Flavour Physics: Introduction

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The context

- The Higgs discovery at LHC run I completes the Standard Model. No compelling deviations from theory, but some anomalies (mainly in flavour physics).
- This is in contrast to theory expectations, or at least hopes (such as light superpartners).
- Need to revisit preconceptions/prejudices, eg move beyond CMSSM etc. **Likely to be data-driven, by upcoming high-luminosity LHC run and non-LHC intensity-frontier and precision-frontier experiments.**
- The “obvious” next step is precision Higgs physics (branching ratios etc). I will argue that this is on equal footing with a much larger class of measurements including flavour violation, anomalous SM particle properties, etc.
- The UK PP community is a main player across the board

Why and what BSM physics?

Discovery of a fundamental scalar makes the naturalness problem **real,** i.e. more severe than ever. If there is a physical scale M above M_Z, as suggested by near-unification of couplings, the baryon asymmetry, neutrino masses, gravity,... then the weak scale is unstable to quantum corrections.

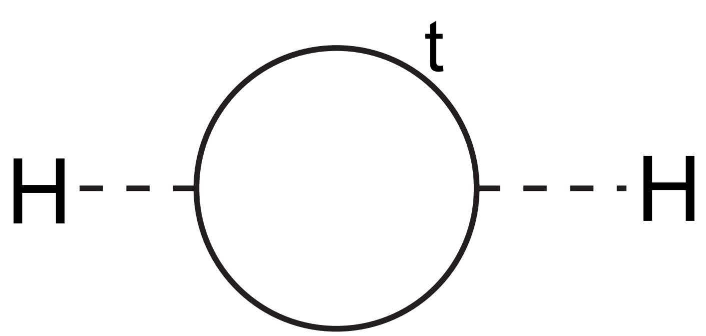
$$\mathcal{L}_{\mathrm{SM}} = \sum_f \bar{\psi}_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$

EW scale setting

$$-\bar{u}_R Y_U \phi^{c\dagger} Q_L - \bar{d}_R Y_D \phi^\dagger D_L - \bar{e}_R Y_E \phi^\dagger E_L - \mu^2 \phi^\dagger \phi - \frac{\lambda}{2} (\phi^\dagger \phi)^2$$

fermion masses and SM flavour physics

Naturalness problem is (mostly) caused by top Yukawa, a flavour-specific term



Physics addressing naturalness should be flavourful, too

This happens in supersymmetry, extra dim/composite Higgs, ...

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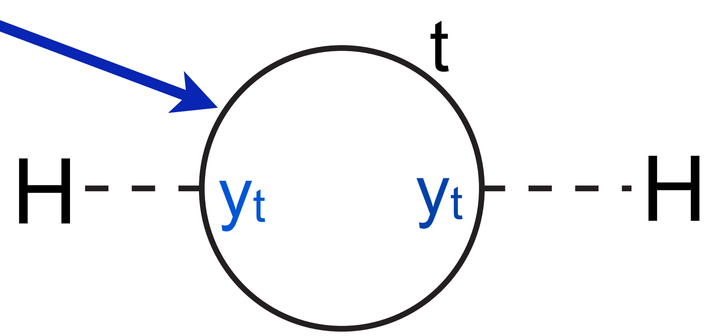

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fermion masses and SM flavour physics

$\propto y_t^2\, M^2$

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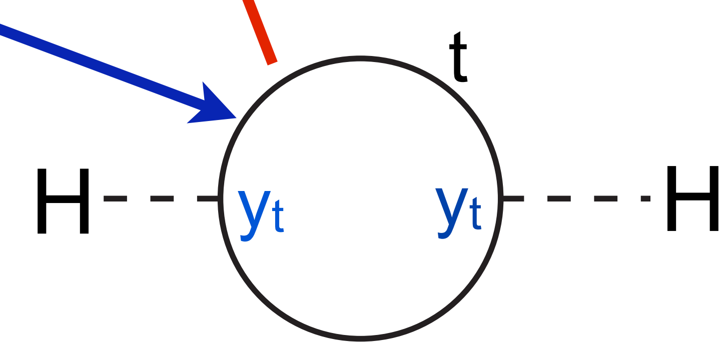

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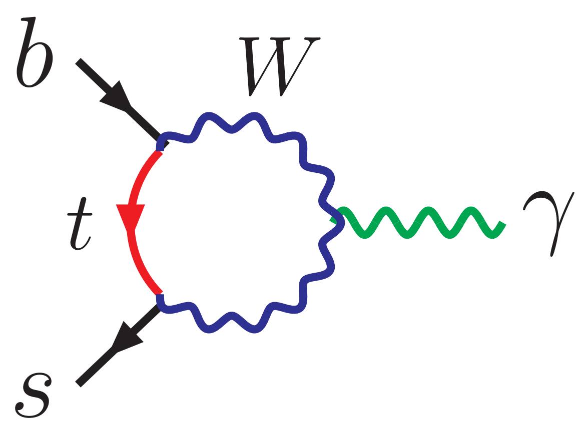
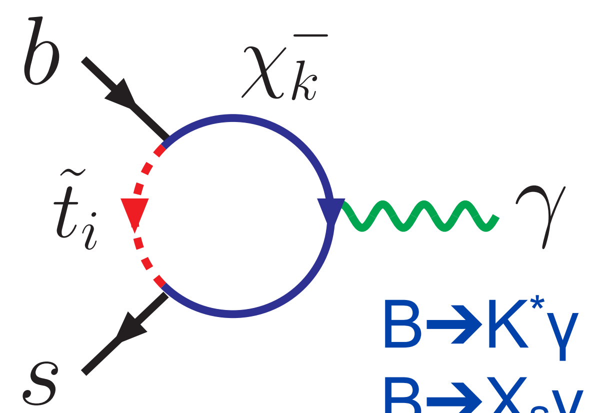
This happens in supersymmetry, extra dim/composite Higgs, ...

BSM flavour

The new particles' couplings tend to mediate flavour changes (they do in all the "natural" proposals for TeV physics)

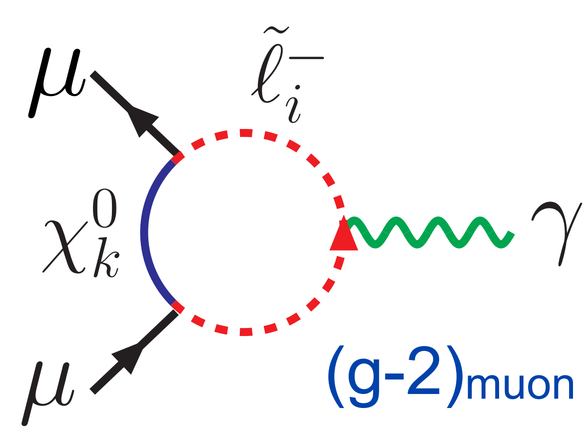
At least they will have CKM-like flavour violations (minimal flavour violation), so will always affect rare decays.





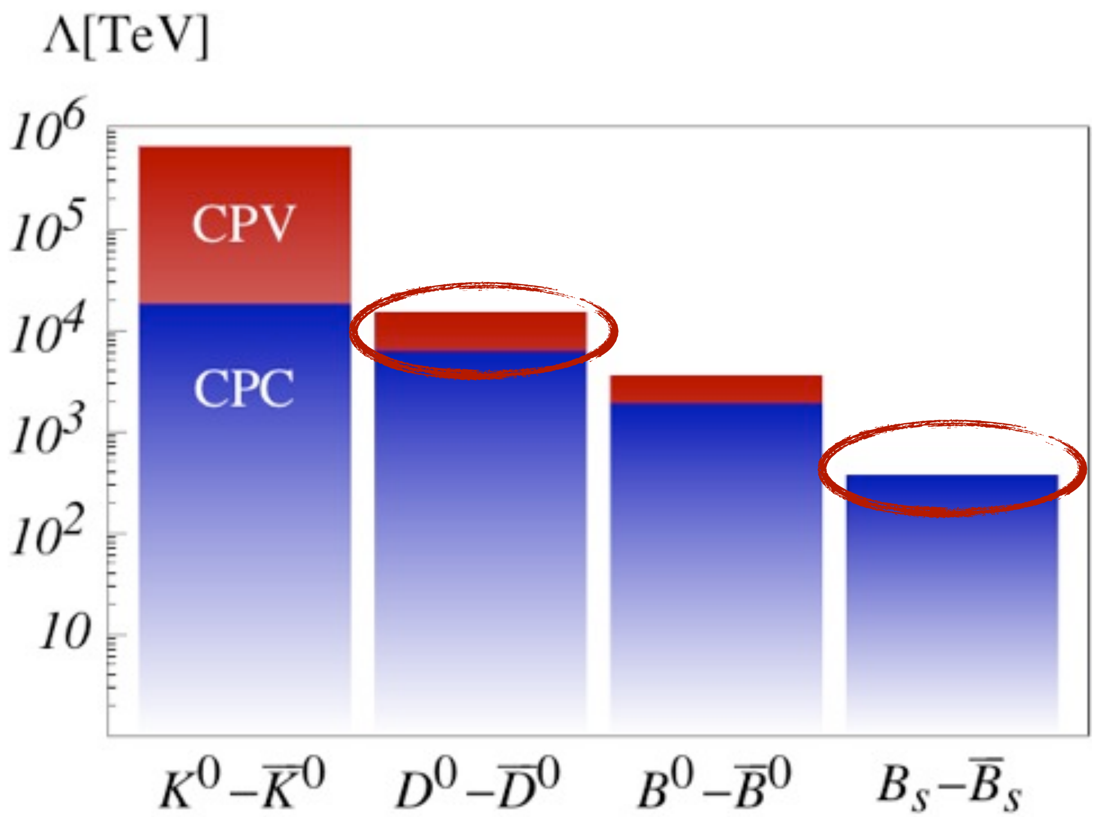
$B \rightarrow K^*\gamma$
$B \rightarrow X_s\gamma$

Of course BSM particles will mediate flavour-*conserving* processes, too.



$(g\text{-}2)_{muon}$

Flavour constrains the new physics scale...



J Kamenik, Beach 2014

(D and B_s CP violation constraints are expt limited; K and B_d, at the moment, theory limited)

... and its flavour-symmetry-breaking structure

Eg supersymmetry (MSSM) is minimally flavour violating (and the EW symmetry unbroken) in the absence of soft SUSY breaking; non-minimal flavour violation probes the SUSY breaking mechanism.

What BSM effects?

Heavy physics with mass scale M described by local effective Lagrangian at energies below M

Effective Lagrangian dimension-5,6 terms describes **all** BSM physics to O(E^2/M^2) accuracy. **Systematic & simple**.

Buchmuller, Wyler 1986
Grzadkowski, Misiak, Iskrzynski, Rosiek 2010

$$
\begin{array}{c|c}
Q_{ll} & (\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t) \\
Q_{qq}^{(1)} & (\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t) \\
Q_{qq}^{(3)} & (\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t) \\
Q_{lq}^{(1)} & (\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t) \\
Q_{lq}^{(3)} & (\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)
\end{array}
$$

operators (vertices) are catalogued for arbitrary (heavy) new physics

Only trace of BSM physics is in their (Wilson) coefficients

Higgs physics (production & decay) probes 19 operators

B physics O(100) operators (more if lepton flavour violation)

Lepton flavour violation O(100)

eg Crivellin, Najjari, Rosiek 2013

(Top physics in principle many more, mostly 3-body hadronic decays.)

What UK activities?

UK has an large and influential flavour physics community

LHCb (11 UK groups)
NA62 (rare kaons)
SHIP (light dark sector)
COMET/PRISM (charge lepton flavour violation)
g-2 (anomalous muon magnetic moment)

covered in this session

further related activities covered in different sessions (neutrinos, EDM,...), also ATLAS/CMS B-physics

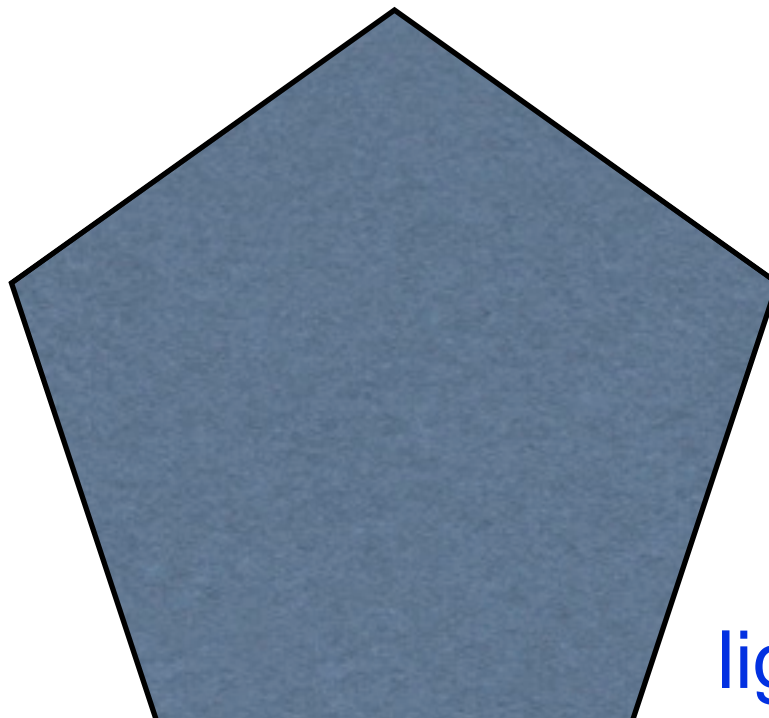
growing flavour theory/phenomenology activity spread across at least 7 institutions (Sussex, Southampton, UCL, Oxford, Liverpool, Durham, Edinburgh)

strong interconnection with UK & lattice QCD

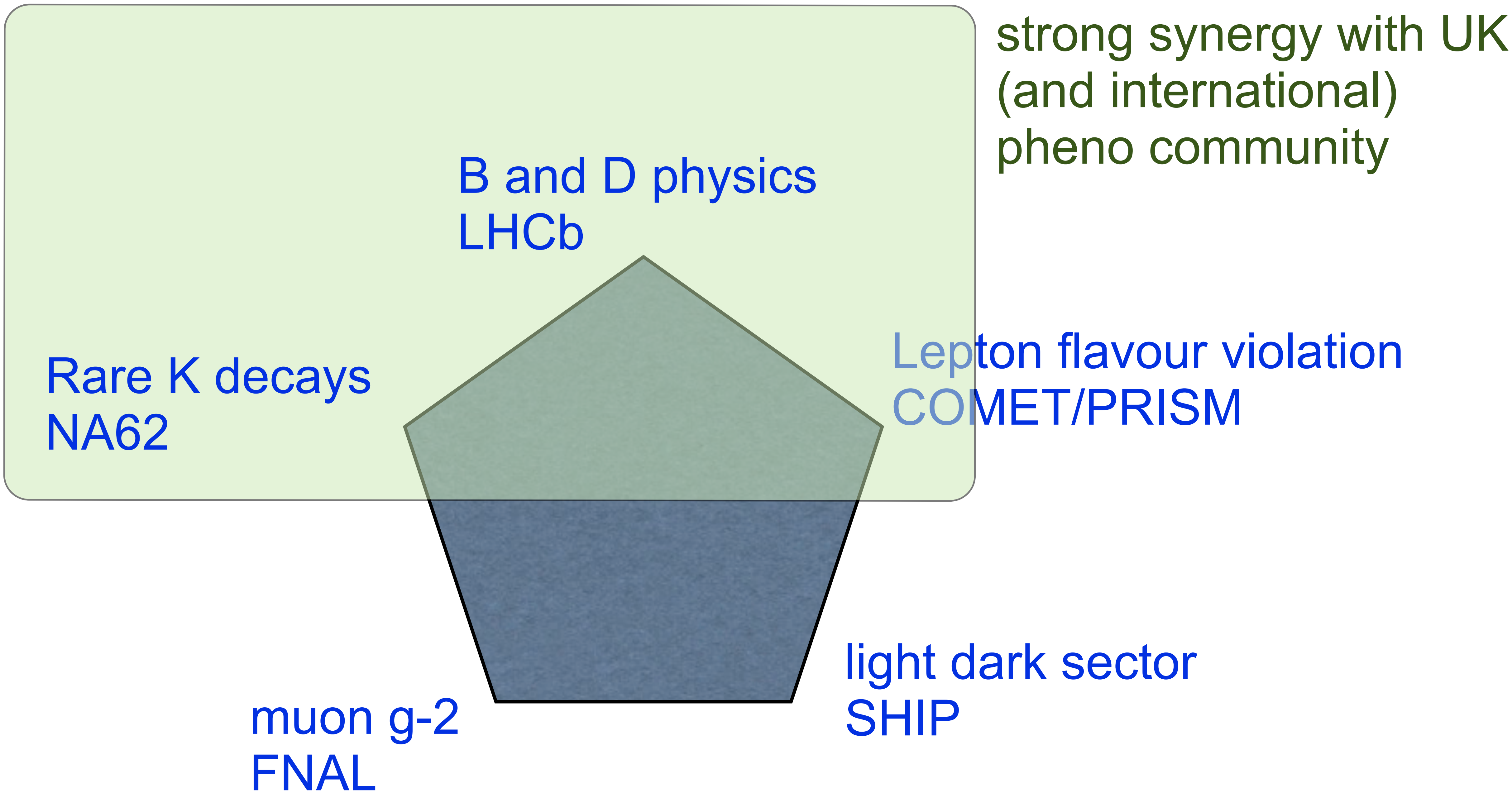
theory/experiment workshops, often led by UK researchers

In 2014 alone, three international flavour conferences in UK (Flasy IV / Sussex&So'ton, Beauty XV/Edinburgh,

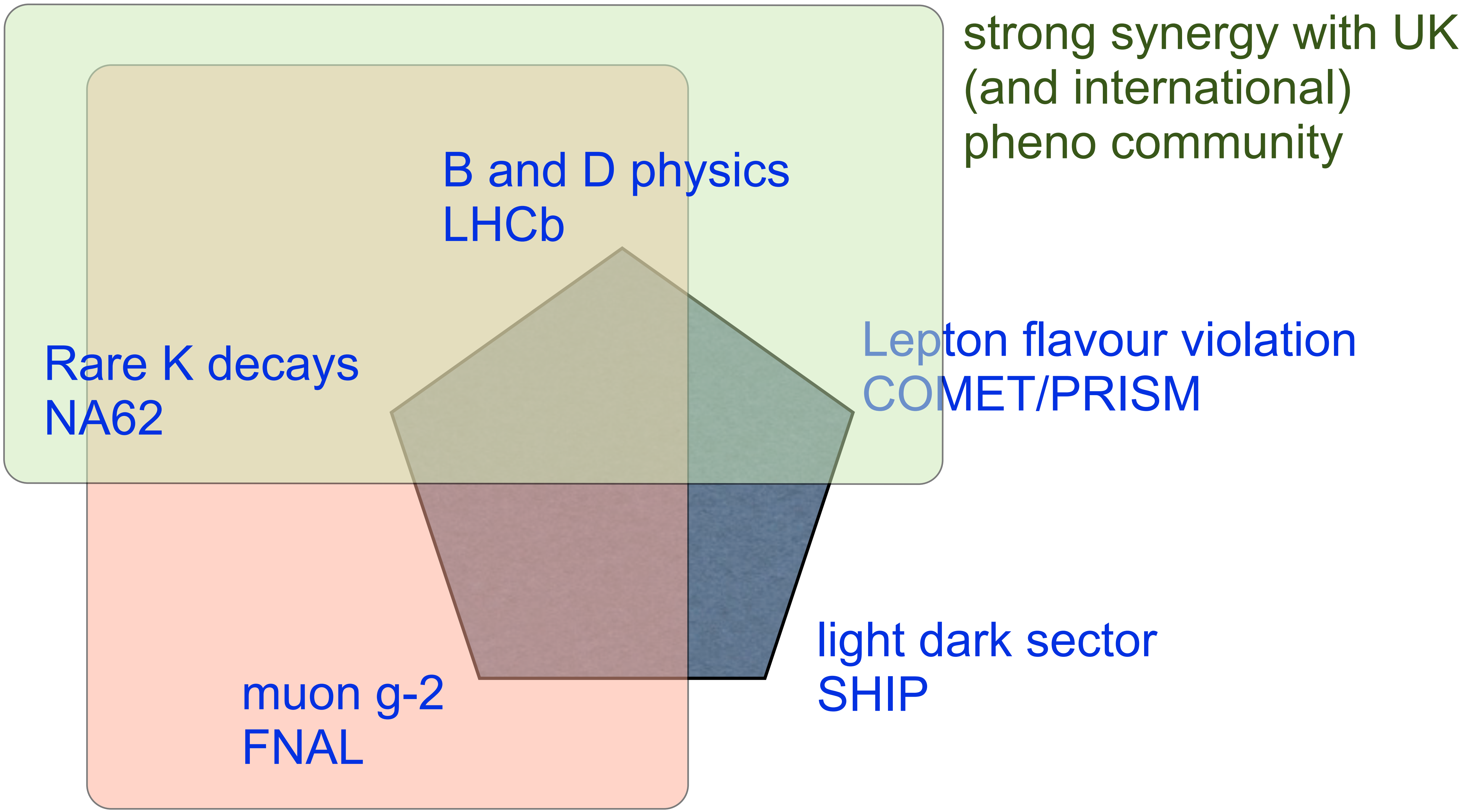
What measurements?



What measurements?



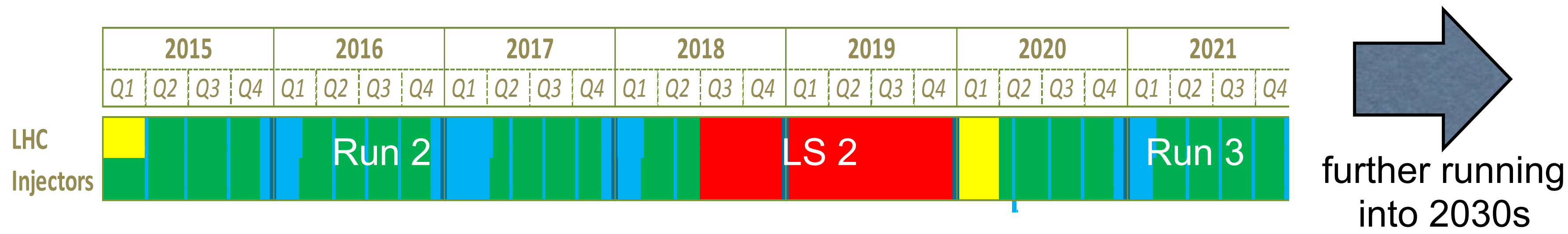
What measurements?



strong interconnection/synergy with lattice QCD community - UK major player (UKQCD, HPQCD, ...)

Timeline

LHC(b)



NA62 — 10-12/2014 low-intensity run; 2015/16/17 full runs
10% measurement of BR(K^+ -> pi^+ nu nu)

COMET/ — 2016 (data)?
measure BR(Al μ^- -> Al e^-) to 10^{-17} accuracy
(factor 10000 improvement relative to PSI Au limit)

PRISM — further factor 200 improvement

g-2 — 2017 (beam)?
factor 4 improvement on precision of
μ anomalous magnetic moment

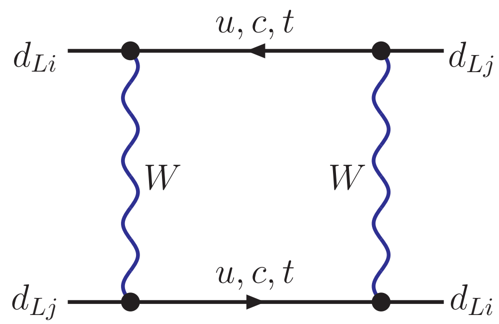
SHIP — **S**earch for **HI**dden **P**articles (CERN/SPS)
early stages; data taking anticipated for 2020's

LHCb

$B_{(s)} - \bar{B}_{(s)}$ mixing

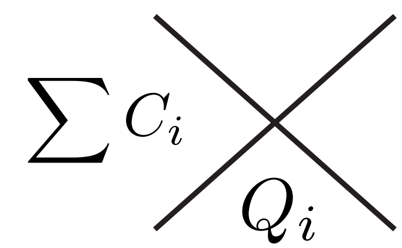
mixing-induced CP violation

- flavour violation: $\mathcal{A}(\bar{M}^0 \to M^0) \propto M_{12} - \frac{i}{2}\Gamma_{12} \neq 0$



+ ?

OPE (m_B/m_W)



M_{12}

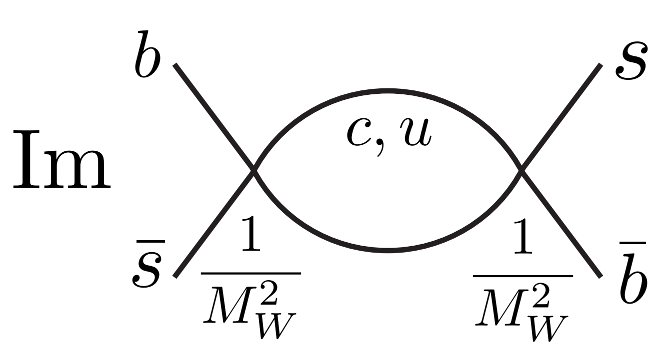
$\Delta M = 2|M_{12}|$

$$\boxed{Q_1 = (\bar{s}^a_L \gamma_\mu b^a_L)(\bar{s}^b_L \gamma^\mu b^b_L),}$$

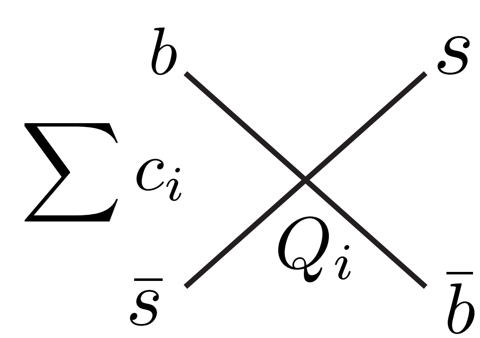
only operator present in SM

$$Q_2 = (\bar{s}^a_R b^a_L)(\bar{s}^b_R b^b_L),$$
$$Q_3 = (\bar{s}^a_R b^b_L)(\bar{s}^b_R b^a_L),$$
$$Q_4 = (\bar{s}^a_R b^a_L)(\bar{s}^b_L b^b_R),$$
$$Q_5 = (\bar{s}^a_R b^b_L)(\bar{s}^b_L b^a_R)$$

+ 3 more



OPE (Λ_{QCD}/m_B)



Γ_{12}

$\Delta\Gamma$

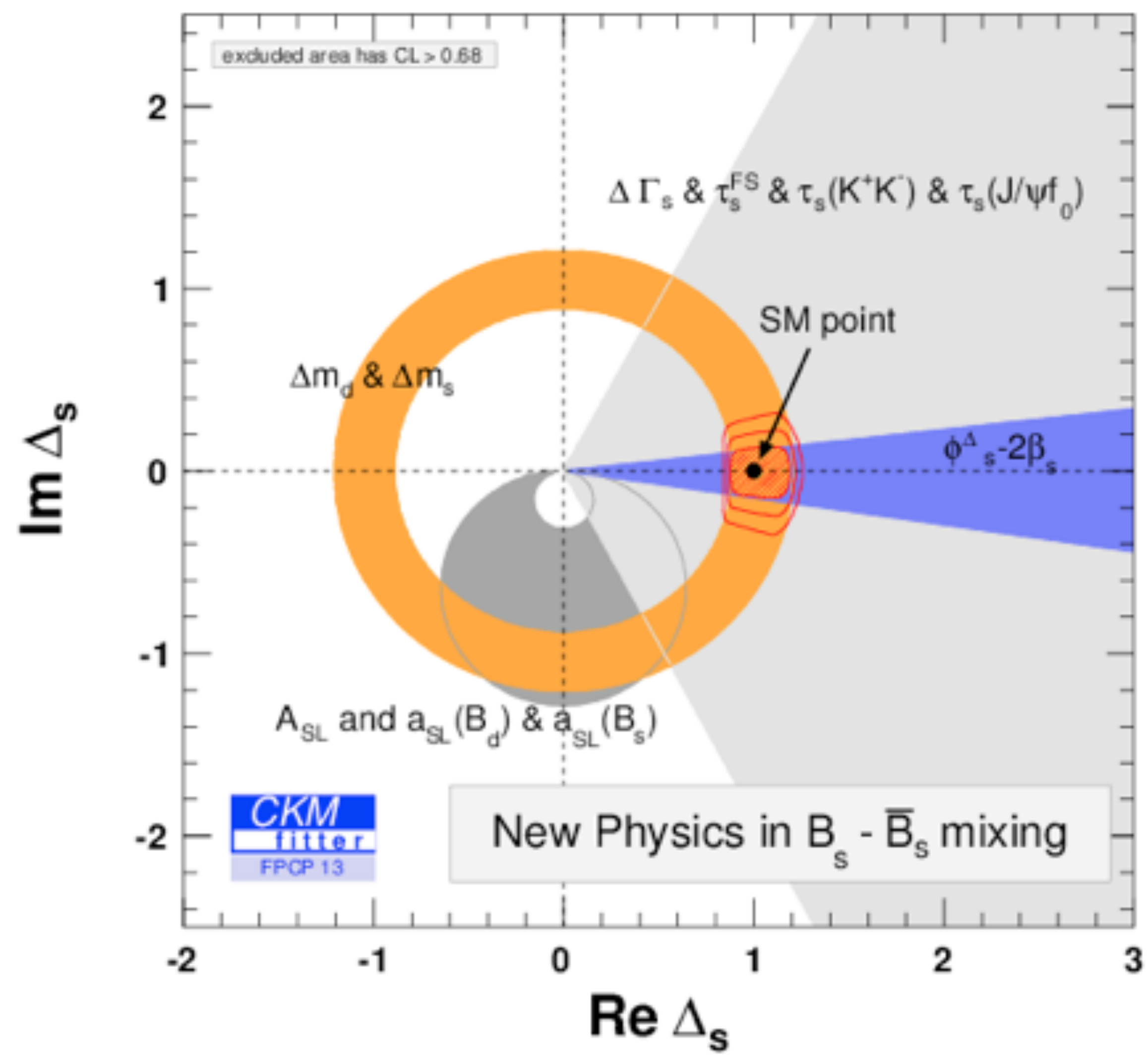
no NP contribution to Γ_{12} unless NP lighter than m_B or NP significantly affects b->c decays (which are tree-level size in the SM)

B mixing: status

Only 3 independent observables in mixing, cannot disentangle different operators. Instead fit to transition amplitude M_{12} (normalised to SM)

Average involving D0, CDF, ATLAS, CMS data.

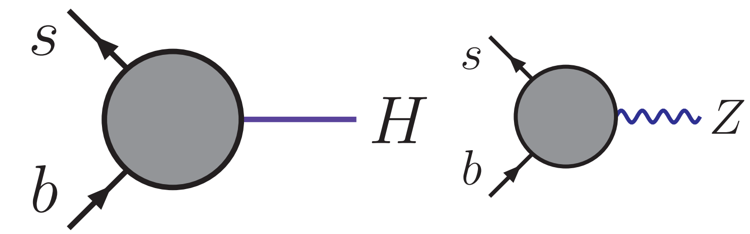
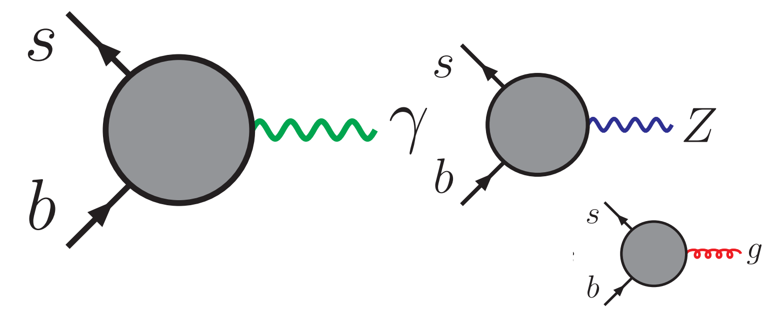
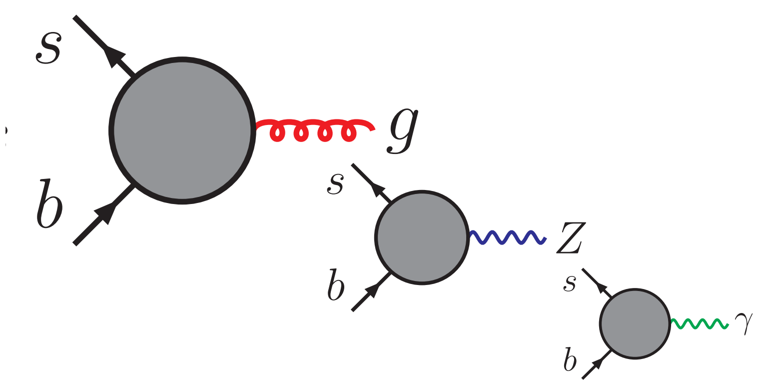
Average dominated by LHCb and CMS.



CKMfitter, based on Lenz et al 2010,2012

see Matt Needham's talk for updates, prospects and details

Exclusive decays at LHCb

final state	strong dynamics	#obs	NP enters through
Leptonic $B \to l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \to K^* l^+ l^-$, $K^*\gamma$	form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \to \pi\pi$, πK, $\phi\phi$, ...	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

Crucial theory input provided by lattice QCD.

Phenomenology: QCD factorisation, light-cone sum rules, fits

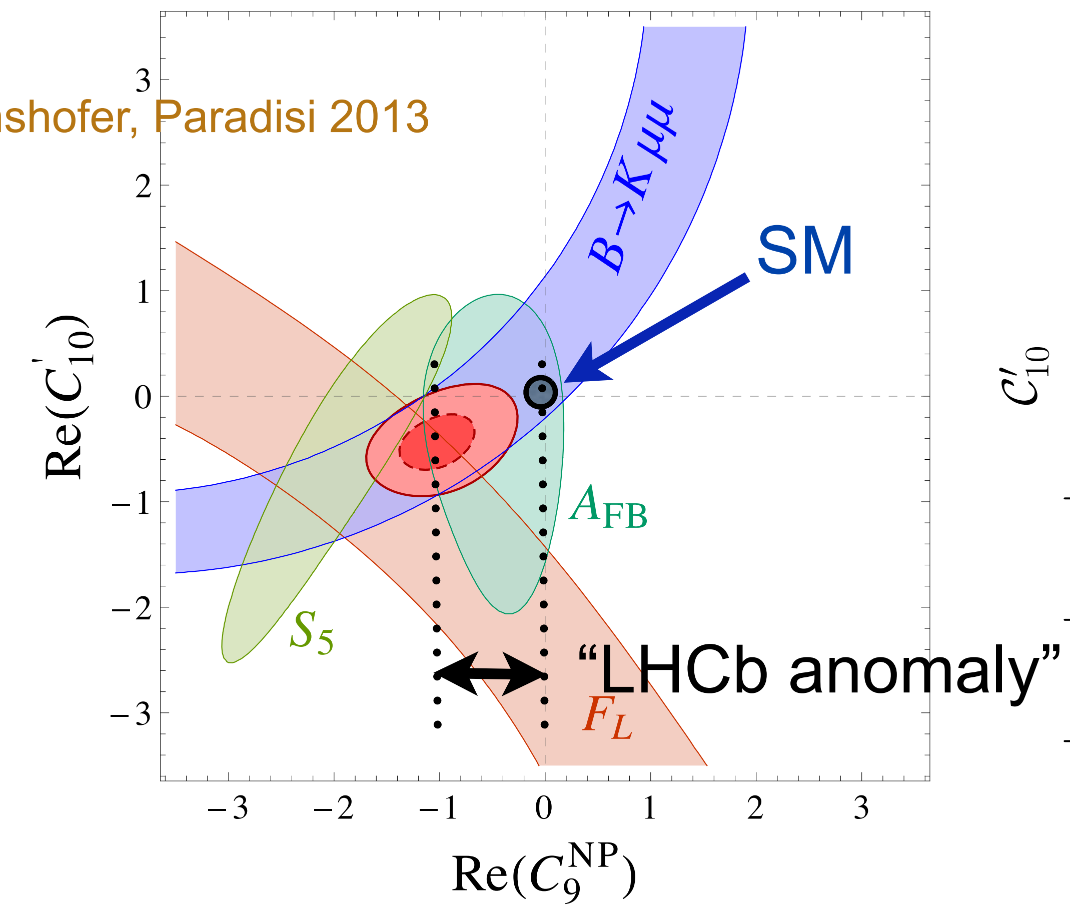
Intense theory-experiment interaction, 5 workshops

Global fits

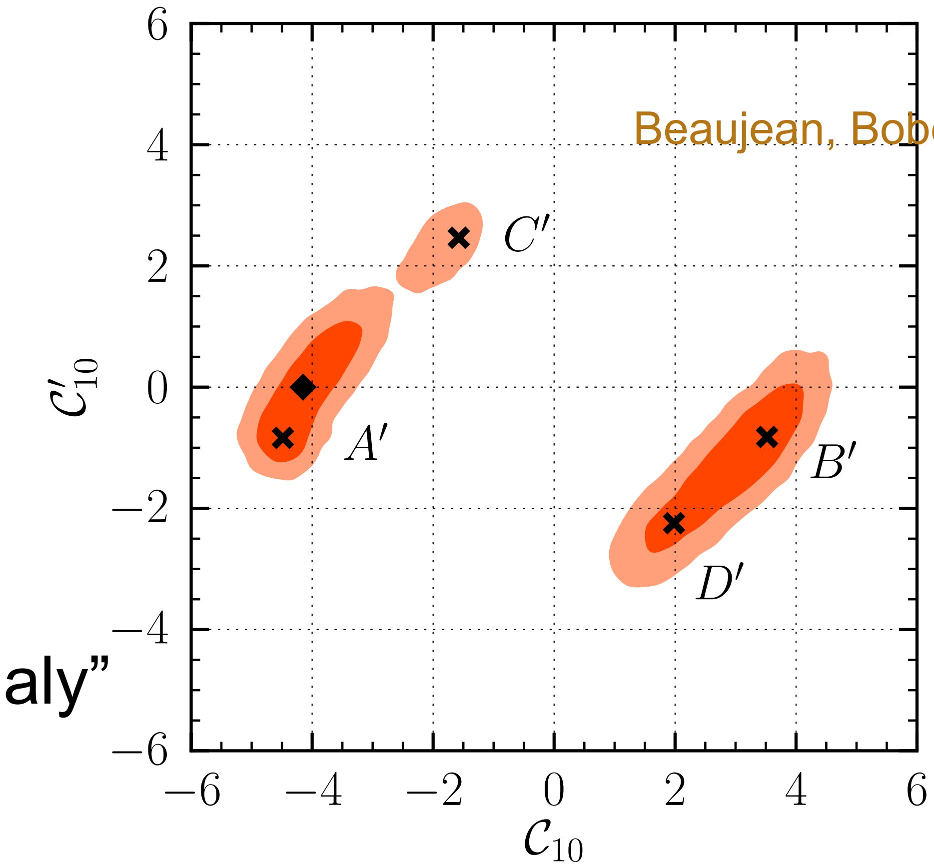
[Altmannshofer, Paradis, Straub 2012;
Altmannshofer, Straub 2013;
Descotes-Genon, Matias, Virto 2013;
Bobeth, Hiller, van Dyk 2011-2012;
Beaujean, Bobeth, van Dyk 2013, ...]

Various theorists: fits to (mostly) B->K* l l angular distribution.

Altmannshofer, Paradisi 2013

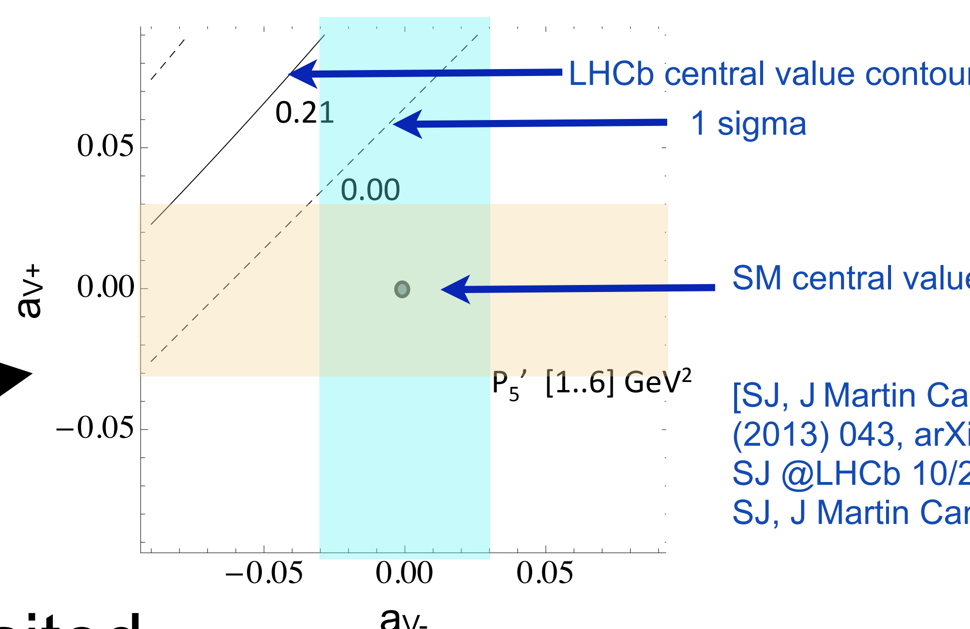


Beaujean, Bobeth, van Dyk 2013



Tension with SM, driven largely by a single bin of a single angular coefficient (S_5 ~ P_5')

Strongly depends on QCD power corrections



[SJ, J Martin Camalich JHEP 1305 (2013) 043, arXiv:1212.2263;
SJ @LHCb 10/2013, Aspen 2014, etc;
SJ, J Martin Camalich, to appear]

LHCb 3 fb^{-1} update eagerly awaited

... and more

$B_{s,d} \rightarrow \mu^+\mu^-$ (and their ratio)
highly BSM sensitive

Lepton universality tests with rare B decays
clean BSM probe

bottom and charm spectroscopy
important for QCD development (NRQCD, QCD potential...)

CKM angle gamma determinations
needed to determine SM “backgrounds” to BSM effects accurately. Very strong UK presence.
Eg CP violation in B_s mixing, charmless hadronic B decays

... and much more (see Matt Needham’s talk)

Beyond LHCb: Belle 2 (Japan) is on its way, will do a number of BSM-sensitive measurements LHCb cannot do.

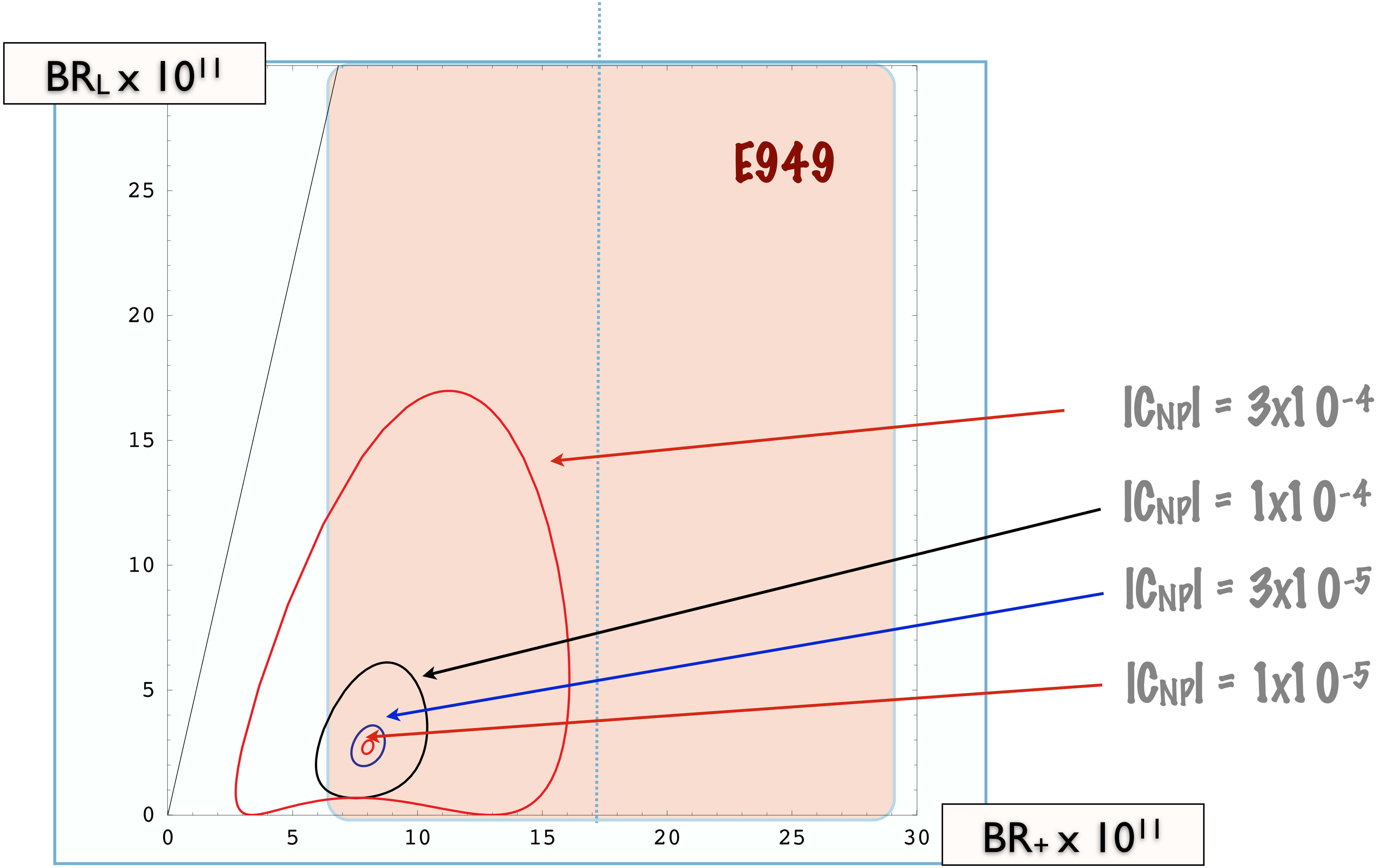
Rare K processes

Operator		$K^+ \to \pi^+ \nu\bar\nu$	$K_L \to \pi^0 \nu\bar\nu$	$K_L \to \pi^0 \ell^+\ell^-$	$K_L \to \ell^+\ell^-$	$K^+ \to \ell^+\nu$	$P_T(K^+ \to \pi^0\mu^+\nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ	ϵ_K	in MSSM?
$O_{lq}^{(1)}$	$(\bar D_L \gamma^\mu S_L)(\bar L_L \gamma_\mu L_L)$	✓	✓	✓	hs	–	–	–	–	–	✓
$O_{lq}^{(3)}$	$(\bar D_L \gamma^\mu \sigma^i S_L)(\bar L_L \gamma_\mu \sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	–	–	✓
O_{qe}	$(\bar D_L \gamma^\mu S_L)(\bar l_R \gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
O_{ld}	$(\bar d_R \gamma^\mu s_R)(\bar L_L \gamma_\mu L_L)$	✓	✓	✓	hs	–	–	–	–	–	[illegible]
O_{ed}	$(\bar d_R \gamma^\mu s_R)(\bar l_R \gamma_\mu l_R)$	–	–	✓	hs	–	–	–	–	–	small
$O_{lq}^{\dagger}$	$(\bar u_R S_L) \cdot (\bar l_R L_L)$	–	–	–	–	✓	✓	✓	–	–	tiny [illegible]
$(O_{lq}^{t})^\dagger$	$(\bar u_R \sigma_{\mu\nu} S_L) \cdot (\bar l_R \sigma^{\mu\nu} L_L)$	–	–	–	–	–	?	?	–	–	tiny (?)
O_{qde}	$(\bar d_R S_L)(\bar L_L l_R)$	–	–	✓	✓	–	–	–	–	–	tiny (?) (PQ ?)
$O_{qde}^{\dagger}$	$(\bar D_L s_R)(\bar l_R L_L)$	–	–	✓	✓	✓	✓	✓	–	–	yes? large $\tan\beta$?
$O_{\varphi q}^{(1)}$	$(\bar D_L \gamma^\mu S_L)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓	(✓)	✓
$O_{\varphi q}^{(3)}$	$(\bar D_L \gamma^\mu \sigma^i S_L)(H^\dagger D_\mu \sigma^i H)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)	✓
$O_{\varphi d}$	$(\bar d_R \gamma^\mu s_R)(H^\dagger D_\mu H)$	✓	✓	✓	hs	–	–	–	✓	(✓)	large $\tan\beta$ (non-MFV)

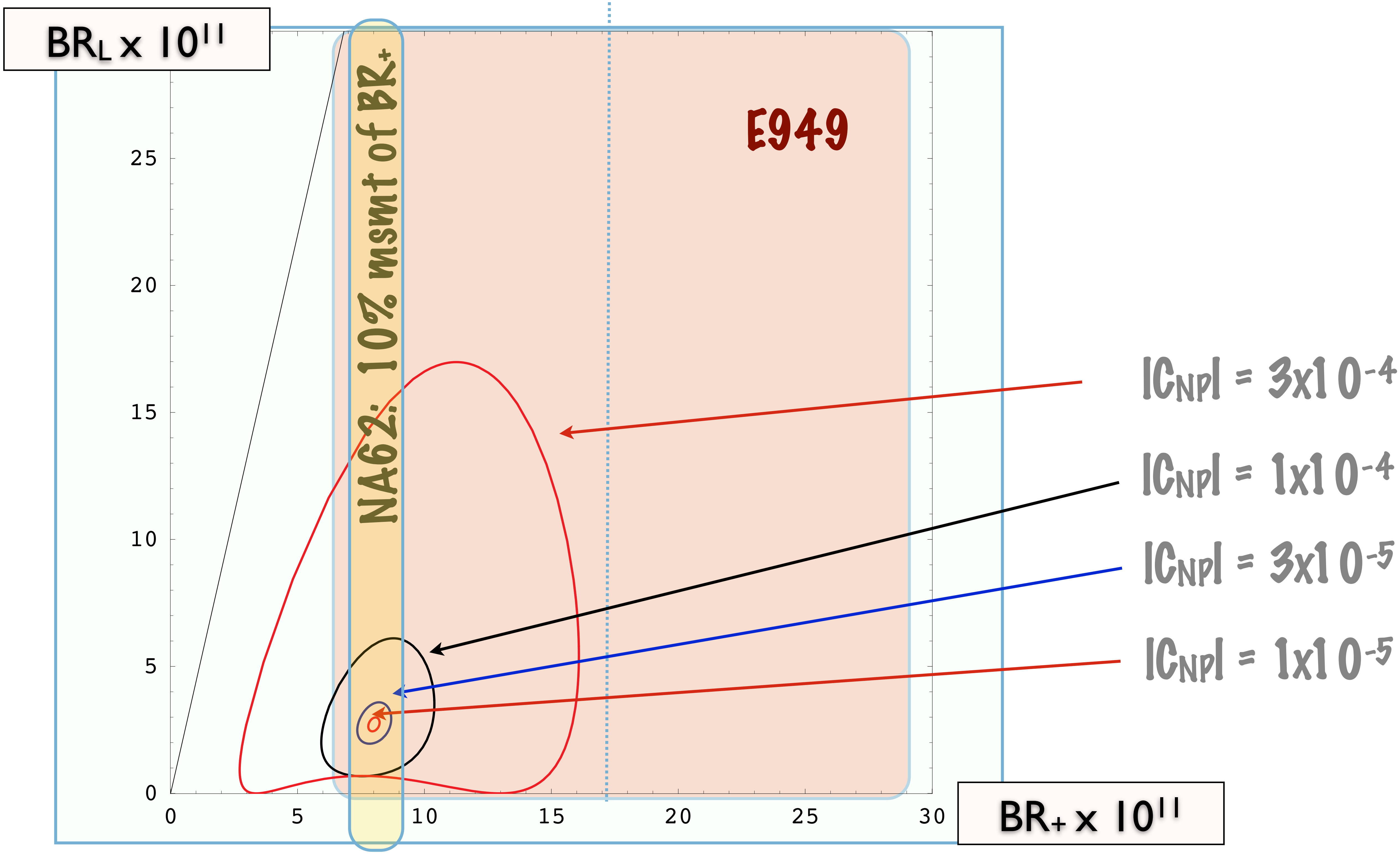
Observable

SJ at 2010 NA62 workshop

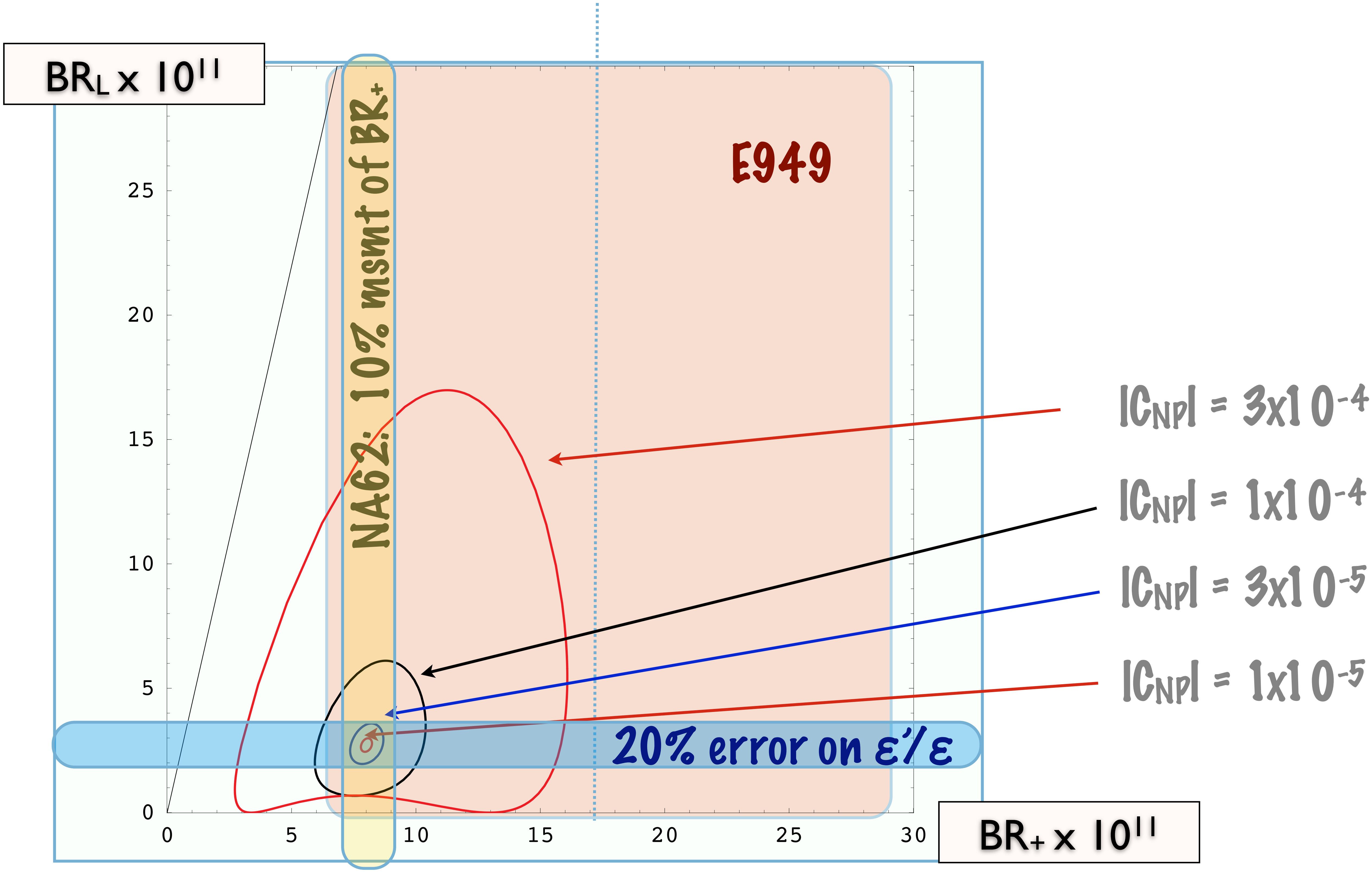
combination



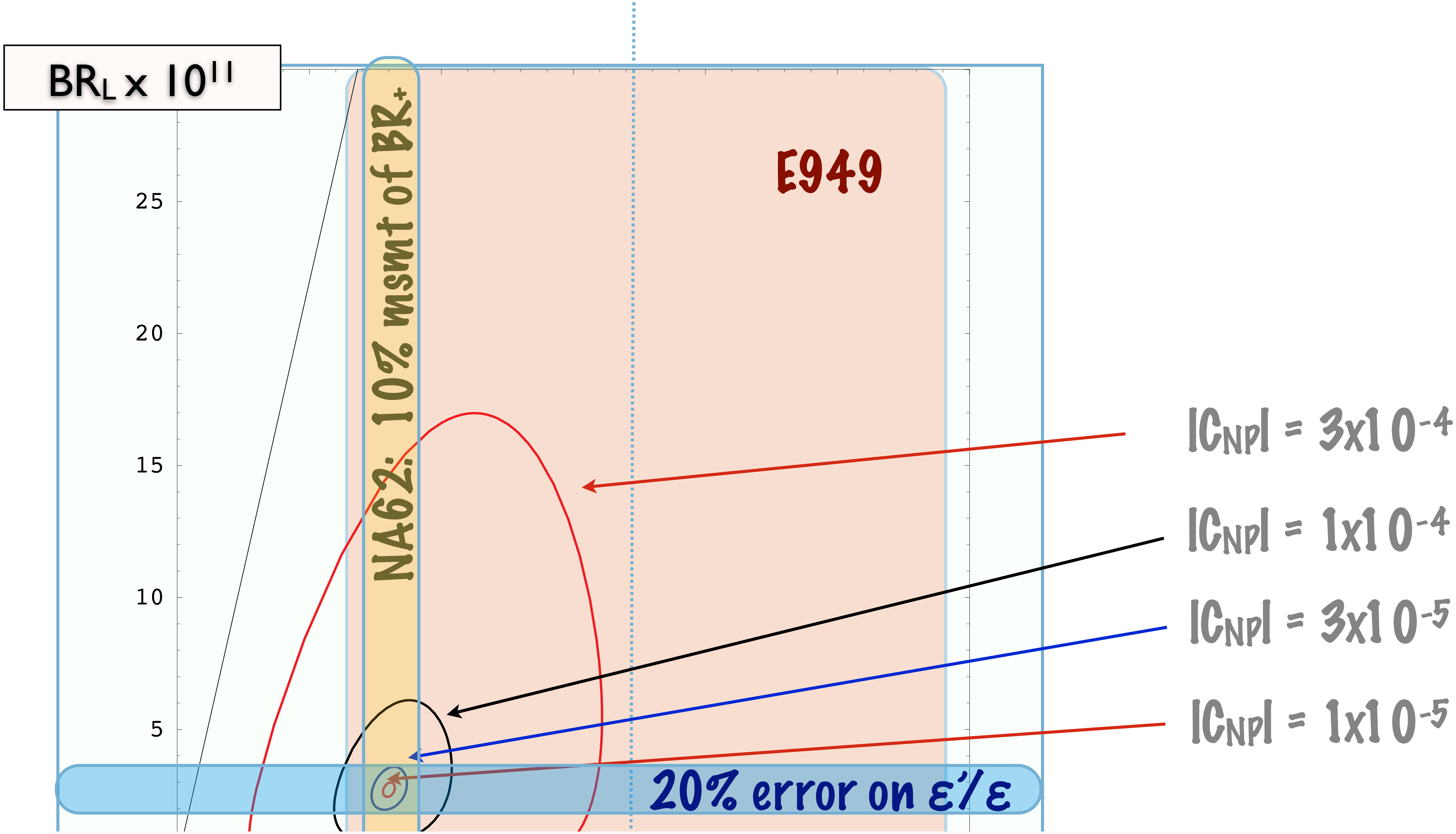
combination



combination

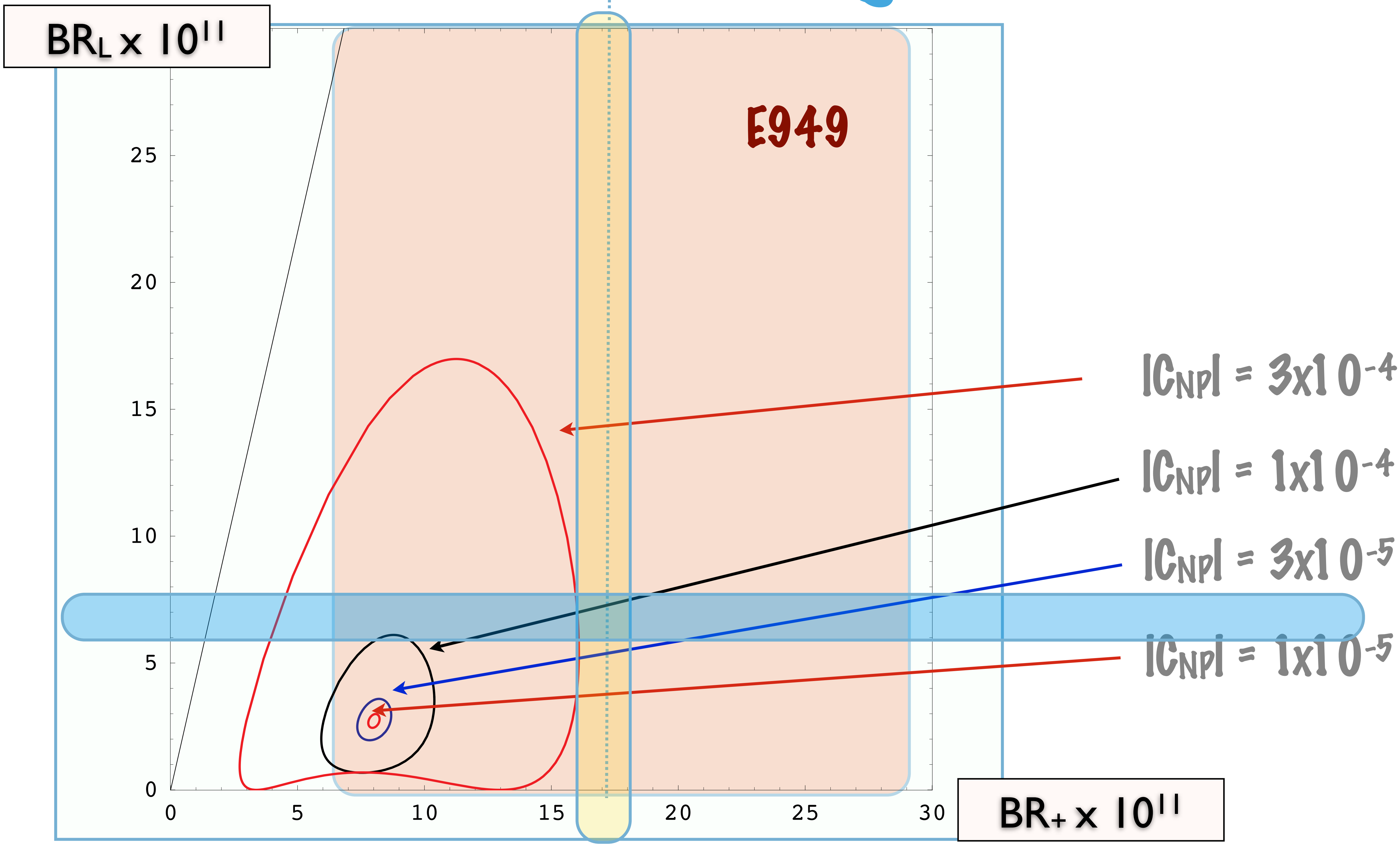


combination



20% precision on ε'/ε seems achievable over timescale of first NA62 run with upcoming RBC/UKQCD lattice calculation

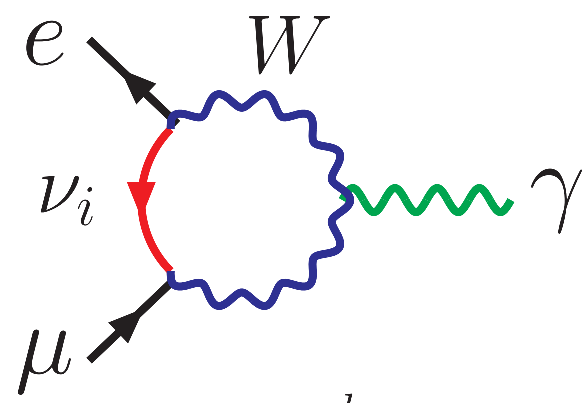
a more exciting scenario



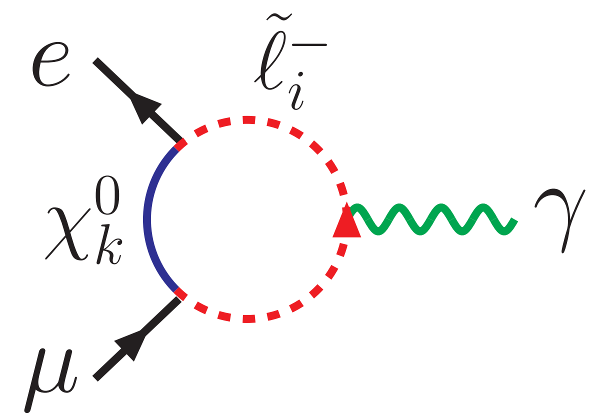
Charged lepton flavour violation

COMET/PRISM (also cLFV final state searches in NA62, LHCb)

1) Very suppressed in the SM
($m_\nu \approx 0$)

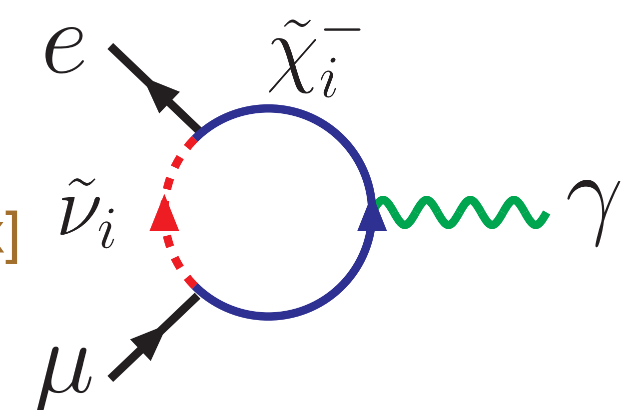


2) New flavour violation in SUSY (for example)



in SUSY GUTs, correlated with quark flavour and usually

Easy to saturate current experimental bounds



e.g.

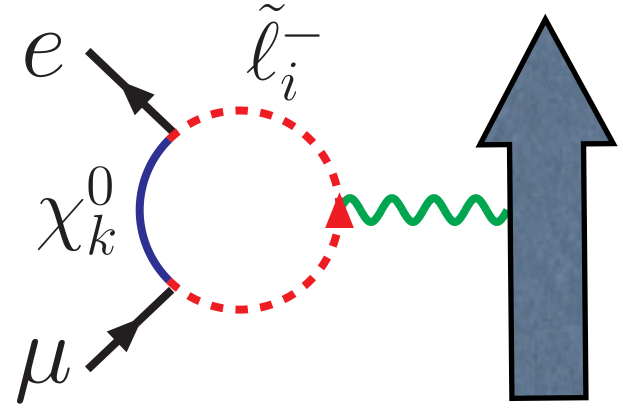
$BR(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$ Babar 1006.0314 [hep-ex]

$BR(\tau \to \mu\gamma) < 4.5 \cdot 10^{-8}$ Belle 0705.0650 [hep-ex]

also $\tau \to e\gamma$, $\mu \to e\gamma$, $\tau \to 3\ell$, $\mu \to e$ conversion in nuclei, etc

COMET/PRISM

Conversion in nuclei (COMET: Al)



(& Z-mediated contributions)

current limit BR(Au μ^- -> Au e^-) < 7 x 10^{-13} [SINDRUM 2 / PSI]

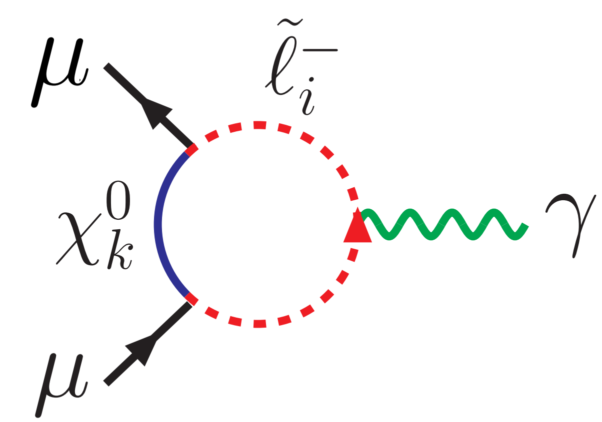
COMET (J-PARC/Japan) aims at 10^{-17} level - 4 orders of magnitude improvement. Long-term: PRISM, 2×10^{-19} level
(COMET competitor experiment: Mu2e, Fermilab)
(other cLFV planned/studied experiments: DeeMe/JPARC; PSI)

see talk by Ajit Kurup

FNAL E989 Muon g-2

Theory/BSM analogous to cLFV, but flavour-conserving.

(Historically goes back to early days of QED.)



Experiment:

$$a_\mu = (116592089 \pm 54 \pm 33) \times 10^{-11}$$ BNL

~ 3.5 sigma deviation from SM

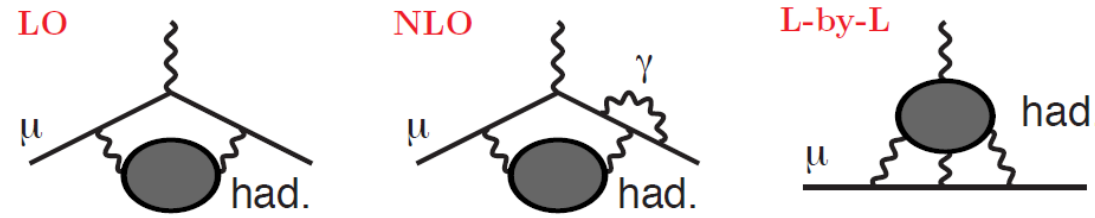


fig S Maxfield

one two-loop effect with hadronic vacuum polarisation
extract from e+ e- data and tau decays

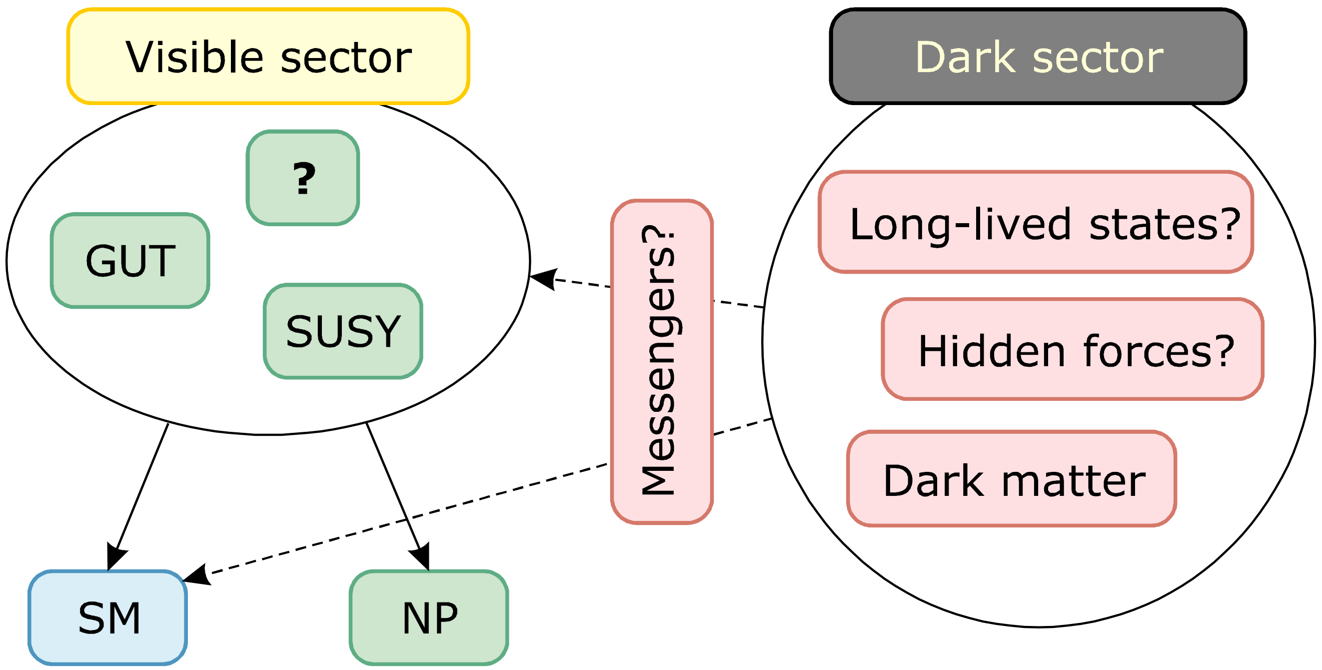
one three-loop effect with hadronic 4-point function (“light-by-light scattering”), no first-principles determination exists, but many different model calculations agree

E989 goal: reduce error to $16\text{x}10^{-11}$, which would give 5 sigma significance

See talk by Steve Maxfield

SHIP

Many models (eg of dynamical SUSY breaking) involve a hidden/dark sector. Some states may be light, even lighter than a few GeV, eg sterile neutrinos Shaposhnikov et al



J Kamenik / C Smith

They can be searched for in production or in **rare** decays (of top, Higgs, B, D, leptons). Need high statistics.

SHIP - proposed beam-dump experiment at CERN-SPS
10^{17} D-mesons, 10^{15} tau over 4-5 years

see talk by A Golutvin (SHIP interim spokesperson)

Summary

After run I of the LHC and the Higgs discovery there is a very strong case for a broad programme of indirect probes of new physics.

UK flavour community very well positioned to make a major impact, based on size, diversity, quality, leadership experience in the relevant experiments (and theory)

This was to provide an intro and context. Please see the detailed experimental presentations for proper accounts of plans and specific physics cases.

LHCb - Matt Needham
NA62 - Evgueni Goudzovski
SHIP - Andrey Golutvin
COMET/PRISM/cLFV - Ajit Kurup
Muon g-2 - Stephen Maxfield

BACKUP

Flavour symmetry group

SM gauge interactions

$$\mathcal{L}_{\text{gauge}} = \sum_f \bar{\psi}_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$

$$f = Q_{Lj}, u_{Rj}, d_{Rj}, L_{Lj}, e_{Rj} \quad j = 1,2,3$$

have a large global (= flavour) symmetry group

$$\boxed{G_{\text{flavor}} = SU(3)^5 \times U(1)_B \times U(1)_A \times U(1)_L \times U(1)_E}$$

$$Q_L \to e^{i(b/3+a)} V_{Q_L} Q_L,\ u_R \to e^{i(b/3-a)} V_{u_R} u_R,\ d_R \to e^{i(b/3-a)} V_{d_R} d_R$$

[Chivukula & Georgi 1987]

The SM Yukawa couplings break this to

to $\quad U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Neutrino mixing break the three lepton numbers
Current data accommodated by the unique dimension-5 operator

$(\widetilde{\varphi}^\dagger l_p)^T C (\widetilde{\varphi}^\dagger l_r)$ If correct, lepton *number* is violated in nature.

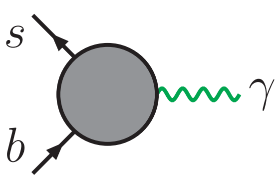
BSM flavour breaking will leave its imprint on the Wilson coefficients (correlations).

weak ΔB=ΔS=1 Hamiltonian

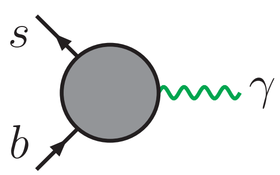
= EFT for ΔB=ΔS=1 transitions (up to dimension six)

$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3\ldots6} C_i P_i + C_{8g} Q_{8g} \right] \qquad C_i \sim g_{\rm NP} \frac{m_W^2}{M_{\rm NP}^2}$$

$$\begin{aligned}\mathcal{H}_{\rm eff}^{\rm sl} = & -\frac{4G_F}{\sqrt{2}} \lambda_t \Big[C_7 Q_{7\gamma} + C_7' Q_{7\gamma}' + C_9 Q_{9V} + C_9' Q_{9V}' + C_{10} Q_{10A} + C_{10}' Q_{10A}' \\ & + C_S Q_S + C_S' Q_S' + C_P Q_P + C_P' Q_P' + C_T Q_T + C_T' Q_T' \Big] .\end{aligned}$$



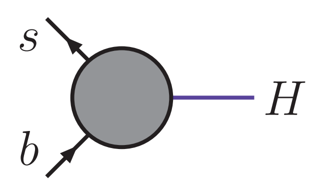
$$\mathcal{O}_7 = \frac{e}{16\pi^2}\, \hat{m}_b\, \bar{s}\sigma_{\mu\nu} P_R F^{\mu\nu} b\,,$$



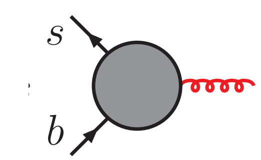
$$\mathcal{O}_V = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)\,,$$

$$\mathcal{O}_S = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l} l)\,,$$

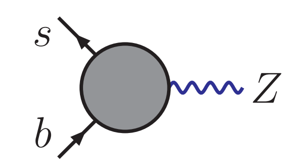
$$\mathcal{O}_T = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s}\sigma_{\mu\nu} P_R b)(\bar{l}\sigma^{\mu\nu} P_R s)\,,$$



$$\mathcal{O}_8 = \frac{g_s}{16\pi^2}\, \hat{m}_b\, \bar{s}\sigma_{\mu\nu} P_R G^{\mu\nu} b\,,$$



$$\mathcal{O}_A = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu\gamma^5 l)_A$$



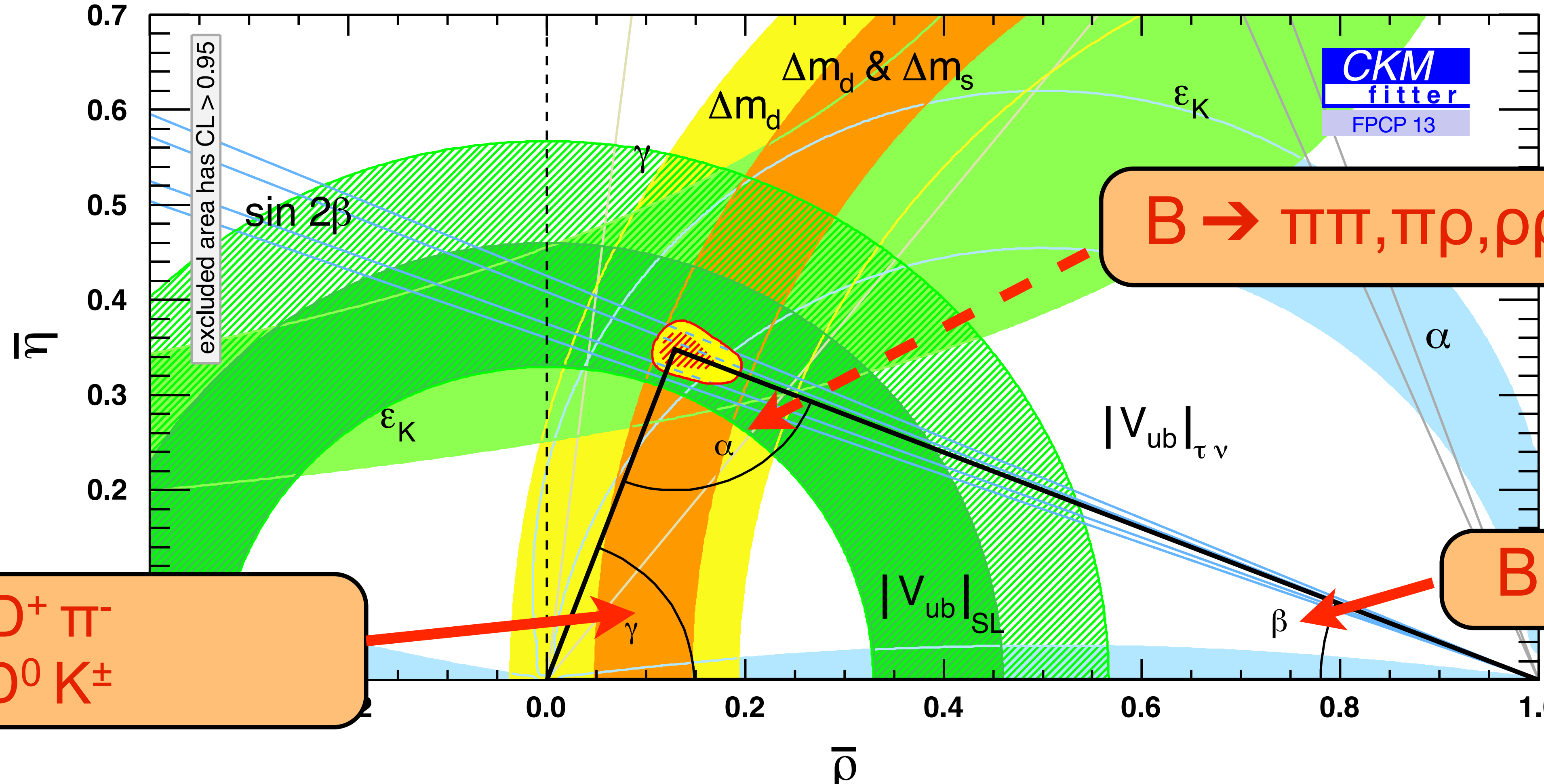
$$\mathcal{O}_P = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l}\gamma^5 l)\,,$$

look for observables sensitive to C_i's, specifically
those that are suppressed in the SM

Global fits to the CKM matrix by two expert groups

CKMfitter http://ckmfitter.in2p3.fr/

UTfit http://utfit.org/



$B \to \pi\pi, \pi\rho, \rho\rho$

$B \to J/\psi\ K_S$

$B^0 \to D^+ \pi^-$

$B^\pm \to D^0 K^\pm$

Each observable constrains $\bar{\rho} + i\bar{\eta}$ to lie on a one-dimensional set (one or more lines). Bands due to uncertainties (theory & expt)

No apparent inconsistencies, CKM paradigm appears to work

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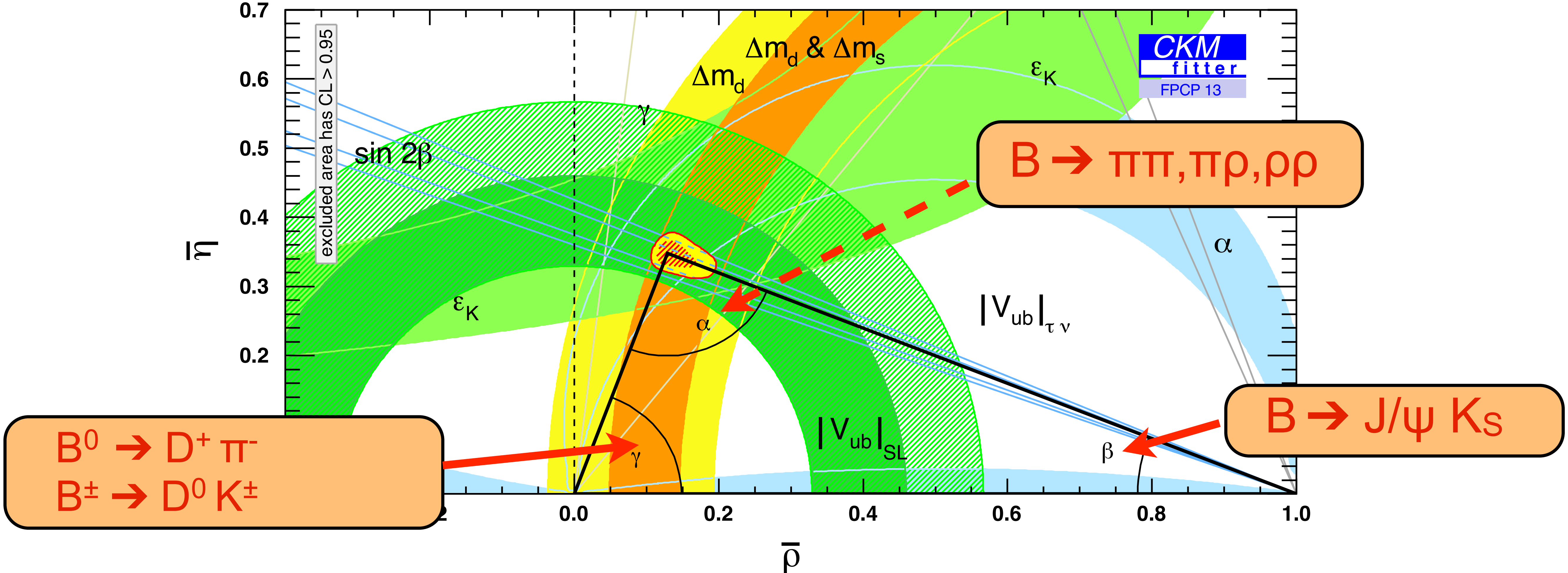

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Of all constraints, **only** the
γ and $|V_{ub}|$ determinations are robust against new physics as they do not involve loops.

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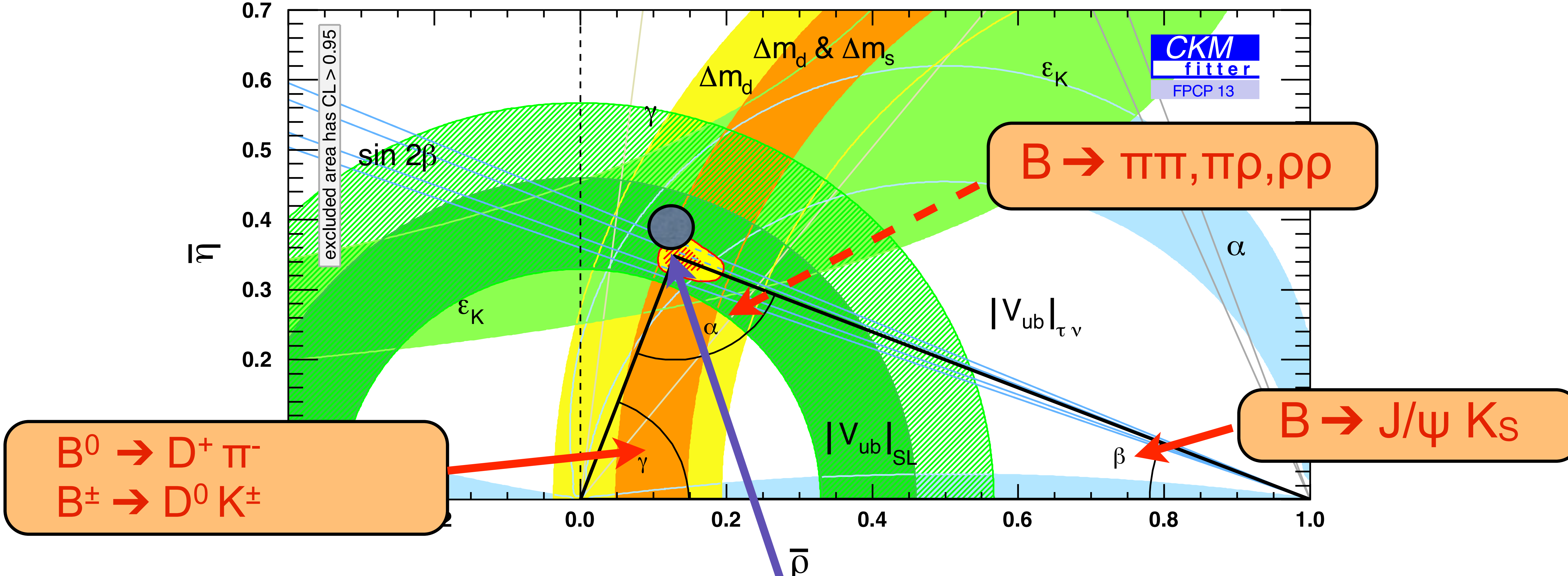

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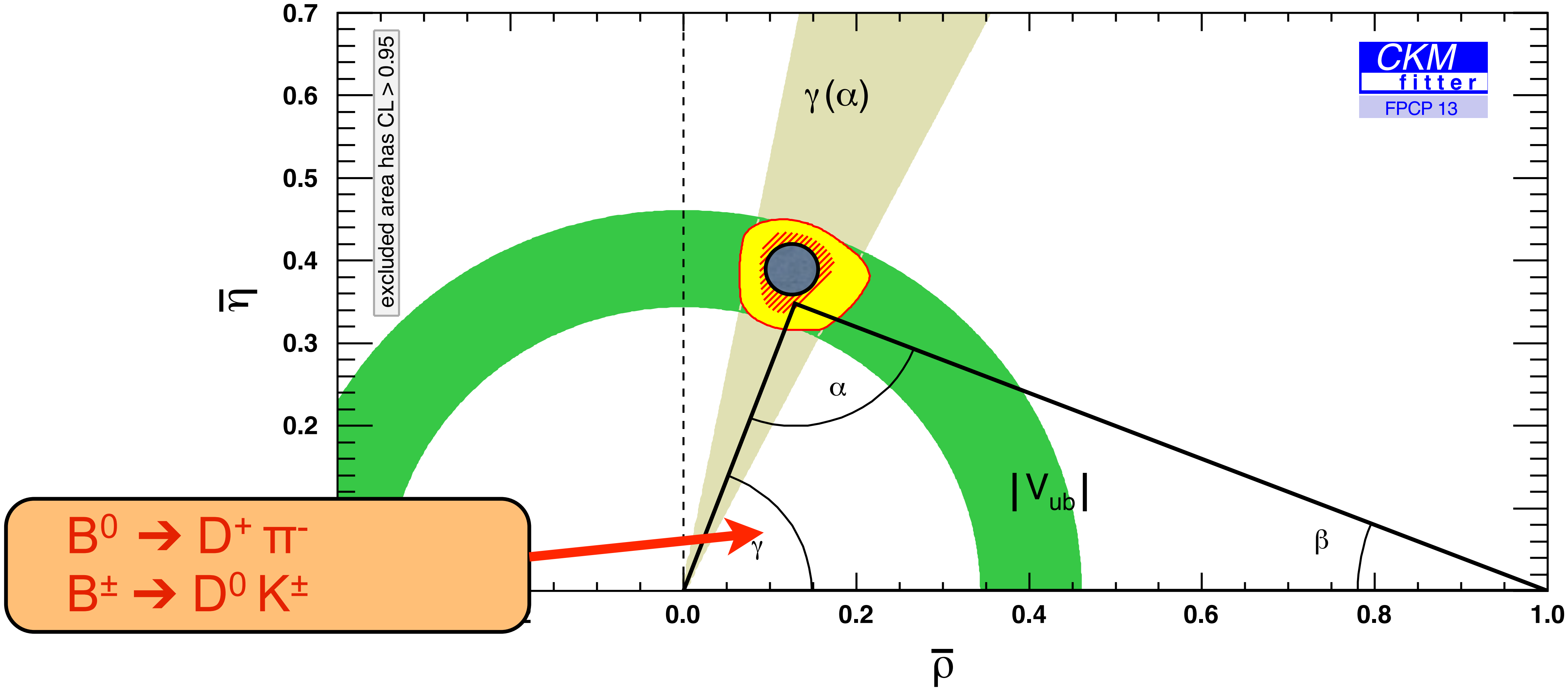
No apparent inconsistencies, CKM paradigm appears to work

Of all constraints, **only** the γ and $|V_{ub}|$ determinations are robust against new physics as they do not involve loops.

It is possible that the TRUE $(\bar{\rho}, \bar{\eta})$ lies here (for example)

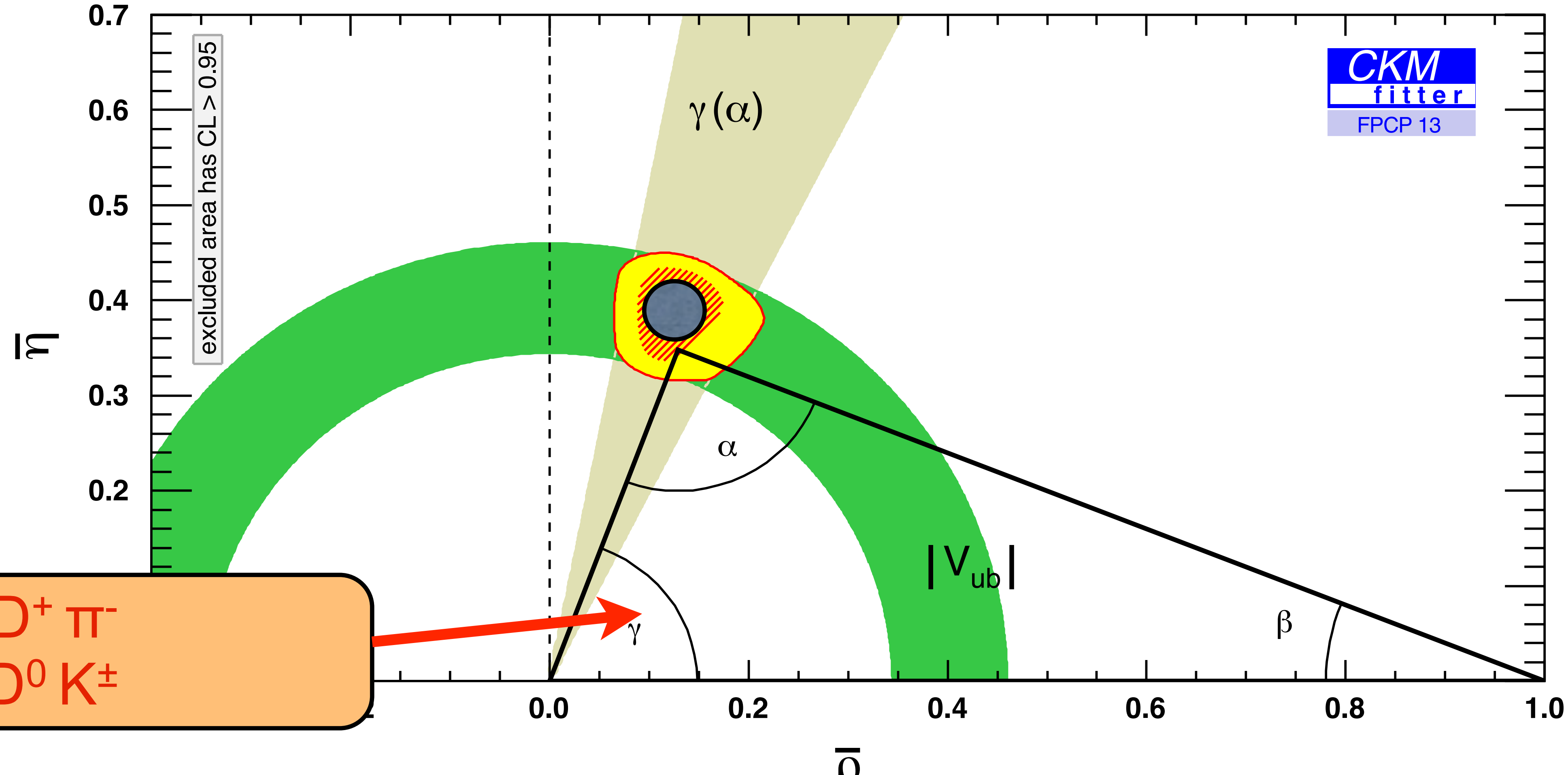
“Tree” determinations



Plot showing only “NP-robust” measurements of γ and $|V_{ub}|$.

Note: the γ(α) constraint shown depends on assumptions (absence of BSM ΔI=3/2 contributions in B->ππ); the “pure tree-level” γ determination (grey band) is more robust. Such determinations will be greatly improved by LHCb.

“Tree” determinations



$B^0 \rightarrow D^+ \pi^-$
$B^\pm \rightarrow D^0 K^\pm$

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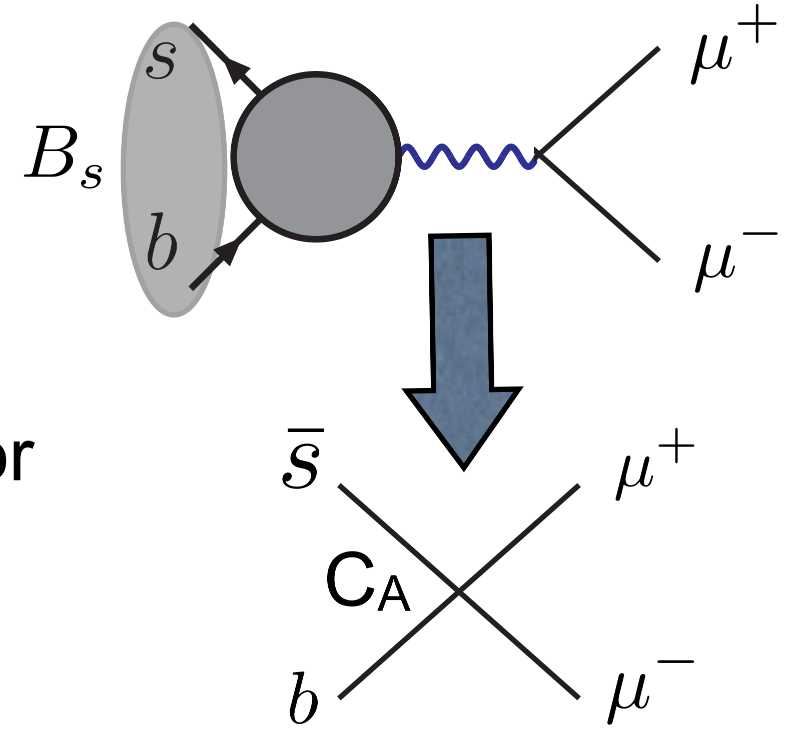
Certainly there is room for O(10%) NP in loop processes as far as UT fits are concerned, moreover UT fit mainly constrains b->d

$B_s \rightarrow \mu^+\mu^-$ Standard Model

- Mediated by short-distance
  Z penguin and box - long distance
  strongly CKM / GIM suppressed



- including QCD corrections, matches onto single relevant effective operator

$$Q_A = \bar{b}_L \gamma^\mu q_L \, \bar{\ell} \gamma_\mu \gamma_5 \ell$$

$$\overline{\mathcal{B}}_{q\ell} = \frac{|N|^2 M_{B_q}^3 f_{B_q}^2}{8\pi \, \Gamma_H^q} \beta_{q\ell} \, r_{q\ell}^2 \, |C_A(\mu_b)|^2 + \mathcal{O}(\alpha_{em})$$

[Buchalla&Buras 93, Misiak&Urban 99; De Bruyn et al 2012; Guadagnoli & Isidori 2012; Buras et al 2012,2013; Bobeth et al 2013]

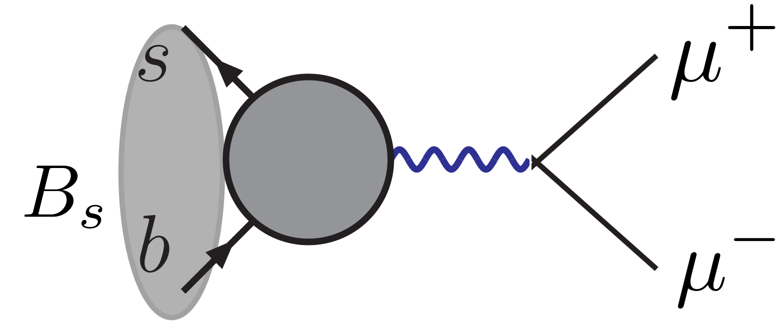
- includes: NNLO QCD, NLO EW (matching); photon bremsstrahlung; time-averaging

- nonperturbative QCD in decay constant and $O(\alpha_{em})$ only
  main uncertainties: decay constant, CKM

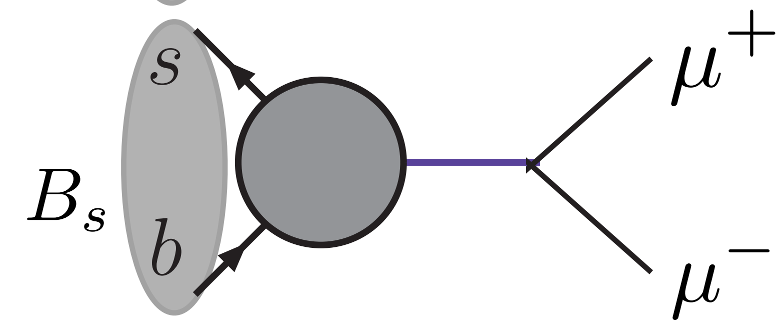
more SM theory: D Guadagnoli talk

Beyond the SM

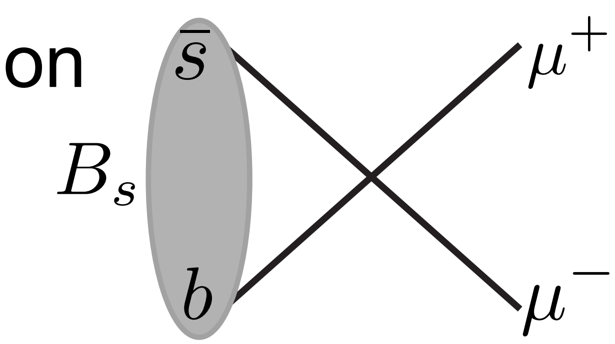
- New physics can modify the Z penguin ....



  ... induce a Higgs penguin ...



  ... or induce (or comprise) four-fermion contact interactions directly



could also violate lepton flavour

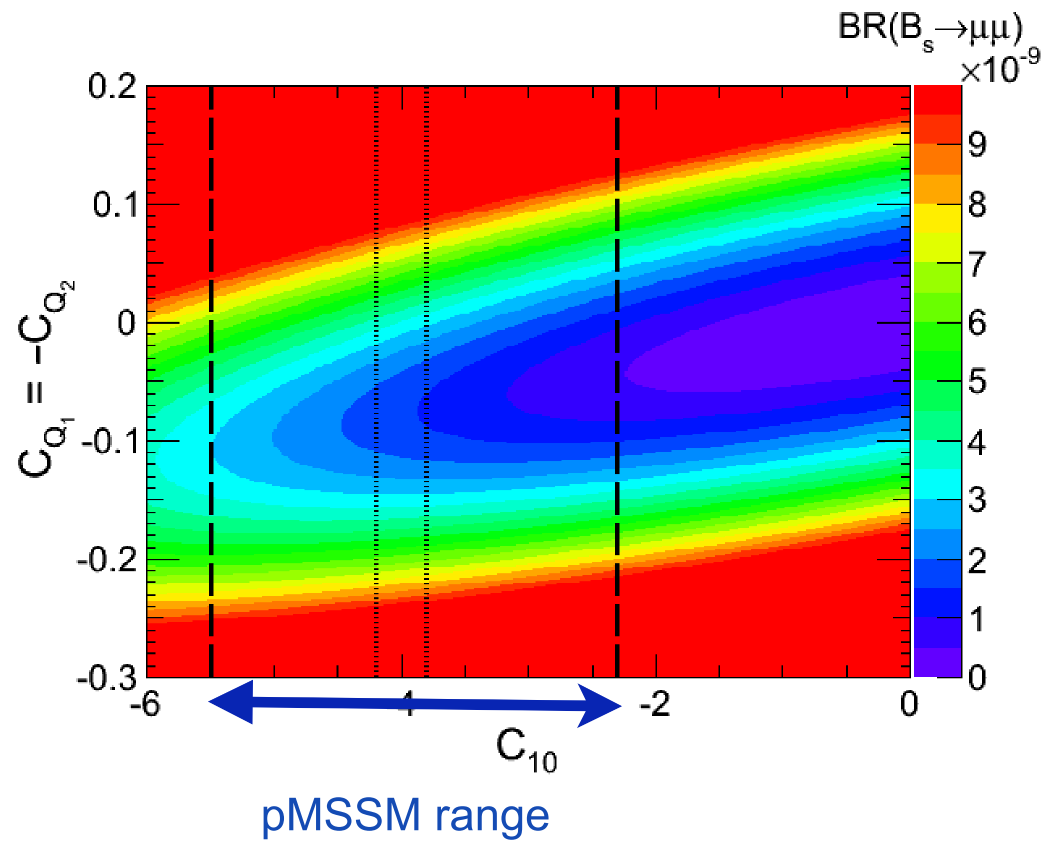
- for the most general effective Hamiltonian,

$$\mathcal{B}\left(\bar{B}_q \to \mu^+\mu^-\right) = \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 \tau_{B_q}}{64\pi^3} |V_{tb}V_{tq}^*|^2 \sqrt{1-4\hat{m}_\mu^2} \left\{ (1-4\hat{m}_\mu^2)|F_S|^2 + |F_P + 2\hat{m}_\mu F_A|^2 \right\}$$

where $$F_{S,P} = M_{B_q}\left[\frac{c_{S,P} m_b - c'_{S,P} m_q}{m_b + m_q}\right], \quad F_A = c_{10} - c'_{10}$$

[Bobeth, Ewerth, Kruger, Urban 2002]

Impact of $B_s \rightarrow \mu^+\mu^-$



Arbey, Battaglia, Mahmoudi, Martinez Santos 1212.4887

- $B_s \rightarrow \mu^+\mu^-$ provides strong constraints on scalar/pseudoscalar operators

  $[C_{Q1} = m_b\, C_S,\ C_{Q2} = m_b\, C_P]$

- in other words, basically fully complementary to semileptonic decays

Role of flavour in constructing the SM

1934 Fermi proposes Hamiltonian for beta decay

$$H_W = -G_F(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$$

1956-57 Lee&Yang propose parity violation to explain "θ-τ paradox".

Wu et al show parity is violated in β decay

Goldhaber et al show that the neutrinos produced in ^{152}Eu K-capture always have negative helicity

1957 Gell-Mann & Feynman, Marshak & Sudarshan

$$H_W = -G_F(\bar{\nu}_\mu\gamma^\mu P_L \mu)(\bar{e}\gamma_\mu P_L \nu_e) - G(\bar{p}\gamma^\mu P_L n)(\bar{e}\gamma_\mu P_L \nu_e) + \ldots$$

V-A current-current structure of weak interactions.

Conservation of vector current proposed

Experiments give G = 0.96 G_F (for the vector parts)

1960-63 To achieve a universal coupling, Gell-Mann&Levy and Cabibbo propose that a certain superposition of neutron and Λ particle enters the weak current. Flavour physics begins!

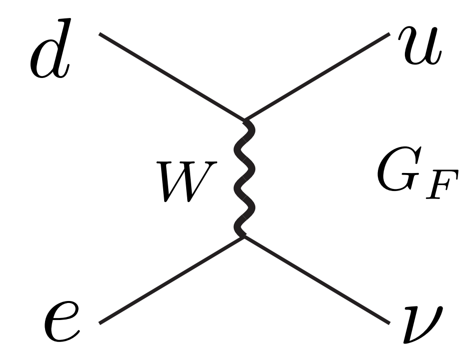
1964 Gell-Mann gives hadronic weak current in the quark model

$$H_W = -G_F J^\mu J_\mu^\dagger$$

$$J^\mu = \bar{u}\gamma^\mu P_L(\cos\theta_c d + \sin\theta_c s) + \bar{\nu}_e\gamma^\mu P_L e + \bar{\nu}_\mu\gamma^\mu P_L \mu$$

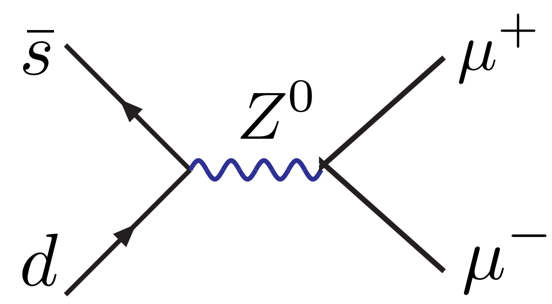
1964 CP violation discovered in Kaon decays (Cronin&Fitch)

1960-1968 J_μ part of triplet of weak gauge currents. Neutral current interactions predicted and, later, observed at CERN.



$$G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

However, the predicted flavour-changing neutral current (FCNC) processes such as $K_L \rightarrow \mu^+\mu^-$ are *not* observed!

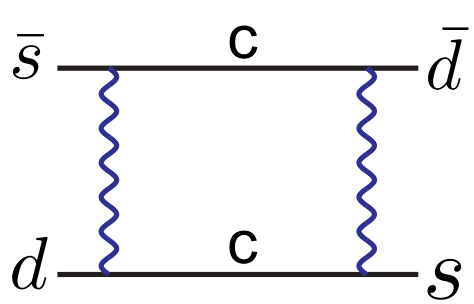


1970 To explain the absence of $K_L \rightarrow \mu^+\mu^-$, Glashow, Iliopoulos & Maiani (GIM) couple a “charmed quark” to the formerly “sterile” linear combination
$-\sin\theta_c d_L + \cos\theta_c s_L$
The doublet structure eliminates the Zsd coupling!

1971 Weak interactions are renormalizable (‘t Hooft)

1972 Kobayashi & Maskawa show that CP violation requires extra particles, for example a third doublet. CKM matrix

1974 Gaillard & Lee estimate loop contributions to the K_L-K_S mass difference
Bound $m_c < 5$ GeV



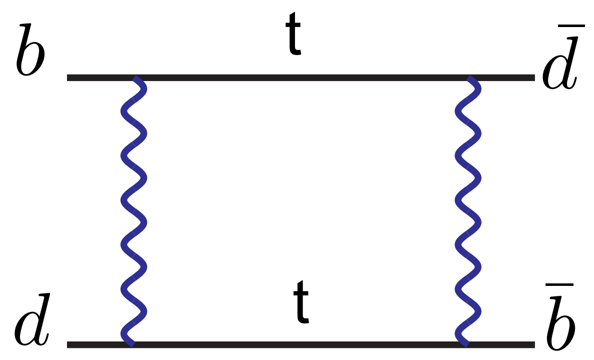
1974 Charm quark discovered

1977 τ lepton and bottom quark discovered

1983 W and Z bosons produced

1987 ARGUS measures B_d - B_d mass difference
First indication of a heavy top

The diagram depends quadratically on m_t



1995 top quark discovered at CDF & D0

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R d_R	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	c_R s_R	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	t_R b_R	$Q = +2/3$ $Q = -1/3$
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$-$ e_R	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$-$ μ_R	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$-$ τ_R	$Q = 0$ $Q = -1$

Precision measurements: masses, running coupling, direct CP violation, B factories, determination of CKM elements, neutrino oscillations, search for electric dipole moments, proton decay, ...