The future of Heavy Flavour

07 Jul 2023

Dan Johnson

UNIVERSITY OF BIRMINGHAM

UNIVERSITY OF BIRMINGHAM

Today's patchwork quilt of flavour physics

CKM unitarity

- CKM angle γ (or ϕ_3) directly measured with $\approx 3.5°$ precision
- Negligible theory uncertainty; clean NP probe
- Indirect determinations have reached 1° precision
  - Direct measurements must challenge them

Charm

- Indirect CP violation in SM $\mathcal{O}(10^{-4})$ or less
- Current precision few $\times 10^{-2}$
  - Measuring it likely beyond the reach of today's experiments

Electroweak penguins

- $B^0 \to \mu^+\mu^- : B_s^0 \to \mu^+\mu^-$ a strong test of NP flavour structures
  - Still dominated by expt. uncertainty at end of the decade

UNIVERSITY OF BIRMINGHAM

Today's patchwork quilt of flavour physics

CKM unitarity

- CKM angle γ (or ϕ_3) directly measured with $\approx 3.5°$ precision
- Negligible theory uncertainty; clean NP probe
- Indirect determinations have reached 1° precision
  - Direct measurements must challenge them

Charm

- Indirect CP violation in SM $\mathcal{O}(10^{-4})$ or less
- Current precision few $\times 10^{-2}$
  - Measuring it likely beyond the reach of today's experiments

Electroweak penguins

- $B^0 \to \mu^+\mu^- : B_s^0 \to \mu^+\mu^-$ a strong test of NP flavour structures
  - Still dominated by expt. uncertainty at end of the decade

Not to mention: CPV in B_s^0, B_c^+, and baryons; LU/LFV (RX, $R(D^*)$); semileptonic asymmetries, spectroscopy

Pursuing precision

- Arguments to improve statistical precision in pursuit of theory uncertainty abound
- Even if they did not, the motivation to exploit our facilities to the utmost, in every domain, is hauntingly clear:

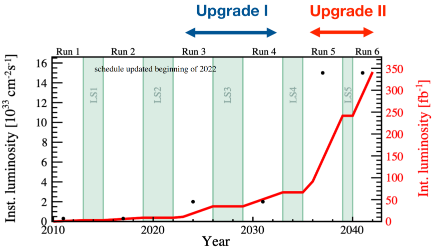
A special search at Dubna was carried out by E. Okonov and his group. They have not found a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays of K_L^0 into charged particles [13] (Anikina et al., JETP, 1962). At that stage the search was terminated by administration of the Lab. The group was unlucky.

(L. Okun - 2001)

UNIVERSITY OF BIRMINGHAM

LHCb upgrades

- 2011 - 2018: 9 fb^{-1}
- 2022 - 2032: 50 fb^{-1}
- 2035 - 2041: 300 fb^{-1}



Flavour fields ripe for harvest:

- U1 does not reach the theory uncertainty
- Where close, reasonable to anticipate theory advances

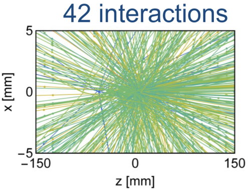
Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_s^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_T^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A_T^{Im} ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

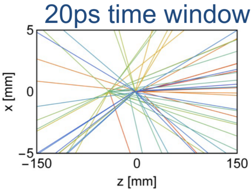
LHCb Upgrade 2: the challenge of pileup

From 2×10^{33} to 1.5×10^{34} requires a revolution

3D ⟶ 4D: vertexing

- 50 ps per hit
- Pixel pitch $55 \mu m$
- Extreme fluence $6 \times 10^{16} n_{eq}/cm^2$





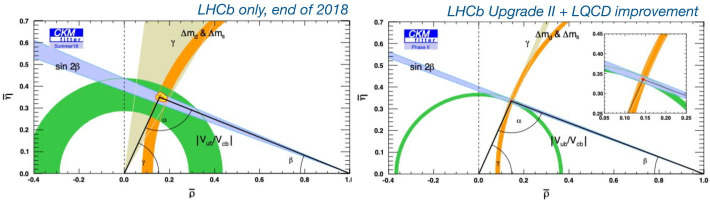
UK groups leading sensor R&D, prototype 4D demonstrator, high-rate read-out technologies

Ambitious detector development

- Tracking: a complete system. New large-area silicon detector (MAPS) downstream; major UK leadership
- PID: LHCb hallmark; enhance with new TOF detector

Interdependency

LHCb Upgrade 2 will challenge the SM as never before:

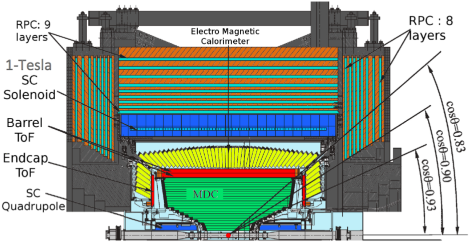


that requires both input from the lattice community...

...and from other experiments

BES-III

Hermetic detector at BEPCII ($\sqrt{s} = 2 - 4.6\,\mathrm{GeV}$)



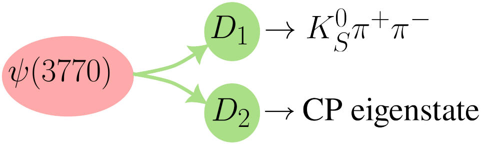
- Central pillar of Chinese HEP programme
- Physics objectives span spectroscopy, charm measurements, study of correlated *D* mesons, semileptonic decays for CKM elements

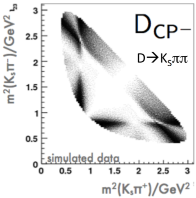
UNIVERSITY OF BIRMINGHAM

BES-III

Strong phase parameters at $\psi(3770)$ a key target for UK participation

- Relate amplitude for D^0 and $\bar{D}^0$ decaying to same final state
- Phase determination requires a system with interference
- $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$: quantum-correlated D-meson pair





Dalitz plot density: $|A|^2 + |\bar{A}|^2 - 2|A||\bar{A}|cos(\delta)$

UNIVERSITY OF BIRMINGHAM

BES-III...

These, and other, strong phases are crucial for LHCb and BELLE II:

- γ (ϕ_3) from variety of B decays, most involving $D^0/\bar{D}^0$
- BES-III inputs define D decay (w/o model dependence)
- UK participation in CLEO-c ($0.8\,\mathrm{fb}^{-1}$): breadth & precision of strong phase parameters. $\sigma(\gamma) \approx 2^\circ$
- UK instrumental to $20\,\mathrm{fb}^{-1}$ at $\psi(3770)$ at BES-III: $\sigma(\gamma) \approx 0.5^\circ$

UNIVERSITY OF BIRMINGHAM

BES-III...

These, and other, strong phases are crucial for LHCb and BELLE II:

- γ (ϕ_3) from variety of B decays, most involving $D^0/\bar{D}^0$
- BES-III inputs define D decay (w/o model dependence)
- UK participation in CLEO-c (0.8 fb^{-1}): breadth & precision of strong phase parameters. $\sigma(\gamma) \approx 2°$
- UK instrumental to 20 fb^{-1} at $\psi(3770)$ at BES-III: $\sigma(\gamma) \approx 0.5°$

BES-III status at the $\psi(3770)$:

- 2010-11: 3 fb^{-1}
- Last 18 months: another 14 fb^{-1}
- Smooth data-taking this year; restarts in November: anticipate full 20 fb^{-1} next year
- 2 UK PIs since 2017: modest, but highly strategic, investment

BES-III... and STCF

These, and other, strong phases are crucial for LHCb and BELLE II:

- γ (ϕ_3) from variety of B decays, most involving $D^0/\bar{D}^0$
- BES-III inputs define D decay (w/o model dependence)
- UK participation in CLEO-c ($0.8\,\mathrm{fb}^{-1}$): breadth & precision of strong phase parameters. $\sigma(\gamma) \approx 2°$
- UK instrumental to $20\,\mathrm{fb}^{-1}$ at $\psi(3770)$ at BES-III: $\sigma(\gamma) \approx 0.5°$

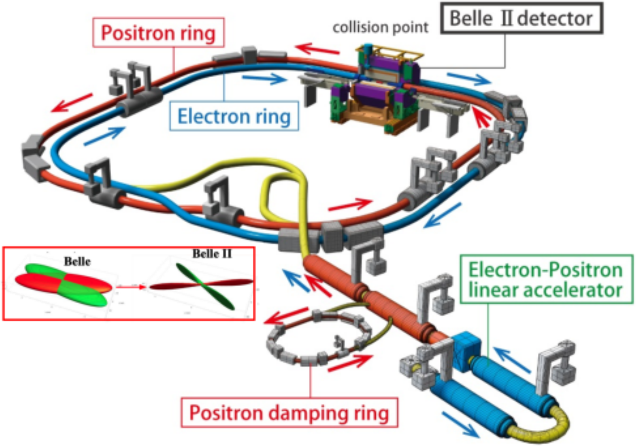
Super τ-charm Factory:

- Proposed e^+e^- collider in China: $\sqrt{s} = 2 \rightarrow 7\,\mathrm{GeV}$ and $\mathscr{L} = 5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Further opportunity for correlated D-pair studies
- UK signatories to CDR

UNIVERSITY OF BIRMINGHAM

Belle II

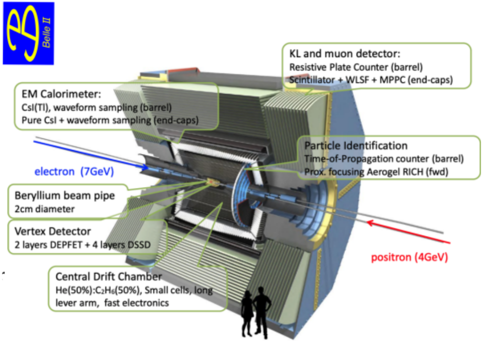
Radical development of KEKB e^+e^- collider:



Nano-beam scheme: 40× larger luminosity

UNIVERSITY OF BIRMINGHAM

Belle II



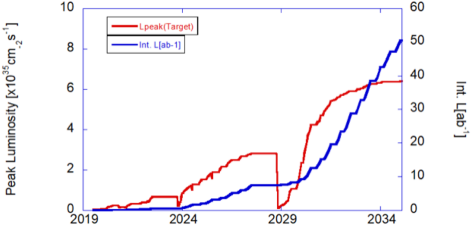
Asymmetric collisions at $\sqrt{s} = m(\Upsilon(4S))$

- Kinematic constraints during reconstruction
- Novelty with respect to LHCb:
  - Advantages for final states with $> 1\pi^0/\gamma$ or neutrinos
  - Wide programme to explore $e^+e^- \to \tau^+\tau^-$
- Commonality: CKM metrology; charm; spectroscopy; anomalies

UNIVERSITY OF BIRMINGHAM

Belle II

- Belle and BaBar: little under $1ab^{-1}$
- Belle II target $50ab^{-1}$



- Reached 428 fb^{-1}; luminosity record $\mathscr{L} = 4.7 \times 10^{34}$
- Restart data-taking end 2023
- UK groups making key contributions to data analysis and vertex detector upgrade: 5-layer DMAPS detector

UNIVERSITY OF BIRMINGHAM

An exciting future

- Despite all that **LHCb** hold in store, all key flavour measurements will be dominated by experimental uncertainty after Run 3/4
- **LHCb U2** will allow to exploit HL-LHC facility fully
- Prolific UK leadership at all levels, past and future. Entering exciting R&D period
- Key HF observables rely on inputs from **τ-charm facilities**. Excellent ROI on modest BES-III investment; replicate at STCF
- Despite challenges of cutting-edge accelerator, **Belle II** will provide tools to keep LHCb honest, whilst providing a wealth of orthogonal physics opportunities.
- Further ahead, prospect of 5×10^{12} Z^0 decays at FCC-ee offers opportunities that in general exceed those available at Belle II, and complement LHC HF programme

Muon Physics

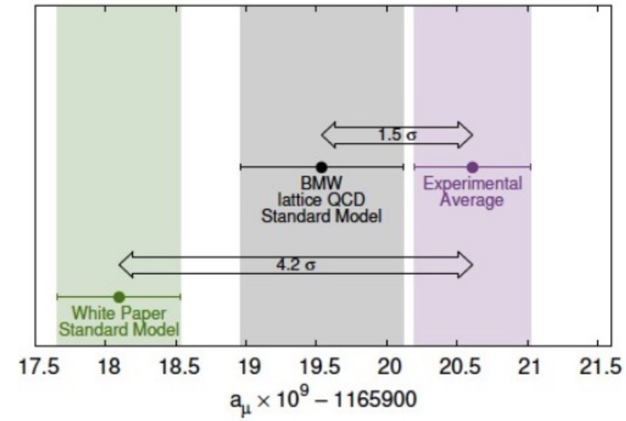
Joe Price

University of Liverpool

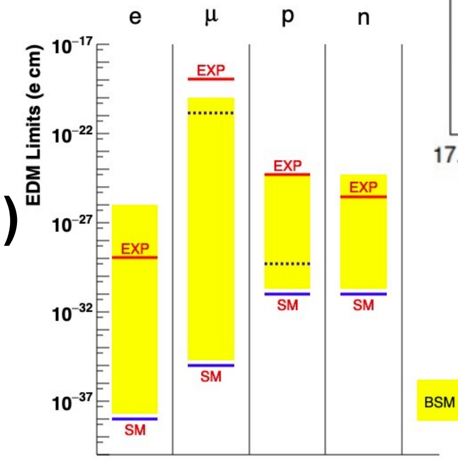
UK Muon Physics Experimental Overview

UNIVERSITY OF LIVERPOOL

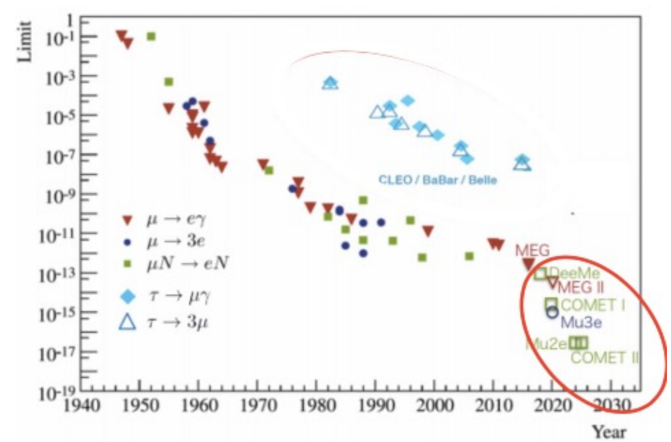
- **Anomalous magnetic dipole moment (g-2)**



- **Electric Dipole Moment (EDM)**



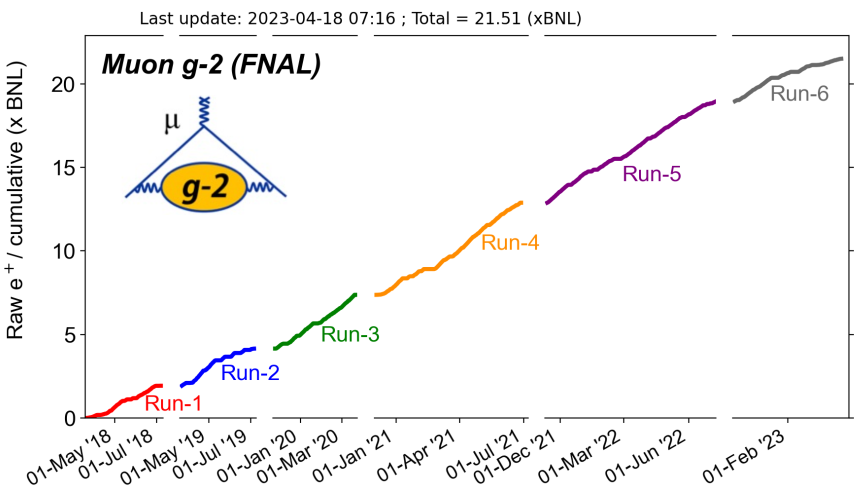
- **Charged Lepton Flavour Violation (CLFV)**



Magnetic Dipole Moment

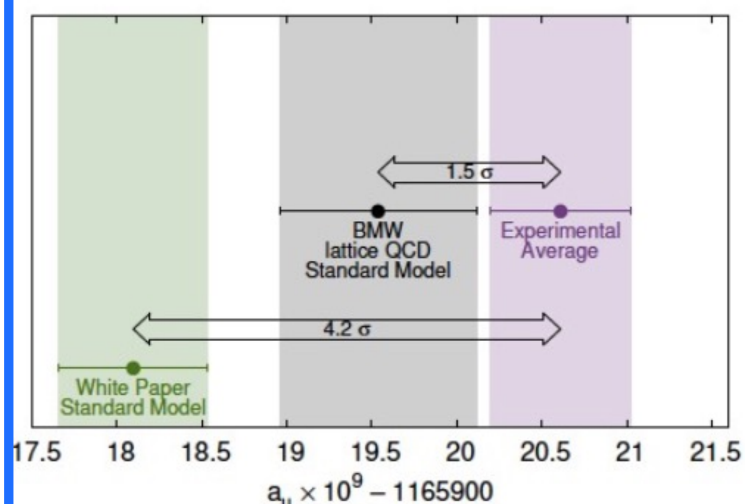
Anomalous magnetic dipole moment

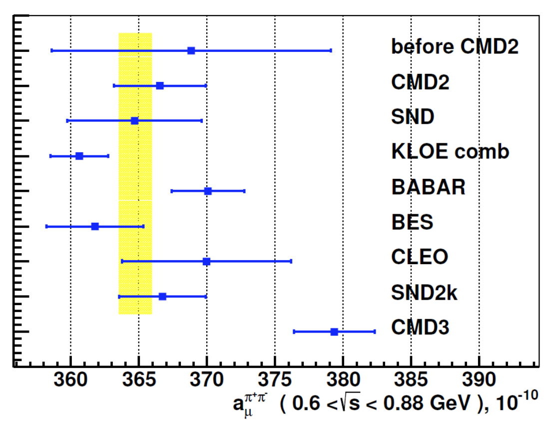
EXPERIMENT



- Run-1 data: 460ppb precision, and 4.2σ tension with the theoretical prediction
- More data to analyse - expect a factor 2 improvement for Run-2/3 analysis
- On course for ~140ppb total uncertainty

THEORY





To get a_μ^{HLO} :

- Data from **e^+e^- scattering**
- Calculate on **Lattice**

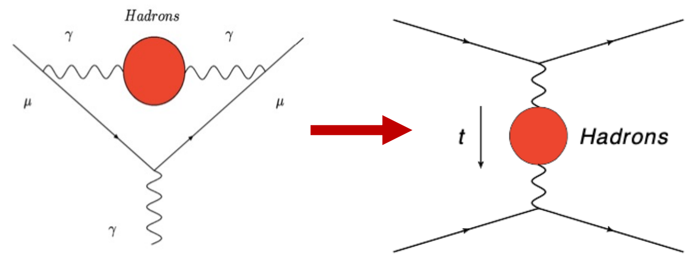
Tension between the 2 methods! – needs resolving (muonE…)

MuonE – spacelike measurement of a_μ^{HLO}

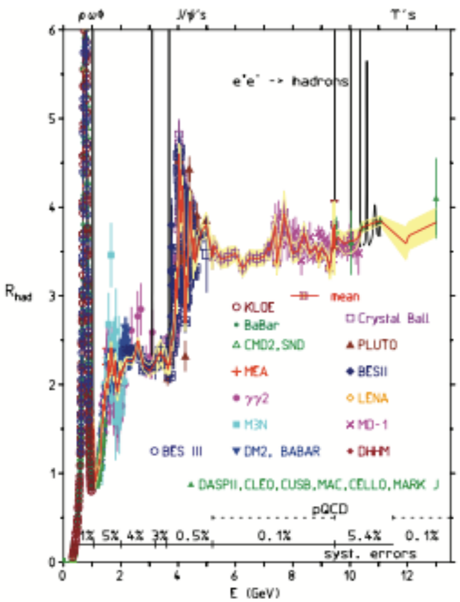
UNIVERSITY OF LIVERPOOL

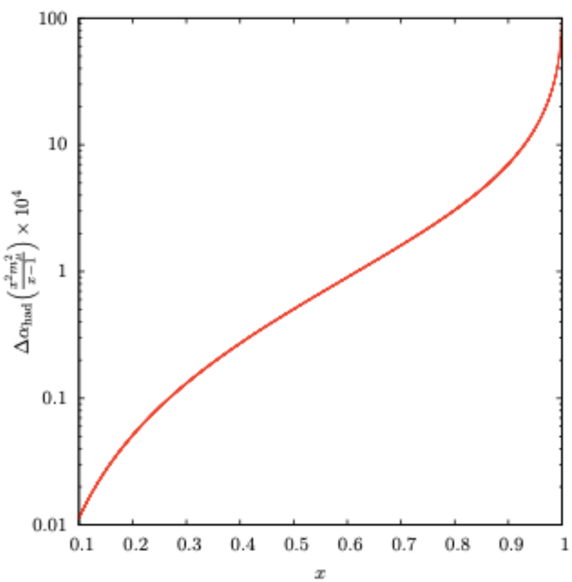
Carloni Calame, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

- Still a data driven evaluation of a_μ^{HLO}
- Move from **time-like** to **space-like**



Time-like $\mapsto$ **Space-like**





Lautrup, Peterman, De Rafael, Phys. Rept. 3 (1972) 193

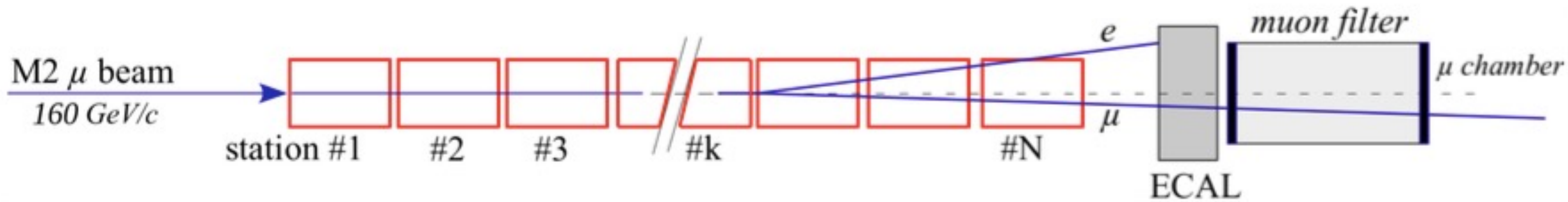
$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

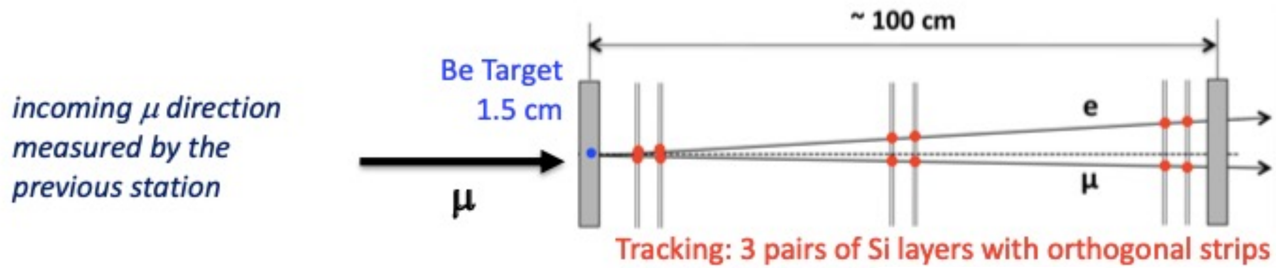
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

- Is a pure t-channel process at tree level

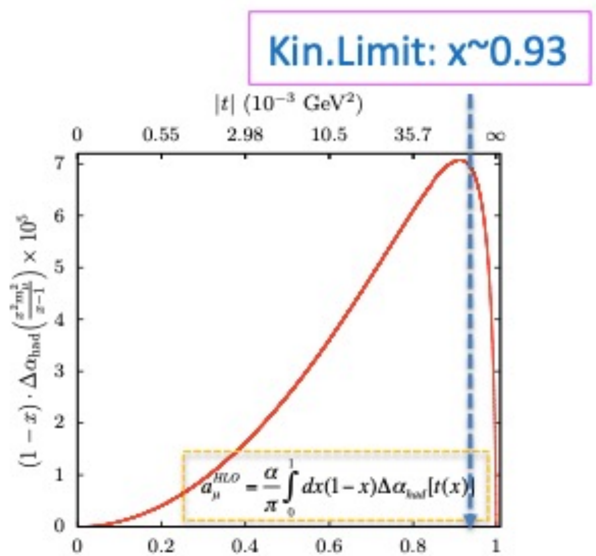
MuonE slides courtesy of R. Pilato, C.M. Carloni Calame, G. Abbiendi

MuonE measurement





- Scatter μ on e in low Z target, measure the scattering angle
- For E(beam) = 160 GeV (CERN SPS) phase space covers ~88% of integral
- Competitive precision 0.35-0.5% on a_{μ}^{HLO} will help solve g-2 puzzle! Data taking after LS3
- **UK contribution**:
  - CMS-2S detectors (ICL)
  - Tracker mechanics (Lpool, Leverhulme)



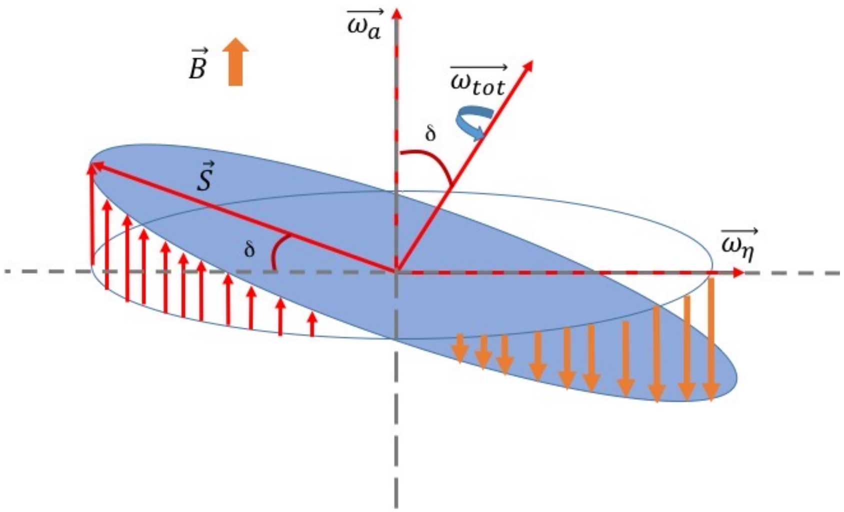
MuonE slides courtesy of R. Pilato, C.M. Carloni Calame, G. Abbiendi

Electric Dipole Moment

EDM Projected Limits @ FNAL

Current best limit is from BNL: $|d_\mu| < 1.9 \times 10^{-19}$ e.cm (95% C.L.)

G. W. Bennett *et al.* Phys. Rev. D 80, 052008



- Causes an increase in muon precession frequency
- Precession plane tilts towards center of ring
- Vertical oscillation is 90° out of phase with the g-2 oscillation

- Run 1 analysis still blinded. Assuming zero signal expecting limit of:

$|d_\mu| < 2.0 \times 10^{-19}$ e.cm (95% C.L.)

- Comparable with current limit, but still statistically limited
- Expect factor of **~10 improvement** for statistics accumulated so far, with tracking improvements can push towards

$|d_\mu| < 1.0 \times 10^{-20}$ e.cm (95% C.L.)

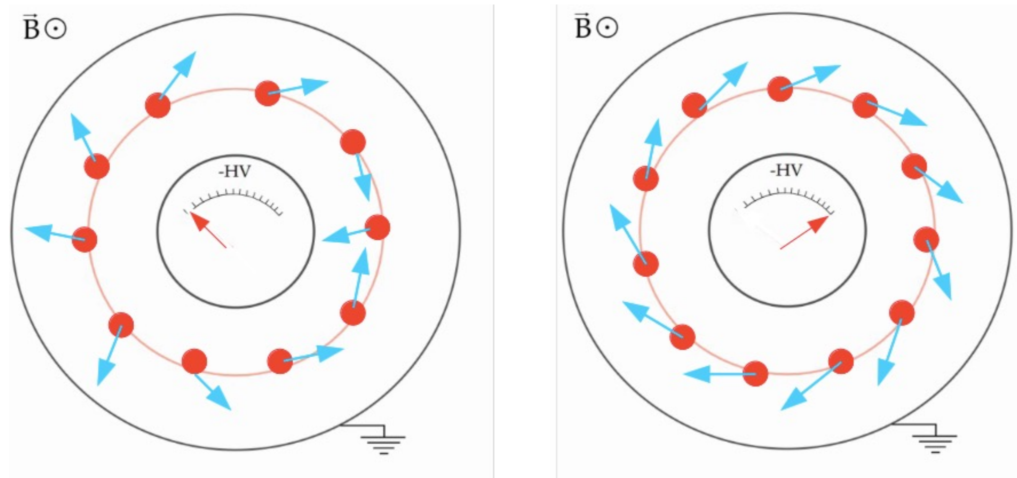
Frozen spin technique @ PSI

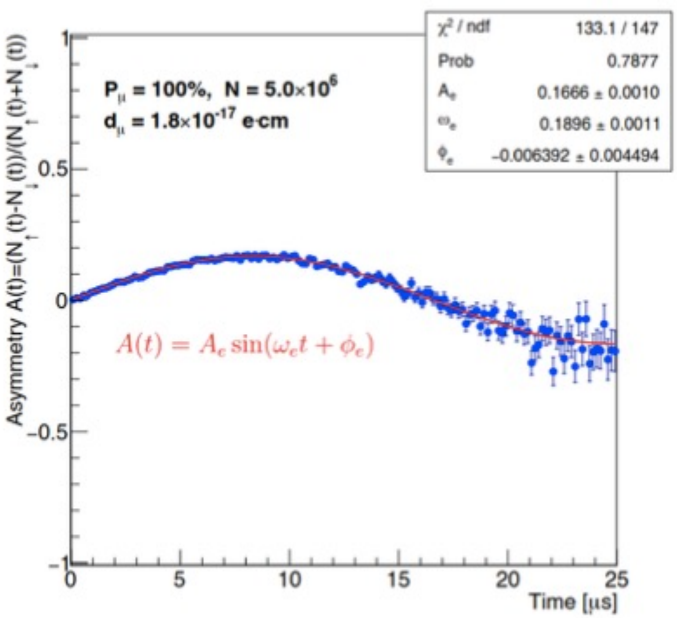
- Relativistic spin precession of a charged particle (Thomas-BMT equation)

$$\vec{\Omega} = -\frac{e}{m_0}\left[a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

g-2 term | EDM term

- By applying an appropriate radial E-field to the muon we negate the g-2 term.

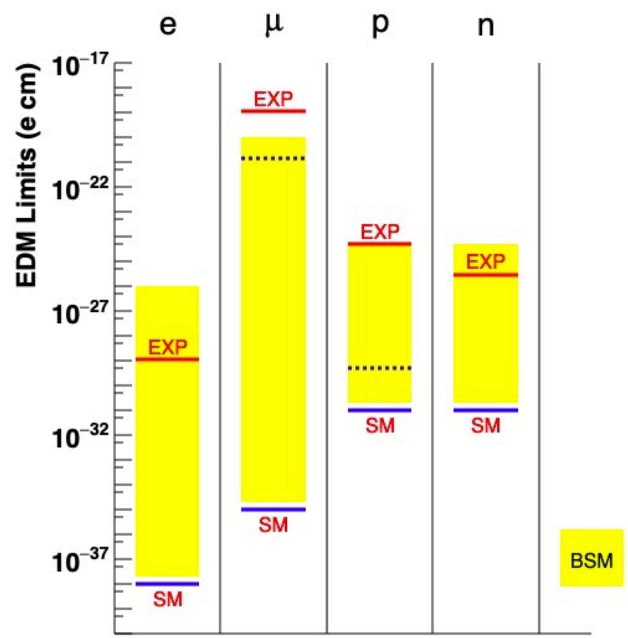




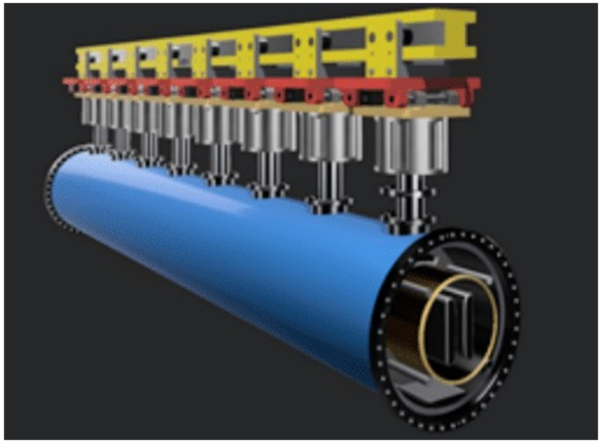
- Spin precession would be due to EDM.
- **Advantage of frozen spin:** Every e^+ is useful!
- **Phase I** – Demonstrate the frozen spin method
- **Phase II** – Measure the muon EDM to **~10^{-23}e.cm**
- Combined **infrastructure proposal** with Mu3e-II, based around ultra low mass HV-MAPS tracking

Frozen spin technique - Proton EDM

- BNL proposing a proton EDM measurement at 10^{-29}e.cm – under P5 review
- Protons at 'magic' momentum at 0.7 GeV/c
- 800m circumference storage ring in the AGS tunnel at BNL
- UK co-designing the electric bending dipoles, providing electric field of 4.5MV/m. These cover 600m of the 800m circumference
- Early Technologies Proposal in preparation to build demonstrator electric deflector



4m electric deflector

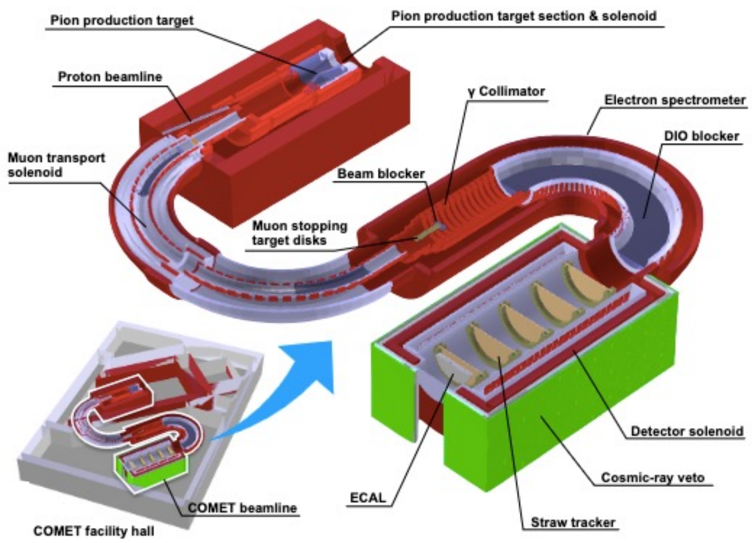


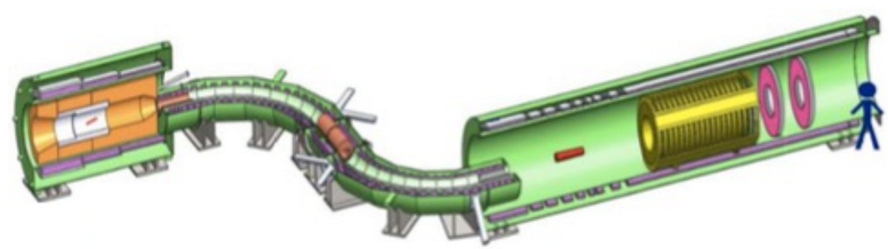
Charged Lepton Flavour Violation

CLFV - COMET and Mu2e

	Best limits	Projected sensitivities (90%CL)
$\mu \to e\gamma$	$< 4.3\times10^{-13}$ MEG (PSI)	4×10^{-14} MEG II (PSI)
$\mu \to eee$	$< 1.0\times10^{-12}$ SINDRUM (PSI)	4×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)
$\mu N \to eN$	$< 7.0\times10^{-13}$ SINDRUM II (PSI) μ Au $\to$ e Au	6×10^{-17} Mu2e (FNAL) 7×10^{-15} COMET I (J-PARC) 6×10^{-17} COMET II (J-PARC)

COMET: Strong UK involvement in planning and operations
Mu2e: STM detector and readout provided by the UK

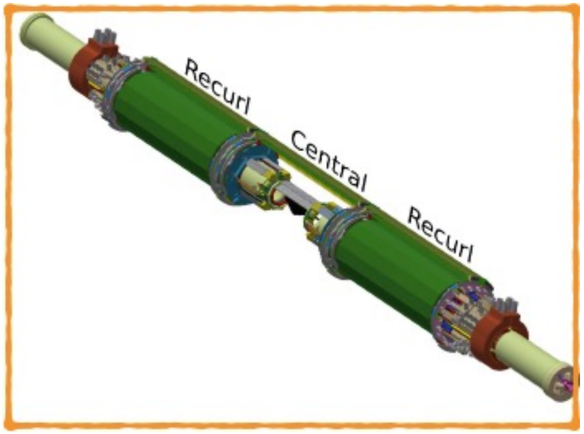


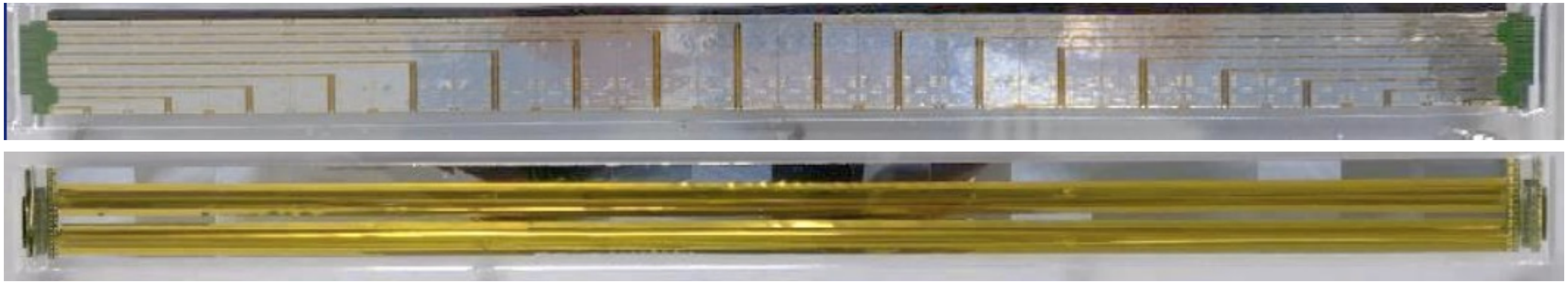


Both experiments start in next few years, upgrade through 2030

CLFV in muons with Mu3e @ PSI

- UK responsible for outer pixel layers detectors at Mu3e and Mu3e-II
- MUPIX low mass (~0.1% X_0) HV-MAPS tracking
- Vertex layer production started
- Outer layer production starts Autumn 2023
- Commissioning with full central tracker 2024





- Physics with complete detector systems in 2025
- **Phase I** – 10^8 μ/s – $\mathrm{BR}(\mu \to eee) < 2\times10^{-15}$
- **Phase II** – After HIMB upgrade - $\mathrm{BR}(\mu \to eee) < 10^{-16}$ ~ 2030, as part of infrastructure proposal with MuEDM

Conclusions

UNIVERSITY OF LIVERPOOL

- UK has grown a broad and internationally competitive muon programme with STFC support and other funding

- **Muon Anomalous magnetic moment**:
  g-2: data taking nearly complete, on course for design goal
  theory: New data and experiments to help solve tension

- **Electric dipole moment**:
  g-2: most sensitive measurement will be made with UK-built tracker
  MuEDM@PSI: frozen spin method 100 times more sensitive

- **Charged Lepton Flavour Violation**:
  COMET/Mu2e: data taking beginning in 2025, upgrades to follow
  Mu3e: tracking detectors built in UK

UK muon institutes: Brisol, Cockcroft, Imperial, Lancaster, Liverpool, Manchester, Oxford, RAL, UCL

Flavour Physics Questions

- ***Balance***: Is there the right balance between funding for science exploitation of existing experiments and construction/R&D for future projects?
- ***Breadth***: Is the current UK Flavour programme too broad/not broad enough?
  - Breadth of areas (quark flavour incl. strange/charm/beauty, charged lepton flavour) vs breadth of projects in one area (e.g. LHCb/Belle 2, tau-charm threshold, muon conversion/decay/anomalous moment, etc).
- ***International***: International Strategic Consideration
  - Is UK well placed in all flavour areas it pursues?
  - How influential is it in international programme?
  - What are the key upcoming opportunities; risks of missing them?