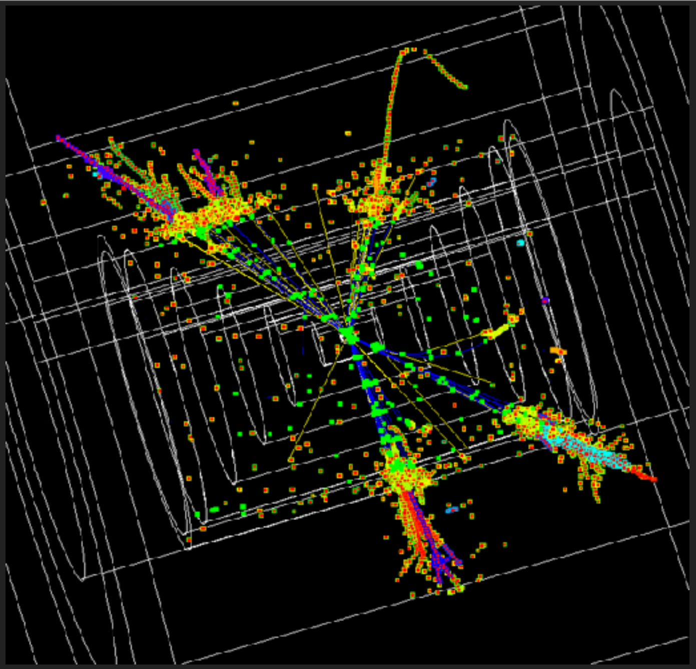
WILL DETMOLD MIT

TRENDS IN LATTICE QCD

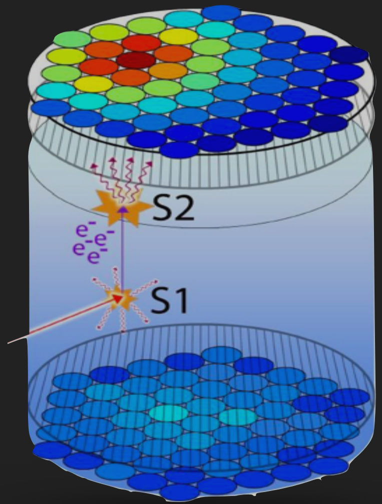
International Committee for Future Accelerators, November 6-9, 2017 — Ottawa, Canada

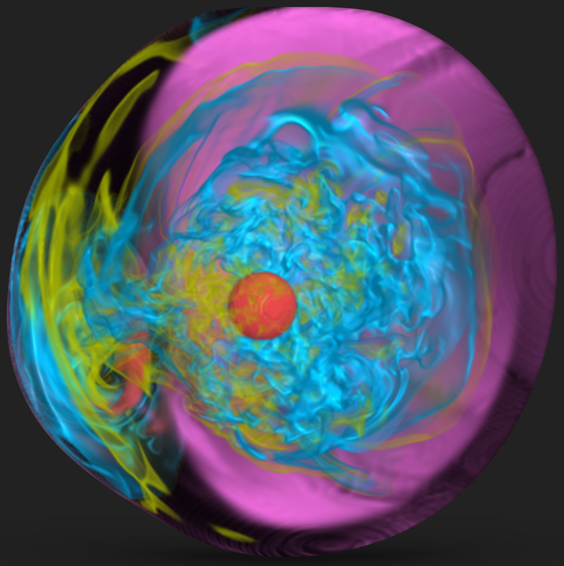
ICFA

QCD AT STRONG COUPLING

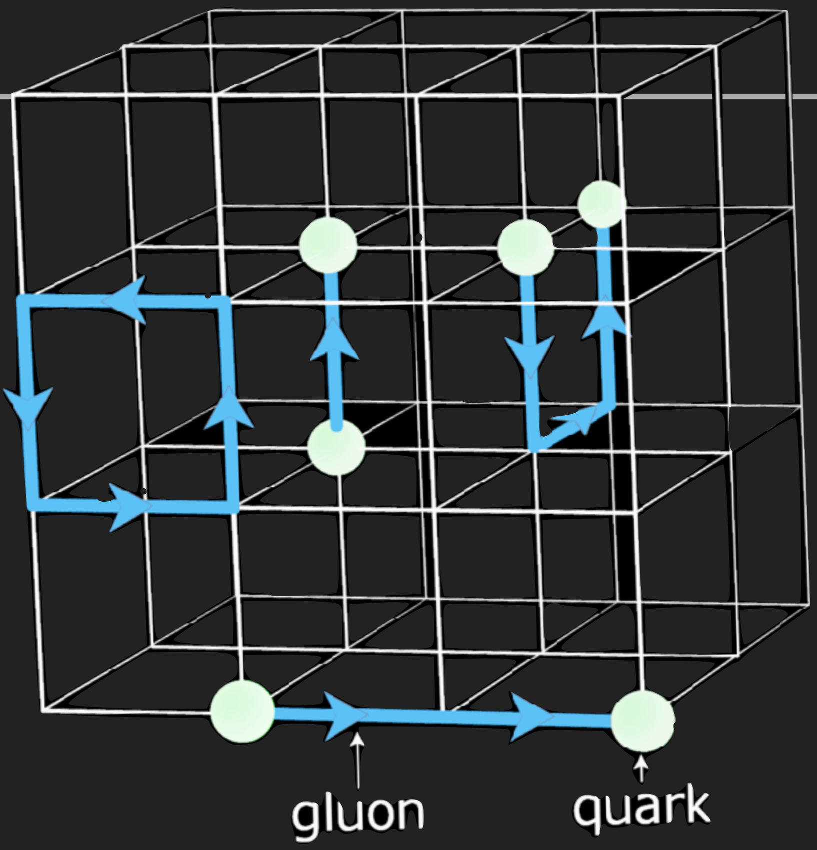


- QCD is everywhere
  - Colliders: PDFs, fragmentation
  - Fixed target: form factors, GPDs
  - DM detectors: nuclear interactions
  - Astrophysical objects: neutron stars,…
  - Early universe
- Strongly coupled at low energy ➡ Lattice QCD

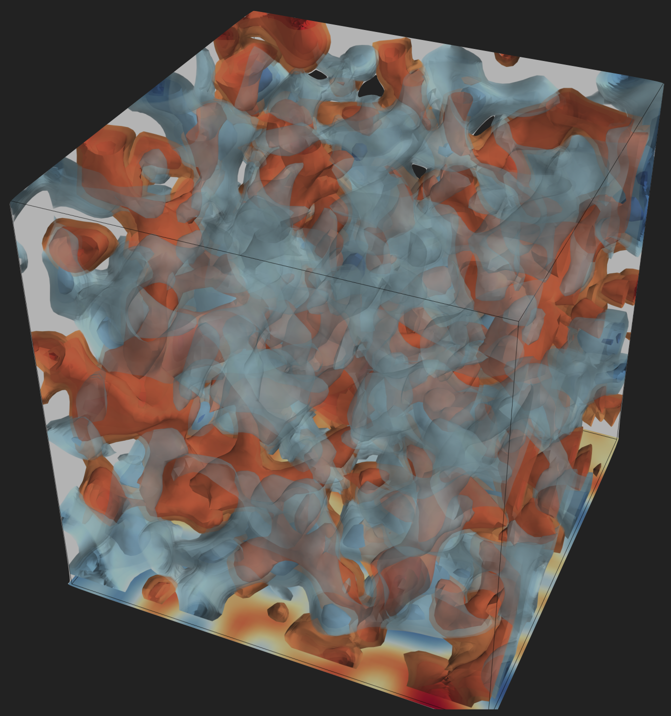




HIGH FIDELITY LATTICE QCD



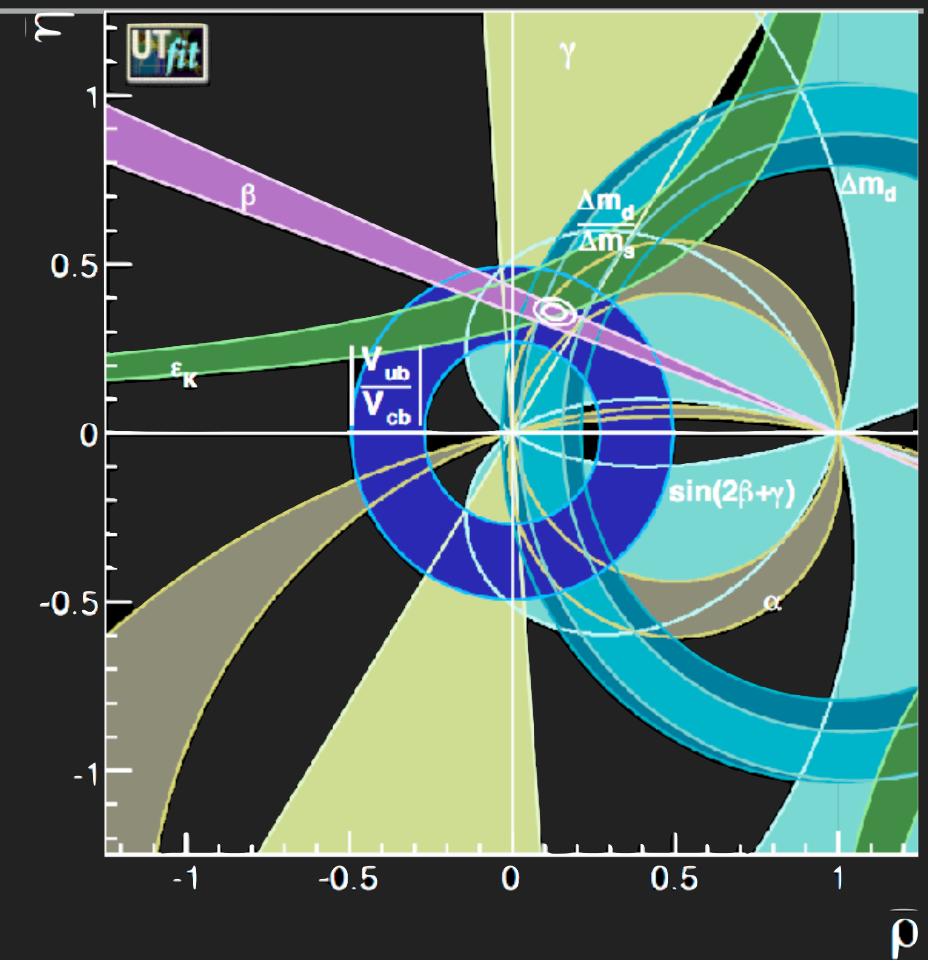
- LQCD: strong coupling definition of QCD and method to handle quarks & gluons
- Numerical LQCD entering precision era
- Modern calculations control all systematics
  - Physical quark masses, infinite volume and continuum limits
  - Blind analyses, multiple independent groups
  - Include QED in numerical calculations
- *QCD is the theory of strong strong interactions*
- This talk: a few relevant/representative topics

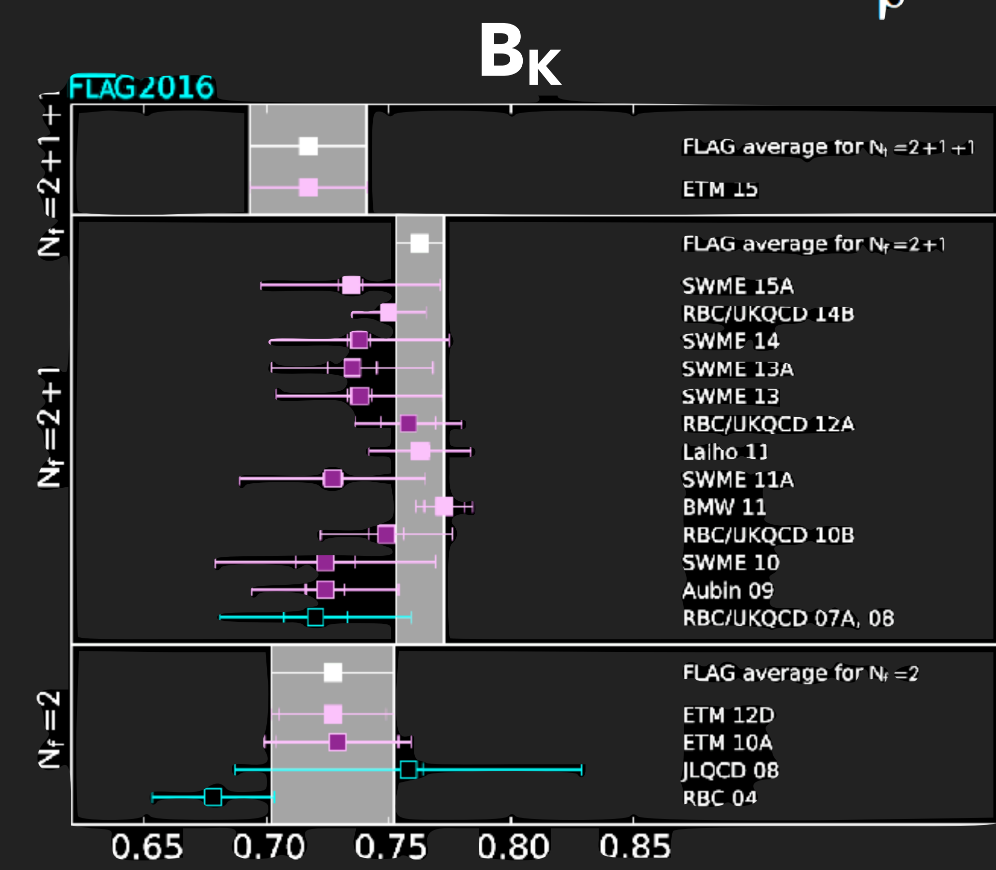


PRECISION FLAVOUR PHYSICS

LATTICE FLAVOUR PHYSICS

- Test CKM paradigm and look for new physics
- Simple quantities: goal is precision & accuracy
  - Decay constants, meson transition form factors, …
  - Status tracked by Flavour Lattice Averaging Group (FLAG)
- Complicated quantities: progressing towards complete calculations
  - Second order EW processes
  - Processes involving multiple hadrons

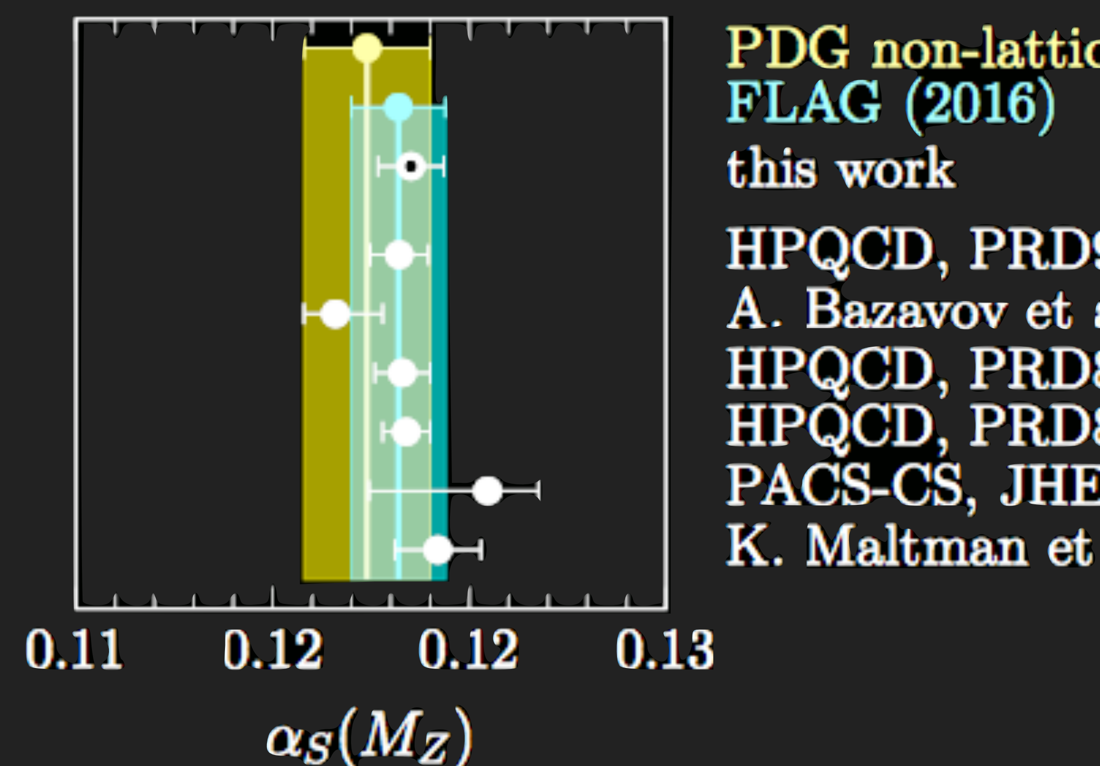


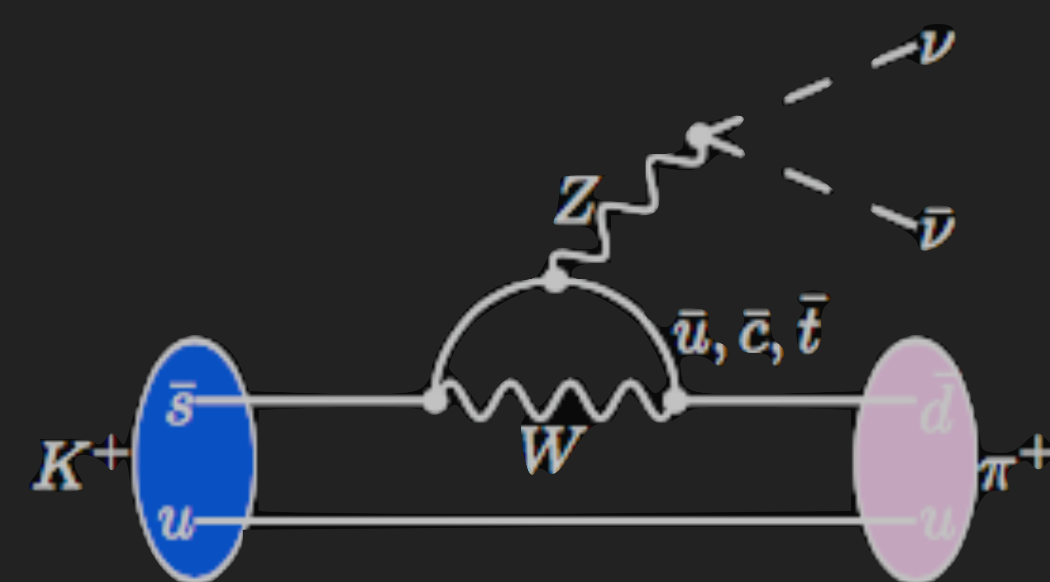


HIGHLIGHTS

- Strong coupling: new independent precise determinations [Sommer et al.]
- QCD understanding of ε'/ε
- Second order weak contributions: K_L-K_S mass diff and rare decays $K^+ \to \pi^+ \nu\nu$,…
- Progress on B→K* treating final state Kπ
- New results on B and D mixing (SM and BSM operators)
- Inclusion of QED in many quantities

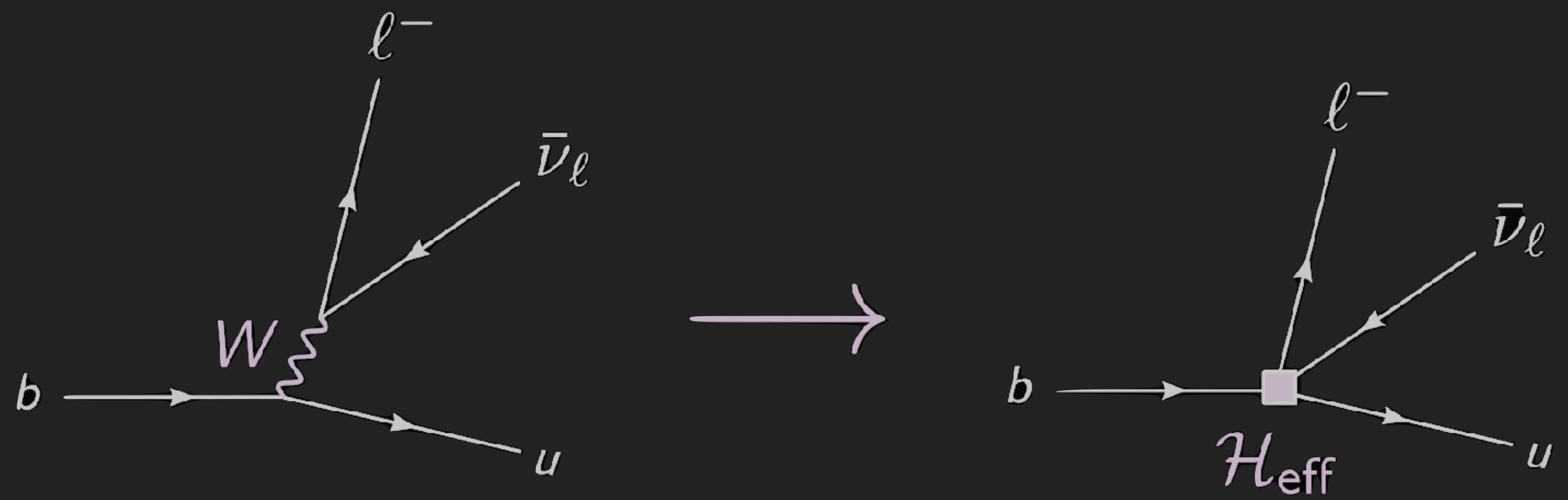
M. Bruno et al. PRL. 119 (2017) 102001





INCLUSIVE VS EXCLUSIVE V_{UB} & V_{CB}

- Long running tension between V_{ub} (and V_{cb}) extractions from inclusive $B \to X_u$ ($B \to X_c$) and exclusive decays $B \to \pi$ ($B \to D$)



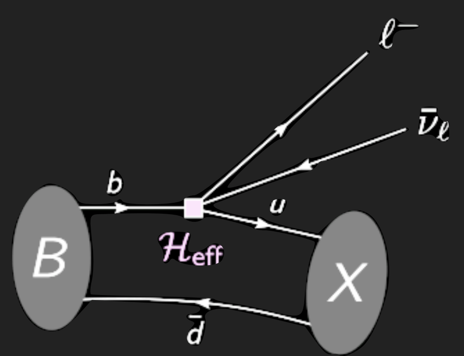
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ub} \underbrace{\bar{u}\gamma^\mu(1-\gamma_5)b}_{\equiv J^\mu} \bar{\ell}\gamma_\mu(1-\gamma_5)\nu$$

INCLUSIVE VS EXCLUSIVE V_{UB} & V_{CB}

- Long running tension between V_{ub} (and V_{cb}) extractions from inclusive $B \to X_u$ ($B \to X_c$) and exclusive decays $B \to \pi$ ($B \to D$)

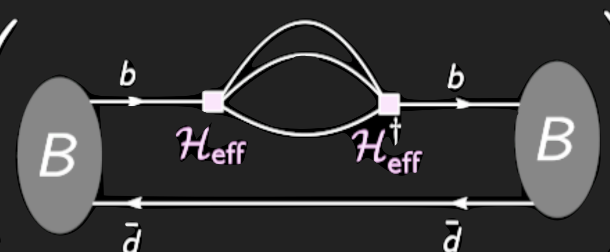
Inclusive

decay rate $\propto \sum_X \Big|$



$\Big|^2$

$\propto \text{Im} \Bigg($



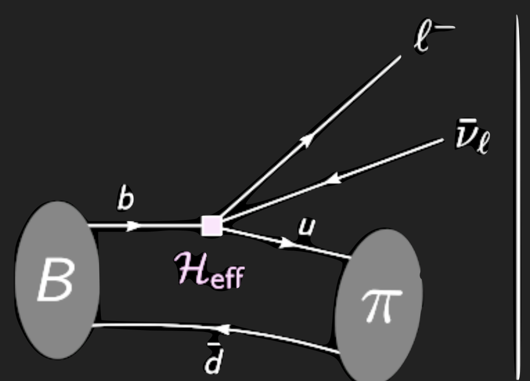
$\Bigg)$

$$\frac{d\Gamma}{dq^2 dE_\ell} \propto |V_{ub}|^2 (\ldots)_{\mu\nu}$$

$$\times \ \text{Im}\Big(\underbrace{-i \int d^4x\, e^{-iq\cdot x} \langle B|\, \mathbf{T}\, J^{\mu\dagger}(x)\, J^\nu(0)\, |B\rangle}_{\text{OPE, HQET}} \Big)$$

Exclusive

decay rate $\propto \Big|$

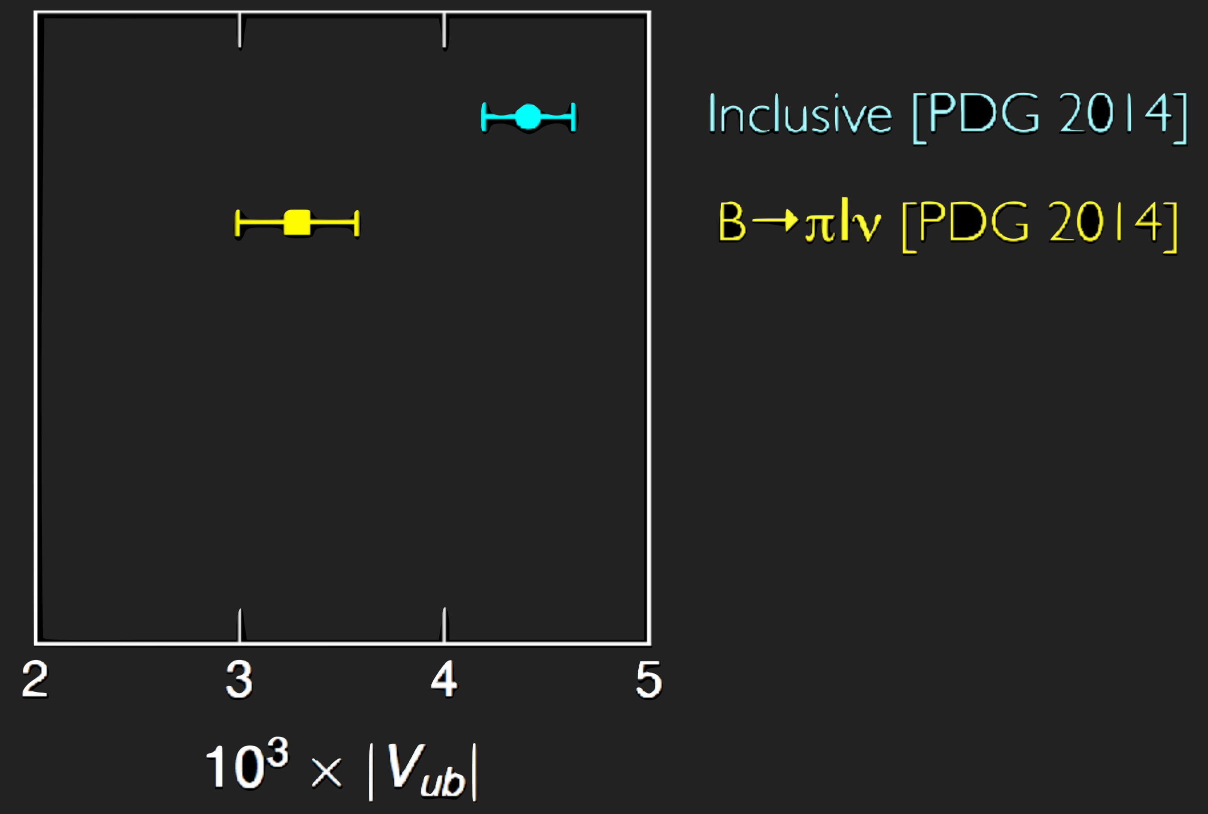


$\Big|^2$

$$\frac{d\Gamma}{dq^2} \propto |V_{ub}|^2 \, \Big| (\ldots)_\mu \underbrace{\langle \pi | J^\mu | B \rangle}_{\text{lattice QCD}} \Big|^2$$

INCLUSIVE VS EXCLUSIVE V_{UB} & V_{CB}

- Long running tension between V_{ub} (and V_{cb}) extractions from inclusive $B \to X_u$ ($B \to X_c$) and exclusive decays $B \to \pi$ ($B \to D$)



INCLUSIVE VS EXCLUSIVE V_{UB} & V_{CB}

- Possible to reconcile through BSM scenarios that produce RH currents at low energy

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ub}^L \left[(1+\epsilon_R)\bar{u}\gamma^\mu b - (1-\epsilon_R)\,\bar{u}\gamma^\mu\gamma_5 b \right] \bar{\ell}\gamma_\mu(1-\gamma_5)\nu$$

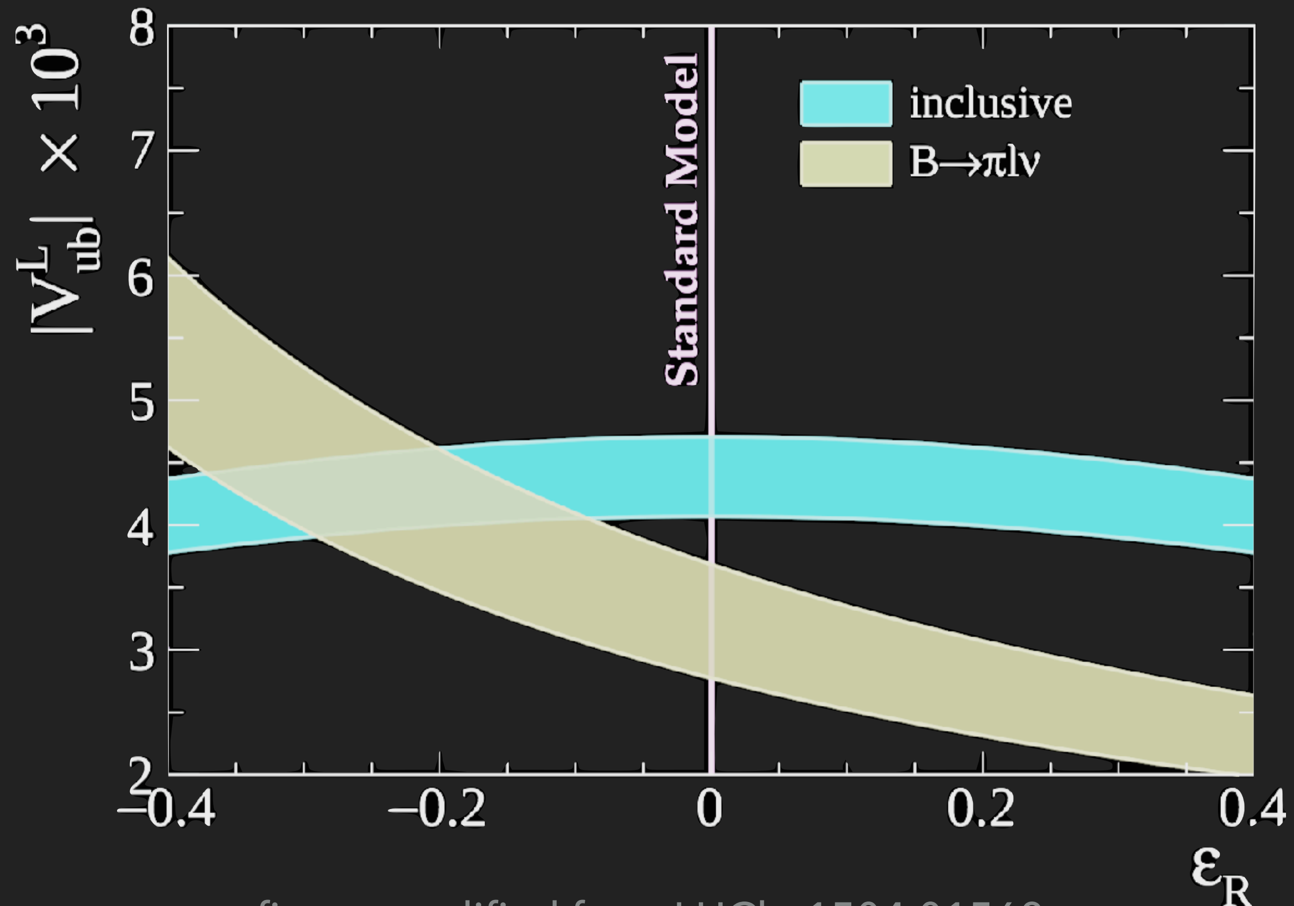


figure modified from LHCb 1504.01568

Λ_B DECAYS

- Bottom baryons provide another exclusive decay channel: $\Lambda_b \to p l \nu$
- LHCb: branching fraction ratio measured

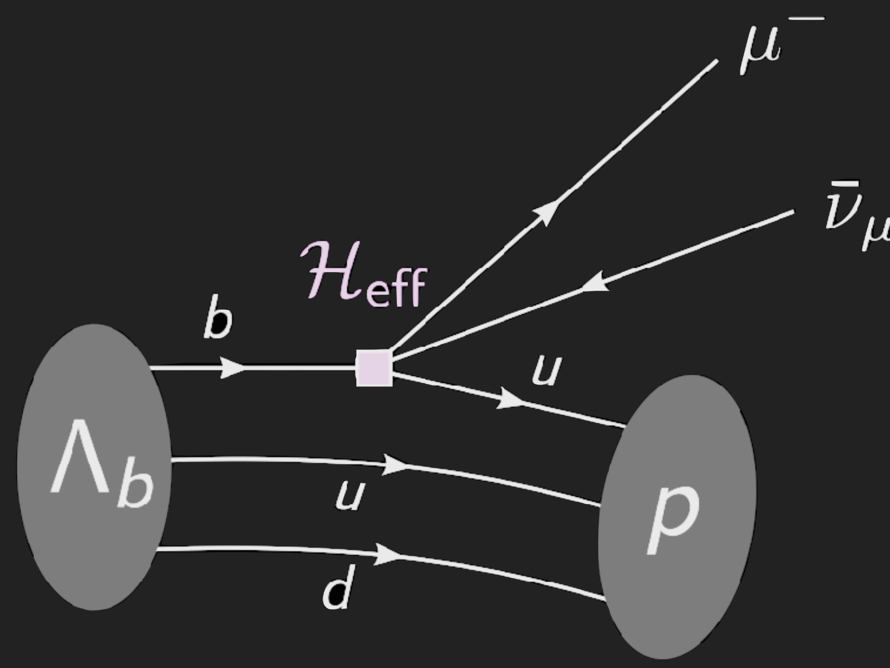
$$\frac{\int_{15\,\mathrm{GeV}^2}^{q^2_{max}} \frac{d\Gamma(\Lambda_b \to p\, \mu^- \bar{\nu}_\mu)}{dq^2} dq^2}{\int_{7\,\mathrm{GeV}^2}^{q^2_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu)}{dq^2} dq^2} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

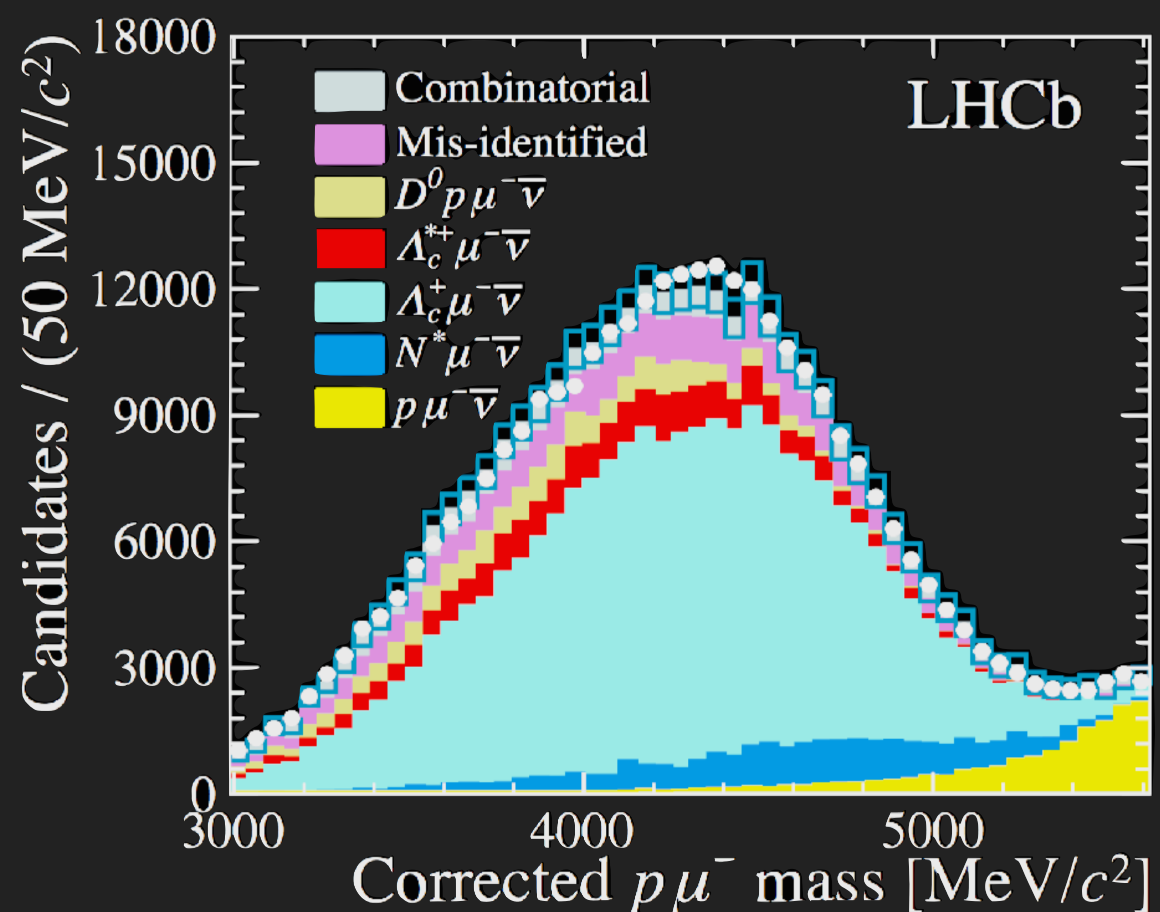
[1504.01568=Nature Phys. 11 (2015)]

- Extraction of $|V_{ub}/V_{cb}|$ requires hadronic matrix elements

$$\langle p \,|\, \bar{u}\gamma^\mu b \,|\Lambda_b\rangle, \quad \langle p \,|\, \bar{u}\gamma^\mu \gamma_5 b \,|\Lambda_b\rangle,$$
$$\langle \Lambda_c| \,\bar{c}\gamma^\mu b \,|\Lambda_b\rangle, \quad \langle \Lambda_c| \,\bar{c}\gamma^\mu \gamma_5 b \,|\Lambda_b\rangle$$

from LQCD





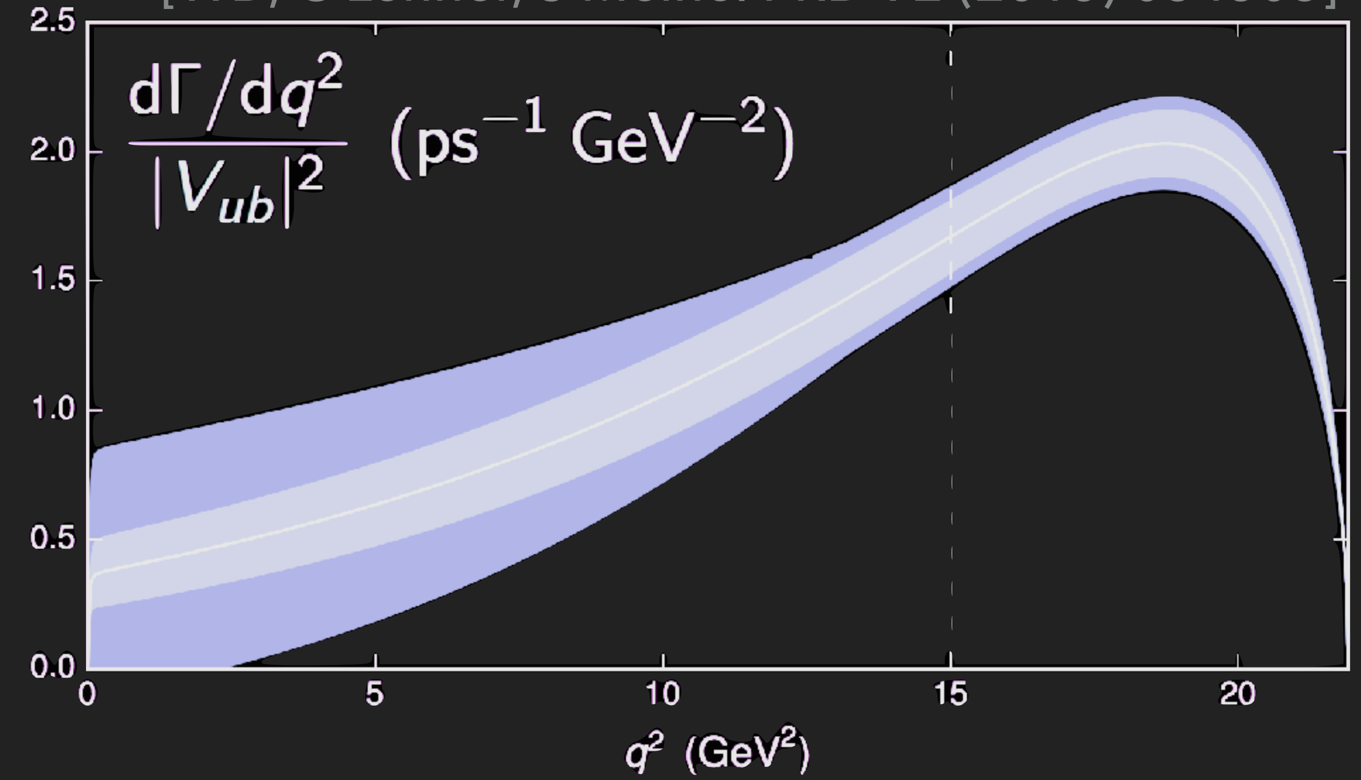
Λ_B DECAYS

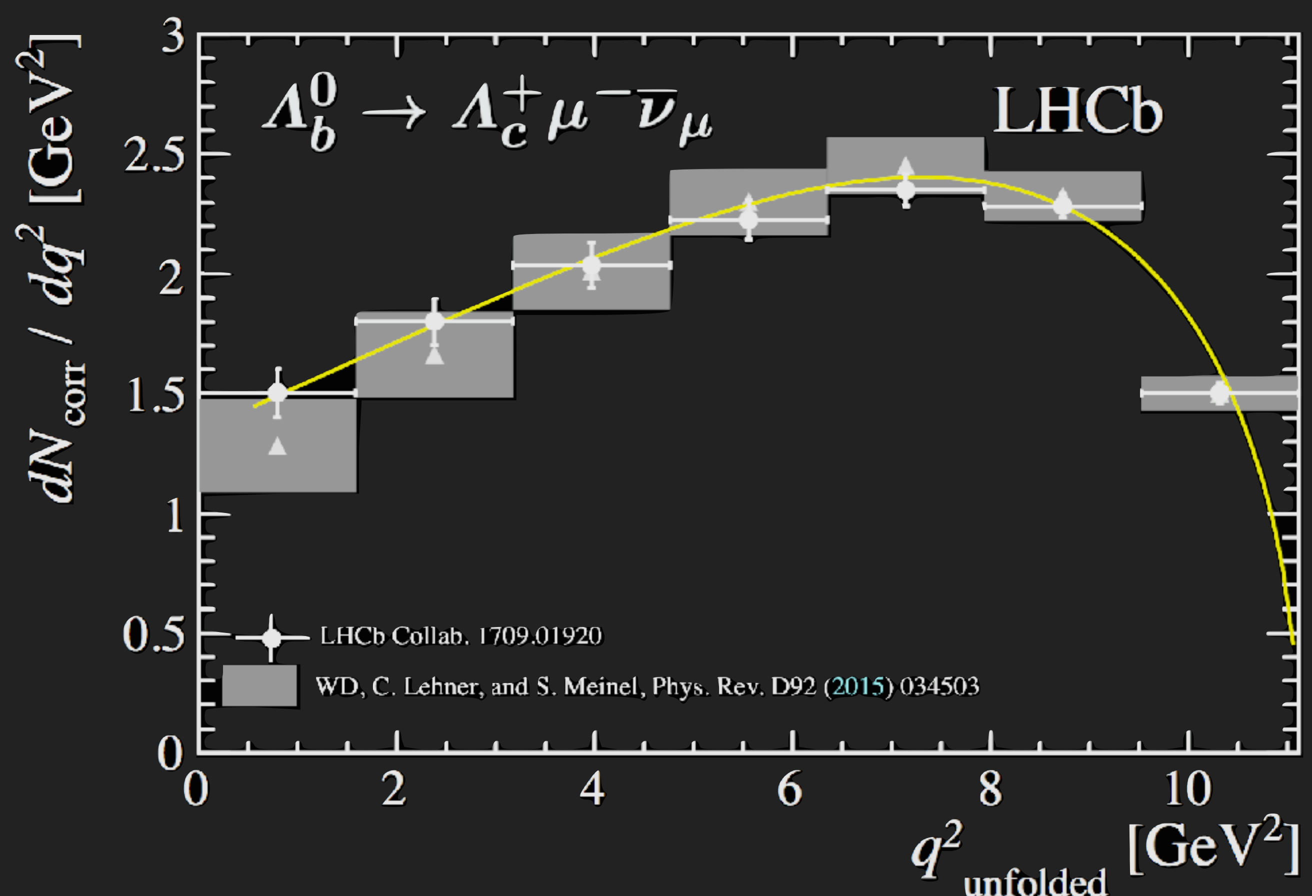
- 12 form factors needed
- Careful consideration of systematic uncertainties
  - Precise at large q^2
- Compare partial integrals

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.083(4)_{\rm expt}(4)_{\rm latt}$$

- Combine with exclusive V_{cb} to get $|V_{ub}|$
- Recent LHCb shape extraction agrees perfectly

[WD, C Lehner, S Meinel PRD 92 (2015) 034503]



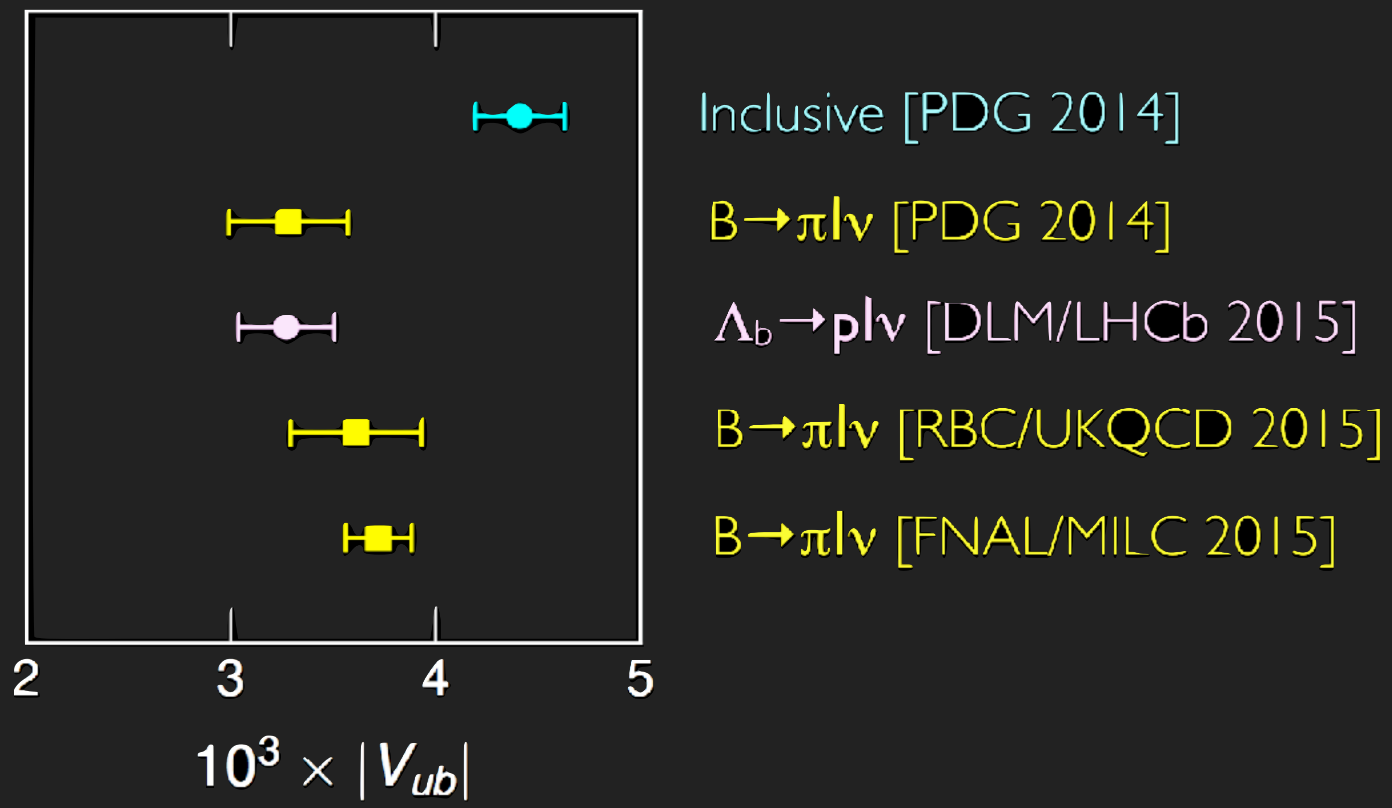


INCLUSIVE VS EXCLUSIVE V_{UB}

- Consistent with mesonic exclusive measurement

$$|V_{ub}| = 3.27(0.15)_{\rm expt}(0.16)_{\rm latt}(0.06)_{V_{cb}} \times 10^{-3}$$

- Disfavours RH currents as a solution to tension



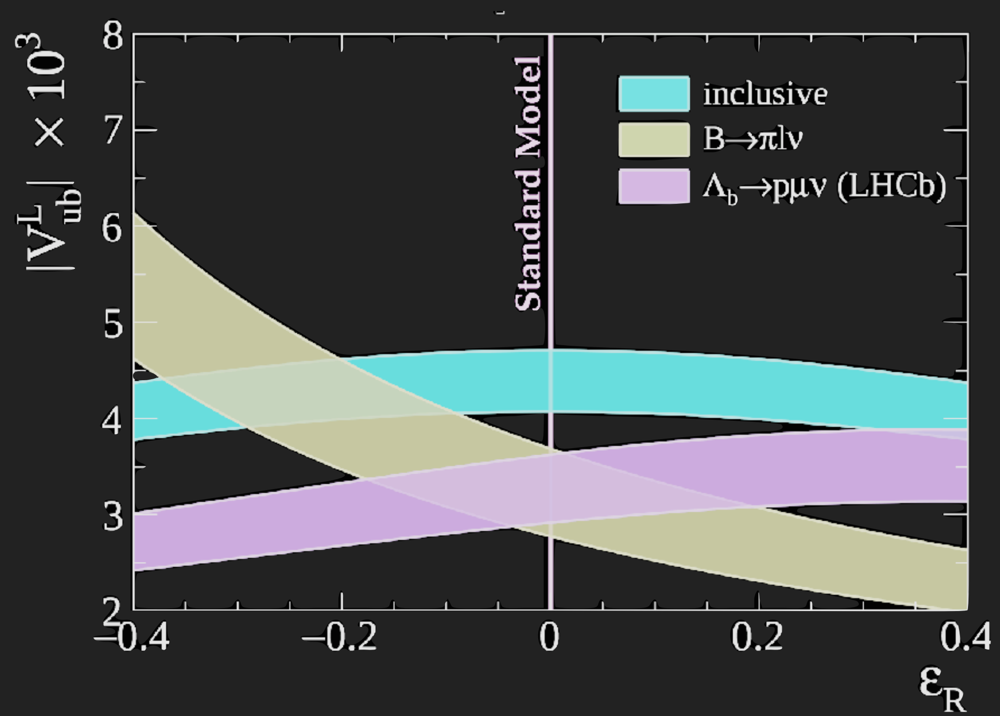
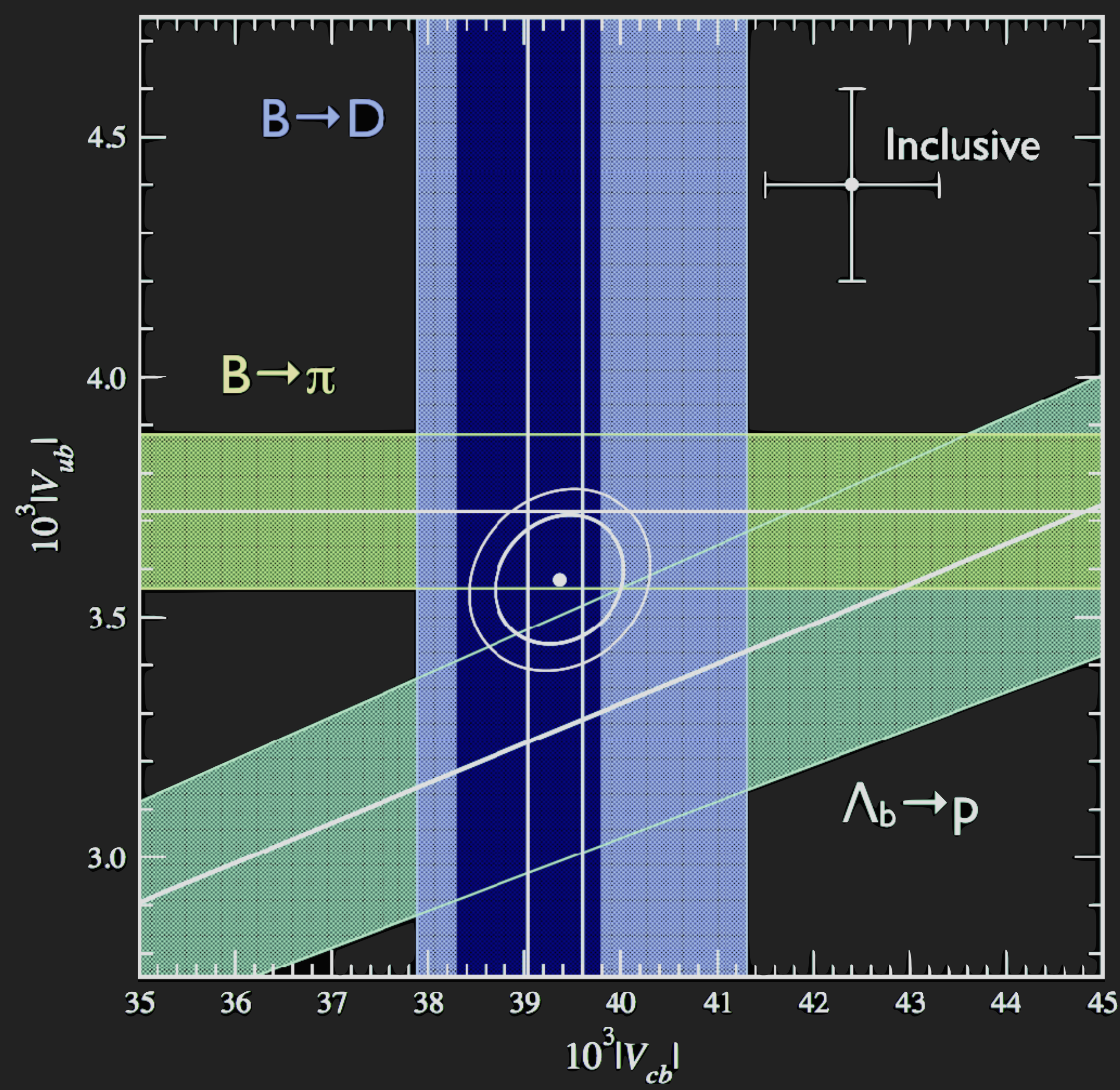


figure modified from LHCb 1504.01568

INCLUSIVE VS EXCLUSIVE V_{UB} & V_{CB}

- Exclusive extractions:
  - very different experimental and theoretical systematics
  - Mutual consistency (p=0.26)
- Inclusive extractions in significant tension
- RH current solutions disfavoured by baryonic extraction
- ?

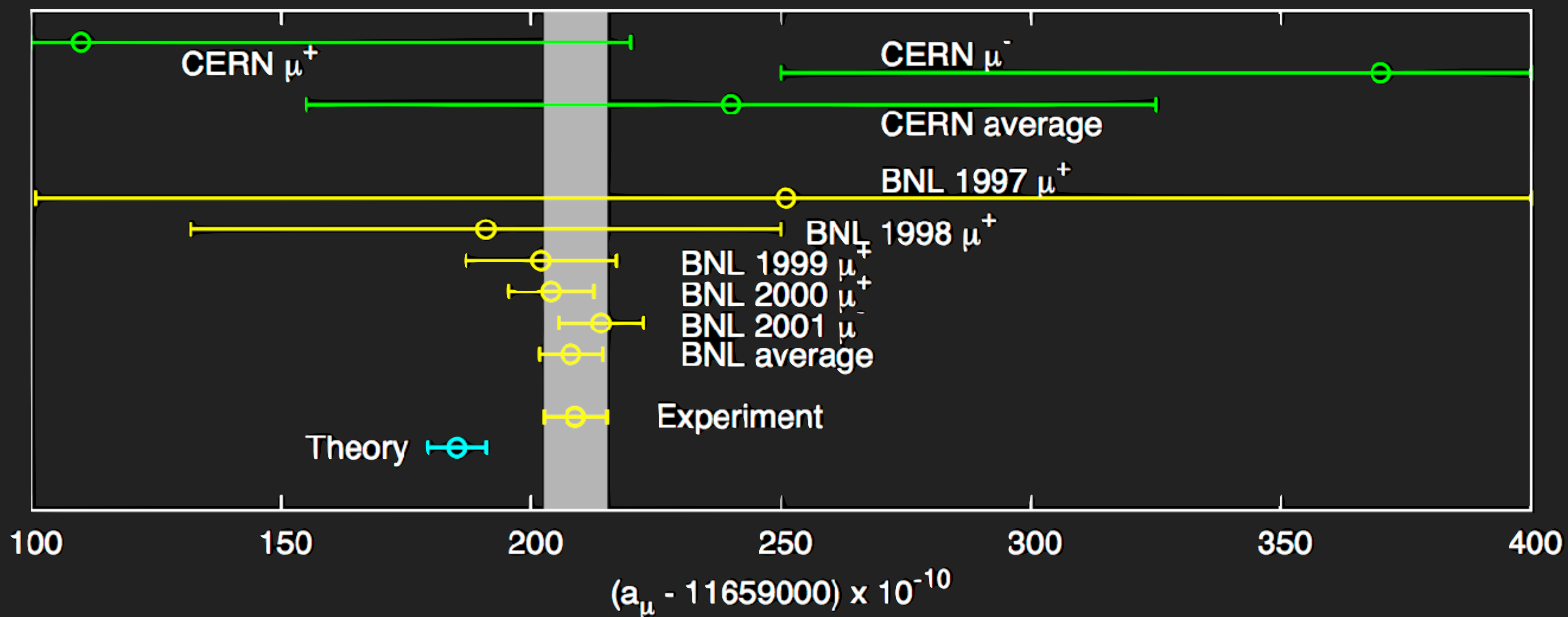
Summary figure from A Kronfeld



MUON ANOMALOUS MAGNETIC MOMENT

STATUS AND CHALLENGES

- Long standing discrepancy between measured value and SM estimate for muon anomalous magnetic moment (~3σ)



- Sign of new physics or problem with theory?
- New experiments aiming at 4-fold uncertainty reduction (E989 @ Fermilab, E34 @ JPARC)
  - Requires commensurate control of theory

Snowmass: The Muon (g-2) Theory Value: Present and Future [T Blum et al. 1311.2198]

STANDARD MODEL (G-2)$_{MU}$

- Measured value

$$a_\mu^{E821} = (116\,592\,089 \pm 63) \times 10^{-11} \quad (0.54\,\text{ppm})$$

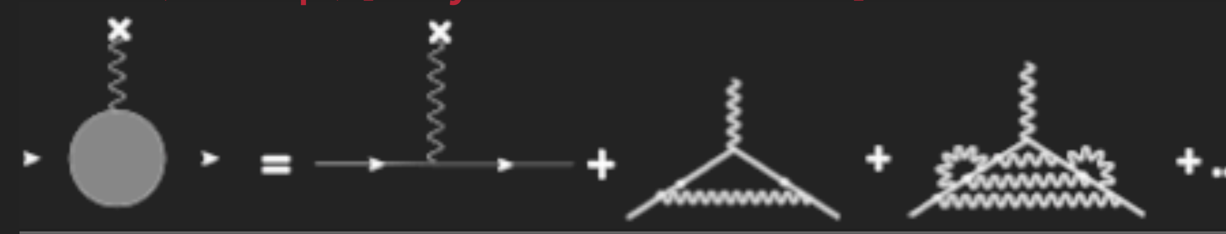
- Breakdown of contributions (2 evaluations of HVP)

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

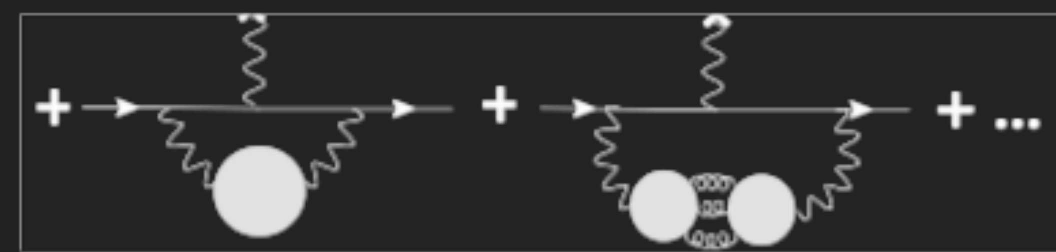
- Deviation

$$\begin{aligned}\Delta a_\mu(\text{E821} - \text{SM}) &= (287 \pm 80) \times 10^{-11}\ [20] \\ &= (261 \pm 78) \times 10^{-11}\ [21]\end{aligned}$$

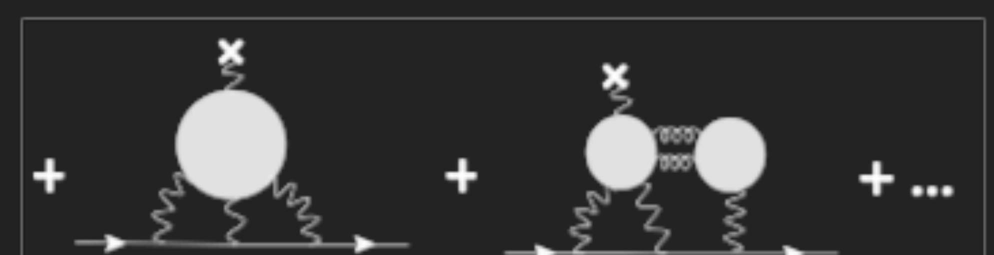
QED (5 loop) [Aoyama et al. 2012]



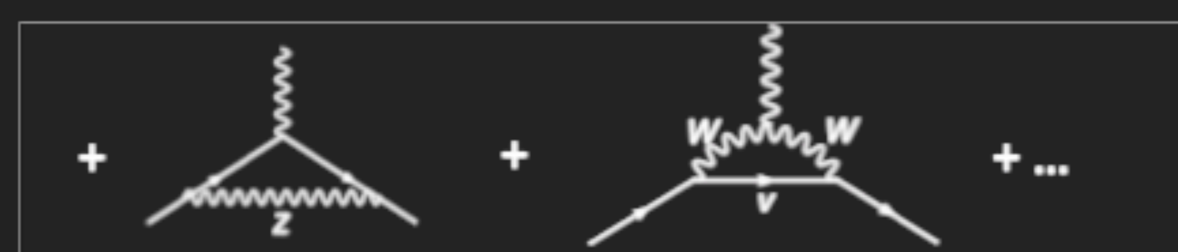
Hadronic vacuum polarisation



Hadronic light-by-light



Electroweak (2 loop) [Czarnecki et al. 2006]



Snowmass: The Muon (g-2) Theory Value: Present and Future [T Blum et al. 1311.2198]

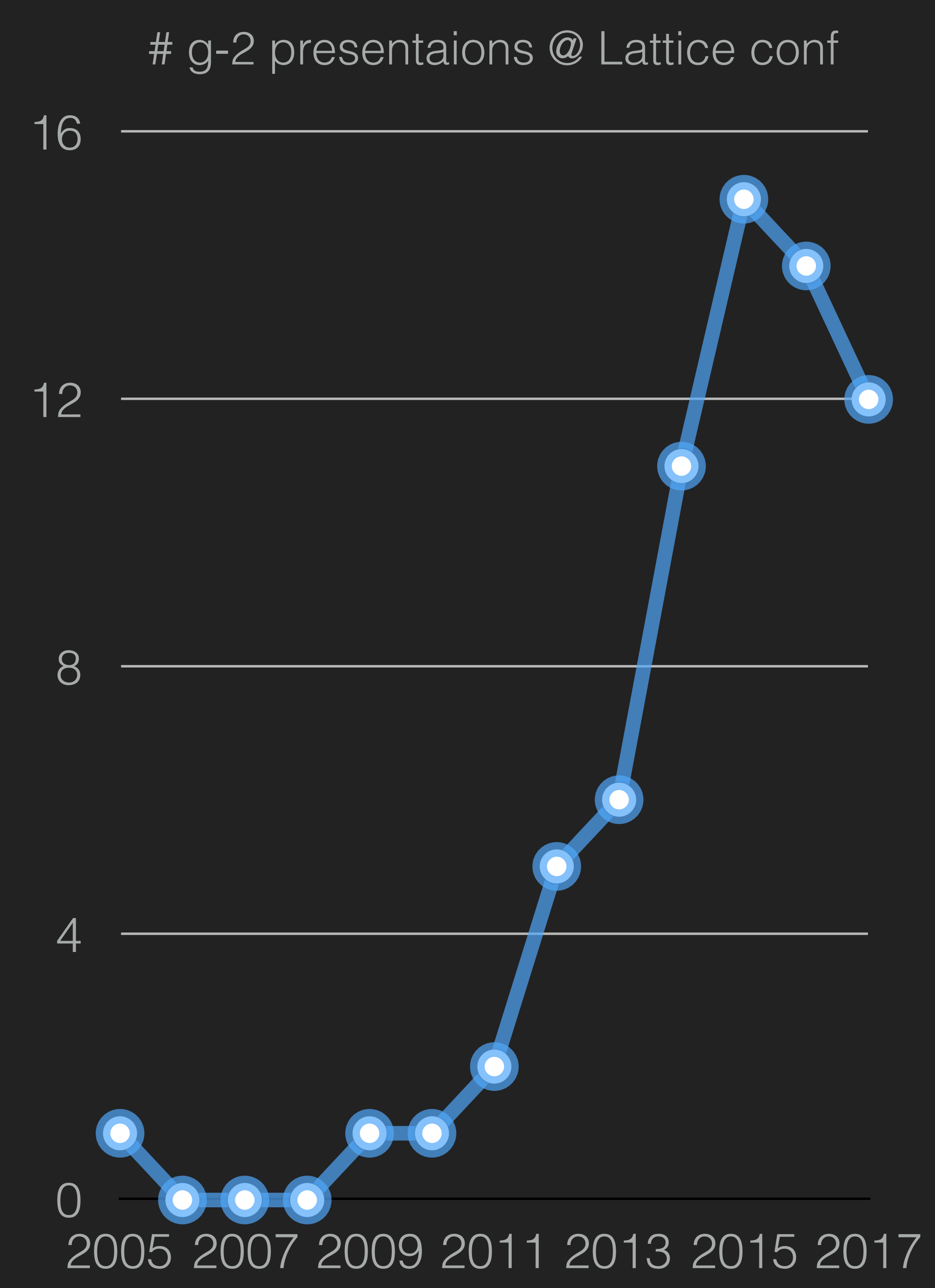
HOT TOPIC IN LQCD

- LQCD requirements

Lattice	precision	timescale	benchmark
HVP	1-2%	Few years	τ -- e+e⁻ discrepancy
HVP	sub-%	This decade	Competitive w/ e+e⁻
hLbL	any	soon	Course Verification of models
hLbL	~30%	3-5 years	Competitive with models
hLbL	~10%	Ultimate goal	Replace models

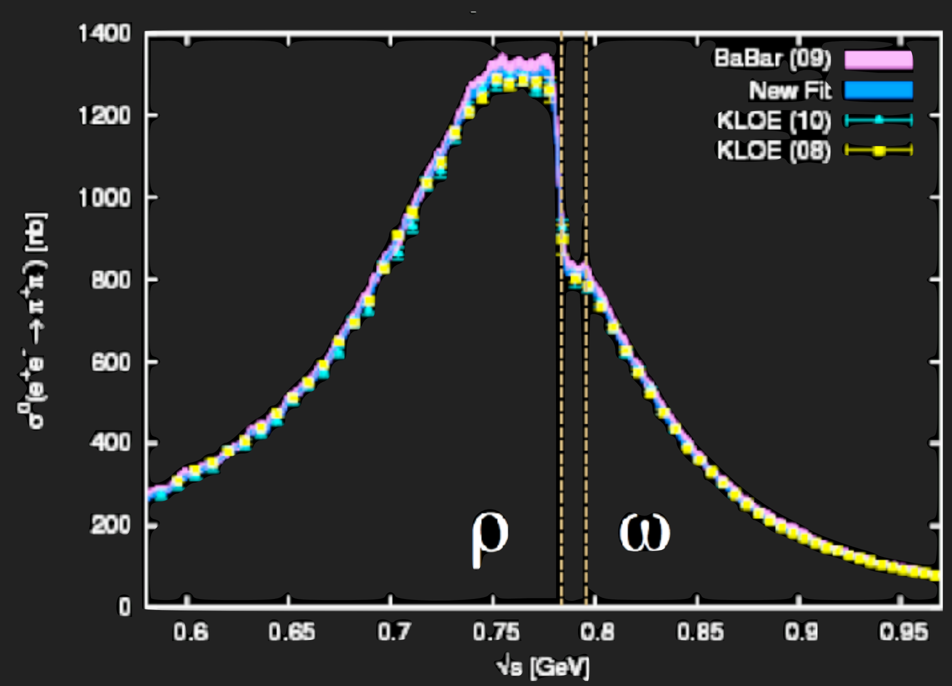
[B Casey Lattice 2014 projections]

- Hugely active area of LQCD
  - Efforts to increase precision on HVP
  - Exploration of techniques to address HLbL



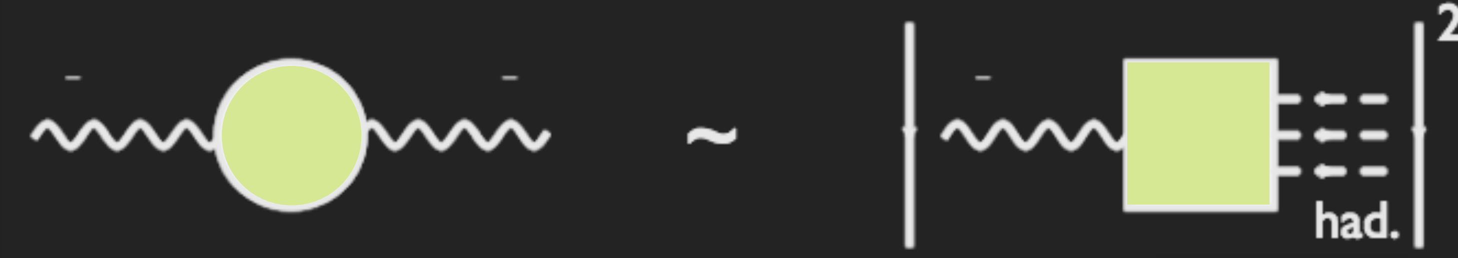
HADRONIC VACUUM POLARISATION

- Current theoretical estimate from dispersive treatment
- Use data on $\sigma(e^+e^- \to \text{hadrons})$ combining many data sets

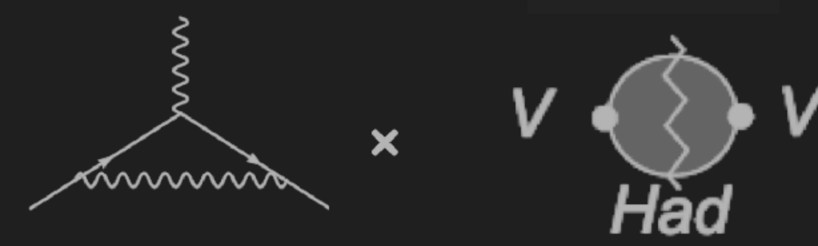


- Complicated analysis (0.6% prec)

$$a_\mu^{\text{HVP,LO}} = (694.91 \pm 4.27) \times 10^{-10}$$



$$a_\mu^{\text{had}} = \int ds$$



$$\Pi_V(k^2) - \Pi_V(0) = \frac{k^2}{\pi} \int_{4m_\pi^2}^{\infty} ds \frac{\text{Im}\Pi_V(s)}{s(s - k^2 - i\epsilon)}$$

$$\text{Im}\Pi_V(s) = \frac{s}{4\pi\alpha} \sigma_{\text{tot}}(e^+e^- \to X)$$

$$a_\mu^{\text{HVP}} = \frac{1}{4\pi^2} \int_{4m_\pi^2}^{\infty} ds K(s) \sigma_{\text{total}}(s)$$

HADRONIC VACUUM POLARISATION

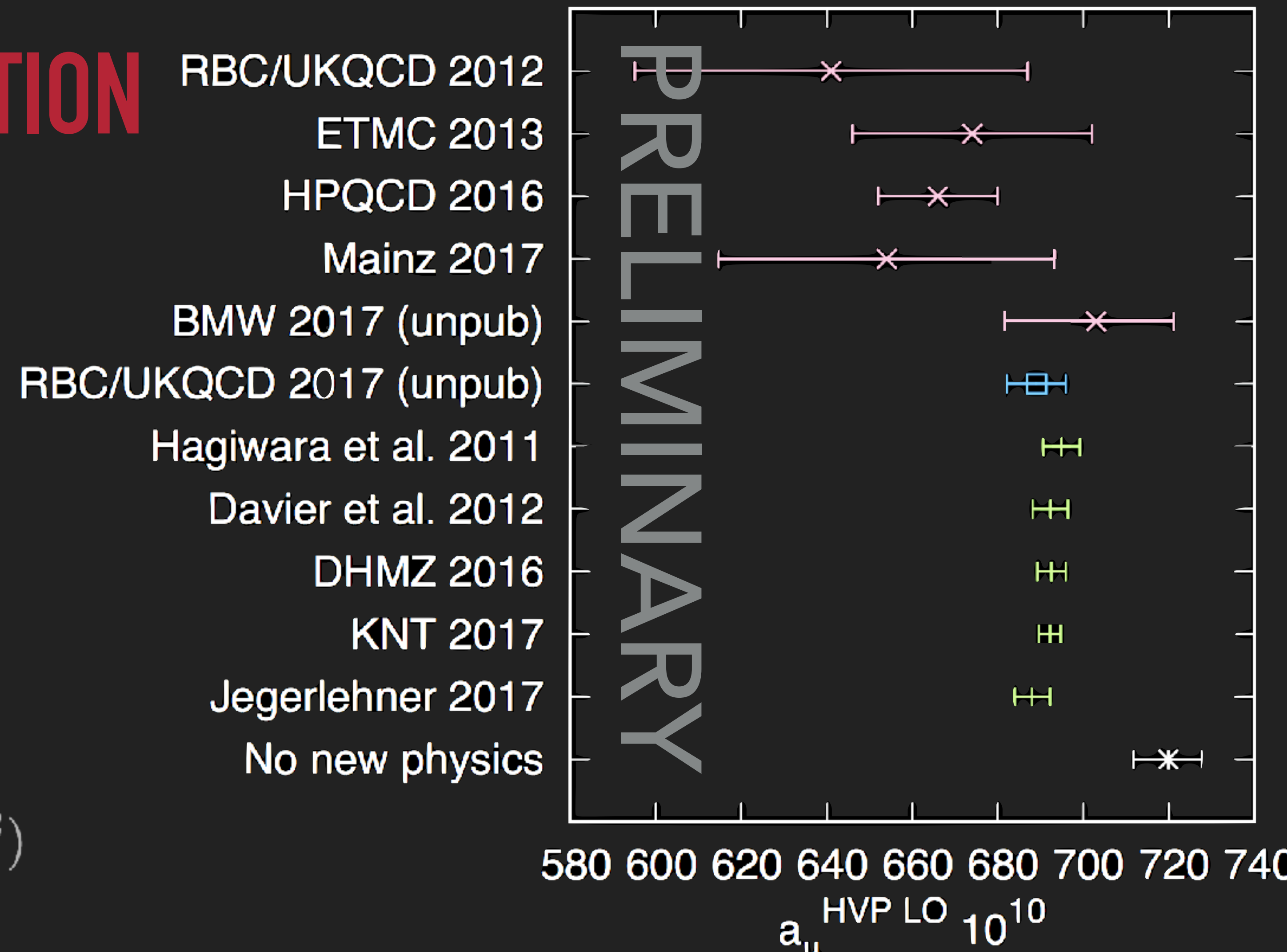
- Can be computed from SM directly [Blum PRL91 (2003) 052001]
- Analytically continue to Euclidean space $K^2 = -q^2 > 0$

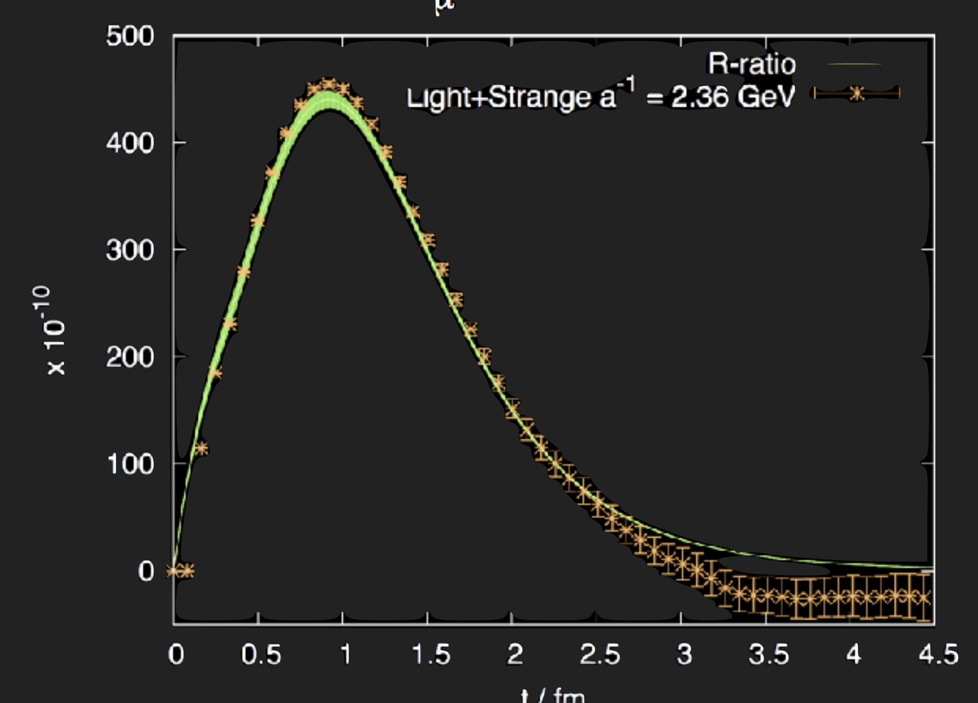
  Use modified kernel

$$a_\mu = \frac{g-2}{2} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dK^2 f(K^2)\hat{\Pi}(K^2)$$

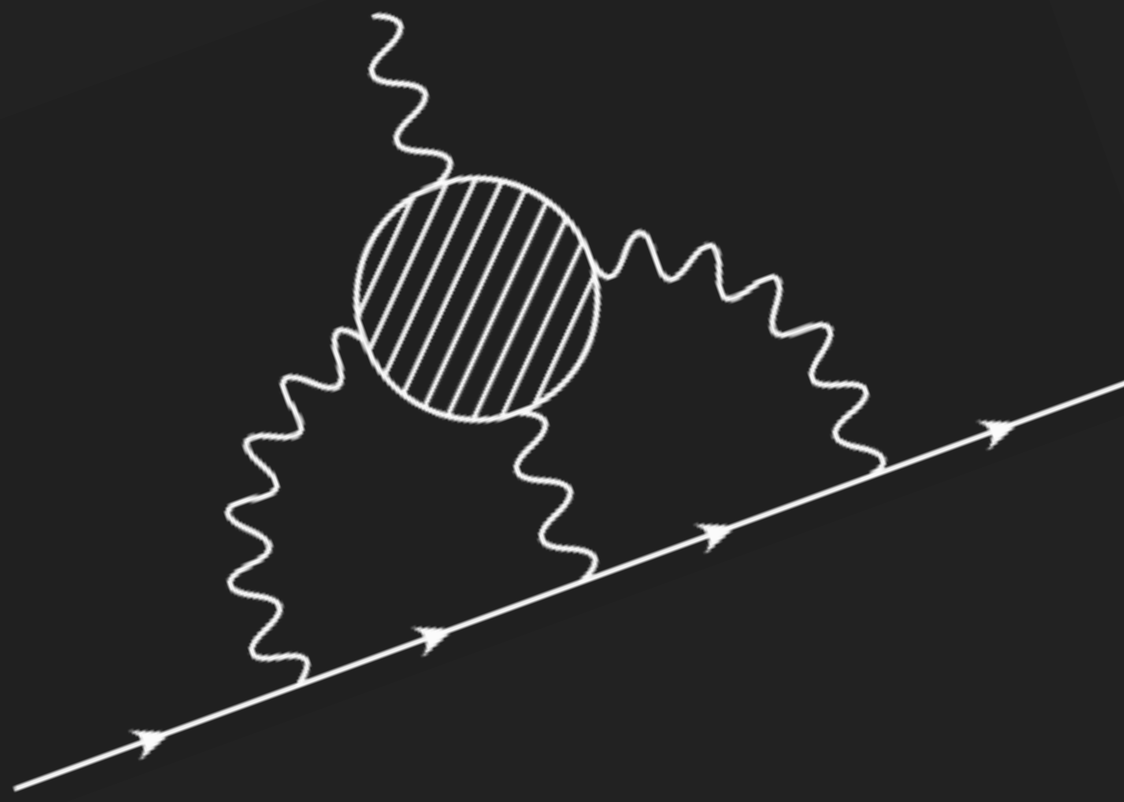
- Precision goal is challenging, but calculations rapidly improving
- Can also combine LQCD and dispersion relations
- Flavour breakdown: light~90%, strange~8% and charm~2%

C Lehner, Lattice 2017

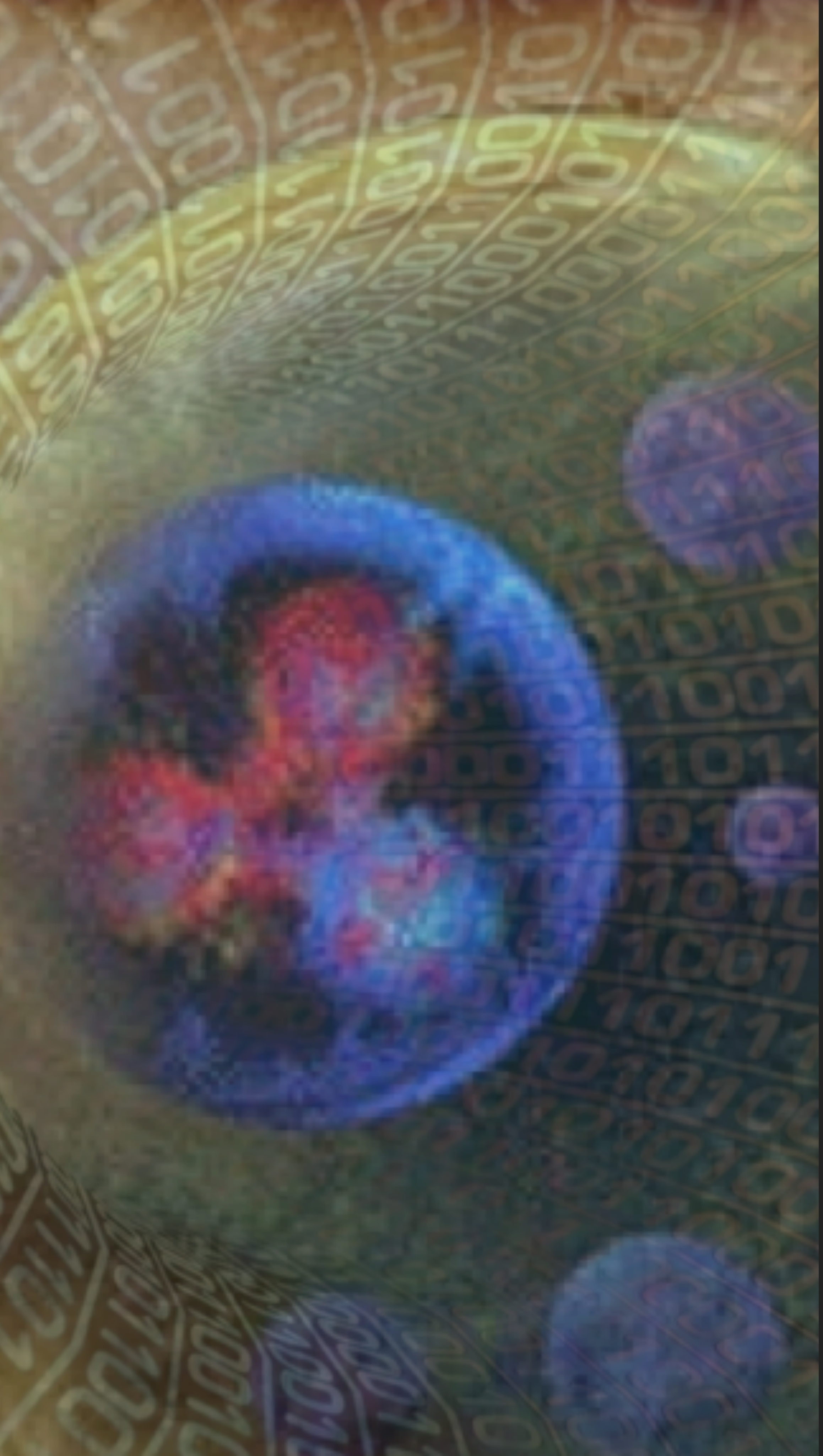




HADRONIC LIGHT-BY-LIGHT



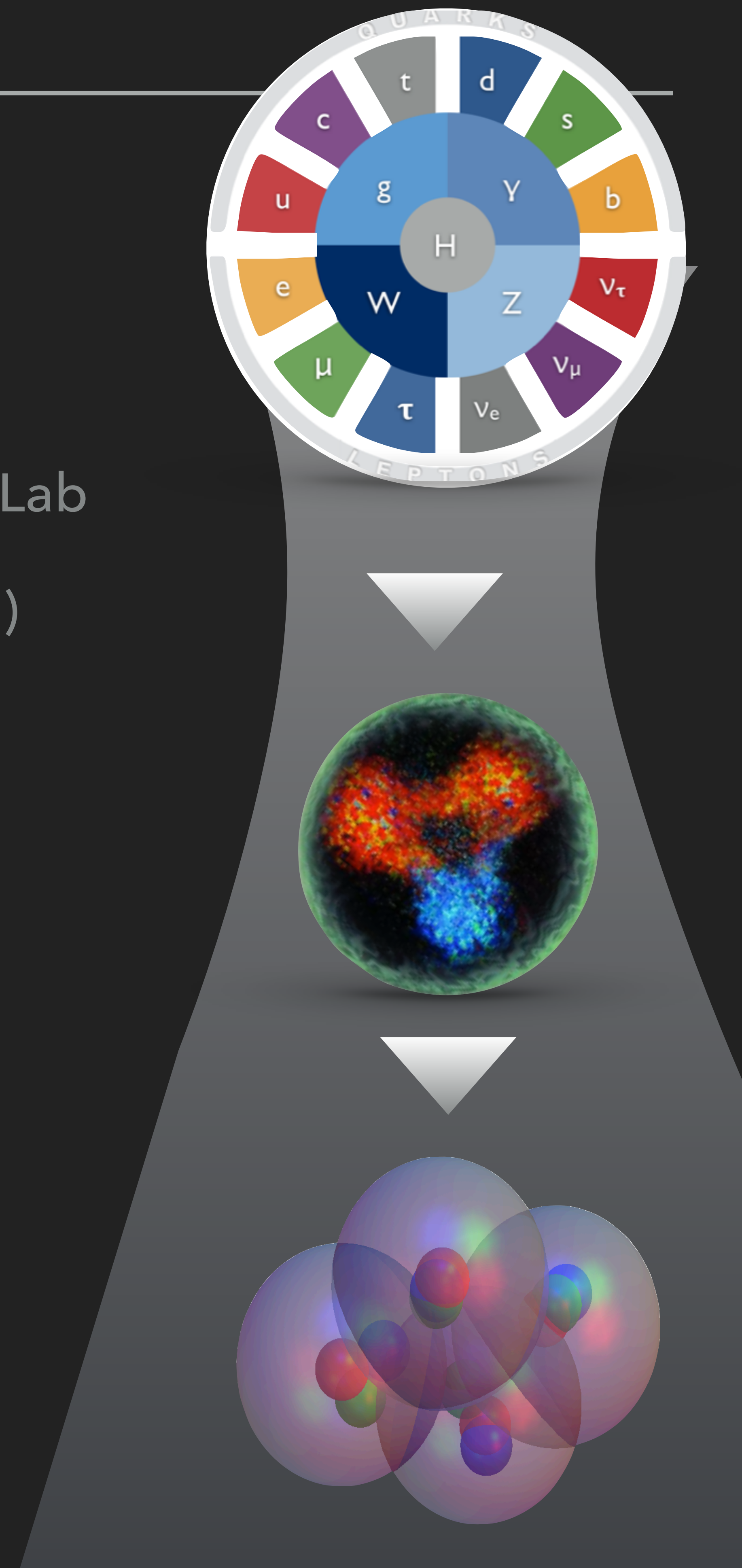
- HLbL smaller but hard to determine
- Currently guesstimated from models
  (Colangelo *et al.*: dispersive analysis of some pieces)
- Various methods being explored
  - QCD+QED simulations
  - QCD with QED inserted pertubatively
  - Direct calculation of 4-pt correlator: 32 relevant tensor structures required for all possible momenta k_1, k_2!
  - Calculation of relevant subprocesses/input to dispersive
- All challenging, but significant progress
  - 10% uncertainty seems reachable in ~5 years



HADRONS AND NUCLEI

HIGHLIGHTS

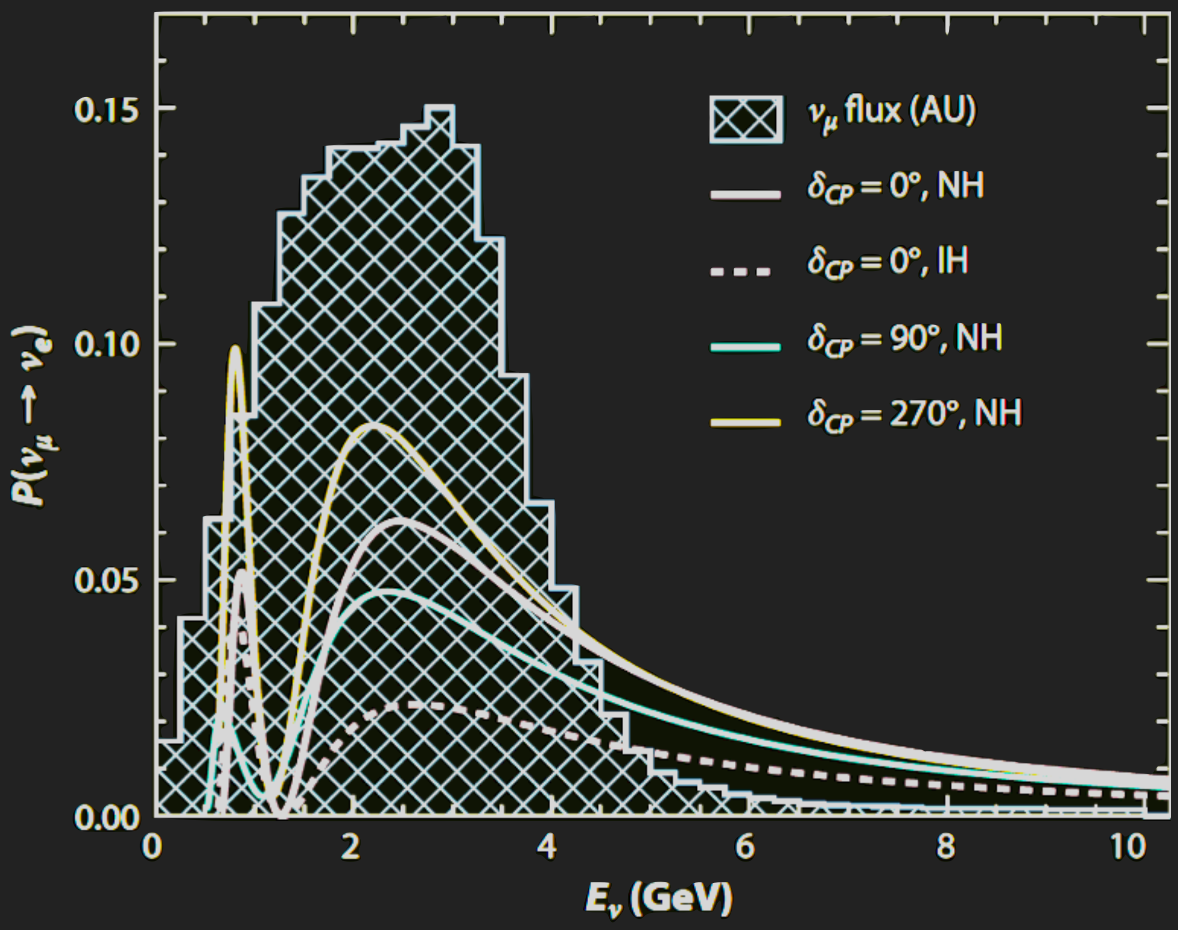
- Hadron spectroscopy
  - Exotic excited states guiding GlueX experiment @ JLab
  - Predictions for hadrons with heavy quarks (Ξ_{cc},Ξ_b',…)
- Hadron structure
  - Complete spin decomposition of the proton
  - New approaches to Bjorken x dependence of PDFs
- Nuclei [see Holt, Monday]
  - Properties (magnetic moments) and interactions (np→dγ, pp-fusion,…) of light nuclei
  - Progress towards double-β decay matrix elements



LONG BASELINE NEUTRINO EXPERIMENTS

- DUNE: extract mass hierarchy and mixing parameters
- Neutrino scattering on argon
- Need fluxes/energies to high accuracy
  - Currently a challenging systematic
  - Axial properties of the nucleon and nuclear effects
  - Wide range of energies: elastic, resonance and DIS

Diwan et al, Ann. Rev. Nucl. Part. Sci. 66, 47 (2016)



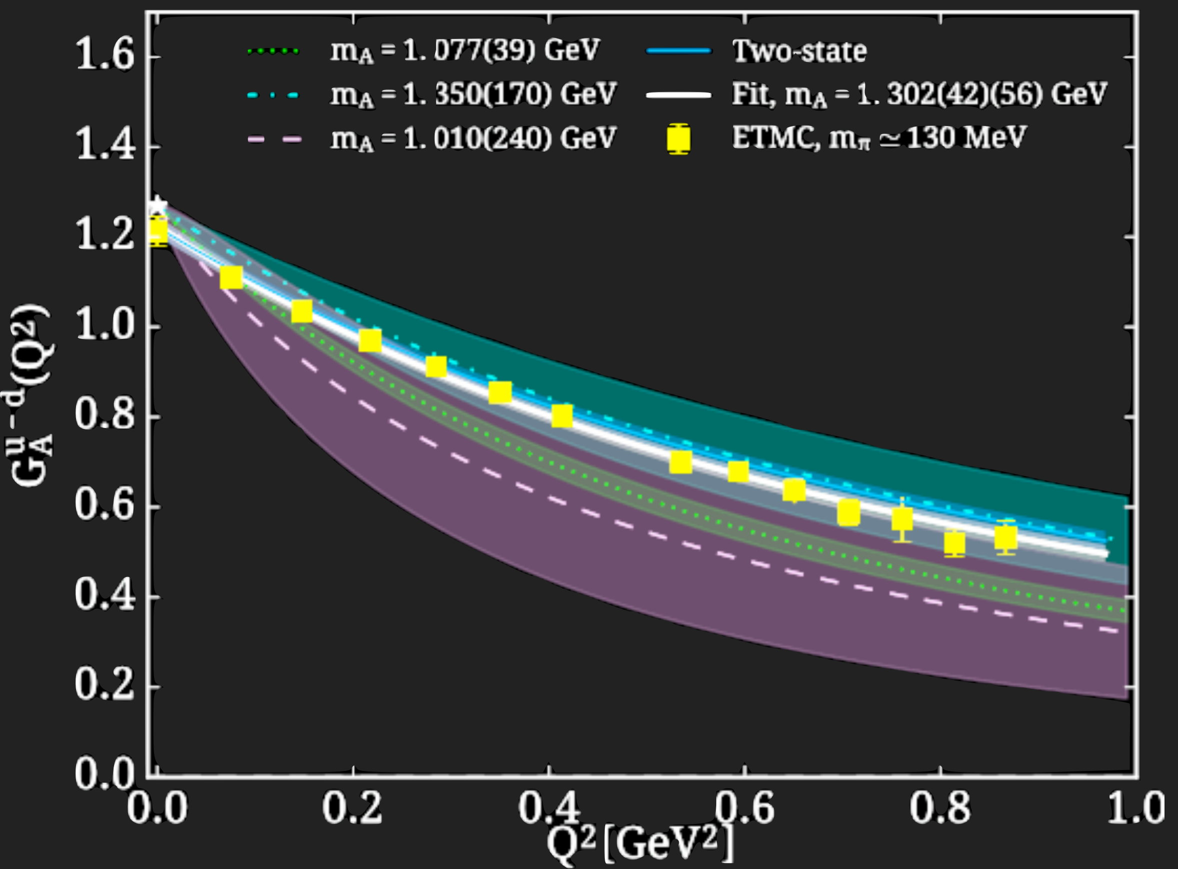
AXIAL FORM FACTORS

- Proton structure calculations in LQCD are challenging
  - Exponentially bad Monte-Carlo sampling (statistical noise)
  - Estimating systematics becomes tricky
- Now reaching necessary sophistication
- Eg: FFs of axial current

$$\langle N_{s'}(p')|J^5_\mu|N_s(p)\rangle = \overline{u}_N(p',s')\left[\gamma_\mu\gamma_5 G_A(q^2) - \frac{iq_\mu}{2M}G_P(q^2)\right]u_N(p,s)$$

  - Calculated by many groups
- Soon will be more precise than phenomenological extractions

C. Alexandou et al. (2016), arXiv:1702.00984

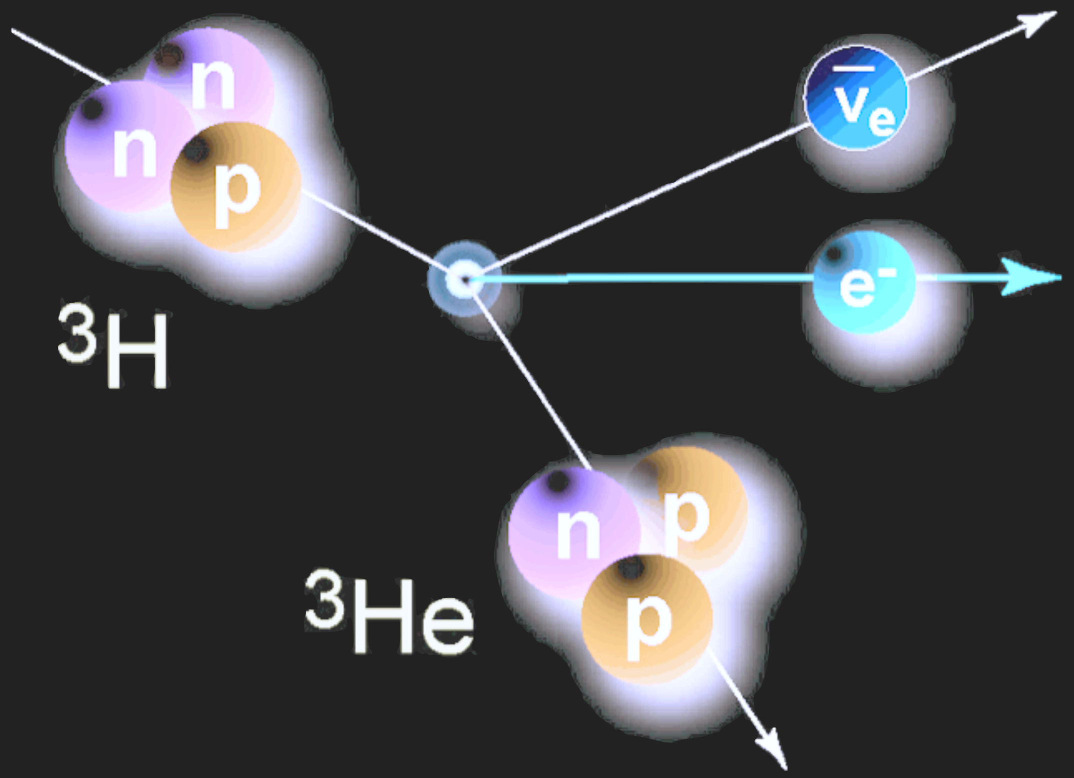


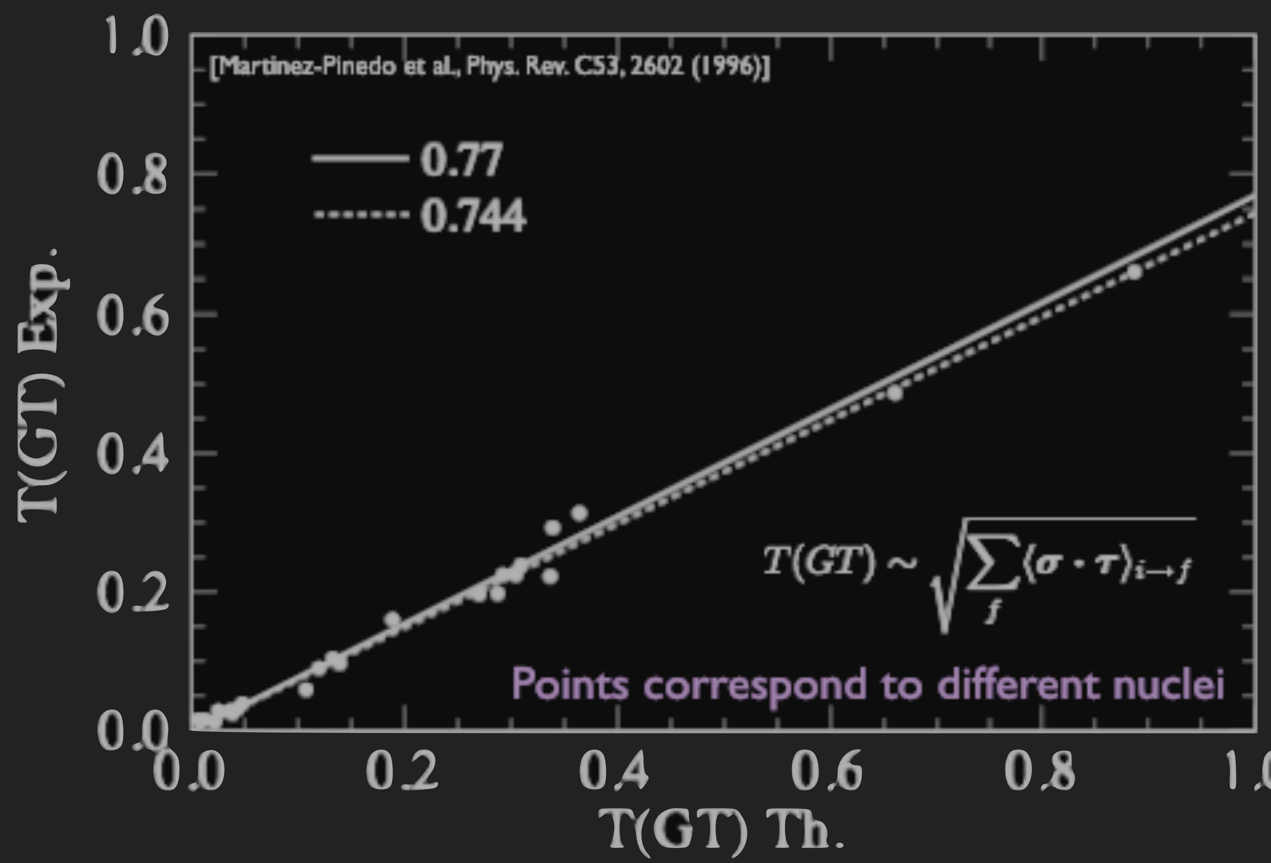
TRITIUM BETA DECAY

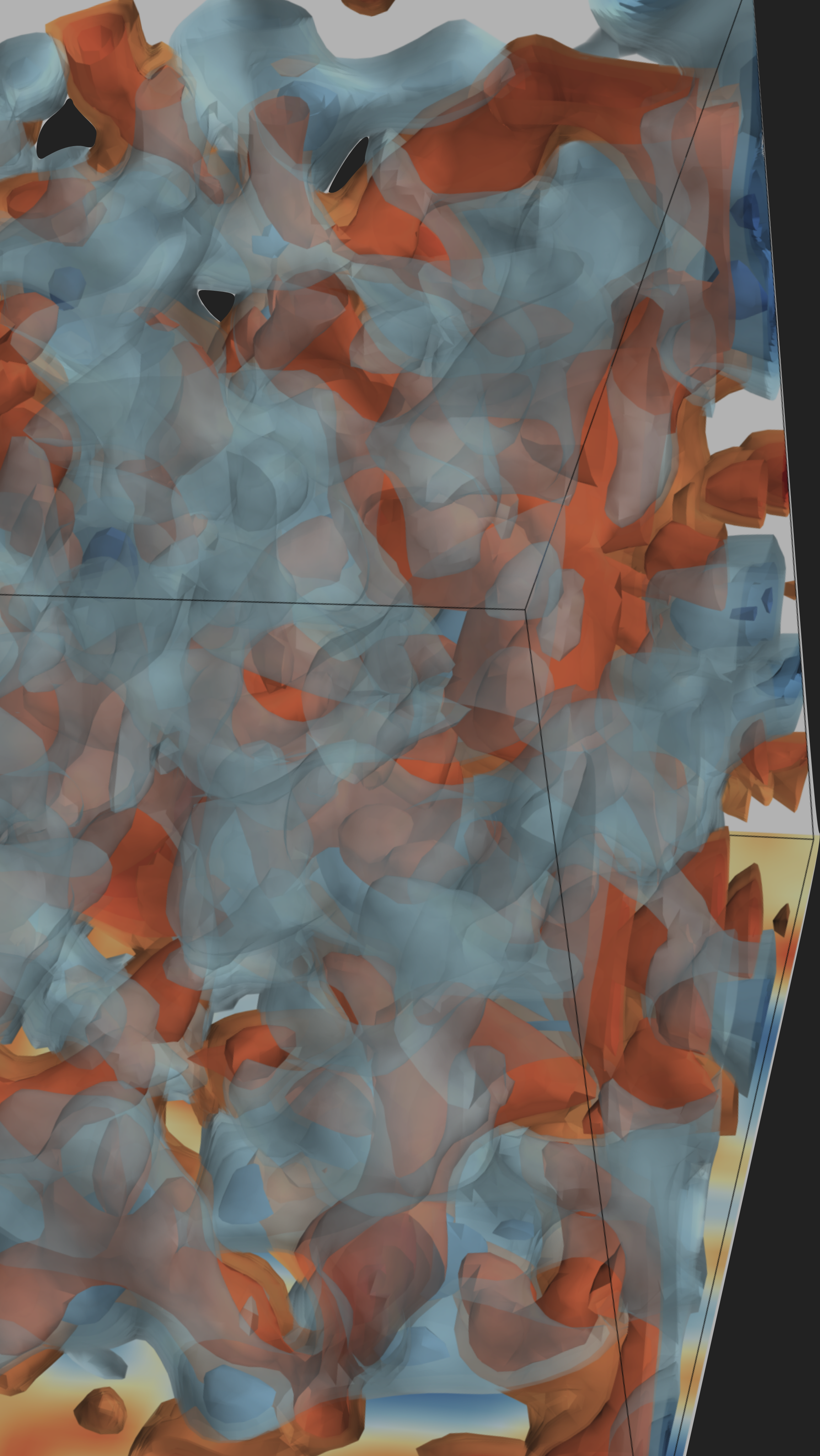
- Electroweak processes in light nuclei: first LQCD calculations
- Tritium decay
  - NPLQCD collaboration

$$\langle {}^3\mathrm{He}|\overline{\mathrm{q}}\gamma_k\gamma_5\tau^-\mathrm{q}|{}^3\mathrm{H}\rangle$$

  - Reproduce reduction of axial charge in nuclei (quenching)
  - Effective field theory for larger nuclei
    - Constrain constants by matching to QCD calculations of light nuclei
- Future: QCD understanding of nuclear axial matrix elements





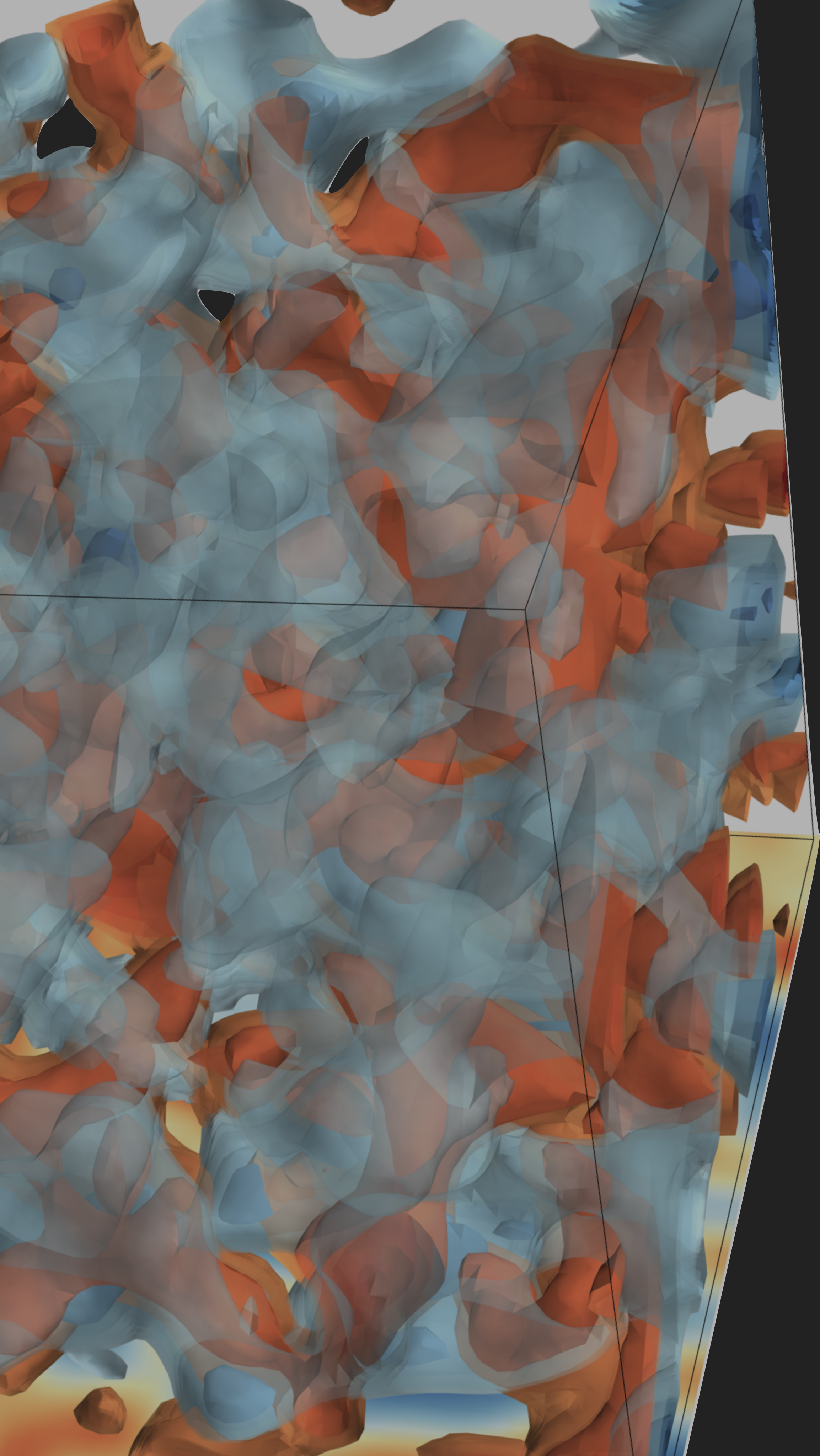


TRENDS IN LQCD

FUTURE

OUTLOOK

- Lattice QCD(+QED) pervasive in particle *and nuclear* phenomenology
  - Exciting opportunities in flavour physics (LHCb, Belle II)
  - $(g\text{-}2)_\mu$: E989 + LQCD HVP and HLbL with 5σ discrepancy??
  - LQCD (+EFT) broadening impact from flavour physics to nuclear physics
  - Many other exciting developments not covered!
- Needs sustained growth of HPC and funding for algorithm and software development and co-design

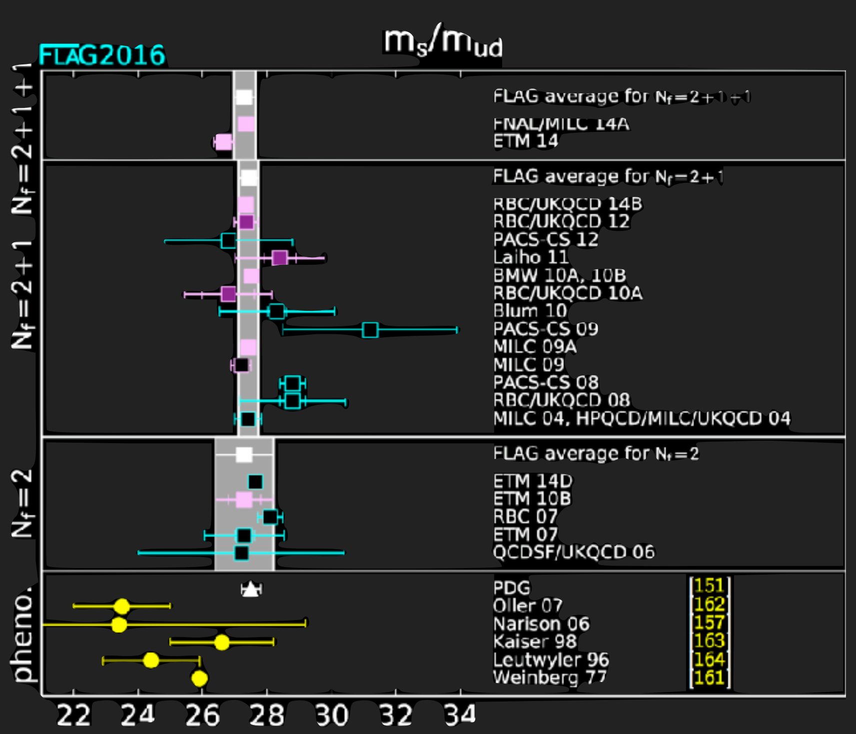


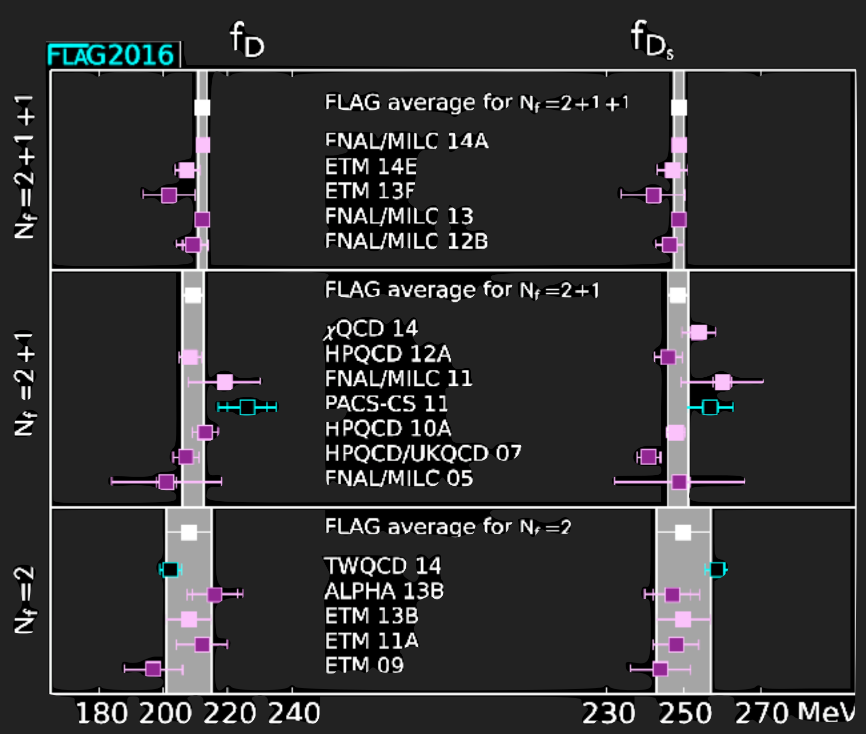
TRENDS IN LQCD

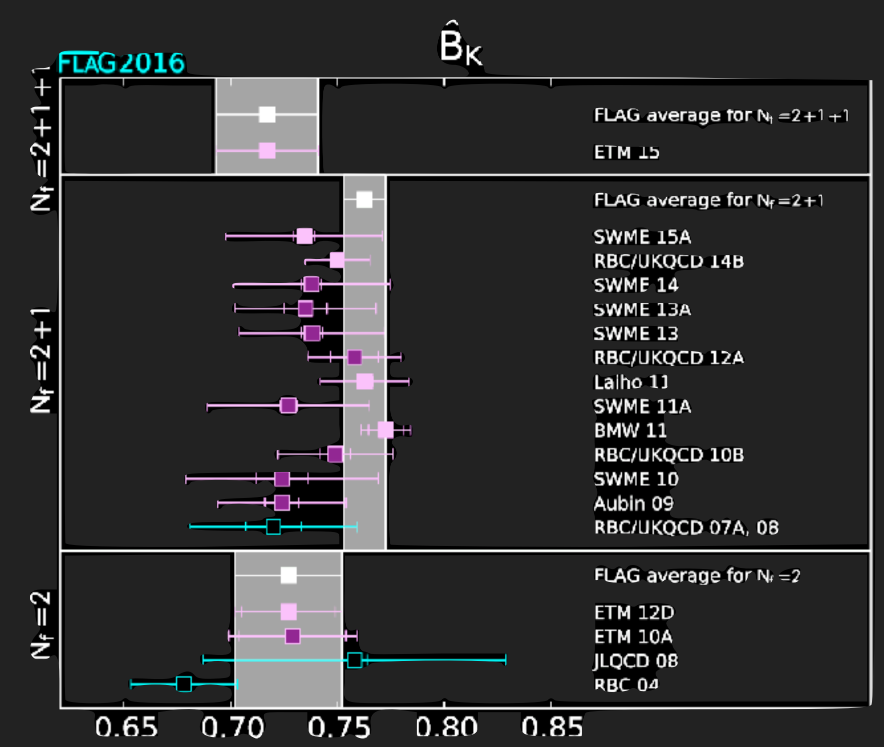
FIN

FLAG: MASSES, DECAY CONSTANTS, KAON BAG PARAMETER

- Quark masses, decay constants, form factors, kaon mixing, LECs…
- Colour coded for quality of calculation (# lattice spacings, volumes,…)

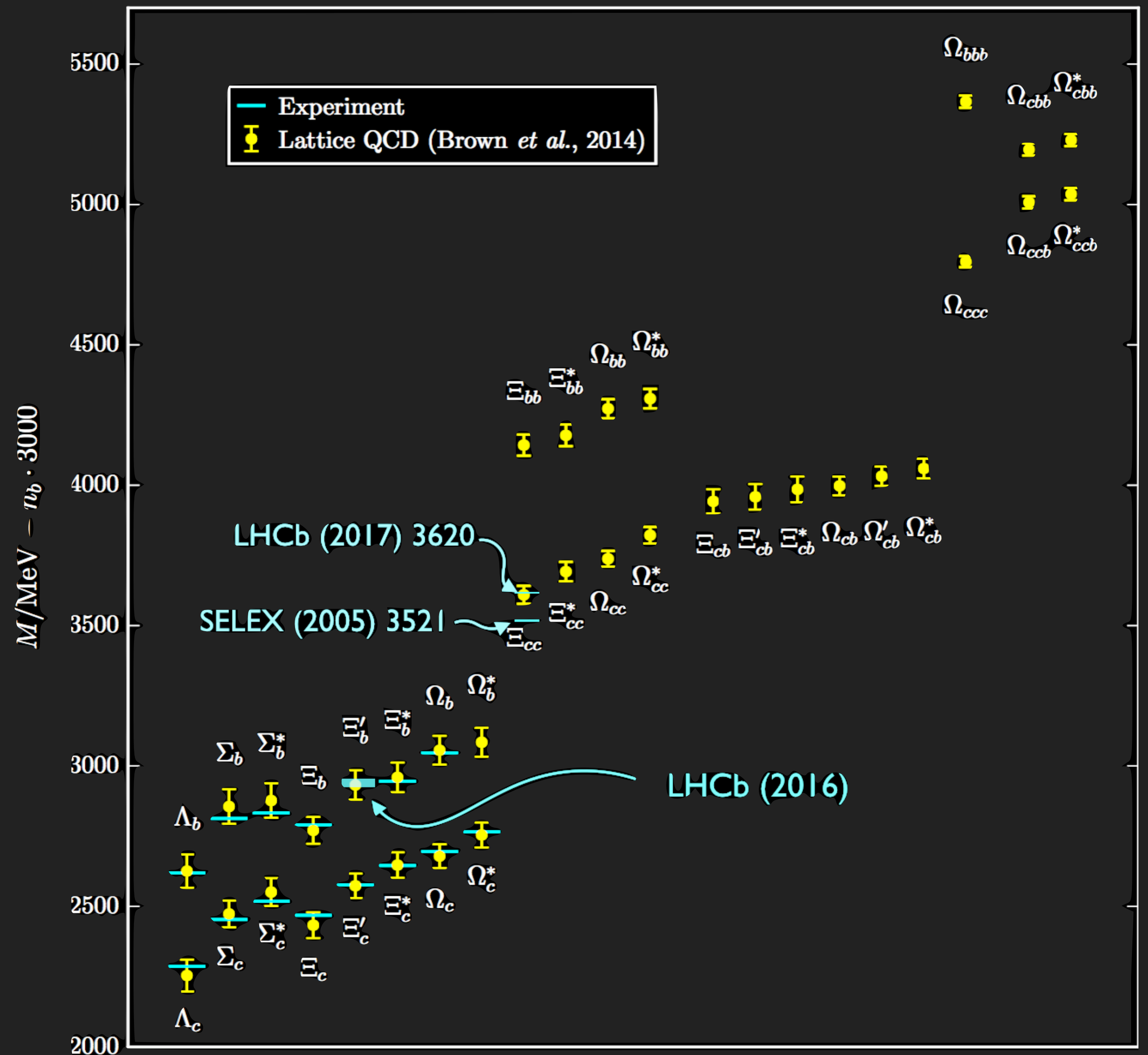






HEAVY HADRONS

- Predictions for baryons containing bottom/charm quarks



[Z Brown et al. PRD 2014]