Beauty physics

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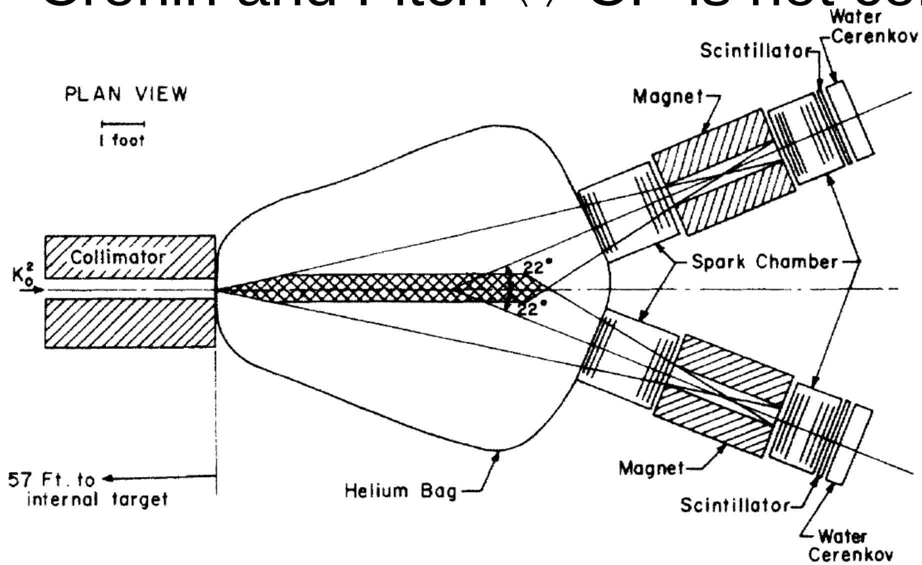
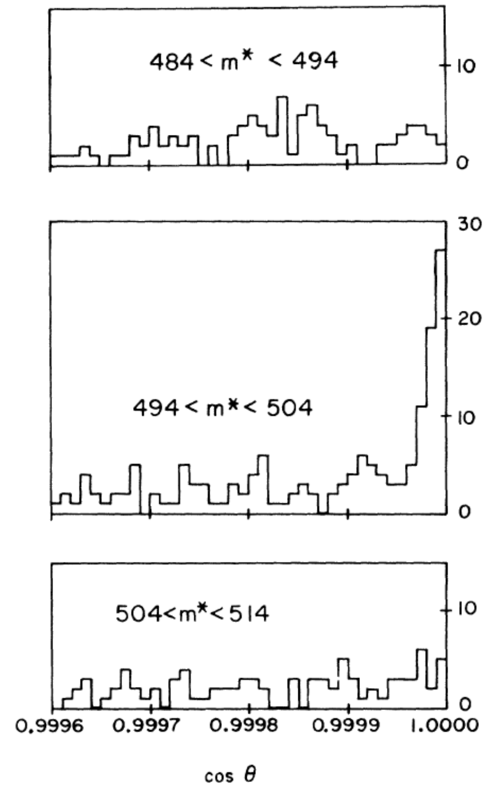
Few warnings:

- Impossible to cover all results
- Try to concentrate on big picture
- Designed more for high-p_T colleagues than experts
- Selection of topics is definitely biased

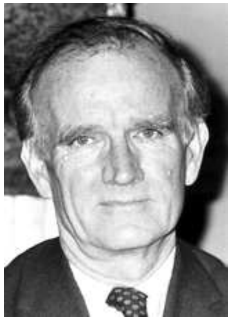
Start of B physics

- Neutral kaon puzzle in late 1950s
- Two particles (K_1, K_2) with same mass, but different lifetime and different decay mode
- K_2 is CP odd and if CP is conserved can decay only to 3 π
- Observation of $K_2 \rightarrow \pi^+\pi^-$ in 1964 by Cronin and Fitch $\Leftrightarrow$ CP is not conserved





PRL 13, 138 (1964)



Start of B physics

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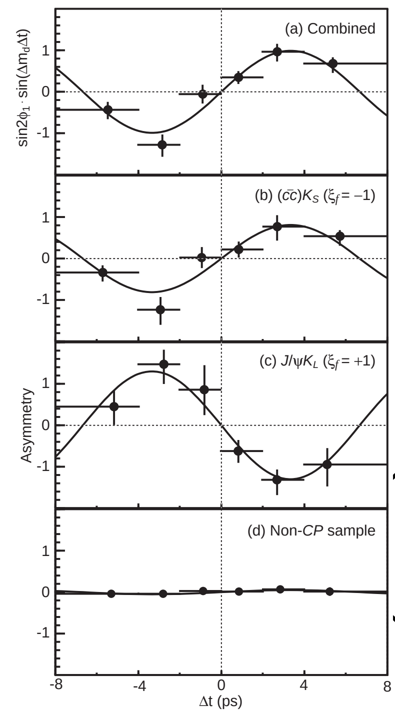
- Observation by Cronin and Fitch requires $\approx 10^{-3}$ admixture of wrong CP state in wave function
- In 1973 Kobayashi and Maskawa concludes that
  - No reasonable way to include CP violation in model with 4 quarks
  - Introduction of CP violation needs new particles
  - One of the suggested ways uses 6 quark model
- CP violation $\Leftrightarrow$ complex phase in quark mixing (CKM) matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

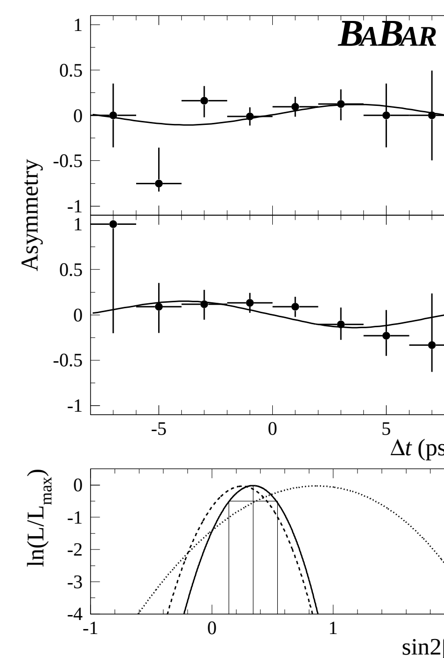
- Nobel prize in 2008

Start of B physics

- When Kobayashi and Maskawa proposed their explanations, only 3 quarks were known
- The six quark model had several implications:
  - Existence of another 3 quarks to be seen by experiment
  - In 1980/1981 several people predicted large CP violation in *B* system
- Start of dedicated *B* physics experiments
- In 2001 Belle and Babar experiments observe large CP violation in B^0 decay
- Not only test of KM, but also production and spectrum have its questions



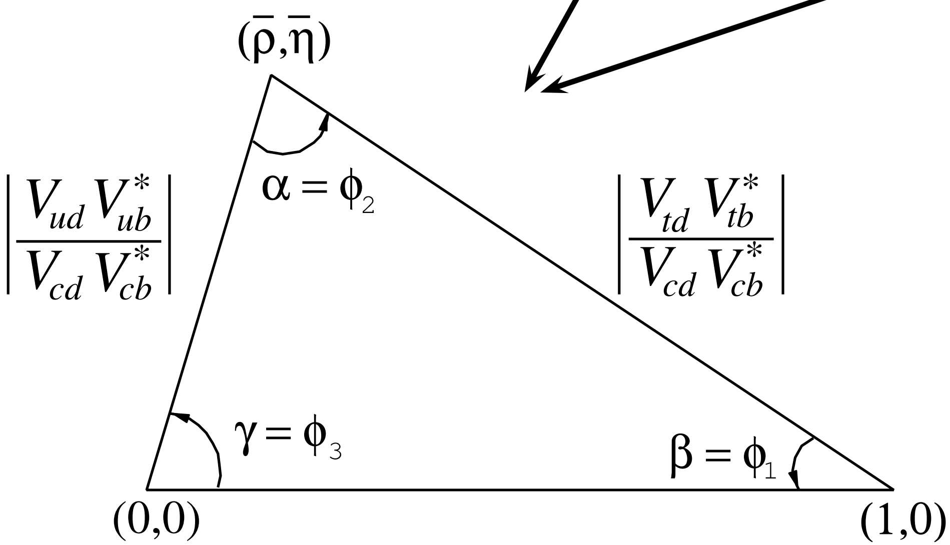
PRL 87, 091802 (2001)

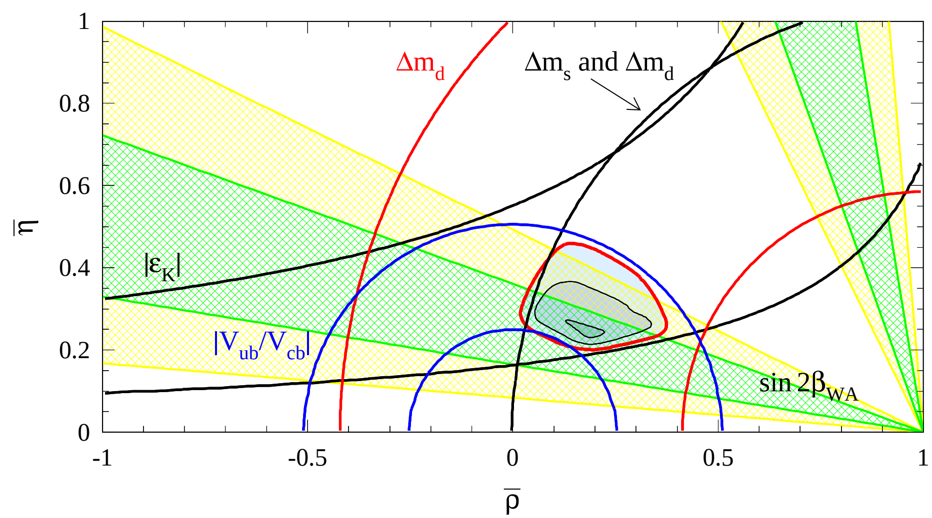


PRL 86, 2515 (2001)

Testing KM mechanism

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

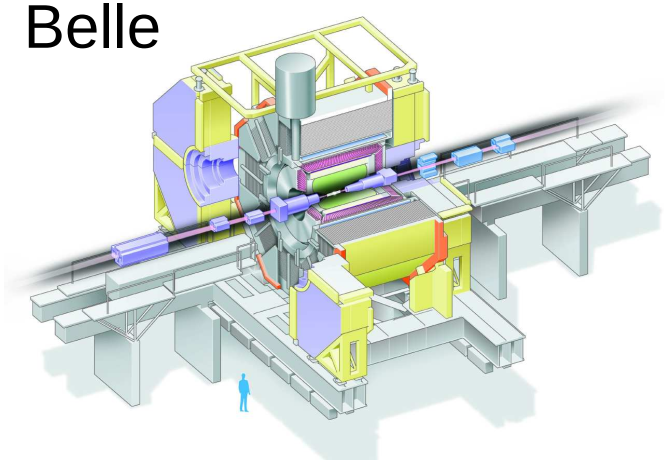




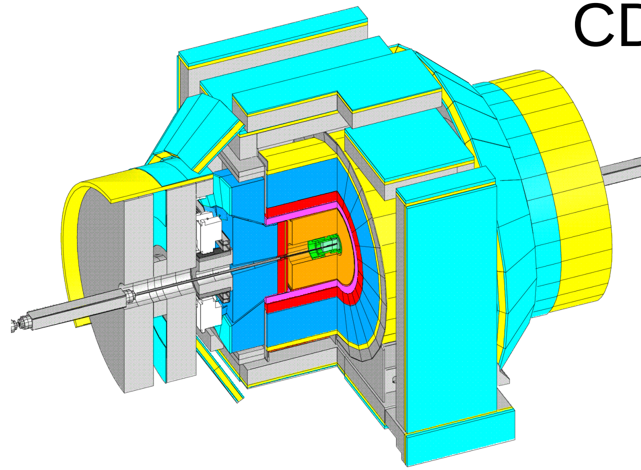
May 2001

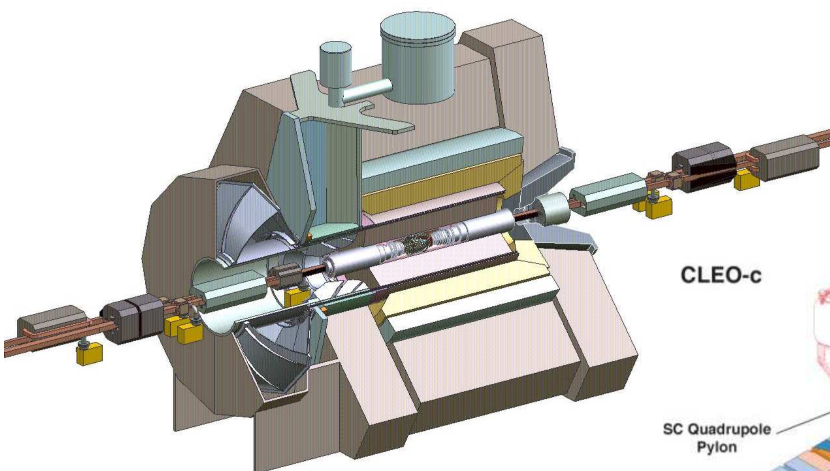
Major players

Belle

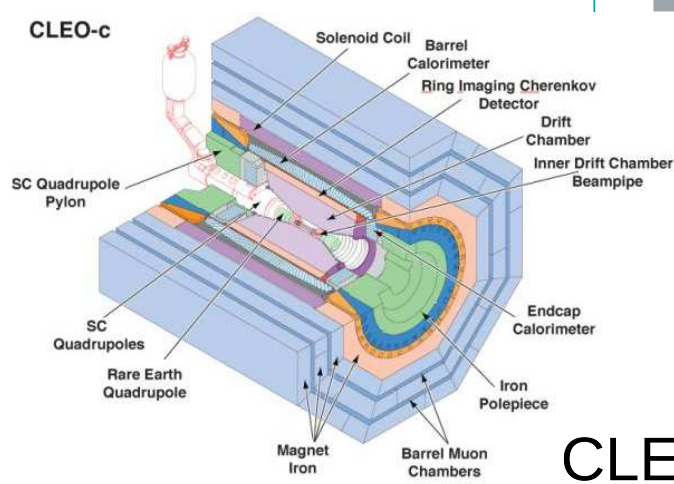


CDF

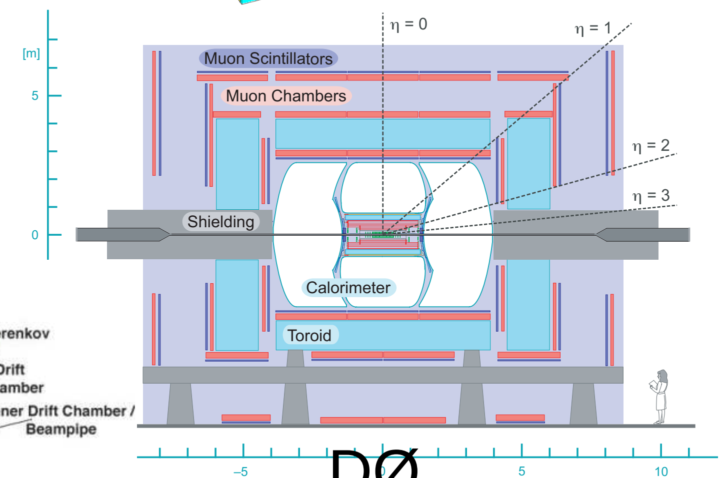




Babar



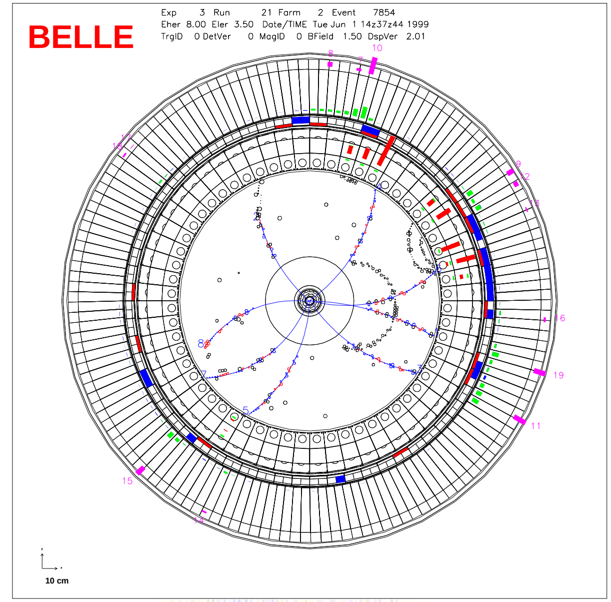
CLEO-c

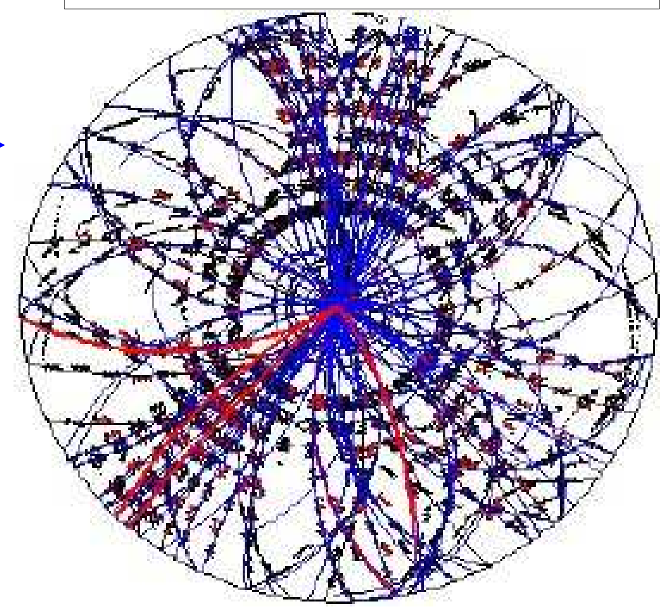


DØ

Pros and cons

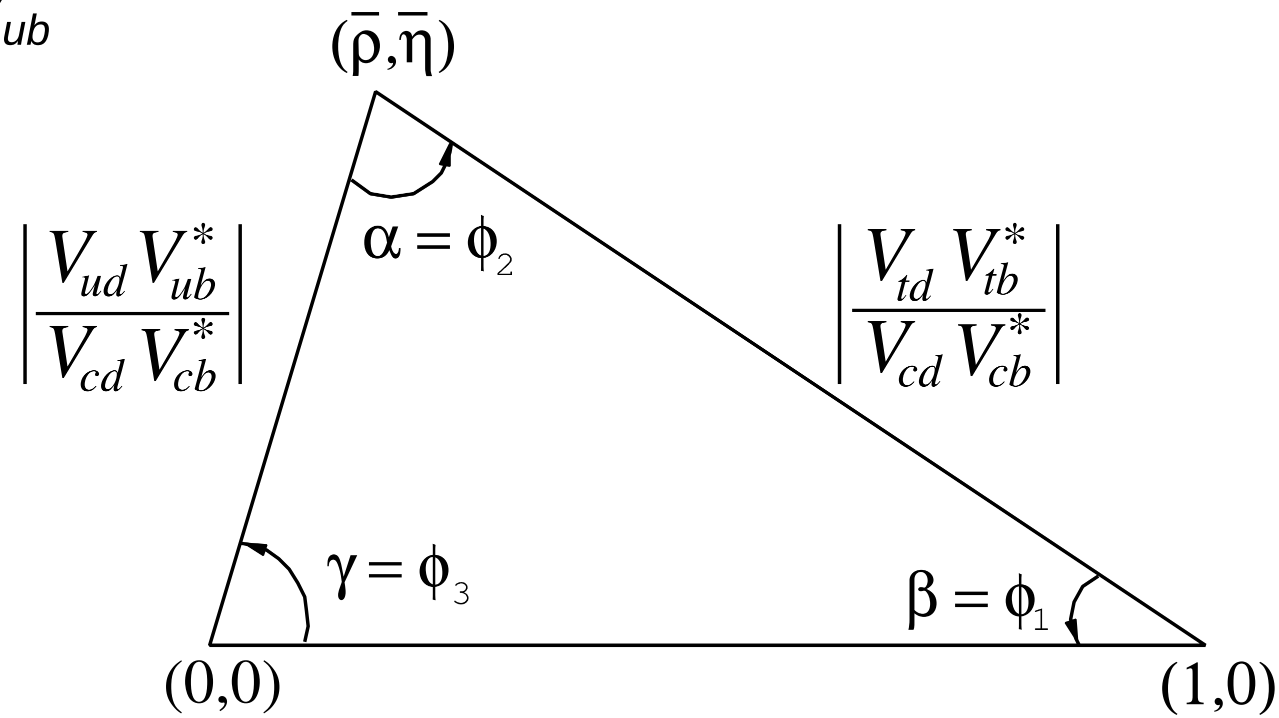
- e^+e^- at $\Upsilon(4S)$ (Belle, Babar)
  - \+ Clean events
  - \+ Good flavor tagging
  - \- Relatively small cross section
  - \- Hard access to hadrons beyond B^+/B^0
- High energy hadron collider (CDF, DØ)
  - \+ Large b cross section
  - \+ Access to all sort of b-hadrons
  - \- Much larger inelastic cross section $\Leftrightarrow$ dirty events
  - \- Much worst flavor tagging





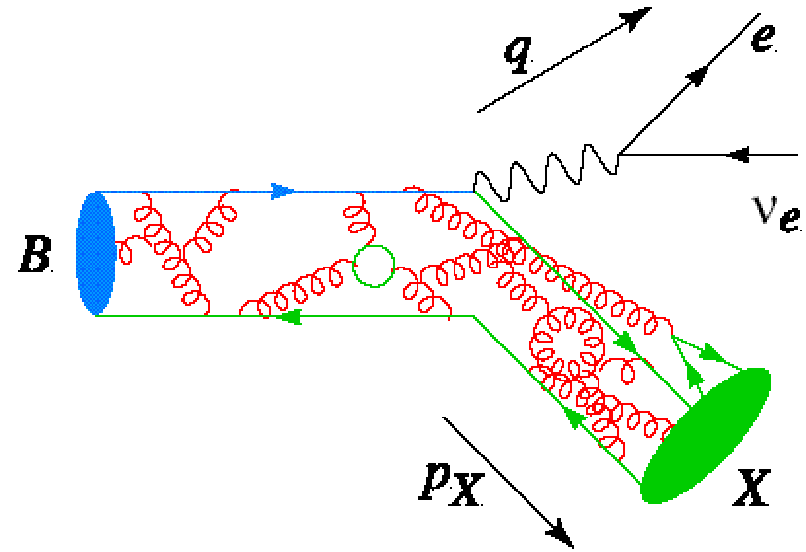
Triangle Sides

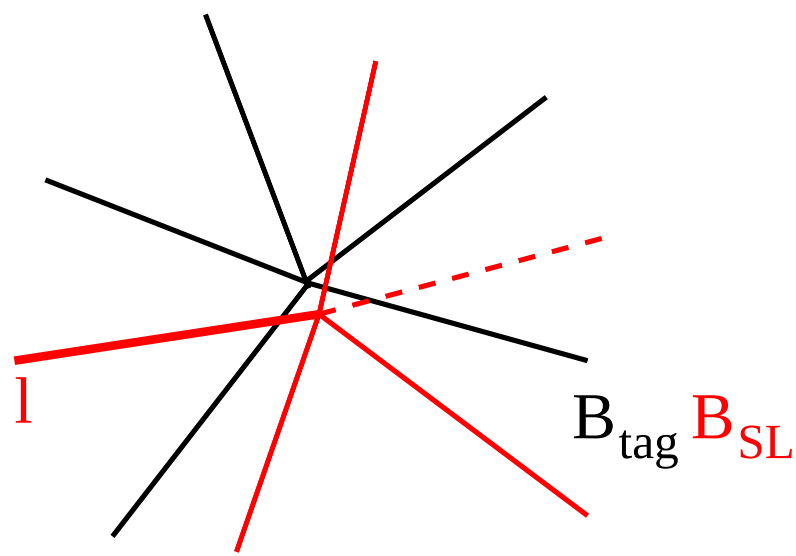
- Left side given by V_{ub} element measured by $b \to ul\nu$
- Right side determined by V_{td}, experimentally from B mixing
- Both need to V_{cb} as normalization (or third side), measured in $b \to cl\nu$
- No change in B mixing in about last 4 years
- Look to V_{cb} and V_{ub}



Measurements of $|V_{cb}|$

- Measured using semileptonic decays
- Inclusive approach
  - Relatively easy for theory (weak decay with QCD corrections)
  - Typically reconstruct one *B* and measure lepton energy or missing mass
  - Understanding backgrounds is challenging
- Exclusive approach
  - Relatively easy for experiment
  - Need form factor = non-perturbative QCD
- Domain of e^+e^- at threshold

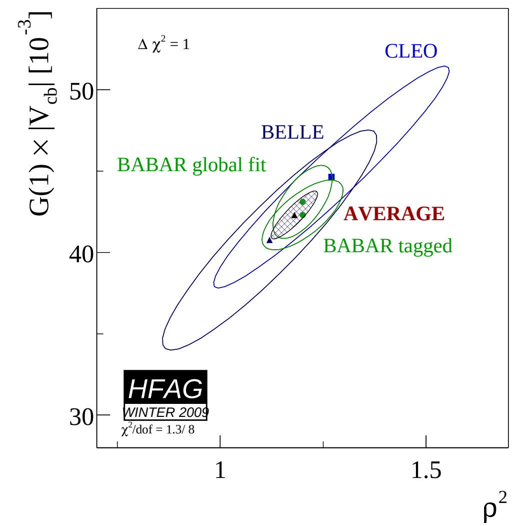




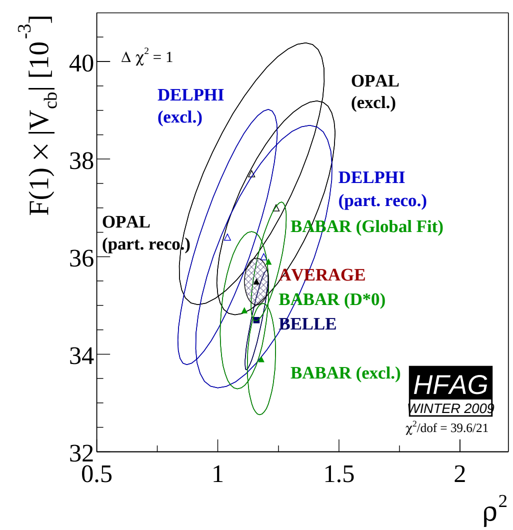
Measurements of $|V_{cb}|$

- B factories now dominate
- Some tension in results for $B \to D^* l\nu$, $\chi^2/dof = 56.9/21$
- Fit to moments (inclusive determinations) always too good (prob ≈ 0.9995)
- Results (10^{-3}):
  $D^* l\nu$: $38.6 \pm 0.5 \pm 1.0$
  $Dl\nu$: $39.4 \pm 1.4 \pm 0.9$
  inclusive: $41.5 \pm 0.44 \pm 0.58$
- Inclusive vs. exclusive $\approx 2.3\sigma$ difference
- Exclusive average 38.8 ± 0.9

$B \to Dl\nu$

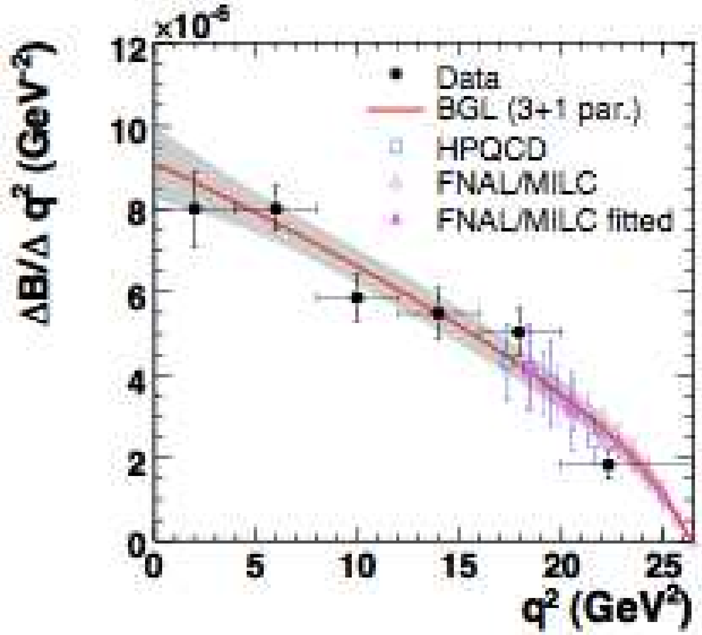


$B \to D^* l\nu$



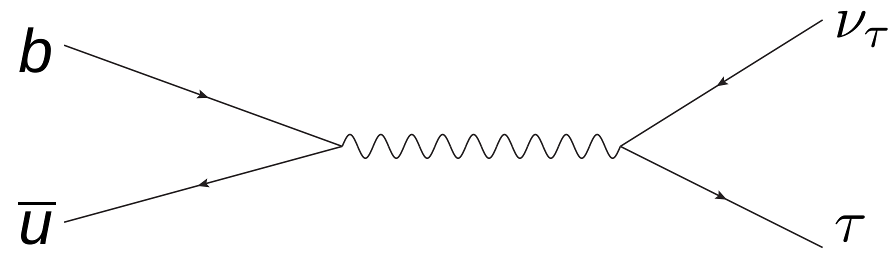
Measurements of $|V_{ub}|$

- Same principle as V_{cb}
- Complication of CKM suppression and dominant $b \to c l \nu$ bg
- Kinematic cuts destroy theory convergence
- Trade between theory and experimental uncertainty
- Several fits to inclusive experimental data (10^{-3})
  $|V_{ub}|(BLNP) = 4.06 \pm 0.15^{+0.25}_{-0.27}$
- Exclusive determination uses $B \to \pi l \nu$
- Usually fit to mixture of experimental data and lattice QCD results
- Latest Babar result
  $|V_{ub}| = 2.95 \pm 0.31 \times 10^{-3}$
- We probably have another $\approx 2\sigma$ discrepancy

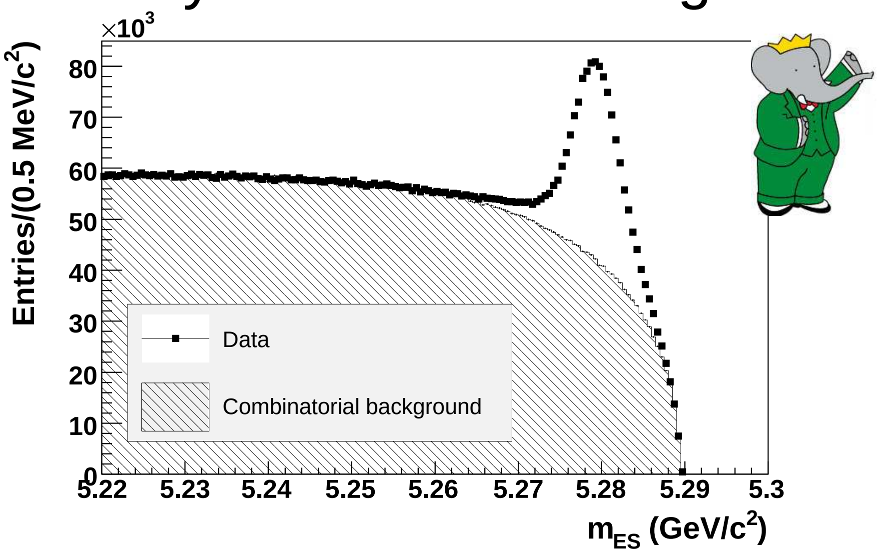


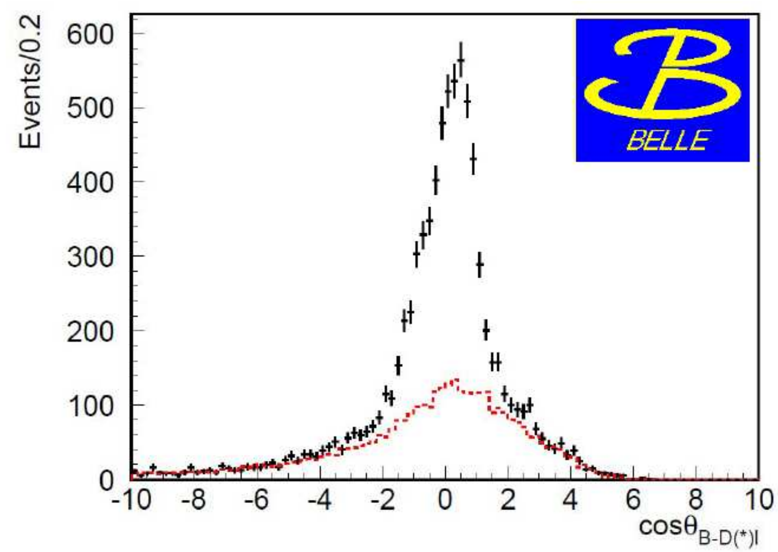
$B \to \tau\nu$

- SM branching fraction given by
  $BF = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$



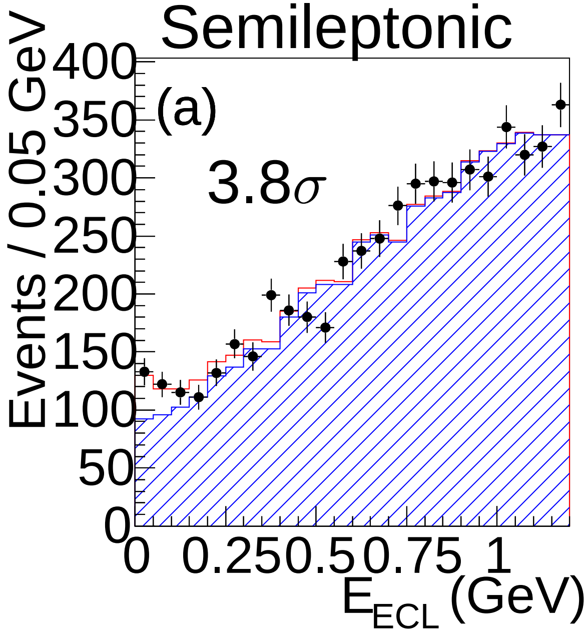
- One can extract f_B or $|V_{ub}|$
- SM $BF = 1.20 \pm 0.25 \times 10^{-4}$
- Practically only B-factories thanks to clean environment
- After reconstructing tag B and all charged particles from signal B, only neutrinos missing



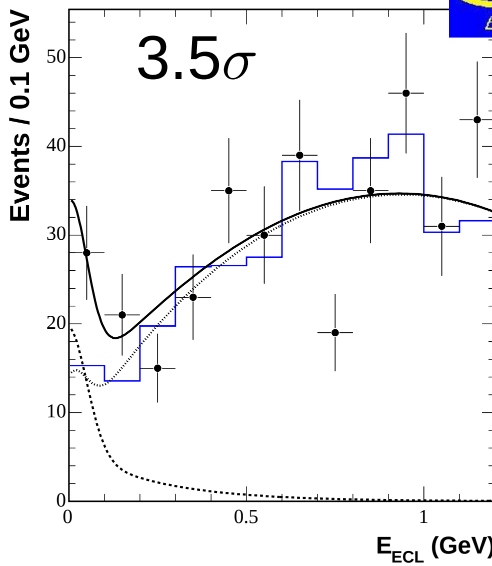


$B \to \tau\nu$

Semileptonic



Hadronic



S: $1.65^{+0.38}_{-0.37}\,{}^{+0.35}_{-0.37} \times 10^{-4}$

H: $1.79^{+0.56}_{-0.49}\,{}^{+0.46}_{-0.51} \times 10^{-4}$

hep-ex/0809.3834,

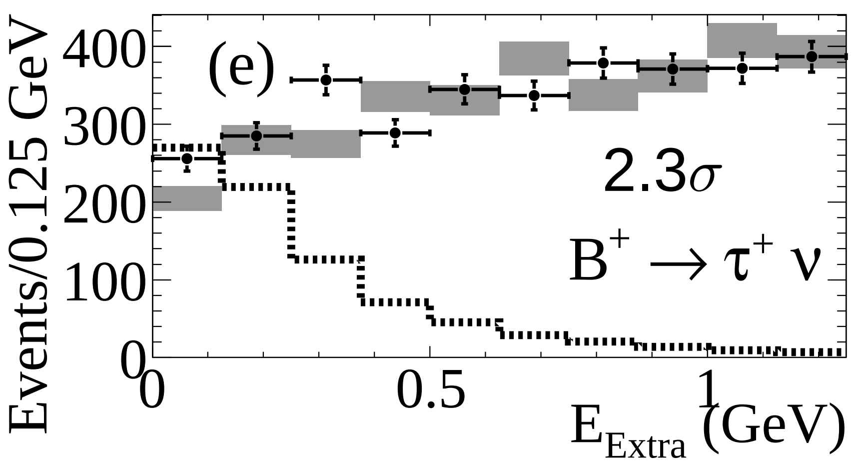
PRL 97, 251802 (2006)

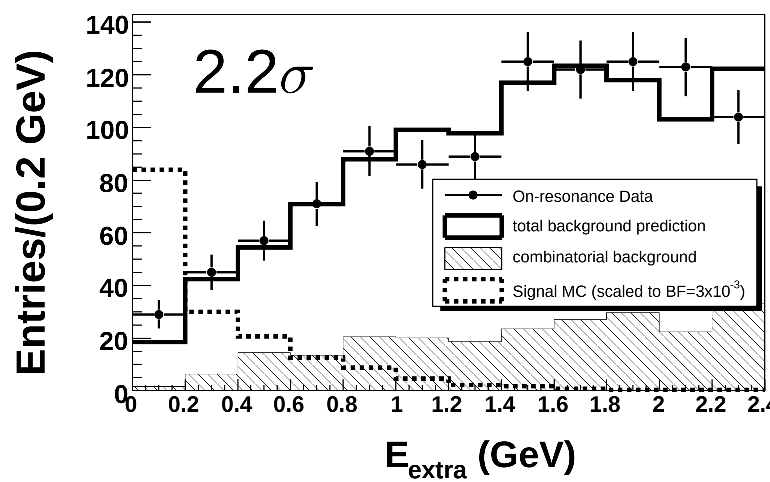
S: $1.7 \pm 0.8 \pm 0.2 \times 10^{-4}$

H: $1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2 \times 10^{-4}$

PRD 81, 051101 (2010)

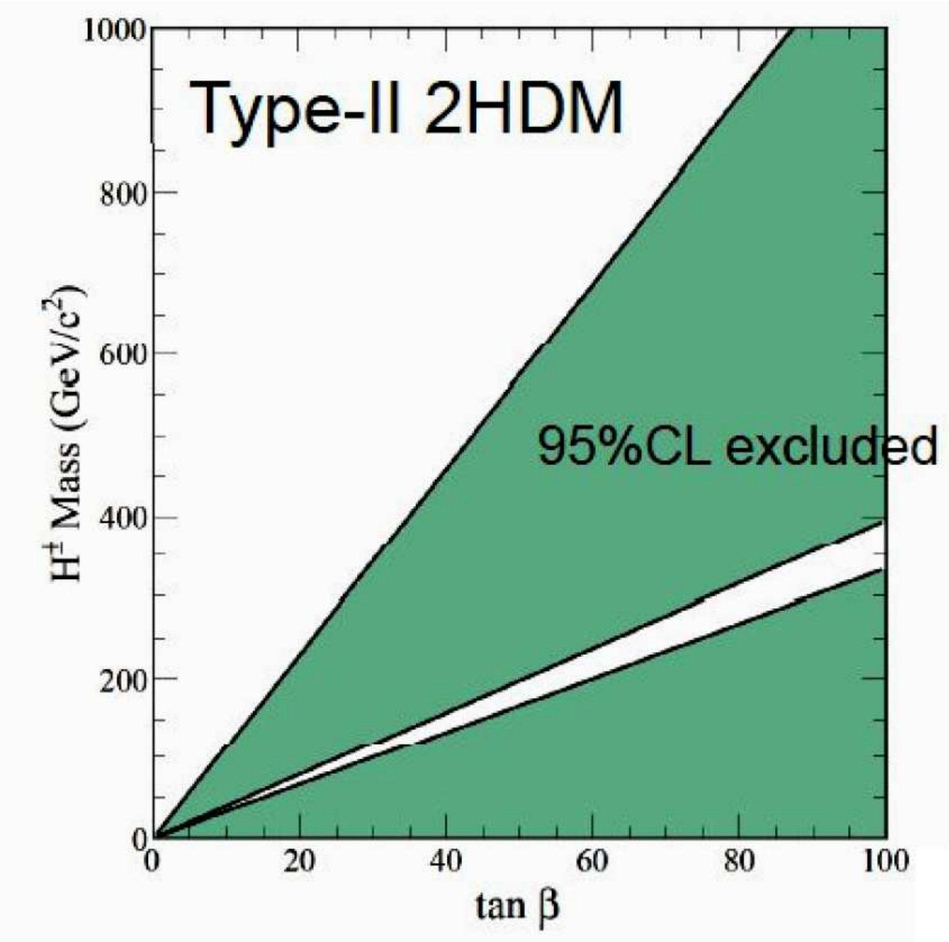
PRD 77, 011107 (2008)





$B \to \tau\nu$

- Naive average of exp. results
  $BF_{exp} = 1.73 \pm 0.35 \times 10^{-4}$
- SM prediction
  $BF_{SM} = 1.20 \pm 0.25 \times 10^{-4}$
- Effect of charged Higgs
  $BF_{exp} = BF_{SM} \times r_H$
  $r_H = \left(1 - \frac{m_B^2 \tan^2\beta}{m_H^2} \frac{1}{1+\epsilon_0 \tan\beta}\right)^2$
- For Type-II 2HDM $\epsilon_0 = 0$

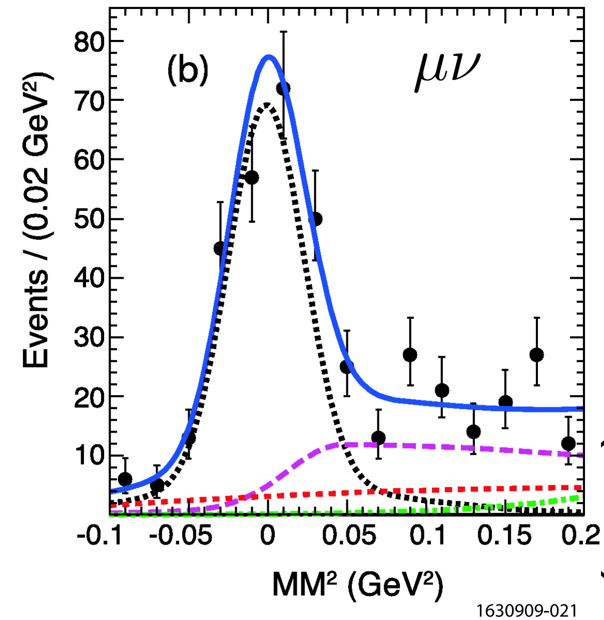


f_{D_s} saga

- $B \to \tau\nu$ needs input from lattice

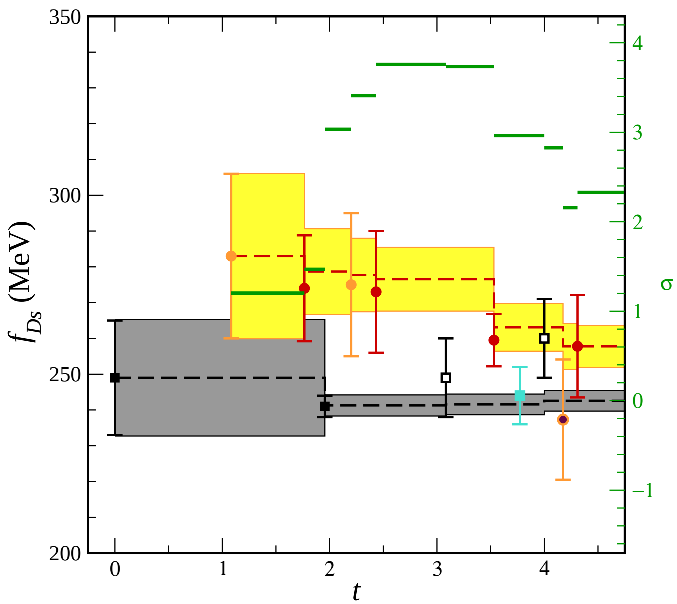
$$BF = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

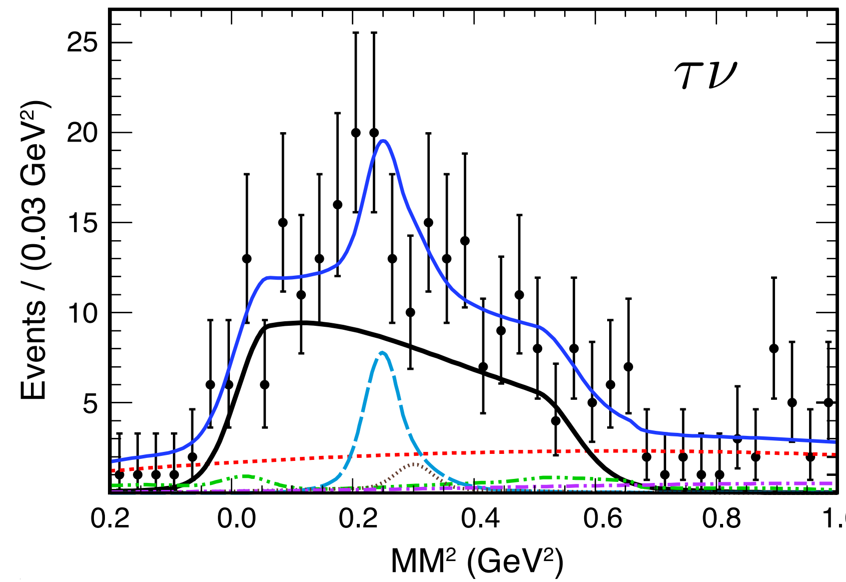
- Can use leptonic D_s to test theory
- Show CLEO data, Belle and Babar contribute also



PRD 79, 052001 (2009)

Kronfeld, arXiv:0912.0543





arXiv:0910.3602

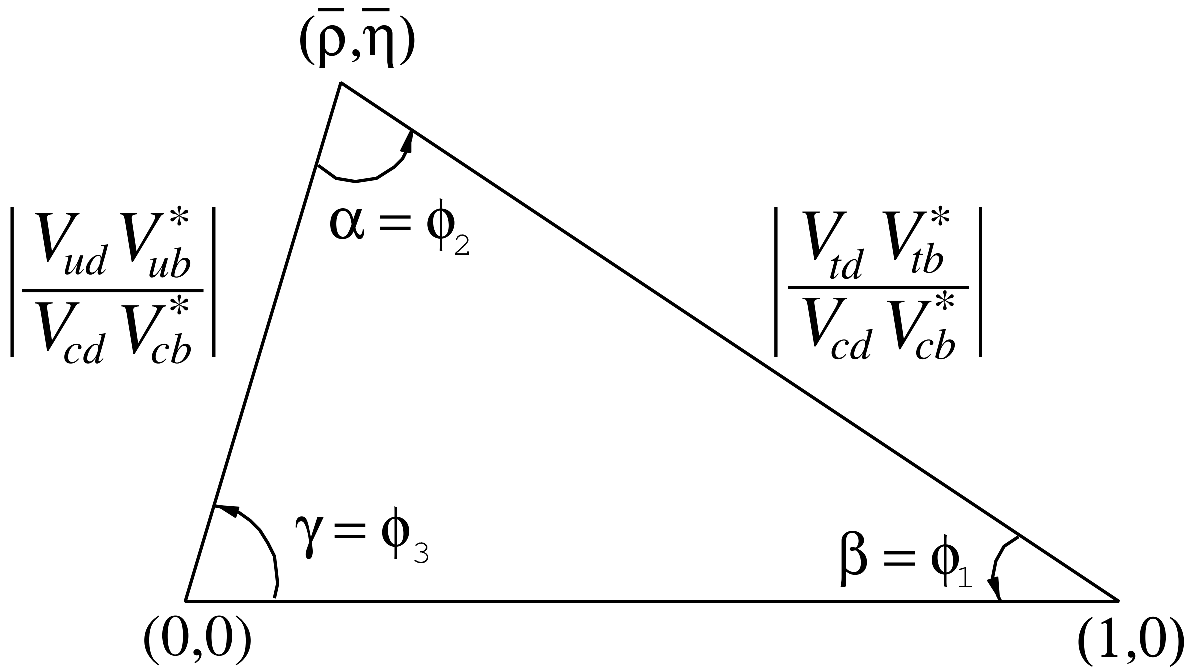
Angles

- Angles are defined through complex phases of the CKM elements
- They are related to CP violation
- Their determination needs measurement of CP violation
- Omit α here

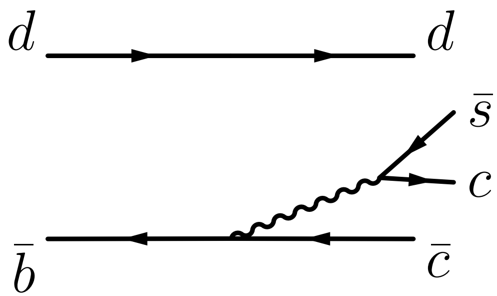
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

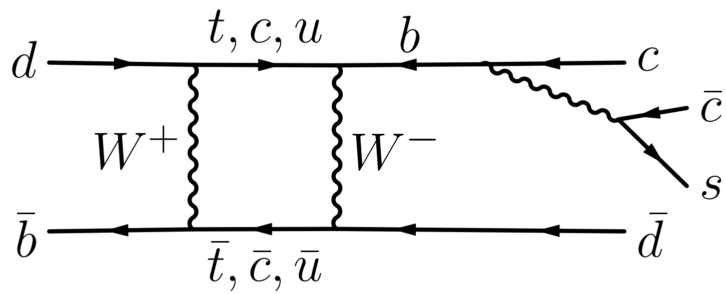
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



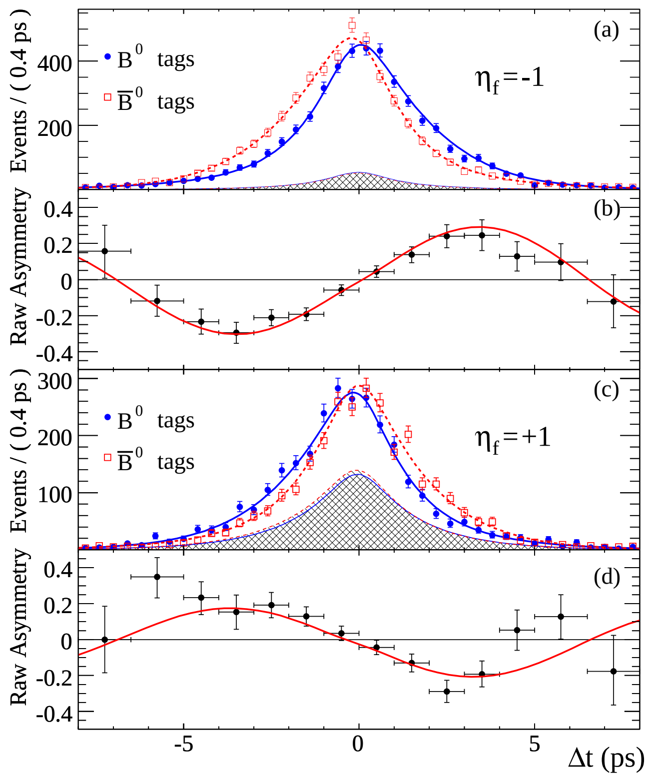
Angle β



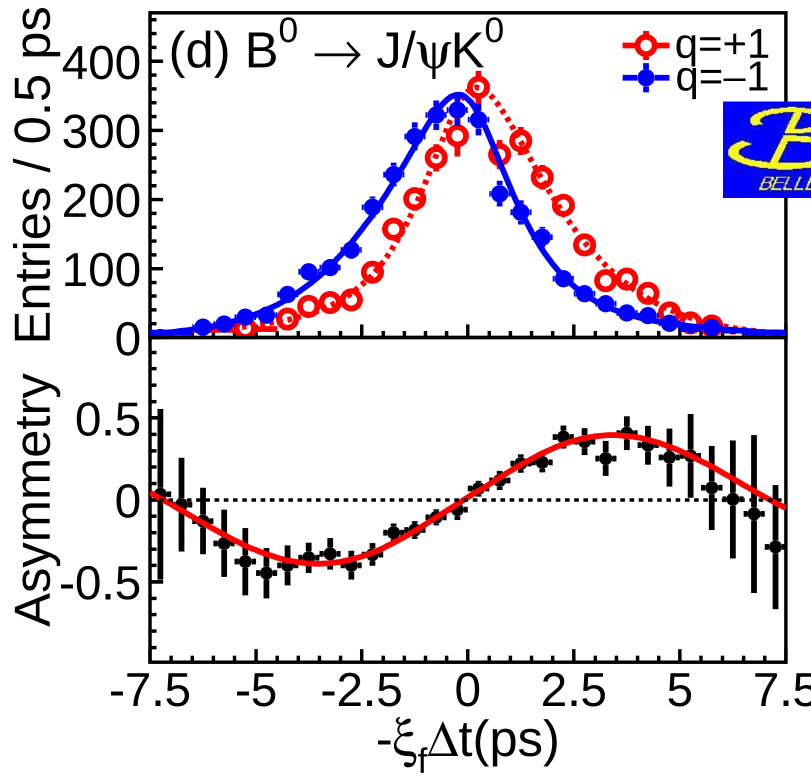


$$A = \frac{N(B,\Delta t) - N(\overline{B},\Delta t)}{N(B,\Delta t) + N(\overline{B},\Delta t)}$$

PRD 79, 072009 (2009)



$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$

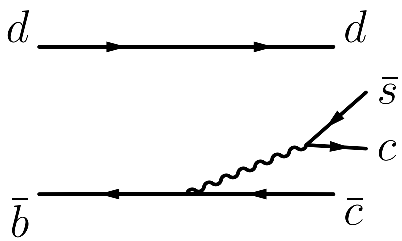


PRL 98, 031802 (2007)

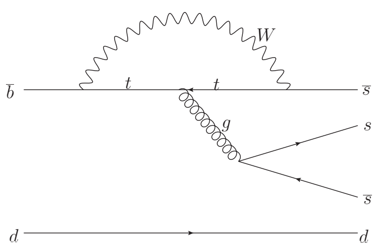
$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$

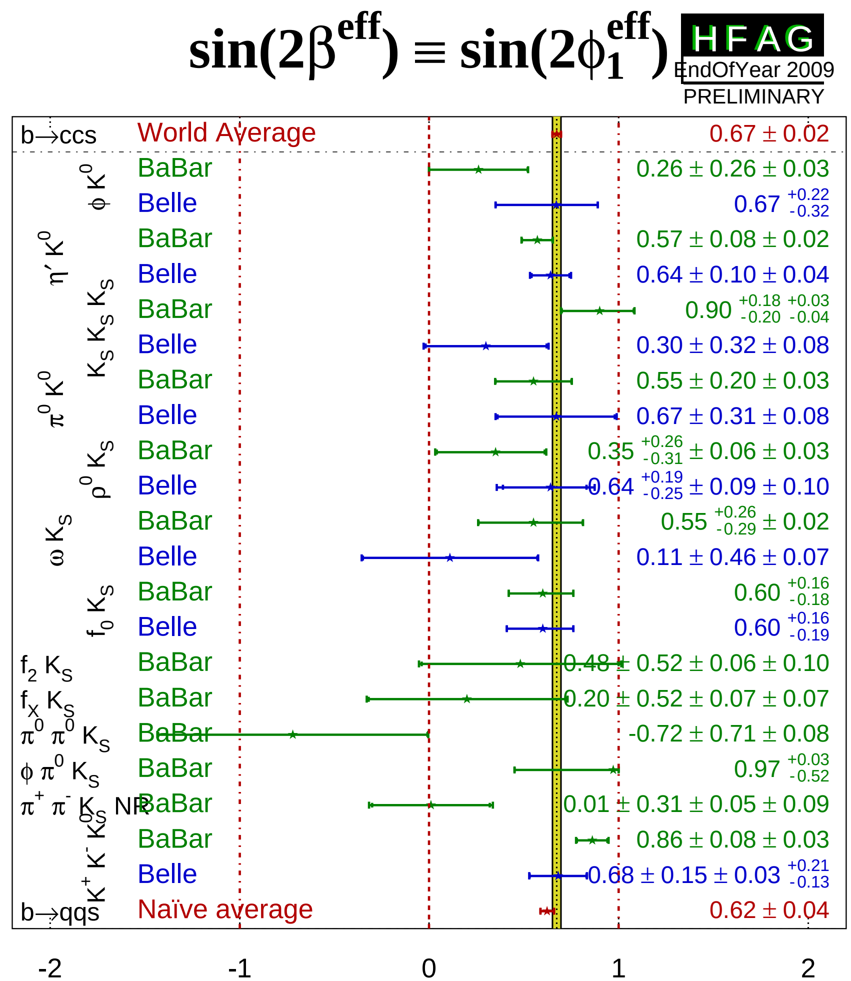
Angle β

- In first order $b \to c\bar{c}s$ confirms SM



- $b \to s\bar{q}q$ more natural place to look for NP

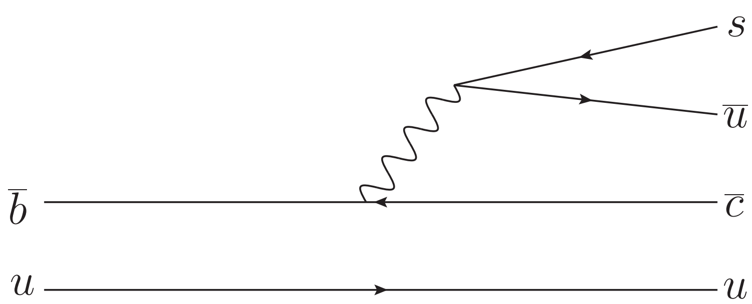


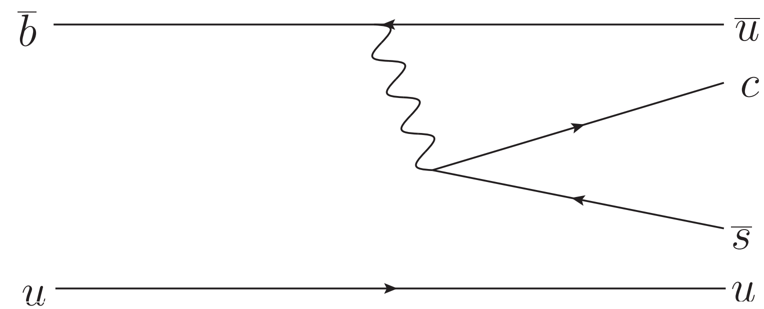


- Used to see some difference between $b \to c\bar{c}s$ and $b \to s\bar{s}s$
- Seems fine now, but need much higher statistics to really probe NP

Angle γ

- CP violation in interference of $b \to c$ and $b \to u$ transitions



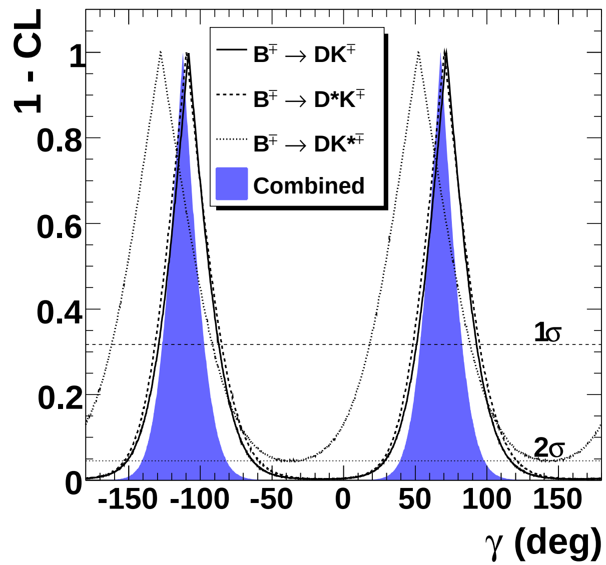


- Need common final state for D^0 and $\overline{D}^0$
- Proceed through tree level diagrams, little sensitivity to NP
- Useful in determining what SM gives us
- Three main methods (depending on D decay):
  - (CF) $D^0 \to K^-\pi^+$ and (DCS) $\overline{D}^0 \to K^-\pi^+$, ADS
  - Two body Cabibbo suppressed channel (K^+K^-, $K_s\pi^0$), GLW
  - Dalitz method ($K_s\pi^+\pi^-$), GGSZ
- Rare decays with small $(b \to u)/(b \to c)$ ratio

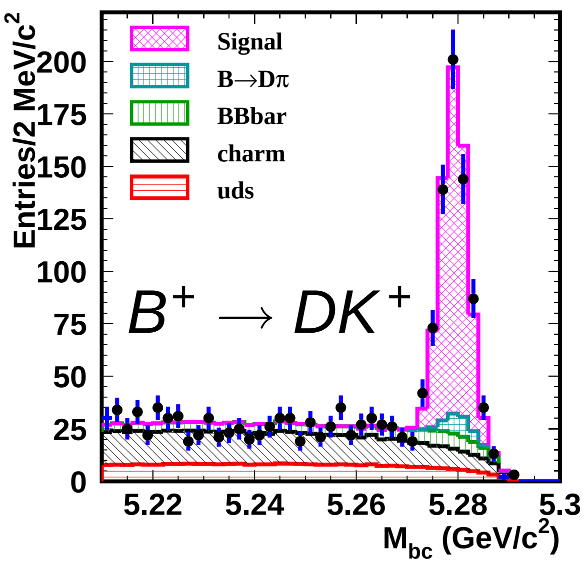
Angle γ

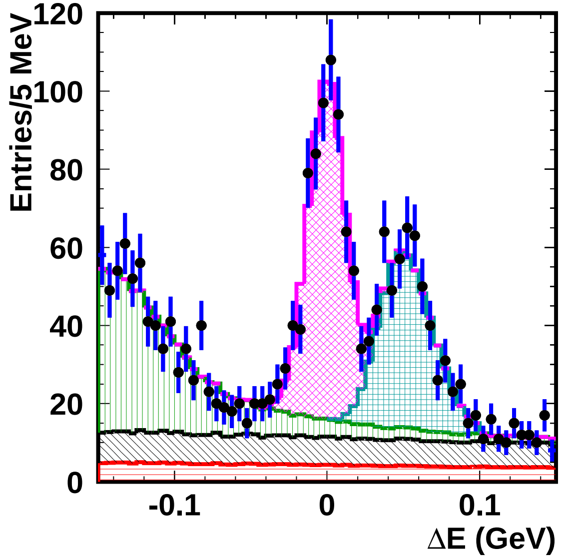
- Most sensitive is GGSZ method with $D^0 \to K_S\pi^+\pi^-$
- Belle and Babar made recent updates
- Both experiments see 3.5σ evidence for CPV
- Belle: $\gamma = (78^{+11}_{-12} \pm 4 \pm 9)^\circ$
- Babar: $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$

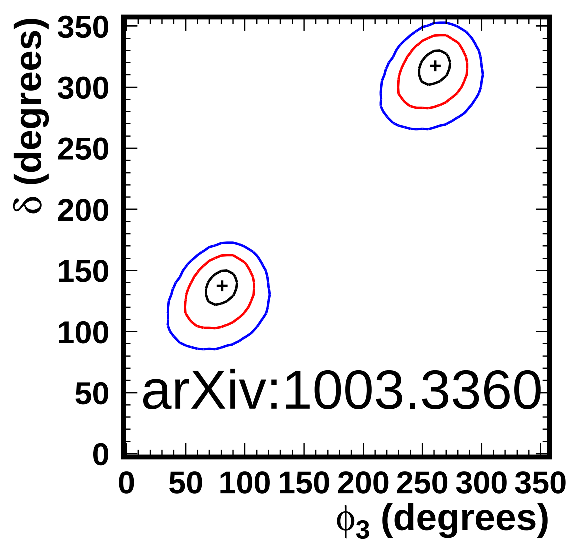
arXiv:1005.1096



Babar



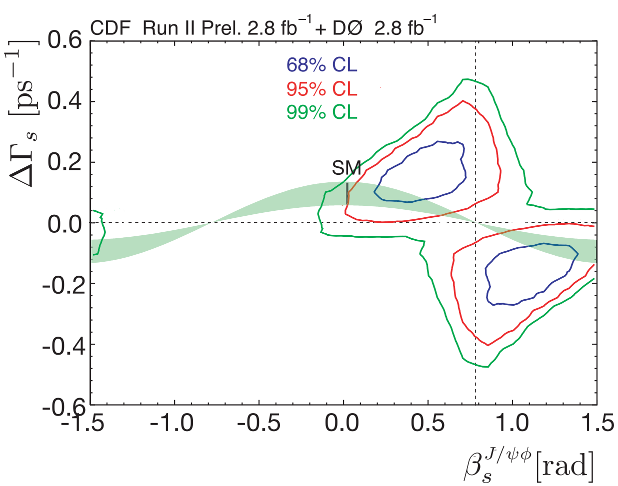


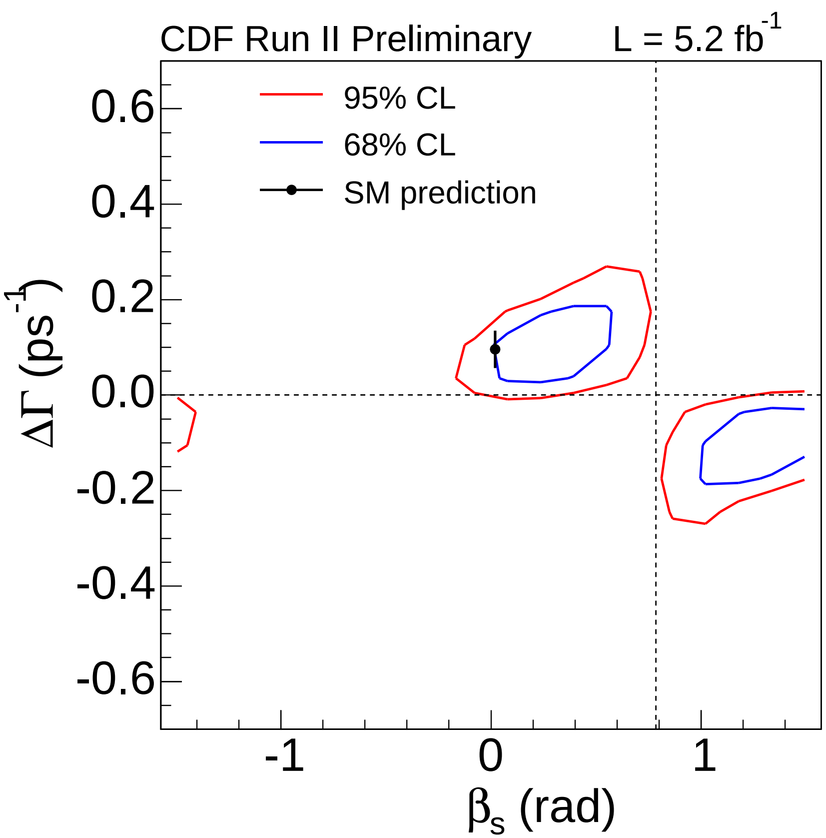


Belle

CP Violation in $B_s \to J/\psi\phi$

- Look for NP contributions in the B_s mixing phase
- Phase in SM tiny (almost real V_{ts})
- Basic logic is similar to $\sin 2\beta$ measurement
- Update from CDF with more data, several improvements
- Move towards SM
- See Elisa Pueschel in afternoon



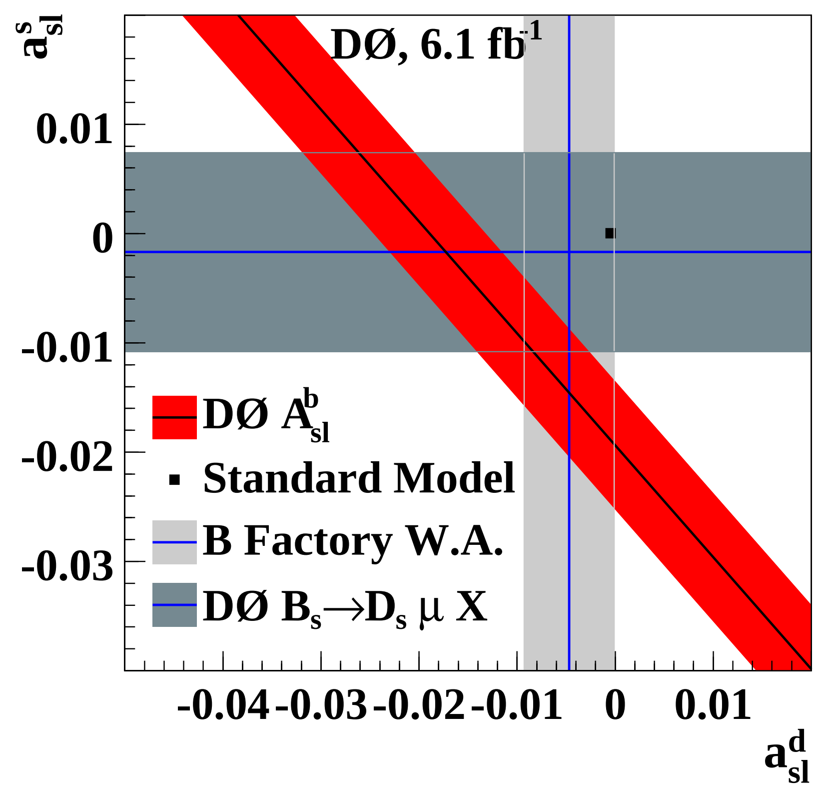


SM p-value 44%

A_{fs} measurement by DØ

- Alternative way to look for NP in mixing phase is to measure A_{fs}
- Connected to phase by $A_{fs} = \Delta\Gamma_q / \Delta m_q \tan\phi_q$
- Traditionally measured using:
  - Semileptonic decays
  - Same charge dimuons
- Recent measurement by DØ
- Measures $A^b_{fs} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$
- Mixture of B^0 and B_s effect
- SM prediction
  $A^b_{fs} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$
- Result:
  $(-96 \pm 25 \pm 15) \times 10^{-4}$
- Details see Iain Bertram

arXiv:1005.2757



Global status of the triangle

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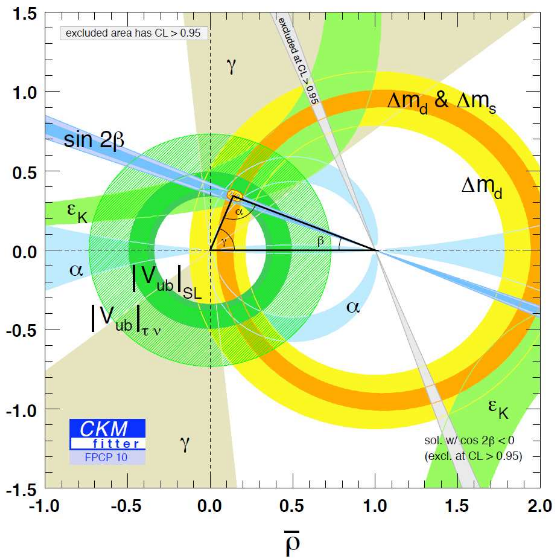
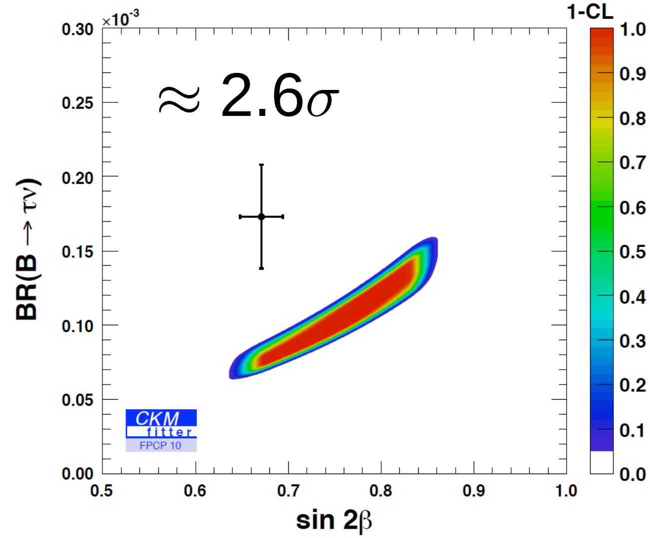
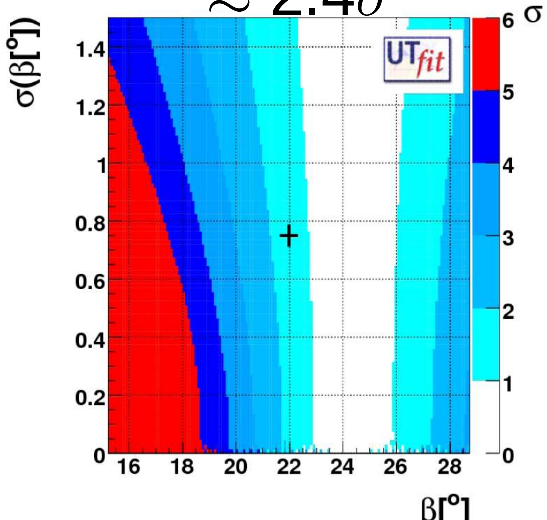


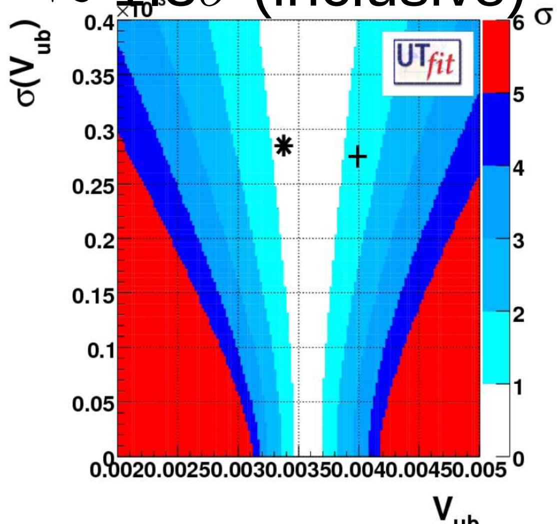


ckmfitter.in2p3.fr

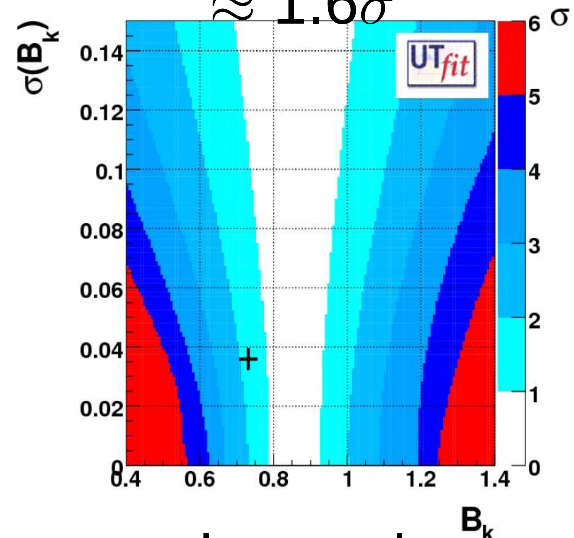
$\approx 2.4\sigma$



$\approx 1.3\sigma$ (inclusive)



$\approx 1.6\sigma$

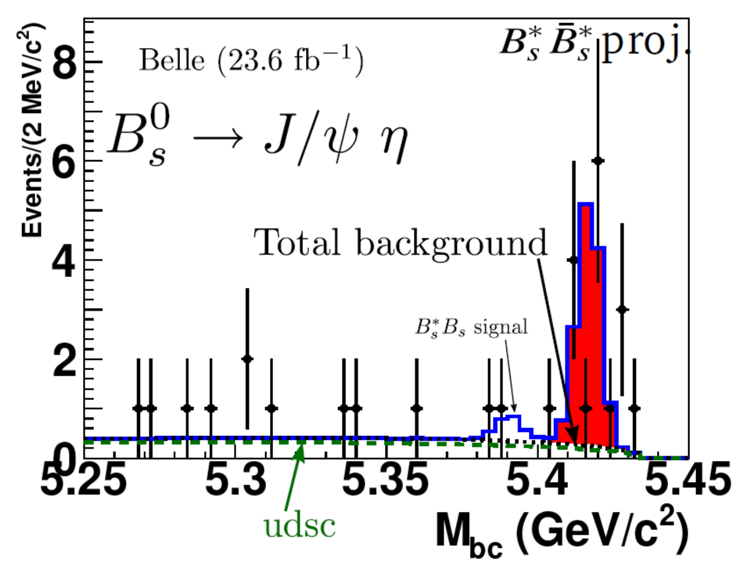


www.utfit.org

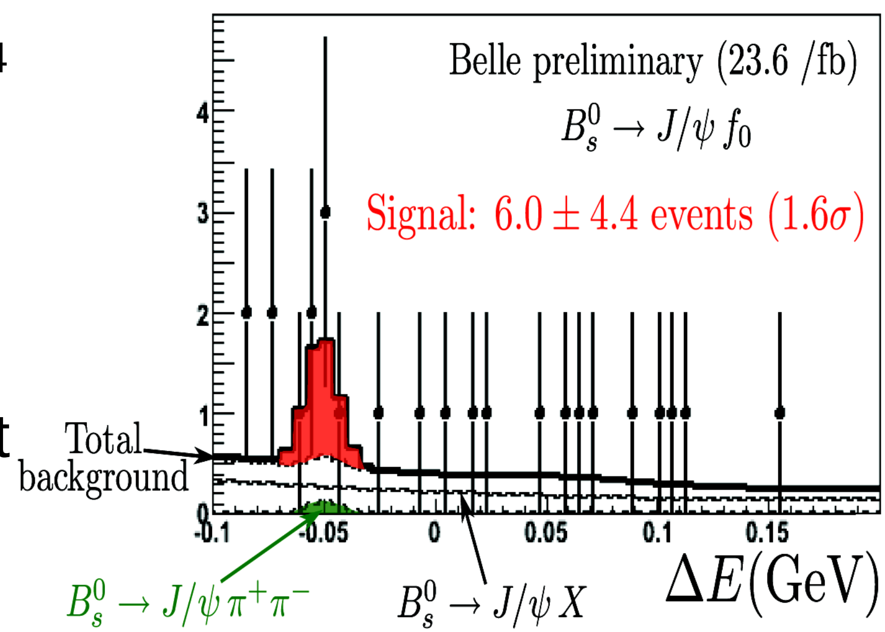
Globally no large discrepancy, but few tensions exist

Other B_s decays

- Belle successfully took data also at $\Upsilon(5S)$
- Provides access to B_s physics
- Cannot resolve B_s oscillations
- Can in principle do absolute BF
- First observation of $B_s \to J/\psi\eta$ with 7.3σ
  $3.32 \pm 0.87^{+0.32}_{-0.28} \pm 0.42(fs) \times 10^{-4}$
- Limit on $B_s \to J/\psi f_0(980)$
  $B(Bs \to J/\psi f_0) \cdot B(f_0 \to \pi^+\pi^-) <$
  1.63×10^{-4} at 90% C.L.
- More details in talk of Jean Wicht

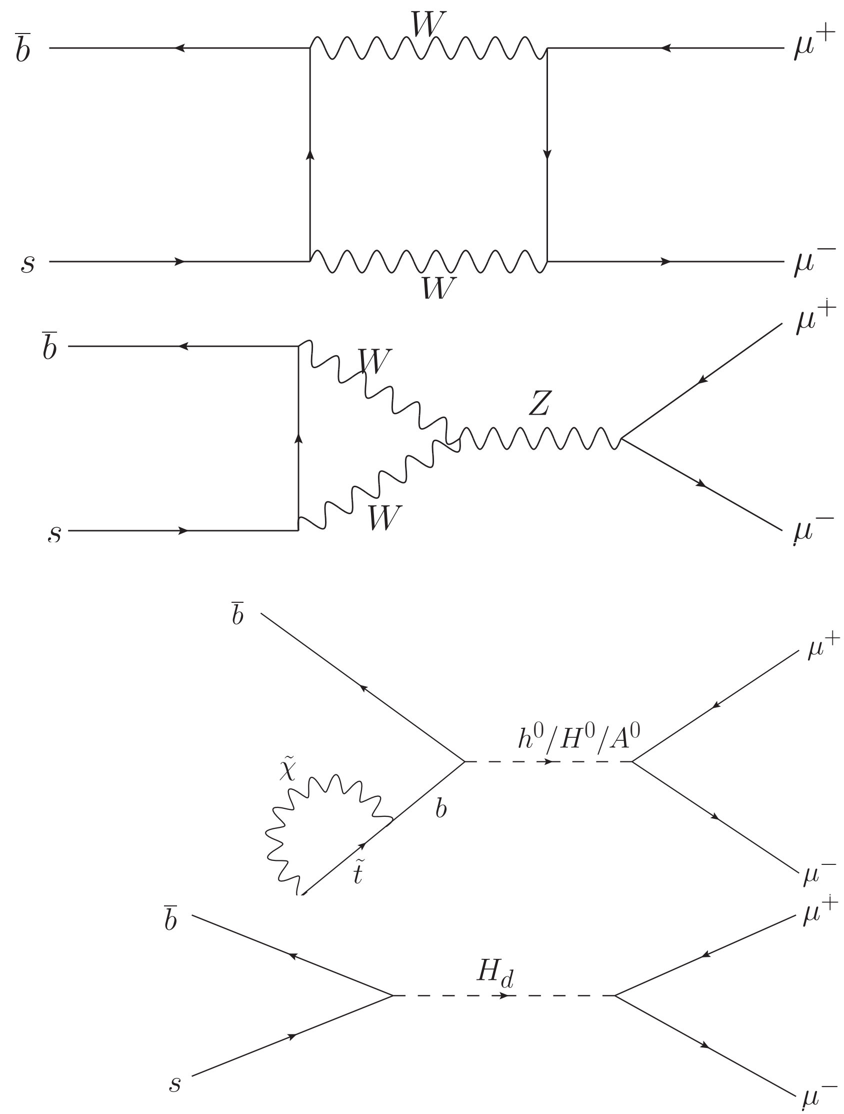


arXiv:0912.1434

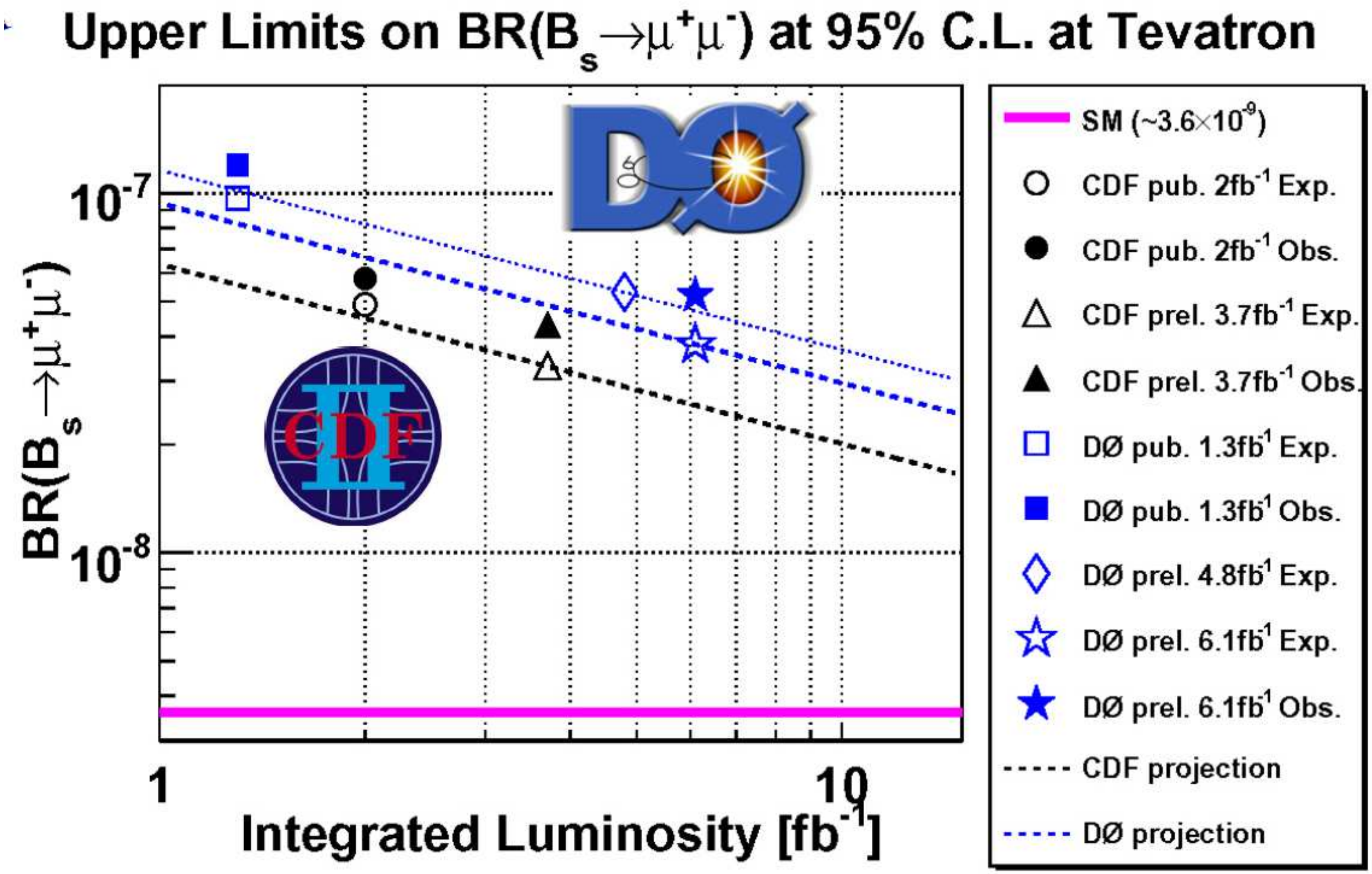


Rare decays - $B_s \rightarrow \mu\mu$

- FCNC decays are good probes of NP
- $B_s \rightarrow \mu\mu$ one of the most watched
- SM prediction (A.J.Buras, hep-ph/0904.4917): $(3.6 \pm 0.3) \times 10^{-9}$
- NP can enhance it by huge factors (many models by several orders of magnitude)
- Hard constraints on NP even without seeing signal
- Signal at Tevatron implies NP



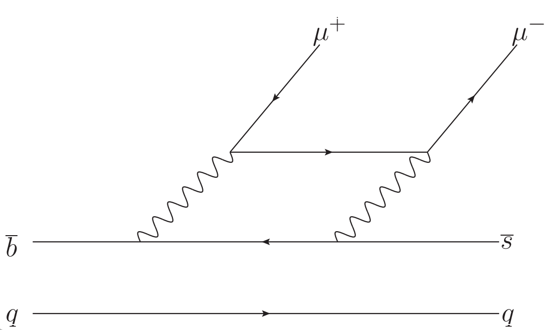
Rare decays - $B_s \to \mu\mu$

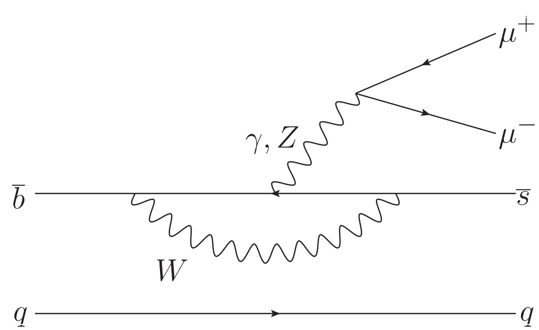


- CDF Preliminary, 3.7 fb^{-1}: $< 4.3 \cdot 10^{-8}$ at 95% C.L.
- DØ Preliminary, 6.1 fb^{-1}: $< 5.2 \cdot 10^{-8}$ at 95% C.L.

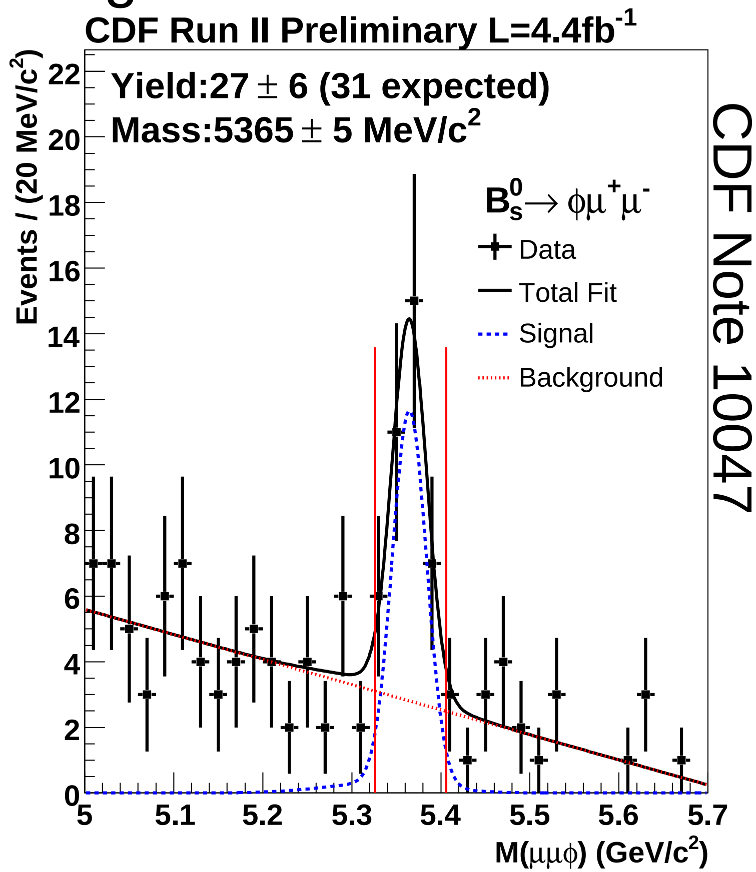
Rare decays - $b \to s\mu\mu$

- Another example of FCNC rare decay
- BF of the order of 10^{-6}
- Study decays:
  - $B^{0/+} \to \mu^+\mu^- K^{0/+}$
  - $B^{0/+} \to \mu^+\mu^- K^{*0/*+}$
  - $B_s \to \mu^+\mu^-\phi$
- NP can show up in (partial) BF, decay polarization or angular distributions





- First observation of $B_s \to \mu^+\mu^-\phi$
- BF=$[1.44 \pm 0.33 \pm 0.46] \cdot 10^{-6}$
- 6.3σ significance



Rare decays - $b \rightarrow s\mu\mu$

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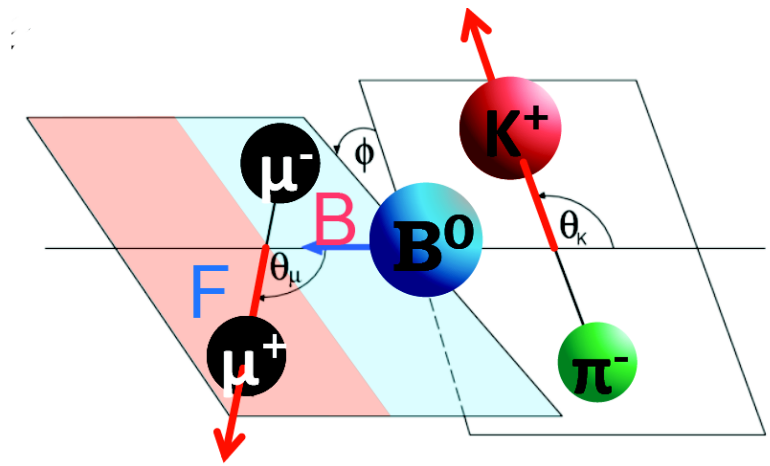
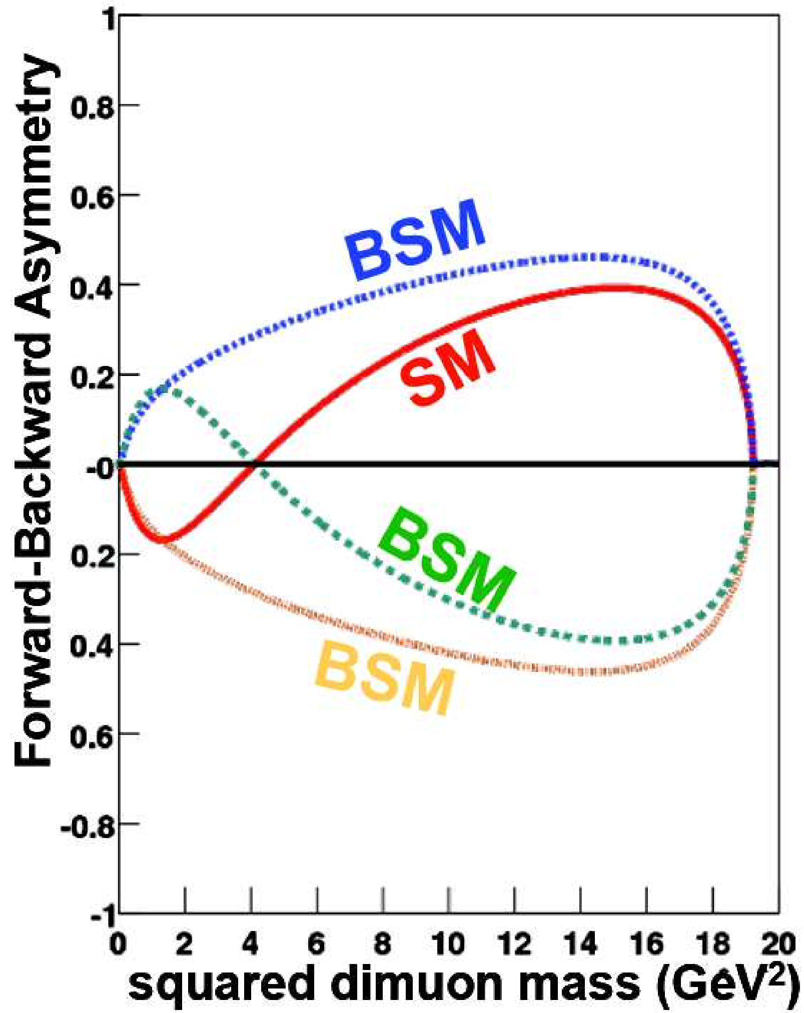


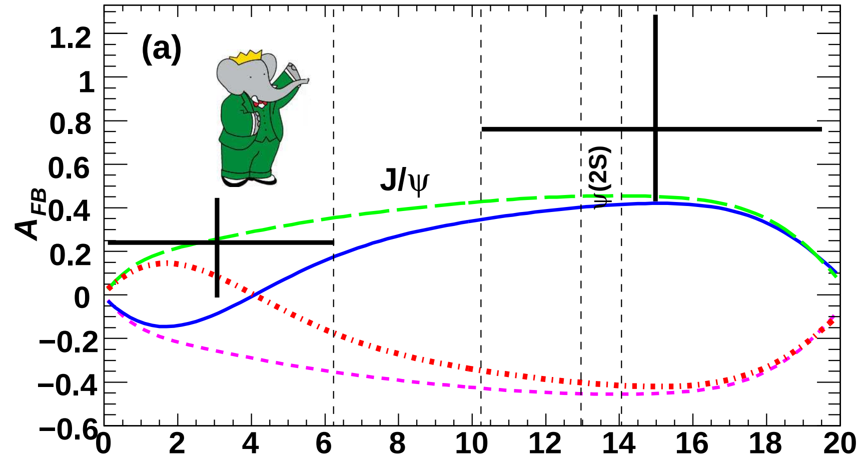
$B^0 \rightarrow K^{*0}\mu\mu$ decay plane

- Looking to observables connected to angular distributions most promising
- Currently mainly
$$A_{FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$
- Other options exist, but no-body tried

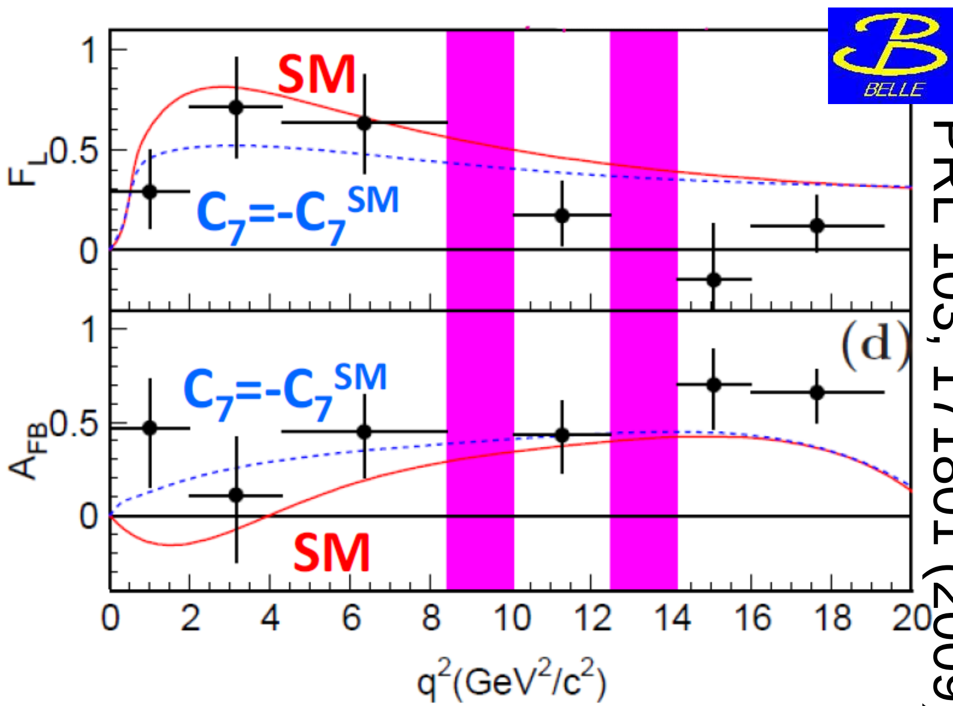


Rare decays - $b \to s\mu\mu$

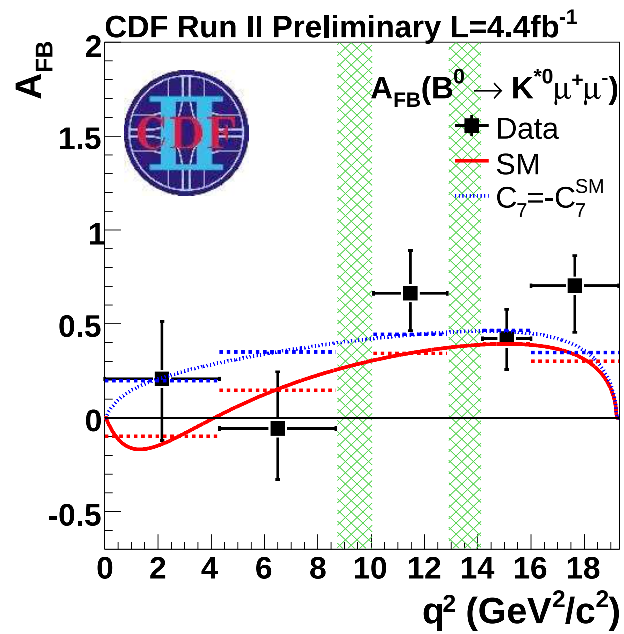
- Three experiments produced result
- Consistent with SM expectation
- Intriguing fluctuation in same direction for all results



PRD 79, 031102 (2009)



PRL 103, 171801 (2009)



CDF Note 10047

Conclusions

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- Tremendous progress in past few years
- There is much more, which I could not cover in short time
  - Charm sector - for status see Thomas Mannel and Jeorg Marks
  - Future (starting) experiments - for LHC prospects see parallel session in afternoon
- In global there is no significant discrepancy with SM
- Nevertheless there are several places which show interesting tensions
- With LHC we are at the beginning of new era, even if existing experiments will do their best in this new era
- I'm sure we are entering interesting era