CP violation and rare decays

(of heavy flavour hadrons)

Rencontres de Blois

28th meeting on Particle Physics and Cosmology

Blois, France, 30 May-3 June 2016

T. Nakada

EPFL-IPHYS-LPHE

Lausanne, Switzerland

To start

- My first experience in participating in a conference in this palace was:
  Workshop on CP Violation and Beauty Factories and Related Issues in Physics, Blois, France, 26 Jun-1 Jul 1989,
  organised by D. Cline and A.Fridman,
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  S. Stone (Session summary: CP violation and rare decays)

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  talking about "The B-meson factory project at the Paul Scherrer Institute (PSI)"
- Among the speakers, there was
  S. Stone (Session summary: CP violation and rare decays)
- That was the time dominated by ARGUS vs CLEO
- World of heavy flavour: almost 30 years later,
  - CESR, DORIS-II, LEP, Tevatron, PEP-II, KEKB, HERA-B completed
  - LHC, BESS-II, VEPP-4, VEPP-2000 are in the middle of physics production.
  - SuperKEKB in construction, LHCb upgrade in preparation

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    Glashow-Iliopoulos-Maiani mechanism(1970),
    Value of m_c Lee&Gaillard (1974)
    Charm discovery Aubert et al., Augustin et al., 1974 (Niu et al. 1971?)
  - CP violation: J.H. Christenson et al. (1964), Br($K^0_L \rightarrow \pi^+\pi^-$) $\neq 0 \Rightarrow$
    Third family introduced by Kobayashi & Maskawa (1973)
    Beauty discovery S. Herb et al. (1977)
  - B^0-$\overline{B}^0$ oscillations (Δm_B): ARGUS (1987) $\Rightarrow$
    $m_t > 50$ GeV/c^2 (NB: UA1 1984 $20 < m_t < 50$ GeV/c^2)
    top discovery by CDF and D0 in 1995 ($m_t = 171.2 \pm 2.1$ GeV/c^2)

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Indirect evidences before the direct discovery!

By the early 90's

- The Standard Model model description of "flavour" through the Cabibbo-Kobayashi-Maskawa mass mixing matrix established well enough (nuclear β decays, kaon decays, charm decays and b decays, in particular with ε_K and Δm_d with little uncertainty from the still unmeasured m_t)

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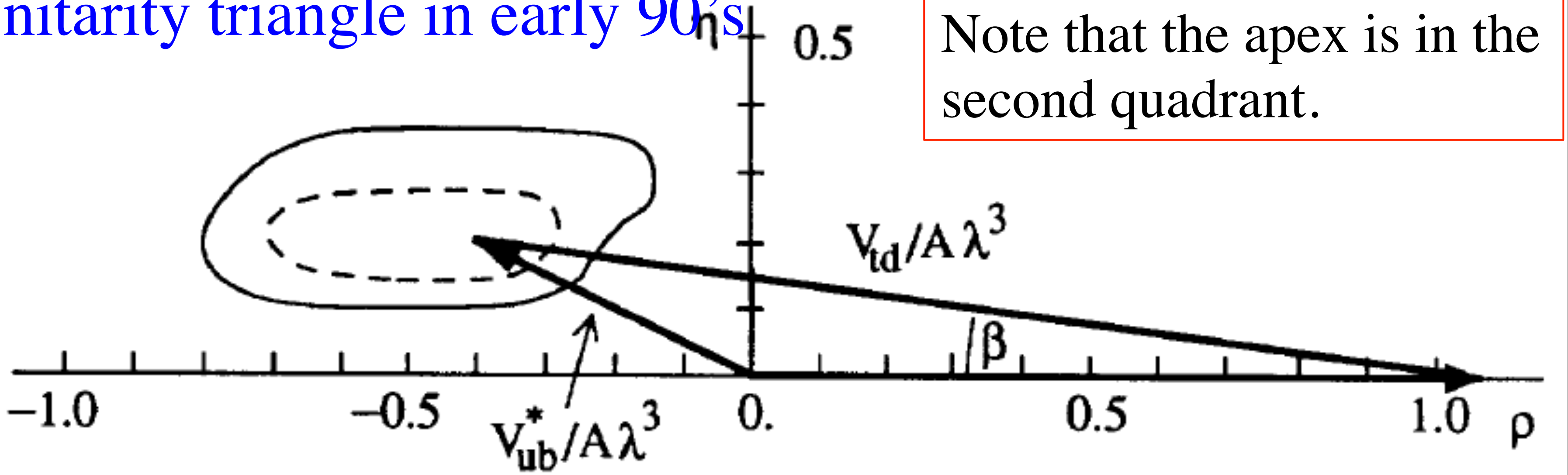
Unitarity triangle in early 90's



Note that the apex is in the second quadrant.

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  – If CPV is generated by the CKM phase, CPV in the $B \to J/\psi K_S$ decays must be observed with >5σ within a few years of running with an asymmetric B factory with a luminosity of ~10^{33}cm^{-2}s^{-1}
- This was the main motivation for asymmetric B factories

Two major events on CPV in 2002

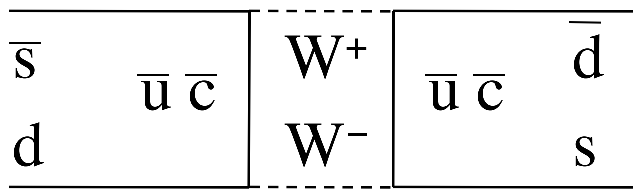
1. Discovery of CP violation in the decay amplitudes, i.e.
   $\mathrm{Re}(\varepsilon'/\varepsilon) \propto |A(\overline{K}^0 \to \pi\pi)| - |A(K^0 \to \pi\pi)| \neq 0$: fixed target
   - Superweak model (Wolfenstein 1964) was finally excluded as a (major) source of CP violation

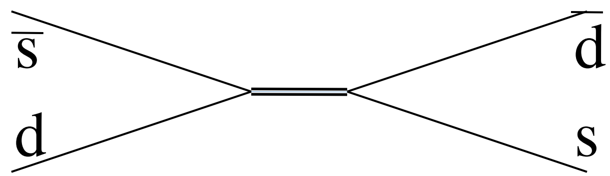
VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

(Received 31 August 1964)

CPV only in $\Delta S = 2$ transitions





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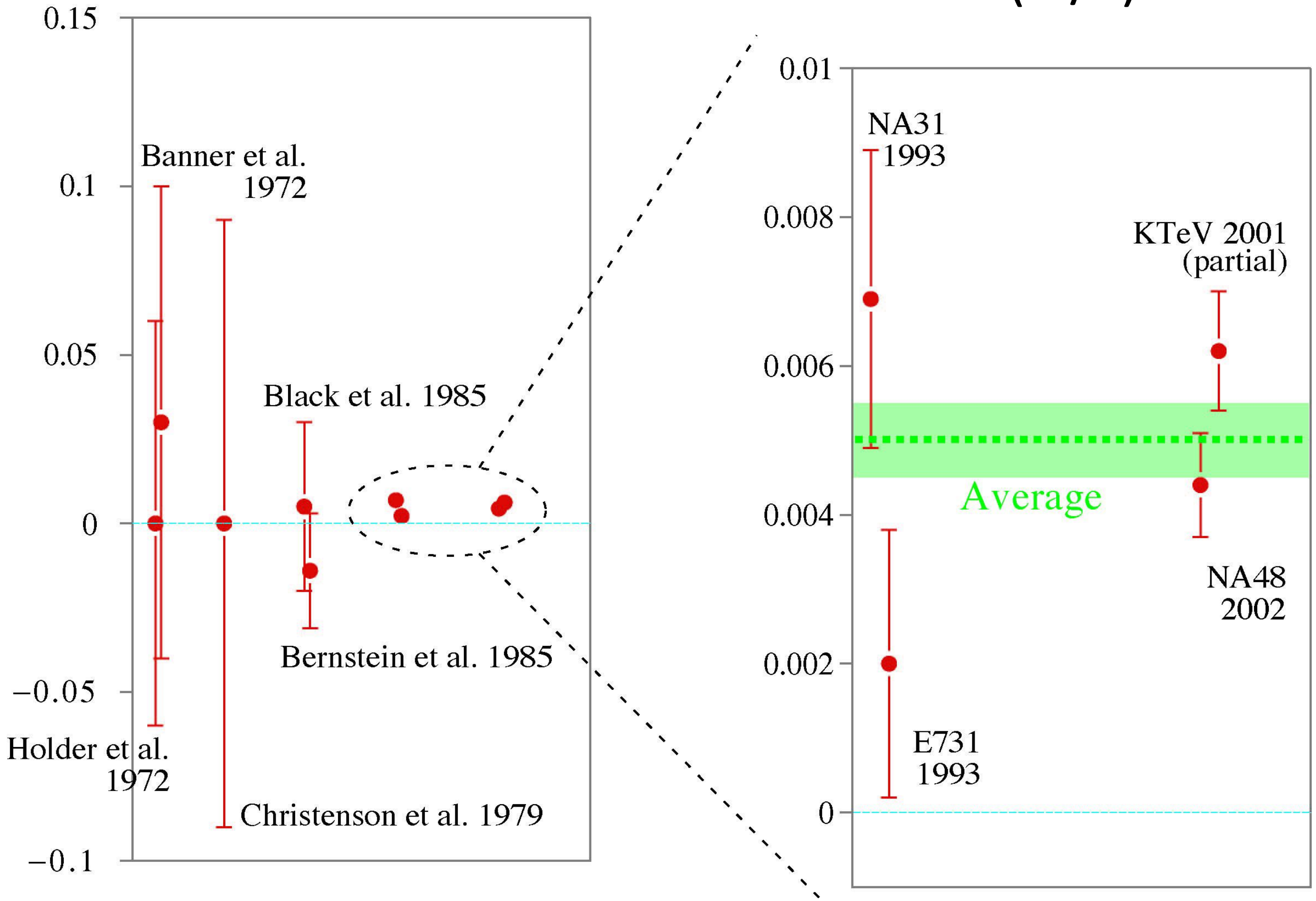
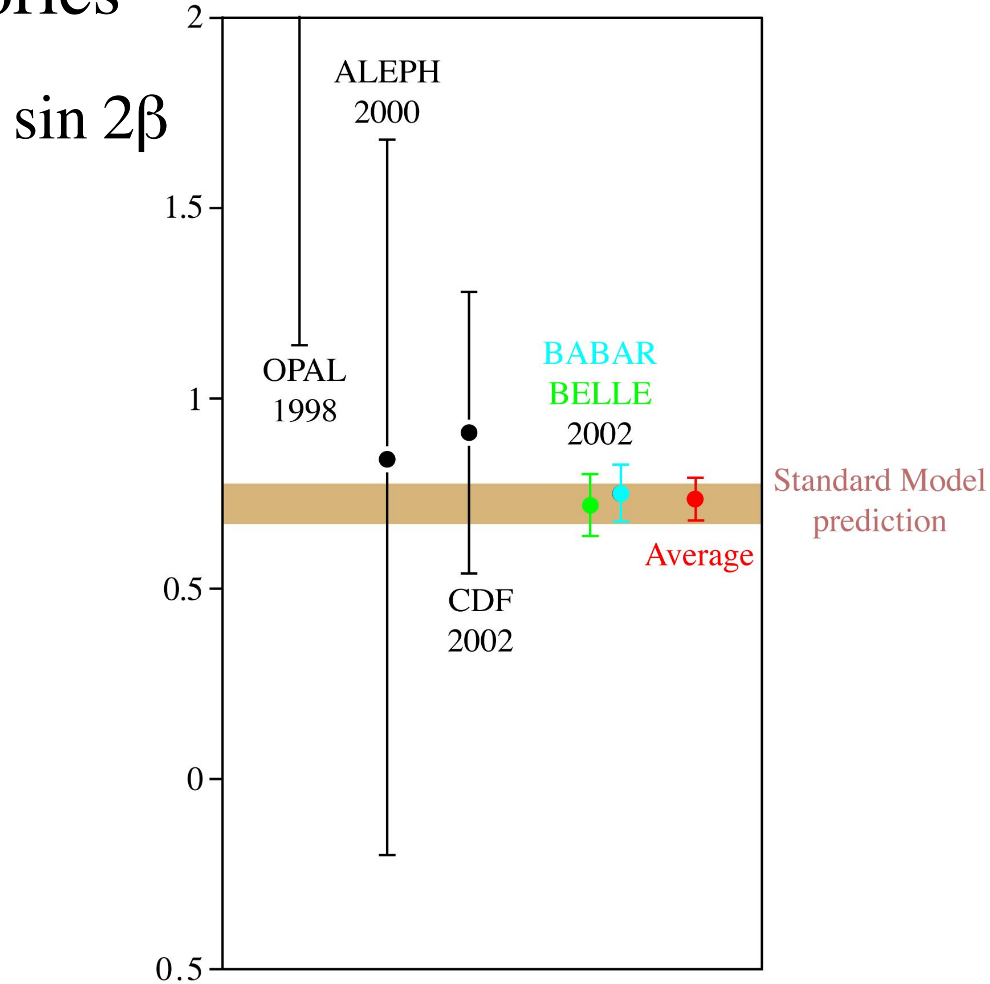
$$1 - |\eta_{00}/\eta_{+-}| = 3Re(\varepsilon'/\varepsilon)$$



Effort over 30 years!

Two major events on CPV in 2002

2. Discovery of CP violation in $B_d \to J/\psi K_S$ decays, i.e.
   $\sin 2\beta \propto N(\overline{B}{}^0_{t=0} \to J/\psi K_S \text{ at } t) - N(B^0_{t=0} \to J/\psi K_S \text{ at } t) \neq 0$
   two e^+e^- B factories



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   two e^+e^- B factories
   – First concrete indication that the Standard Model appears to be the (major) source of CP violation

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Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

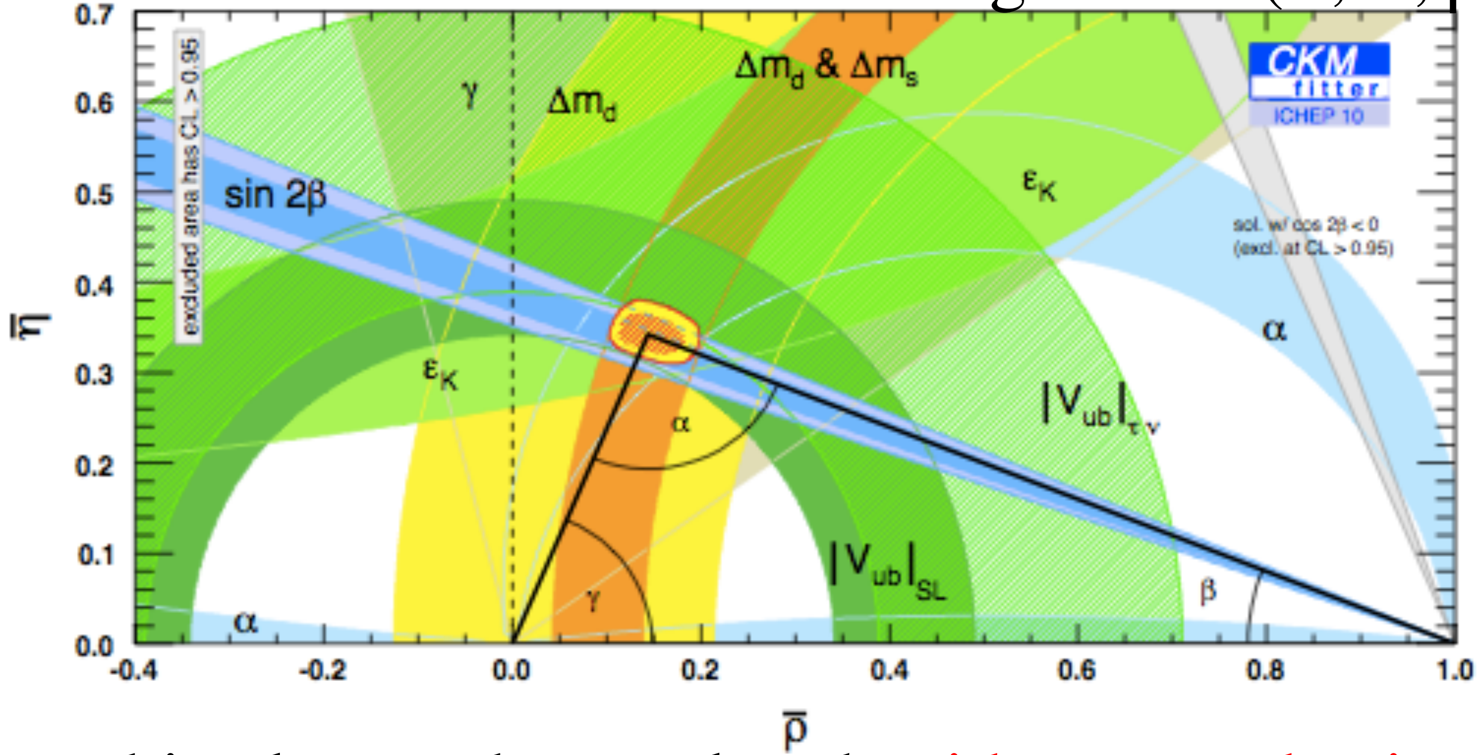
In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Since then till the LHC start up

- BABAR and Belle, with high statistics B_u and B_d sample, successfully demonstrated that the quark flavour can be quantitatively well described by the CKM mechanism of the Standard Model, including CP violation. Their analysis went well beyond the original expectations, e.g. angle γ (ϕ_3) measurement.
- CDF and D0 have started to explore the B_s meson system: e.g. discovery of $\overline{B}_s$-B_s oscillations:
- However, CP violation in the B_s system remained as a largely unexplored territory, as well as very rare decays, e.g. $B_{s,d} \rightarrow \mu^+\mu^-$, and high statistic decay topology studies of rare decays, e.g. $B_d \rightarrow K^{*0}\mu^+\mu^-$.
- Several evidences were seen for D-$\overline{D}$ oscillations, but statistics were not enough to explore CP violation.

Triumph of the CKM description

- All the flavour changing processes are described by the four parameters of the CKM mass mixing matrix (λ, A, ρ, η)



- From this plot, we know already either new physics energy scale is >> TeV (far beyond LHC) or the flavour structure of new physics is very special.

NB: Parallel session talks relevant to this subject

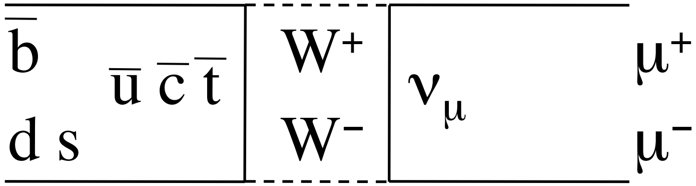
- See for more detailed information and references
  - Rare decays at LHCb
    Eluned Smith (ICL, GB)
  - Recent results on B-meson decays at BaBar and Belle
    Guy Wormser (LAL, FR)
  - Rare Decays of $B^0_{(s)}$ Mesons to Muon Pairs with the ATLAS Detector (Run 1)
    Wolfgang Walkowiak (Siegen, DE)
  - CP violation in B and charm decays at LHCb
    Simon Akar (CPPM, FR)
  - Charm Physics at BESIII
    Peilian Liu (IHEP, CN)
  - Recent heavy flav. Tevatron
    Rick Van Kooten (Indiana, US)
  - Probing new physics with rare kaon decays at CERN SPS
    Venelin Kozhuharov (LNF, IT and Sofia, BG)

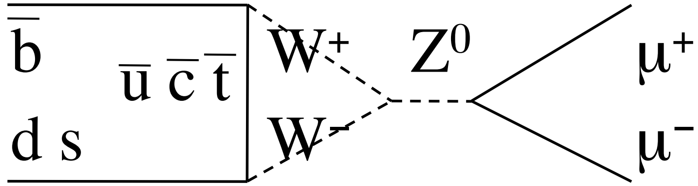
And now: test of the CKM picture

- Confirming the CKM picture ⇒ search for new physics
  - $\Gamma(b\rightarrow u\ell\nu)$, γ… trees: not (much) affected by BSM
  - Δm, CPV($B\rightarrow J/\psi+K_S$ or ϕ), CPV(K-K), $B\rightarrow\mu\mu$… boxes and penguins: can be affected by BSM

Some of the relevant diagrams…

- Box generated rare decays: B_s, $B_d \to \mu^+\mu^-$

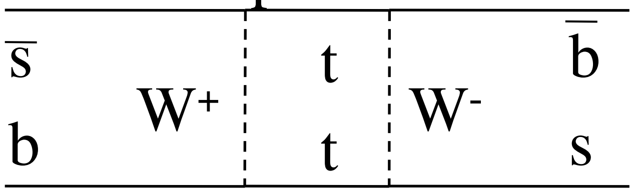




+ new virtual particles?

- CPV in B_s-$\bar{B}_s$ oscillations: $\bar{B}_s \to B_s \neq B_s \to \bar{B}_s$

dispersive



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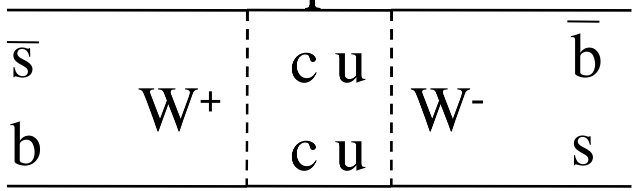

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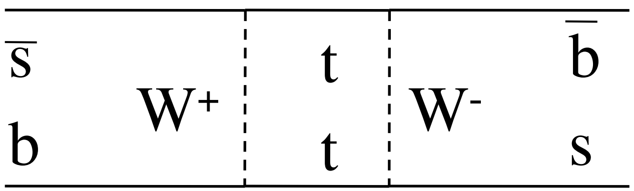
- CPV in oscillations ⊗ decay: $\bar{B}_s \to J/\psi\phi \neq B_s \to J/\psi\phi$



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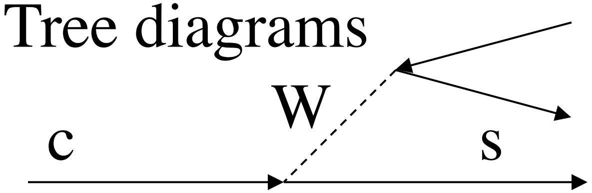
Tree diagrams



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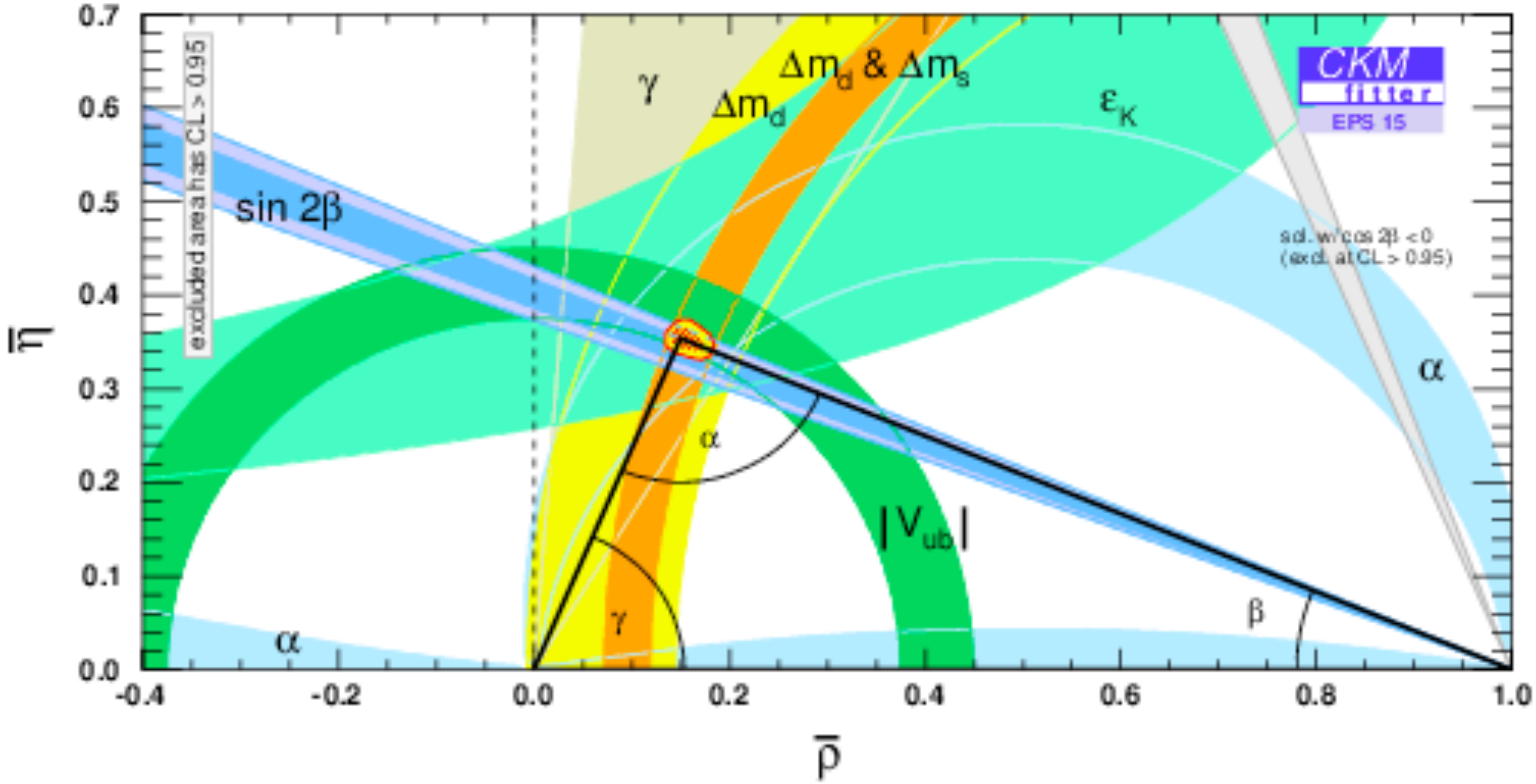

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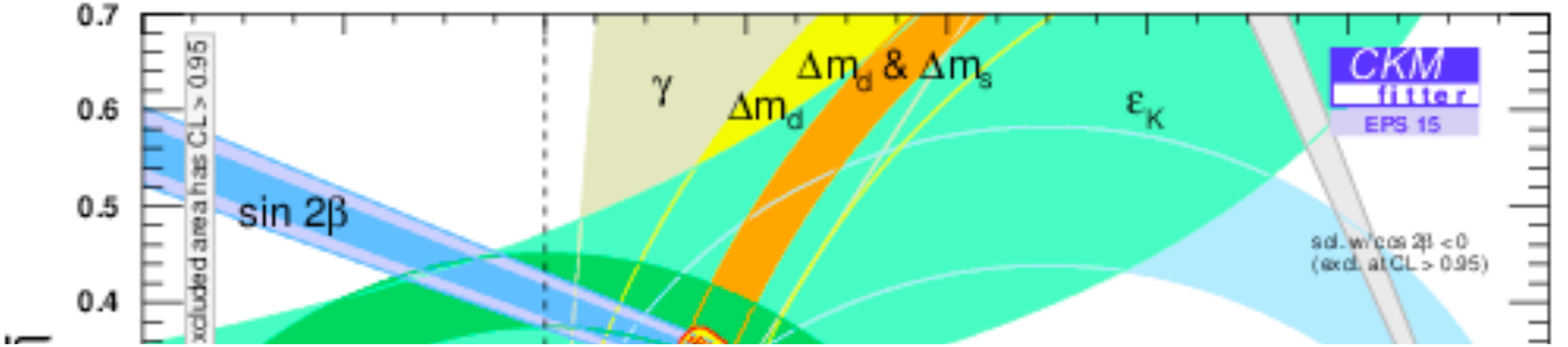
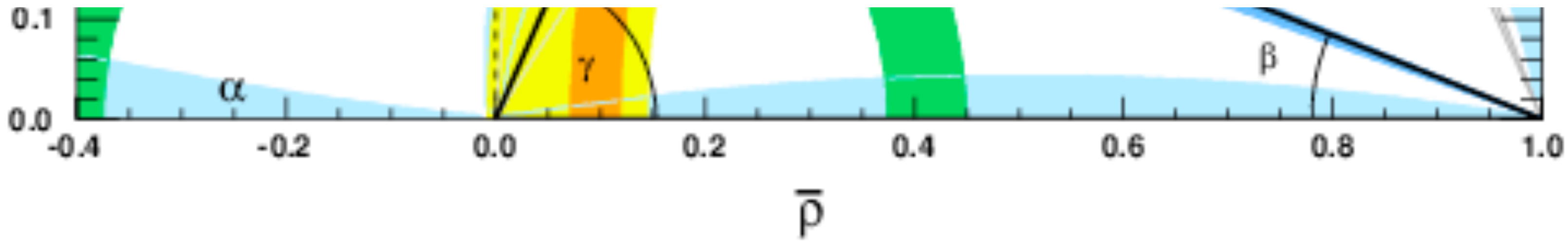


Agreement with the CKM picture is still good!
(flavour problem for new physics)



No real sign of new particles in loops yet!

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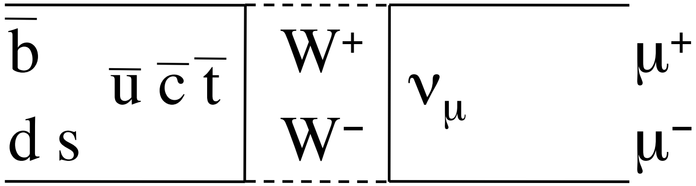

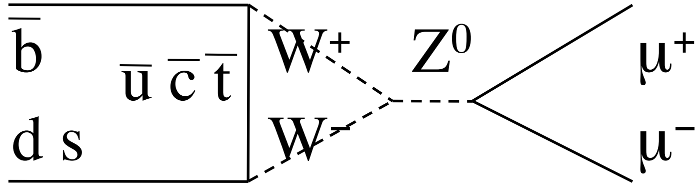

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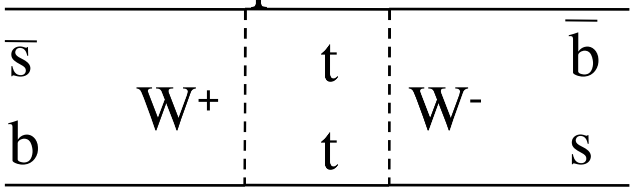

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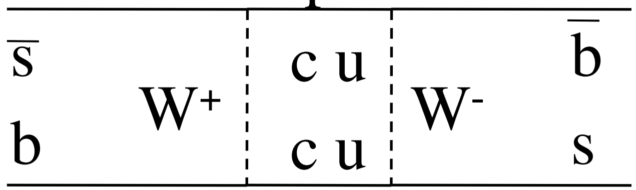

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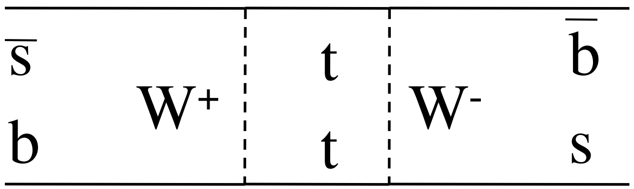

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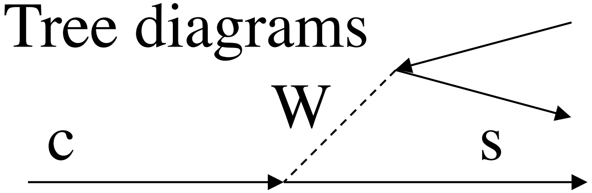

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The CKM picture still works well, but

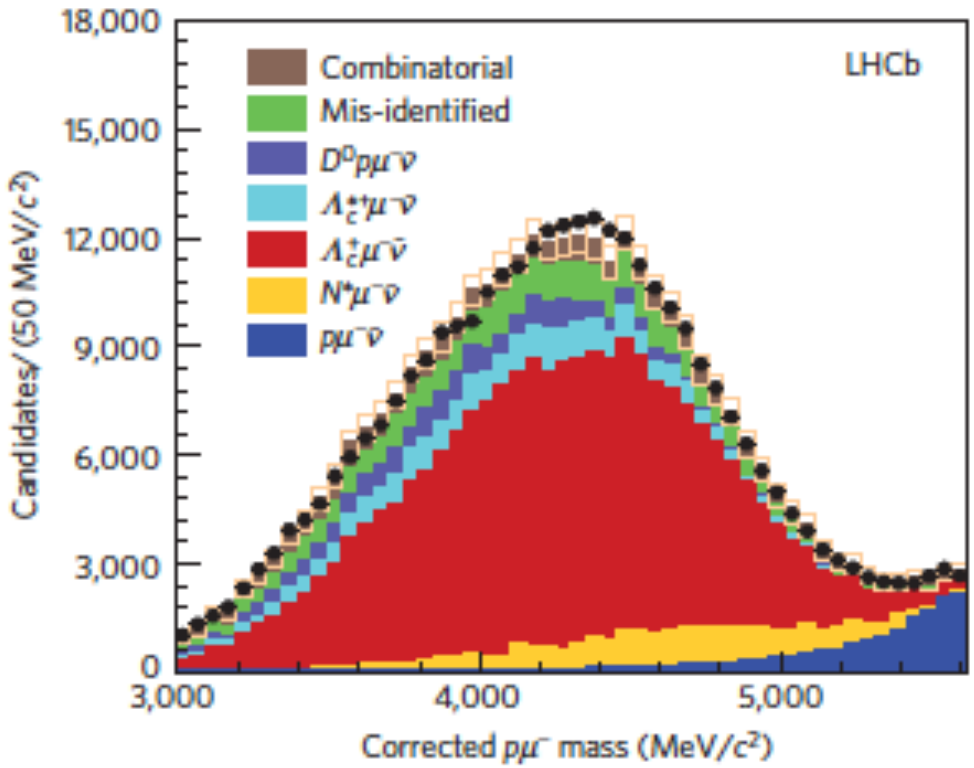
- Improvements are needed for: inclusive versus exclusive measurements of $|V_{ub}|$ (and $|V_{cb}|$)
  Primarily a theoretical issue, but experiments can help by providing more data (precision and extending scope):
  - future Belle II for $B \rightarrow X_u \ell \nu$ decays
  - Exclusive b-baryon decays by LHCb (beyond meson decays) currently, $|V_{ub}|$ extracted from the $\Lambda_b \rightarrow p \ell \nu$ decays agrees with $|V_{ub}|$ extracted from the exclusive B meson decays.

$|V_{ub}|$ exclusive vs inclusive

B inclusive $(4.41 \pm 0.15\ ^{+0.15}_{-0.19}) \times 10^{-3}$
B exclusive $(3.28 \pm 0.29) \times 10^{-3}$
} PDG 2014

Λ_b exclusive $(3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$

Nature Physics 11, 743–747 (2015)



$\Lambda_b \to p\ell\nu$
\+ lattice QCD

compared to B-$\rho l\nu$, $\pi l\nu$
much less background

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- Angle γ measurements need to improve.

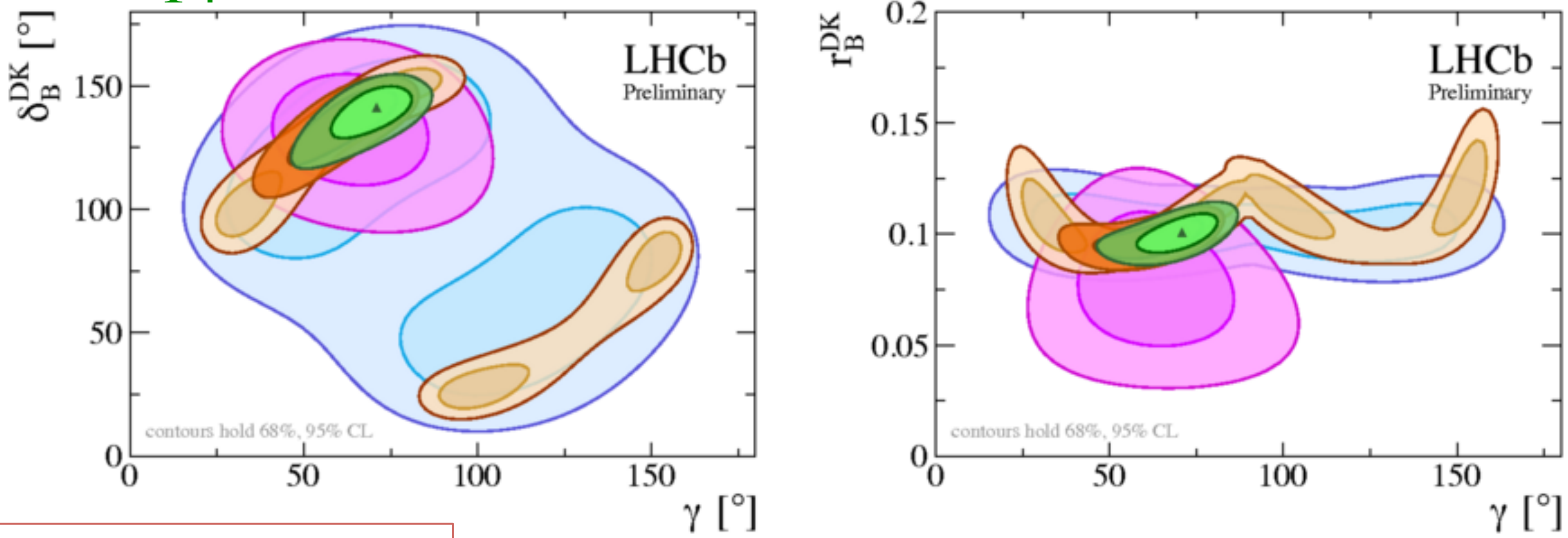
Angle γ (Akar)

- BABAR&BELLE→LHb and future BELLE II&LHCb

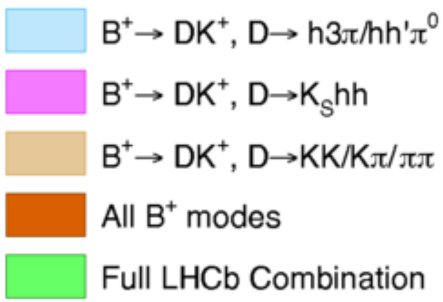
$\gamma = (69^{+17}_{-16})°$ PRD2013

$\phi_3 = (68^{+15}_{-14})°$ CKM2013

$\gamma = (70.9^{+7.1}_{-8.5})°$ LHCb-CONF-2016-001



c.f.
γ from a global fit
$= (66.85^{+0.94}_{-3.44})°$
CKM2015



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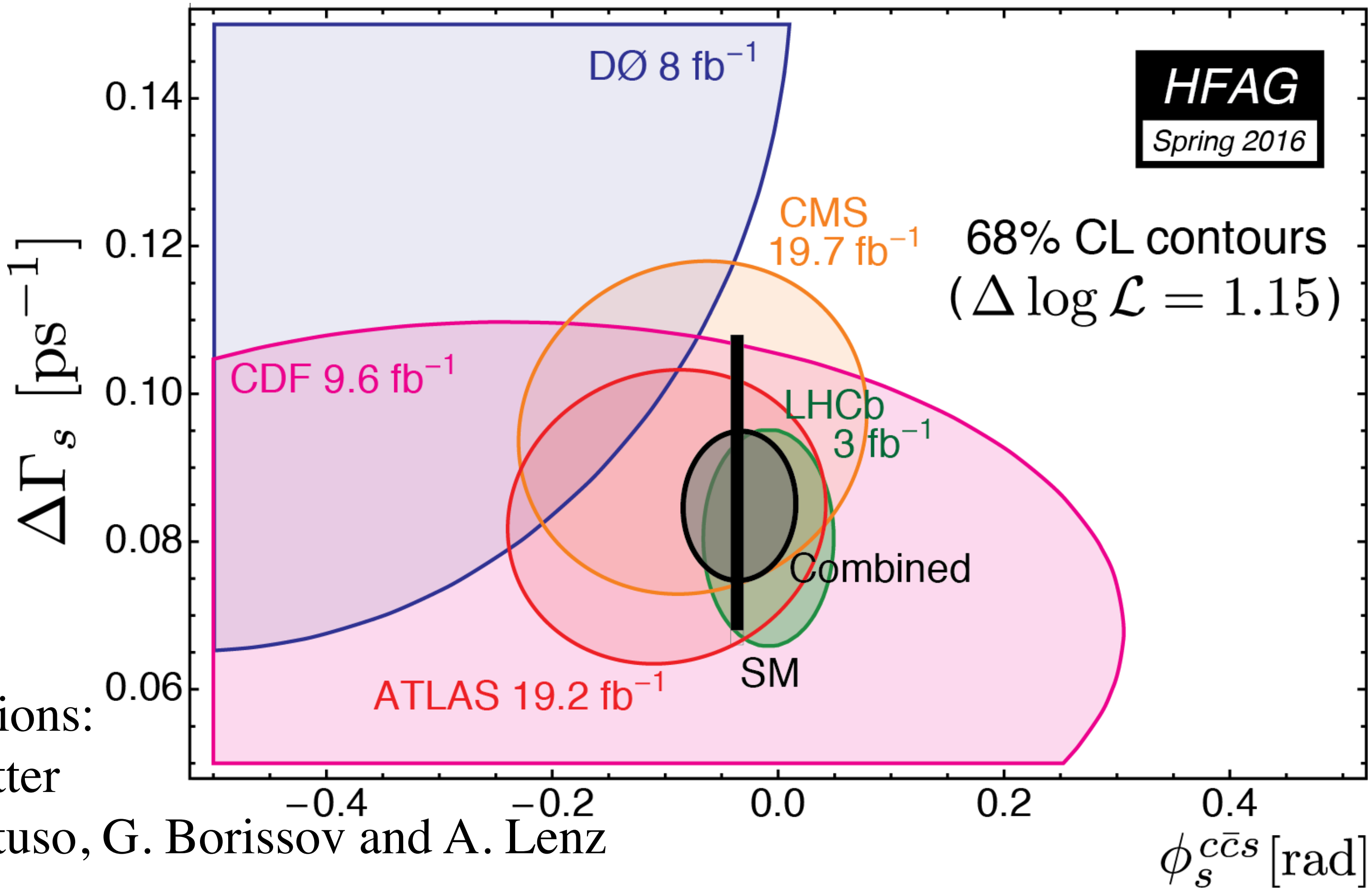
- Angle γ measurements need to improve.
- Need to reduce the error on ϕ_s (CPV in $B_s \to J/\psi KK$ and $J/\psi\pi\pi$) to ~$O(10^{-2})$ rad, i.e. at a level of the SM expectation

Current status of ϕ_s measurements



SM predictions:
ϕ_s: CKM fitter
$\Delta\Gamma_s$: M. Artuso, G. Borissov and A. Lenz

Quite some way to go to reach a SM level sensitivity:
LHC experiments

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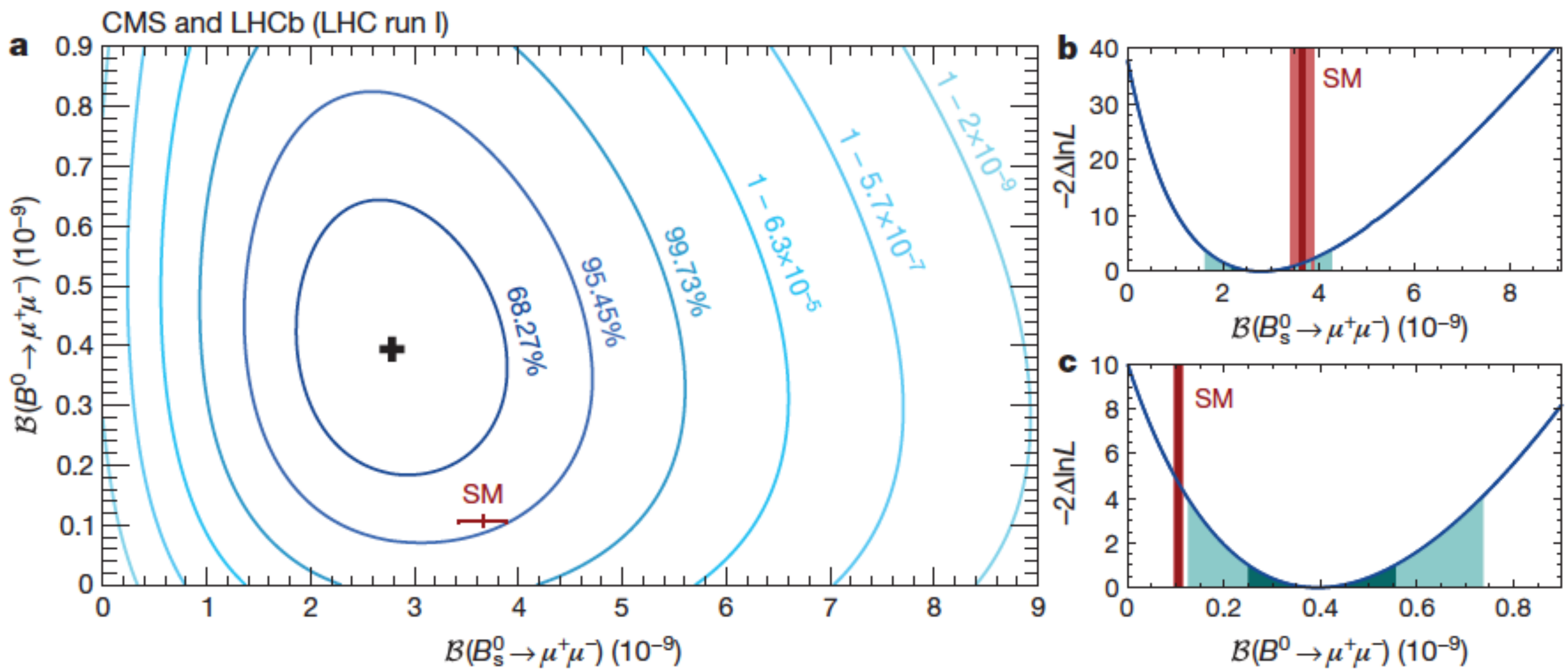
B_d, $B_s \to \mu\mu$ from CMS+LHCb (Smith)

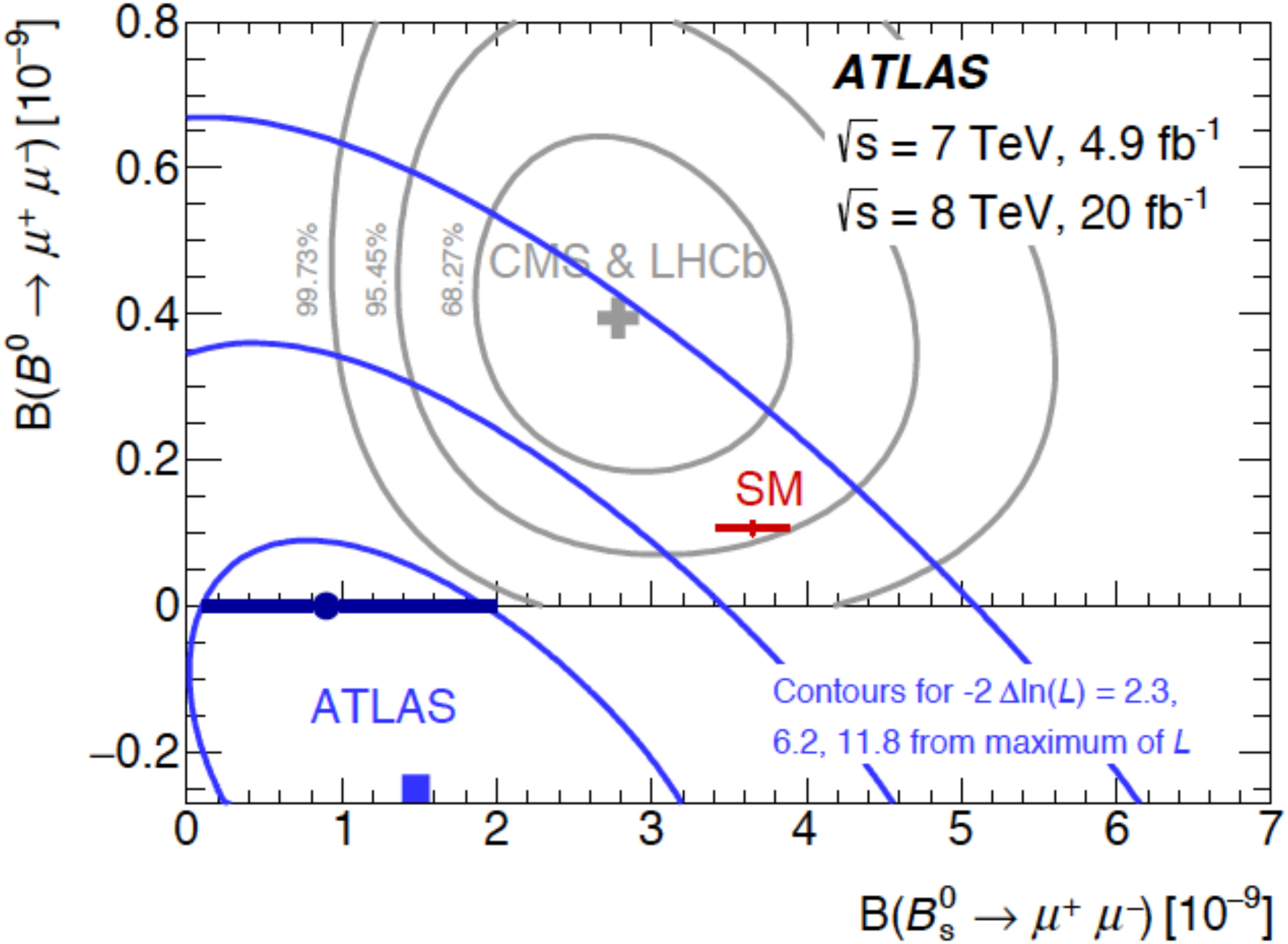


Branching fractions

$(3.9^{+1.6}_{-1.4})\times10^{-10}$ (B_d) 3.2σ

$(2.8^{+0.7}_{-0.6})\times10^{-9}$ (B_s) 6.2σ

Now joined by ATLAS (Walkowiak)



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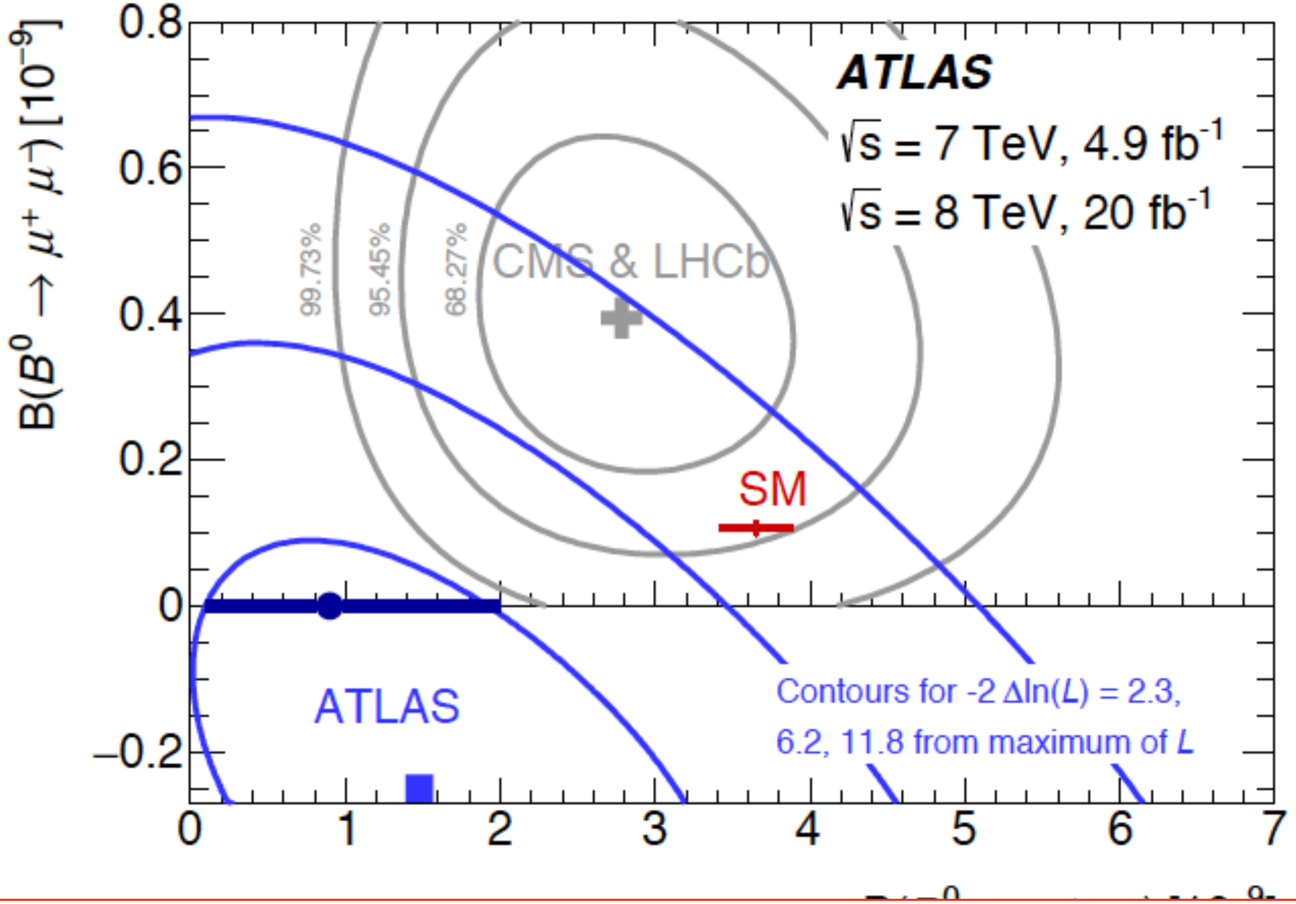

Further improvements on Br($B_s \rightarrow \mu\mu$)

Establish $B_d \rightarrow \mu\mu$ decay for the LHC experiments

NB: possible background: ~O(10^5) more $B_d \rightarrow \pi\pi$

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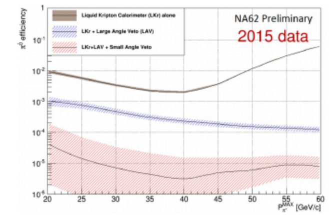
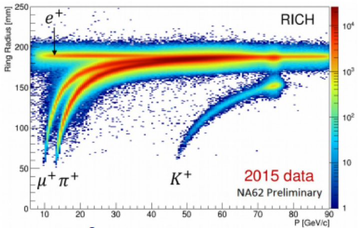
- Need to reduce experimental errors in $B_d, B_s \to \mu^+\mu^-$
- Also beyond b-hadron decays:
  - $K^+ \to \pi^+ \nu\nu$ for $|V_{ts}V_{td}|$ (NA62)
  - $K_L \to \pi^0 \nu\nu$ for "η" (height of the triangle) measurement (KOTO)
  - Improving lattice calculations for ε'/ε.

NA62 (Kozhuharov) and KOTO

NA62 prospects



Measurement of the π^0 rejection efficiency from 2015 data reached the statistical limit



- O(10²) π/μ separation
- 80 % efficiency for π^+ in 2015

- NA62 currently takes data – 200 days run in 2016
  - Excellent particle veto efficiency
  - Excellent momentum resolution
  - Particle ID efficiency
  - Kaon flux – 10^{13} K^+ **decays** in the fiducial volume
- **10% measurement of Br($K^+ \to \pi^+ \nu\nu$) expected**

Rich physcs programme

- Standard model and low energy QCD
  - R_K (lepton universality), $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^0\pi^0 e/\mu^+\nu$
- LNV and/or LFV
  - $K^+ \to \pi^+\mu^+e^-$, $K^+ \to \pi^+\mu^-e^+$, $K^+ \to \pi^- l^+ l^+$, $K^+ \to \mu^-\nu e^+ e^+$, $K^+ \to e^-\nu\mu^+\mu^+$
- π^0 programme
  - $\pi^0 \to$ invisible, $\pi^0 \to 3$ or 4 γ, $\pi^0 \to U\gamma$
- Dark sector
  - long living dark photon, long living ALPs
- Search for new particles (& heavy neutrino)
  - $K^+ \to \pi^+ X^0$, $K^+ \to \pi^+\chi\chi$, $K/D \to l\nu_h$, $\nu_h \to \pi l$

Summary

T. Nomura
Talk at J-PARC PAC

* In 2015 runs, the amount of collected data reached about 20 times more than May 2013 run
  – Single event sensitivity of 2013 run was 1.3×10^{-8}.
  * Brief data checks were done so far. We'll proceed more after detector upgrade.
* Construction of inner barrel (IB) is almost finished. Installation is scheduled in mid-February.
* After IB installation we want to have a beam time for commissioning (several days) and physics data (at least 10 days) before summer 2016.
  * After that, we want to take as many physics data as possible.

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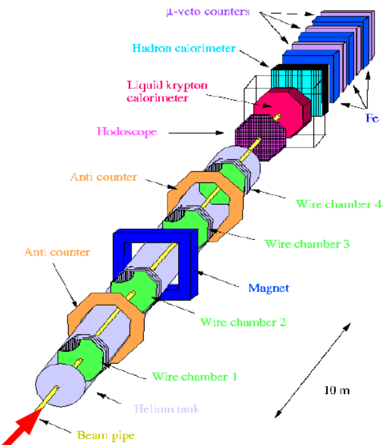
Magnetic spectrometer (DCH)
4 drift chambers
$p_\perp^{kick}$ = 121 MeV/c
$\Delta p/p = 1\% \oplus 0.044{*}p$ [GeV/c]

Hodoscope
$\sigma(t)$ = 150 ps

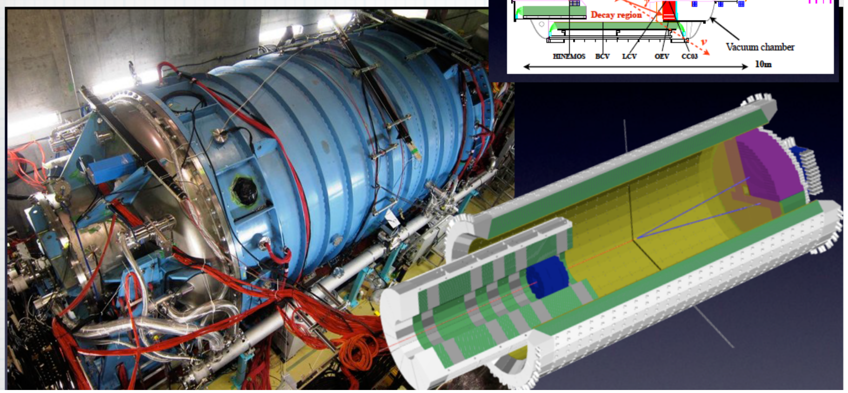
Liquid Krypton Calorimeter
$\Delta E/E \cong 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$

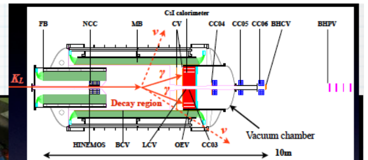
Hadron Calorimeter, Muon counters, Anticounters, Kaon Beam Spectrometer



~ 2x10¹¹ $K^\pm$ decays in the fiducial volume

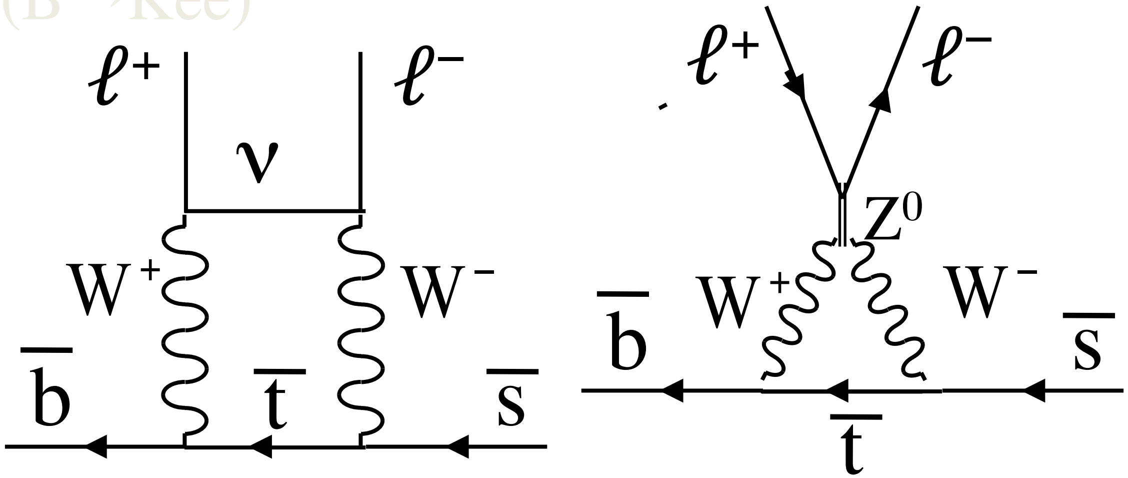
Photo of the vacuum tank and 3D image inside



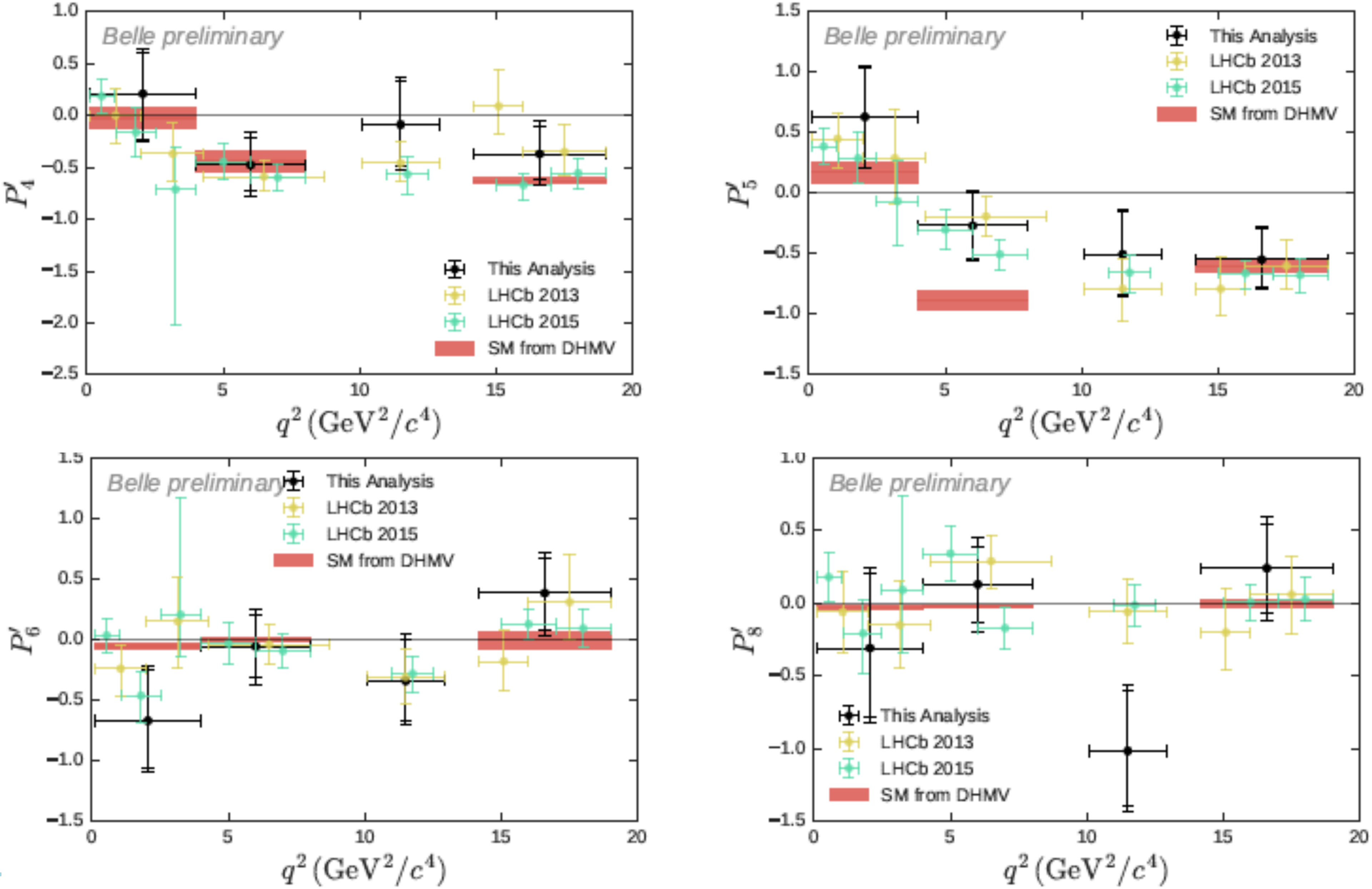


Interesting signals in semileptonic decays?

- With $b \rightarrow s\ell\ell$ loop decays:
  - Angular distribution of the $B \rightarrow K^{*0}\ell\ell$ decays (Lorentz structure)
  - $B(K)= Br(B\rightarrow K\mu\mu)/Br(B\rightarrow Kee)$



$B^0 \to K^{*0}\ell^+\ell^-$ (ℓ=e&μ) (Smith, Wormser)



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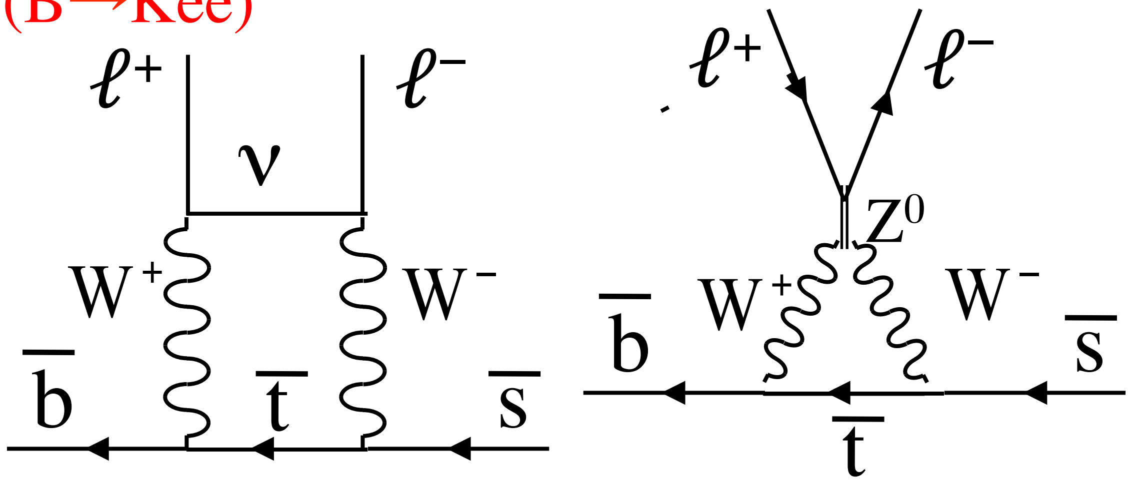
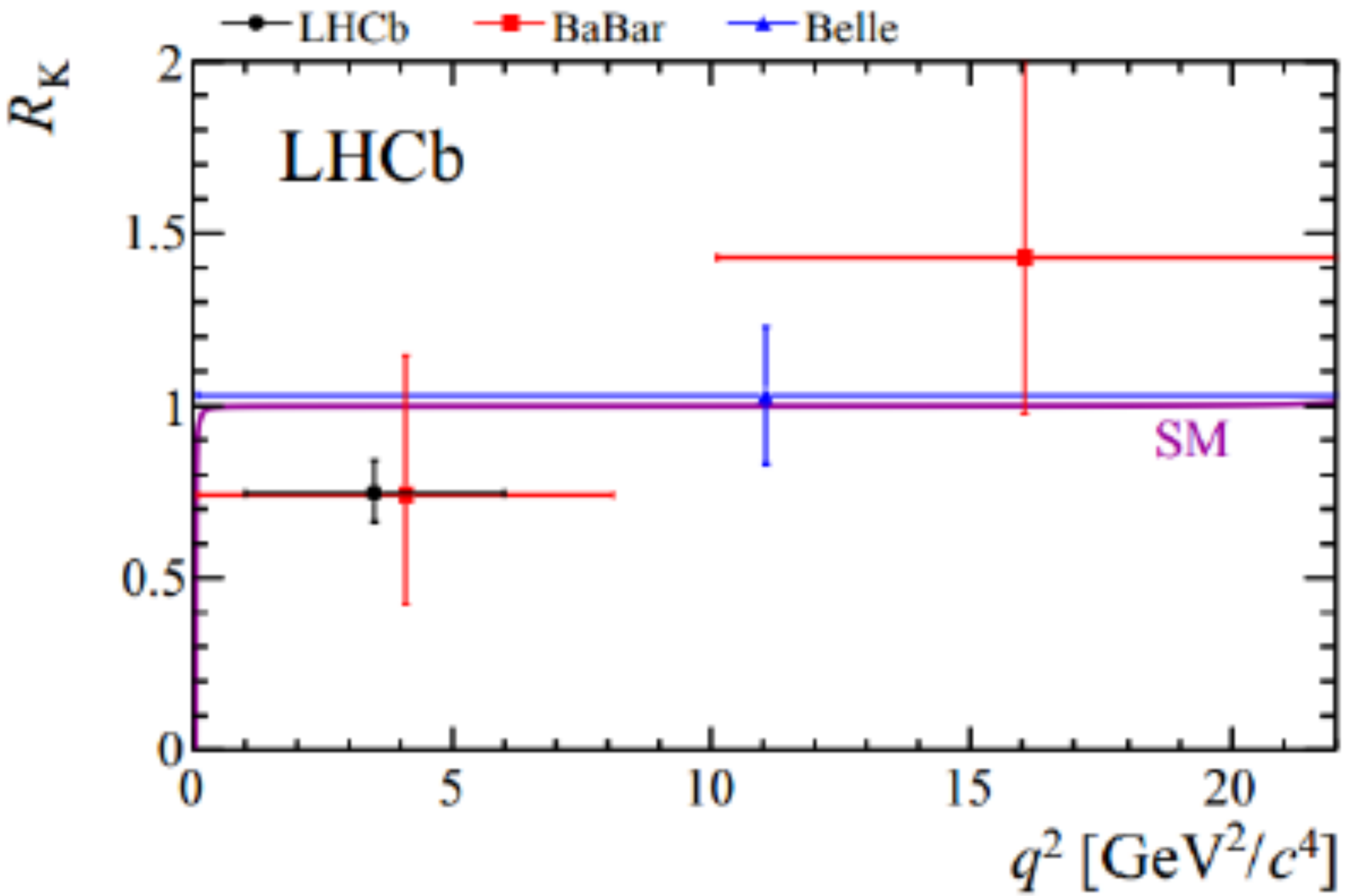


R(K) Status (Smith)



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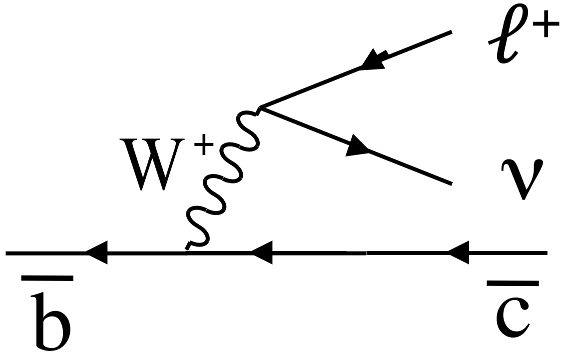
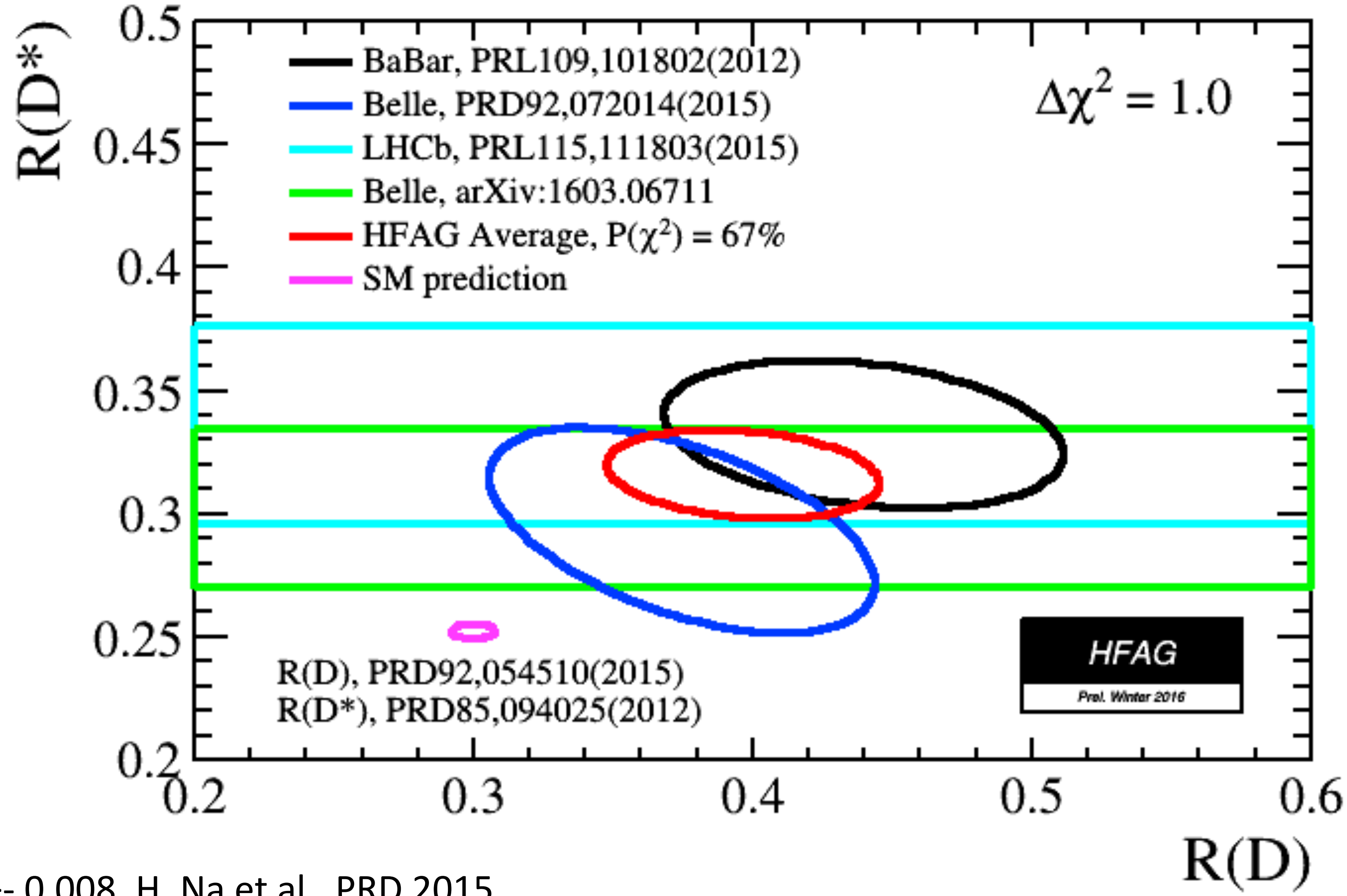
- With $b \to c\ell\nu$ tree decays:
  - $R(D^{(*)}) = Br(B \to D^{(*)}\tau\nu)/Br(B \to D^{(*)}\mu\nu)$



$R = Br_{B\to D^{(*)}\tau\nu} / Br_{B\to D(*)\mu\nu}$ including new Belle result



R(D) =0.300 +- 0.008, H. Na et al., PRD 2015
R(D*)=0.252 +- 0.003, S.Fajfer, J.F.Kamenik, and I.Nisandzic, PRD 2012

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Will a consistent picture emerge?
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LHCb will improve the $R(D^*)$. And clever trick for $R(D)$?
Improvement by BELLE II
Also $B \to \tau\nu$ remains to be an interesting channel ($B \to \mu\nu$, $B_c \to \tau\nu$?)

A note added

- Charm sector seems to behave "normally", again, for the moment (Acar, Liu)
  - No CPV observed
    indication of large CPV observed by LHCb not confirmed
  - D-$\overline{\mathrm{D}}$ mixing firmly established, but SM prediction difficult due to large hadronic effects
- CPV in B_s-$\overline{B}_s$ oscillation not confirmed (Acar)

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And apology for neglecting many other interesting results!

Also important to remember

- Results will come from
  - charge lepton violating μ decays; $\rightarrow 3e$, $\rightarrow e\gamma$, μ-e conversion and, and τ decays, $\rightarrow 3\mu$, $\rightarrow \mu\gamma$, $\rightarrow e\gamma$
  - Flavour conserving quantities such as neutron electric dipole moment and $(g-2)_\mu$
    i.e. flavour should be considered more globally.
- Accurate Standard Model predictions are essential in the precision measurements. Strong interactions are still the most problematic issue in many measurements ⇒ help from our theory friends are always needed!
- By the way, axions have not been discovered so far, and $\theta_{QCD} < 10^{-10}$ appears to me as another "fine tuning"…

Reflection

- CP violation & rare decays made essential contributions to establish the flavour structure of the SM in the past.
- With LHC data, possibility of large BSM physics in the B_s sector has been eliminated, and overall status with current data involving quark flavour is in good agreement with the CKM picture, including processes with loop diagrams.
- Despite of cosmological "proof" for new physics as well as the neutrino mass, and many clever theoretical works, we have little idea for the energy threshold of new physics.
- We need to observe a clear sign of BSM, directly or indirectly, in particle physics, to figure out the energy scale. And I am afraid there is no obvious road for a discovery, thus pursuits must be carried away as wide as possible

More Reflection

- In quark flavour physics, there are interesting indications involving semileptonic final states: statistical flacuation? Soft-QCD not yet well understood? Or new physics in electroweak penguins, charged Higgs, leptoquark, etc. etc. etc..
  We should remain prudent (we saw so many "tantalising" signal disappeared), but not be shy.
- And the exploitation at LHC has just started (Run-2, Run-3, Run-4, …)!

My standard joke of the past years…

My hope, expectation and possible realities matrix for 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

Oh, no more space left…

Particle Physics in LHC Era, T. Nakada — XXVIII Encontro Nacional de Física de Partículas e Campos, Brazil, 2007 — 62/63