Lattice QCD at the particle frontier

DPF2015
AUG 4-8 | ANN ARBOR, MI
Meeting of the **Division of Particles & Fields** of the American Physical Society

William Detmold, MIT

Lattice QCD at the particle frontier

I. Flavour physics

II.(g-2)

III. Future prospects: dark matter, neutrinos and ILC

[Many topics not covered]

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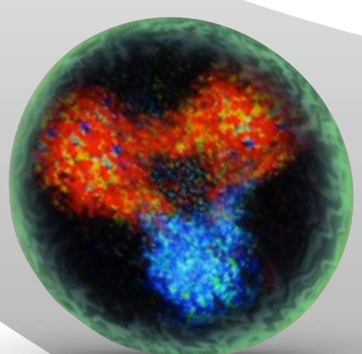
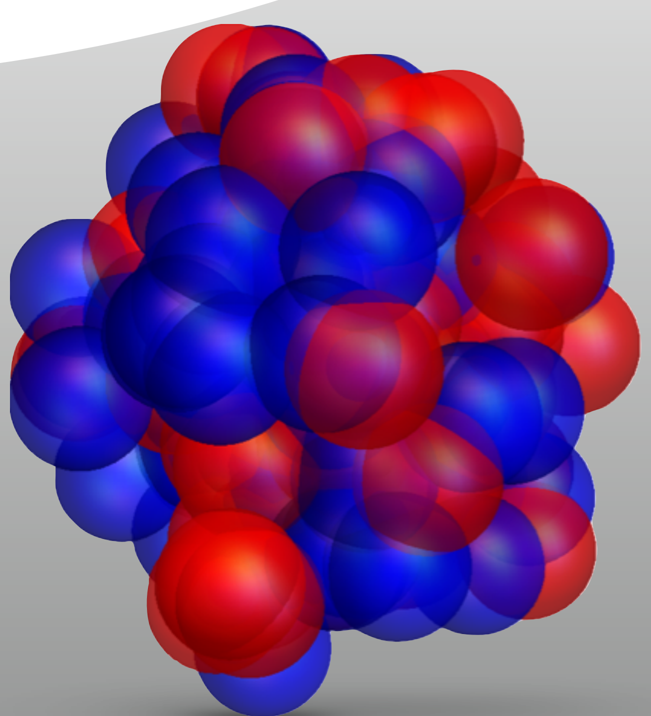
Lattice QCD

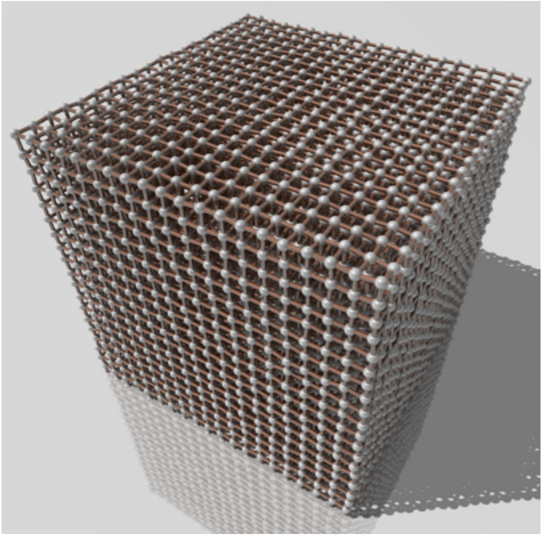
- Provide accurate, predictive calculational capability at hadronic scales enabling tests of the SM and searches for physics beyond it
- Understand the emergence of hadrons, nuclei and extreme forms of matter (RHIC, n-stars)
- Useful toolkit to study strongly interacting field theories beyond the SM

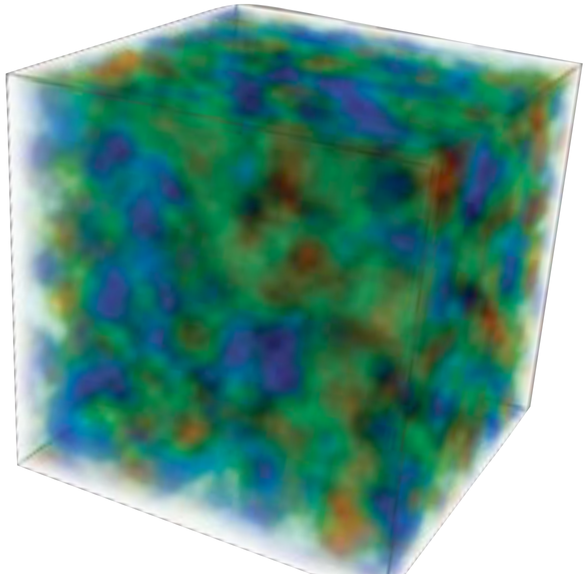




Quantum Chromodynamics

- Lattice QCD: tool to deal with quarks and gluons
  - Correlation functions as functional integral over quark and gluon d.o.f. on R4
    $$\langle \mathcal{O} \rangle = \int dA_\mu dq d\bar{q}\, \mathcal{O}[q, \bar{q}, A] e^{-S_{QCD}[q, \bar{q}, A]}$$
    perform quark integrals exactly
  - Discretise and compactify system
    - Finite but large number of d.o.f (10^{10})
  - Numerically integrate via importance sampling (average over important configurations)
  - Undo the harm done in previous steps
    - Lattice QCD ⇒ QCD

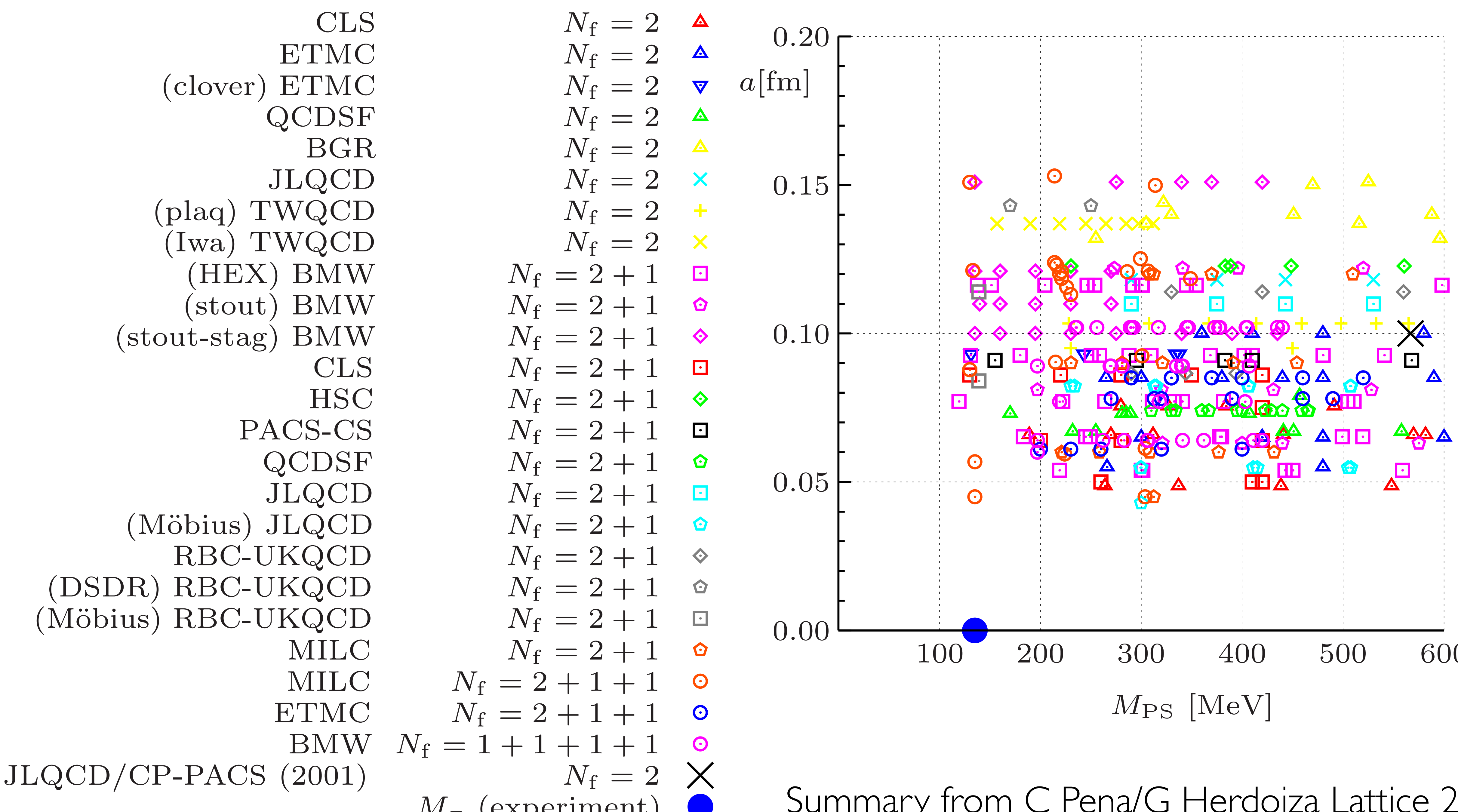




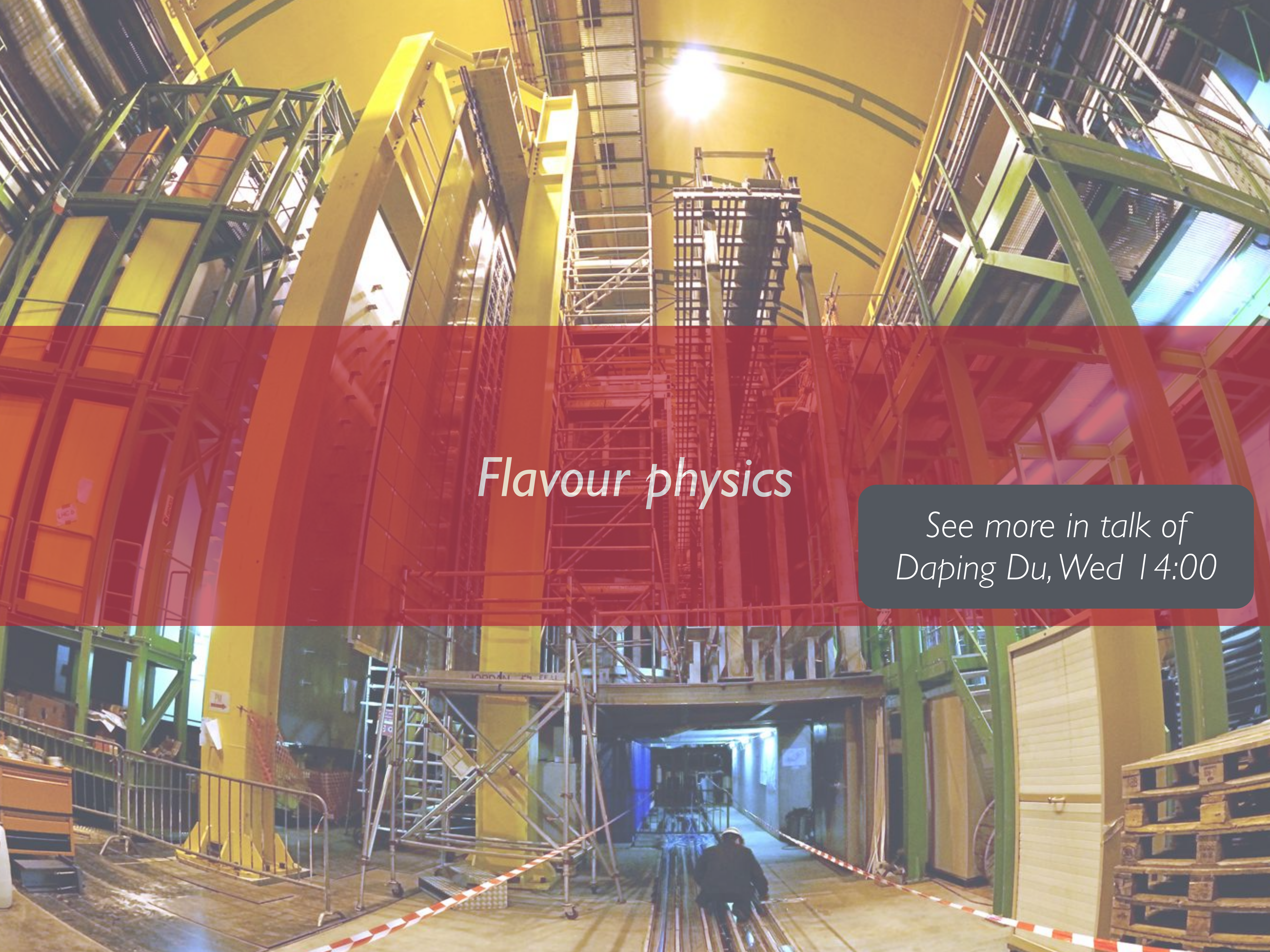
LQCD status report

- Lattice QCD has advanced markedly in the last 5 years
  - Faster computers and better algorithms
  - New approaches to physics challenges
- State-of-the-art calculations address all systematics (discretisation, finite size, …)
  - Sub percent accuracy on some quantities
  - Necessitates consideration of small effects: QED, isospin breaking (significant intellectual challenges to overcome)
- Scope increasing from meson physics to baryons and to light nuclei

- Different groups around the world using many technically different approaches to LQCD (c.f. 2001 state-of the-art)



Summary from C Pena/G Herdoiza Lattice 2015



Flavour physics

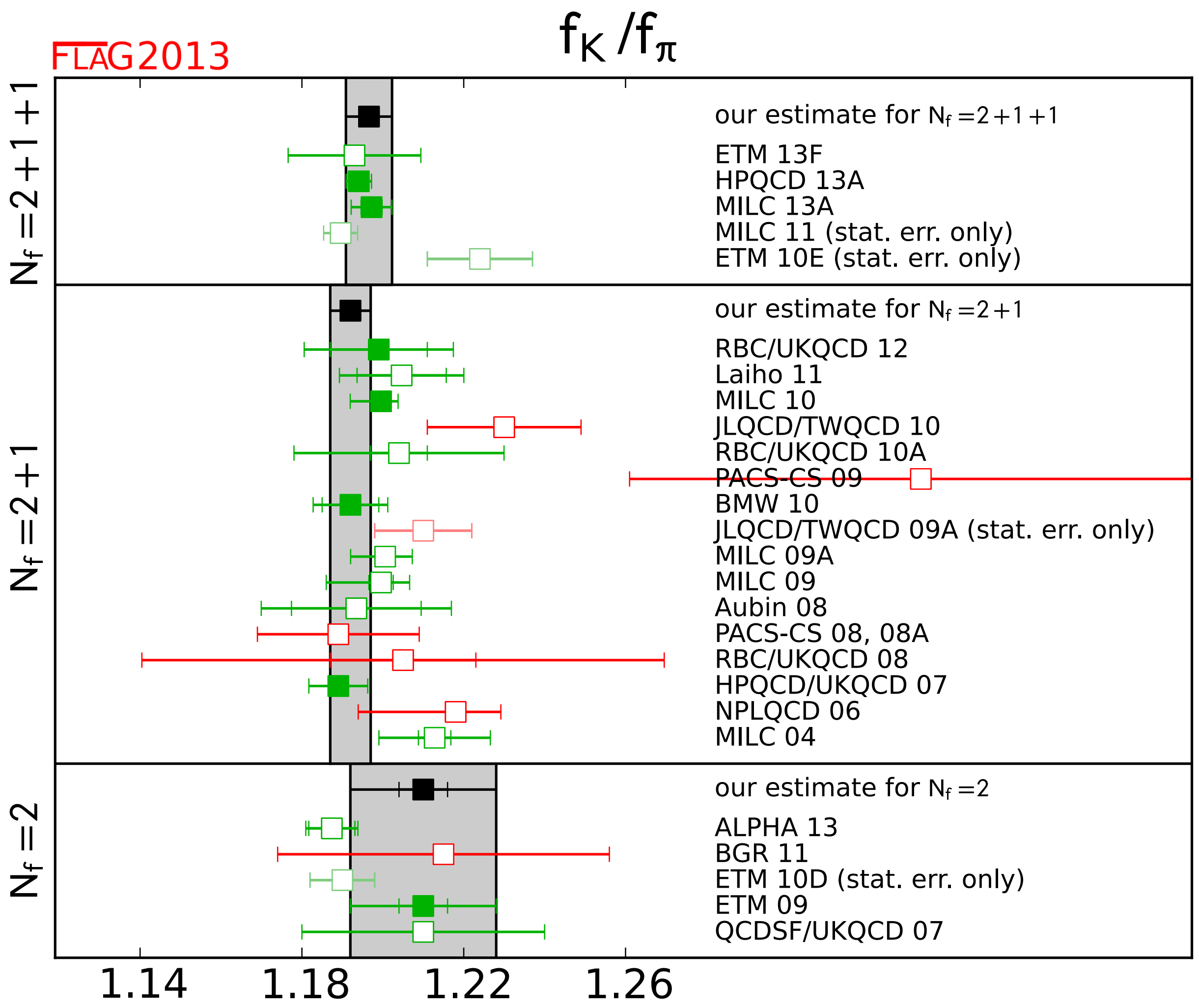
See more in talk of Daping Du, Wed 14:00

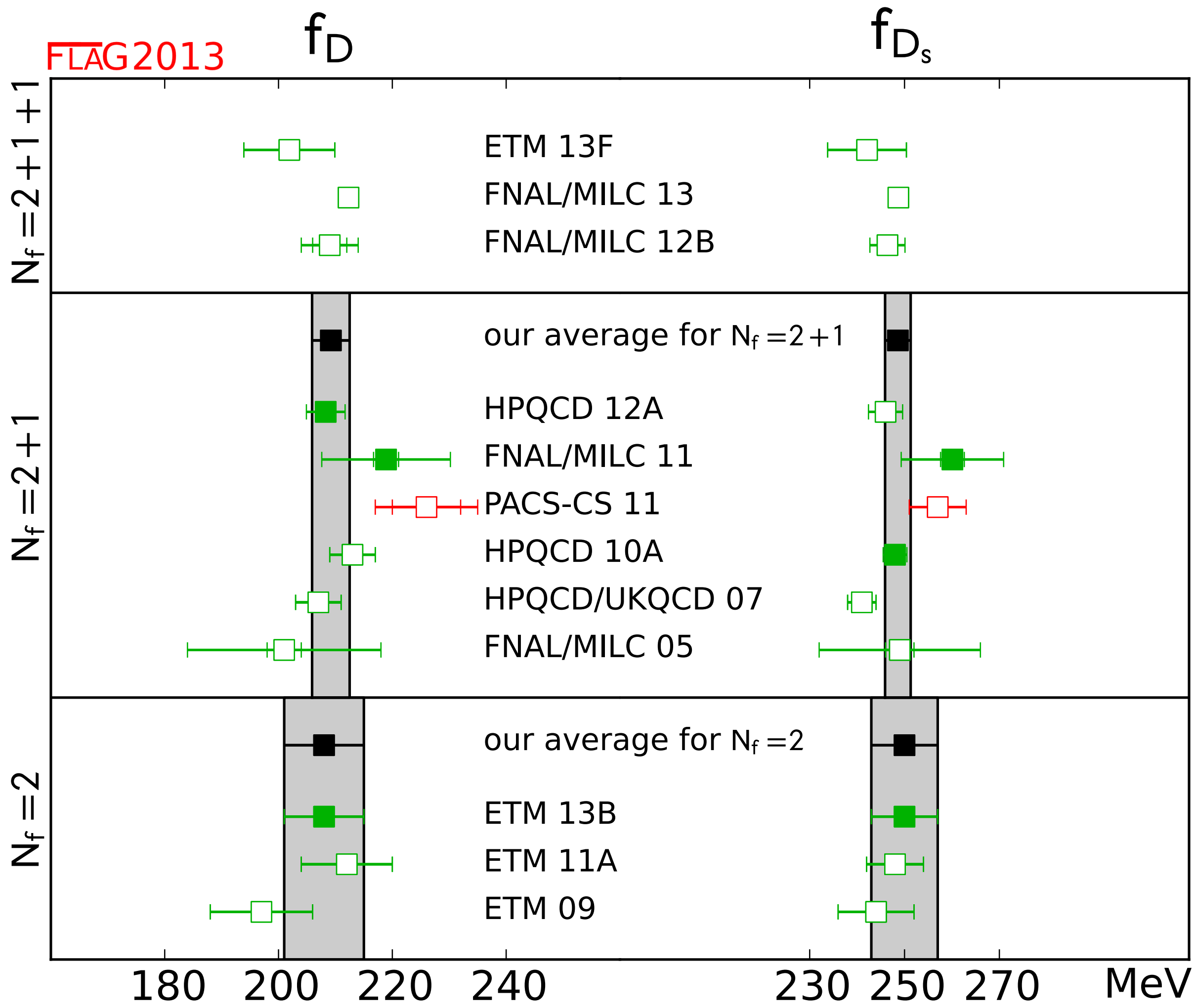
FLAG = Flavour Lattice Averaging Group

- Flavour physics has been a mainstay of LQCD
- Many calculations of what are now "simple" quantities
- FLAG (PDG for LQCD)
  - Members from most of the major collaborations
  - Evaluates and grades different aspects of each calculation
  - Provides averages as the "LQCD community consensus" value for a given quantity
  - Summary report every couple of years
    1105.3453, 1304.5422
  - New version early 2016: expanded scope and coverage

FLAG example: decay constants

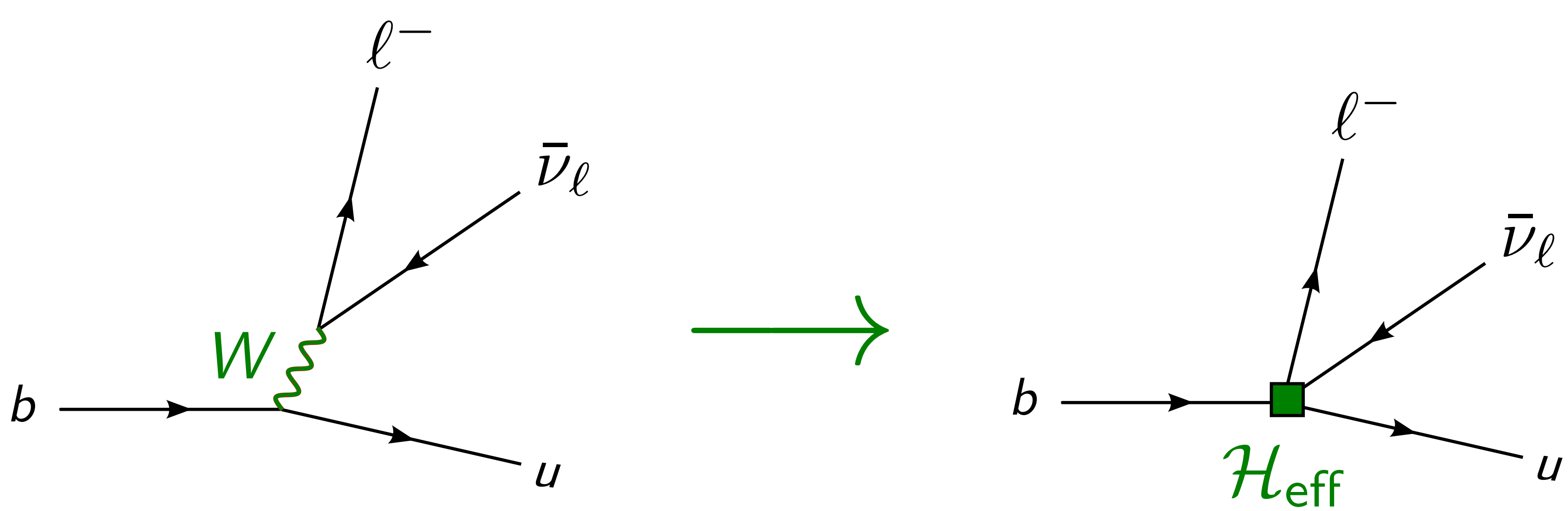
- Quark masses, decay constants, form factors, kaon mixing, LECs…
- Colour coded for quality of calculation (# lattice spacings, volumes,…)





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 $B \to \pi$ ($B \to D$)

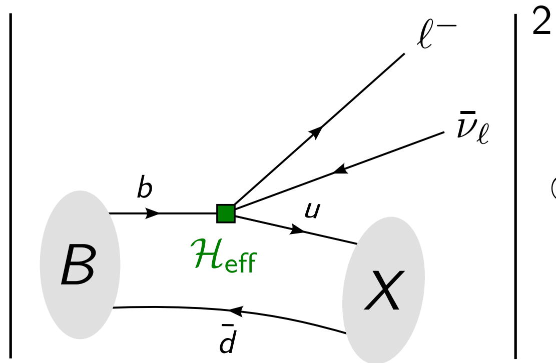


$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} V_{ub} \underbrace{\bar{u}\gamma^{\mu}(1-\gamma_5)b}_{\equiv J^{\mu}} \bar{\ell}\gamma_{\mu}(1-\gamma_5)\nu$$

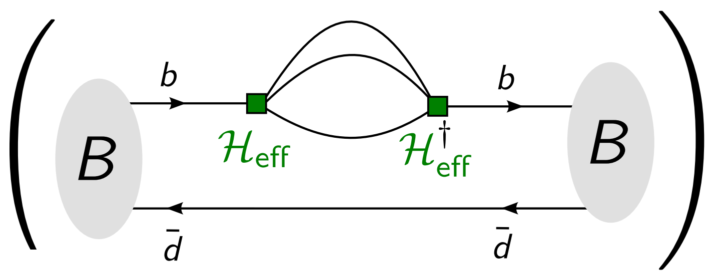
- Long running tension between V_{ub} (and V_{cb}) extractions from inclusive $B \to X_u$ ($B \to X_c$) and exclusive decays $B \to \pi$ ($B \to D$)

Inclusive

decay rate $\propto \sum_X$



$\propto$ Im

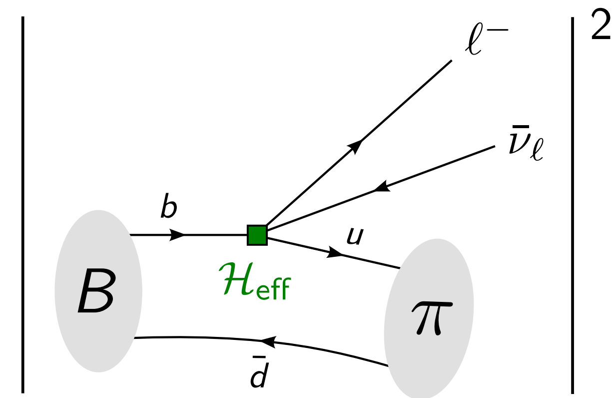


$$\frac{d\Gamma}{dq^2 dE_\ell} \propto |V_{ub}|^2 (\ldots)_{\mu\nu}$$

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

Exclusive

decay rate $\propto$



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

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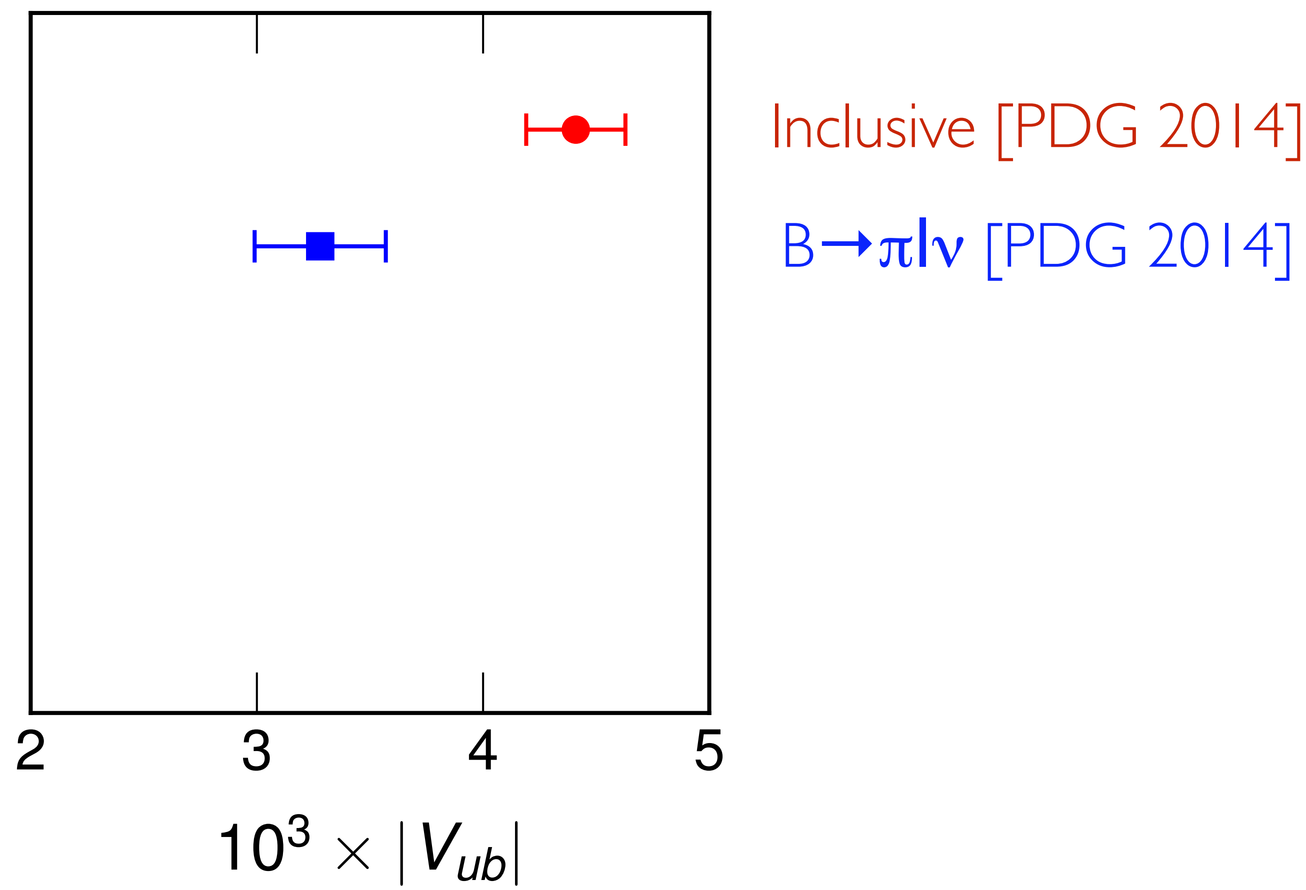


- Possible to reconcile through BSM scenarios that produce RH currents at low energy

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

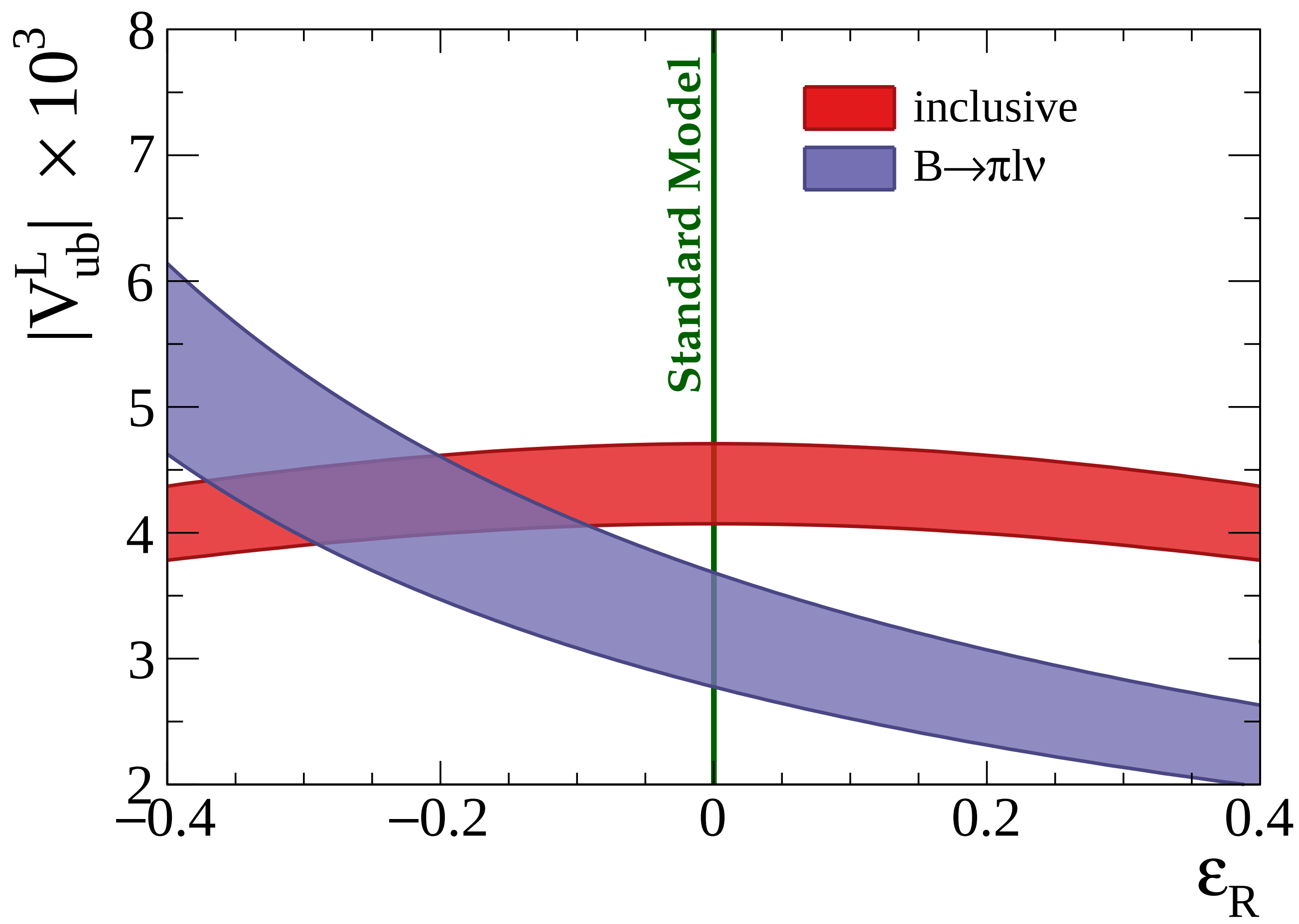
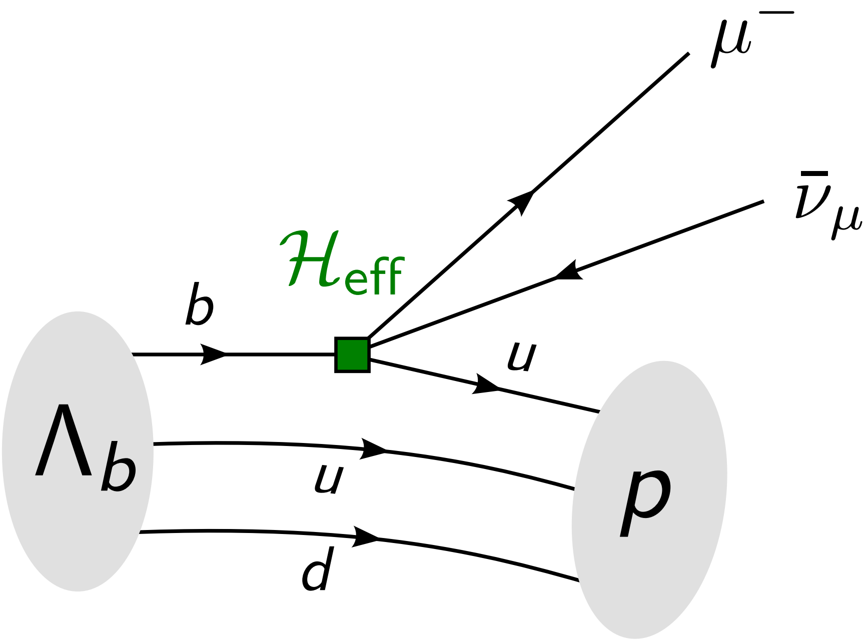


figure modified from LHCb 1504.01568

See more in talk of
Mike Williams, Th 08:30

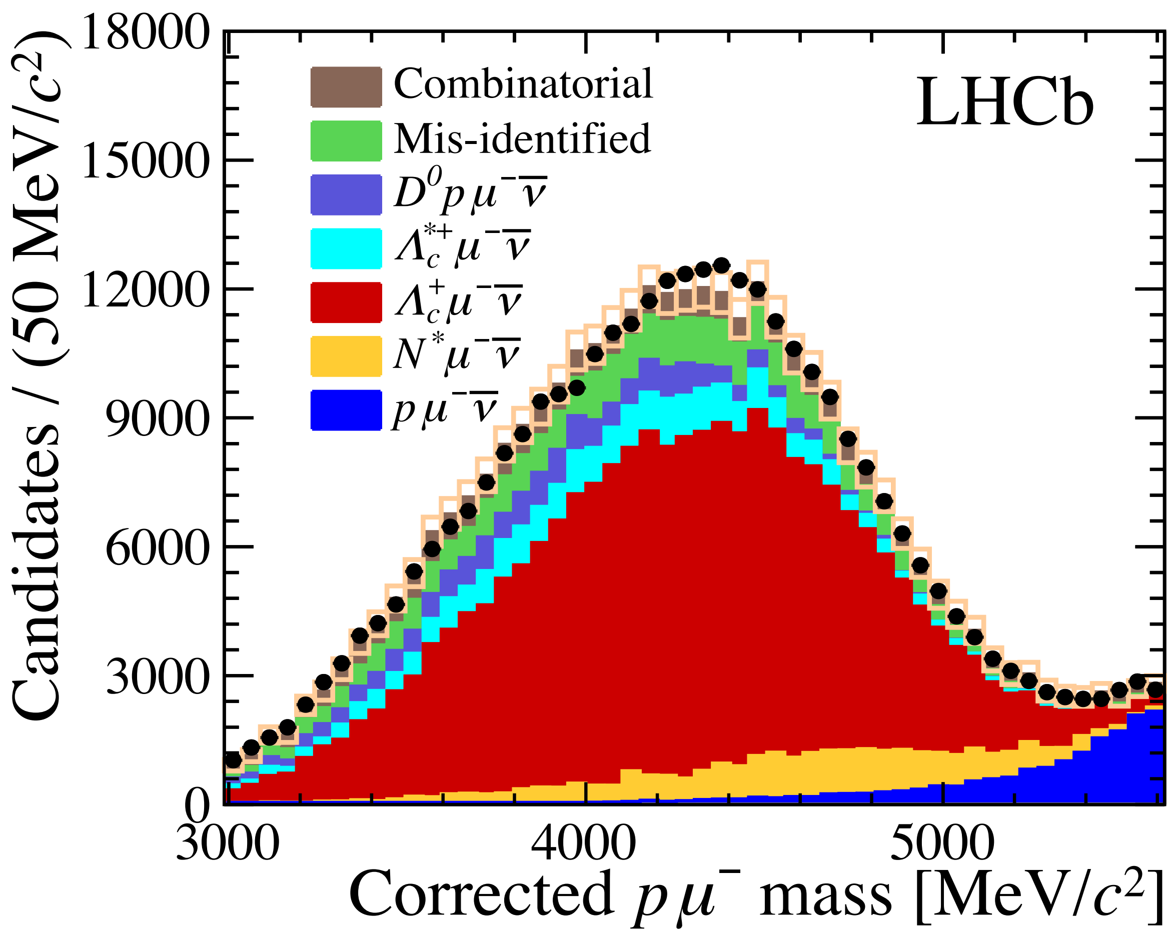
- Bottom baryons provide another exclusive decay channel: $\Lambda_b \rightarrow p l \nu$



- LHCb: branching fraction ratio measured

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

[1504.01568=Nature Phys. 11 (2015)]



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

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

from LQCD

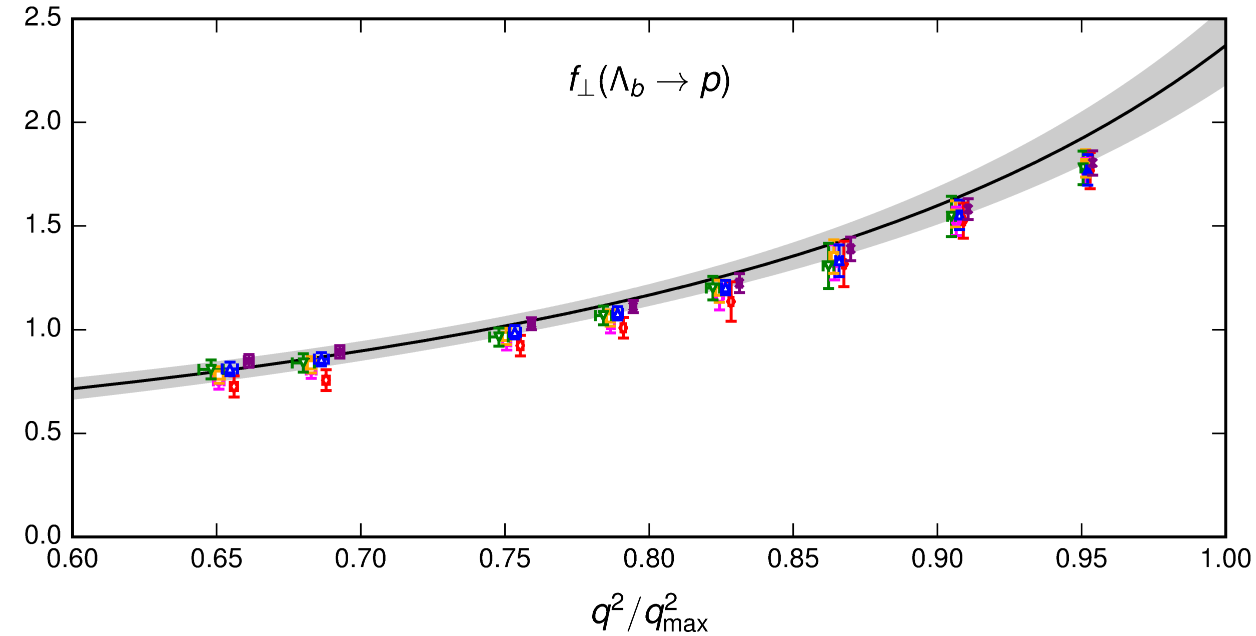
LQCD calculation

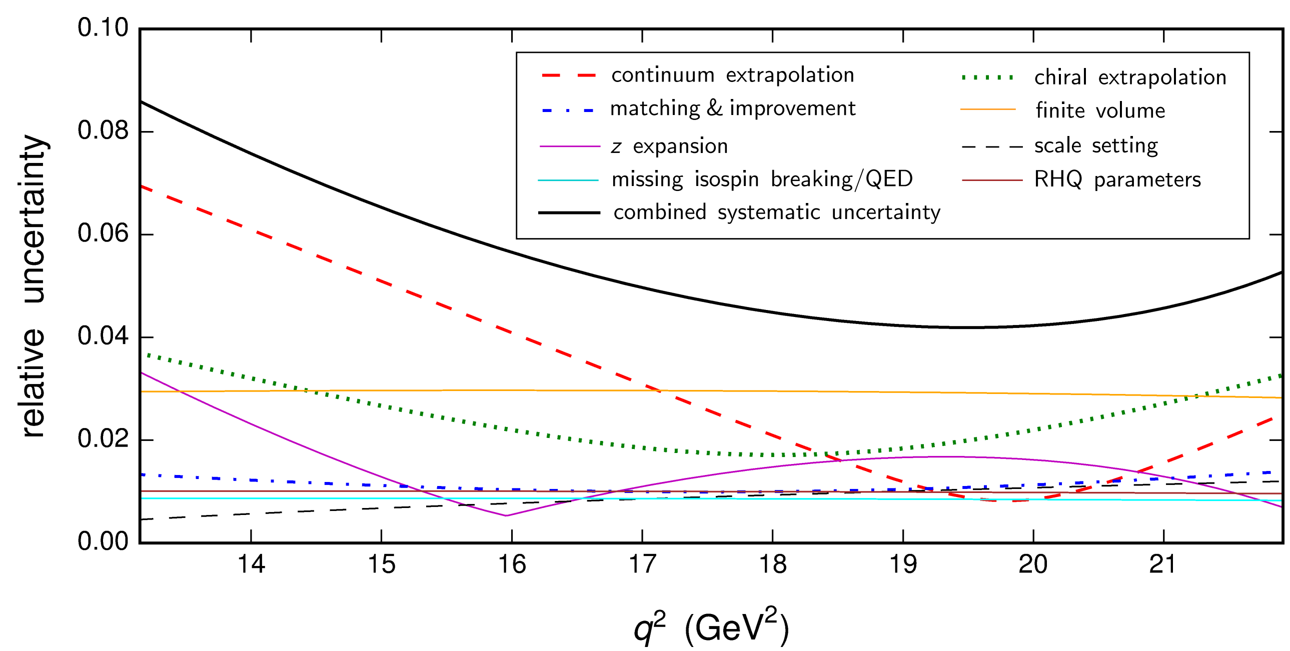
[WD, C Lehner, S Meinel PRD 92 (2015) 034503]

- 12 form factors needed
- Careful consideration of systematic uncertainties
  - Precise at large q^2
- Coordinated with LHCb (ffs needed during analysis)
- 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 $|V_{ub}|$





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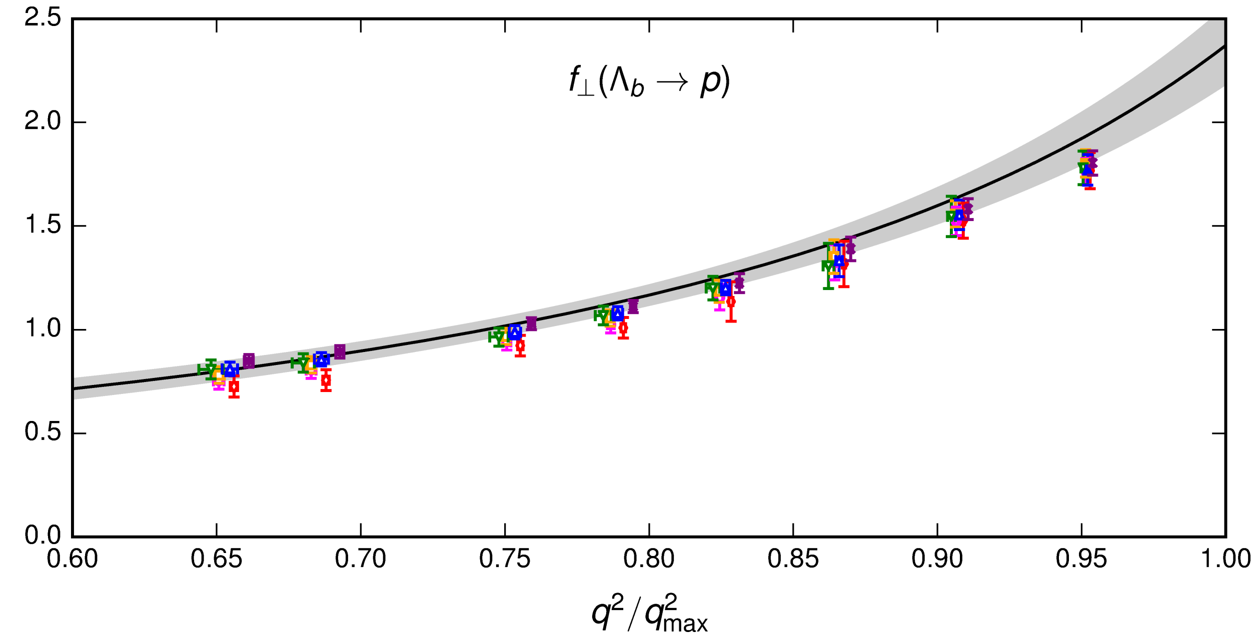
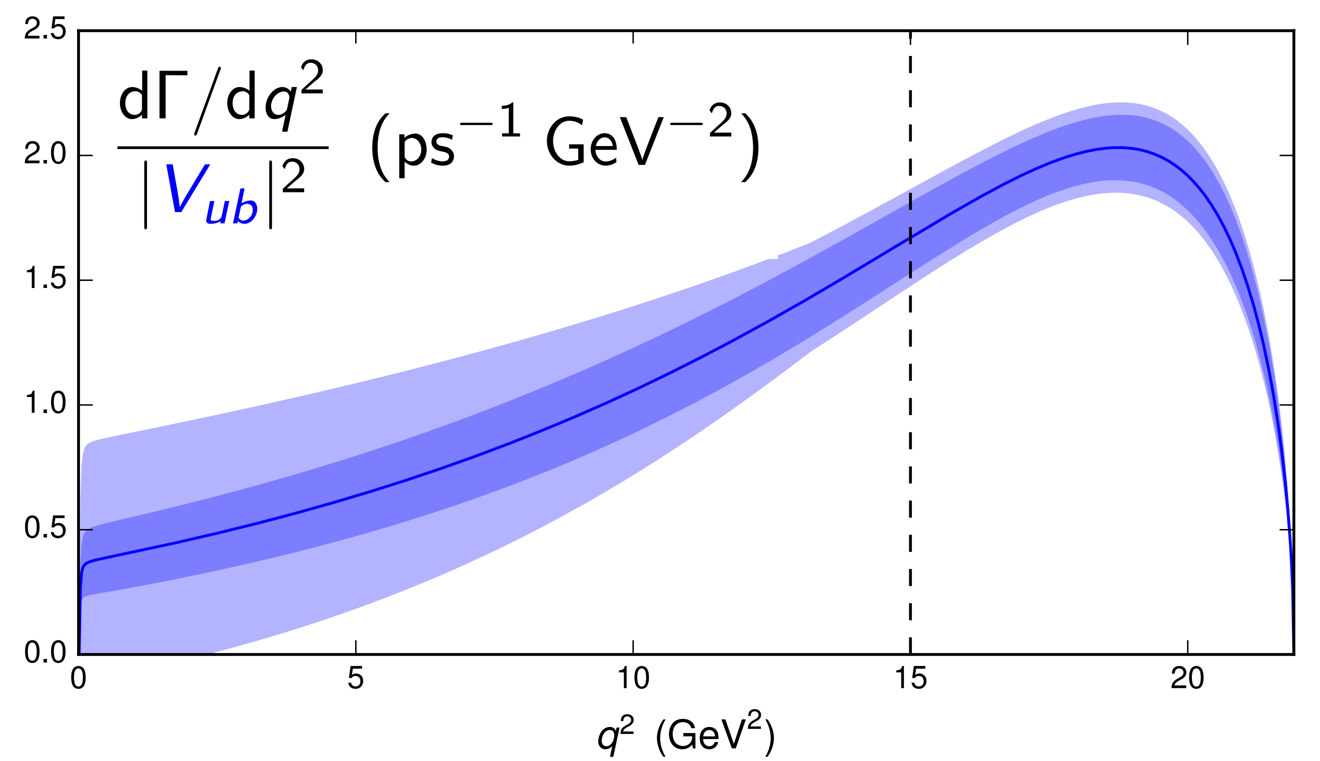
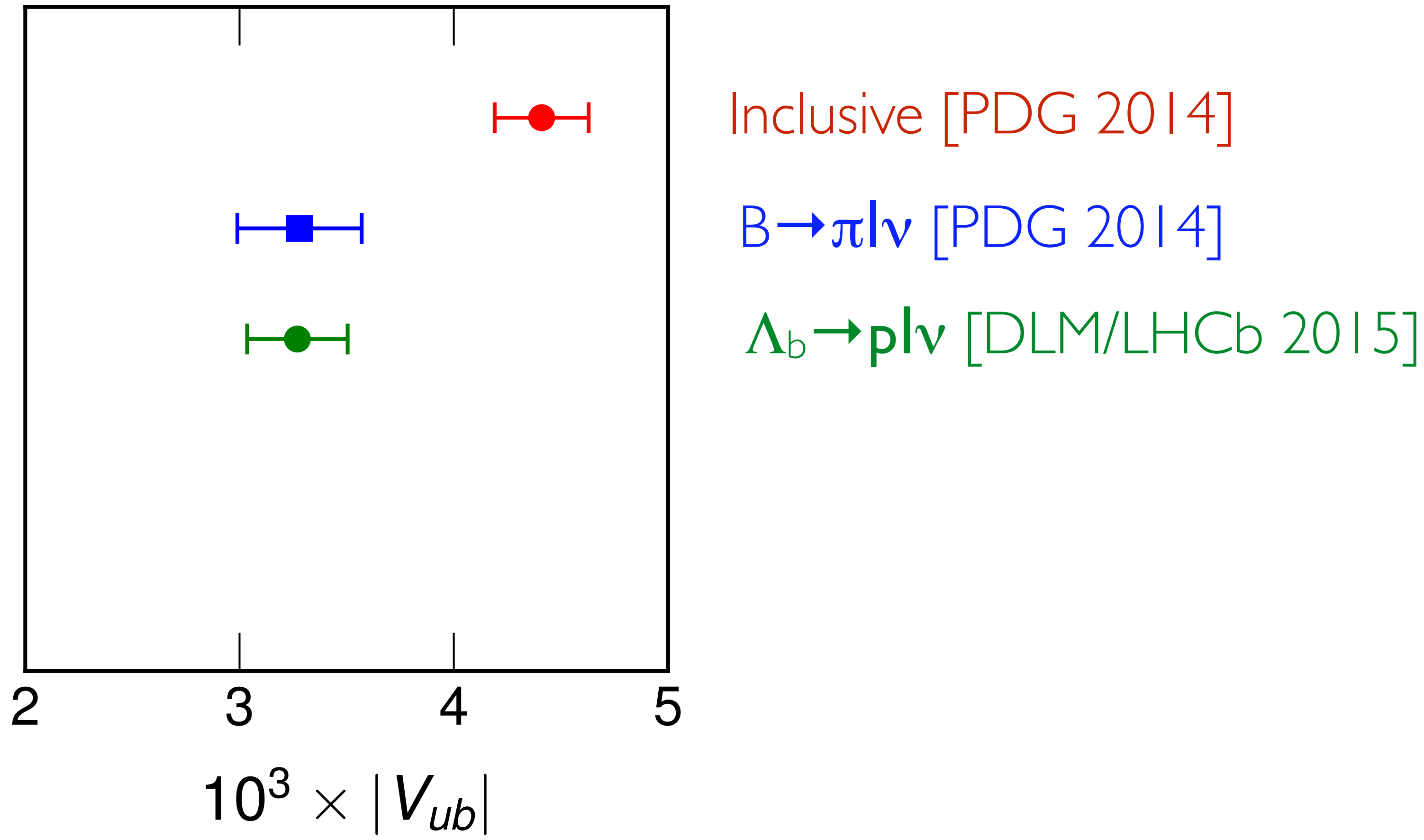




- Consistent with mesonic exclusive measurement

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



Inclusive vs exclusive V_{ub}

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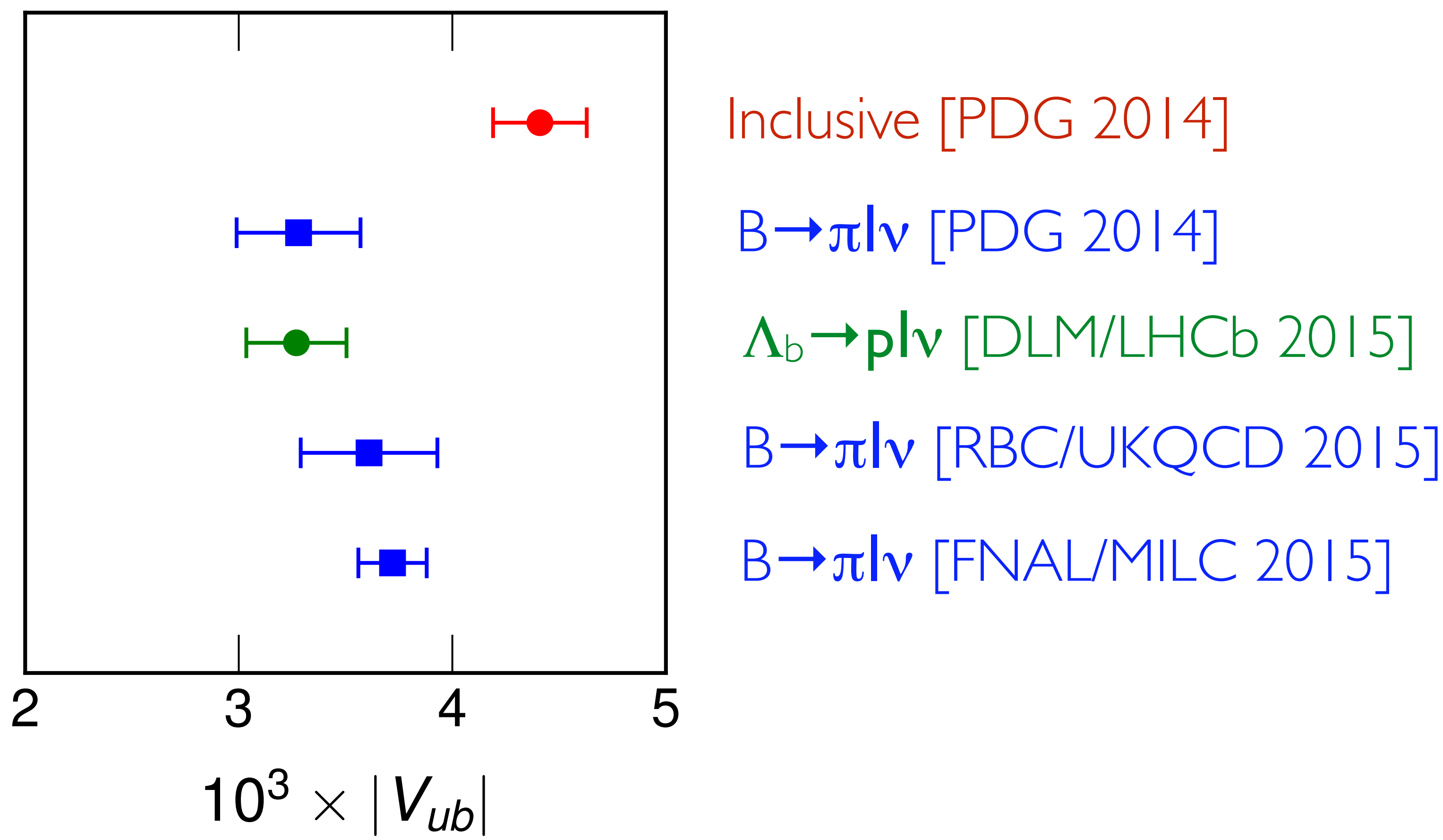


- New LQCD calculations for B→π decays too!

- Different dependence of baryon decay disfavours RH currents as a solution to inclusive/exclusive tension

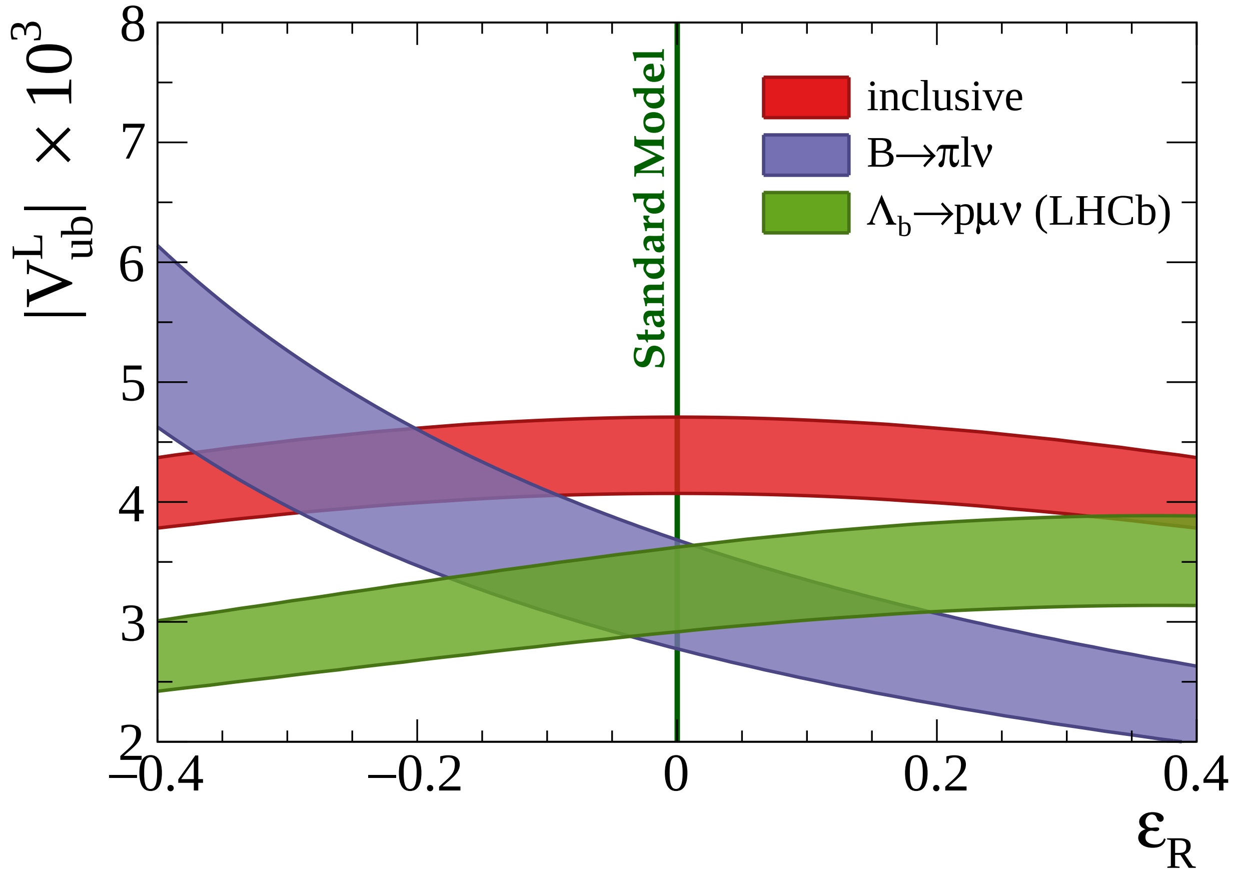
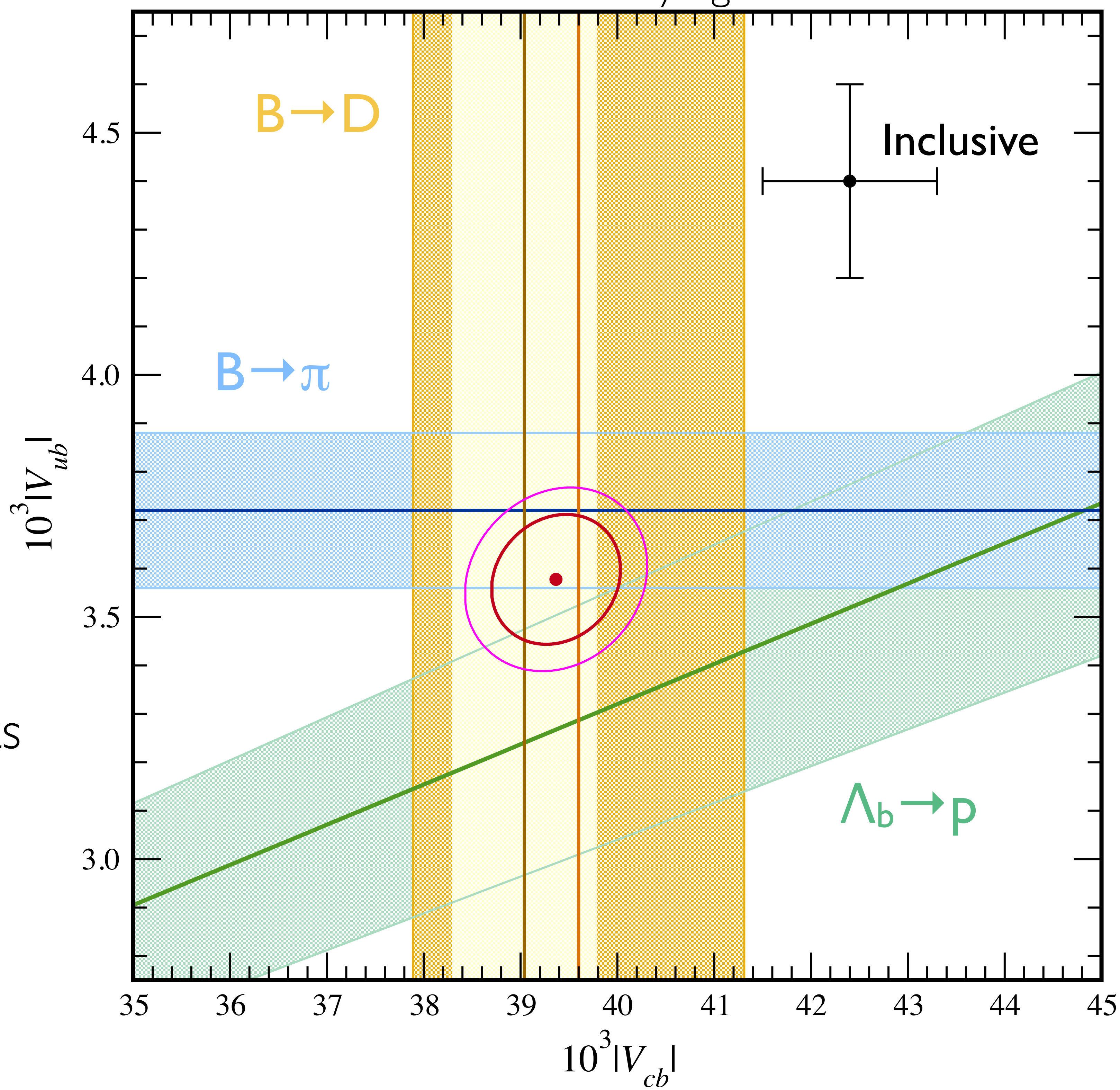


figure modified from
LHCb 1504.01568

Inclusive vs exclusive V_{ub} & V_{cb}

- Exclusive extractions:
  - very different experimental and theoretical systematics
  - Mutual consistency (p=0.26)
- Inclusive extractions creates significant tension
- Solution from RH currents disfavoured by baryonic extraction
- ??????

Summary figure from A Kronfeld



Neutral kaon system

- Neutral kaon systems of intense interest for 50+ years
  - Physical states are combinations of CP eigenstates

$$|K_L\rangle \sim |K^0_-\rangle + \bar\epsilon\,|K^0_+\rangle$$
$$|K_S\rangle \sim |K^0_+\rangle + \bar\epsilon\,|K^0_-\rangle$$

$$|K^0_\pm\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle \mp |\overline{K}^0\rangle\right]$$

$$K^0 = \bar{s}\gamma_5 d$$
$$\overline{K}^0 = \bar{d}\gamma_5 s$$

  - First observation of CP violation [Christenson, Cronin, Fitch & Turlay 1964]
  - Both direct and indirect CP violation

$$|K_L\rangle \sim |K^0_-\rangle + \bar\epsilon\,|K^0_+\rangle$$

direct ~ **ϵ'**

indirect ~ **ϵ~ϵ̄** (not CP eigenstate)

$$|\pi\pi\rangle \qquad\qquad |\pi\pi\rangle$$

  - PDG values

$$\mathrm{Re}\,\epsilon = (1.657 \pm 0.021) \times 10^{-3}$$
$$\mathrm{Im}\,\epsilon = (1.572 \pm 0.022) \times 10^{-3}$$

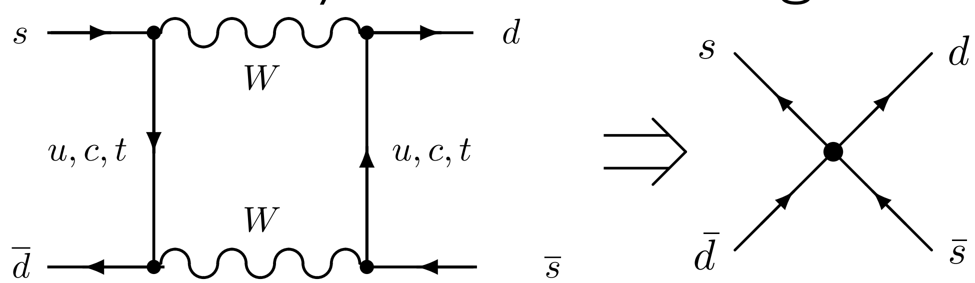
$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (1.67 \pm 0.26) \times 10^{-3}$$

Neutral kaon mixing

- Indirect CP violation arises from mixing

$$i\frac{d}{dt}\begin{pmatrix}|K^0\rangle \\ |K^0\rangle\end{pmatrix} = \begin{bmatrix} H_{00} & H_{0\bar{0}} \\ H_{\bar{0}0} & H_{\bar{0}\bar{0}}\end{bmatrix}\begin{pmatrix}|K^0\rangle \\ |K^0\rangle\end{pmatrix}$$

- Predominantly from box diagram (ΔS=2 4q operator)



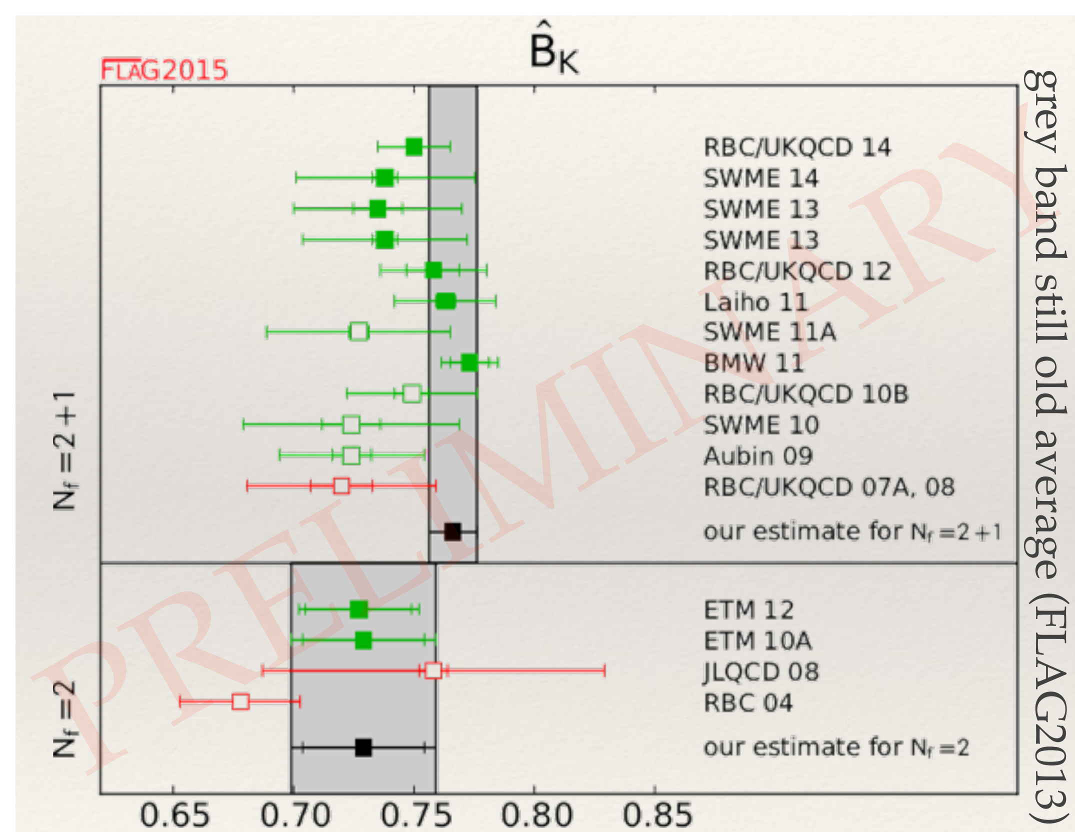
$$|\epsilon| = \frac{\mathrm{Im}\langle \bar{K}^0|\mathcal{O}_{LL}|K^0\rangle}{\Delta M_K} + \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}$$

- Conventional approach: take expt for Im A_0/Re A_0, ΔM_K, "bag parameter" from LQCD

$$\langle \bar{K}^0|\mathcal{O}_{LL}^{\Delta S=2}|K^0\rangle = \frac{8}{3}F_K^2 M_K^2 B_K(\mu)$$

- B_K under precise control

$$\hat{B}_K = \left(\frac{\bar{g}(\mu)^2}{4\pi}\right)^{-\gamma_{\mathcal{O}}/2\beta_0} \exp\left\{\int_0^{\bar{g}(\mu)} dg\left(\frac{\gamma(g)}{\beta(g)} + \frac{\gamma_0}{\beta_0 g}\right)\right\} B_K(\mu)$$



from A Juettner, Lattice 2015

K→ππ decays

- Decays through either **ΔI**=1/2, 3/2 (**ΔS**=1) with amplitudes (δ_I= strong scattering phases)

$$A(K \to \pi\pi_I) \equiv A_I e^{i\delta_I} \qquad I = 0, 2$$

- Long standing puzzle (**ΔI**=1/2 rule)

$$\omega = \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} \sim \frac{1}{22}$$

- Amplitudes relate to CP violating parameters as

$$\epsilon' = \frac{i\omega}{\sqrt{2}} e^{i(\delta_2 - \delta_0)} \left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} \right]$$

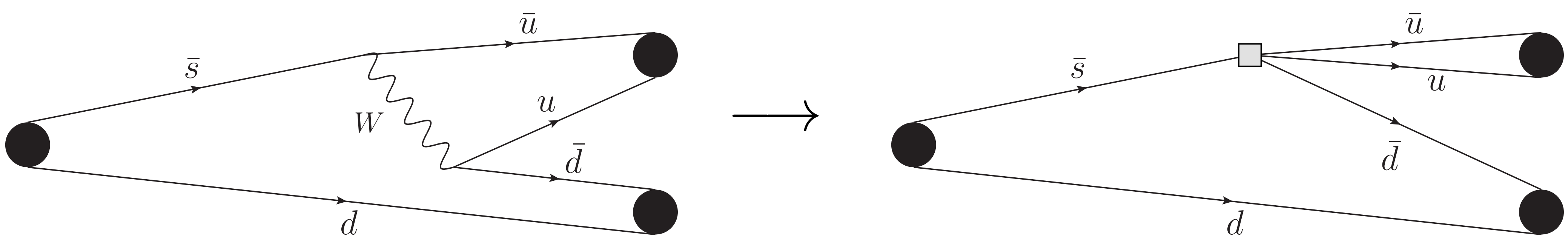
$$|\epsilon| = \frac{\mathrm{Im}\langle \bar{K}^0 | \mathcal{O}_{LL} | K^0 \rangle}{\Delta M_K} + \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}$$

K→ππ decays

- Many new developments by the RBC/UKQCD collaboration
  - Quantitative understanding of $\Delta I=1/2$ rule
    [P Boyle et al . *(RBC/UKQCD) Phys.Rev.Lett. 110 (2013) 15, 152001;*
    T Blum et al. (RBC/UKQCD) Phys.Rev. D91 (2015) 7, 074502 *]*
  - Important progress in calculating all pieces of ε and ε'
    directly from SM
    - Full calculations of decay amplitudes
      [Z Bai, *et al. (RBC/UKQCD),* 1505.07863]
    - Kaon mass difference: long distance contributions
      [Z Bai, *et al. (RBC/UKQCD)* Phys.Rev.Lett. 113 (2014) 112003]
- Additional progress on rare kaon decays
  [N Christ et al *(RBC/UKQCD)* 1507.03094]

K→ππ decays: ΔI=1/2 rule

- Decays through weak **ΔI**=1/2, 3/2 (**ΔS**=1) process



- Ten relevant operators in effective Hamiltonian (weak decays, QCD and EW penguin operators)

$$\mathcal{H}_{\Delta S=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1}^{10} \left[V_{ud} V_{us}^* z_i(\mu) - V_{td} V_{ts}^* y_i(\mu) \right] \mathcal{Q}_i^{\overline{MS}}(\mu)$$

- Short distance physics in Wilson coefficients $z_i(\mu)$ and $y_i(\mu)$

- LQCD to determine matrix elements

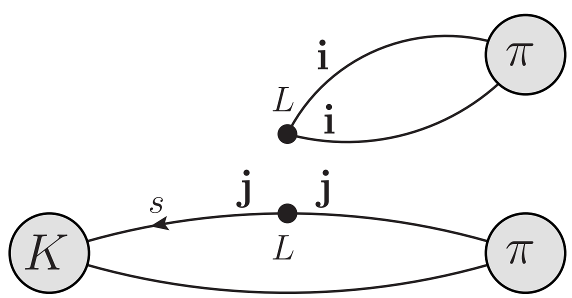
$$\langle \pi\pi | \mathcal{Q}_j'^{\mathrm{latt}} | \bar{K}^0 \rangle \qquad \mathcal{Q}_i^{\overline{MS}}(\mu) = Z_{ij}^{latt \to \overline{MS}}(\mu, a) \mathcal{Q}_j'^{\mathrm{latt}}$$

(need to convert lattice operators to MSbar scheme)

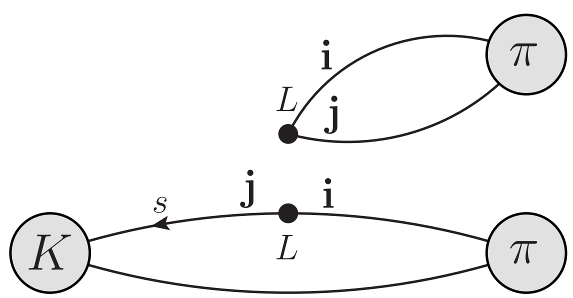
K→ππ decays: ΔI=1/2 rule

- Consider operator $Q^{3/2}_{(27,1)} = (\bar{s}^i d^i)_L\{(\bar{u}^j u^j)_L - (\bar{d}^j d^j)_L\} + (\bar{s}^i u^i)_L(\bar{u}^j d^j)_L$
- Matrix element evaluation can be Fierzed into two "colour contractions"

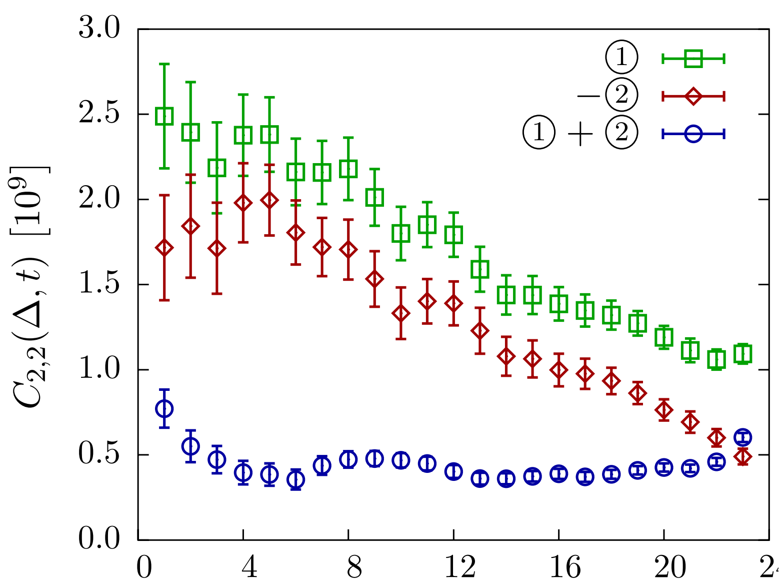
i,j colour indices



Contraction ①



Contraction ②



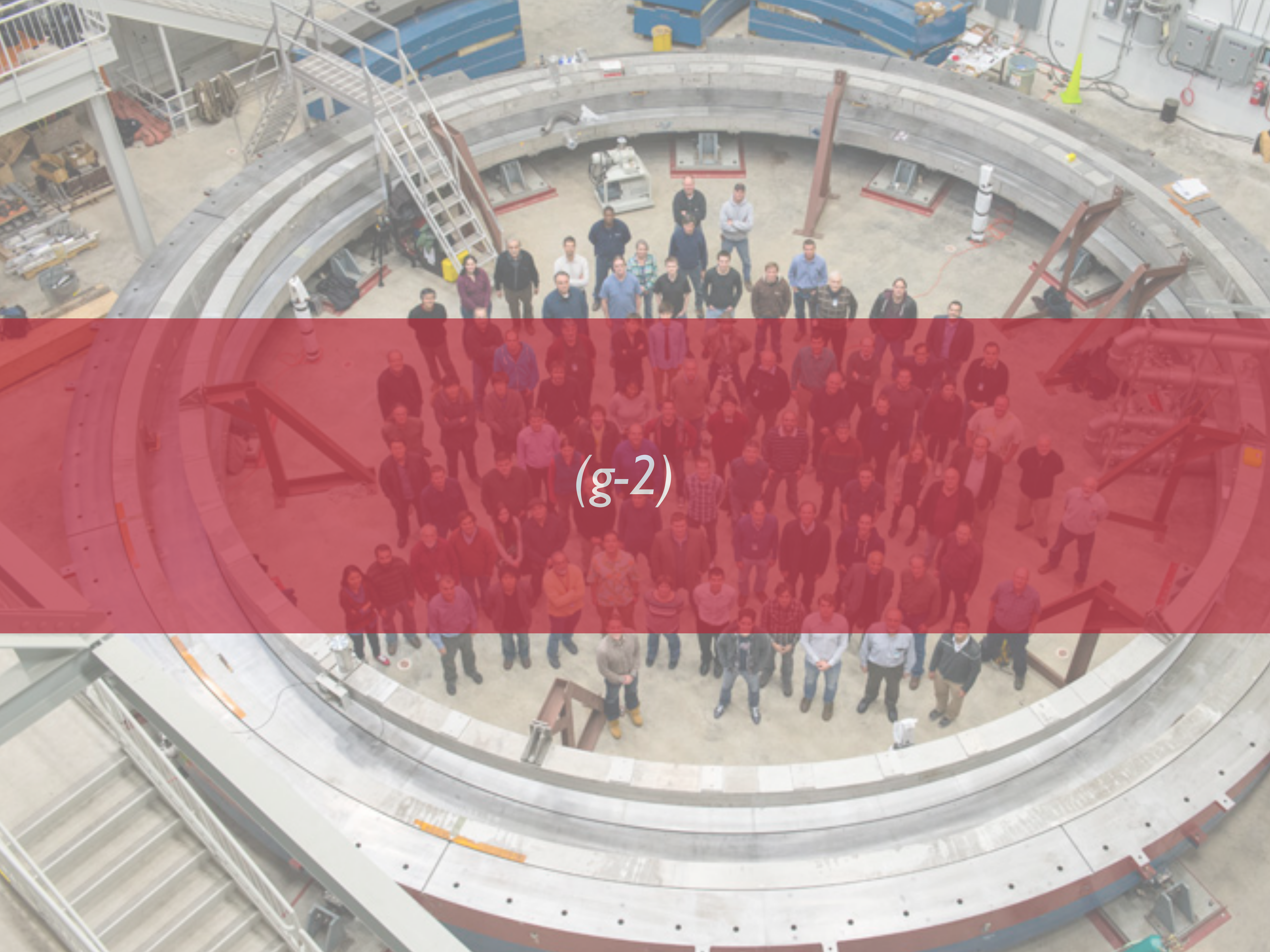
P Boyle et al. *PRL. 110 (2013)*

  - Vacuum saturation would give ② ~1/3 ①
    Numerical evaluation gives ② ~-0.7 ①

- For **ΔI**=3/2 contributions add ① + ② so significant cancelation

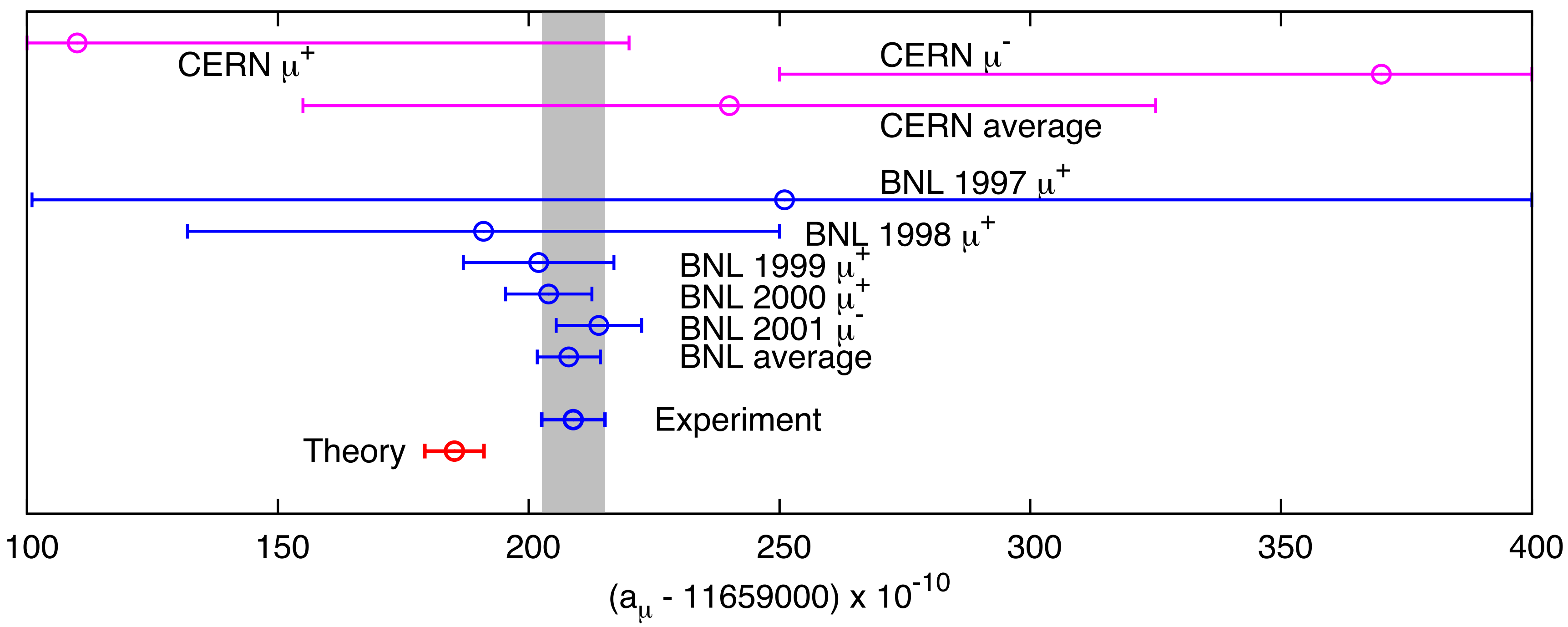
- More complex for **ΔI**=1/2, but roughly enhanced rather than suppressed

$$\frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} \sim \frac{① + ②}{2\,② - ①} \sim 10\text{–}15$$


(g-2)

Muon g-2

- 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

Standard Model $(g\text{-}2)_\mu$

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

- Measured value

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

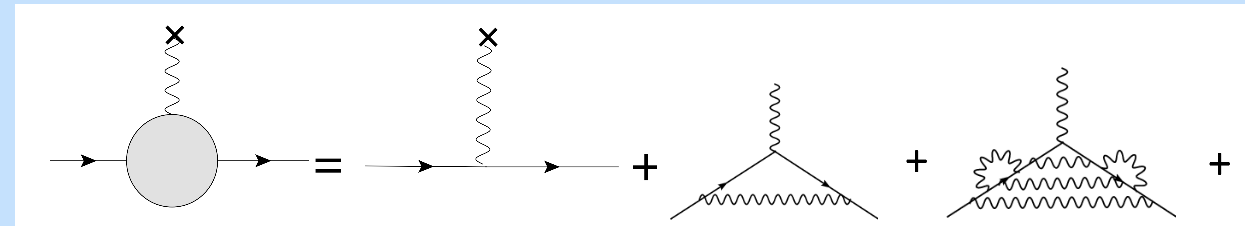
- Breakdown of contributions (2 evaluations of HVP)

	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]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

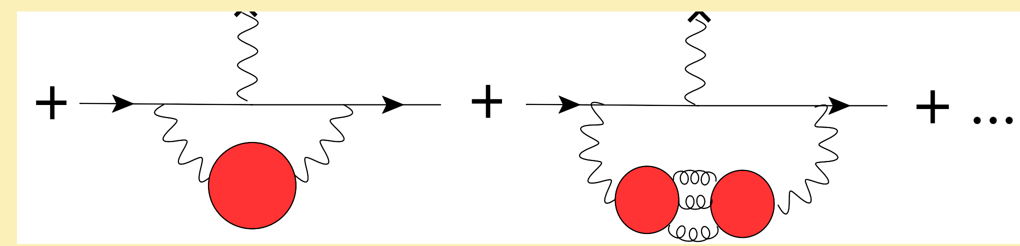
- Deviation

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

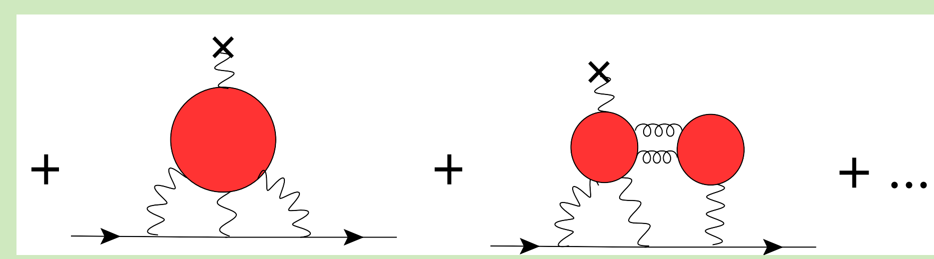
- QED (5 loop) [Aoyama et al. 2012]



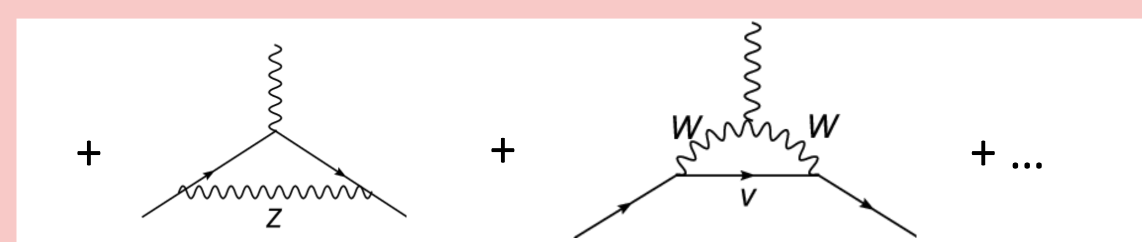
- Hadronic vacuum polarisation



- Hadronic light-by-light



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



Standard Model $(g-2)_\mu$

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

- Measured value

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

- Breakdown of contributions (2 evaluations of HVP)

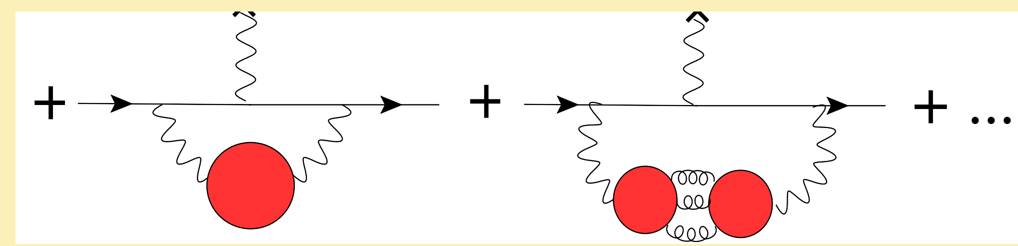
	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm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

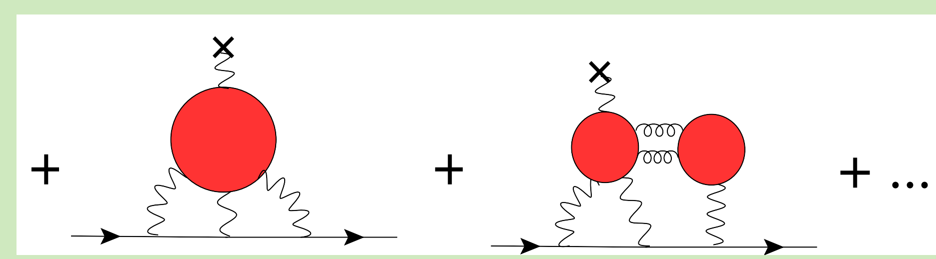
$$\begin{aligned} \Delta a_\mu(\mathrm{E821} - \mathrm{SM}) &= (287 \pm 80) \times 10^{-11}\ [20] \\ &= (261 \pm 78) \times 10^{-11}\ [21] \end{aligned}$$

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

- Hadronic vacuum polarisation



- Hadronic light-by-light



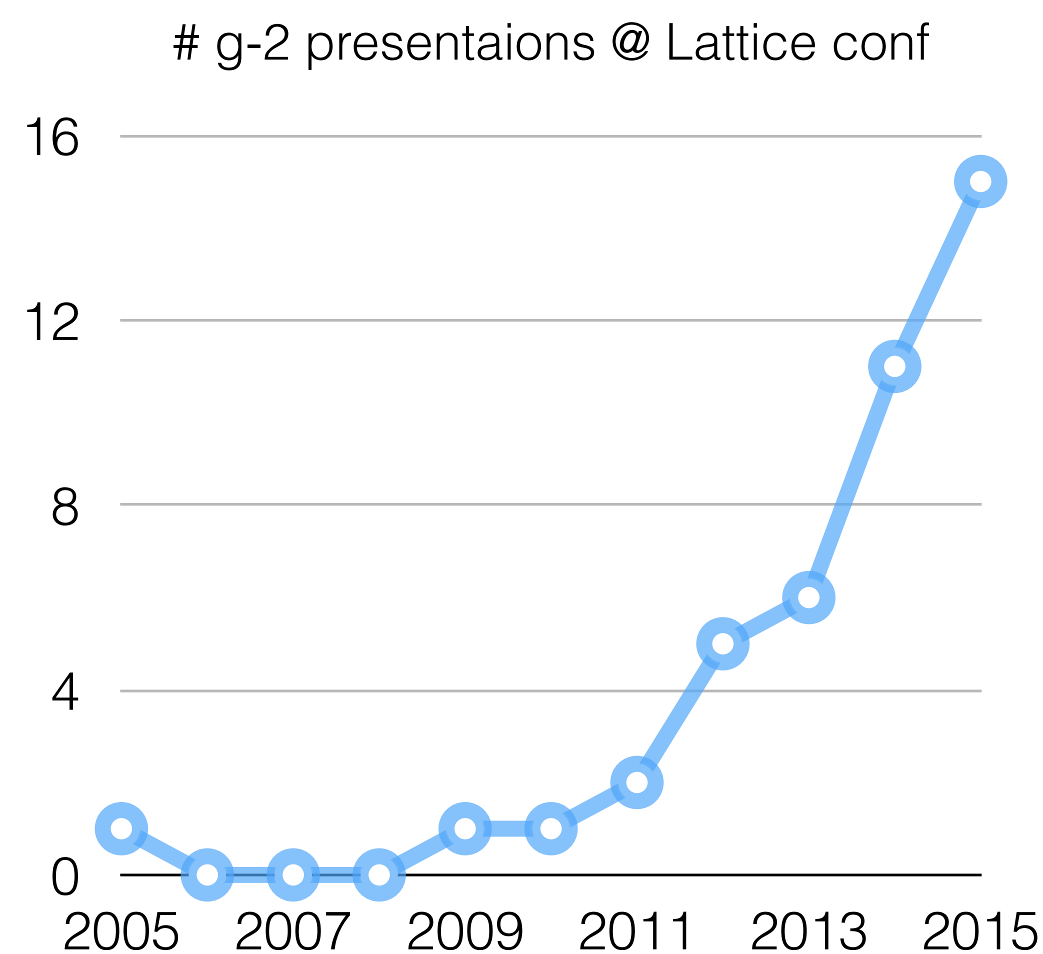
- Electroweak (2 loop) [Czarnecki et al. 2006]

Hot topic in LQCD

- LQCD requirements

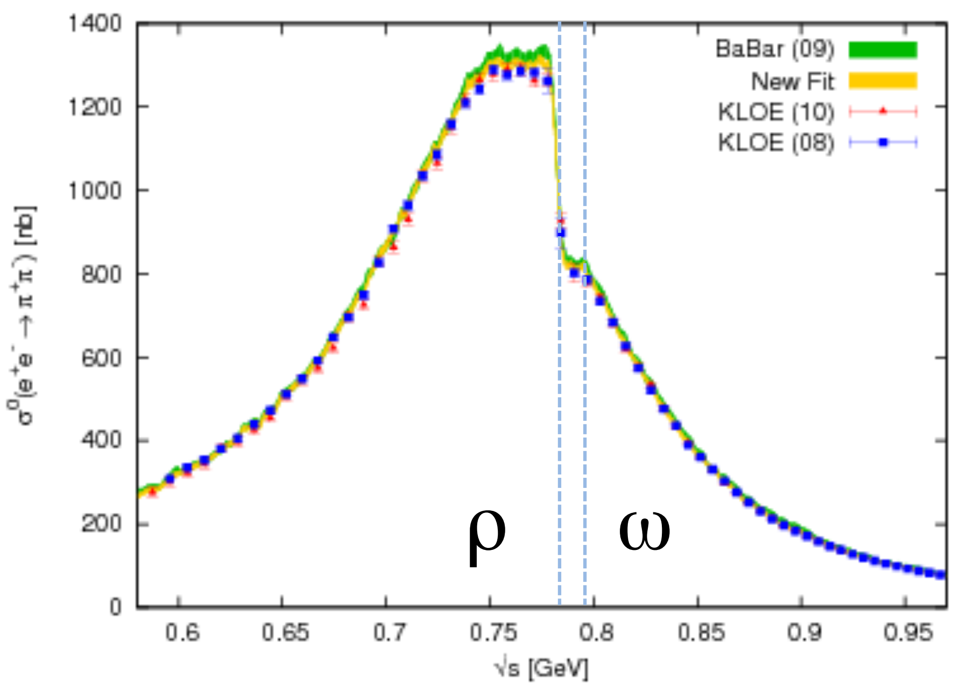
Lattice	precision	timescale	benchmark
HVP	1-2%	Few years	τ -- e+e⁻ discrepancy
HVP	sub-%	This decade	Competitive w/ e+e⁻
hLbL	any	soon	Course Verification of models
hLbL	~30%	3-5 years	Competitive with models
hLbL	~10%	Ultimate goal	Replace models

[B Casey Lattice 2014 projections]



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

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



- Complicated analysis (0.6% prec)

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

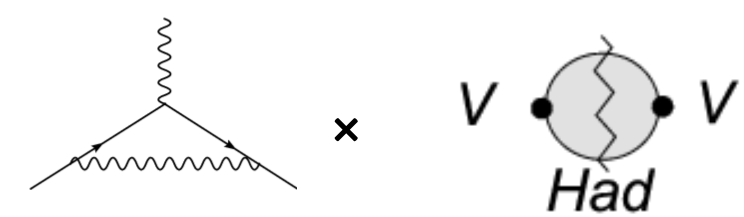
$$(q^2 g_{\mu\nu} - q_\mu q_\nu)\Pi_V(q^2)$$

$$s = q^2$$

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

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

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



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

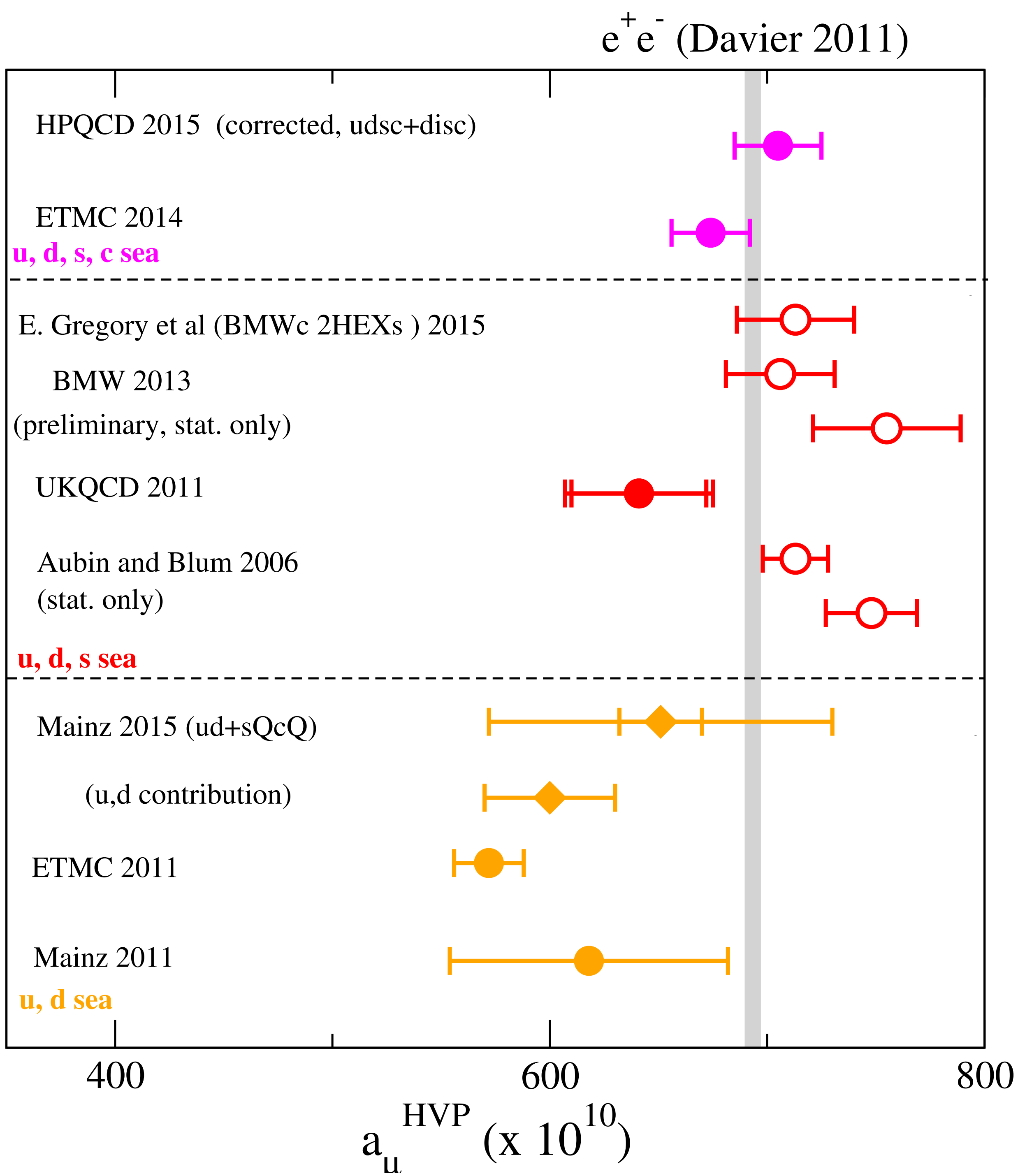
- Can be computed from SM directly [Blum PRL91 (2003) 052001]
- Analytically continue to Euclidean space [T Blum PRL91 (2003) 052001]

$$K^2 = -q^2 > 0$$

Use modified kernel

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

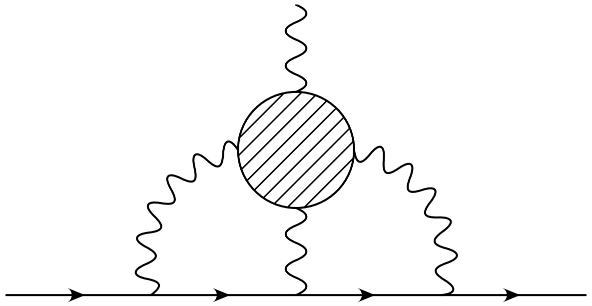
- Precision goal is challenging, but calculations rapidly improving
  - Major technical improvements at low K^2 where $f(K^2)$ is peaked
  - Ready for large scale calculations



T Izubuchi Lattice 2015 (already out of date)

Hadronic light-by-light

- HLbL smaller but hard to determine
- Currently guesstimated from models
  (see Colangelo *et al.* for dispersive analysis of some pieces)
- Accessible in LQCD from 4-pt correlator

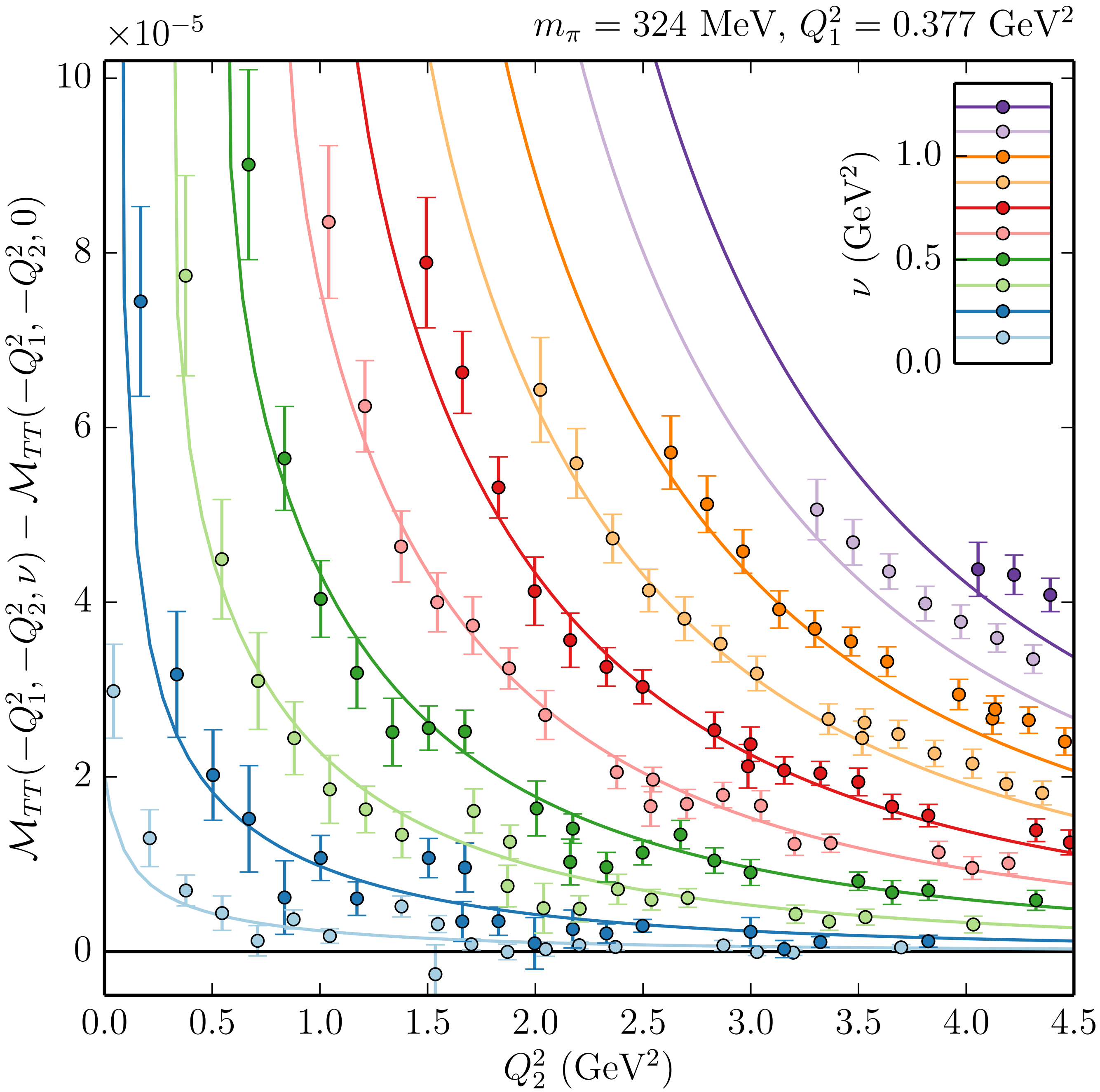


$$\Gamma_\mu^{(\mathrm{Hlbl})}(p_2,p_1) = ie^6 \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{\Pi^{(4)}_{\mu\nu\rho\sigma}(q,k_1,k_3,k_2)}{k_1^2\,k_2^2\,k_3^2} \times \gamma_\nu S^{(\mu)}(p_2+k_2)\gamma_\rho S^{(\mu)}(p_1+k_1)\gamma_\sigma$$

$$\Pi^{(4)}_{\mu\nu\rho\sigma}(q,k_1,k_3,k_2) = \int d^4x_1\,d^4x_2\,d^4x_3\,\exp[-i(k_1\cdot x_1+k_2\cdot x_2+k_3\cdot x_3)] \times\langle 0|T[j_\mu(0)j_\nu(x_1)j_\rho(x_2)j_\sigma(x_3)]|0\rangle$$

  - 32 relevant tensor structures!
  - Required for all k_1, k_2!

- Recent calculation at fixed kinematics [Green et al., 1507.01577]
  - Comparison to model derived from dispersive analysis of $\gamma^*\gamma^* \to$ hadrons
- Not viable for all kinematics but may help constrain models



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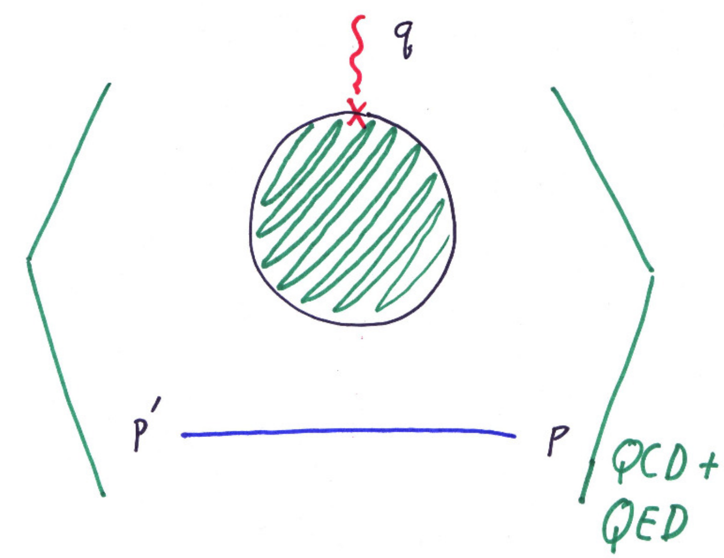
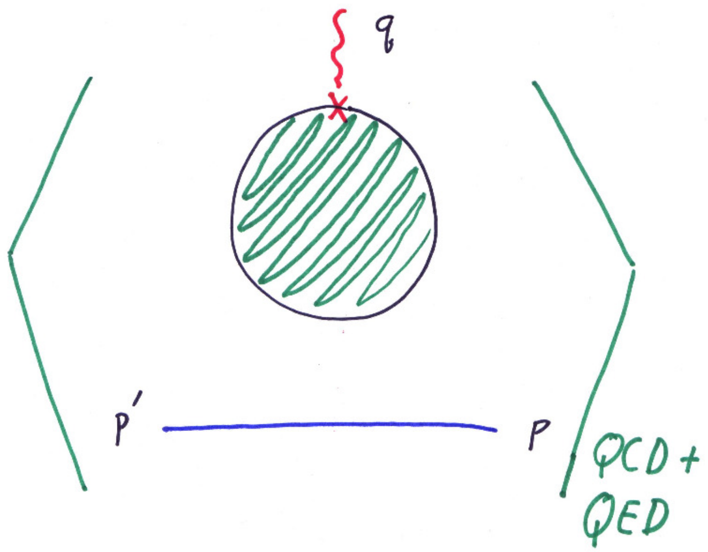


Sketches from T Blum

- Potentially simpler to evaluate in QCD+QED [T Blum et al.]



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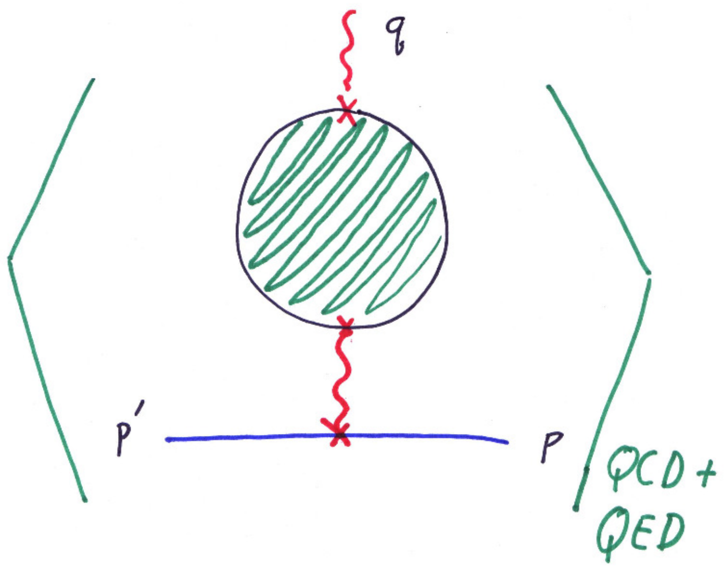
  - Keep one photon explicit



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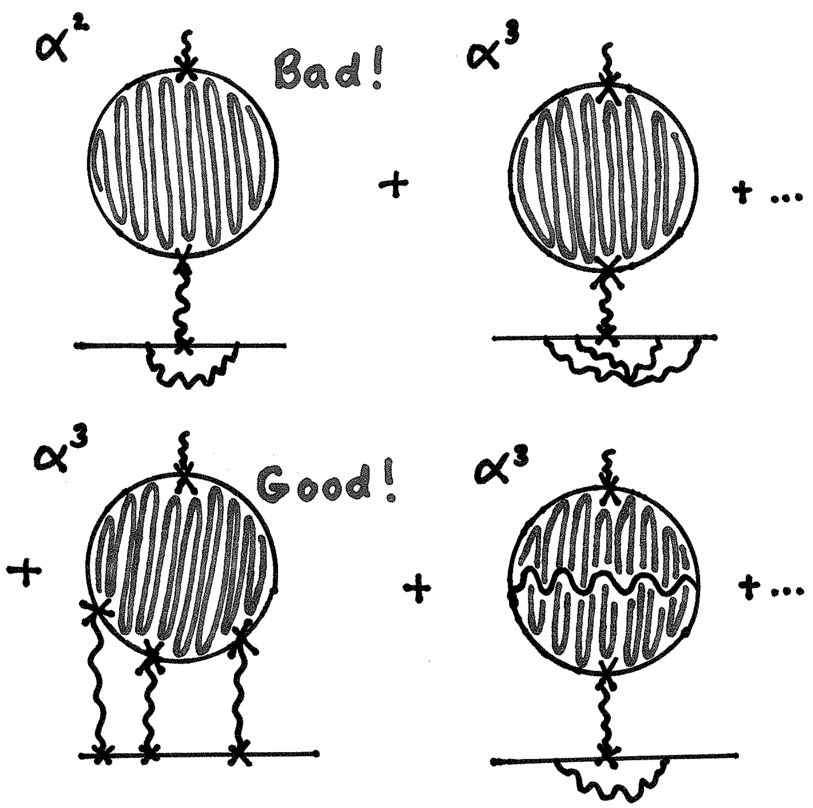

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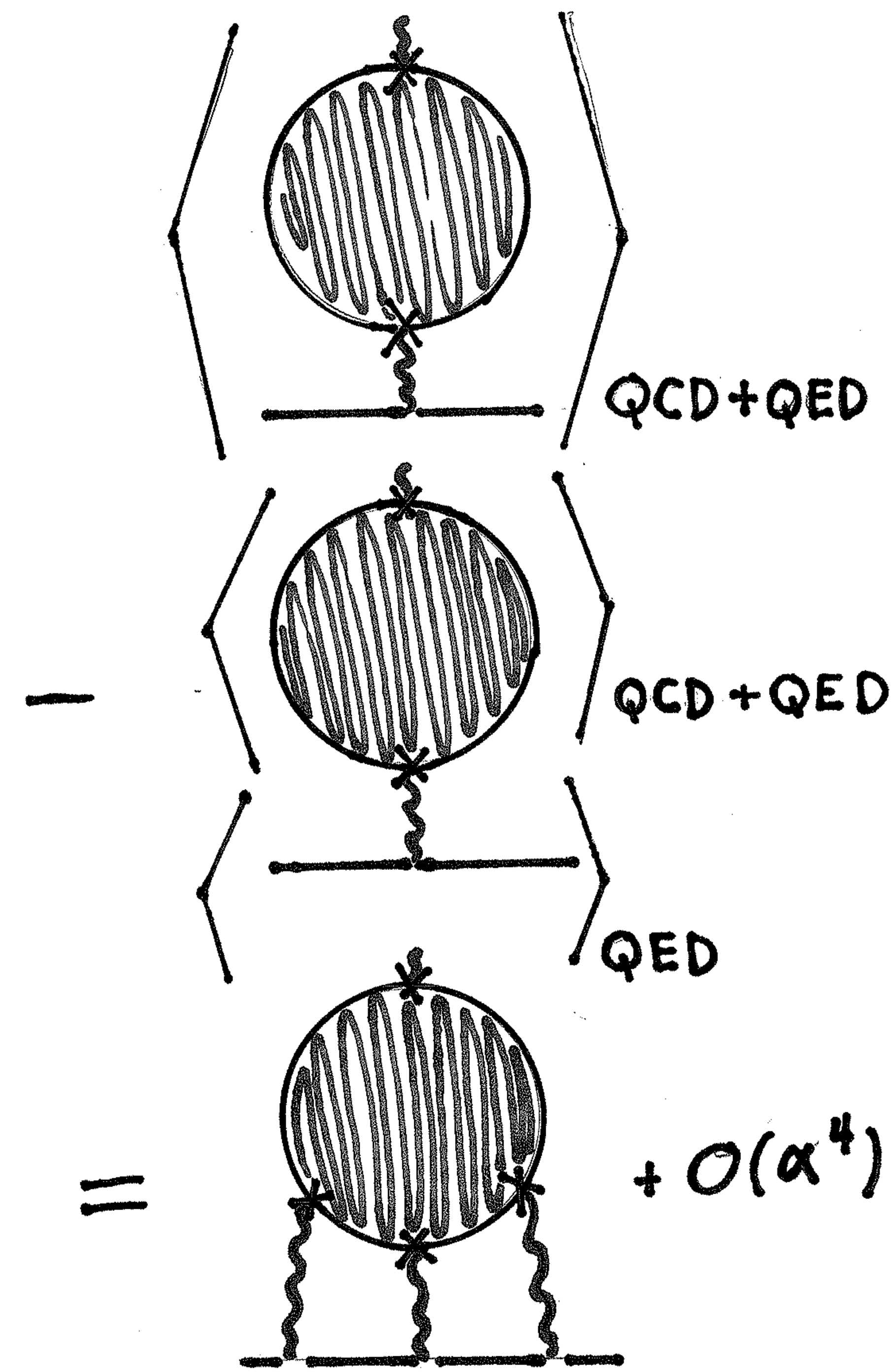

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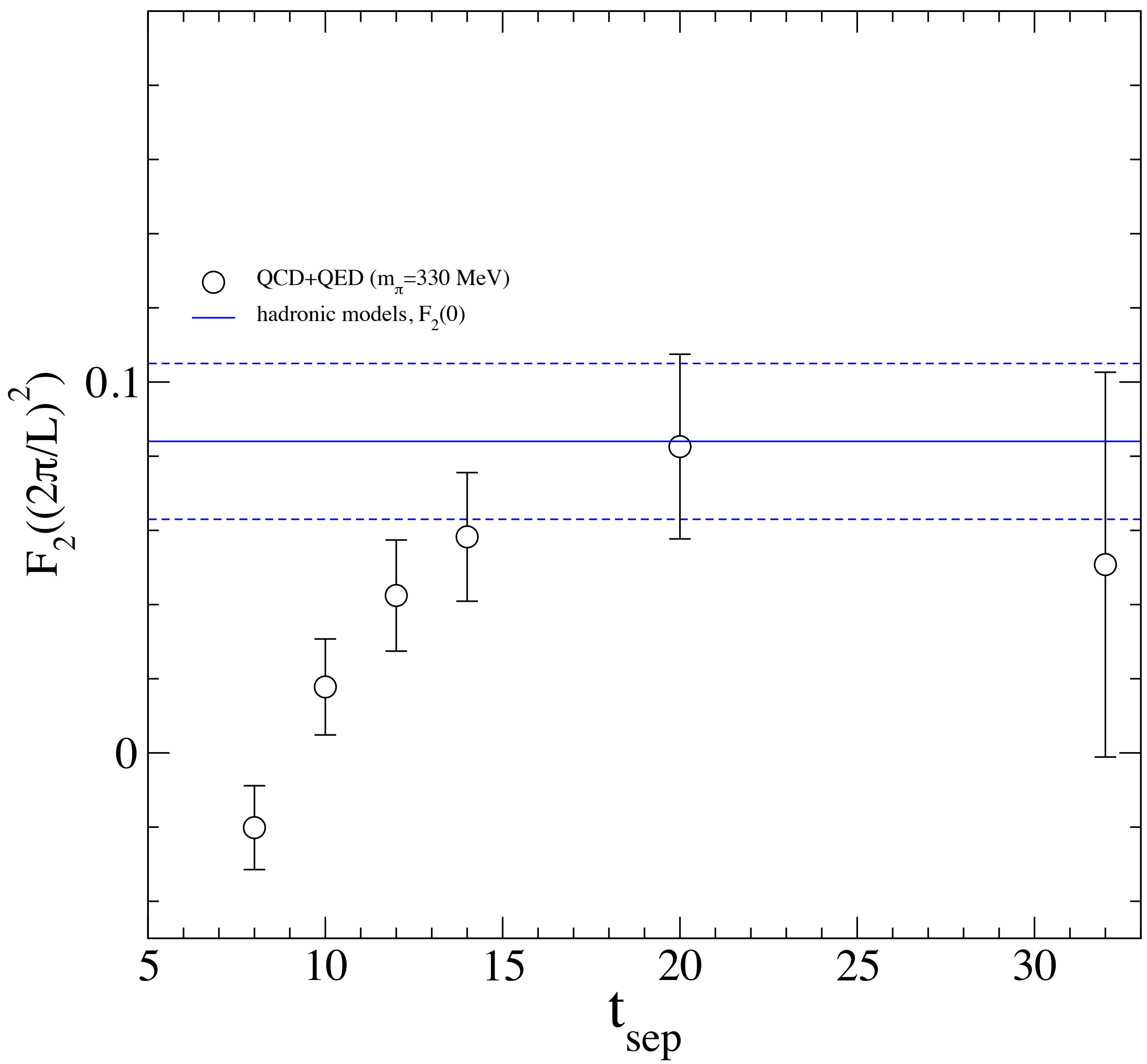
  [Blum, Chowdhury, Hayakawa, Izubuchi 1407.2923]



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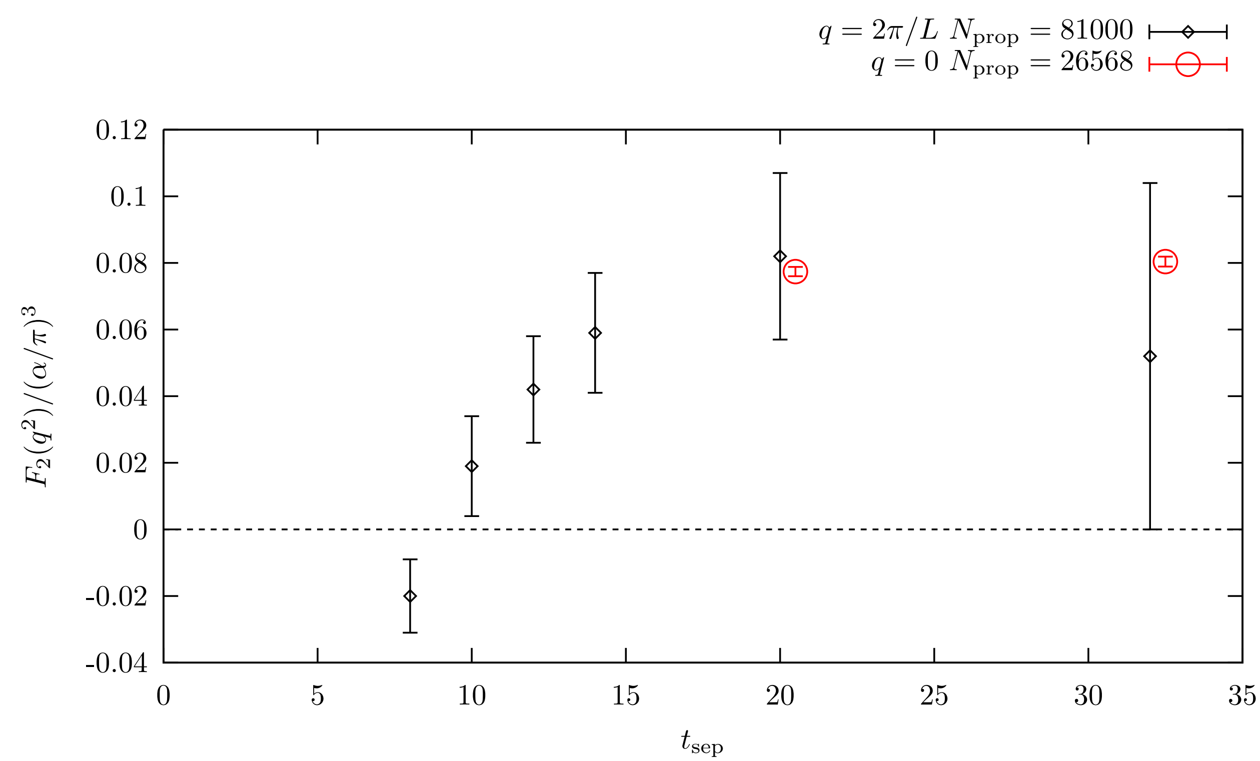
  [Jin et al, Phys.Rev.Lett. 114 (2015) 1, 012001]



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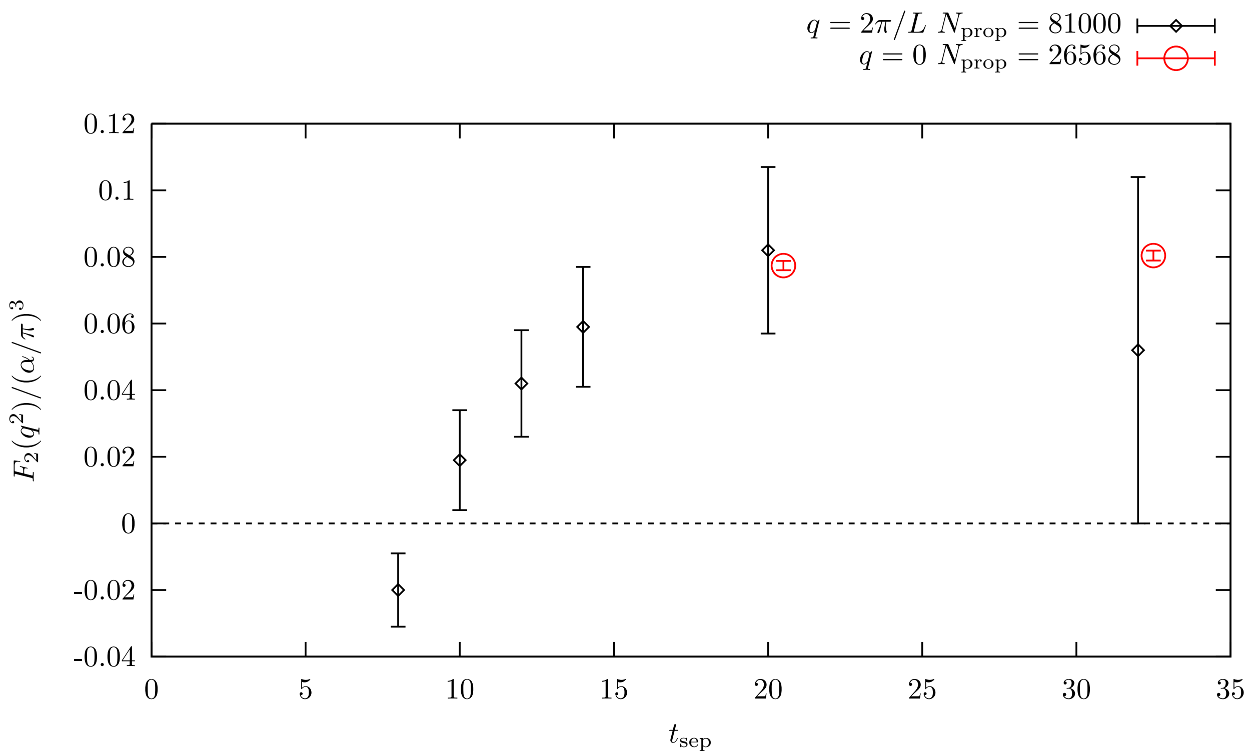
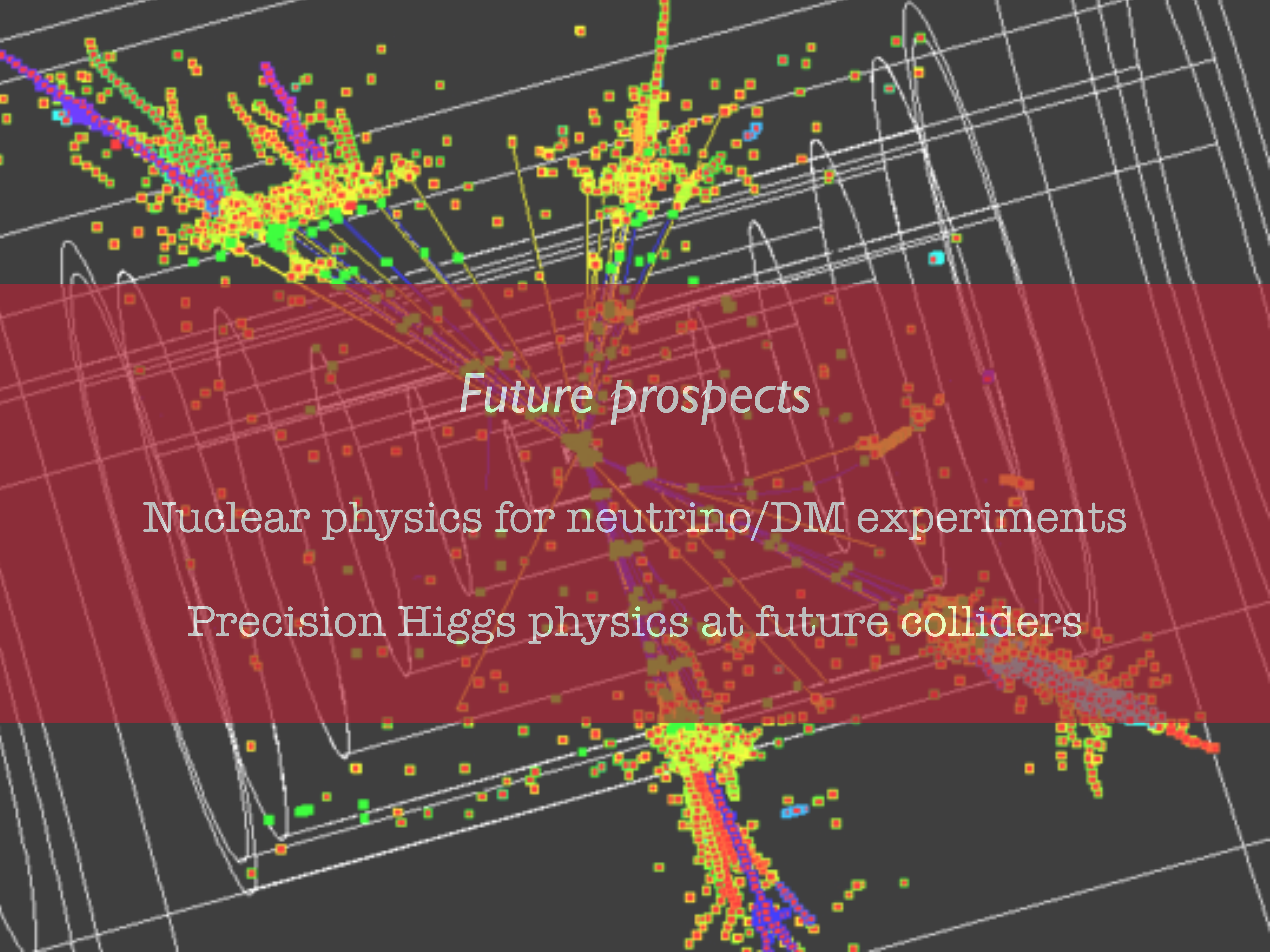
- Still requires many further improvements to get final answer





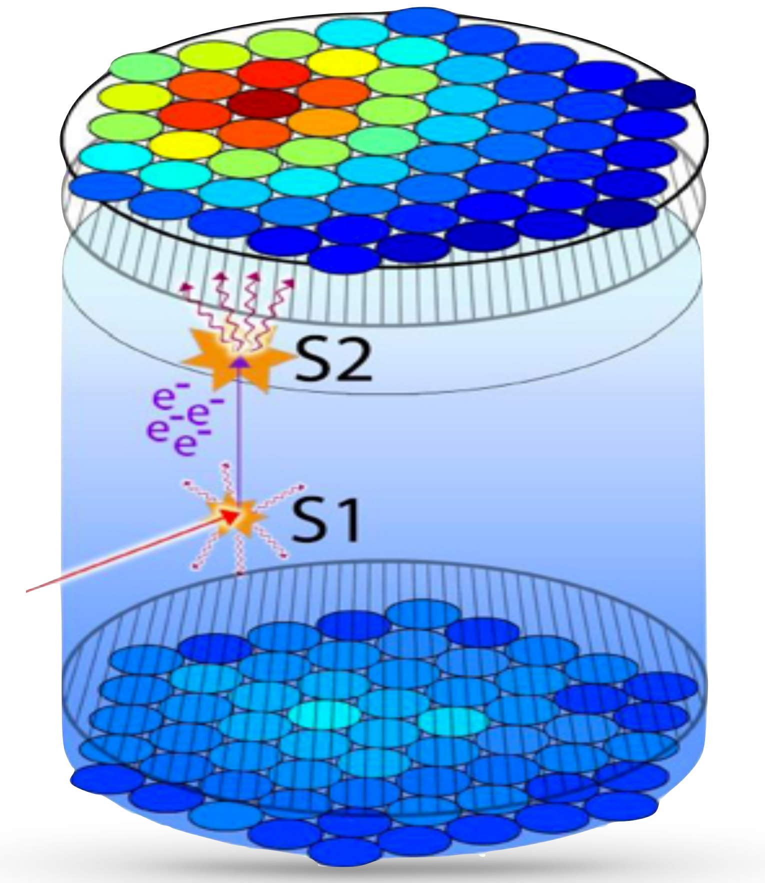
Future prospects

Nuclear physics for neutrino/DM experiments

Precision Higgs physics at future colliders

Dark matter direct detection

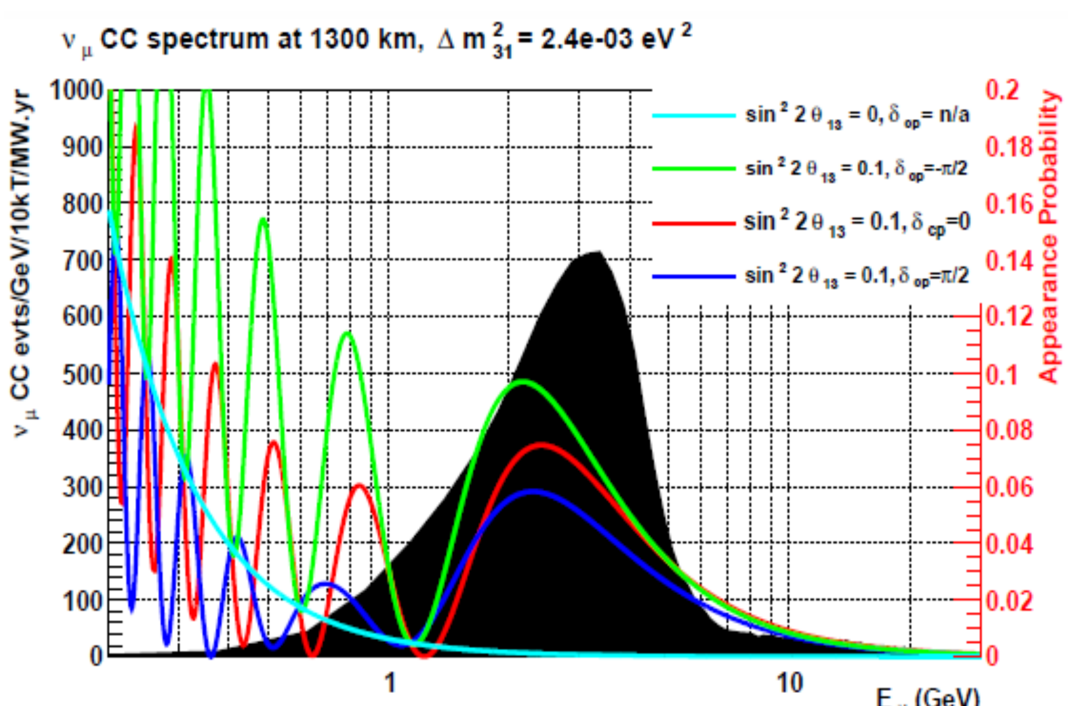
- Prospect of unambiguous detection of dark matter is very exciting
- Typical DM detector: look for recoil in large bucket of nuclei
- Post-detection: aim to determine the nature of the interaction with nucleus
  - Understand target dependence and effects
  - Requires SM calculations of nuclear matrix elements of possible currents to distinguish them
- Potentially understand seemingly conflicting positive (DAMA/CoGeNT, CDMS-Si) and negative signals (LUX, XENON,…)



http://www.hep.ucl.ac.uk/darkMatter/

Neutrino scattering

- Important goal of LBNF/DUNE: extraction of neutrino mass hierarchy and precise mixing parameters
- Requires knowing energies/fluxes to high accuracy
  - Neutrino scattering on argon target
    - Nuclear axial & transition form factors
    - Resonances
    - Neutrino-nucleus DIS
  - ~10% uncertainty on oscillation parameters [C Mariani, INT workshop 2013]

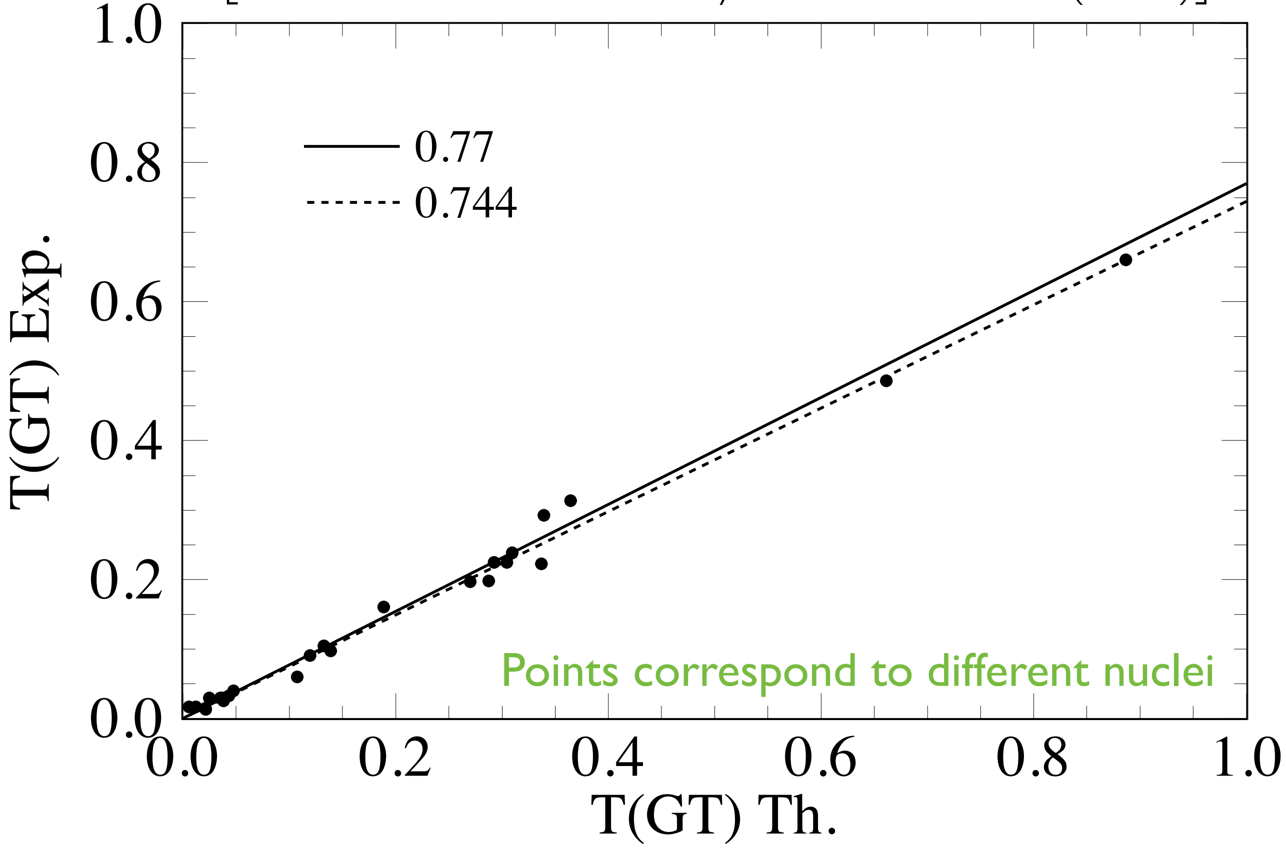


[U Mosel FSNu NP town meeting]

Nuclear uncertainties

- Nuclear matrix elements are not well understood
- Gamow-Teller transitions in nuclei are a stark example of problems (analogue of neutron decay)
- Best nuclear structure calculations are systematically off by 20–30%
  - Nuclei (30<A<60) where spectrum is well described
  - QRPA, shell-model,...
- Correct for it by arbitrarily "quenching" axial charge in nuclei
- Can NP become rigorous?

[Martinez-Pinedo et al., Phys. Rev. C53, 2602 (1996)]

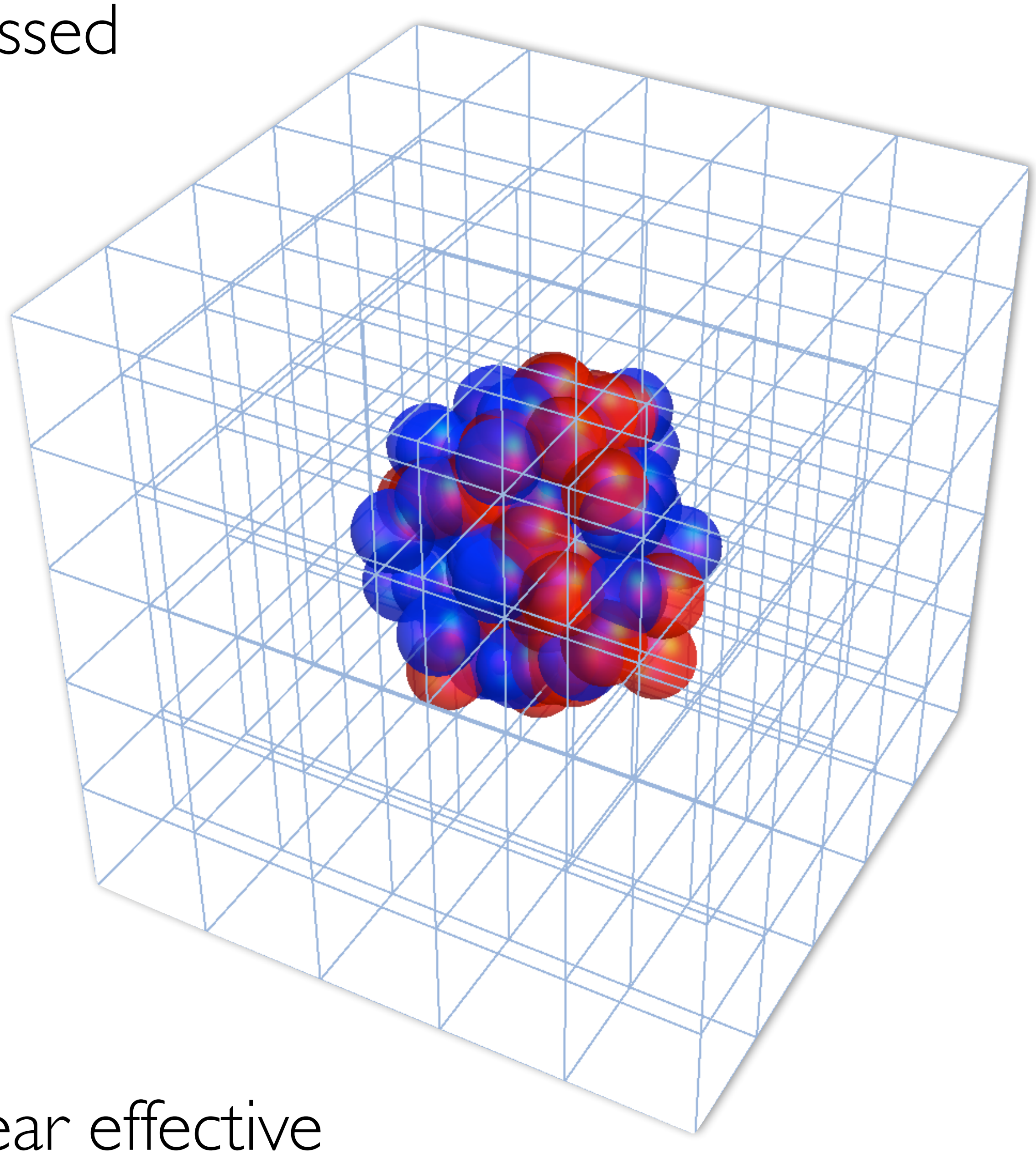


$$T(GT) \sim \sqrt{\sum_f \langle \boldsymbol{\sigma} \cdot \boldsymbol{\tau} \rangle_{i \to f}}$$

$$\langle \boldsymbol{\sigma\tau} \rangle = \frac{\langle f || \sum_k \boldsymbol{\sigma}^k \boldsymbol{t}^k_\pm || i \rangle}{\sqrt{2J_i + 1}}$$

LQCD for Nuclear Physics

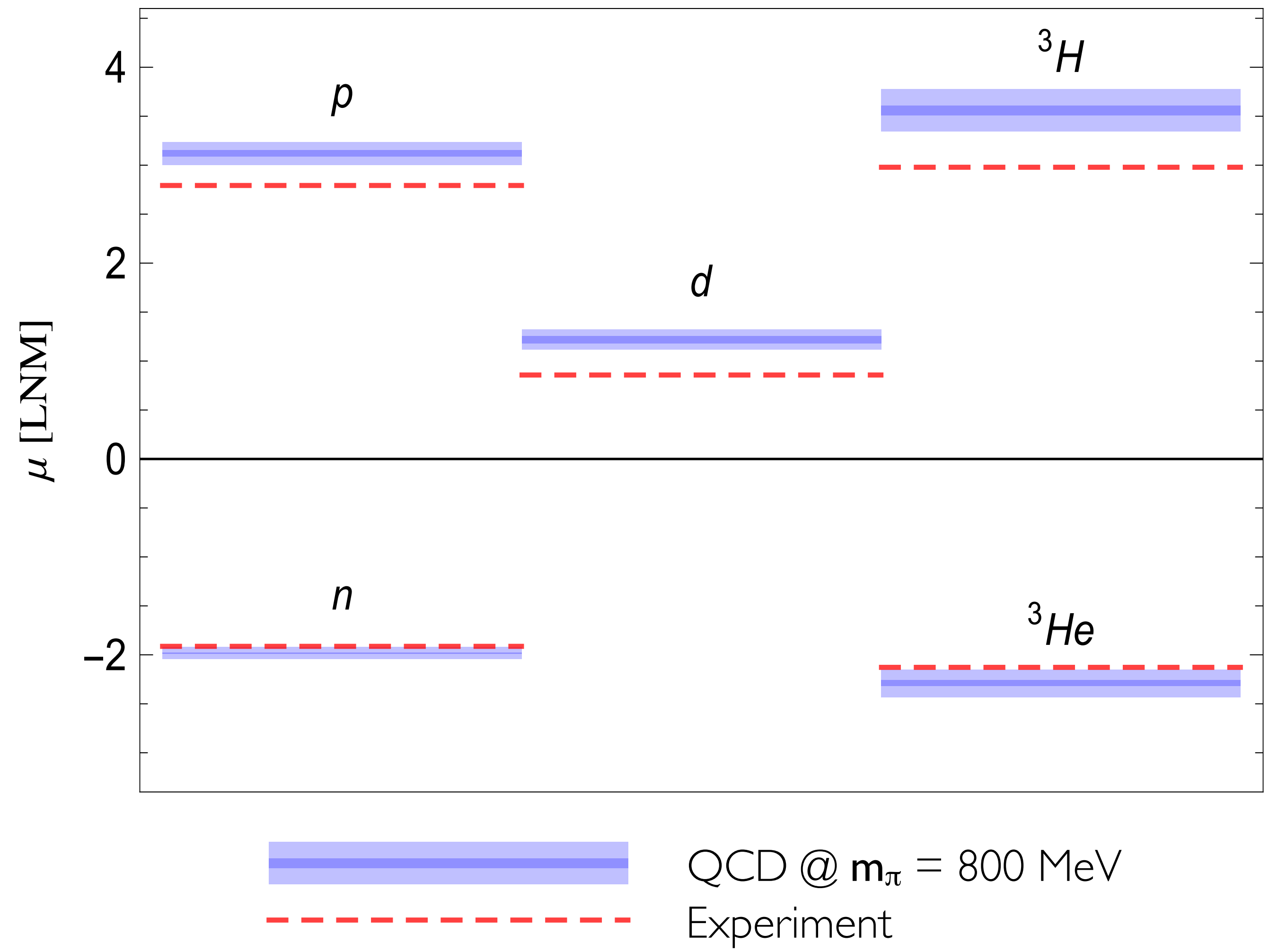
- Nuclei arise from SM, so can be addressed using LQCD
- In practice: a hard problem
  - Multiple exponentially difficult challenges
- Recent progress shows light nuclei can be studied rigorously
  - Spectroscopy
  - Matrix elements
- Connect to larger nuclei through nuclear effective field theory [Weinberg 1991;Kaplan Savage Wise 1995,…]



Magnetic moments of nuclei

[NPLQCD PhysRevLett. 113 (2014) 25, 252001]

- First QCD study of structure of nuclei
  - Magnetic moments and polarisabilities for A<5
  - Patterns very interesting but calculations not physical
- Similar studies underway for weak current, scalar currents,…
  - Expect significant progress in this area



	n	p	d	3	3
μ	-1.98(1)(2)	3.21(3)(6)	1.22(4)(9)	-2.29(3)(12)	3.56(5)(18)

In units of appropriate nuclear magnetons (heavy M_N)

Precision Higgs physics

- Future ILC will determine Higgs couplings to unprecedented accuracy: further quantitative tests of SM
  - Requires precise SM inputs and calculations
    - High order pQCD calculations
    - Commensurately precise b, c quark masses, strong coupling
- Recent study [Lepage, Mackenzie & Peskin 1404.0319] of prospects for reaching requisite precision for relative uncertainties in Higgs partial widths

$$\delta_A = \frac{1}{2}\frac{\Delta\Gamma(h \to A\overline{A})}{\Gamma(h \to A\overline{A})} \quad \Rightarrow \quad \begin{aligned} \delta_b &= 1. \cdot \delta m_b(10) \oplus (-0.28) \cdot \delta\alpha_s(m_Z) \\ \delta_c &= 1. \cdot \delta m_c(3) \oplus (-0.80) \cdot \delta\alpha_s(m_Z) \\ \delta_g &= 1.2 \cdot \delta\alpha_s(m_Z) \end{aligned}$$

- Consider expected growth in computing resources in ILC timeframe [1404.0319]

	$\delta m_b(10)$	$\delta \alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

- Allows finer lattice spacings (LS, LS^2) and higher statistical precision (ST) (also requires higher order lattice perturbation theory matching)

- Will be an important contribution to Higgs program

Summary

- LQCD has come of age in the last decade and is a precision tool for many quantities
  - Flavour physics, charged leptons, nuclear effects, SM parameters
  - Not discussed: thermodynamics, hadron spectroscopy and structure, strongly interacting models of EWSB, composite DM,...
- Progress on many fronts
  - Increase precision (deal with newly relevant systematics: QED, isospin breaking)
  - Ways to compute new observables (nuclei, multi-body decays, non-local operator matrix elements
  - New computational tricks to get more from less flops
- Lots more to come

fin

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