GdL Flavour

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Walk-through

- The role of flavour
- Not going through the "ballistic program" nor new technologies
- Focus on recent developments only
  - theory
  - Kaons and heavy flavours
  - EDM and g-2
- References

https://agenda.infn.it/conferenceDisplay.py?confId=9357

  - CSN1 white paper

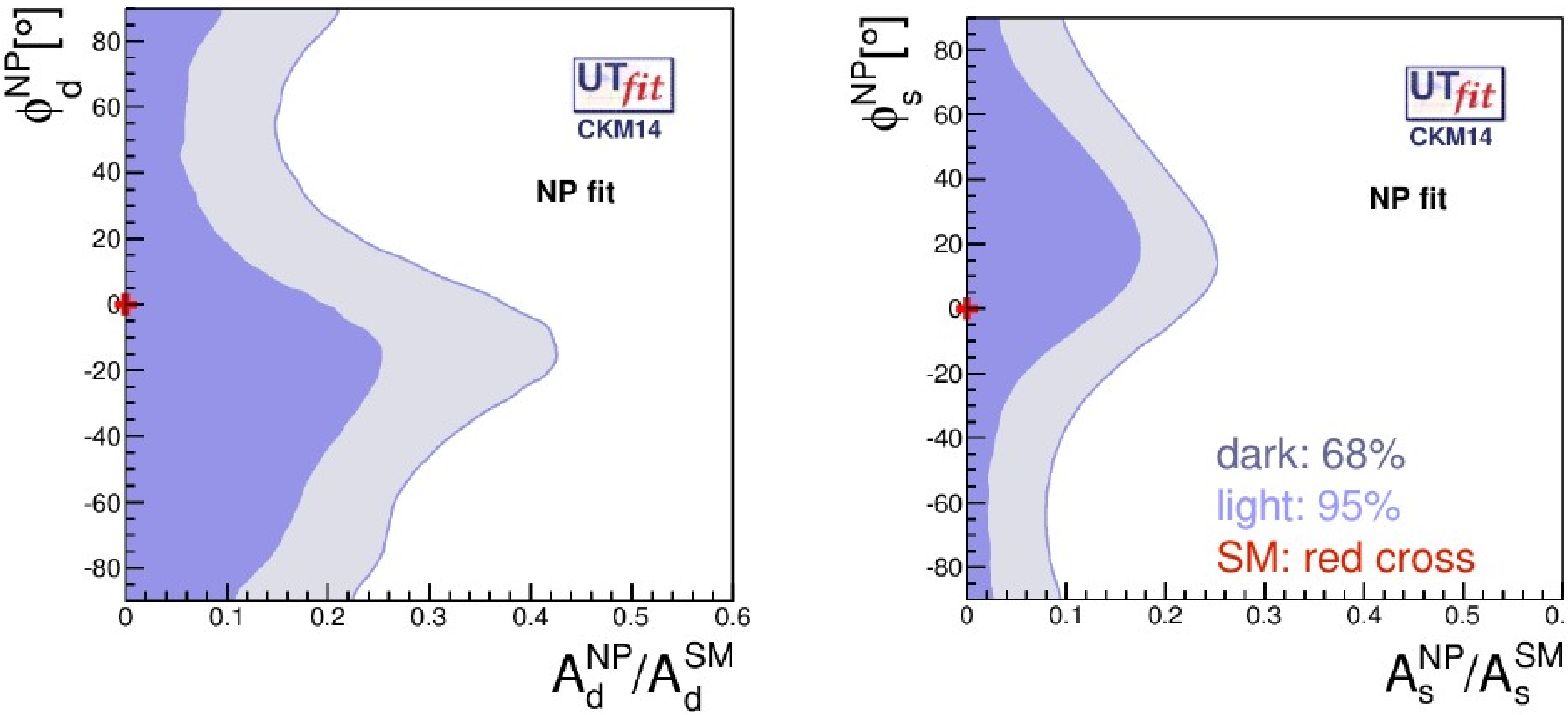
http://www.pi.infn.it/~bedeschi/CSN1/WhitePaper/

The role of flavour

- Most of the discovery of the past ~50 years anticipated by arguments or indirect evidence
  - GIM, unitarization of Fermi theory, KM, B mixing, EW fits,…
- Now we are left with arguments only
  - hierarchy problem, WIMP "miracle", gauge coupling unification
- In parallel with increasing the energy probed by the direct searhes, seek for indirect evidence!
- In the framework of future experimental developments, flavour physics should:
  - Guarantee that the flavour structure of any directly discovered NP can be efficiently probed, and/or
  - Push the NP scale that can be indirectly probed up by (at least) one order of magnitude

NP parameter results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\varphi_q^{NP} - \varphi_q^{SM})}\right) A_q^{SM} e^{2i\varphi_q^{SM}}$$



The ratio of NP/SM amplitudes is:

< 25% @68% prob. (42% @95%) in B_d mixing

< 17% @68% prob. (25% @95%) in B_s mixing

Silvestrini

M. Bona @ CKM2014

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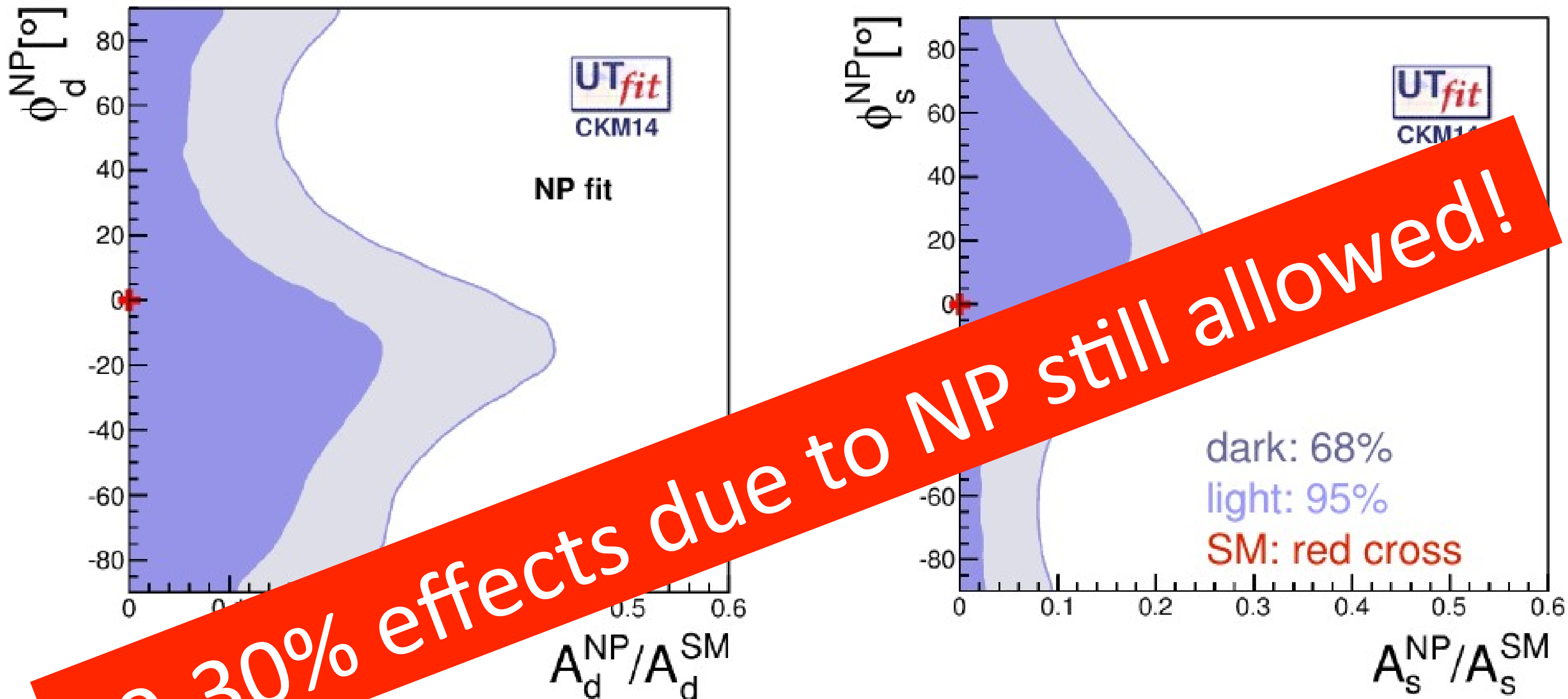

20-30% effects due to NP still allowed!

ratio of NP/SM amplitudes is:

< 25% @68% prob. (42% @95%) in B_d mixing

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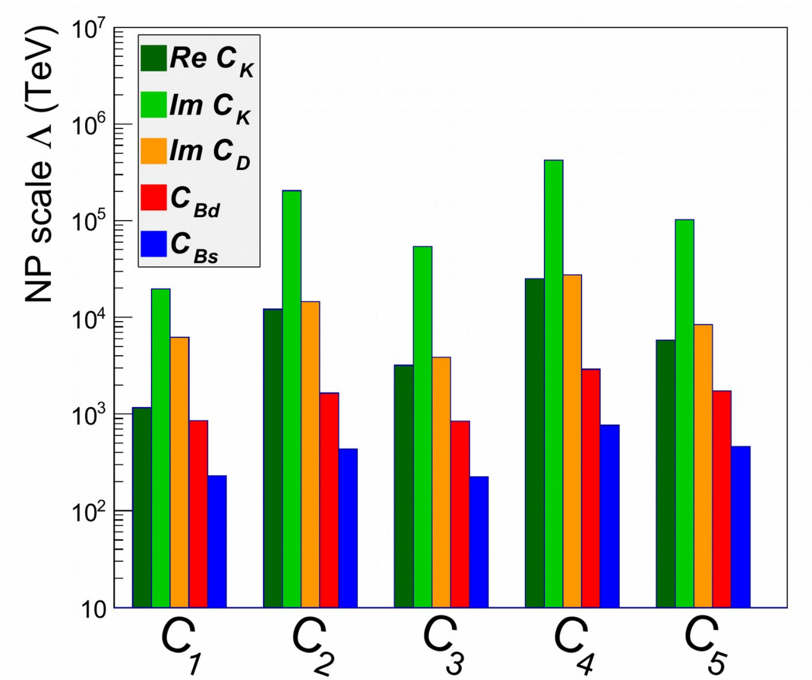
Present bounds on NP

Bounds from $\Delta F=2$ processes

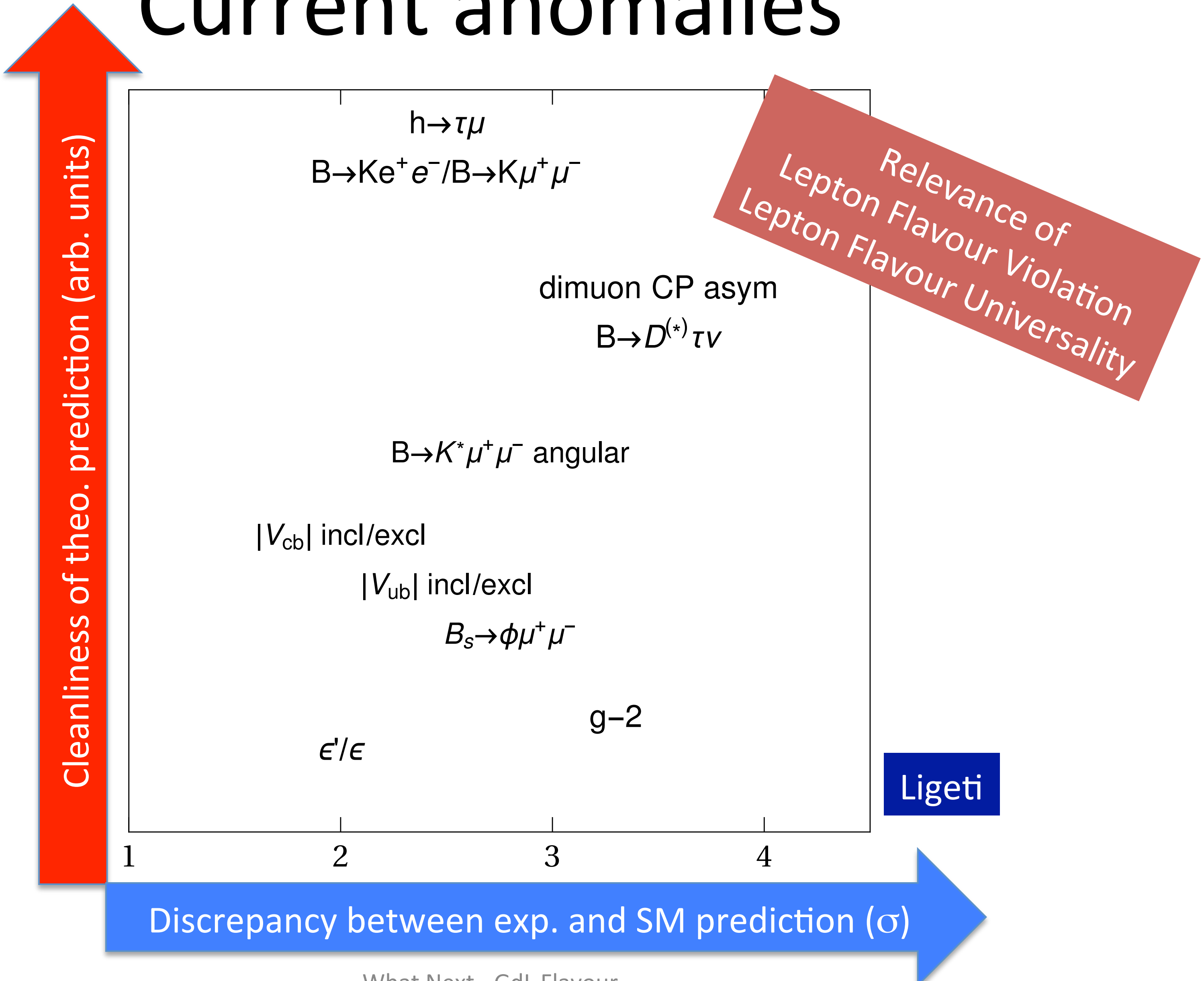


$$A_{SM}+A_{NP}=K_{SM}\frac{\alpha_W}{4\pi}\frac{F_{CKM}}{M_W^2}+K_{NP}L\frac{F_{NP}}{\Lambda^2}$$

- Best bound from ε_K, dominated by CKM error
- CPV in charm mixing follows, exp error dominant
- Best CP conserving from Δm_K, dominated by long distance
- B_d and B_s behind, error from both CKM and B-params

Silvestrini

Current anomalies



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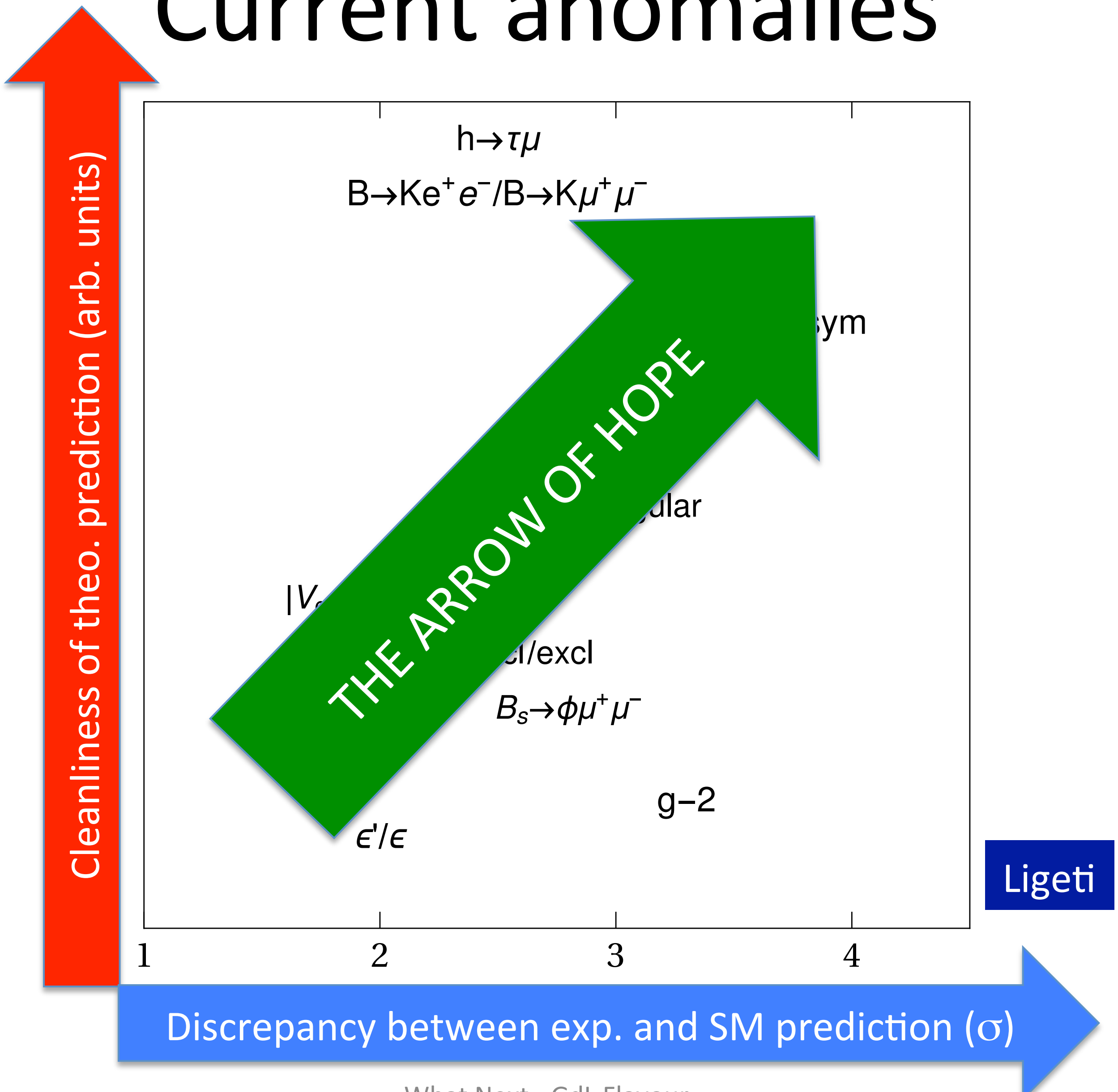
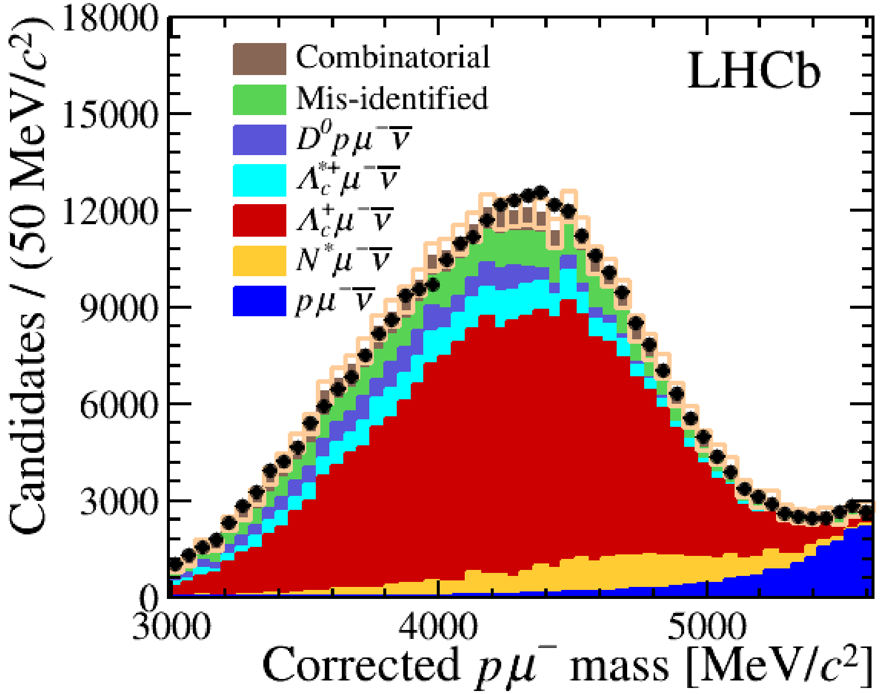
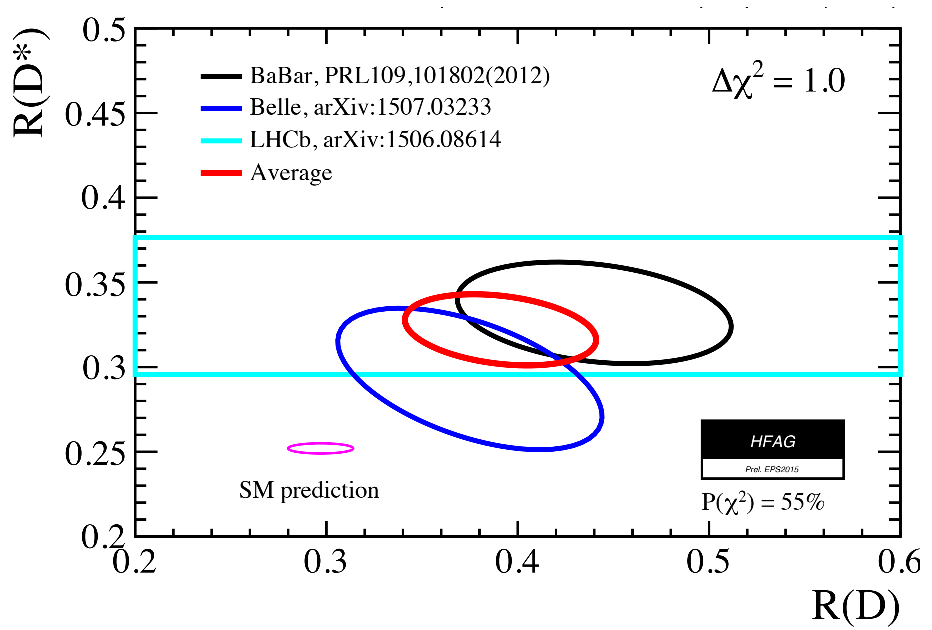


The non-ballistic side of ballisticness

Measuring $|V_{ub}|$ and $B \longrightarrow D^{*}\tau\nu$ at hadron colliders



$\Lambda_b \rightarrow p\mu\nu$



$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$$

Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]	FLAG 2013 [1310.8555]	2025 [What Next]
$f_+^{K\pi}(0)$	- First Lattice result in 2004 [0.9%]	[0.4%]	[0.1%]
$\hat{B}_K$	[17%]	[1.3%]	[0.1-0.5%]
f_{Bs}	[13%]	[2%]	[0.5%]
f_{Bs}/f_B	[6%]	[1.8%]	[0.5%]
$\hat{B}_{Bs}$	[9%]	[5%]	[0.5-1%]
B_{Bs}/B_B	[3%]	[10%]	[0.5-1%]
$F_{D^*}(1)$	[3%]	[1.8%]	[0.5%]
$B\to\pi$	[20%]	[10%]	[<1%]

Tarantino
LTS1
Elba 2014

More unpredictable but more surprising progresses can occur for the observables that today are very difficult (or infeasible): $K \to \pi \nu \bar{\nu}$, $K \to \pi l^+ l^-$, $K \to \pi \pi$, Δm_K

Tarantino

Significant progress in 2015

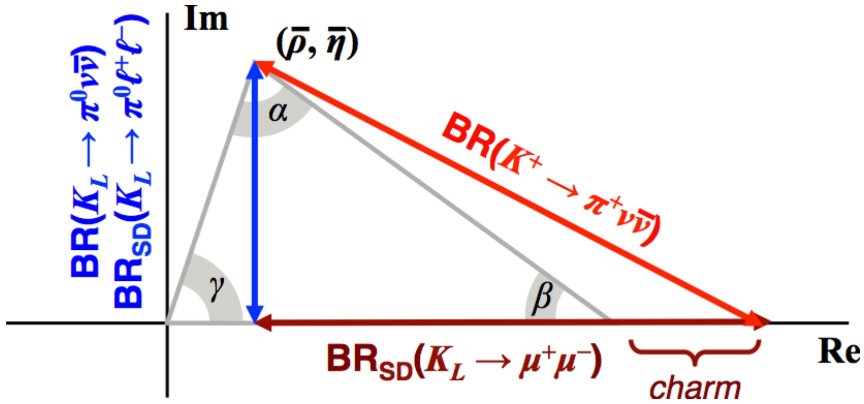
- Long distance contributions to $K \to \pi \nu \nu$ and $K \to \pi l^+ l^-$, shown to be computable on the Lattice in an exploratory study by G.Isidori, G. Martinelli and P.Turchetti [hep-lat/0506026], have been recently extended and updated by RBC-UKQCD [1507.0309]
- $K \to \pi \pi$, too difficult/unfeasible until few years ago, being studied by RBC/UKQCD [1206.5142,1212.1474,1502.00263,1505.07863]
  - $\Delta I=3/2$ @10%, $\Delta I=1/2$ investigated with unphysical kinematics], $Re(A_0)$ @35%, in agreement with experiments, $Re(\varepsilon'/\varepsilon)$ explored for the first time, expect @10% in 5 years
- Δm_K @35% accuracy by RBC/UKQCD (unfeasible until few years ago) [1212.5931,1406.0916] with Finite Size Effects studied by N.H. Christ, X. Feng, G. Martinelli and C.T. Sachrajda [1504.01170]
- Long distance contributions in the charm sector not been explored yet. They are more difficult (more intermediate states), but recent progress teaches us that they are NOT unfeasible

Rare kaon decays: $K \to \pi\nu\bar{\nu}$

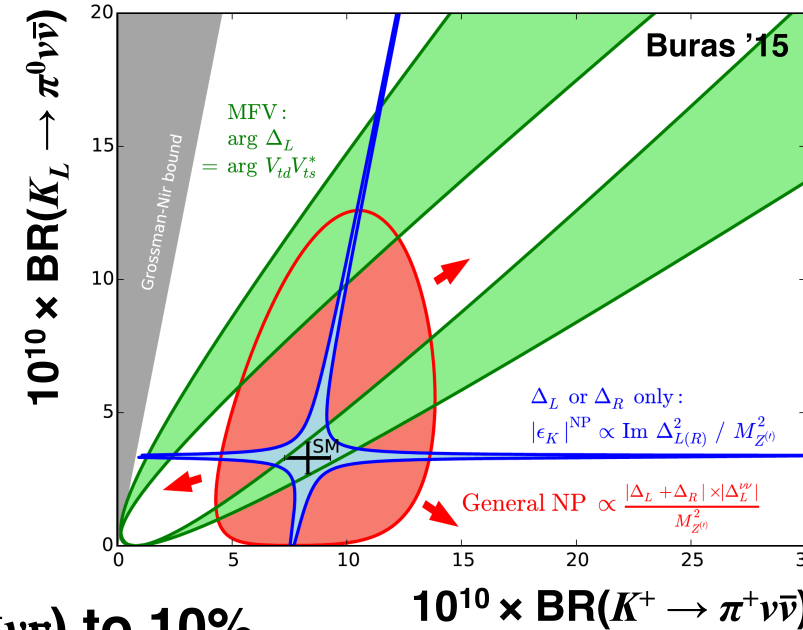
Moulson

Precise BR measurements of $K \to \pi\nu\nu$ offer:

- **unique constraints on CKM unitarity**
- **potential evidence for new physics**



Important to measure both K^+, K_L:
New physics affects channels differently



Within next the 2-3 years:

- **NA62** (CERN) will measure **BR($K^+ \to \pi^+\nu\nu$) to 10%**
- **KOTO** (JPARC) will observe **a few $K_L \to \pi^0\nu\nu$ events**

Longer term: KOTO Step 2 with ~100 $K_L \to \pi^0\nu\nu$ event sensitivity?

Can a competitive measurement of $K_L \to \pi^0\nu\nu$ be made at the CERN SPS?

- High-energy experiment: Complementary approach to KOTO
- Possibile to re-use NA48 calorimeter, experimental infrastructure?
- Feasibility studies near conclusion (NA62 Italy PRIN project 2013-2016)

$K_L \to \pi^0 \nu\bar{\nu}$ at the SPS ?

Moulson

Primary beam:
400 GeV p+Be, 10^{19} pot/yr
Extracted at 2.4 ± 0.3 mrad

Secondary beam:
5×10^{12} K_L decay/yr
Mean $p(K_L)$ = 90 GeV

K_L decays: **4 MHz**
Beam neutrons: **2 GHz**
Beam photons: **12 GHz**

Current studies show that careful design of
- beam sweeper
- Small and large angle photon vetoes
- Main π^0 detector with extra photon veto

would reduce neutron and photon rates to ~200 and ~100MHz

Expected results with 5 yrs of data:

$\pi^0\nu\bar{\nu}$ cand. with 2γ on LKr, nothing else
Vertex in FV with $p_\perp(\pi^0) > 0.12$ GeV

70 signal events
S/B ~ 1 ($\pi^0\pi^0$ background)
Comparable to KOTO Step-2

An “Extreme Flavour” (XFX) experiment?

- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events and hadronic final states, but limited in luminosity, 50 fb^{-1} vs 3000 fb^{-1}
- Would an experiment capable of exploiting the full HL-LHC luminosity for flavour physics be conceivable?
  - Aiming at collecting O(100) times the LHCb upgrade luminosity → 10^{14} b and 10^{15} c hadrons in acceptance at $L=10^{35}$ $cm^{-2}s^{-1}$

Punzi

XFX CKM UT fit (preliminary!)

Parameter	SM fit error		NP fit error	
	now	extreme	now	extreme
$\bar{\rho}$	16%	0.4%	26%	1.5%
$\bar{\eta}$	4%	0.1%	13%	1.4%
$\mathrm{Im}\lambda_t$	2.8%	0.8%	13%	1.4%
$\mathrm{Re}\lambda_t$	2.9%	0.8%	7.4%	2.1%
$\lvert V_{td}/V_{ts}\rvert$	2.3%	0.09%	5%	0.15%
C_{ϵ_K}	–	–	0.16	0.034
C_{B_d}	–	–	0.16	0.029
ϕ_{B_d}	–	–	3.2°	0.41°
C_{B_s}	–	–	0.08	0.028
ϕ_{B_s}	–	–	2.0°	0.023°

Silvestrini

LHCb @ 300fb^{-1} ?

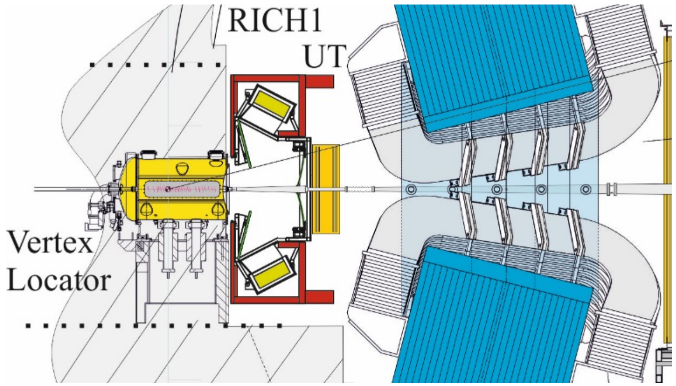
E. Thomas

- Even after the LHCb upgrade, many key flavour observables will not reach the "ultimate" precision:
  - CKM angle γ, B_s mixing phase ϕ_s, CPV asymmetries in semileptonic B_d and B_s decays, CPV in $B \rightarrow \mu\mu$, gluonic penguins decays $B_s \rightarrow \Phi\Phi$, K^*K^*
- Sensitivity to rare/forbidden decays will need to be improved:
  - $\tau \rightarrow \mu\mu\mu$, $D^0 \rightarrow \mu\mu$, $B \rightarrow e\mu$, $D^0 \rightarrow e\mu$
- ...not to mention existing anomalies which might still be persisting...
- ...or the unique reach in other areas
  - Hadron spectroscopy, EW physics, top (and Higgs?) physics

High Lumi options

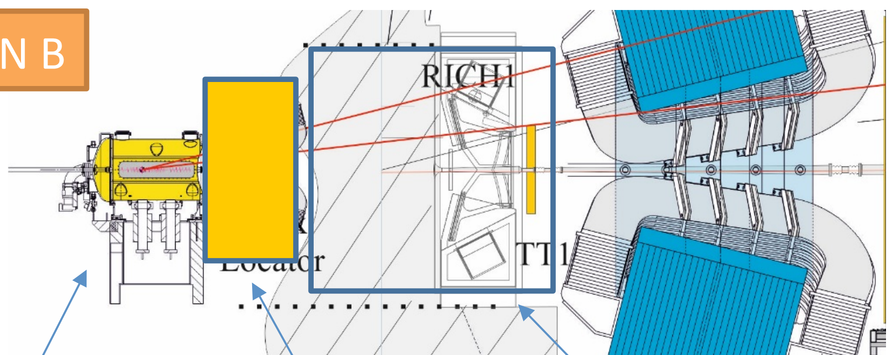
E. Thomas

OPTION A



Less modifications to layout of LHC, but major redesign of detectors in order to cope with higher rates

OPTION B



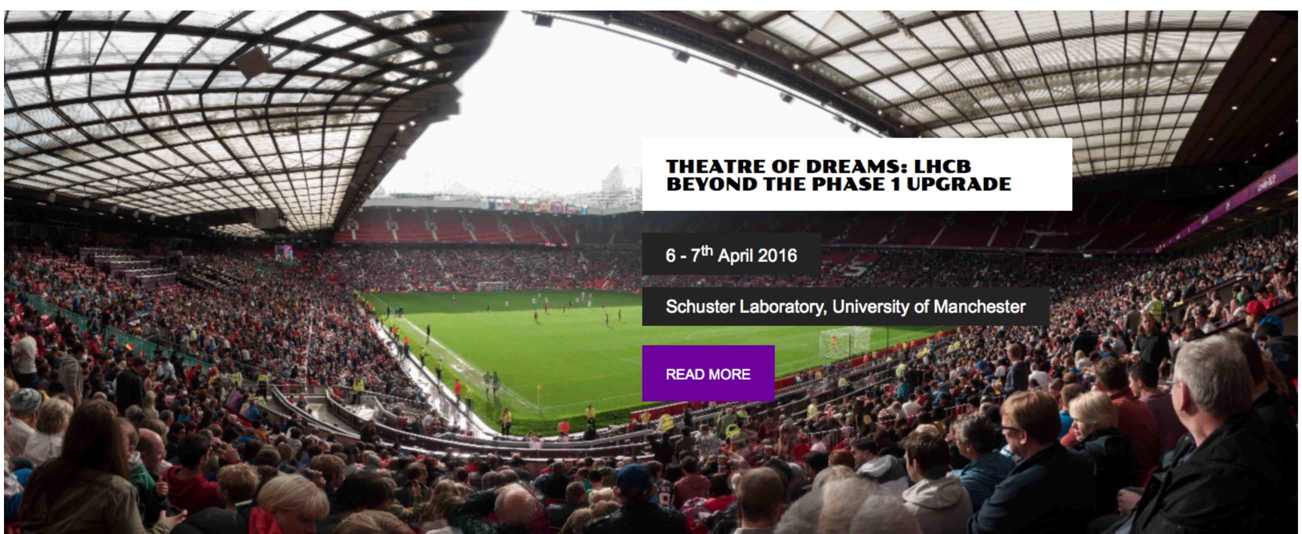
Shifted IP and VELO

New Dipole

Space available for detectors with wide angle coverage: tracking and RICH (as now) + Calo, Muon…

What next?

- Feedback from LHC so far:
  - Substantially more luminosity in LHCb should have limited impact on ATLAS/CMS luminosities
  - Experimental scheme can be implemented in the machine
  - Need to evaluate shielding
- Workshop on detector and physics in Manchester:



Search for permanent Electric Dipole Moments (EDM)

- Measurements of electric dipole moments are a unique, extraordinarily sensitive way to probe for a physical phenomenon of profound significance, violation of microscopic time-reversal invariance.
- They currently put the best limits on the θ parameter, and offer the most plausible means to determine that fundamental parameter.

- They also constrain many implementations of supersymmetry, a much-anticipated extension of the Standard Model, that supports quantitative unification of the basic forces of Nature.
- If supersymmetry is valid, it very plausibly leads to electric dipole moments not far beyond present-day limits, and within the scope of known experimental technique.

F. Wilczek, Jan. 2014

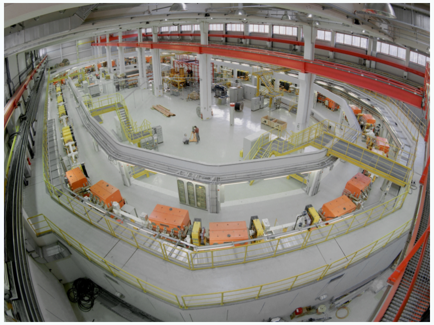
Search for EDM of charged particles (p, d) in storage rings:

Key technologies:

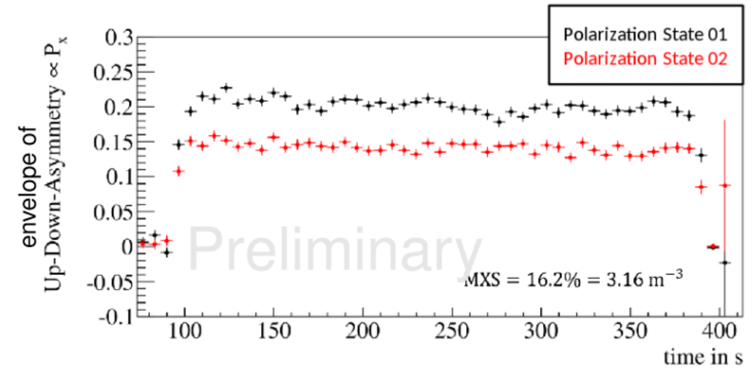
- Polarimetry – detect spin rotation of 1 *nrad/s*
- Spin coherence time – at least 1000 *s*
- E/B benders – high electric fields > 10 *MV/m*
- Beam position – relative measurement; feedback
- Shielding of external fields
- (…)

Towards the first deuteron EDM measurement

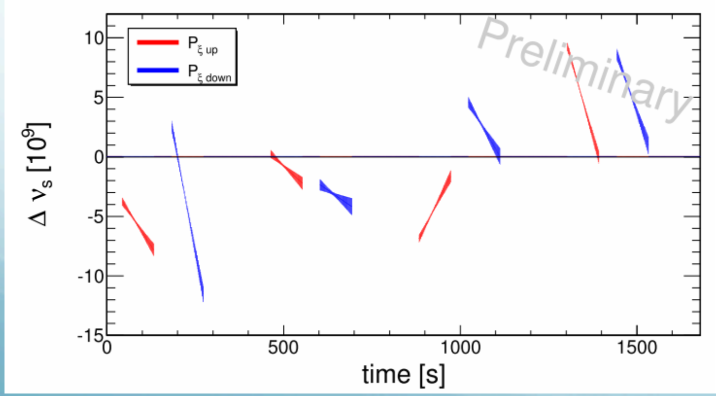
- COSY at Juelich
- Perfect R&D machine
- Mesurement planned in 2018
- Injector for dedicated ring



Recent results obtained at COSY:

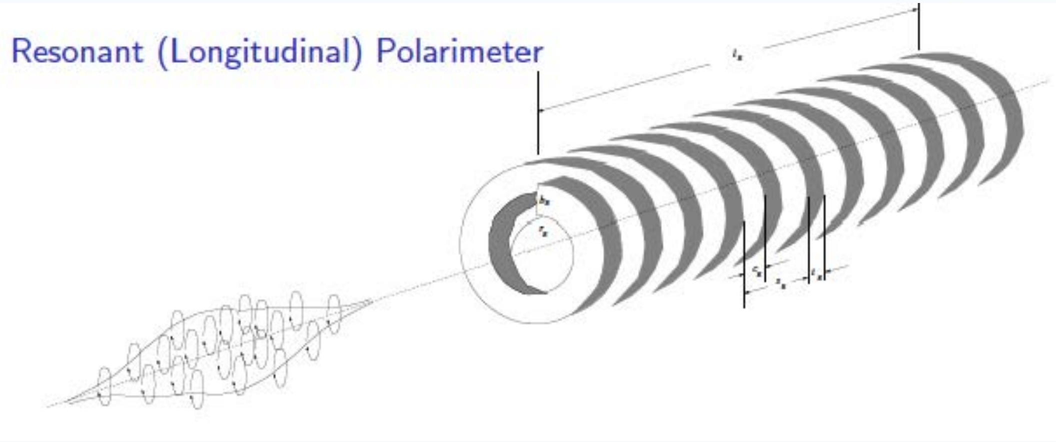


- Spin coherence time a few 1000 s
- Previous best ≈ 10 s @ Novosibirsk



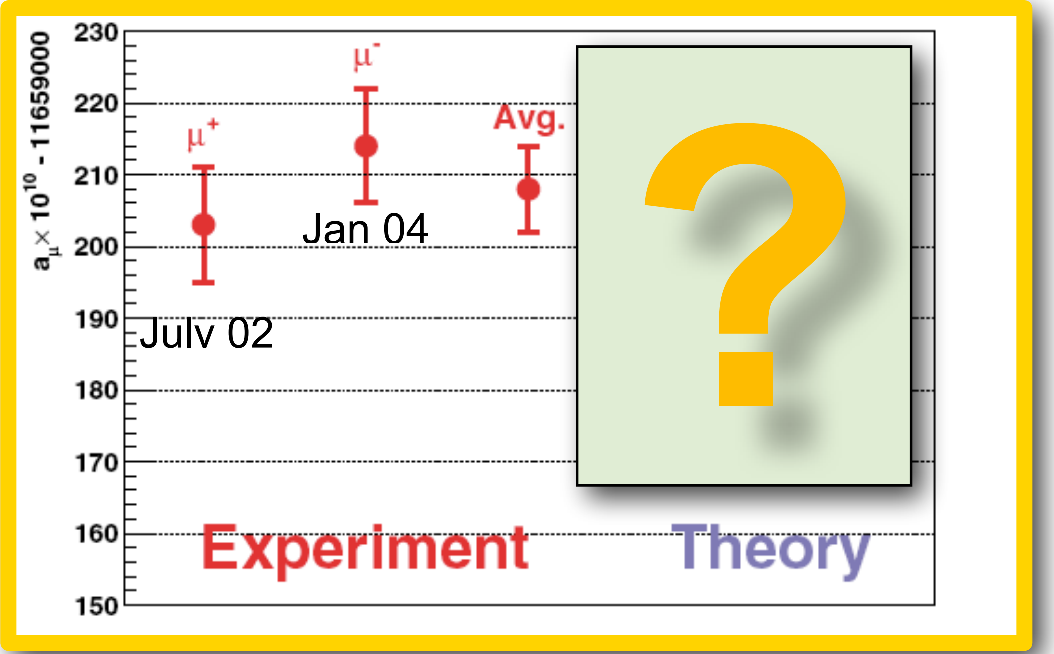
- Precision spin tune measurement 10^{-10} per cycle.
- Compare to (g-2)ν_s: 3×10^{-8} in one year
- $\nu_s=\gamma G$: most precise measurement of energy

RF resonant polarimetry:
a possible key towards the (electron) EDM?



- Longitudinal polarized beam approaching a SC helical resonator.
- High-Q transverse polarimetry proposed by Derbenev in 1995
- Test at ELSA (Bonn) under consideration
- Can be extended to other experiments.

The muon g-2: experimental status



- **Today:** $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys})\text{x}10^{-11}$ [0.5ppm].
- **Future:** new muon g-2 experiments at:
  - **Fermilab E989:** aiming at $\pm 16\text{x}10^{-11}$, ie 0.14ppm. Beam expected in 2017. First result expected in 2018 with a precision comparable to that of BNL E821.
  - **J-PARC proposal:** aiming at 2019 Phase 1 start with 0.4ppm.
- Are theorists ready for this (amazing) precision? Not yet

Muon g-2 @FNAL
(>13 FTE)

- **Sept 2014 – May 2015**

– Reassembly of the storage ring with cryogenic system; fully operational

- **June 2015**

– Start of cooling

- **July-August 2015**

– CD2/3 received

- **September 2015**

– Magnet cooled, ON (5300 A, 1.45T)
– 8 months needed for shimming

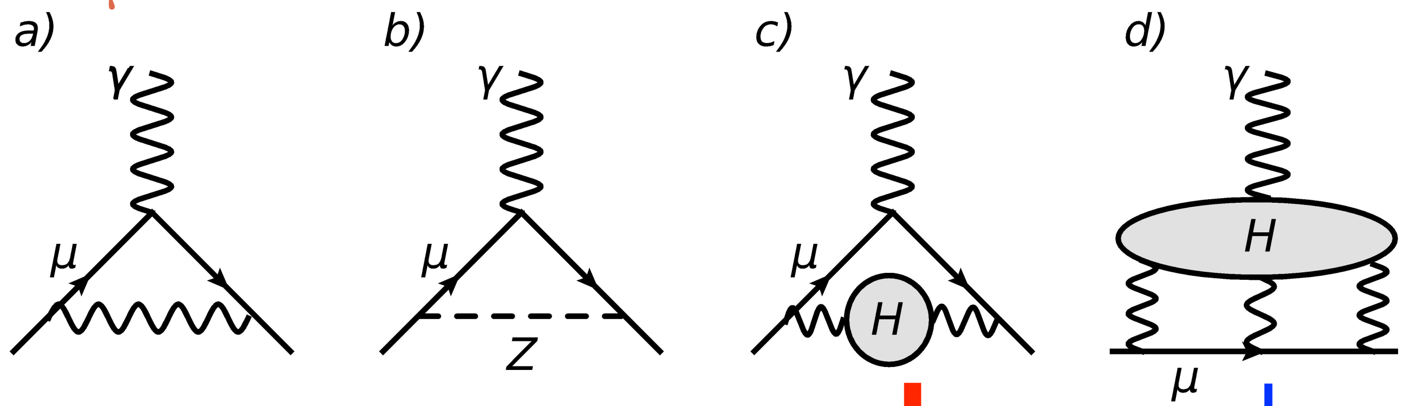
INFN contribution:

Laser monitoring system for calorimeter calibration
Gain stability 10^{-4} per hour

READY FOR BEAM APRIL 2017

RISE EU-grant MUSE with Mu2e starting Jan 2016

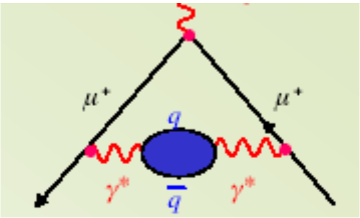
a_μ(SM): There are really 2 numbers in play here



	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)	$6\,923 \pm 42$
HVP(lo)	$6\,949 \pm 43$
HVP(ho	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

A new approach to measure a_μ^{HLO}

$a_\mu=(g-2)/2$



[*C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni* Phys.Lett. B746 (2015) 325-32]

- **Measure** the hadronic contribution to the effective electromagnetic coupling in the space-like region $\Delta\alpha_{had}$ (t) from **Bhabha** scattering.
- It gives the **full** contribution to a_μ^{HLO} w/o any theoretical correction (isospin, FSR)
- It requires to measure the Bhabha cross section at relatively small angles at (better than) **10^{-4}** accuracy.
- Feasibility study at low energy **flavour** factories (1–10 GeV) planned

Outlook

- In a global strategy for new physics searches, improving the accuracy on flavour observables has a key role to ensure that
  - We increase the sensitivity of indirect searches and search for NP at very high energies, opening the road for more direct explorations
  - We are able to determine the flavour structure of any NP directly seen, and hopefully understand its origin; roughly 3x in M_{NP} → 10x in exp & th → 100x in L
- Ballistic program will keep indirect searches in sync with direct ones
- Non-ballistic program looks very promising for large sensitivity improvements in the future

Backup

NEWS from Lattice QCD
w.r.t. last What Next (2014)
where well known Lattice inputs were considered
and extrapoletd in accuracy up to ~2030

Tarantino

More unpredictable but more surprising progresses can occur for observables that
yesterday were infeasible
today are very difficult (but are being explored)

TOMORROW…

significant progress in 2015

Long distance contributions to $K \to \pi \nu \nu$ and $K \to \pi l^+ l^-$ have been shown to be computable on the Lattice in an exploratory study by G.Isidori, G. Martinelli and P.Turchetti [hep-lat/0506026], recently extended and updated by RBC-UKQCD [1507.0309]

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- $\Delta I=3/2$ [10%] (too difficult until few years ago)
- $\Delta I=1/2$ [investigated with unphysical kinematics] (infeasible until few years ago)
  - $Re(A_0)$ determined with 35% accuracy, in agreement with experiments
    - $Re(\varepsilon'/\varepsilon)$ explored for the first time (2.1σ different from the experimental value, 500% uncertainty improvable to 10% in 5 years)

Δm_K determined with 35% accuracy by RBC/UKQCD (infeasible until few years ago)[1212.5931,1406.0916]
with Finite Size Effects studied by N.H. Christ, X. Feng, G. Martinelli and C.T. Sachrajda [1504.01170]

Long distance contributions in the charm sector have not been explored yet.
They are more difficult (more intermediate states),
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PRIN studies: $K_L \to \pi^0 \nu\nu$ at the SPS

Moulson

Primary beam:
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Extracted at 2.4 ± 0.3 mrad

Secondary beam:
5 × 10^{12} K_L decay/yr
Mean $p(K_L)$ = 90 GeV

K_L decays: **4 MHz**
Beam neutrons: **2 GHz**
Beam photons: **12 GHz**

Current status of design studies:

Beam sweeper	Monocrystalline Ir converter: Reduces γ to ~100 MHz, mostly low energy
Large angle photon vetoes	26 ring-shaped stations, scintillator/tile design Hermetic coverage only needed to 100 mrad Realistic efficiency assumptions (same as for CKM VVS)
Main π^0 detector, extra photon veto	NA48 LKr calorimeter Efficiency assumptions same as for NA62
Small angle photon vetoes	Only need high efficiency (10^{-4}) for $E_\gamma > 30$ GeV Monocrystalline W absorber tiles + Si pads? 11 X_0 = 11 mm = 0.1 λ_{int}: Reduce neutron interactions to ~200 MHz Excellent σ_t + backstop detectors for n/γ discrimination

Expected results with 5 yrs of data:

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Vertex in FV with $p_\perp(\pi^0) > 0.12$ GeV

70 signal events

S/B ~ 1 ($\pi^0\pi^0$ background)

Comparable to KOTO Step-2

A new approach to measure a_μ^{HLO}

[C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni
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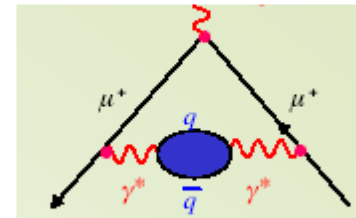

$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$

$$t = \frac{x^2 m_\mu^2}{x-1} \quad 0 \le -t < +\infty \qquad t = -s\sin^2\left(\frac{\vartheta}{2}\right)$$

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \quad 0 \le x < 1;$$

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