Heavy Flavors at the Tevatron

Moriond Electroweak
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Introduction:

- Heavy flavor production and triggers at Tevatron
- Quick overview of main Tevatron HF results

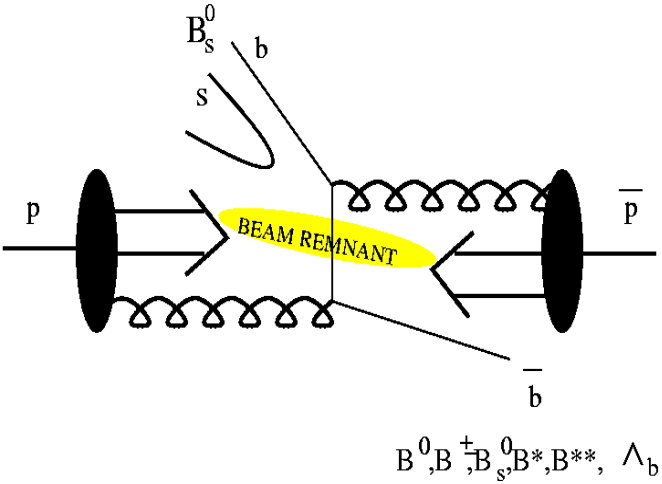
Remarks:

- *"B physics at Tevatron" is a huge and very rich field for Tevatron experiments: > 140 Run II papers published till now ! For details, see:*

CDF results: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
DØ results: http://www-d0.fnal.gov/Run2Physics/WWW/results/b.html

- *Not covered many yet outstanding results on b-production, charm mixing & CPV, charmed baryons and many B_d measurements which gave results comparable to B factories.*
- *Focus today is mostly on B_s system on which Tevatron opened the way, LHCb now being the key player.*

Heavy Flavor Physics at Tevatron



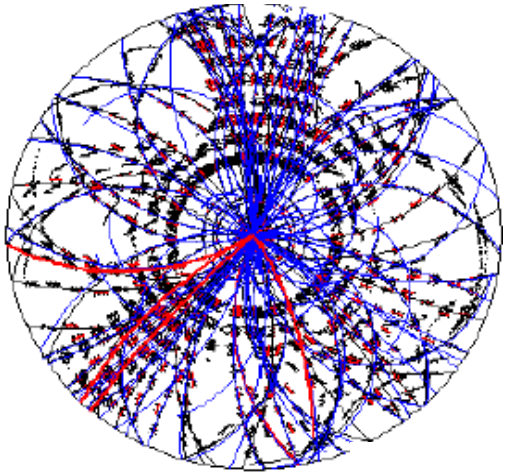
- All *B* species produced:

  $B_u, B_d, B_s, B_c, \Lambda_b, \Xi_b \ldots$

- With production fractions:

  $f_u : f_d : f_s : f_\Lambda \approx 4 : 4 : 1 : 1$

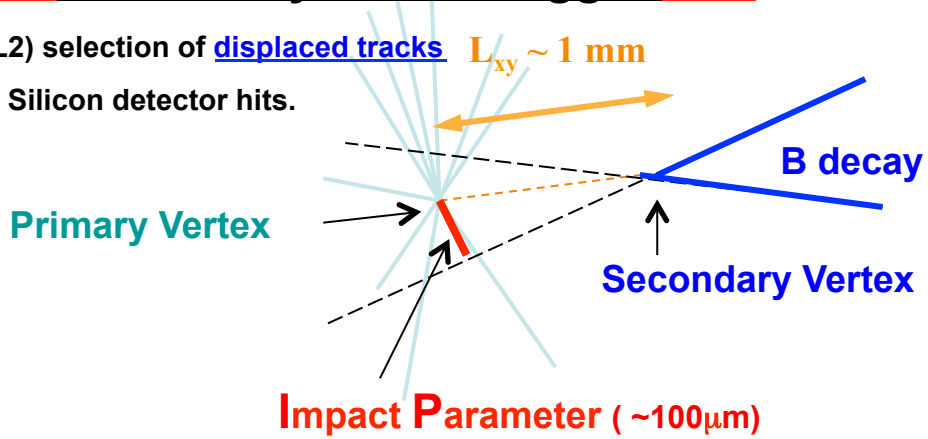
- Acceptance for other B is 20-40%

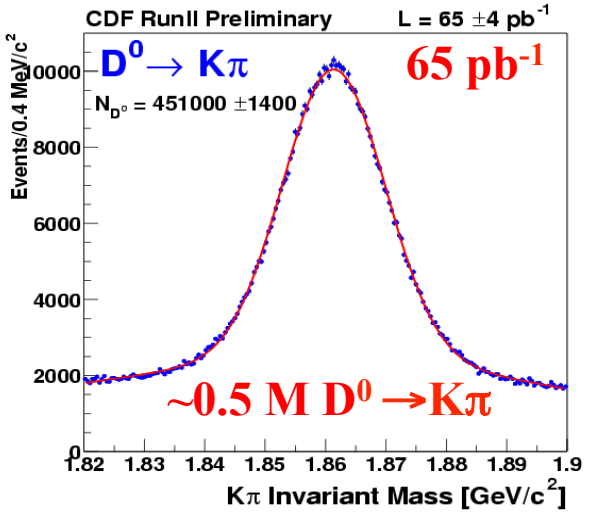


BUT: $\sigma(pp) \sim 100$ mb = 10^3-10^4 x $\sigma(bb) \Rightarrow$ B have to be selected with specific Triggers

the CDF Secondary Vertex Trigger SVT

- Online (L2) selection of displaced tracks based on Silicon detector hits.





- b production is very large (~300 Hz @ 10^{32} cm^{-2} Hz) → trigger on specific decays (w or w/o leptons)

B physics triggers at Tevatron

Conventional at colliders (Run I / D0)

Di-Muon (J/ψ)

Pt(μ) > 1.5 GeV

J/ψ modes down to low Pt(J/ψ)~0 (Run II)

+

With SVT trigger (at CDF)

1-Displaced track + *lepton* (*e*, *μ*)

120 μm < I.P.(trk) < 1mm

P_T(*lepton*) > 4 GeV

Semileptonic modes

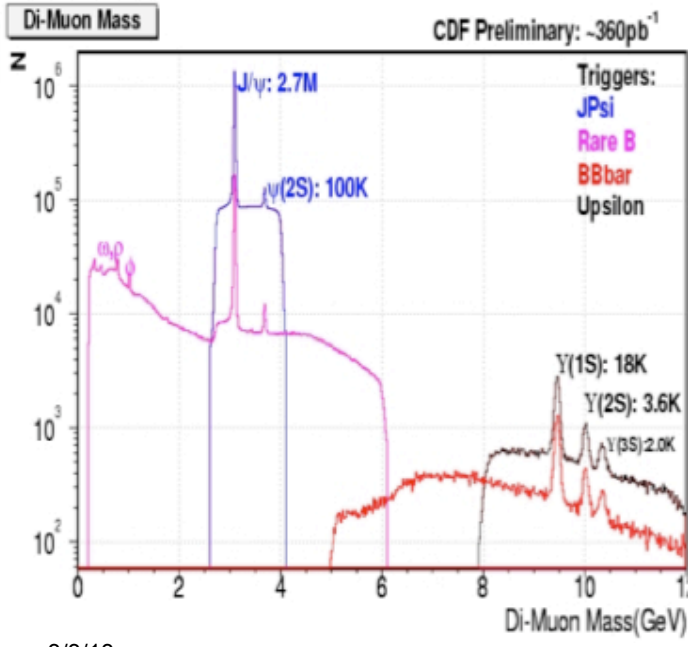
2-Displaced tracks

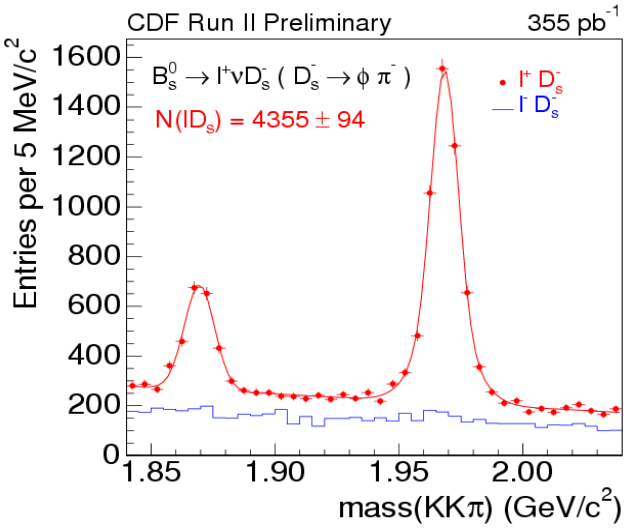
P_T(trk) > 2 GeV

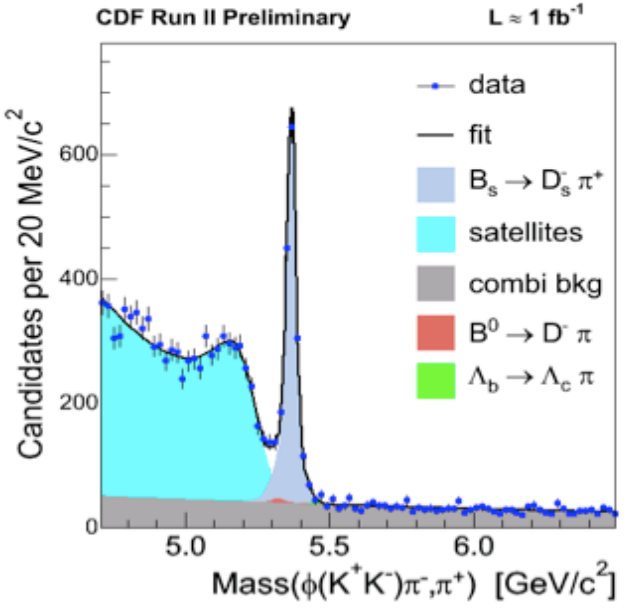
120 μm < I.P.(trk) < 1mm

Σp_T > 5.5 GeV

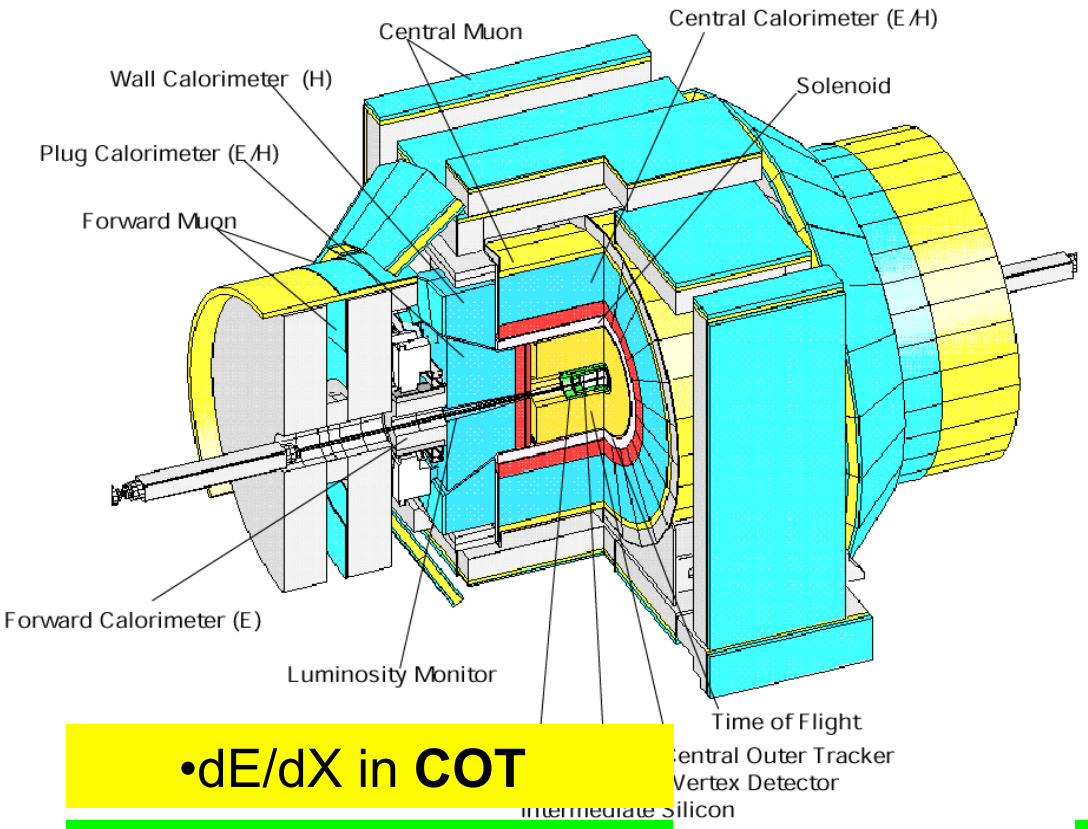
fully hadronic modes

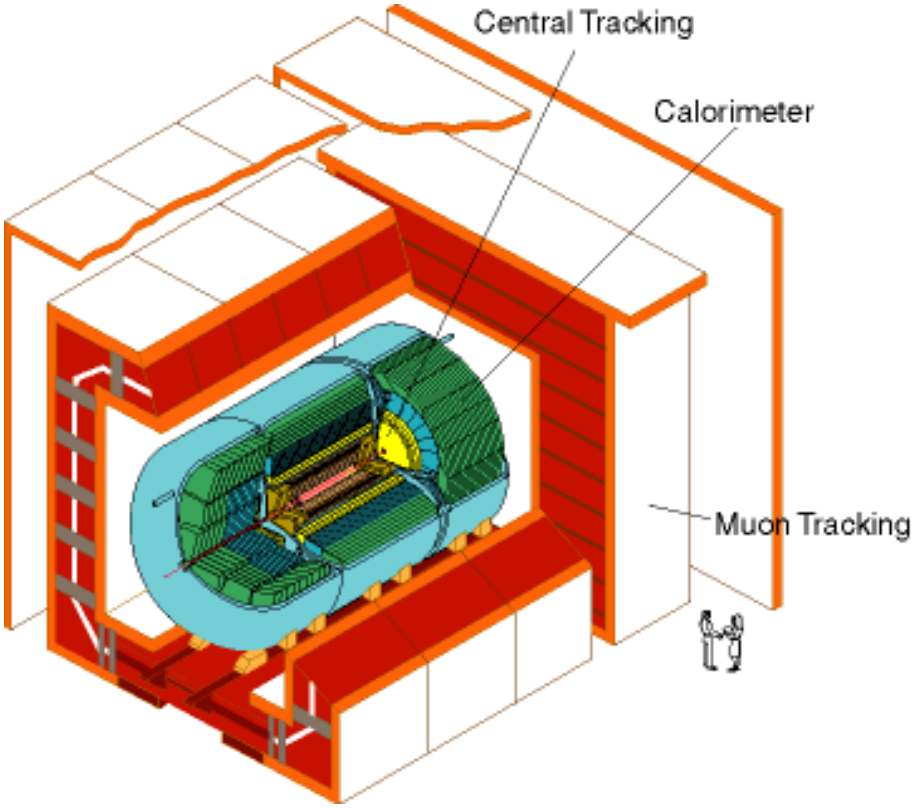






Tevatron detectors





•dE/dX in **COT**

•**T**ime **O**f **F**light detector

Muons: CMU, CMP, CMX ($|\eta|<1.1$)

Electrons: CEM (EM calorimeter)
CPR (pre-shower detector)

• **B-layer** to improve tracking resolution

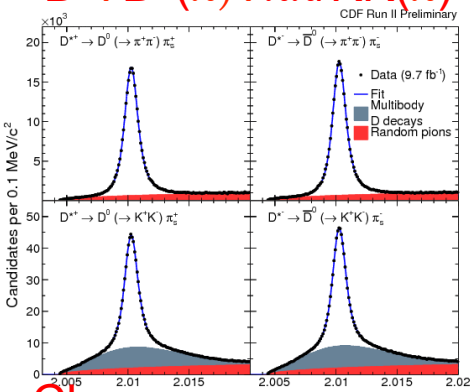
Muons: larger coverage ($|\eta|<1.8$)

Electrons: liquid argon ECAL

reversal of central & outer B fields

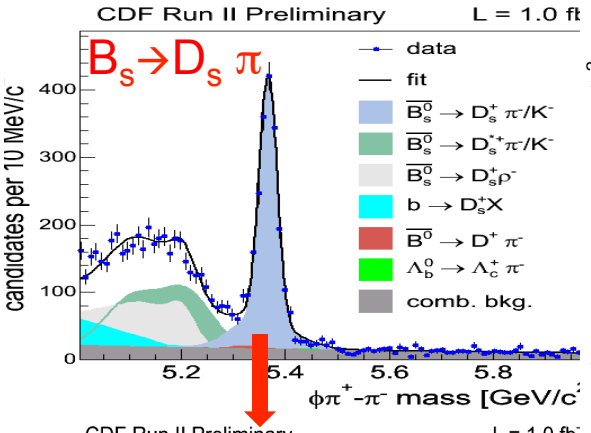
1 slide Tevatron H.F. results overview

$D^* \to D^0(\pi) \to \pi\pi/KK(\pi)$

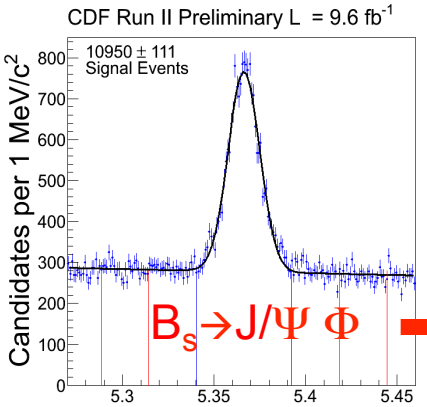


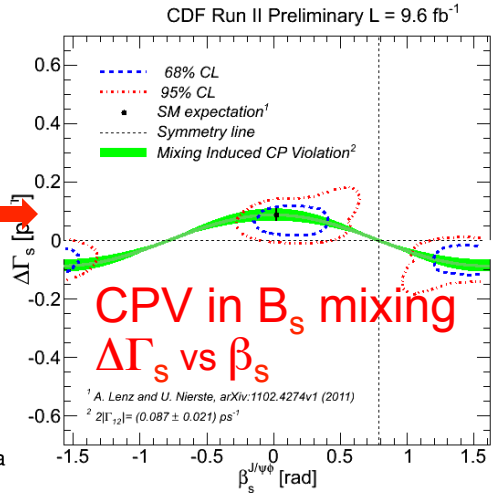
Charm mesons

$B_s \to D_s \pi$



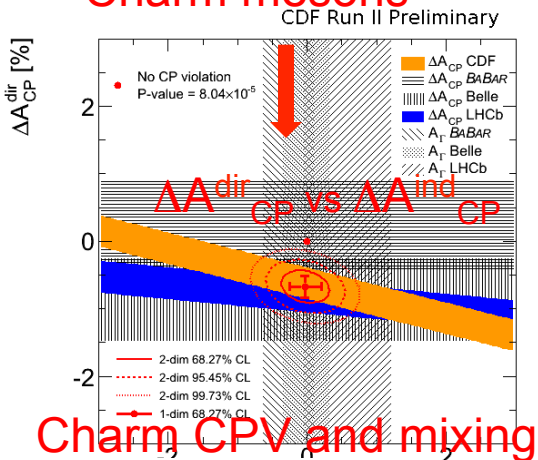
$B_s \to J/\Psi\,\Phi$





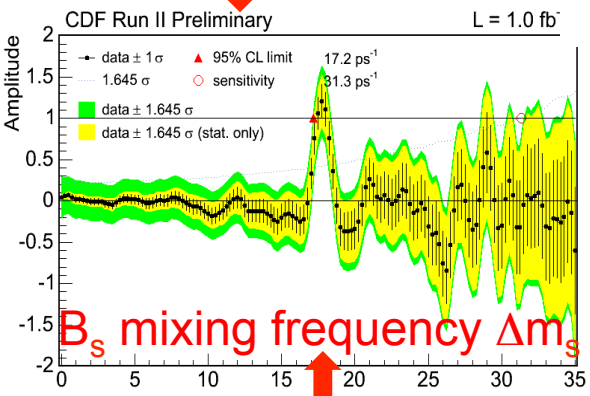
CPV in B_s mixing

$\Delta\Gamma_s$ vs β_s

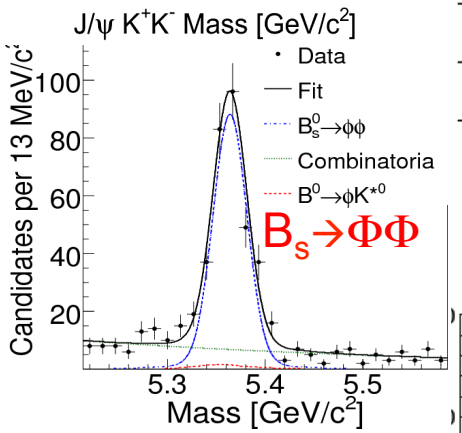


ΔA^{dir}_{CP} vs ΔA^{ind}_{CP}

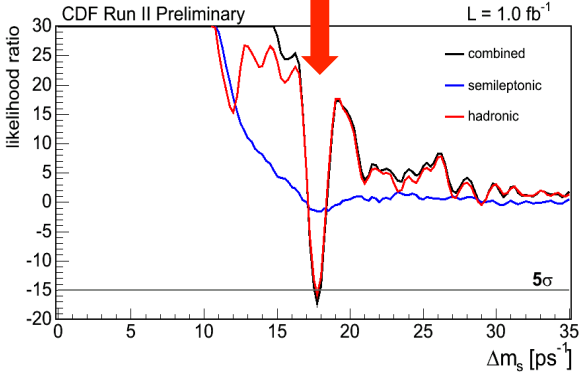
Charm CPV and mixing

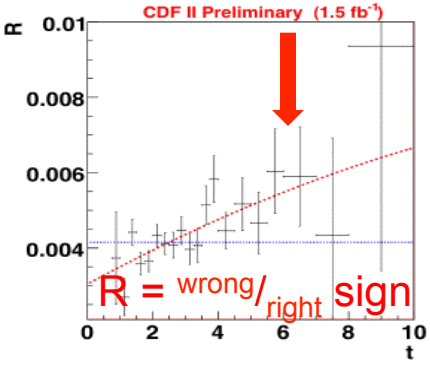


B_s mixing frequency Δm_s

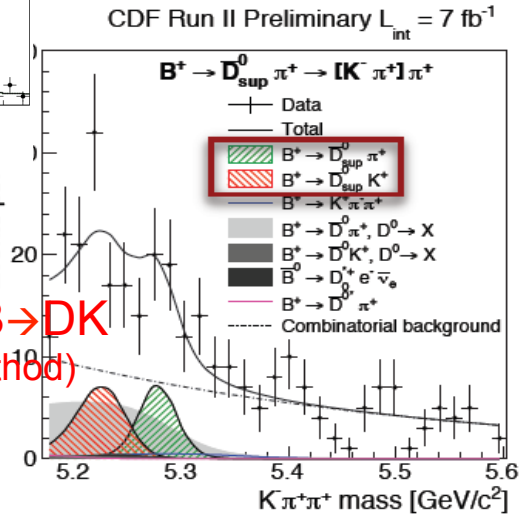


$B_s \to \Phi\Phi$





$R = {}^{wrong}/_{right}\ sign$



CPV in B→DK

(ADS method)

In this talk:

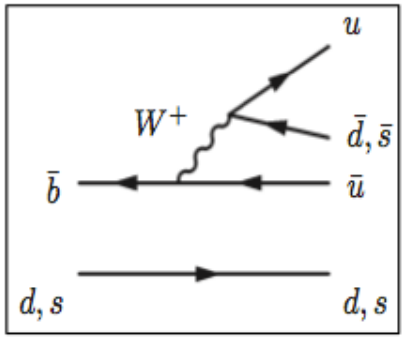
- New/updates since last Moriond (end 2012, beginnig 2013):
  - CP violation in charm-less $B_{s,d}$ decays. (CDF)
  - CP violation in B_s and B_d semi-leptonic decays. (D0)
  - Studies on $b \to s\, \mu^+\mu^-$ decays. (CDF)
  - Search for $B_s \to \mu^+\mu^-$ decay. (D0)
- Summary and conclusions

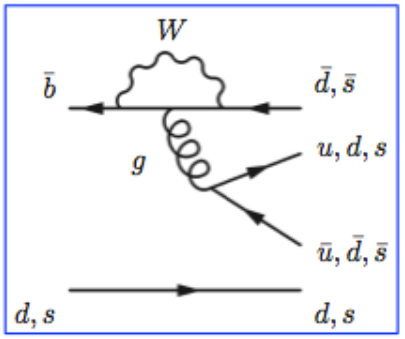
Latest results:

CDF results: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
DØ results: http://www-d0.fnal.gov/Run2Physics/WWW/results/b.html

CPV in charm-less b-hadron decays

- Important to improve knowledge of strong interactions dynamics
- Significant contribution from higher-order (penguin) transitions provides sensitivity to NP
- Sensitive to CKM angle γ





- Unique to Tevatron (CDF) for B_s and Λ_b, first observations:

$B^0_s \to K^+K^-$, PRL 97, 211802 (2006)

$B^0_s \to K^-\pi^+$, $\Lambda^0_b \to p\pi^-$, $\Lambda^0_b \to pK^+$, PRL 103, 031801 (2009)

and CPV:

$A_{CP}(B^0_s \to K^-\pi^+)$, $A_{CP}(\Lambda^0_b \to p\pi^-)$, $A_{CP}(\Lambda^0_b \to pK^+)$
PRL 106, 181802 (2011)

- Most recent results from CDF:
  First evidence for $B^0_s \to \pi^+\pi^-$ and
  bounds on $B^0 \to K^+K^-$

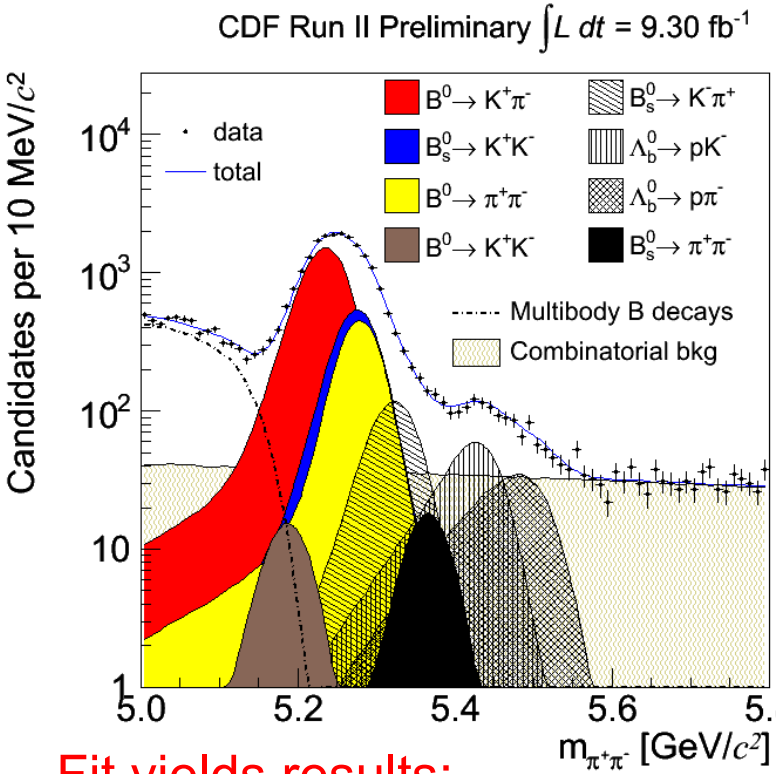
Define A_{CP} in flavor specific final states (ex.: $f = K^+\pi^-$), as:

$$\frac{\mathcal{B}(b \to f) - \mathcal{B}(\bar{b} \to \bar{f})}{\mathcal{B}(b \to f) + \mathcal{B}(\bar{b} \to \bar{f})} = \frac{N_{b\to f} - c_f N_{\bar{b}\to\bar{f}}}{N_{b\to f} + c_f N_{\bar{b}\to\bar{f}}}$$

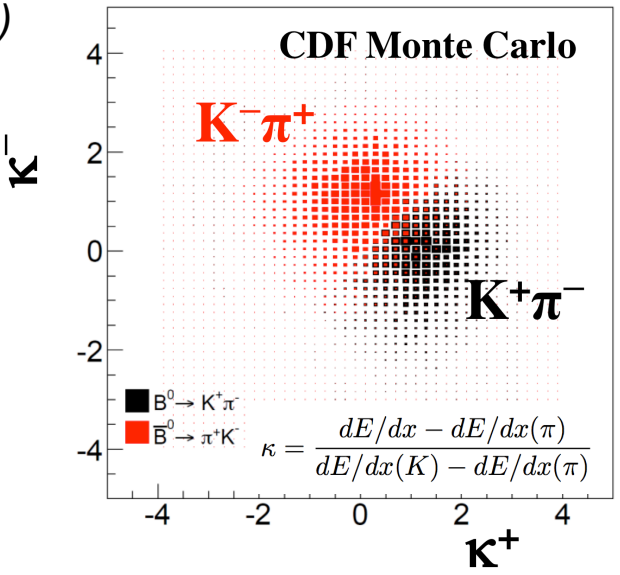
Exploit Tevatron symmetric b-bbar production
Correct for detector effects (cf) using large yields of identified Kaons and pions from charm decays.

CPV in charmless b-hadron decays

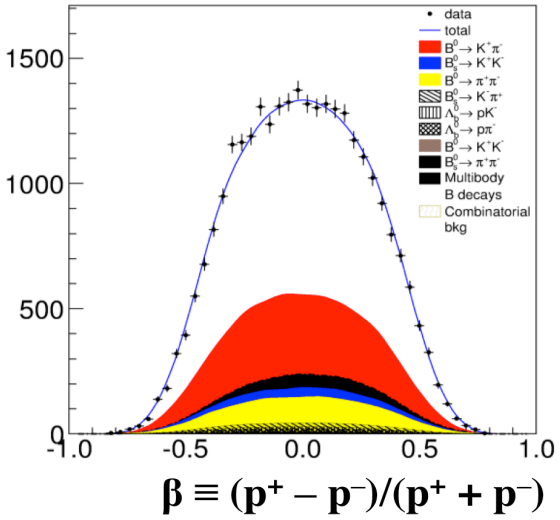
- Displaced vertex trigger *(~2% efficient @ pT(B)>4 GeV, |η(B)| < 1.0)*

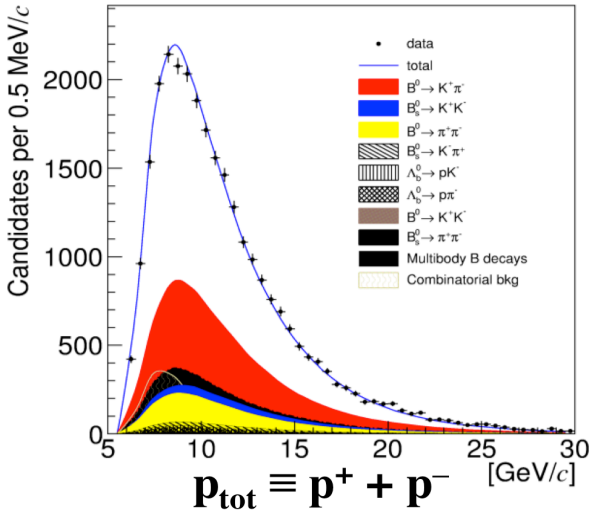


- dE/dx to construct 'kaonness' for positive and negative particles κ+, κ−, (K/π separation up to 1.5σ)



- Likelihood-fit to with 3 kin. variables *(m, β, p_{TOT})* + *particle ID*

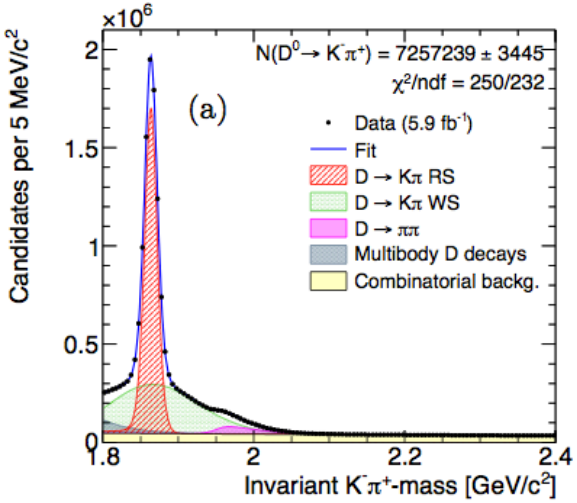




Fit yields results:

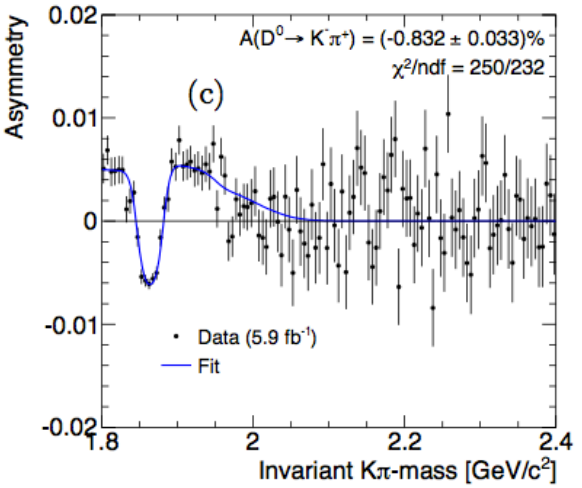
Mode	$\mathcal{N}_{b\to f}$	$\mathcal{N}_{\bar{b}\to \bar{f}}$
$B^0 \to K^+\pi^-$	6348 ± 117	5313 ± 109
$B_s^0 \to K^-\pi^+$	354 ± 46	560 ± 51
$\Lambda_b^0 \to p\pi^-$	242 ± 24	206 ± 23
$\Lambda_b^0 \to pK^-$	271 ± 30	324 ± 31

CPV in charm-less b-hadron decays



Correct for detector induced charge asymmetries:

- Use O(10^7) $D^0 \rightarrow Kp$ sample
- Asymmetry corrections O(1%) determined with ~0.1% accuracy



CP Asymmetries results:

$$A_{CP}(B^0 \rightarrow K^+\pi^-) = (-8.3 \pm 1.3 \pm 0.3)\%$$
$$A_{CP}(B_s^0 \rightarrow K^-\pi^+) = (22 \pm 7 \pm 2)\%$$

$$A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = (7 \pm 7 \pm 3)\%$$
$$A_{CP}(\Lambda_b^0 \rightarrow pK^-) = (-9 \pm 8 \pm 4)\%$$

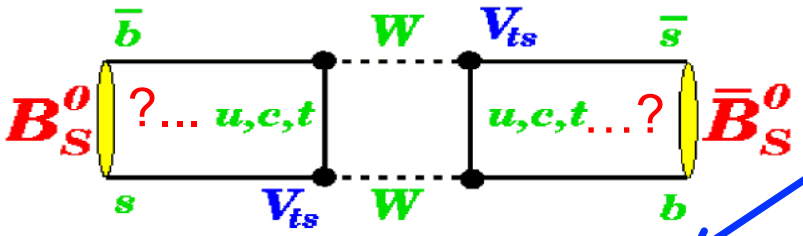
Competitive measurement for B^0.
For B_s^0 confirm LHCb result with same resolution.

new CDF = 0.22 +- 0.07 +- 0.02
LHCb = 0.27 +- 0.08 +- 0.02

Strong evidence ($4.5\,\sigma$) combining CDF and LHCb measurements:
$A_{CP}(B_s^0 \rightarrow K^+\pi^-) = (24.2 \pm 5.4)\%$

http://www-cdf.fnal.gov/physics/new/bottom/120628.blessed-Bhh9fb/cdf10726_acp_bhh_9fb_public.pdf

CP Asymmetries in B_s and B_d mixing



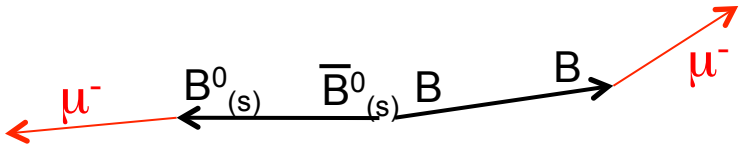
- CPV in neutral B mesons oscillations is possible by CKM phase Φ which can lead to non vanishing CP asymmetry in CP defined final states (ex.: a_{SL}).
- SM prediction is very small but: NP could enter with additional phase.

$$a^q_{\rm sl} = \frac{\Gamma(\bar{B}^0_q(t) \to \mu^+ X) - \Gamma(B^0_q(t) \to \mu^- X)}{\Gamma(\bar{B}^0_q(t) \to \mu^+ X) + \Gamma(B^0_q(t) \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

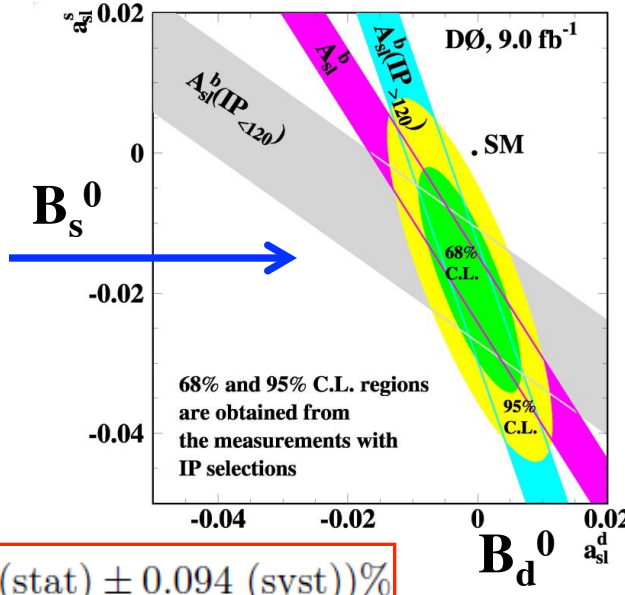
$$a^d_{\rm sl}({\rm SM}) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$$
$$a^s_{\rm sl}({\rm SM}) = (2.1 \pm 0.6) \times 10^{-5}$$

In 2011, D0 published a like-sign di-muon based measurement of A_{sl}:

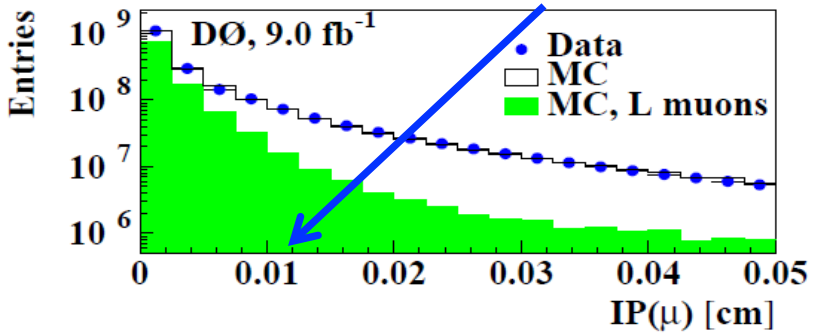
- A_{sl} for mixture of B_d and B_s (see 2D plane), correct for mixing and for detector asymmetry (B field reversal)



$$A^b_{\rm sl} \equiv \frac{N^{++}_b - N^{--}_b}{N^{++}_b + N^{--}_b} = C_d a^d_{\rm sl} + C_s a^s_{\rm sl}$$



- B purity enhanced with impact parameter cut.



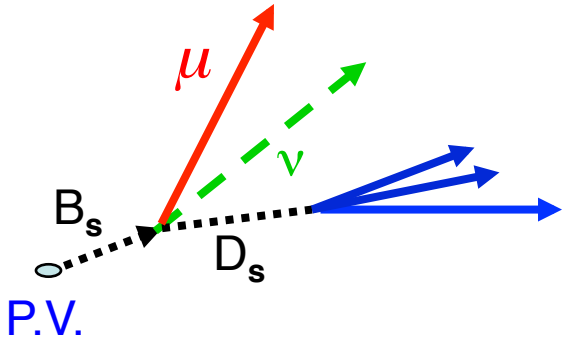
Surprising result:

$$A^b_{\rm sl}(IP_{>120}) = (-0.579 \pm 0.210\ ({\rm stat}) \pm 0.094\ ({\rm syst}))\%$$

3-4 sigma inconsistency with SM:

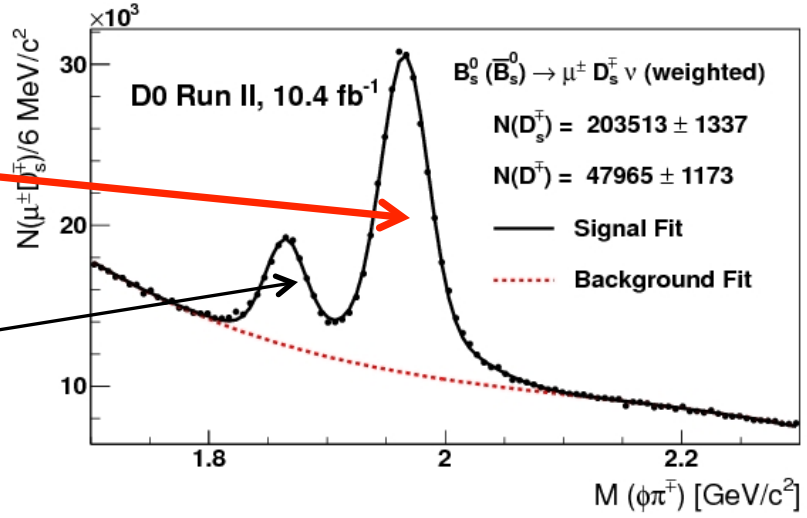
→ *important to independently measure $a_{sl}(B_s)$ and $a_{sl}(B_d)$* →

CPV in B_s and B_d semileptonic decays



$B_s \rightarrow \mu D_s^+$ with $D_s \rightarrow \Phi\pi$

$B_d \rightarrow \mu D^+$

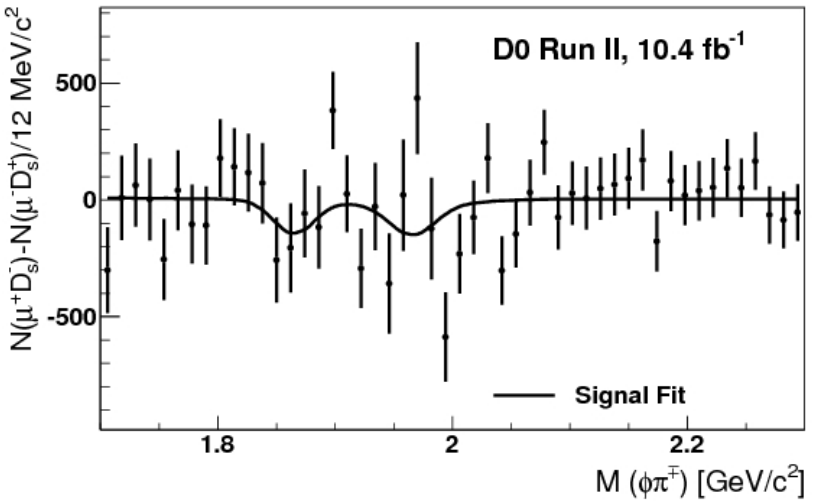


Measure raw Asymmetry A: $A = \dfrac{N_{\mu^+ D_s^-} - N_{\mu^- D_s^+}}{N_{\mu^+ D_s^-} + N_{\mu^- D_s^+}}$

counting μD_s yields (weighted for B field reversal)

define a_{sl} as: $a_{sl}^q = \dfrac{A - A_{BG}}{F_{B_s}^{osc}}$

where A_{BG} is detector related asym. (K^+ vs K^-) and F^{osc}_{Bs} is the fraction of μD_s candidates from oscillated Bs (~50%)

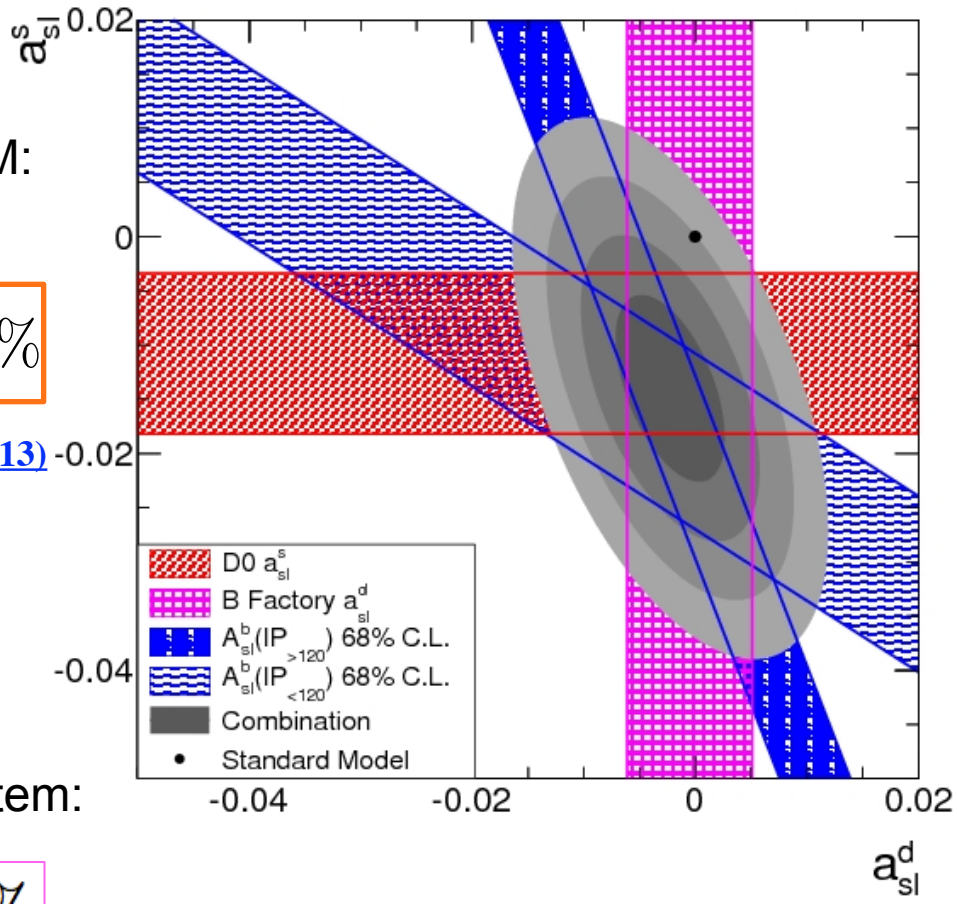


CPV in B_s semileptonic decays (10.4 fb^{-1})

Most precise result on $a_{sl}(B_s)$ consistent with SM:

$$a_{\rm sl}^s = [-1.12 \pm 0.74\,({\rm stat}) \pm 0.17\,({\rm syst})]\,\%$$

Phys. Rev. Lett. 110, 011801 (2013)

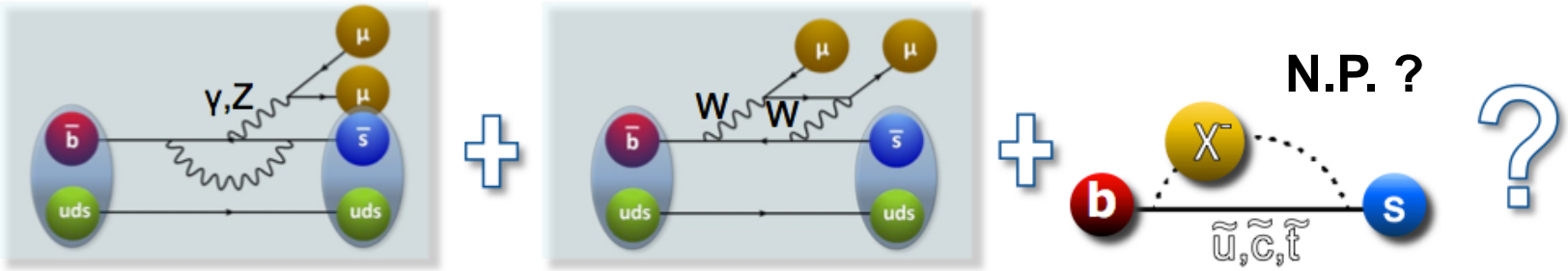


Also, with equivalent approach $a_{sl}(B_d)$ in B_d system:

$$a_{\rm sl}^d = [0.68 \pm 0.45\ ({\rm stat.}) \pm 0.14\ ({\rm syst.})]\%$$

Phys. Rev. D 86, 072009 (2012)

$b \to s\,\mu^+\mu^-$ decays



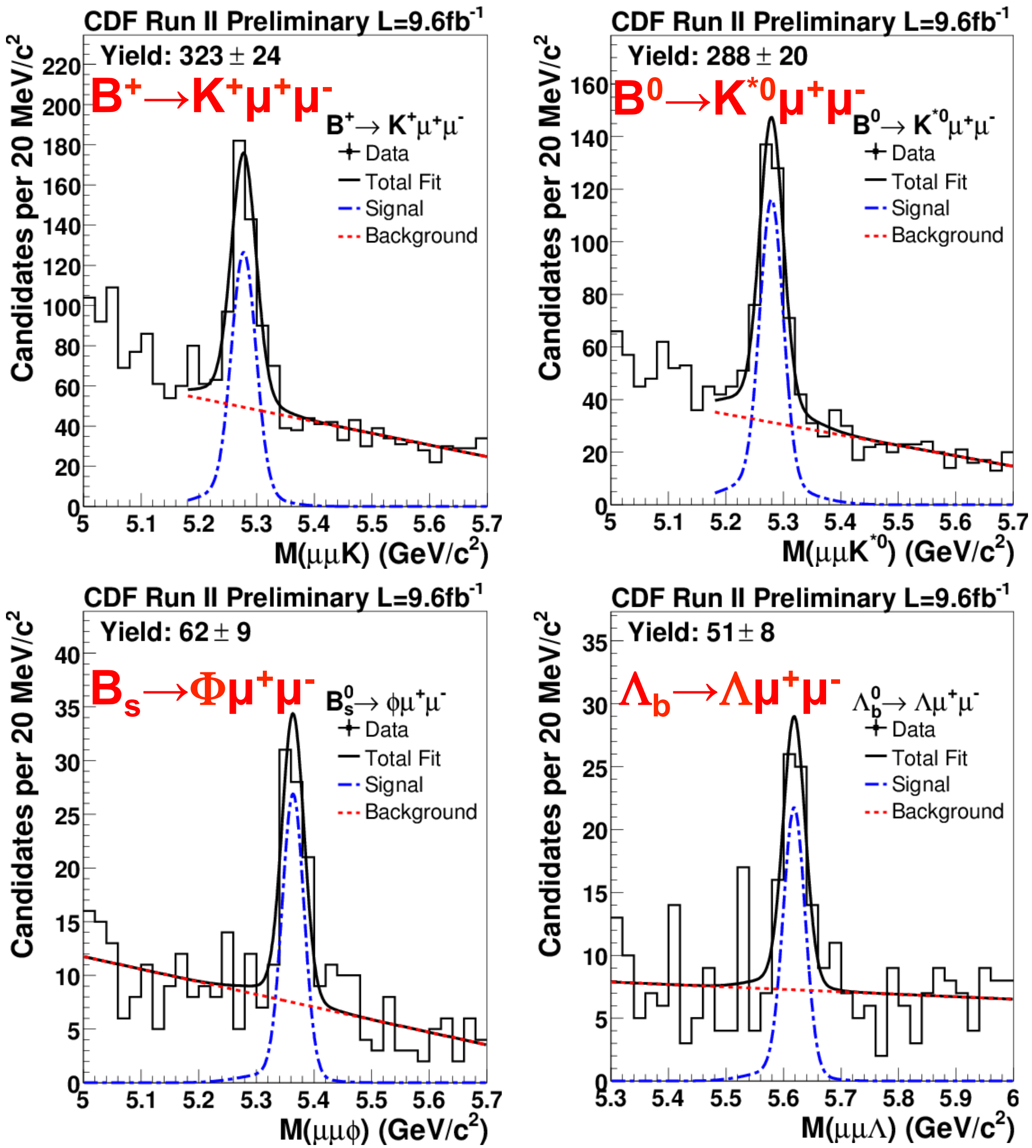
- Rare decays with BR ~O(10^{-6}) in SM; good probes of NP
- Flavor changing Neutral Currents

- Look for NP in kinematic distributions: differential BR, FB asymmetries, …

- Various channels available:
  - $B^0 \to K^{*0}\mu\mu$
  - $B^+ \to K^+\mu\mu$
  - $B^+ \to K^{*+}\mu\mu$
  - $B^0 \to K^0_S\mu\mu$,

  and also, first observed by *CDF:*
  - $B_s \to \Phi\mu\mu$ (PRL106,161801 (2011))
  - $\Lambda_b \to \Lambda\mu\mu$ (arXiv:1107.3753)

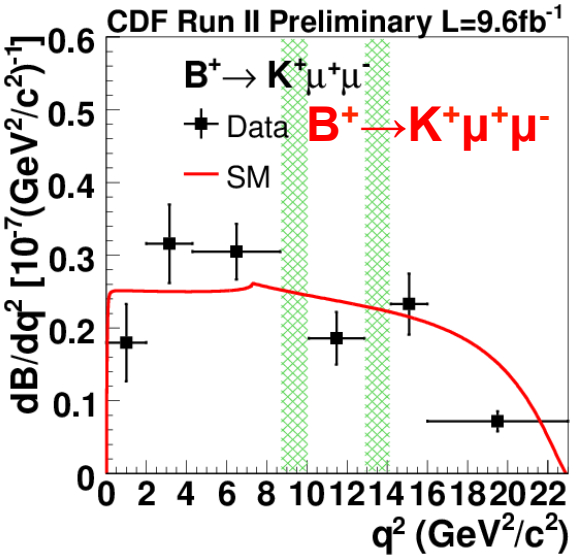
Yields in b → s $\mu^+\mu^-$ decays (9.6 fb^{-1})

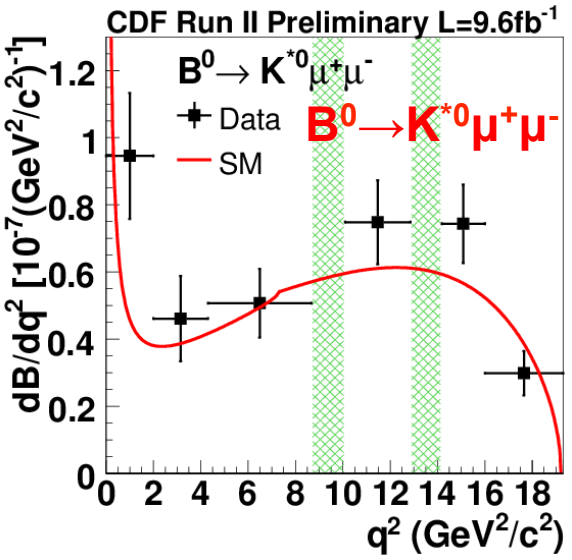


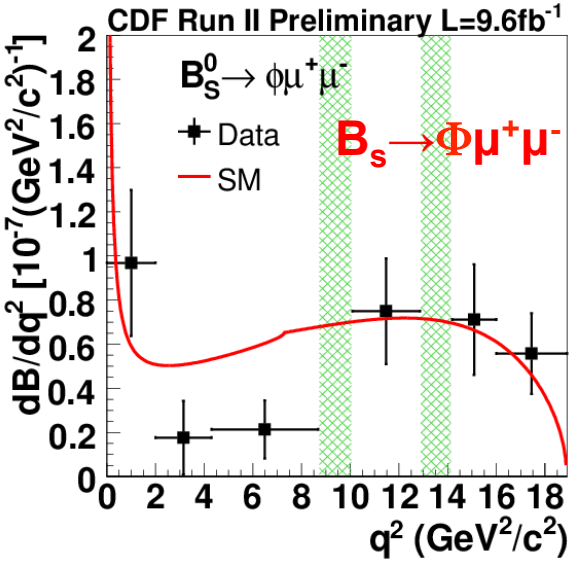
$B^+ \rightarrow K^+\mu^+\mu^-$: 319±23 (15.6σ)
$B^0 \rightarrow K^{*0}\mu^+\mu^-$: 288±20 (15.8σ)
$B^0 \rightarrow K_S^0\mu^+\mu^-$: 32±8 (4.6σ)
$B^+ \rightarrow K^{*+}\mu^+\mu^-$: 24±6 (4.2σ)
$B_s^0 \rightarrow \varphi\mu^+\mu^-$: 62±9 (8.9σ)
$\Lambda_b^0 \rightarrow \Lambda\mu^+\mu^-$: 51±7 (7.6σ)

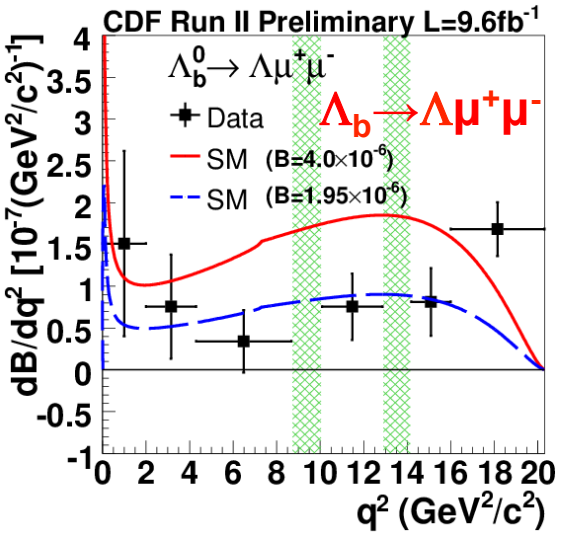
http://www-cdf.fnal.gov/physics/new/bottom/120628.blessed-b2smumu_96/public_b2smumu.pdf

Differential BR in b → s $\mu^+\mu^-$ decays









differential BR w.r.t. the di-muon system q^2

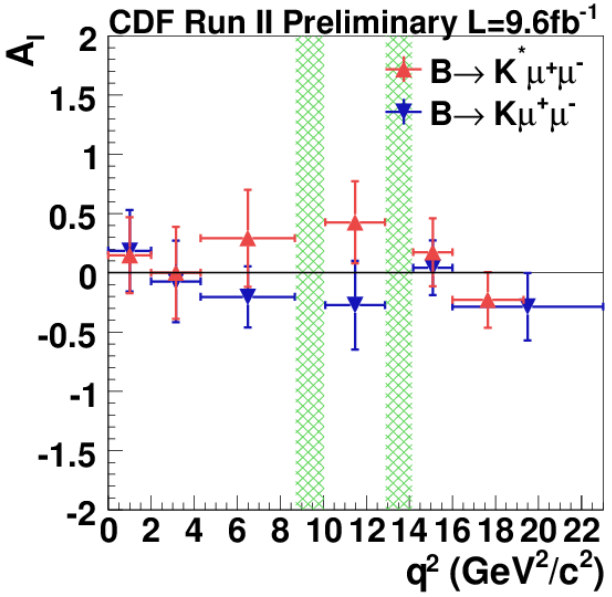
Picture overall consistent with Standard Model

http://www-cdf.fnal.gov/physics/new/bottom/120628.blessed-b2smumu_96/public_b2smumu.pdf

$b \to s\,\mu^+\mu^-$ decays properties

- Isospin Asymmetry A_I :

$$A_I^{(*)} \equiv \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

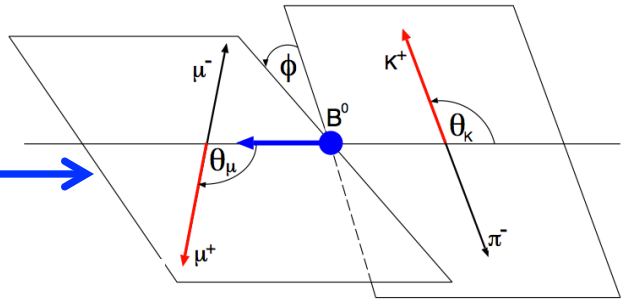


consistent with SM.
(LHCb reported 3σ in high q^2)

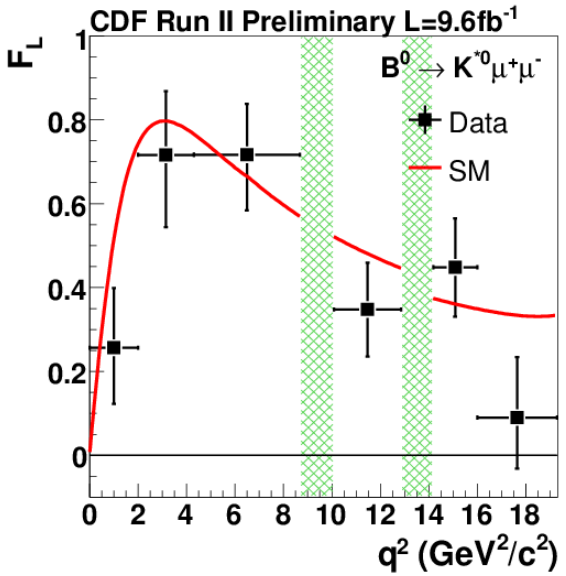
CDF $\quad -0.29 \pm 0.28(\text{stat}) \pm 0.06(\text{syst})$

LHCb $\quad -0.52^{+0.18}_{-0.22}$ arXiv:1205.3422

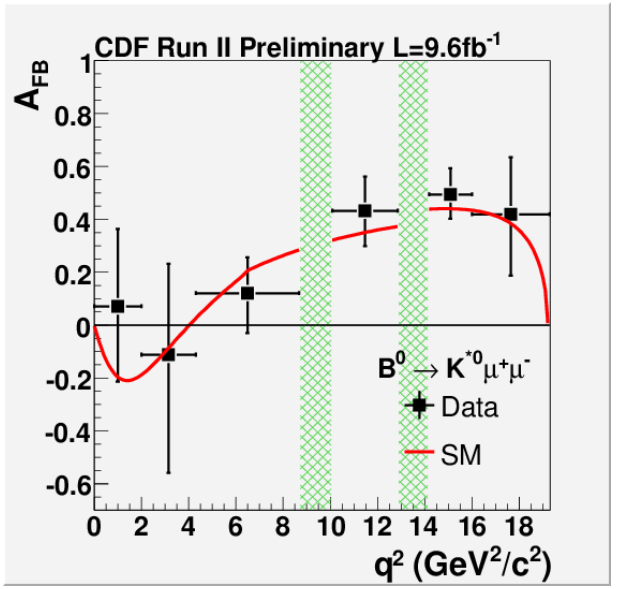
- from $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis:



K* polarization



Forward-backward Asymmetry



consistent with SM

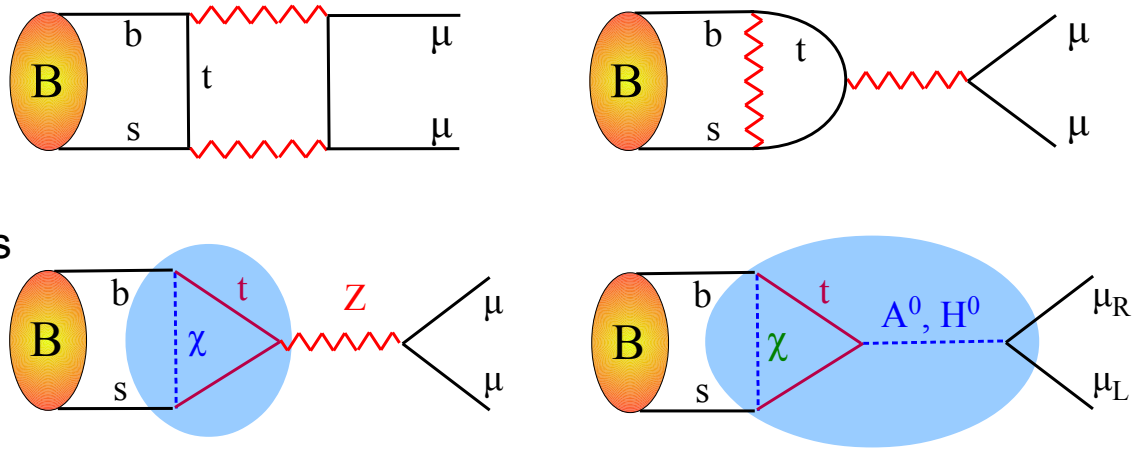
http://www-cdf.fnal.gov/physics/new/bottom/120628.blessed-b2smumu_96/public_b2smumu.pdf

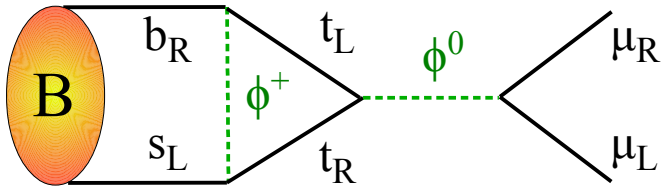
Search for $B_s \to \mu^+\mu^-$ rare decay

SM contributions:

elicity suppressed
theoretically very clean
sensitive to FCNC scalars and Z penguins

Possible non-SM contributions:





- In MSSM proportional to $(\tan\beta)^6$
- Probe of the Yukawa interaction (Higgs sector)

$$\overline{BR}_{s,SM} = (3.54 \pm 0.30)\times 10^{-9}$$

SM prediction
time integrated (tacking into account B_s mixing)

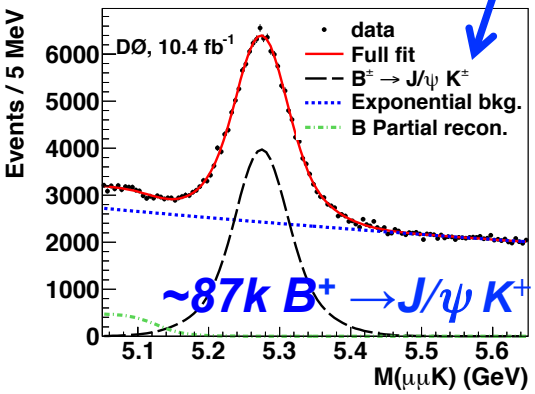
$B_s \to \mu\mu$ analysis strategy

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = \frac{N_{B_s^0}}{N_{B^+}} \frac{\alpha_{B^+}}{\alpha_{B_s^0}} \frac{\varepsilon_{B^+}^{trig}}{\varepsilon_{B_s^0}^{trig}} \frac{\varepsilon_{B^+}^{reco}}{\varepsilon_{B_s^0}^{reco}} \frac{1}{\varepsilon_{B_s^0}^{NN}} \frac{f_u}{f_s} \mathcal{B}\left(B^+ \to J/\psi K^+\right) \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$$

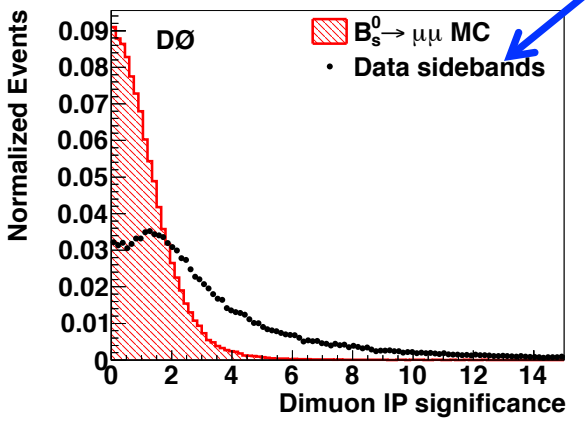
Measure yield relative to normalization mode:

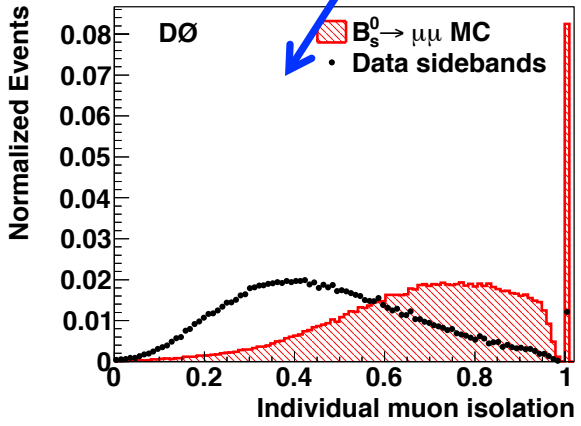
Efficiencies & Acc. from data & MC

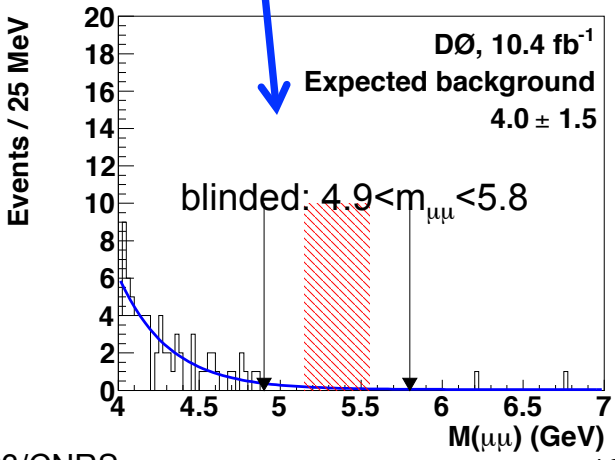
Fragmentation fractions and BR from PDG



- Many systematics cancel in ratio
- Use PV pointing and μ isolation into multivariate discr. (BDT's)
- Evaluation of physics & detector backgrounds from SB fit.

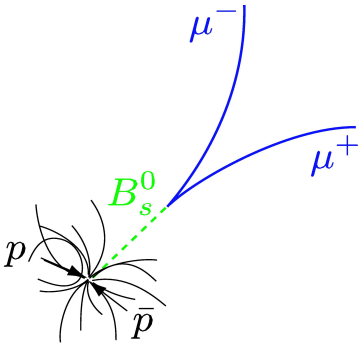




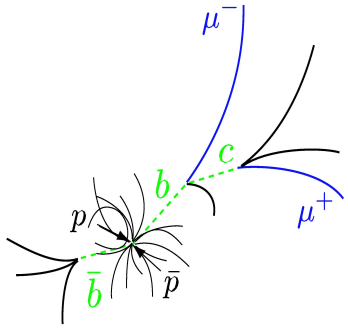


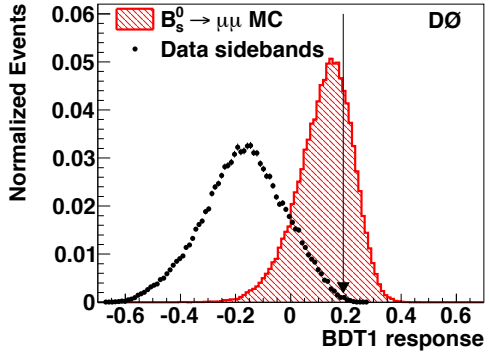
Search for $B_s \to \mu^+\mu^-$ decay update (10.4 fb^{-1})

Signal topology:

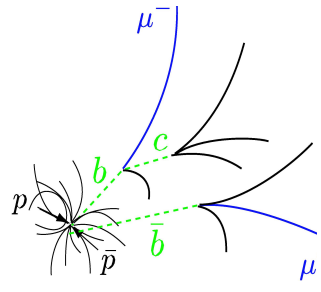


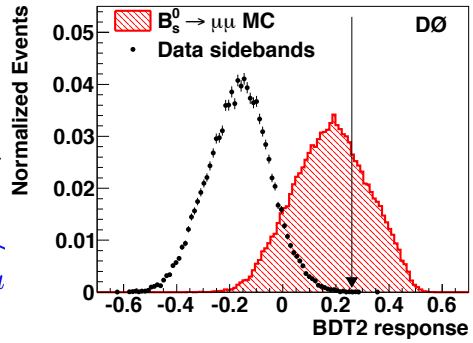
sequential B decay background:

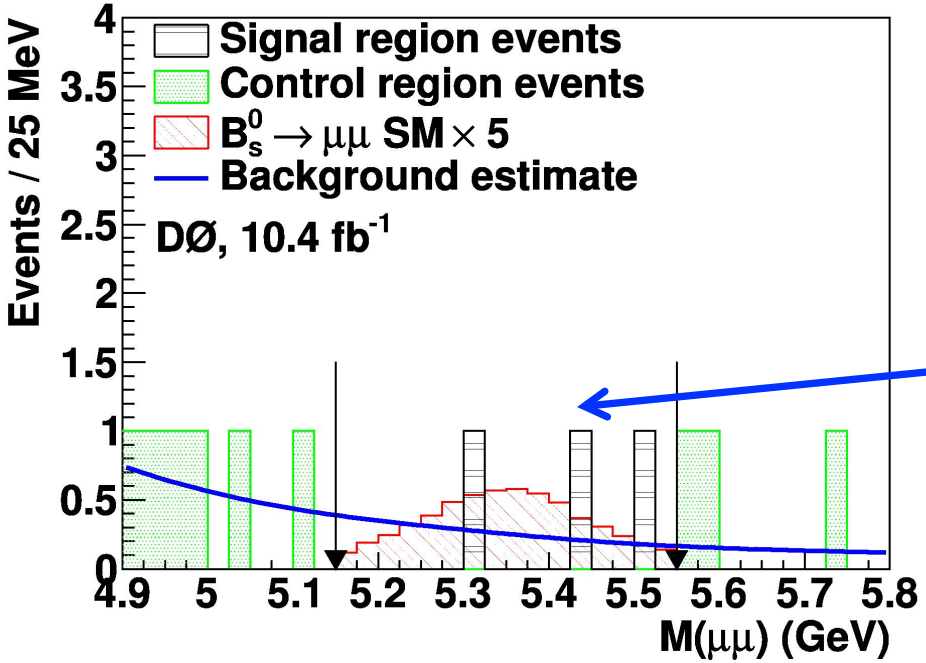




double semilep decay background:







After optimized selection expect:

- SM Signal: 1.23 ± 0.13
- Background: 4.3 ± 1.6
- Limit: BR($B_s \to \mu^+\mu^-$) = 23x10^{-9}

Observed 3 events, limit at 95% CL:

BR($B_s \to \mu^+\mu^-$) < 15 x 10^{-9}

(CDF: 31x10^{-9})

http://arxiv.org/abs/1301.4507

Submitted to Phys. Rev. D

→ *for more details: talk from Michelle Prewitt in Monday YSF*

Summary

- Search for NP in CPV and rare decays of the B_s meson has been updated, mixing phase Φ_s shows increased consistency with SM.
- Many CPV studies performed at Tevatron on B_s system as well as on B_d showing results comparable to B-factories in terms of precision and also close to first LHC run results form LHCb.
- Search for NP in the B_s to $\mu\mu$ mode update from D0. Closes the loop on the full Tevatron data sample. CDF shows slight excess with moderate statistical significance. Competition with LHC first on rare B decays.
- Still more (unexpected?) to come with full TeVatron statistics.
- *Conclusive remarks:*
  - Tevatron opened the way to high precision Heavy Flavor physics at collider experiments, both through detector and trigger strategies and through advanced analysis techniques.
  - HF physics at collider has been demonstrated to be fully competitive especially for hadronic modes and very rare decays. Ex. B_s mixing, B_s to $\mu\mu$, charm physics. Weak points are decays involving neutrals (π^0, γ) in the final state.
  - We are (almost) at the end of our physics program but are leaving a rich legacy on HF physics to LHCb and B factory which are taking over. For the time being enjoy though competition!

Thank you !

Backup

$b \to s\, l^+ l^-$ status

# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb^{-1}	CDF 2011 9.6 fb^{-1}	LHCb 2011/12 1 fb^{-1}
$B^0 \to K^{*0}\, \ell\bar{\ell}$	$137 \pm 44^{\dagger}$	$247 \pm 54^{\dagger}$	288 ± 20	900 ± 34
$B^+ \to K^{*+}\, \ell\bar{\ell}$			24 ± 6	76 ± 16
$B^+ \to K^+\, \ell\bar{\ell}$	$153 \pm 41^{\dagger}$	$162 \pm 38^{\dagger}$	319 ± 23	1232 ± 40
$B^0 \to K^0_S\, \ell\bar{\ell}$			32 ± 8	60 ± 19
$B_s \to \phi\, \ell\bar{\ell}$			62 ± 9	77 ± 10
$B_s \to \mu\bar{\mu}$				emerging
$\Lambda_b \to \Lambda\, \ell\bar{\ell}$			51 ± 7	
$B^+ \to \pi^+\, \ell\bar{\ell}$		limit		25 ± 7

- CP-averaged results
- vetoed q^2 region around J/ψ and ψ' resonances
- † unknown mixture of B^0 and $B^{\pm}$

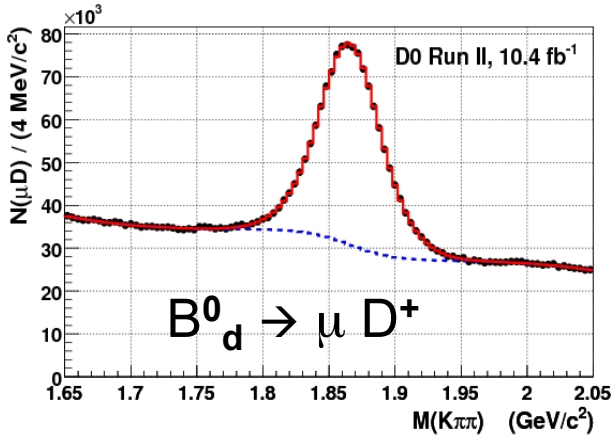
Babar arXiv:1204.3933

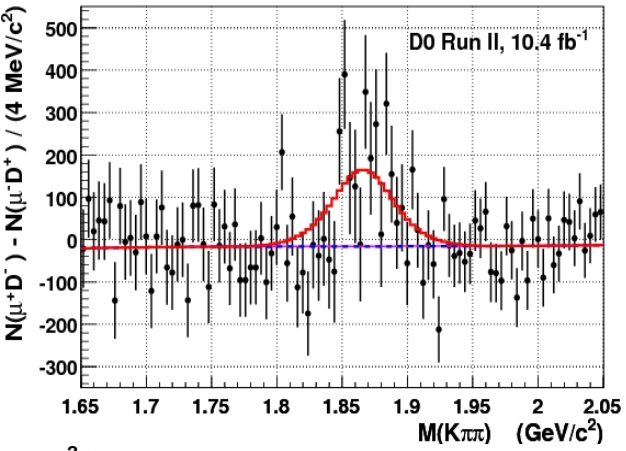
Belle arXiv:0904.0770

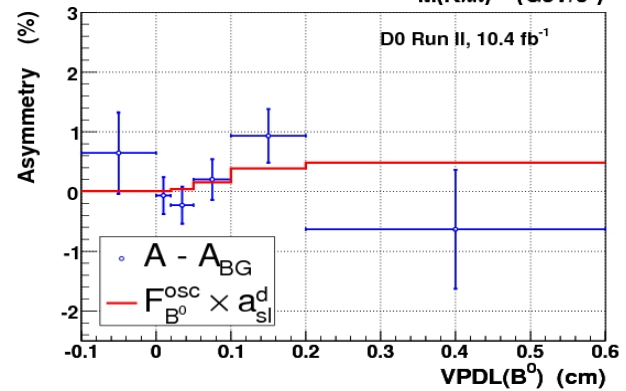
CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012

LHCb LHCb-CONF-2012-008 (-003, -006), arXiv:1205.3422 + 1209.4284 + 1210.4492 + 1211.2674

CPV in B_d semileptonic decays (10.4 fb^{-1})







$$a_{\rm sl}^d = [0.68 \pm 0.45\ (\text{stat.}) \pm 0.14\ (\text{syst.})]\%$$

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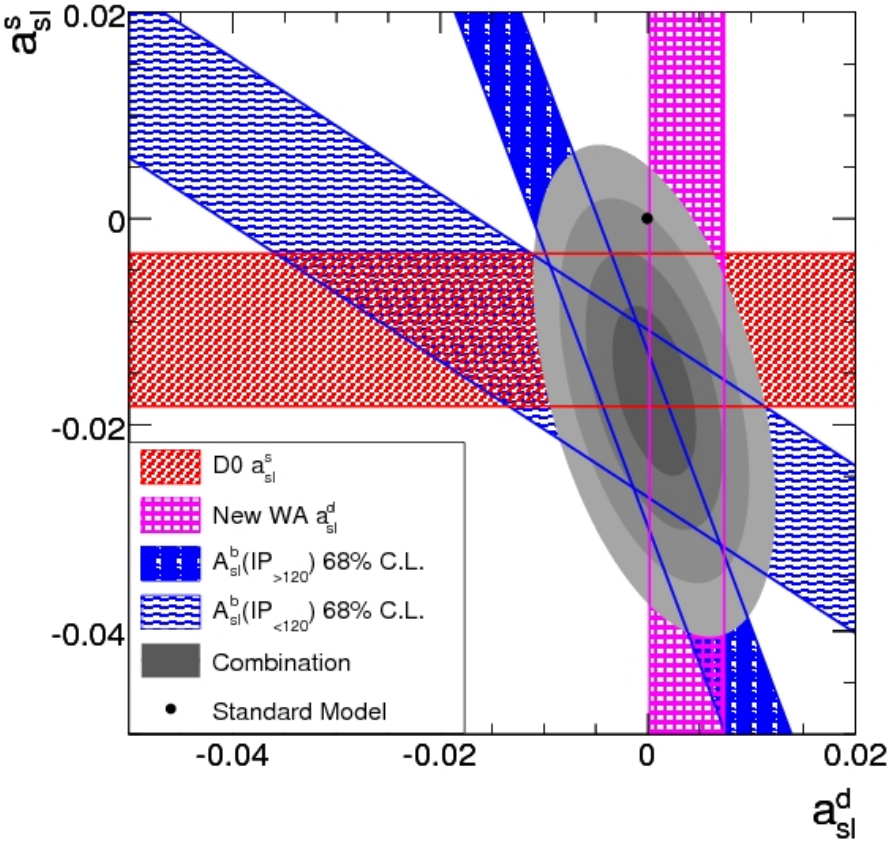
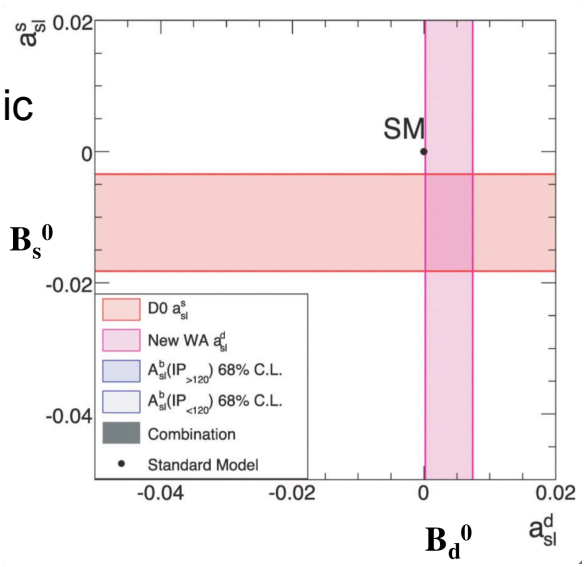
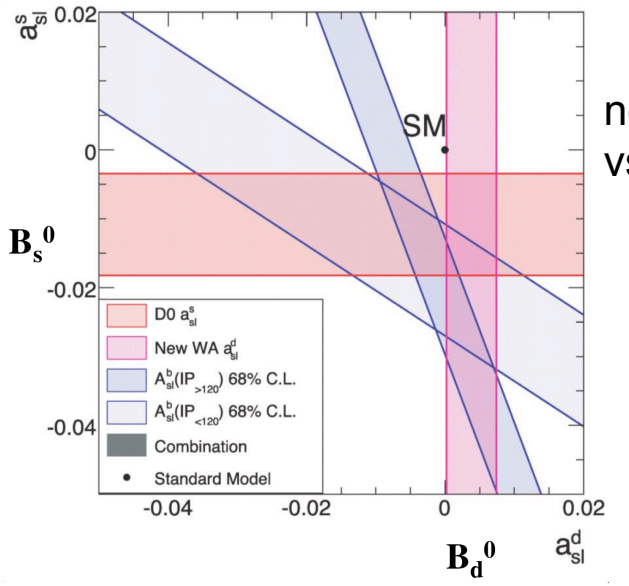


CP Asymmetries in $B_{s,d}$ mixing status:

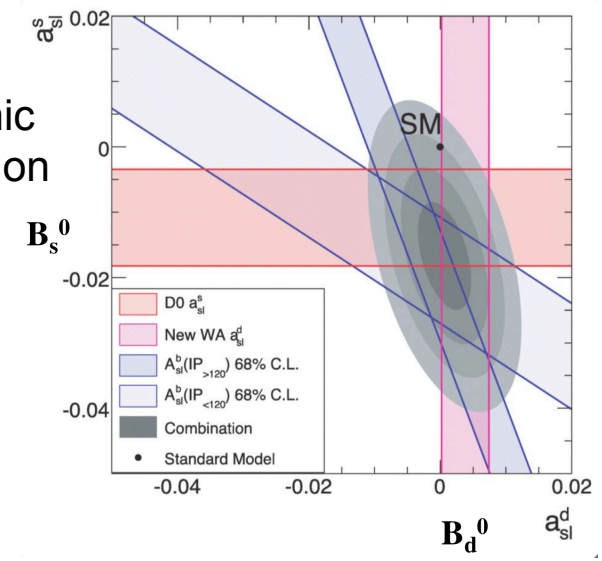
new D0 semileptonic

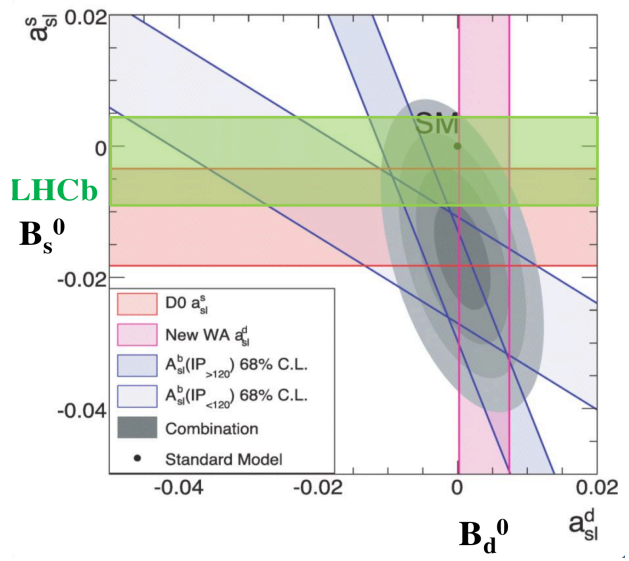




new D0 semileptonic vs D0 like sign dimuon

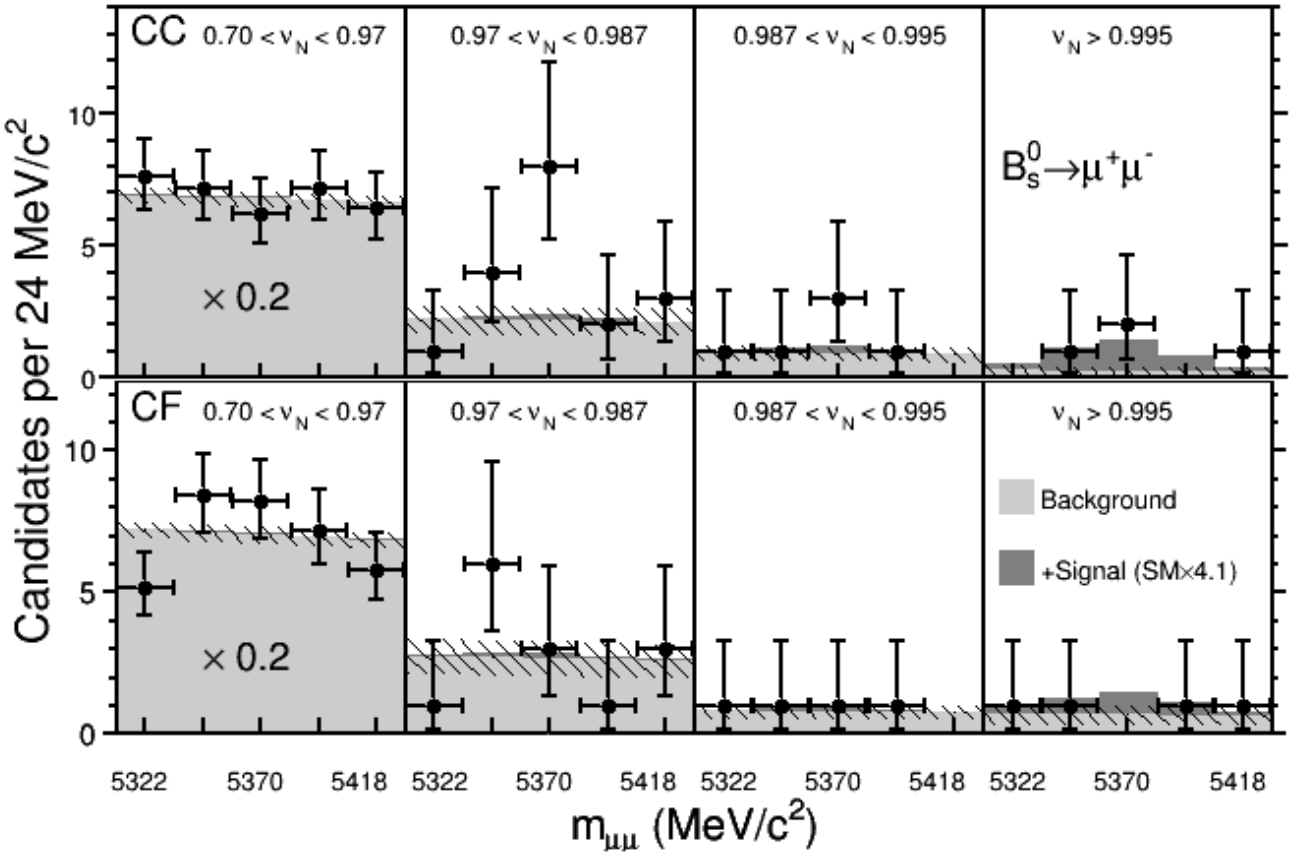
new D0 semileptonic + D0 like sign dimuon combination





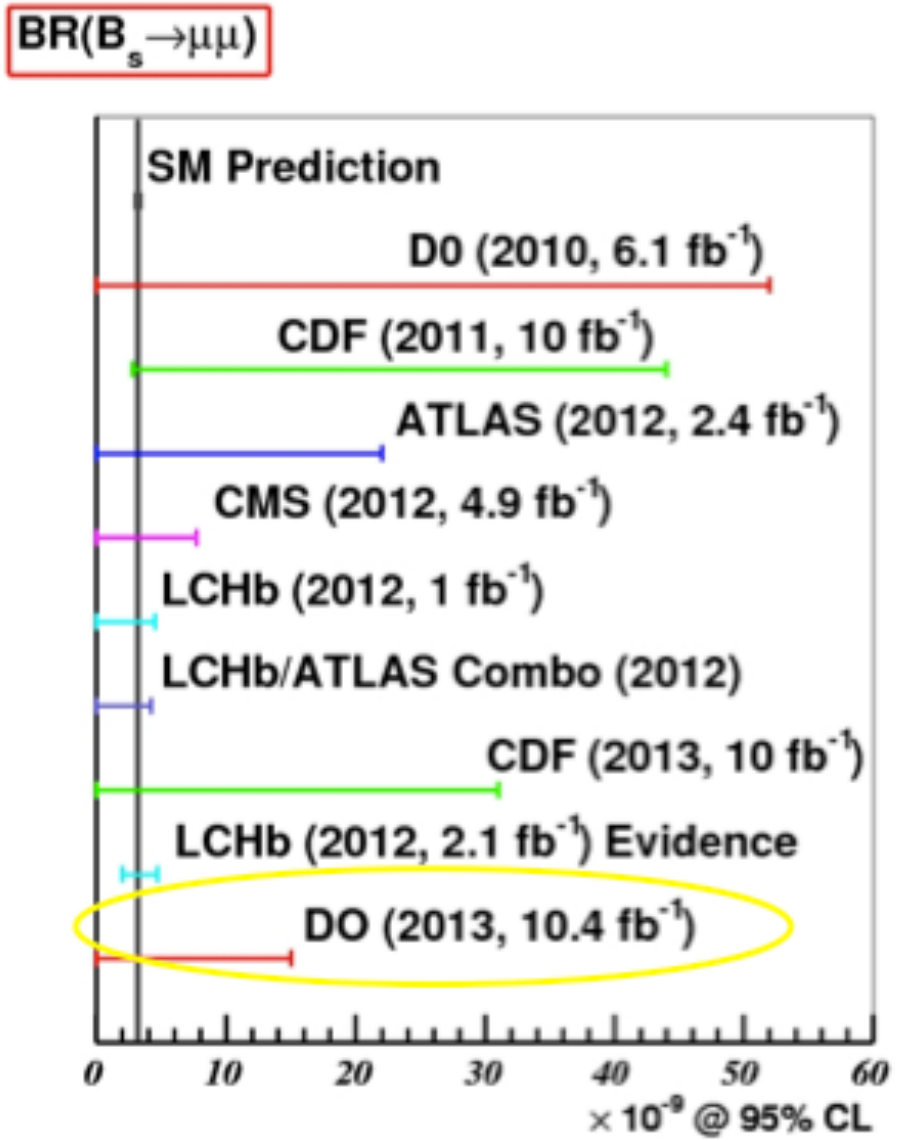
LHCb B_s result

$B_s \to \mu^+\mu^-$ search with 9.7 fb^{-1} @ CDF

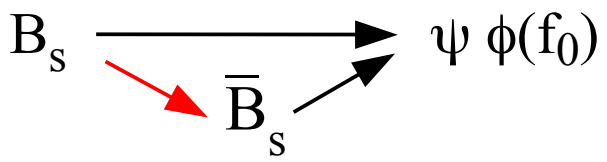


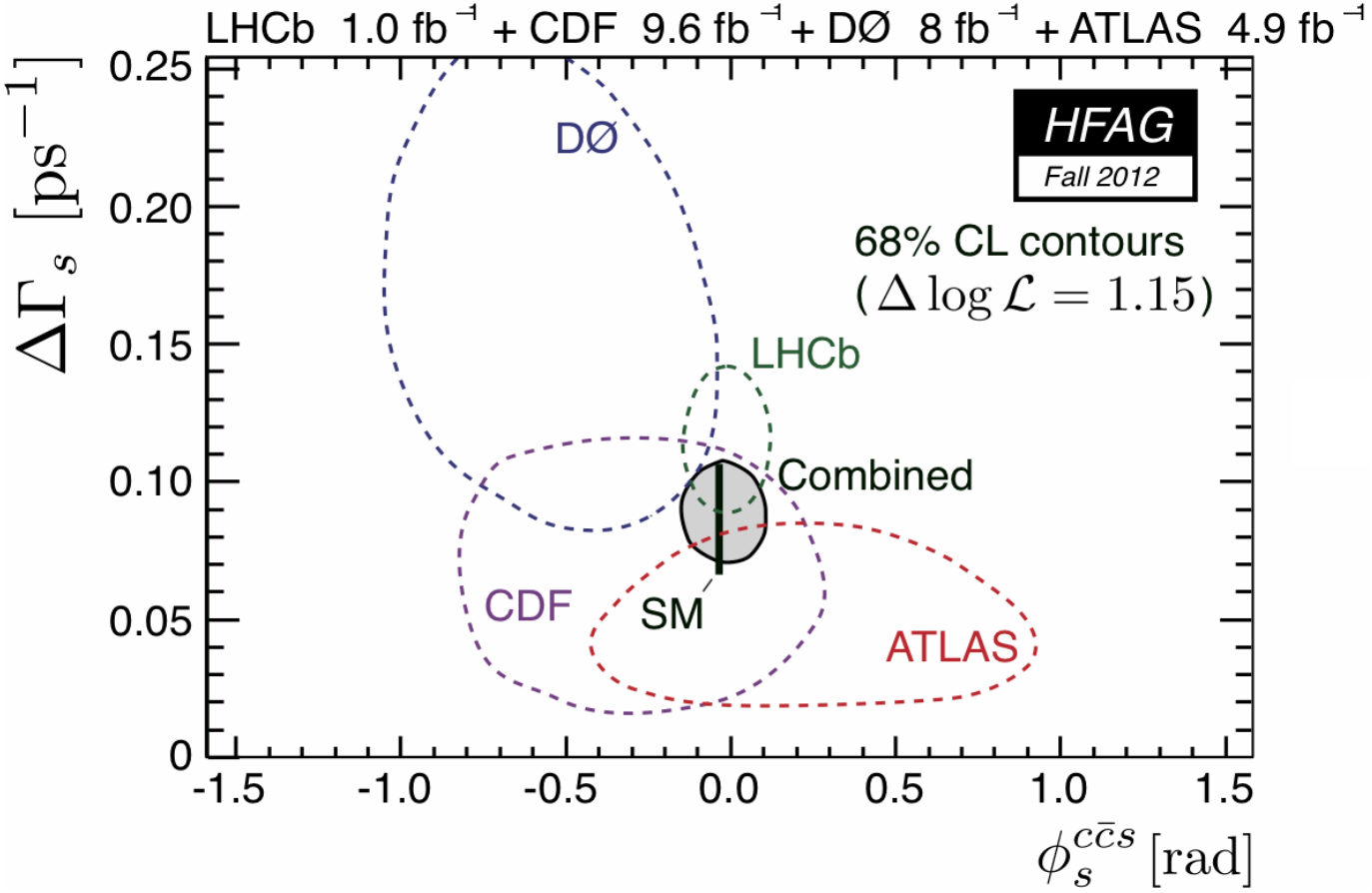
- Prob. of a background fluctuation become 0.94% (7.1% for bkg+SM signal), was 0.27%/1.9%
- Considering two highest bin only p-value are 2.1% (22.4% for bkg+SM)
- Two sided bound: $0.22 \times 10\text{-}8 < Br < 3.0 \times 10\text{-}8$ @ 90% C.L. [$Br(B_s \to \mu^+\mu^-) = 1.0^{+0.8}_{-0.6} \times 10^{-8}$ @1σ]
- UL 95% (90%) C.L.using CL_s is 3.1×10^{-8} (2.7×10^{-8})

$B_s \to \mu^+ \mu^-$ decay search status



CP Violation in $B_s \to J/\Psi\Phi$ status:





$$S_{\psi\varphi}^{SM} = -\sin(\phi_s)$$
$$= 0.041 \pm 0.01$$