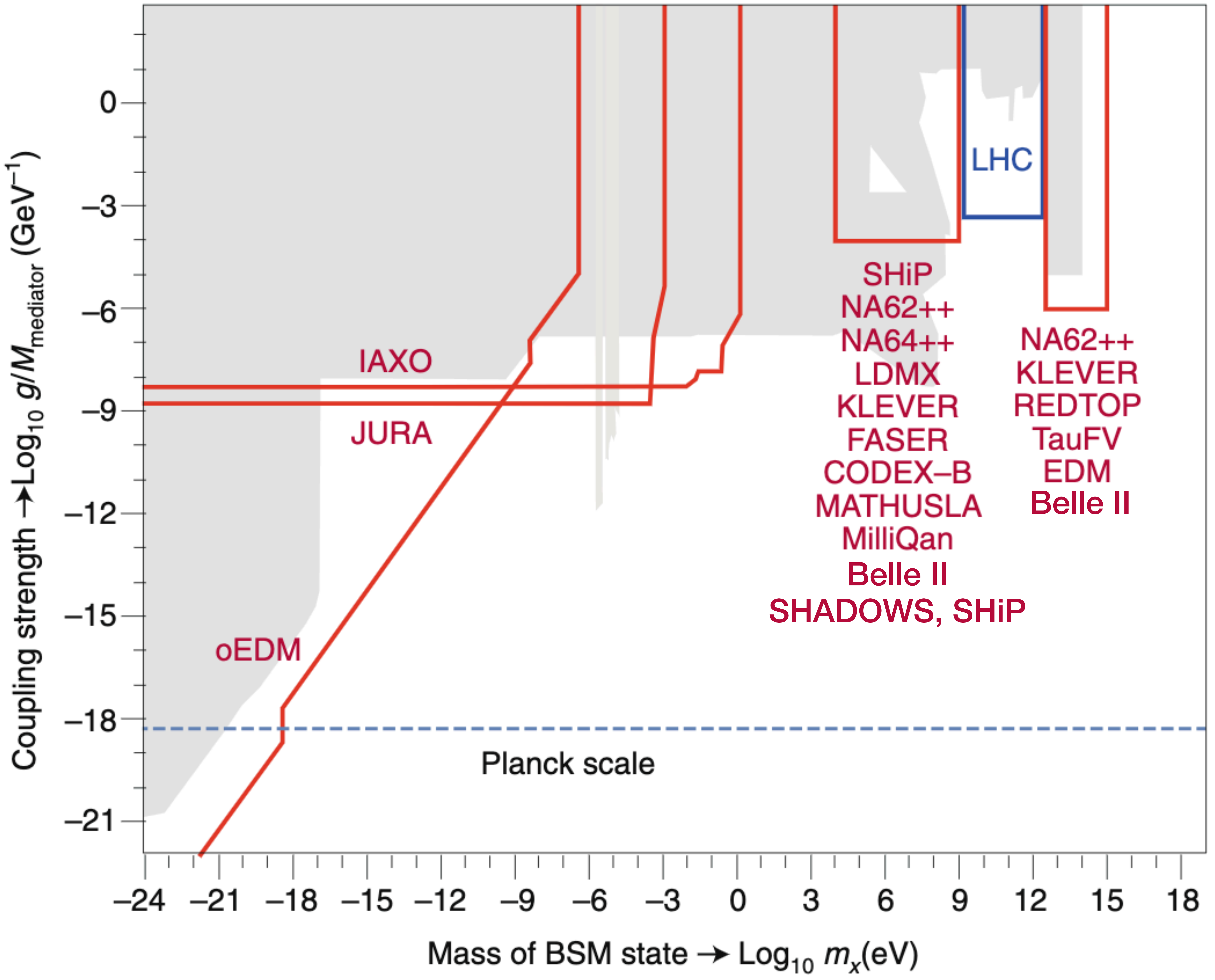


What alternatives do we have for the Standard Model?

- Wishlist for a good new theory:
  - Contains existing SM as low energy approximation
  - Predictive power: Predicts new falsifiable phenomena
  - Simplicity: Has mathematically (!) simpler structure
  - Deductibility: Fewer ad-hoc assumptions and fewer free parameters
  - Completeness: Gives reasons for non-observance of otherwise allowed effects ("everything that is not forbidden is allowed")

- There is an incredibly large number of possible BSM extensions!

New particles could be very heavy or/and very weakly coupled



Credit: Nature Physics volume 16, 393–401 (2020)

Order in the chaos 1: Portal models

- $\mathscr{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$
  - O_{SM} is an operator composed from SM fields and O_{DS} is an operator composed from dark sector fields
- Only keep lowest dimensional renormalisable portals
  - this makes them rather simple theoretically, which in turn makes them very popular
- Keeps the theoretical structure (and all symmetries) of the SM intact
- Predict experimental signatures, but not couplings or mass

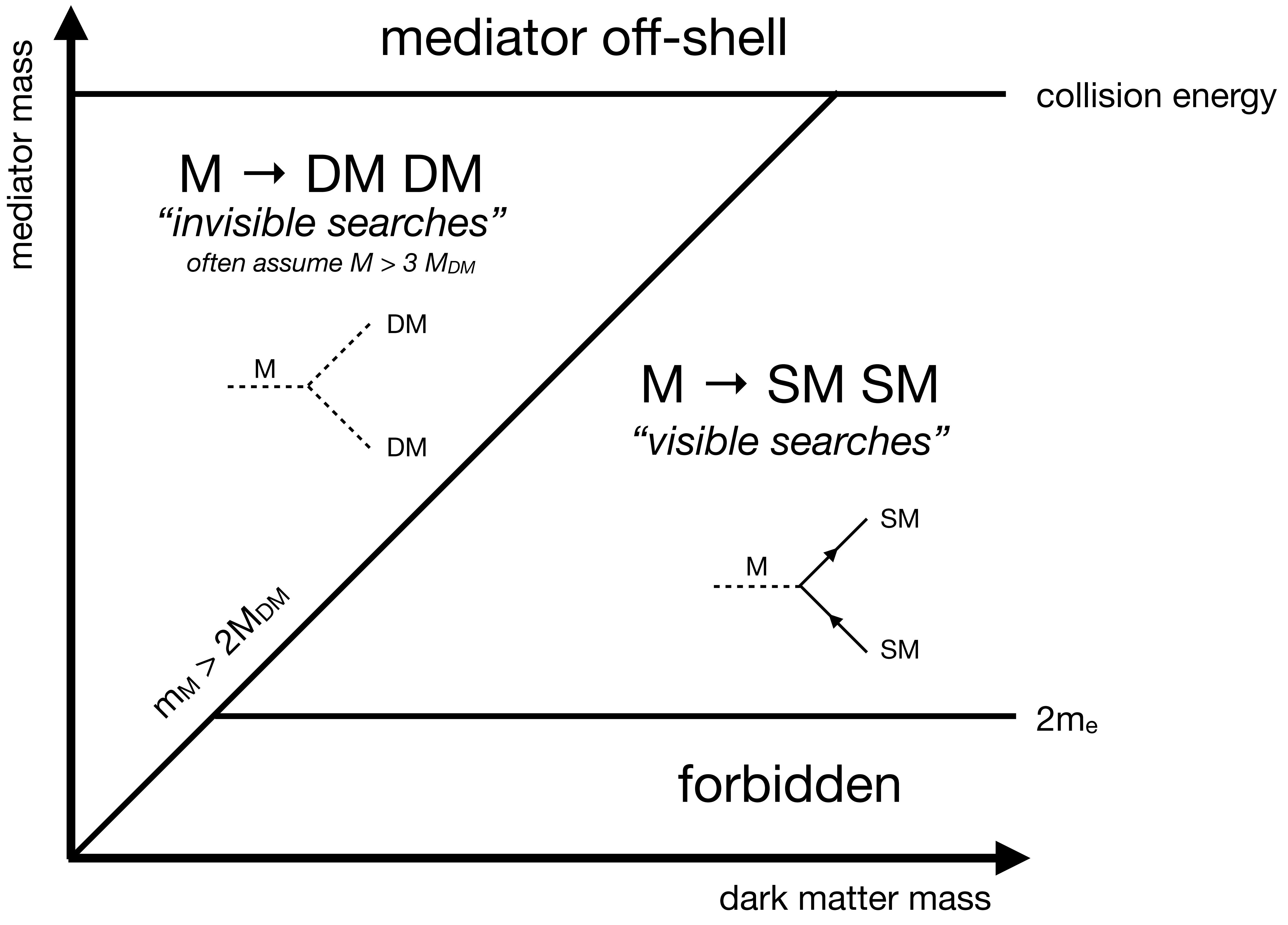
Order in the chaos 1: Portal models

Portal	Coupling
Vector portal (**F** is the dark photon field which couples to the hypercharge field B)	$-\frac{\epsilon}{2\cos(\theta_W)} F'_{\mu\nu} B^{\mu\nu}$
Higgs portal (**S** is a scalar singlet that couples to the SM Higgs doublet H with **μ** (dim. less) and **λ** (dimensional))	$(\mu S + \lambda S^2) H^\dagger H$
ALP portal (**a** is a pseudoscalar axion that couples to a dimension-4 di-photon, di-fermion or di-gluon operator)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}^{\mu\nu}_i, \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$
Neutrino portal (**N** is a neutral fermion that couples to one of the left-handed doublets L of the SM and the Higgs field H with a Yukawa coupling y_N)	$y_N L H N$

While for QCD axions mass and coupling have a fixed relation, axion-like particles can have any mass and coupling.

New BSM particles could decay into other BSM particles

- Resonance searches (or "bump hunts") generally search for unstable particles and reconstruct the invariant mass from decay products
- Typically sensitive to new mediators (e.g. heavy or light Z' bosons)
- Decays could happen into other BSM particles, incl. invisible DM candidates

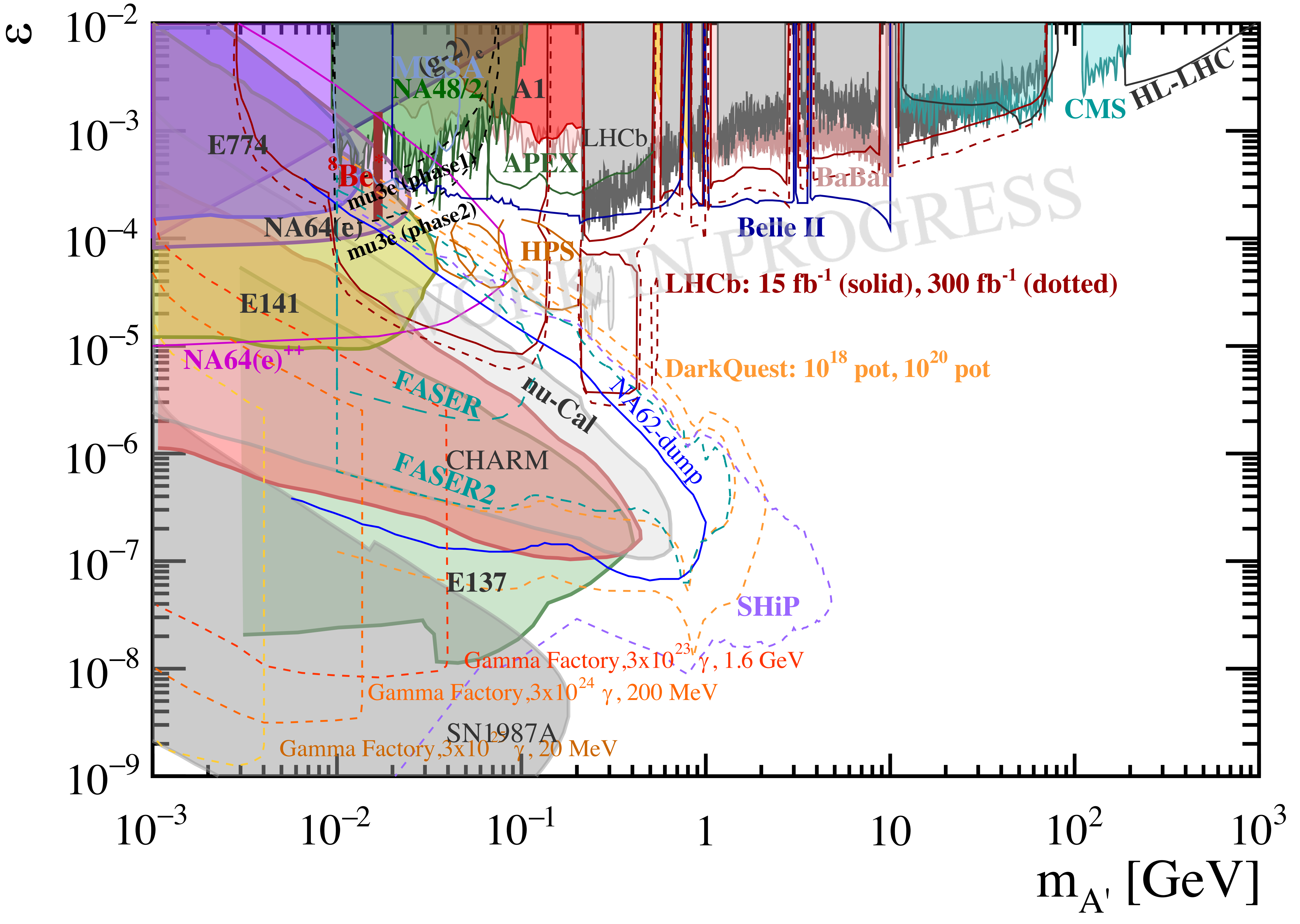


Look-Elsewhere Effect (LEE)

- Experimental searches for unknown (!) parameters generally test many (can be tens of thousands…) different hypothesis on the same dataset
- Probability of a significant result due to statistical fluctuations increases with the number of test-hypotheses
- So call “trial factors” are usually determined using simulation to correct for this effect
- In publications “local significance” refers to uncorrected values, “global significance” refers to corrected values

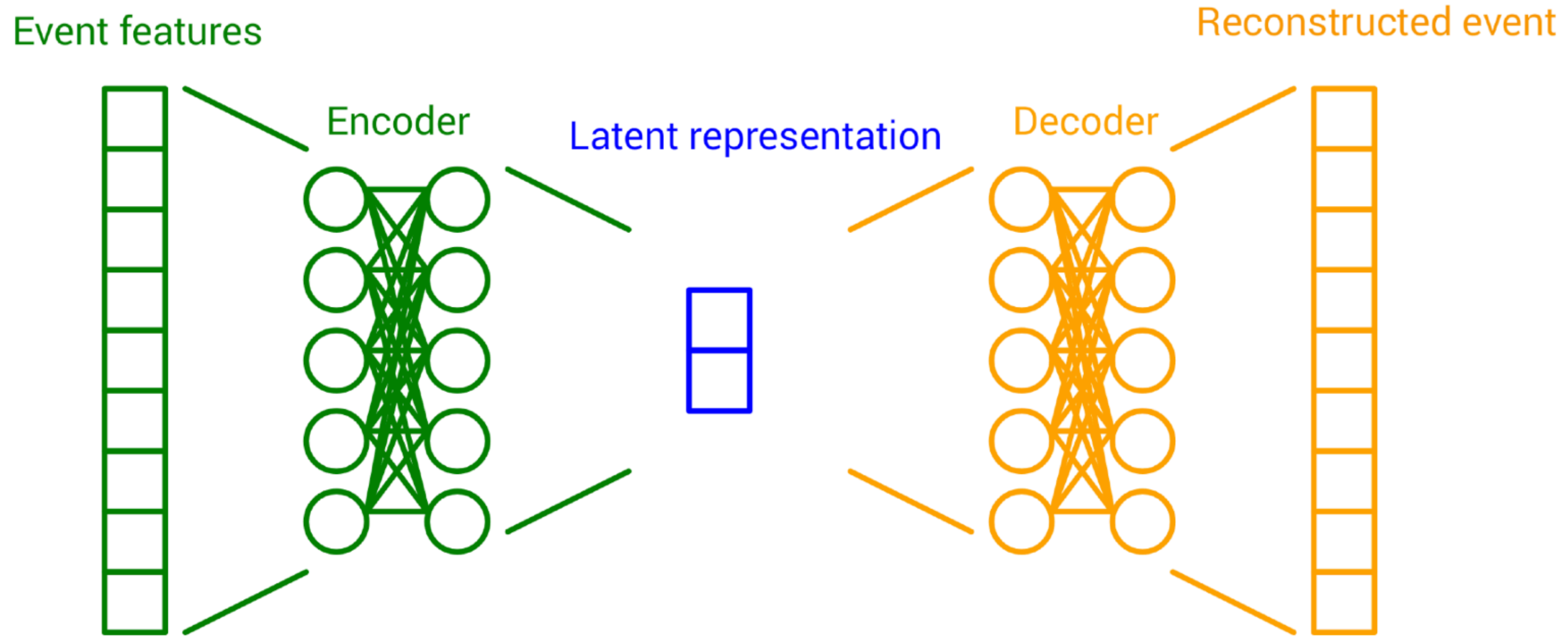
Example portal model: Dark photons

- The most famous: massive Dark Photons
- Mix with SM photons and decay back into pairs of SM particle (like a virtual SM photon)
- Requires very high production rates of SM photons: Beam dumps and high-intensity colliders like Belle II



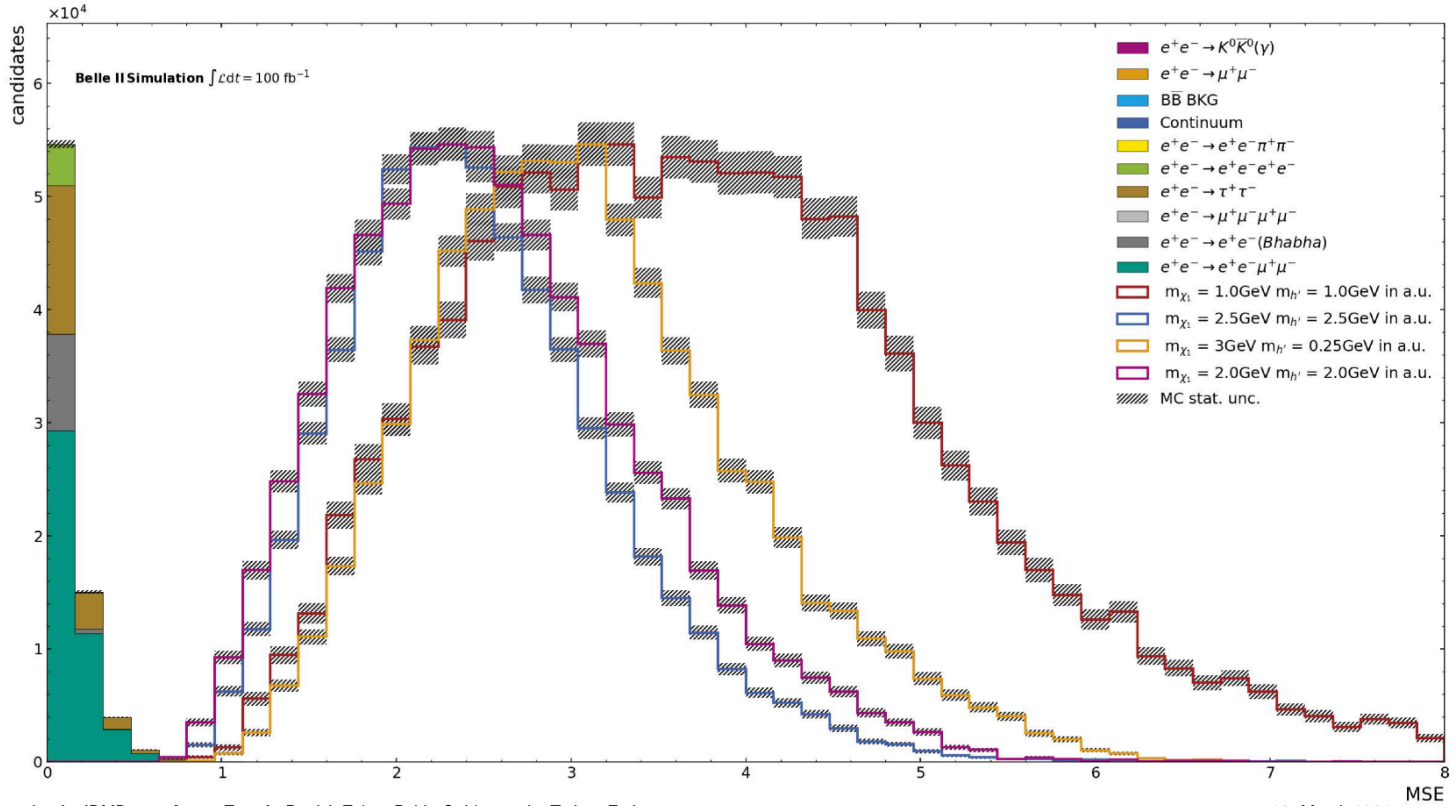
Reduce model dependency: Anomaly Detection

- State of the art development: Unsupervised Machine Learning trained on known backgrounds but not on unknown (and hence often assumed) signal model



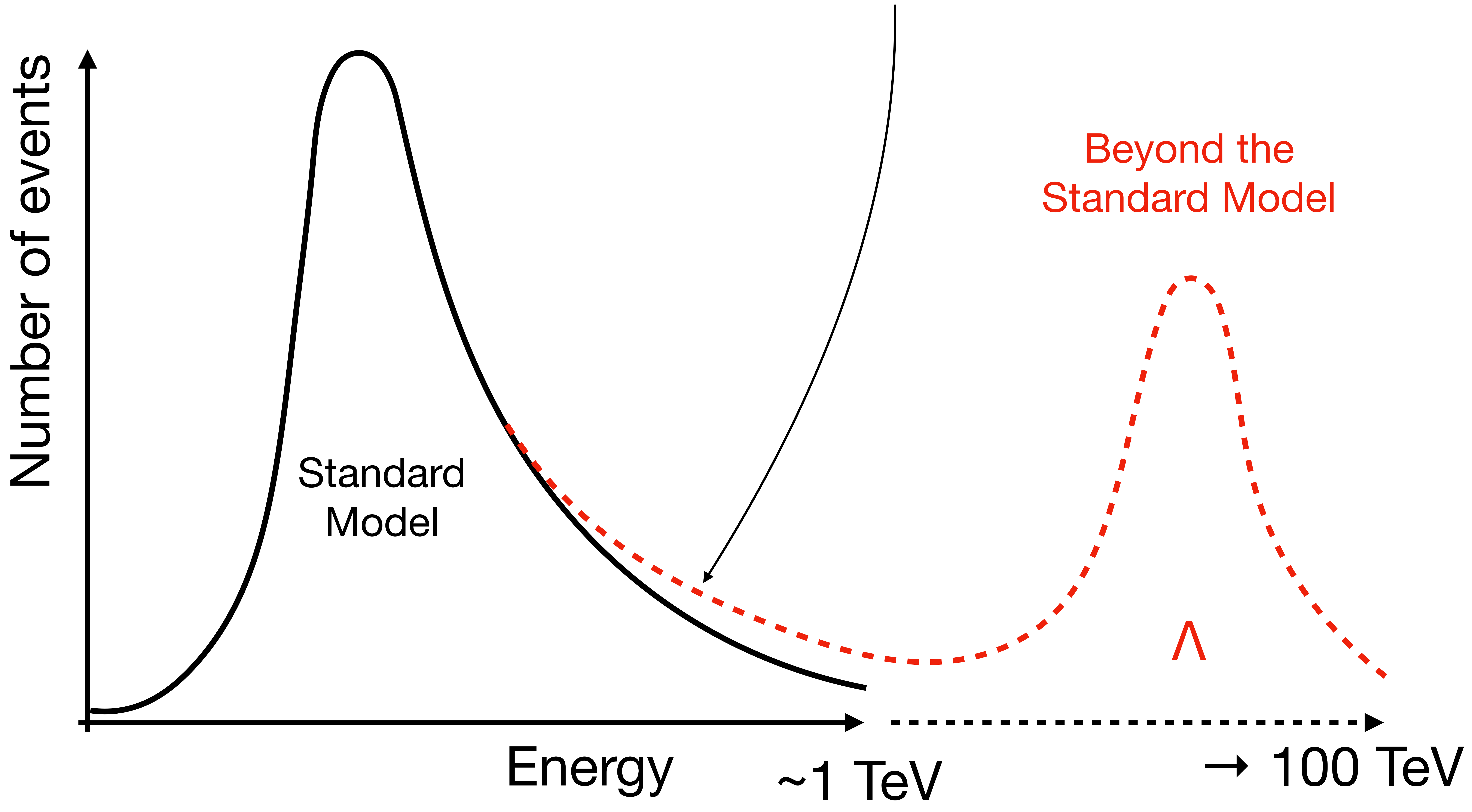
- ML learns to encode and decode event signatures it has been trained on

- BSM physics that was not part of the training sample perform worse in this process



Finding new physics: Tail of the whale

- Energy scale Λ of new physics may be beyond our direct reach
  - → instead of resonance peaks, we will see small deviations from predictions



Finding new physics: Tail of the whale

- Example from history: Discovery of the Z boson (compare lecture 12)

$$\frac{2s}{\pi}\frac{1}{N_c^{\mathrm{f}}}\frac{d\sigma_{\mathrm{ew}}}{d\cos\theta}(\mathrm{e^+e^-}\to \mathrm{f\bar{f}}) \;=\;$$

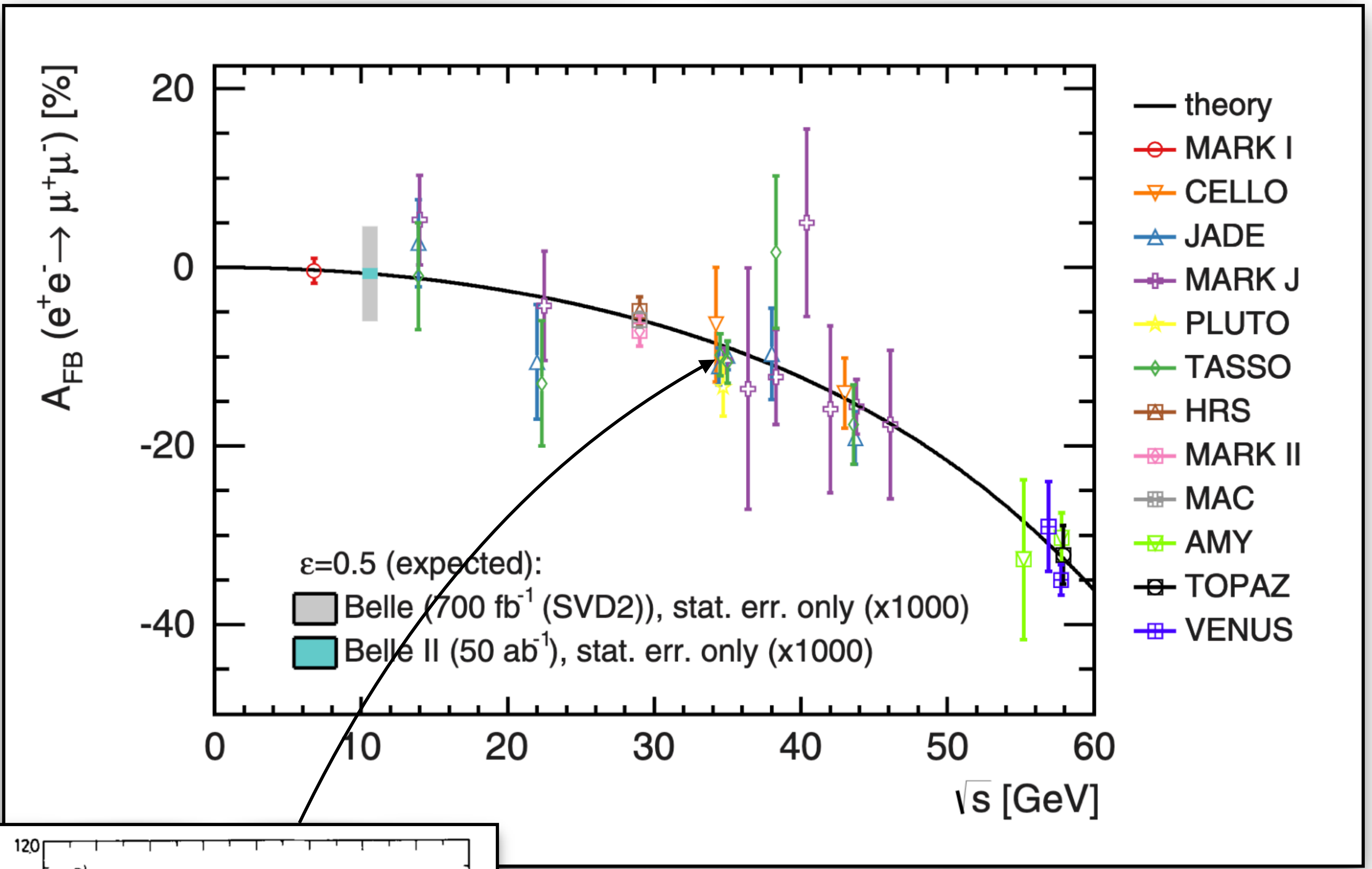
$$\underbrace{|\alpha(s)Q_{\mathrm{f}}|^2\,(1+\cos^2\theta)}_{\sigma^\gamma}$$

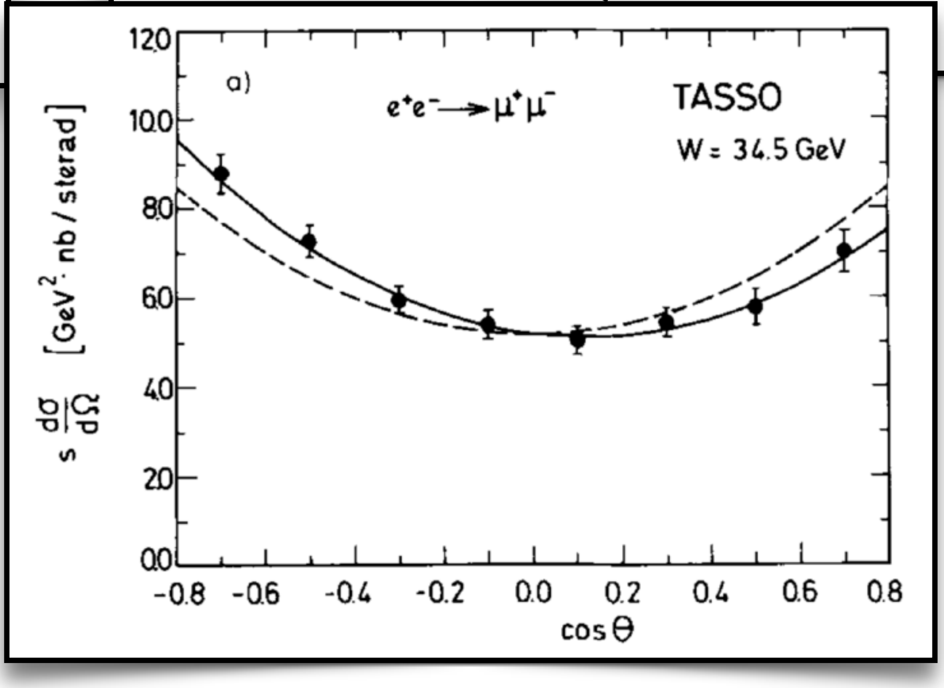
$$\underbrace{-8\Re\left\{\alpha^*(s)Q_{\mathrm{f}}\chi(s)\left[\mathcal{G}_{\mathrm{Ve}}\mathcal{G}_{\mathrm{Vf}}(1+\cos^2\theta)+2\mathcal{G}_{\mathrm{Ae}}\mathcal{G}_{\mathrm{Af}}\cos\theta\right]\right\}}_{\gamma\text{–Z interference}}$$

$$\underbrace{\begin{array}{c}+16|\chi(s)|^2\left[(|\mathcal{G}_{\mathrm{Ve}}|^2+|\mathcal{G}_{\mathrm{Ae}}|^2)(|\mathcal{G}_{\mathrm{Vf}}|^2+|\mathcal{G}_{\mathrm{Af}}|^2)(1+\cos^2\theta)\right.\\ \left.+8\Re\left\{\mathcal{G}_{\mathrm{Ve}}\mathcal{G}_{\mathrm{Ae}}{}^*\right\}\Re\left\{\mathcal{G}_{\mathrm{Vf}}\mathcal{G}_{\mathrm{Af}}{}^*\right\}\cos\theta\right]\end{array}}_{\sigma^{\mathrm{Z}}}$$

with:

$$\chi(s) \;=\; \frac{G_{\mathrm{F}}m_{\mathrm{Z}}^2}{8\pi\sqrt{2}}\,\frac{s}{s-m_{\mathrm{Z}}^2+is\Gamma_{\mathrm{Z}}/m_{\mathrm{Z}}}\,,$$





Order in the chaos 2: Effective field theories (EFT)

- Well known example that precision calculations are possible without knowing details of the underlying theory: Fermi theory of β-decay
- Idea: Expand SM Lagrangian in powers of $1/\Lambda$

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \cancel{\sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cancel{\sum_i \frac{C_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)}} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

Lepton-number violating

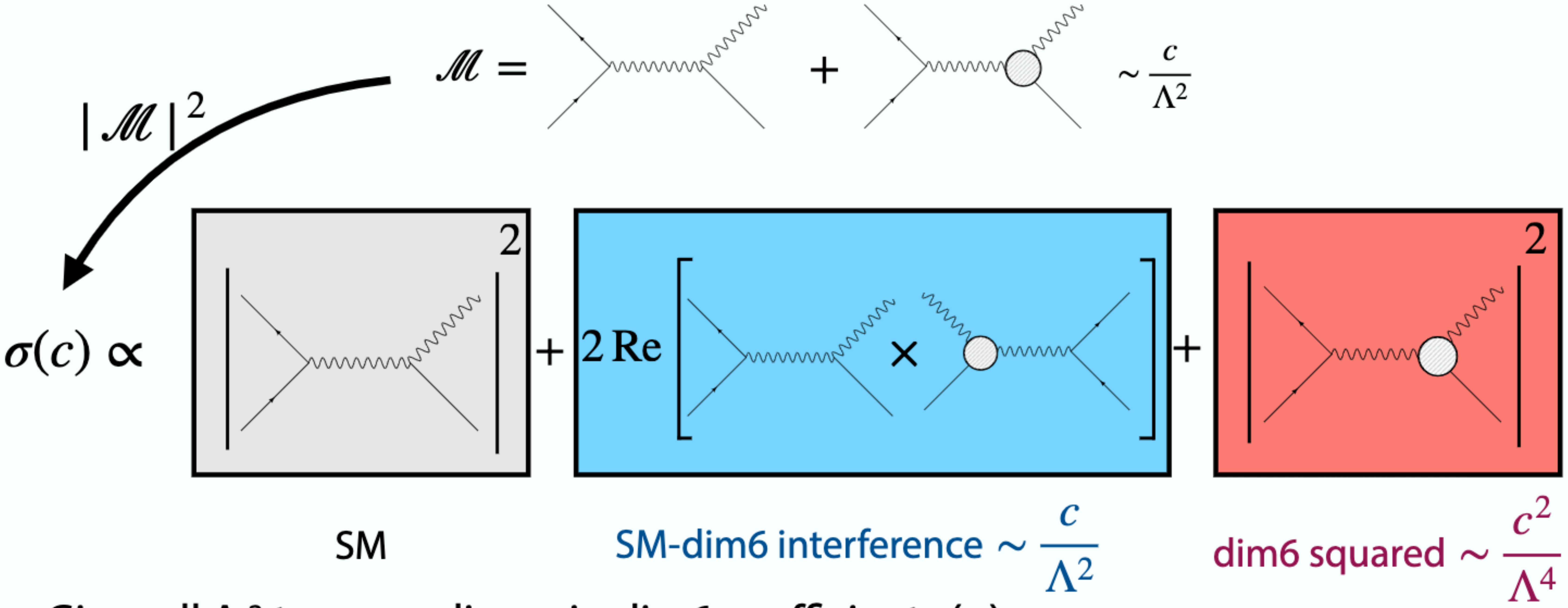
Violates B-L

$\mathcal{O}_i$: operators = interaction terms at a given expansion order

C_i : operators = Wilson coefficients, free parameters

Order in the chaos 2: SM Effective field theories (SMEFT)

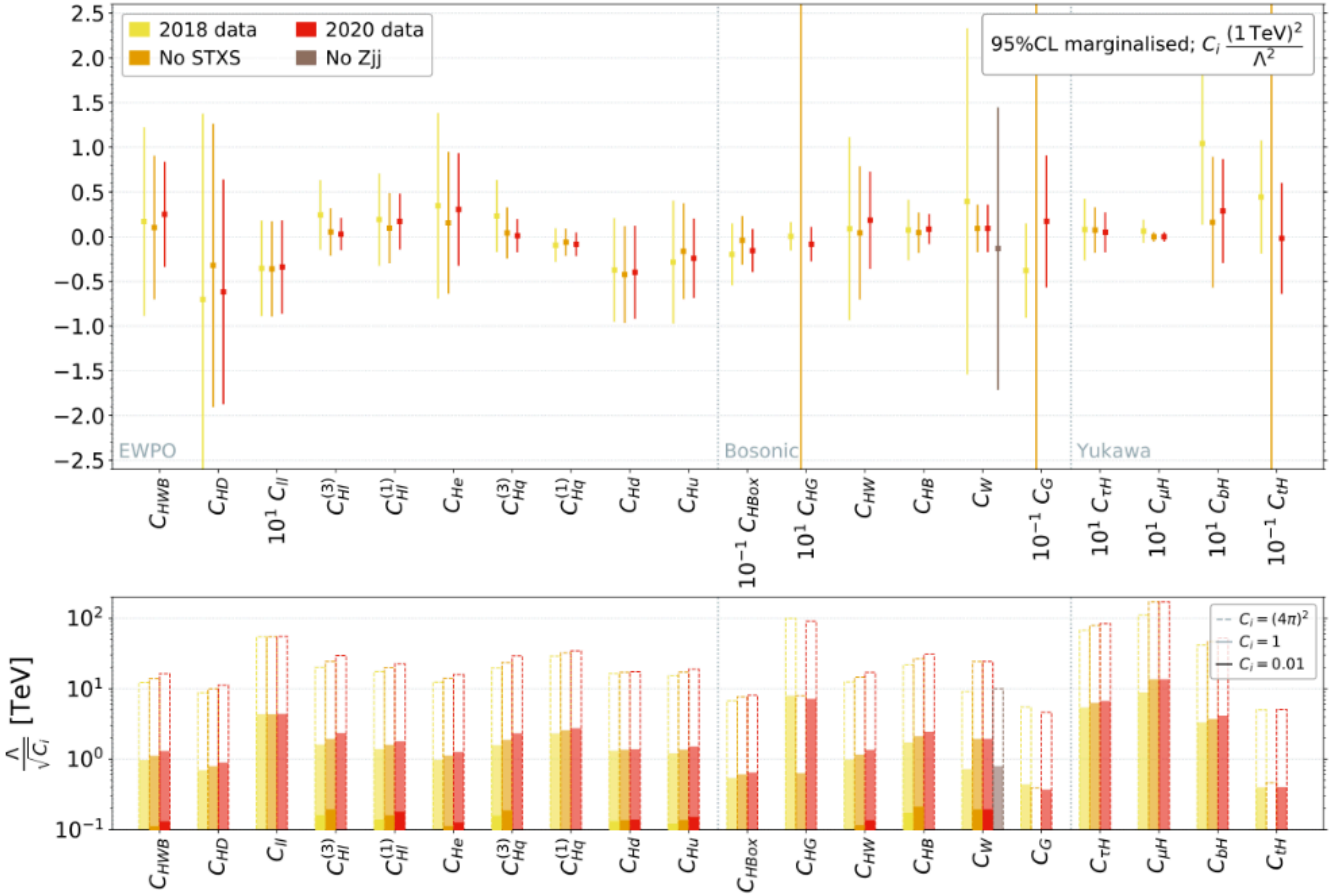
- Some redundancy for full set of all operators: 2499 in total

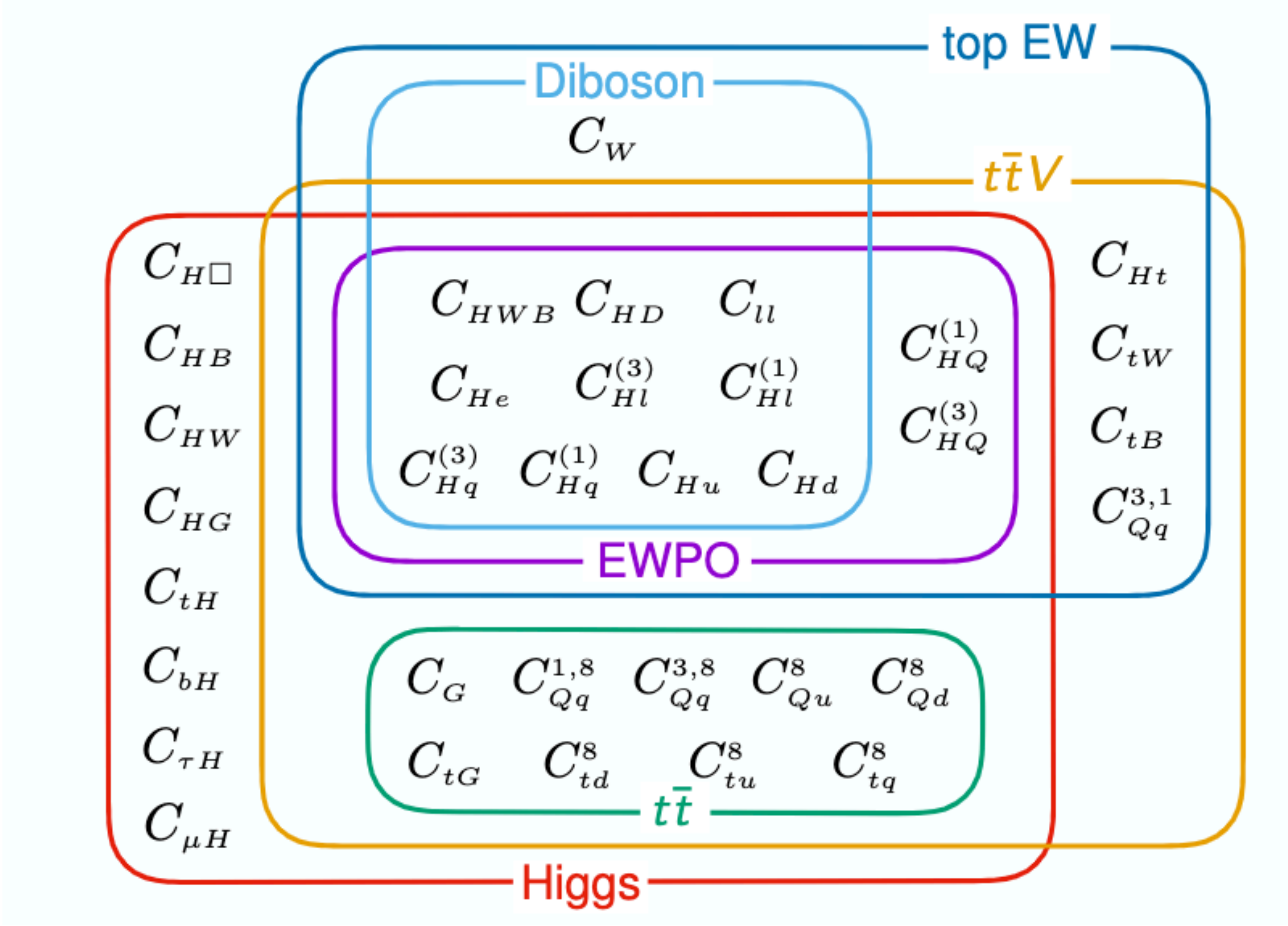


- Gives all Λ^{-2} terms linear in dim6 coefficients (c_i)
- But Λ^{-4} incomplete neglects SM-dim8 interference at the same order
- In practice parameterisations may neglect quadratic c^2 terms
  - Ideally: dim-6 squared small, but for many measurements not the case

Order in the chaos 2: SM Effective field theories (SMEFT)

- Even after applying symmetry arguments, one is usually left with a few ten operators
- Usually many observables (differential cross sections, angular distributions, …) are combined in global fits



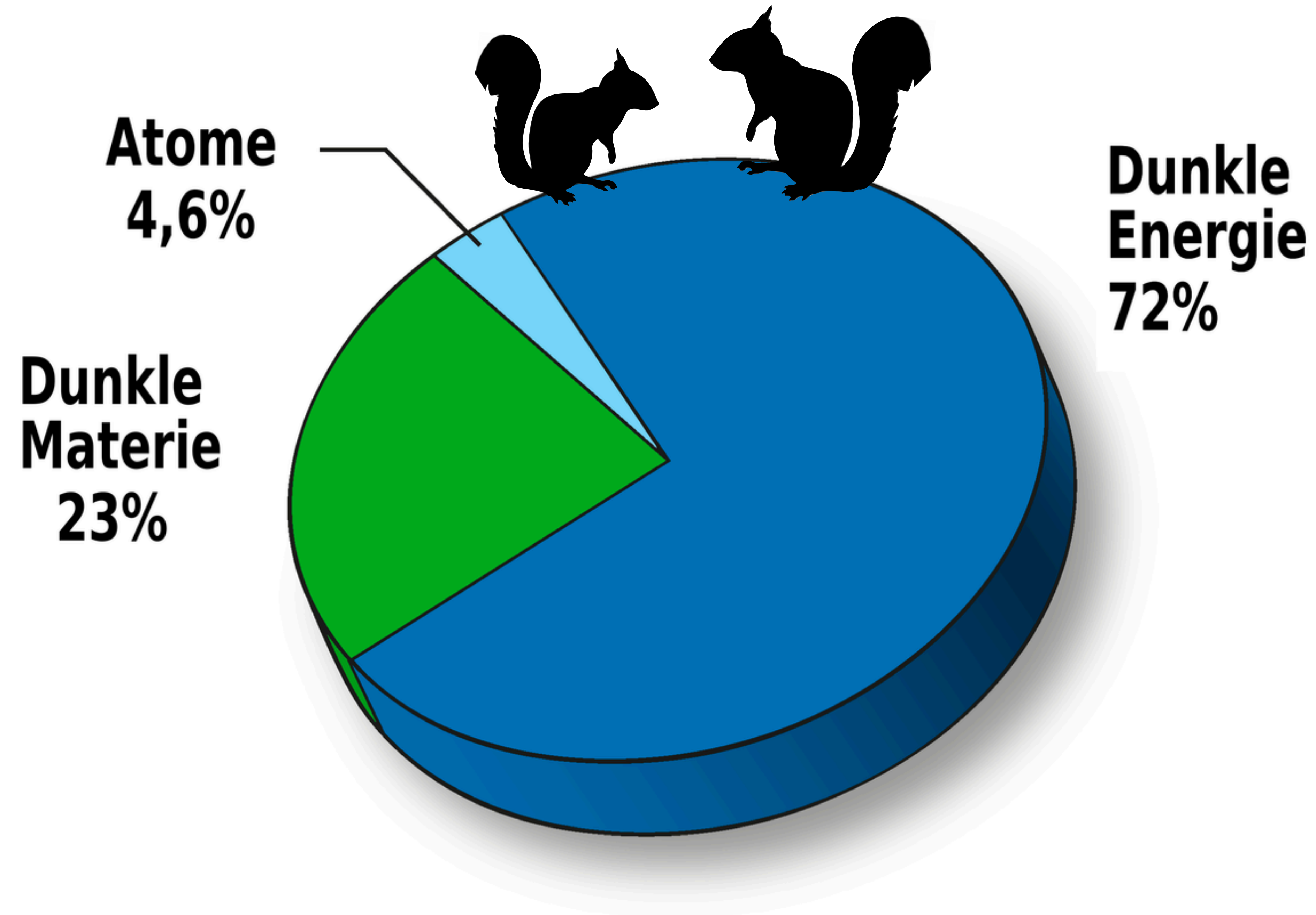


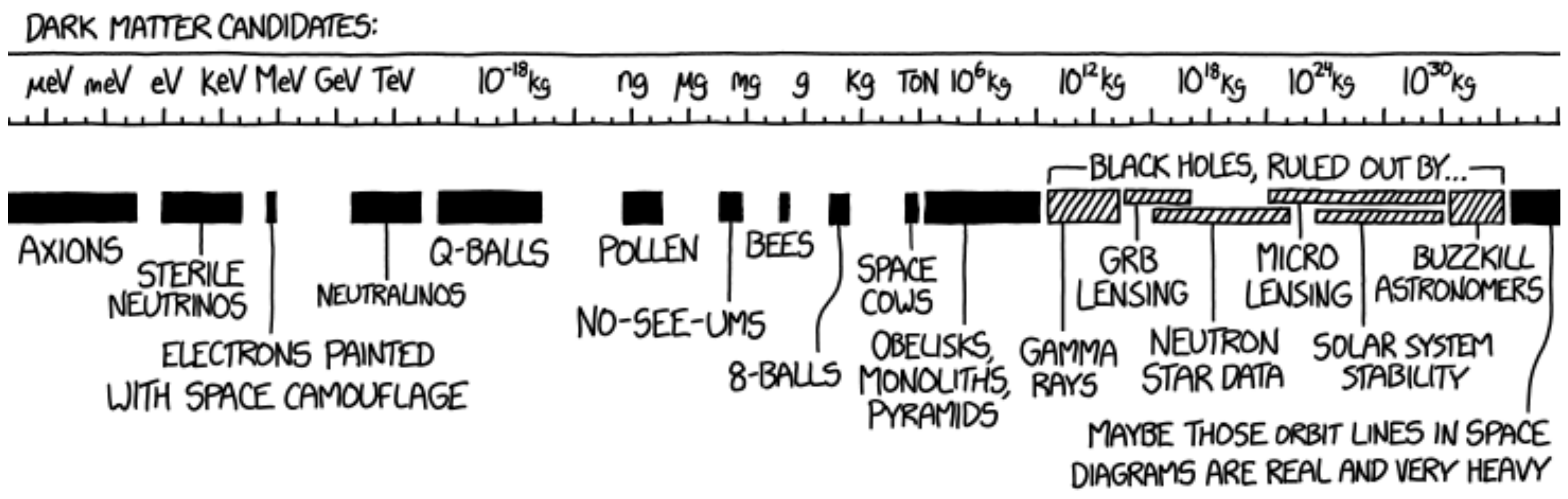
https://arxiv.org/abs/2012.02779

Unexplained phenomena: Dark Matter

Theoretical problem!

- Astrophysical observations of different observables require additional matter (and/or modifications of general relativity)
- The SM has not particle candidate that can constitute Dark Matter (DM)
- The effect is so large and in so strong disagreement with the SM, that worldwide efforts are underway to search for DM
- More in the next lecture!





Unexplained phenomena: Matter/Antimatter Asymmetry

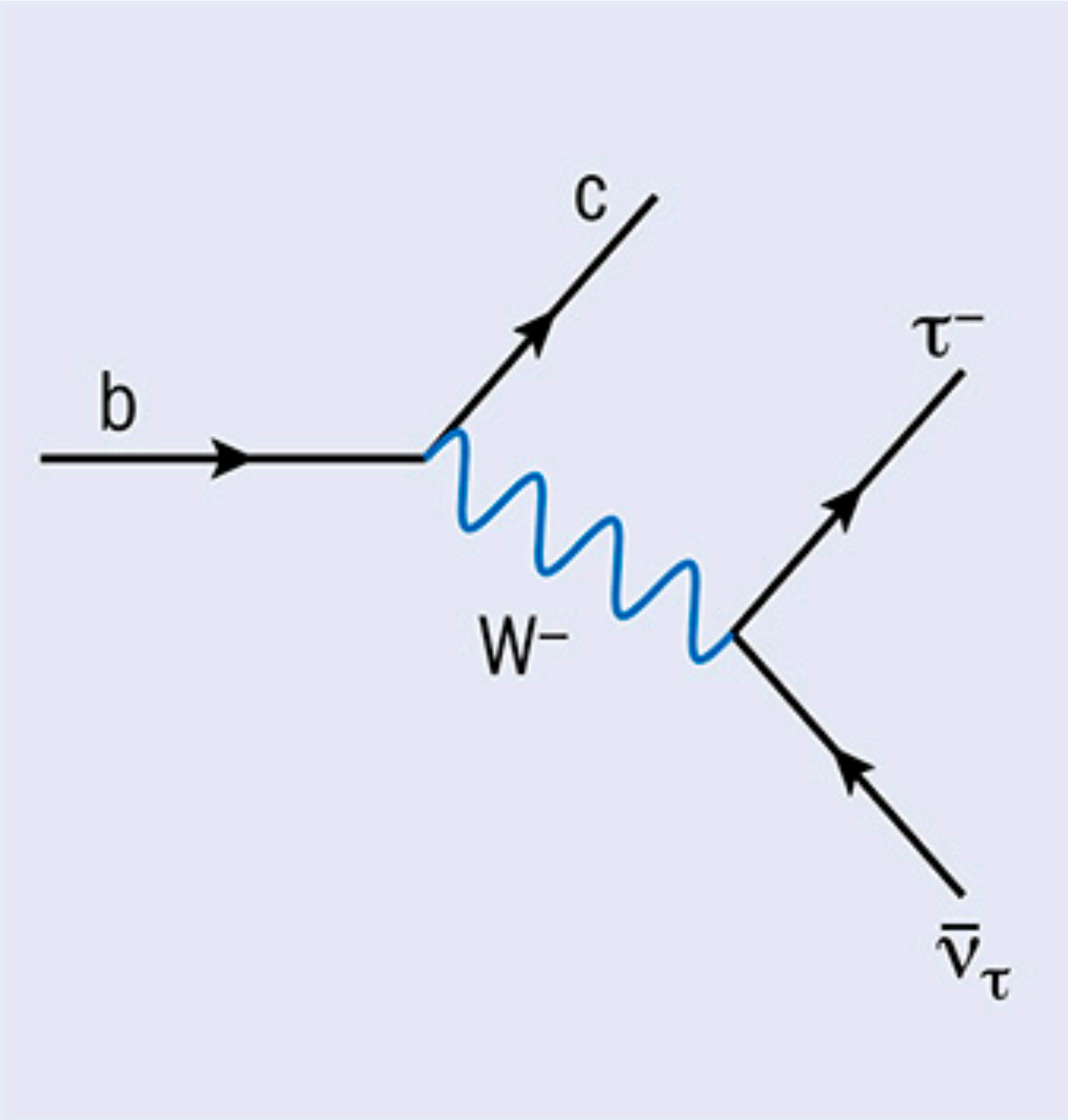
- Imbalance of baryonic and anti-baryonic matter in the universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-9}$$ (better expressed using the entropy density)

- Sakharov conditions:
  - Baryon number B violation (e.g. proton decay)
  - C- and CP-symmetry violation (CKM matrix in the SM, but the effect is tiny → CPV in the neutrino sector?)
  - Interactions out of thermal equilibrium (production rate of asymetry generating processes smaller than expansion of the universe
- No explanation in the SM!

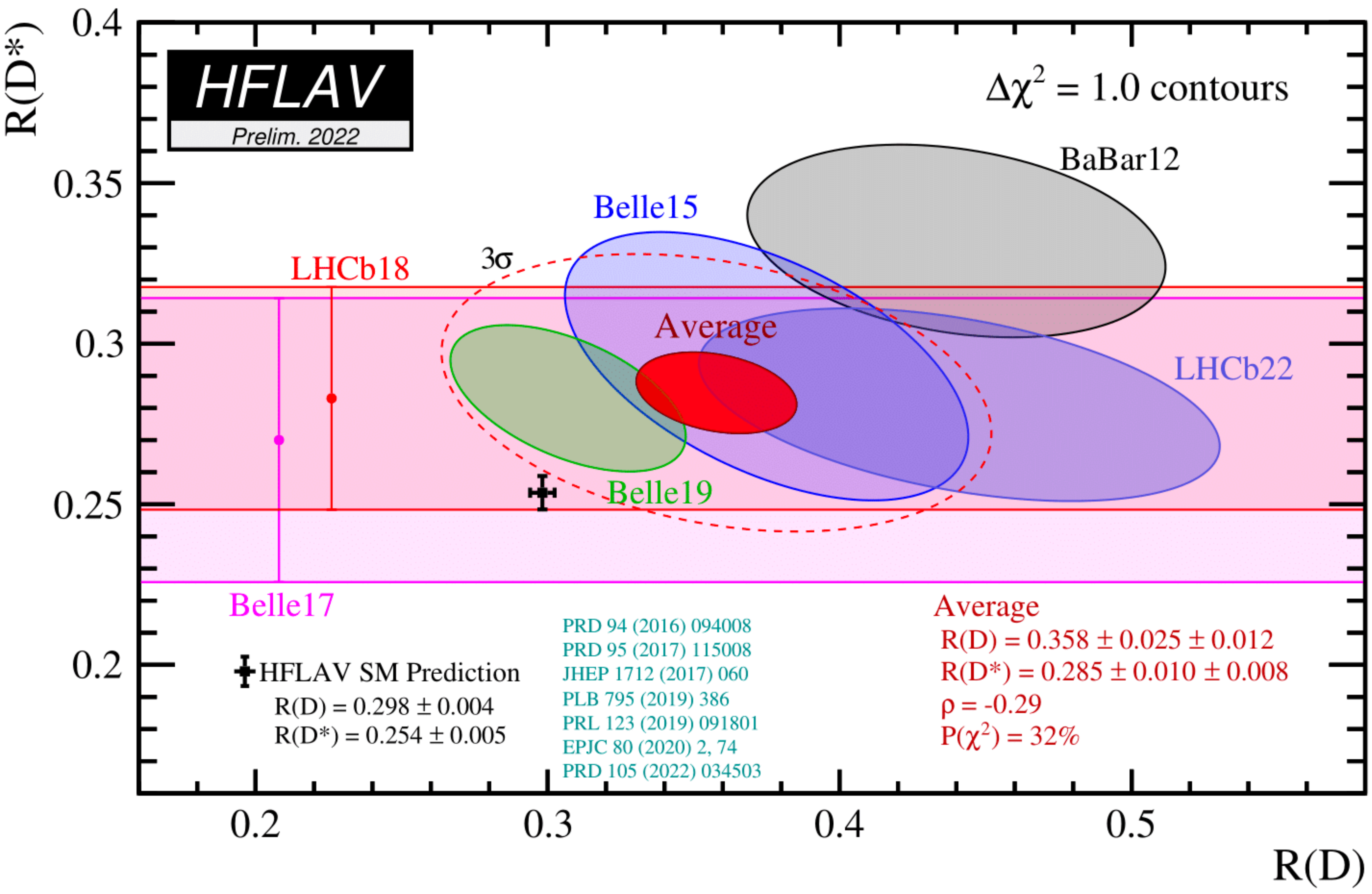
Anomaly: R(D*)

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

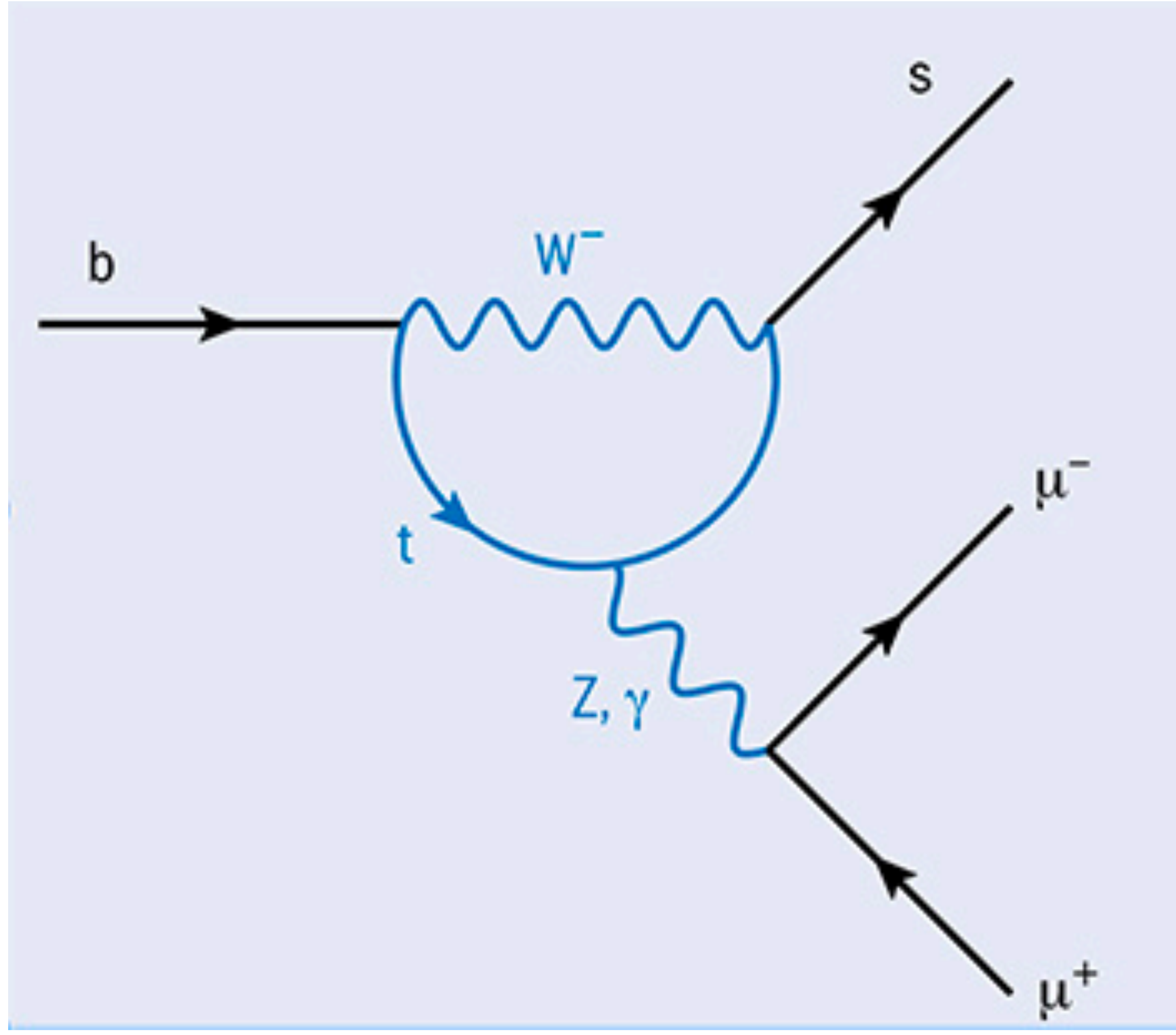


Anomaly: R(D*) at 3.2σ

Experimental problem?



Anomaly: R(K) and R(K*) in $b \to s\ell\ell$ transitions



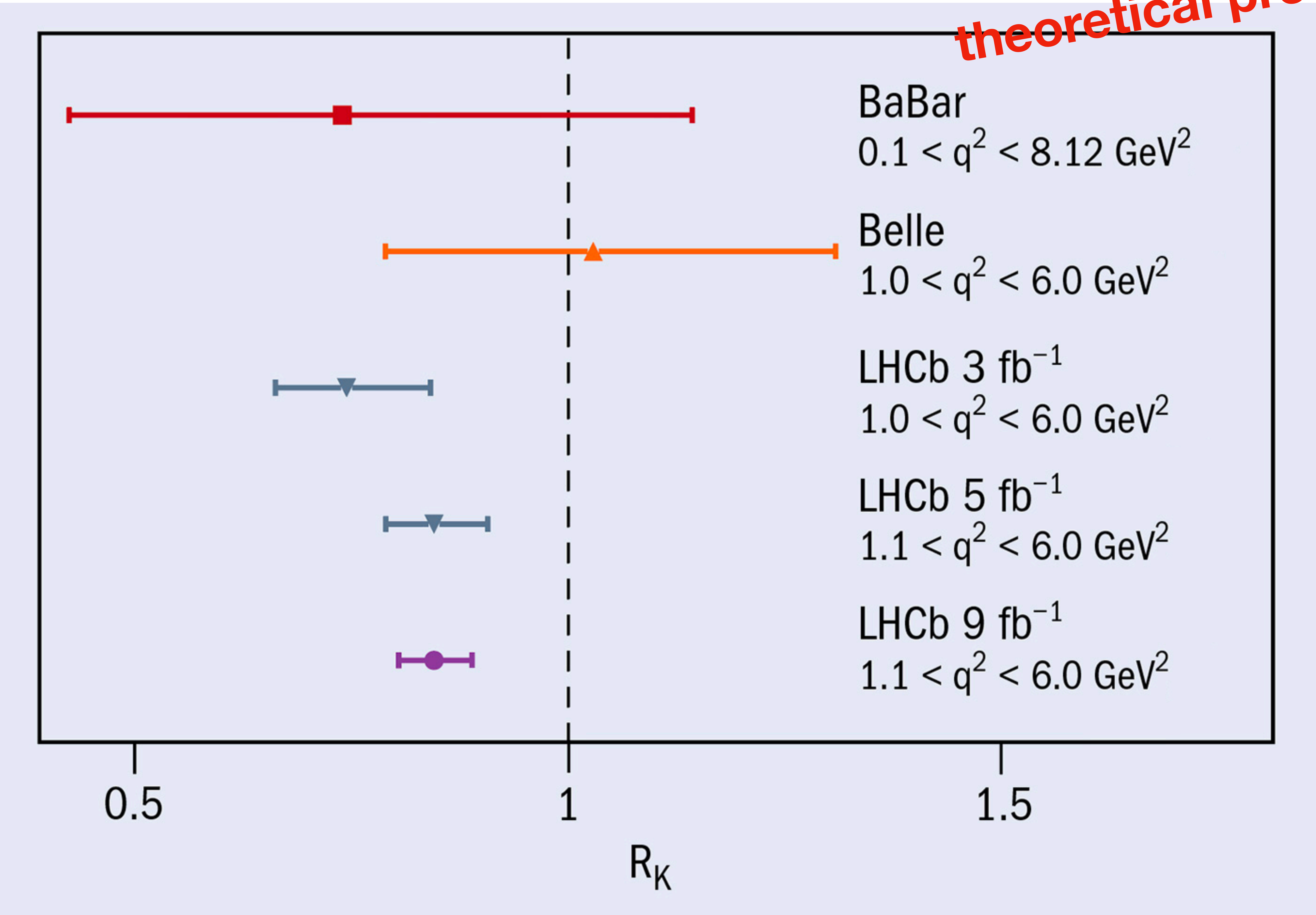
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

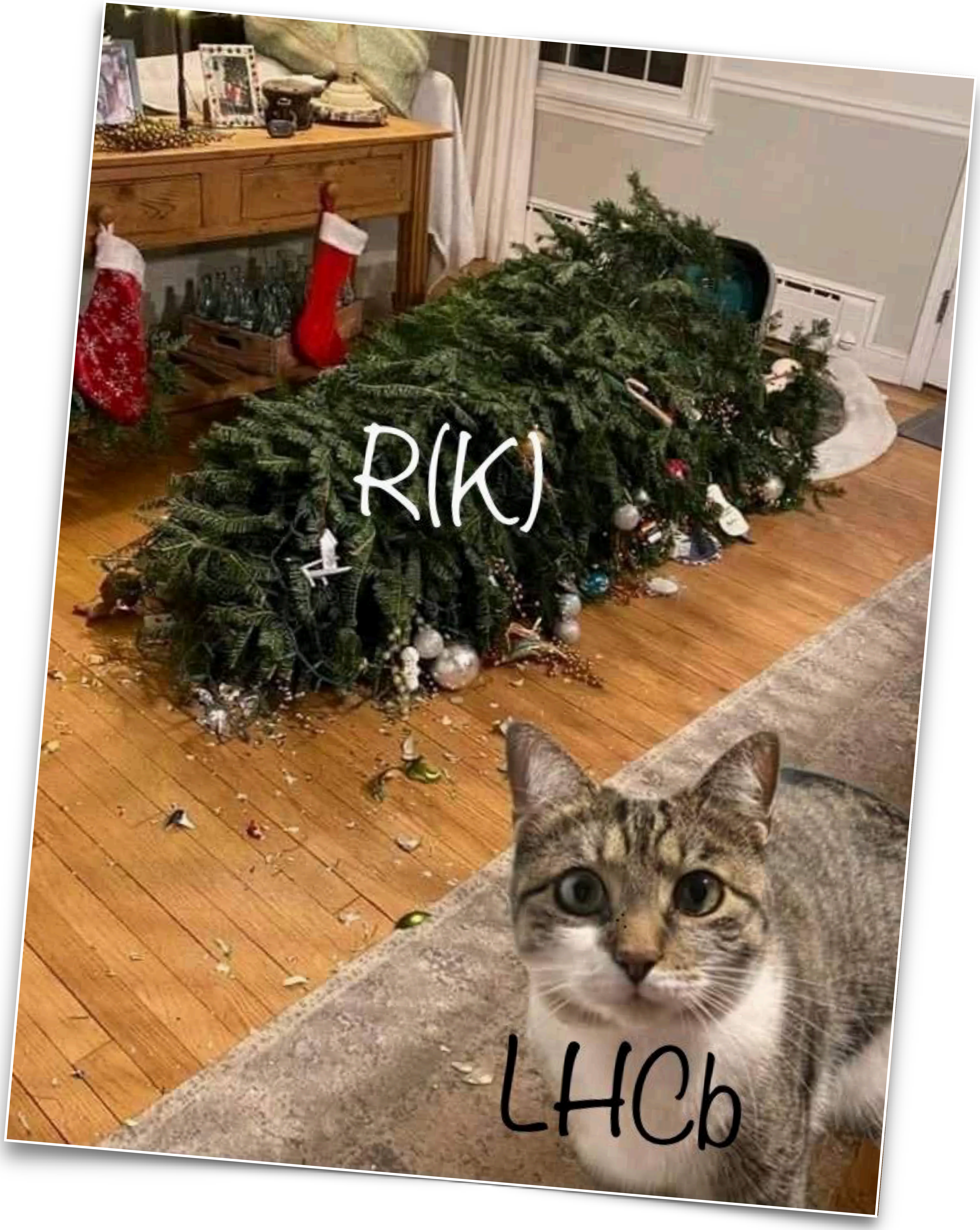
$$R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}$$

$$R_\phi = \frac{\mathcal{B}(B_s \to \phi\,\mu^+\mu^-)}{\mathcal{B}(B_s \to \phi\,e^+e^-)}$$

Anomaly: R(K) 2021

Experimental or theoretical problem?

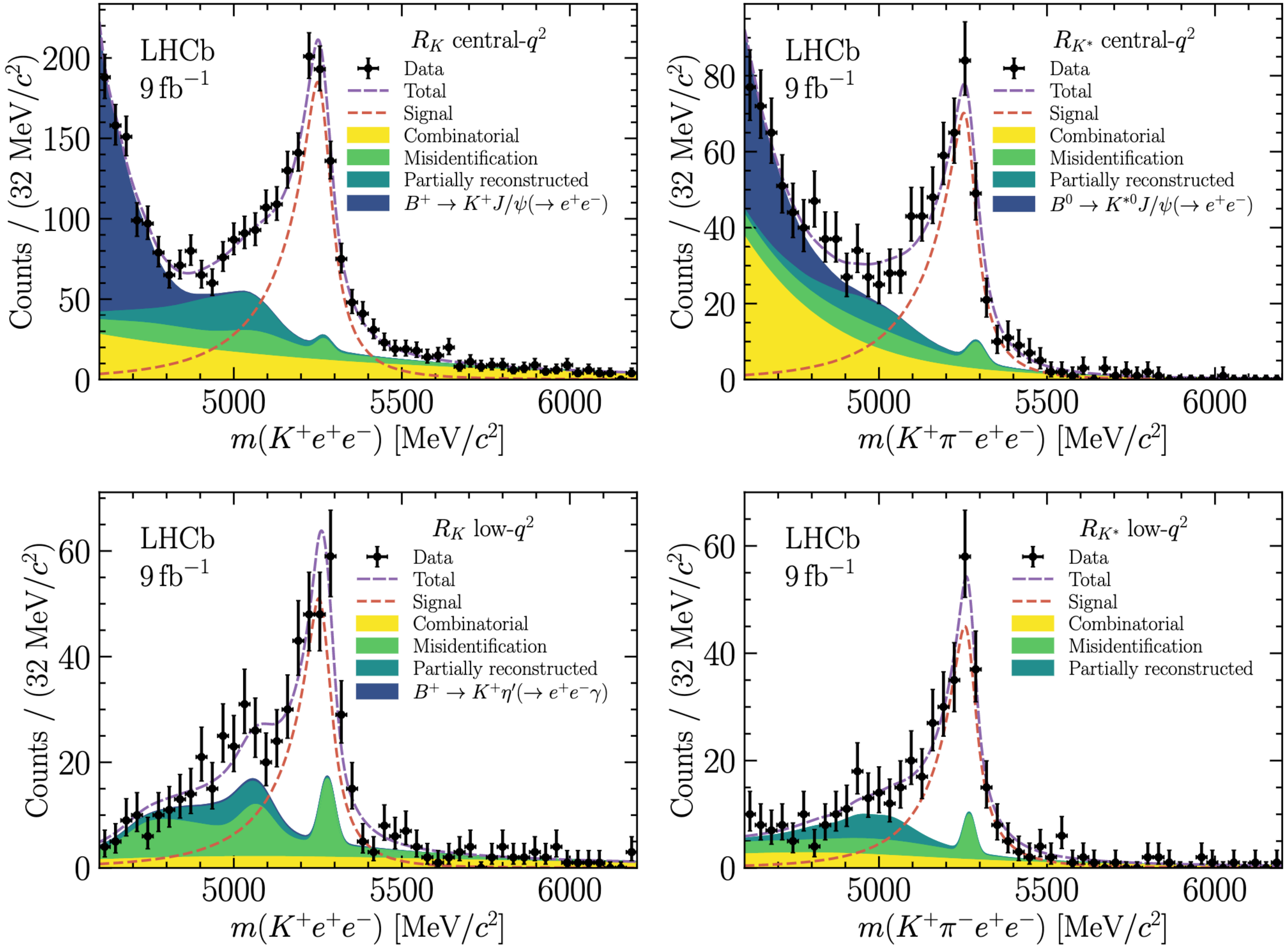




R(K)
LHCb

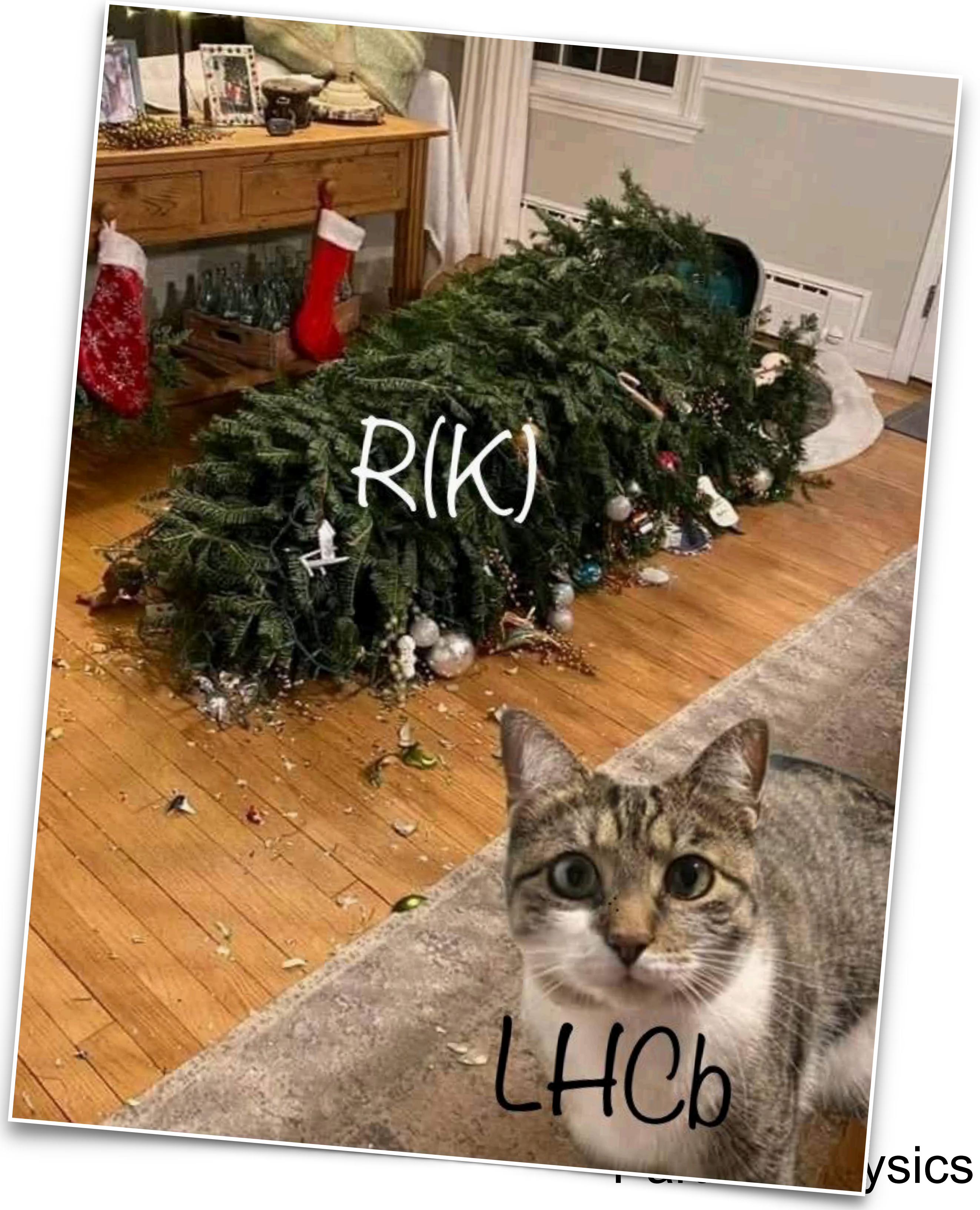
~~Anomaly~~: R(K) 2022

Experimental problem!



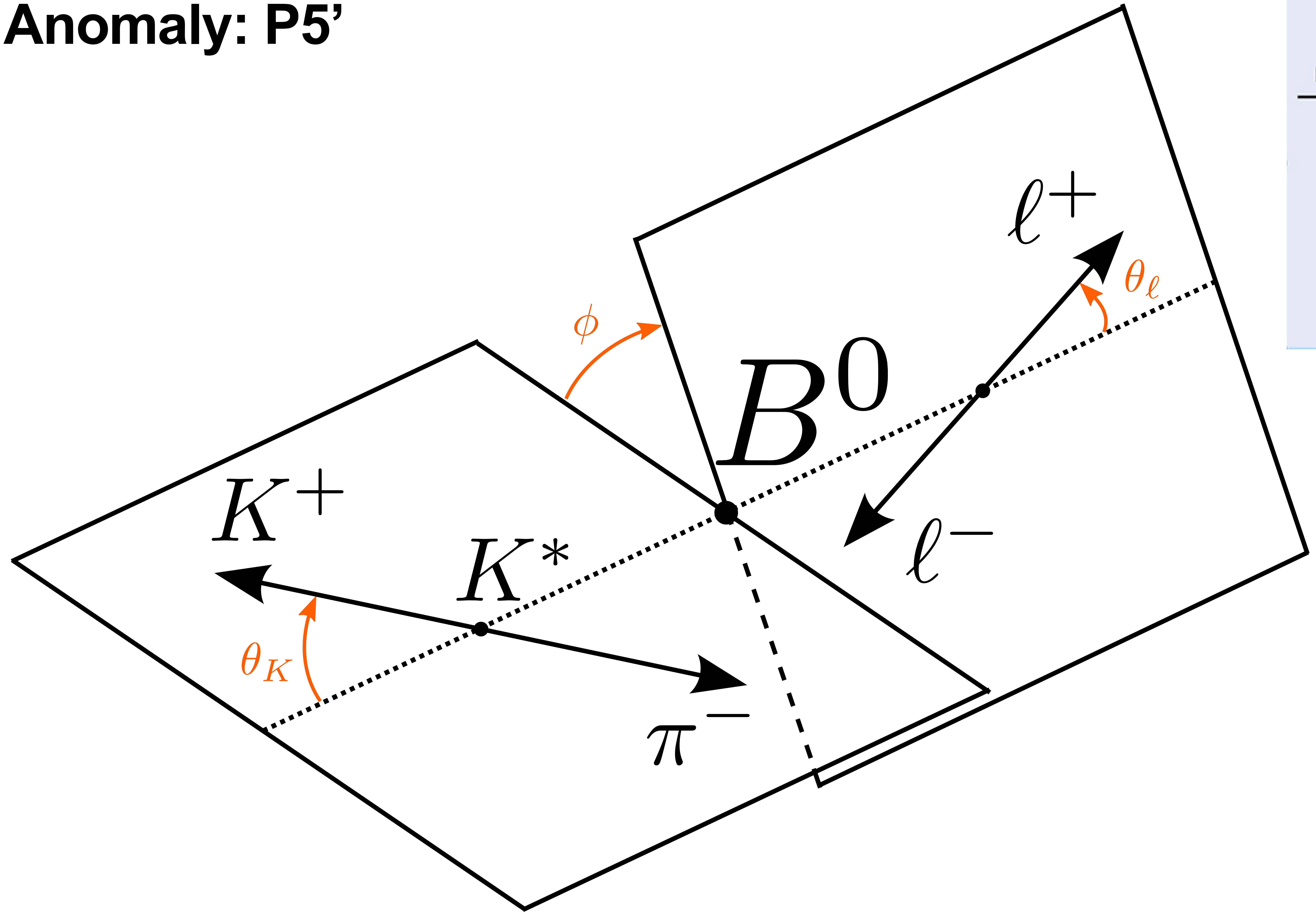
$$\text{low-}q^2 \begin{cases} R_K &= 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})\,^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} &= 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})\,^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

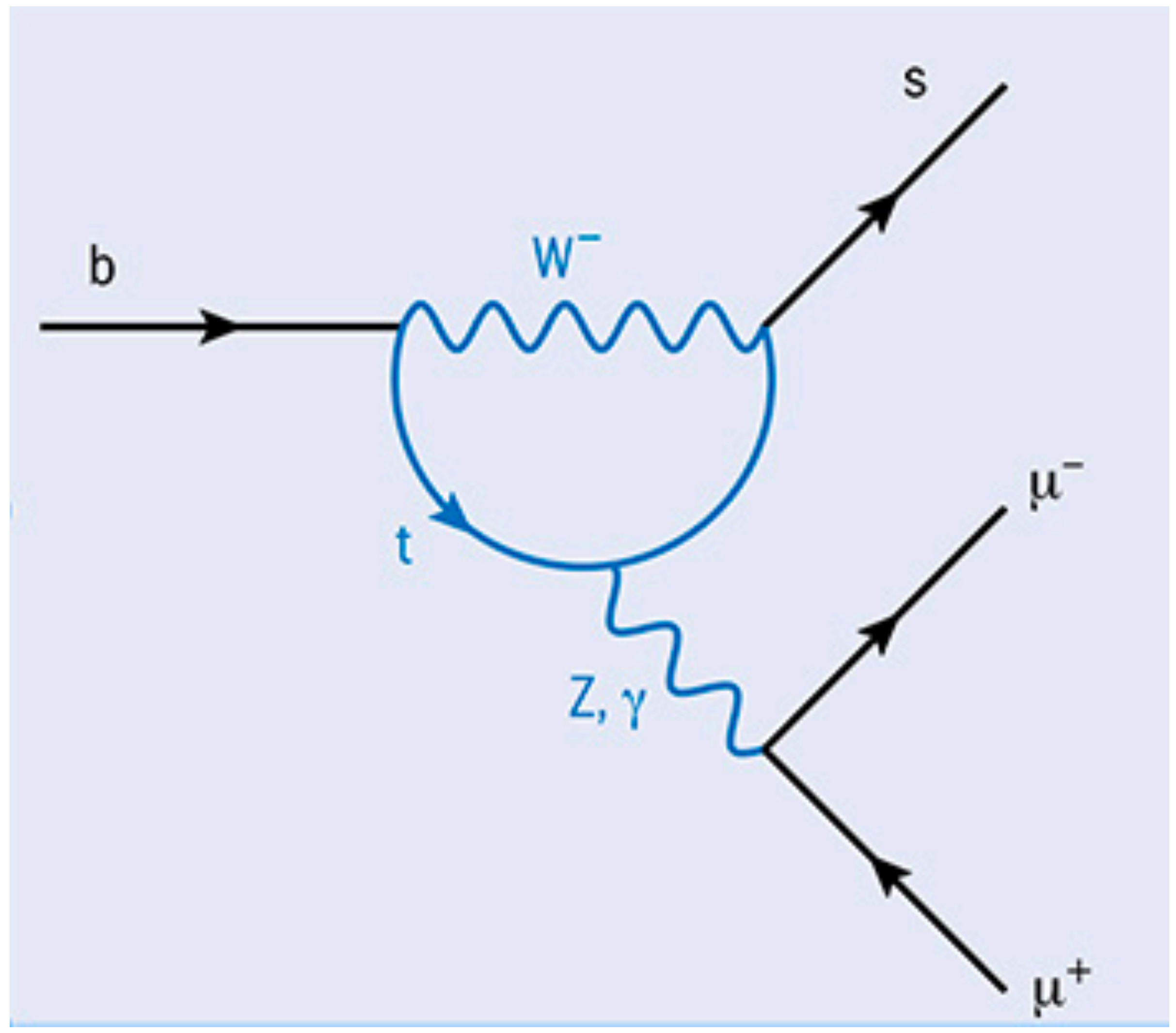
$$\text{central-}q^2 \begin{cases} R_K &= 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} &= 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})\,^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$



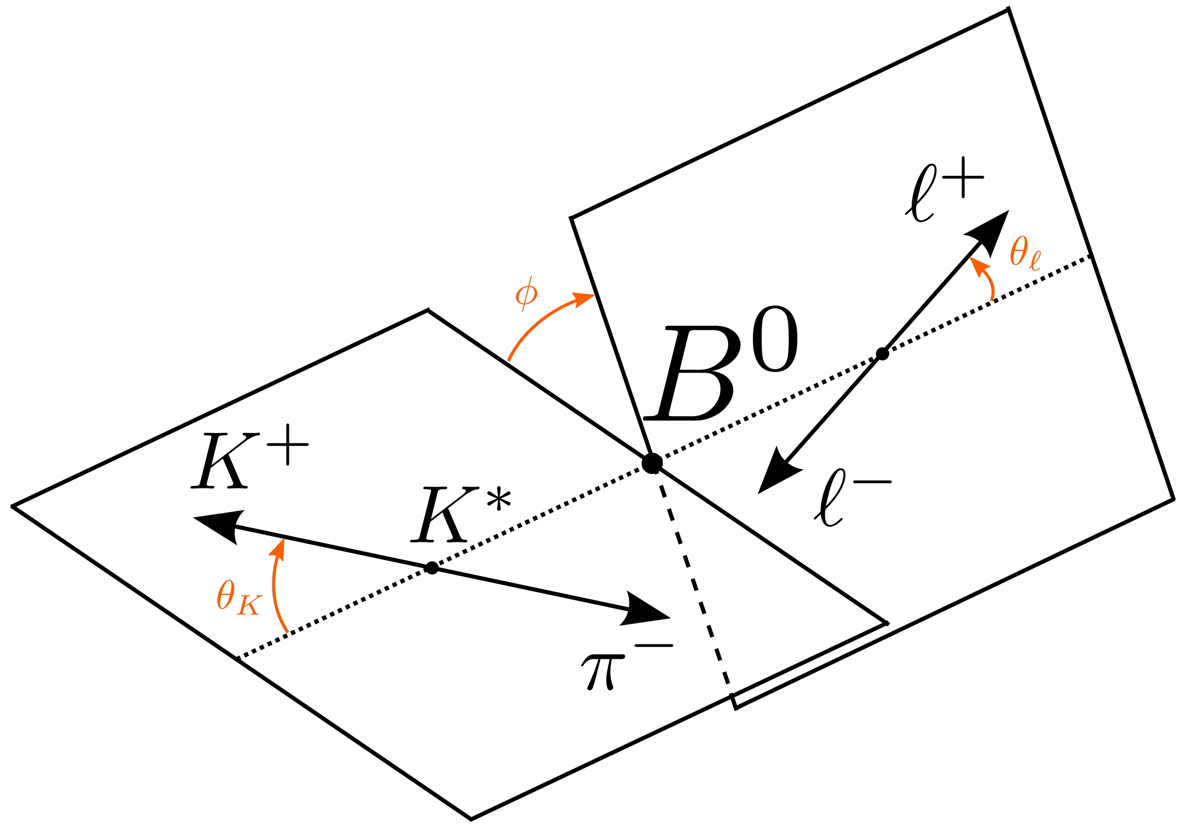
LHCb collaboration. Preprint at https://arxiv.org/abs/2212.09153 (2022).
LHCb collaboration. Preprint at arXiv https://arxiv.org/abs/2212.09152 (2022).
LHCb Collaboration. Nature Phys. 18, 277–282 (2022).

Anomaly: P5’





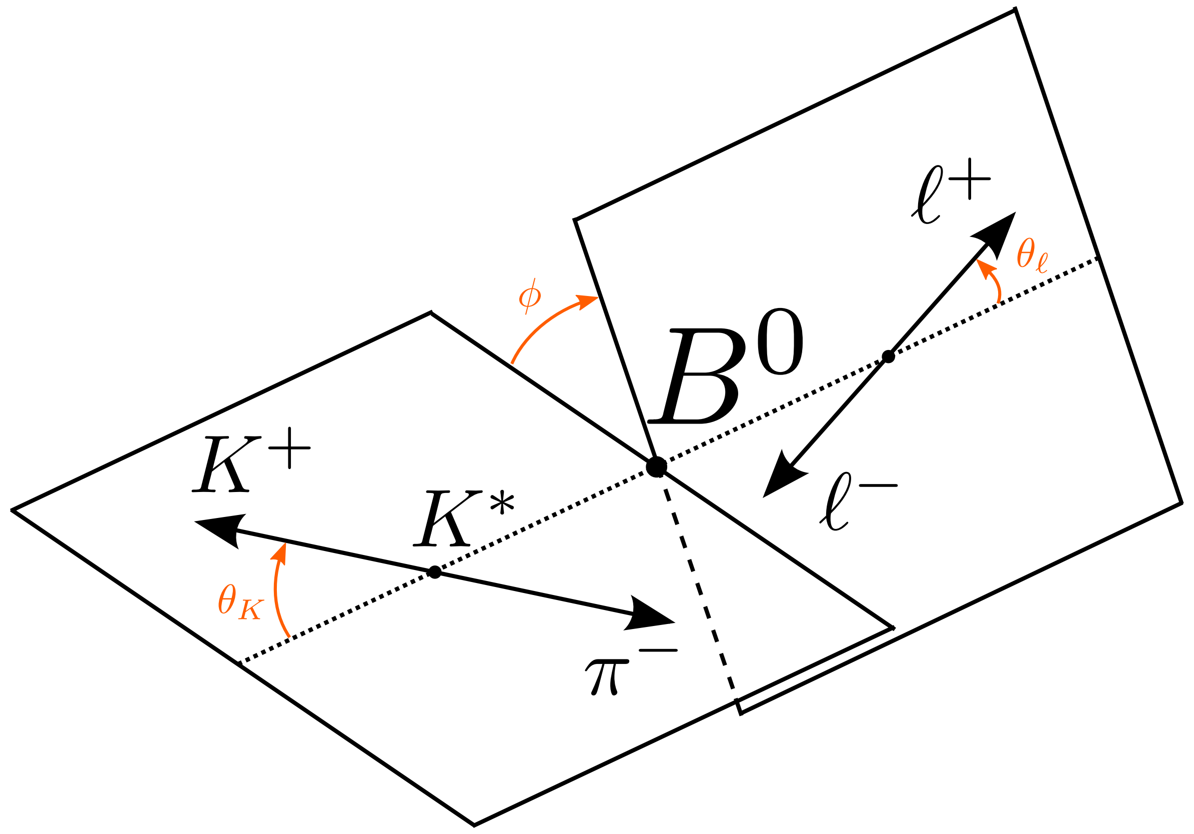
Anomaly: P5'



$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\ \mathrm{d}\cos\theta_K\ \mathrm{d}\phi\ \mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

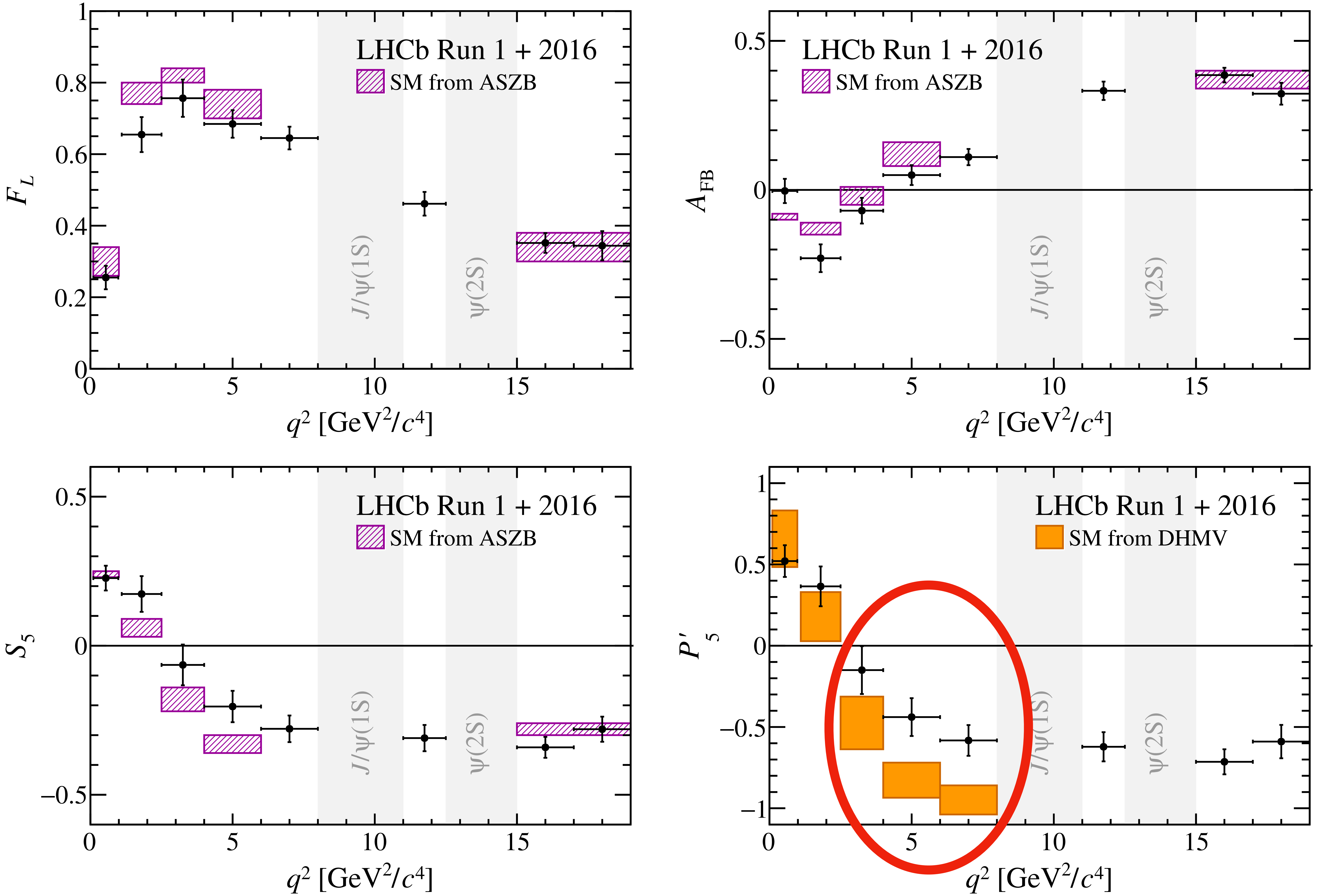
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

Anomaly: P5’



Theoretical or experimental problem?

Phys. Rev. Lett. 125, 011802



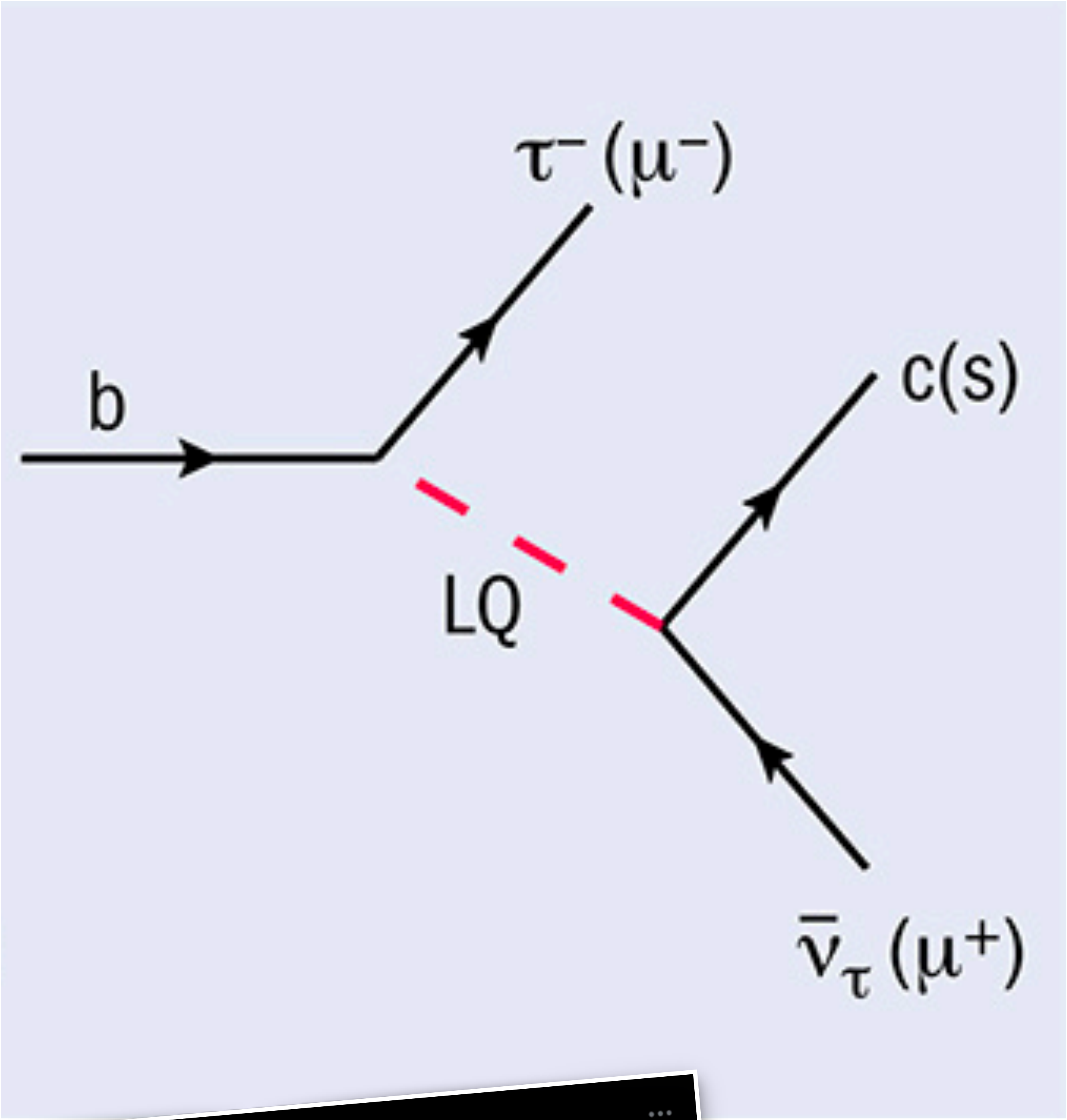
3σ

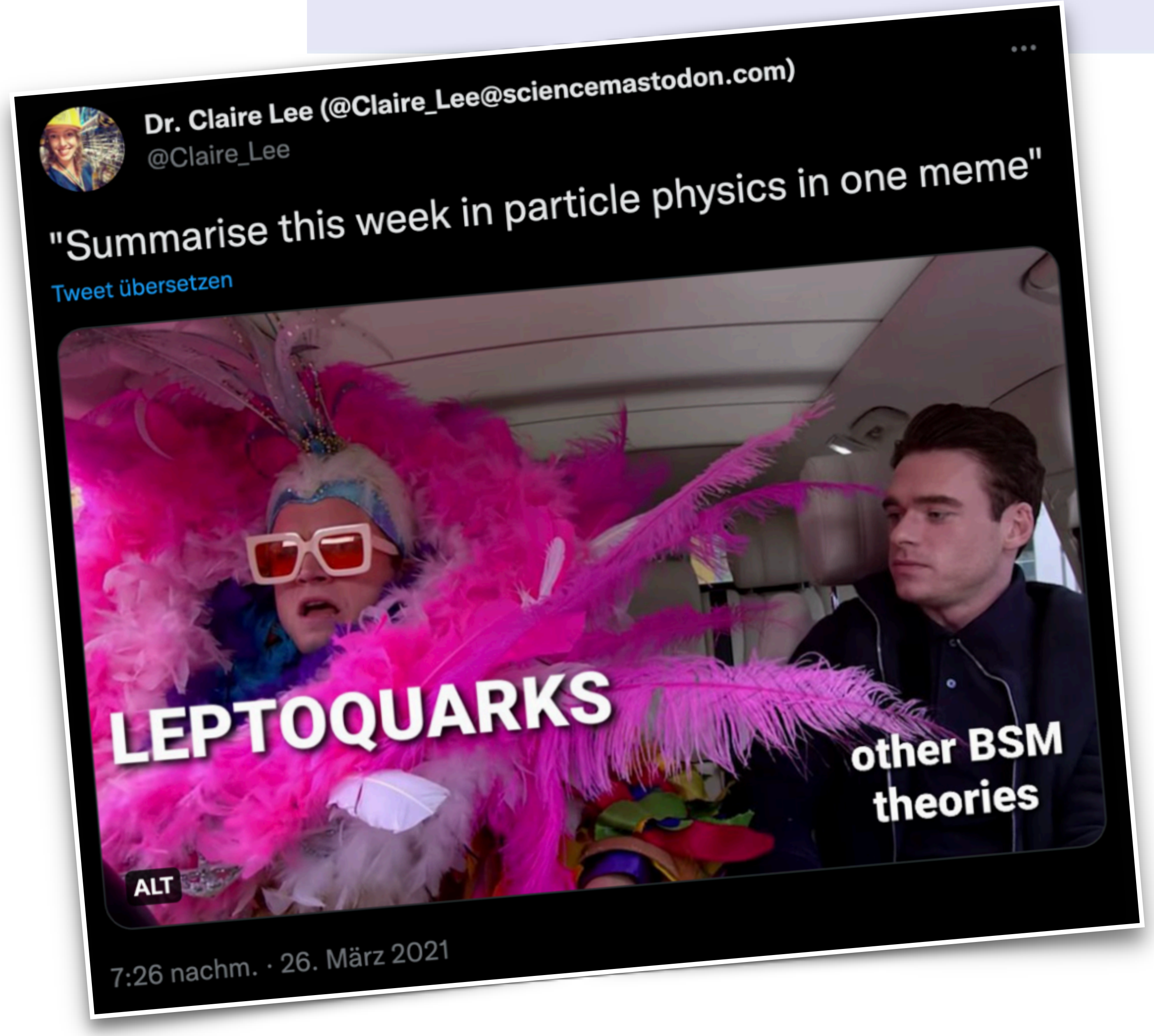
Flavour Anomalies; Next steps

- $B \to K^{(*)}\nu\bar{\nu}$ (observed by Belle II 2023)
  - Much harder experimentally, much smaller theory uncertainty, but angular analysis is limited to using the K …

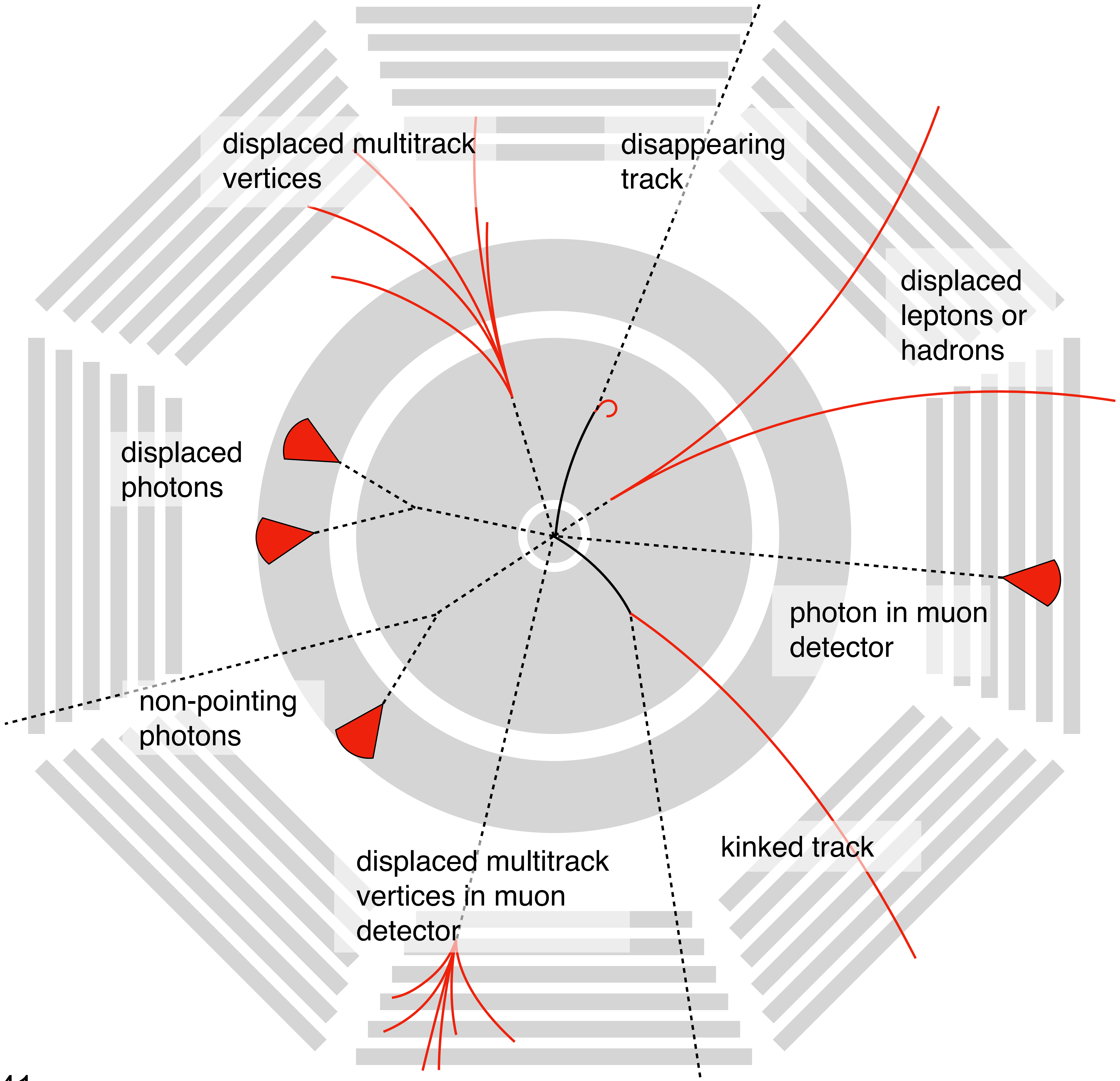
- $B \to K^{(*)}\tau^+\tau^-$ (only upper limits so far)
  - Much harder experimentally…

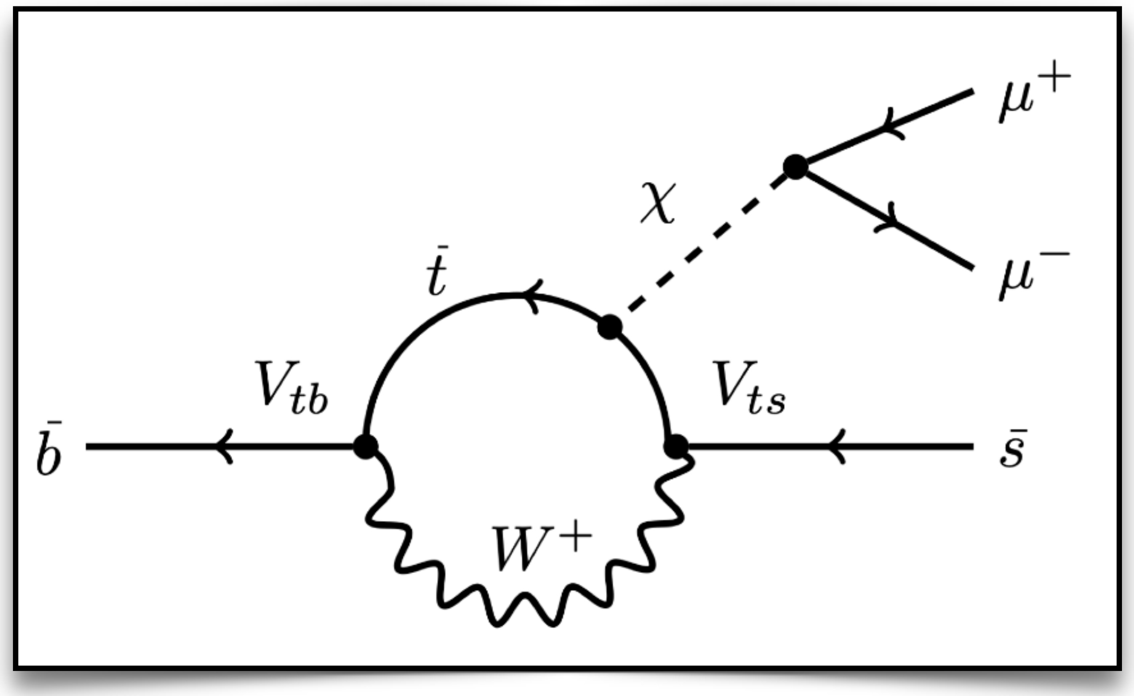
- Did we break the SM? (Very heavy) Leptoquarks?

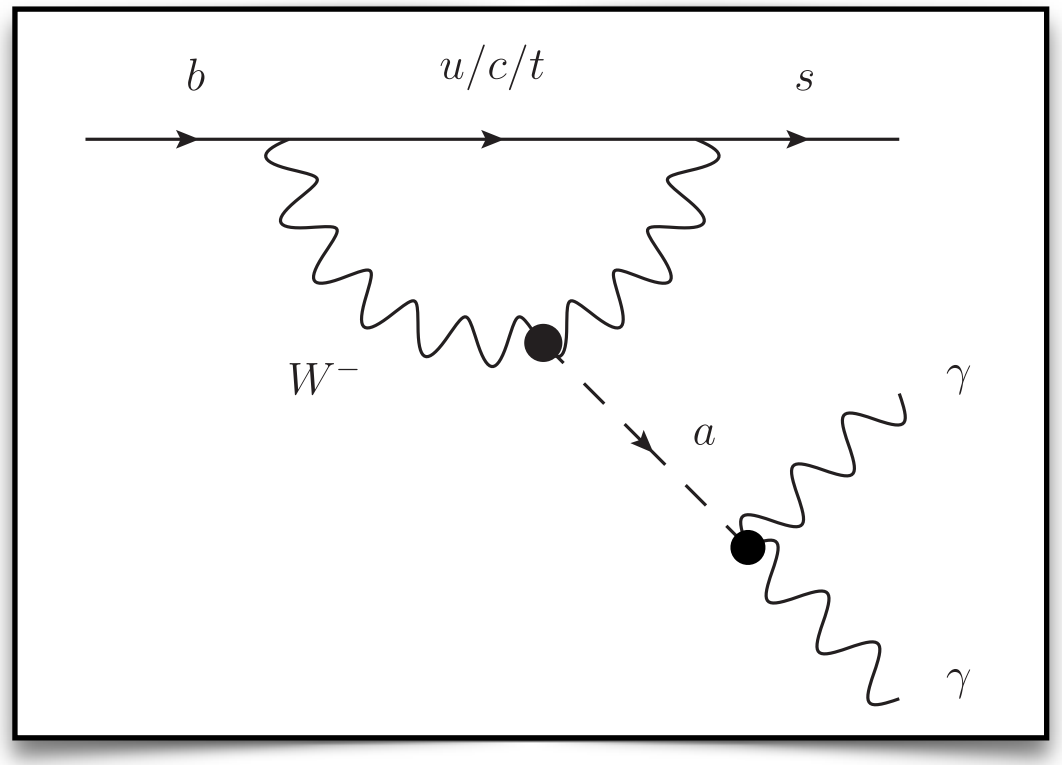




Long-lived particles (LLPs)



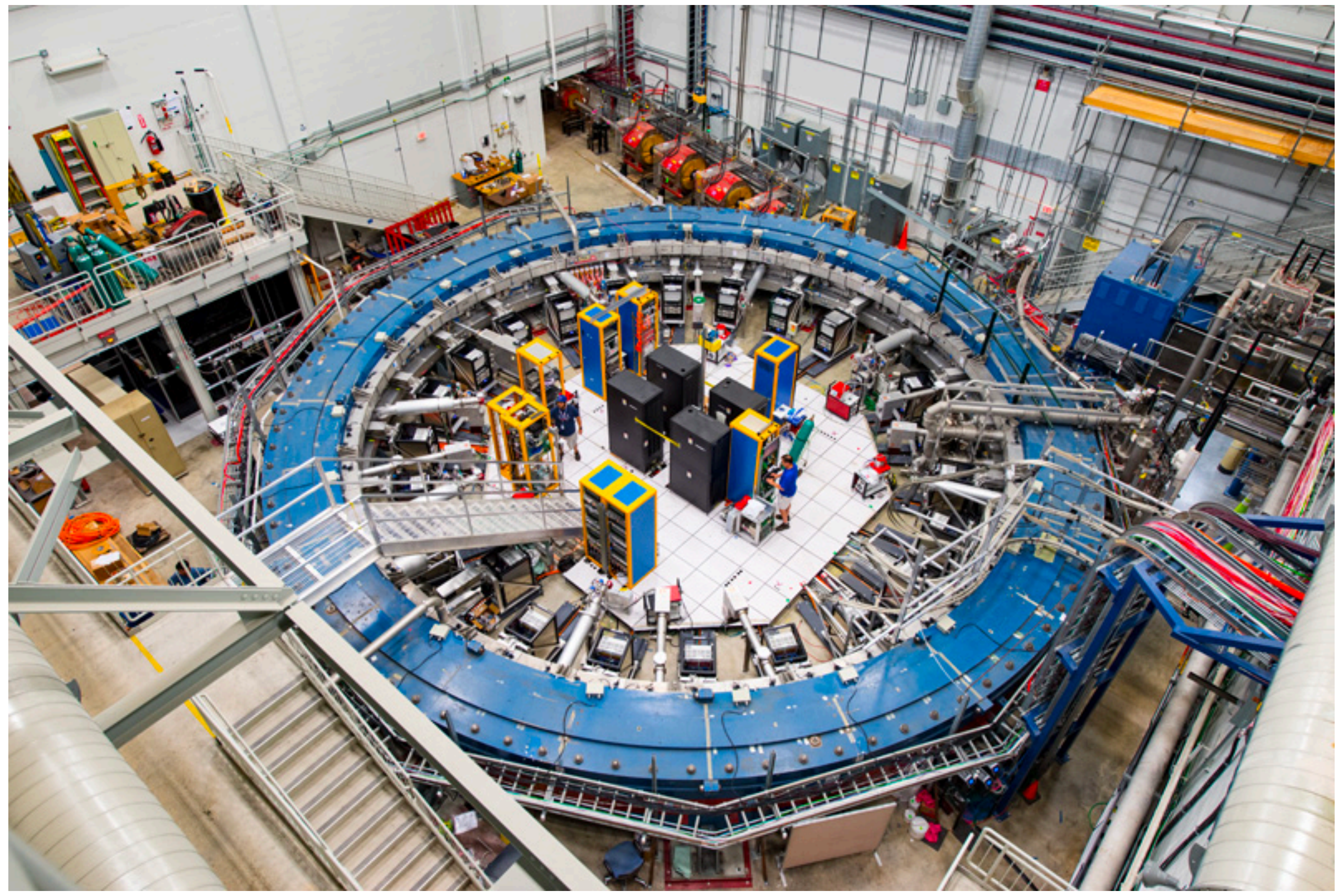




- Small couplings often lead to rather long lifetimes
- Reconstruction algorithms or analysis selections may have rejected such signatures

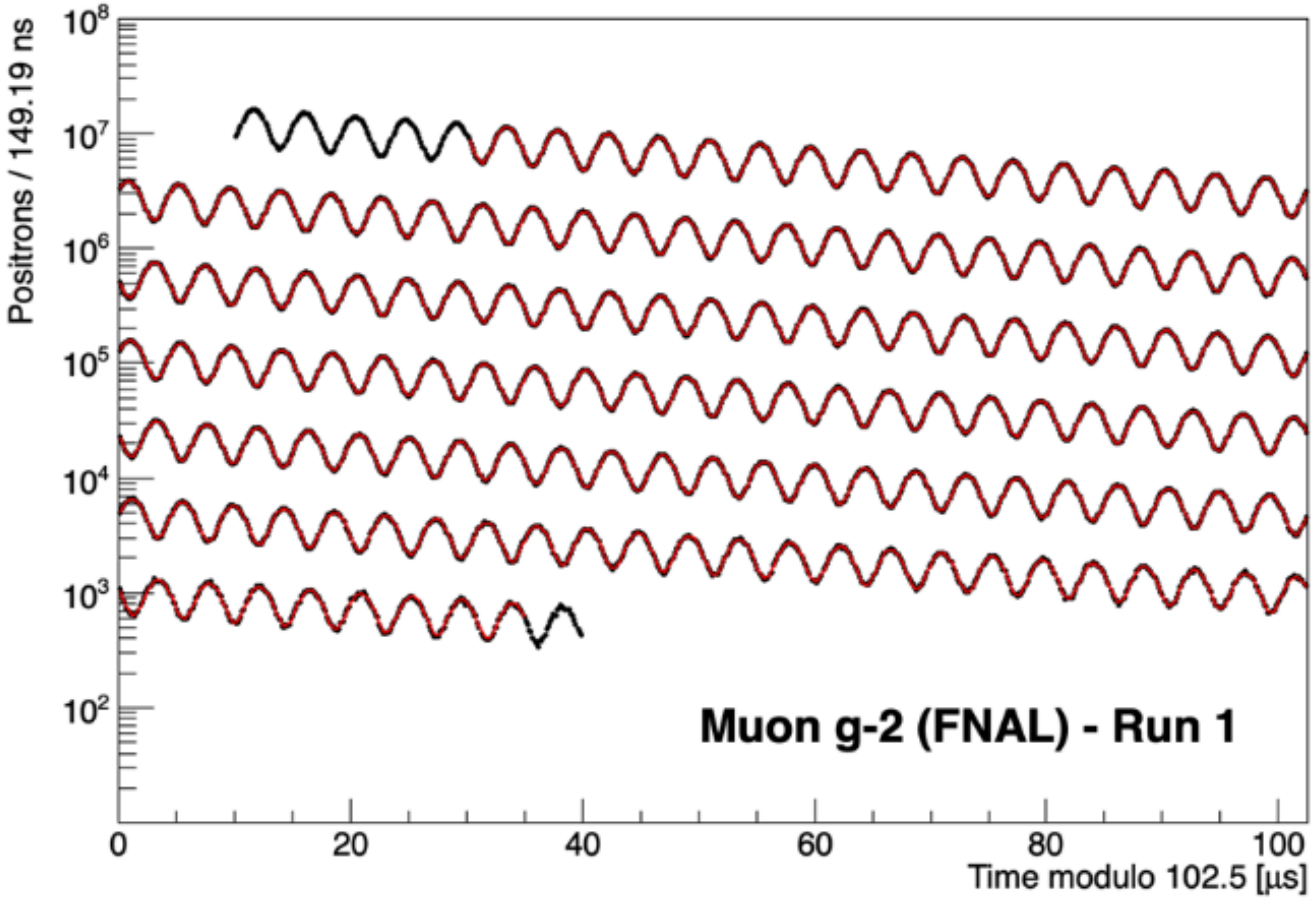
Anomaly: g-2

- Precision measurement of the anomalous magnetic dipole moment of a muon (Lande factor)
  - The “anomalous” part is the deviation from g=2, introduced by higher order corrections
- 24 calorimeters distributed inside (why?) the ring measure energy and time of decay electrons from $\mu \rightarrow e\nu_e\nu_\mu$ decays



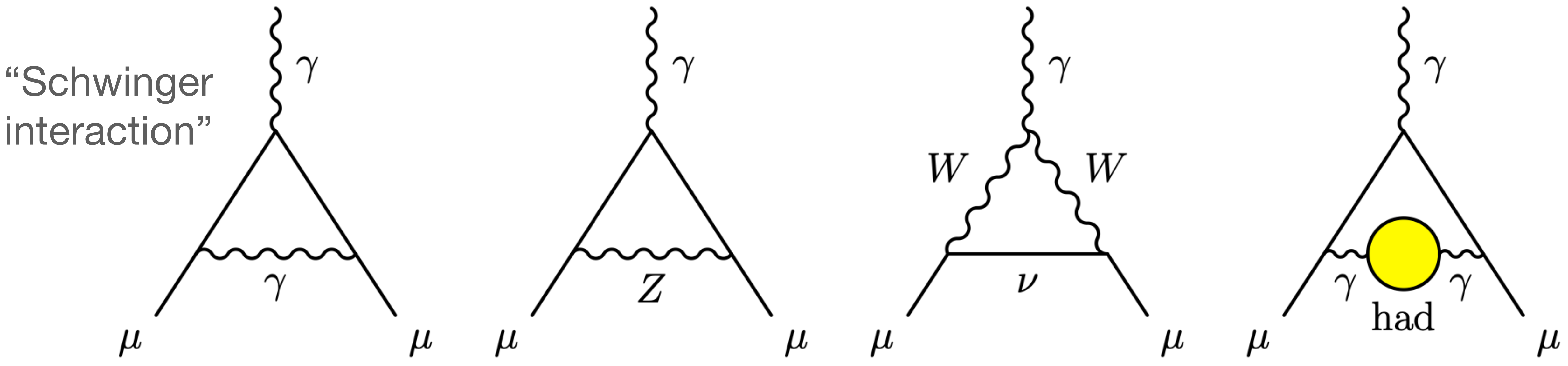
Credit: Fermilab

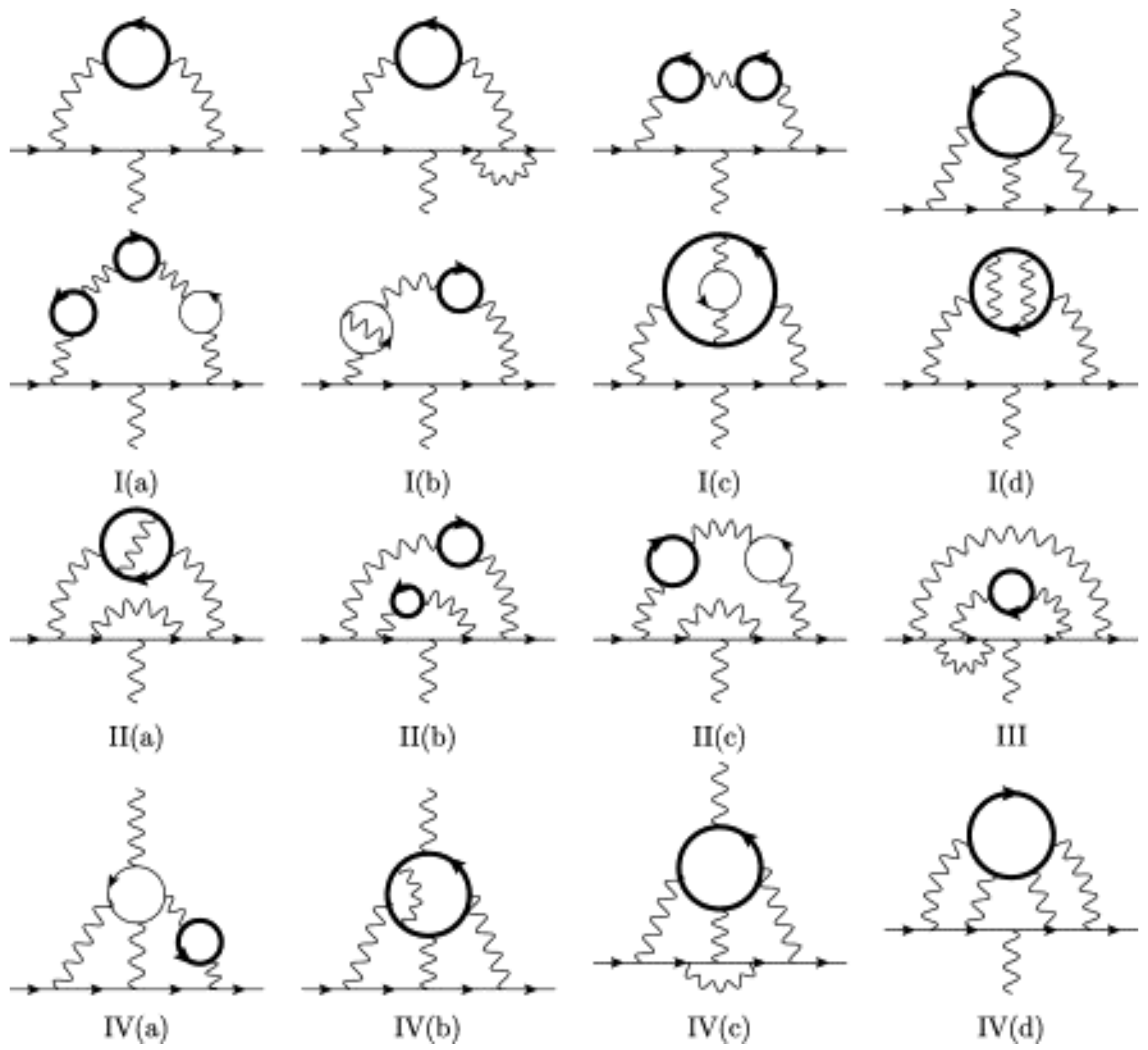
$$N(t) = N_0 e^{-t/\tau}\left[1 + A(E)\cdot\cos(\omega_a \cdot t + \varphi)\right]$$



Anomaly: g-2

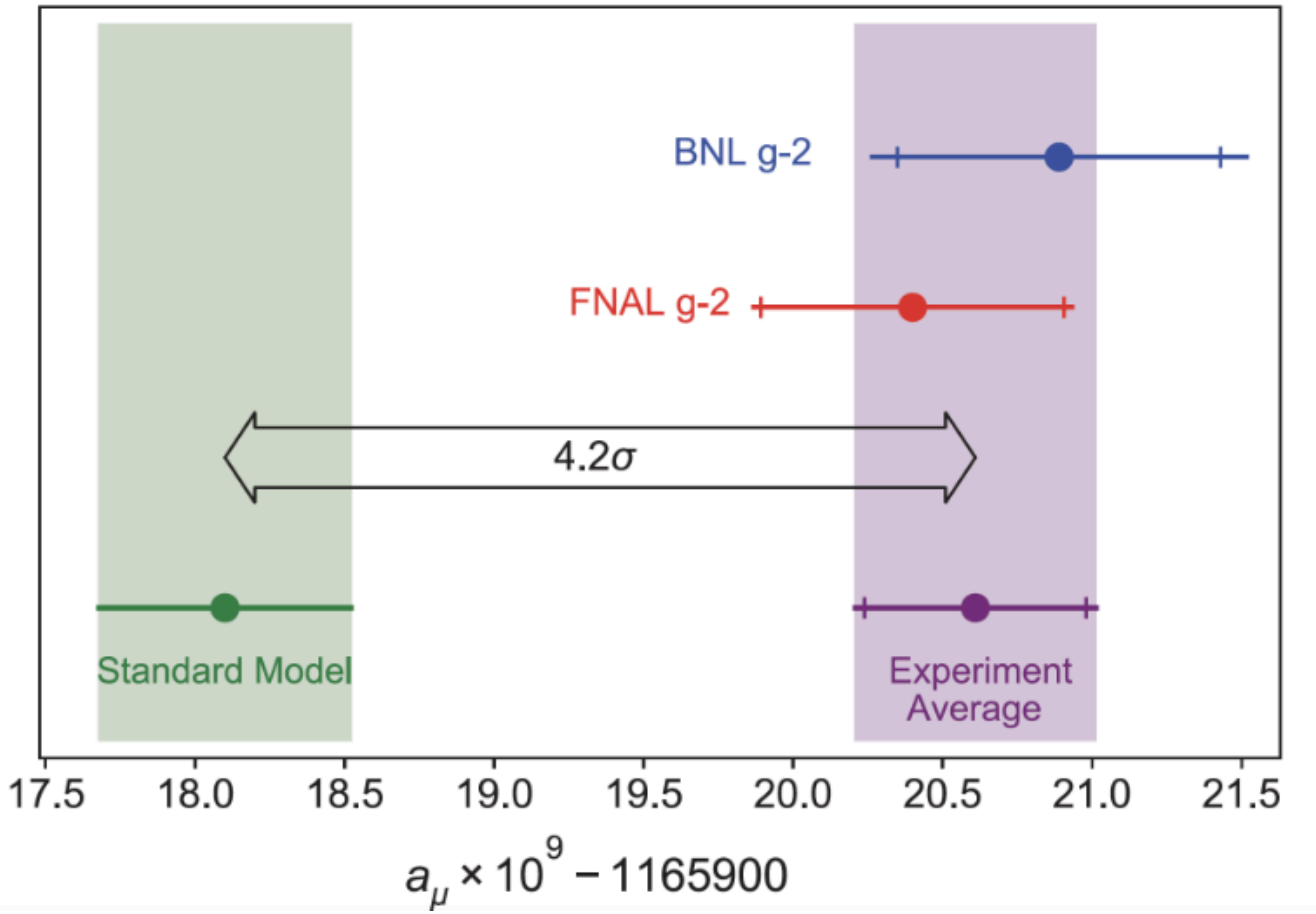
- Requires very (!) precise theory calculations





Experimental problem?

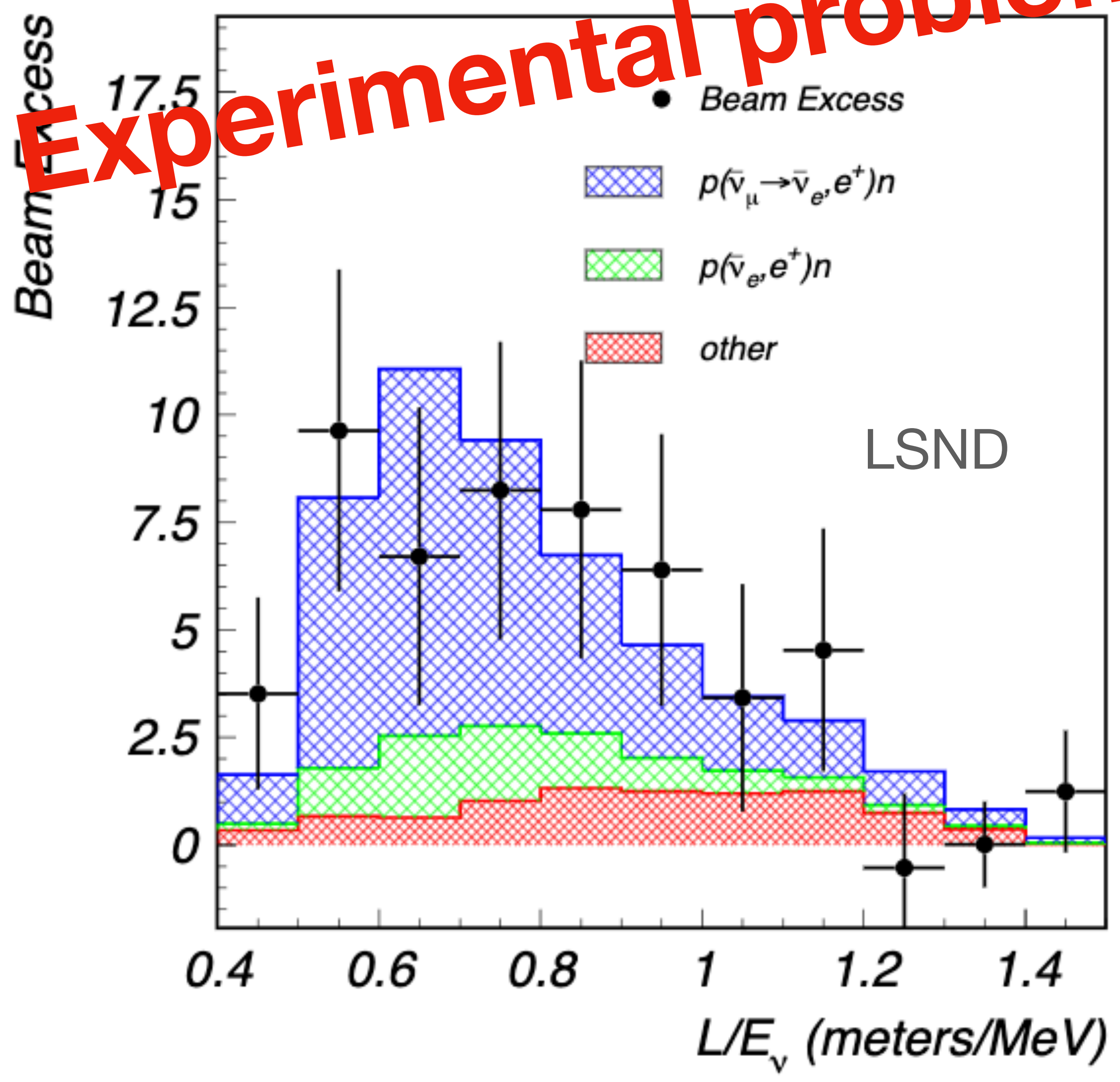
$$a_\mu^{FNAL} = 116\ 592\ 040(54) \times 10^{-11}\ [0.46\ \text{ppm}]$$



Anomaly: Neutrino anomalies

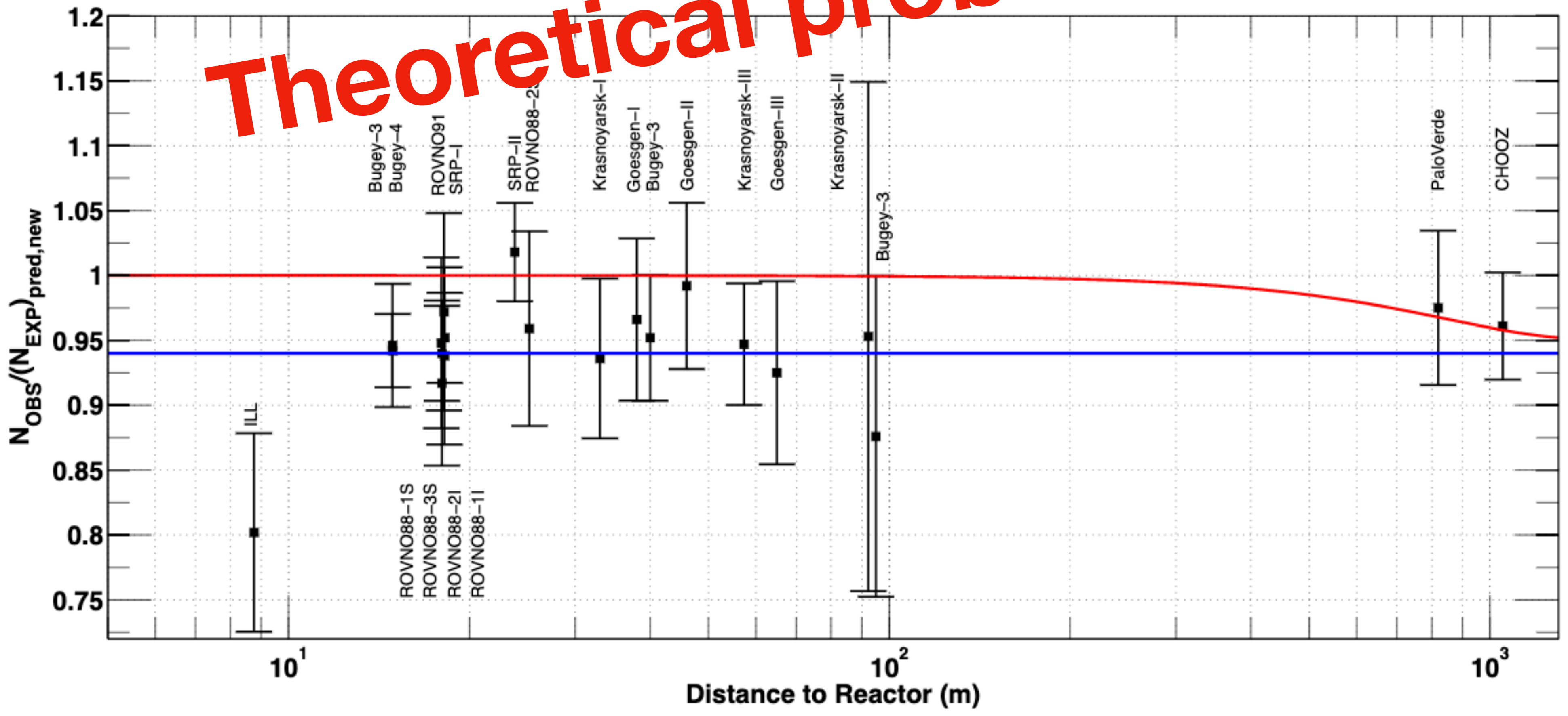
- All neutrino oscillation experiments agree with a three-flavour oscillation… with two exceptions: MiniBooNE and LSND see an excess of ν_e at low energies
  - Incompatible with each other and with a fourth “sterile” neutrinos
- Reactor experiments see a slight excess (incompatible with LSND and MB)
  - Difficulties in calculations of antineutron yields in nuclear cores

Experimental problem?



blue: oscillation into $\bar{\nu}_\mu$ with large Δm?

Theoretical problem?



blue: oscillation into $\bar{\nu}_\mu$ with large Δm?

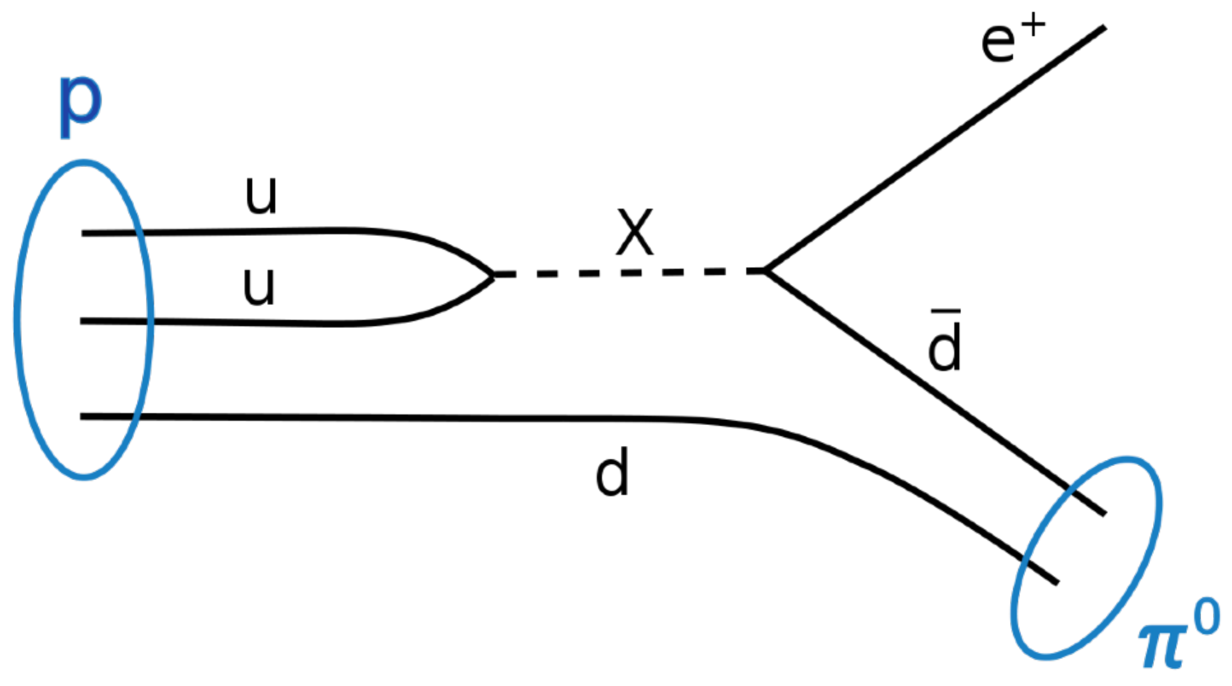
LSND: https://arxiv.org/abs/hep-ex/0104049

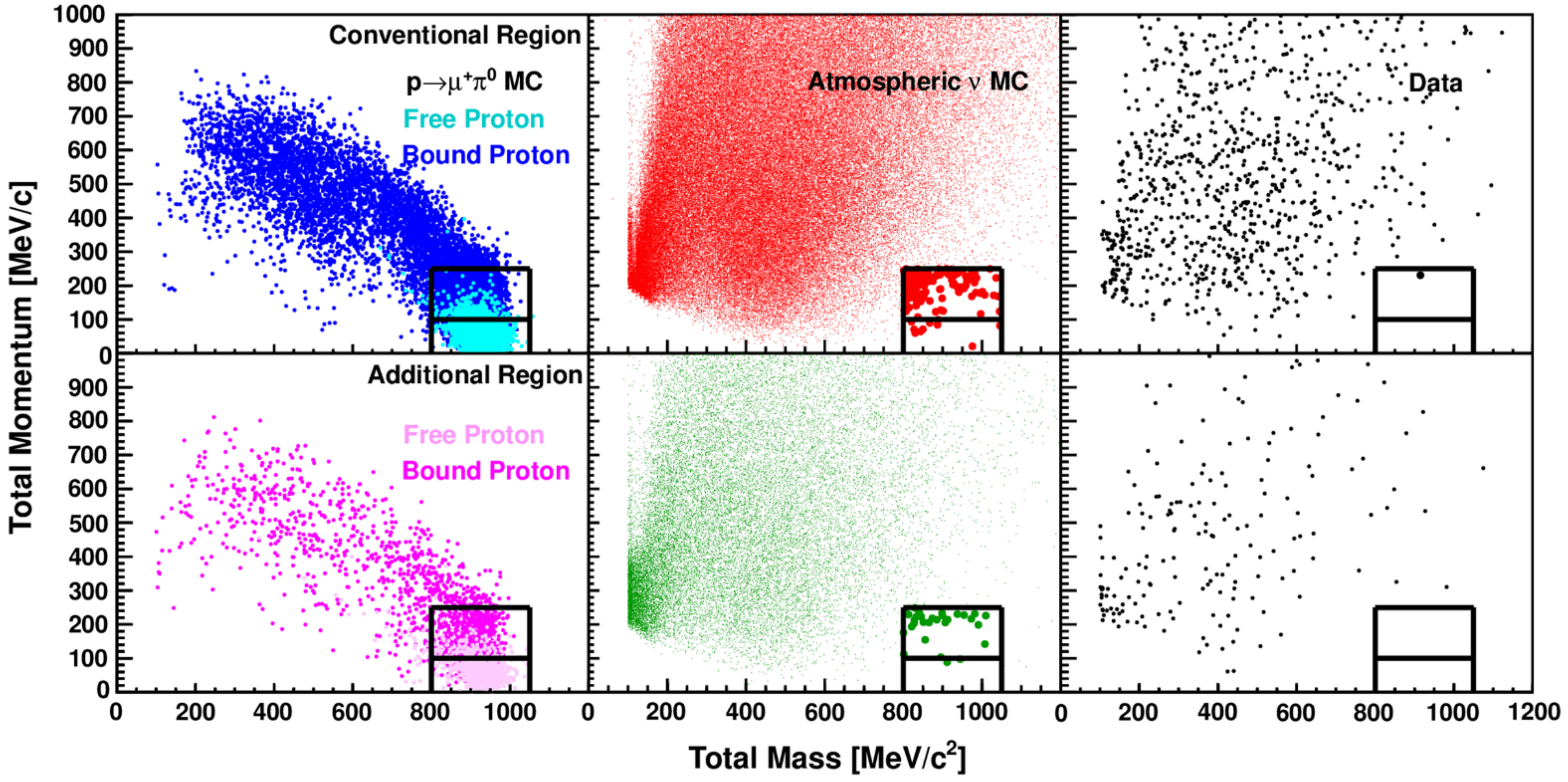
reactor anomaly: https://arxiv.org/abs/1101.2755

reactor theory: https://arxiv.org/abs/2110.06820

A BSM benchmark: Proton decay

- Free proton is the only stable composite particle of the SM
  - Baryon number is conserved in the SM and the proton is the lightest baryon
- Various BSM theories predict proton decays, often with the dominant decay mode $p \to e^+ + \pi^0$
  - Violates baryon number B (1 → 0) and lepton number L (0 → -1), but conserves difference B-L (1 → 1)
- Half life $T_{1/2} > 1.67 \times 10^{34}$y (by Super-Kamiokande)





more: Phys. Rev. D 102, 112011 (2020)

What questions do you have?