High-energy colliders as tests of the Born rule

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This presentation is based on arXiv:2505.07510, which was written with Antony Valentini.

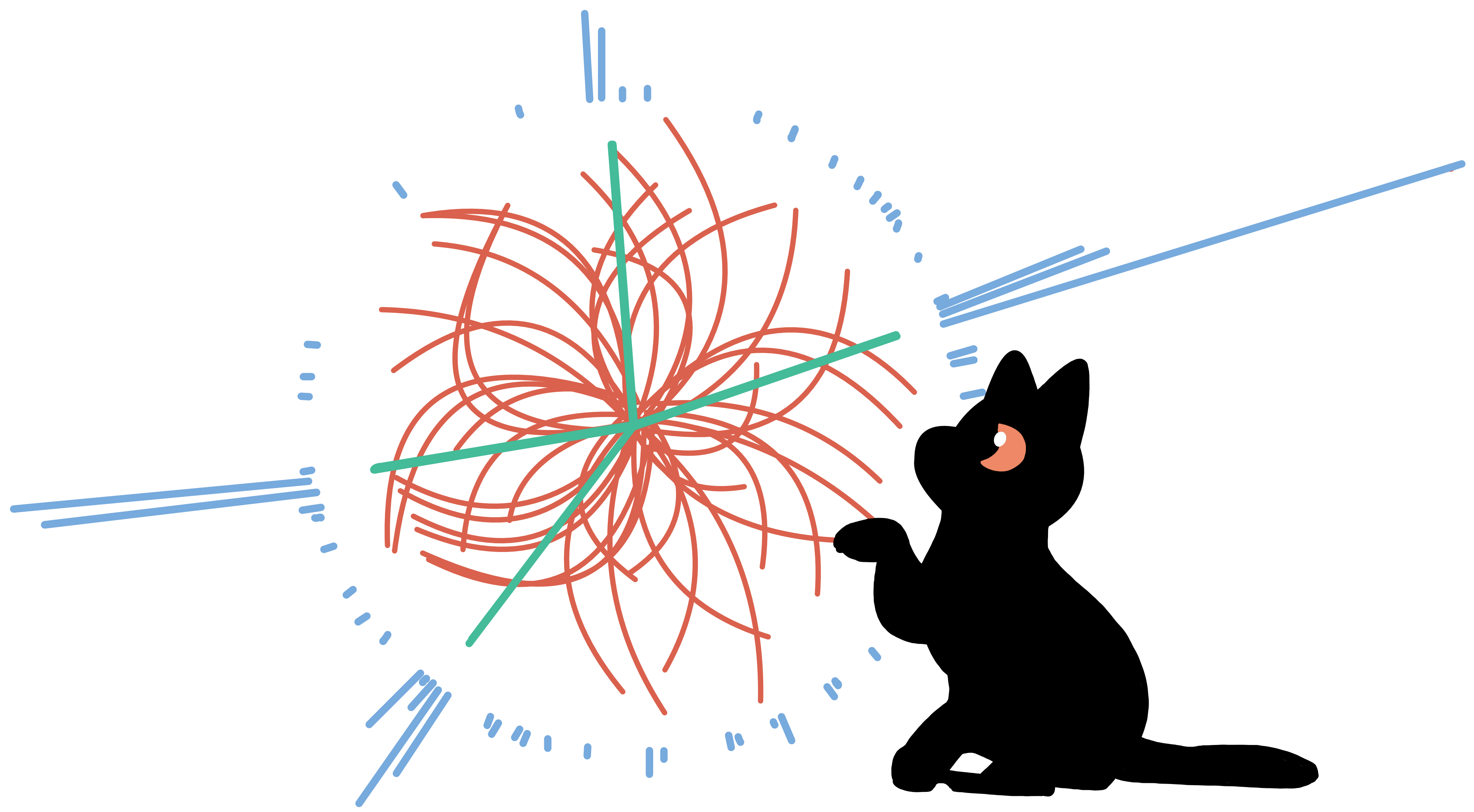
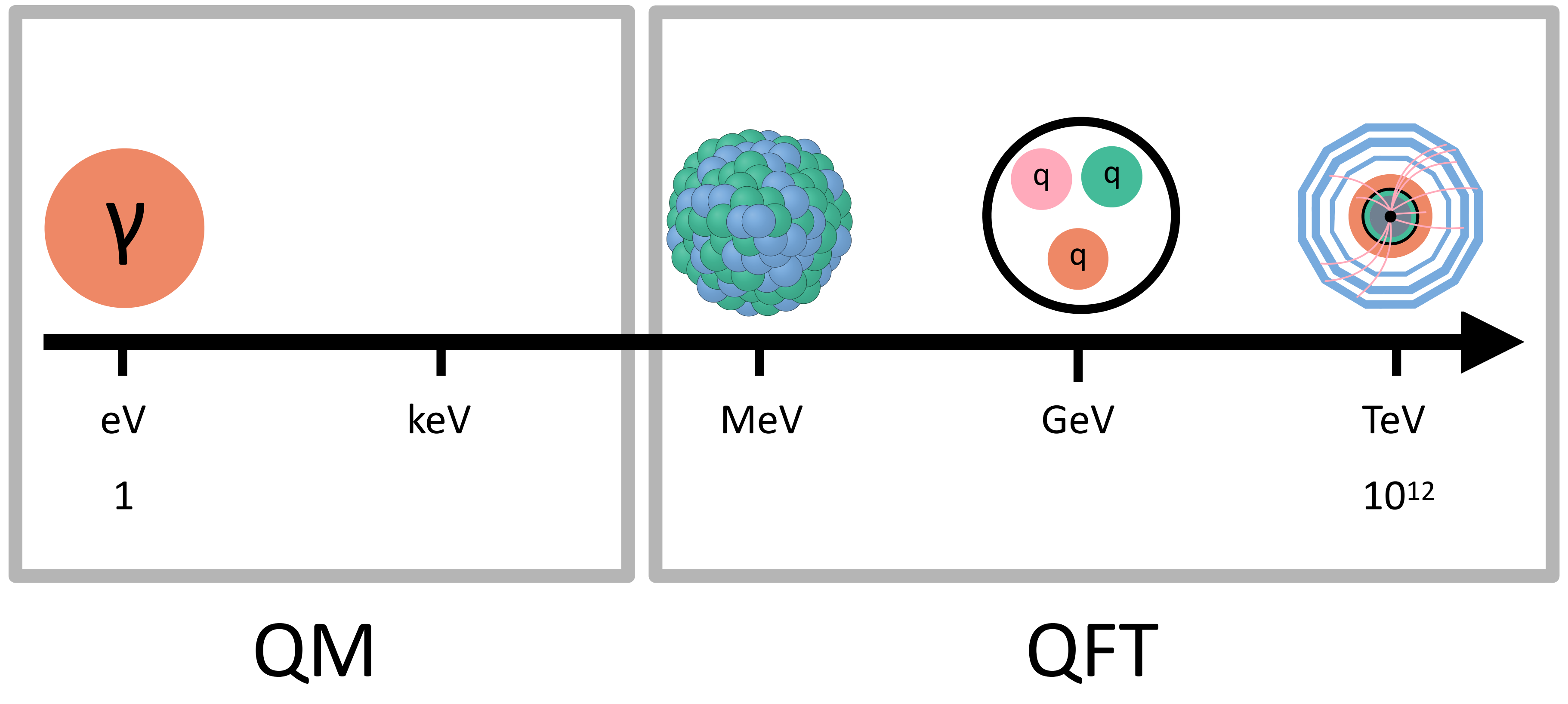


Image adapted from G. Fontana (qftoons)

Collider physics assumes the Born rule, yet no experiment has tested it at high energies.

- High-energy collider experiments could probe new physics not by discovering new particles, but by directly testing QM itself in extreme conditions.

- This approach opens a new direction: using collider data to test the foundations of QM, not just its consequences.



R. Sorkin, Mod. Phys. Lett. A (1994) 9:33, 3119-3127

Sorkin parameter

- Three slit interference

$$\kappa_S \equiv \frac{1}{P}(P_{abc} - P_{ab} - P_{ac} - P_{bc} + P_a + P_b + P_c)$$

  - Subscripts a, b, c denote closed slits
  - If Born's rule holds, $\kappa_S = 0$

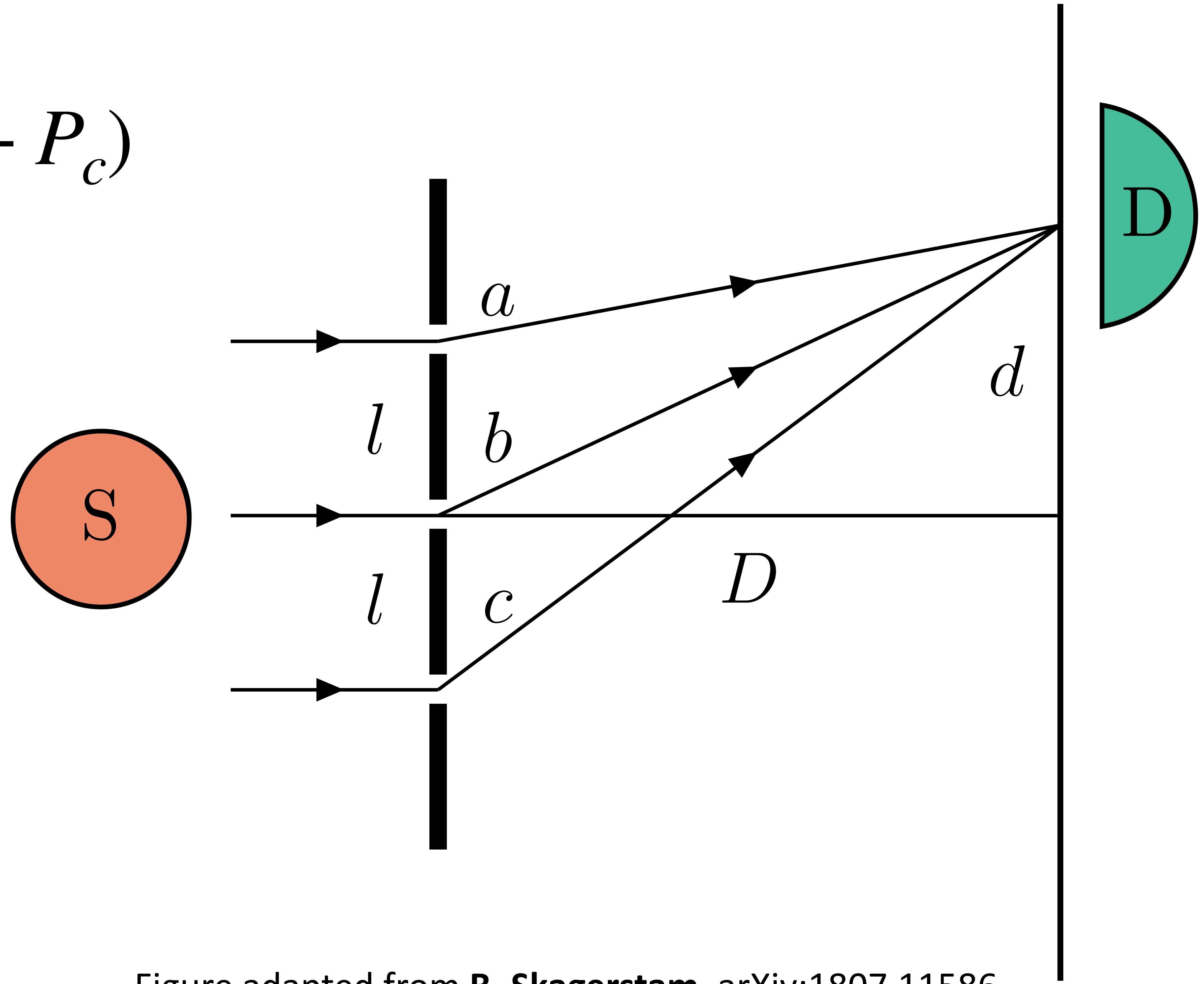


Figure adapted from **B. Skagerstam**, arXiv:1807.11586

Two-part proposal

- **Now:** use mean τ lepton helicity asymmetry in $Z \to \tau^+\tau^-$ to search for deviations from the Born rule.

- **Later:** design new measurements of photon polarization in short-timescale processes where new physics may arise.

We focus on the Born rule for a two-state system.

J. Bell, Rev. Mod. Phys. 38 (1966) 447

Bell's two-state hidden variable model

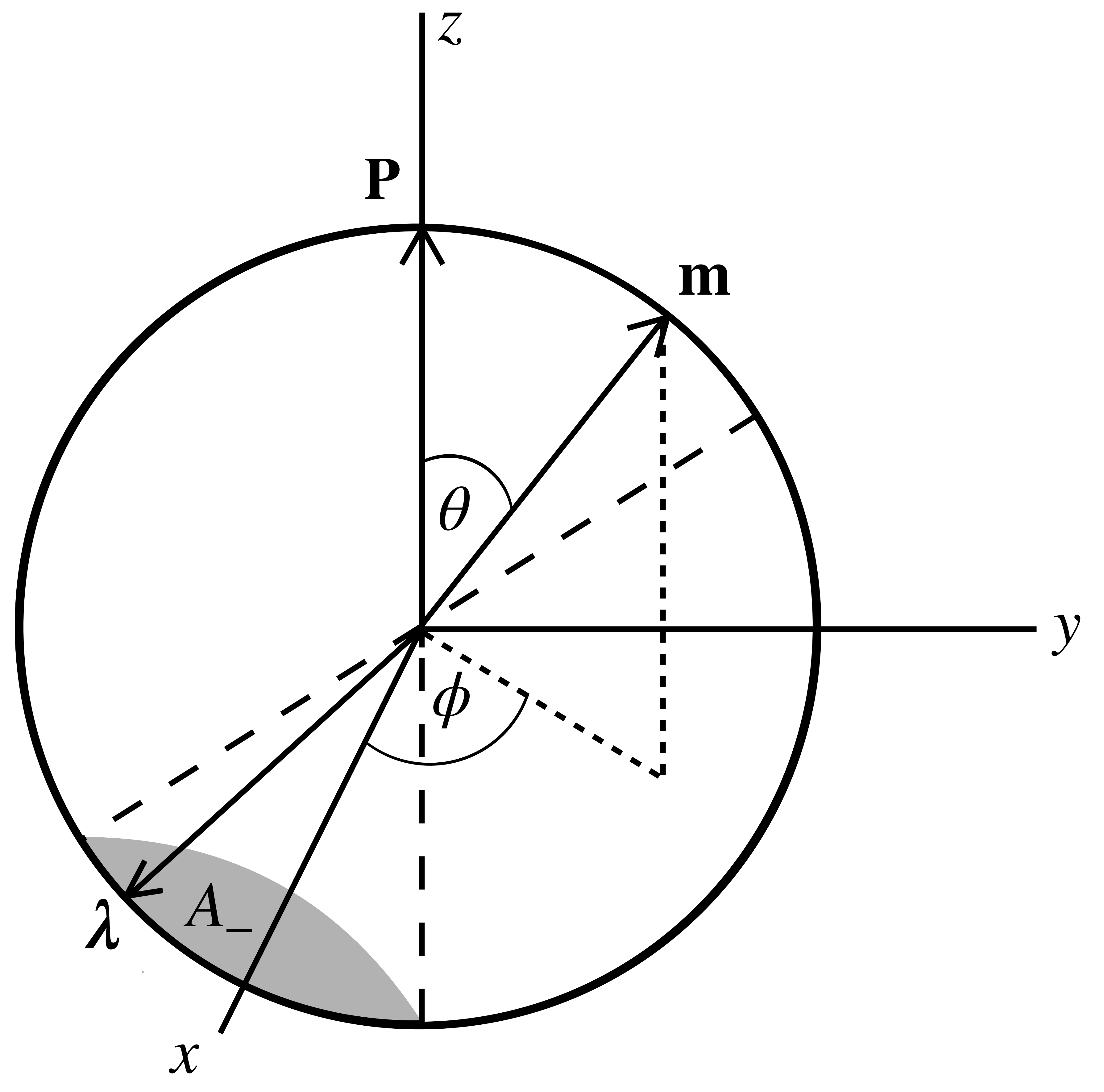
- Deterministic outcome:

$$\sigma(\mathbf{m},\lambda) = \text{sign}\left[(\lambda + \mathbf{P})\cdot\mathbf{m}\right]$$

  - where λ is hidden variable, $\mathbf{m}$ is measurement axis, $\hat{\sigma} = \mathbf{m}\cdot\vec{\sigma}$ is spin operator

- Ensemble average:

$$\langle\sigma\rangle_{\mathbf{m}} = E(\mathbf{m}) = \int d\lambda\,\rho(\lambda)\,\sigma(\mathbf{m},\lambda)$$



J. Bell, Rev. Mod. Phys. 38 (1966) 447

Born-rule deviation

- In equilibrium, we recover standard QM

$$\rho = \frac{1}{4\pi} \quad \Rightarrow \quad \langle \sigma \rangle_{\mathbf{m}} = \mathbf{P} \cdot \mathbf{m}$$

- In general, we have anisotropic ρ

Leading expansion: $\langle \sigma \rangle_{\mathbf{m}} = \mathbf{P} \cdot \mathbf{m} + \underbrace{R_{ijk} m_i m_j m_k}_{\text{measurable}} + \cdots$

- Dipole along $z \Rightarrow$ angular prediction

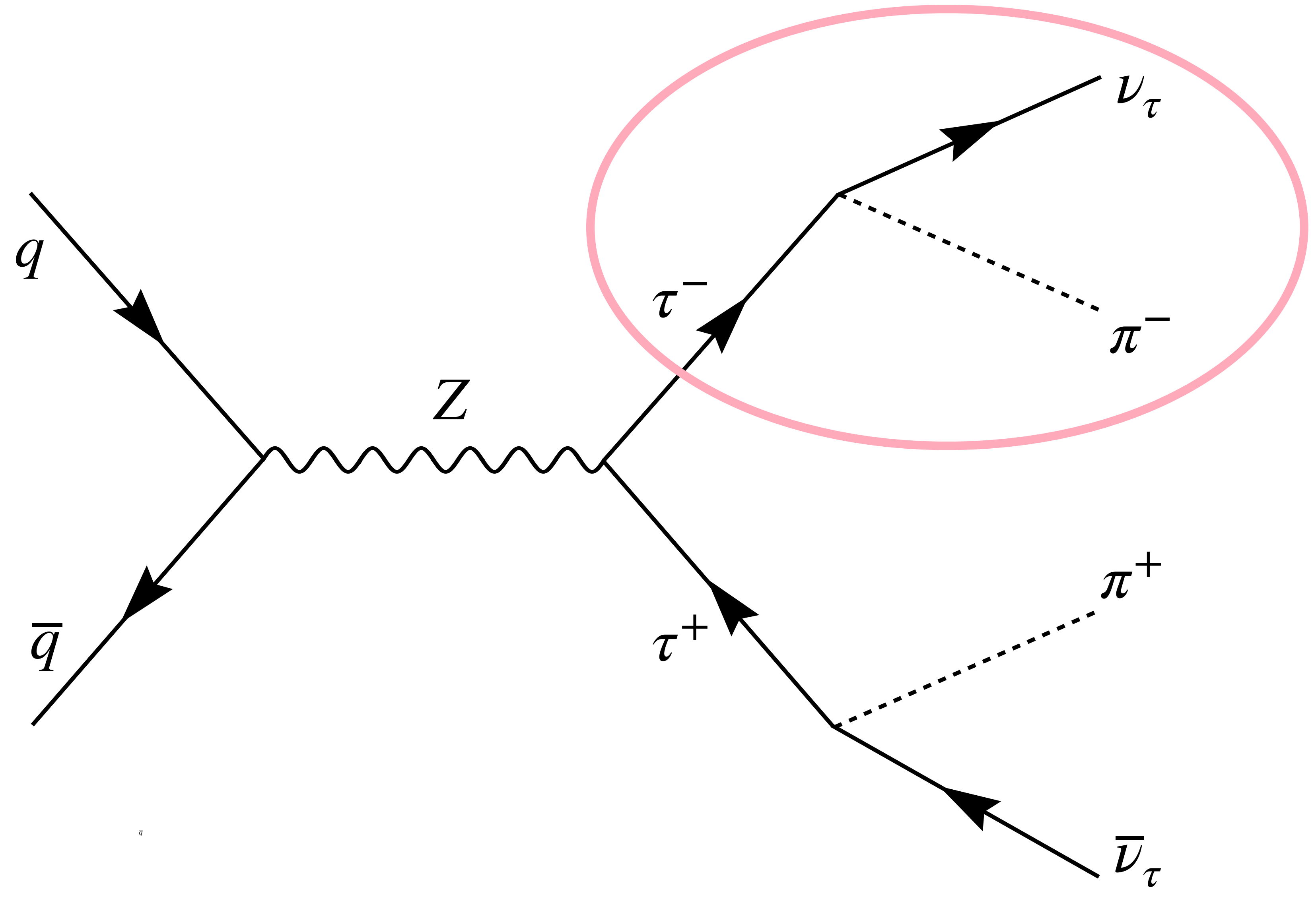
$$P_+(\theta) = \underbrace{\cos^2\theta}_{\text{Malus' law}} + \frac{1}{2} R_{zzz} \cos^3(2\theta)$$

$\sigma(-\mathbf{m}, \lambda) = -\sigma(\mathbf{m}, \lambda)$ symmetry

What we can do now

Average polarization measurements

- Study **τ polarization** in $Z \to \tau\tau$
- Z-boson lifetime $\sim 10^{-25}$ s
- Focus on $\tau^- \to \pi^- \nu_\tau$

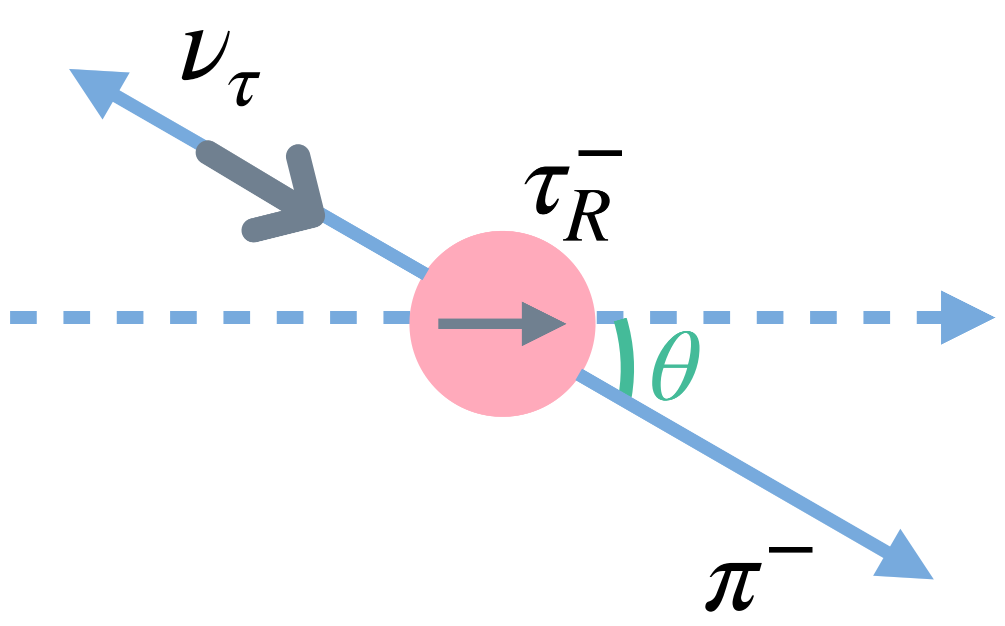


τ and π spins are perfectly correlated

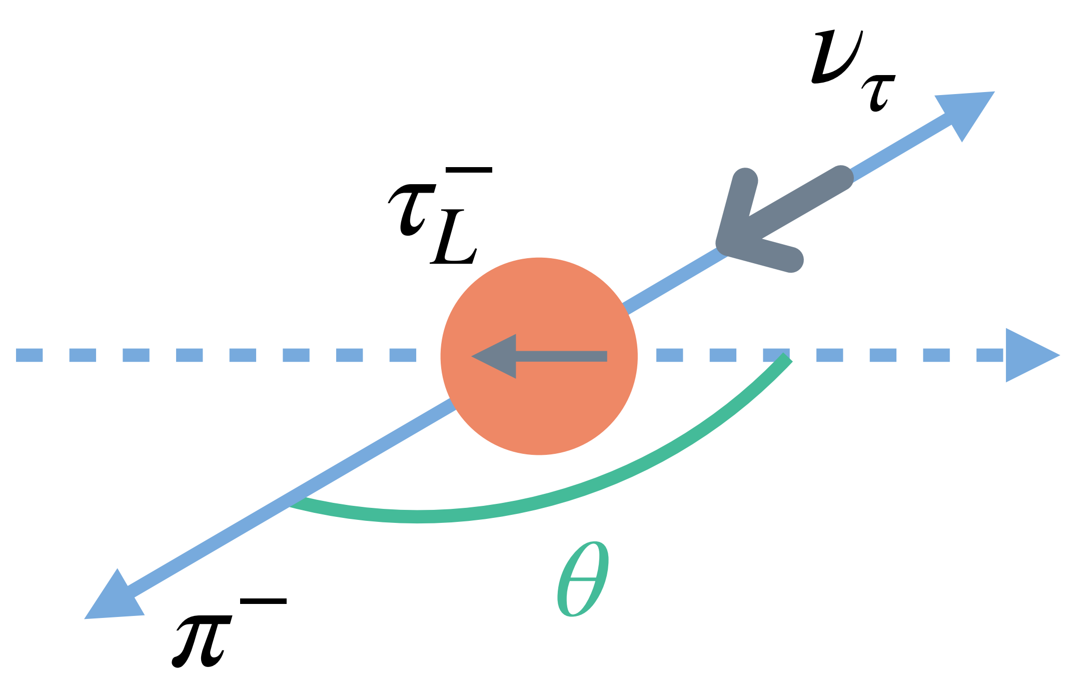
- A τ^- with spin $+1/2$ emits the π^- along the spin direction
- A τ^- with spin $-1/2$ emits the π^- opposite the spin direction

CMS, JHEP 01 (2024) 101

Polarization asymmetry



forward (N_f): $\cos\theta > 0$



backward (N_b): $\cos\theta < 0$

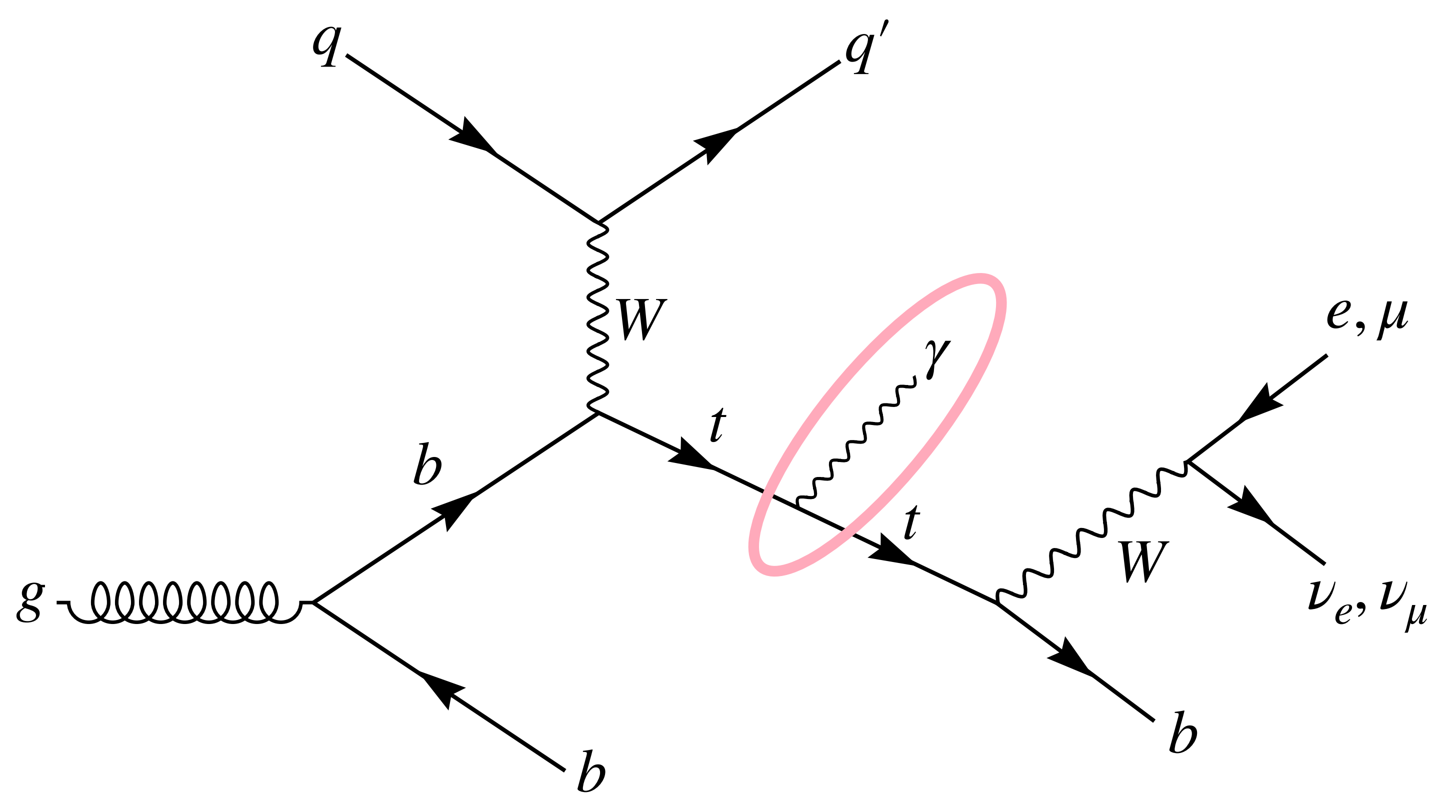
- Mean helicity ≡ average longitudinal polarization
- Longitudinal polarization: $\langle P_{\text{obs}} \rangle = \dfrac{N_f - N_b}{N_f + N_b}$
- Measurement axis is τ direction ($\mathbf{m} = \hat{p}_\tau$)

Look for deviations from $\mathbf{P}_{\text{obs}} = \langle \mathbf{P} \cdot \hat{p}_\tau \rangle$

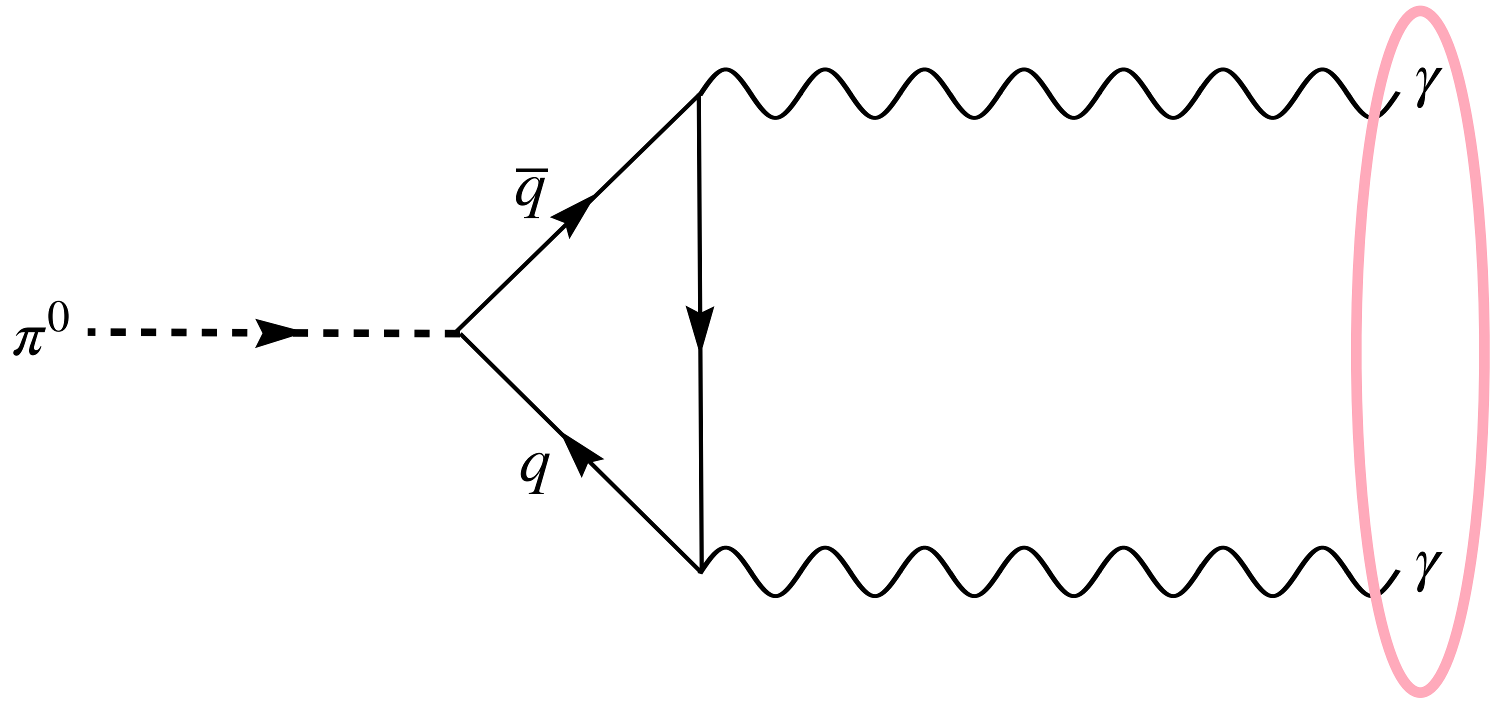
What we can do later

ATLAS, Phys. Rev. Lett. 131, 181901
RHIC-f, Phys. Rev. Lett. 124, 252501

Photons from short-timescales



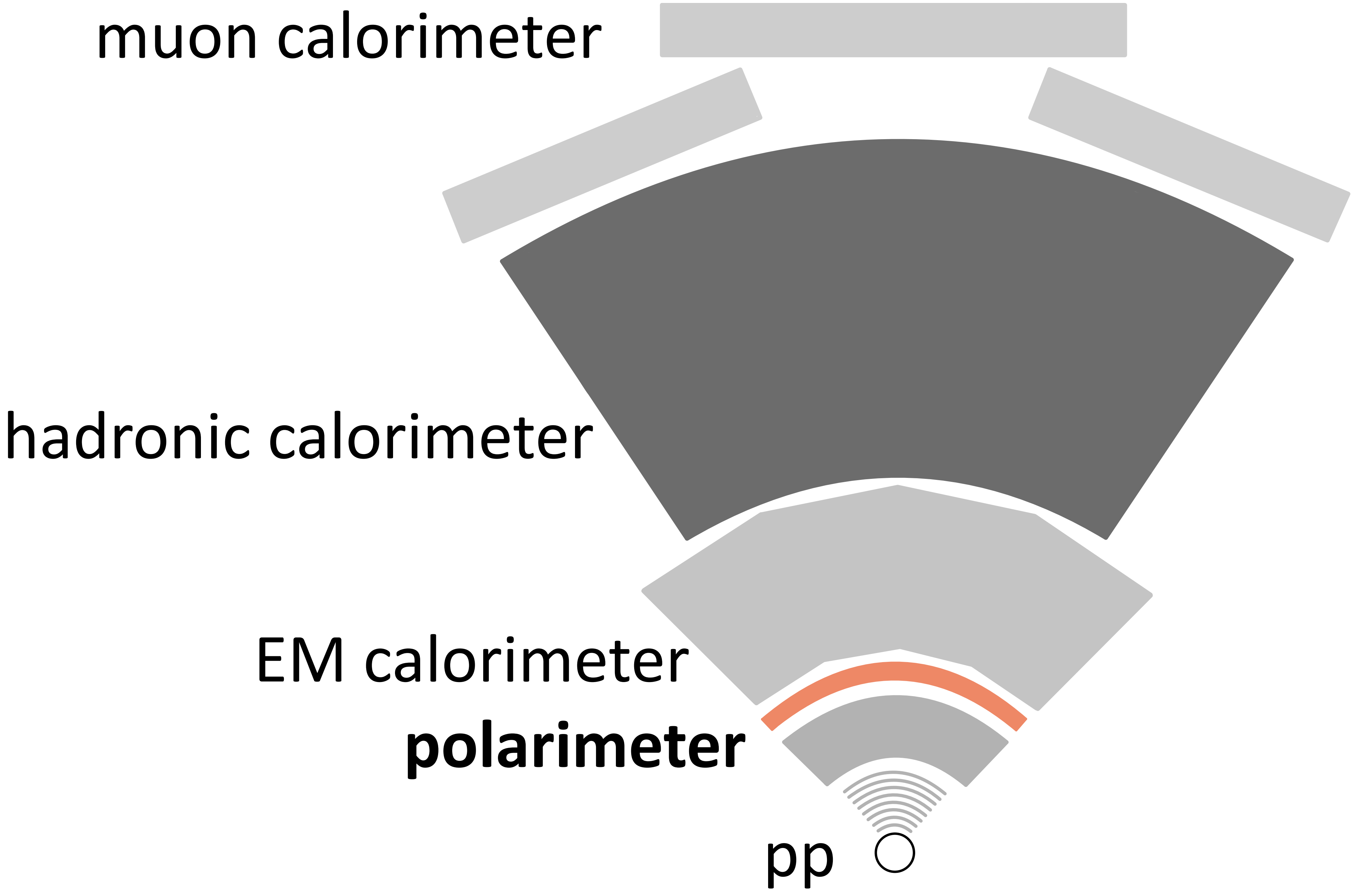
Photons radiated from top quarks (ATLAS/CMS)

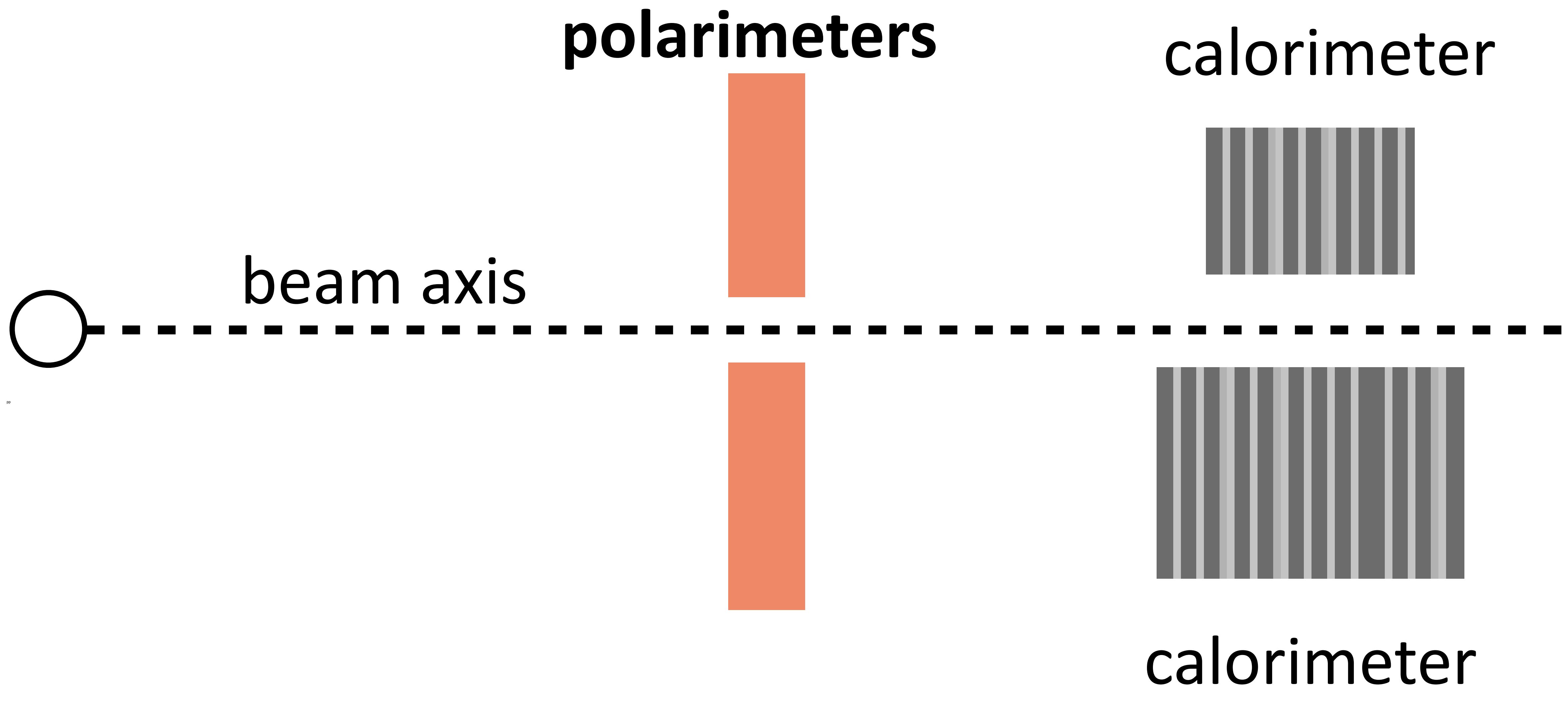


Neutral pion decay to two photons (RHIC)

Decay	Advantage	Lifetime	# of Events
$t \to bW\gamma$	very short timescale; decays before hadronization	$\sim 10^{-25}$ s	$\sim$ 5,000
$\pi^0 \to \gamma\gamma$	extremely clean channel; BR ≈ 98.8%	$\sim 10^{-17}$ s	$\sim$ 200,000

<u>**Our proposal**</u>: Add a non-invasive polarization measurement (for all photons) before calorimeters.





Summary

- High-energy physics experiments can be used to test the Born rule at TeV energies and 10^{-25} s timescales, 12 orders of magnitude shorter than atomic physics.
- Existing data can be repurposed to test the Born rule using τ average polarization measurements.
- In the future, one could add polarimeters to probe photons on these extremely short timescales.