Heavy Flavor Physics at the Tevatron

Centered on B_s physics

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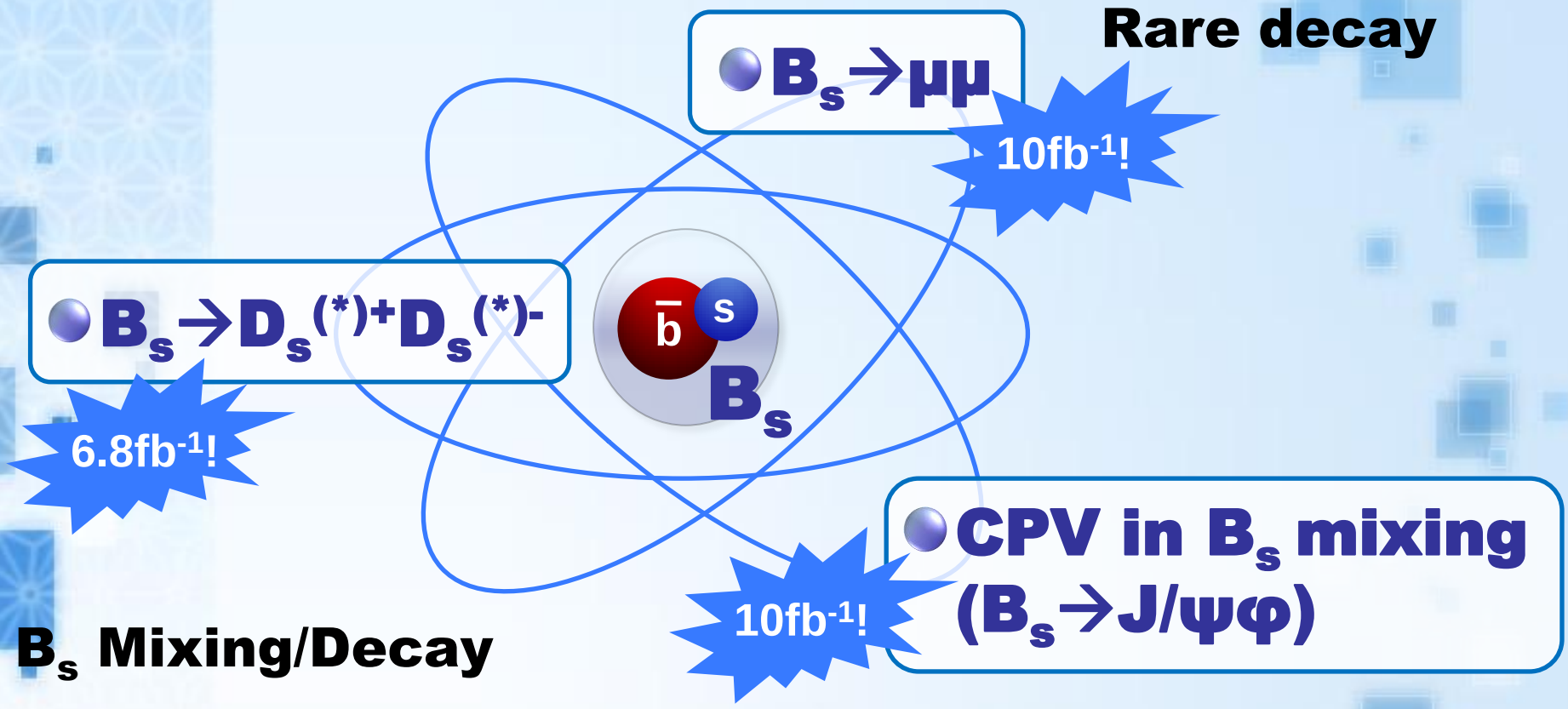
on behalf of the CDF and DØ collaborations

XXVI Rencontres de Physique de la Vallée d'Aoste
La Thuile, Aosta Valley, Italy
February 29, 2012

To be covered in my talk

- B_s related hot topics



B_s Mixing/Decay

Tevatron

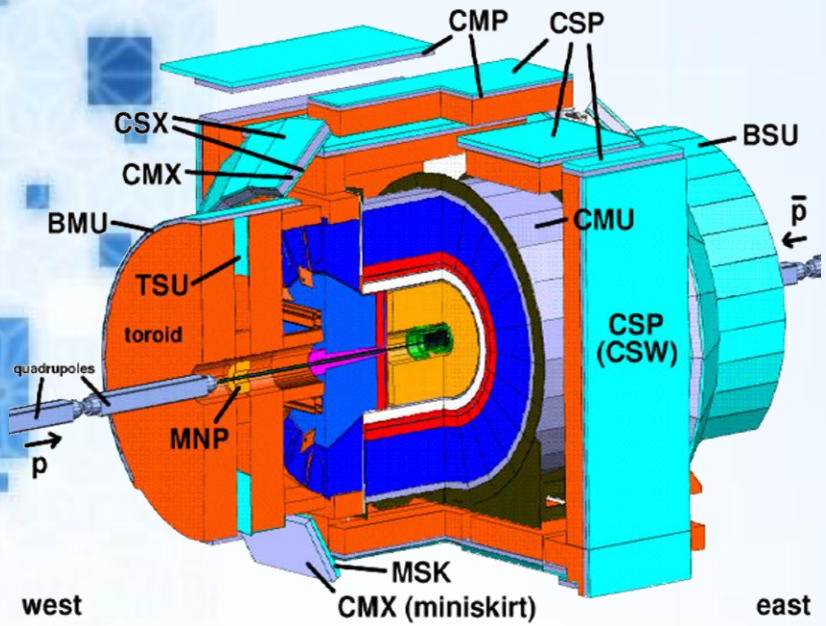
- $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV
  - Typical initial luminosities of $3.5\times10^{32}cm^{-2}s^{-1}$
  - >50 pb^{-1} collected per week
- Shutdown after 30 years operation
- Delivered $12fb^{-1}$ and recorded ~$10fb^{-1}$

Tevatron Experiments

CDF II Detector

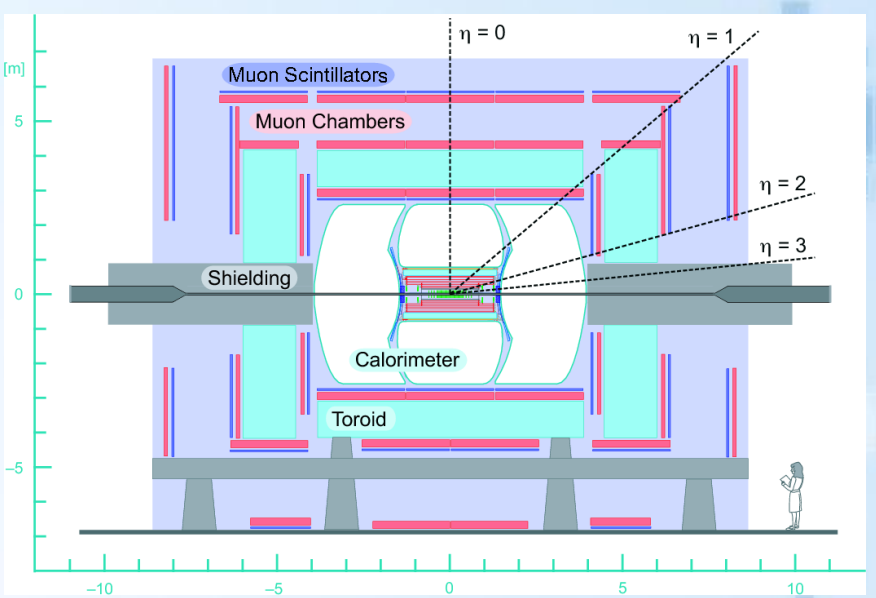
- Silicon vertex detector
- Central tracking
- Calorimeter & muon systems (dimuon trigger)

- Silicon vertex trigger (two track trigger)
- Particle ID (TOF and dE/dx)
- Excellent mass resolution



DØ Detector

- Single muon trigger
- Excellent electron & muon ID
- Excellent tracking acceptance

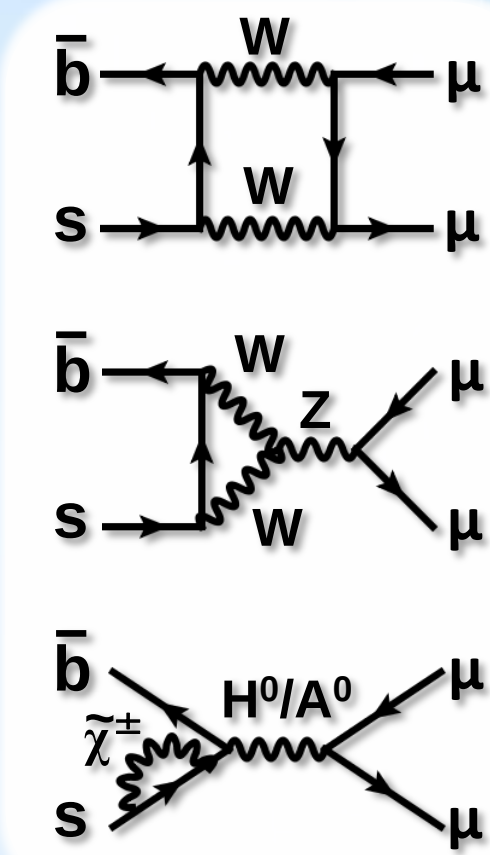


B→μμ

- **Highly suppressed in the SM**

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

A. J. Buras, JHEP09,106 (2010)

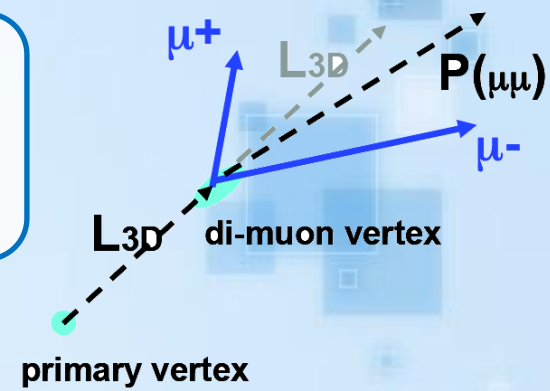


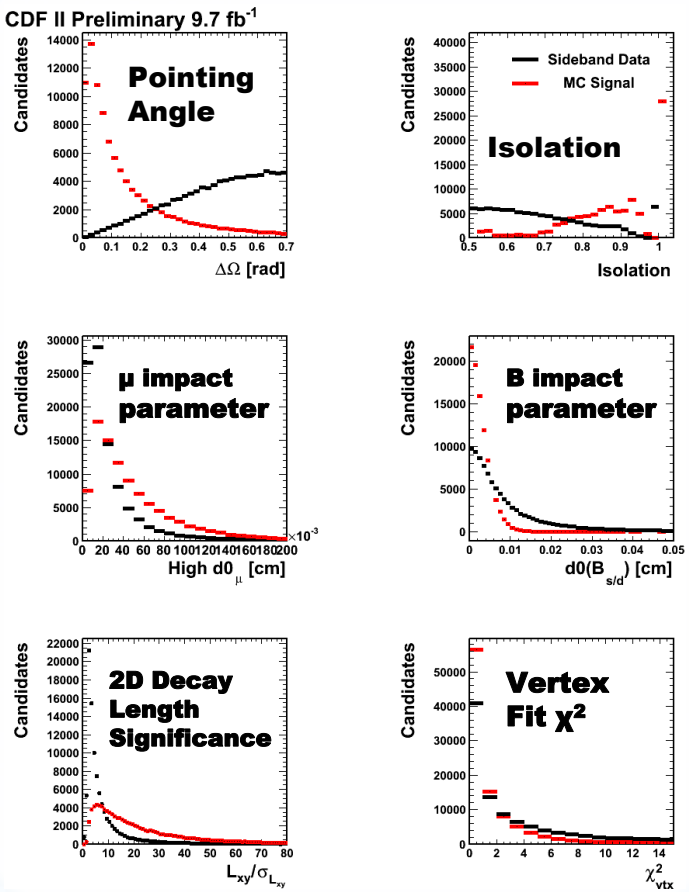
- **Enhanced in NP (up to 100x)**
  - e.g. MSSM: BR(B→μμ) $(\tan\beta)^6$

- **Experimental status**
  - **CDF** $Br(B_s \to \mu\mu) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$ PRL107, 191801 (2011)
  - **DØ** $Br(B_s \to \mu\mu) < 5.1 \times 10^{-8}$ @95% C.L. PLB693, 539 (2010)
  - **LHCb** $Br(B_s \to \mu\mu) < 1.4 \times 10^{-8}$ @95% C.L. PLB 708, 55 (2012)
  - **CMS** $Br(B_s \to \mu\mu) < 1.9 \times 10^{-8}$ @95% C.L. PRL107, 191802 (2011)

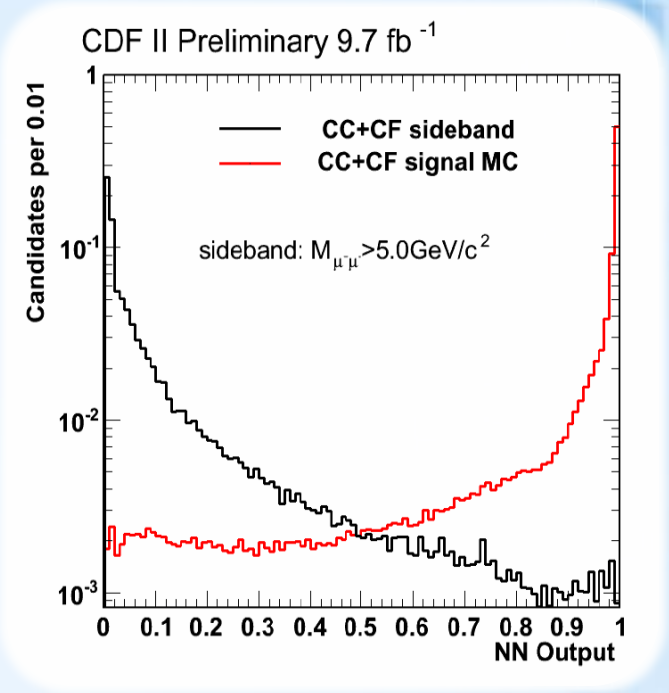
B→μμ: event selection

- Dimuon trigger
- Optimized event selection using NN
- Normalized by control sample ($B^+ \to J/\psi(\to \mu\mu)K^+$)





14 Discriminating variables



B→μμ: BG estimation

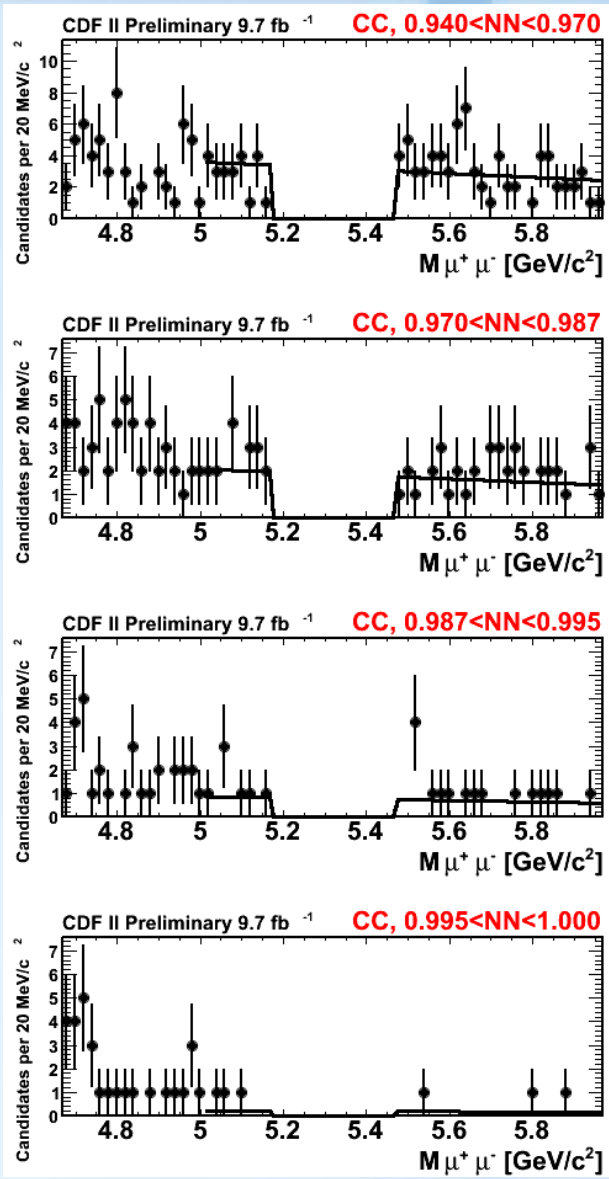
- **Dominant BG: combinatorial**
  - Mostly rejected by NN discriminant

- **Peaking BG: B→hh**
  - Estimated using MC and D*-tagged $D^0 \to K^- \pi^+$ data
  - Only 10% of combinatorial BG in B_s

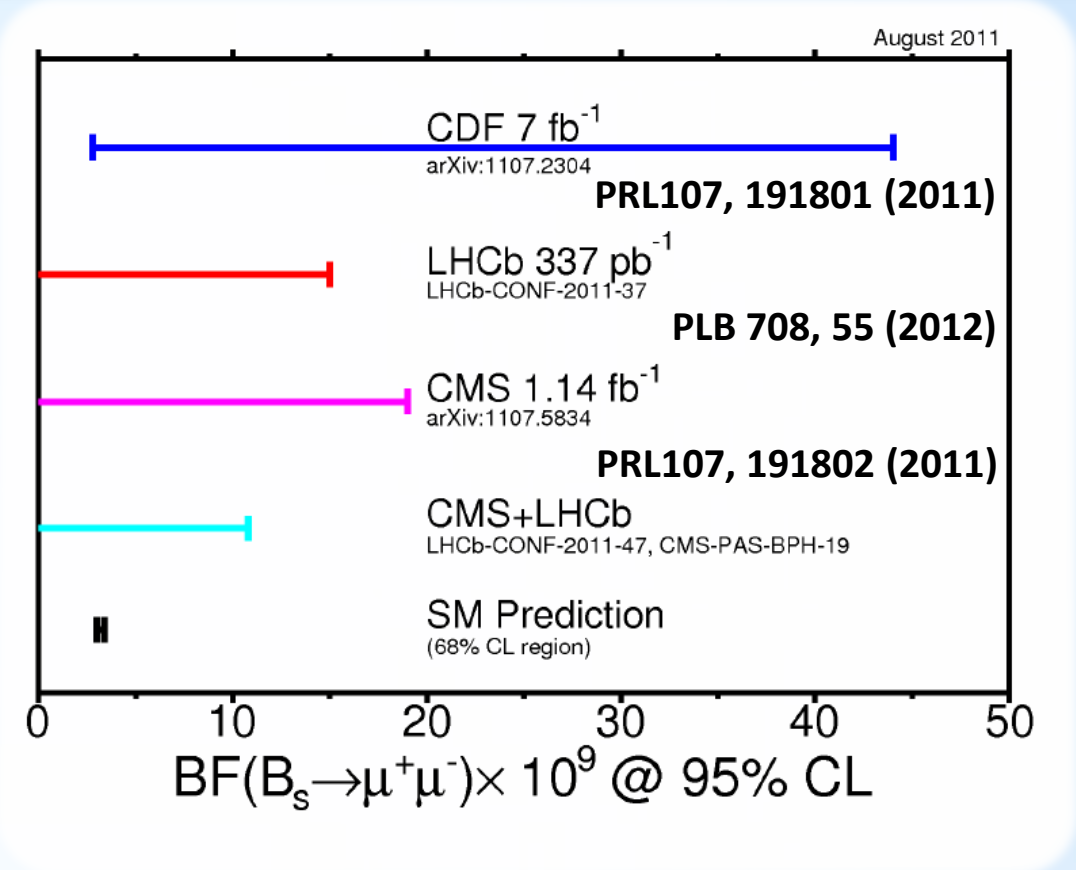
- **Well controlled**
  - Checked by various control samples

sample	NN cut	CC pred	CC obsv	CC prob(%)
OS-	0.700<NN<0.760	268.8±(14.3)	249	82.3
	0.760<NN<0.850	320.8±(16.1)	282	95.1
	0.850<NN<0.900	150.3±(9.9)	156	36.5
	0.900<NN<0.940	146.2±(9.7)	158	23.0
	0.940<NN<0.970	146.2±(9.7)	137	72.9
	0.970<NN<0.987	100.4±(7.8)	98	58.3
	0.987<NN<0.995	78.8±(6.8)	59	97.0
	0.995<NN<1.000	41.2±(4.8)	42	47.2

- Negative lifetime
  - Same/opposite sign
- Reverse muon ID

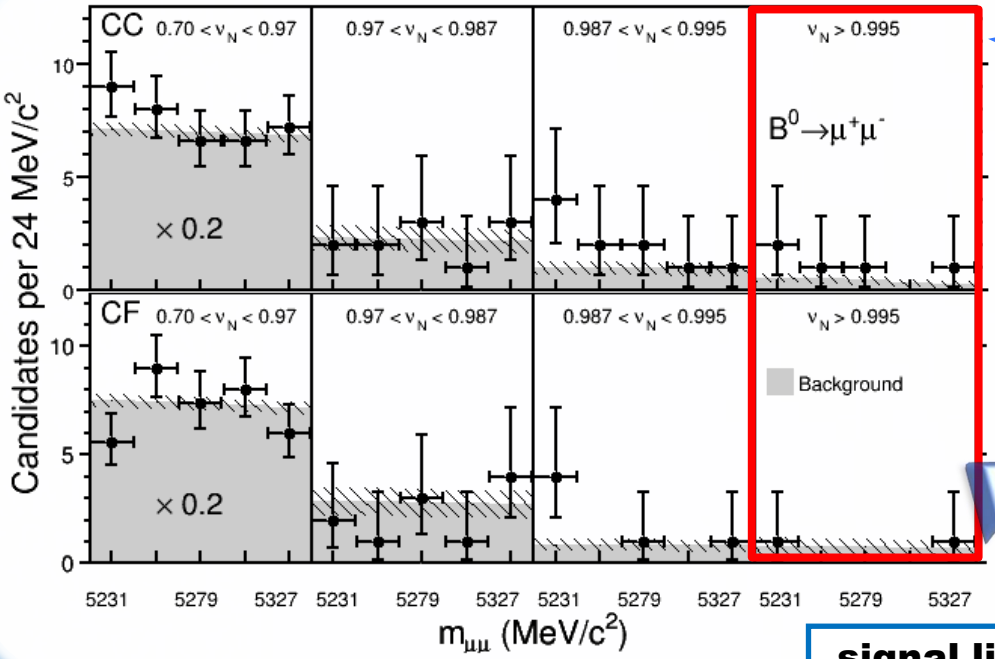


$B_s \rightarrow \mu\mu$: recap of 2011



- Interesting >2.5σ excess of B_s over BG observed by CDF in $7fb^{-1}$
- Compatible with all other results, but could be first indication of a signal
- CDF updates the analysis with whole Run II dataset (+30% data) while keeping the analysis unchanged

$B_d \rightarrow \mu\mu$: results with $10fb^{-1}$

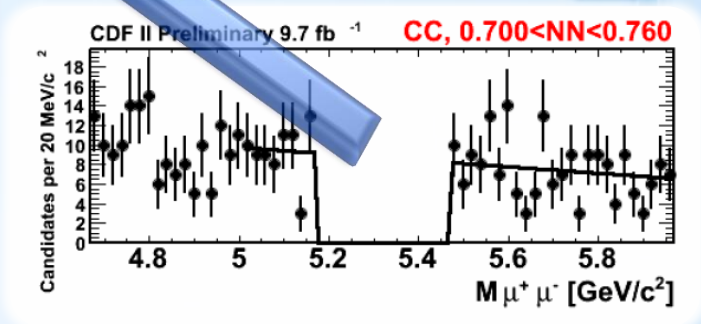


New!

- Divide signal region by NN discriminant
- Estimate BG from each mass sideband

CC: both central muon
CF: central+forward muon

signal like

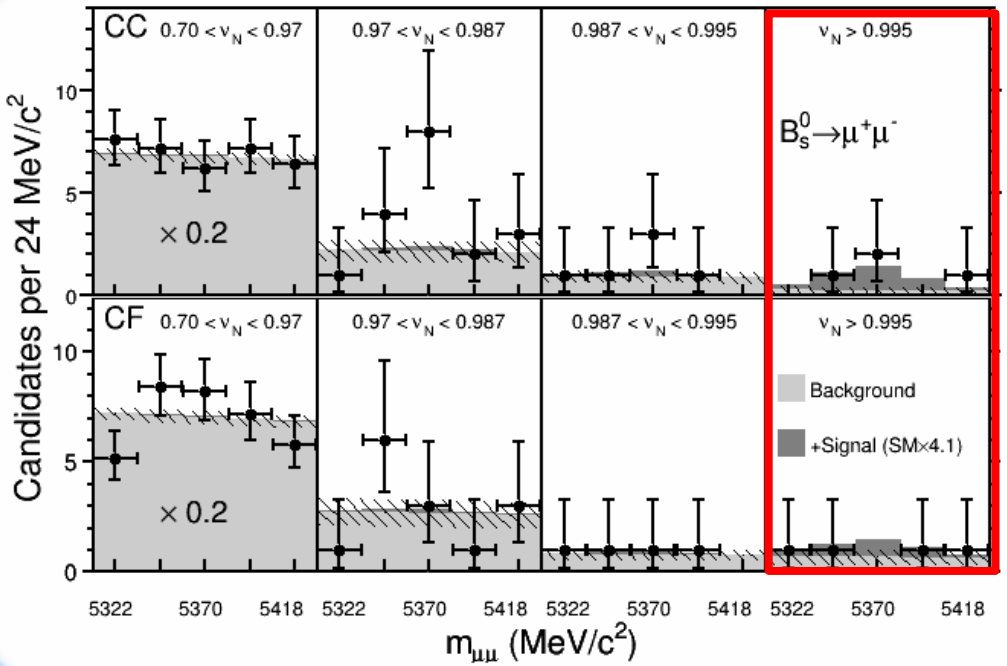


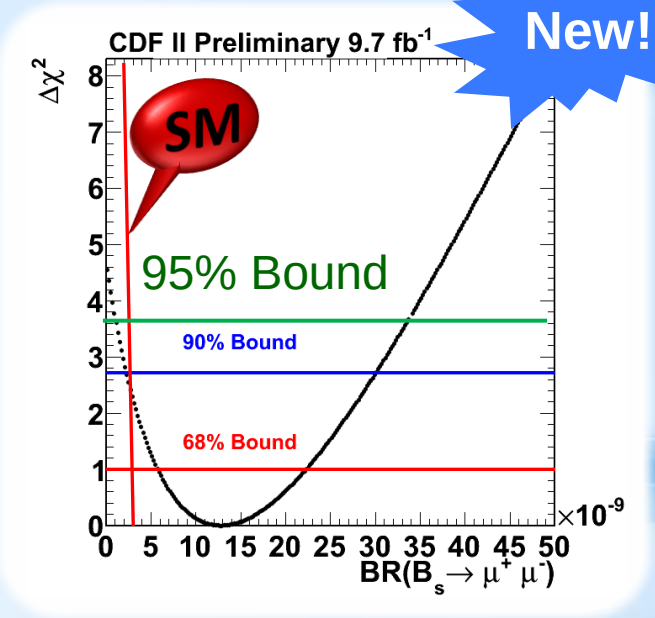
- **Good consistency with expected limit:**
  $BR(B_d \rightarrow \mu^+\mu^-)_{exp} < 4.2 \times 10^{-9}$ at 95% C.L.

$BR(B_d \rightarrow \mu^+\mu^-) < 4.6 \times 10^{-9}$ at 95% C.L.

- **Consistent with SM**

$B_s \rightarrow \mu\mu$: results with $10 fb^{-1}$





- **Summer excess not reinforced by new data, but still there**
  - **Keep observing a >2σ fluctuation over BG only, which allows us to quote a BR**

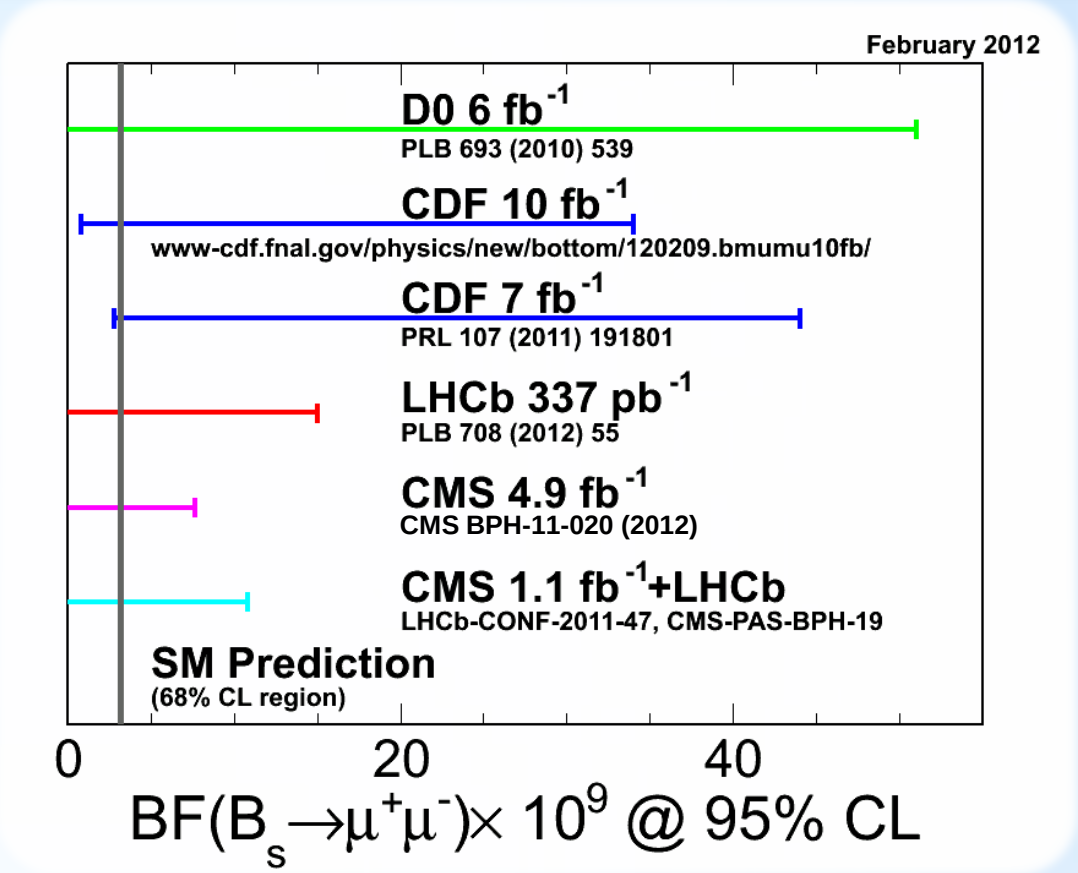
$BR(B_s \rightarrow \mu^+\mu^-) = (1.3^{+0.9}_{-0.7}) \times 10^{-8}$

$0.8 \times 10^{-9} < BR(B_s \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-8}$ 95% C.L.

Summer'11

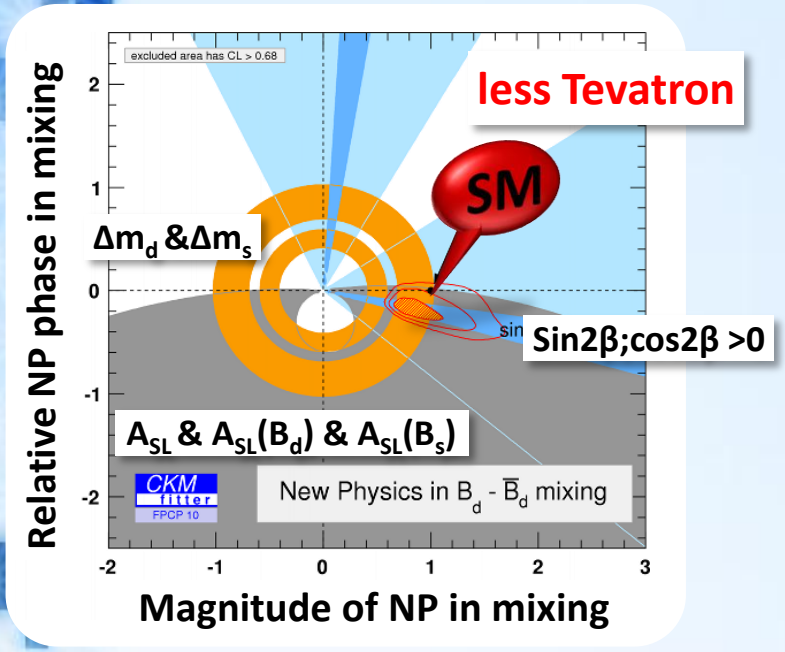
$BR(B_s \rightarrow \mu\mu) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$

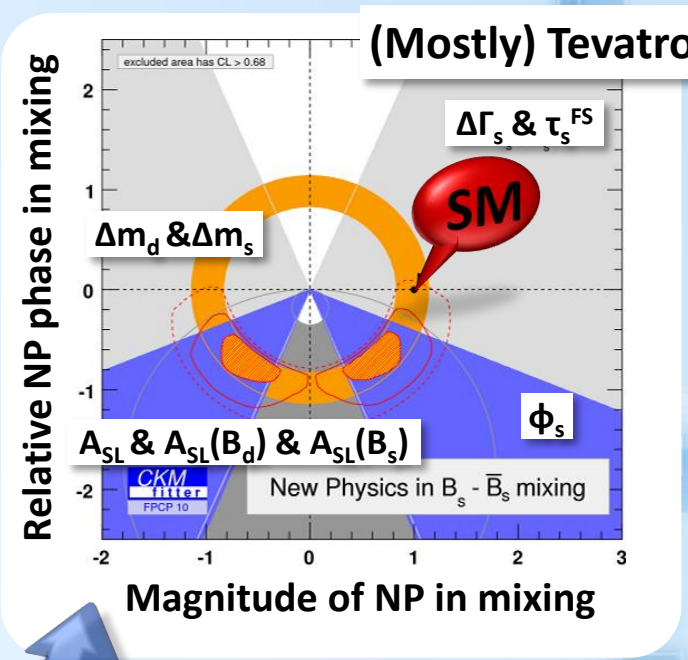
$B_s \rightarrow \mu\mu$: comparison



- Compatible with SM and other experiments

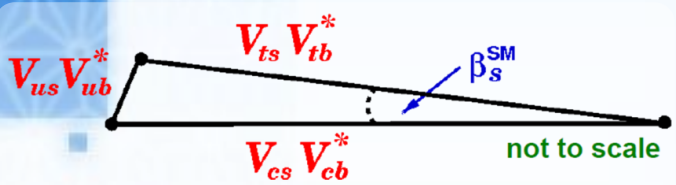
CP violation in B_s system





No large NP is present in leading B transitions

The possibility of NP in the B_s transitions

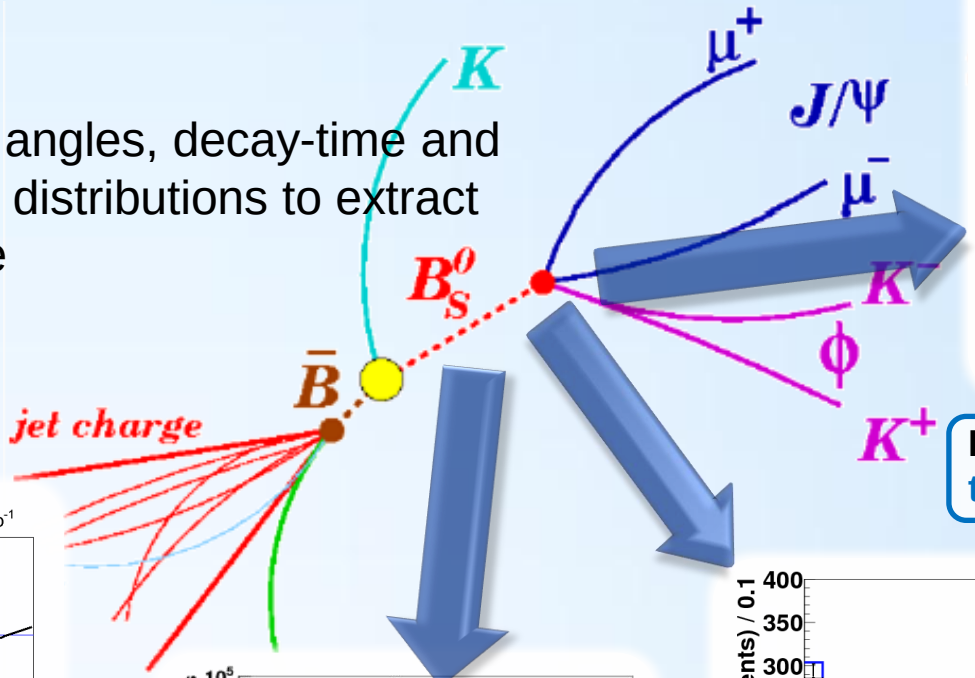


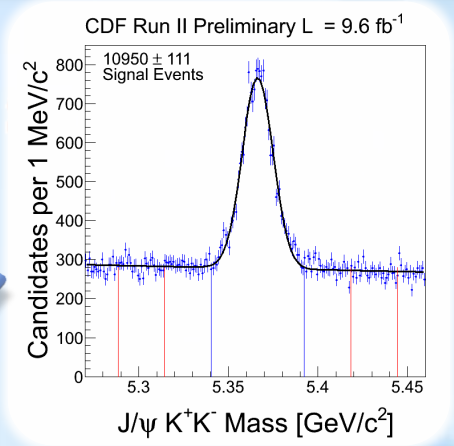
"Squashed" Triangle!

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & \boxed{V_{ts}} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

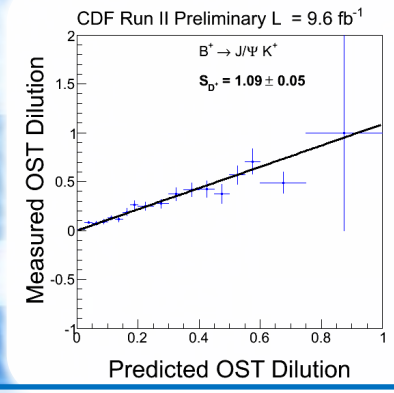
β_s measurement: outline

Joint fit to mass, angles, decay-time and production flavor distributions to extract the mixing phase

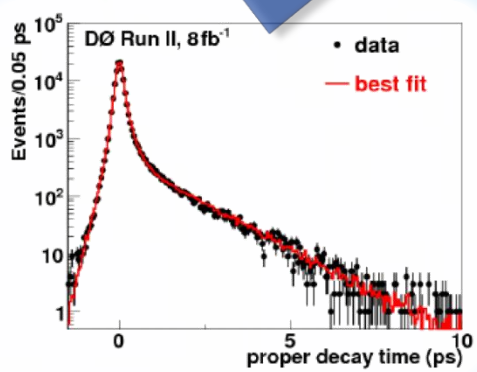




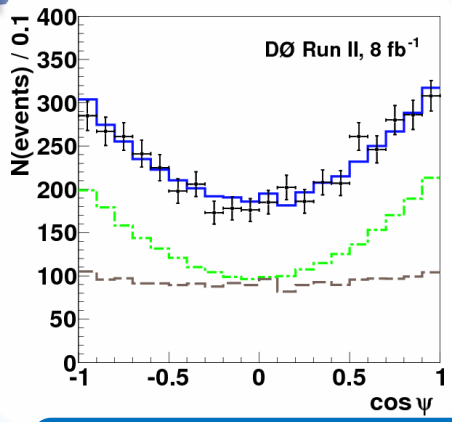
B_s invariant mass fit
to separate signal from BG



Flavor tagging
to determine initial B_s flavor



Decay time measurement
to know time evolution



Angular analysis
to separate CP-even/odd

$B_s \rightarrow J/\psi\phi$: signal

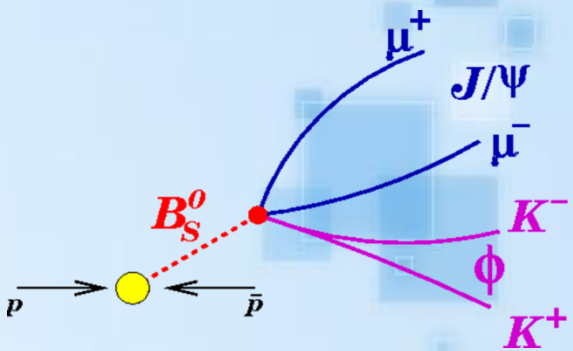
The golden channel to measure β_s

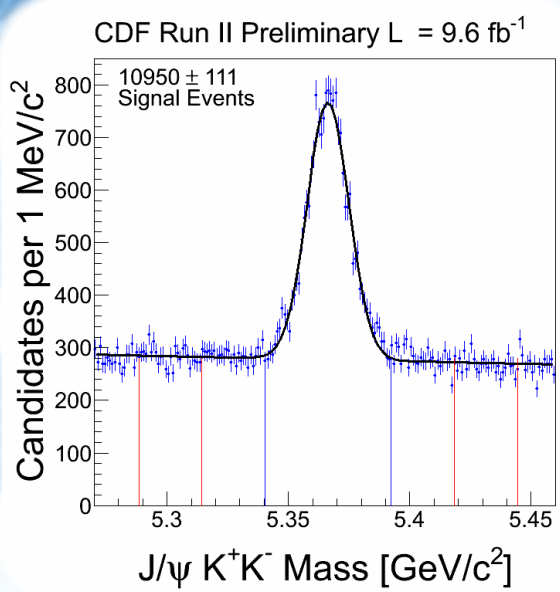
- dominated by $b \rightarrow c\bar{c}s$ tree ~theoretically clean

$B \rightarrow VV$ decay: three partial waves

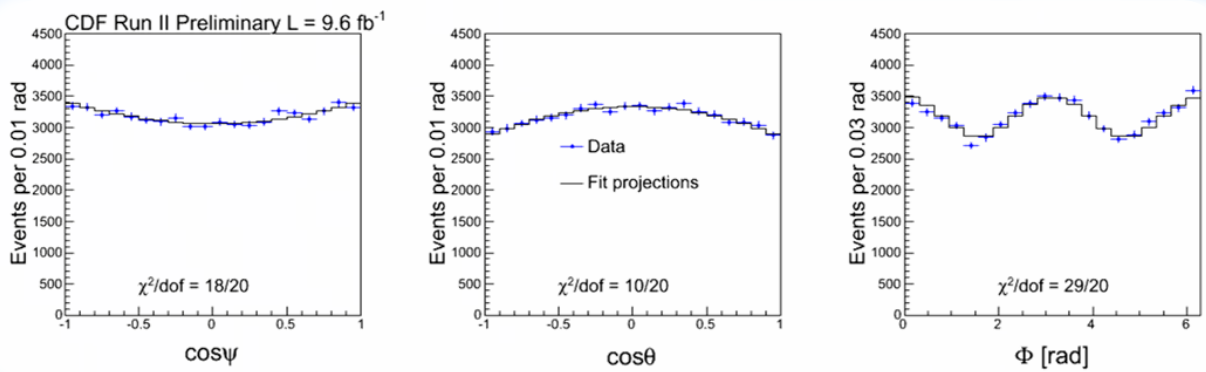
- L=0,2 (CP even)
- L=1 (CP odd)

Need angular analysis





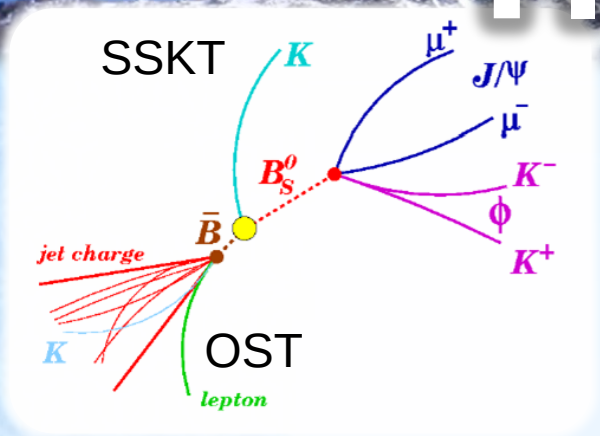
$N(B_s^0) \sim 11000$

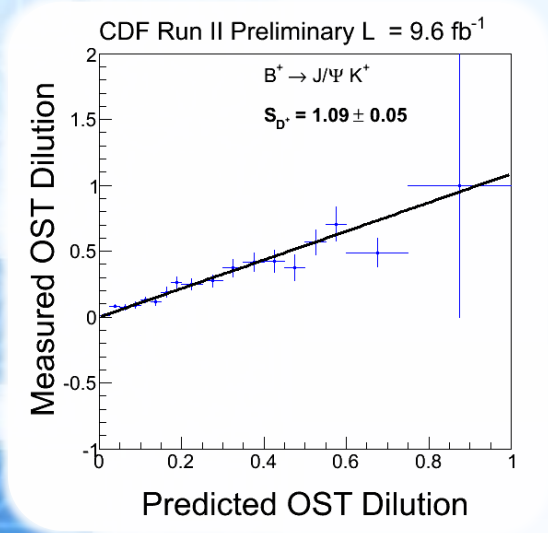


$B_s \rightarrow J/\psi\phi$ angular distributions (Transversity basis)

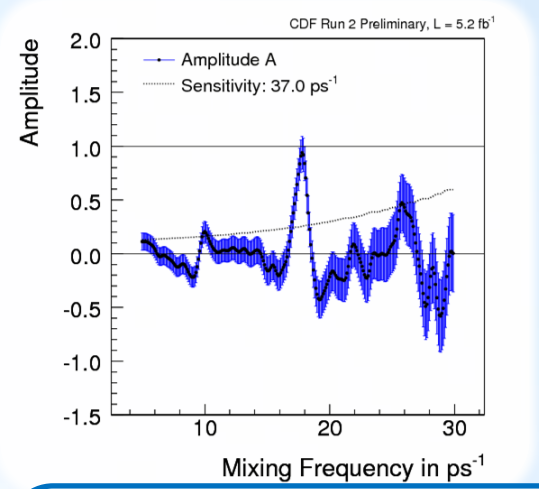
+ Non resonant J/psiKK with KK in S wave

Flavor tagging





- determine initial B_s flavor at the production
  - Employ two different techniques



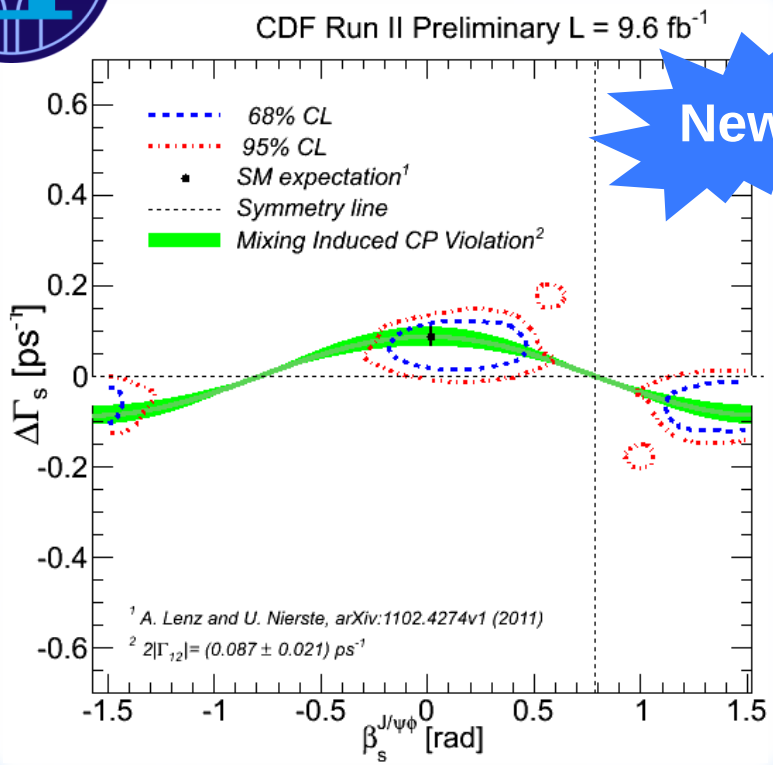
- SSKT(Same Side Kaon Tagger)
  - Exploit correlation with particles produced in fragmentation
  - Total tagging power: 3.5%

- OST(Opposite Side Tagger)
  - Exploit decay products of other b-hadron
  - Total tagging power: 1.3%

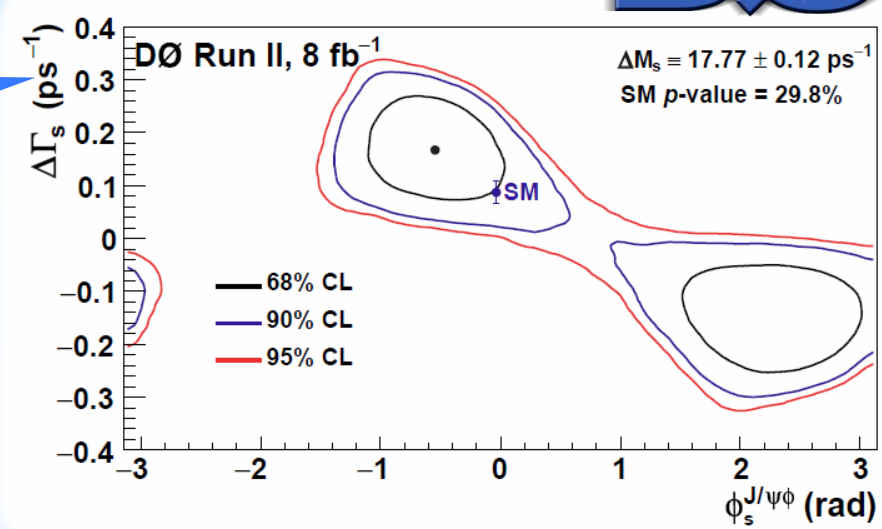
- For CDF full data analysis
  - OST: used for whole data
  - SSKT: used for first 5.2fb^{-1}

$B_s \rightarrow J/\psi\varphi$: results

CDF Public Note 10778



New!



- **Consistent with SM ~1σ**

arXiv:1109.3166
(accepted by PRD)

$\Phi_s = -0.55^{+0.38}_{-0.36}$ (rad)
$\beta_s = 0.28^{+0.18}_{-0.19}$ (rad)

- **NEW result using full data!**
- **Consistent with SM <1σ**

β_s within [-π/2,-1.51] U [-0.06,0.30] U [1.26,π/2] at the 68% C.L.

$B_s \to D_s^{(*)+} D_s^{(*)-}$

- Predominately CP-even (purely CP-even: $D_s^+ D_s^-$)
- May give dominant contribution to B_s width difference in SM
- Possible to infer $\Delta\Gamma_s/\Gamma_s$ by measuring $BR(B_s \to D_s^{(*)+} D_s^{(*)-})$
  - under some assumptions: $$2\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) \sim \frac{\Delta\Gamma_s}{\Gamma_s + \Delta\Gamma_s/2}$$

Aleksan *et. al.*, PLB 316, 567 (1993)
Dunietz *et. al.*, PRD 63, 114015 (2001)

- BR not precisely measured so far

CDF result: PRL 100, 021803 (2008)

$$\mathrm{BR}(B_s \to D_s^+ D_s^-) = (0.94^{+0.44}_{-0.42})\%$$

DØ result: PRL 102, 091801 (2009)

$$\mathrm{BR}(B_s \to D_s^{(*)+} D_s^{(*)-}) = (3.5 \pm 1.0 \pm 1.1)\%$$

Belle result: DPF2011 preliminary

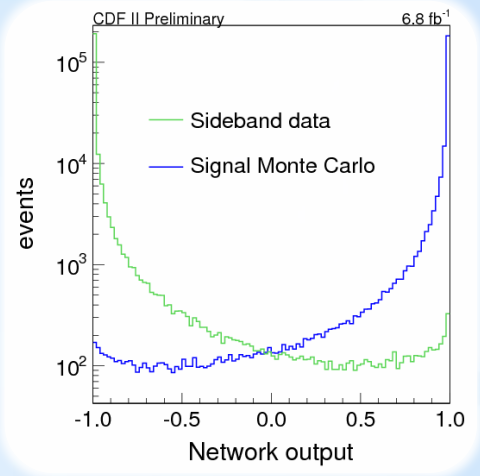
$$\mathrm{BR}(B_s \to D_s^{(*)+} D_s^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%$$

need more data to be conclusive

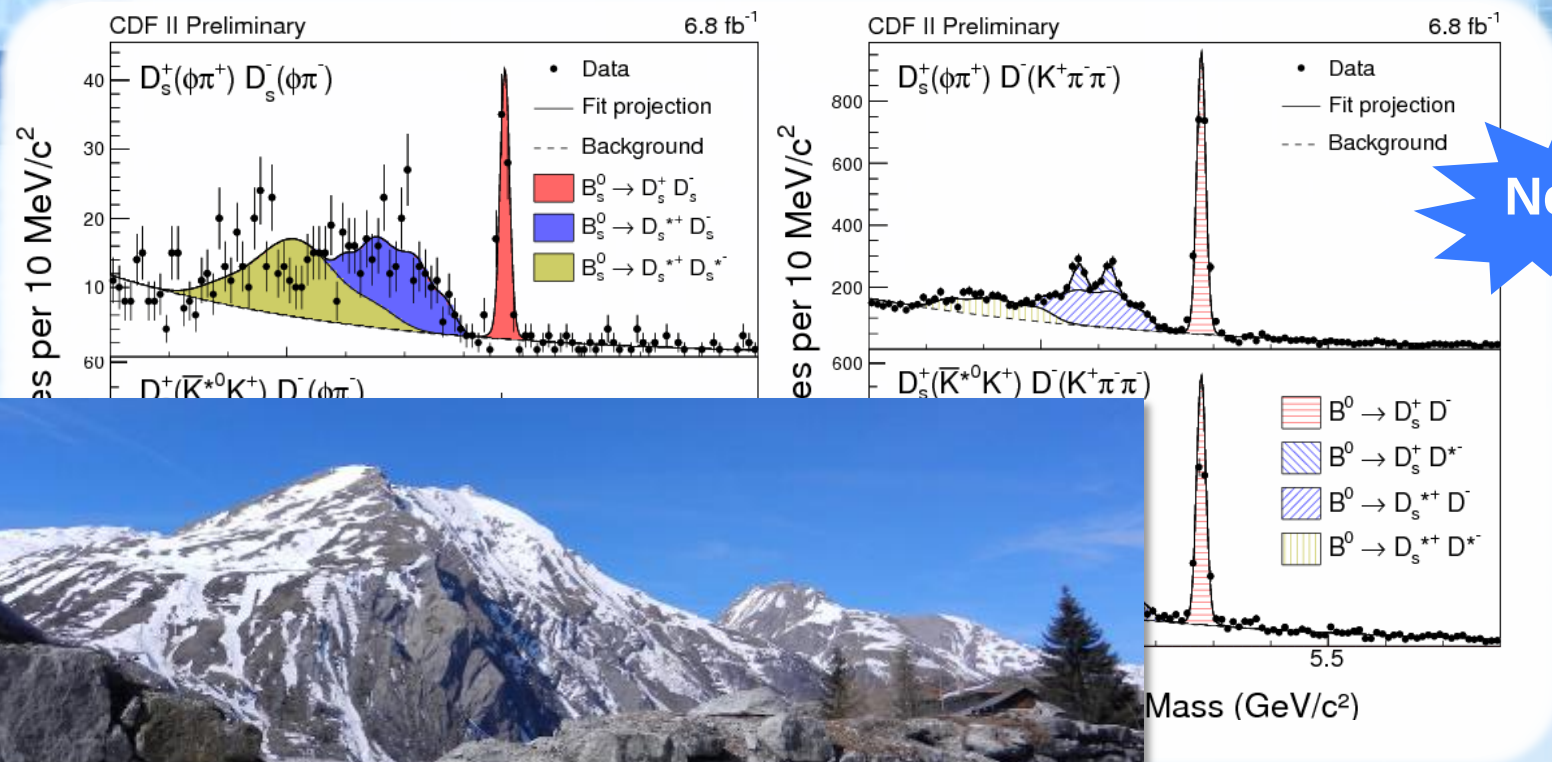
$B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$: analysis

- CDF update from 355pb^{-1} analysis PRL100,021803 (2008)
  - Use 6.8fb^{-1} two track trigger data

- Event selection:
  - Partial reconstruction ($B_s \rightarrow D_s^+ D_s^- X$) since neutral from D_s^* is hard to reconstruct
  - BR normalized by $B^0 \rightarrow D^+ D_s^-$
  - Final state: combination of D_s subdecays
    - $D_s \rightarrow K^{*0} K$ or $\phi\pi \rightarrow KK\pi$
    - $D \rightarrow K\pi\pi$ for normalization channel
  - Use D_s Dalitz structure for accurate acceptance determination and reduce systematic uncertainty
  - Optimized by neural network
  - Simultaneous fit to the four decays as a way to better constrain all the yields
    - cross feeds calibrated



$B_s \to D_s^{(*)+} D_s^{(*)-}$: results



New!

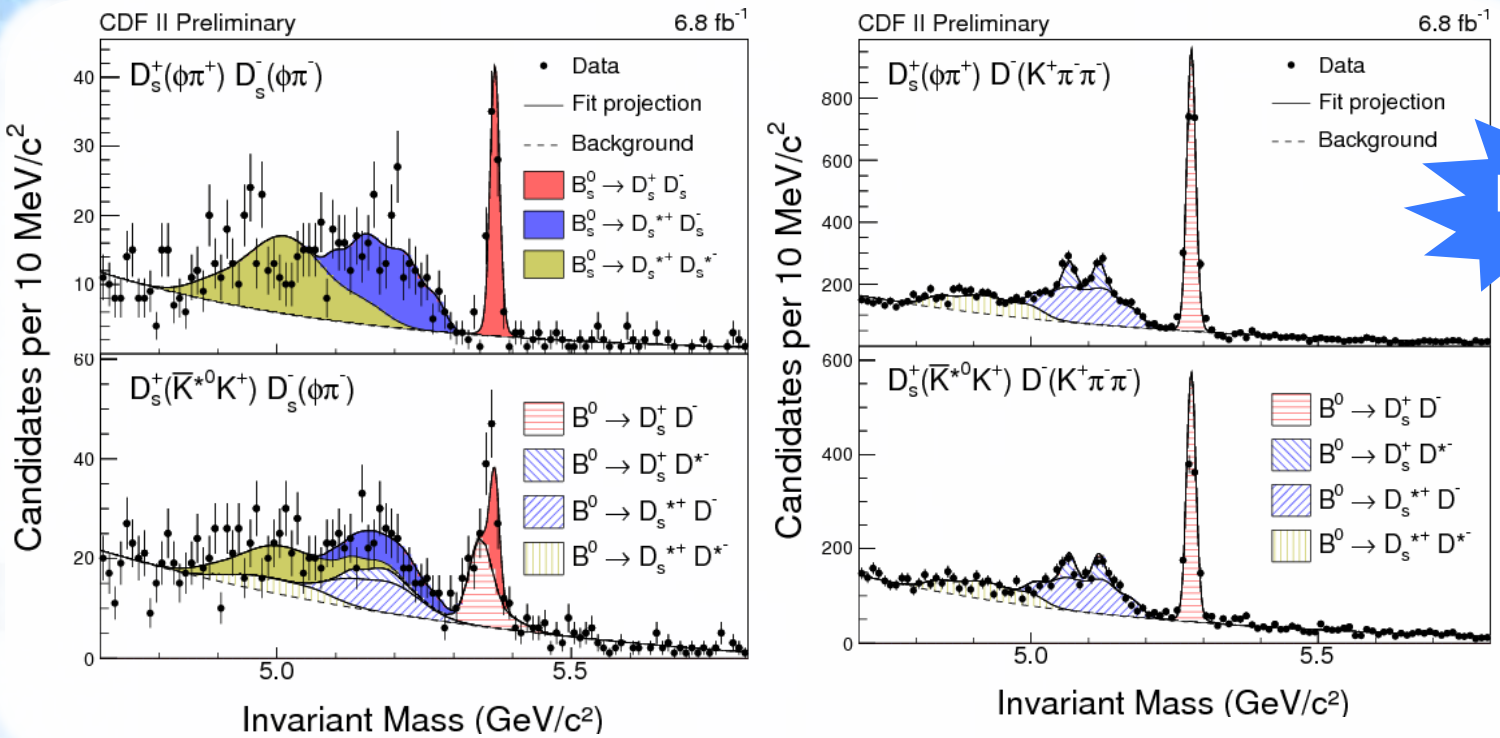
- Simultaneously fit each fraction of the final states from $D_s D_{(s)}$ mass distribution

$BR(B_s \to D_s^+ D_s^-) = (0.49 \pm 0.06 \pm 0.05 \pm 0.08)\ \%,$
$BR(B_s \to D_s^{*\pm} D_s^{\mp}) = (1.13 \pm 0.12 \pm 0.09 \pm 0.19)\ \%,$
$BR(B_s \to D_s^{*+} D_s^{*-}) = (1.75 \pm 0.19 \pm 0.17 \pm 0.29)\ \%,$
$BR(B_s \to D_s^{(*)+} D_s^{(*)-}) = (3.38 \pm 0.25 \pm 0.30 \pm 0.56)\ \%,$

$\Delta\Gamma_s / \Gamma_s = (6.99 \pm 0.54 \pm 0.64 \pm 1.20)\%.$

Most precise BR for these modes!

$B_s \to D_s^{(*)+} D_s^{(*)-}$: results



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Most precise BR for these modes!

Conclusion

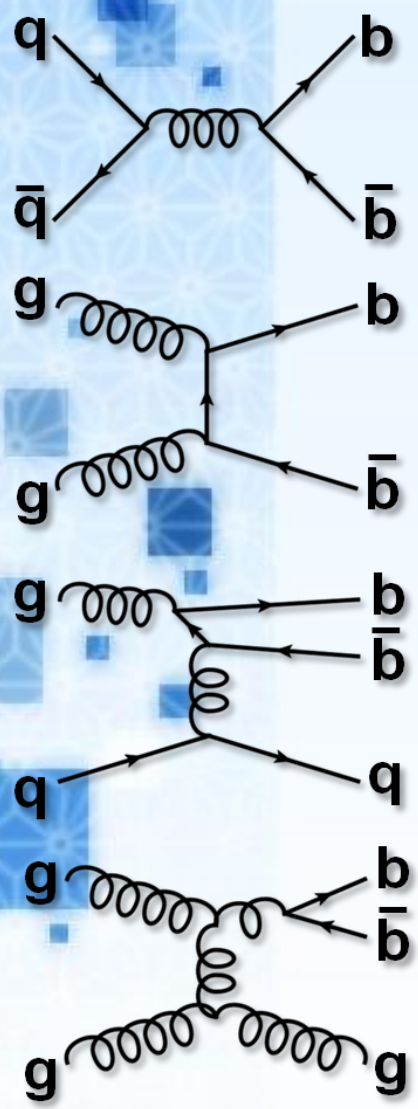
- B_s sector: exciting frontier to pursue BSM
- Tevatron Run II allowed dramatic breakthrough in the B_s sector

- Analysis of full dataset achieved!
  - $B_s \rightarrow \mu\mu$ ($10 fb^{-1}$)
  - CPV in B_s mixing ($B_s \rightarrow J/\psi\varphi$) ($10 fb^{-1}$)
  - $B_s \rightarrow D_s^{*+} D_s^{*-}$ ($6.8 fb^{-1}$)

Don't relax yet, a few more aces up our sleeve!

Backup

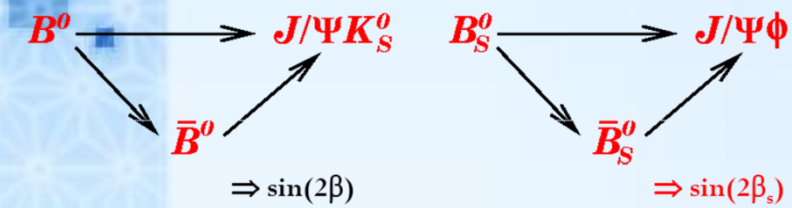
B production @ Tevatron



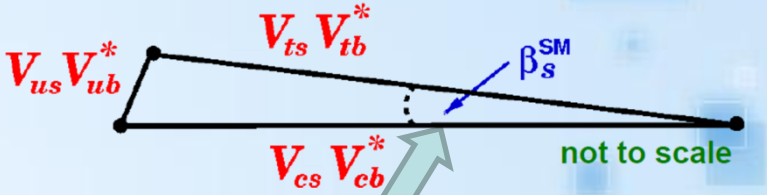
- **Pros**
  - Enormous cross-section
  - All species of b-hadrons
    - $B_u, B_d, B_s, B_c, \Lambda_b, \Sigma_b$…
- **Cons**
  - QCD background x10^3 larger than $\sigma(b\bar{b})$
  - Collision rate ~2MHz
    - tape writing limit ~100Hz
    - Sophisticated triggers are very important!
  - Difficulty in π^0 reconstruction

CP Violation in B_s System

- Analogously to the neutral B^0 system, CP violation in B_s system occurs through interference of decays with and without mixing:



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



B_s Mass eigenstates: B_s^L, B_s^H

Mass difference $\Delta m_s = m_H - m_L \sim 2|M_{12}|$

Width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$

CP violating phases :

$$\phi_s = \arg(-\frac{M_{12}}{\Gamma_{12}}) \qquad \phi_s^{SM} \sim 0.004$$

$$\beta_s \qquad \beta_s^{SM} = \arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb}) \sim 0.02$$

A. Lenz and U. Nierste, JHEP 06, 072(2007)

- ϕ_s^{NP} contributes to both ϕ_s and β_s

$$-2\beta_s = -2\beta_s^{SM} + \phi_s^{NP}$$

If ϕ_s^{NP} dominates : $-2\beta_s \sim \phi_s^{NP}$

Same sign dimuon asymmetry

- Same sign di-lepton asymmetry very small in SM ~*O(10^{-4})* → sensitive NP probe

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

$$a^q_{\rm sl} = \frac{\Gamma(\bar{B}^0_q(t) \to \mu^+ X) - \Gamma(B^0_q(t) \to \mu^- X)}{\Gamma(\bar{B}^0_q(t) \to \mu^+ X) + \Gamma(B^0_q(t) \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q \quad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

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

$$C_d = 0.594 \pm 0.022,$$
$$C_s = 0.406 \pm 0.022.$$

HFAG, arXiv 1010.1589 [hep-ex] (2010)

- SM prediction $A^b_{\rm sl} = (-0.028^{+0.005}_{-0.006})\%$

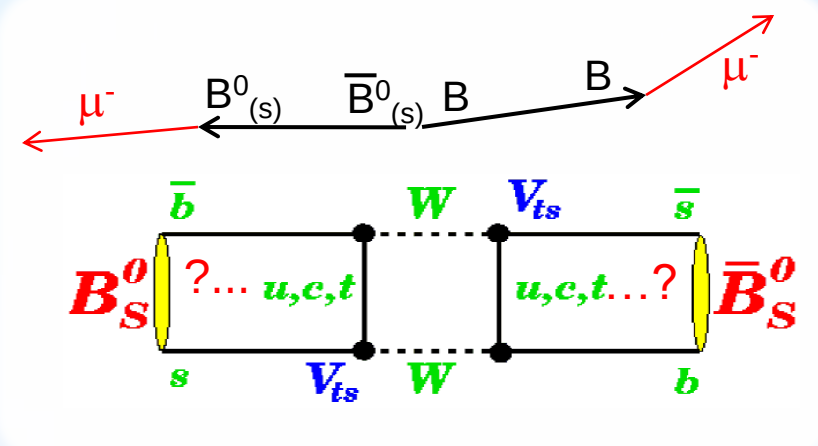
Lentz, Nierste, JHEP 0760, 072 (2007)

- Initial D0 measurement with 6 fb^{-1}

Abazov,PRD 82, 032001(2010), Abazov, PRL 105, 081801 (2010)

$$A^b_{\rm sl} = -0.00957 \pm 0.00251\,({\rm stat}) \pm 0.00146\,({\rm sys})$$

was 3.2σ away from SM expectation



Same sign dimuon asymmetry

- D0 updates the analysis with 9 fb^{-1} from previous 6 fb^{-1}

- Improved muon selection:
  - 13% increase in statistics due to looser muon longitudinal momentum selection
  - 20% reduction in K and π decay in flight backgrounds

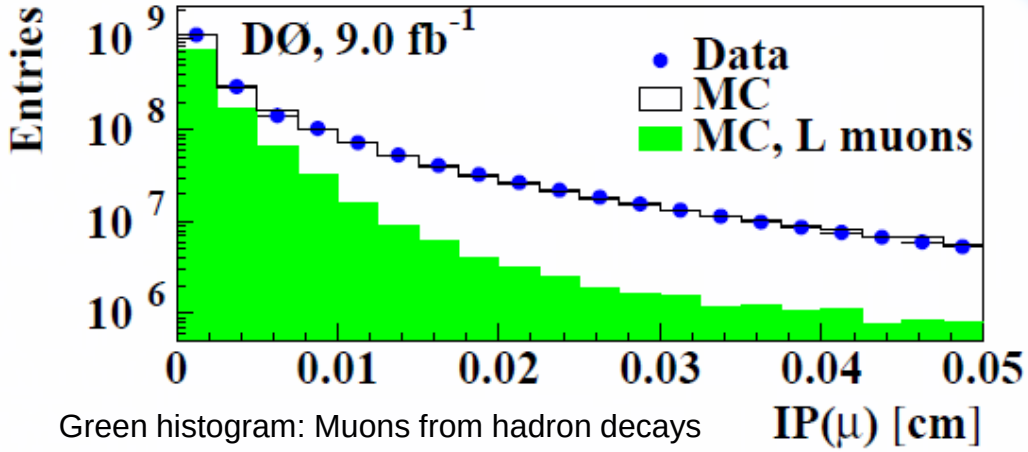
- Muon impact parameter studies support hypothesis that muons are indeed from B decays

- New result is 3.9σ away from the SM expectation:

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

- Good agreement between muon impact parameter distributions in data and MC

-



Green histogram: Muons from hadron decays and from punch-through