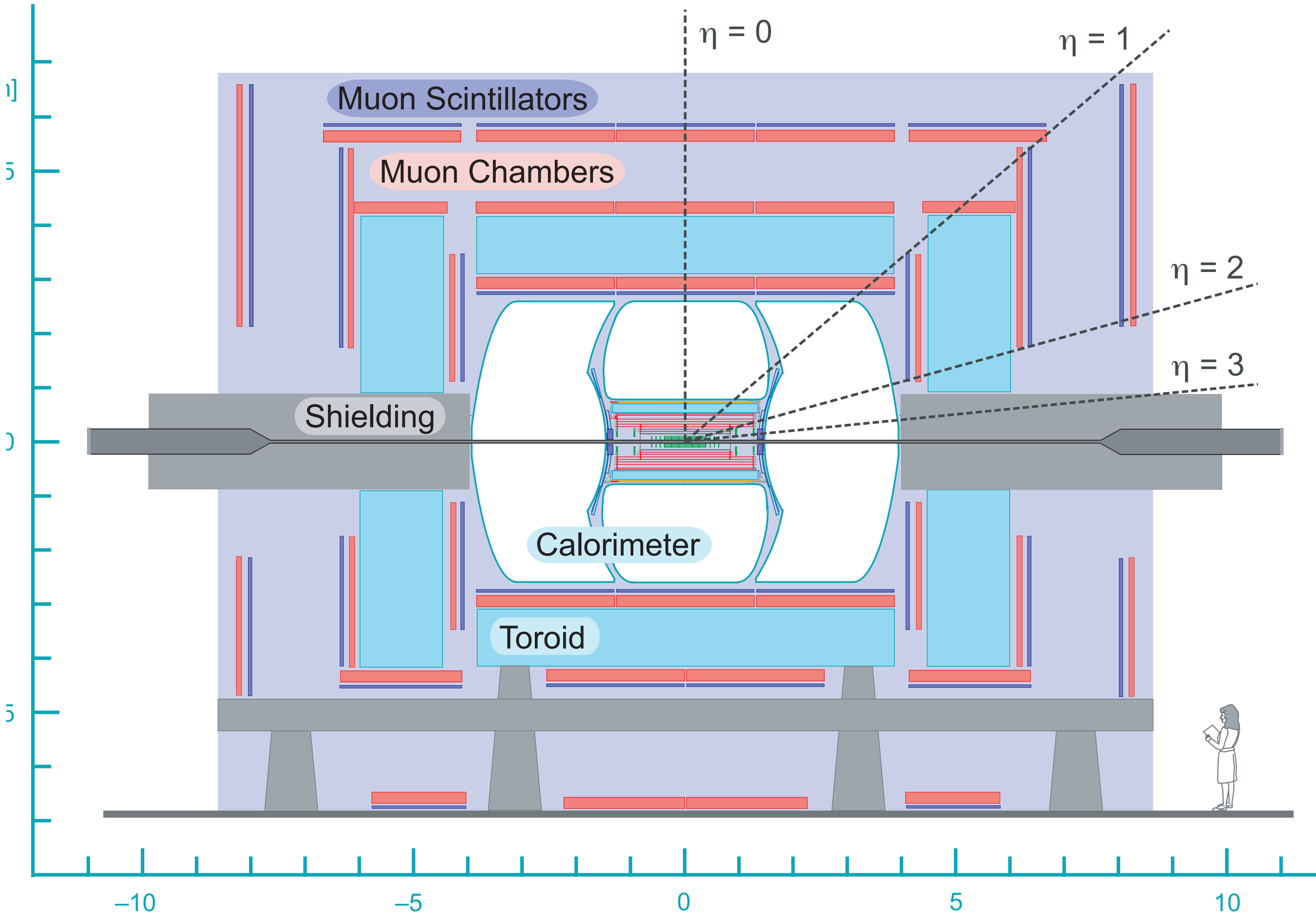
DØ B-Physics

Iain Bertram
Department of Physics
Lancaster University
for the D0 Collaborations

16th September 2010

DØ Experiment



- Key facts:
  - Extensive muon coverage - high statistics
  - Reversal of magnetic field every two weeks - cancellation of most detector related asymmetries

B_s Mixing

B Mixing and Oscillations

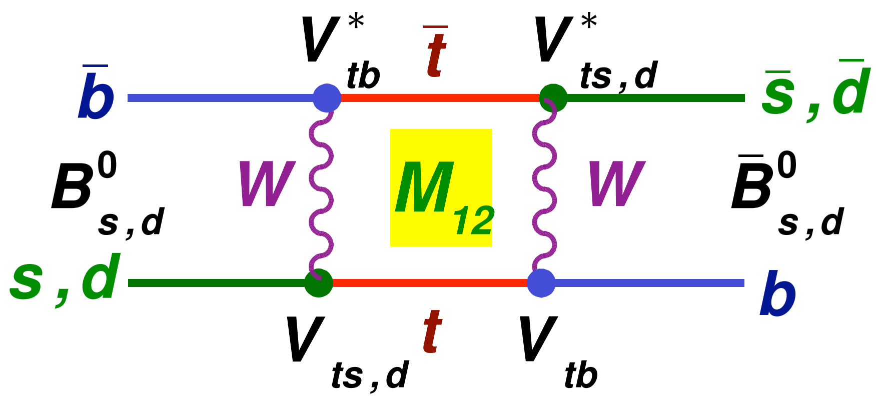
$$i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

CP Eigenstates: $\left|B^{\rm even}\right\rangle = \left|B^0\right\rangle + \left|\bar{B}^0\right\rangle \quad \left|B^{\rm odd}\right\rangle = \left|B^0\right\rangle - \left|\bar{B}^0\right\rangle$

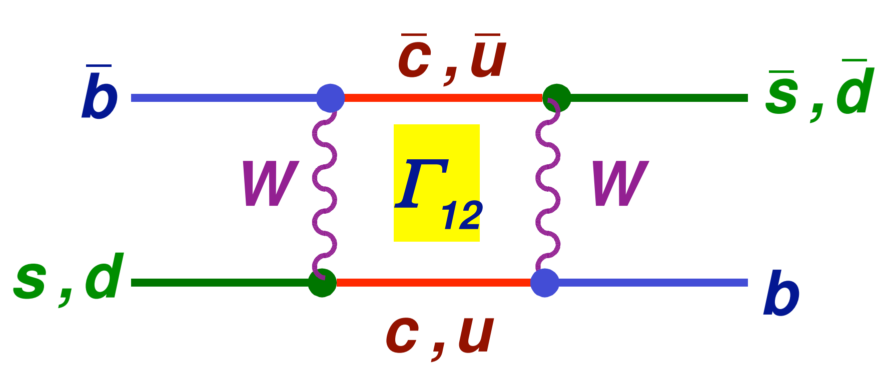
Mass Eigenstates: $\left|B^H\right\rangle = p\left|B^0\right\rangle + q\left|\bar{B}^0\right\rangle \quad \left|B^L\right\rangle = p\left|B^0\right\rangle - q\left|\bar{B}^0\right\rangle$

- Mass Difference: $\Delta m = M_H - M_L \sim 2|M_{12}|$ directly probes V_{td} and V_{ts} in oscillations of B_d & B_s

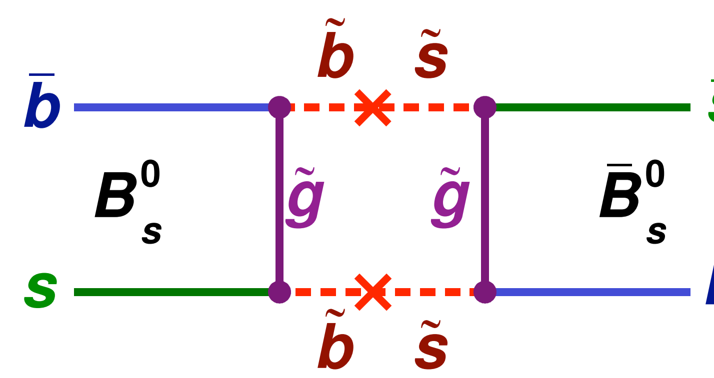
$$\Delta m_d \propto \left|V_{tb}^* V_{td}\right|^2$$
$$\Delta m_s \propto \left|V_{tb}^* V_{ts}\right|^2$$



Sens. to NP



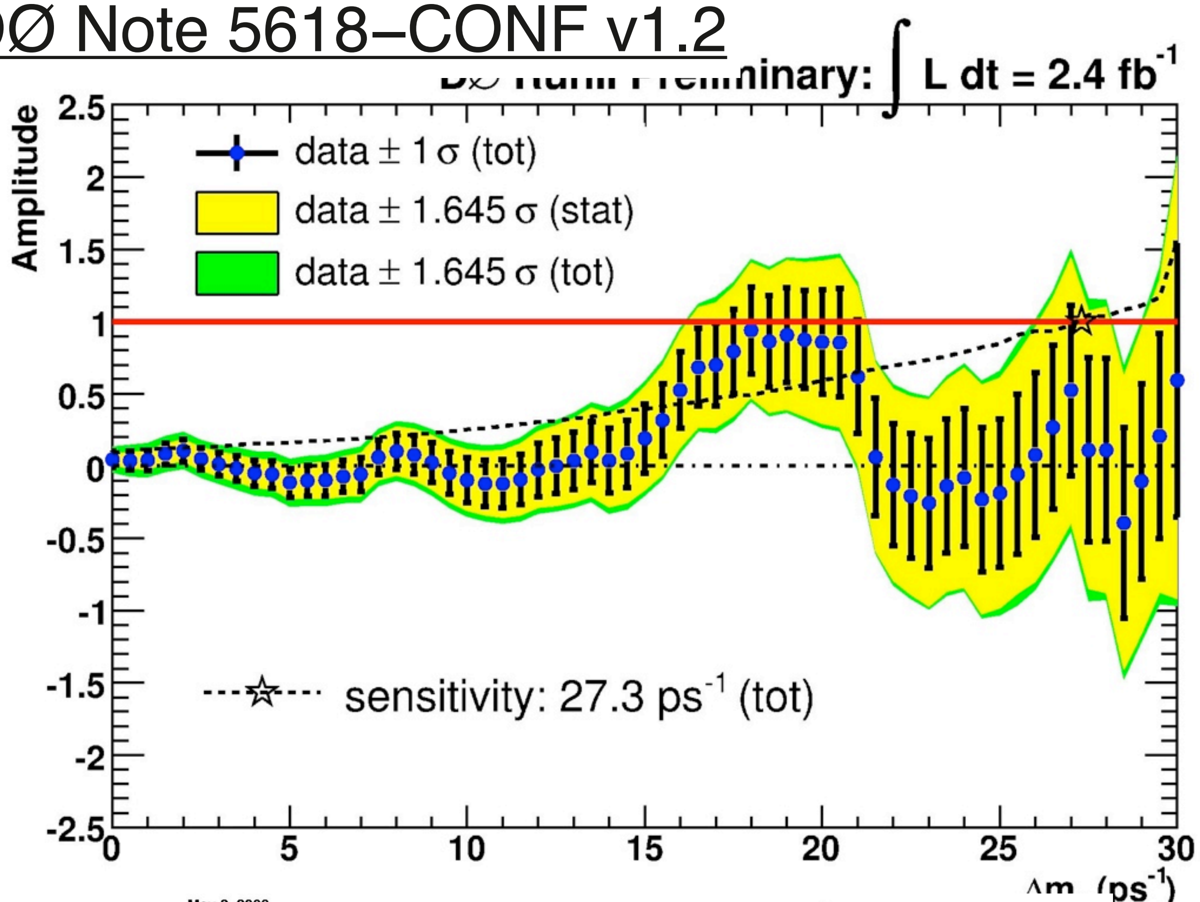
less sens. to NP



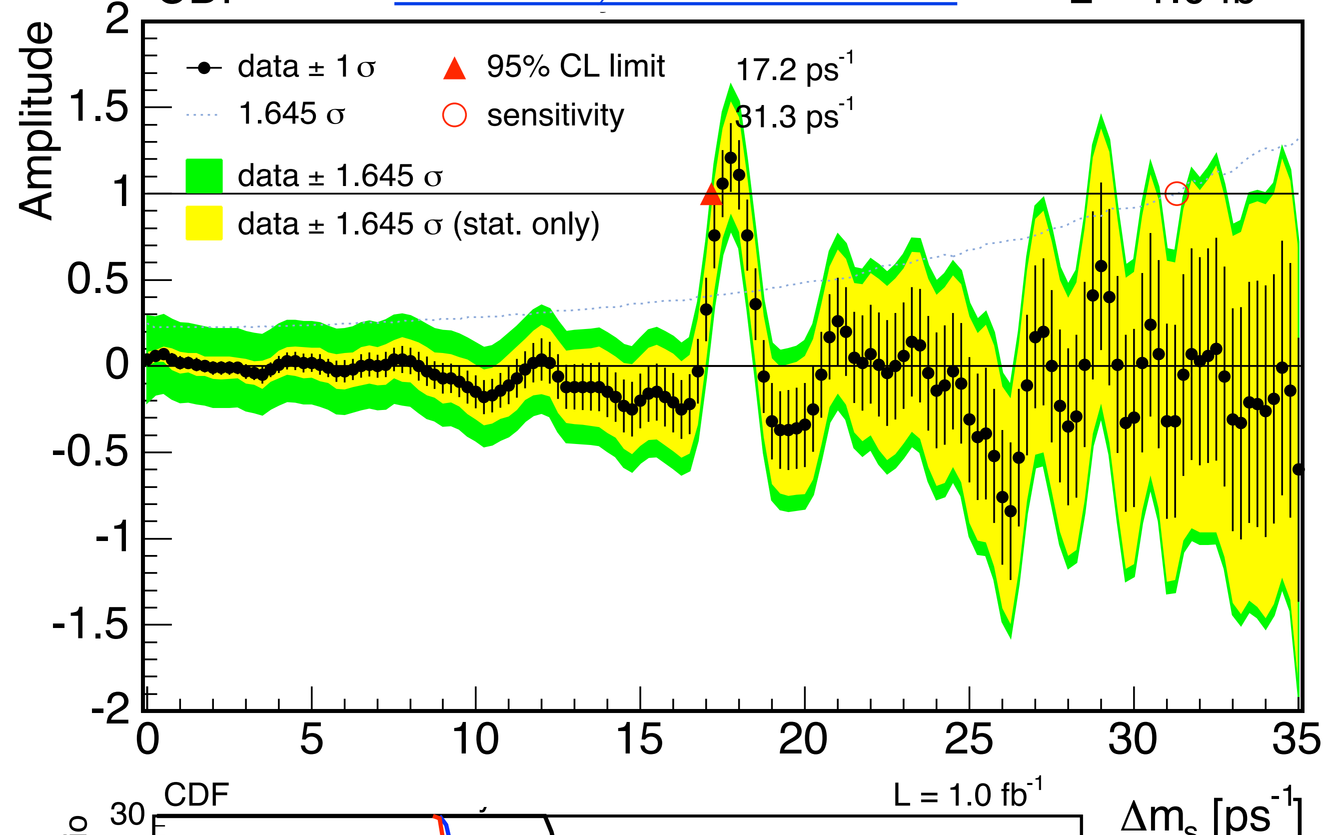
SUSY

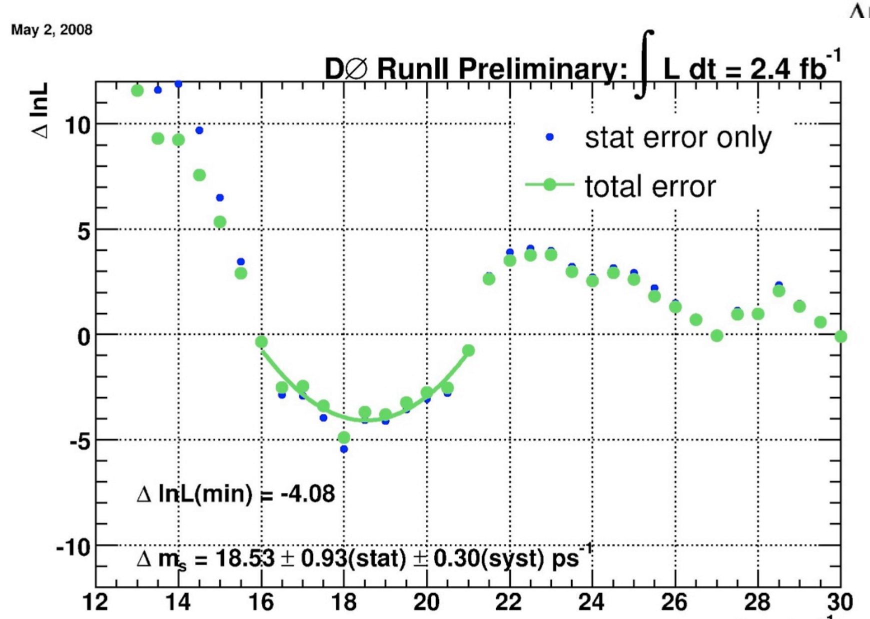
Δm_s Measurements

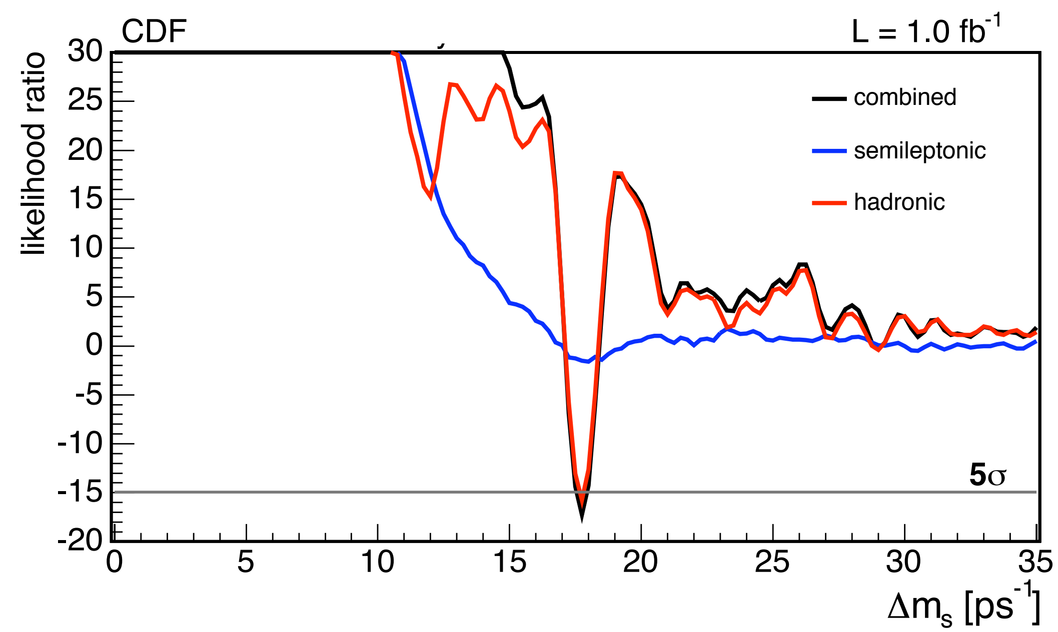
DØ Note 5618–CONF v1.2



PRL 97, 242003 2006







DØ: 2.9 σ significance
Δms = 18.53 ± 0.93(stat) ± 0.30(syst) ps^{-1}

CDF: >5σ significance
Δms = 17.77 ± 0.10(stat) ± 0.07(sys)

Vts & Vtd

$$\left|\frac{V_{td}}{V_{ts}}\right|^2 = \xi^2 \left(\frac{\Delta m_d}{\Delta m_s}\right)\left(\frac{M_{B_s}}{M_{B_d}}\right)$$

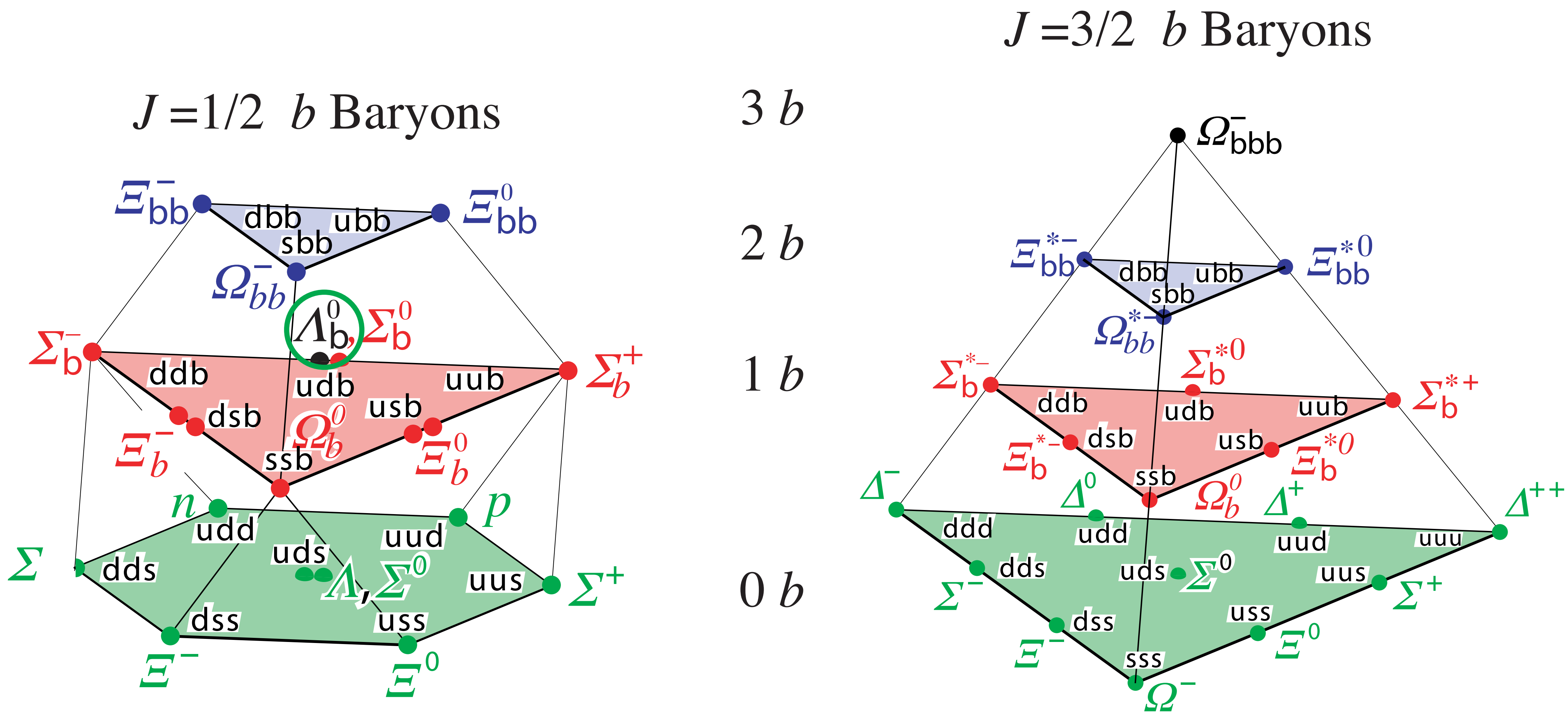
D0: 0.2018 ±0.0053(exp) ± 0.0010(Δmd) +0.0078-0.0058(ξ)
CDF: 0.2060 ±0.0007(exp) ± 0.0010(Δmd) +0.0080-0.0060(ξ)

Ave: 0.2059 ±0.0007(exp) ± 0.0010(Δmd) +0.0080-0.0060(ξ)

- Uncertainty driven by theoretical calculation of ξ.
- Full Uncertainties (added in naive quadrature)
  - D0 - 4.3% CDF - 3.5%
  - Require theoretical improvements to progress here...

Spectroscopy

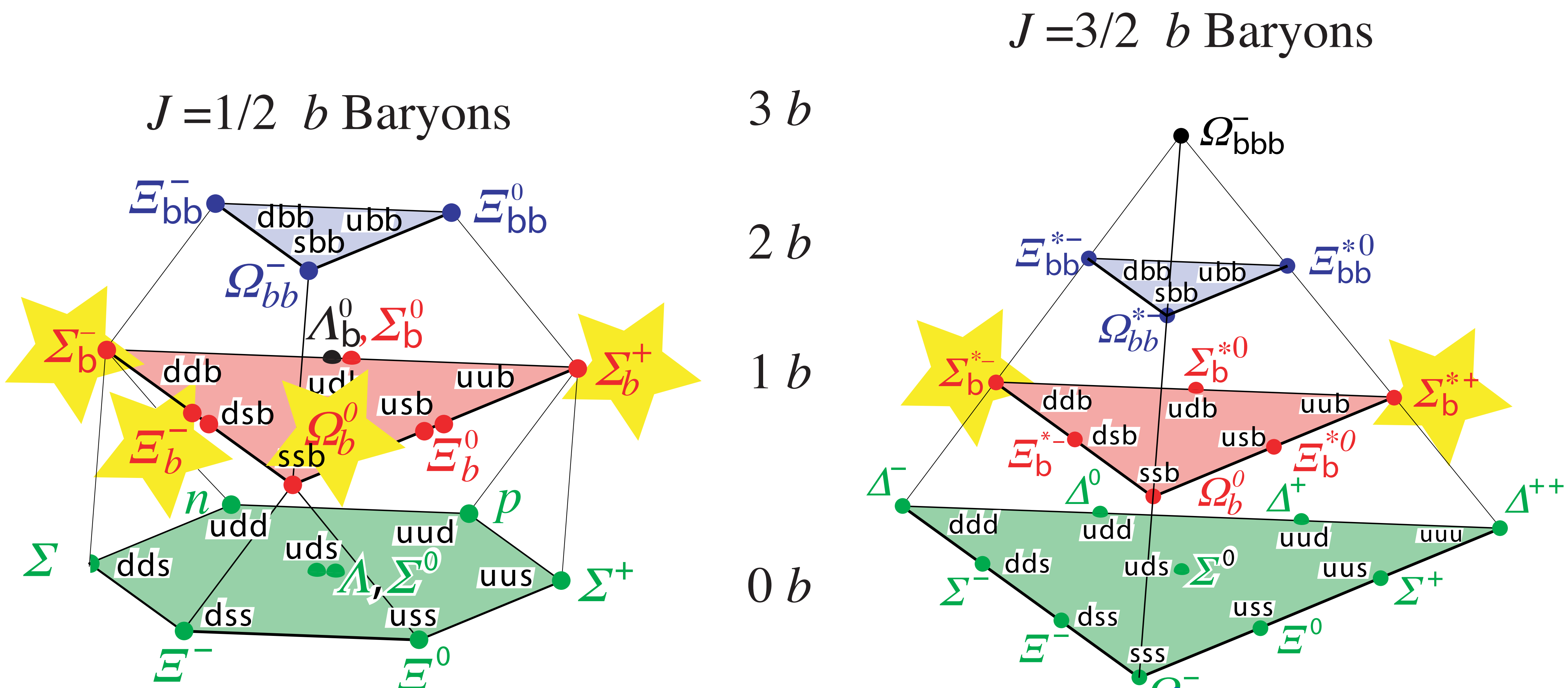
Heavy Baryons



- Until recently only Λ_b had been observed directly

Λ_b^0= |bud〉 D0 and CDF

Heavy Baryons



- Until recently only Λ_b had been observed directly
- High statistics searches

$\Lambda_b^0 = |bud\rangle$ D0 and CDF

$\Xi_b^- = |bds\rangle$ D0, CDF

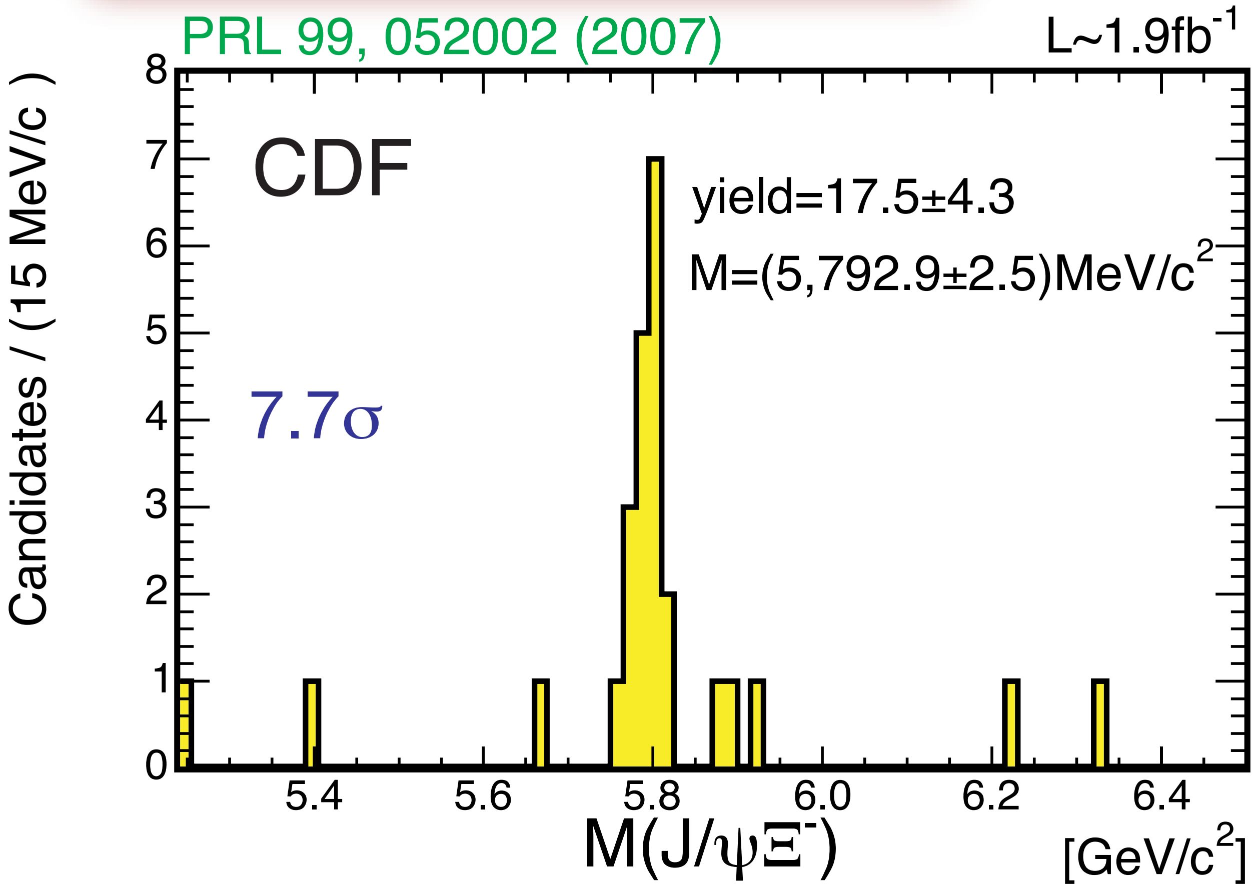
$\Omega_b^- = |bss\rangle$ D0, CDF

$\Sigma^{\pm} = |bqq\rangle$ (q=u,d) CDF

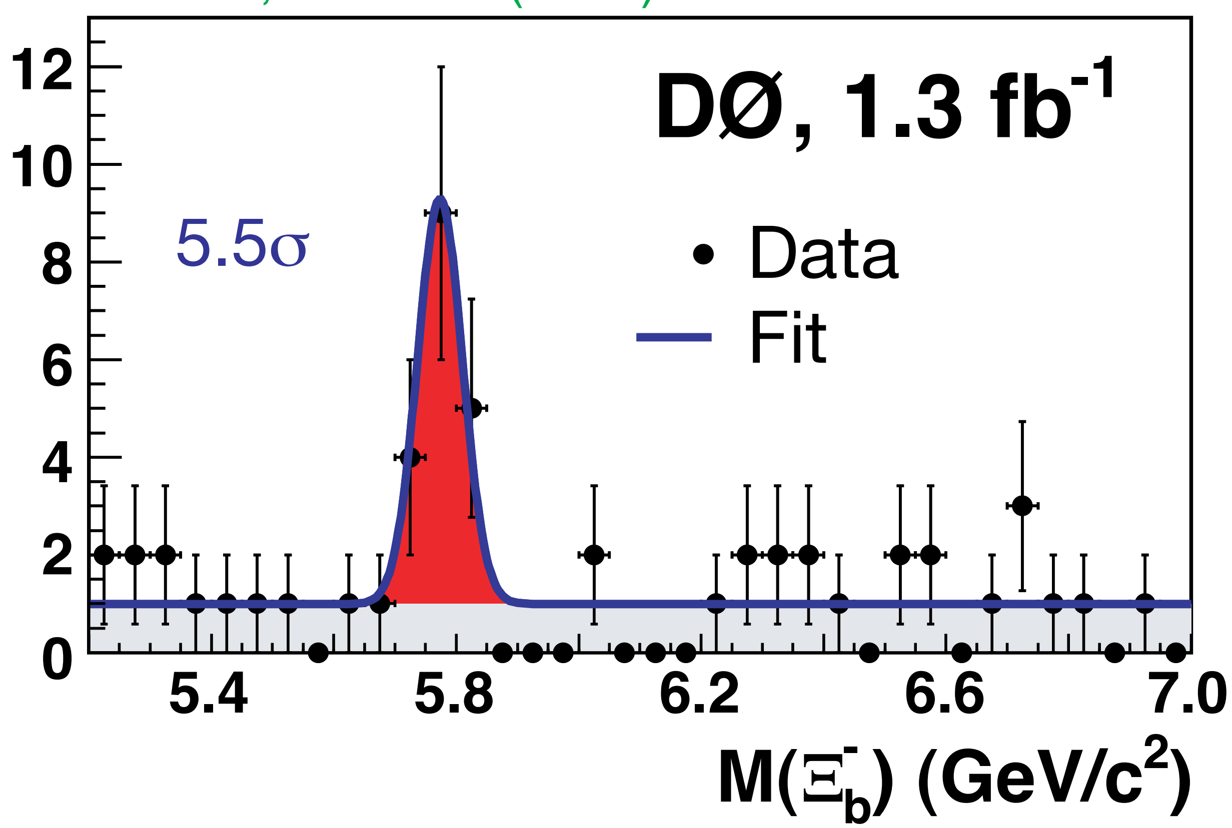
Ξ_b Heavy Baryon

Phys. Rev. Lett. **99**, 052001 (2007),

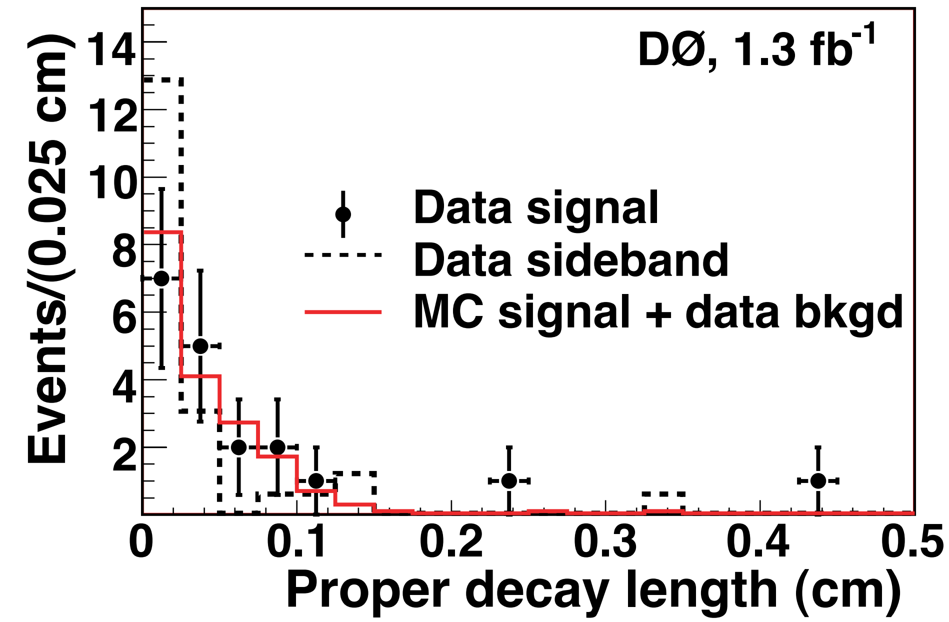
PRL 99, 052002 (2007)



PRL 99, 1052001 (2007)



- DØ: many checks that no signal in wrong-sign $\Lambda\pi$ combinations, Ξ sidebands, J/ψ sidebands
- CDF also has signal in $\Xi_b^{\pm} \to \Xi_c^0 \pi^{\pm}$ channel
- DØ: lifetime consistent with expectations:

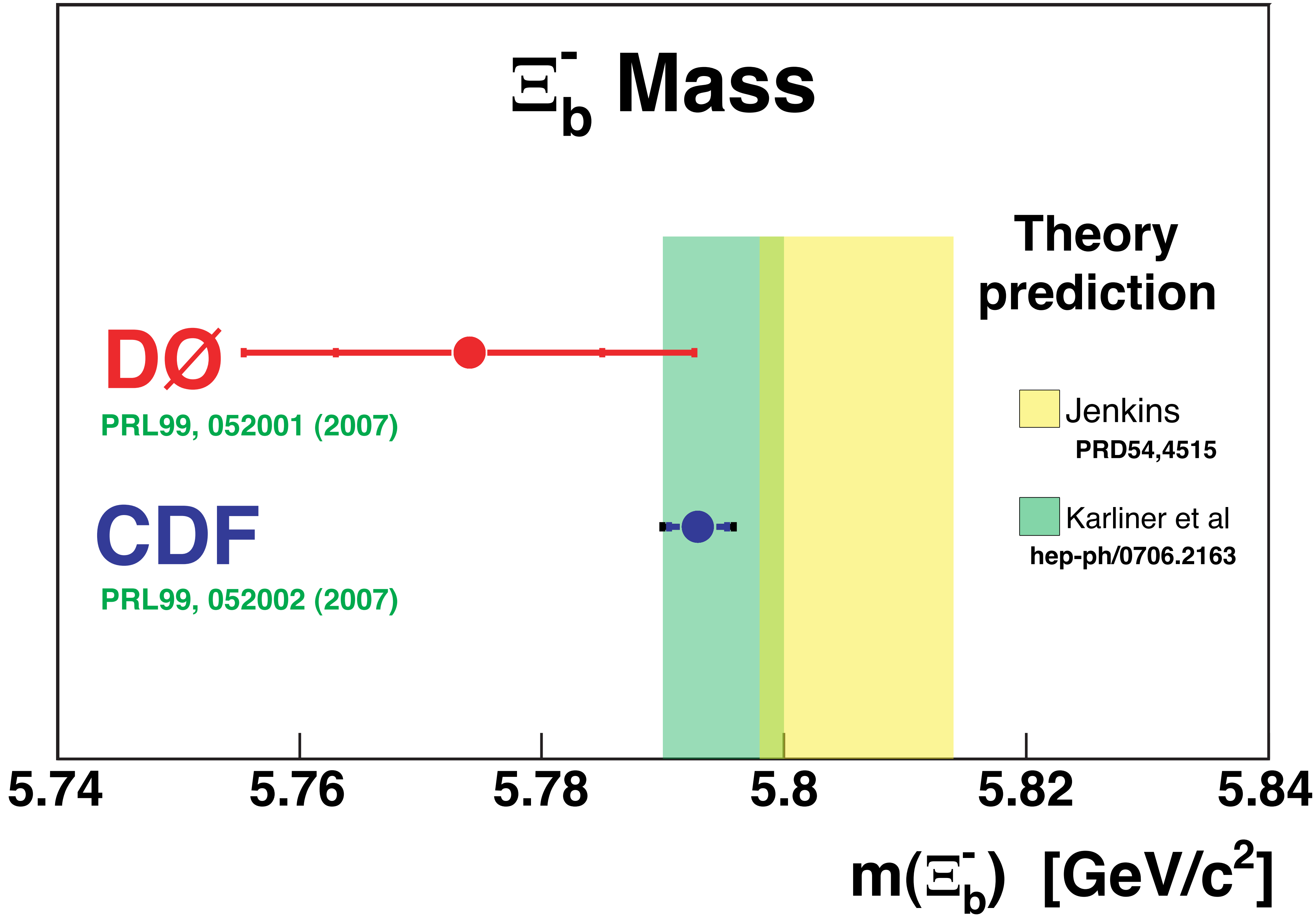


CDF *now updated (later)*

$$M(\Xi_b) = 5792.9 \pm 2.4 \pm 1.7\,\mathrm{MeV}$$

DØ

$$M(\Xi_b) = 5774 \pm 11 \pm 15\,\mathrm{MeV}$$



Ξ_b^- Mass
DØ
PRL99, 052001 (2007)
CDF
PRL99, 052002 (2007)
Theory prediction
Jenkins
PRD54,4515
Karliner et al
hep-ph/0706.2163
5.74
5.76
5.78
5.8
5.82
5.84
$m(\Xi_b^-)$ [GeV/c^2]

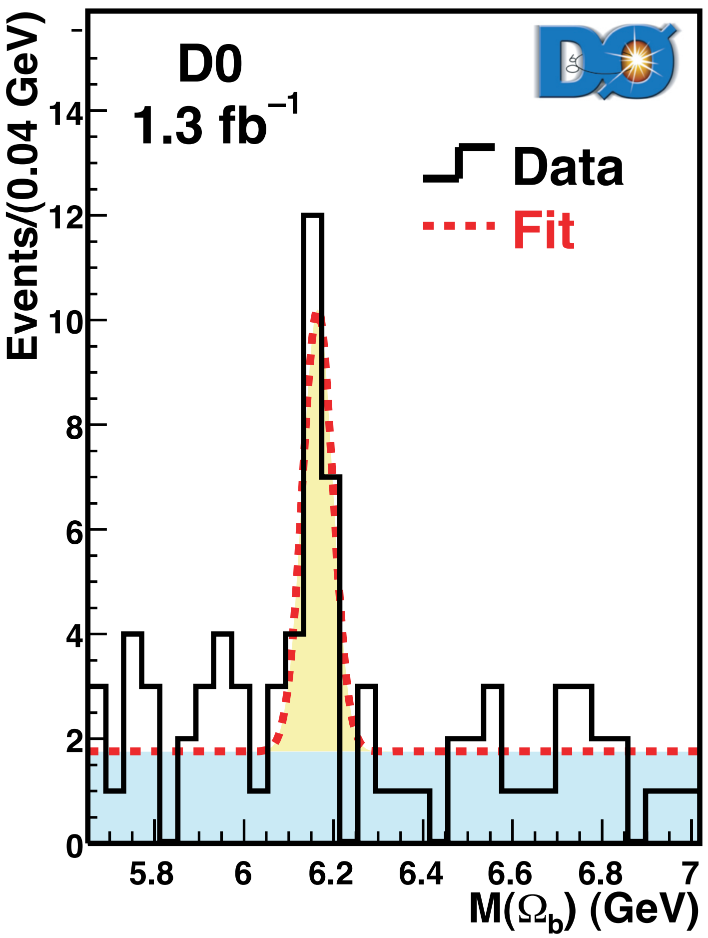
Phys. Rev. Lett. **101**, 232002 (2008)

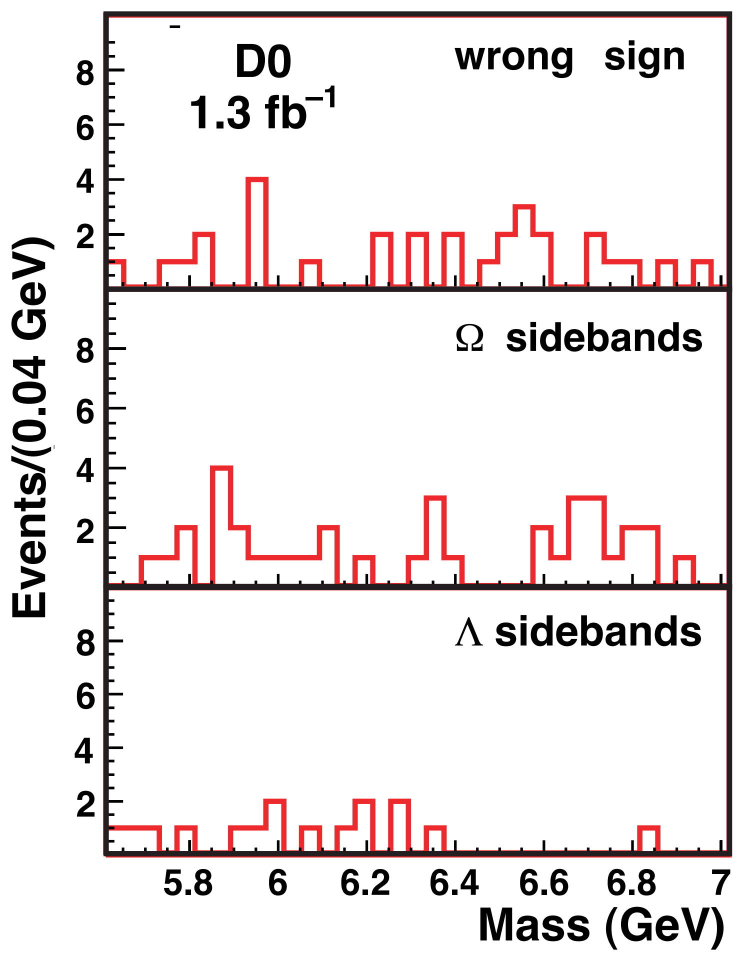
Ω_b Baryon

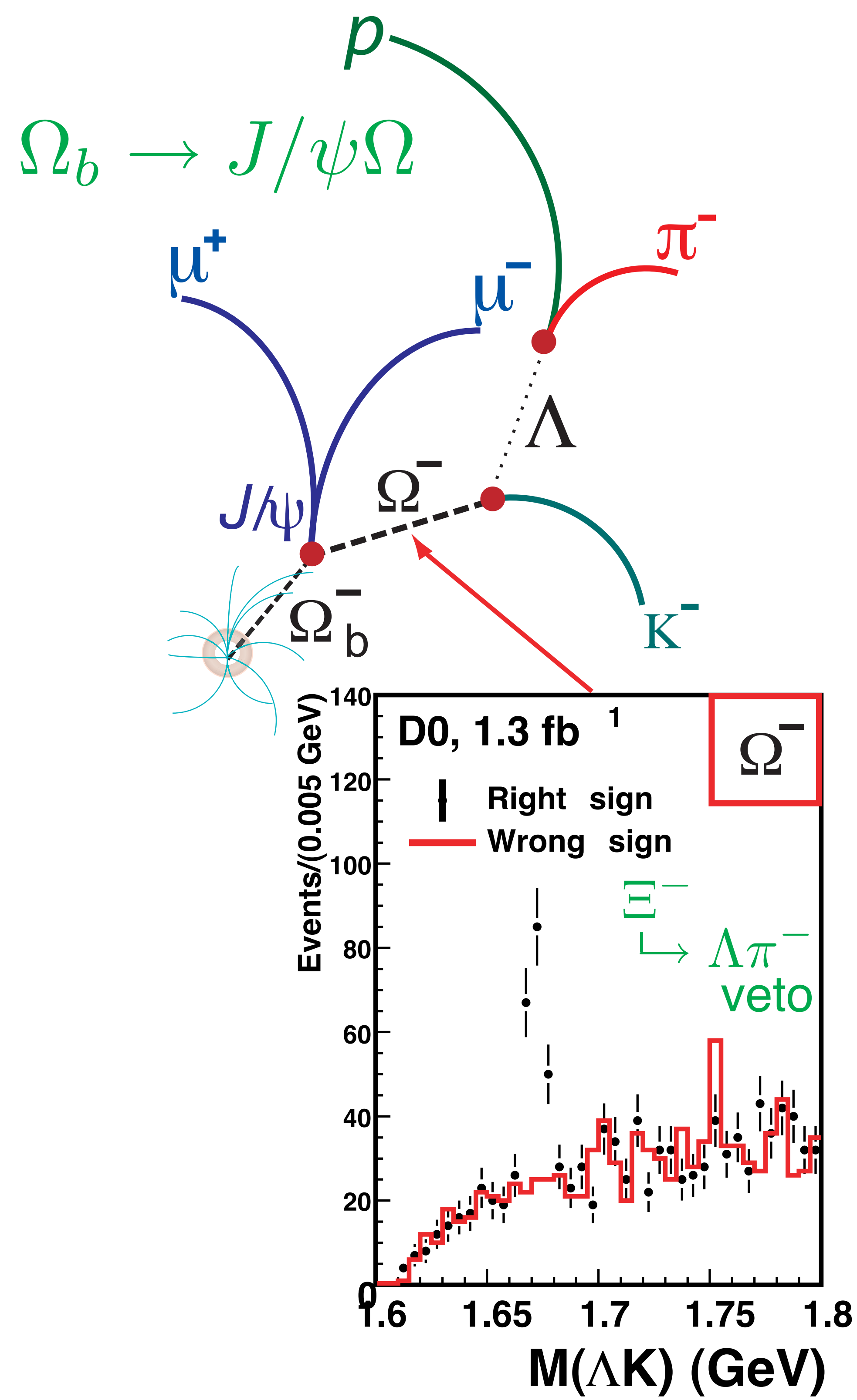
...doubly strange $|bss\rangle$

- Summer 2008, DØ analysis, 1.3 fb^{-1} building on previous Ξ_b^- observation

PRL **101**, 232002 (2008)







- Yield 17.8 ± 4.9 ± 0.8 candidates
- Likelihood ratio, stat. significance = 5.4σ
  Include "trials" factor, significance = 5.05σ
  Remains > 5σ with syst. checks
- After special track reprocessing, large impact parameter tracks

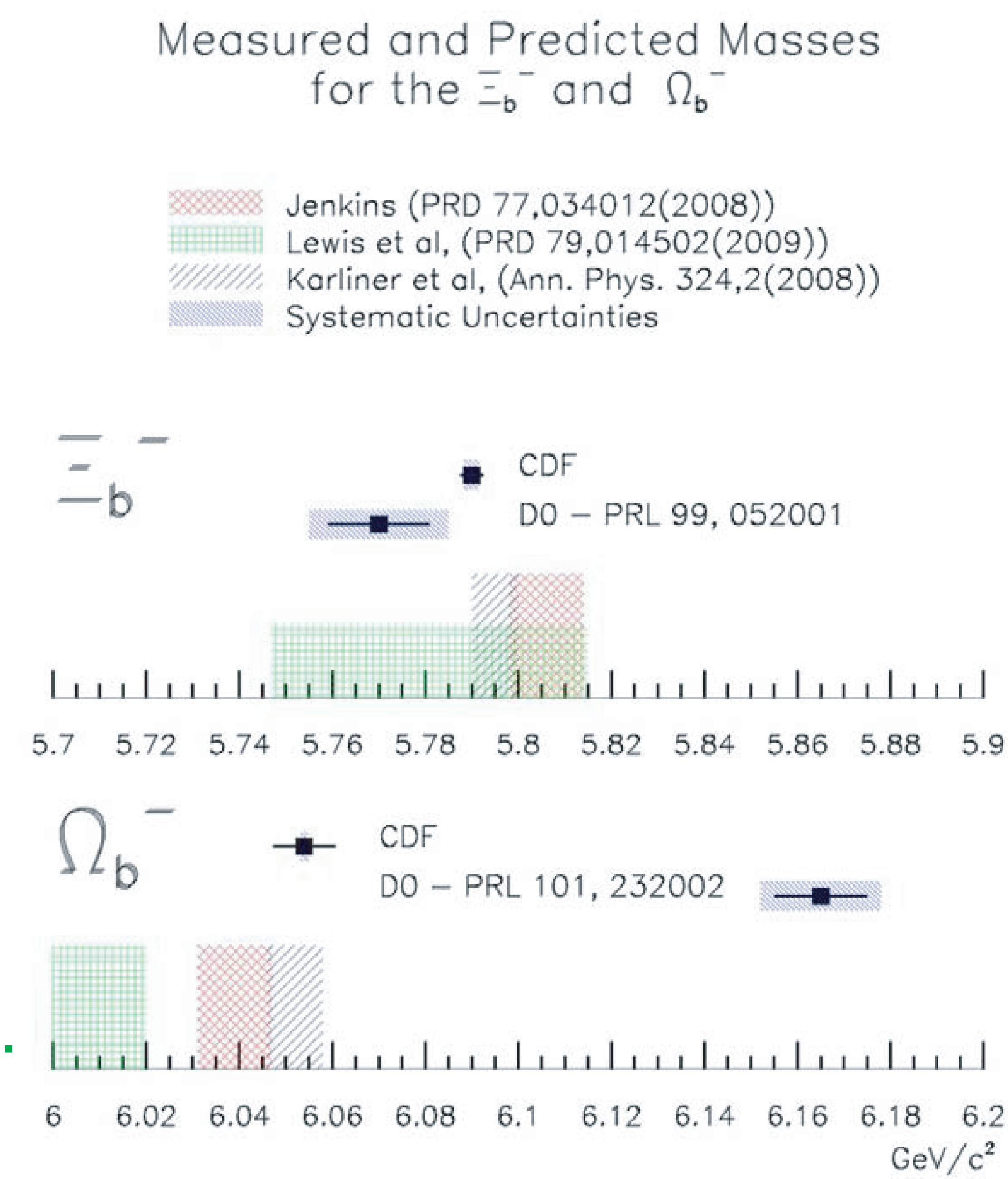
Ω_b Baryon : Comparison

Difference of measured masses:

$$m(\Omega_b^-)^{\text{DØ}} - m(\Omega_b^-)^{\text{CDF}} = 111 \pm 12 \pm 14 \text{ MeV}$$

Significant (~6σ) disagreement!

- DØ's largest mass systematic unc. is 10 times less than this difference
- DØ is working on an update of this measurement with an increased data set that may help address discrepancy.



Relative rates:

DØ: $$\frac{f(b \to \Omega_b^-) \cdot \mathcal{B}(\Omega_b^- \to J/\psi\Omega^-)}{f(b \to \Xi_b^-) \cdot \mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}$$

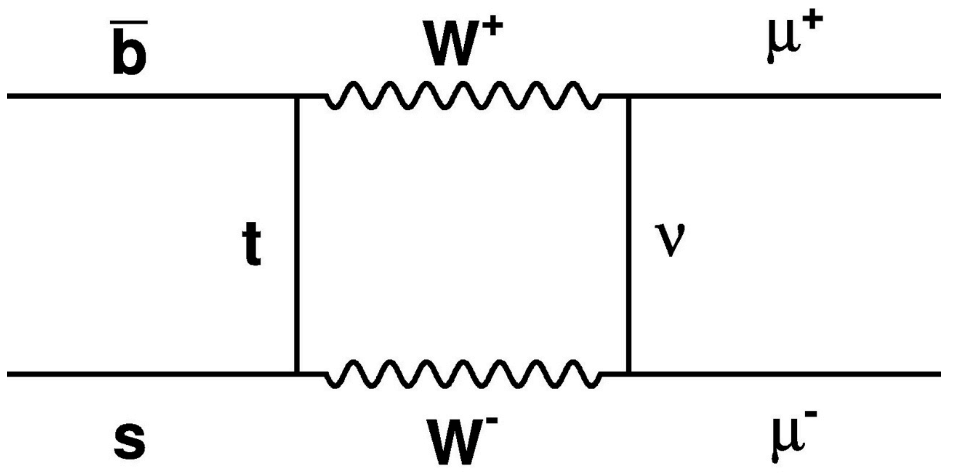
CDF: $$\frac{\sigma \cdot \mathcal{B}(\Omega_b^- \to J/\psi\Omega^-)}{\sigma \cdot \mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.27 \pm 0.12 \pm 0.01$$

1.3σ difference (assuming Gaussian unc.)

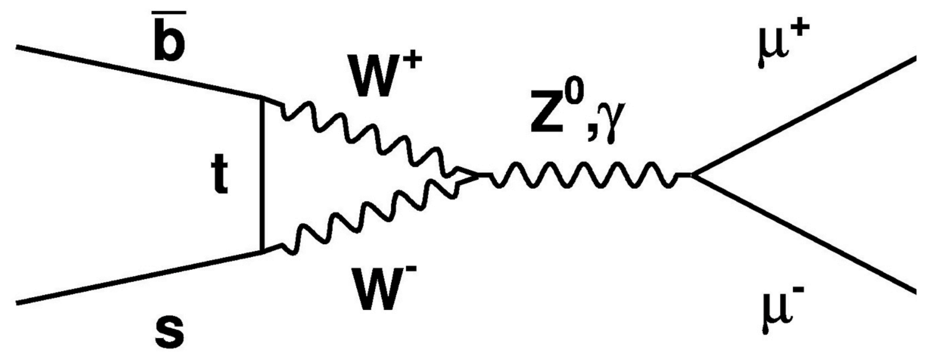
Rare Decays

$B_s \to \mu\mu$

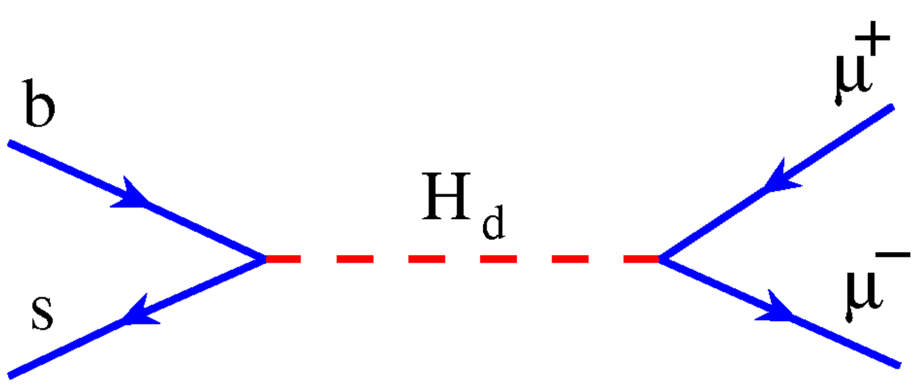
- Current SM Prediction:
  Buras: hep-ph/0904.4917
  - ➡ $BR(B_s \to \mu\mu) = (3.6 \pm 0.3) \times 10^{-9}$
  - ➡ $BR(B_d \to \mu\mu) = (1.1 \pm 0.1) \times 10^{-10}$



- Can be enhanced by the presence of non-SM physics
  - ➡ MSSM ($BR \propto \tan^6\beta$)
  - ➡ GUT SO(10)
  - ➡ SUSY R-parity violating models
  - ➡ Flavour Violating models



- SM signal beyond detectors sensitivity.



Outline of Measurement

$$\mathcal{B}\left(B_s^0 \rightarrow \mu^+\mu^-\right) = \frac{N(B_s^0)}{N(B^+)} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B_s}} \cdot \boxed{\frac{f_u}{f_s} \cdot \mathcal{B}(B^+)}$$

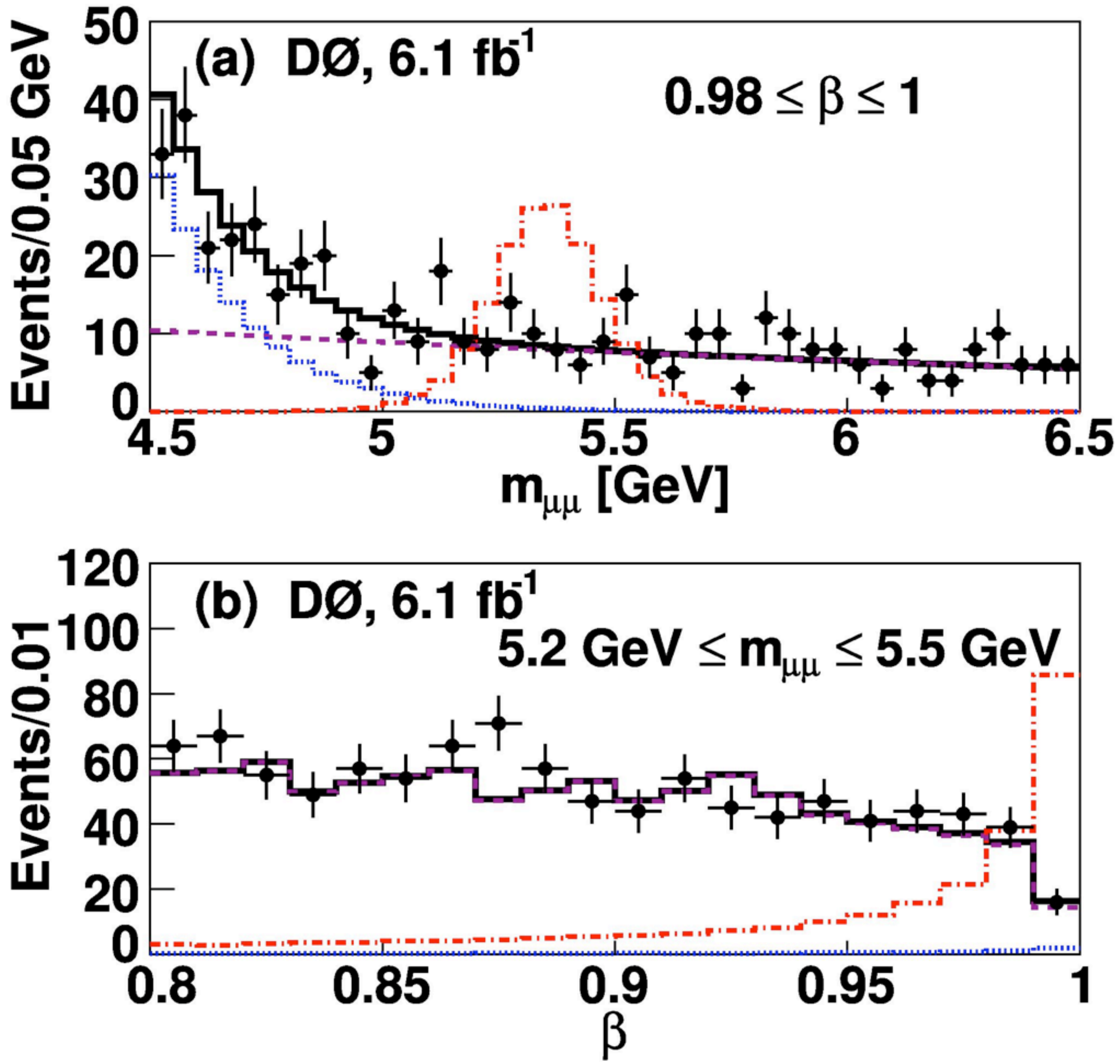
1. Measure number of possible signal events in B_s mass window
2. Normalise to number of $B^+ \rightarrow J/\psi K^+$ events
3. Correct for relative reconstruction efficiencies
4. Correct for Fragmentation Functions and Branching ratio.
   Particle Data Group (W.M. Yao et al.). 2006.
   Both CDF and D0 use the LEP numbers.

f_u/f_s is the dominant source of systematic uncertainties at 15%

D0's Latest Result (Summer 2010)

- arXiv:1006.3469v1 [hep-ex]
  submitted to Phys. Lett. B
- 6.1fb^{-1} data (split into Run 2a 1.3fb^{-1} and Run 2b 4.8fb^{-1})
- Many improvements
  - Acceptance Gain (Muons ~10%, Trigger ~16%)
  - Bayesian Neural Networks
  - Improved understanding of discriminating variables
  - Improved MC and Data modelling
  - 2D fit of BNN output and mass spectrum

D0 Results



In highest sensitivity region:

51 ± 4 expected bkg events,

55 data events

BF < 51 x 10^{-9} (95% CL)

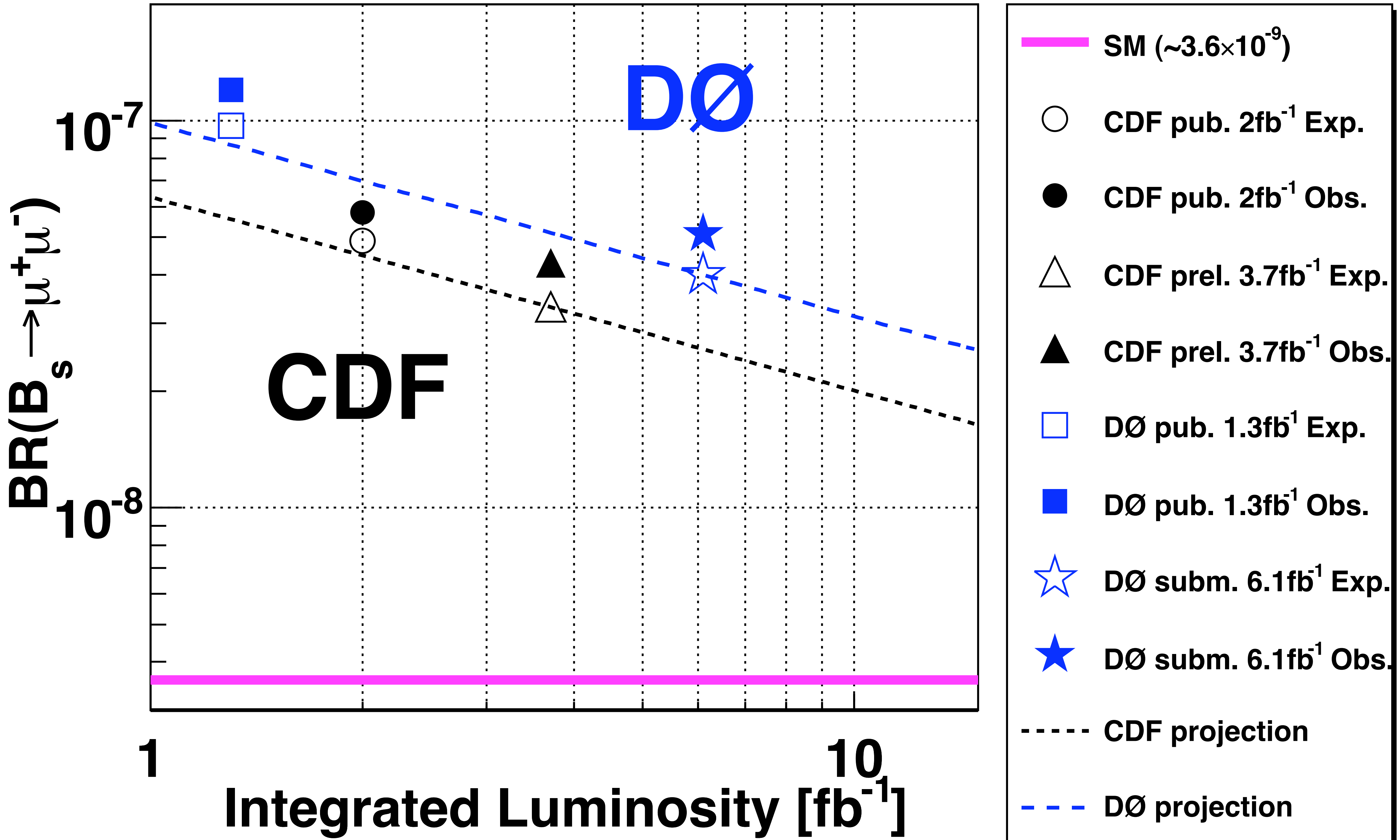
14x SM

Expected limit: 40 x 10^{-9}

11x SM

arXiv:1006.3469v1 [hep-ex]

Upper Limits on BR($B_s \to \mu^+\mu^-$) at 95% C.L. at Tevatron

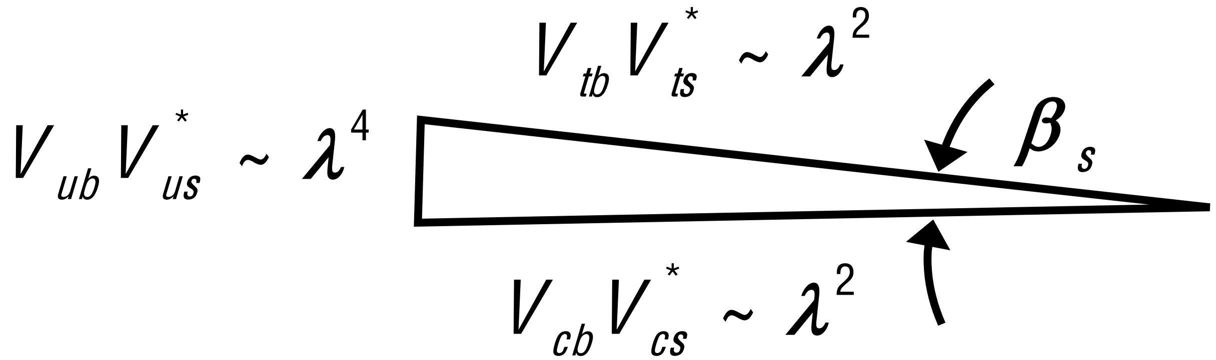


CP Violation

$B_s \rightarrow J/\psi\phi$

- Look for CP Violation in B_s mixing using $B_s \psi \rightarrow J/\psi$
- CP Violation is described using the mixing angle $\phi^{J/\psi\phi}$ which can be related to the angle β_s of the unitarity triangle:

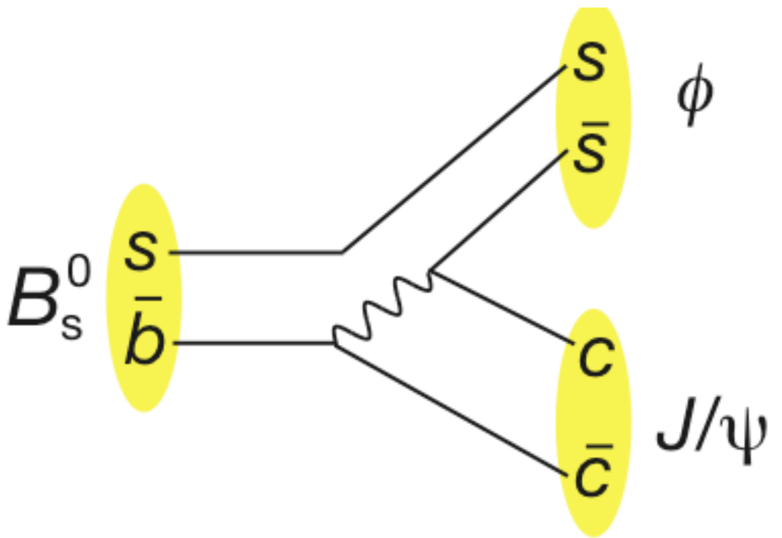
$$\phi^{J/\Psi\phi,\mathrm{SM}} = -\beta_s = 2\arg\left(-\frac{\mathrm{V_{tb}V_{ts}^*}}{\mathrm{V_{cb}V_{cs}^*}}\right) = -0.038 \pm 0.002$$

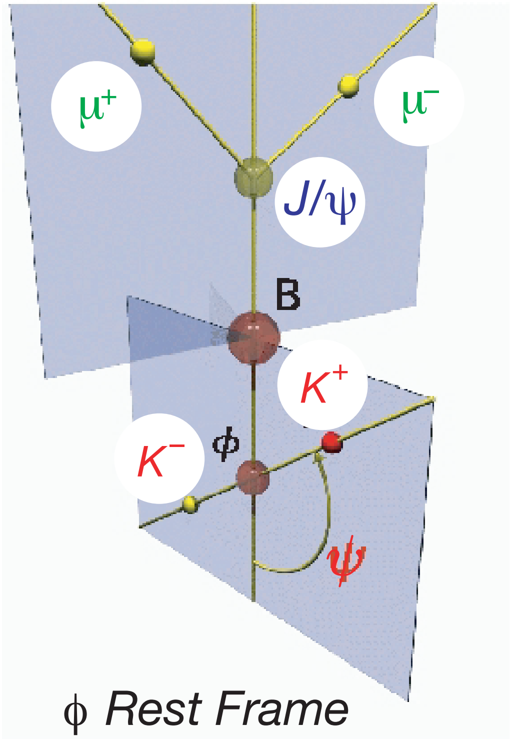


- This can be enhanced by new phenomena

$$\phi^{J/\Psi\phi} = \phi^{J/\Psi\phi,\mathrm{SM}} + \phi_s^{\mathrm{NP}}$$

$B_s \rightarrow J/\psi\phi$

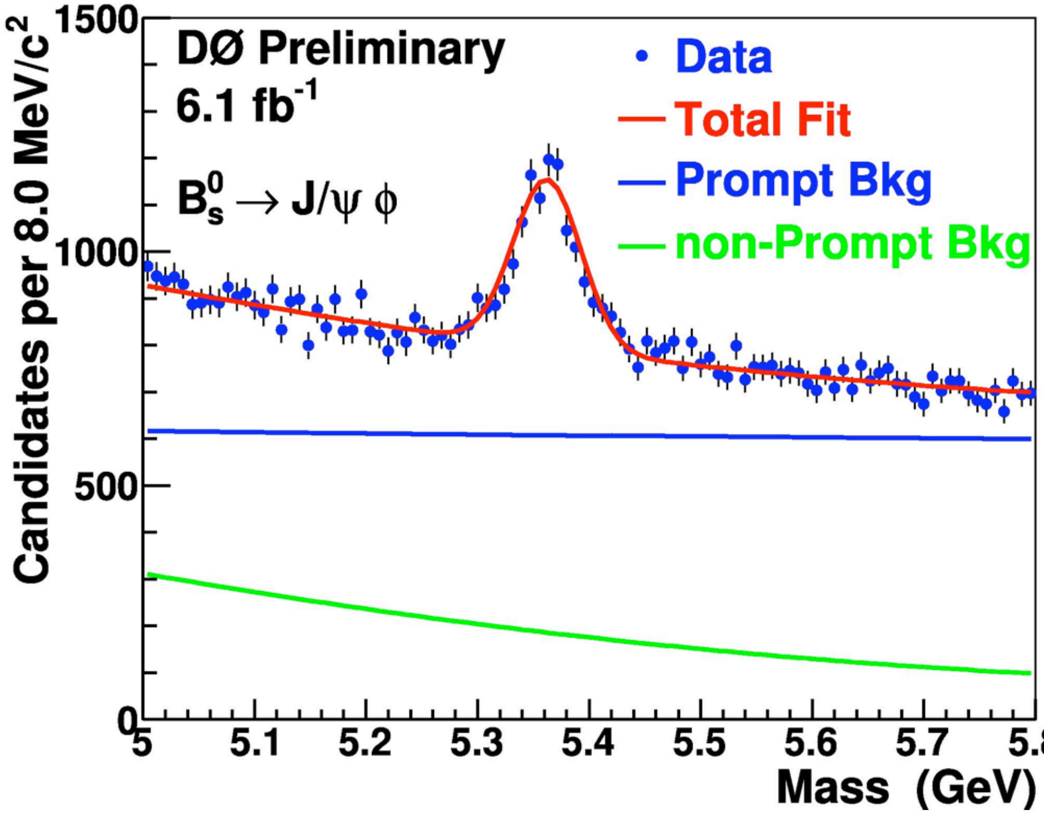


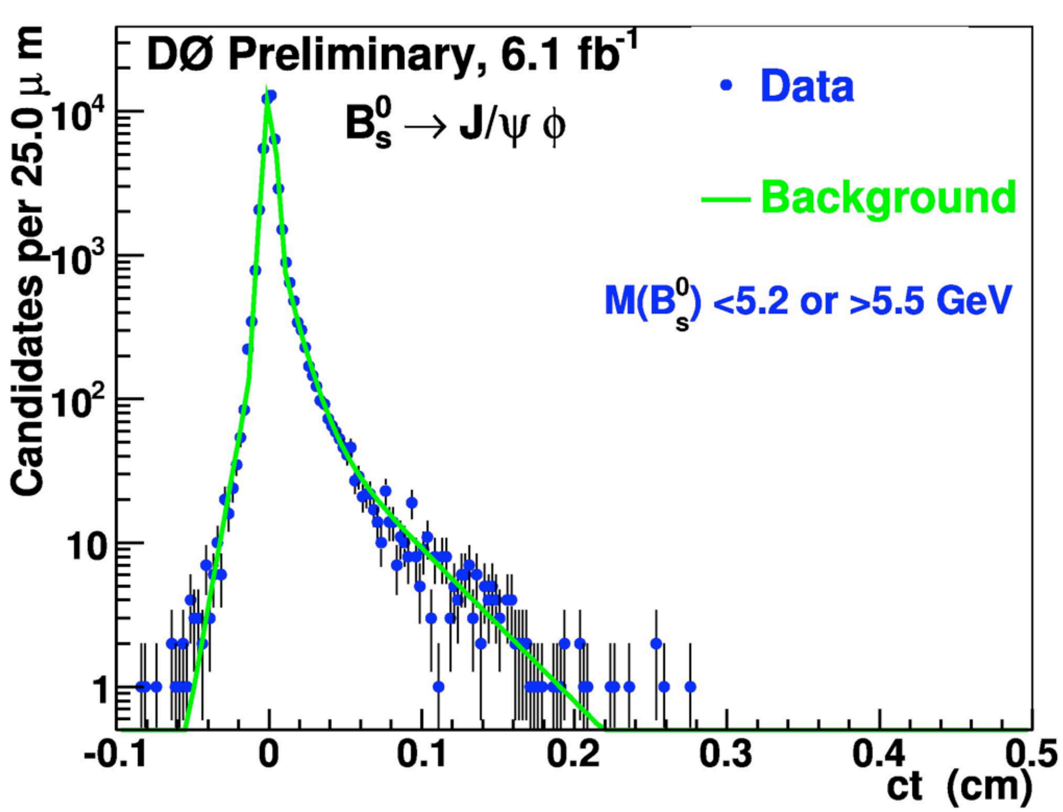


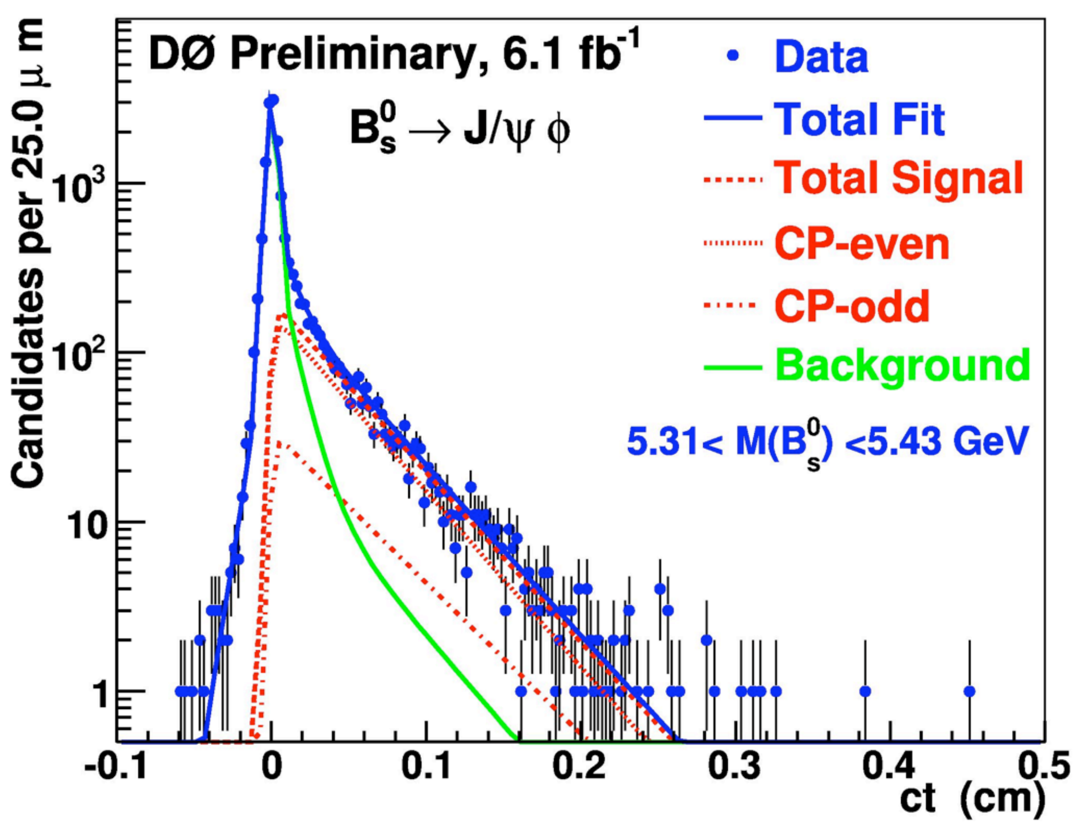
- Decays into two vector mesons that are either CP-odd (L=1) or CP-even (L= 0,2)
- Angular Analysis of decay products and lifetimes
  - $A_\perp$ - transverse perpendicular - CP odd
  - $A_{||}, A_0$ - transverse parallel & longitudinal - CP-even

$B_s \to J/\psi\phi$

- 6.1 fb^{-1} of data
  - Vertex Constraint
  - Kinematic J/ψ mass constraints
  - Multidimensional unbinned likelihood fit
  - 3435 ± 84 signal events

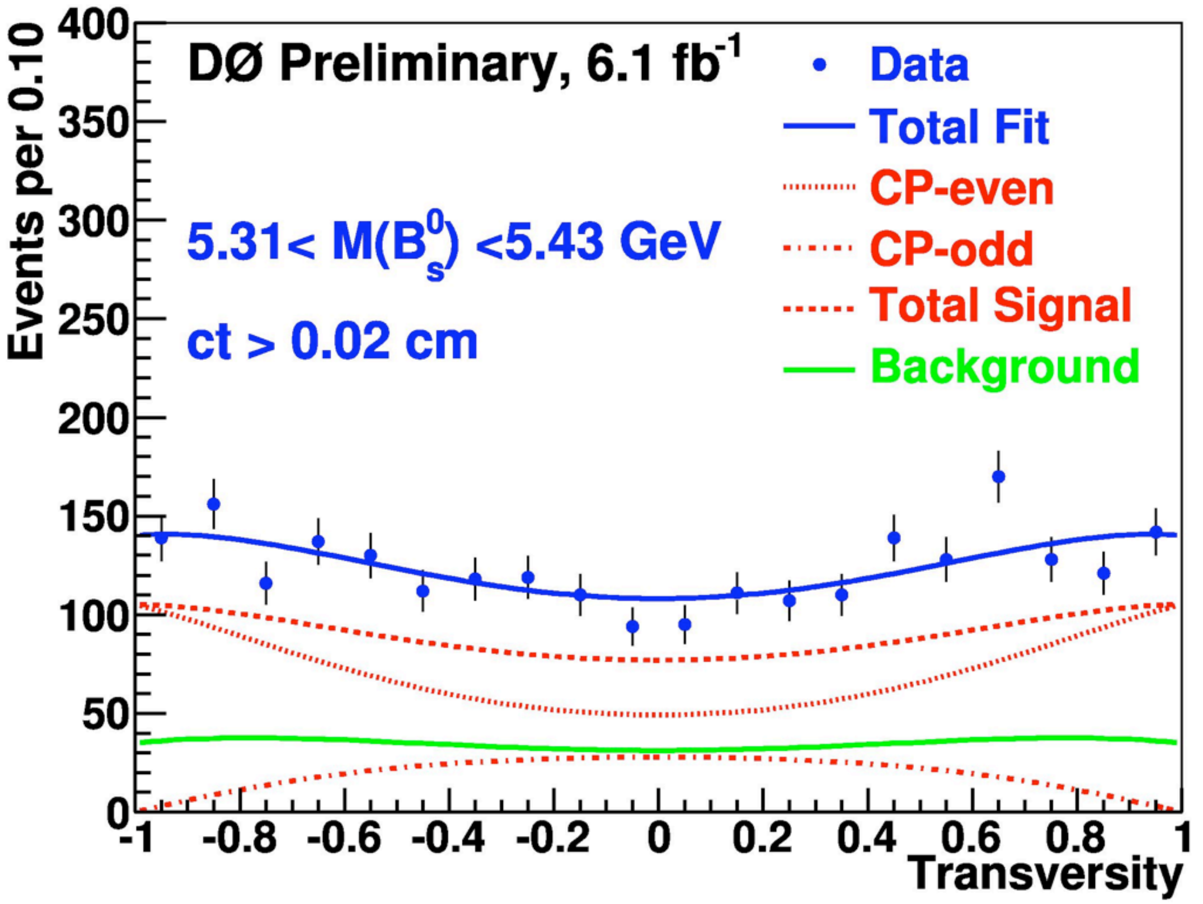


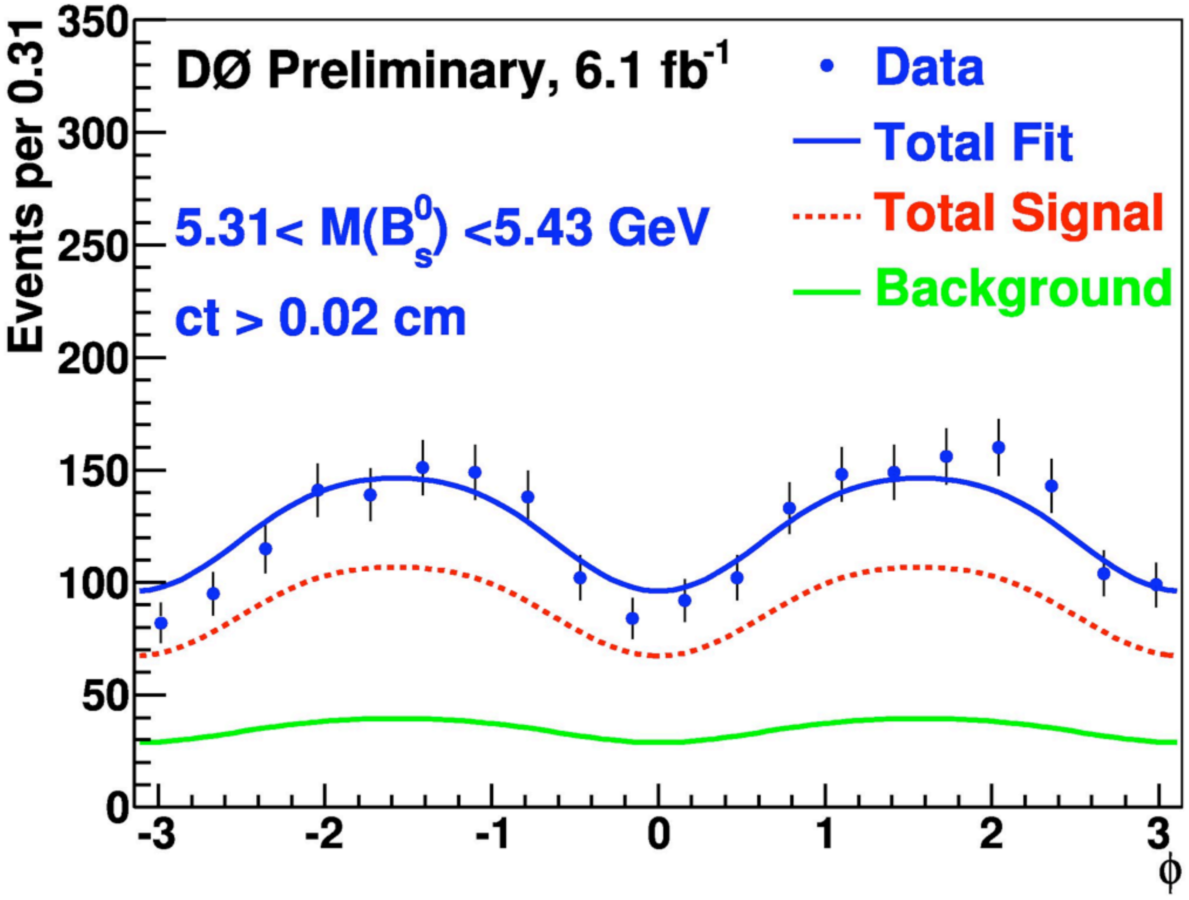




$B_s \to J/\psi\phi$

- Fit data to extract CP-even and odd contributions
  - Use MC simulation to determine efficiency and detector smearing.
  - Assume K^+K^- is in P-wave



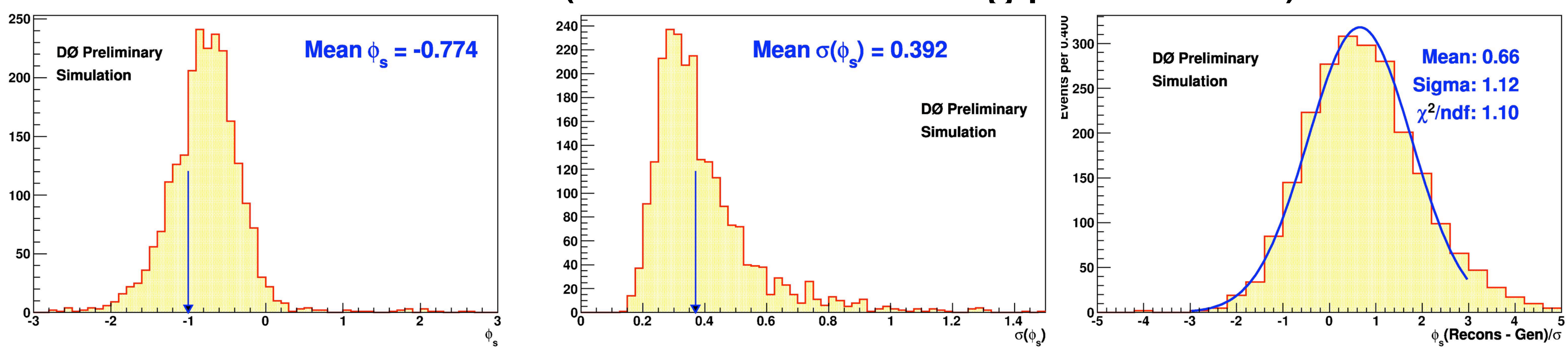


$B_s \to J/\psi\phi$

- Constraints:
  - Gaussian for $\Delta M_s = 17.77 \pm 0.12\ ps^{-1}$[2]
  - Strong phases between polarisation amplitudes constrained by $B_d\ \psi \to J/\psi K^*$

$$\delta_1 = -\delta_{\parallel} + \delta_{\perp} = -0.42 \pm 0.18$$
$$\delta_2 = -\delta_0 + \delta_{\perp} = 3.01 \pm 0.14$$

- Check with full MC simulation of CP violating processes
  - no obvious bias observed
  - Ensemble tests (biases seen if strong phase floats)



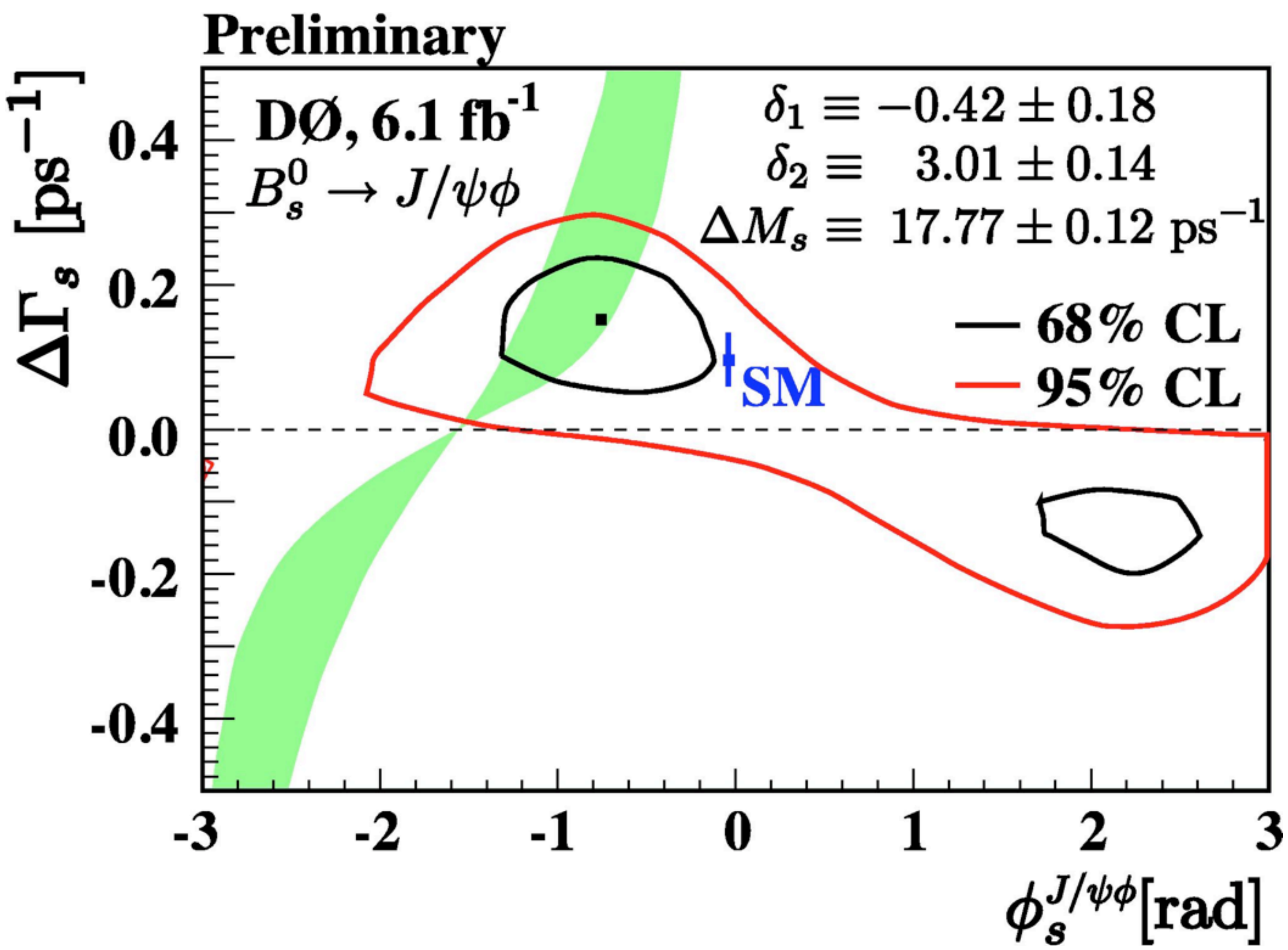
$B_s \to J/\psi\phi$

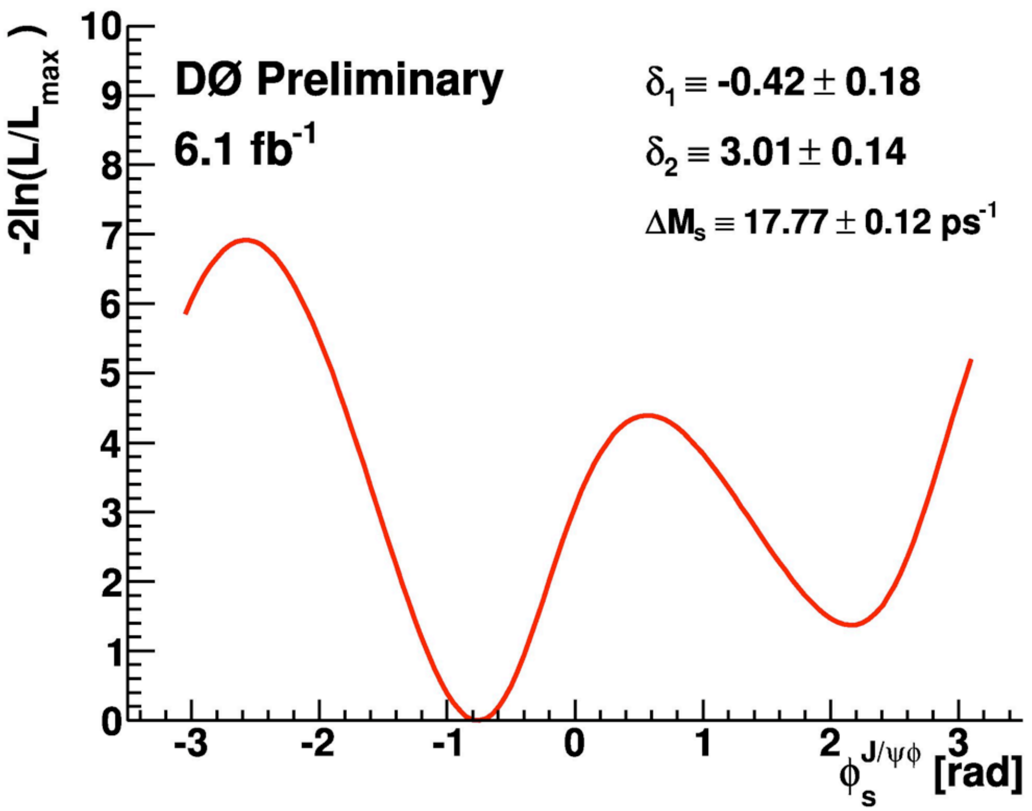
D0Note 6098-CONF

$$\bar{\tau}_s = 1.45 \pm 0.04 \pm 0.01\,\text{ps}$$
$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01\,\text{ps}^{-1}$$
$$\phi_s^{J/\psi\phi} = -0.76^{+0.38}_{-0.36} \pm 0.02$$

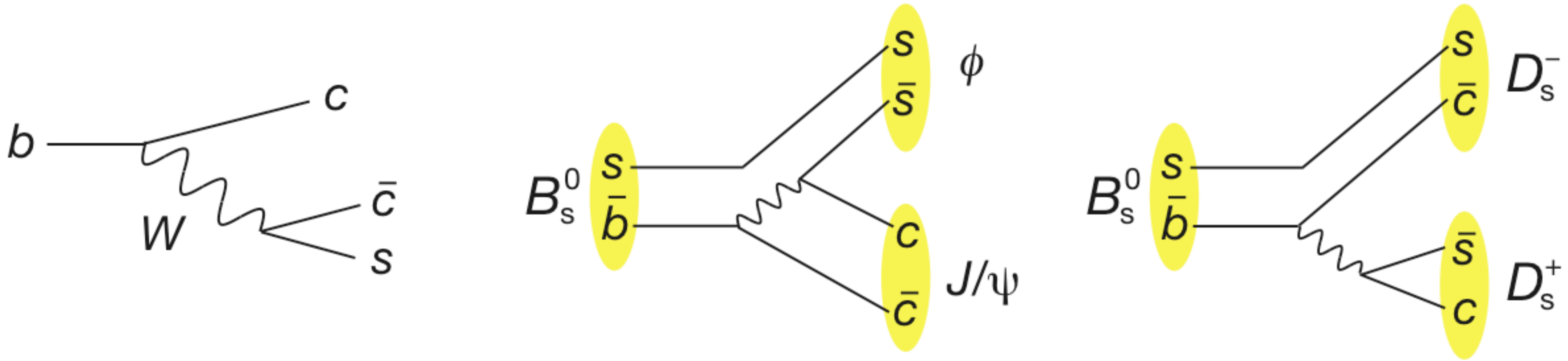
$A_\perp(t=0)\,, |A_0(0)|^2 - |A_\parallel(0)|^2$

consistent with $B_d^0 \to J/\psi K^*$





$B_s \to D^{(*)}_s D^{(*)}_s$



- $B_s \to D_s^{(*)} D_s^{(*)}$ is almost a pure CP-even (theory assumptions)

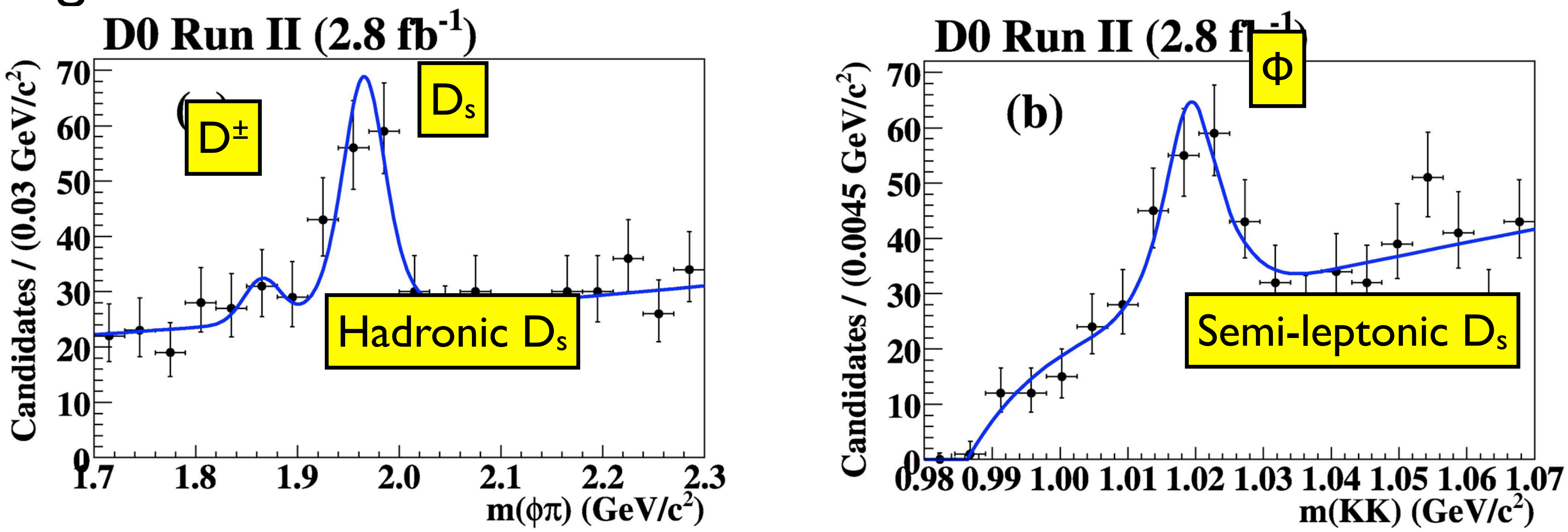
$$\frac{\Delta\Gamma_s^{\mathrm{CP}}}{\Gamma_s} \simeq \frac{2\mathcal{B}\left(B_s \to D_s^{(*)} D_s^{(*)}\right)}{1 - \mathcal{B}\left(B_s \to D_s^{(*)} D_s^{(*)}\right)}$$

- Select events in both the hadronic & semi-leptonic channels:

$$D_s \to \phi\pi \qquad \text{where } \phi \to K^+K^-$$
$$D_s \to \phi\mu\nu \qquad \text{where } \phi \to K^+K^-$$

$B_s \to D^{(*)}_s D^{(*)}_s$

- Fit to 2-dim. distribution m(φπ) of hadronic D_s vs. m(KK) of semi-leptonic Ds. 4 components:
  - Correlated D_sD_s signal,
  - (2×) uncorrelated D_s signal with D_s background,
  - correlated D_sD_s background
  - cc, $B_s \to D_s^{(*)}\varphi\mu\nu$, $B_s \to D_s^{(*)}D_s^{(*)}KX$)
- Signal template extracted from $B_s \to D_s^{(*)}\mu\nu$ by removing peaking backgrounds



26.6 ± 8.4 signal events (3.2σ)

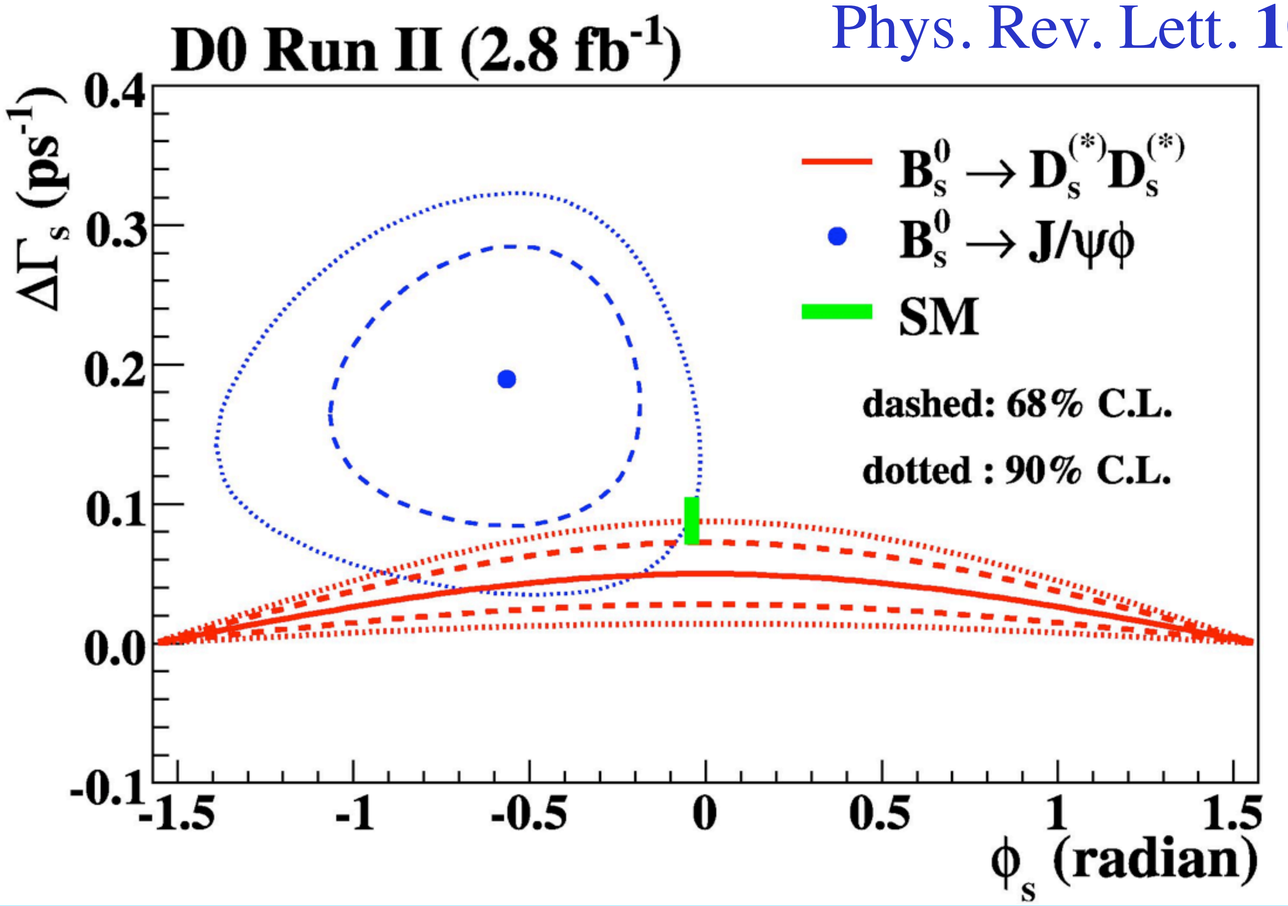
Extraction of $\Delta\Gamma_s^{CP}/\Gamma_s$

$$\mathcal{B}\left(B_s \to D_s^{(*)} D_s^{(*)}\right) = 0.035 \pm 0.010\,(\text{stat}) \pm 0.008\,(\text{exp syst}) \pm 0.007\,(\text{ext syst})$$

- Using heavy quark hypothesis (Phys. Lett. B316 (1993) 567) and assuming no CP-odd component obtain $\Delta\Gamma_s^{CP}$:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \simeq \frac{2\mathcal{B}\left(B_s \to D_s^{(*)} D_s^{(*)}\right)}{1-\mathcal{B}\left(B_s \to D_s^{(*)} D_s^{(*)}\right)} = 0.072 \pm 0.021\,(\text{stat}) \pm 0.022\,(\text{syst})$$

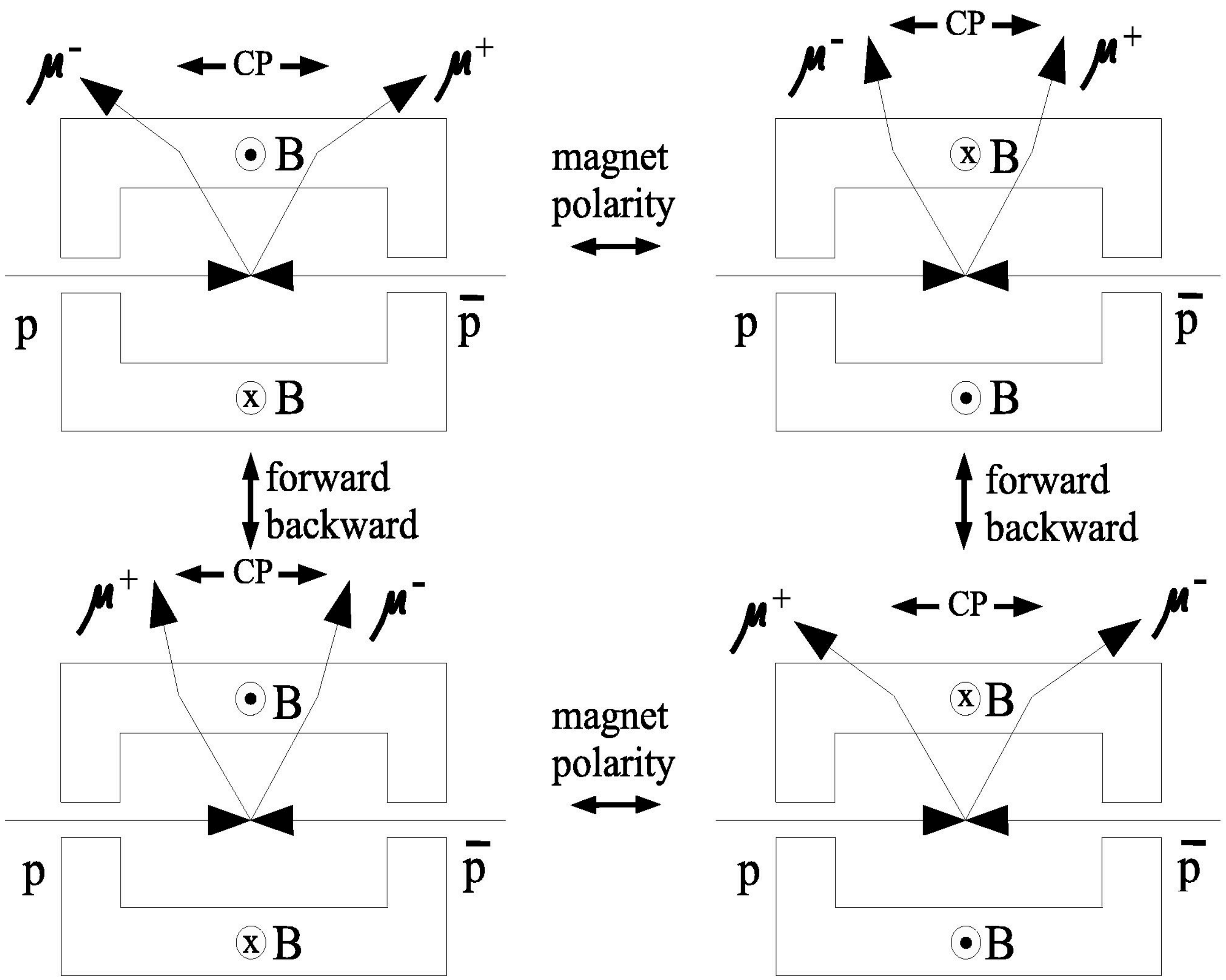
Phys. Rev. Lett. **102**, 091801 (2009),



Reversing the Magnet

$$n_q^{\beta\gamma} = \frac{1}{4} N e^{\beta} (1+qA)(1+q\gamma A_{fb}) (1+\gamma A_{\text{det}})(1+q\beta\gamma A_{\beta\gamma q})(1+\beta\gamma A_{\beta\gamma})$$

- Use detector to solve acceptance issues
  - A - a_{sl} - charge asymmetry
  - A_β - Toroid Asymmetry
  - A_γ - North/South detector (A_{det})
  - $A_{q\gamma}$ - Beam related (A_{fb})
  - $A_{q\beta}$ - toroid efficiency
  - $A_{\beta\gamma}$ - forward backward toroid asymmetries
  - $A_{q\beta\gamma}$ - range out asymmetries (A_{ro})
- Have eight samples based on charge of muon, solve.

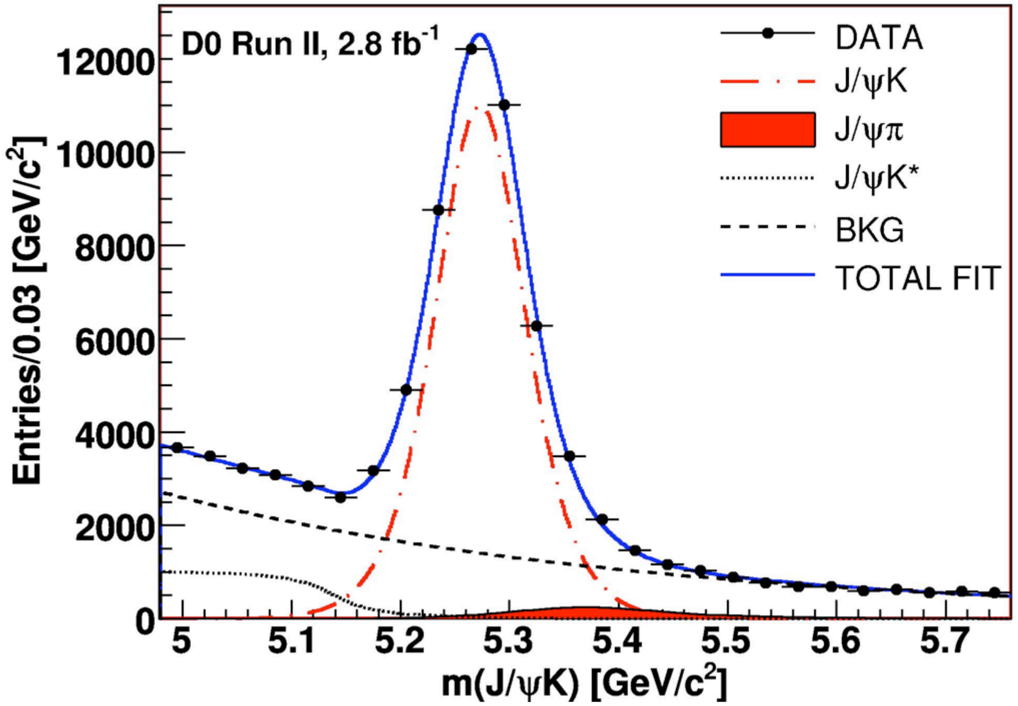


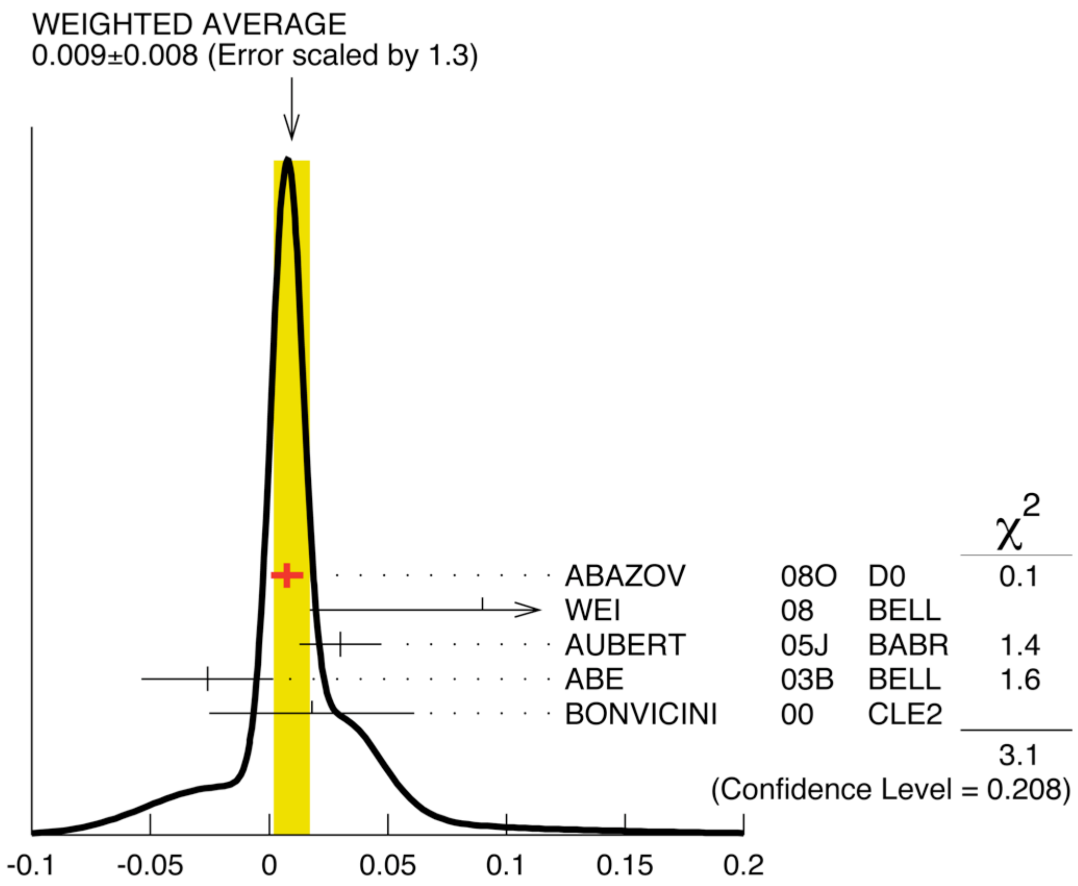
$B^+ \to J/\Psi K^+$ Decays

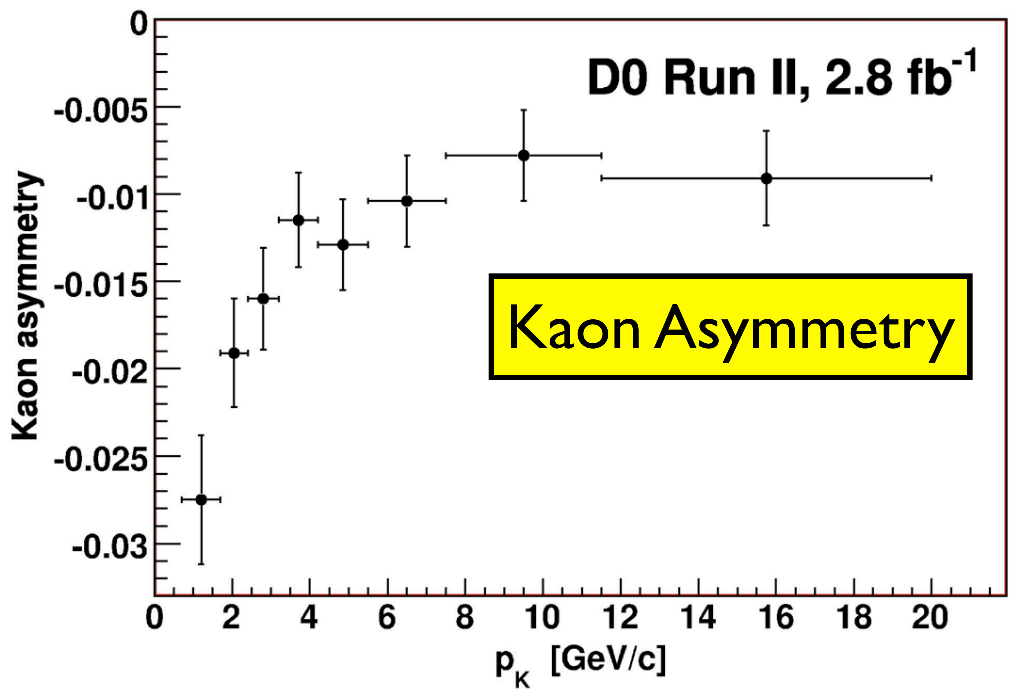
$$A_{CP}(B^+ \to J/\Psi K^+) = -0.0075 \pm 0.0061\,(\mathrm{stat}) \pm 0.027\,(\mathrm{sys})$$
$$A_{CP}(B^+ \to J/\Psi \pi^+) = -0.09 \pm 0.08\,(\mathrm{stat}) \pm 0.03\,(\mathrm{sys})$$

- Solve for detector asymmetries
- Subtract Kaon asymmetry

Phys. Rev. Lett. **100**, 211802 (2008),



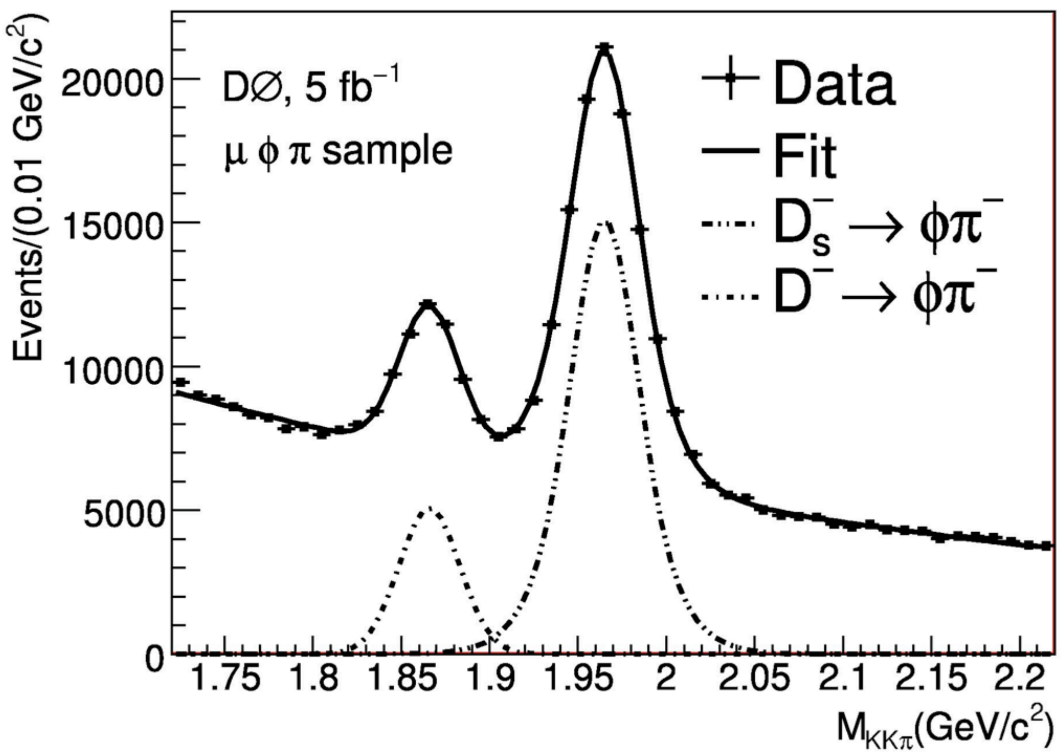


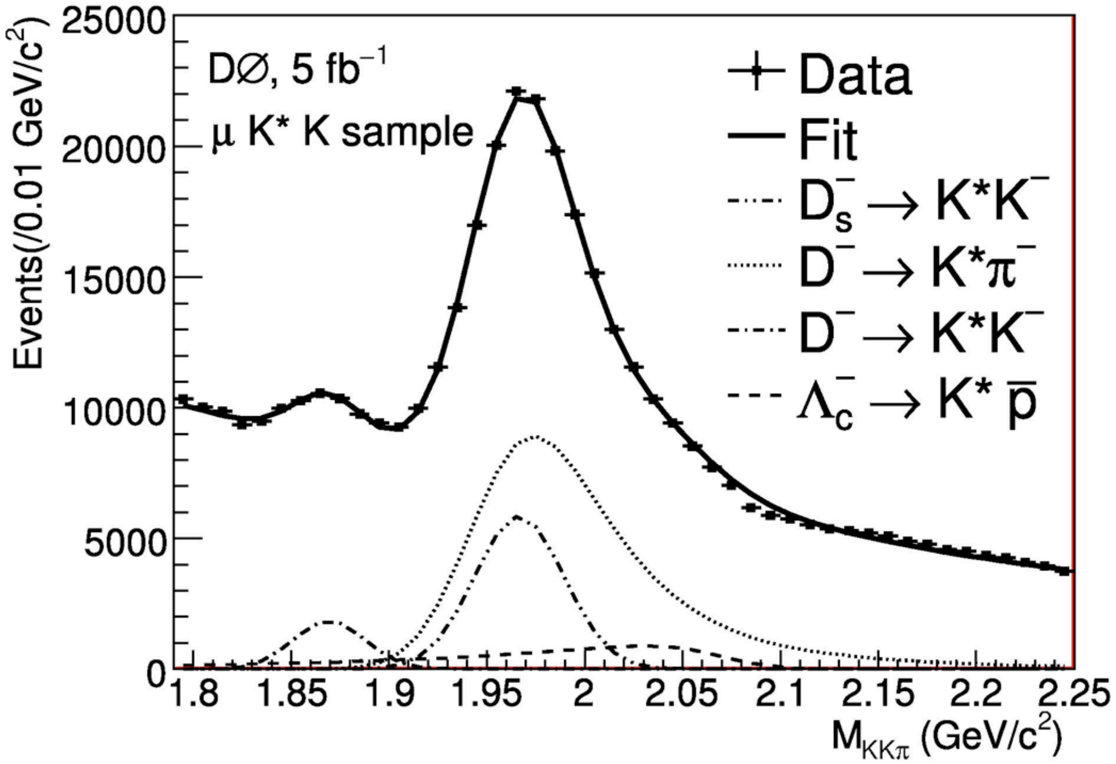


a^s_{sl}: $Bs \rightarrow Ds^-\mu^+\nu X$ decays

$$a^s_{fs} = \frac{\Gamma_{\overline{B_s}(t)} - \Gamma_{B_s(t)}}{\Gamma_{\overline{B_s}(t)} + \Gamma_{B_s(t)}} = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

- Time dependent analysis
  - Removes dependence on B_d result
  - Two reconstructed Decays



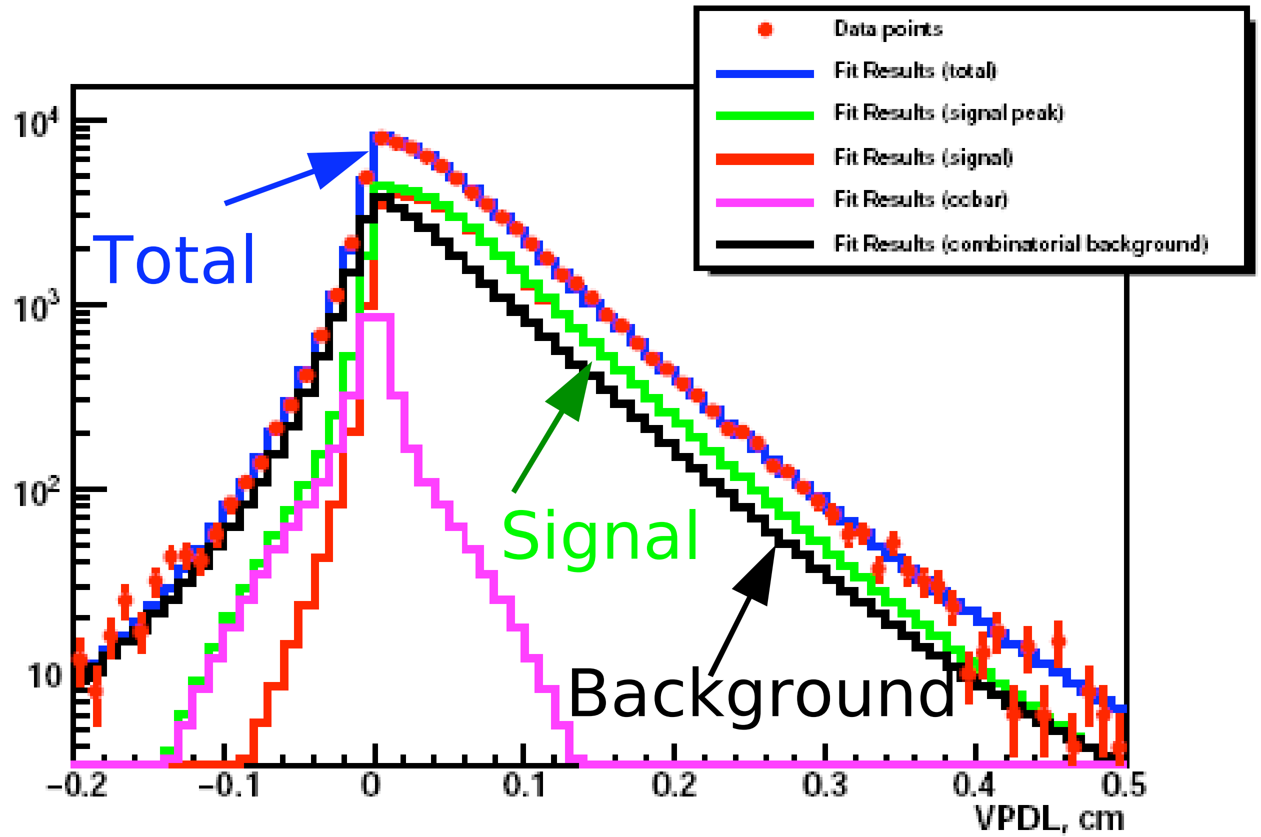


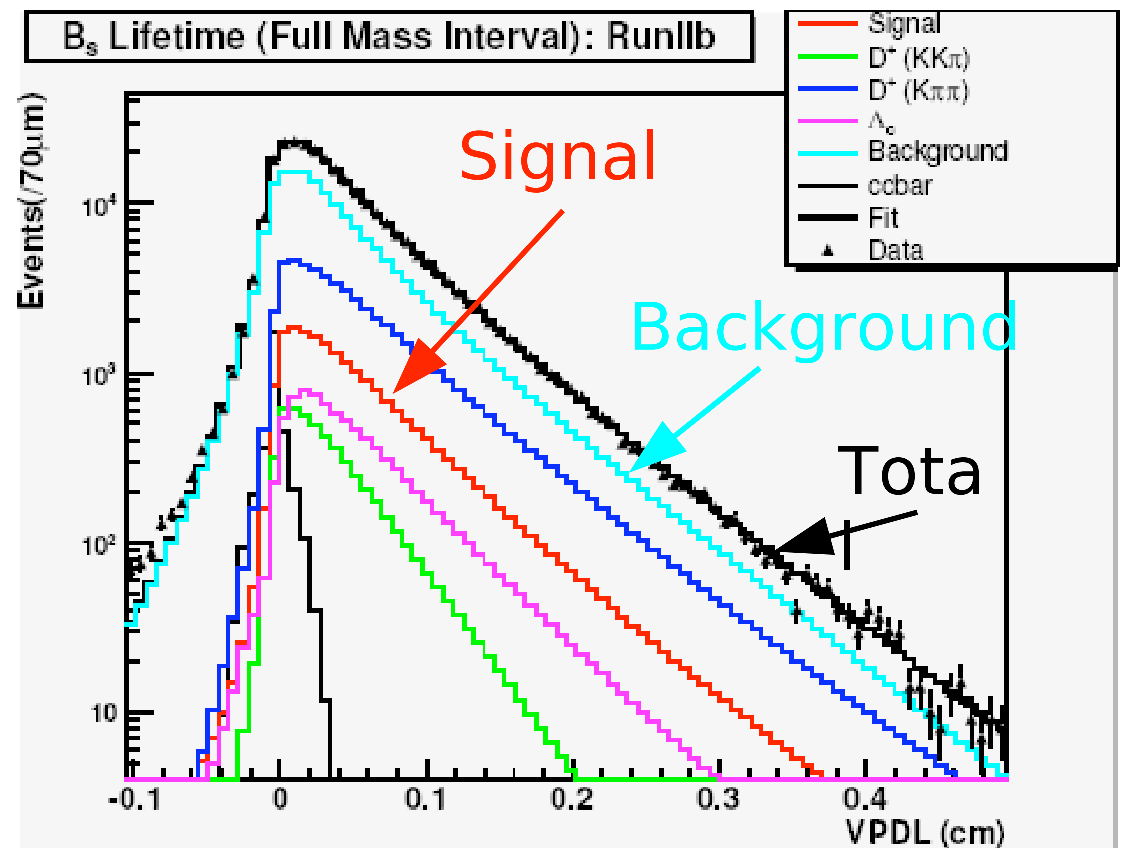
$$D_s^- \rightarrow \phi\pi^-; \quad \phi \rightarrow K^+K^-$$
$$D_s^- \rightarrow K^{0*}K^-; \quad K^{0*} \rightarrow K^+\pi^-$$

$B_s \to D_s^- \mu^+ \nu X$ decays

$$\Gamma_{B_s(t)\to\bar{f}} = N_f \left|\bar{A}_{\bar{f}}\right|^2 \left(1 - a_{fs}^s\right) \exp\left[-\Gamma_s t \frac{\cosh\left(\Delta\Gamma_s t/2\right) - \cos\left(\Delta m_s t\right)}{2}\right]$$

- Unbinned likelihood fit
  - depends on tagging, decay length, decay length resolution, and background fractions
- Extract Signal Amounts





$B_s \to D_s^- \mu^+ \nu X$ decays

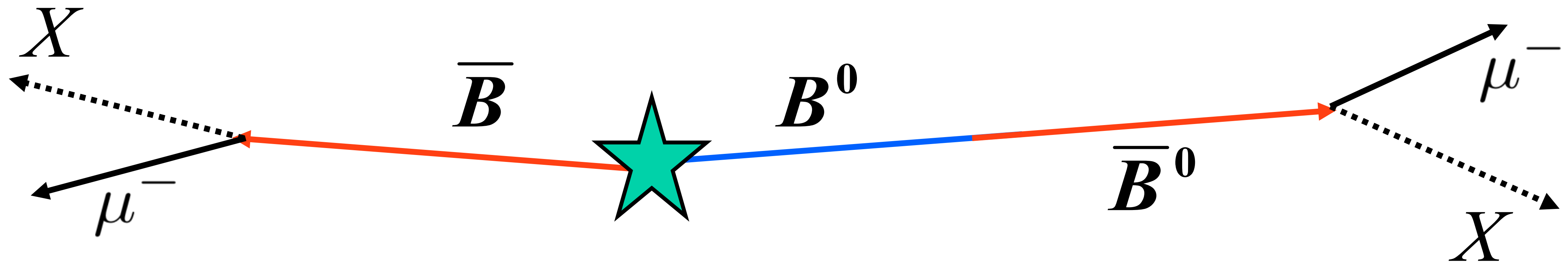
Asymmetries with statistical uncertainties			
	$\mu^+\phi\pi^-$	$\mu^+K^{0*}K^-$	Combined
$a^s_{fs} \times 10^3$	-7.0 ± 9.9	20.3 ± 24.9	-1.7 ± 9.1
$a^d_{fs} \times 10^3$	-21.4 ± 36.3	50.1 ± 19.5	40.5 ± 16.5
$a^{\text{bkg.}}_{fs} \times 10^3$	-2.2 ± 10.6	-0.1 ± 13.5	-3.1 ± 8.3
$A_{fb} \times 10^3$	-1.8 ± 1.5	-2.0 ± 1.5	-1.9 ± 1.1
$A_{\text{det}} \times 10^3$	3.2 ± 1.5	3.1 ± 1.5	3.1 ± 1.1
$A_{\text{ro}} \times 10^3$	-36.7 ± 1.5	-30.2 ± 1.5	-33.3 ± 1.1
$A_{\beta\gamma} \times 10^3$	1.1 ± 1.5	0.2 ± 1.5	0.6 ± 1.1
$A_{q\beta} \times 10^3$	4.3 ± 1.5	2.0 ± 1.5	3.1 ± 1.1

$$A^s_{fs} = \left[-1.7 \pm 9.1\,(\text{stat})\,\frac{+1.2}{-2.3}\,(\text{sys})\right] \times 10^{-3}$$

Factor 2 improvement over previous result.

Phys. Rev. D **82**, 012003 (2010)

Anomalous Dimuon



- Asymmetry in “same-sign” muons from decays of mixed neutral B mesons:

$$a^b_{sl} \equiv \frac{\Gamma\left(\bar{B} \to \mu^+ X\right) - \Gamma\left(B \to \mu^- X\right)}{\Gamma\left(\bar{B} \to \mu^+ X\right) + \Gamma\left(B \to \mu^- X\right)}$$

$$A^b_{sl} \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

Grossman, Nir, Raz, Phys.Rev.Lett.97:151801,2006.

- Extract in multiple ways
  - Time dependent tagged decays (e.g. DØ B_S semi-leptonic decays lifetime analysis arxiv.org:0904.3907)
  - asymmetry in single muon, or same sign dimuon events

At the Tevatron

- Inclusive, untagged analysis has contributions form both B_d and B_s. Take the measured production fractions (CDF) and mixing properties:

$$A^b_{sl} = (0.506 \pm 0.043)\, a^d_{sl} + (0.494 \pm 0.043)\, a^s_{sl}$$

- Large contribution from B_s
- Can be written in terms of CP-violating mixing phase:

$$a^q_{sl} = \frac{\left|\Gamma^{12}_q\right|}{\left|M^{12}_q\right|} \sin\theta_q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\theta_q$$

- and in the SM it is given by:

$$A^b_{sl}\,(\mathrm{SM}) = \left(-2.3^{+0.5}_{-0.6}\right) \times 10^{-4}$$

Lenz, Nierste, JHEP 0706:072,2007

Measurement

- Measure both dimuon asymmetry A and inclusive asymmetry a:

$$A^{\mu\mu} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (0.564 \pm 0.053)\,\%$$

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}} = (0.955 \pm 0.003)\,\%$$

- Both A & a contain contributions from A^{b}_{sl} and backgrounds

$$A = K \times A^{b}_{sl} + A_{\text{bkg}},\ a = k \times A^{b}_{sl} + a_{\text{bkg}}$$

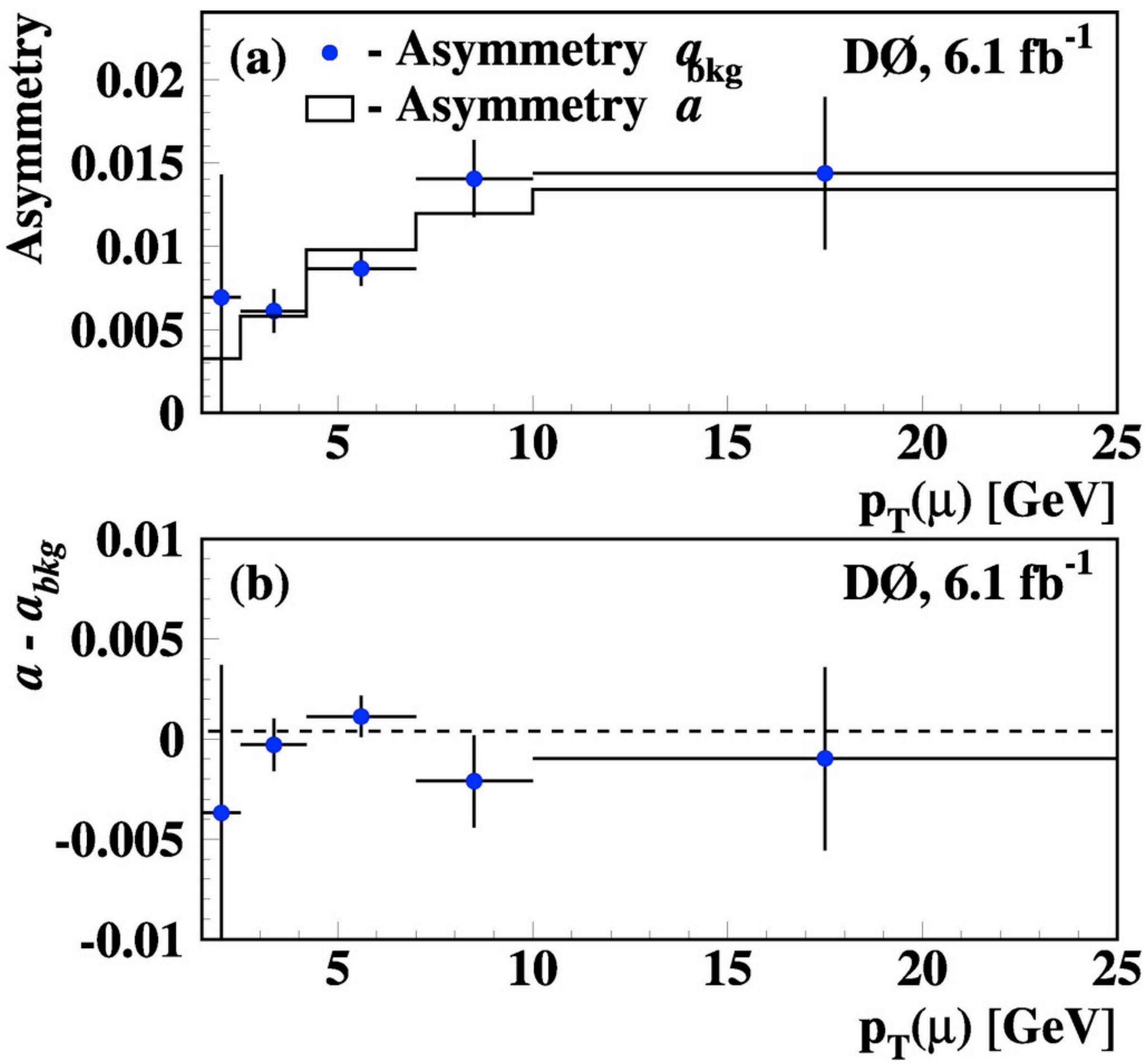
  - contribution from A^{b}_{sl} is suppressed by background k=0.041± 0.003

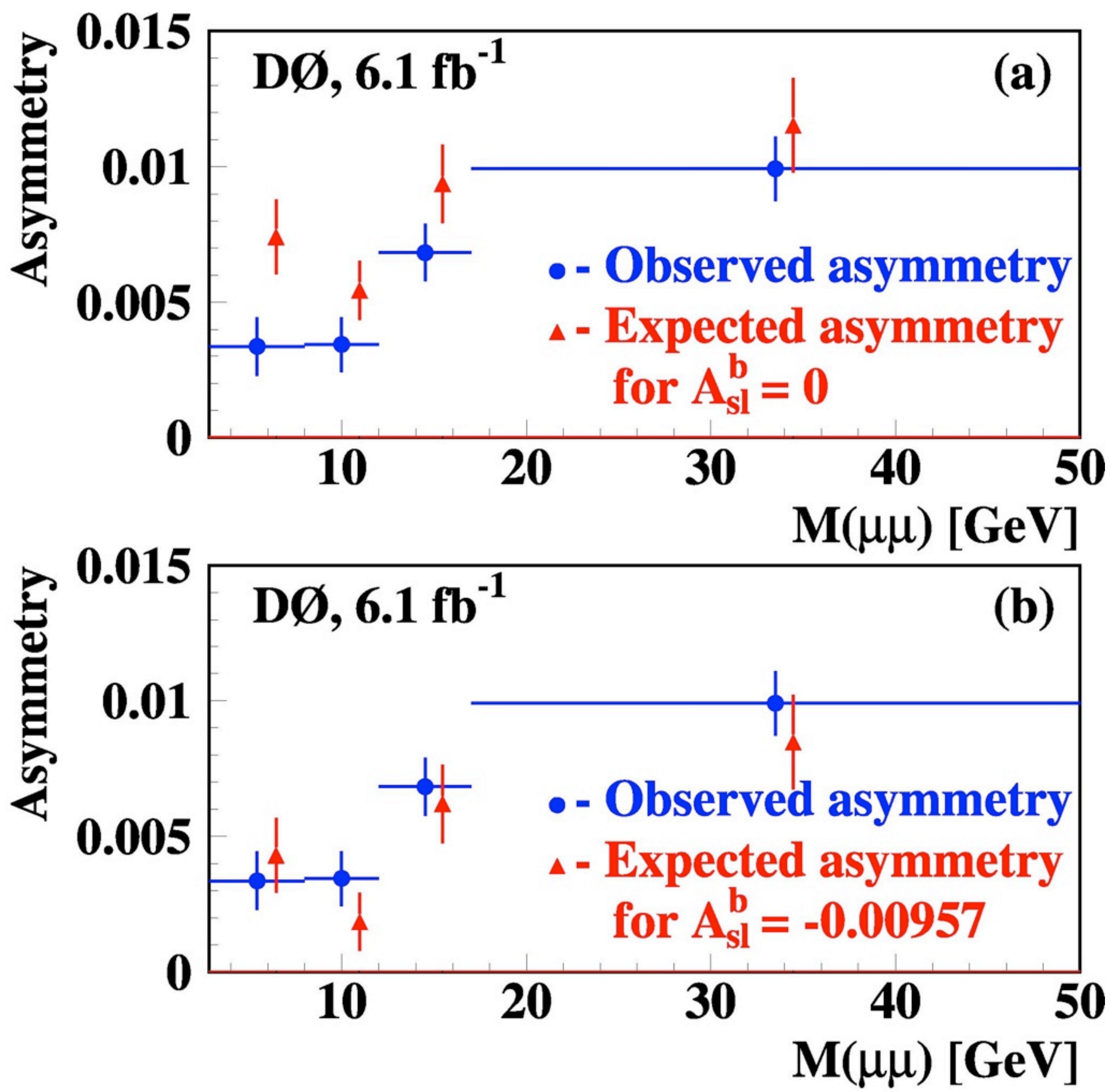
- Determine background from data with minimal use of simulation

- Exploit correlations between backgrounds to minimise uncertainty.

Cross Check - rebin in dimuon Mass

- Compare a and a_{bkg} to verify description of background
- χ^2 = 2.4/5 d.o.f.



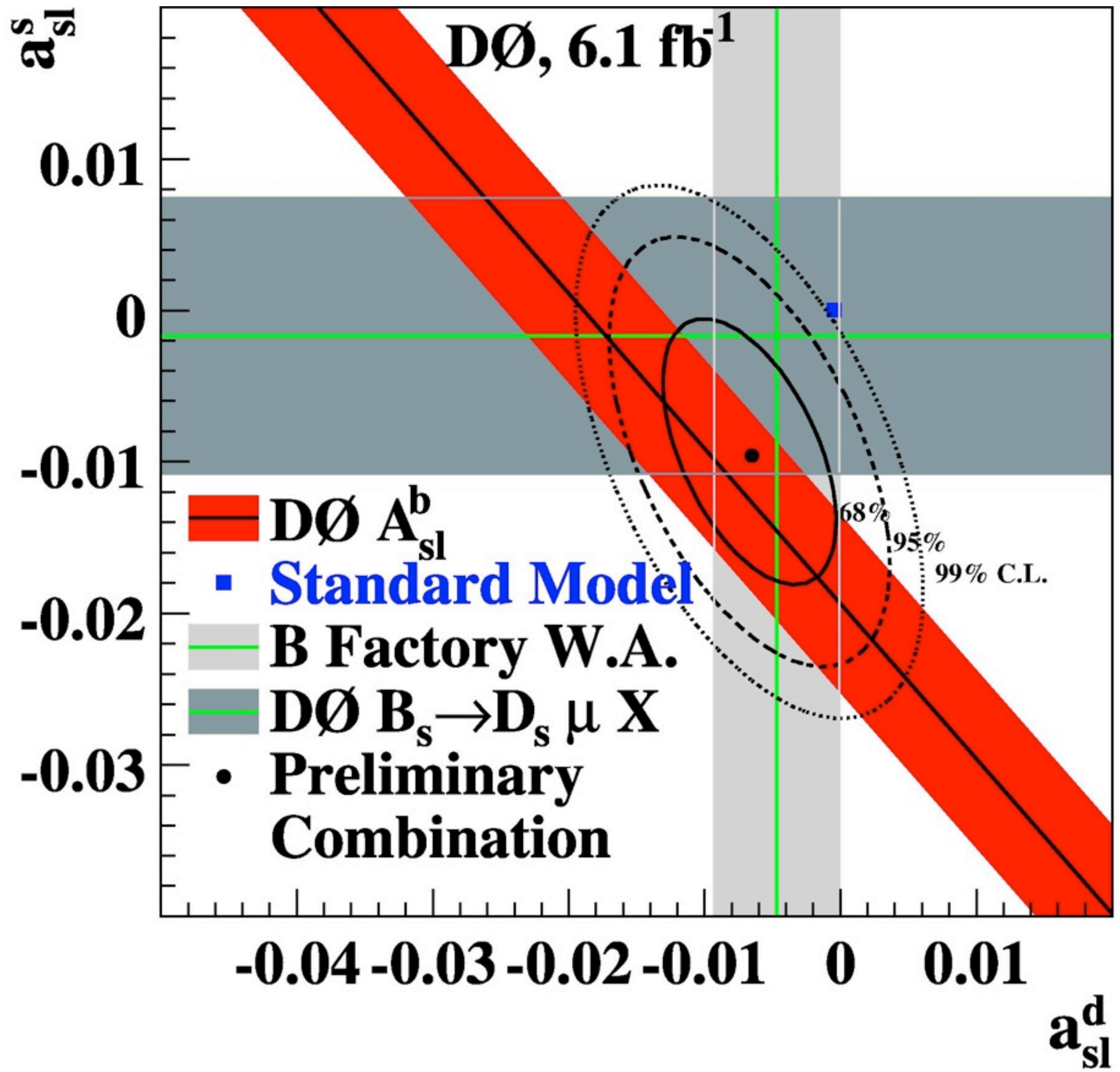


- Compare the expected and observed dimuon charge asymmetry for different dimuon mass bins

Anomalous Dimuon

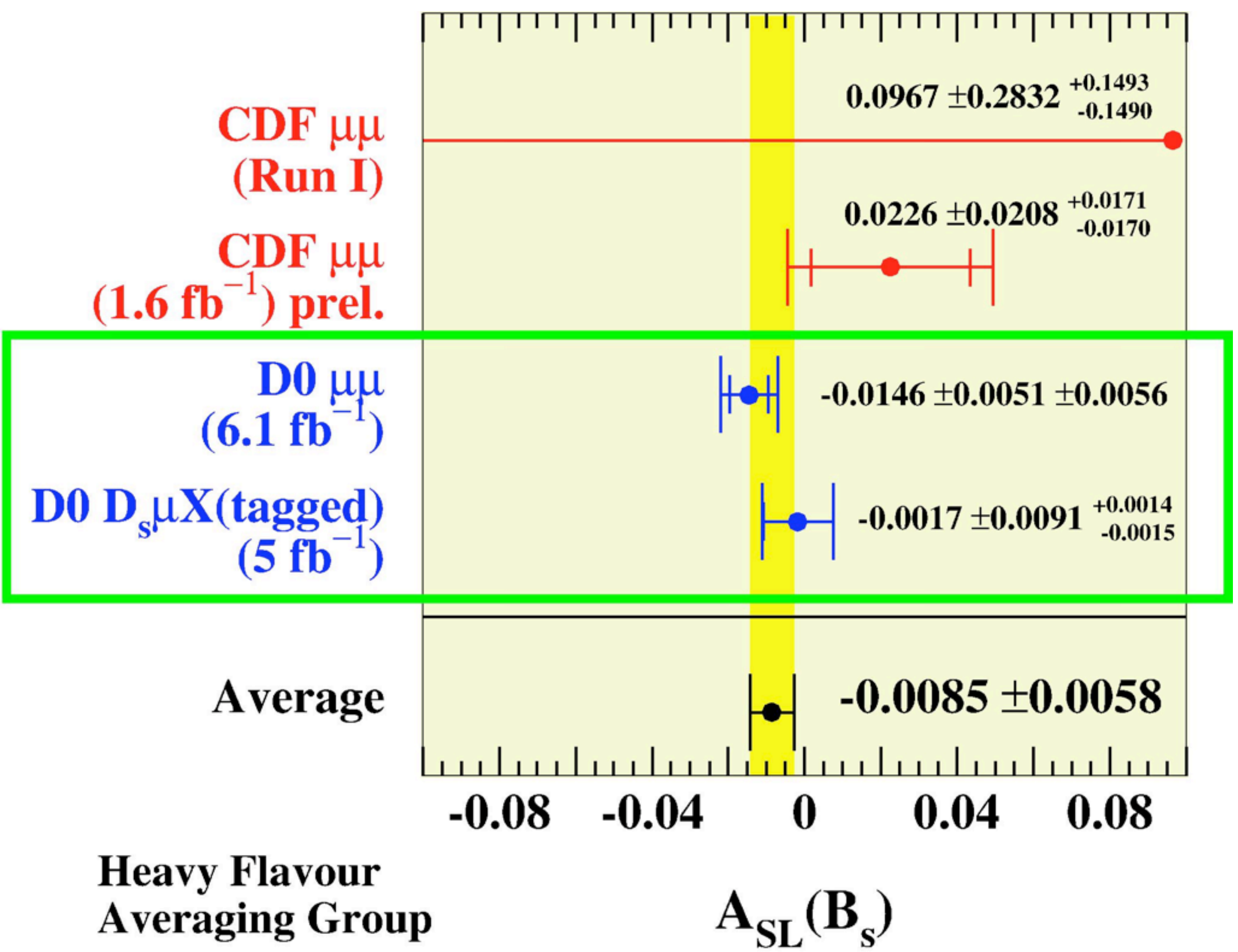
$$A^b_{sl} = (-0.957 \pm 0.251\,(\mathrm{stat}) \pm 0.146\,(\mathrm{syst}))\,\%$$

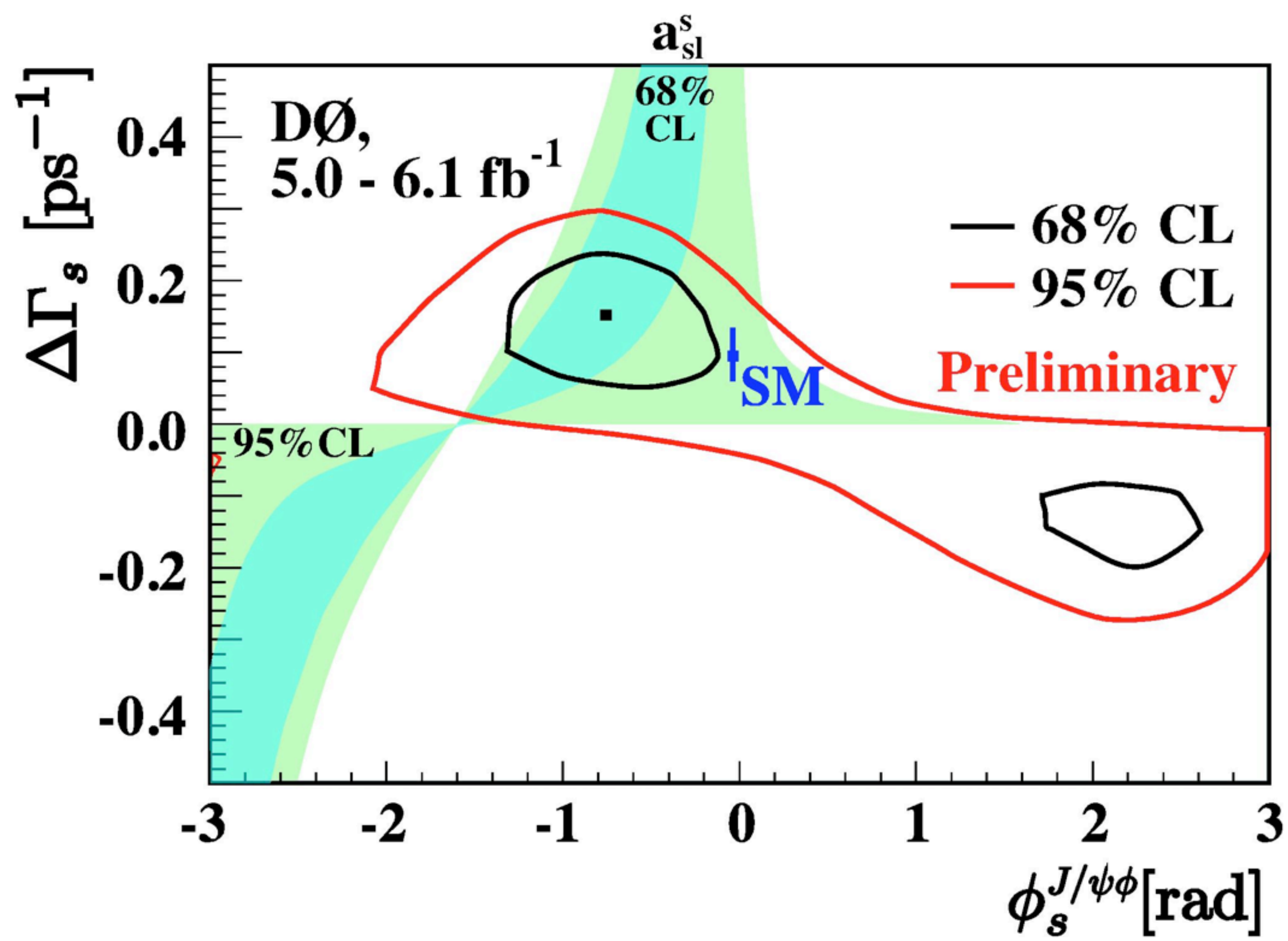
- Use to extract a band on the a^d_{sl} vs. a^s_{sl} plane
- Compared with B-factories and other D0 results



Phys. Rev. D **82**, 032001, (2010),
Phys. Rev. Lett. **105**, 081801 (2010)

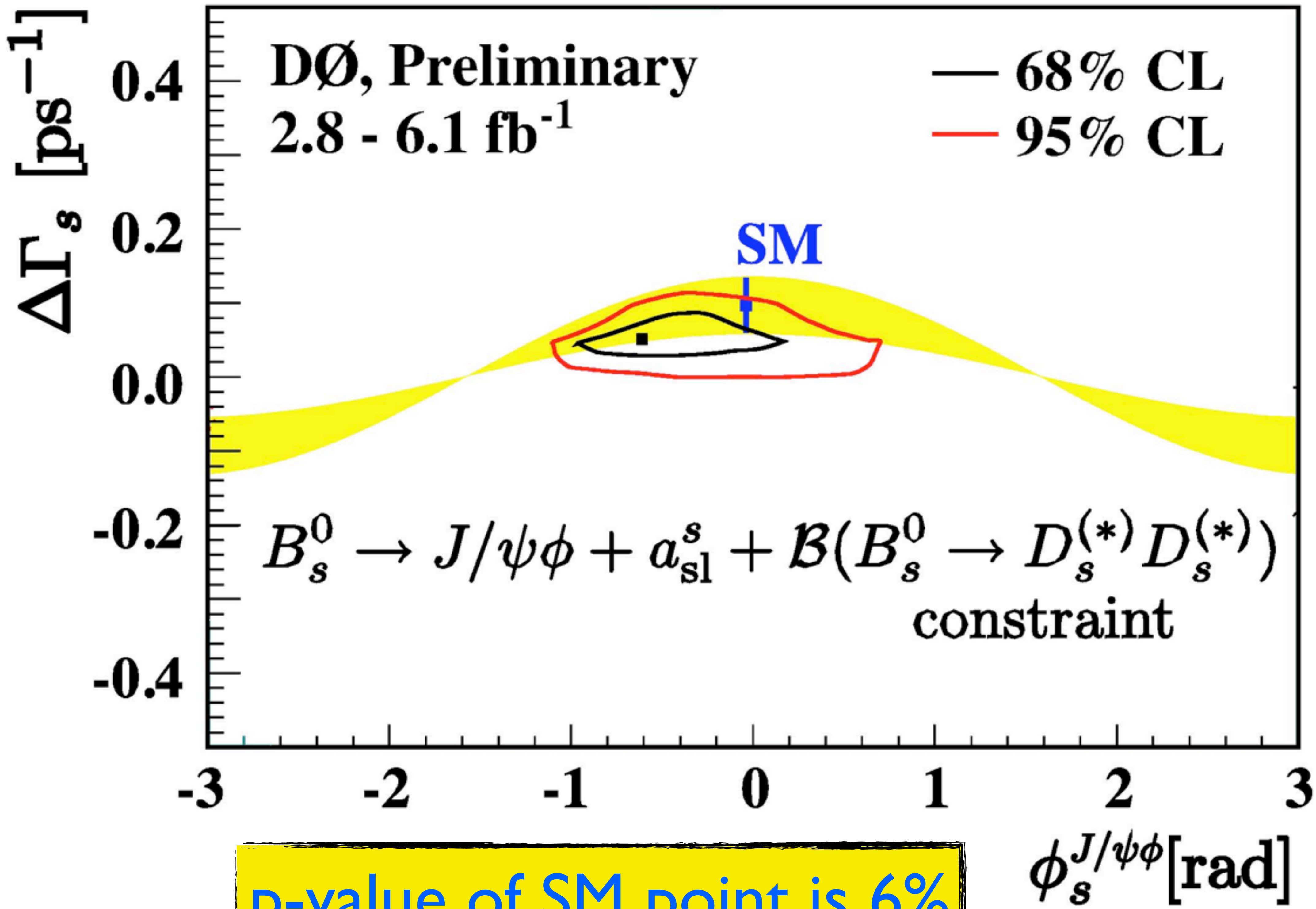
Combination of DØ Results





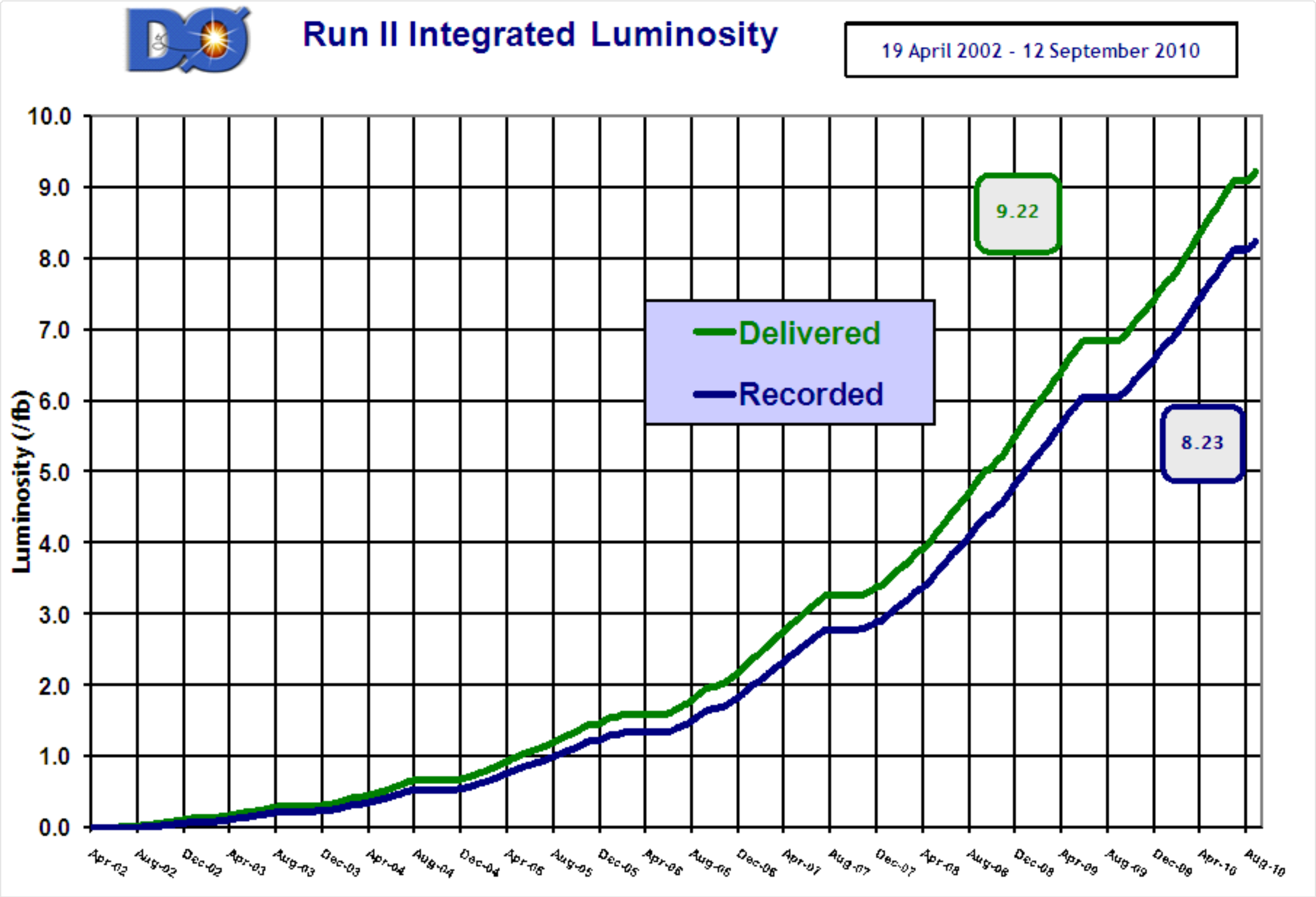
DØ Note 6093-CONF

Combination of DØ Results



p-value of SM point is 6%

Prospects - Current Data Taking



Last Words

- D0 has a broad and interesting b-physics programme
- Tevatron aims to run until 2014 and collect up to 16 fb^{-1}
- Aim to concentrate on strengths and uniqueness: CP violation
  - Anomalous dimuons.
  - $B_s \rightarrow J/\psi\phi$
  - Aim to improve sensitivity in key measurables.