

Physics on target:

Rare processes and hidden sectors

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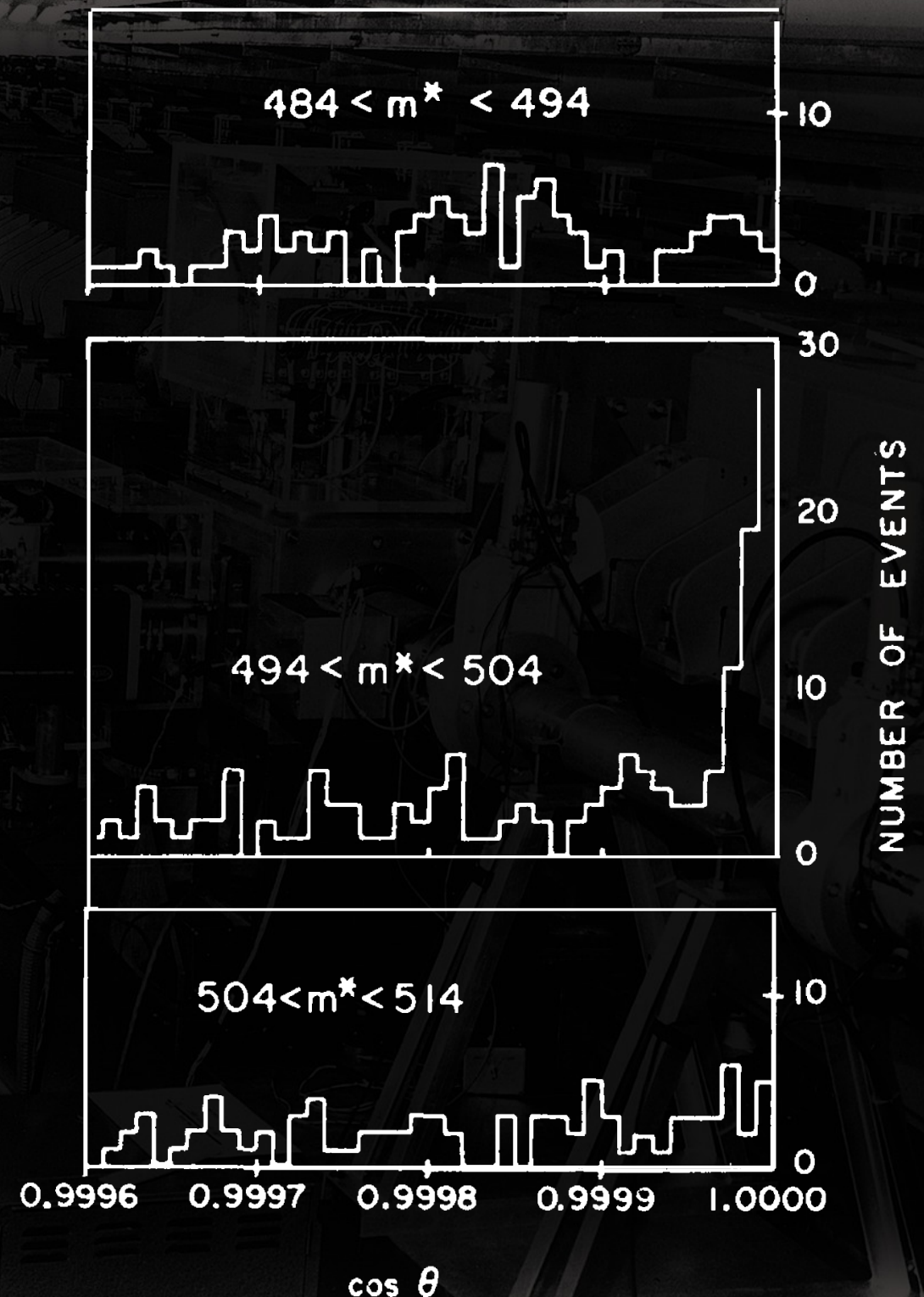


Light and feebly coupled

- Dark matter outweighs ordinary matter five to one
- LHC to the TeV scale: no sign of new physics
- New particles can couple more strongly at the GeV scale
- Embarking on the **intensity frontier**

Two pions in the beam

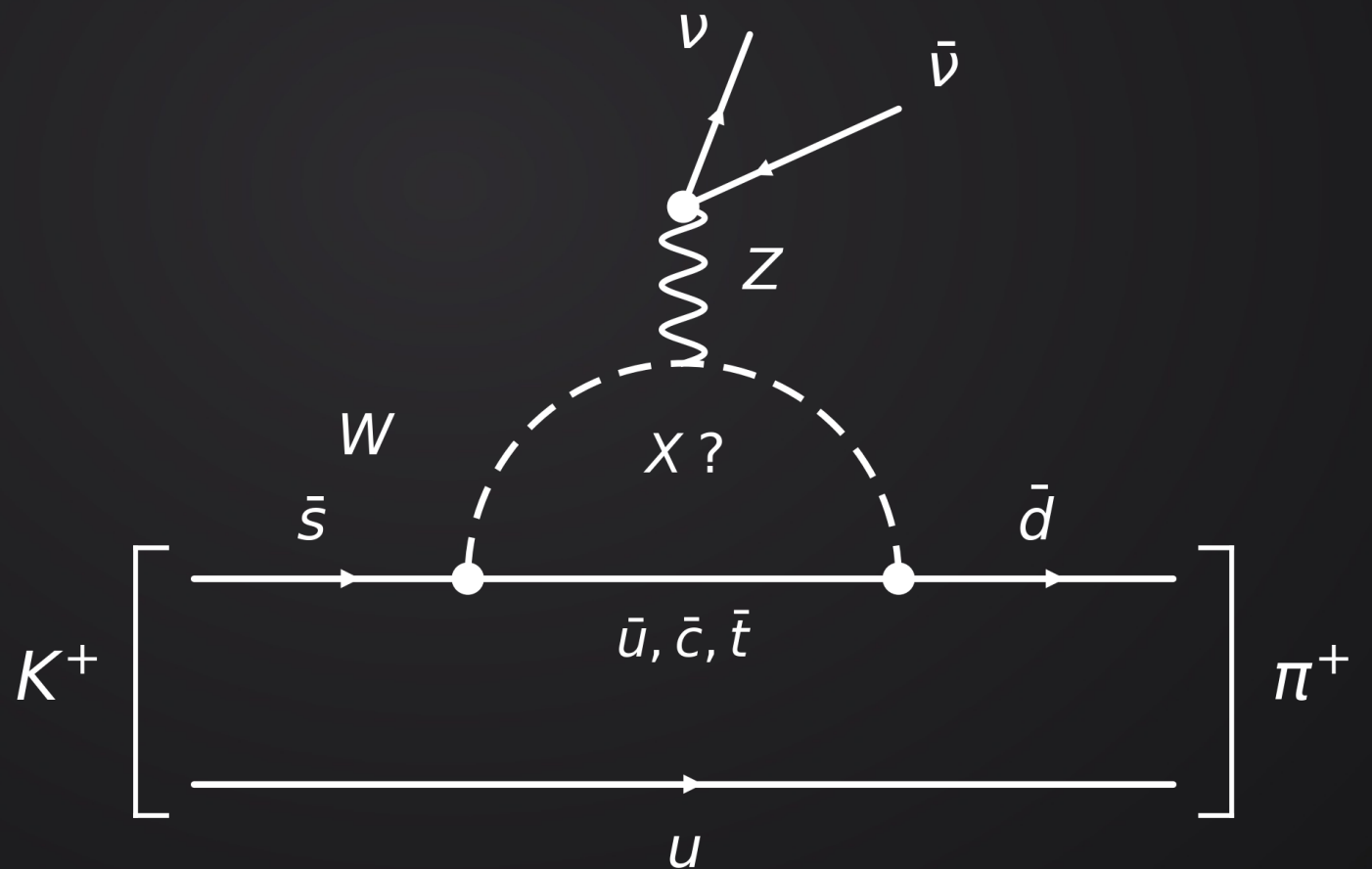
- A K_L beam: fly far enough and only the long-lived state survives
- **CP forbids** $K_L \rightarrow \pi^+ \pi^-$
- 45 events in 22700 contain forbidden decays
- Matter and antimatter are not exact mirror images



Christenson, Cronin, Fitch & Turlay, AGS tunnel, Brookhaven, 1966

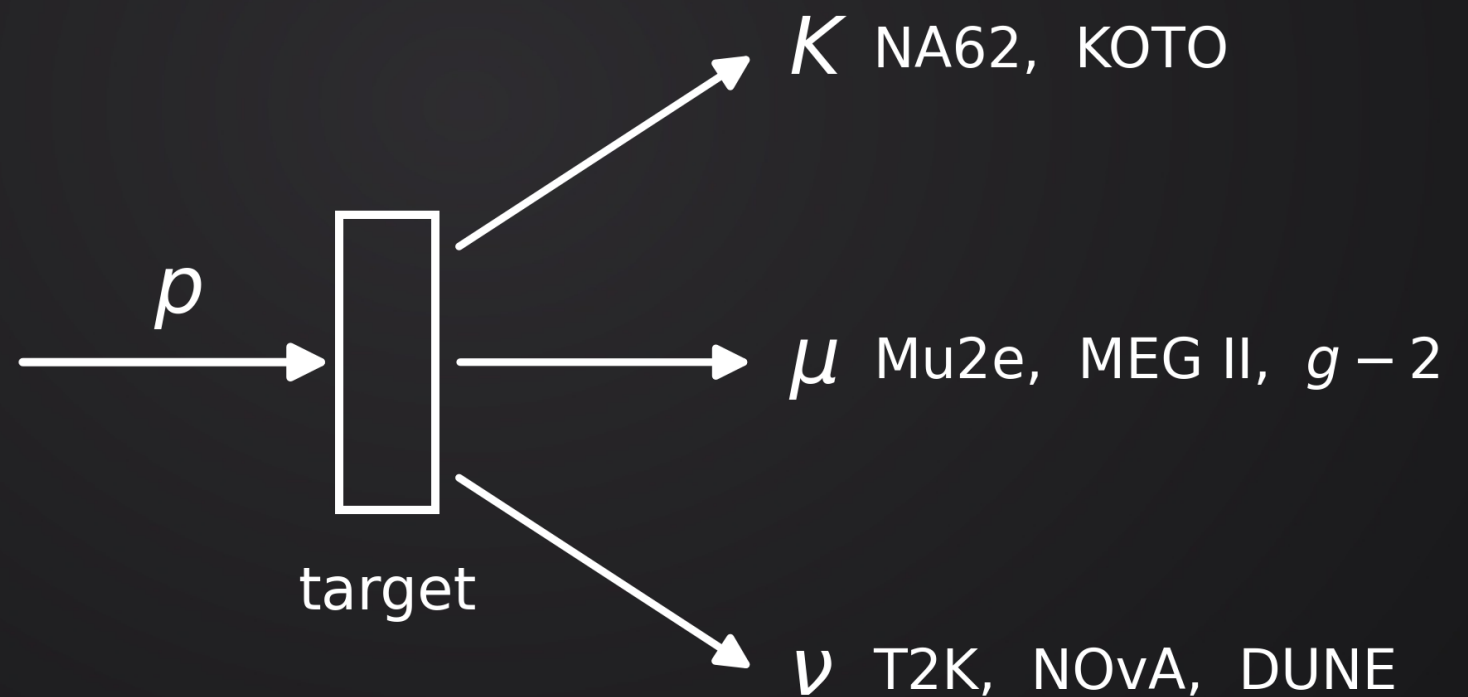
Why rare processes?

- Such decays happen only through **loop** diagrams
- Tiny branching fraction
- Can be computed to a few percent level
- New heavy particles can contribute to the loop
- Measuring at 10^{-11} reaches $10^2 - 10^5$ TeV



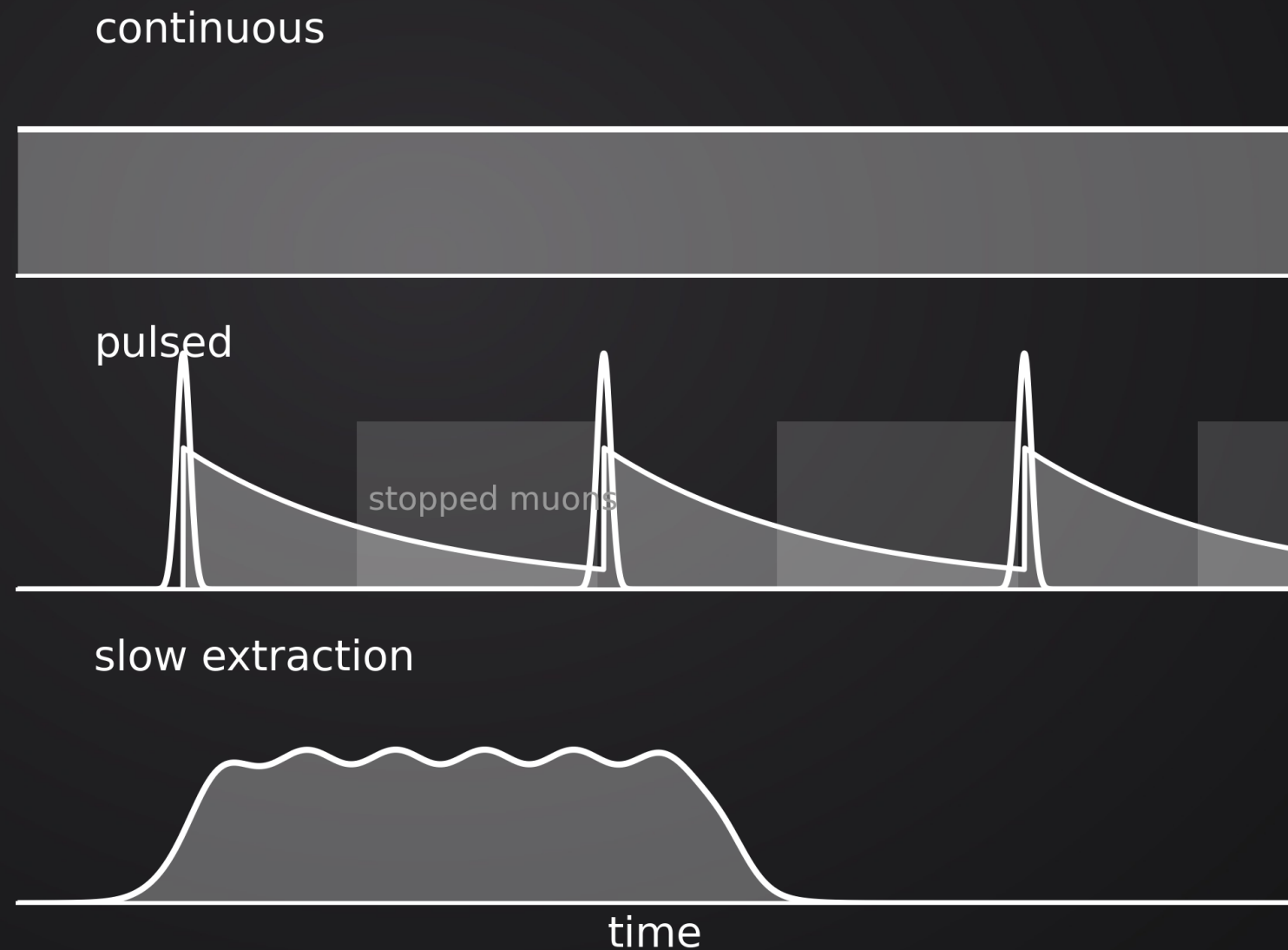
The intensity frontier

- **Protons** from SPS, Main Injector, J-PARC, PSI: 0.6-400 GeV
- Graphite or beryllium to make beams; tungsten to stop them
- Out come kaons, muons, neutrinos
- 10^{13} kaons, 10^{18} muons, 10^{21} protons on target



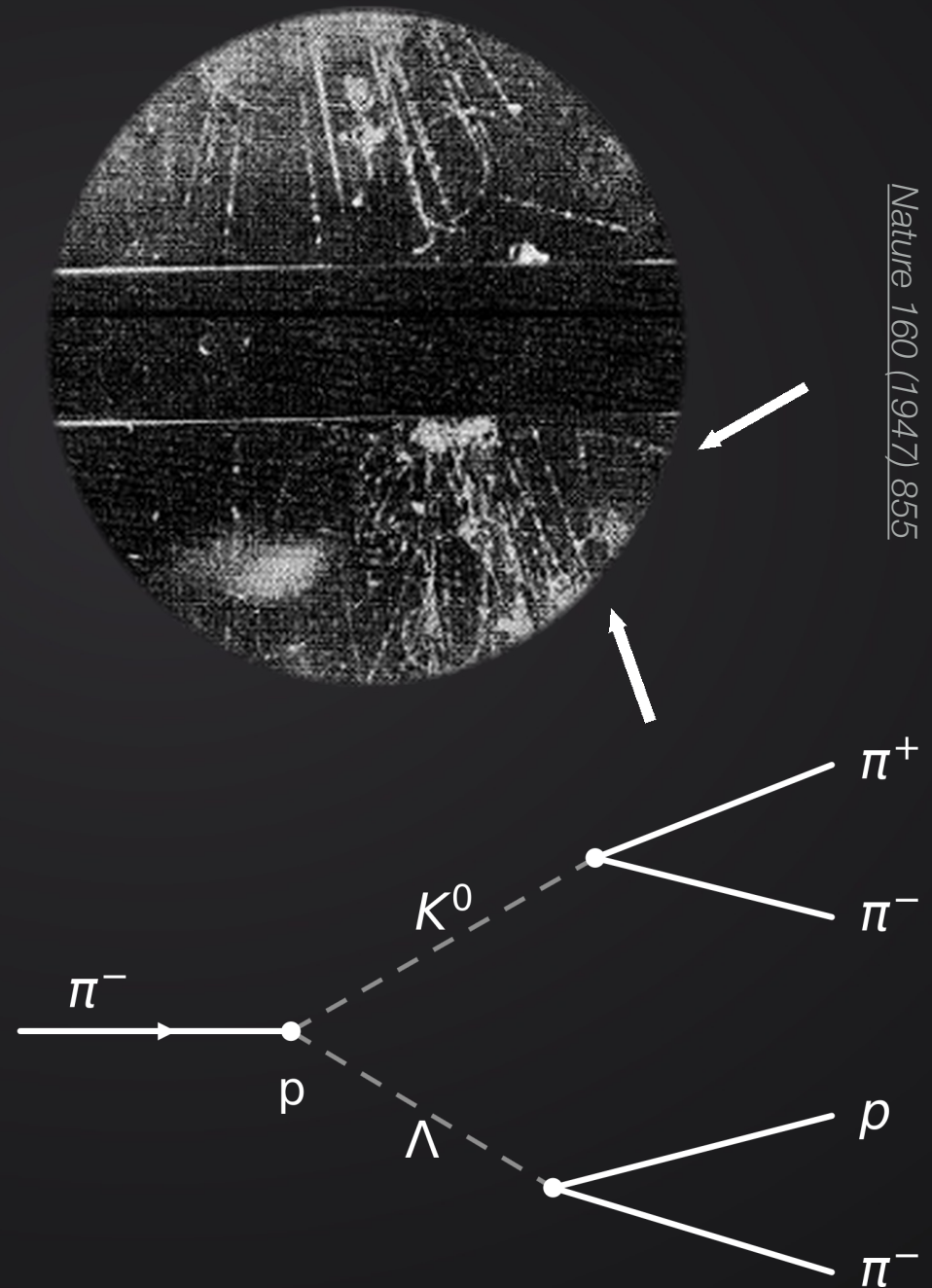
Continuous, pulsed, or slow

- PSI: cyclotron, duty factor ≈ 1
— accidentals scale as rate^2
- Fermilab: pulses 1695 ns apart — delayed window after prompt background
- SPS, J-PARC: slow extraction, 4.8 s spill, duty factor ≈ 0.15
- **Time structure** is selected against the dominant background



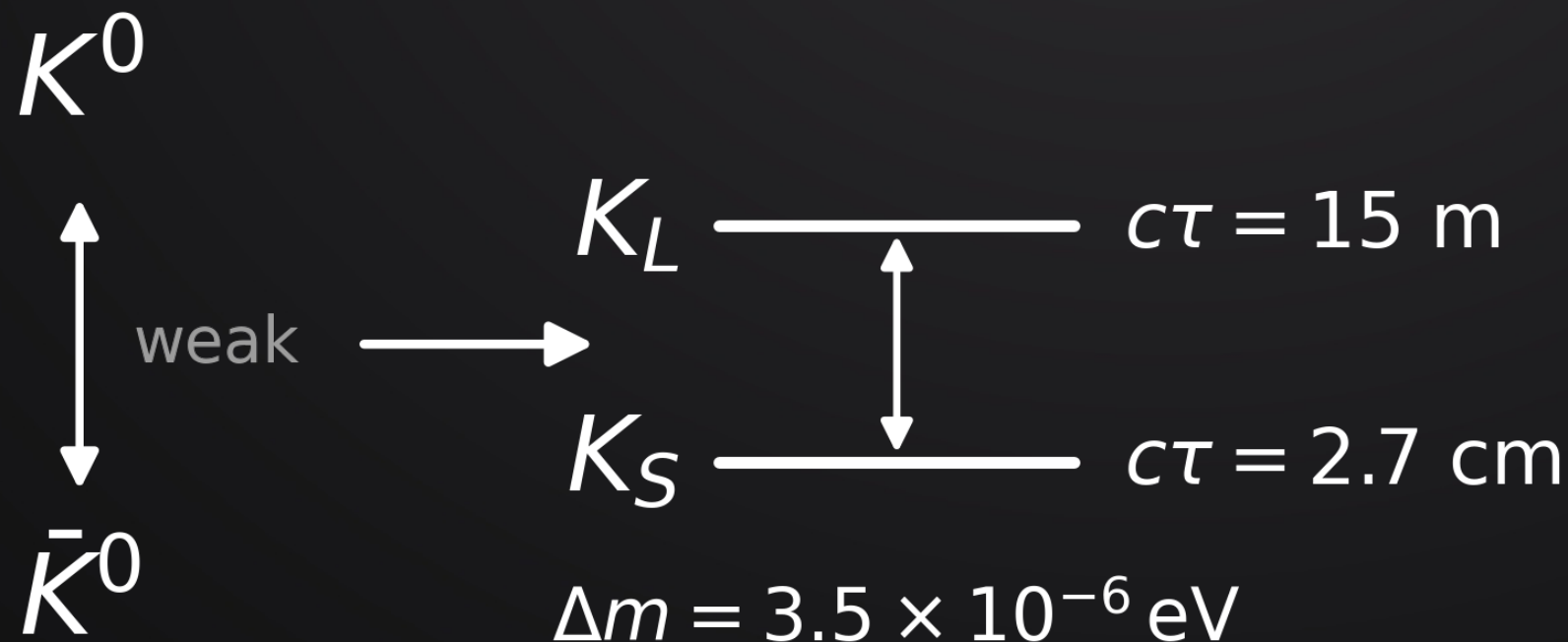
Strange particles

- Rochester & Butler: forked tracks in cosmic-ray cloud chambers
- Produced copiously in pairs, yet decaying only after 10^{-10} s
- **Strangeness**: conserved by the strong force, broken by the weak
- Cosmotron, 1953: made an on-demand discovery



The two-state kaon

- K^0 and $\bar{K}^0$ mix: the propagating states are K_S and K_L
- $\Delta m = 3.5 \times 10^{-6} \text{ eV}$ - among the smallest mass differences measured
- CP violation can be in the mixing (ϵ) or in the decay (ϵ')
- NA48 and KTeV, 1999: $\epsilon'/\epsilon \approx 1.7 \times 10^{-3}$ - both are real



What the kaon predicted

- The long-lived kaon decays to two muons far too rarely
- A fourth quark cancels the amplitude: **charm**, four years before the J/Ψ
- CP violation needs a phase - impossible with only four quarks
- A 2×10^{-3} decay implied six quarks: b in 1977, t in 1995

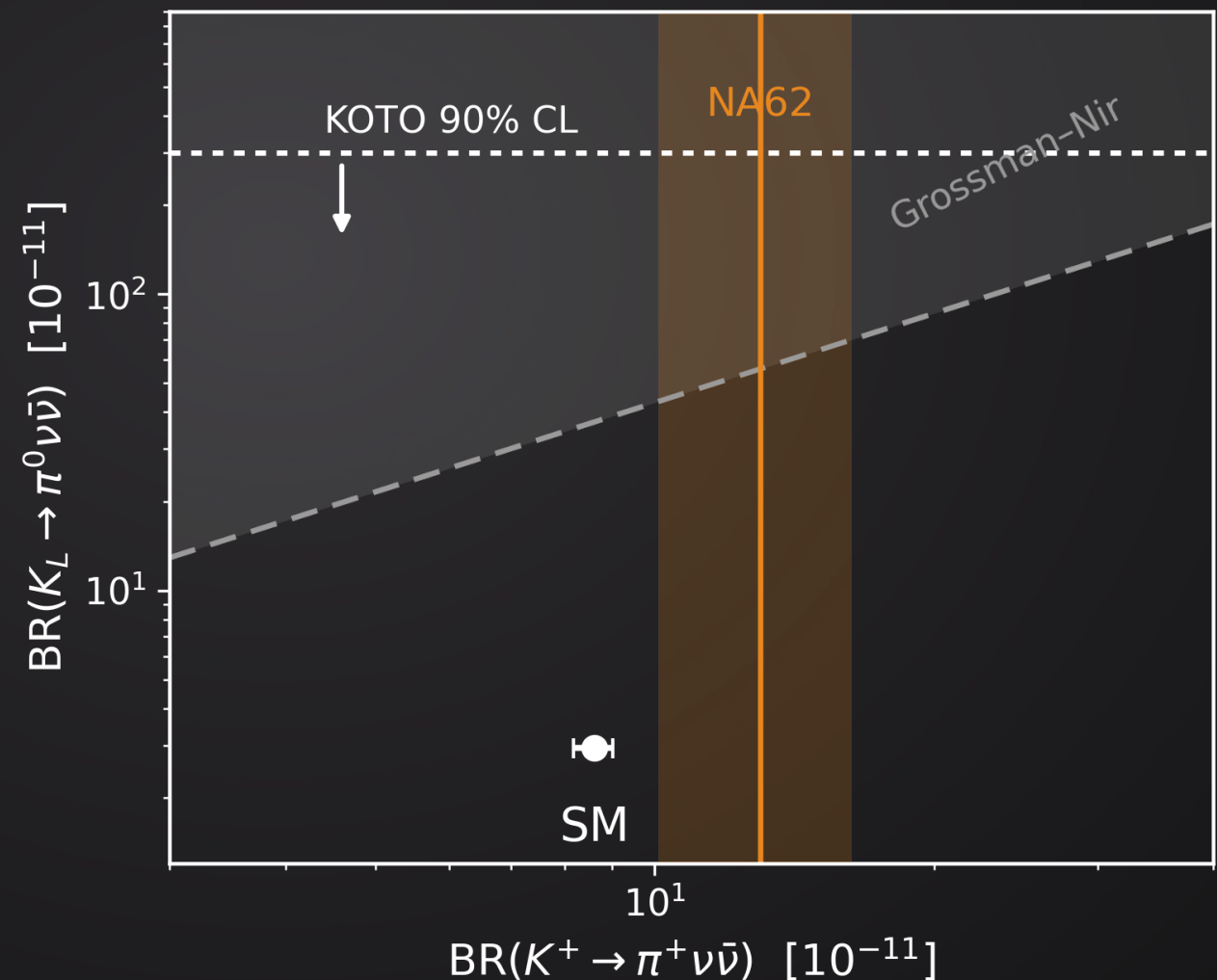


The diagram shows two Feynman diagrams for the transition of an s quark to a d quark. In the first diagram, a dashed line labeled 'u' connects two vertices on a solid line between 's' and 'd'. In the second diagram, a dashed line labeled 'c' connects two vertices on a solid line between 's' and 'd'. The two diagrams are separated by a minus sign, and the entire expression is followed by a proportionality symbol and the difference of squared masses.

$$s \text{ --- } \overset{\text{u}}{\text{---}} \text{ --- } d \quad - \quad s \text{ --- } \overset{\text{c}}{\text{---}} \text{ --- } d \quad \propto m_c^2 - m_u^2$$

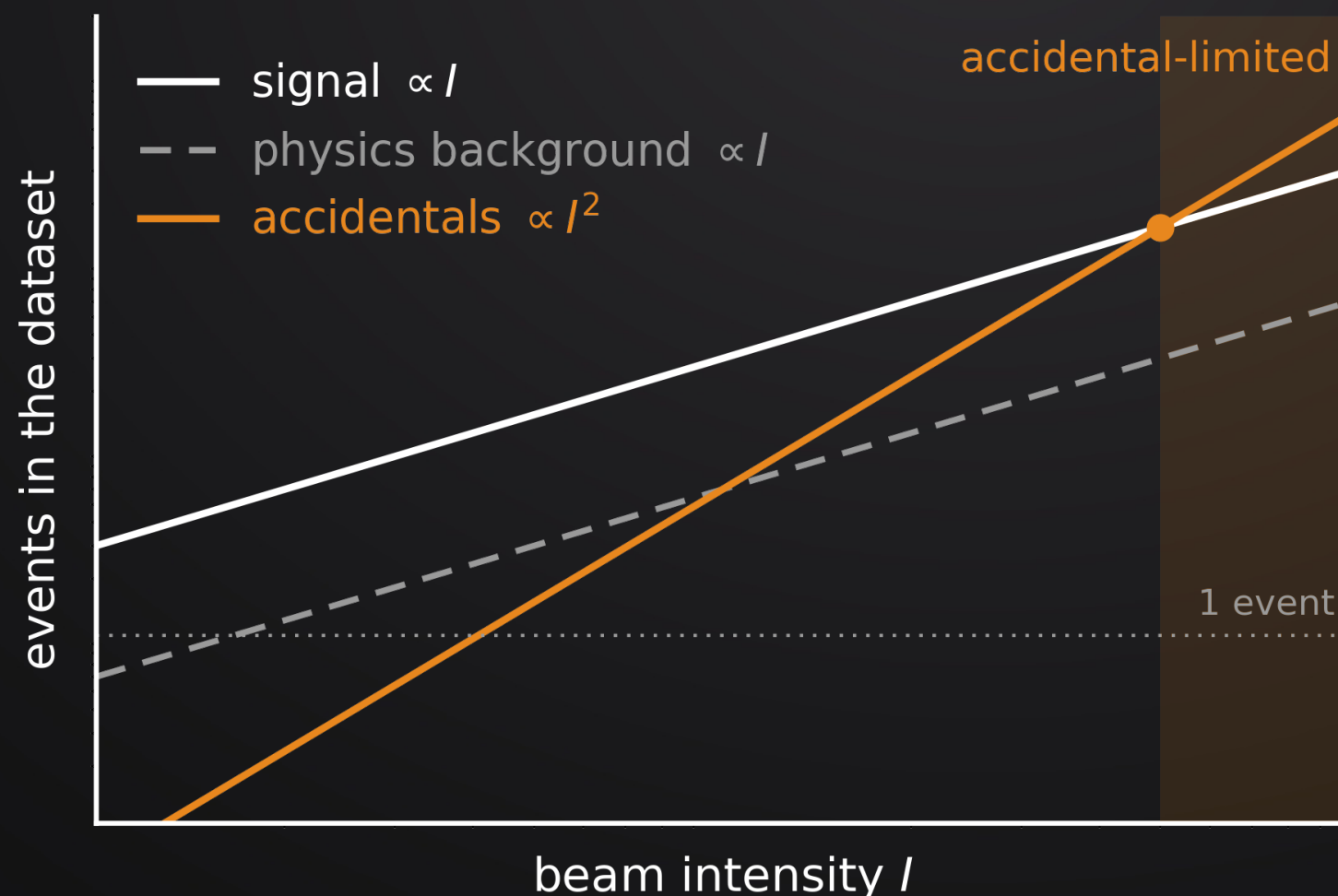
The golden channels

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$:
loop-only, CKM-suppressed
- The one QCD input is measured, not computed
- SM: 8.6×10^{-11} and 2.9×10^{-11} ,
to a few percent
- Any significant deviation is **new physics**, up to 100 TeV



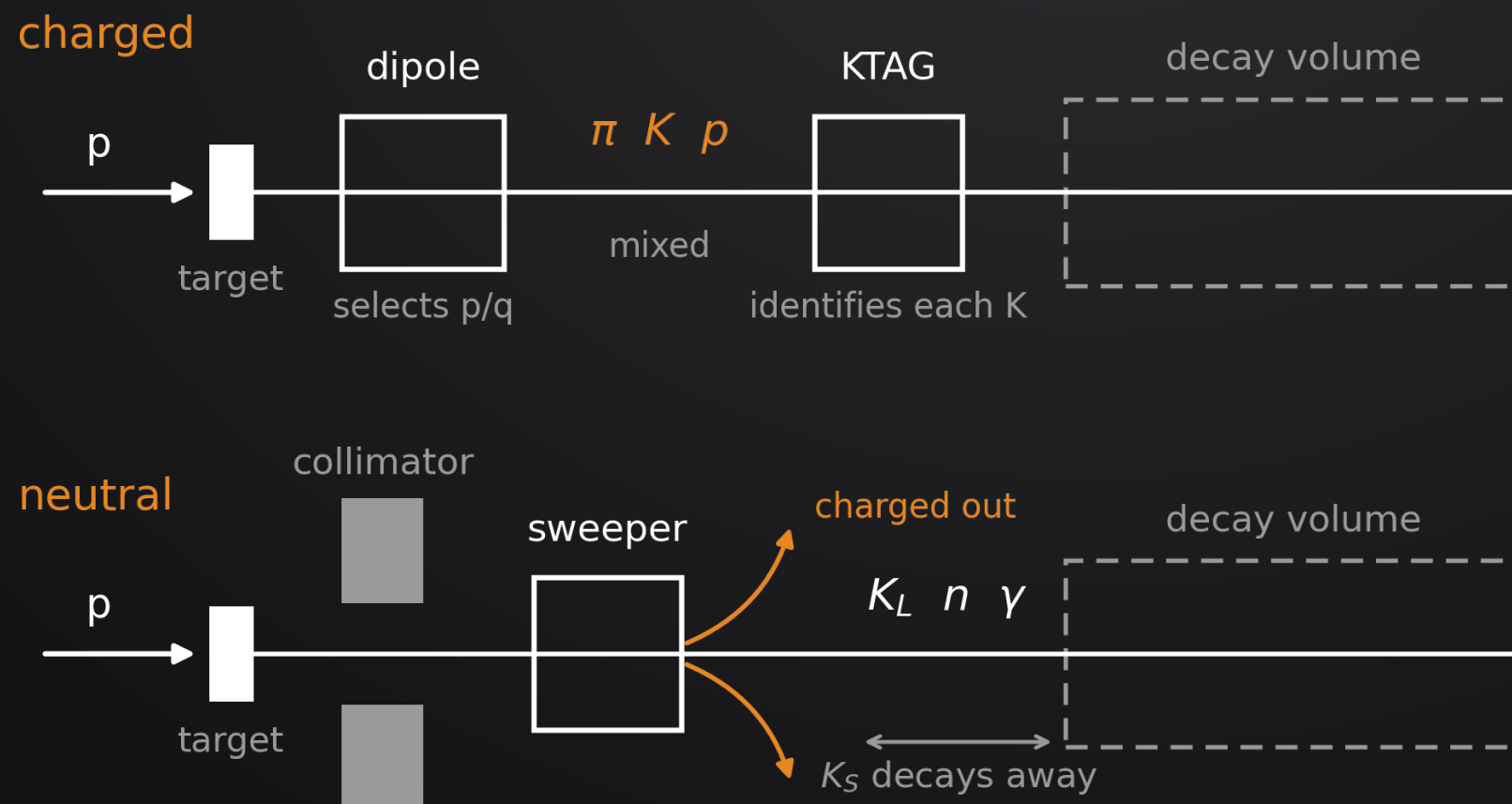
Background-free

- Expected background **below one event**
- Sensitivity improves as $1/N$
- Multiple selections: ID, kinematics, vetoes, timing
- Accidental background grows as intensity²: there is an optimal beam intensity to run on



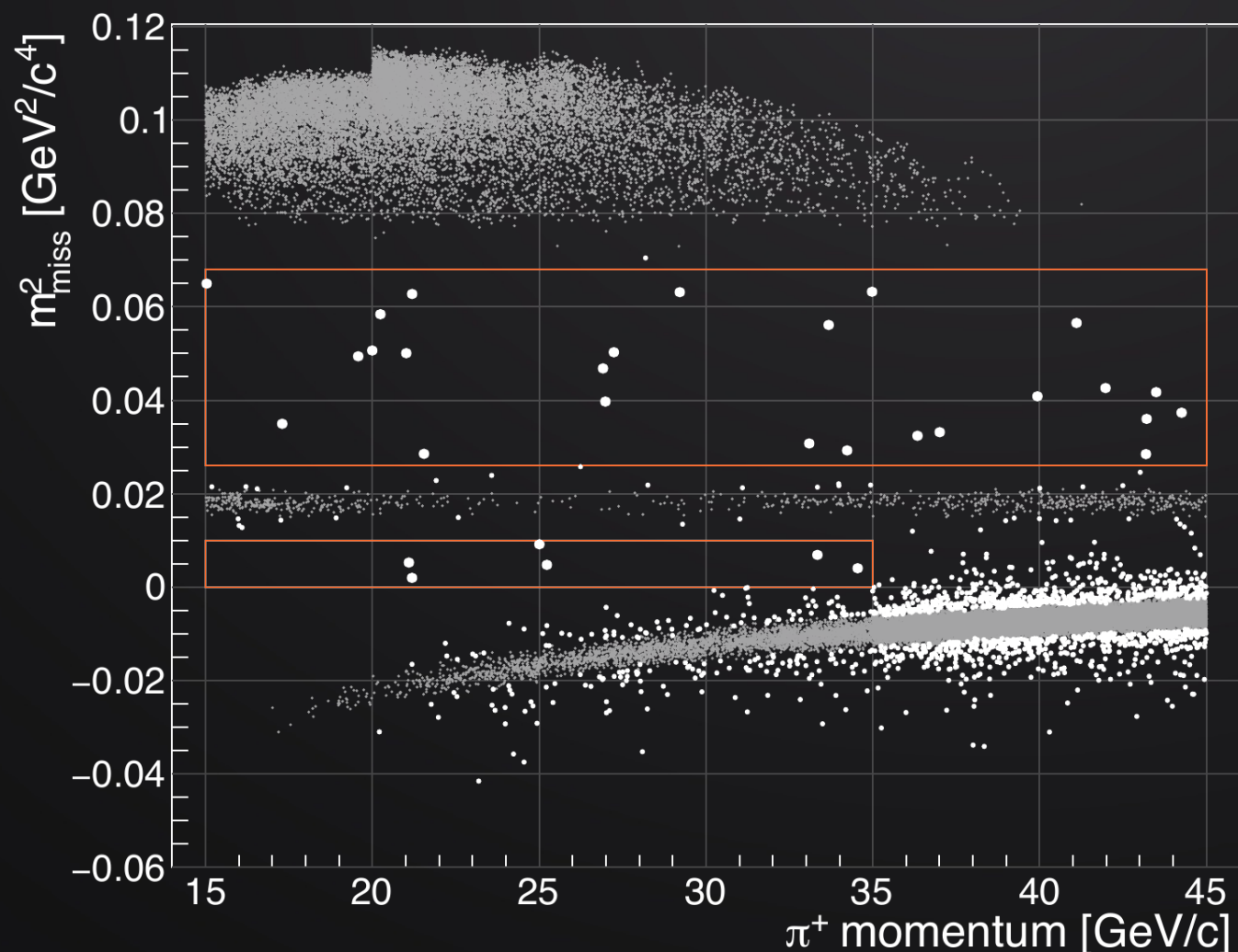
Making kaon beams

- Momentum-selected secondary beam: magnets set p/q
- NA62 at 75 GeV/c: kaon fraction $\approx 6\%$; kaon identified (KTAG)
- Neutral beams: collimation and sweeping only; K_S decays away
- **Beam composition and timing** enter the background estimate



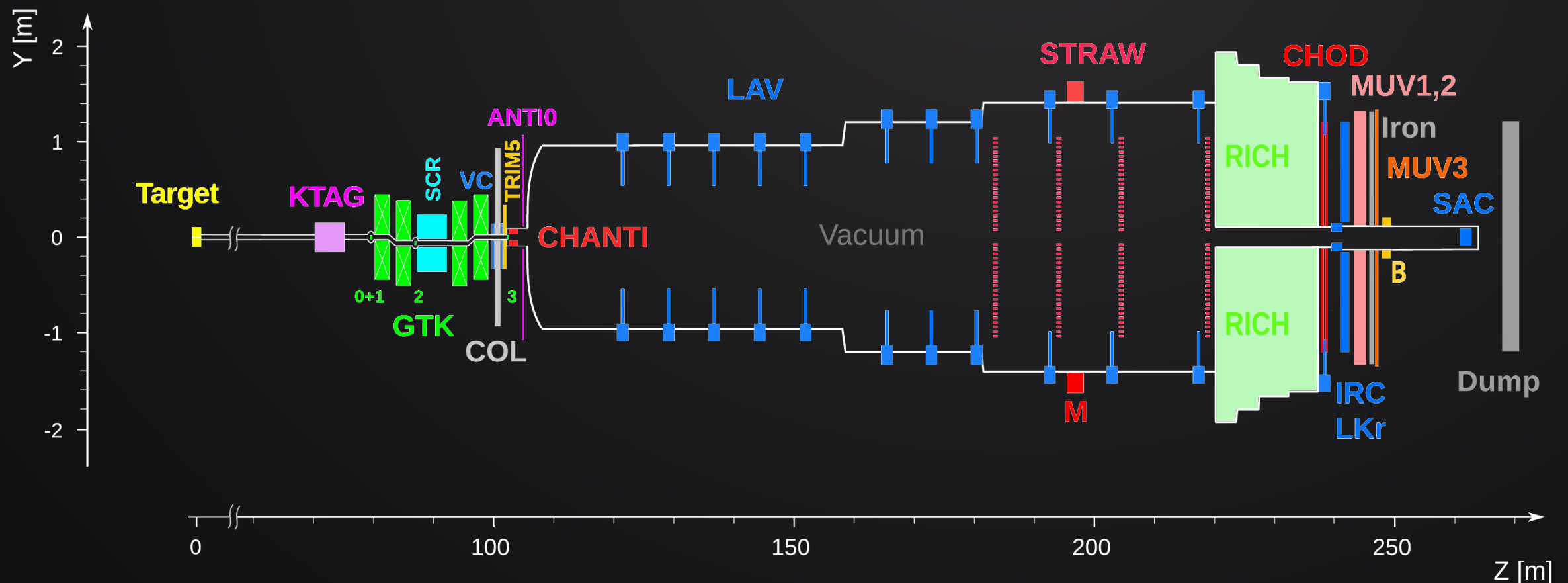
Counting kaons at NA62

- Decay in flight: incoming and outgoing tracks both measured
- Signal windows in m_{miss}^2 , either side of the π^0 peak
- Dominant $K^+ \rightarrow \mu^+ \nu$ (63%) and $K^+ \rightarrow \pi^+ \pi^0$ (21%) at fixed m_{miss}^2
- Observed at 5σ in 2024, BR $\approx 13 \times 10^{-11}$: now a **precision test**



Veto

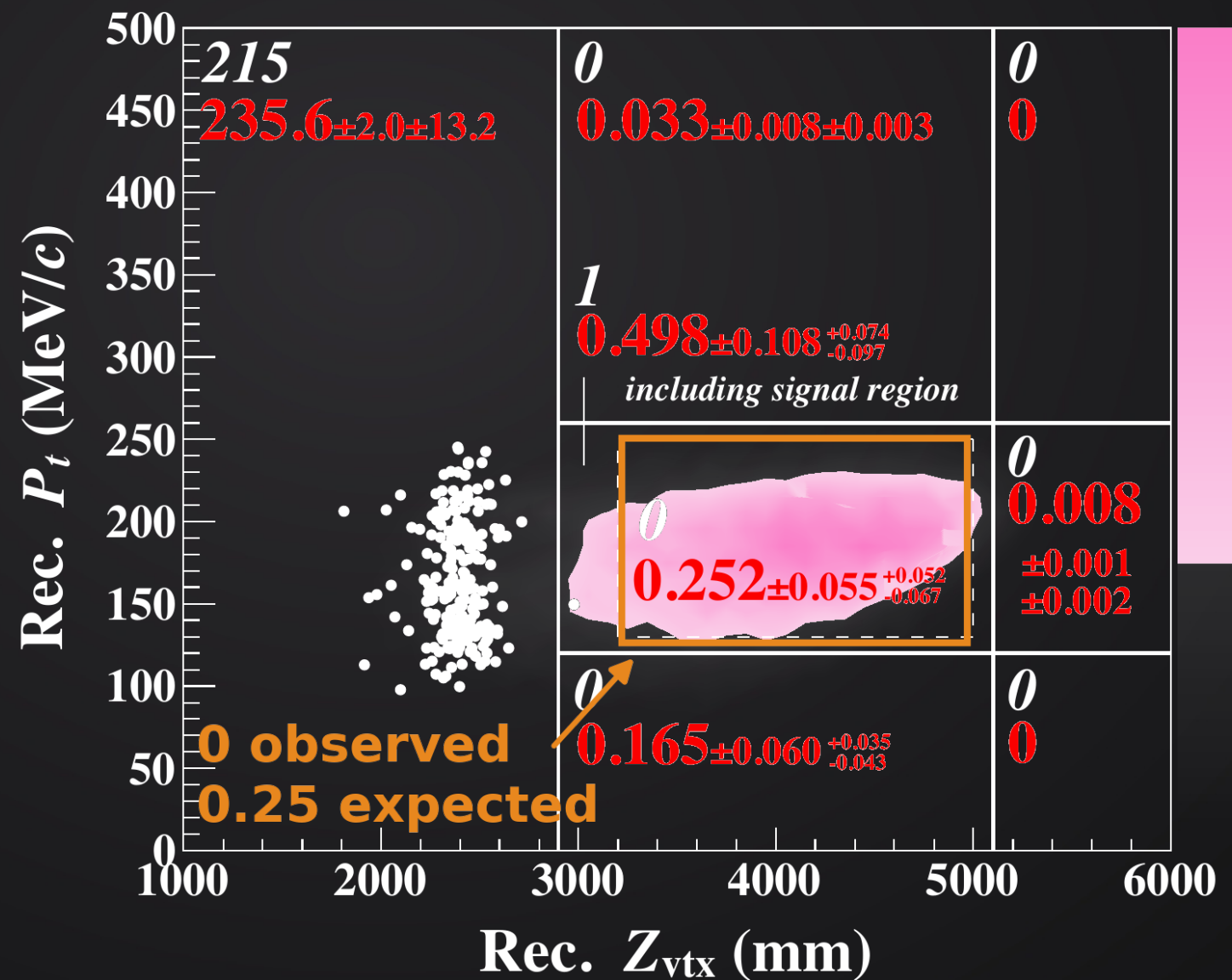
- Upstream: KTAG tags the kaon, GTK measures it to 100 ps
- 65 m evacuated decay volume, straw tracker inside the vacuum
- Photon vetoes tile 0-50 mrad; π^0 rejected to 1.7×10^{-8}
- **Signal topology:** no photon, no muon, no extra track



The neutral golden mode

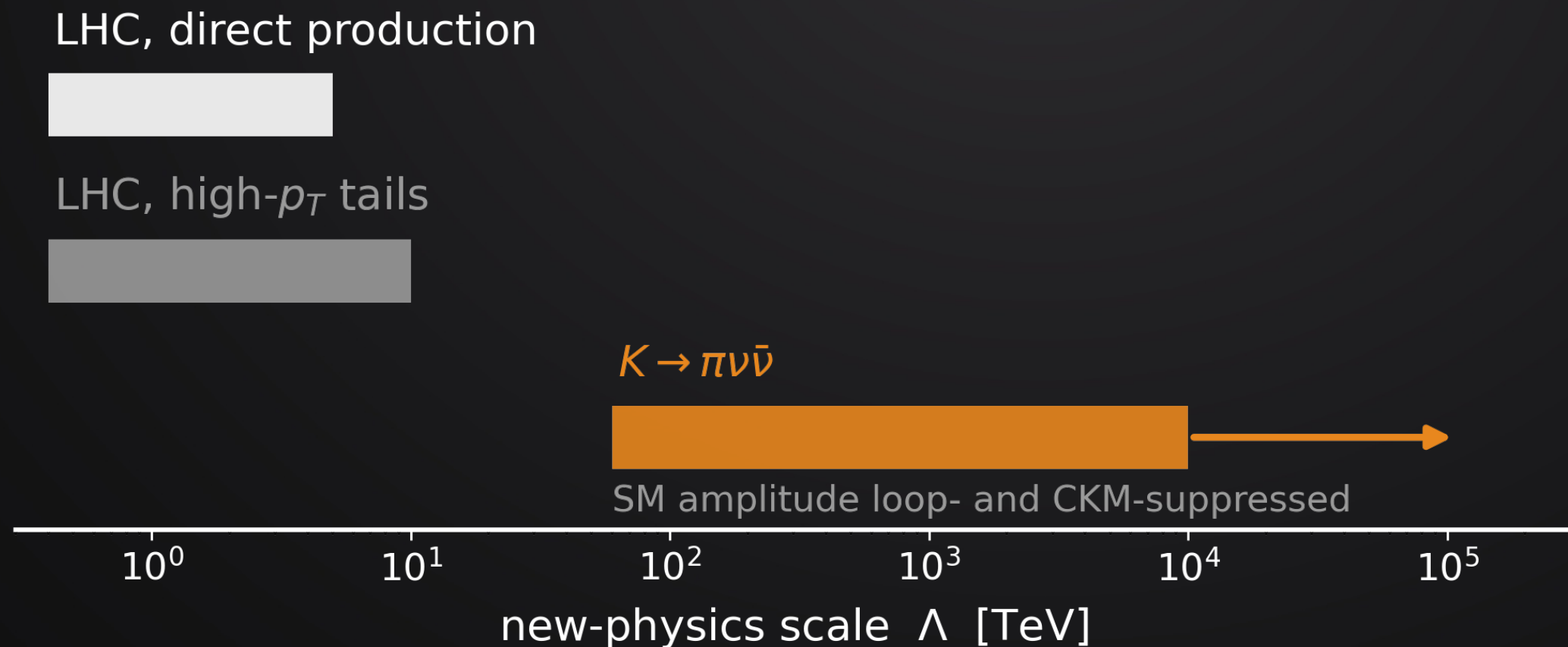
- Search for $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at KOTO: **extremely rare**
- Two photons, missing momentum, nothing else
- No incoming track
- Zero events, $\text{BR} < 2.2 \times 10^{-9}$; SM at 3×10^{-11}
- Directly CP-violating

Phys. Rev. Lett. 134 (2025) 081802



Kaons' reach

- **Reach O(100) TeV**: the SM amplitude is loop- and CKM-suppressed
- Complementary to ***B*** physics: same CKM, independent systematics
- Sixty years from the CP violation discovery to precision instrument
- Theory limited by $|V_{cb}|$



The muon: a scale in itself

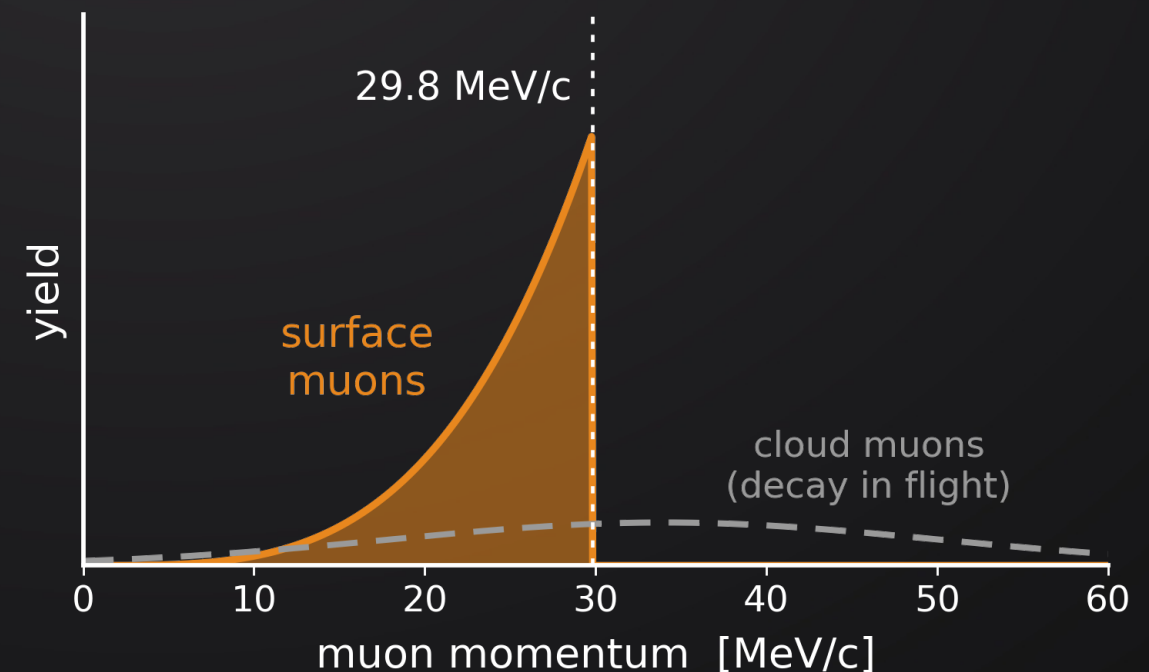
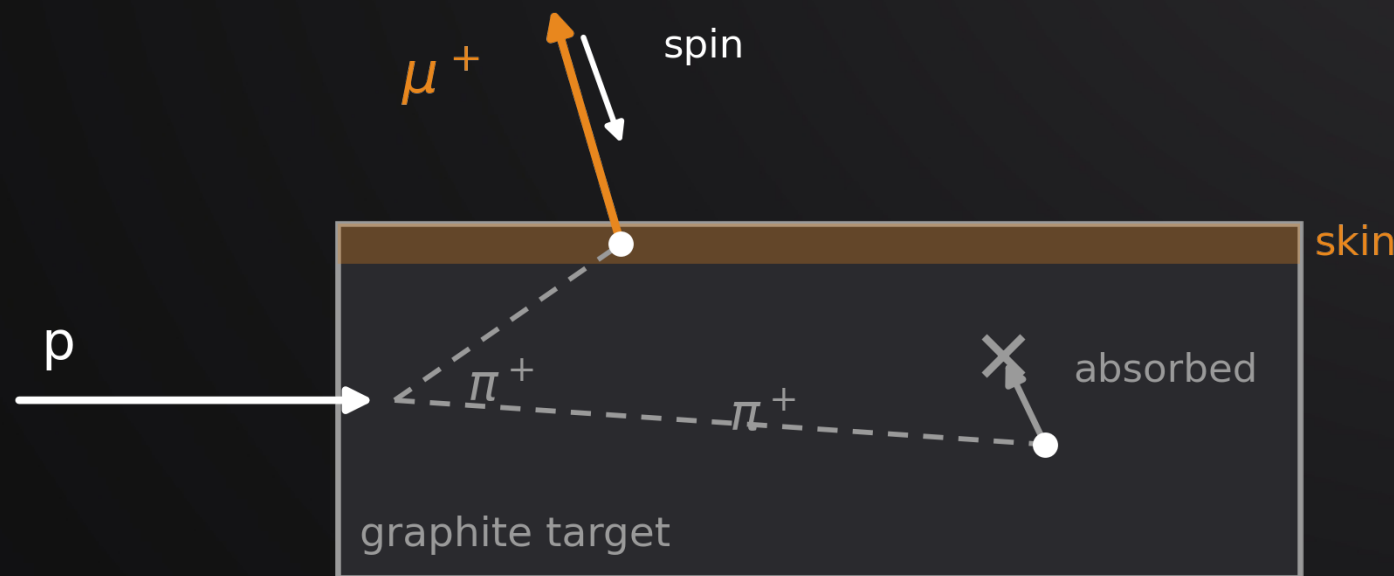
- Mass **207x the electron**; dipole operators scale as m^2
- Gain over the electron: $(m_\mu/m_e)^2 \approx 4 \times 10^4$
- Minimum-ionising: crosses metres of iron
- Lifetime 2.2 μs : long enough to store, short enough to decay

	e	μ	τ	
mass	0.511 MeV	105.7 MeV	1777 MeV	
lifetime	stable	2.2 μs	0.29 ps	
$(m/m_e)^2$	1	4×10^4	1×10^7	

The diagram illustrates a muon-muon interaction. Two muons, labeled μ_L and μ_R , are shown as horizontal lines with arrows indicating their direction. They interact via a virtual photon, represented by a wavy line labeled γ . An orange arc above the photon line is labeled $X ?$, suggesting a potential new interaction or decay channel.

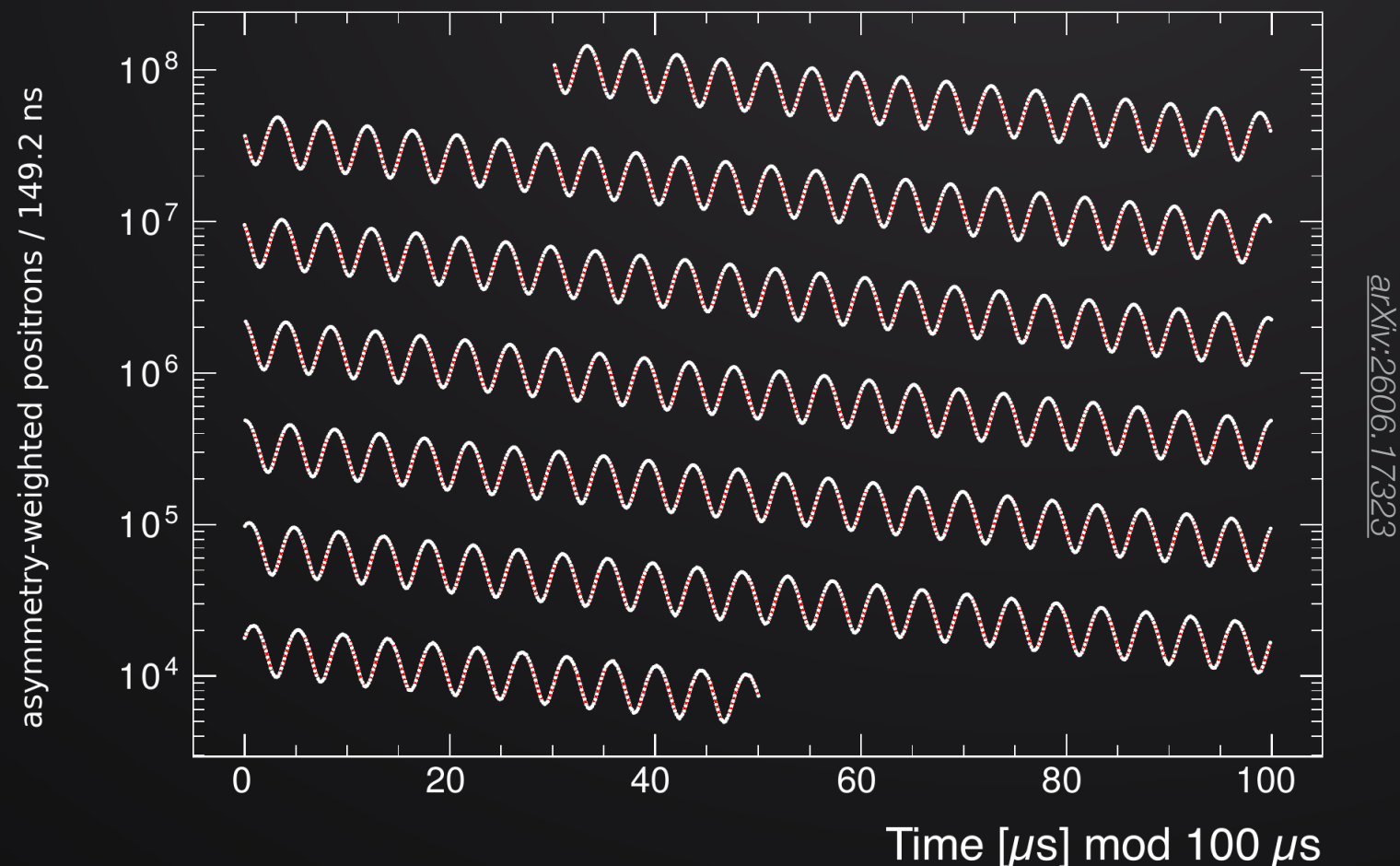
Making muon beams

- PSI HIPA: 590 MeV cyclotron, 1.4 MW continuous proton beam
- Up to 10^8 muons per second, the HiMB upgrade targets 10^{10}
- Surface muons: π^+ stopped in the target skin decay at rest
- **Monochromatic** at 29.8 MeV/c, fully polarized, stops in < 1 mm



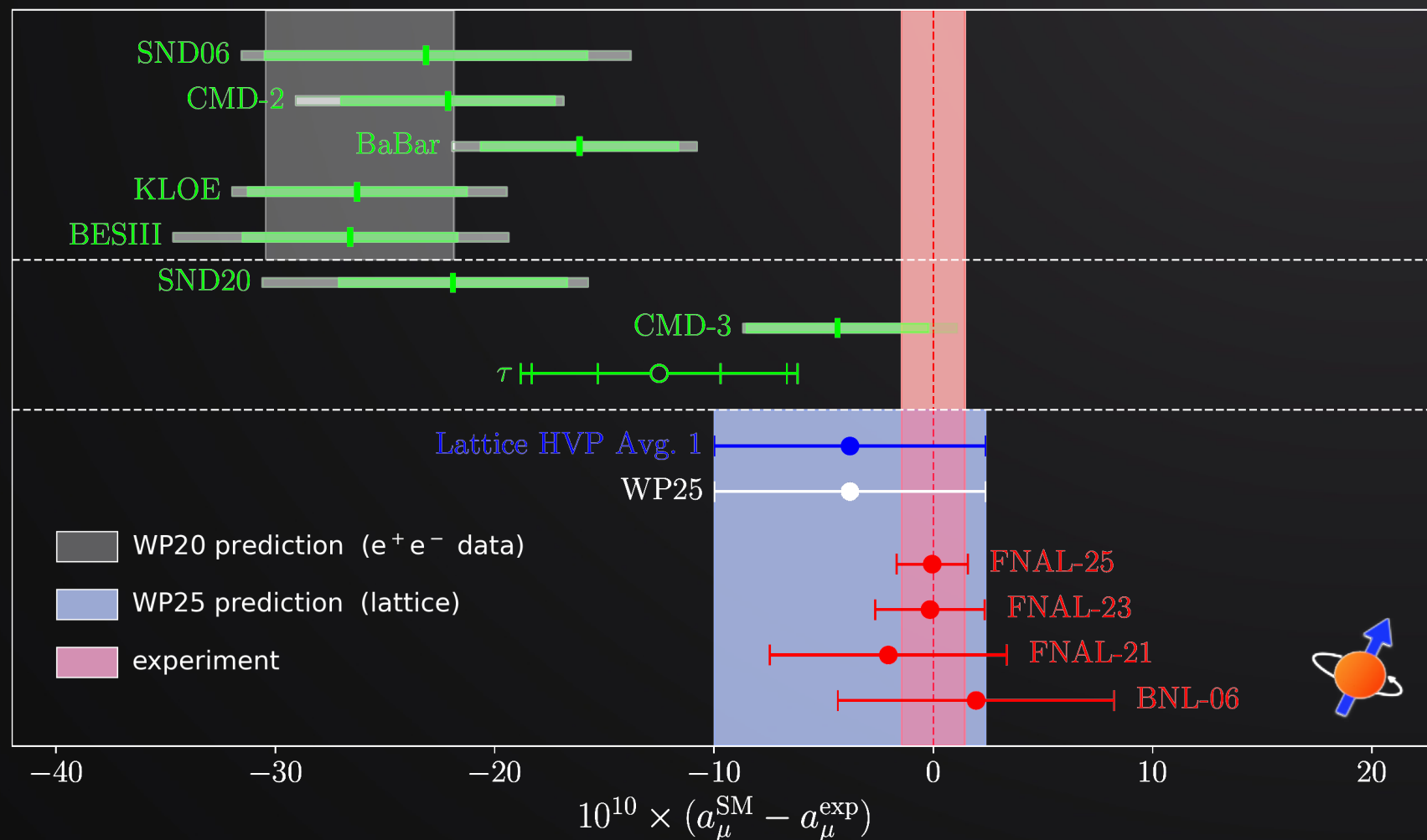
g-2: the magic trick

- $a_\mu = (g - 2)/2$: every particle in the SM contributes
- Spin precession exceeds cyclotron rotation by: $\omega_a = a_\mu eB/m$
- Electric focusing would twist the spin unless $\gamma = 29.3$
- **Magic momentum 3.094 GeV/c; Fermilab reached 127 ppb**

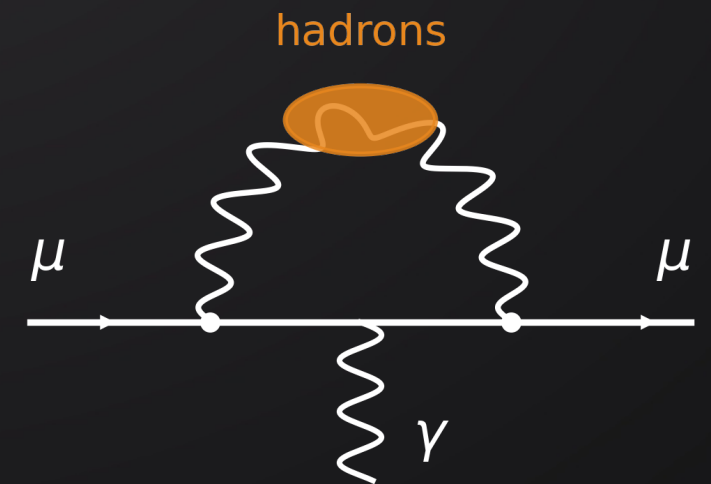


g-2: in agreement?

- Uncertainty is dominated by hadronic vacuum polarization (HVP)
- Data-driven ($e^+e^- \rightarrow \text{hadrons}$) and lattice QCD disagreed
- WP25 takes the lattice average: **theory now agrees**
- The tension moved into the e^+e^- data itself

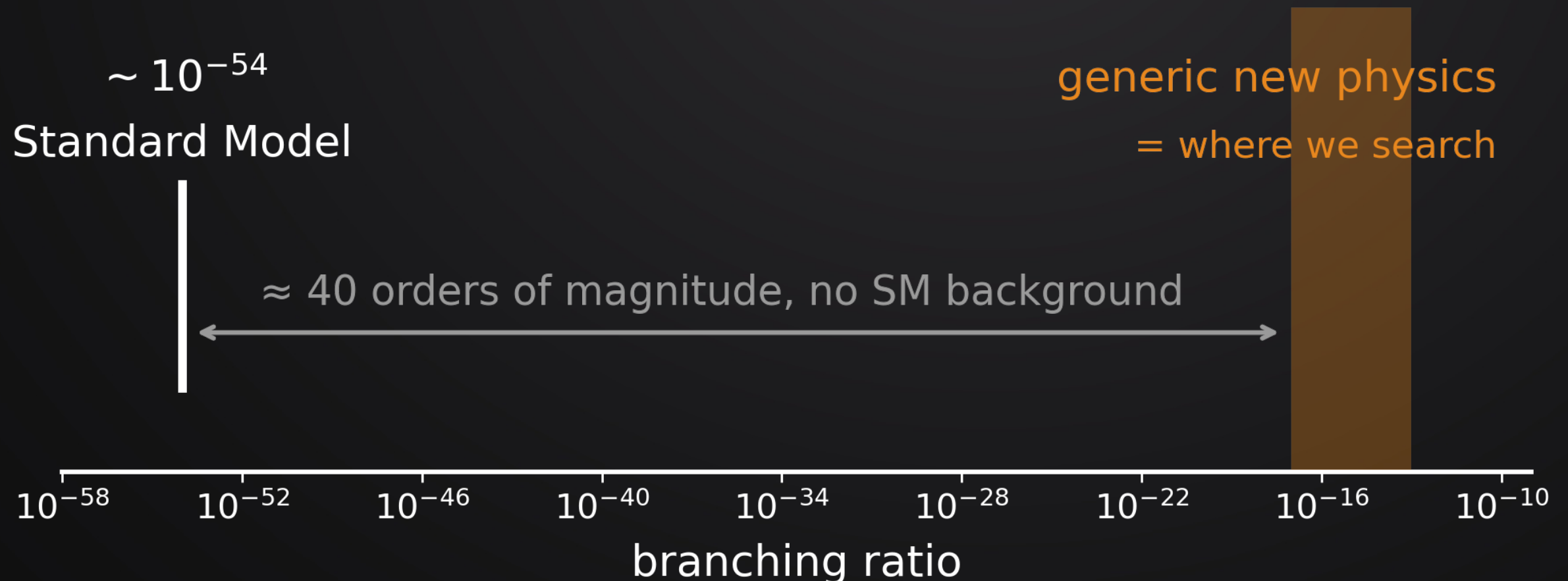


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Charged lepton flavor violation

- $\mu \rightarrow e\gamma, \mu \rightarrow 3e, \mu N \rightarrow eN$: the lepton flavor changes
- SM rate with neutrino masses: $\approx 10^{-54}$, GIM-suppressed
- Generic new physics predicts $10^{-13} - 10^{-17}$: within reach
- **A few events** would be unambiguous new physics



Three ways

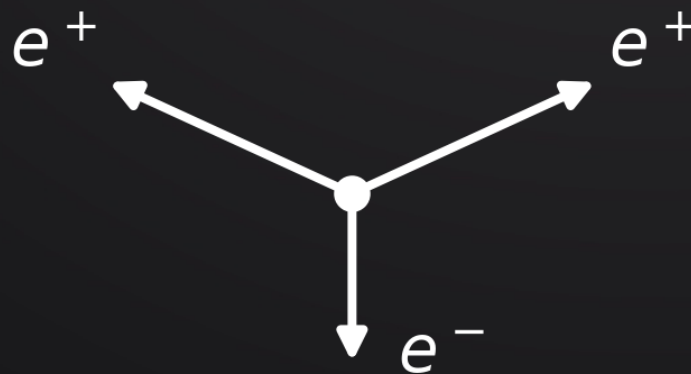
- $\mu \rightarrow e\gamma$: MEG II, two-body kinematics - $< 1.5 \times 10^{-13}$
- $\mu \rightarrow 3e$: Mu3e, three charged tracks - aiming at 10^{-16}
- $\mu N \rightarrow eN$: Mu2e, COMET, a 105 MeV electron - aiming at 10^{-17}
- One channel would prove new physics, three would **identify** it

$$\mu \rightarrow e\gamma$$



back-to-back, 52.8 MeV each

$$\mu \rightarrow 3e$$



$$\Sigma p = 0, \quad \Sigma E = m_\mu$$

$$\mu N \rightarrow eN$$

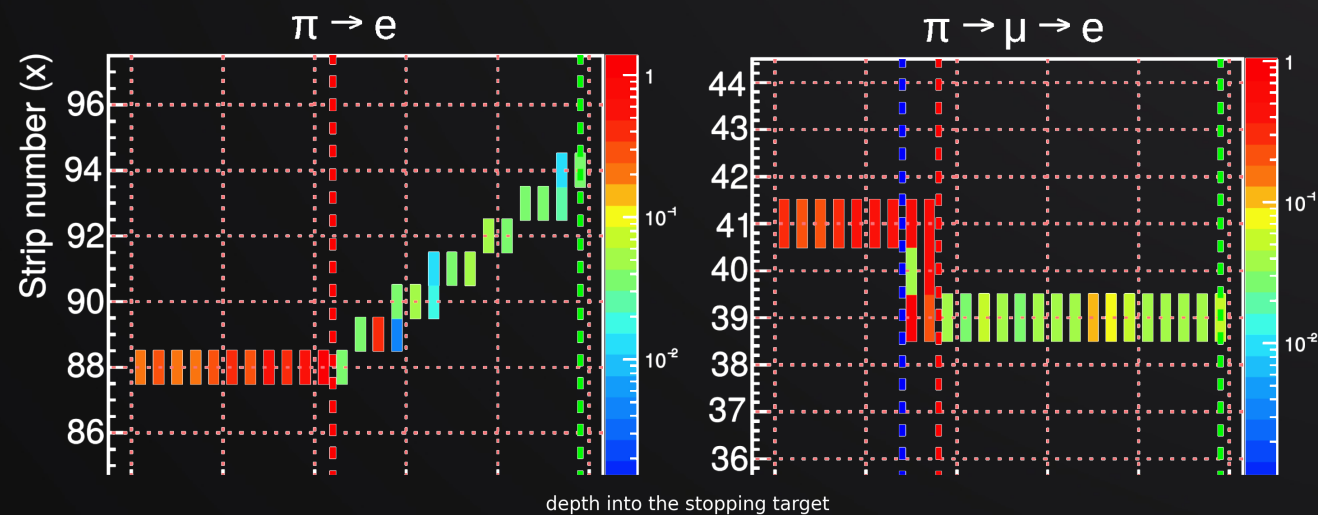
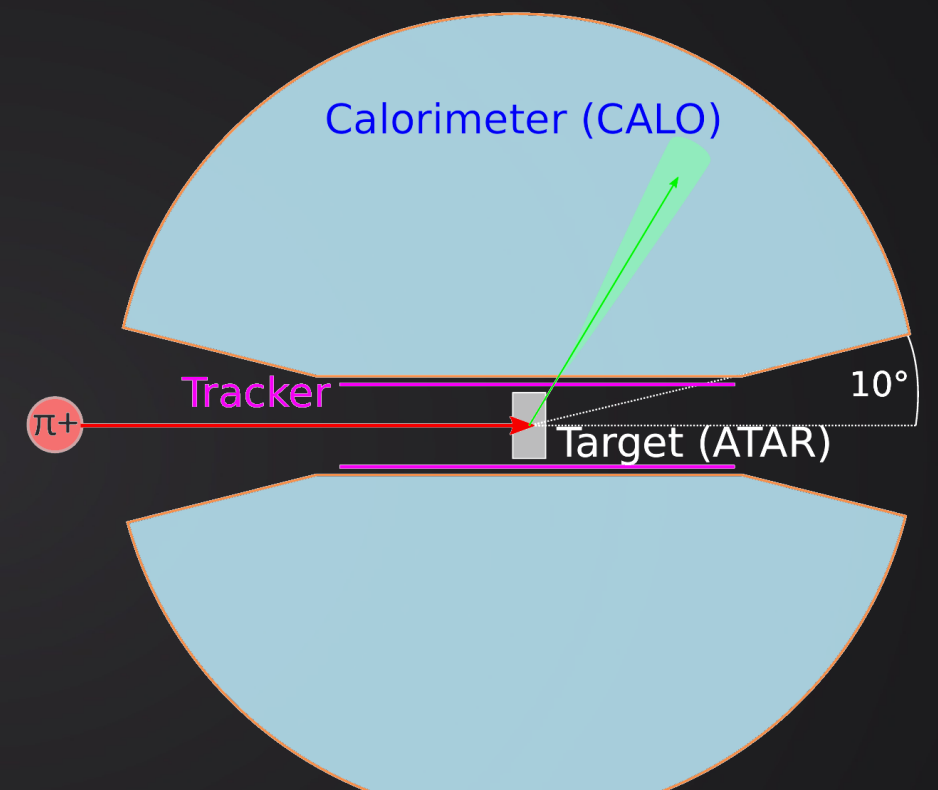


nucleus

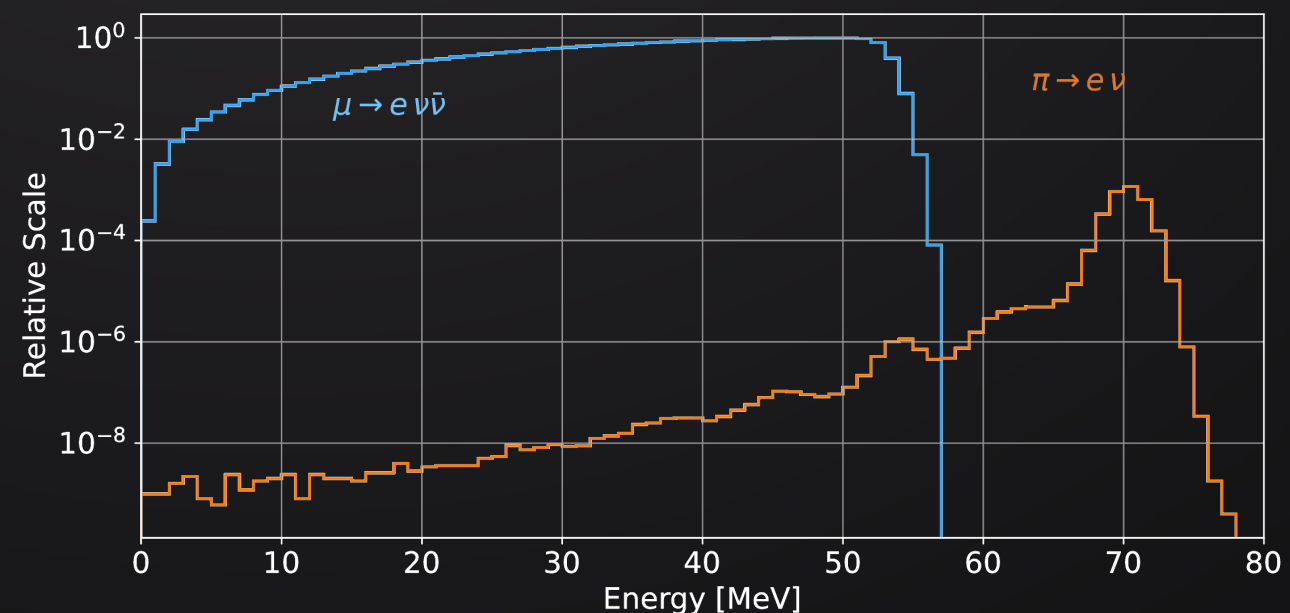
single track, 105 MeV

The pion

- $\pi \rightarrow e\nu$ vs $\pi \rightarrow \mu\nu$: helicity suppression by $(m_e/m_\mu)^2$
- The decay constant cancels: SM gives $R = 12352(2) \times 10^{-4}$
- PIENU: 0.1% agreement - a razor test of $e - \mu$ universality
- PIONEER at PSI aims for better precision

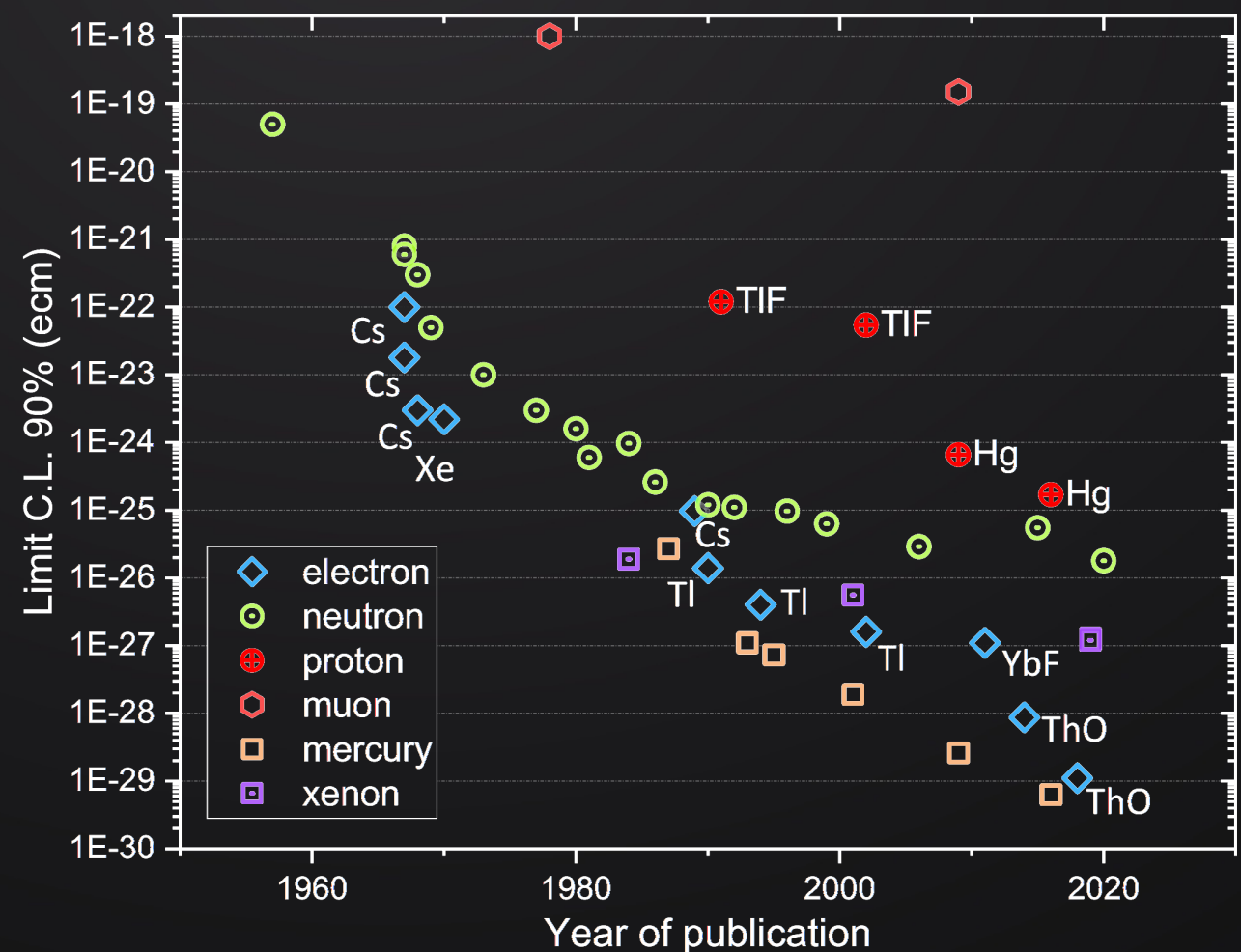
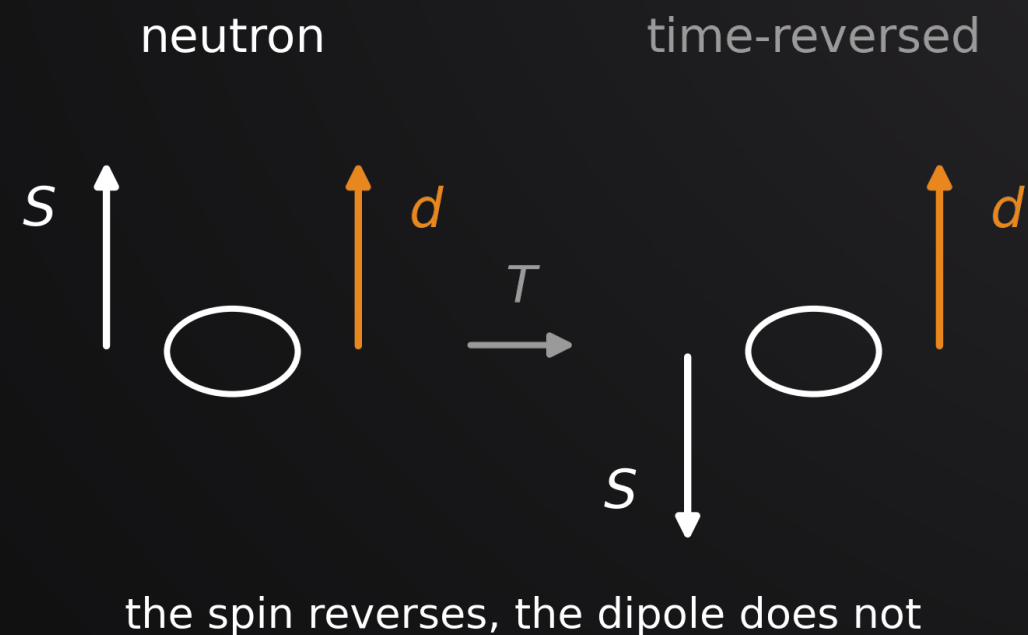


[arXiv:2203.01981](https://arxiv.org/abs/2203.01981)



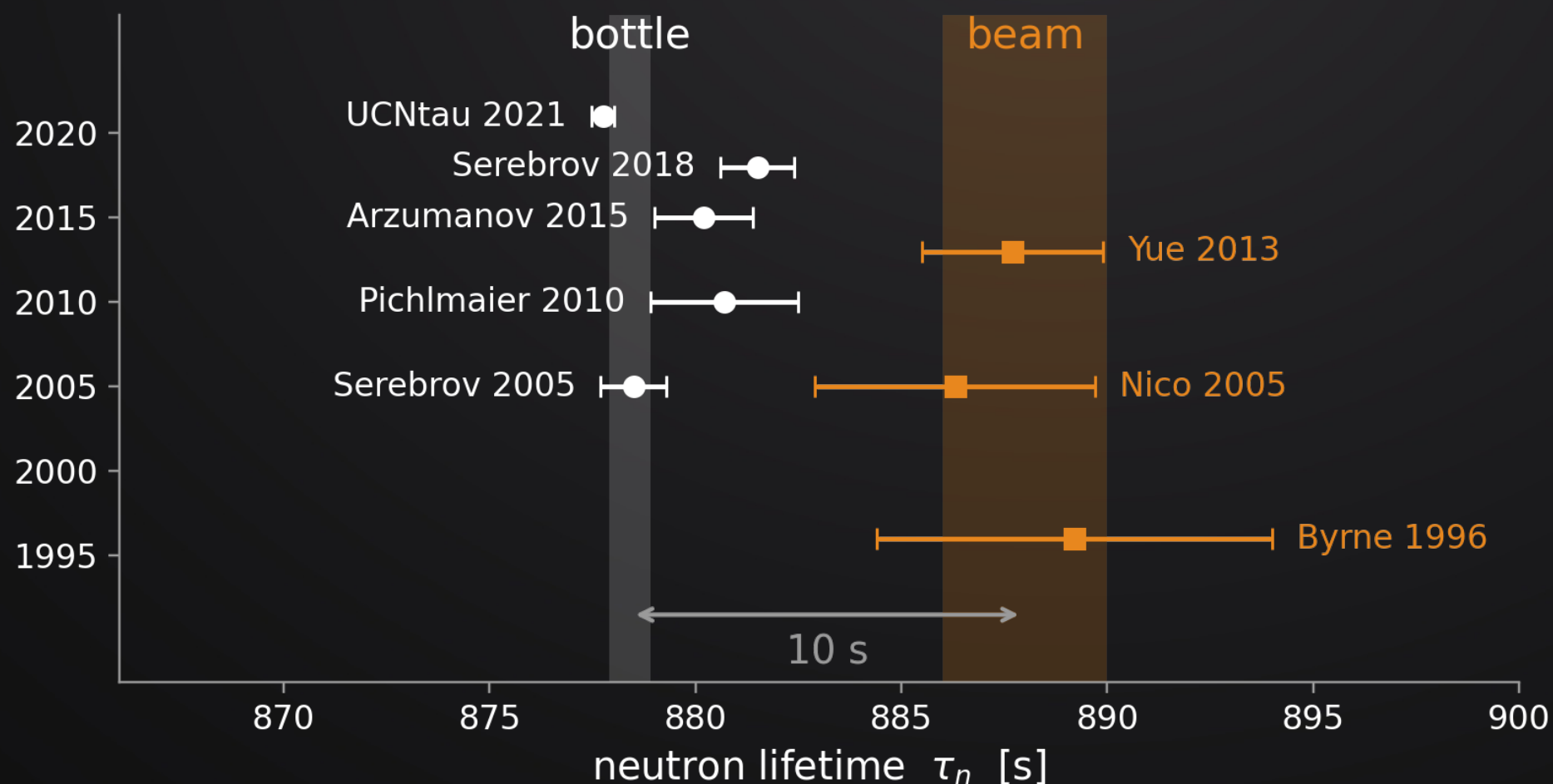
EDM: CP violation at rest

- An EDM must point along the spin: it violates T, so CP
- Neutrons, atoms, molecules: spin precession with E reversed
- nEDM at PSI: $|d_n| < 1.8 \times 10^{-26}$ e·cm, against the SM at 10^{-32} e·cm
- Baryogenesis needs **new CP sources** — potential source



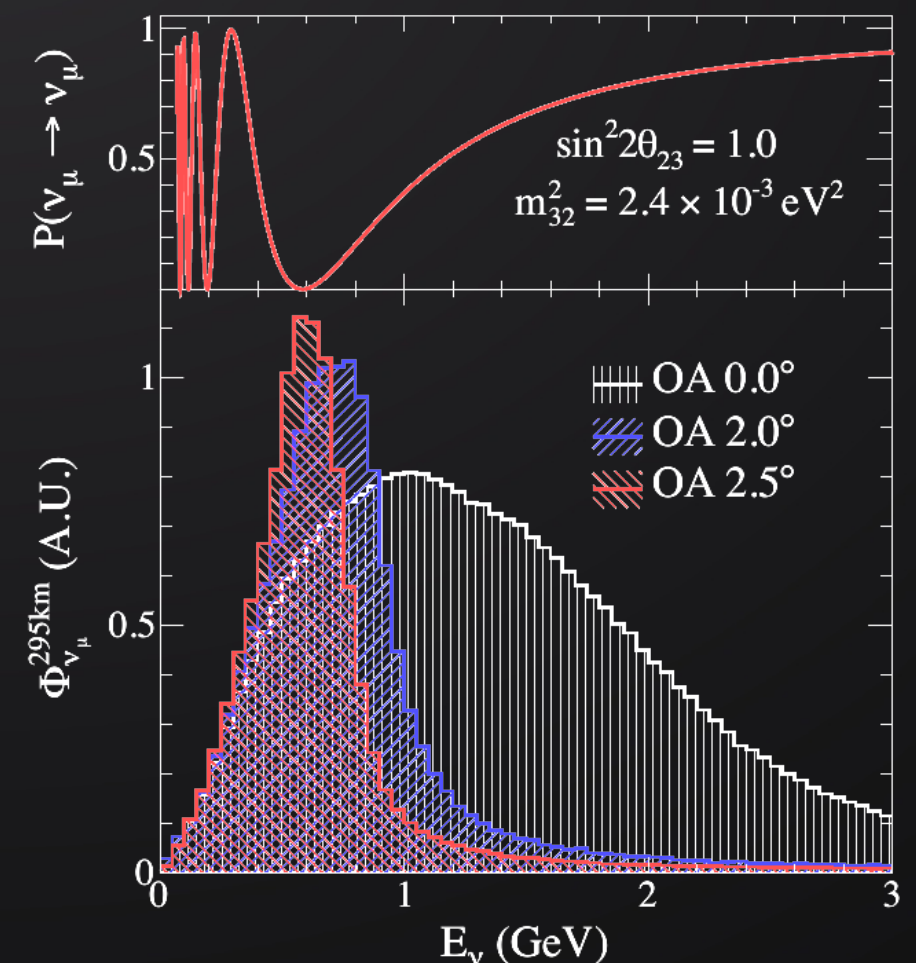
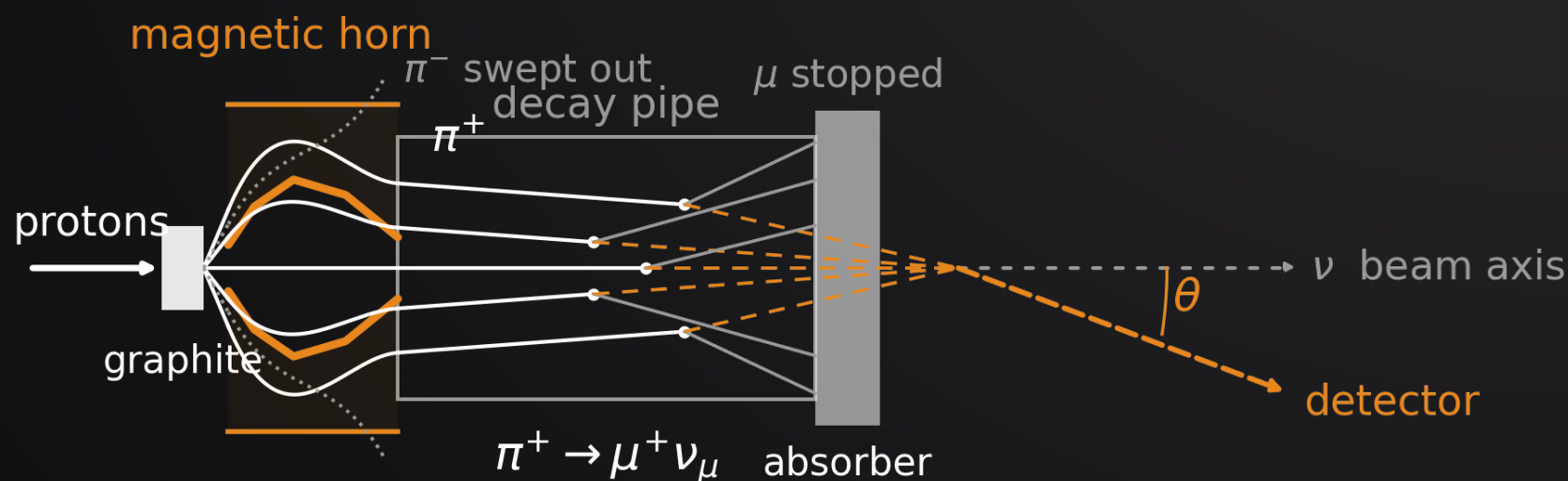
The neutron lifetime puzzle

- Bottle: store ultracold neutrons, count survivors - 877.8 s
- Beam: count the decay protons produced - 887.7 s
- **Ten seconds apart**, about 4σ : what vanishes vs what appears
- τ_n sets the primordial He abundance and gives V_{ud}
- An invisible 1% decay channel would split them this way



Making a neutrino beam

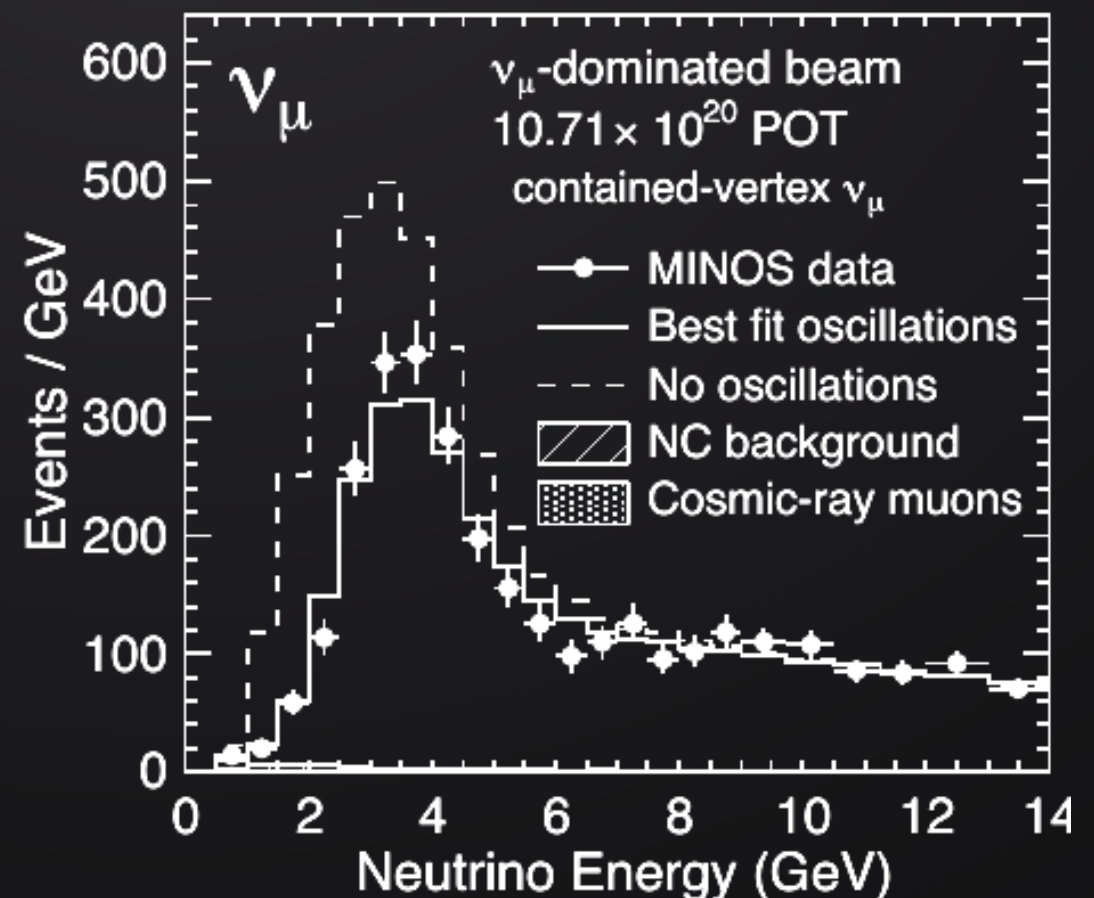
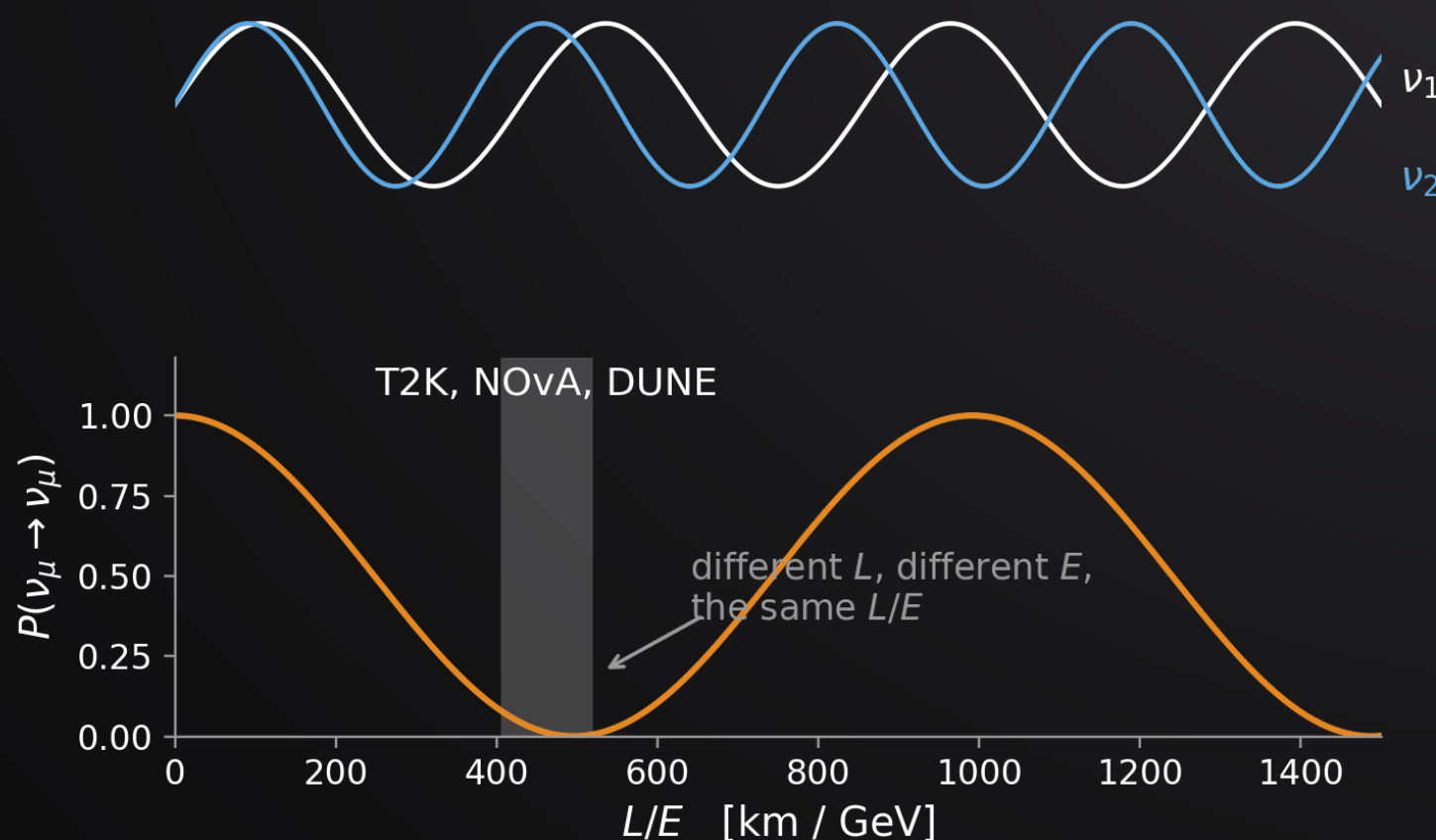
- Protons on graphite; a magnetic horn focuses one charge
- $\pi^+ \rightarrow \mu^+ \nu_\mu$ in a long decay pipe; an absorber takes the rest
- Reverse the horn current and the ν beam becomes $\bar{\nu}$
- $E_\nu = 0.43 \cdot E_\pi / (1 + \gamma^2 \theta^2)$: off axis, **the spectrum narrows**
- T2K sits 2.5° off axis (0.6 GeV), NOvA 0.8° (2 GeV)



Oscillation as interference

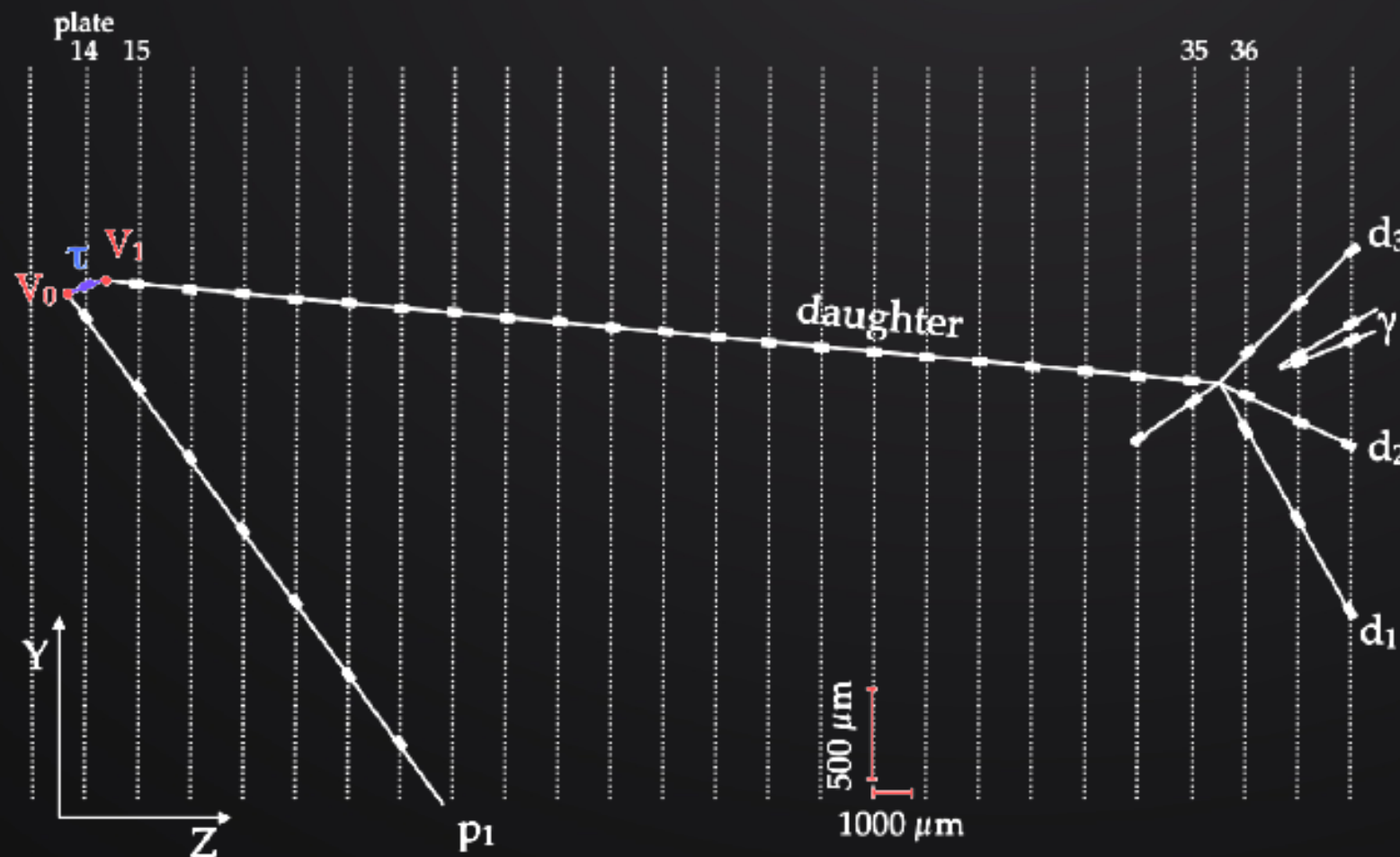
- Flavour states are superpositions of mass states (PMNS)
- $P \propto \sin^2 2\theta \cdot \sin(\Delta m^2 L/4E)$: mixing sets the amplitude
- Δm_{32}^2 is given; the experiment chooses $L/E \approx 500 \text{ km/GeV}$
- K2K (2003): atmospheric disappearance reproduced with **a made beam**
- T2K (2011): ν_e appearance opened the last angle, θ_{13}

different masses, different phases



The tau neutrino

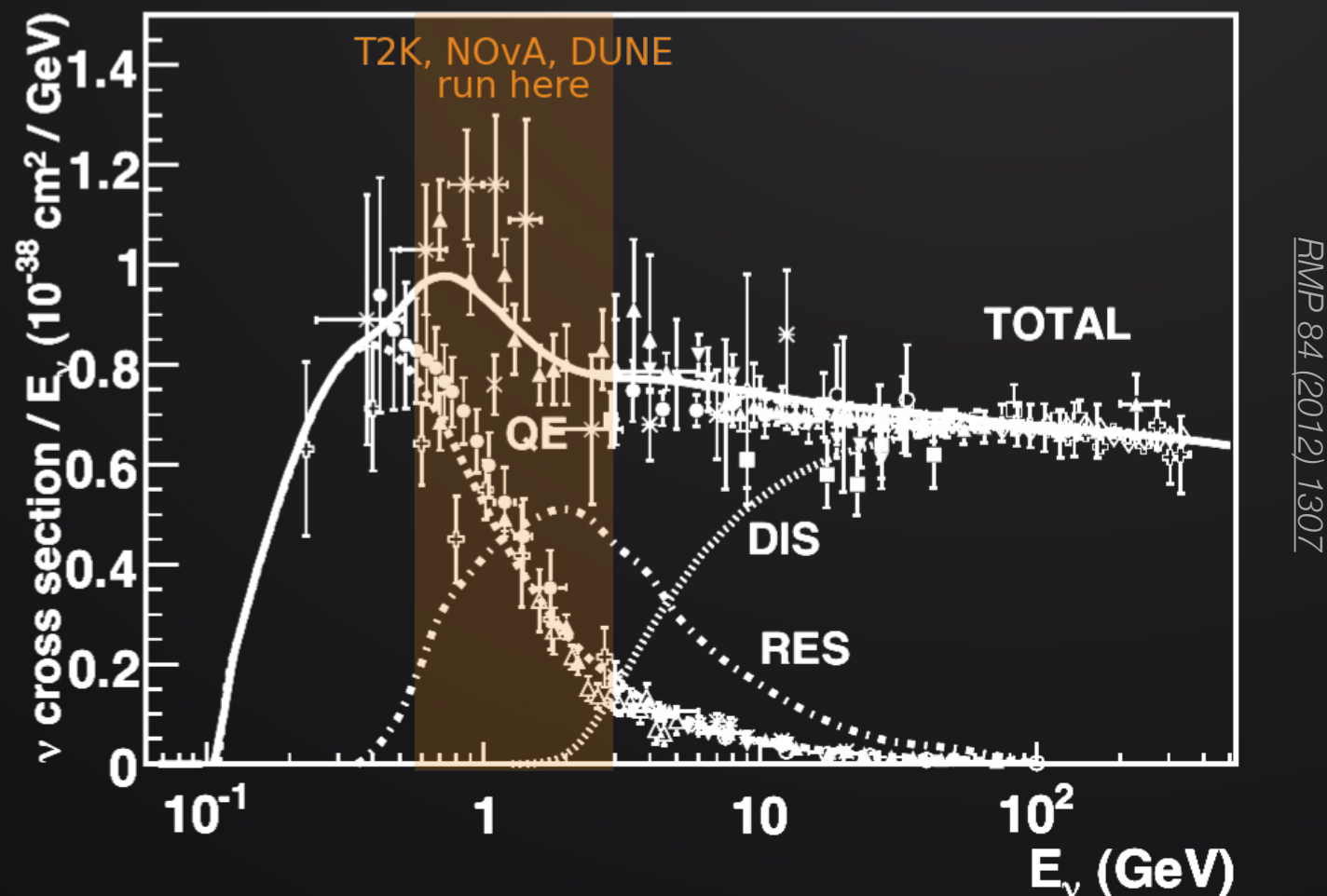
- DONUT: 800 GeV protons on a tungsten dump: $D_s \rightarrow \tau \nu_\tau$
- **Emulsion sees the signature:** a 1 mm track ending in a kink
- Four events (2000): the last SM fermion observed directly
- OPERA: a ν_μ beam 730 km from CERN to Gran Sasso



PRL 115 (2015) 121802

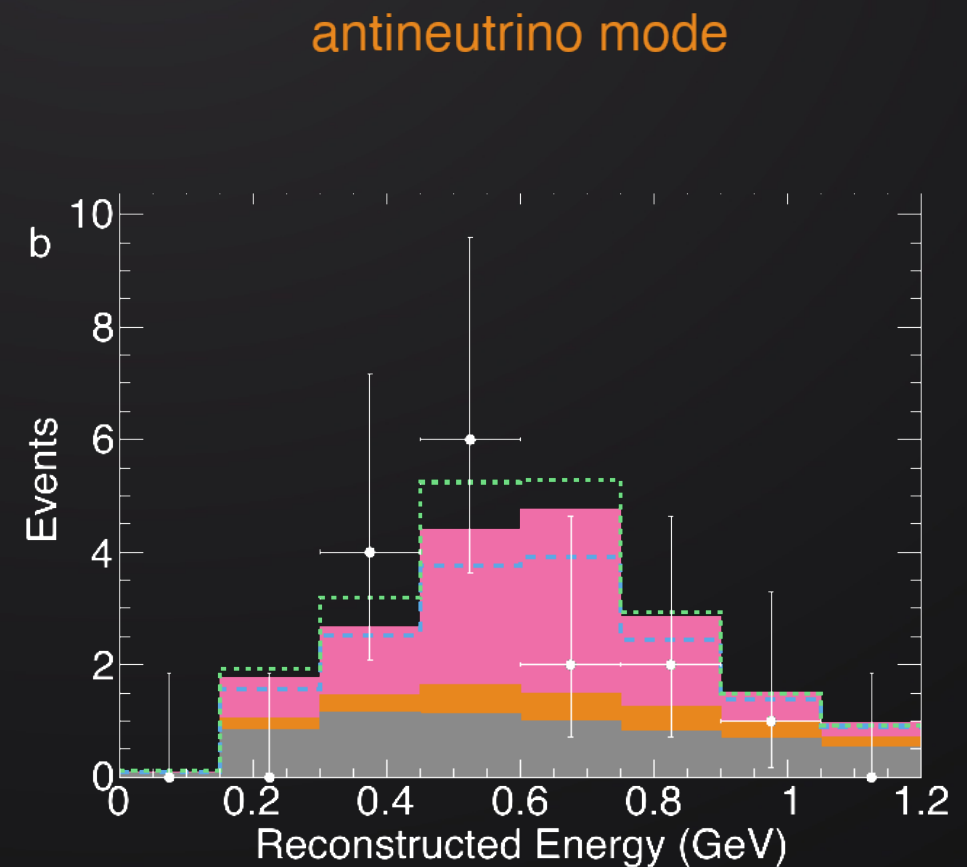
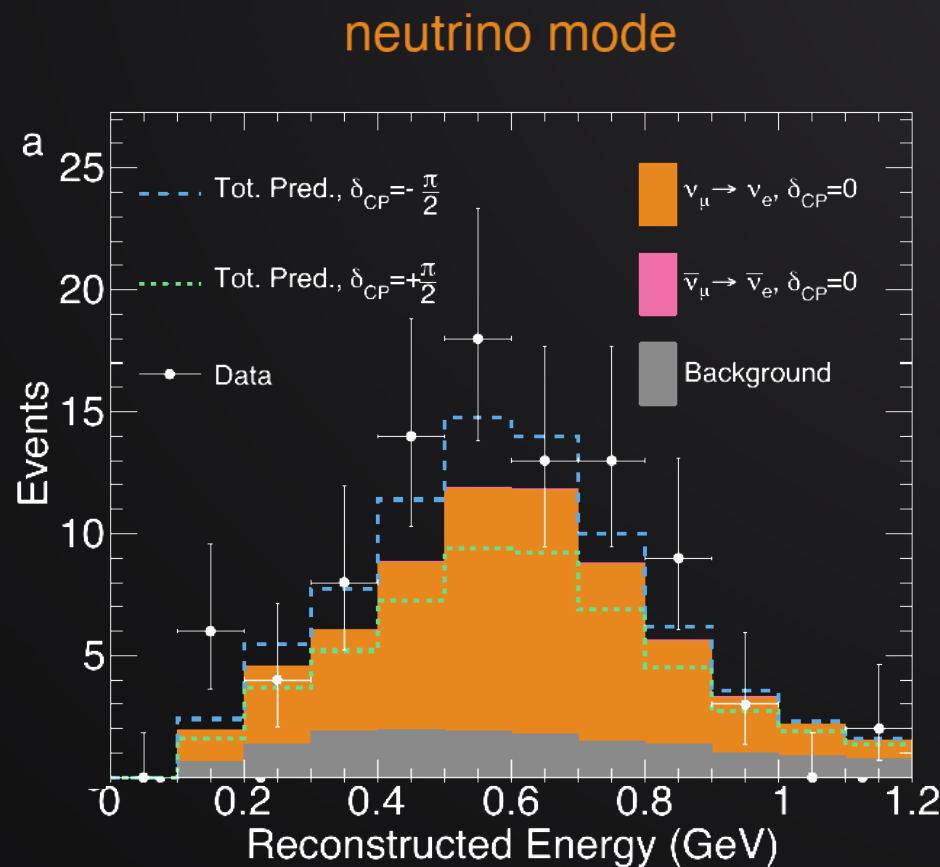
The systematics wall

- The far detector measures a rate; a probability needs $\sigma(\nu + A)$
- No event-by-event energy tag: E_ν comes from the final state
- Quasi-elastic, two-nucleon, resonance, final-state effects
- Known to 5-20%; the CP programme **needs a few percent**
- MINERvA: He, C, H₂O, Fe, Pb in one flux - the EMC effect again



CP violation, again

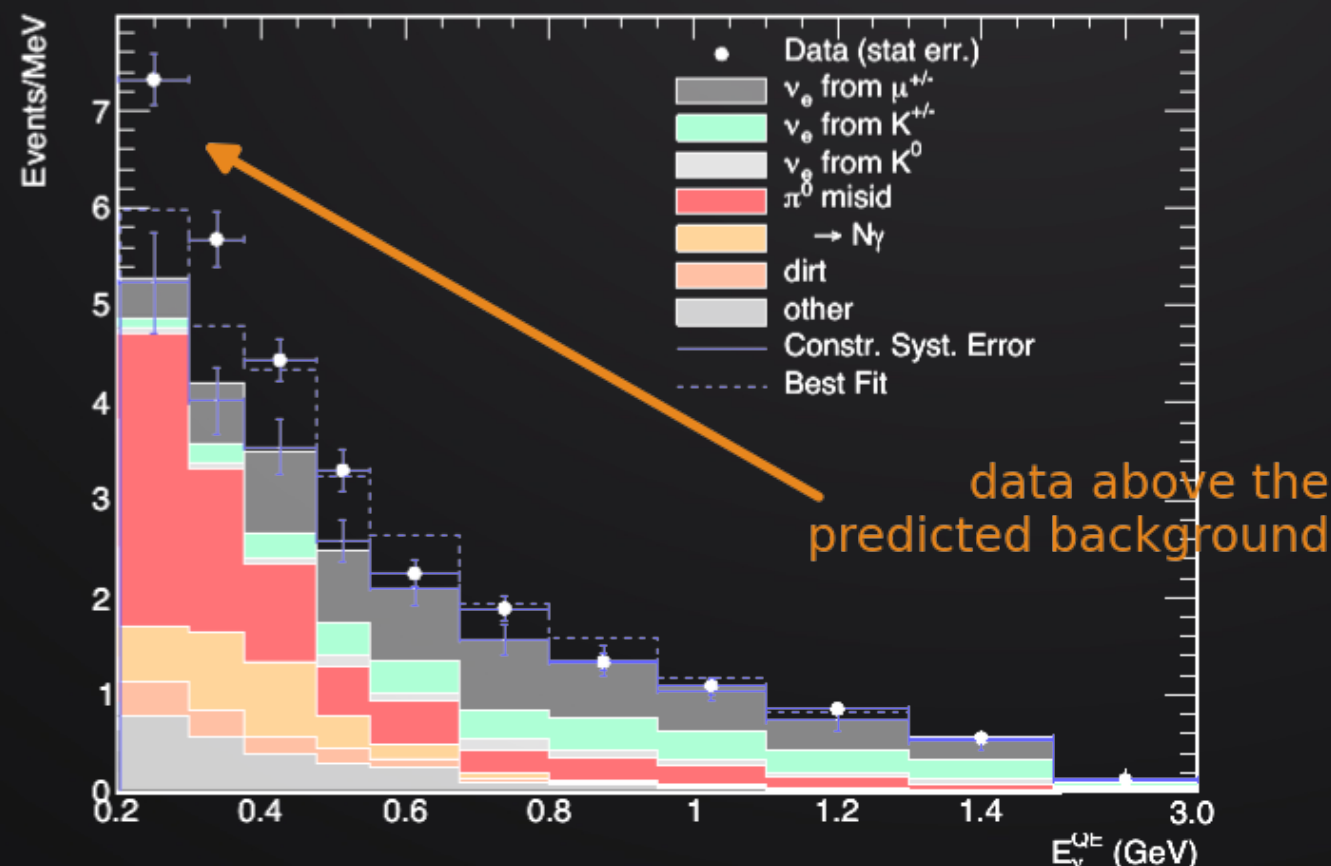
- PMNS has one irreducible phase δ_{CP} , exactly as CKM does
- Measure $\nu_\mu \rightarrow \nu_e$, **flip the horn**, measure $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Matter fakes an asymmetry: the Earth has electrons only
- T2K disfavours CP conservation at 2σ ; NOvA does not agree
- DUNE (1300 km, 40 kt argon) and Hyper-K are built for it



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The short-baseline puzzle

- LSND: a $\bar{\nu}_e$ excess at 30 m - it needs $\Delta m^2 \approx 1 \text{ eV}^2$ sterile
- MiniBooNE: same L/E, another beam, 4.8σ electron-like
- A Cherenkov ring cannot separate e from a converted γ
- MicroBooNE (argon, 2021): **no simple electron-like excess**
- SBN: SBND at 110 m, ICARUS at 600 m - oscillation grows with L



PRD 103 (2021) 052002

The portals

- All dark-matter evidence is gravitational: **mass unconstrained**
- Light and feebly coupled: intensity helps, energy does not
- Vector: $\epsilon F'_{\mu\nu} F_{\mu\nu}$ - a dark photon coupling as ϵe
- Scalar: $S |H|^2$. Fermion: (LH)N - heavy neutral leptons
- Pseudoscalar: $a F \tilde{F} / f_a$ - axions and axion-like particles

Standard Model

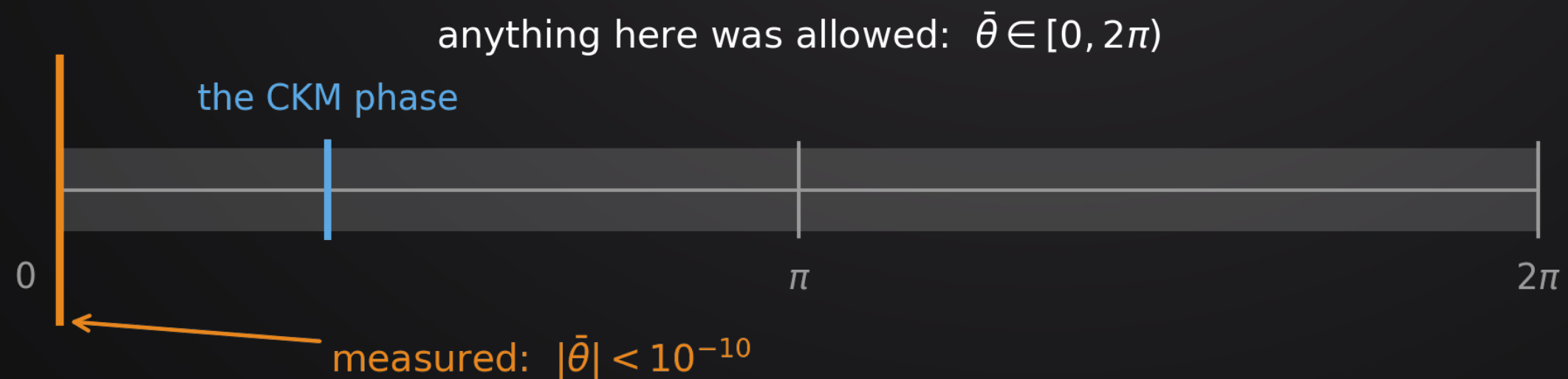
hidden sector



operators of dimension 4 or less are renormalisable; the axion coupling is suppressed by f_a

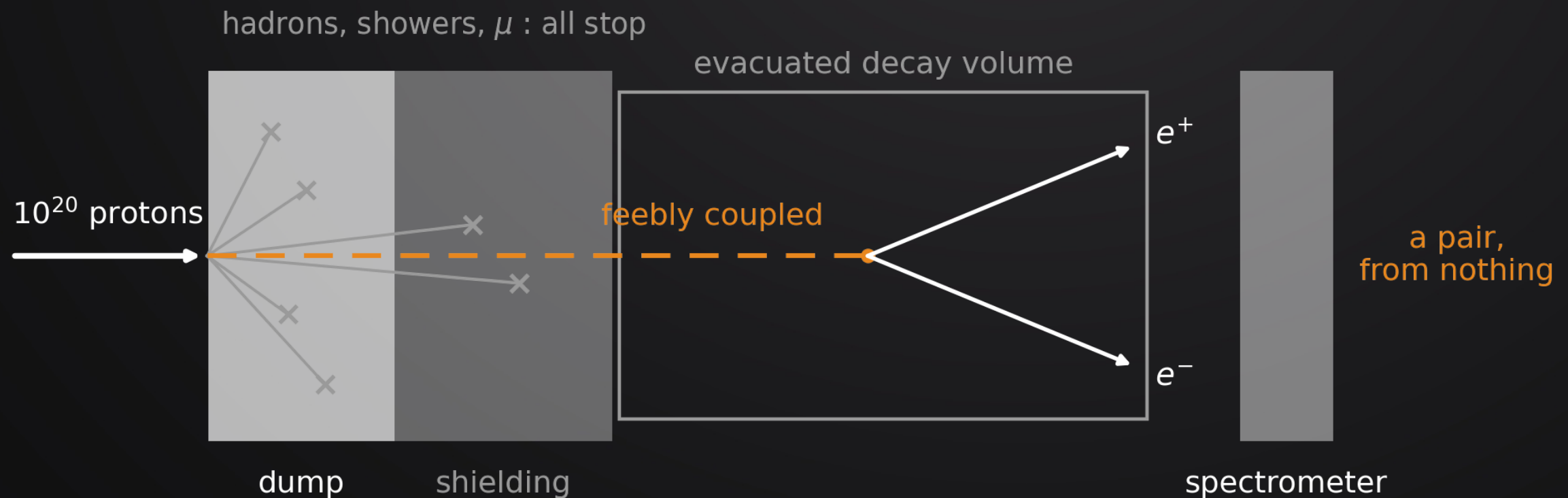
The strong CP problem

- QCD allows a CP-violating gluon term, $\bar{\theta}G\tilde{G}$
- Its clean signature: a neutron electric dipole
- Not seen: $\bar{\theta} < 10^{-10}$, while the CKM phase is $\approx 65^\circ$
- Peccei-Quinn: turn $\bar{\theta}$ into a field that relaxes to zero (non-perturbative)
- That field is the **axion**: μeV - meV , or heavier at beam dumps



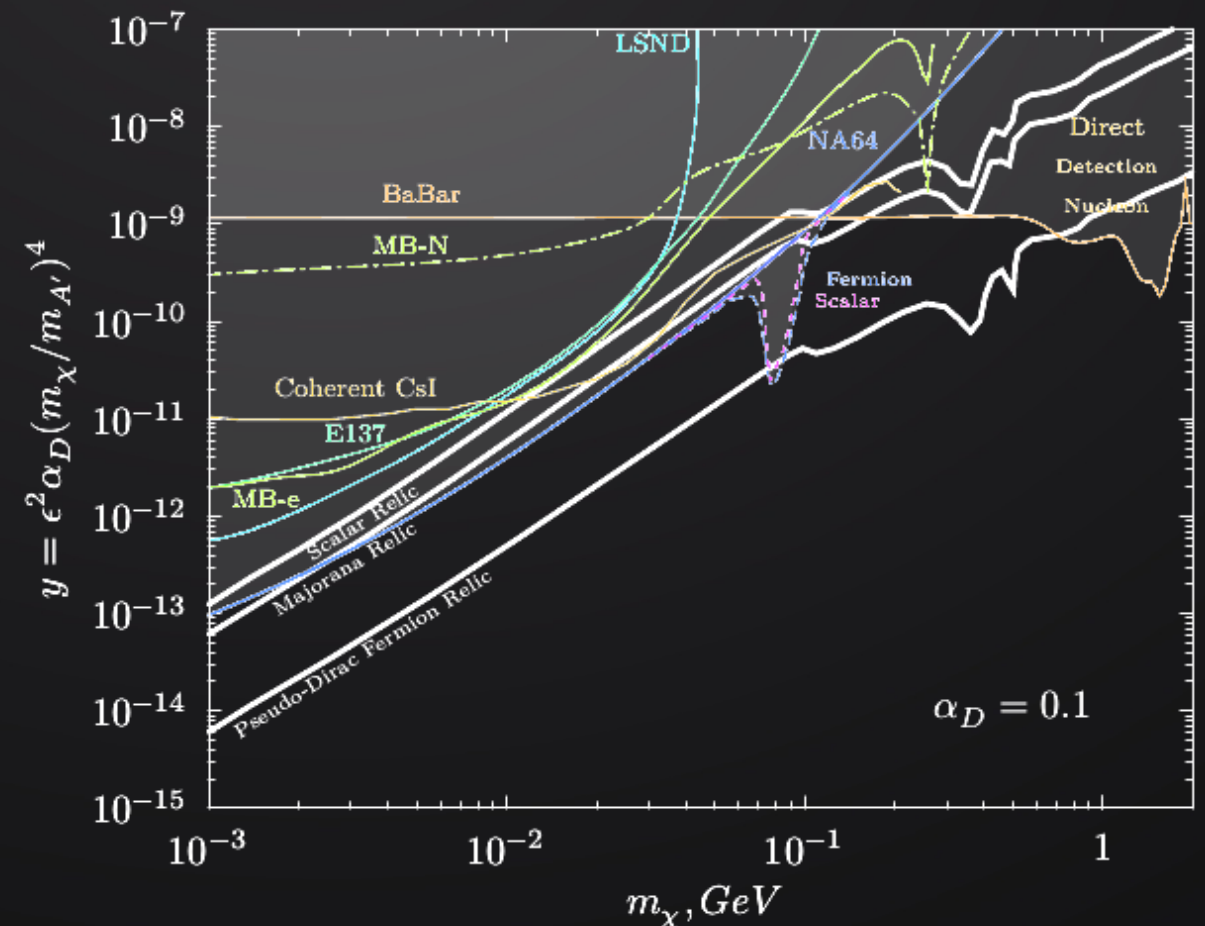
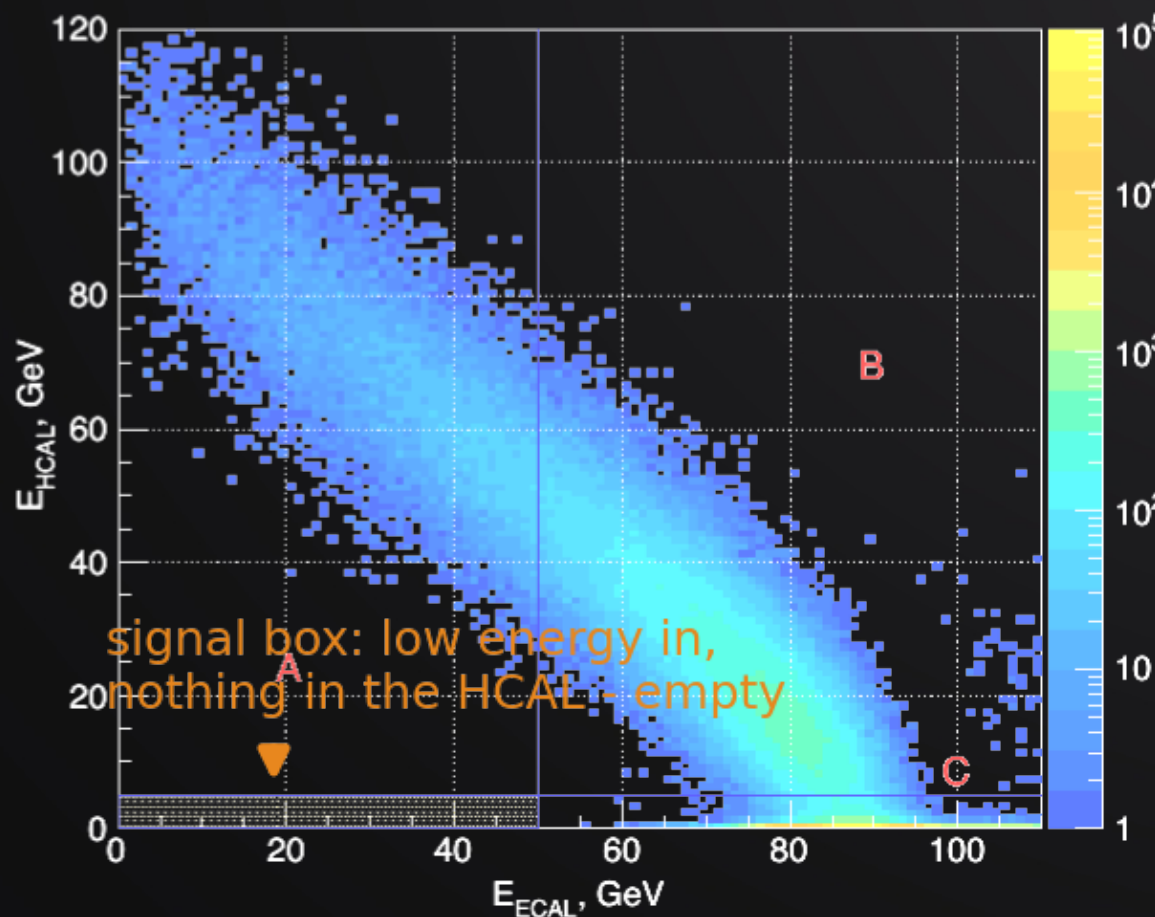
Beam dumps

- 10^{20} particles into metres of metal: **everything SM stops**
- Only neutrinos pass - and anything coupled feebly enough
- Behind it: vacuum, then a spectrometer. A pair from nothing
- The boost sets the geometry: $\gamma c\tau$ of tens of metres
- E137, CHARM, NuCal: 1980s data still set limits today



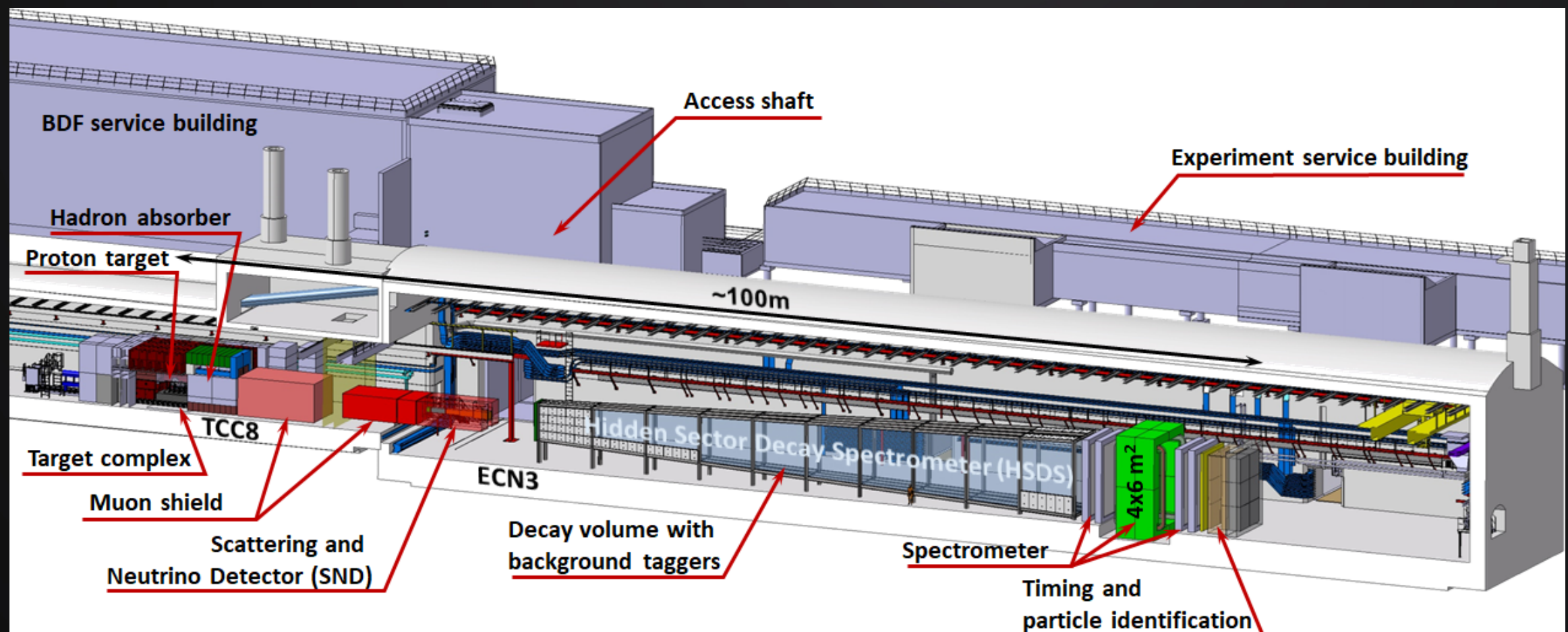
Missing energy

- NA64: 100 GeV electrons counted singly into an active dump
- Signal: full beam energy in, **little out**, no downstream deposit
- Hermetic to 10^{-12} per electron; synchrotron tagging of each e^-
- $A' \rightarrow \chi\bar{\chi}$ gives a relativistic χ beam and better detection
- The relic abundance fixes a target line in y versus m_χ



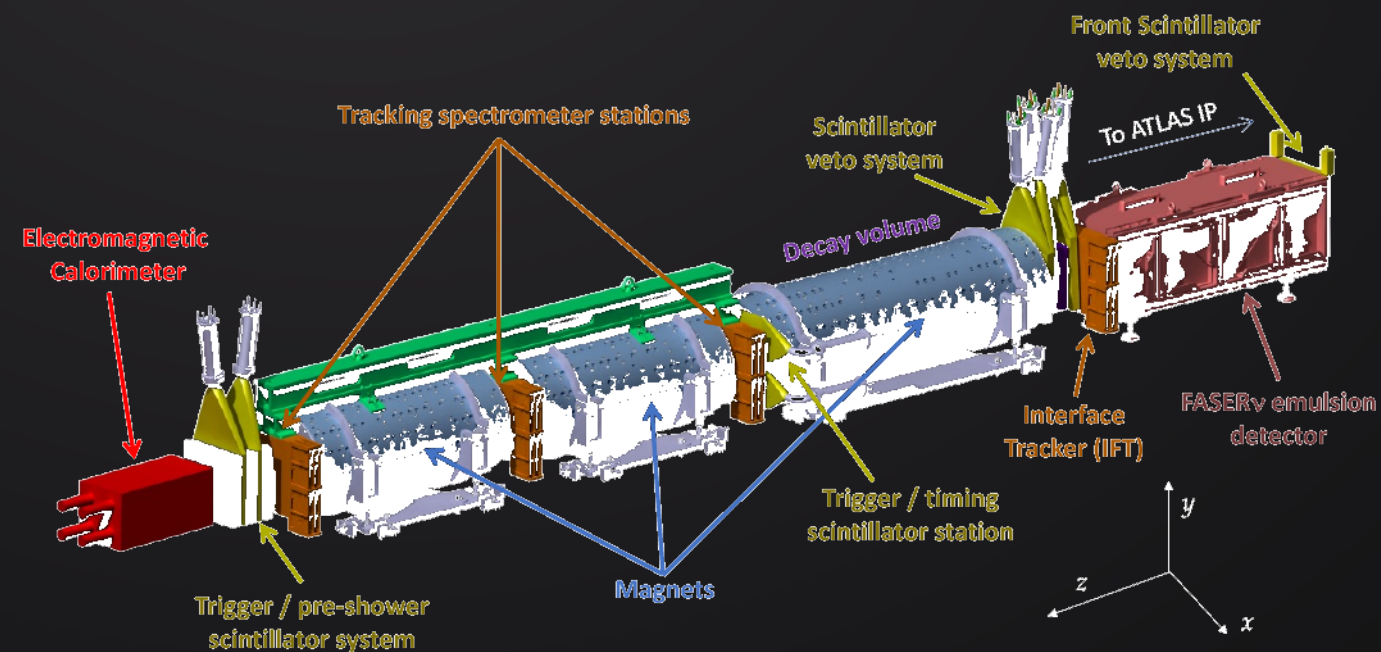
SHiP

- Approved 2024 at the SPS Beam Dump Facility; data from ≈ 2031
- 4×10^{19} protons; the **target reabsorbs** π and K before decay
- 10^{11} muons/s swept aside by a 35 m active magnetic shield
- ~ 50 m of He, then a spectrometer: a vertex from nothing
- Bonus: its neutrino detector collects ν_τ ; the world has nine



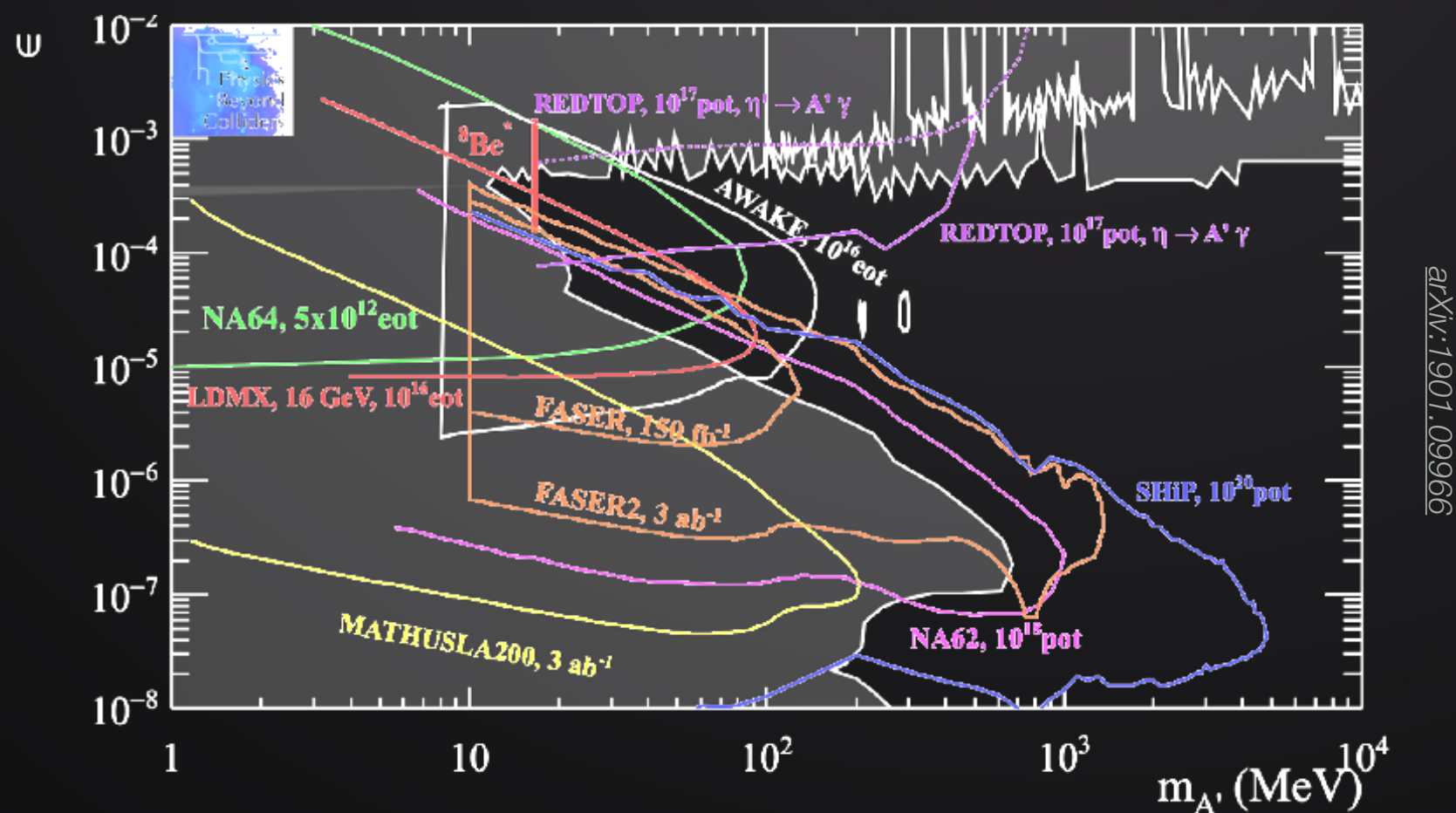
The LHC as a beam dump

- The forward cone ATLAS ignores carries an enormous flux
- 480 m downstream in T112, behind 100 m of untouched rock
- 2023: the first neutrinos ever **detected at a collider**
- FASERv measured ν_e and ν_μ cross sections at TeV energies
- The same design catches long-lived particles decaying



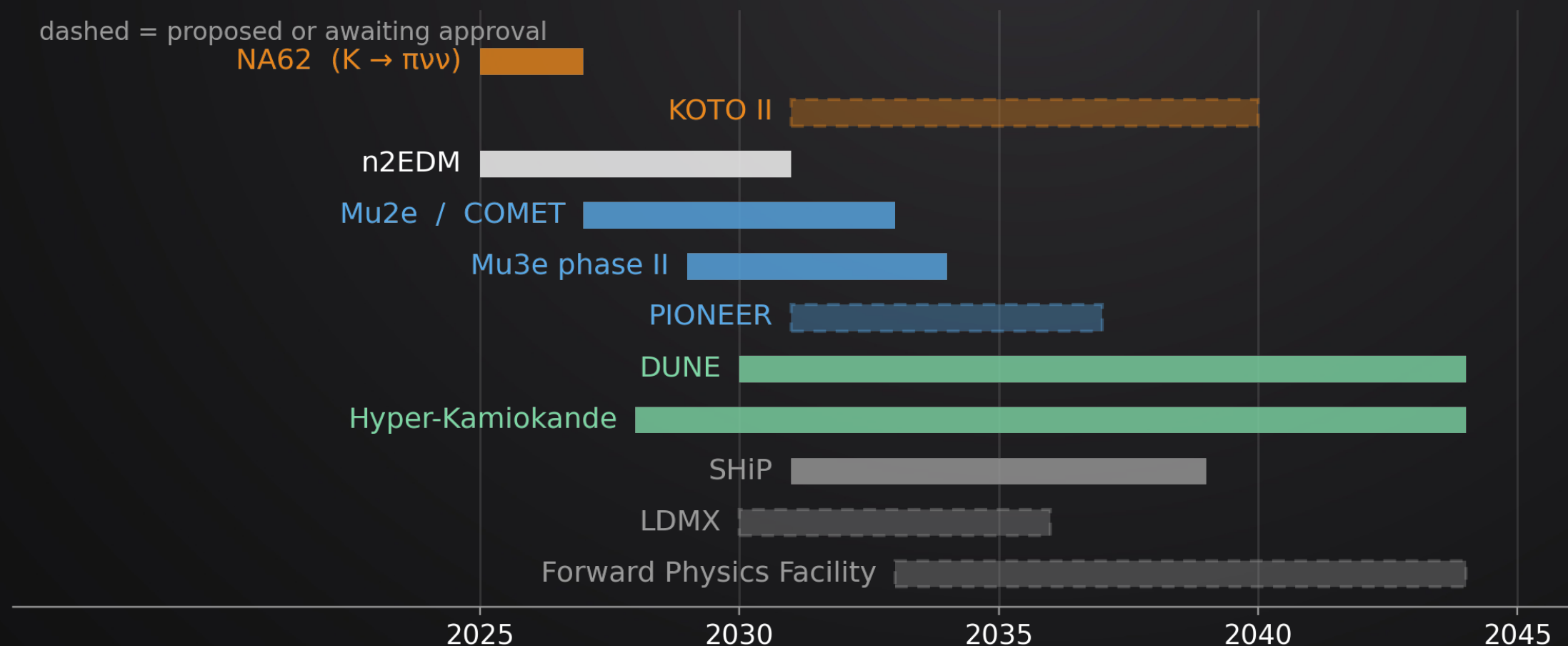
One shared map

- Dark-photon plane: kinetic mixing ϵ against mass $m_{A'}$
- Small ϵ gives a long lifetime, reached only by beam dumps
- Large ϵ gives prompt decay: spectrometers and colliders
- Rare meson decays and $g-2$ exclude further regions
- Unprobed: $\epsilon \approx 10^{-5}-10^{-7}$ at MeV-GeV, targeted by SHiP and LDMX



The roadmap

- Late 2020s: NA62 final data, Mu2e and COMET, n2EDM, KOTO II
- 2030s: SHiP, DUNE and Hyper-K, Mu3e II, PIONEER, LDMX
- Solid: approved or under construction. Dashed: proposed



Not the End

- Rare processes rewrote the theory: CP 1964, charm 1970
- Direct reach ends near $\sqrt{s}/2$; loops reach 10^2 - 10^5 TeV
- To watch out: NA62, KOTO II, Mu2e, n2EDM, DUNE, Hyper-K, SHiP
- Tested here: CP, flavour, lepton number, hidden sectors

