Rare processes

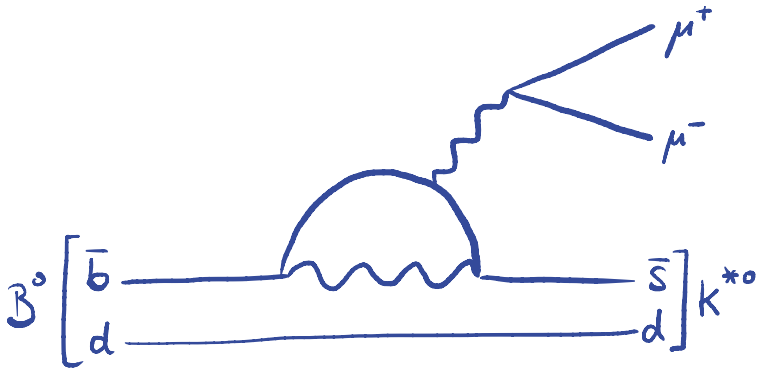
Time evolution of neutral mesons
CP violation
Constraining the CKM triangle: the angle γ

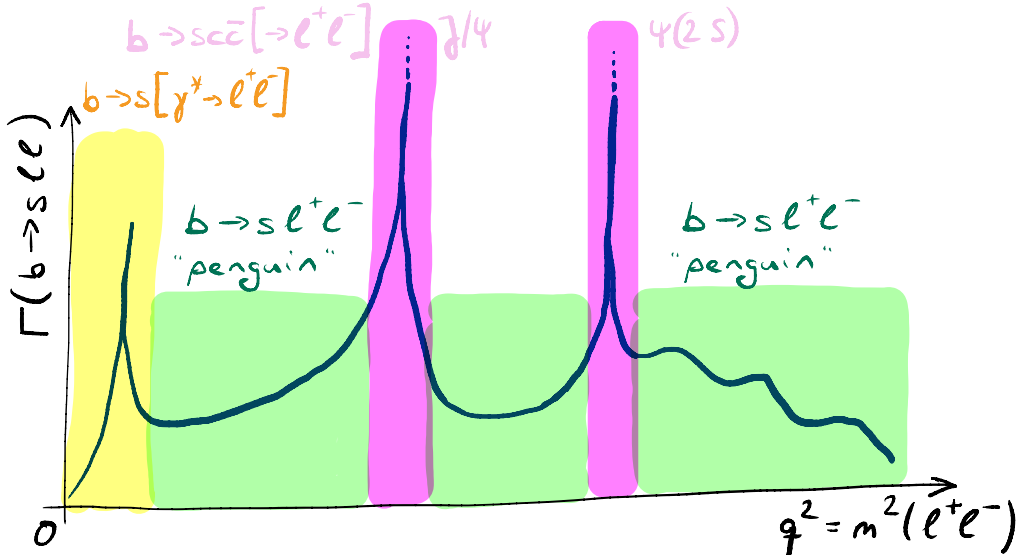
What's rare?

- Allowed but suppressed in SM
  - Typically not considered rare:
    - Colour suppression
    - Cabibbo-suppression
  - Most common rare processes:
    - Flavour-changing neutral currents (FCNC)
- Technically allowed, but suppressed to unmeasurable levels
  - Lepton-flavour violating processes (allowed via neutrino oscillations)
  - Discovery is unabiguous sign of physics beyond the SM
- Forbidden processes
  - Lepton number violation (may have contribution via Majorana neutrinos)
  - Baryon number violation

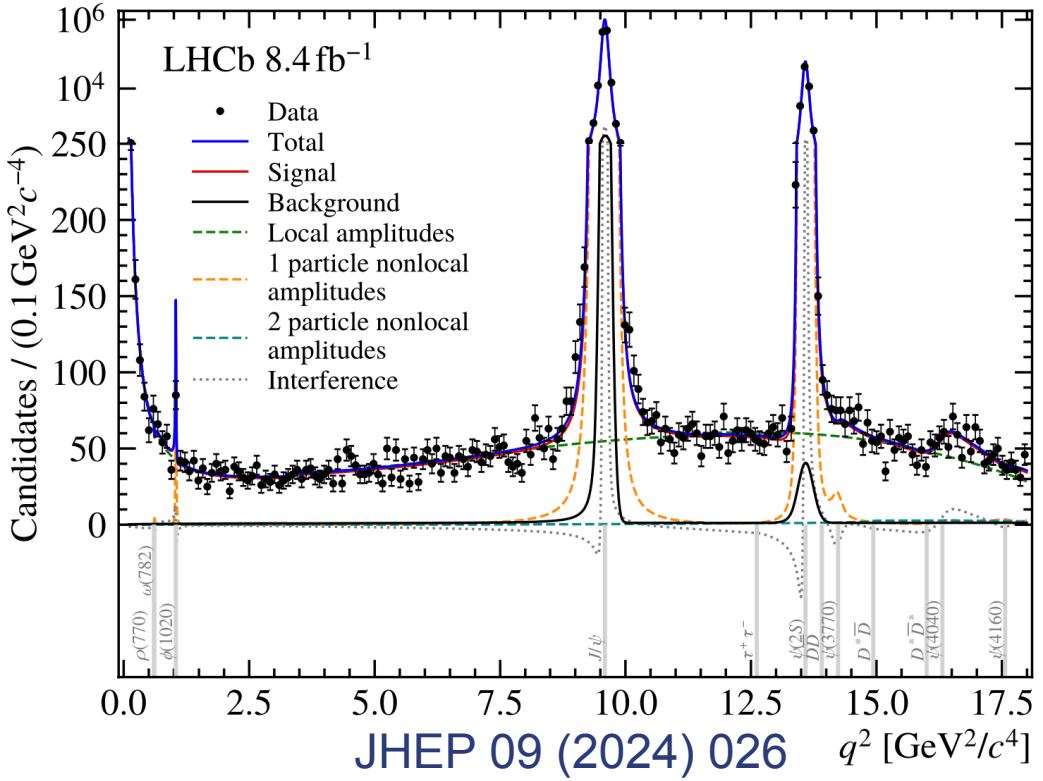

Source: WikiCommons

B→K*μμ





- Flavour-changing neutral current decay
- Not so rare: BF ~10^{-6}
- Recent LHCb analysis is first comprehensive model-based analysis of the full decay amplitude, including
  - Local amplitudes:
    direct decay into $\mu^+\mu^-$ final state
  - 1-particle non-local amplitudes:
    $\mu^+\mu^-$ produced through resonances, e.g. ϕ, J/ψ, ψ(2S)
  - 2-particle non-local amplitudes:
    $\mu^+\mu^-$ produced through rescattering from $D^{(*)}\bar{D}^{(*)}$ or $\tau^+\tau^-$
  - Interference of the above



JHEP 09 (2024) 026

B→K*μμ

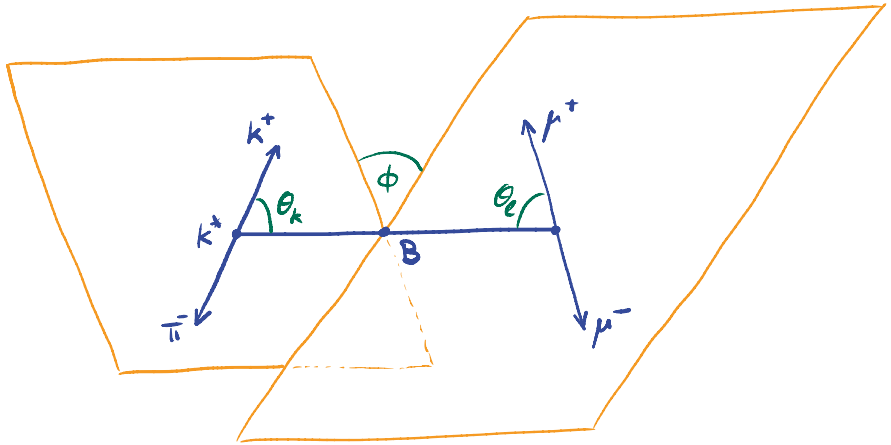
- Analysis involves decay plane angles defined by di-muon and di-hadron systems
  - Large set of angular observables incl. P'_5
- Use Weak Effective Theory:

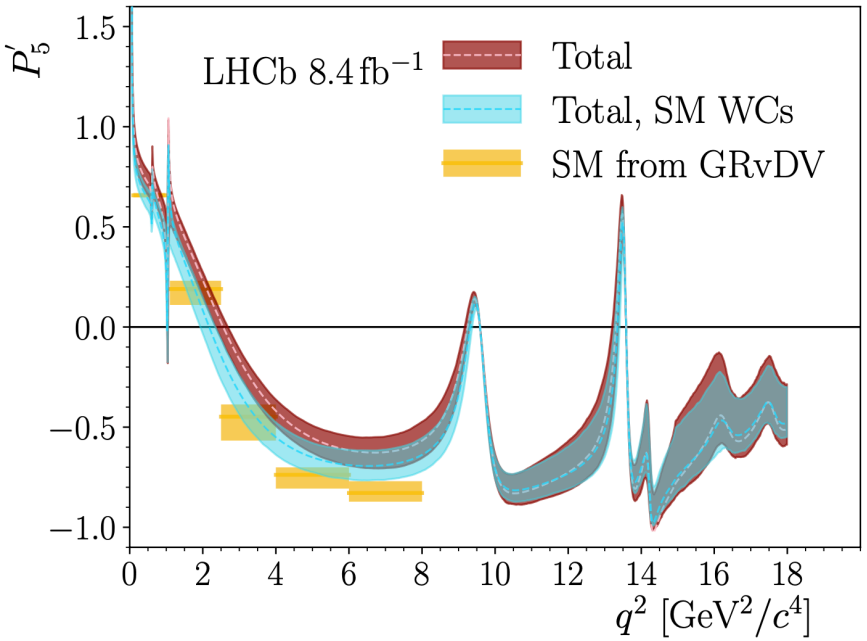
$$\mathcal{H}_{\rm WET} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \mathcal{C}_i^{(\prime)}(\mu)\mathcal{O}_i^{(\prime)}(\mu)$$

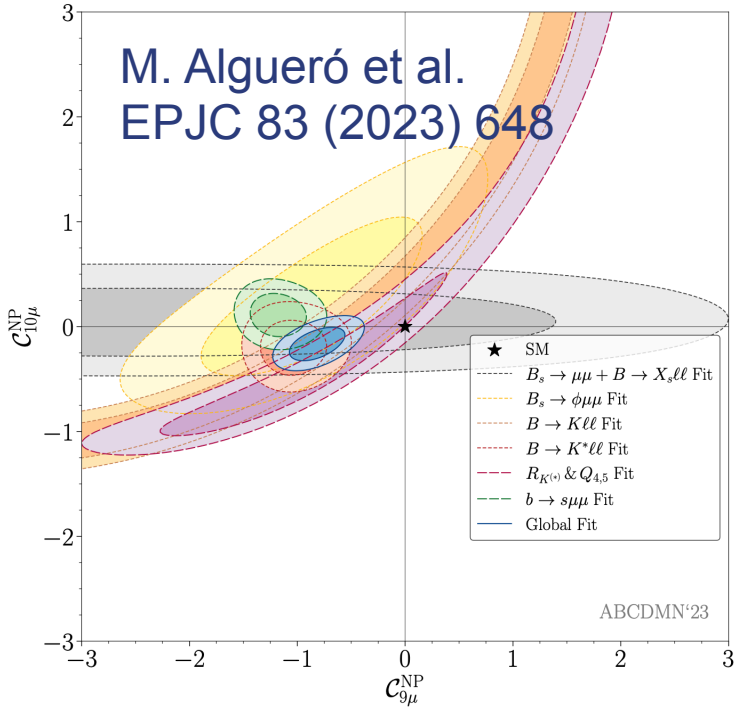
- $\mathcal{O}$perators relate to different types of local interactions
- Wilson $\mathcal{C}$oefficients describe their relative strength

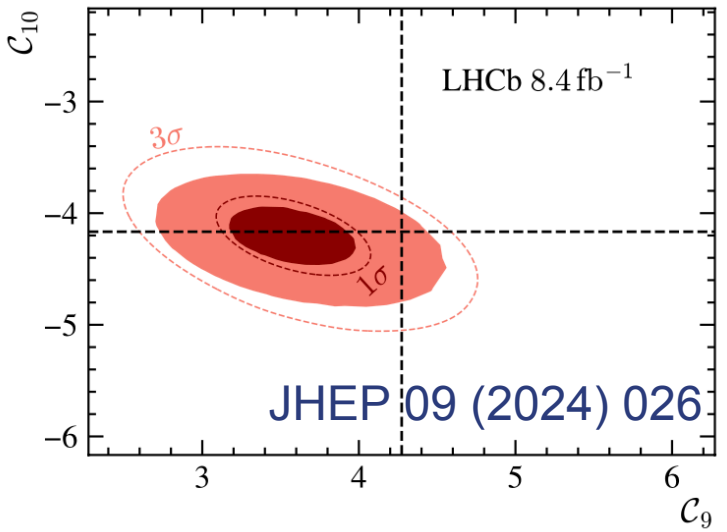
$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2}\,(\bar{s}_L\gamma_\mu b_L)\,\bar{\ell}\gamma^\mu\ell,$$

$$\mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2}\,(\bar{s}_L\gamma_\mu b_L)\,\bar{\ell}\gamma^\mu\gamma_5\ell$$





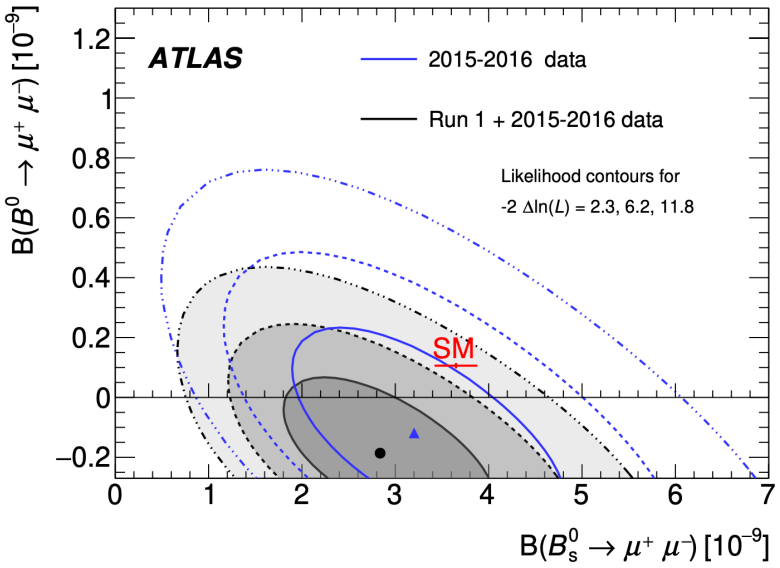




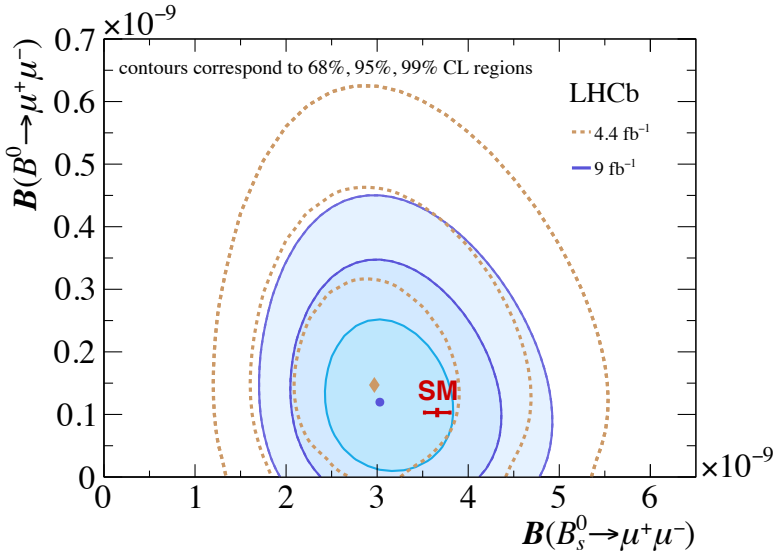
$B^0_{(s)} \to \mu^+\mu^-$

- Very rare decays broadly in agreement with SM, lowish values of B_d decays intriguing
- Effective lifetime measurements of additional interest; will become interesting with more data

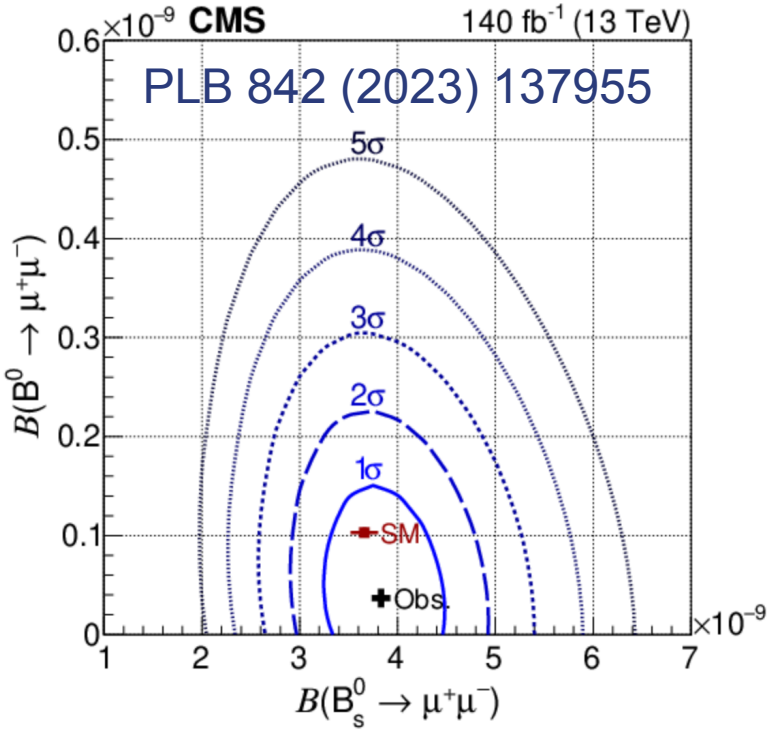
JHEP 04 (2019) 098



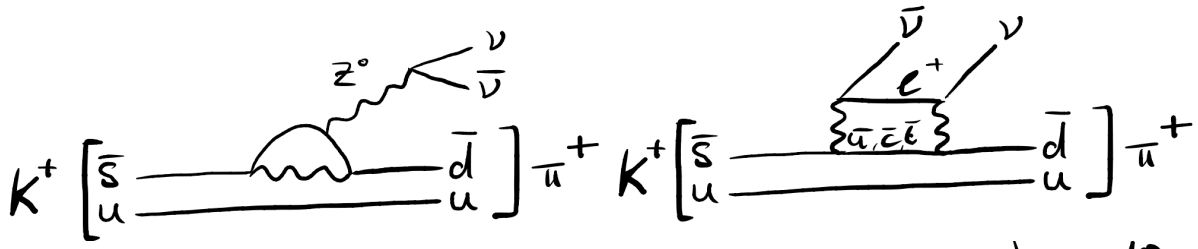
PRL 128 (2022) 041801



PLB 842 (2023) 137955

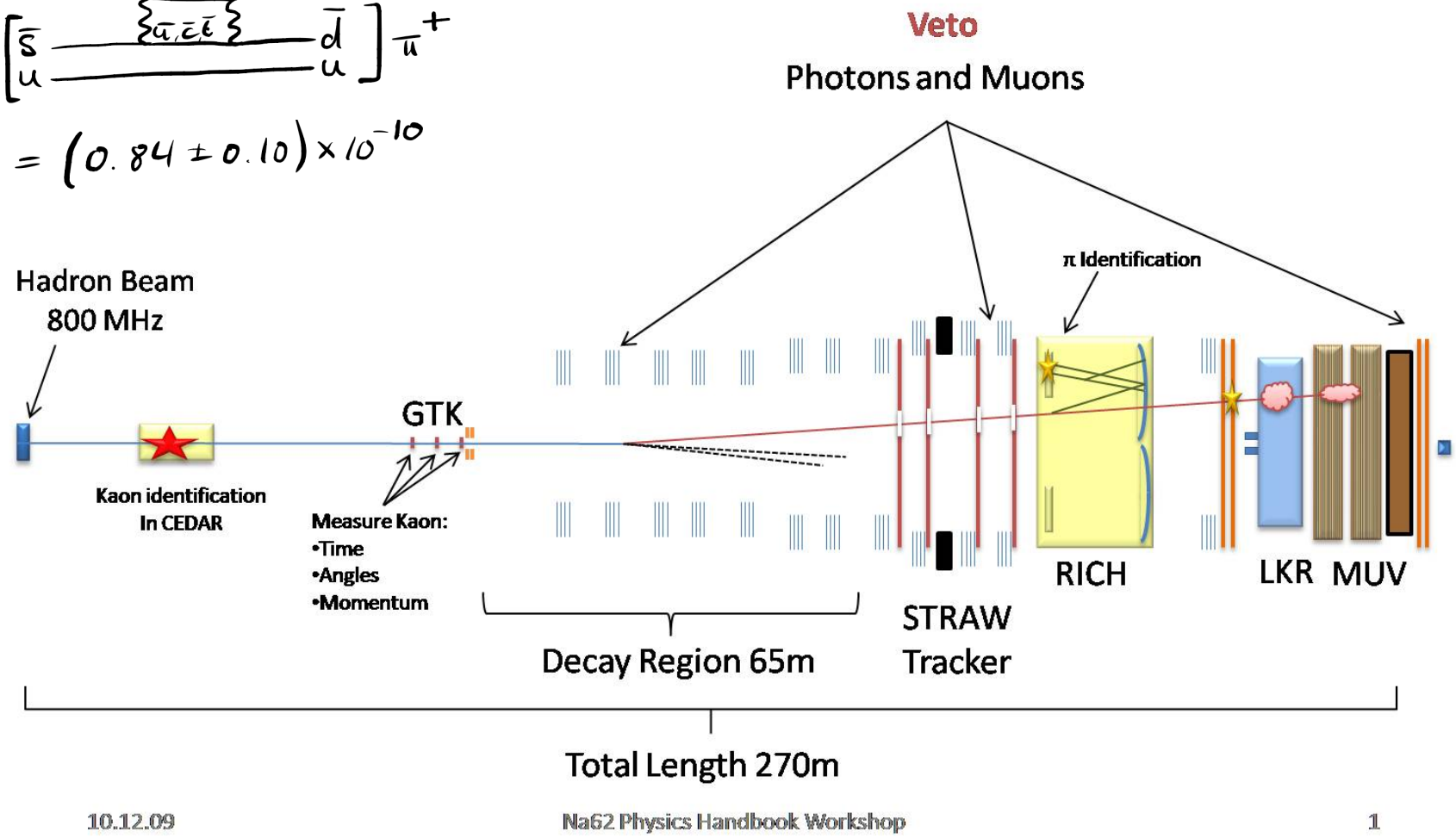


NA62: looking for almost nothing

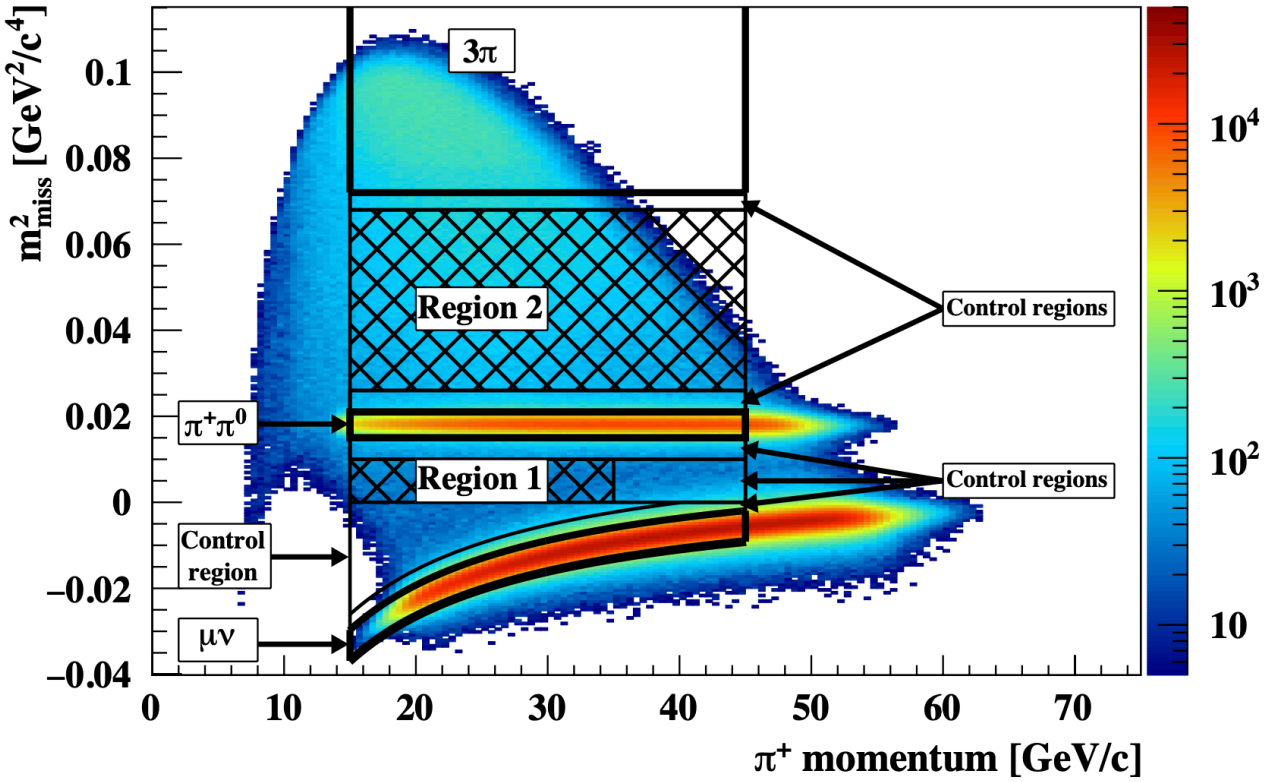


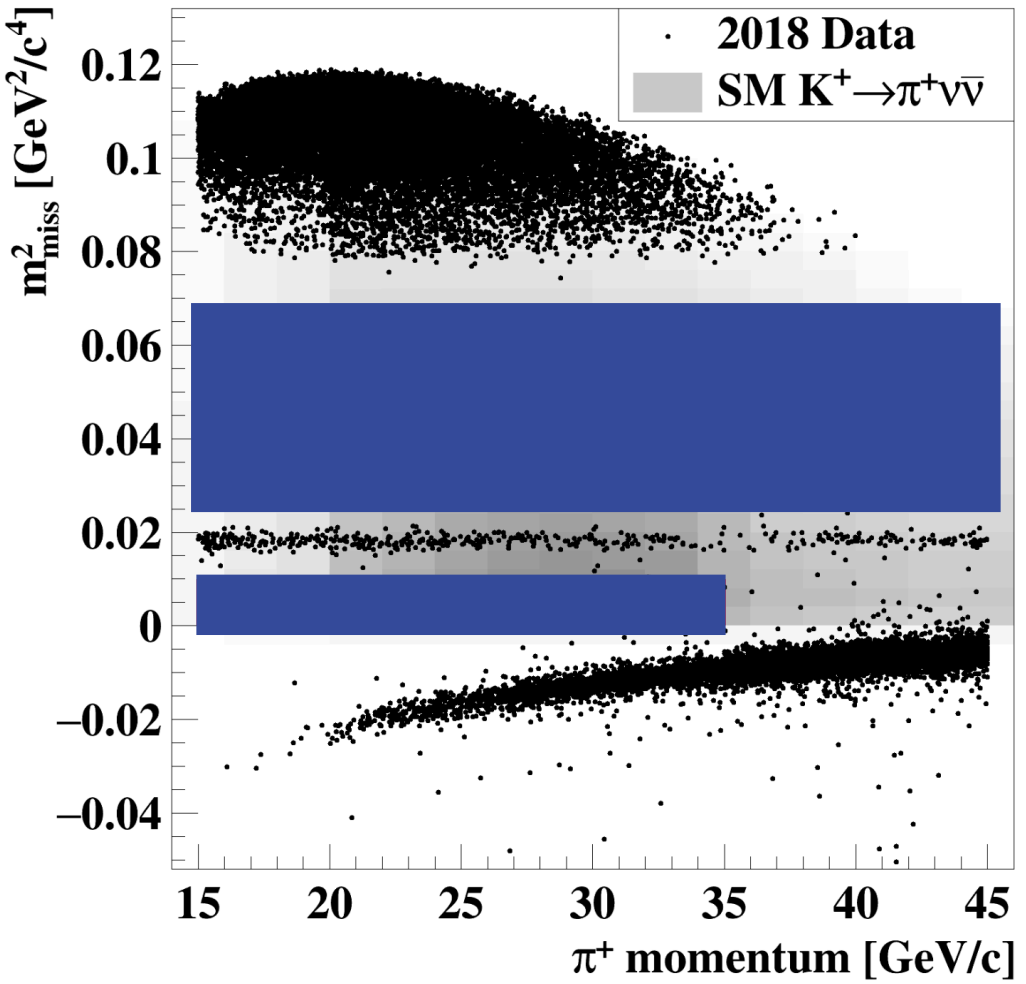
Buras et al., JHEP 11 (2015) 33

- Searching for $K^+ \to \pi^+ \nu\bar{\nu}$
- Only one detectable final-state particle
  - Need to measure K^+ momentum
- Requires hermetic veto coverage to suppress background from other decays



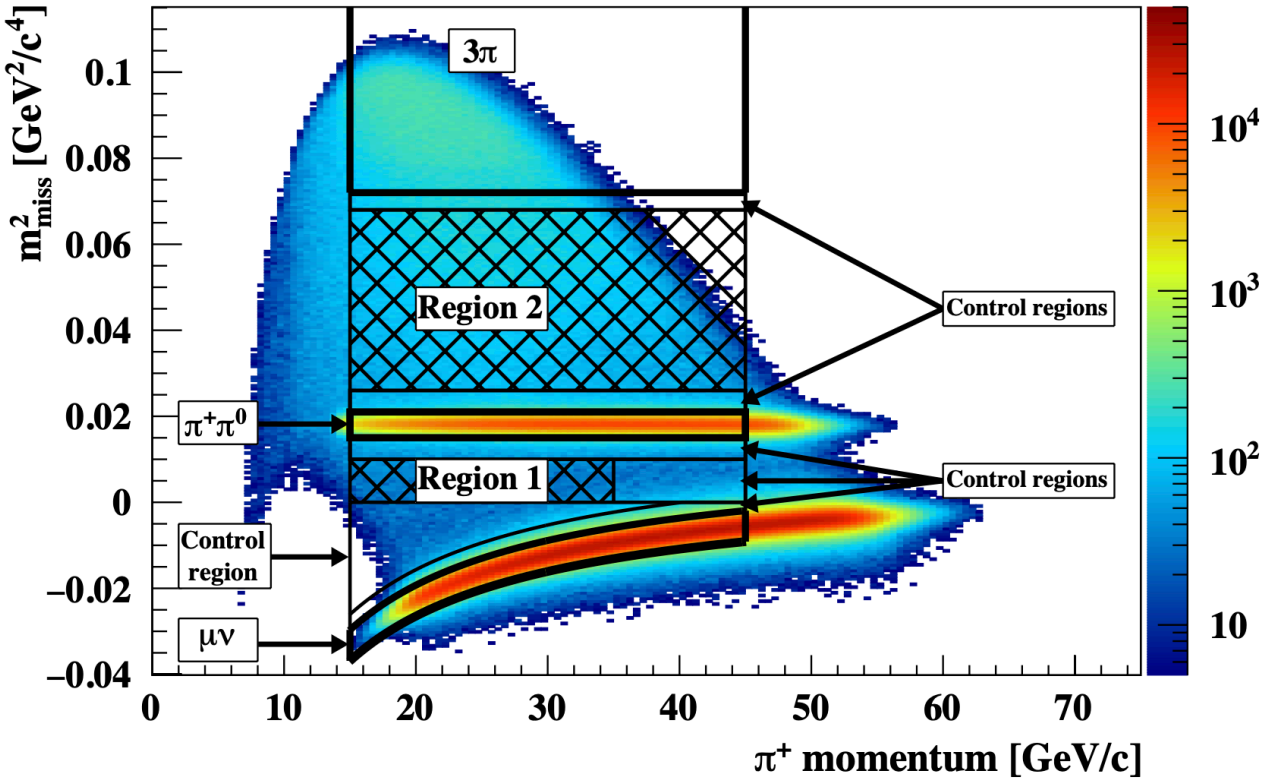
NA62 results

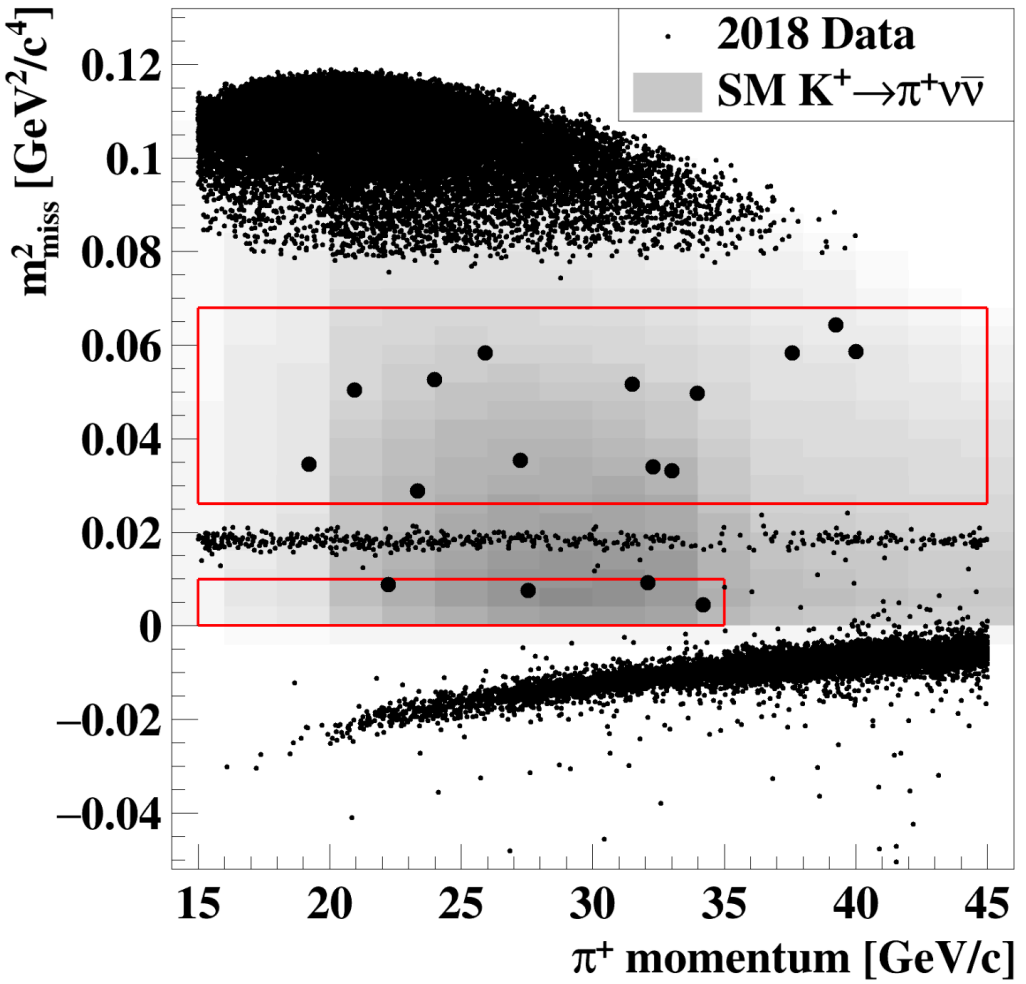




- Signal Region 1+2:
  - Expected 5±1 background events
  - Expected 8±1 signal events

NA62 results





- Signal Region 1+2:
  - Expected 5±1 background events
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Credit: Fermilab

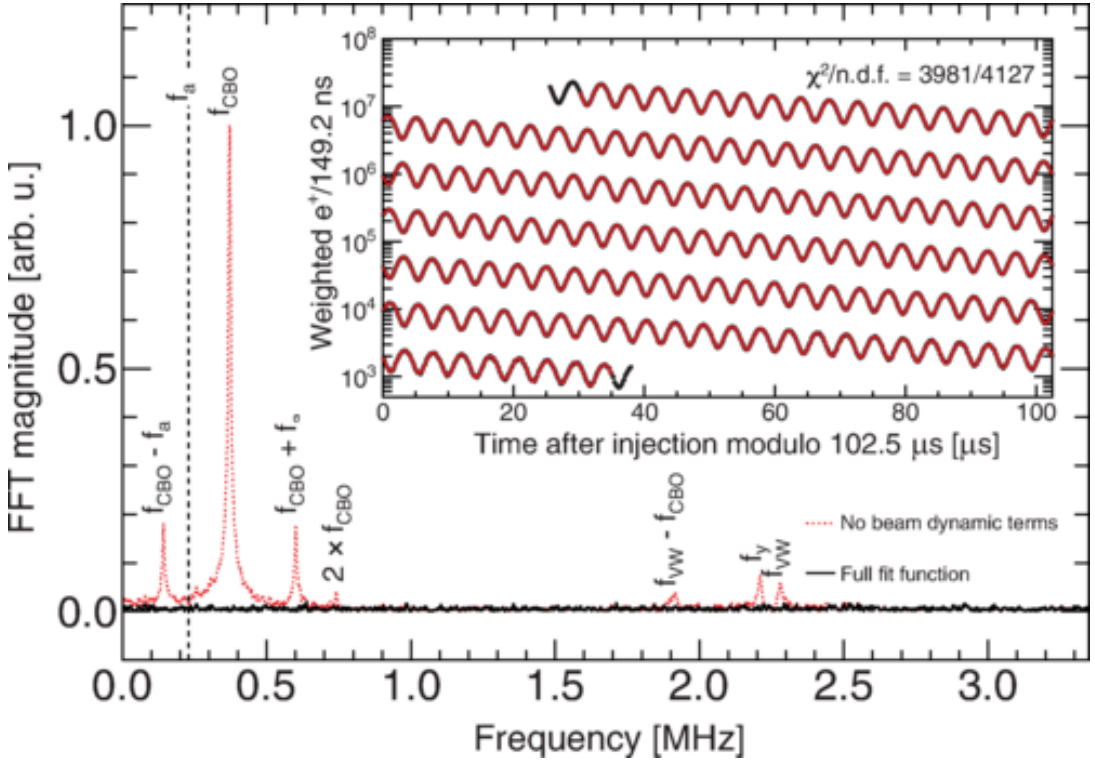
Muon anomalous magnetic moment

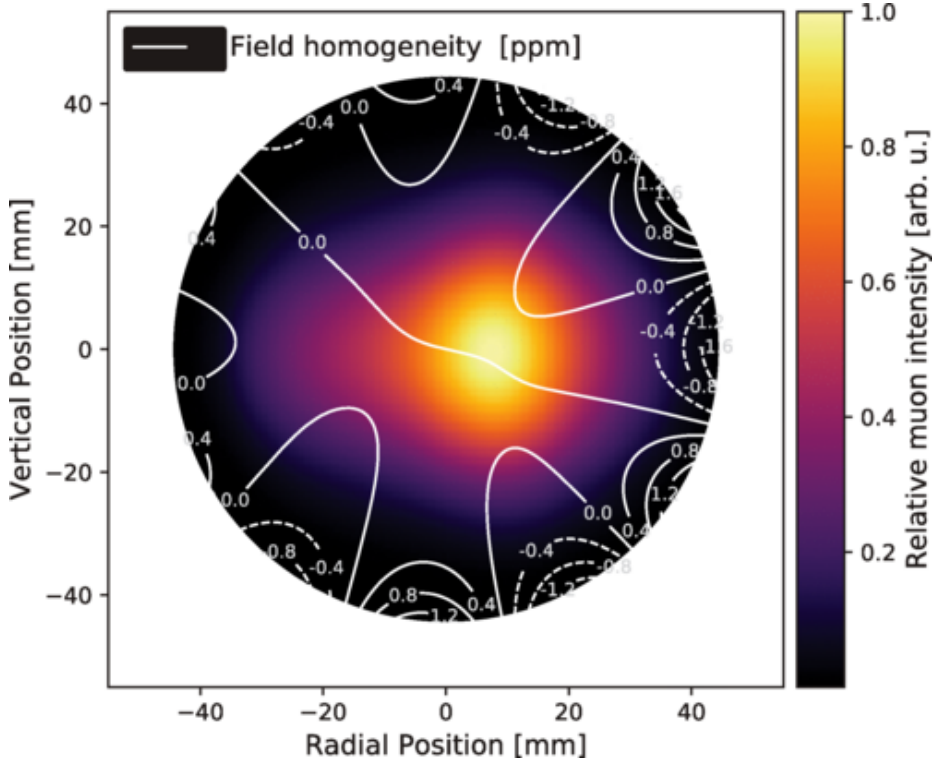
$$N(t) = N e^{-\frac{t}{\gamma \tau_\mu}} \left[1 - A \cos(\omega_a t + \phi)\right]$$

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

$= 0$ for $\gamma = 29.1$

- $a_\mu = (g_\mu - 2) / 2$
- SM extremely well known, need ≪ppm precision
- Measurement with storage ring of polarised muons, measure electrons from muon decays
- Need superb control of magnetic field and of several other oscillation frequencies

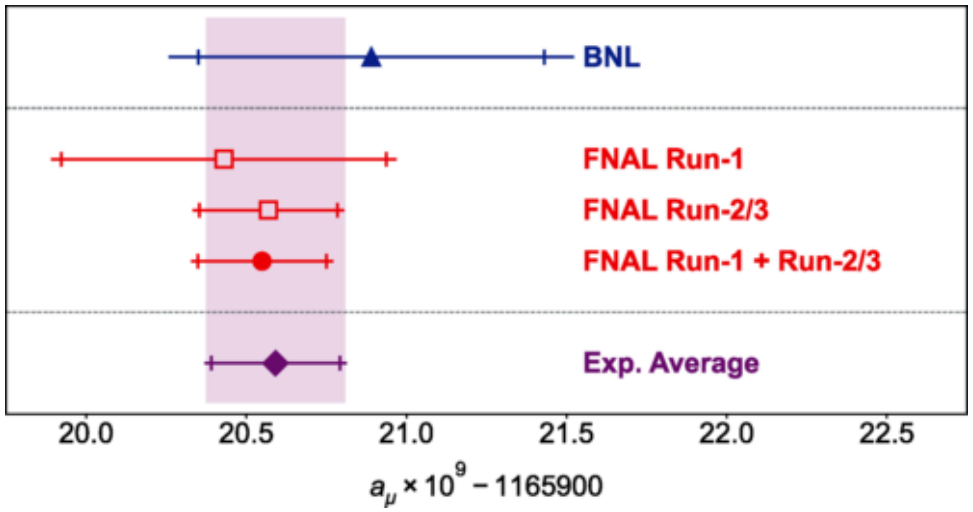


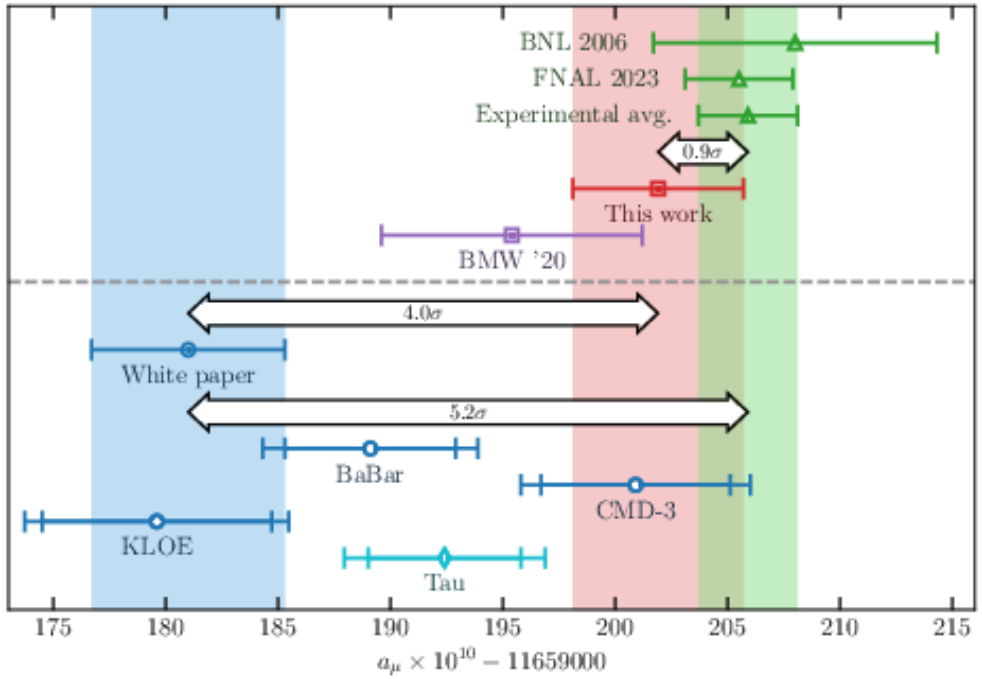


Muon anomalous magnetic moment — Results

- Approximately 1/3 of FNAL experiment data analysed
  - Run 1 achieved similar sensitivity to old BNL experiment
- Theoretical situation unclear
  - Largest uncertainty from hadronic vacuum polarisation contribution
  - Dispersive approach (incl. White paper) uses experimental inputs
    - Tensions between KLOE, BaBar and CMD-3
  - Lattice (BMW Collaboration) recently published results of competitive precision
    - In agreement with BNL & FNAL measurements

FNAL Mu g-2, PRL 131 (2023) 161802



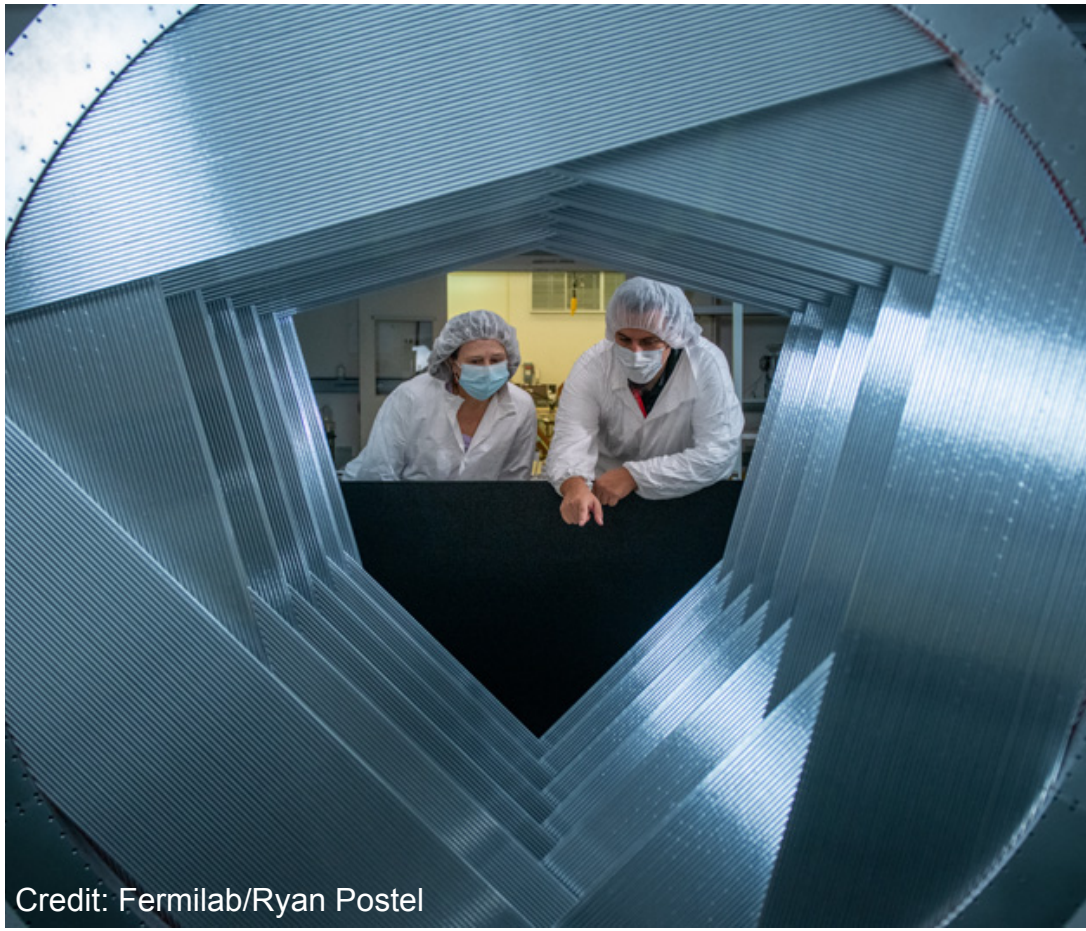


Boccaletti et al., arXiv:2407.10913

Other muon experiments

- J-PARC preparing g-2 measurement with μ^+ beam
  - Data taking planned from 2028
- MUonE experiment: precise measurement of hadronic leading order corrections to a_μ with elastic μ-e scattering
  - Proposed run in 2025
- Several other past and ongoing experiments contributing relevant results

- Charged lepton flavour violation
  - $\mu \rightarrow e\gamma$: MEGII experiment data taking ongoing
  - $\mu \rightarrow eee$: Mu3e experiment in construction, data from 2025
  - $\mu N \rightarrow eN$: COMET/Mu2e in construction, data over next 10 years
  - Complementary sensitivity to BSM physics


Credit: Fermilab/Ryan Postel

Recap

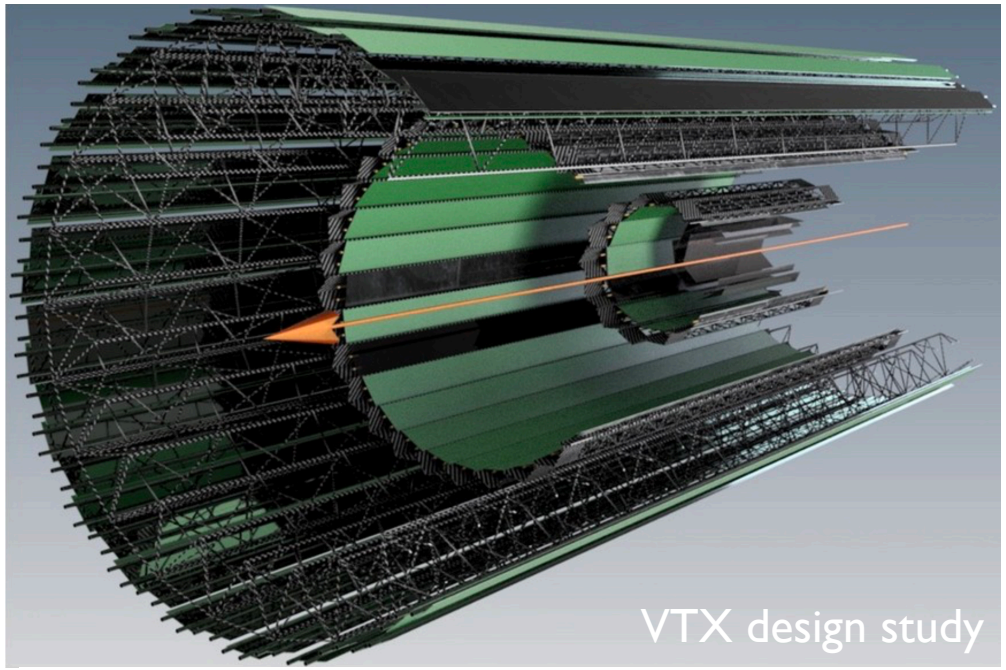
- Rare hadron decays
  - Many rare decay measurements transitioning to precision measurements that explore multi-dimensional observables
  - Some tensions persist in $b \to s\ell\ell$ transitions (many more variants under study than the two shown here)
  - NA62 establishing extremely rare decay $K^+ \to \pi^+ \nu\bar{\nu}$
- Charged lepton physics under very active study
  - Muon anomalous magnetic moment experiment confirming BNL results
  - Theory picture rather unclear with several additional theoretical and experimental studies under way
  - Charged leptopn flavour violation under study with complementary set of experiments

Future flavour

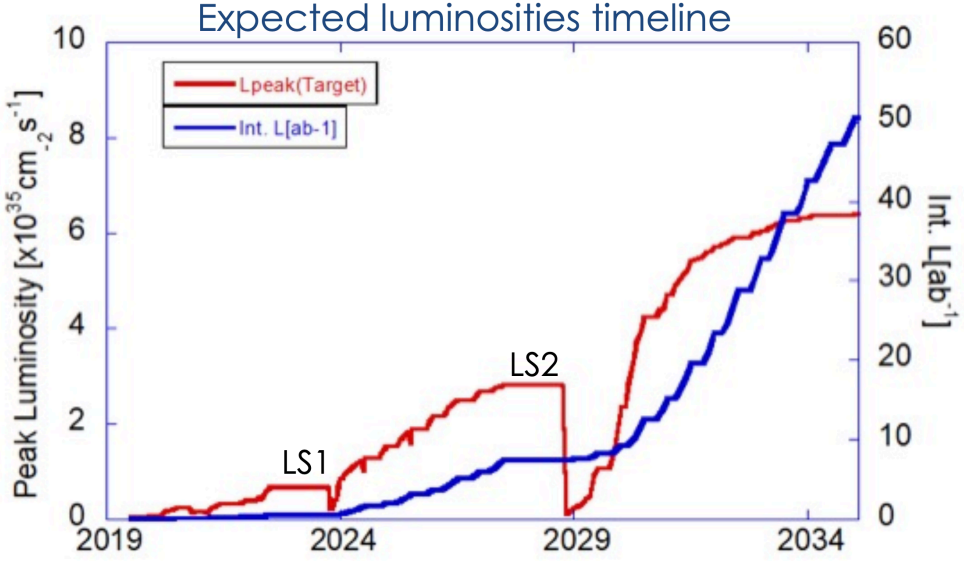
Time evolution of neutral mesons
CP violation
Constraining the CKM triangle: the angle γ

Belle II

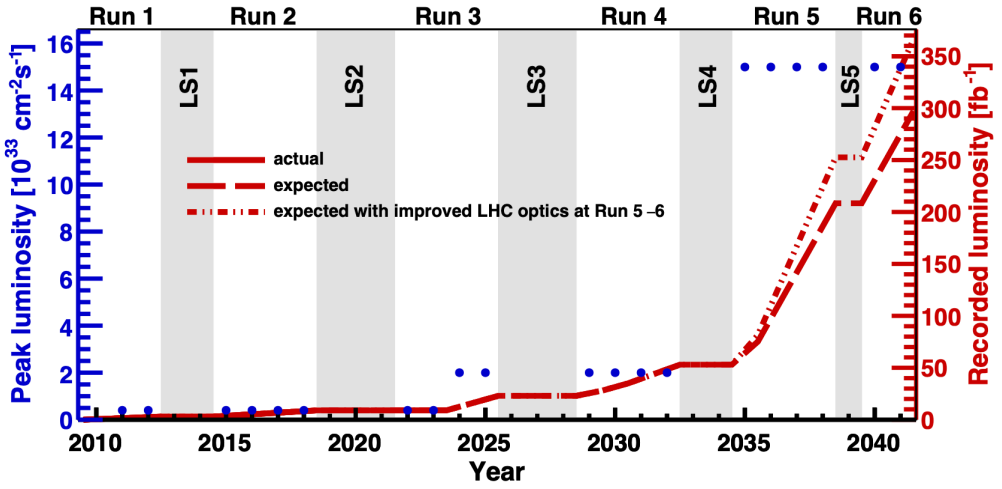
- Data taking post LS1
  - Should surpass Belle dataset in near future, but already operating with much improved performance
- LS2 anticipated before end of the decade
- New interaction region to achieve
  $\mathcal{L}_{peak}$ = 6.5×1035 cm−2s−1
- New vertex detector likely required, other detector upgrades being evaluated
- Studies started for future upgrades

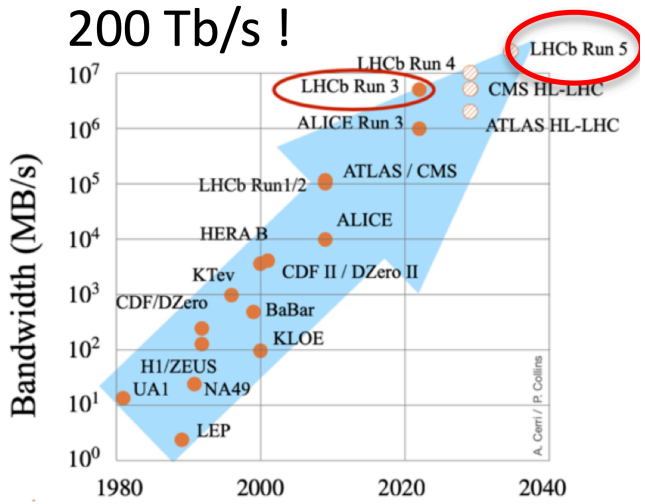


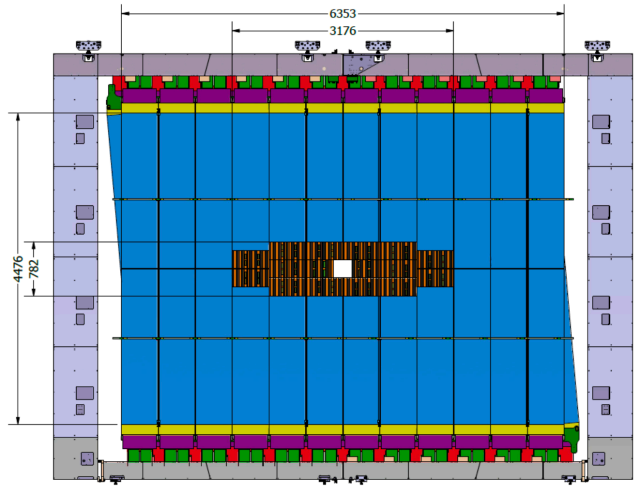
Expected luminosities timeline

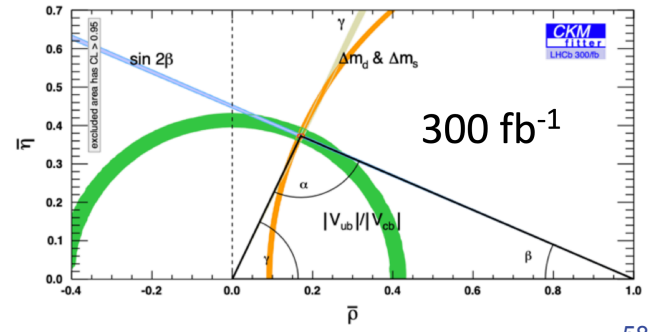


LHCb Upgrade II





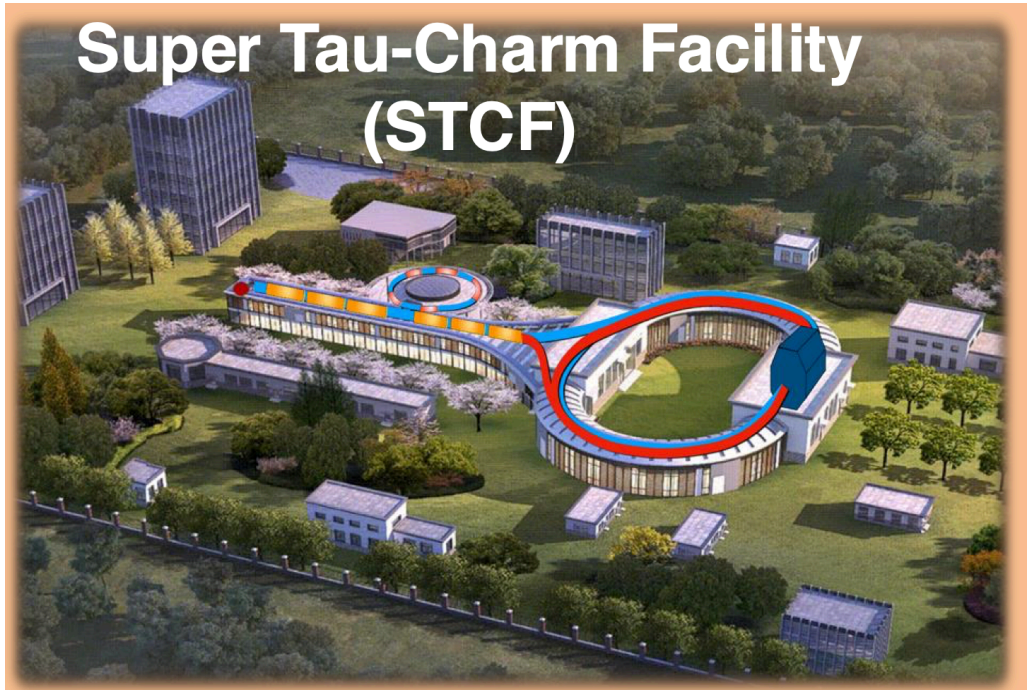




- LHCb Upgrade I introduced full 40 MHz readout and more granular detector to operate at greater instantaneous luminosity with improved performance
- LHCb Upgrade II planned to introduce a further step change in instantaneous luminosity
  - Requires even better granularity paired with time resolution to resolve collisions within one bunch crossing
  - Scoping document being discussed with LHCC and funding agencies
  - TDRs planned for 2026 and installation in LS4 (2033/34)
  - Challenging detector and data processing requirements
  - Increase total luminosity to 300 fb^{-1}

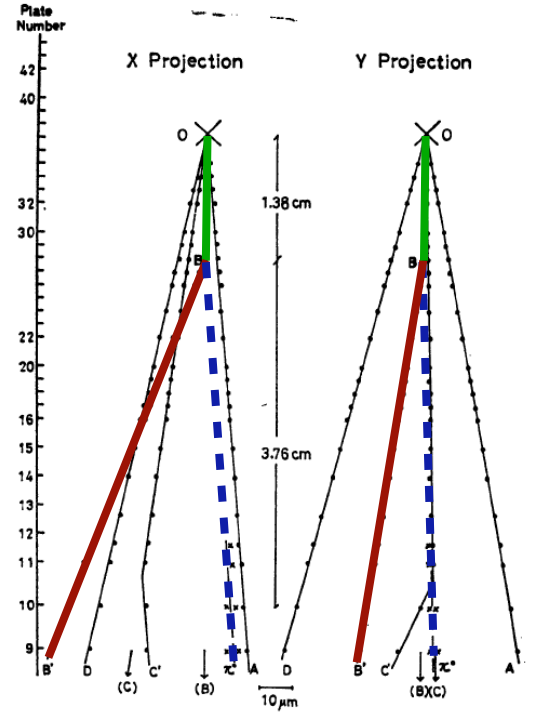
Other flavour initiatives

- NA62 still taking data at CERN but future HIKE programme not pursued by CERN
- KOTO taking data and plans for KOTO II
- ATLAS and CMS will continue to contribute including at HL-LHC
- EDM experiments not mentioned at all here but only for lack of time
- BESIII experiment taking data at higher centre-of-mass energies including accelerator upgrade
- Super Tau-charm factory plans at Hefei
- Long term: Flavour at FCCee/CepC run as Z factory

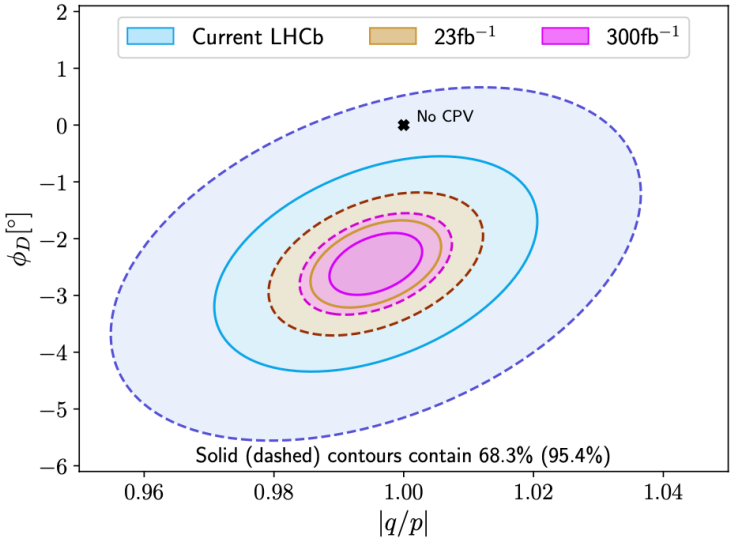


Conclusions

- Flavour physics is conducted by a broad range of specialised experiments, built on a long history of important discoveries
  - With some important contributions from non-specialists
- Flavour tagging, hadron identification and vertex resolution are crucial design requirements
- CP violation now established in all neutral meson systems
- CKM tested to great accuracy (γ~1°) with no obvious discrepancies
  - Some tensions in CKM element magnitudes
- Rare decays being studies in great detail with some tensions in b→sll processes
- Muon g-2 being tested to fantastic precision with theoretical questions
- Several exciting prospects for charged lepton flavour violation in coming decade
- Major upgrade planned with LHCb Upgrade II with other experiments specialising in kaons (KOTO II), charm (STCF) and beauty (Belle II++) being considered for coming decade and futher opportunities at future e^+e^- colliders
- Lots of potential for exciting flavour discoveries



Niu, Mikumo, Maeda, Prog. Theor. Phys. 46 (1971) 5



CERN-LHCC-2021-012