Current Status of CP Violation, Rare Decays & Heavy Flavor Physics

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ICFA Seminar, October 2011

Seeking new physics through quark flavor

- Precision measurements of SM parameters
  - » Quark flavor measurements have established a consistent picture of the weak interaction sector of the SM
  - » Consistency & increasing precision for CKM parameters offers opportunities for discovering new physics
- CP violation and CP violating phases
  - » Interference of amplitudes required for CP inherently sensitive to introduction of new phases
- Rare decays
  - » Processes with new BSM amplitudes, phases and helicity properties will produce final states with different BR, angular distributions, and phases
  - » There are many examples of SM-suppressed FCNC transitions where new physics effects can be large

The Players

B Factories, BES-III

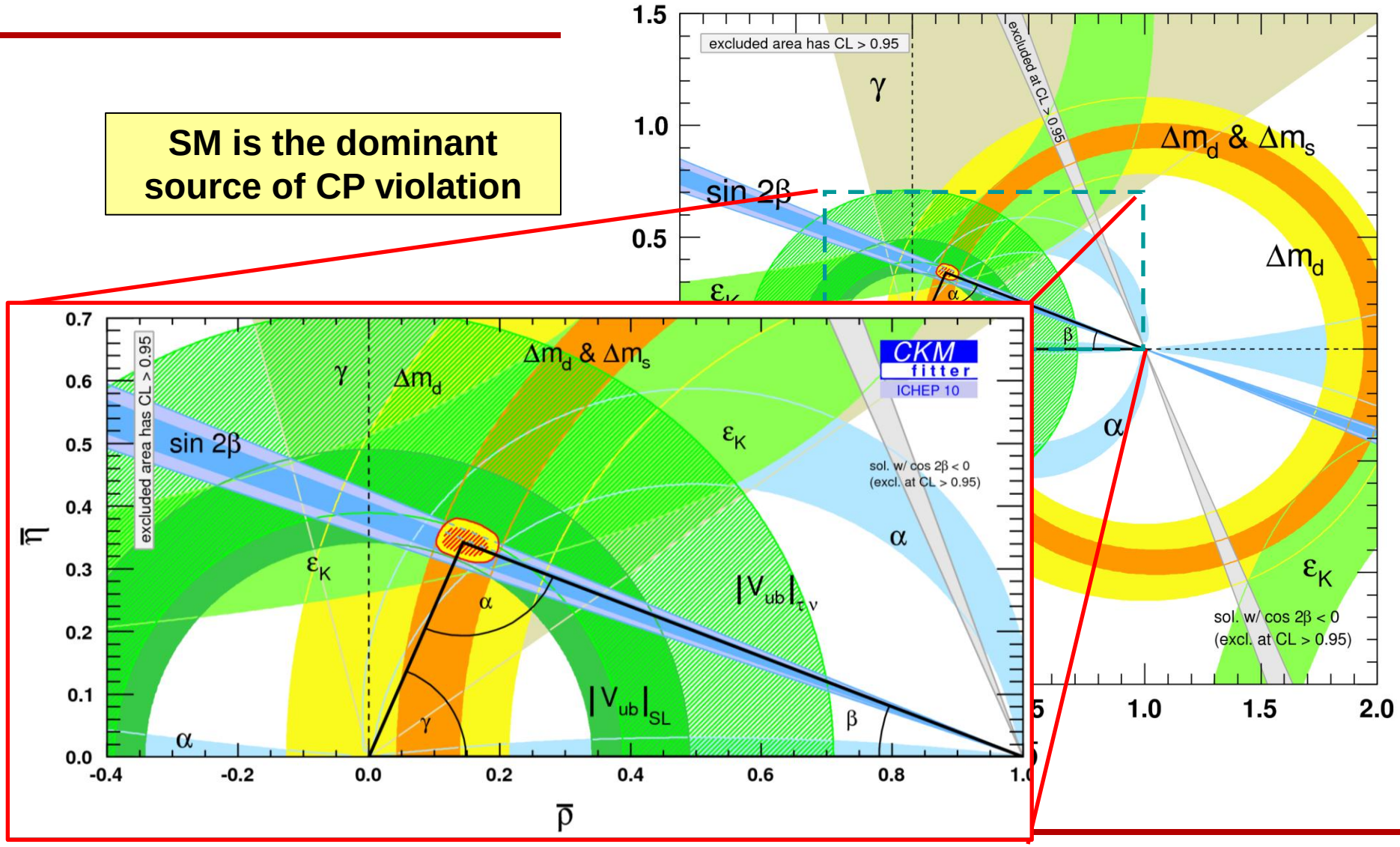
Upgraded LHCb, Super Flavor Factories: Next talk

Tevatron, LHC

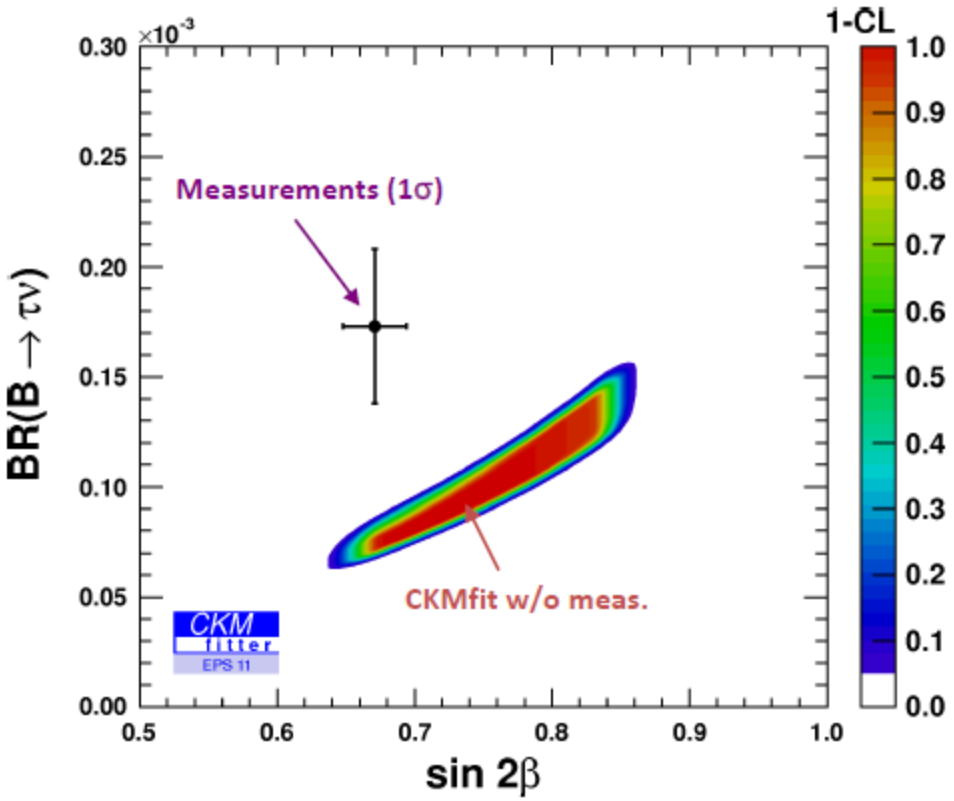
Much of the material for this talk drawn from LP2011 plenary talks

Status of the quark flavor sector of the SM

SM is the dominant source of CP violation



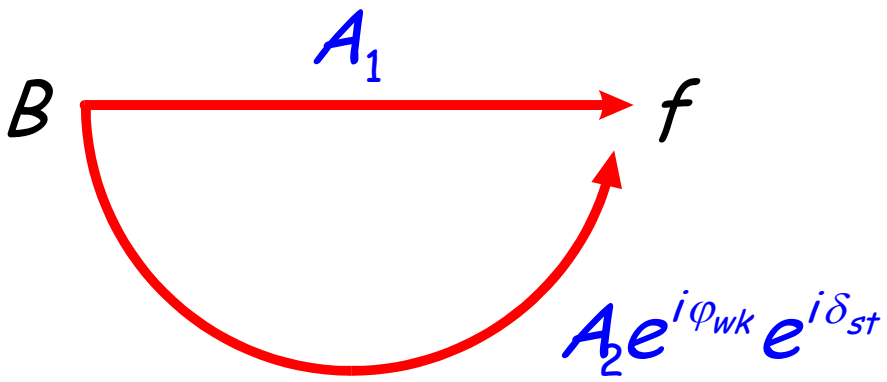
Hint of problem with current CKM measurements



- Tension between observed values of $\sin(2\beta_{cc})$ and $BF(B^{\pm} \to \tau^{\pm}\nu)$ with predictions from fit
  - » BF too high or sin2β too low
- BF measurements are consistent between BABAR & Belle
- LQCD calculations for BF factor $f_{B_d}^2 B_{B_d}$ in good agreement with observation

Seeking new physics in CP violation

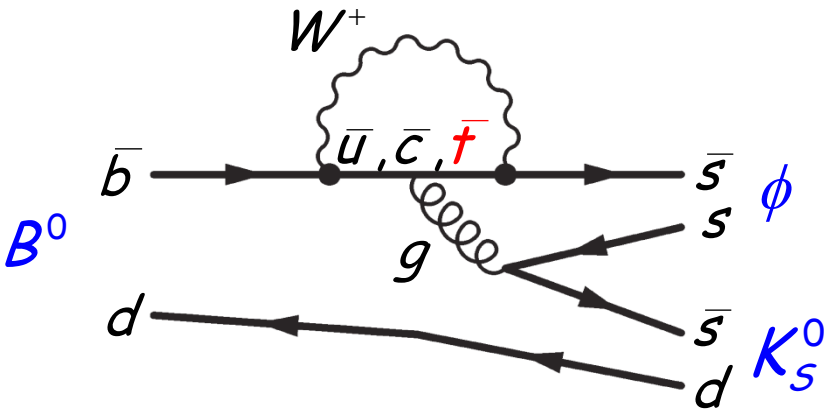
- Sources
  - » CPV through interference of decay amplitudes
  - » CPV through interference between mixing and decay amplitudes
  - » CPV through interference of mixing diagram
- Sensitivity to new physics
  - » Interference of amplitudes required for CP inherently sensitive to introduction of new phases

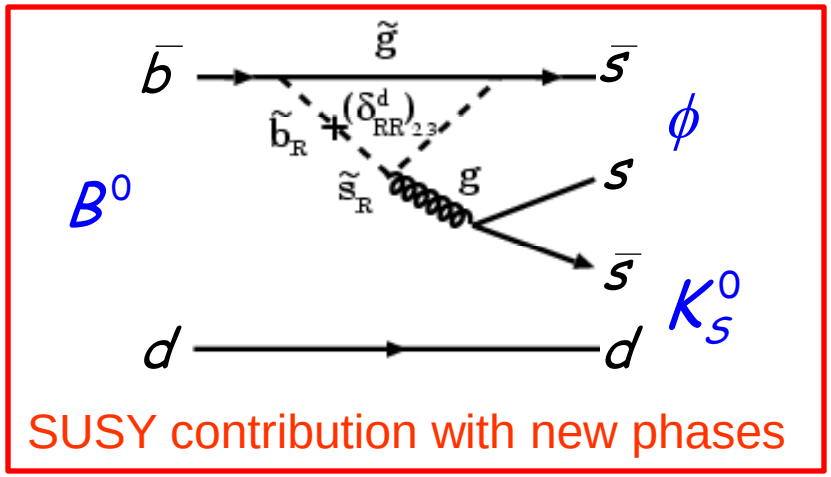


$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$
for $\varphi_{wk} \neq 0$ and $\delta_{st} \neq 0$

New physics by comparing like quantities

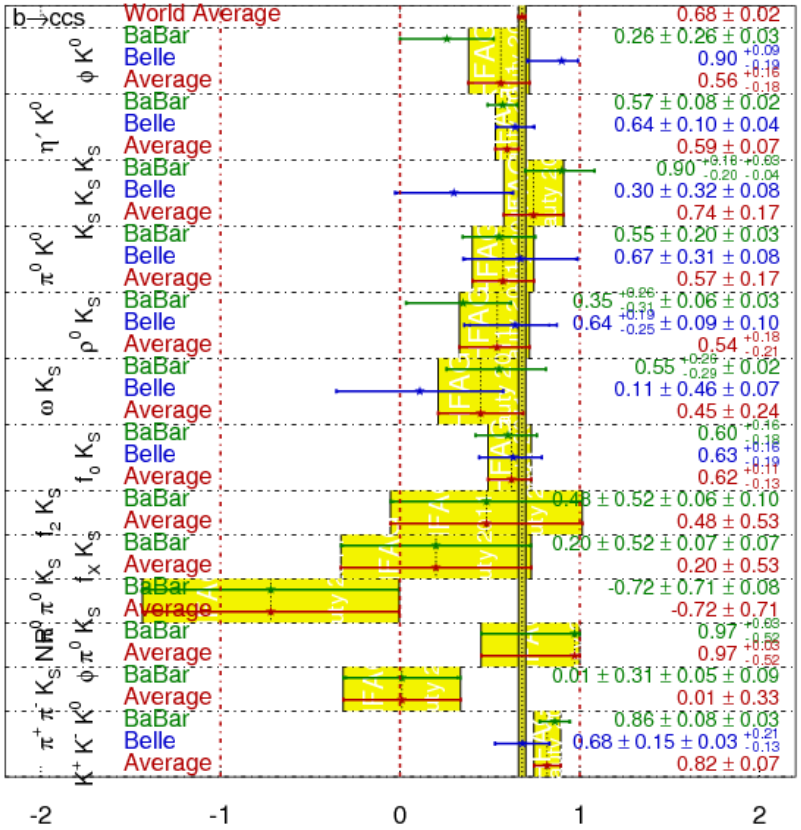
$B^0 \to \phi K^0$





SUSY contribution with new phases

$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$ HFAG Beauty 2011 PRELIMINARY

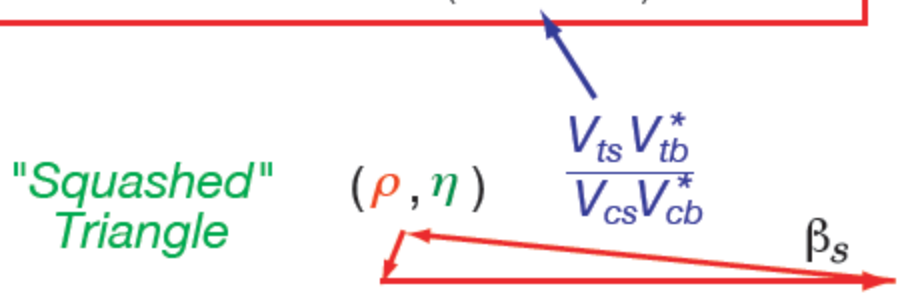


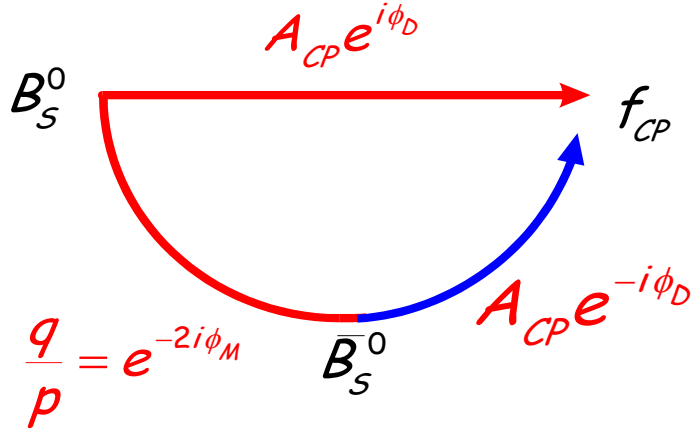
sin2β from penguin & golden modes should be and are consistent

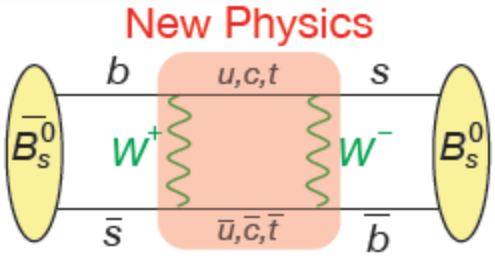
Search for NP in B_s mixing phase

- B_s mixing phase has been measured in both $B_s \rightarrow J/\psi\,\phi$ and $B_s \rightarrow J/\psi\,f_0$ decays

$$\phi_s^{J/\psi\phi} \approx -2\beta_s = \underbrace{-2\beta_s^{SM}}_{-(0.038 \pm 0.002)} + \phi_s^{NP}$$



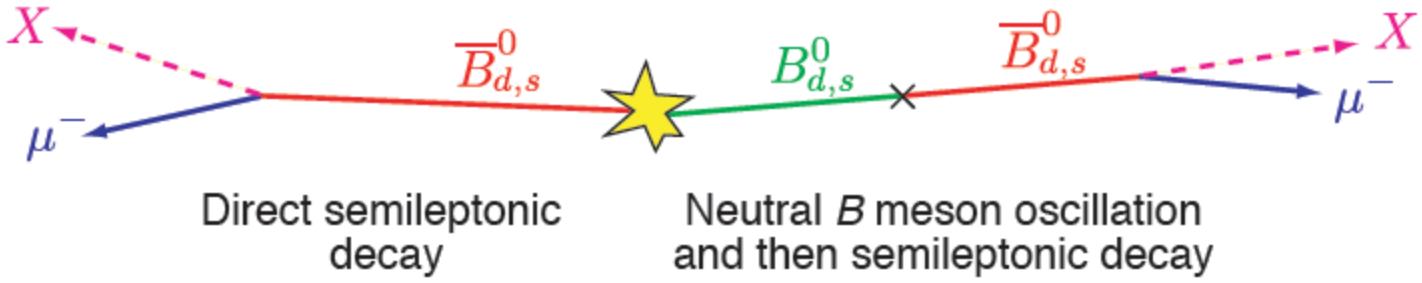




- NP can add large phases in the box: ϕ_s^{NP}

Dimuon charge asymmetry measurement at D0

Measurable: Like-sign dimuon charge asymmetry:



$$A^b_{Sl} = \frac{N^{++}_{b\bar{b}} - N^{--}_{b\bar{b}}}{N^{++}_{b\bar{b}} + N^{--}_{b\bar{b}}} = C_d a^d_{Sl} + C_s a^s_{Sl}$$

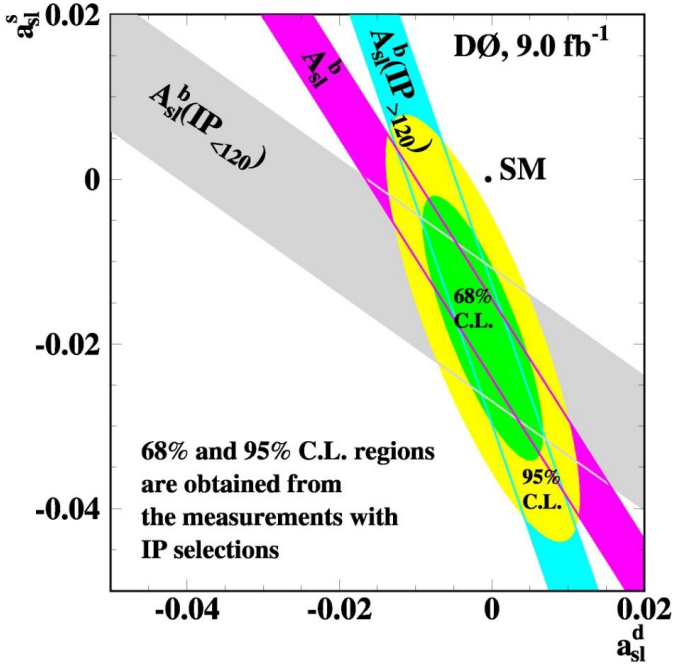
D0 observes:

$$A^b_{Sl} = (-0.787 \pm 0.172(stat) \pm 0.093(syst))\%$$

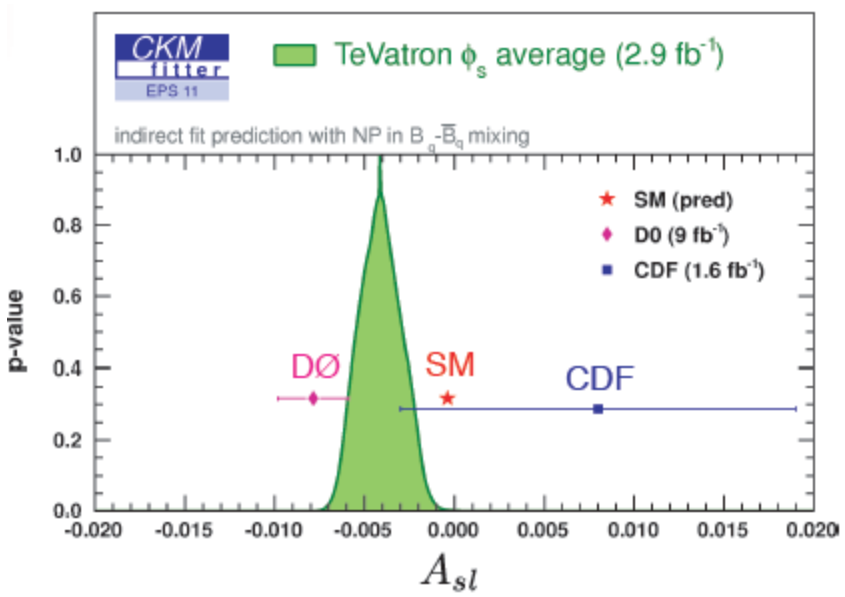
versus Standard Model expectation:

$$A^b_{Sl}(SM) = (-0.028^{+0.005}_{-0.006})\% \quad (3.9\sigma \text{ difference})$$

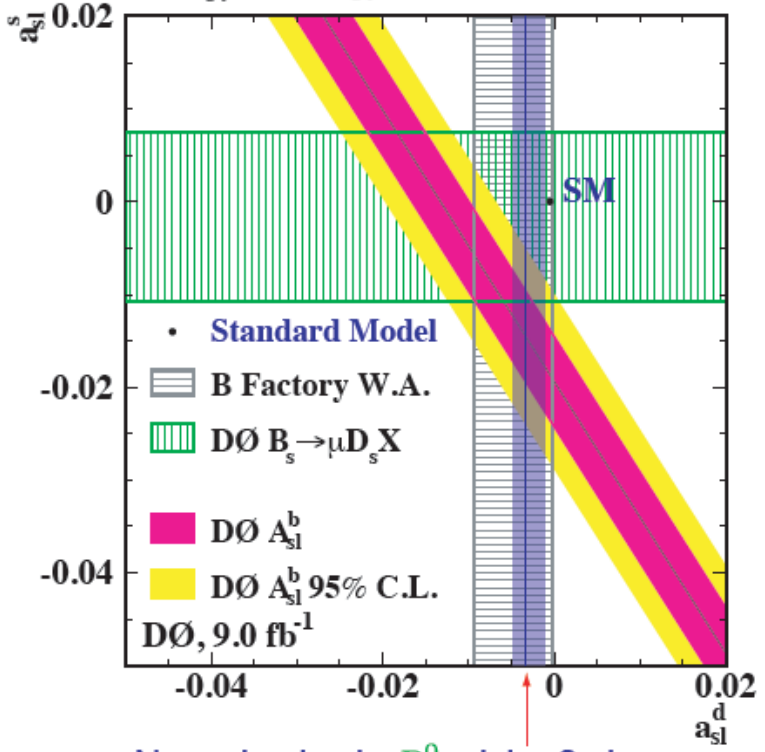
V.M.Abazov, et al. (D0 Collab), FERMILAB-PUB-11-307-E



Asymmetry measurement from D0



- Result consistent with other measurements of a^d_{sl} and a^s_{sl}



New physics in B^0_s mixing? since a^d_{sl} constrained by "sin2β" in global fits:

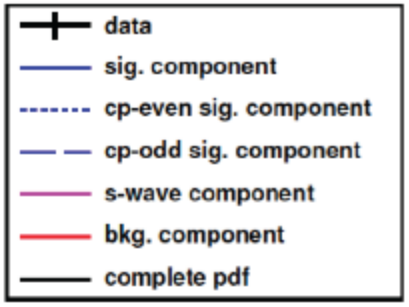
$a^d_{sl}(\text{pred.}) = (-36^{+23}_{-11}) \times 10^{-4}$ PRD **83**, 036004 (2011)

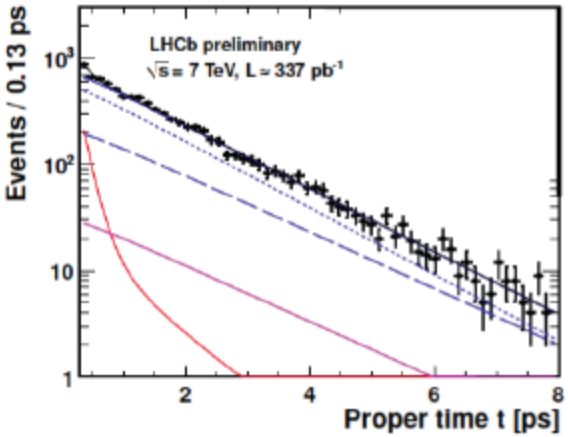
LHCb measurements of ϕ_s from $B_s \rightarrow J/\psi\ \phi$

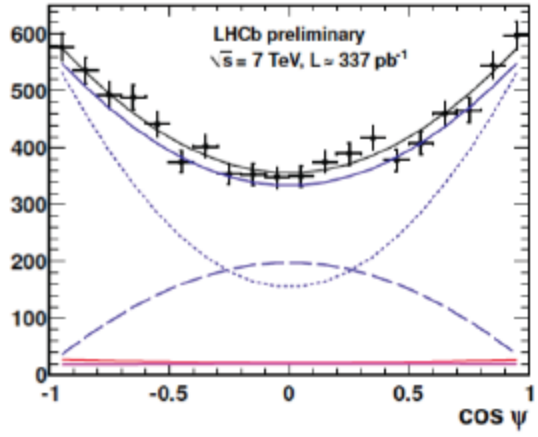
PS to VV final state:

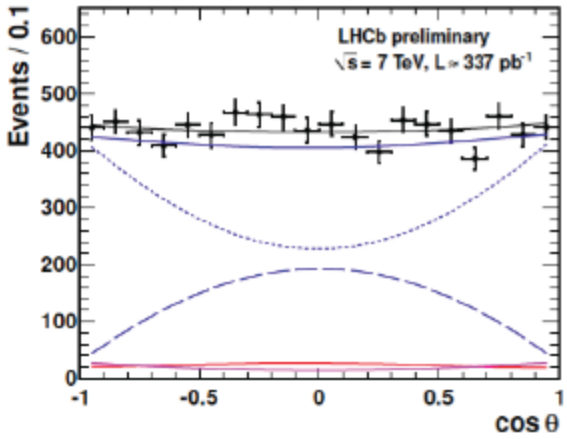
Need full angular time-dependent CP analysis, performed in transversity basis

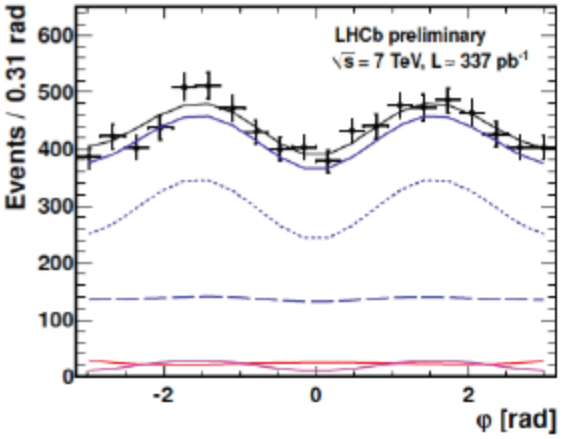
LHCb sample of 8300 B_S signal events with superimposed fit results



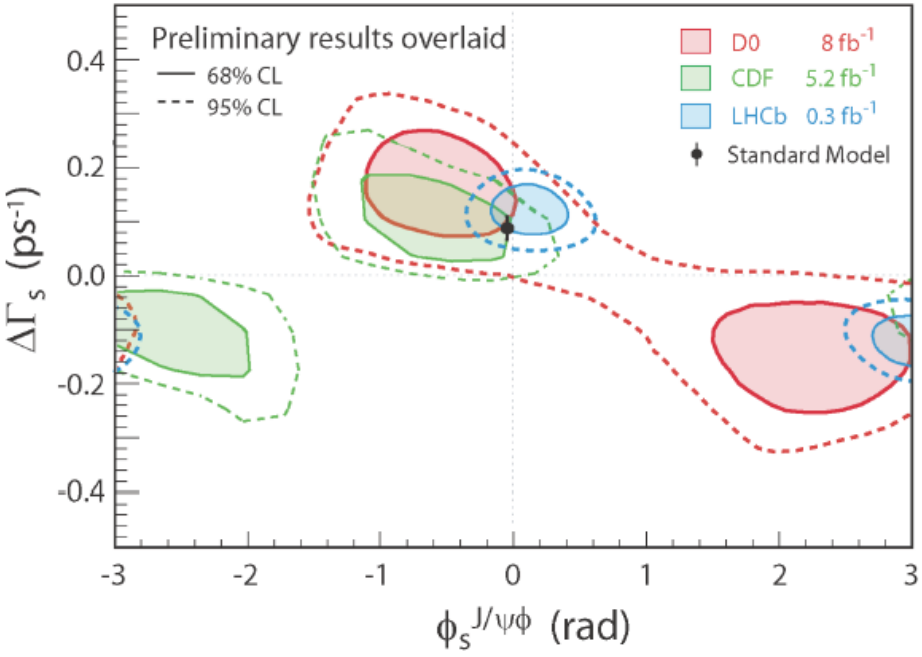






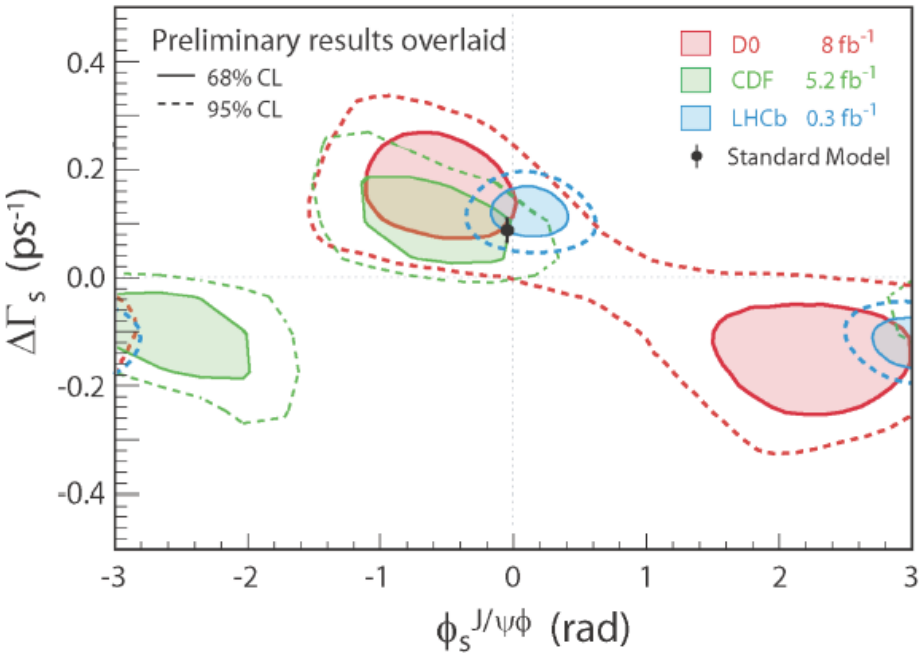


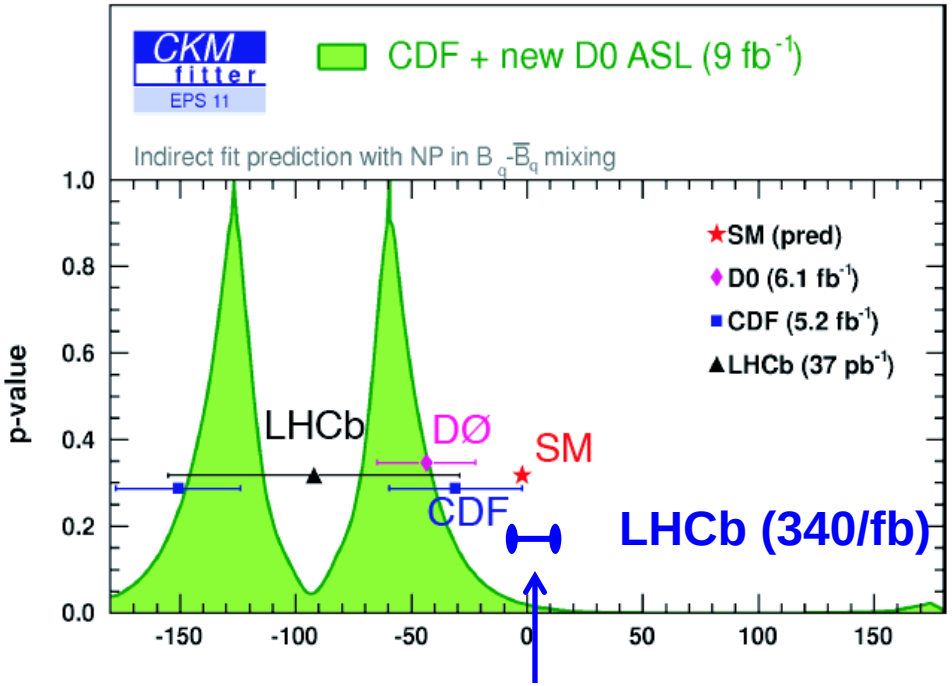
LHCb measurements of ϕ_s from $B_s \rightarrow J/\psi\, \phi$



- Single most precise measurement of ϕ_s
  - » $\phi_s = 0.13 \pm 0.18$ (stat) $\pm$ 0.07 (syst) rad
  - » Consistent with SM
- 4σ Evidence for $\Delta\Gamma_s \neq 0$:
  - » $\Delta\Gamma s = 0.123 \pm 0.029$ (stat) $\pm$ 0.008 (syst) ps^{-1}
  - » $\Gamma s = 0.656 \pm 0.009$ (stat) $\pm$ 0.008 (syst) ps^{-1}

Summary of ϕ_s from $B_s \rightarrow J/\psi\,\phi$

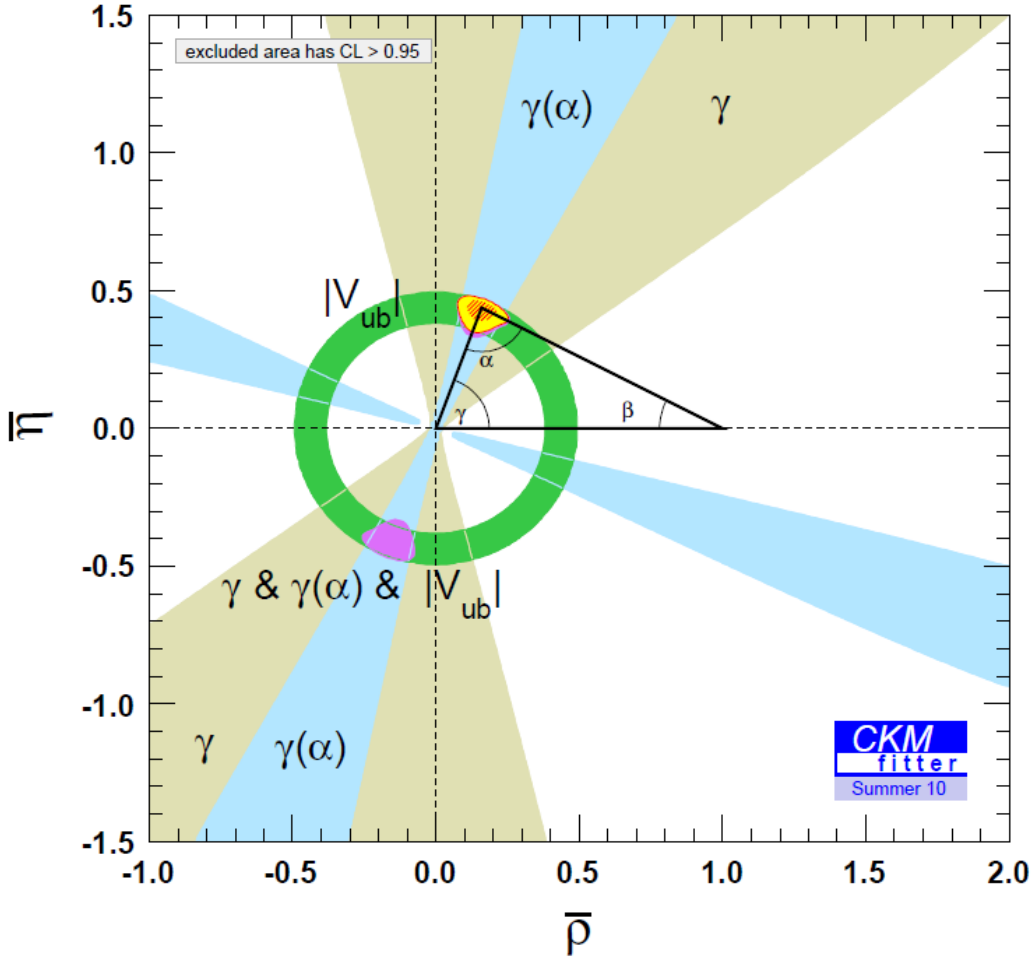




$$\phi_s = 0.03 \pm 0.16 \pm 0.07$$

Combined $J/\psi\phi, J/\psi f_0$

Exploiting redundancy in CKM constraints



Subset of tree-level processes that are not affected by new physics in mixing

$$|V_{ud}|, |V_{us}|, |V_{cb}|, |V_{ub}|, \gamma,$$

$$\gamma(\alpha) = \pi - \alpha - \beta_{cc}$$

Use to constrain new physics in box diagrams

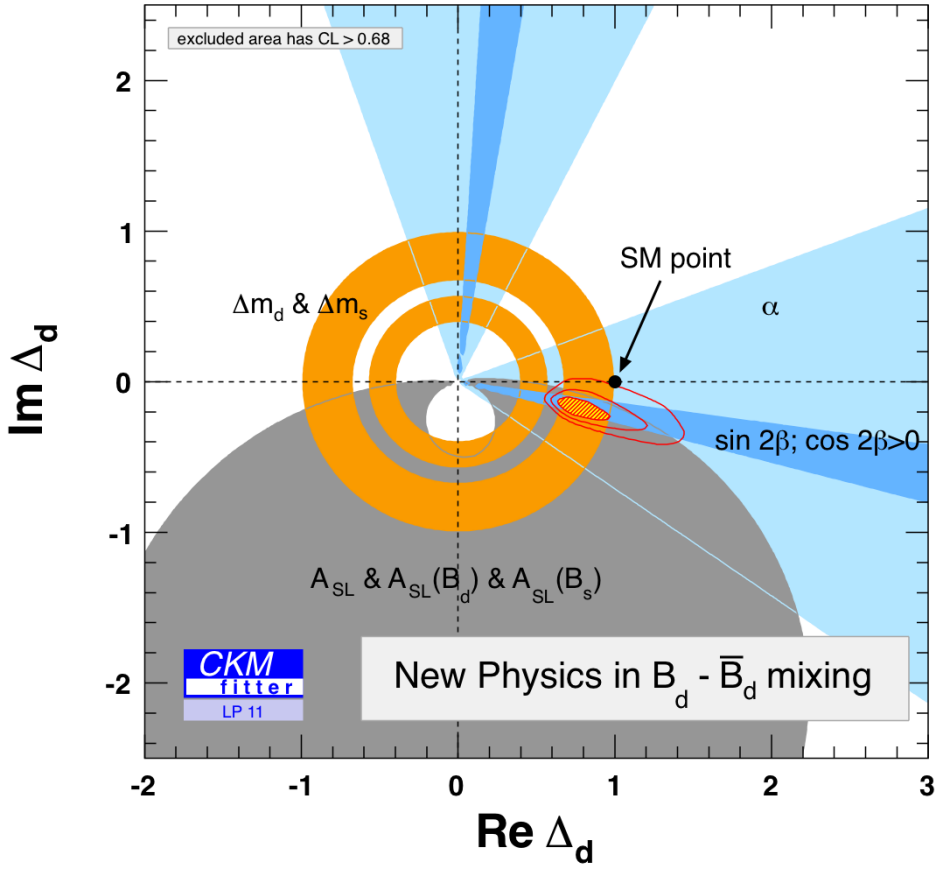
New physics in B_d^0-$\overline{B}_d^0$ mixing diagram

One way to parameterize NP:

(JHEP **706** (2007) 72; PRD **34** (2011) 717)

$$\frac{M_{12}^q}{M_{12}^{SM,q}} = |\Delta_q| e^{2i\phi_q^{NP}}$$

$$\Delta m_q \to |\Delta_q^{NP}| \times \Delta m_q^{SM}$$
$$2\beta \to 2\beta^{SM} + \phi_d^{NP}$$
$$2\beta_s \to 2\beta_s^{SM} - \phi_s^{NP}$$
$$2\alpha \to 2(\pi - \beta^{SM} - \gamma) - \phi_d^{NP}$$
$$\phi_q \to \phi_q^{SM} + \phi_q^{NP}$$



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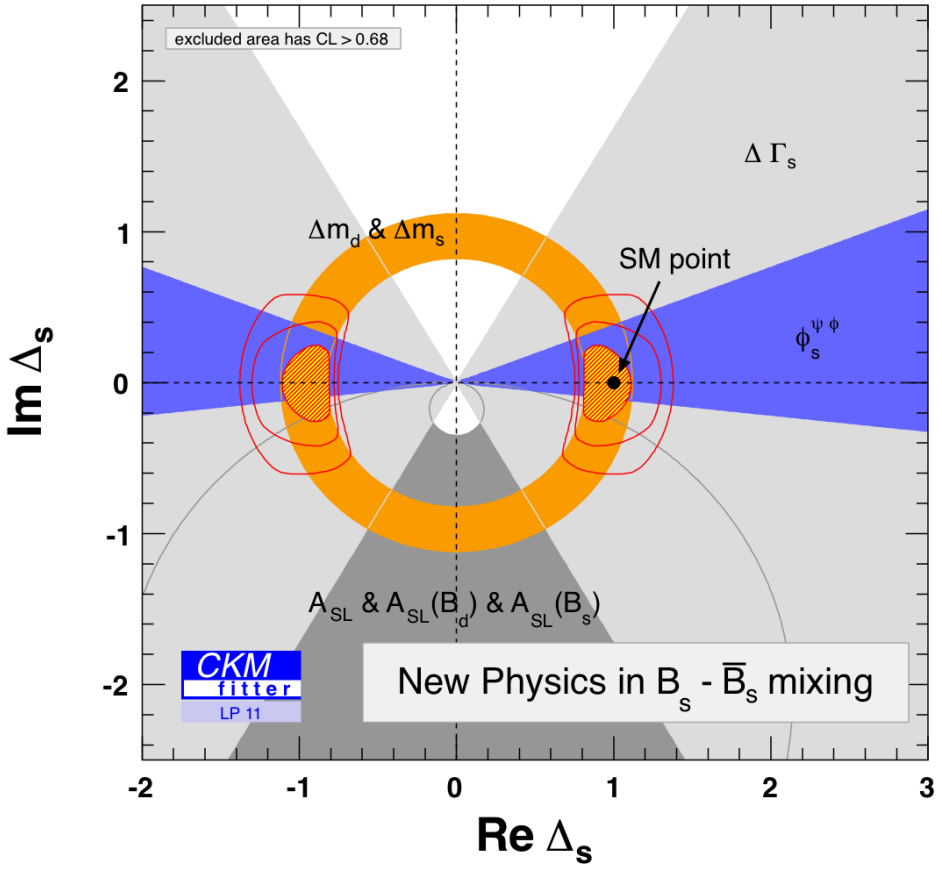
$$\phi_q \to \phi_q^{SM} + \phi_q^{NP}$$

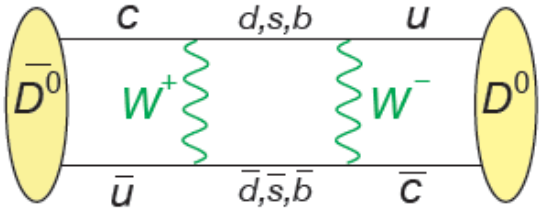


D^0-$\bar{D}^0$ mixing

$$x = \frac{\Delta m}{\Gamma}$$

$$y = \frac{\Delta \Gamma}{2\Gamma}$$

Short Distance



Effective CKM & GIM suppression

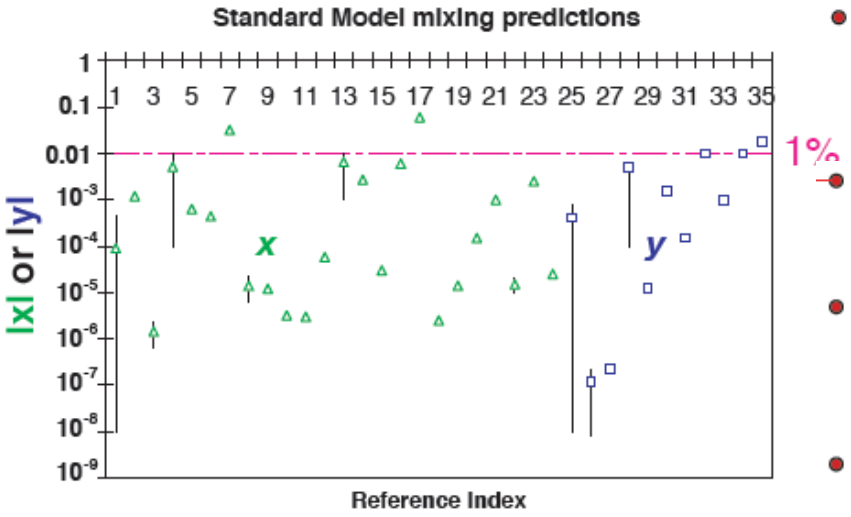
$|x|,\ |y| \leq 10^{-3}$

+

Long Distance

Contribution from hadronic intermediate states

$x,\ y \simeq$ up to 1%



A. Petrov, Int.J.Mod.Phys.A21, 5686

- Large uncertainty in SM mixing rate
  more difficult to identify New Physics contributions
- In contrast to *B* mixing, would involve FCNC processes to *up*-type quarks
- Measurements of *x* and *y* still provide very useful constraints on many New Physics models
- In general, New Physics, increases *x* mostly, i.e., $|x| \gg |y|$

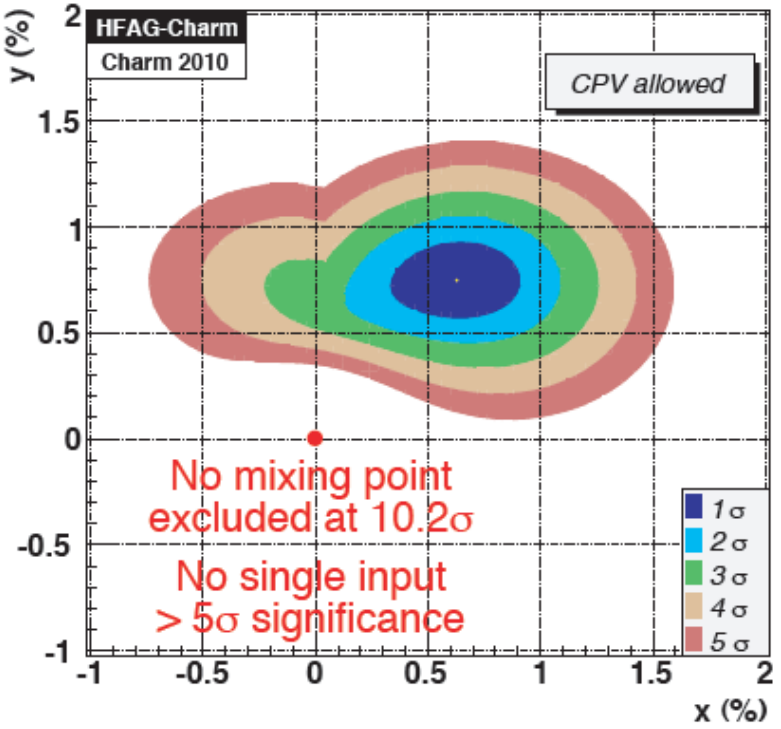
D^0-$\bar{D}^0$ mixing measurements

$$\frac{dN(D^0 \to f)}{dt} \propto \left| \langle f|D^0\rangle + \frac{q}{p}\left(\frac{ix+y}{2}\langle f|\overline{D^0}\rangle\right)\right|^2$$

- Tag initial state flavor at production using strong decay $D^{*+} \to D^0\pi^+$

Final state f	Belle	BaBar	CDF	Cleo	E791	Focus
$K^+\pi^-$	✓	■	■	✓	✓	✓
$KK, \pi\pi$	■	■		✓	✓	✓
$K^0_S\pi\pi$	✓	✓		✓		
$K^0_S KK$	✓	✓				
$K^+\pi^-\pi^0$		■				
$K^+\pi^-\pi^-\pi^+$		✓				
$K^+\ell^-\nu_\ell$	✓	✓		✓	✓	

- measurement made; ■ - evidence for mixing

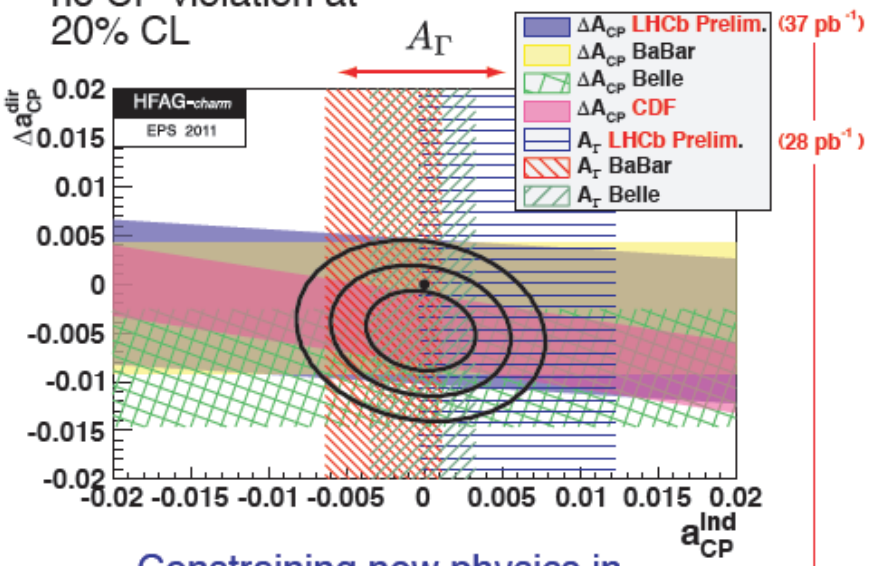


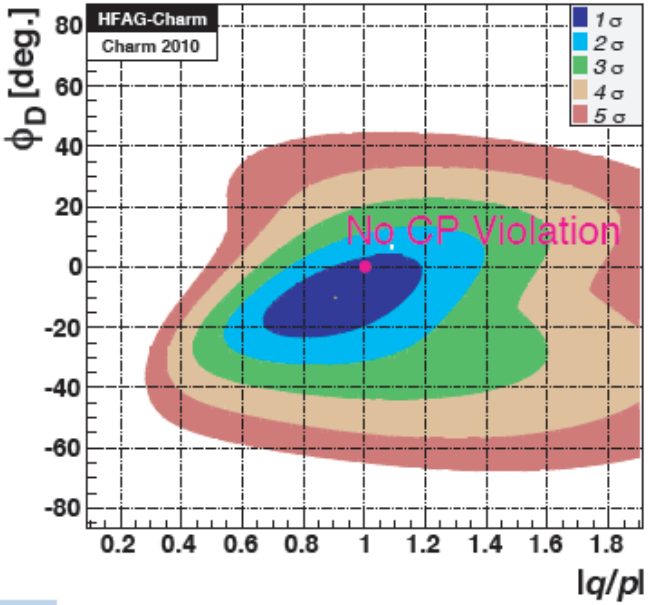
- Mixing small, but still larger than anticipated
- Presence of *D* mixing now allows searches for new physics in CP-violating effects!

$$x = (0.63 \pm 0.20)\%$$
$$y = (0.80 \pm 0.13)\%$$

CP violation in charm mixing

Data consistent with no CP violation at 20% CL





Constraining new physics in charm mixing

Conclusions

- The WA of *x* and *y* seem consistent with SM expectations
- Provide strong constraints for some New Physics models

- Large CPV $\mathcal{O}(1\%)$ already excluded in many modes
- Updated fits $\phi_D \sim \pm 0.10$
  $\phi_D(\mathrm{SM}) \sim 0.01$ (Kagan et al.)

  Still room for New Physics!

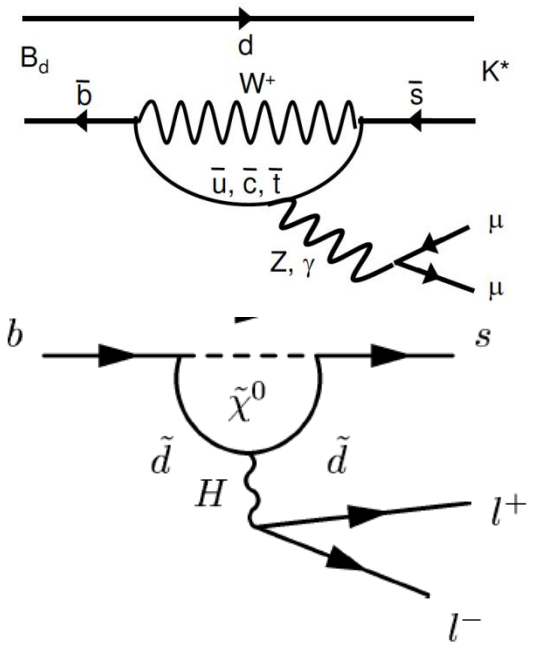
Seeking new physics through rare decays

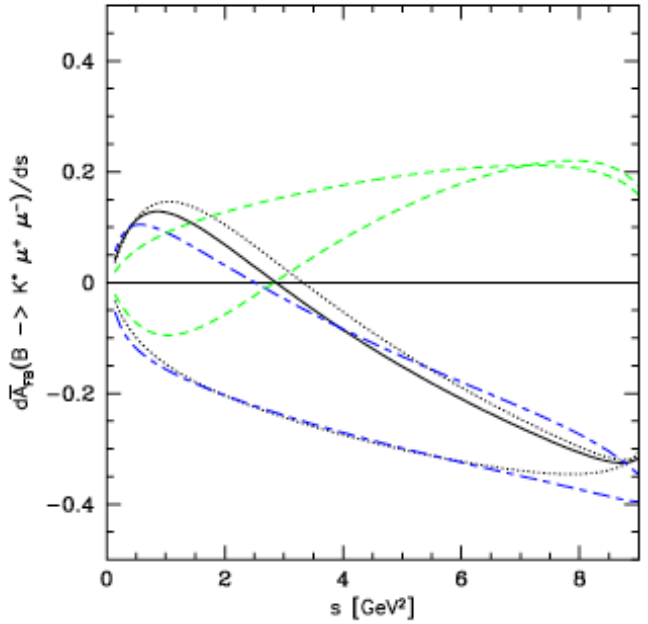
- Diagrams with new BSM amplitudes, phases and helicity properties will produce final states with different BR, angular distributions, and phases

Example: $B_d \rightarrow K^* \mu\mu$ forward backward asymmetry in different SUSY models

SM penguin

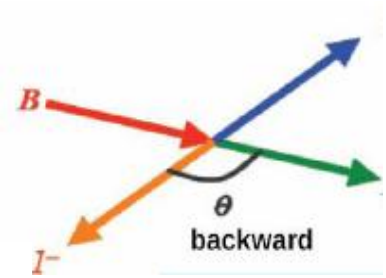
NP penguin





AFB in $B_d \rightarrow K^* \mu\mu$: experimental status

- Early results have shown intriguing hints of deviations from SM but statistics were too poor to claim any evidence

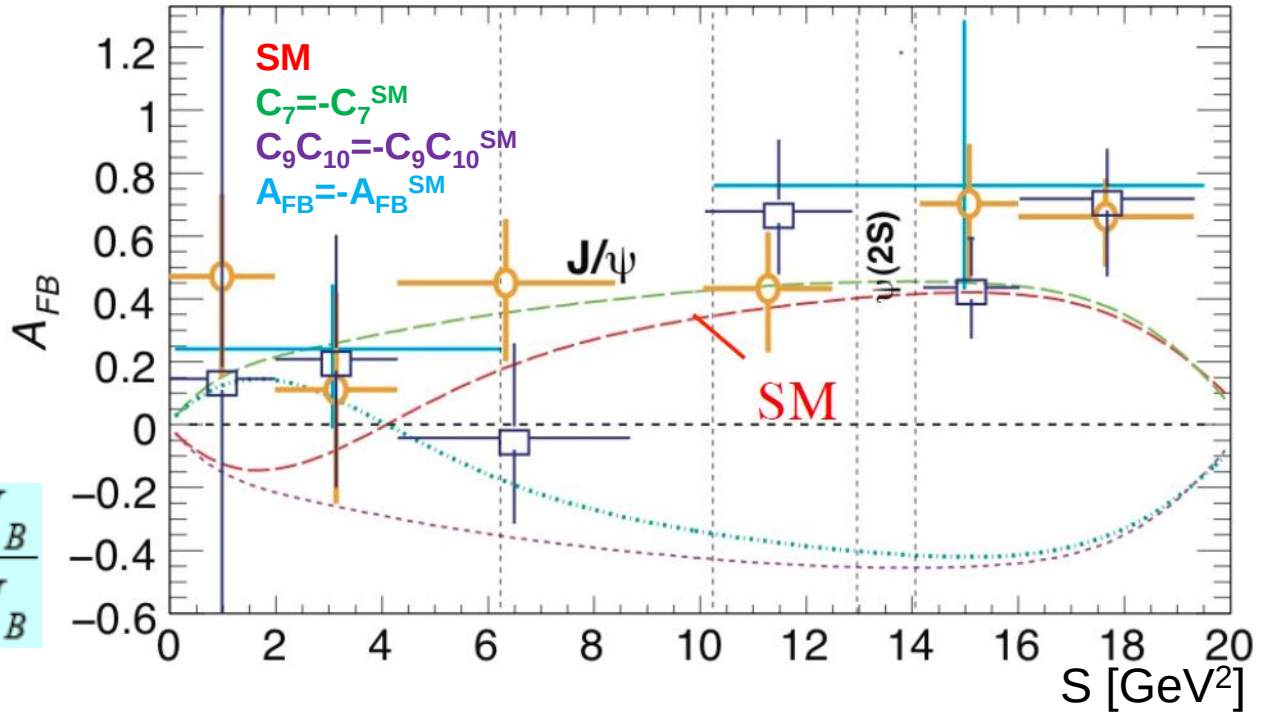


$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$

250 events [PRL 103 (2009) 171801]

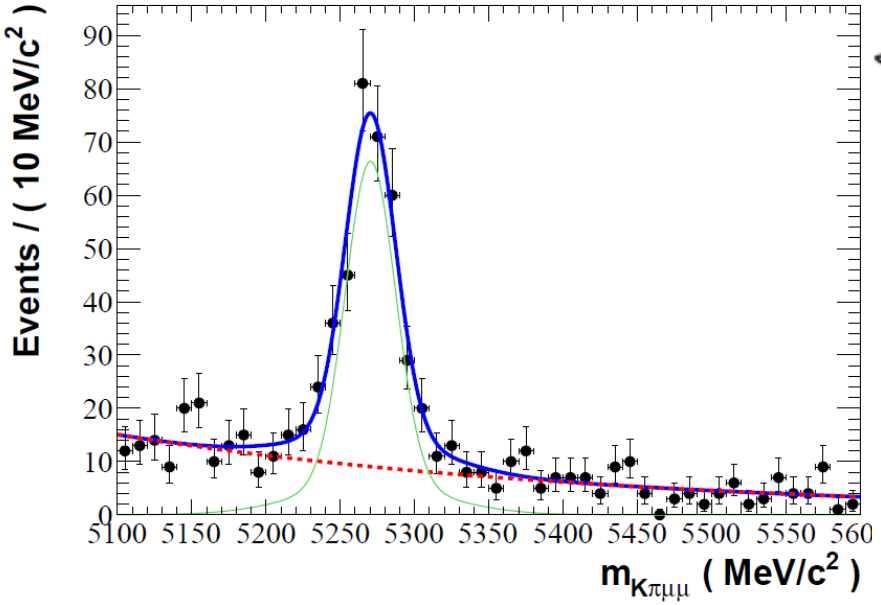
60 events [PRD 79 (2009) 031102]

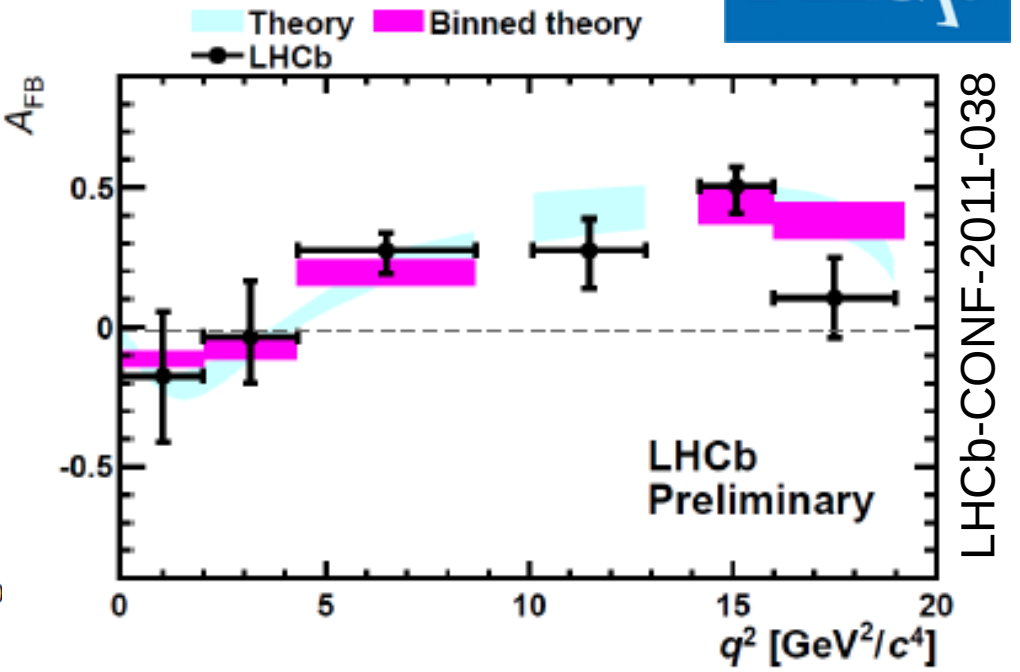
100 events [4.4 fb^{-1}, CDF note 10047]



AFB in $B_d \rightarrow K^* \mu^+ \mu^-$: enter LHCb at EPS11

- Based on 309 pb^{-1} and 300 candidates: largest sample in the world, just as clean as at the B factories
- Data are consistent with SM predictions within present sensitivity



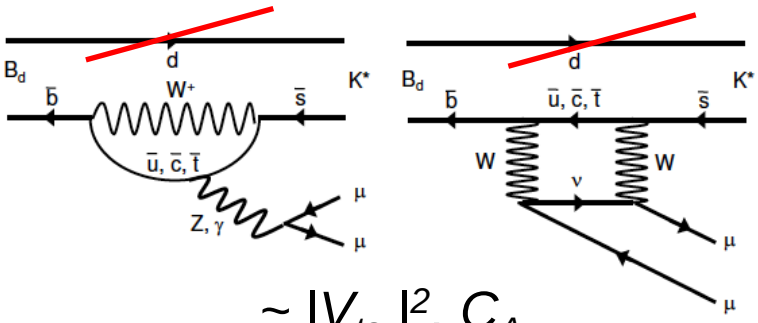


Theory predictions: C. Bobeth et al, arXiv 1105.0376v2

Search for NP in $B_{s,d}$→μμ decays

- $B_{(d,s)}$→ μμ is the good way to constrain the parameters of the extended Higgs sector in MSSM, fully complementary to direct searches

Main SM diagrams



FCNC & helicity suppressed in SM

$B_d \rightarrow \mu^+\mu^- = (1.0 \pm 0.1) \times 10^{-10}$

$B_s \rightarrow \mu^+\mu^- = (3.2 \pm 0.2) \times 10^{-9}$

Buras et al., arXiv:1007.5291 and references therein

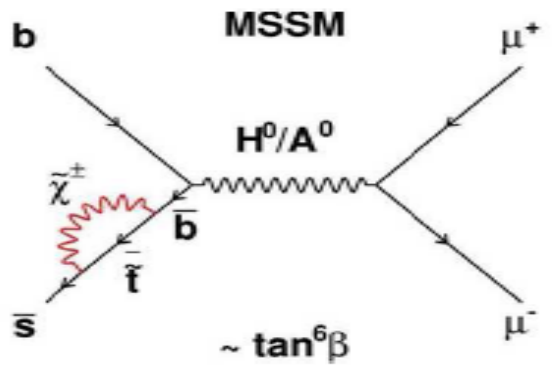
$\sim |V_{ts}|^2, C_A$

Sensitive to NP contributions in the scalar/pseudo scalar sector

$$(C_{S,P}^{MSSM})^2 \propto \left(\frac{m_b m_\mu \tan^3\beta}{M_A^2}\right)^2$$

MSSM, large tanβ approximation

+

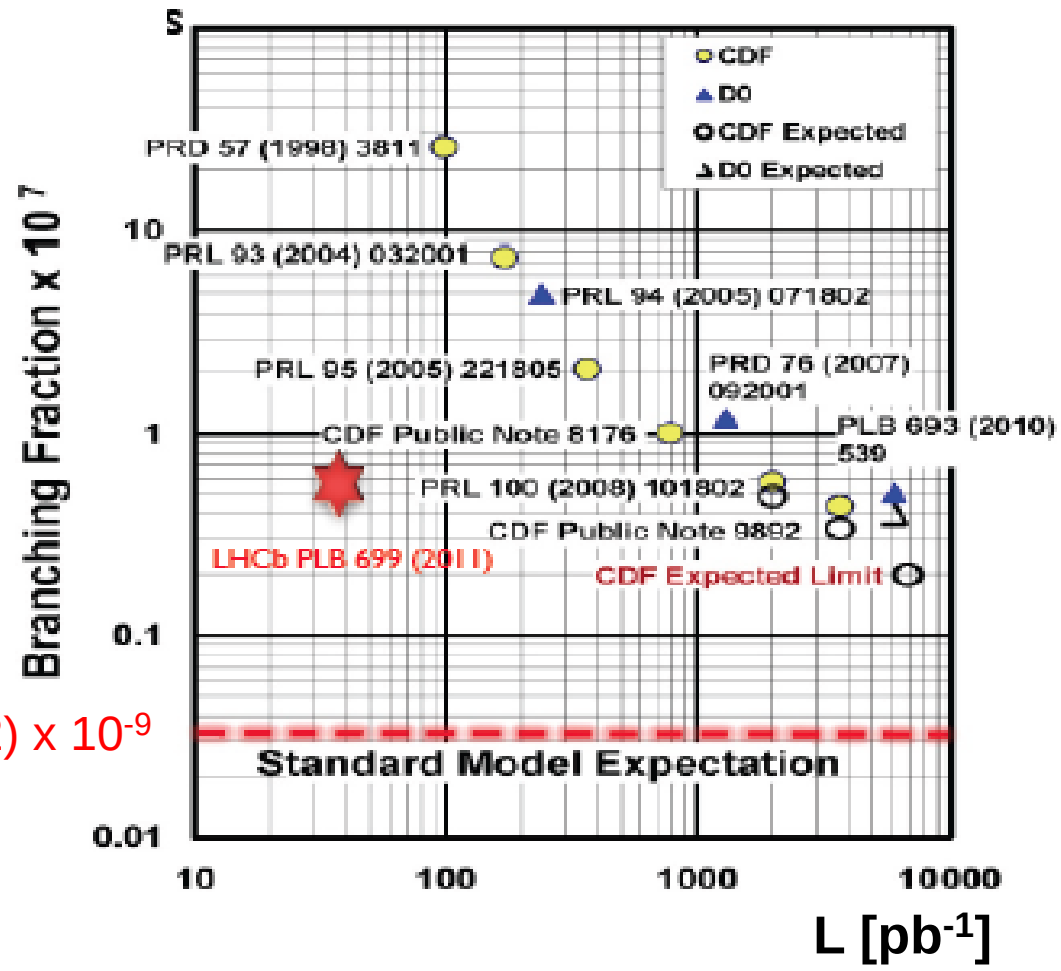


Experimental results (before summer 2011)

Published $B_s \rightarrow \mu\mu$ limits @ 95% CL

	Data set	Limit
CDF	3.7 fb^{-1}	4.3 x 10^{-8}
D0	6.1 fb^{-1}	5.1 x 10^{-8}
LHCb	0.036 fb^{-1}	5.6 x 10^{-8}

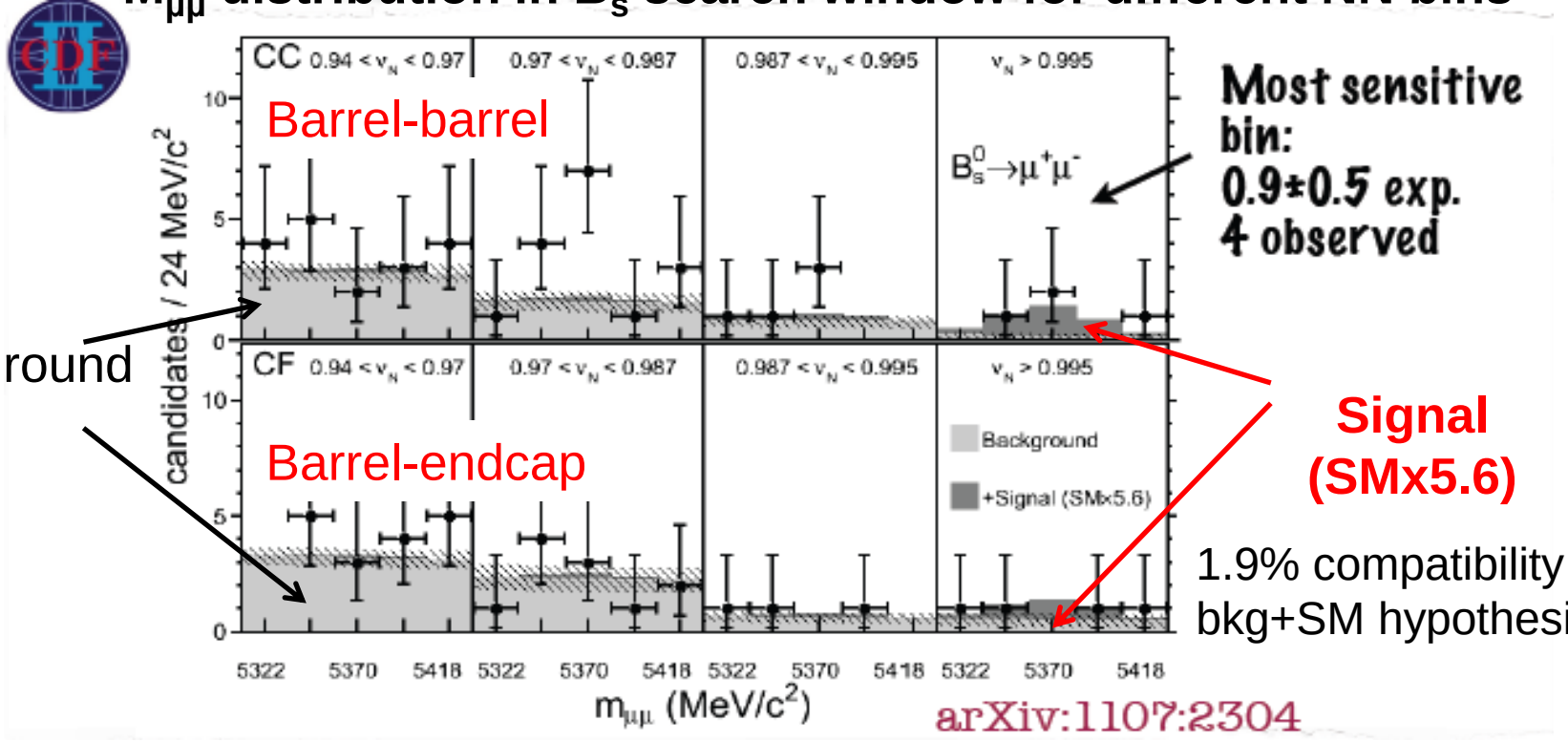
SM prediction: $(3.2 \pm 0.2) \times 10^{-9}$



New CDF result from July

- Results based on 7 fb^{-1}, improved muon acceptance & NN

$M_{\mu\mu}$ distribution in B_s search window for different NN bins



Most sensitive bin:
0.9±0.5 exp.
4 observed

background

Signal (SMx5.6)

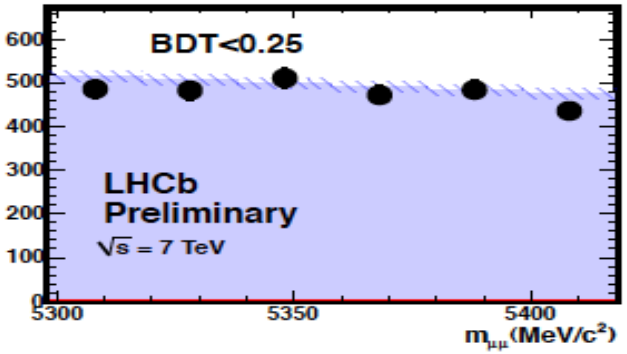
1.9% compatibility with bkg+SM hypothesis

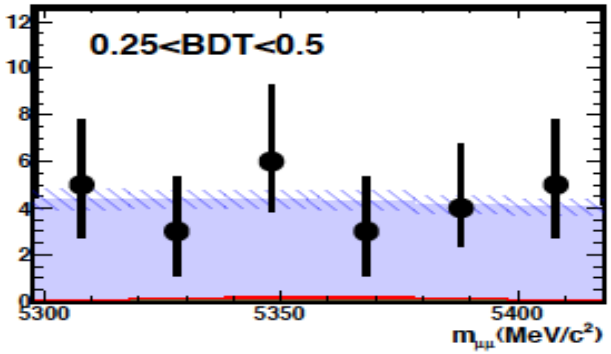
$0.46 \times 10^{-8} < BR < 3.9 \times 10^{-8}$ @ 90% CL or $BR = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$

LHCb search in the B_s mass window

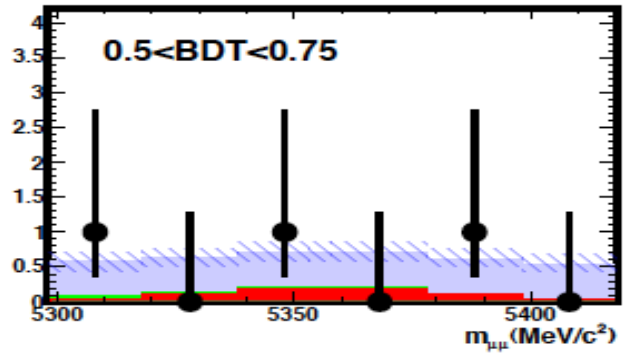
- Data in Boosted Decision Tree bins

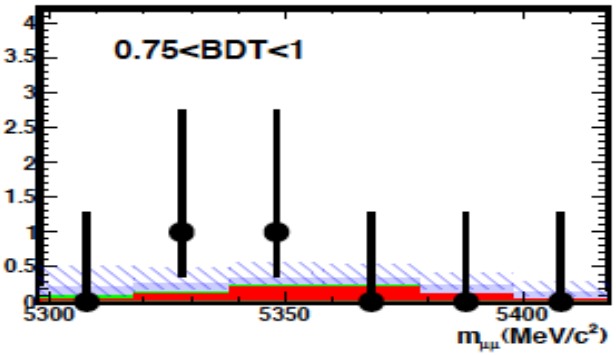
Combinatorial background





Data

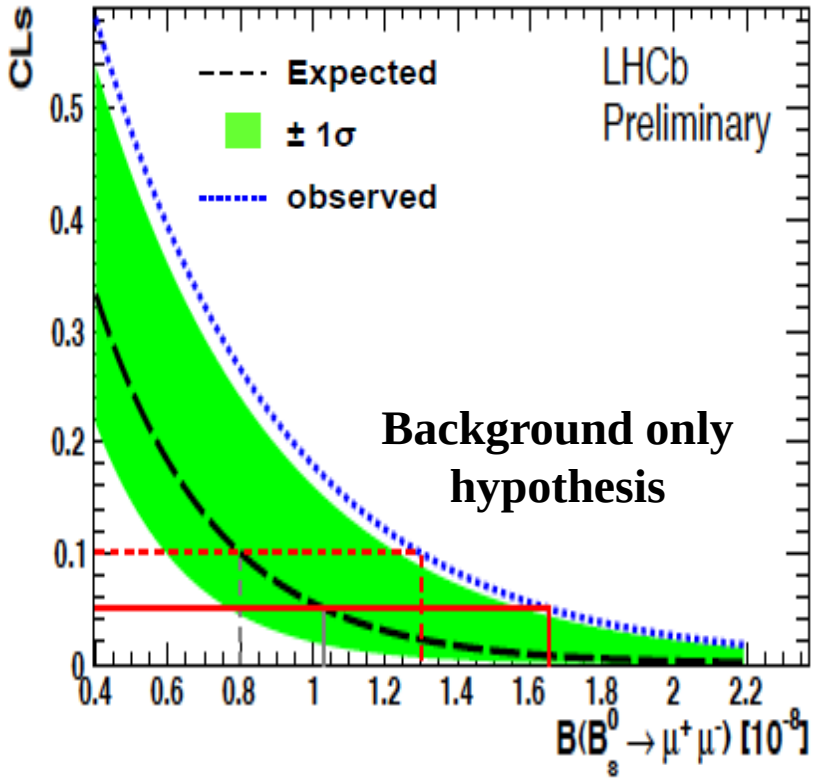


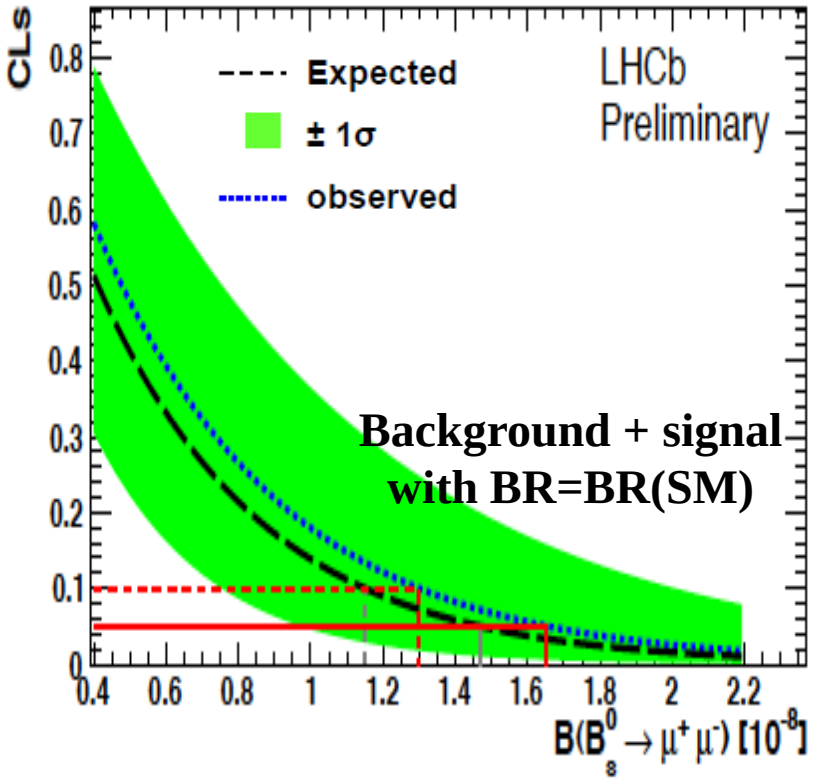


B→hh misid background
0.1±0.1 events in each BDT bin

Signal with SM BR

New LHCb preliminary limit with ~340 pb^{-1}

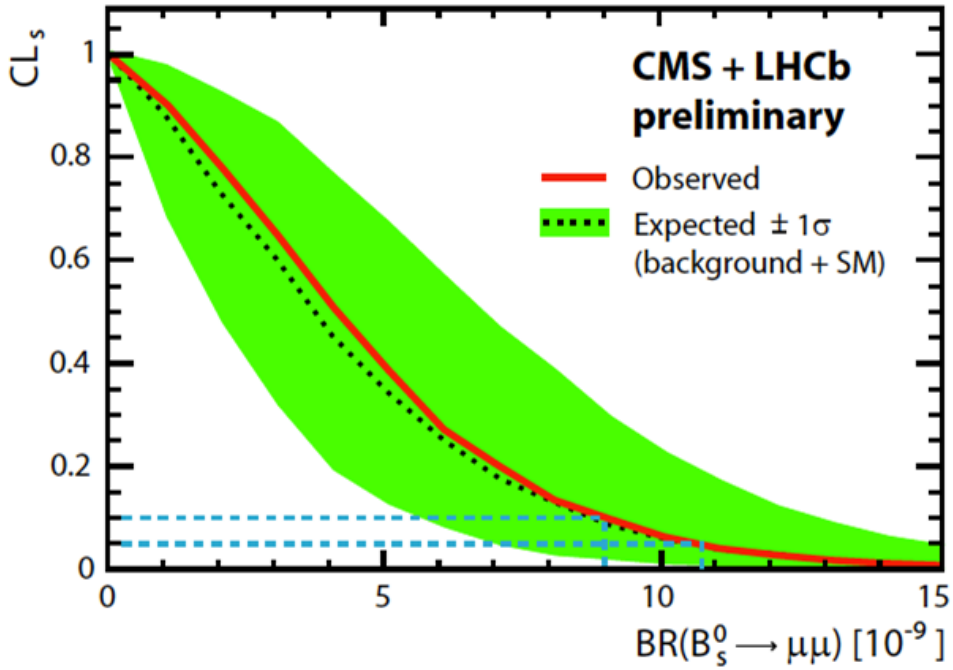




	90% CL	95% CL
LHCb 2011 only	1.3×10^{-8}	1.6×10^{-8}
LHCb 2011 & 2010	1.2×10^{-8}	1.5×10^{-8}

LHCb-CMS combination

- Combination has been performed by LHCb just adding 2 CMS bins (1 for barrel, 1 for endcap):



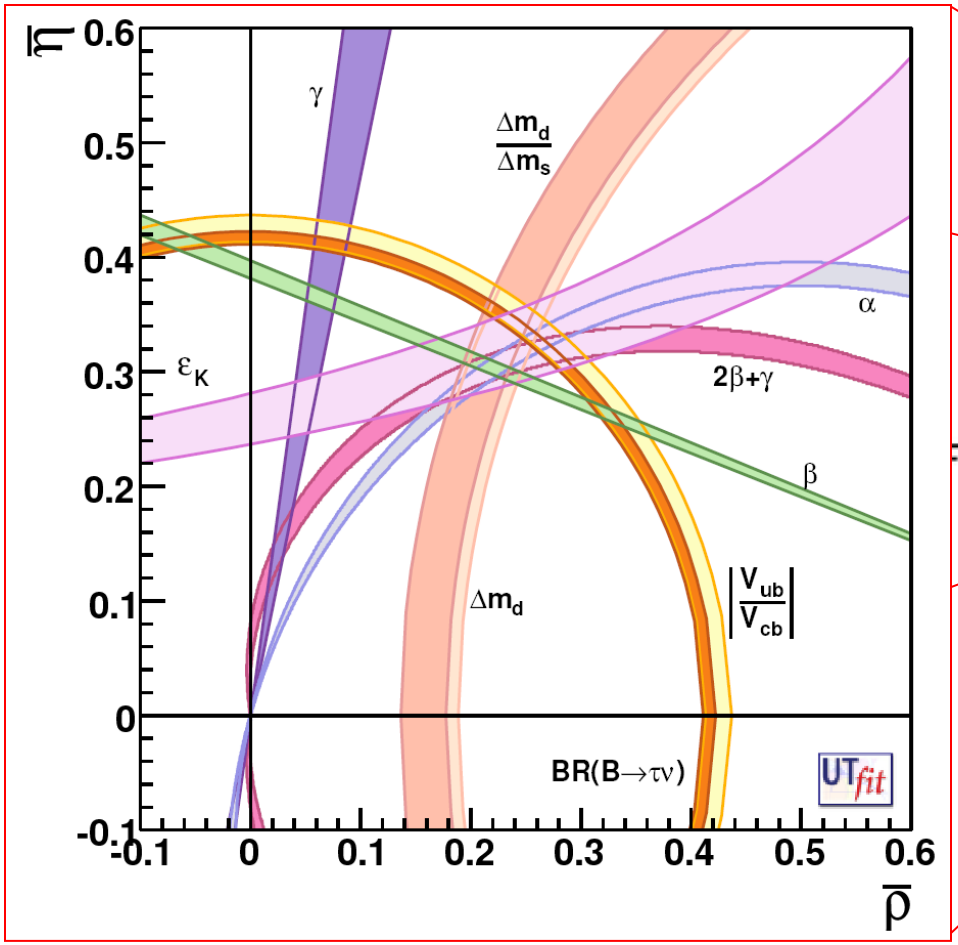
[LHCb-CONF-047, CMS-PH-11-019-pas]

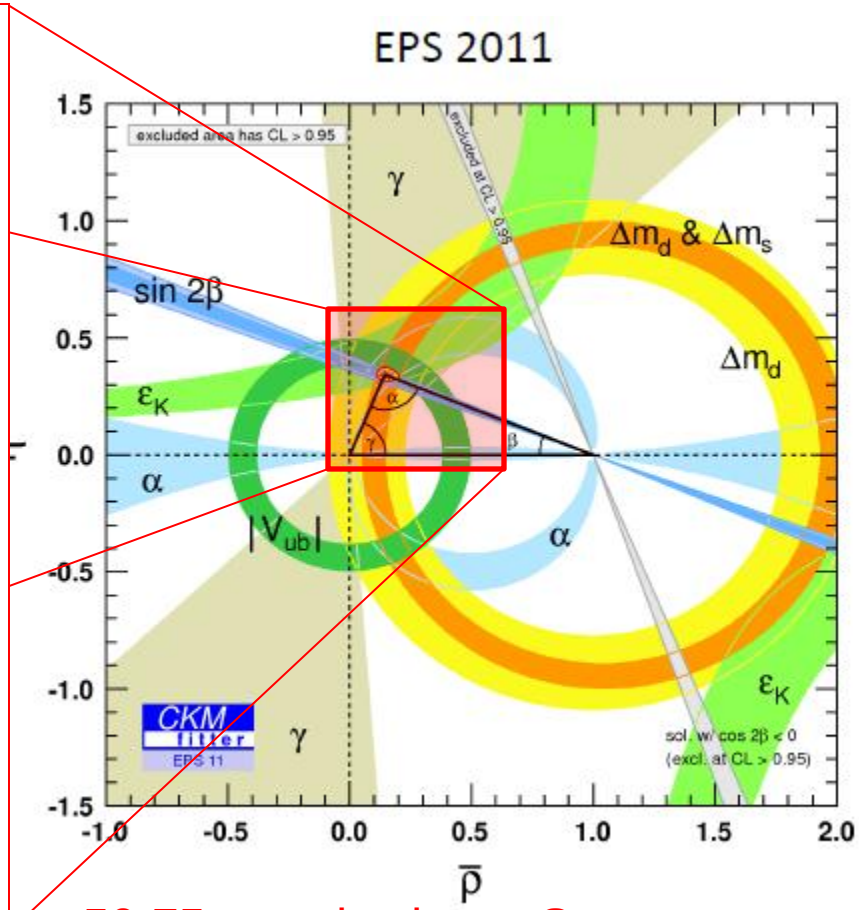
BR($B_s \to \mu\mu$) (LHCb+CMS) < 1.1 x 10^{-8} @ 95% CL (3.4xSM)
Excess seen by CDF not confirmed

Conclusions & Outlook

- Flavor physics remains an essential window into new physics through quantum loop processes
  - » Some recent hints for deviations from the SM seem to have been resolved, but other anomalies remain
  - » Still room for new physics in rare decay, CP violation and mixing processes
- Many other areas of important work not covered here
  - » Spectroscopy, new measurements of gamma and other rare B decays, tau and charm physics
- Renaissance of contributions from hadron collider experiments and LHCb
  - » Promise significant sensitivity improvements in the near term
- Super Flavor Factories and upgrades to LHCb offer order-of-magnitude reductions in errors for many of these processes

Conclusions & Outlook





x50-75 sample size at Super Flavor Factories in early 2020's