B_s^0 Decays and Leptonic B Decays

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(DØ Collaboration)

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Outline

B_s^0 Decays Leftover pieces, assembling...

- What we want to know about the system, $\square\square_s$
- Decay into specific CP eigenstate: $Br(B_s^0 \to D_s^{(*)+} D_s^{(*)\square})$
- Implications on $\square\square_s$, world averages $Br(B_s^0 \to \square\square)$

Leptonic B Decays

- Purely leptonic $B_d^0, B_s^0 \to \square^+\square^\square$
  - FCNC decay $B_s^0 \to \square\square^+\square^\square$
- Purely leptonic $B_d^0 \to \square^+\square^\square$
- Purely leptonic $B^+ \to \square^+\square$

B_s^0 Decays

Want to probe *all* the parts of:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

$$|B_H\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$

Heavier mass eigenstate

$$|B_L\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$

Lighter mass eigenstate

$$\Delta m_s = M_H - M_L \sim 2|M_{12}|$$

Talks from
J. Piedra
G. Gomez-Ceballos

$$\boxed{\Delta\Gamma_s = \Gamma_L - \Gamma_H} \sim 2|\Gamma_{12}|\cos\phi$$

$\phi \sim 0.3^\circ$ in SM

If CP conserved,
in mixing

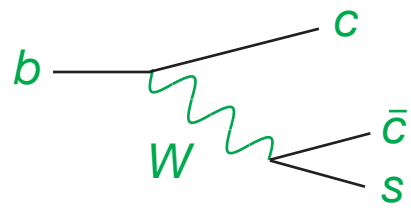
$$|B_L\rangle = |B^{\text{CP-even}}\rangle$$

$$|B_H\rangle = |B^{\text{CP-odd}}\rangle$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \; ; \quad \tau = \frac{1}{\Gamma_s} \; ; \quad \tau_L = \frac{1}{\Gamma_L} \; ; \quad \tau_H = \frac{1}{\Gamma_H}$$

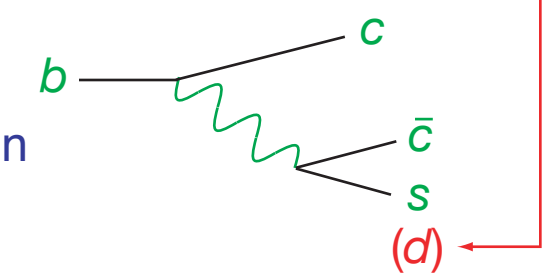
Width Difference, $\Delta\Gamma_s$

- $\Delta\Gamma_{12}$ dominated by decay $b \to c\bar{c}s$ from decays into final states common to both B_s^0 $(\bar{b}s)$ and $\bar{B}_s^0$ $(b\bar{s})$



Width Difference, $\Delta\Gamma_s$

For B_d^0 , analogous diagram
Cabibbo suppressed, Γ_{12} negligible



- Γ_{12} dominated by decay $b \to c\bar{c}s$ from decays into final states common to both B_s^0 $(\bar{b}s)$ and $\bar{B}_s^0$ $(b\bar{s})$

- $\Delta\Gamma_s$: CP-even final states, $\Delta\Gamma_s \uparrow$
  CP-odd final states, $\Delta\Gamma_s \downarrow$

$B_s^0 \to D_s^+ D_s^-$ is pure CP even, and under various theoretical assumptions,
$B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ inclusive, also CP even to ~5%

(Phys. Lett. **B316** (1993) 567)

Likely needs re-examination!!

$$\frac{\Delta\Gamma_s}{\Gamma_s} \sim \frac{2Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-})}{1 - Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-})/2} \qquad (\Delta\Gamma = 0)$$

New measurements from CDF, DØ, and Belle

CDF Br($B_s^0 \to D_s^+ D_s^-$)

- Branching ratio measured in the decay mode:

$B_s^0 \to D_s^+ D_s^-$

$D_s^+ \to \pi\pi^+$ (3π, K^*K) Hadronic

$D_s^- \to \pi\pi^-$ (3π, K^*K) Hadronic

$\pi \to K^+K^-$

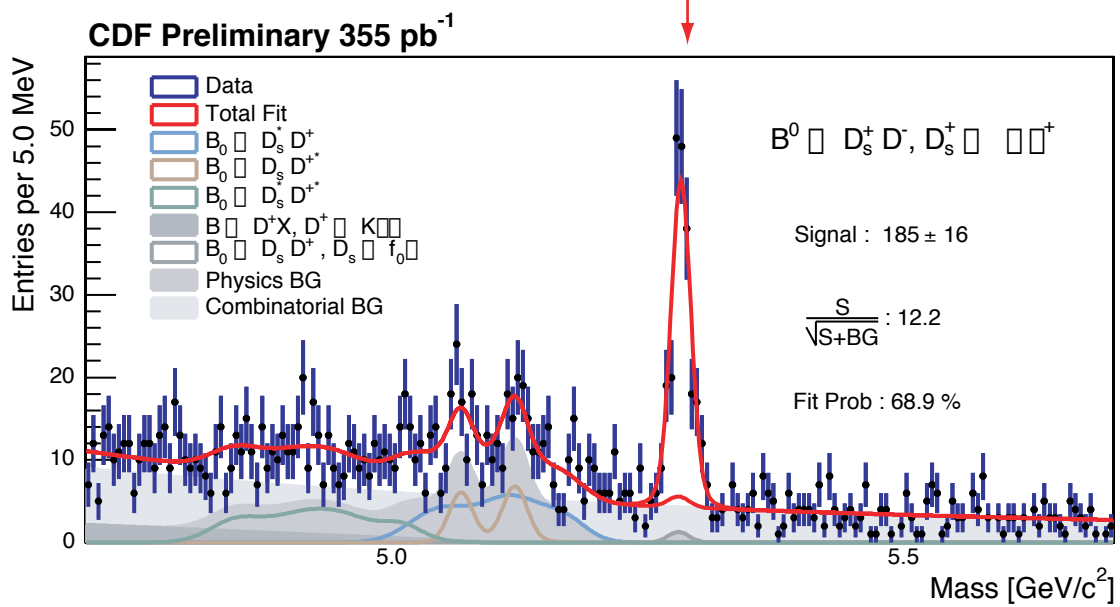
- Normalized to:

$B_s^0 \to D_s^+ D^-$

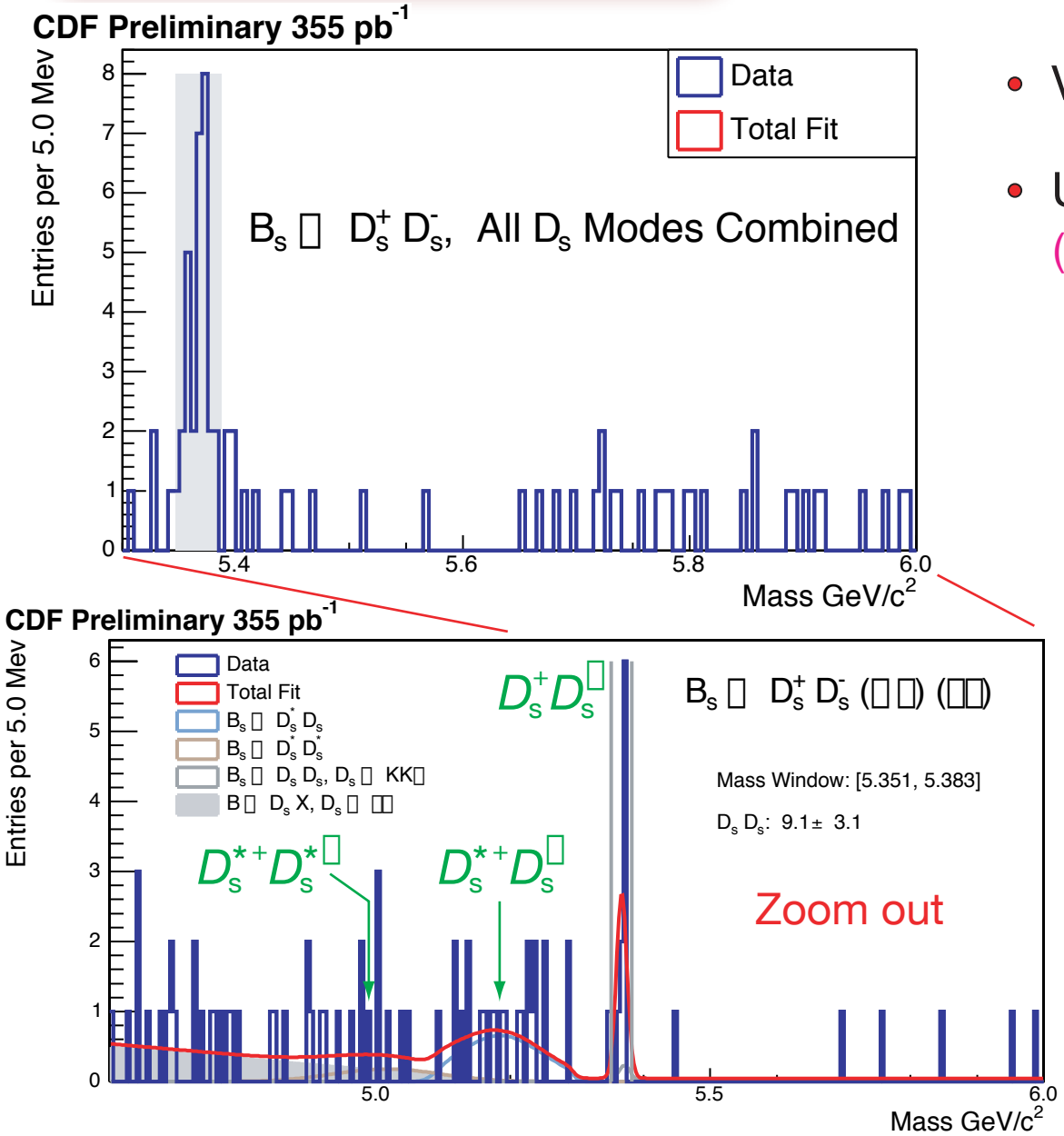
$D^+ \to K\pi\pi$

$D^- \to \pi\pi^-$ (3π, K^*K)

- Plus many more channels with similar topology studied in detail with higher statistics (exclusive hadronic, two secondary resonances with 3 tracks each)



CDF Br($B_s^0 \to D_s^+ D_s^{\square}$)



- Number signal 23.5 ± 5.5 cand.
- Very clean! Negligible backg.
- Use Br($D_s \to \square\square$) from PDG
  (waiting for PDG combo w/ BaBar)

$$\frac{Br(B_s^0 \to D_s^+ D_s^{\square})}{Br(B_s^0 \to D_s^+ D^{\square})} =$$

$$= 1.67 \pm 0.41\ (\text{stat.}) \pm 0.12\ (\text{syst.}) \pm 0.24\ (f_s/f_d) \pm 0.39\ (Br_{\square\square})$$

- First observation of this fully reconstructed decay
- CDF working on its use to extract $\square\square_s$
  (hints for other modes there, good prospects with 1 fb$^{\square 1}$)

DØ Br($B_s^0 \to D_s^{(*)+} D_s^{(*)\square}$)

- Branching ratio measured in the decay mode:

$\square\square^+\square$ Semileptonic

$B_s^0 \to D_s^{(*)+} D_s^{(*)\square}$

$\square\square\square$ Hadronic

$\square \to K^+K^\square$

- Normalized to:

$B_s^0 \to D_s^{(*)+}\square^\square\square$

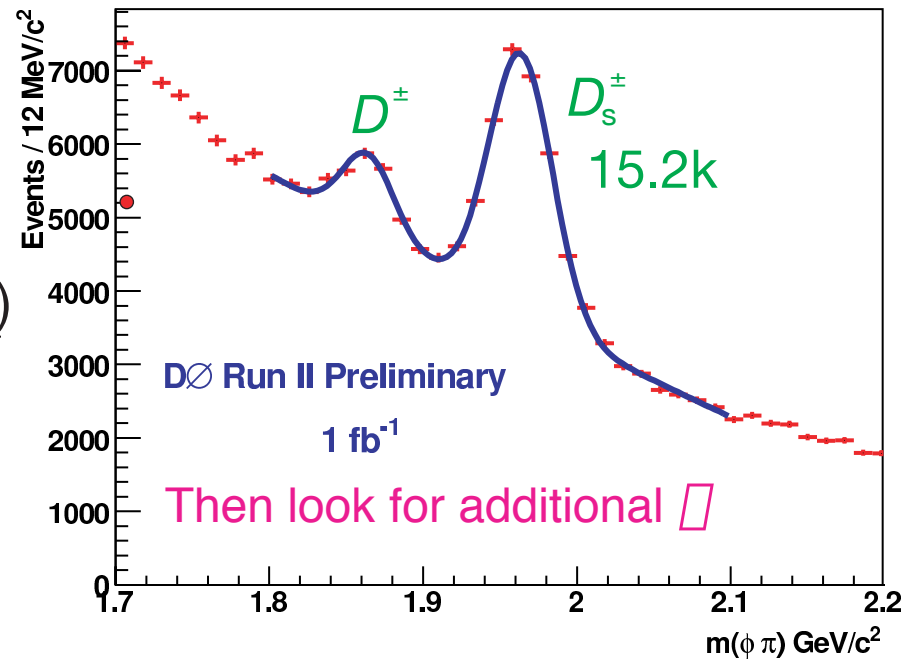
$\square\square^+$

- Measure ratio:

$$R = \frac{Br(B_s^0 \to D_s^{(*)+} D_s^{(*)\square}) \cdot Br(D_s \to \square\square\square)}{Br(B_s^0 \to \square\square D_s^{(*)\square})}$$

(many systematics cancel in the ratio)

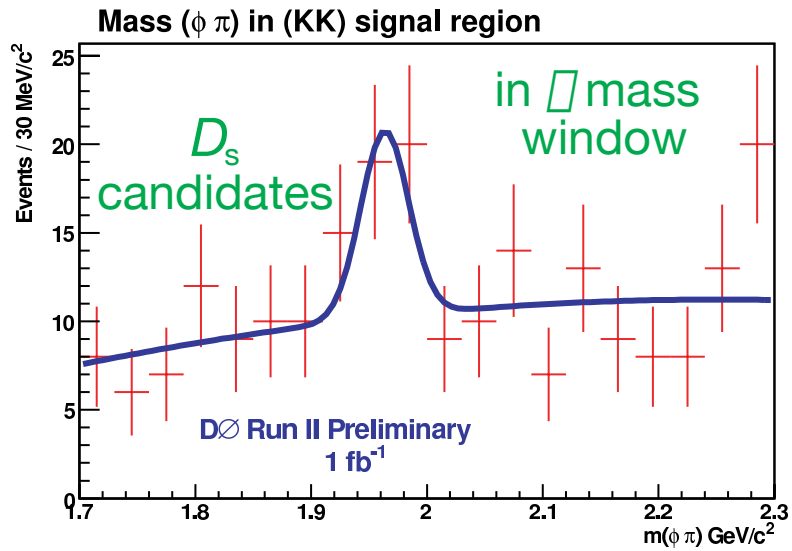
With associated muon:

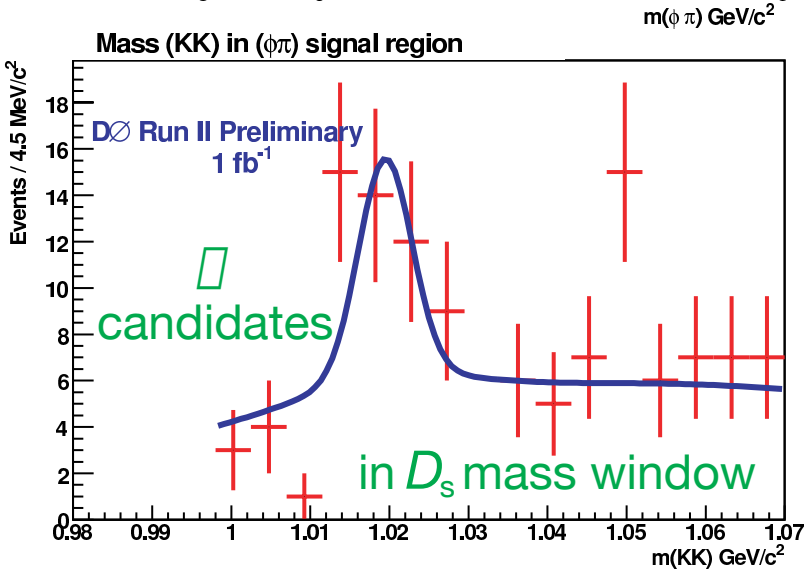


Then look for additional $\square$

Mass and width used as input parameters in following fits

DØ Br($B_s^0 \to D_s^{(*)+} D_s^{(*)-}$)





Simultaneous unbinned likelihood fit, including in the mass sidebands

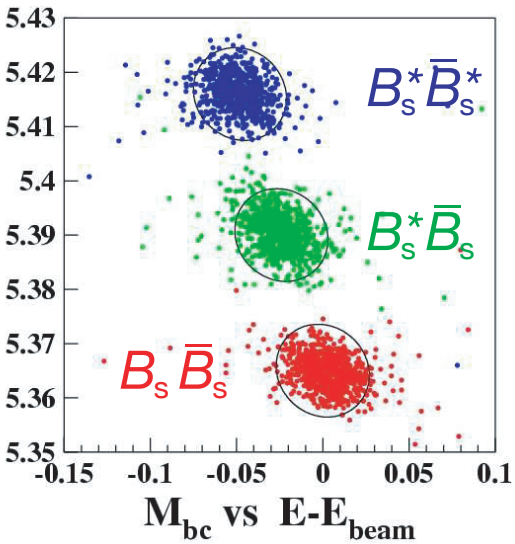
- Number found: $N(\phi\phi D_s) = 19.3 \pm 7.8$
- Backgrounds:
  - $B \to D_s^{(*)+} D_s^{(*)-} K X$ — 0.44 ± 0.30
  - $B_s^0 \to D_s^{(*)+} D_s^{(*)-} X$ — suppressed
  - $B_s^0 \to \phi\phi D_s^{(*)} \phi X$ — 1.27 ± 1.14
  - $c\bar{c} \to \phi\phi D_s^{(*)}$ — lifetime cuts
- Use new Br($D_s \to \phi\phi$) from BaBar, combined w/ PDG

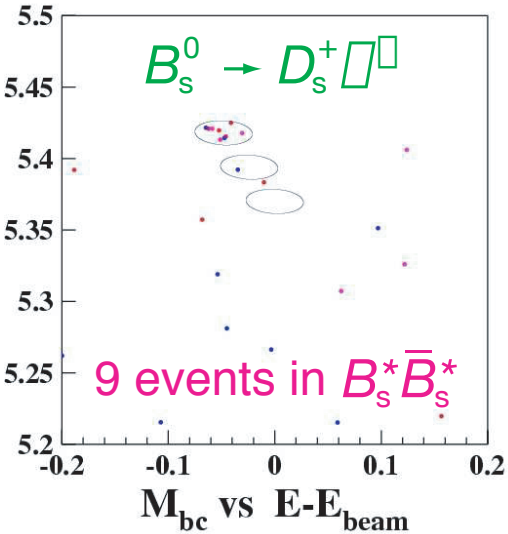
$$Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = 0.071 \pm 0.032\,(\text{stat})\,^{+0.029}_{-0.025}\,(\text{syst})$$

Belle Br($B_s^0 \to D_s^{(*)+} D_s^{(*)-}$)

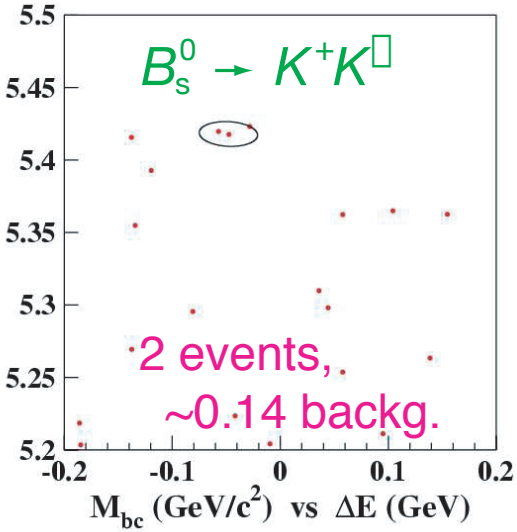
Runs at Υ(5S). Joining the party!

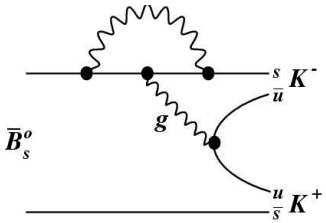
- 3 day engineering run in June 2005, collected 1.86 fb^{-1} (can do ~1 fb^{-1}/day!)



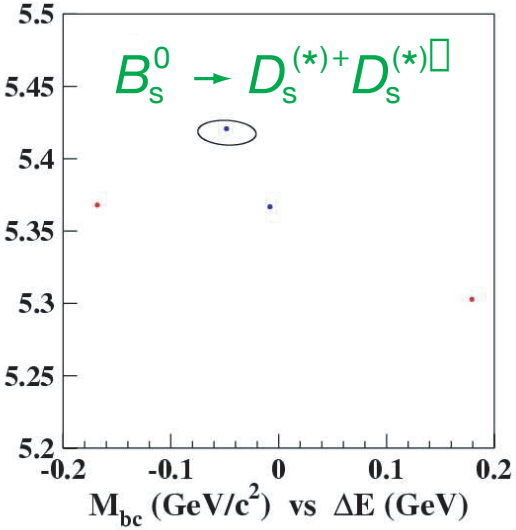


- First look at penguins:





- ...and *Br* concerned:



@ 90% C.L.

$Br(B_s^0 \to D_s^+ D_s^-) < 7.1\%$

$Br(B_s^0 \to D_s^{(*)+} D_s^-) < 12.7\%$

$Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) < 27.3\%$

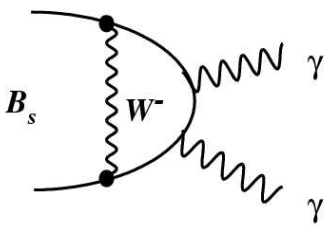
...and with 50 fb^{-1}, expect, e.g.,

$Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = (12 \pm 3)\%$

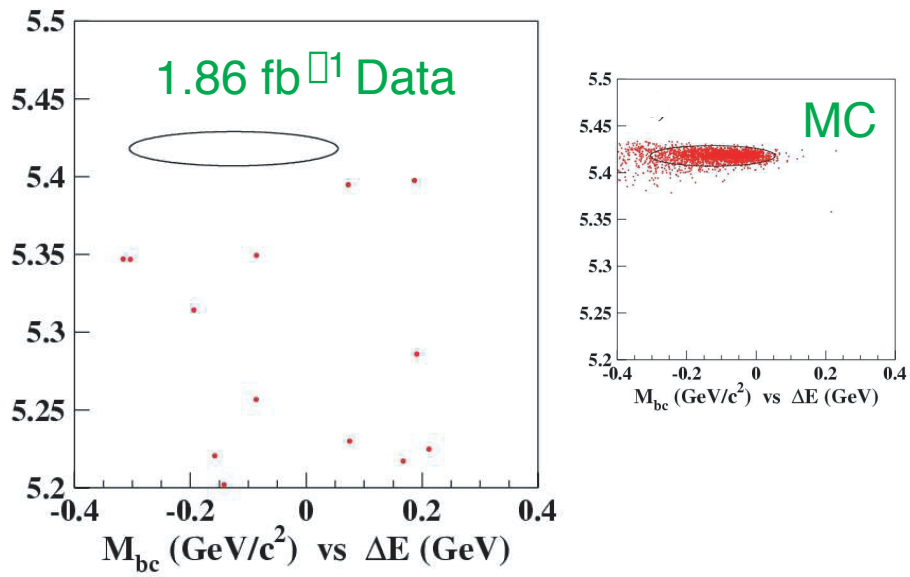
Belle Br($B_s^0 \to \gamma\gamma$)

Improved limit already!
(and for completeness...)

- More sensitive to certain new physics models than other penguins (e.g., 4th generation models, *R*-parity violating SUSY)



- SM:
  $Br(B_s^0 \to \gamma\gamma) = (0.5 - 1.0) \times 10^{-6}$
  (but new physics can increase it by ~ two orders of magnitude)

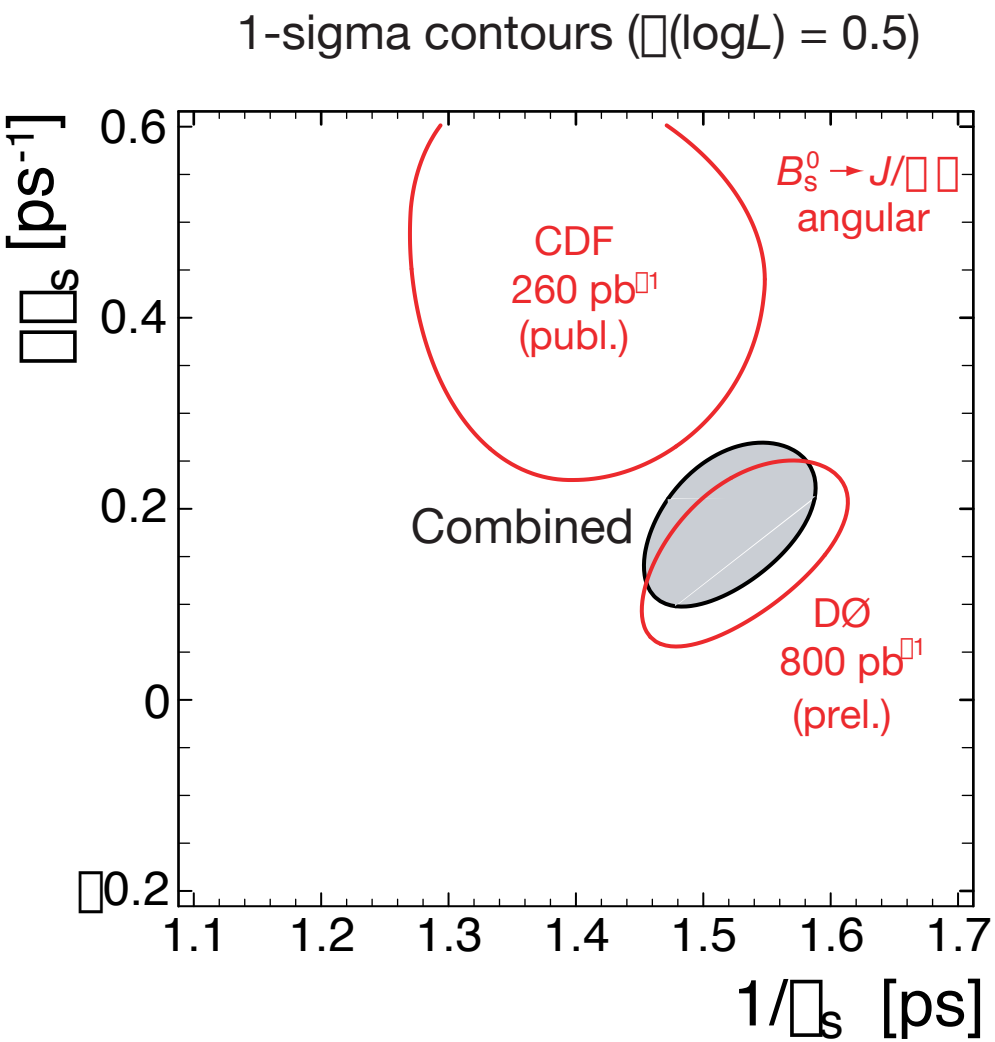


$Br(B_s^0 \to \gamma\gamma) < 0.56 \times 10^{-4}$ @ 90% CL

(c.f. PDG: $< 1.48 \times 10^{-4}$
factor of 3 improvement)

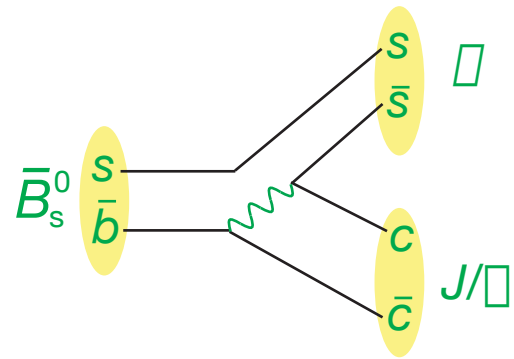
□□s

Putting the pieces together...



- Separation of CP-even and CP-odd states from angular distributions of J/ψ and ϕ decay products; simultaneous fit to lifetimes

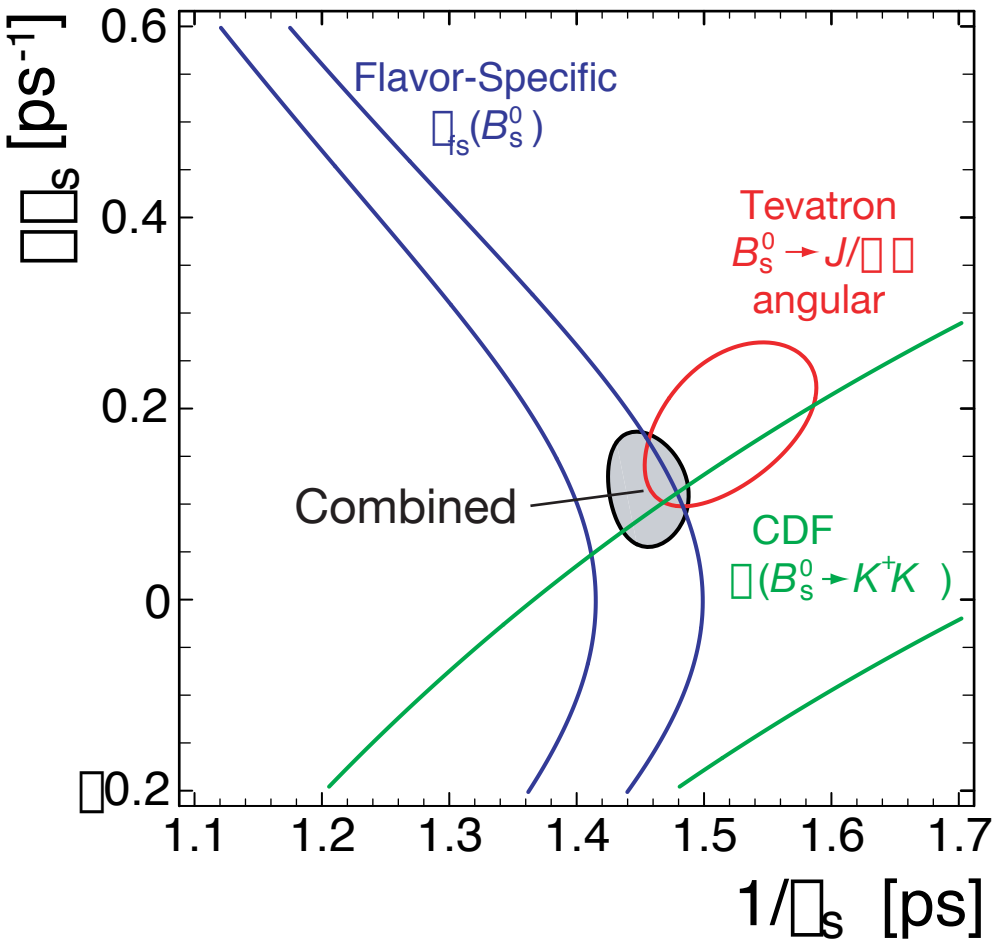
  (see J. Piedra's talk)



- (17 ± 4)% CP-odd at time, t = 0

  (weighted average, CDF & DØ)

1-sigma contours ($\Delta(\log L) = 0.5$)



- Flavor-specific decays, e.g.,

  $B_s^0 \to D_s^+ \ell^- \nu$ $\quad \bar{B}_s^0 \to D_s^- \ell^+ \nu$

  50% CP odd, 50% CP even at time, $t = 0$

- Fit to single exponential,

$$\tau_{fs}(B_s^0) = \frac{1}{\Gamma_s}\,\frac{1 + (\Delta\Gamma_s/2\Gamma_s)^2}{1 - (\Delta\Gamma_s/2\Gamma_s)^2}$$

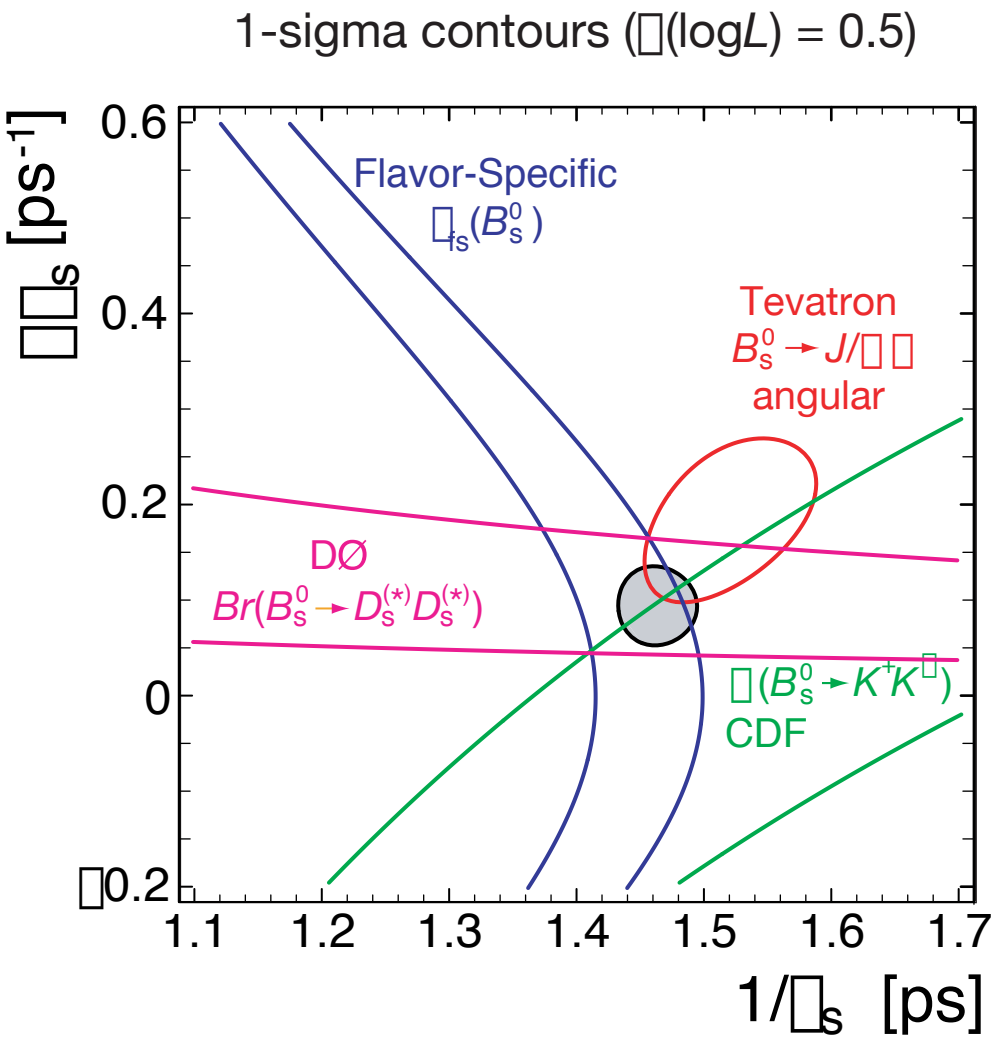
- $B_s^0 \to K^+K^-$ is CP even (within 5%), hence lifetime measures:

$$\tau_L = \frac{1}{\Gamma_L}$$

(problems in the penguin decay?)

CDF:

$\tau(B_s^0 \to K^+K^-) = 1.53 \pm 0.18 \pm 0.02$ ps

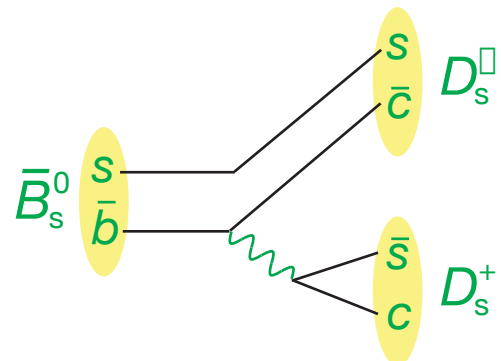


- Use branching ratio

$$\frac{\Delta\Gamma_s}{\Gamma_s} \sim \frac{2Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-})}{1 - Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-})/2}$$

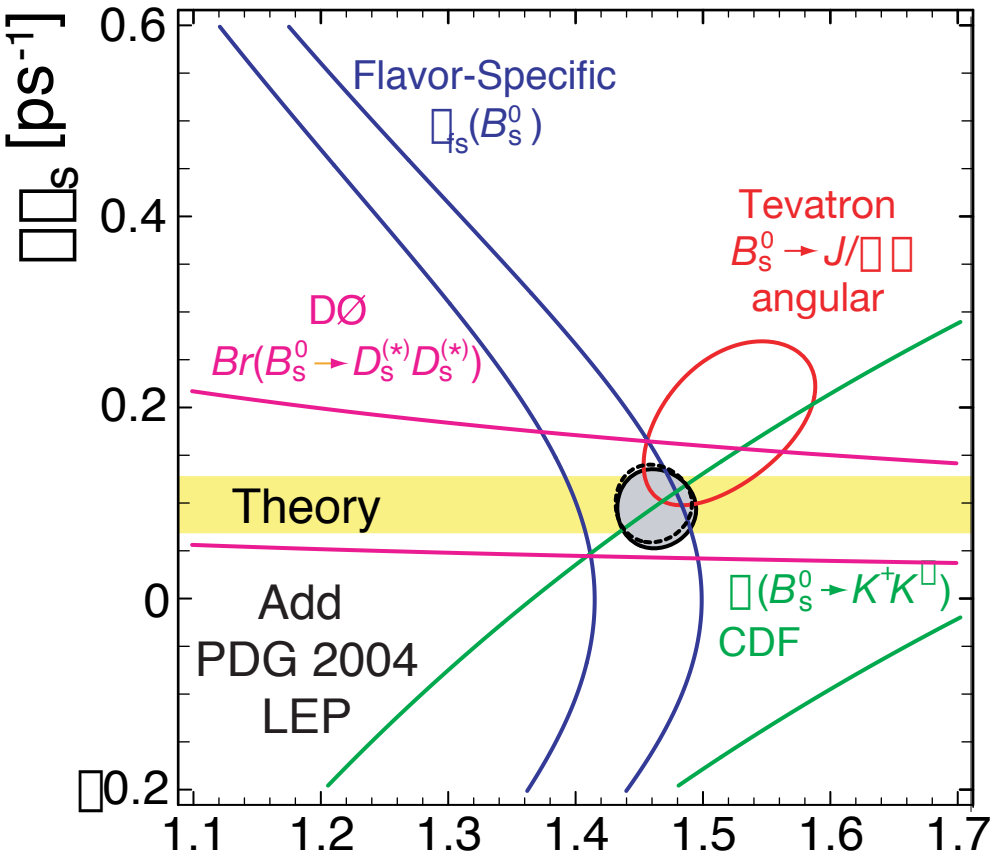
with additional 5% theory systematic added in quadrature

(caveat! possibly more CP-odd component?)



- Either compare to previous combination (consistency with SM)
- Or assume SM and include in average

1-sigma contours ($\Delta(\log L) = 0.5$)



Have
come a
long way!

- PDG 2004 (LEP) includes ALEPH measurement of
  $Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$
- Theoretical prediction:

$$\Delta\Gamma_s = 0.10 \pm 0.03\ \text{ps}^{-1} \left(\frac{f_{B_s}}{260\ \text{MeV}}\right)^2$$

(Update (Nierste) of
Phys.Lett. **B459** 631,1999)

- Unofficial world average

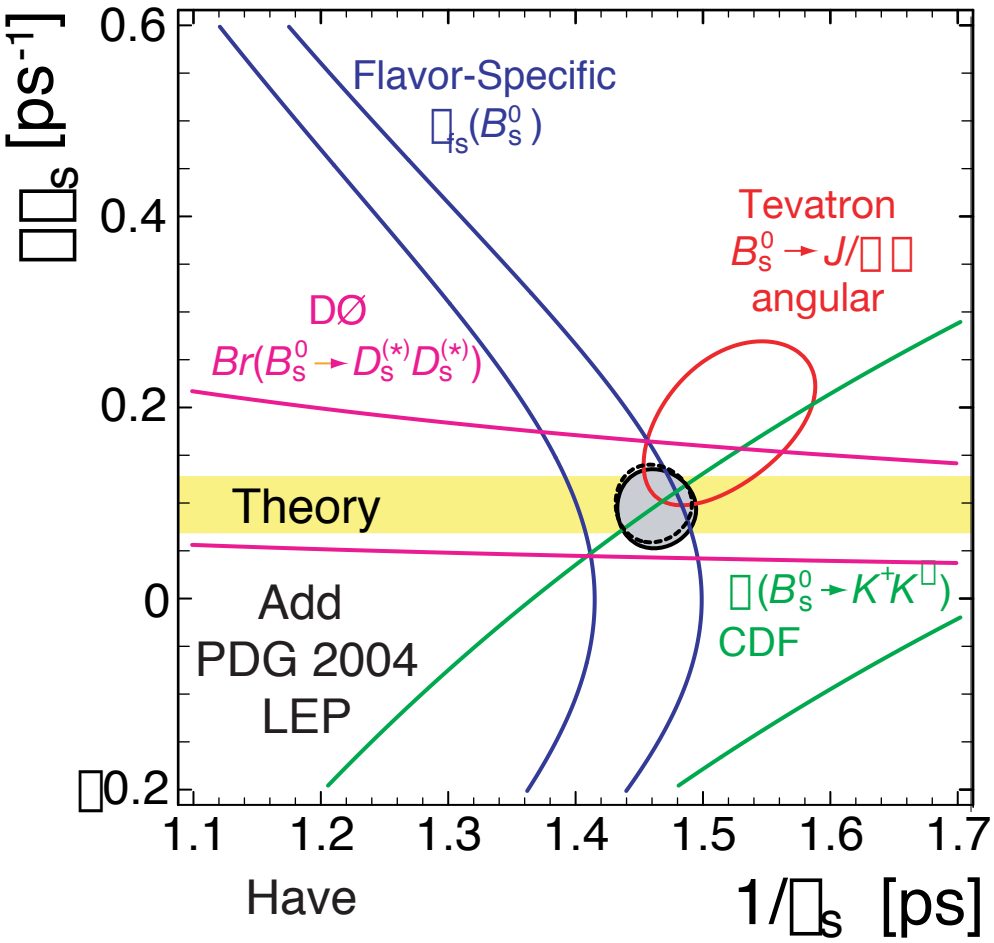
$$\Delta\Gamma_s = 0.097\ {}^{+0.041}_{-0.042}\ \text{ps}^{-1}$$

$$\tau = \frac{1}{\Gamma_s} = 1.461 \pm 0.030\ \text{ps}$$

$$\tau_L = \frac{1}{\Gamma_L} = 1.364\ {}^{+0.047}_{-0.045}\ \text{ps}$$

$$\tau_H = \frac{1}{\Gamma_H} = 1.573\ {}^{+0.060}_{-0.061}\ \text{ps}$$

1-sigma contours ($\Delta(\log L) = 0.5$)



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$$\Delta\Gamma_s = 0.097\ {}^{+0.041}_{-0.042}\ \text{ps}^{-1}$$

$$\bar{\tau} = \frac{1}{\Gamma_s} = 1.461 \pm 0.030\ \text{ps}$$

2.3σ from zero,

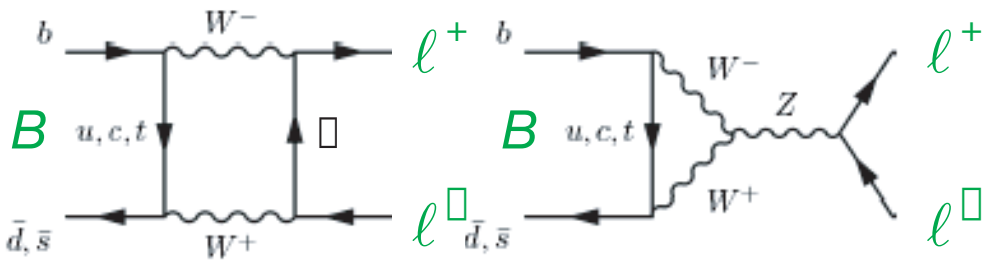
$$\Delta\Gamma_s \sim 2\,|\Gamma_{12}|\cos\phi$$

new physics tends to *reduce* the measured $\Delta\Gamma_s$

Leptonic Decay: $Br(B_d, B_s \to \ell^+\ell^-)$

Muons in "sweet spot"

- Excellent window into new physics, enhance rates
- Forbidden at tree level, highly helicity suppressed by $(m_\ell / m_B)^2$ in SM

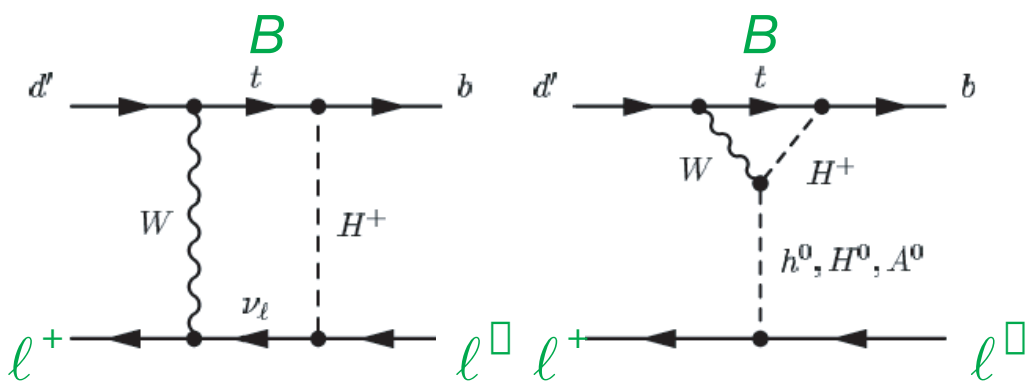


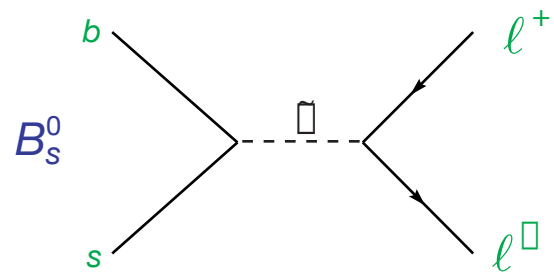
Predicted by SM:

$Br(B_s \to \ell^+\ell^-) = (3.4 \pm 0.5) \times 10^{-9}$

$Br(B_d \to \ell^+\ell^-)$ suppressed by another factor of $|V_{td}/V_{ts}|^2 \sim 0.04$

- Br grows as $\tan^6\beta$ in the MSSM, as $\tan^4\beta$ in 2HDM models



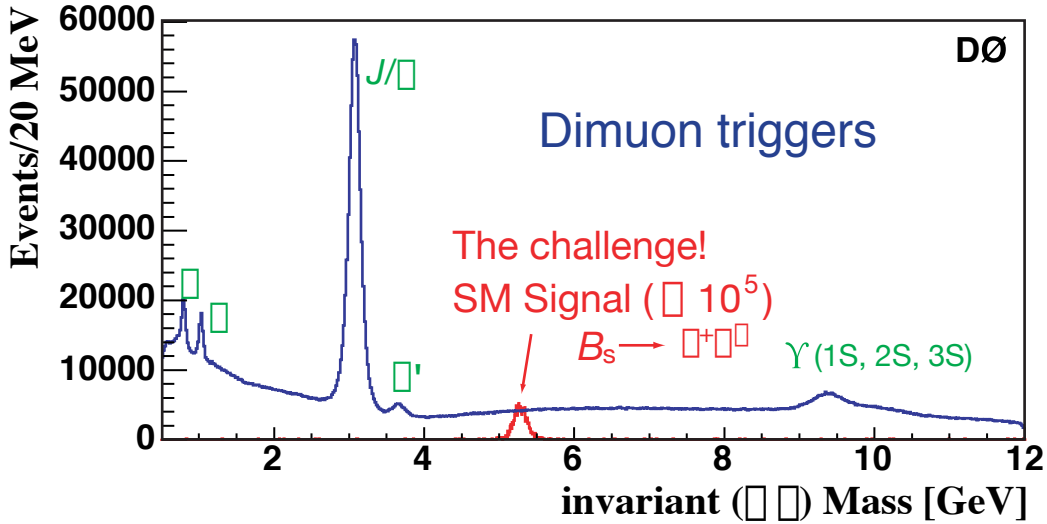


R-Parity Violating SUSY

- Very attractive probe for any new physics with extended Higgs sectors

Leptonic Decay: $Br(B_d, B_s \to \mu^+\mu^-)$

Limits now dominated by Tevatron experiments

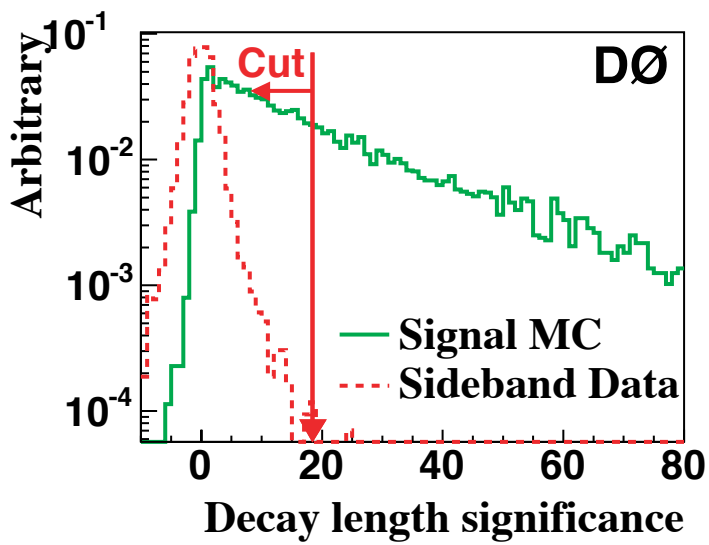


Backgrounds:

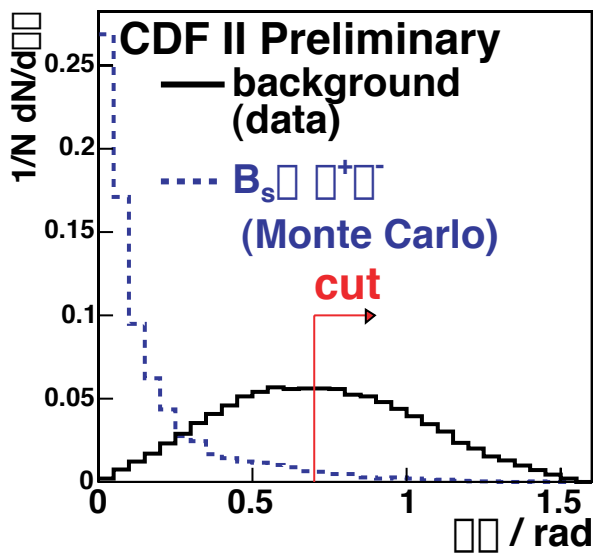
- Drell-Yan $\mu^+\mu^-$ continuum
- Sequential semileptonic $b \to c \to s$
- Double semileptonic $b\bar{b} \to \mu^+\mu^- X$
- $b/c \to \mu^+ X$ + *fake*
- *fake* + *fake*

Discriminating variables:

- Tranverse decay length significance or probability (B_s has lifetime...)



- angle between μμ vector and decay length vector ("pointing consistency")



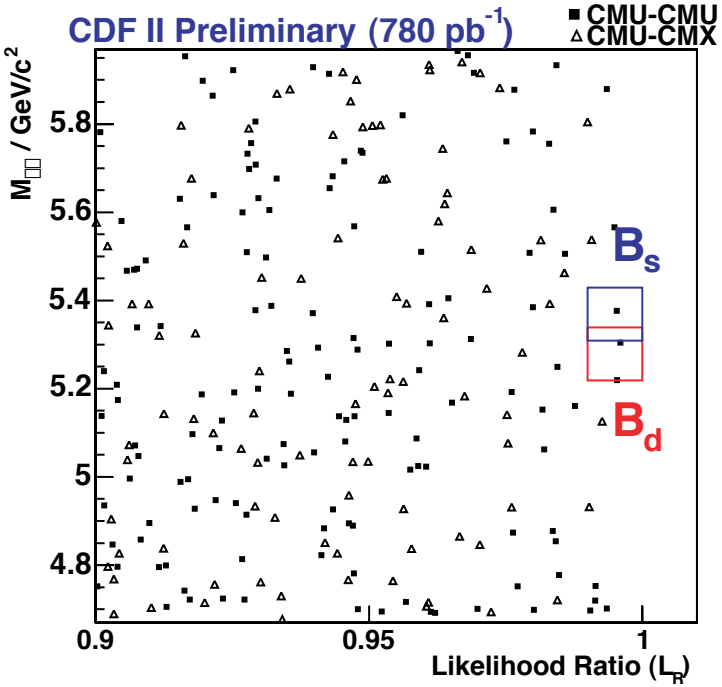
- Isolation

Both experiments similar variables

CDF likelihood ratio

DØ random grid search

Leptonic Decay: $Br(B_d, B_s \to \mu^+\mu^-)$

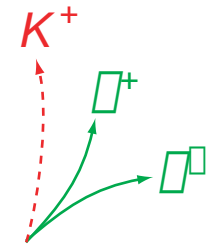


At 95% CL (Bayesian):

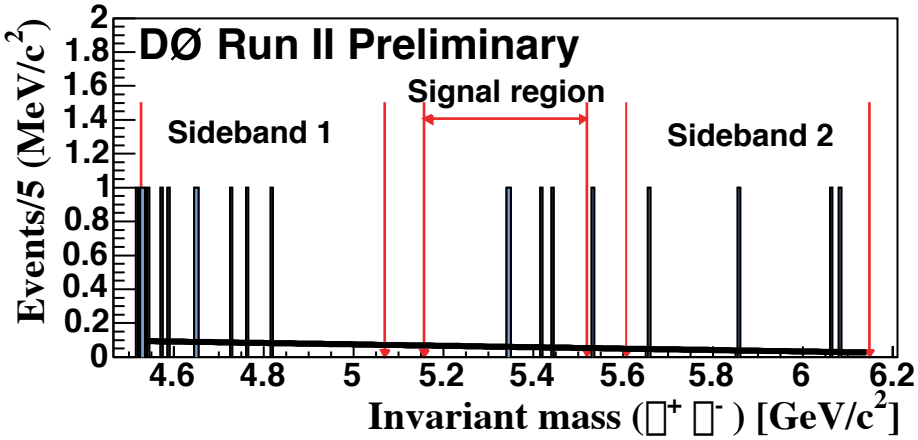
$Br(B_d^0 \to \mu^+\mu^-)$

$< 3.0 \times 10^{-8}$ CDF, prel., 780 pb^{-1}

Factor ~3 more stringent than next best (BaBar)



- Both normalize to $B^+ \to J/\psi\, K^+$
  (well known, high stats, muon effic. same)



- DØ: mass resolution: can't separate B_d and B_s
  Assume no B_d contribution (conservative)

$Br(B_s^0 \to \mu^+\mu^-)$

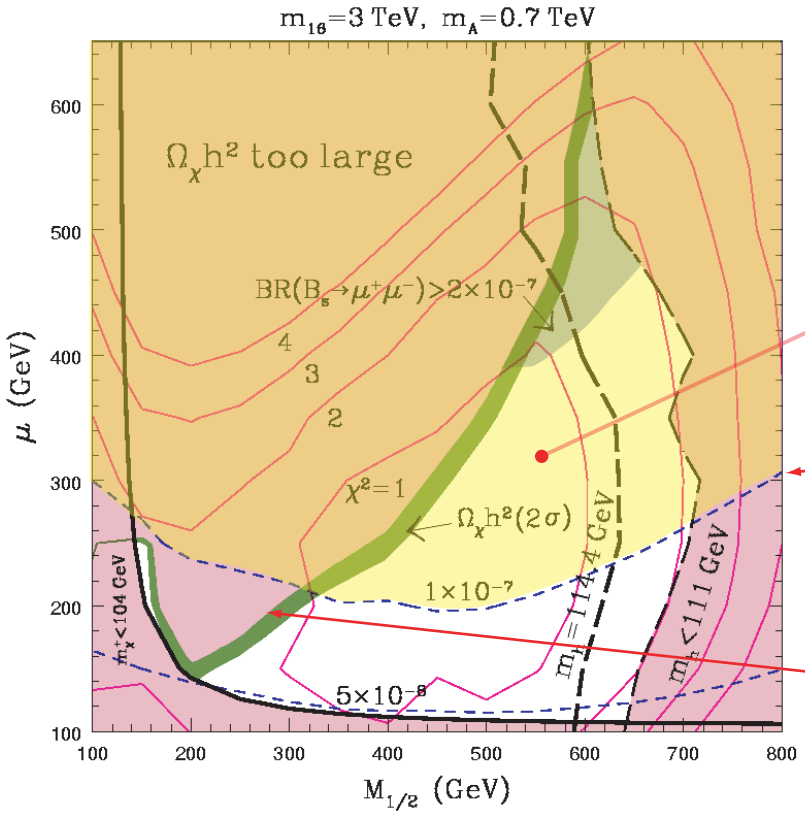
$< 1.0 \times 10^{-7}$ CDF, prel., 780 pb^{-1}

$< 1.5 \times 10^{-7}$ CDF & DØ, each ~300 pb^{-1}

$< 2.3 \times 10^{-7}$ DØ, prel. exp.limit, 700 pb^{-1}

$< 4.0 \times 10^{-7}$ DØ, prel., 300 pb^{-1}

Only a factor of 30 from SM prediction

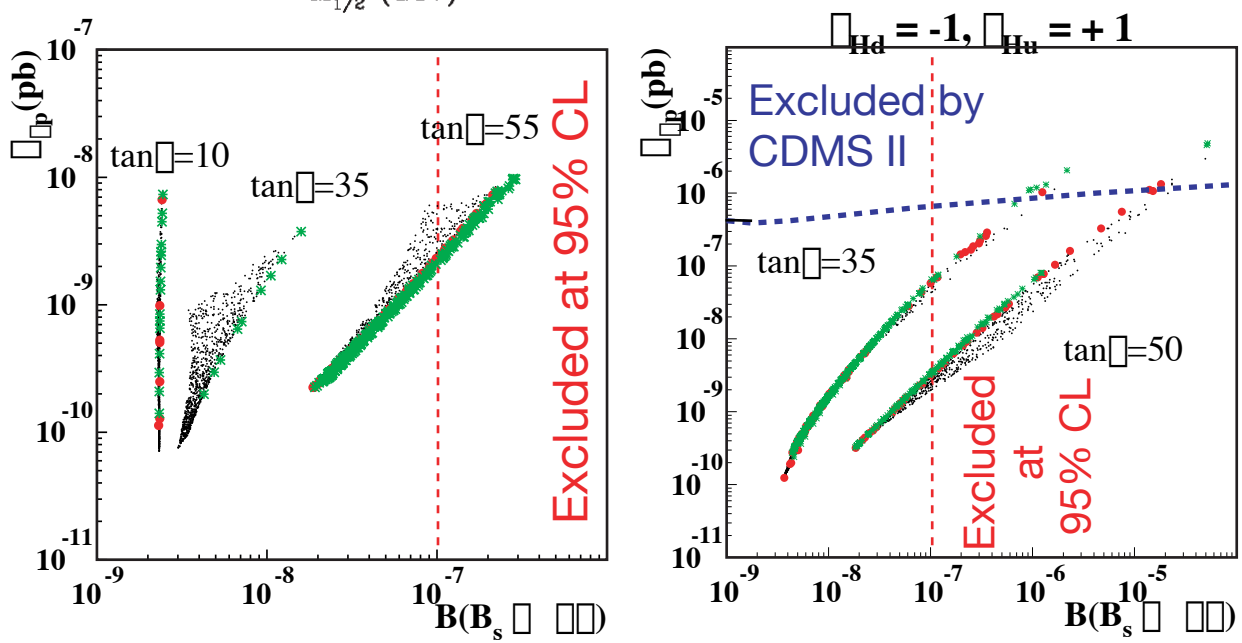


e.g., Dermisek et al., hep-ph/0507233
dark matter and S0(10) with soft SUSY breaking, other experimental constraints

Excluded at 95% CL! (CDF Limit)

Contour of equal $Br(B_s \to \mu^+\mu^-)$

Allowed by dark matter constraints



e.g., Baek et al., JHEP 0502 (2005) 067
mSUGRA model, constrain neutralino cross sections consistent with relic density

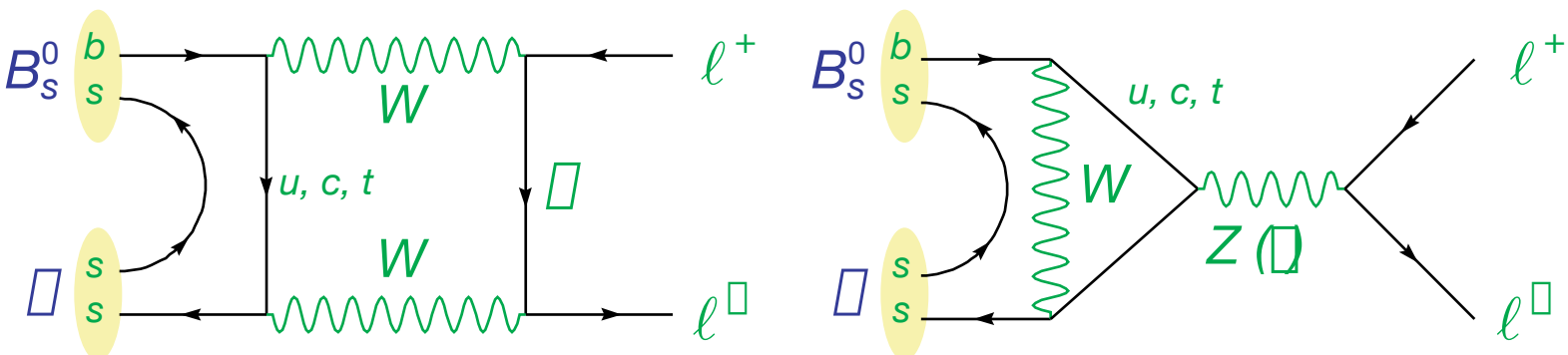
FCNC Decay $Br(B_s \to \phi\mu^+\mu^-)$

- Long term goal: investigate FCNC $b \to s\,\ell^+\ell^-$ transitions in B_s^0

  (Inclusive $B \to X_s\,\ell^+\ell^-$, exclusive $B \to K^{(*)}\ell^+\ell^-$ observed @ B factories, agree with SM)

Predicted in SM:

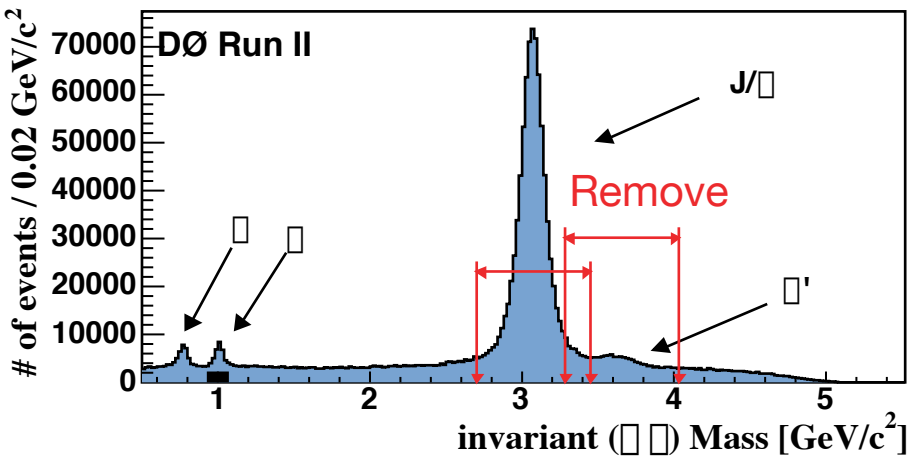
$Br(B_s \to \phi\mu^+\mu^-) \sim 1.6 \times 10^{-6}$



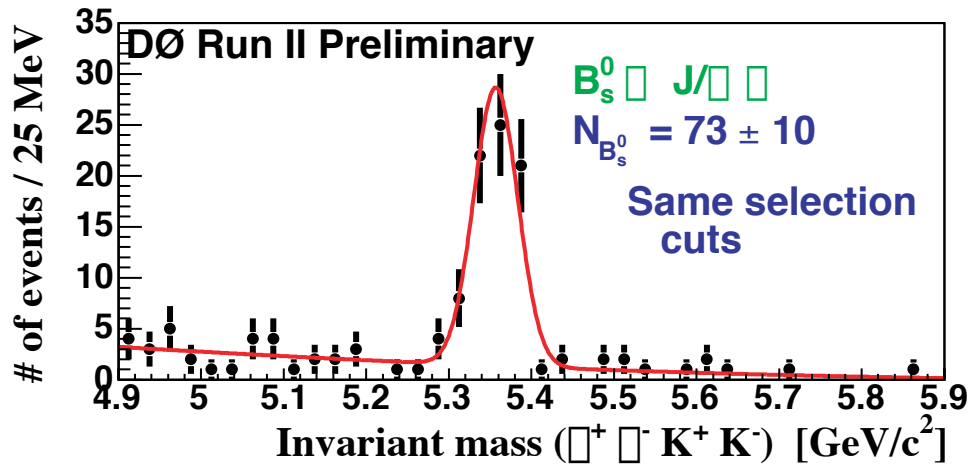
- Potential enhancement in various SUSY and 2HDM's
- DØ: search for exclusive mode $B_s^0 \to \phi\mu^+\mu^-$
  - Similar to DØ $B_s^0 \to \mu^+\mu^-$ analysis, add and vertex $\phi \to K^+K^-$
  - Same discrimination variables: decay length significance, pointing angle, isolation; different cut optimization
  - Want non-resonant mode:

FCNC Decay $Br(B_s \to \mu\mu^+\mu^-)$

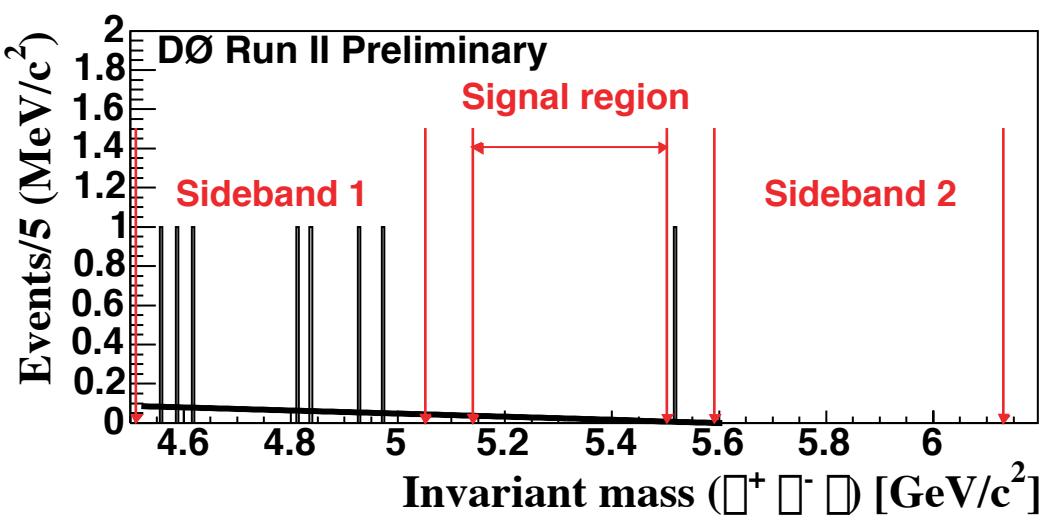
- Focus on non-resonant decay, cut out J/ψ and ψ':



- Normalize to resonant decay:



- Open the box, sidebands for backg.



$Br(B_s^0 \to \mu\mu^+\mu^-) < 4.1 \times 10^{-6}$ @ 95% CL

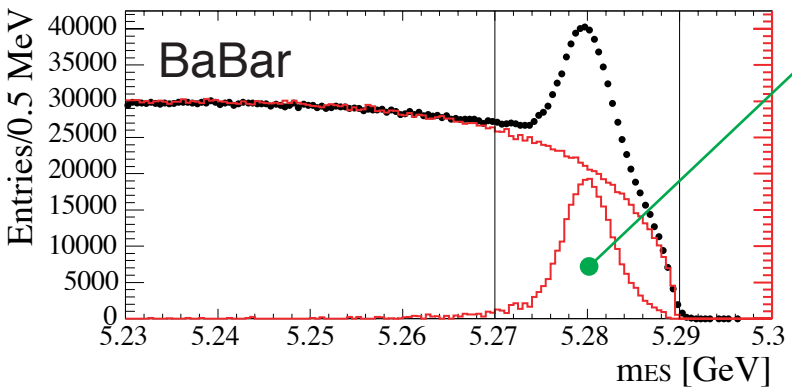
Factor 10 improvement over previous limit

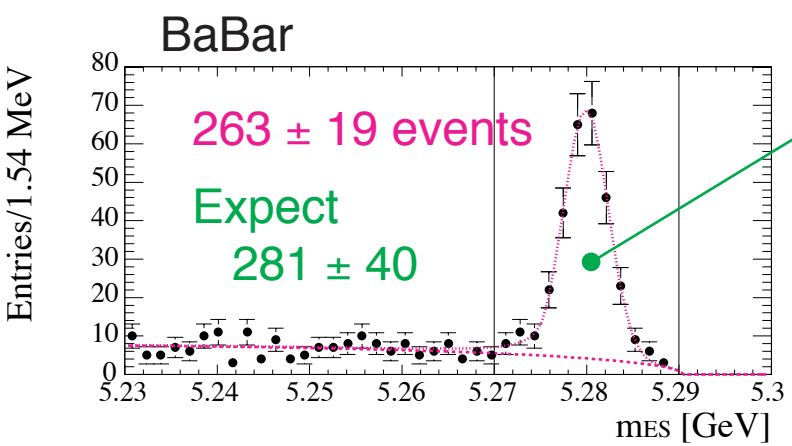
~ factor 3 more than SM prediction, should be able to observe before end of Run 2b

Leptonic Decay: $Br(B_d \to \tau^+\tau^-)$

Least helicity suppressed...

- First ever limit on this channel (hep-ex/0511015)
  - Loophole in which theorists gleefully played
  - Constrains leptoquark couplings and SUSY tanβ enhancements
- It's tough!
  - 2 – 4 missing neutrinos





- Start with 280k fully reconstucted $B_d^0 \to D^{(*)}X$
- Look for two 1-prong tau decays in rest of the event
- Remove all K_S, K_L, and $K^{\pm}$'s
- Kinematics of charged daughter momenta and residual energy in calorimeter are fed into a neural network to separate signal from backg.
- Survivors

$$Br(B_d^0 \to \tau^+\tau^-) < 3.4 \times 10^{-3} \text{ @ 90\% C.L.}$$

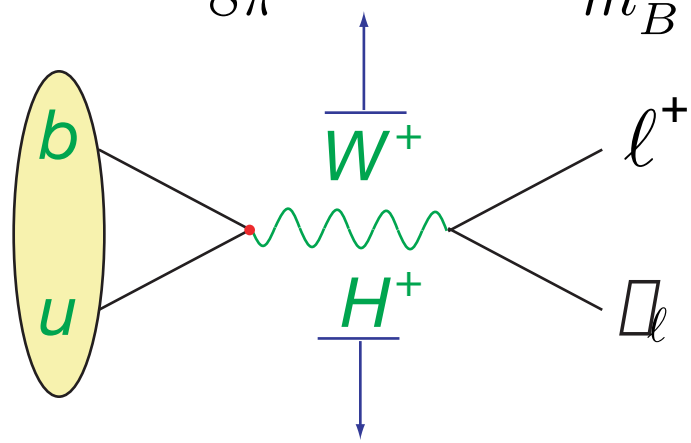
SM: $Br(B_d^0 \to \tau^+\tau^-) = 1.2 \times 10^{-7}$

Leptonic Decay: $Br(B^+ \to \ell^+ \nu_\ell)$

- Proceeds through a *W*-annihilation diagram in the SM, but sensitive to new physics

Access to:

$$Br(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 (1 - \frac{m_\ell^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$



Access to:

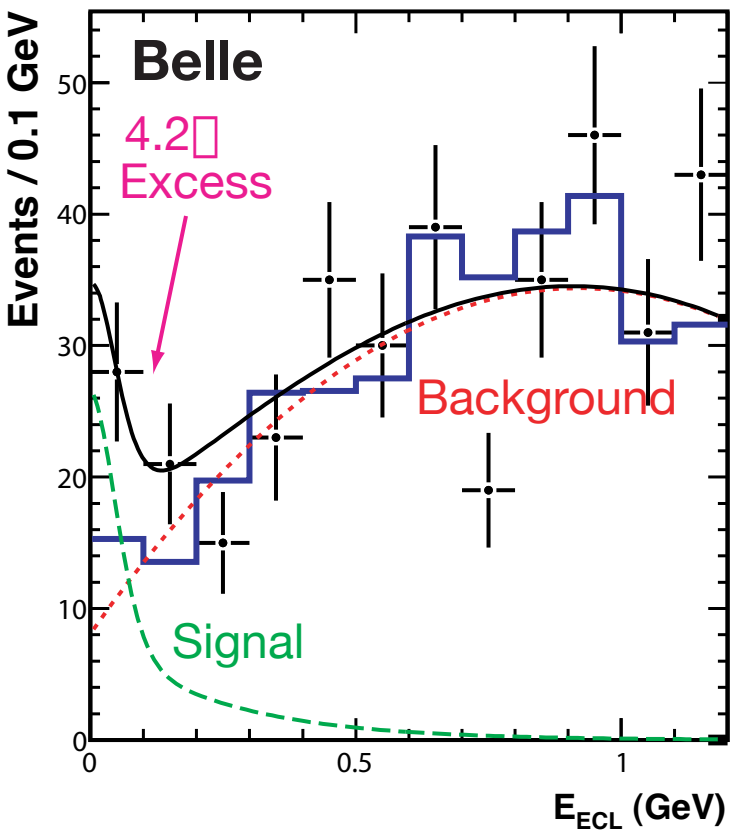
$$Br(B^+ \to \ell^+ \nu_\ell) = Br^{SM}(B^+ \to \ell^+ \nu_\ell)(1 - (\tan^2\beta / m_H^2) m_B^2)^2$$

- No new results in $B^+ \to e^+ \nu_e$, or $B^+ \to \mu^+ \nu_\mu$ since 2004; excitement in $B^+ \to \tau^+ \nu_\tau$

Leptonic Decay: $Br(B^+ \to \tau^+\nu_\tau)$

First Observation!

- Similar to $B_d^0 \to \tau^+\tau^-$, fully reconstruct one B_d^0
- In remainder of event, look for 1- or 3-prong tau decays (5 modes), compare properties of event remainder with expected signal and background
- Demand small extra energy in calorimeter:
- Verify with double-tag events



$Br(B^+ \to \tau^+\nu_\tau) =$

$= (0.106\ ^{+0.034}_{-0.028}\ ^{+0.018}_{-0.016})\%$

Belle, hep-ex/0604108

$< 2.6 \times 10^{-3}$ BaBar, hep-ex/0507069

$[\ = (0.13\ ^{+0.10}_{-0.09})\%\ ]$

$f_B |V_{ub}| = (7.73\ ^{+1.24}_{-1.02}\ ^{+0.66}_{-0.58}) \times 10^{-4}$ GeV

Leptonic Decay: $Br(B^+ \to \tau^+ \nu_\tau)$

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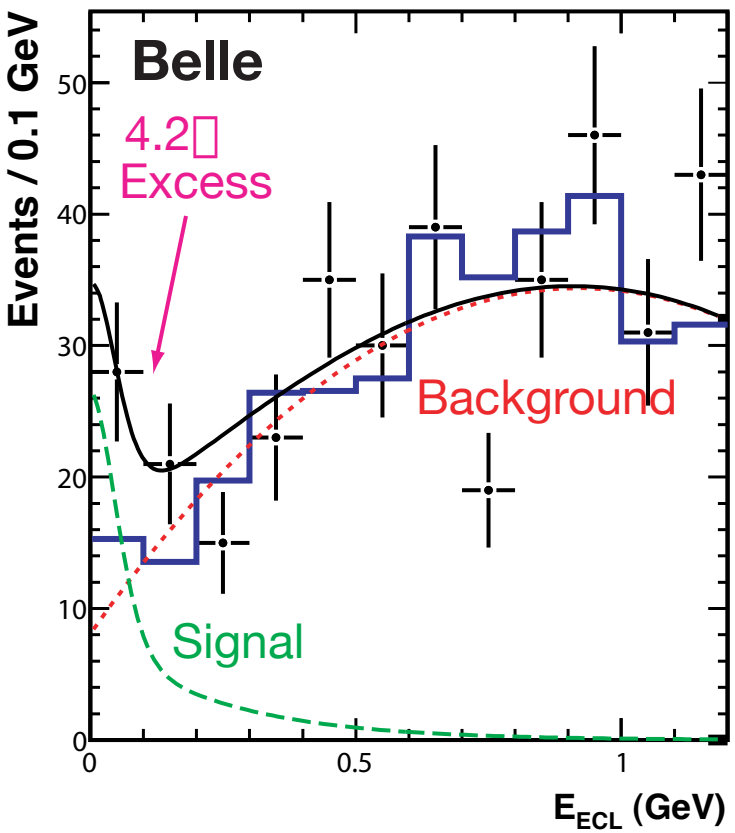

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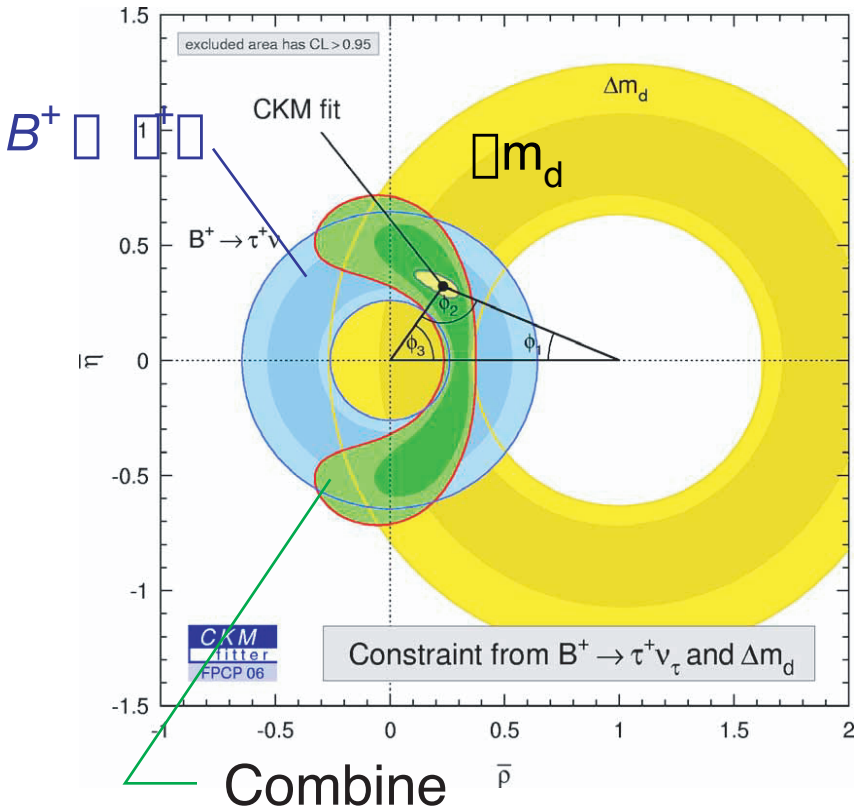
Leptonic Decay: $Br(B^+ \to \tau^+ \nu_\tau)$

- Standard Model:



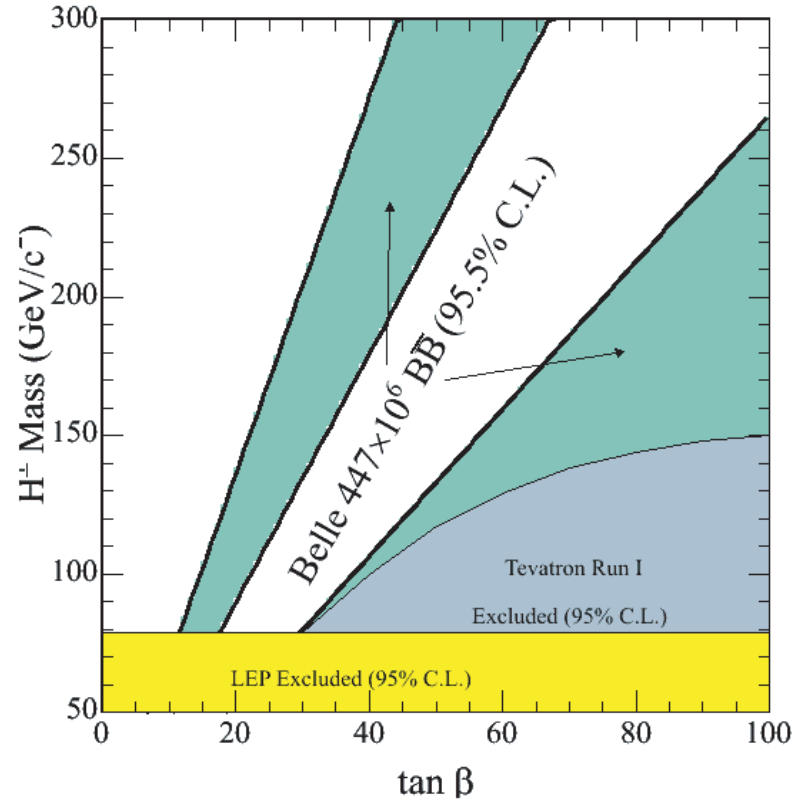
Combine (f_B cancels out), or

$$f_B = 0.176 \; {}^{+0.028}_{-0.023} \; {}^{+0.020}_{-0.018} \text{ GeV}$$

(using HFAG $|V_{ub}|$)

First Direct Measurement!

- New Physics (2HDM):



Summary

B_s^0 Decays

- Being probed from all sides now:
  Br's, lifetimes of CP states, oscillations
- $\Delta\Gamma_s$ World average 2.4σ from zero, consistent with SM

$$\Delta\Gamma_s = 0.097 \begin{smallmatrix} +0.041 \\ -0.042 \end{smallmatrix} \text{ ps}^{-1} \qquad \bar{\tau} = \frac{1}{\Gamma_s} = 1.461 \pm 0.030 \text{ ps}$$

Leptonic B Decays

- Purely leptonic $B_d^0, B_s^0 \to \ell^+\ell^-$
  - FCNC decay $B_s^0 \to \mu\mu^+\mu^-$

  Best limits from Tevatron, approaching SM, strong constraints on new physics, will improve

- Purely leptonic $B_d^0 \to \ell^+\ell^-$

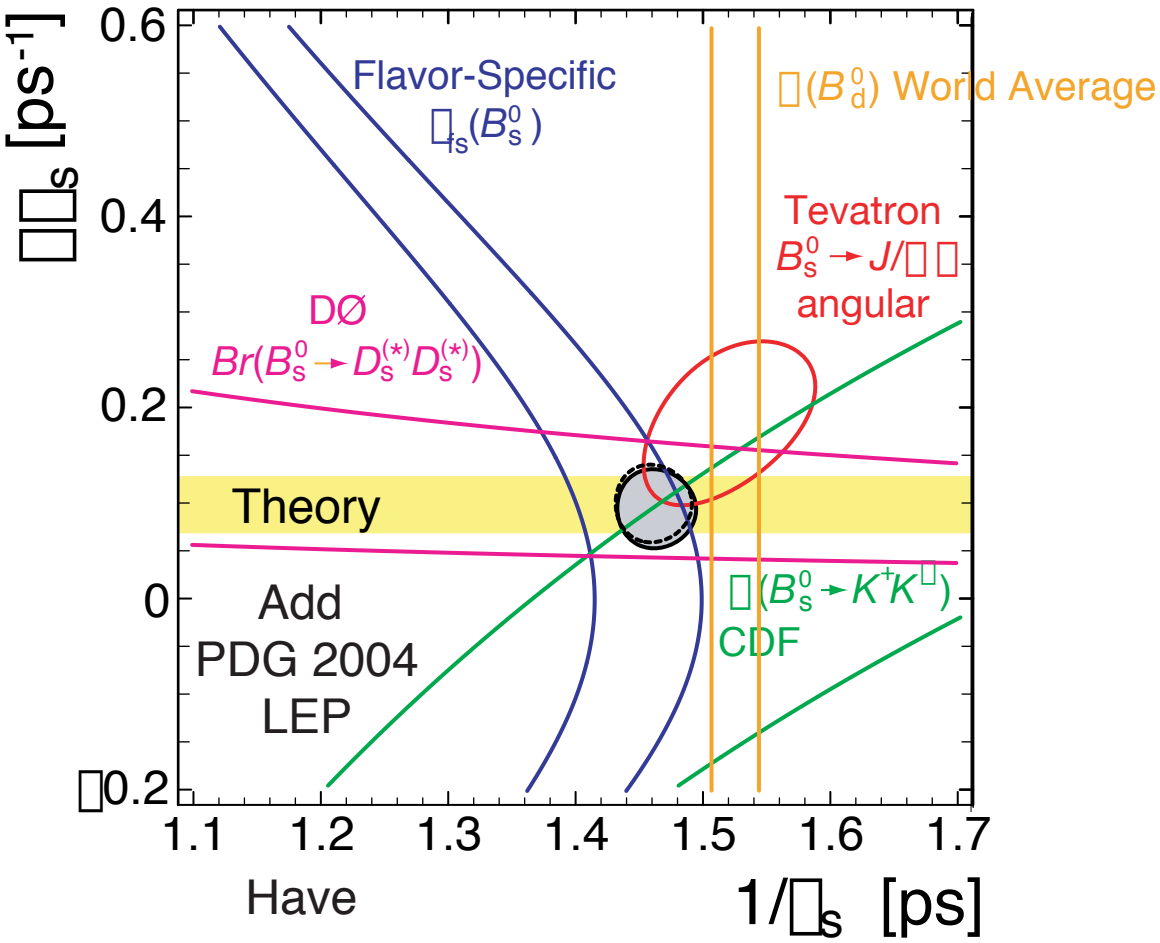
  First ever limit!

- Purely leptonic $B^+ \to \ell^+\nu$

  First ever evidence!
  First direct measurement of f_B !

Back-up

1-sigma contours (□(log*L*) = 0.5)



Have
come a
long way!

$$\frac{\Delta\Gamma_s}{\Delta m_s} \approx \left|\frac{\Gamma_{12}}{M_{12}}\right| = \mathcal{O}\left(\frac{m_b^2}{M_W^2}\right) \approx 4 \times 10^{-3}$$

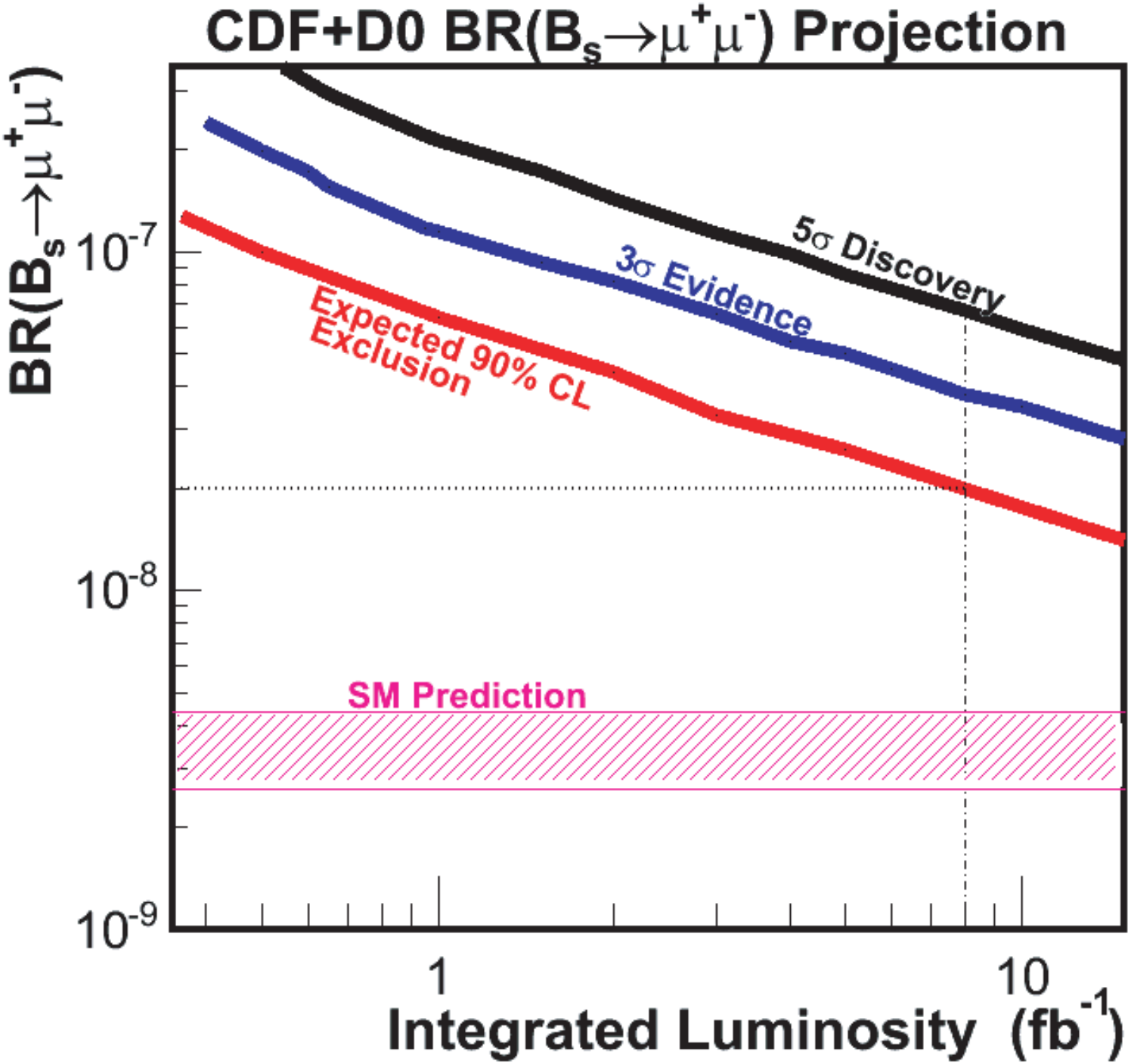
SM Prediction:

$$\frac{\Delta\Gamma_s}{\Delta m_s} = (47 \pm 8) \times 10^{-4}$$

(Update (Nierste) of
Phys.Lett. **B459** 631,1999)

Experiment:

$$\frac{\Delta\Gamma_s}{\Delta m_s} = \frac{0.097 \pm 0.042\,\mathrm{ps}^{-1}}{17.33^{+0.42}_{-0.21} \pm 0.07\,\mathrm{ps}^{-1}} = (56 \pm 24) \times 10^{-4}$$


CDF+D0 BR(B_s→μ+μ-) Projection
BR(B_s→μ+μ-)
10^-7
10^-8
10^-9
5σ Discovery
3σ Evidence
Expected 90% CL
Exclusion
SM Prediction
1
10
Integrated Luminosity (fb^-1)