Flavor Physics & CP Violation

FPCP

26–30 MAY 2014

Marseille France

Experimental outlook

Tim Gershon
University of Warwick

30th May 2014

European Research Council

Flavor Physics & CP Violation

FPCP

26–30 MAY 2014
Marseille France

not a summary!

Experimental outlook

Tim Gershon
University of Warwick

30th May 2014

European Research Council

No need for a summary ...

Godot and the New Physics

(or conference highlights: FPCP 2011 … FPCP 2014)

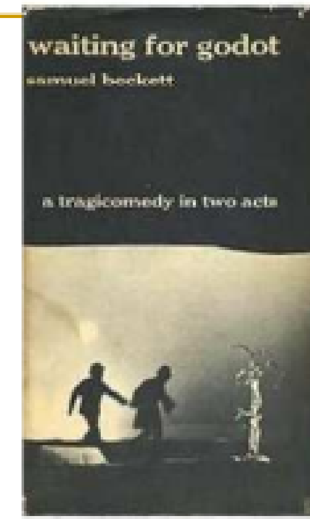
… it was given 5 years ago!

"Are we there yet?"

Guy Wilkinson
University of Oxford

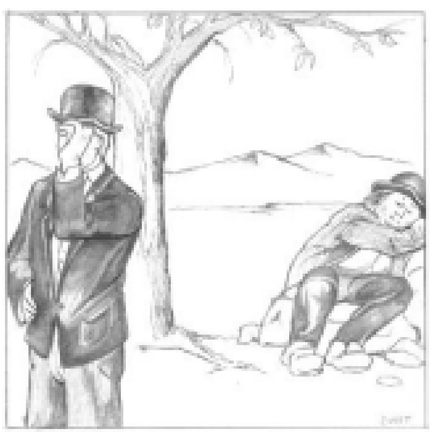
Godot and the New Physics
Guy Wilkinson, FPCP 09 1

Waiting for Godot – a parable for the flavour physics community ?



Samuel Beckett's play (1949) a landmark of modern theatre.

Two tramps, Vladimir and Estragon, await the arrival of the mysterious Godot. He does not come, although other sinister characters pass through whom they mistake for Mr G. They pass their time in meaningless activities and talk.

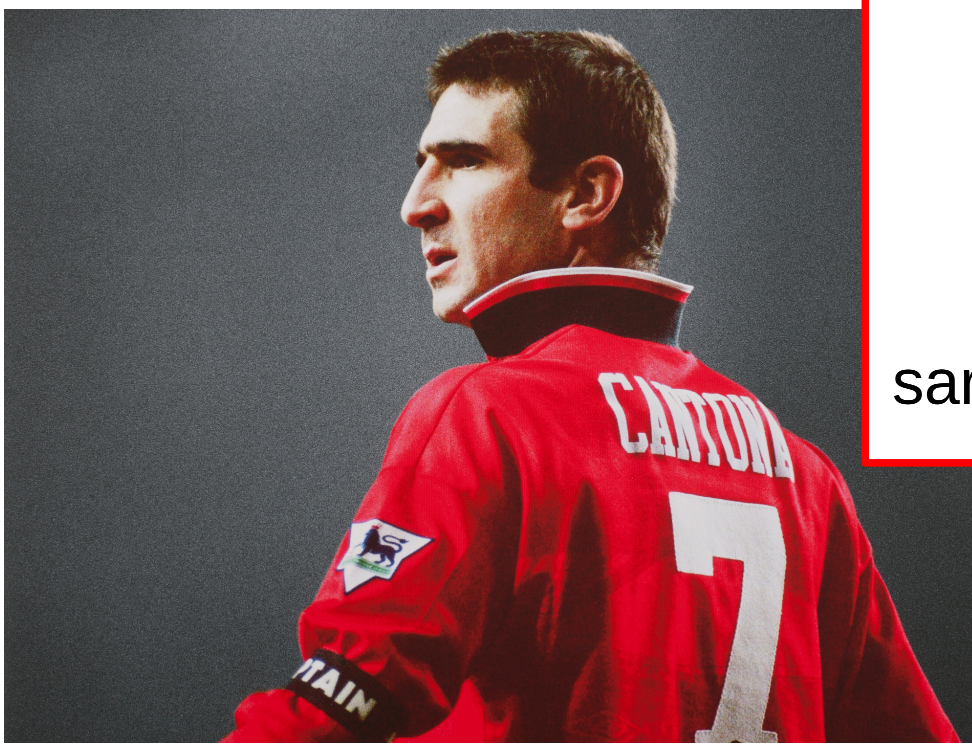


A play of existentialist angst focused on the futility of the human condition…

…or a parable of the search for new physics in the flavour sector ?

(which in turn could be seen as a tale of existentialist angst focused on the futility of the human condition)

More existential philosophy



Éric Daniel Pierre Cantona
b. 24 May 1966 in Marseille

“When the seagulls follow the trawler, it's because they think sardines will be thrown into the sea.”

In this talk, I will follow the trawler of exciting new results, in the hope of catching some big fish

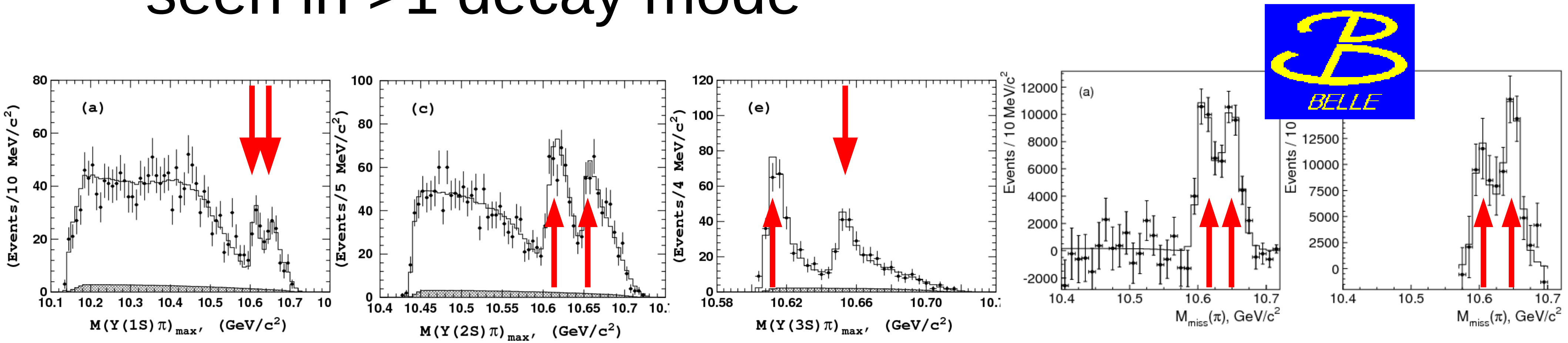
QCD

"The absence of exotics is one of the most obvious features of QCD"

(R.L. Jaffe hep-ph/0409065)

“Exotic” onia-like states

- Several “exotic” onia-like states have now been seen in >1 decay mode

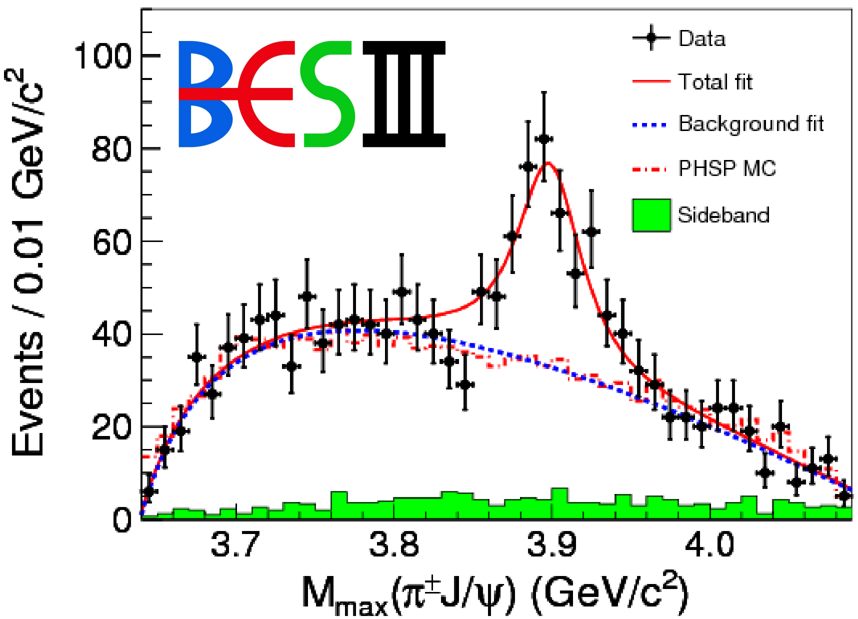


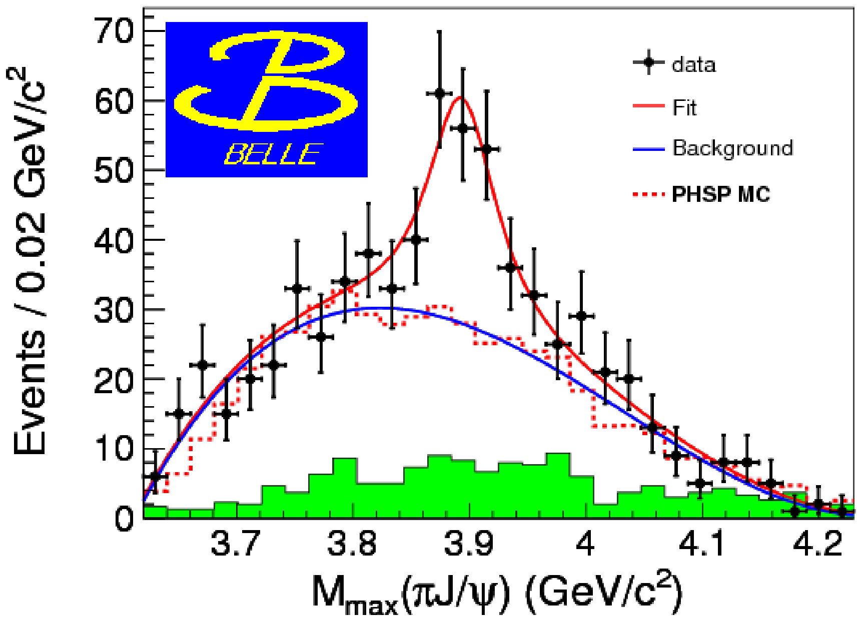
$Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ seen in $\Upsilon(1,2,3S)\pi^\pm$ and $h_b(1,2S)\pi^\pm$

Belle PRL 108 (2012) 122001 and arXiv:1403.0992

“Exotic” onia-like states

- Several “exotic” onia-like states have now been seen in >1 decay mode OR by >1 experiment





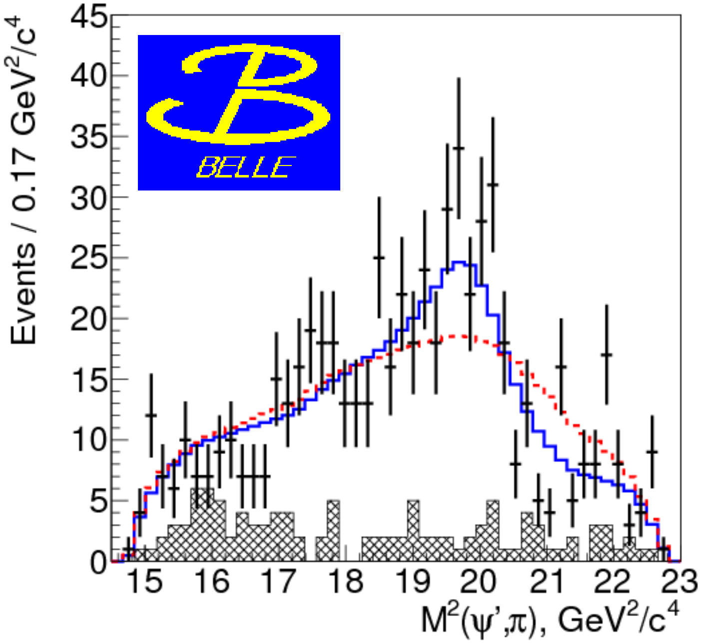
$Z_c(3900)^{\pm}$ seen in $Y(4260) \rightarrow Z_c(3900)\pi$, $Z_c(3900)^{\pm} \rightarrow J/\psi\pi^{\pm}$

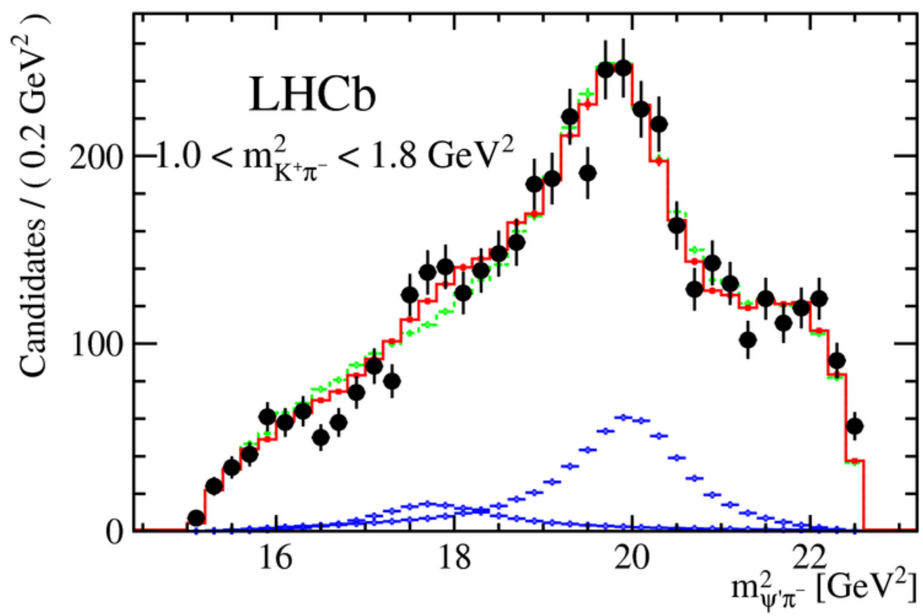
BES PRL 110 (2013) 252001 and Belle PRL 110 (2013) 252002

… and others

“Exotic” onia-like states

- Several “exotic” onia-like states have now been seen in >1 decay mode OR by >1 experiment



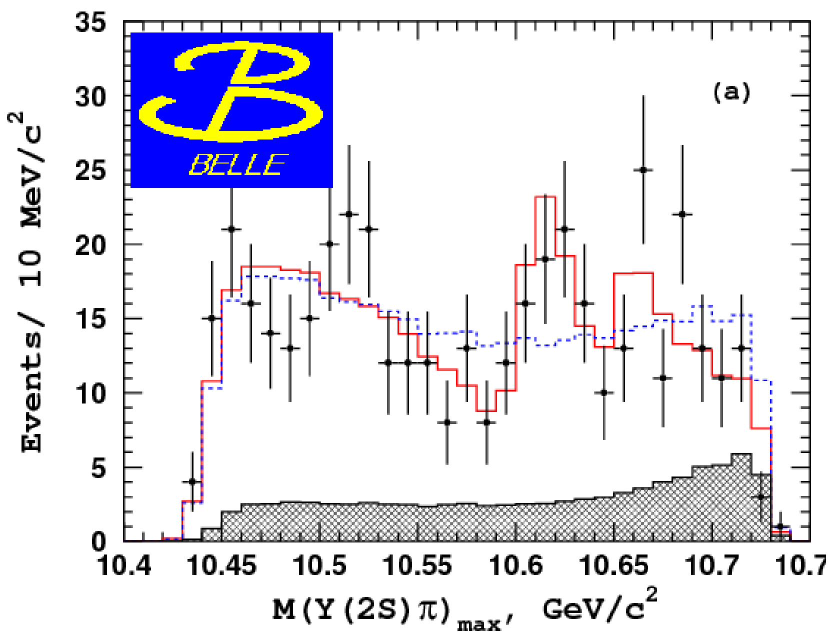


$Z_c(4430)^\pm$ seen in $B^0 \to Z_c(4430)K$, $Z_c(4430)^\pm \to \psi(2S)\pi^\pm$

Belle PR D88 (2013) 074026 [following PR D80 (2009) 031104 & PRL 100 (2008) 142001] & LHCb arXiv:1404.1903

"Exotic" onia-like states

- Some appear to have isospin partners



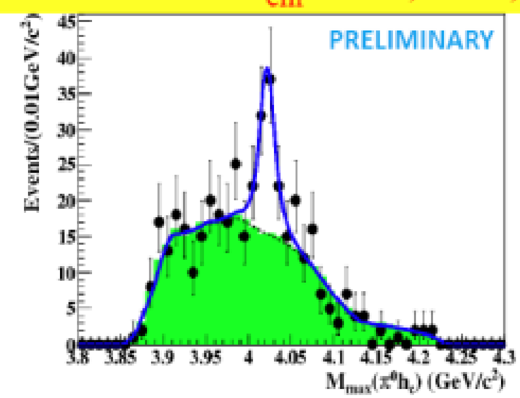
$Z_b(10610)^0$ seen in $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$

Belle PR D88 (2013) 052016

BESIII

$e^+e^- \to \pi^0 Z_c^0(4020) \to \pi^0\pi^0 h_c(1P)$

Summed results at E_{cm}=4.23, 4.26, 4.36GeV



Simultaneous fit to 4.23/4.26/4.36GeV Data and 16 η_c modes;

$\Gamma(Z_c^0(4020))$ is fixed to value of $\Gamma(Z_c^\pm(4020))$;

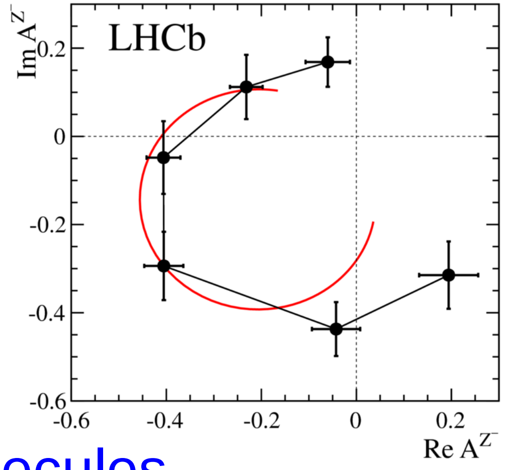
Interference is neglected;

$M(Z_c^0(4020)) = 4023.6 \pm 2.2 \pm 3.9$ MeV/c^2;

Significance : $> 5\sigma$.

BESIII new PRELIMINARY

Lessons from exotica

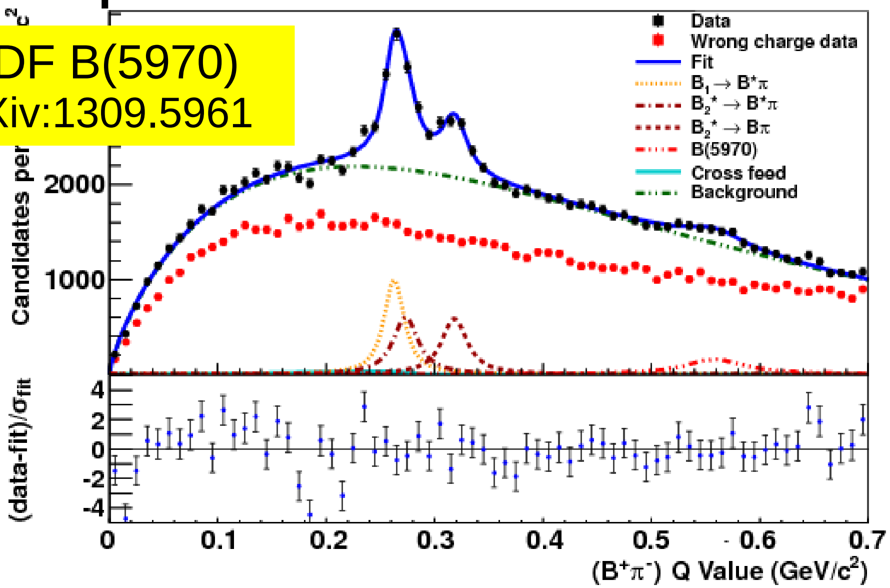


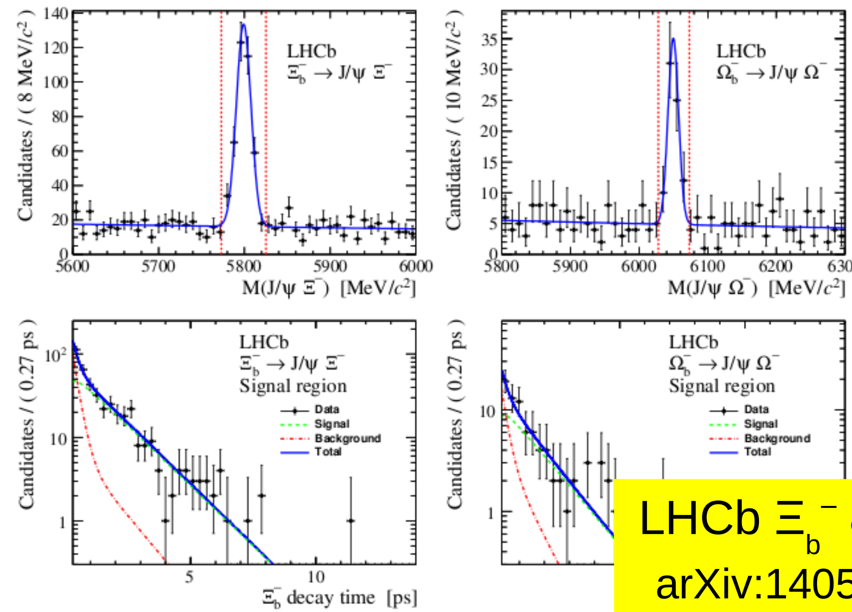
- The Z(4430) seen by Belle in 2007 is confirmed
  - … but it could easily not have been
  - No substitute for thorough amplitude analysis
  - Must demand same rigour to confirm other claimed states
- What is correct description of these states? Meson molecules, tetraquarks, hybrids, something else?
  - n.b. Care needed with language – premature to claim tetraquark observation
  - Mixing with conventional states (e.g. X(3872)–χ_{c1}(2P)) allowed
  - Do meson molecules warrant the adjective "exotic"?
- Many more studies needed to clarify picture
  - Since we have charged onia-like states, why not also neutral charmed-strange (or charged beauty-strange) states?

Open flavour spectroscopy

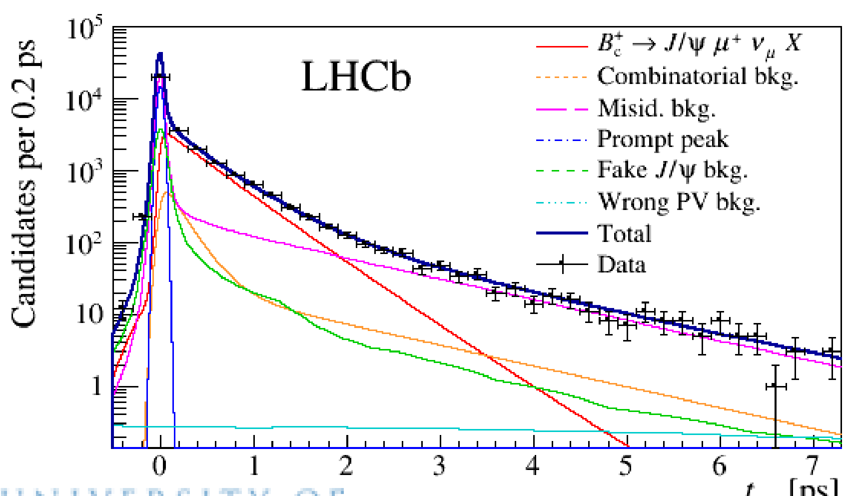
Looking forward to many more new discoveries and precise measurements of masses, widths/lifetimes

CDF B(5970)
arXiv:1309.5961

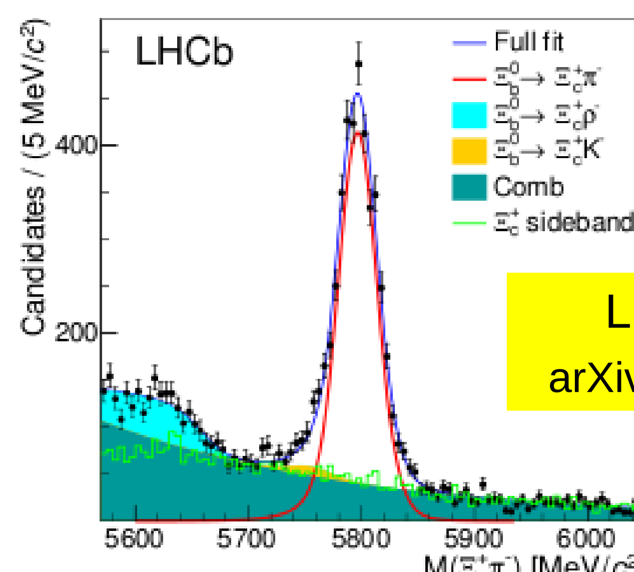




LHCb Ξ_b^- & Ω_b^-
arXiv:1405.1543



LHCb B_c
EPJ C74 (2014) 2839



LHCb Ξ_b^0
arXiv:1405.7223

QCD and the CKM matrix

the strong interaction can be seen either as the "unsung hero" or the "villain" in the story of quark flavour physics

I. Bigi, hep-ph/0509153

V_{xb} inclusive vs. exclusive problem

Over the last ~5 years, a discrepancy between inclusive and exclusive determinations of V_{xb} from semileptonic B decays has emerged

PDG 2006

$$|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3} \text{ (inclusive)}$$
$$|V_{cb}| = (40.9 \pm 1.8) \times 10^{-3} \text{ (exclusive)}.$$

$$|V_{ub}| = (4.40 \pm 0.20 \pm 0.27) \times 10^{-3} \text{ (inclusive)},$$
$$|V_{ub}| = (3.84 \, {}^{+0.67}_{-0.49}) \times 10^{-3} \text{ (exclusive)}.$$

PDG 2013

$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)}$$
$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)}$$

$$|V_{ub}| = (4.41 \pm 0.15 \, {}^{+0.15}_{-0.17}) \times 10^{-3} \text{ (inclusive)},$$
$$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \text{ (exclusive)}.$$

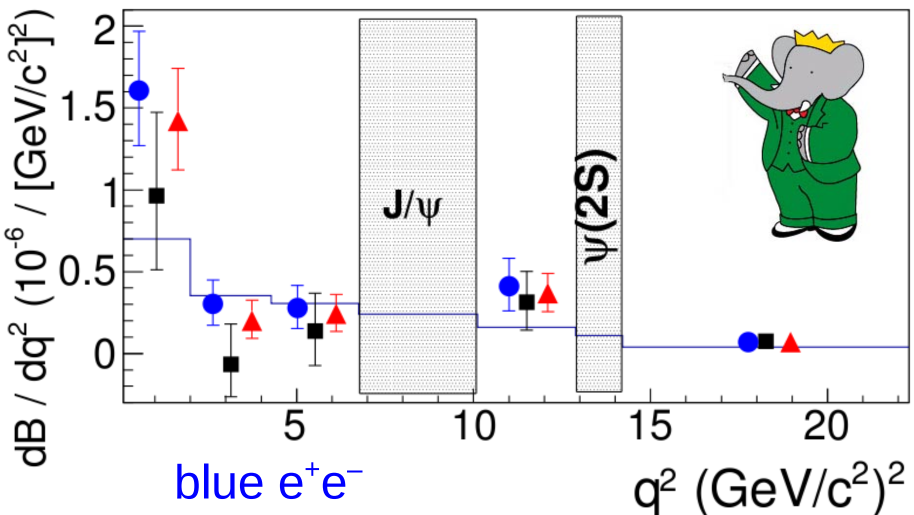
n.b. Significant progress in lattice calculations helps reduction of uncertainties in exclusive determination (together with new experimental results) – also for V_{cx}

Understanding this will involve a great deal of effort, but is essential for continued progress in the field

Inclusive vs. exclusive in $b \to s l^+ l^-$

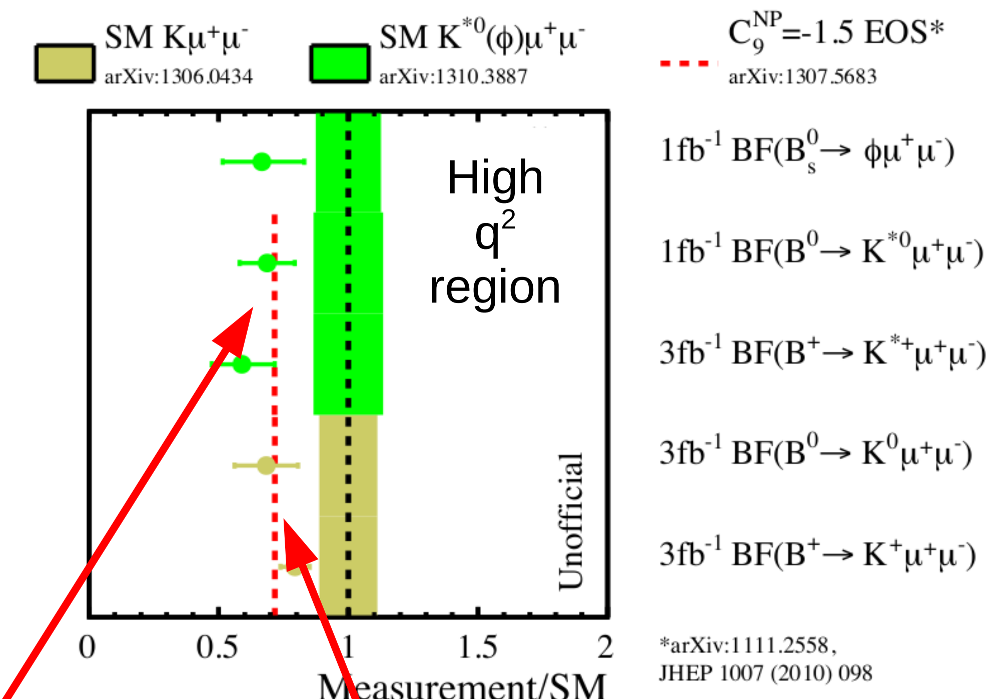
Is a similar tension emerging in $b \to s l^+ l^-$ decays?

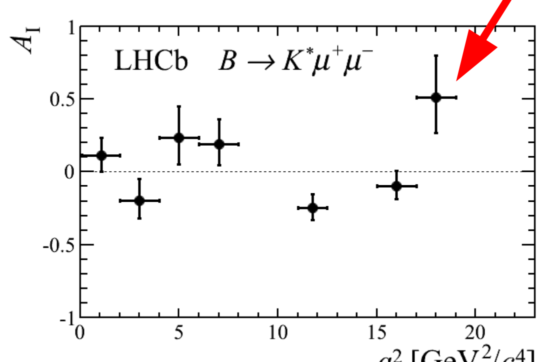
BaBar arXiv:1312.5364

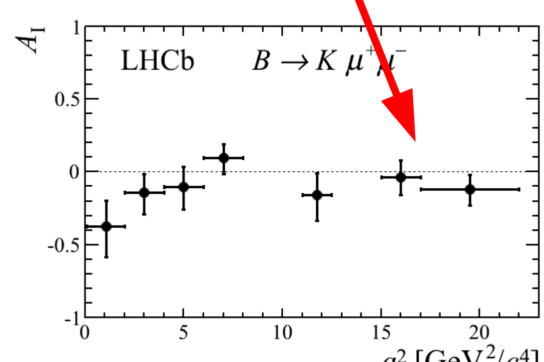


blue e^+e^-
black $\mu^+\mu^-$
red average
histogram theory (±20%)

M. Patel @ Moriond EW
Data from LHCb arXiv:1403.8044





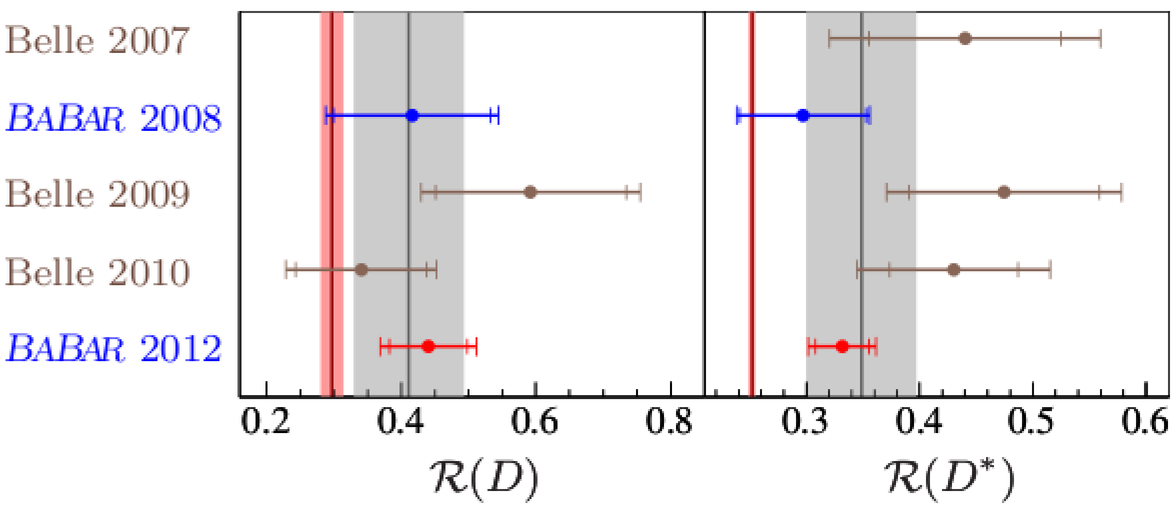


isospin asymmetries consistent with SM

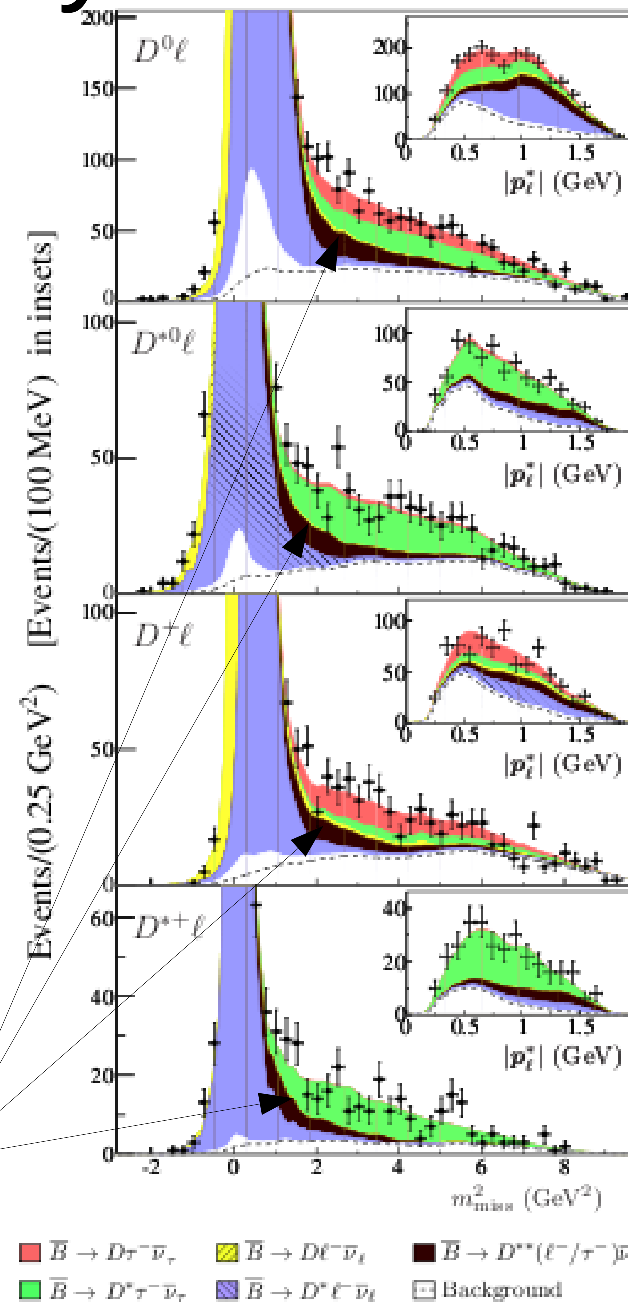
Lepton universality

Essential to understand strong interaction effects, otherwise potential new physics signatures have too much room to hide

Excess of B → D$^{(*)}$τν relative to D$^{(*)}$μν & D$^{(*)}$eν



BaBar PRL 109 (2012) 101802 & PRD 88 (2013) 072012
New Belle/LHCb data urgently needed!



Need also improved knowledge of b → clν background shapes

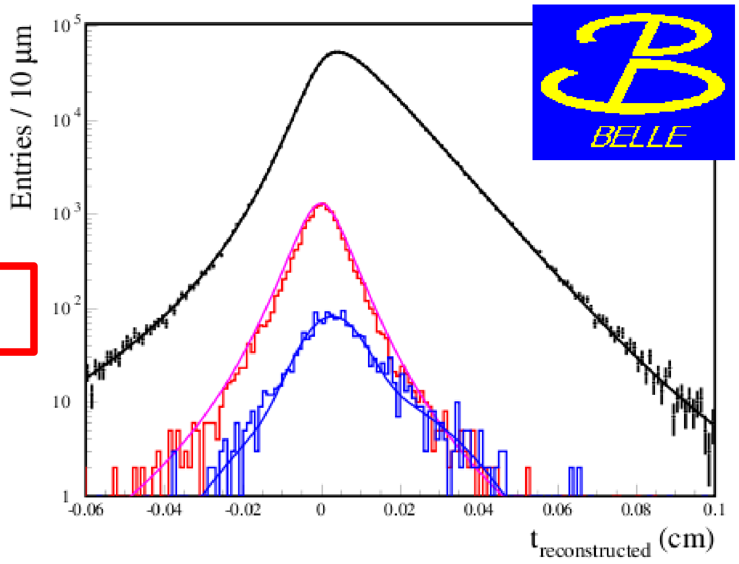
Aside on the τ lepton

- τ lepton an increasing important tool for new physics searches
  - (semi) leptonic B&D decays $B \to \tau\nu$, $D_{(s)} \to \tau\nu$, $B \to D^{(*)}\tau\nu$
    - and hopefully $B \to K^{(*)}\tau\tau$, $B_{(s)} \to \tau\tau$ soon
  - τ lepton flavour violation searches
  - Higgs & Higgs-like decays $H \to \tau\tau$, $A^0 \to \tau\tau$
- New τ lifetime measurement

Belle PRL 112 (2013) 031801

$\tau(\tau) = (290.17 \pm 0.53(\text{stat.}) \pm 0.33(\text{syst.}))$ fs

provides strong test of lepton universality



The $B \to K\pi$ puzzle

- QCD may also be a cause of apparently anomalous CP violation effects

$$\Delta A_{CP}(K\pi) = A_{CP}(K^+\pi^-) - A_{CP}(K^+\pi^0) \neq 0$$

-0.082 ± 0.006	$+0.040 \pm 0.021$	HFAG averages
e.g. LHCb PRL 110 (2013) 221601	e.g. Belle PR D87 (2013) 031103	most precise single measurement

- Look for similar effects in $K^*\pi$ & $K\rho$ systems
- Exploit U-spin symmetry
  - $B^0 \leftrightarrow B_s^0$, $K^+\pi^- \leftrightarrow \pi^+K^-$, $K^+K^- \leftrightarrow \pi^+\pi^-$, $D_s^+K^- \leftrightarrow D^+\pi^-$, etc.

A huge number of U-spin based tests are possible
Better quantification of U-spin breaking effects needed to best exploit them

The $B \to K\pi$ puzzle

- QCD may also be a cause of apparently anomalous CP violation effects

$$\Delta A_{CP}(K\pi) = A_{CP}(K^+\pi^-) - A_{CP}(K^+\pi^0) \neq 0$$

-0.082 ± 0.006	$+0.040 \pm 0.021$	HFAG averages
e.g. LHCb PRL 110 (2013) 221601	e.g. Belle PR D87 (2013) 031103	most precise single measurement

- Look for similar effects in $K^*\pi$ & $K\rho$ systems

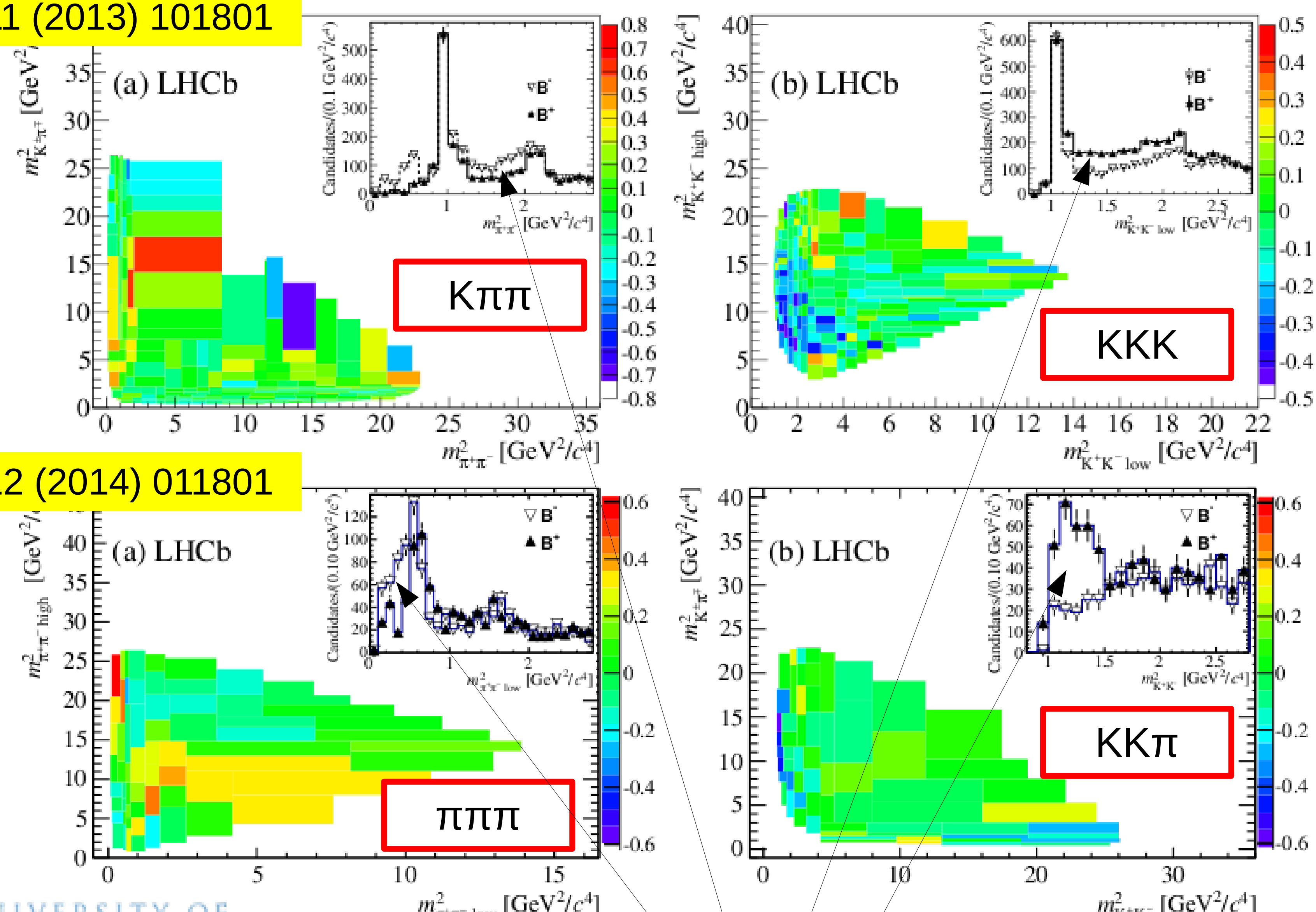
$K^*\pi$	-0.23 ± 0.06 e.g. BaBar PR D83 (2011) 112010	-0.39 ± 0.13 e.g. BaBar NEW PRELIMINARY
$K\rho$	$+0.20 \pm 0.11$ e.g. BaBar PR D83 (2011) 112010	$+0.37 \pm 0.11$ BaBar PR D78 (2008) 012004 & Belle PRL 96 (2006) 251803

Interesting pattern emerging? **Need new results from Belle & LHCb**

CP violation in B → 3h

PRL 111 (2013) 101801

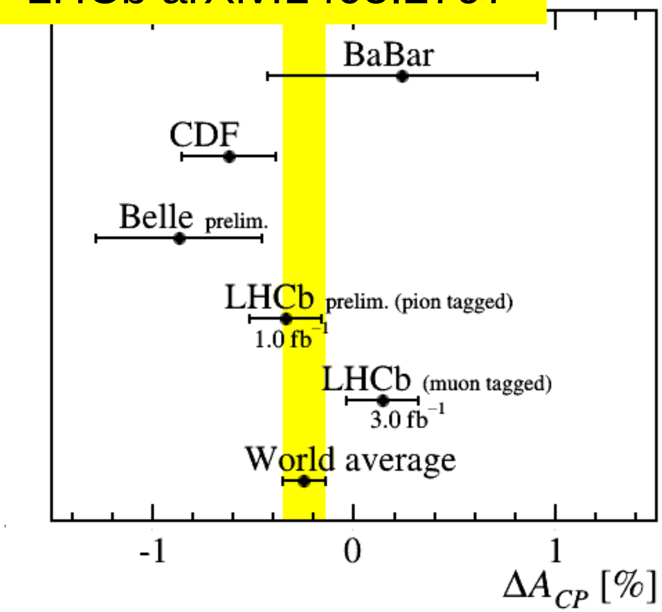
PRL 112 (2014) 011801

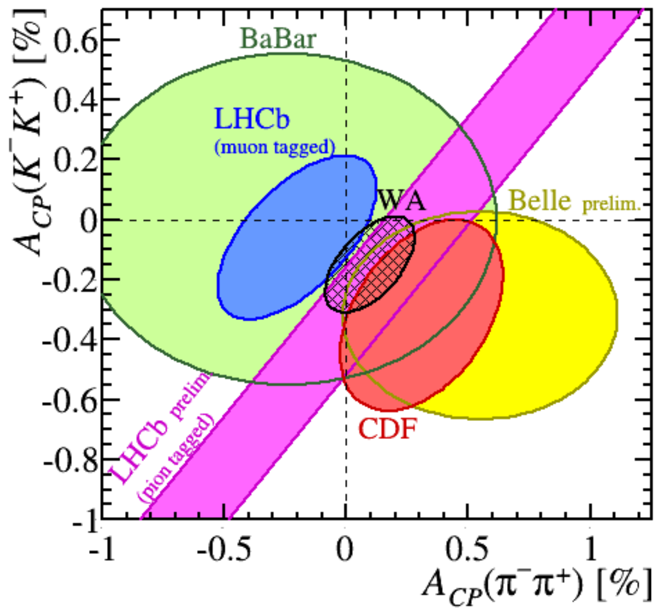


Large CPV effects not associated with resonances –
QCD effects to be understood

How large can CP violation in D be?

LHCb arXiv:1405.2797

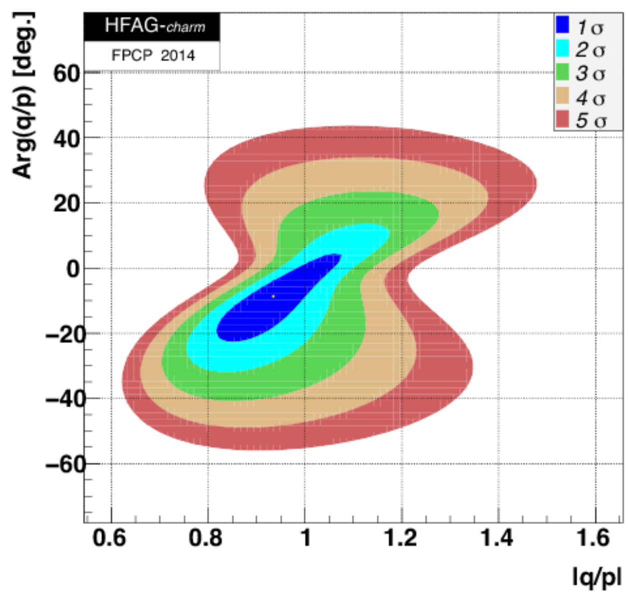


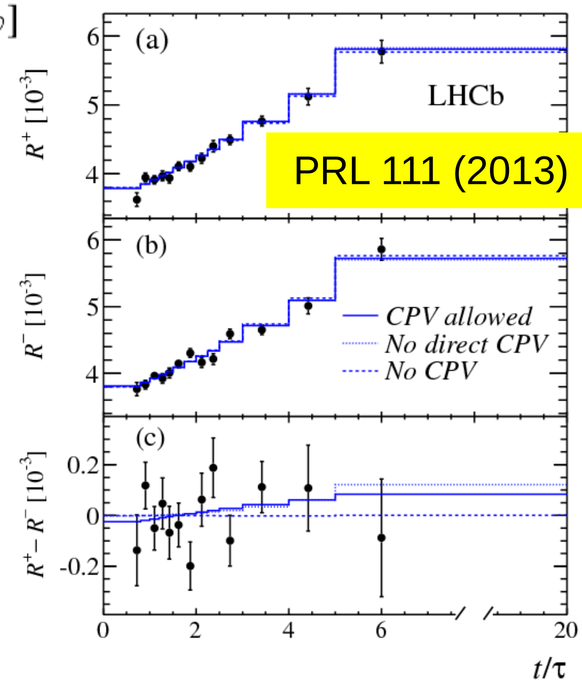


New results give world averages of $|A_{CP}(K^+K^-)| \sim |A_{CP}(\pi^+\pi^-)| \sim 10^{-3}$, with opposite sign, as originally expected.

(CP violation effect not significantly non-zero)

See also Belle arXiv:1404.2412



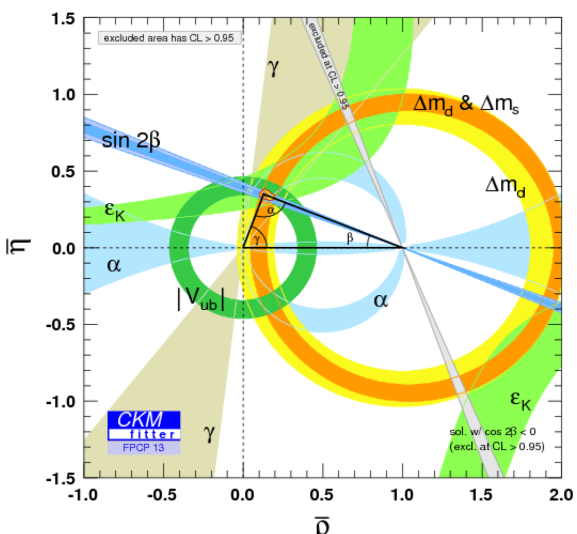


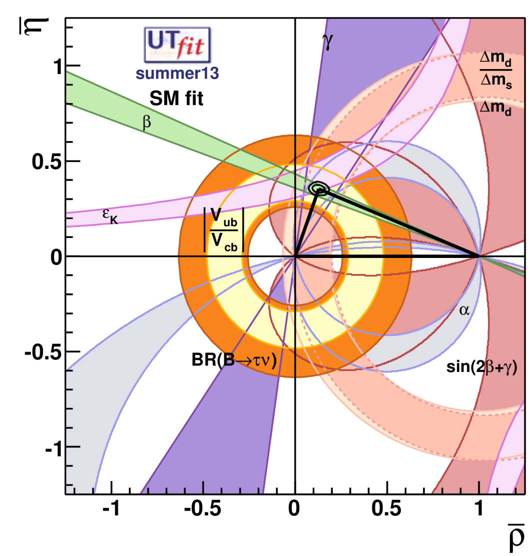
PRL 111 (2013) 251801

Much stronger constraints on |q/p| & φ_D assuming no DCPV, but still room for NP effects in charm mixing

Tim Gershon
Experimental outlook

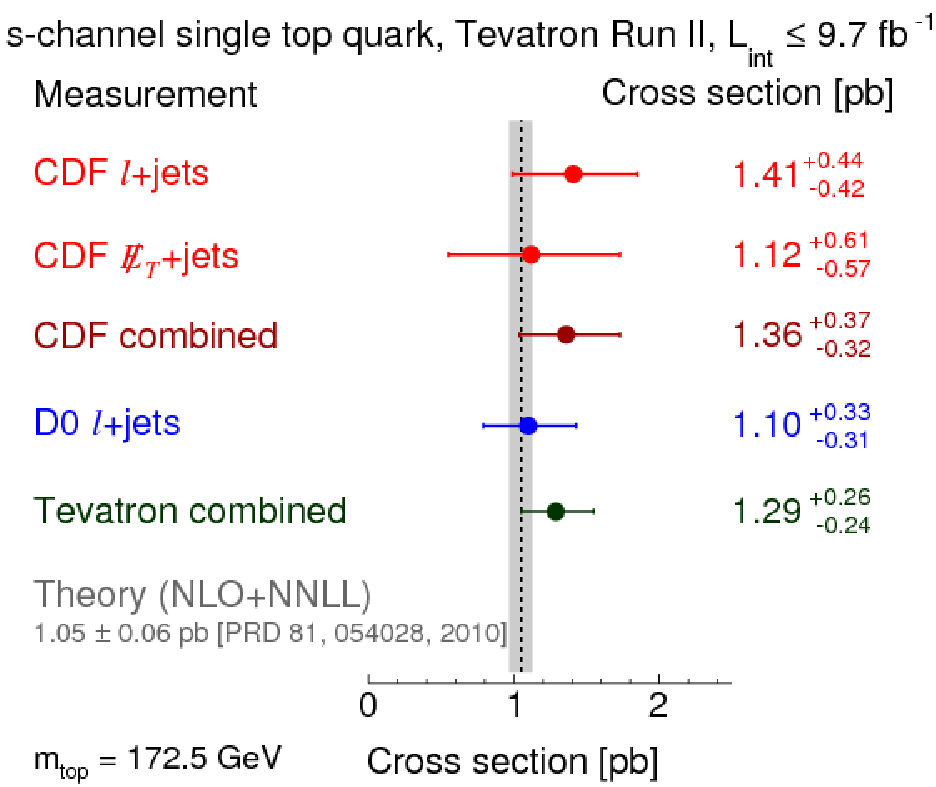
QCD-free (or -nearly-free) observables in the quark sector





Top

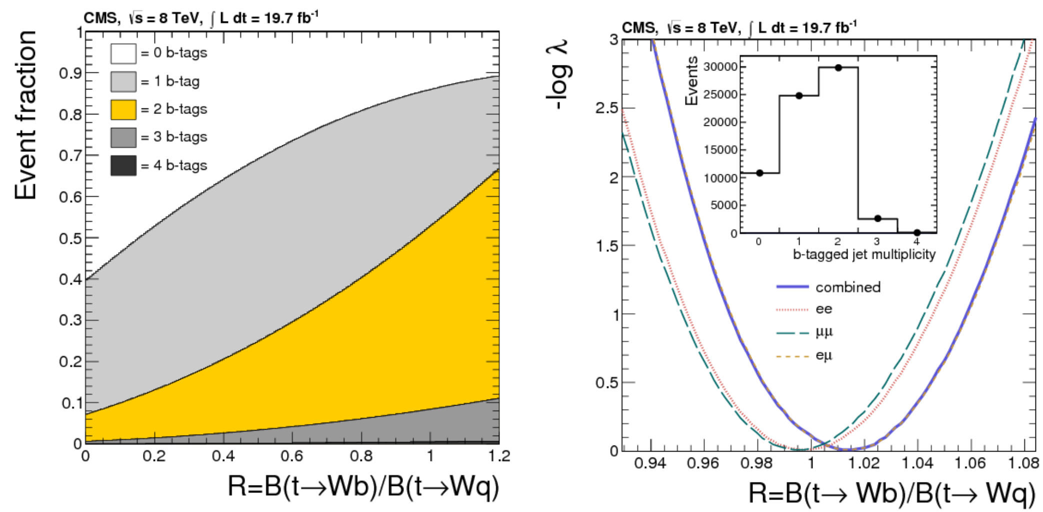
CDF+D0 arXiv:1402.5126



s channel production observed
tW channel observed by CMS (arXiv:1401.2942) & ATLAS (ATLAS-CONF-2013-100)

CMS arXiv:1404.2292

Measurement of $B(t\to Wb)/B(t\to Wq)$ from $t\bar{t}$ production with dilepton final state



$|V_{tb}| > 0.975$ @ 95% CL

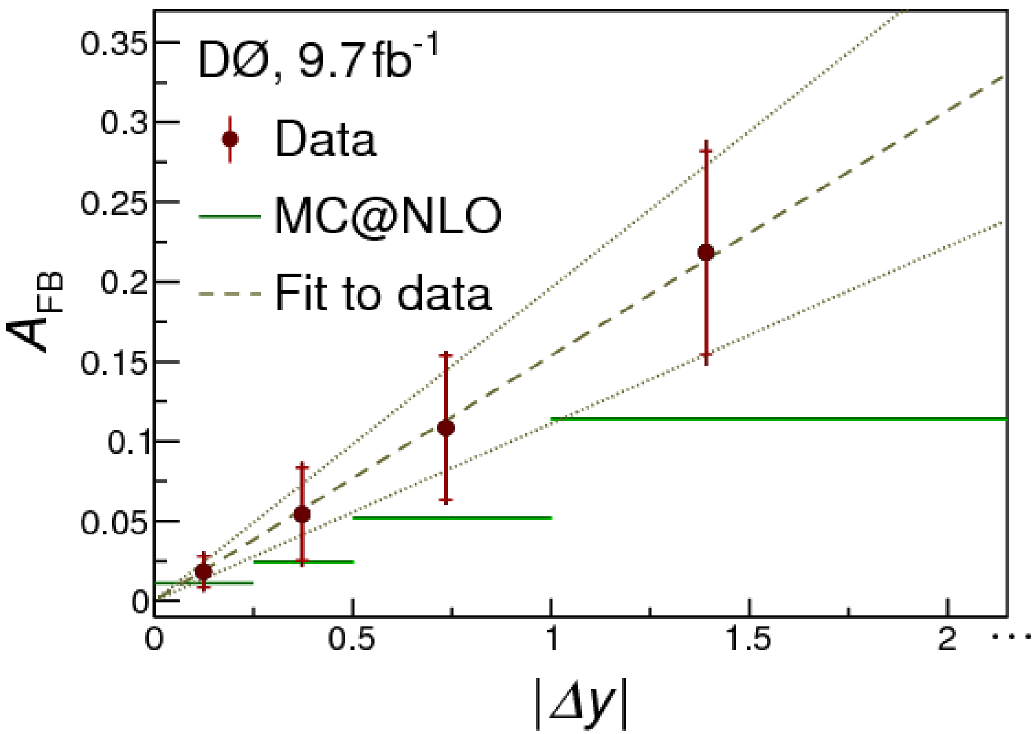
Most precise value but assumes CKM unitarity

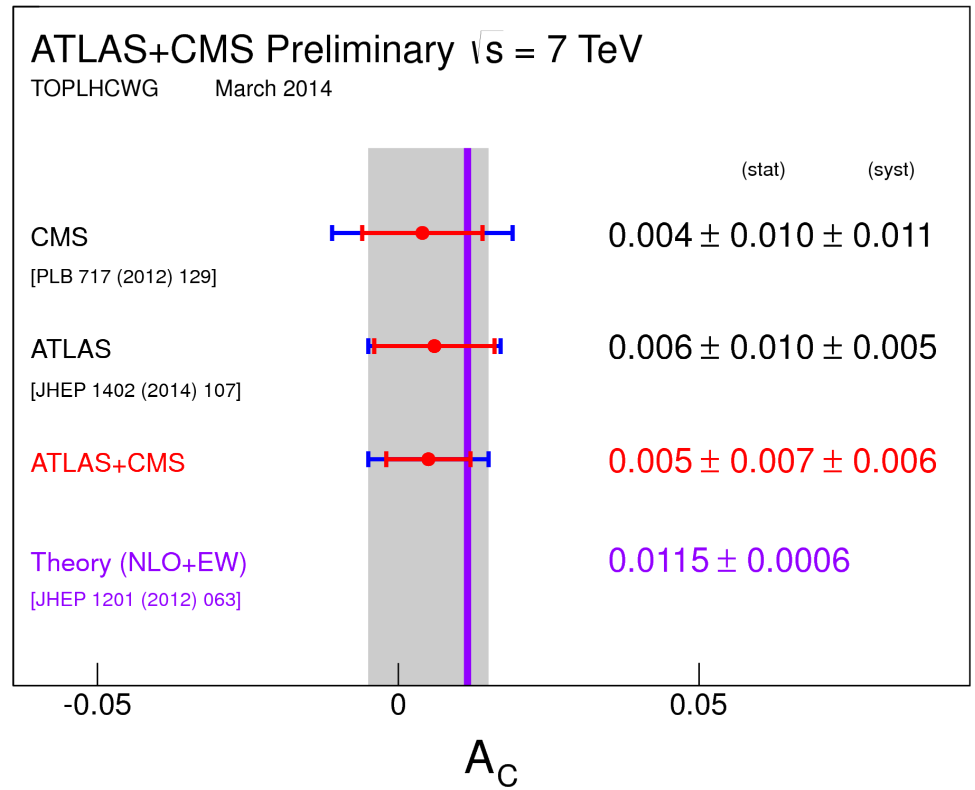
Measurements based on single top are catching up (e.g. CMS JHEP 12 (2012) 035) and are not systematically limited

$t\bar{t}$ asymmetries

D0 arXiv:1405.0421

ATLAS+CMS TOPLHCWG





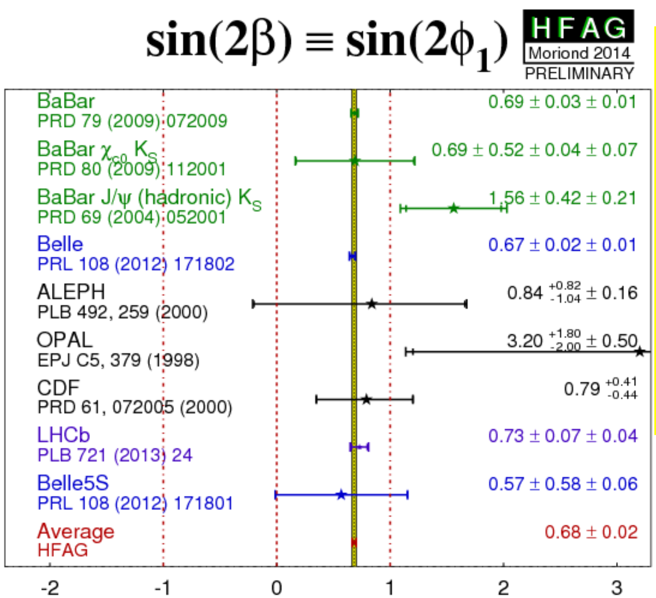
$A_{FB} = (10.6 \pm 3.0)$ %
Consistent with Standard Model

No significant asymmetry seen at LHC

Forward-backward asymmetry can be measured at $p\bar{p}$ collider

Forward-central asymmetry in pp collisions probes similar phenomena

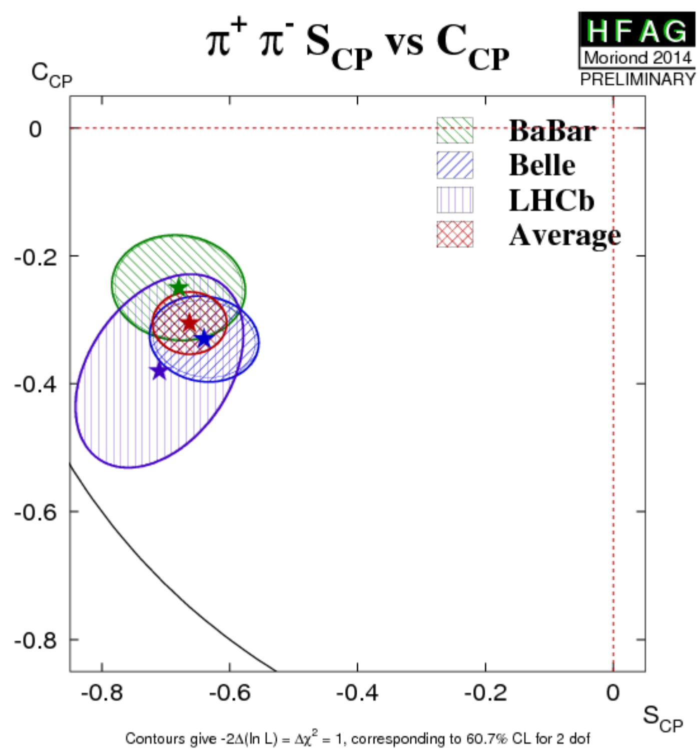
The UT angles

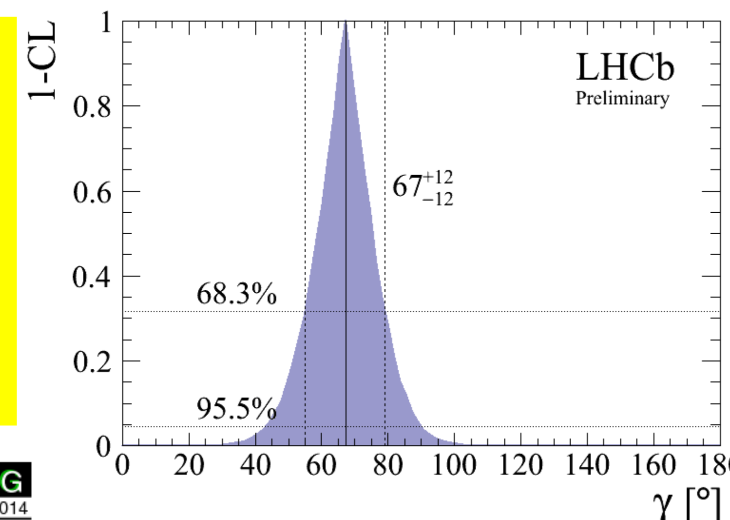


Latest results on sin(2β)
LHCb PLB 721 (2013) 24

Latest results on α ($\pi^+\pi^-$)
BaBar PRD 87 (2013) 052009
Belle PRD 88 (2013) 092003
LHCb JHEP 10 (2013) 183

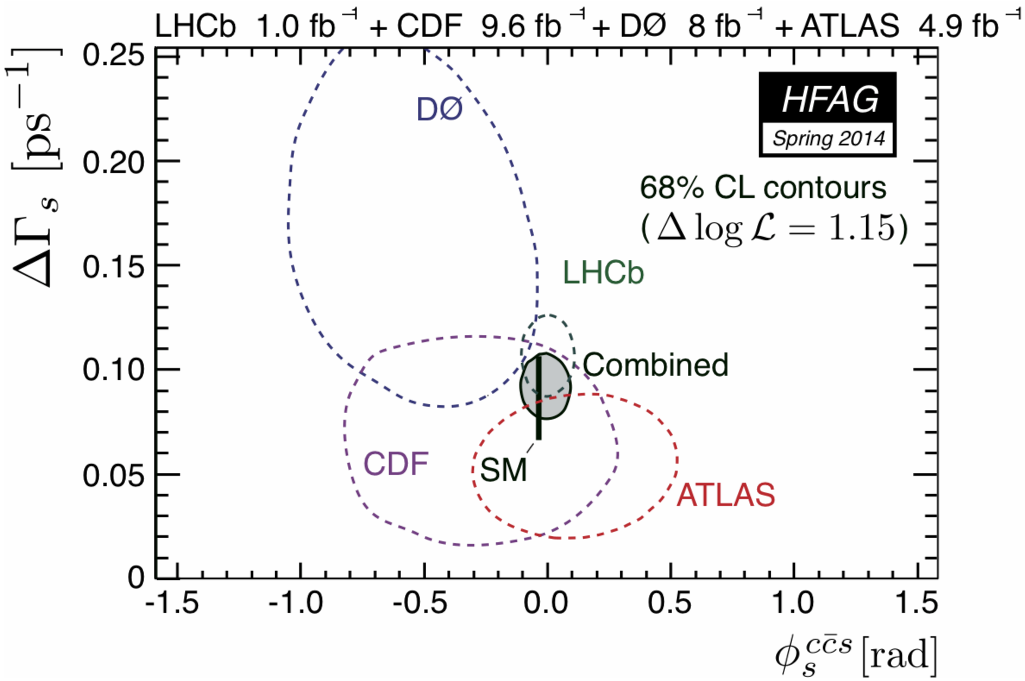
α ($\pi^+\pi^-\pi^0$)
BaBar PRD 88 (2013) 012003



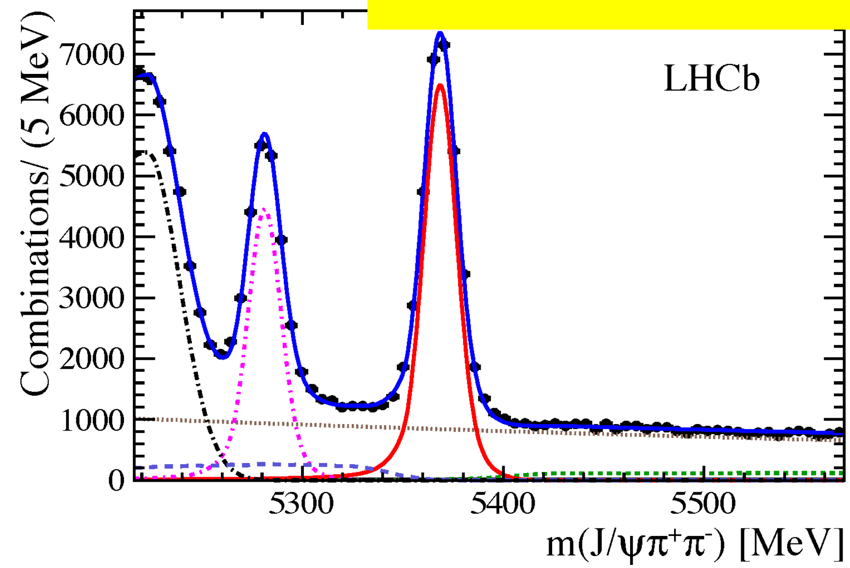


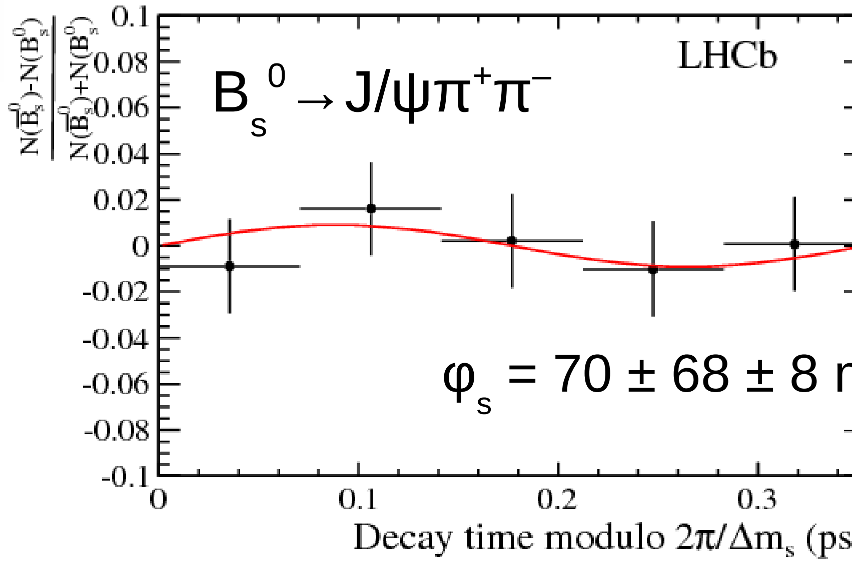
Latest results on γ
LHCb-CONF-2013-004
LHCb-CONF-2013-006

φ_s or $-2\beta_s$



LHCb arXiv:1405.4140



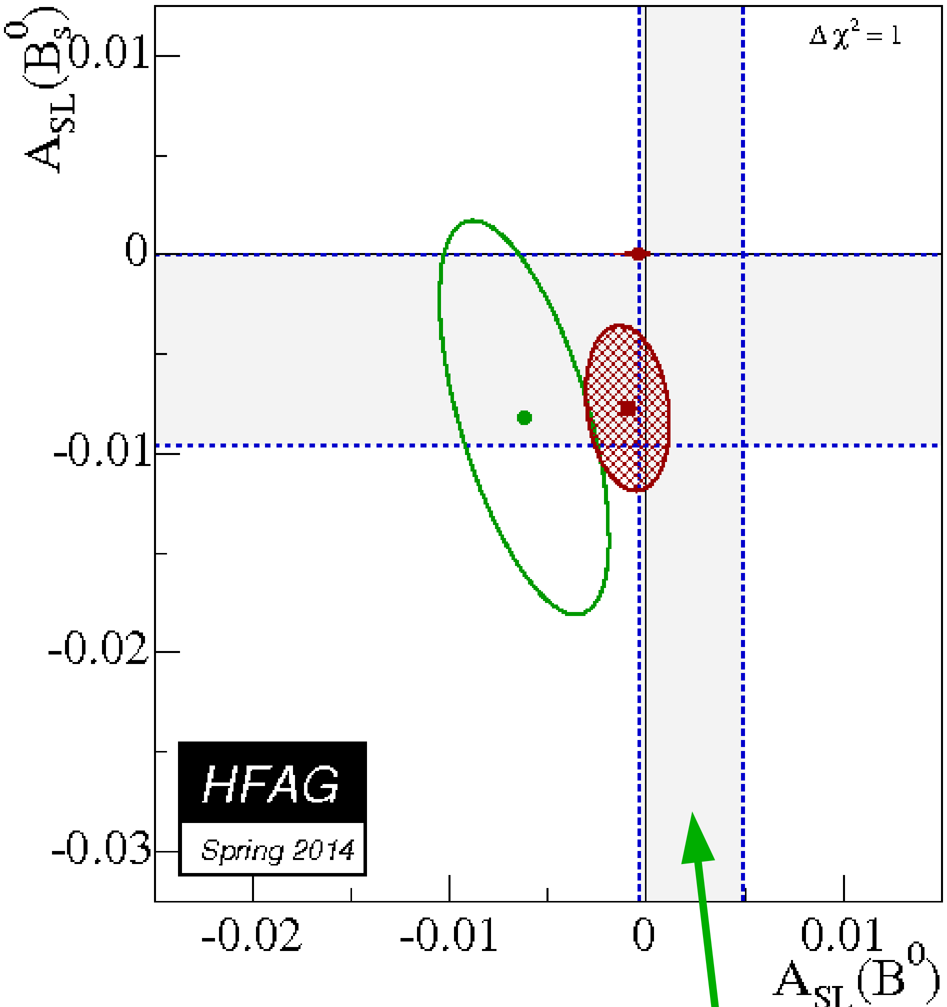


$\varphi_s = 70 \pm 68 \pm 8$ mrad

Consistent with the SM

World average not yet including full Run 1 dataset results from LHCb & ATLAS (& CMS to come?)

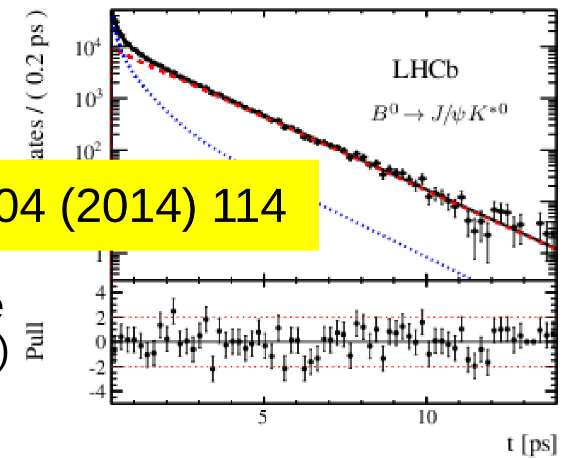
Semileptonic asymmetries



D0 PR D89 (2014) 012002

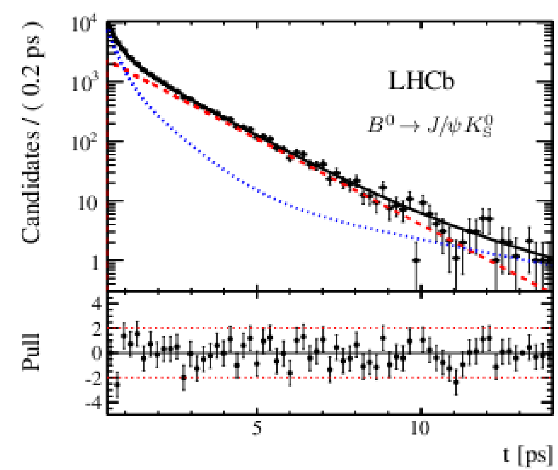
Could tension be due to non-SM $\Delta\Gamma_d$?
(PR D87 (2013) 074020)

I hope so, but latest measurements don't show any discrepancy (errors still large)

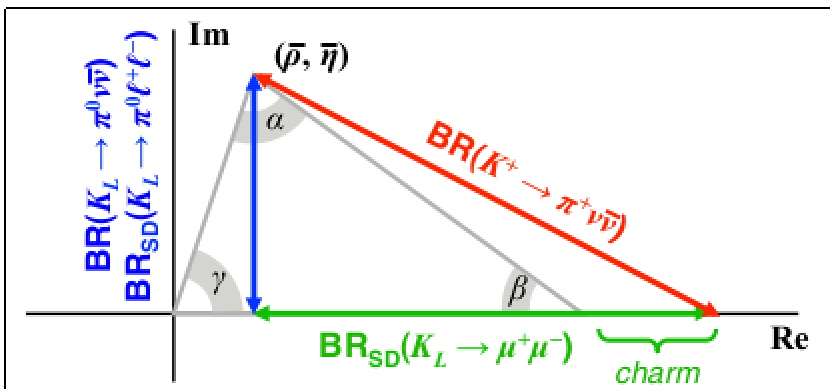


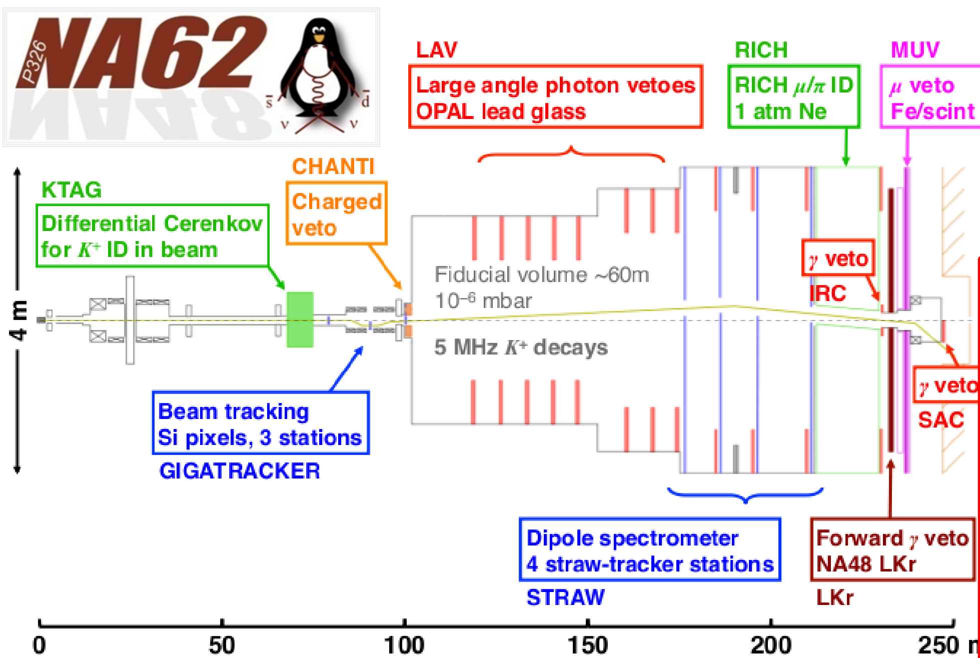
LHCb JHEP 04 (2014) 114

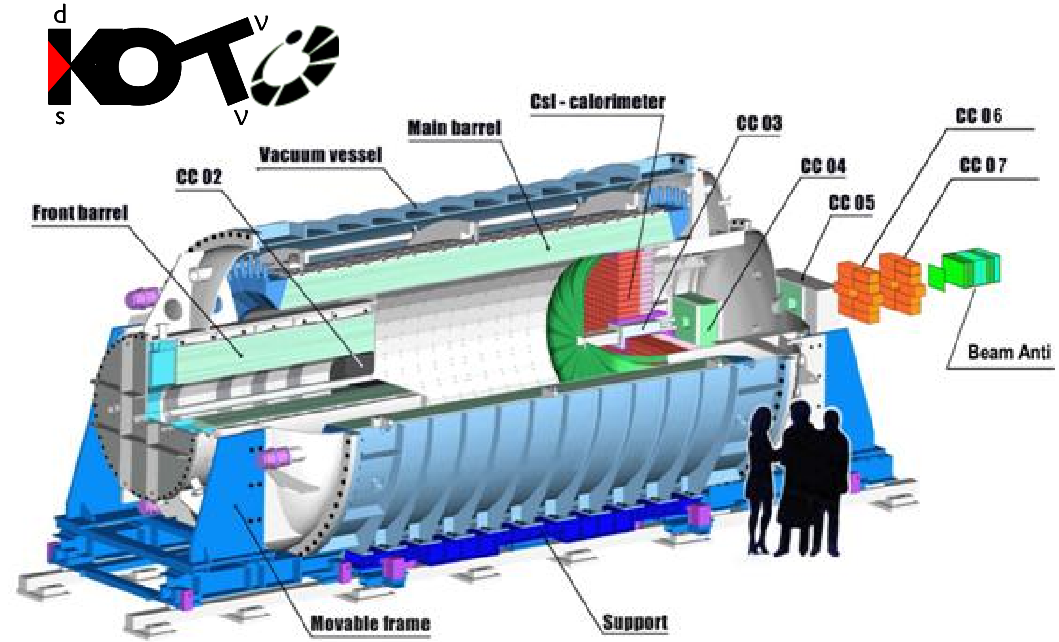
See also Belle PR D85 (2012) 071105



$K \to \pi\nu\bar{\nu}$





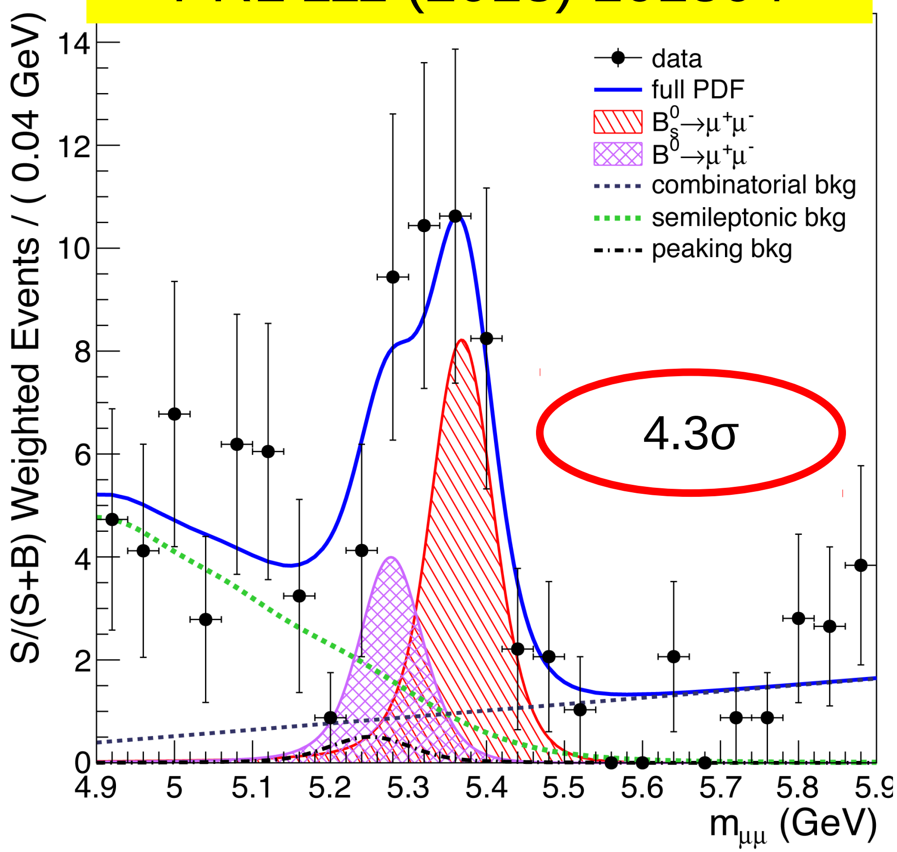


- KOTO completed detector construction for 1st physics run and took physics data in May 2013
  - Original goal: to cross the Grossman-Nir limit
  - Achieved: ~4 day run with 24kW beam; accumulated ~1/5 of planned POT
- We are now analyzing the data, expecting we can improve KEK-E391a upper limit.
- Preparation for next-level physics run is also underway.
  - Fabrication of Inner Barrel, etc...

From J-PARC PAC meeting Sept.2013

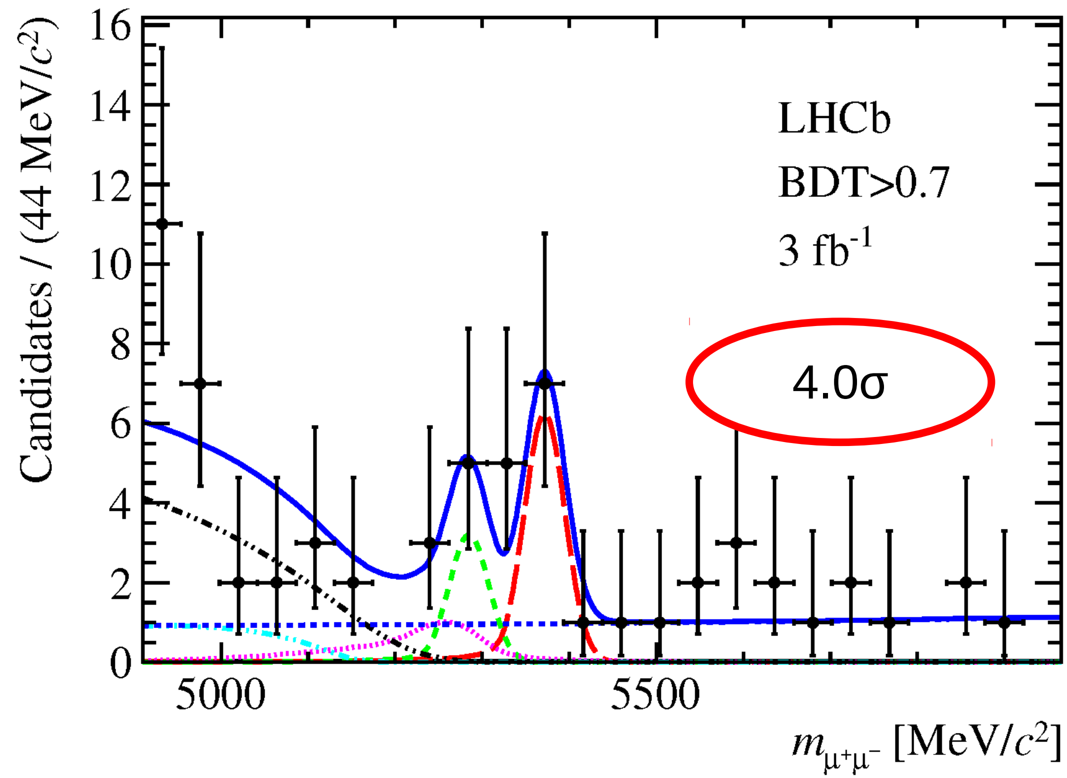
$B_{(s)}^0 \to \mu^+\mu^-$

CMS
PRL 111 (2013) 101804



Events weighted by S/(S+B)

LHCb
PRL 111 (2013) 101805

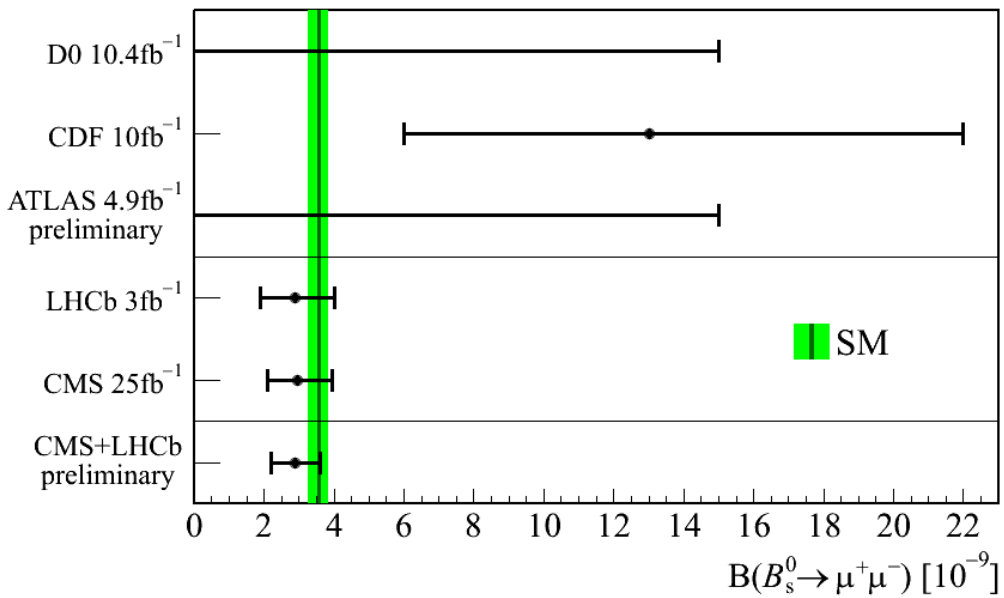


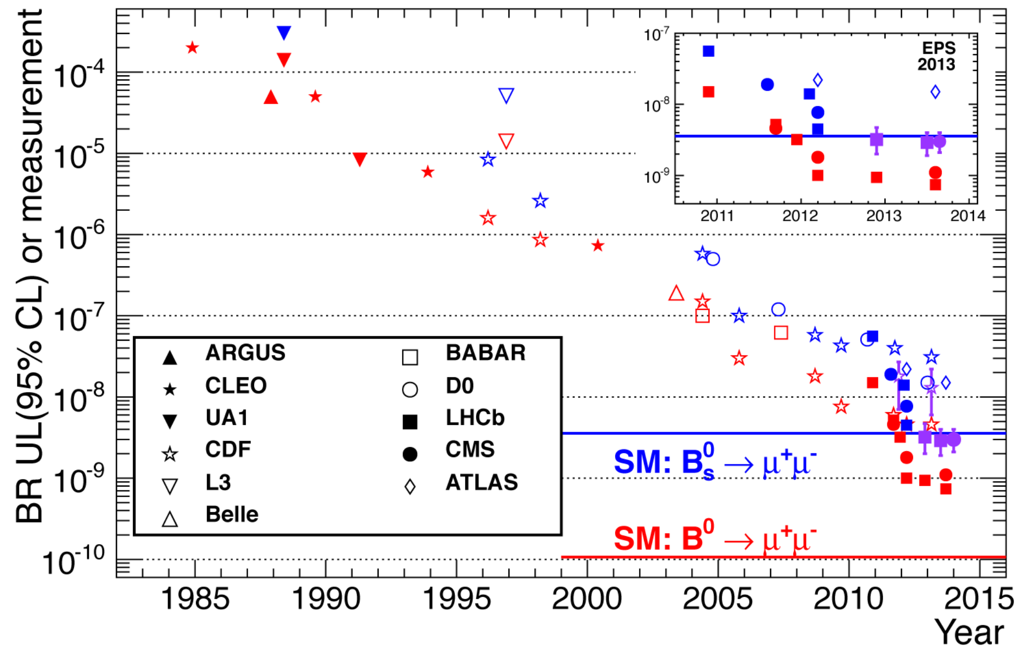
Only events with BDT > 0.7

Updated results confirm earlier evidence from LHCb (PRL 110 (2013) 021801)

$B_{(s)}^0 \to \mu^+\mu^-$ – combined results

LHCb-CONF-2013-012
CMS-PAS-BPH-13-007





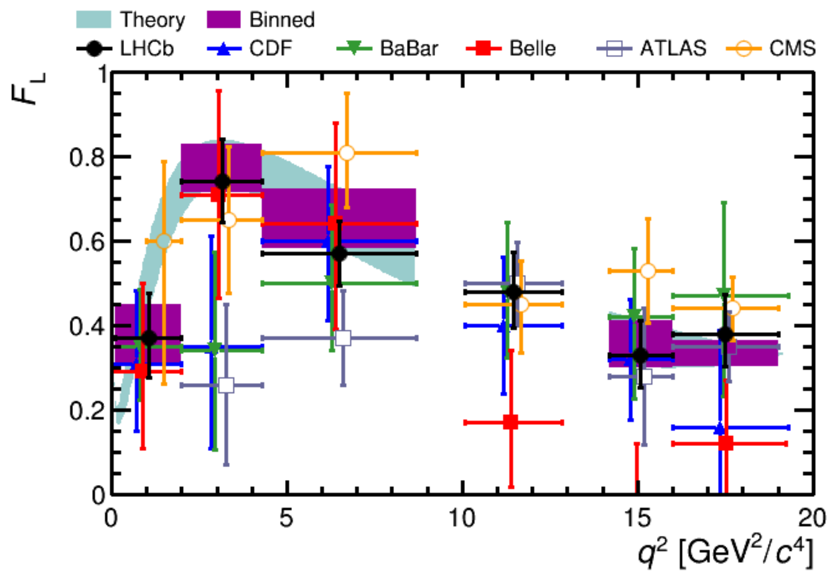
$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

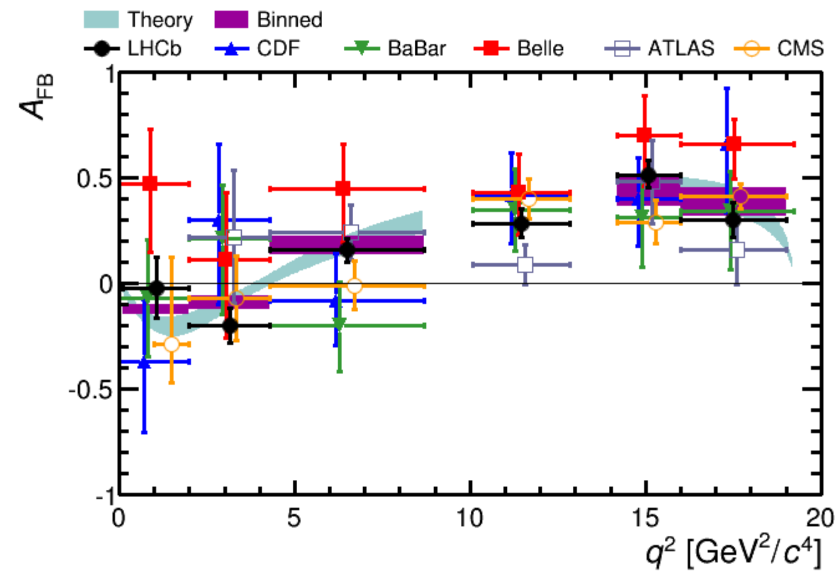
Order of magnitude improvement every ~ 5 years

Next:
- Search for $B^0 \to \mu^+\mu^-$ and measure $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
- Measure effective lifetime for $B_s^0 \to \mu^+\mu^-$
- Search for other leptonic decays (e.g. $B_s^0 \to \tau^+\tau^-$)

Angular analyses of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

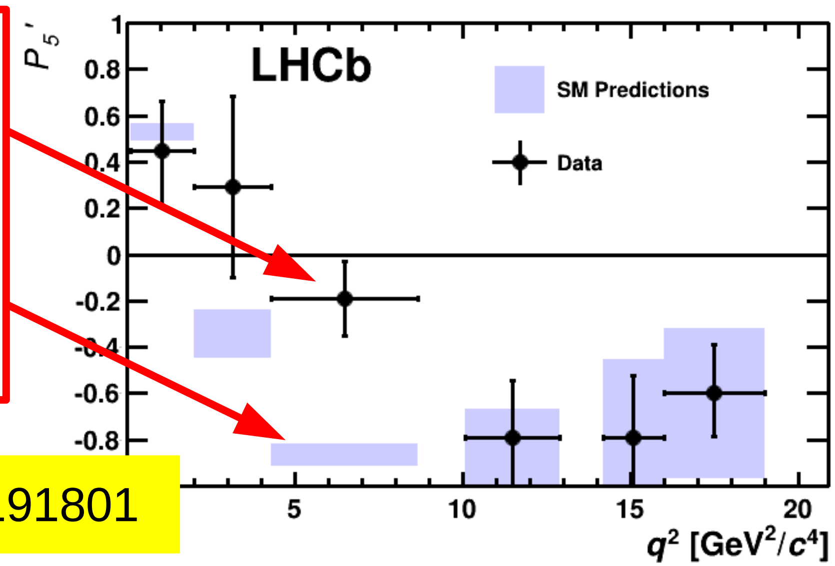
LHCb JHEP 08 (2013) 131, CDF PRL 108 (2012) 081807, BaBar PR D86 (2012) 032012
Belle PRL 103 (2009) 171801, ATLAS-CONF-2013-038, CMS PL B727 (2013) 77





Good agreement with SM in most, but not all, observables.
Improved measurements needed.

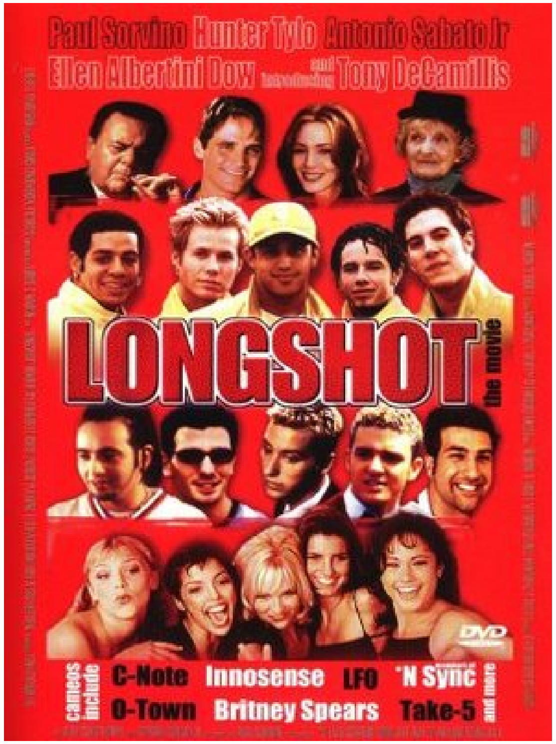
Reduced QCD uncertainties, but by how much? More theory work needed.



PRL 111 (2013) 191801

Tim Gershon
Experimental outlook

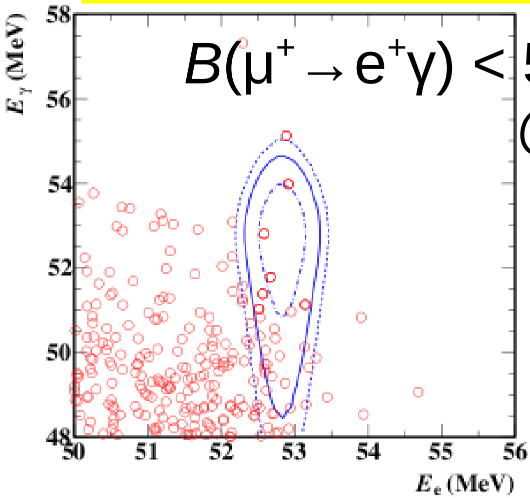
The lepton sector

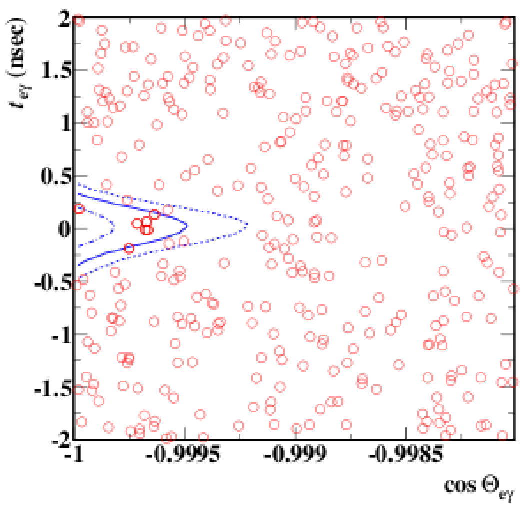


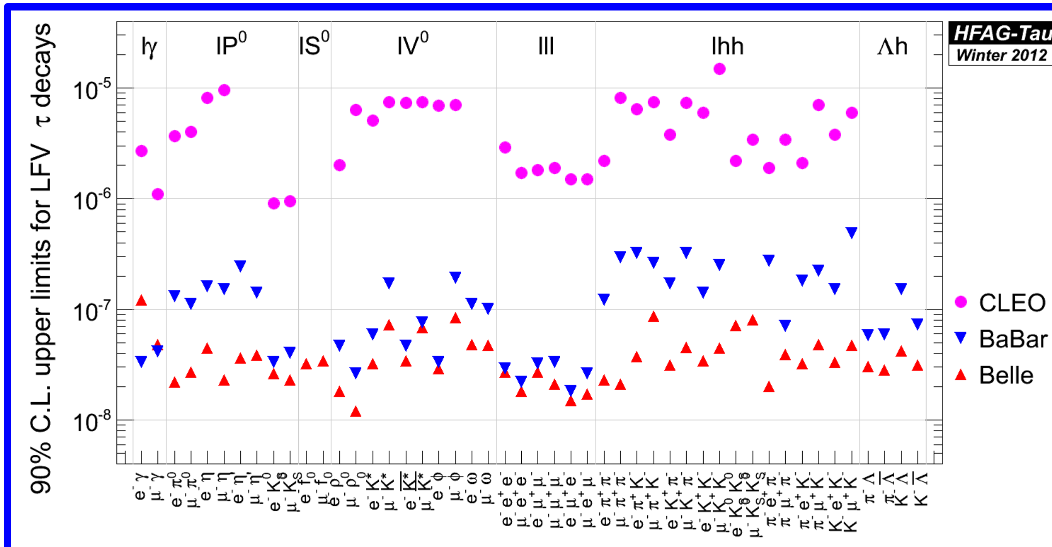
Charged lepton flavour violation

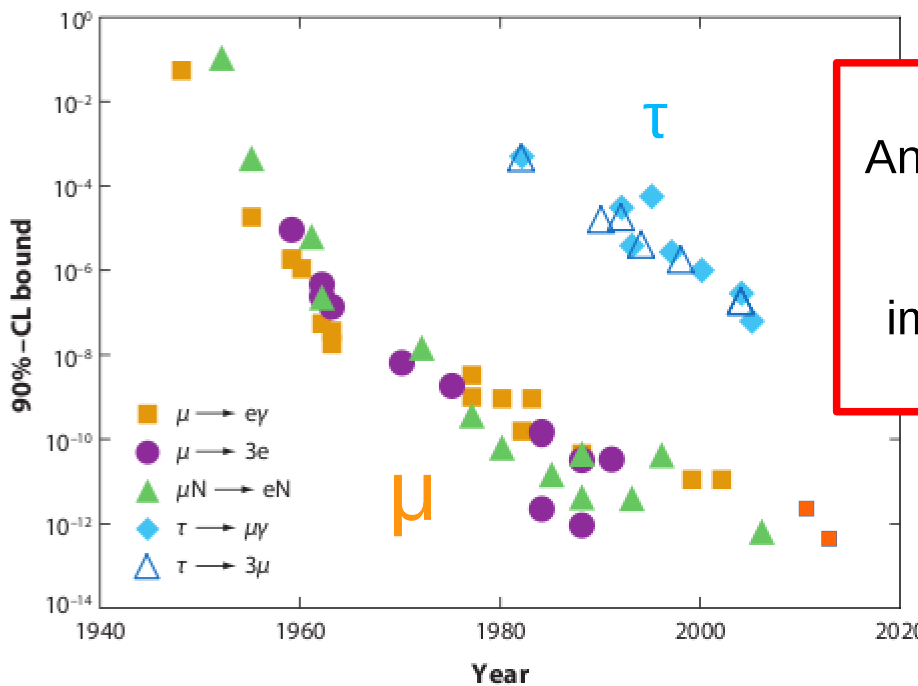
MEG PRL 110 (2013) 201801

$B(\mu^+ \to e^+\gamma) < 5.7\ 10^{-13}$ @ 90% CL









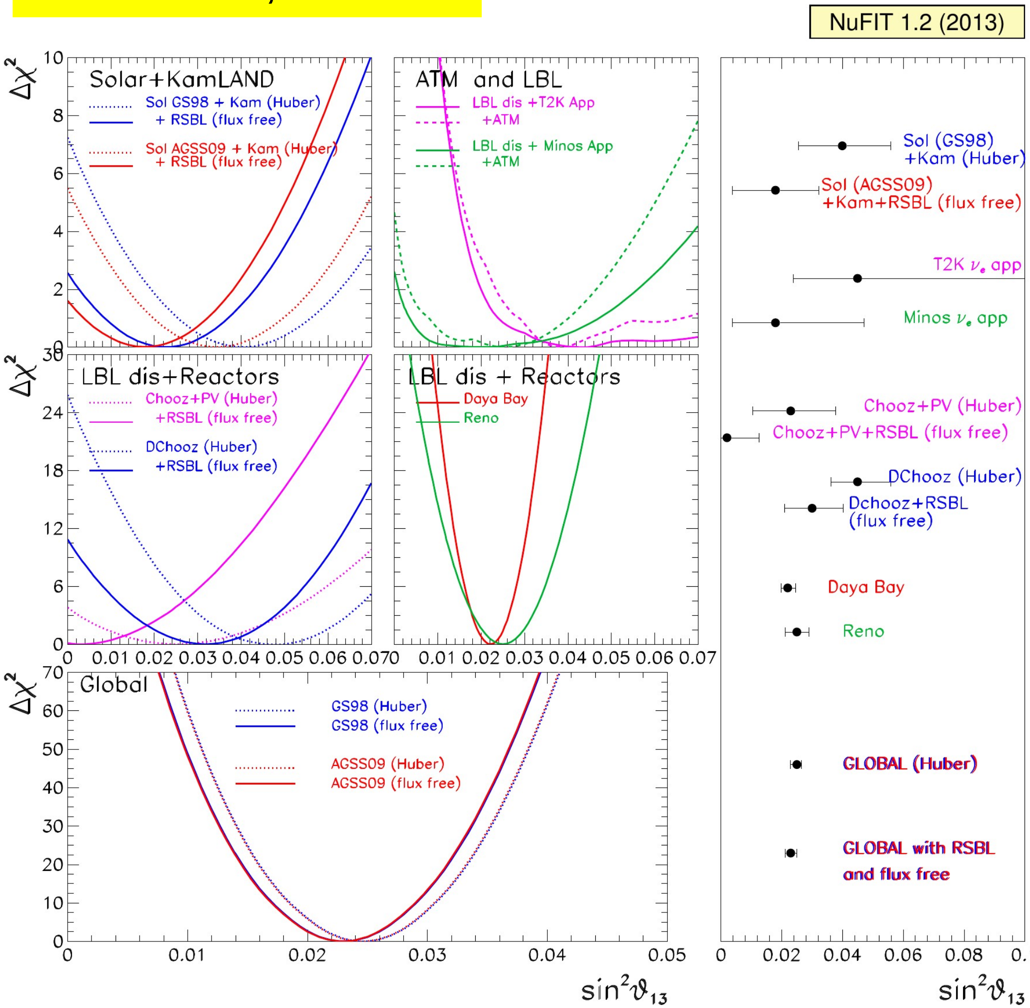
Modified from
Ann. Rev. 58 (2008) 315

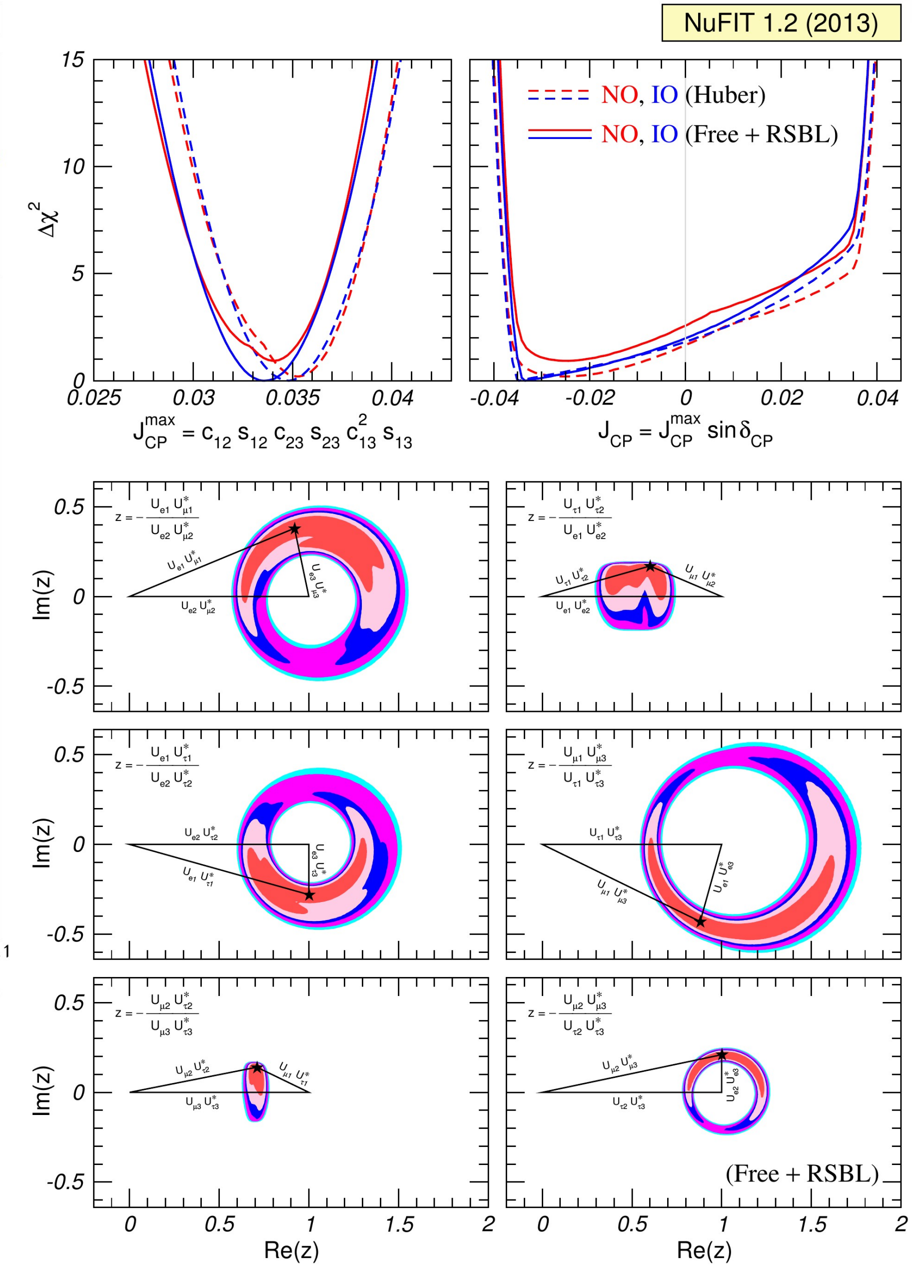
Order of magnitude improvement every ~8 years

Other fitting groups are available

Data from Daya Bay, RENO, T2K, MINOS, Double Chooz, etc.

Neutrino oscillations

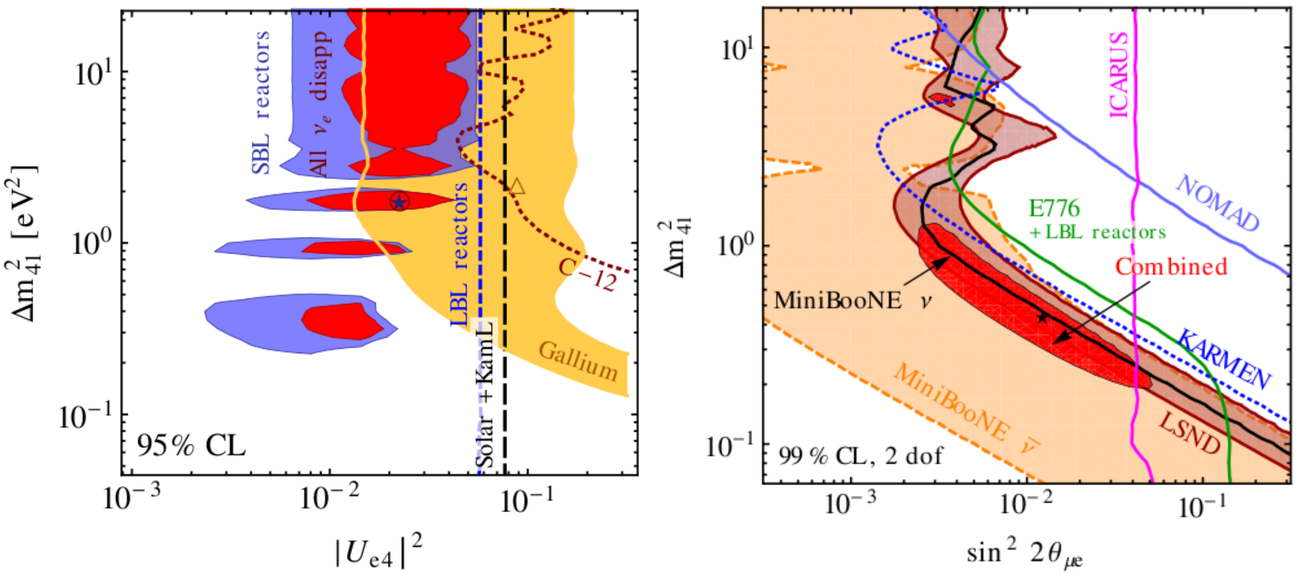




Exciting prospects for CP violation …
but watch out for non-Gaussian errors

Are there sterile neutrinos?

Hints from LSND, MiniBooNE, Gallium & SBL reactor expts.



No sign of excess in same sign leptons for ν mass of O(1 GeV) at LHCb or O(100 GeV) at ATLAS/CMS

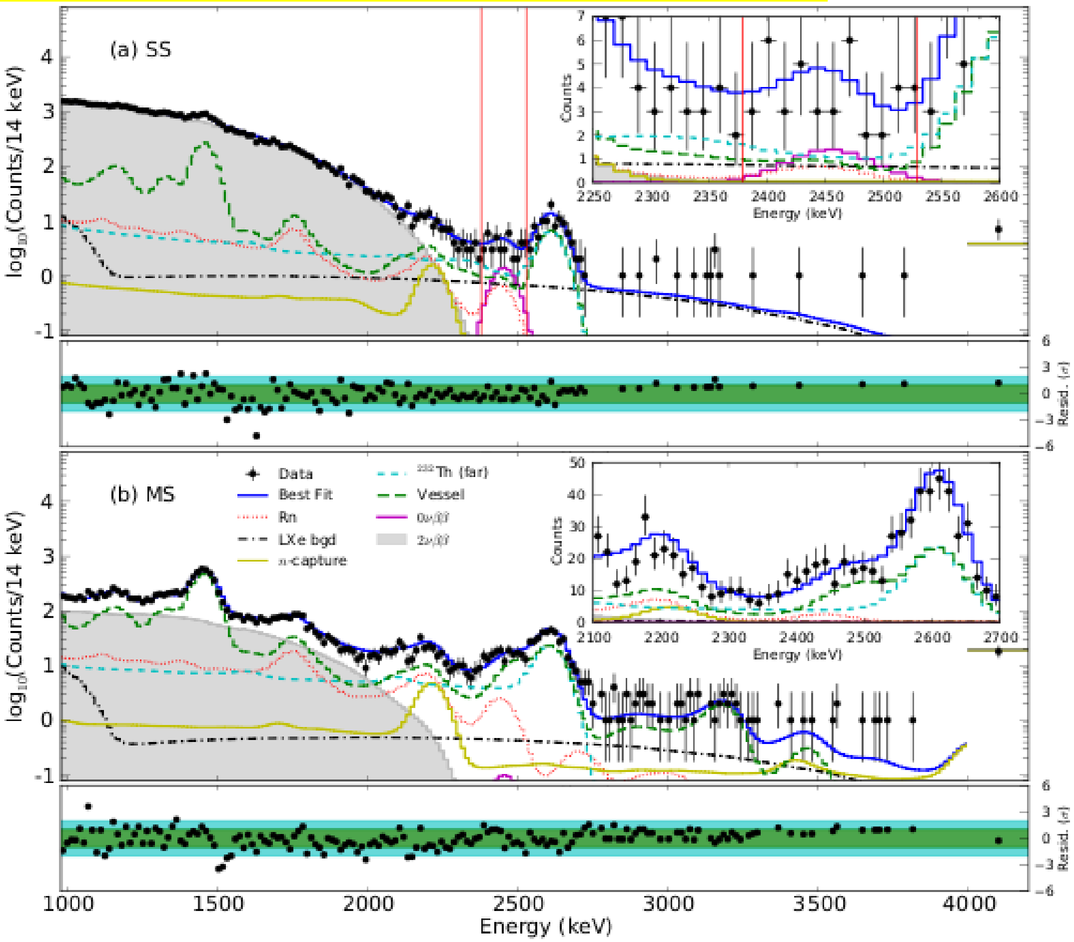
However: • sterile neutrino models fail to explain satisfactorily **all** the experimental data:

Requirement	(3+0)	(2+2)	(3+1)	(3+2)	(1+3+1)
Ordinary neutrino oscillation data	OK	NO	OK	OK	OK
$\bar{\nu}_e \to \bar{\nu}_e$: SBL reactor & gallium data	NO	OK	OK	OK	OK
$\bar{\nu}_\mu \to \bar{\nu}_e$: LSND & MB $\bar{\nu}$ data	NO	OK	OK	OK	OK
$\nu_\mu \to \nu_e$: MB high-energy ν data	OK	POOR	POOR	OK	OK
$\bar{\nu}_\mu \to \bar{\nu}_e$: MB low-energy excess	NO	POOR	POOR	OK	OK
$\bar{\nu}_\mu \to \bar{\nu}_\mu$: disappearance data	OK	OK	NO	NO	NO
Constraints from cosmology	OK	NO	OK	NO	NO

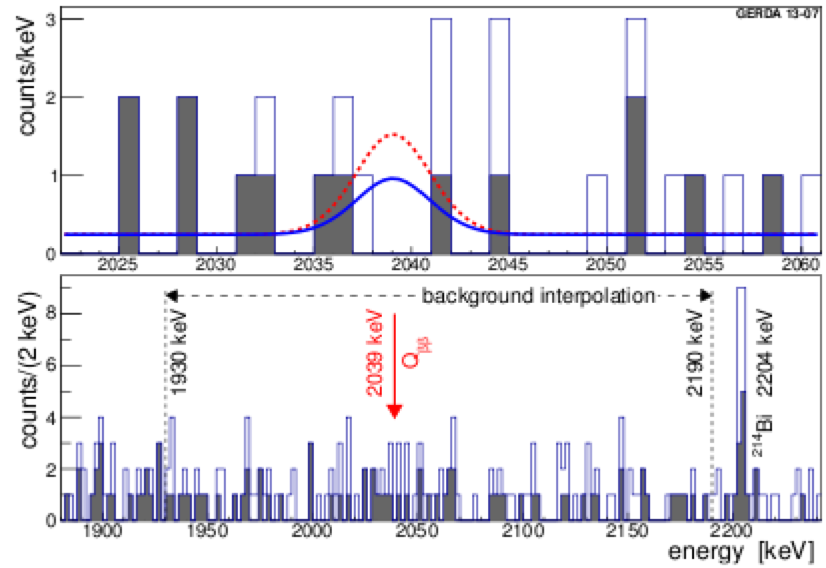
M. Maltoni @ Moriond EW
JHEP 05 (2013) 050

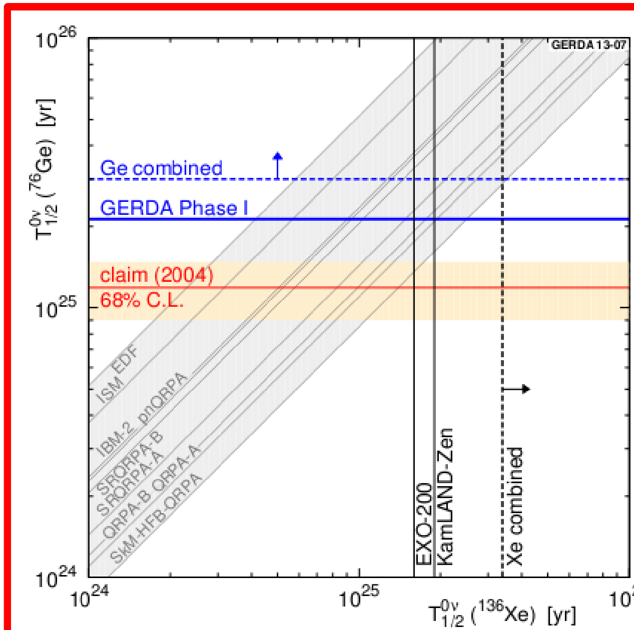
Are neutrinos Majorana?

EXO-200 arXiv:1402.6956
See also KAMLAND-Zen PRL 110 (2013) 062502



GERDA PRL 111 (2013) 122503



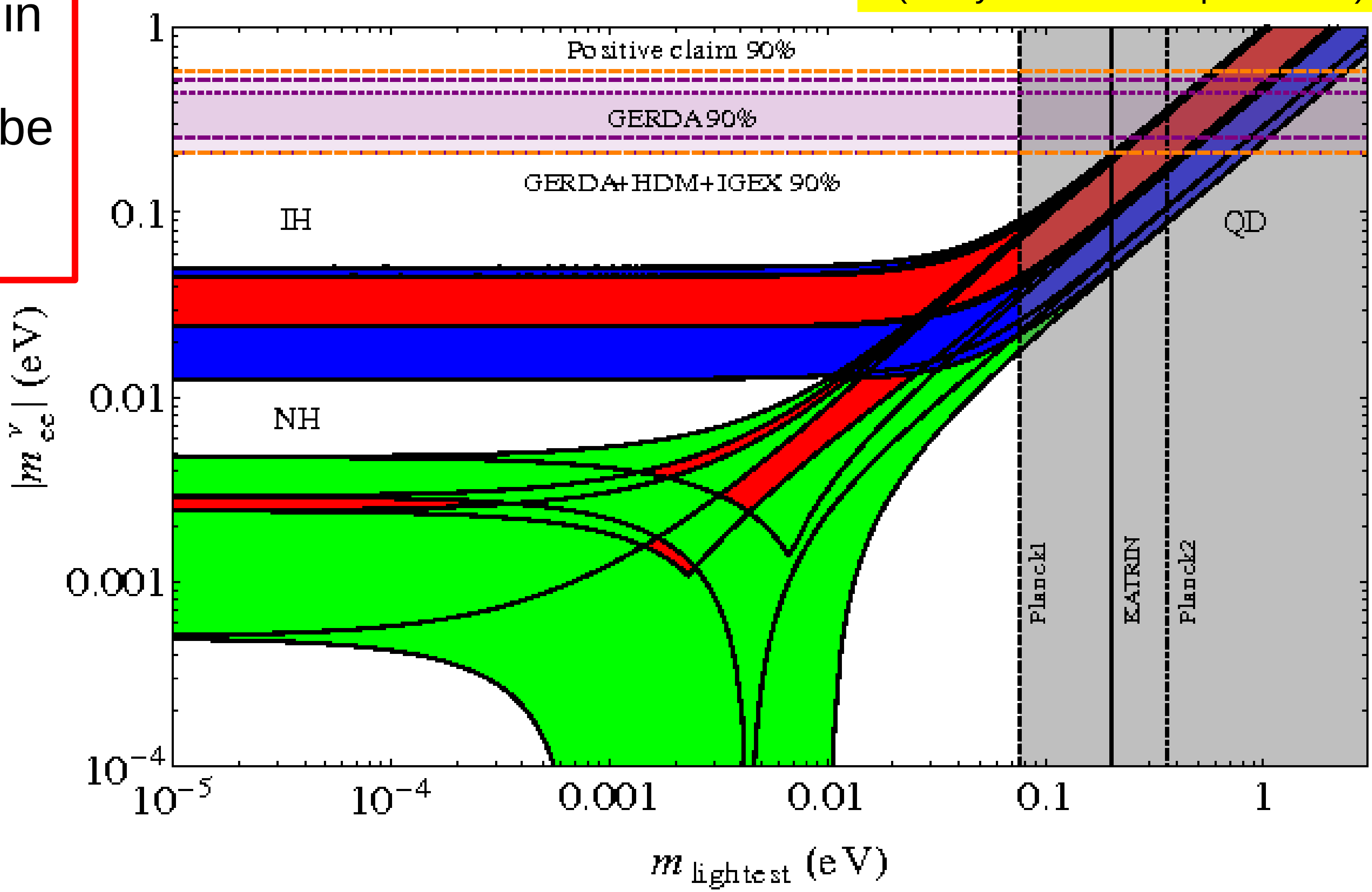


No strong evidence as yet
… but new results appearing
and new experiments coming

Are neutrinos Majorana?

One more order of magnitude in sensitivity needed to probe inverted hierarchy

From arXiv:1310.6218
(Many other similar plots exist)



Further improvements from "direct" mass measurements and cosmology also expected

Future experiments

Upgrade LHCb

NA62

LBNF
LONG-BASELINE NEUTRINO EXPERIMENT AT SANFORD UNDERGROUND LABORATORY

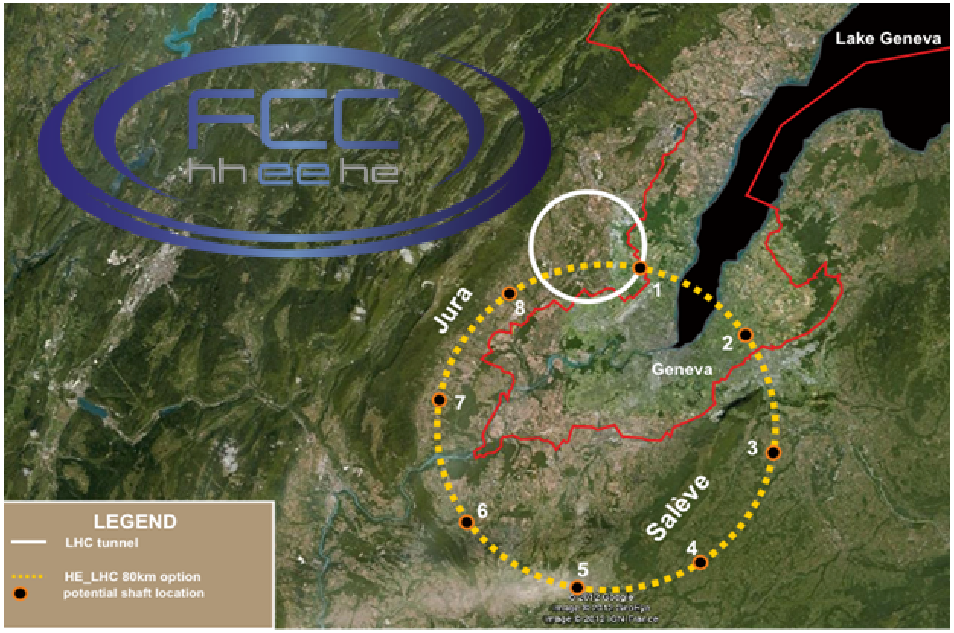
KOTO

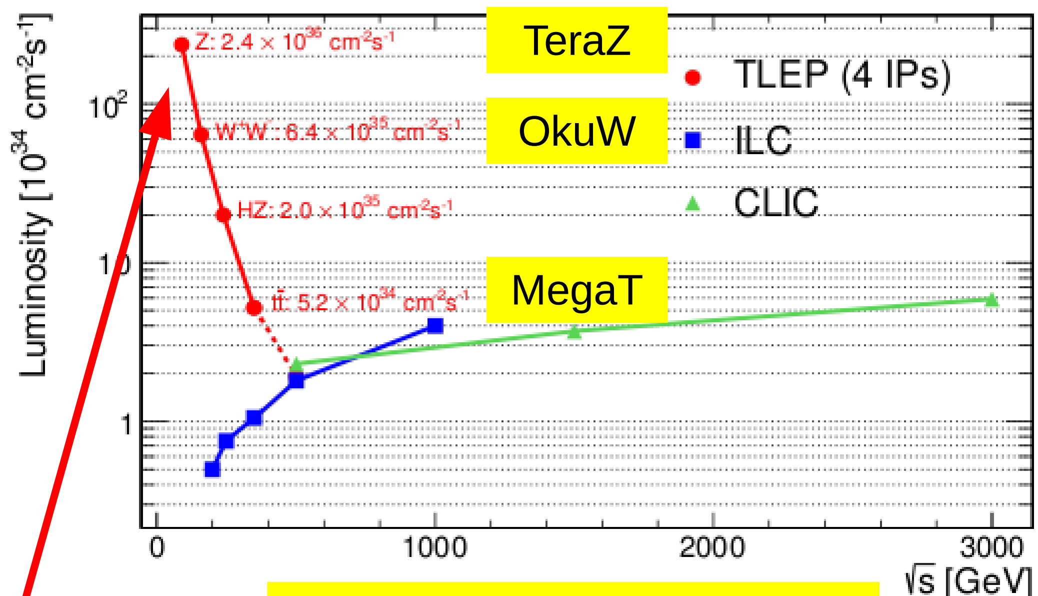
Mu2e

Belle II

… plus many others discussed at this conference, and some that weren't

Future circular colliders





JHEP 01 (2014) 164

- Future circular collider (FCC) study ongoing at CERN
  - pp, ee, ep & heavy ion options
  - e^+e^- esp. interesting for flavour physics
- Similar studies elsewhere globally (e.g. China)

TeraZ gives $O(10^{12})$ Z events in 1 year
$B(Z \to b\bar{b}, c\bar{c}, \tau\tau)$ ~ 15, 12, 3%

Need thought about what can be done with these samples:
e.g. <10% precision on $B(B_s \to \tau\tau)$

(Obviously good prospects for top physics at these facilities)

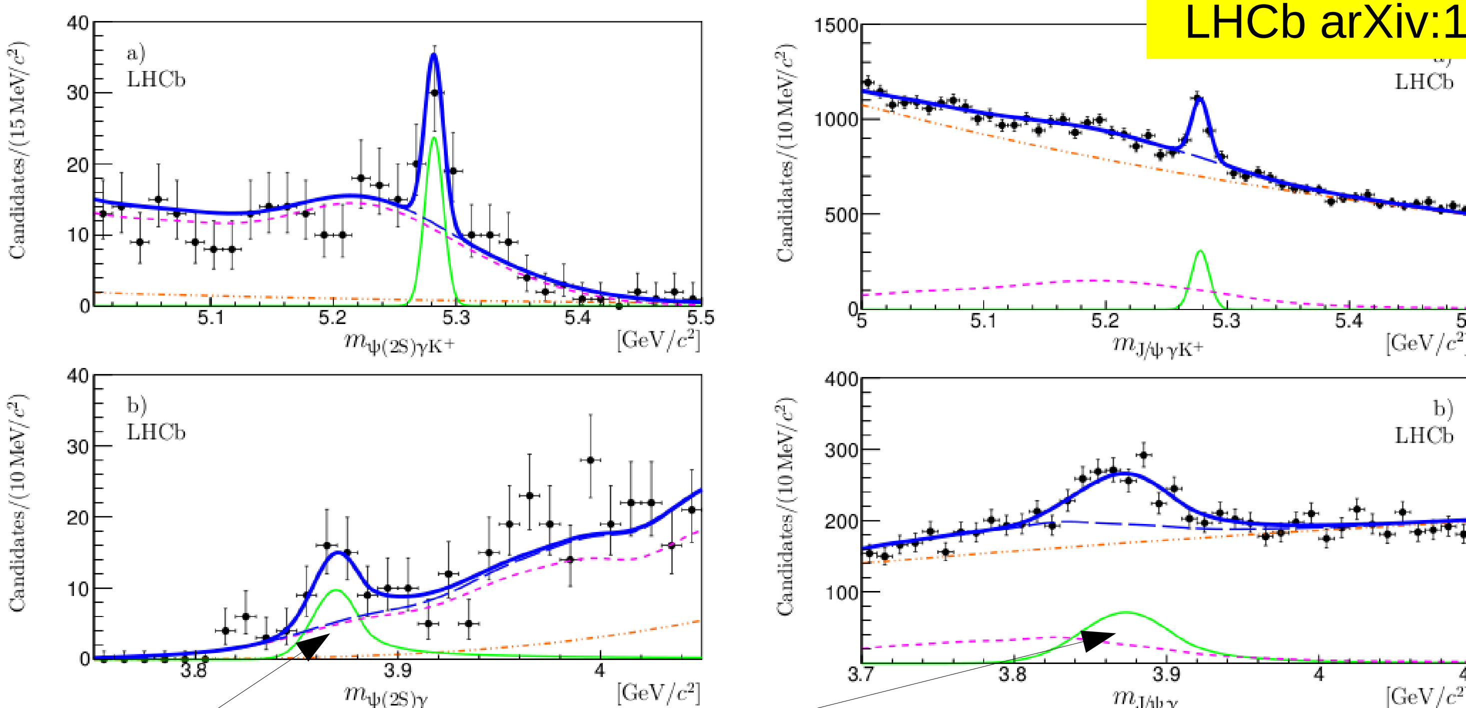
Conclusion

- (Flavour physics and) CP violation studies just getting started …
- Exciting prospects for progress in short-, mid- and long-term
  - LHC(b), NA62, K0T0
  - Belle2 + LHC(b) upgrades
  - g–2, MEGIII, μ2e, COMET, …
  - LBNE, Hyper-K, PINGU, 0ν2β, ...


BACKUP

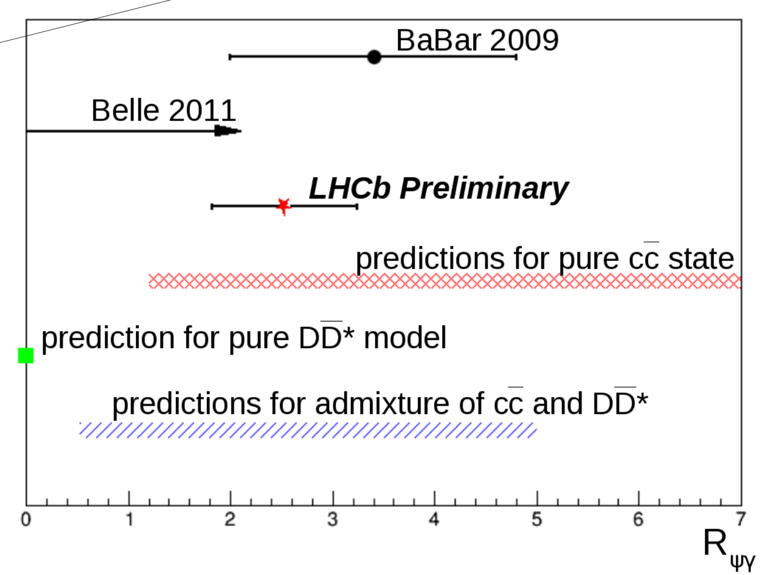
X(3872) is not a pure DD* molecule

LHCb arXiv:1404.0275



Ratio of branching fractions of ψ(2S)γ and J/ψγ decays (both seen in B → X(3872)K)

Where is the orthogonal partner?



The holy grail of kaon physics: $K \to \pi\nu\nu$

Highest CKM suppression of the $s \to d$ coupling:

$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$

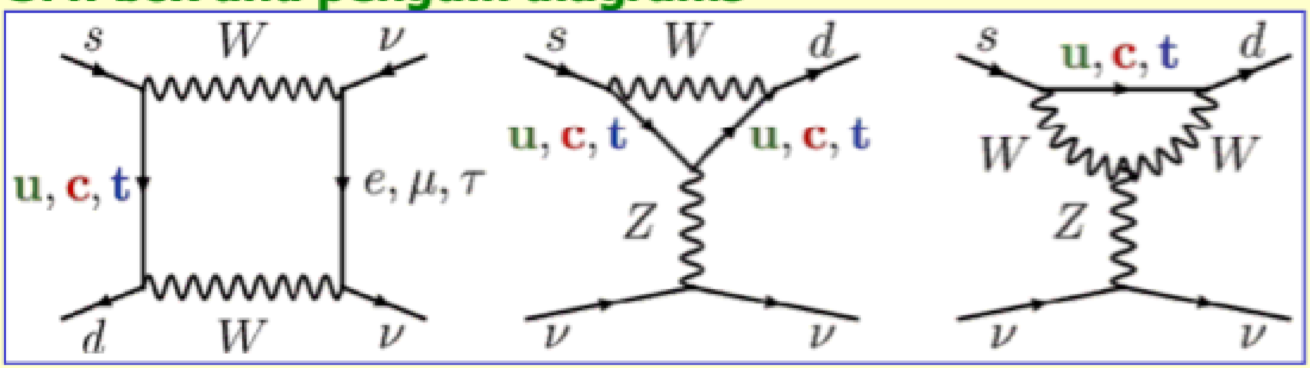
SM branching ratios

(Brod, Gorbahn, Stamou; PRD83 (2011) 034030)

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \to \pi^0 \nu\bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

CKM parametric (mainly $|V_{ts}|$) — Intrinsic

SM: box and penguin diagrams



Next generation experiments should measure these decays for the 1st time

- $K^+ \to \pi^+\nu\nu$ (NA62, CERN + ORKA, FNAL)
- $K^0 \to \pi^0\nu\nu$ (K0T0, J-PARC)

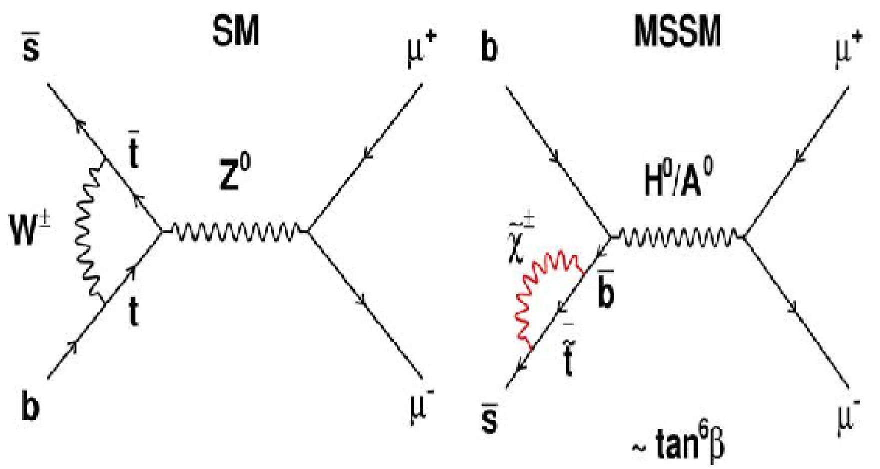
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

Very rare in Standard Model due to

- absence of tree-level FCNC
- helicity suppression
- CKM suppression

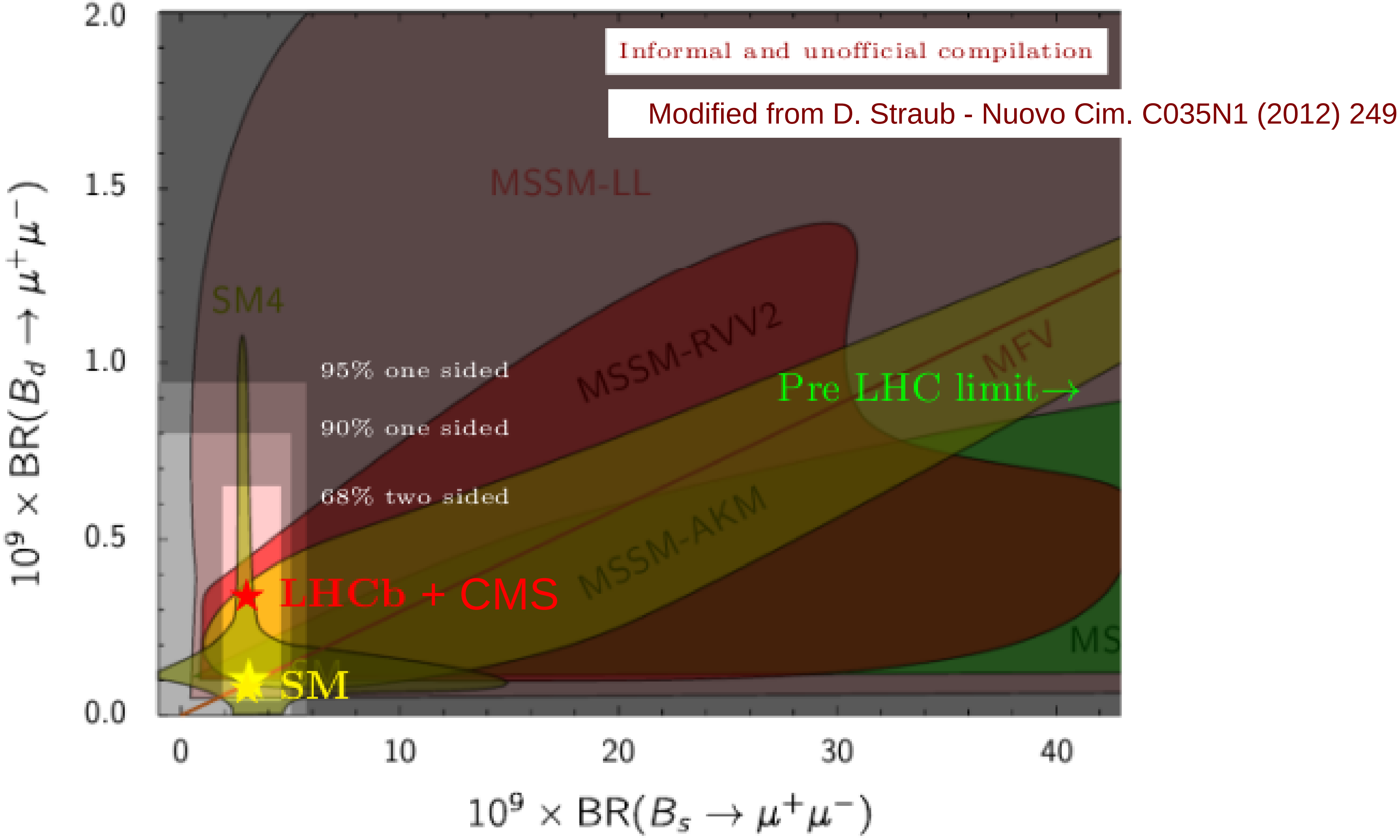
… all features which are not necessarily reproduced in extended models



$$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.2 \pm 0.3) \times 10^{-9} \qquad \mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta/M^4_{A0}$$

Buras et al, EPJ C72 (2012) 2172
N.B. Should be corrected up by 9% since measurement is of the time-integrated branching fraction (PRL 109 (2012) 041801)

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



New observables in $B^0 \to K^{*0}\mu^+\mu^-$

LHCb PRL 111 (2013) 191801

Full angular distribution (B^0 and $\bar{B}^0$ averaged):

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

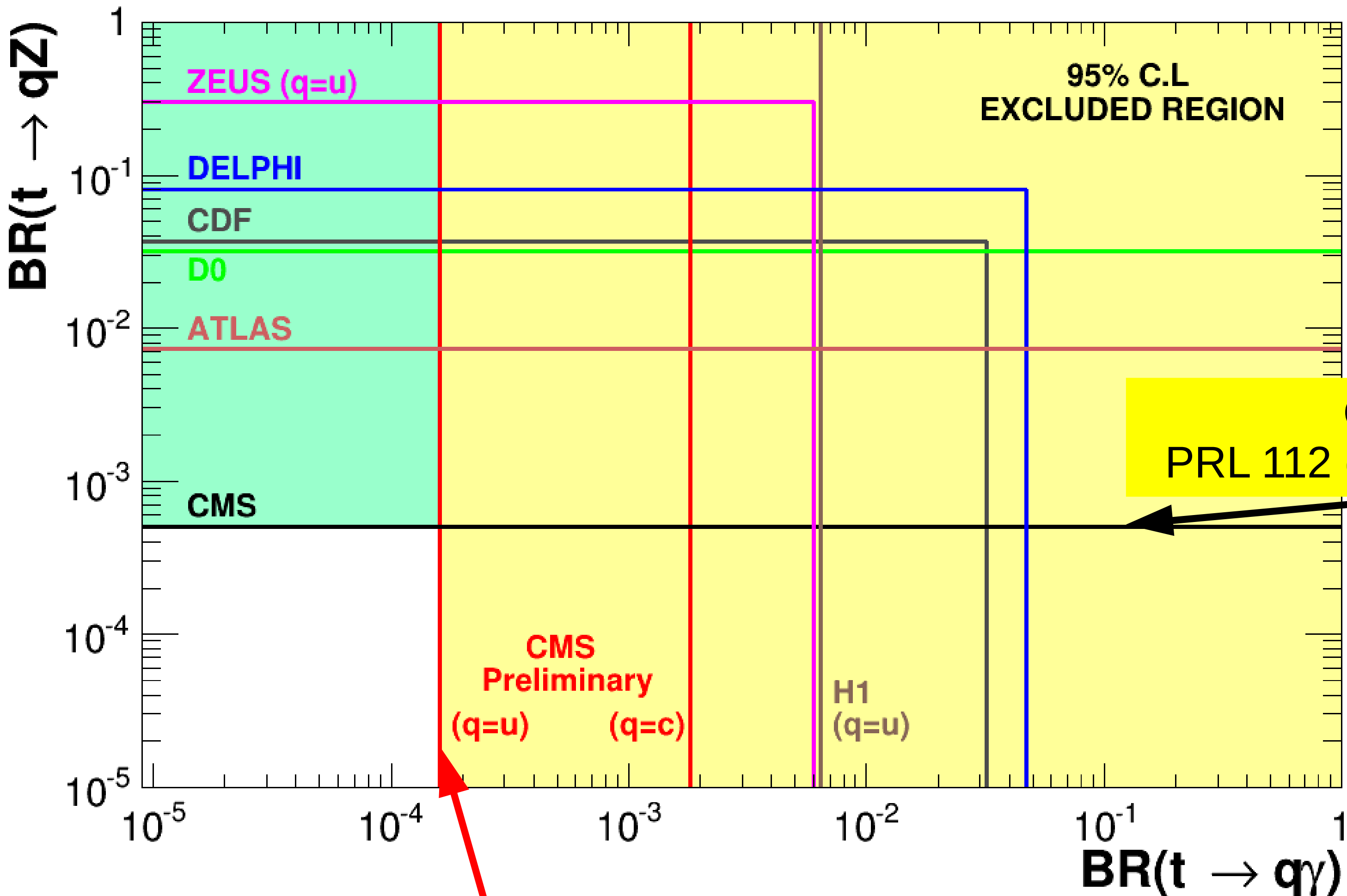
Previously measured by LHCb (JHEP 08 (2013) 131) F_L, S_3, $A_{FB} \sim S_6$, $A_9 \sim S_9$

New analysis measures remaining terms, but in a basis with reduced form-factor uncertainty

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.$$

Key point is that each observable corresponds to a different angular distribution
Therefore each is sensitive to different combinations of operators →
enhanced sensitivity to possible sources of new physics

Top FCNC



CMS
PRL 112 (2014) 171802

CMS-PAS-TOP-14-003

See also ATLAS arXiv:1403.6293
for limit on t → qH (H → γγ)

Future experiments

Upgrade LHCb

NA62

LBNF

LONG-BASELINE NEUTRINO EXPERIMENT AT SANFORD UNDERGROUND LABORATORY

KOTO

Mu2e

Belle II

… plus many others discussed at this conference, and some that weren't