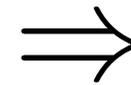
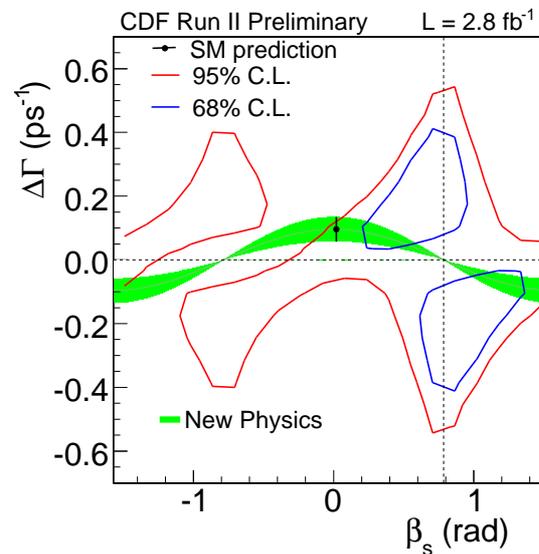
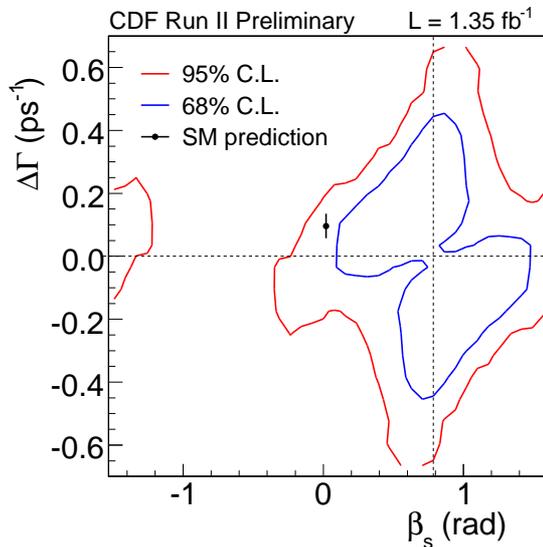


Measurement of CP Violation in $B_s \rightarrow J/\psi\phi$ at CDF

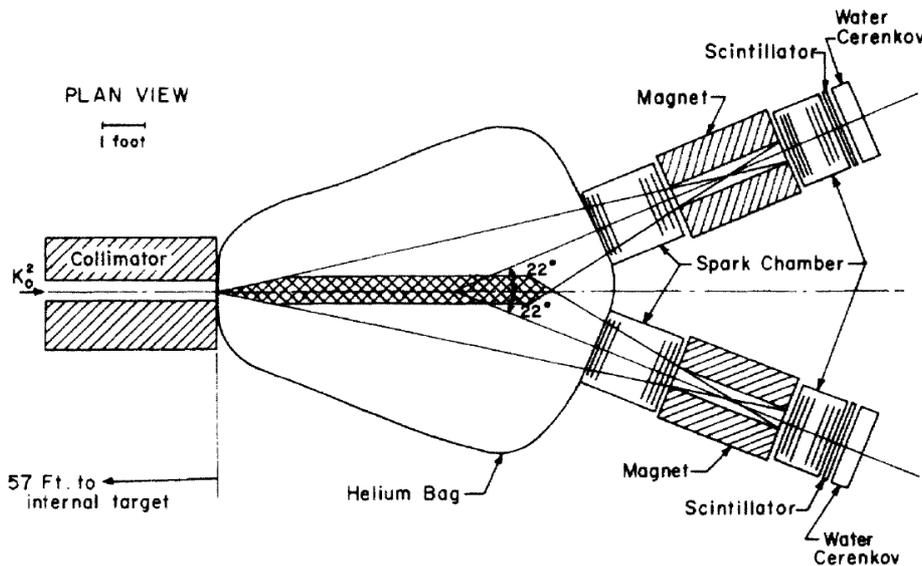
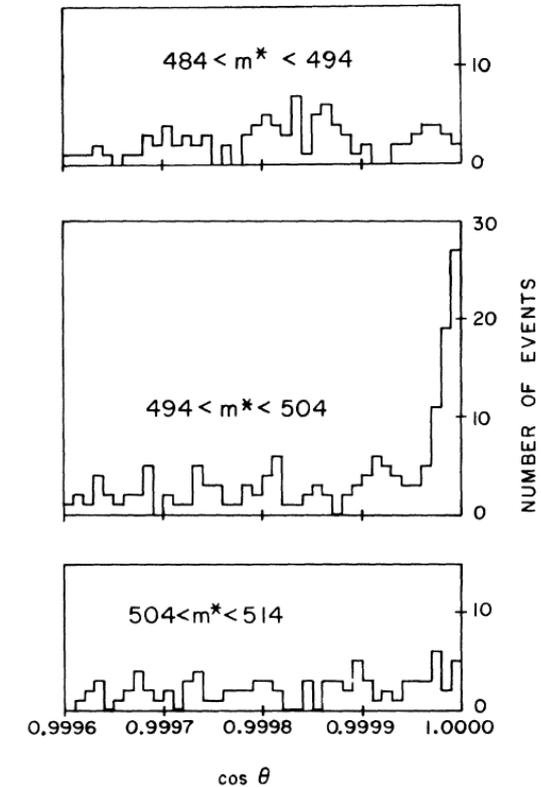
Michal Kreps for the CDF collaboration



?

Discovery of CP violation

- Neutral kaon puzzle in late 1950s
- Two particles (K_1 , K_2) with same mass, but different lifetime and different decay mode
- K_2 is CP odd and if CP is conserved can decay only to 3π
- Observation of $K_2 \rightarrow \pi^+\pi^-$ in 1964 by Cronin and Fitch \Leftrightarrow CP is not conserved



Explaining CP violation

- Observation by Cronin and Fitch requires $\approx 10^{-3}$ admixture of wrong CP state in wave function
- In 1973 Kobayashi and Maskawa concludes that
 - No reasonable way to include CP violation in model with 4 quarks
 - Introduction of CP violation needs new particles
 - One of the suggested ways uses 6 quark model
- CP violation \Leftrightarrow complex phase in quark mixing (CKM) matrix

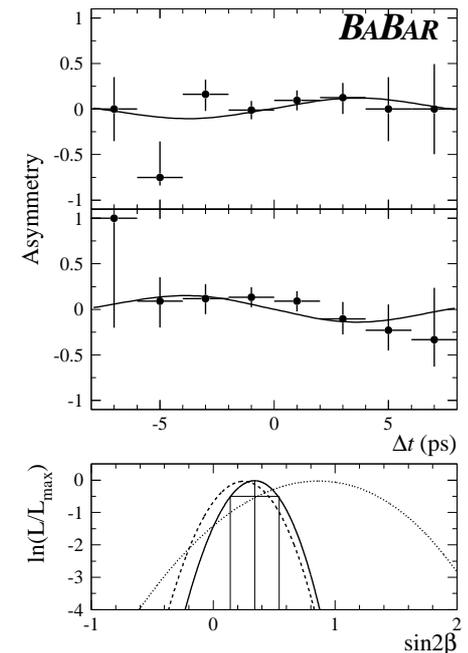
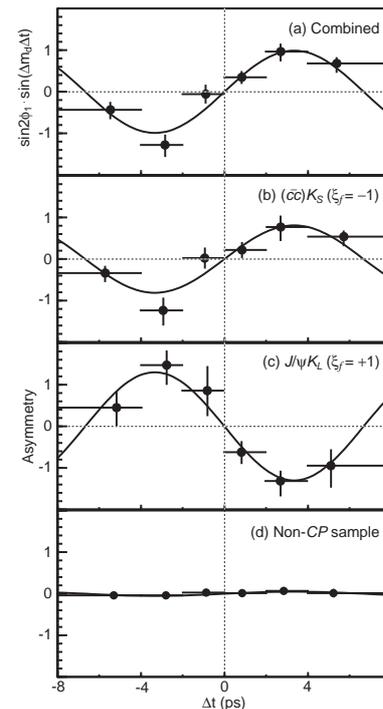
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Nobel prize in 2008



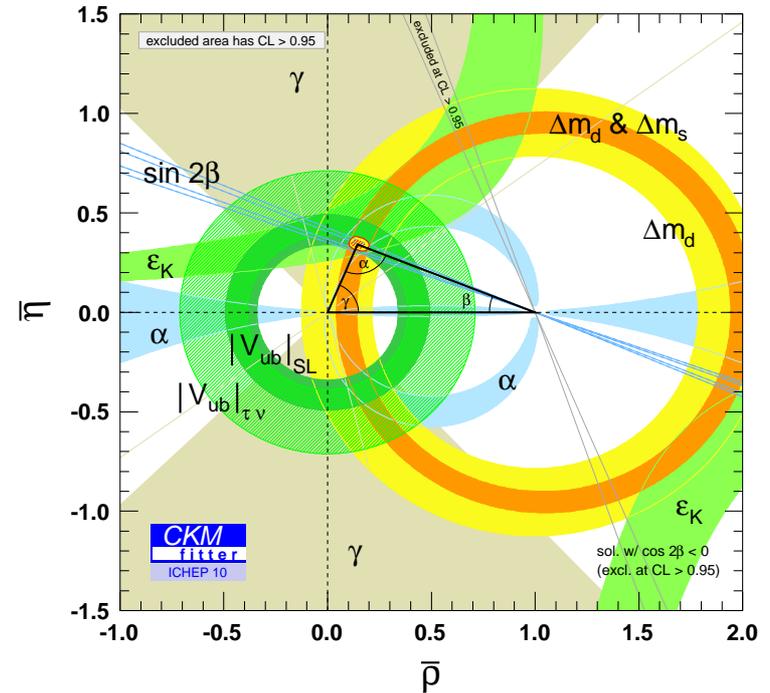
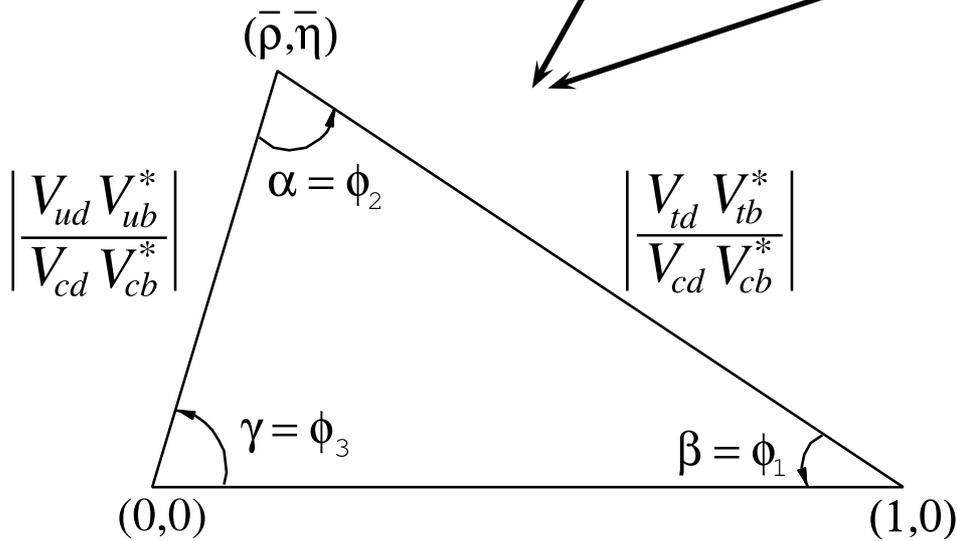
Implications

- When Kobayashi and Maskawa proposed their explanations, only 3 quarks were known
- The six quark model had several implications:
 - Existence of another 3 quarks to be seen by experiment
 - In 1980/1981 several people predicted large CP violation in B system
- Start of dedicated B physics experiments
- In 2001 Belle and Babar experiments observe large CP violation in B^0 decay
- Since then many measurements performed to check idea



Global status

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Are we done?

- Does not look to be case
- Many unanswered questions
 - SM has many free parameters
 - What is the meaning of generation, why we need more than one?
 - What is the origin of dark matter and dark energy?
 - How current matter-antimatter asymmetry is generated?
 - No baryon number violation in SM
 - CP violation in SM is many order of magnitude too small
 - In SM cannot generate needed phase transition
- SM is probably just low energy approximation of final big theory of everything

Role of flavor physics

- Several extensions of SM exists, each postulating new particles
- Some examples
 - Fourth generation introduces two additional quark, V_{CKM} is changed to 4×4 matrix
 - Supersymmetry has partner for each SM particle
 - In supersymmetry squarks/sleptons mix through 3×3 matrix

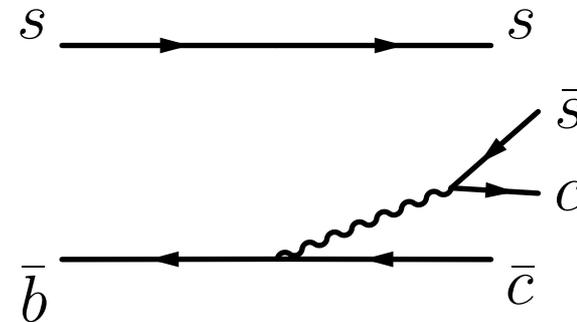
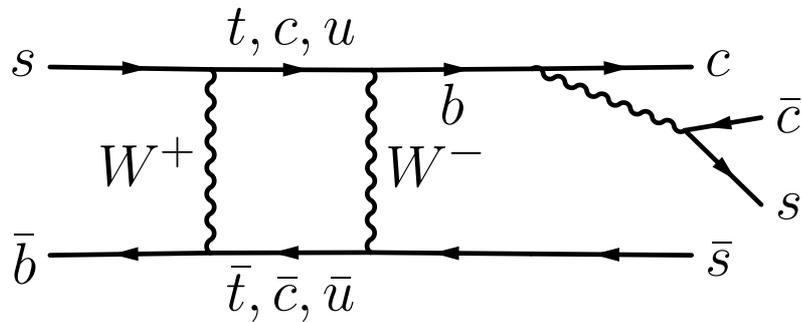
$$\begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^2 \end{pmatrix}$$

- Looking for indirect effects of new physics to discover it
- If new physics is discovered, understand which model is right one

CPV in $B_s \rightarrow J/\psi\phi$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- V_{ts} known from unitarity
- Need to check also by experiment
- Best testing ground is decay $B_s \rightarrow J/\psi\phi$



- New physics in mixing can have large effect on CP violation
- Search for large CP violation in $B_s \rightarrow J/\psi\phi$

Sidenote on phases

- B_s system is described by equation

$$i \frac{d}{dt} \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2} \mathbf{\Gamma} \right) \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix}$$

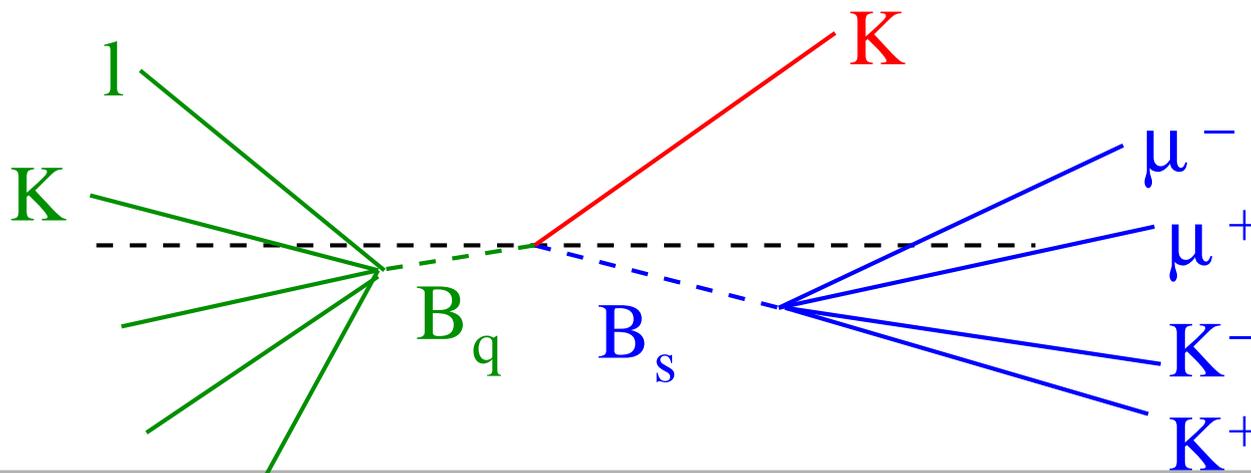
- Box diagram of mixing give rise to M_{12} and Γ_{12}
- Interesting quantities and relation to observables:
 - $\Delta M_s = 2 |M_{12, s}^{\text{SM}}| \cdot |\Delta_s|$
 - $\phi_s = \arg(-M_{12}/\Gamma_{12}) = \phi_s^{\text{SM}} + \phi_s^{\Delta}$, in SM $\phi_s = (4.2 \pm 1.4) \cdot 10^{-3}$
 - $\Delta\Gamma_s = 2 |\Gamma_{12, s}| \cdot \cos(\phi_s^{\text{SM}} + \phi_s^{\Delta})$
- CP Violation in $B_s \rightarrow J/\psi\phi$ measures
 - $\phi_s^{J/\psi\phi} = -2\beta_s + \phi_s^{\Delta} + \delta_{\text{Peng.}}^{\text{SM}} + \delta_{\text{Peng.}}^{\text{NP}}$
in SM $2\beta_s = 2 \arg(-V_{ts} V_{tb}^* / V_{cs} V_{cb}^*) \approx 0.04$
- With current CDF precision we really test presence of large ϕ_s^{Δ}

Analysis logic

- Principle is to measure time dependent asymmetry of CP eigenstate

$$A = \frac{N(B, t) - N(\bar{B}, t)}{N(B, t) + N(\bar{B}, t)}$$

- We need to find in data
 - $B_s \rightarrow J/\psi\phi$ decays
 - Measure decay time
 - Find out whether it was produced as B or \bar{B}



Likelihood anatomy

- Signal PDF for single tag

$$P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) = \frac{1 + \xi \mathcal{D}}{2} P(t, \vec{\rho} | \sigma_t) \epsilon(\vec{\rho}) + \frac{1 - \xi \mathcal{D}}{2} \bar{P}(t, \vec{\rho} | \sigma_t) \epsilon(\vec{\rho})$$

- $\xi = -1, 0, 1$ is tagging decision
- \mathcal{D} is event-specific dilution
- $\epsilon(\vec{\rho})$ - acceptance function in angular space
- $P(t, \vec{\rho} | \sigma_t)$ ($\bar{P}(t, \vec{\rho} | \sigma_t)$) is PDF for B_s (\bar{B}_s)

Likelihood anatomy

$$\begin{aligned} \frac{d^4 P(t, \vec{\rho})}{dt d\vec{\rho}} &\propto |A_0|^2 \mathcal{T}_+ f_1(\vec{\rho}) + |A_{\parallel}|^2 \mathcal{T}_+ f_2(\vec{\rho}) + |A_{\perp}|^2 \mathcal{T}_- f_3(\vec{\rho}) \\ &+ |A_{\parallel}| |A_{\perp}| \mathcal{U}_{\pm} f_4(\vec{\rho}) + |A_0| |A_{\parallel}| \cos(\delta_{\parallel}) \mathcal{T}_+ f_5(\vec{\rho}) \\ &+ |A_0| |A_{\perp}| \mathcal{V}_{\pm} f_6(\vec{\rho}) \end{aligned}$$

$$\mathcal{T}_{\pm} = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta\Gamma t/2) \mp \eta \sin(2\beta_s) \sin(\Delta m_s t)],$$

$$\begin{aligned} \mathcal{U}_{\pm} = \pm e^{-\Gamma t} &\times [\sin(\delta_{\perp} - \delta_{\parallel}) \cos(\Delta m_s t) \\ &- \cos(\delta_{\perp} - \delta_{\parallel}) \cos(2\beta_s) \sin(\Delta m_s t) \\ &\pm \cos(\delta_{\perp} - \delta_{\parallel}) \sin(2\beta_s) \sinh(\Delta\Gamma t/2)], \end{aligned}$$

$$\begin{aligned} \mathcal{V}_{\pm} = \pm e^{-\Gamma t} &\times [\sin(\delta_{\perp}) \cos(\Delta m_s t) \\ &- \cos(\delta_{\perp}) \cos(2\beta_s) \sin(\Delta m_s t) \\ &\pm \cos(\delta_{\perp}) \sin(2\beta_s) \sinh(\Delta\Gamma t/2)]. \end{aligned}$$

Issue of s-wave

- We reconstruct $B_s \rightarrow J/\psi \phi$ with $\phi \rightarrow K^+ K^-$
- But wide resonance $f_0(980)$ can also decay to $K^+ K^-$ and $B_s \rightarrow J/\psi K^+ K^-$ is also possible (called s-wave)
- There are arguments that s-wave can be large
 - Stone et al, PRD79, 07024 (2009) predicts

$$\frac{B(B_s \rightarrow J/\psi f_0(980)) B(f_0(980) \rightarrow \pi\pi)}{B(B_s \rightarrow J/\psi \phi) B(\phi \rightarrow KK)} \simeq 0.2 - 0.3$$

- Best upper bound from Belle

$$B(B_s \rightarrow J/\psi f_0(980)) B(f_0(980) \rightarrow \pi\pi) < 1.63 \cdot 10^{-4} \text{ at 90\% C.L.}$$

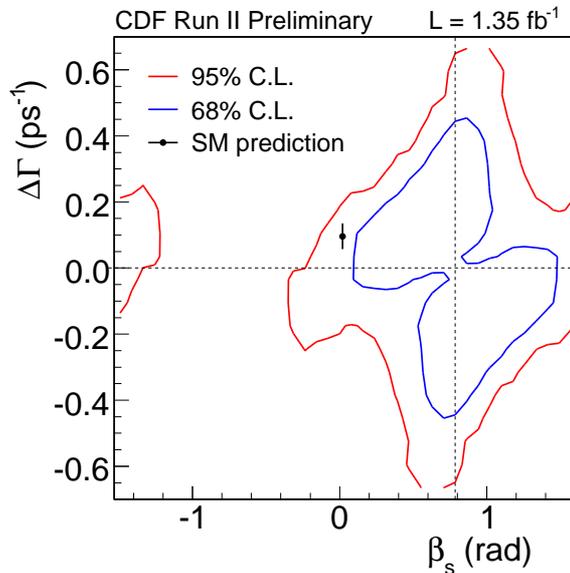
- S-wave can contribute to reconstructed signal
- It is CP-odd eigenstate with its own angular and time dependence
- Sizeable contribution which is not accounted for can bias result

⇒ Account for it in the likelihood

Treatment of s-wave

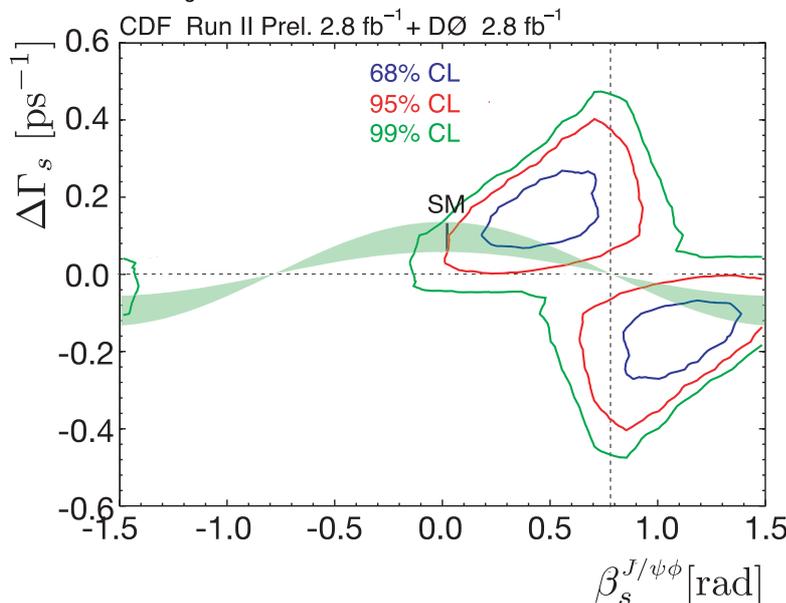
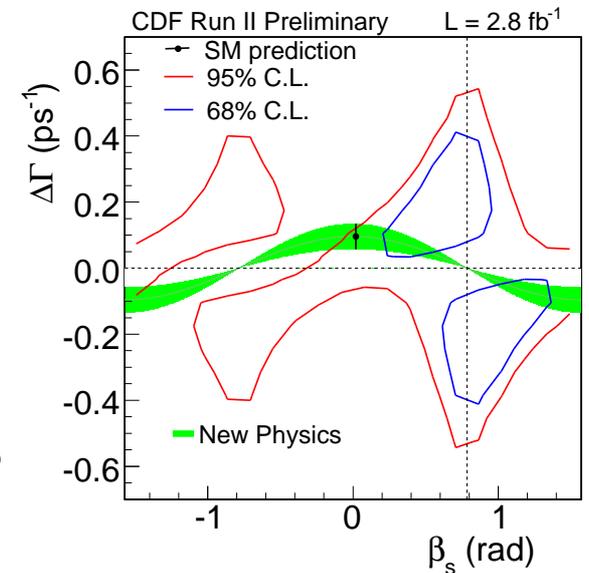
- Add amplitude for s-wave \Leftrightarrow four angular terms (amplitude² + 3 interference terms)
- S-wave amplitude is pure CP-odd eigenstate with its own angular dependence
- Strong phases vary over resonance
- \Rightarrow Need to start with K^+K^- mass included
 - Relativistic Breit-Wigner propagator for p-wave
 - Constant for s-wave
- Keep K^+K^- mass as unobserved \Leftrightarrow integrate over it
- Interference between p-wave and s-wave could break last symmetry
- Full math spelled out in arXiv:1008.4283

Previous results



CDF 1.35 fb⁻¹
 p-value = 15%

CDF 2.8 fb⁻¹
 p-value = 7%

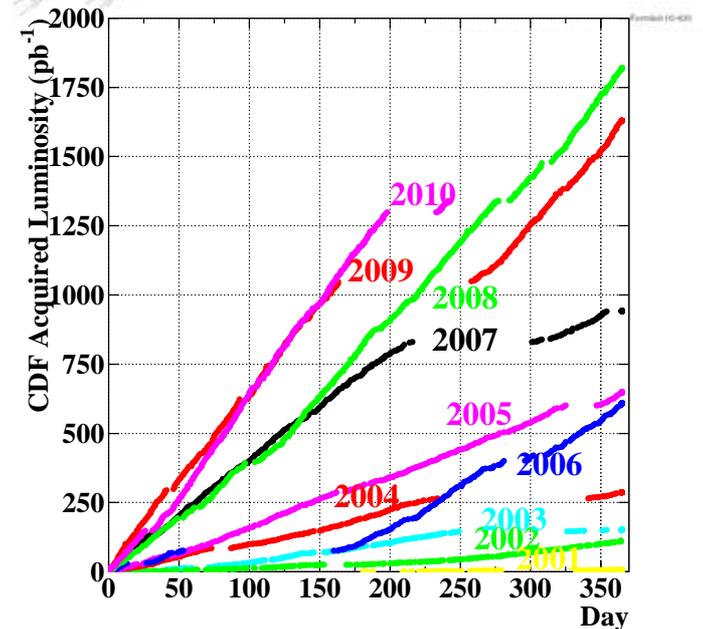
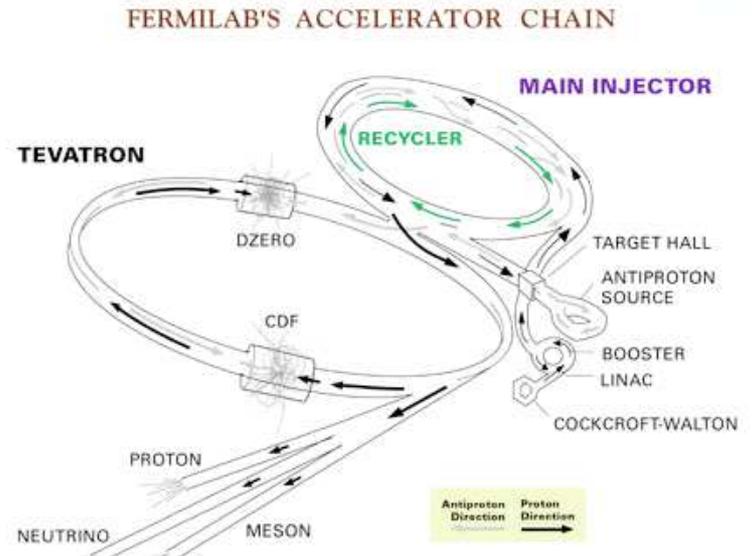
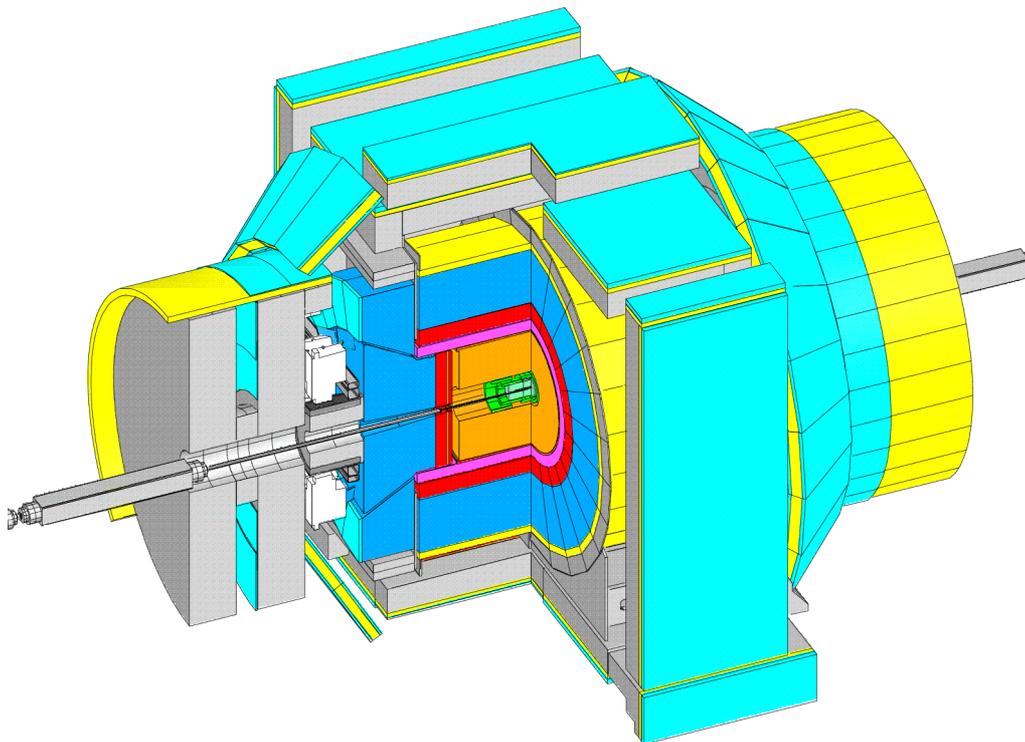


CDF 2.8 fb⁻¹ + DØ 2.8 fb⁻¹
 p-value = 3.4%

What next?

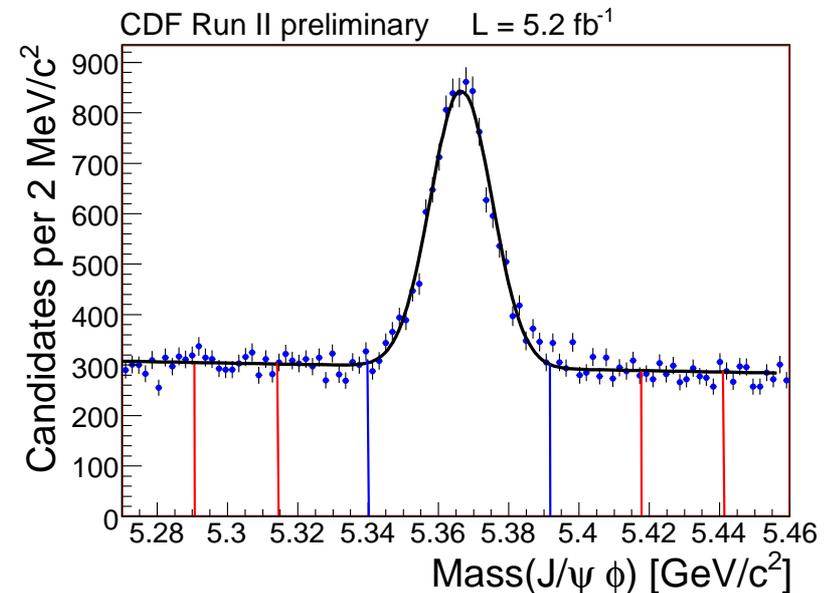
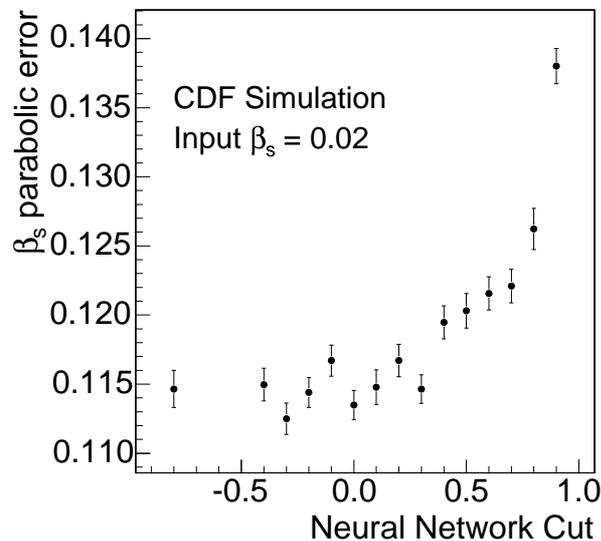
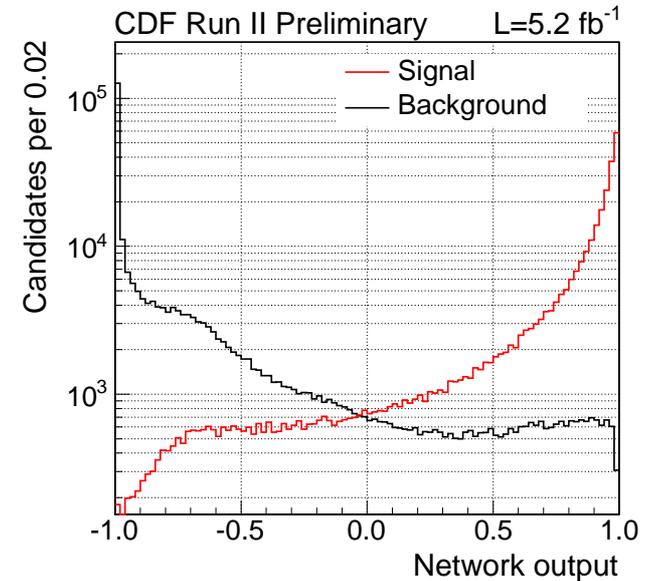
Tevatron and CDF experiment

- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- Peak luminosity $\approx 3.5 - 3.8 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Collected about $\approx 7\text{fb}^{-1}$

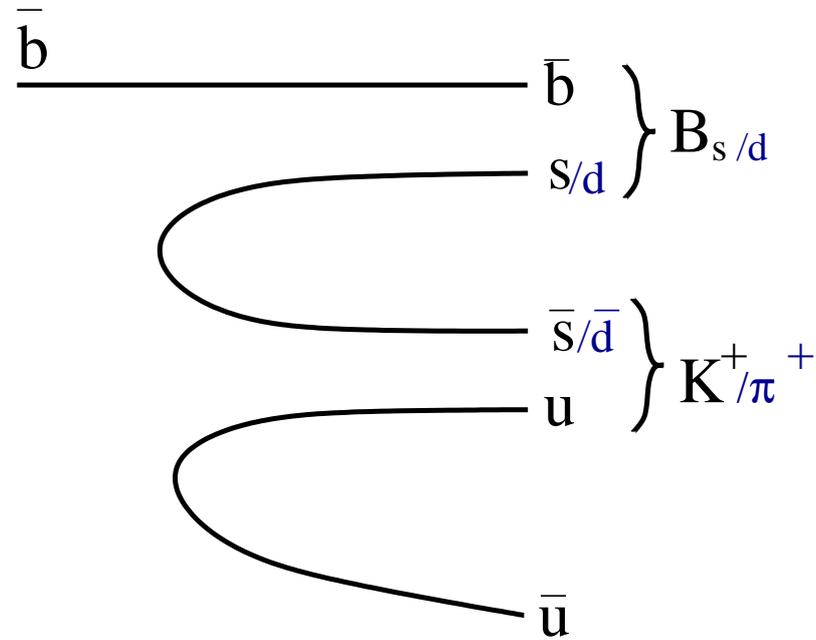
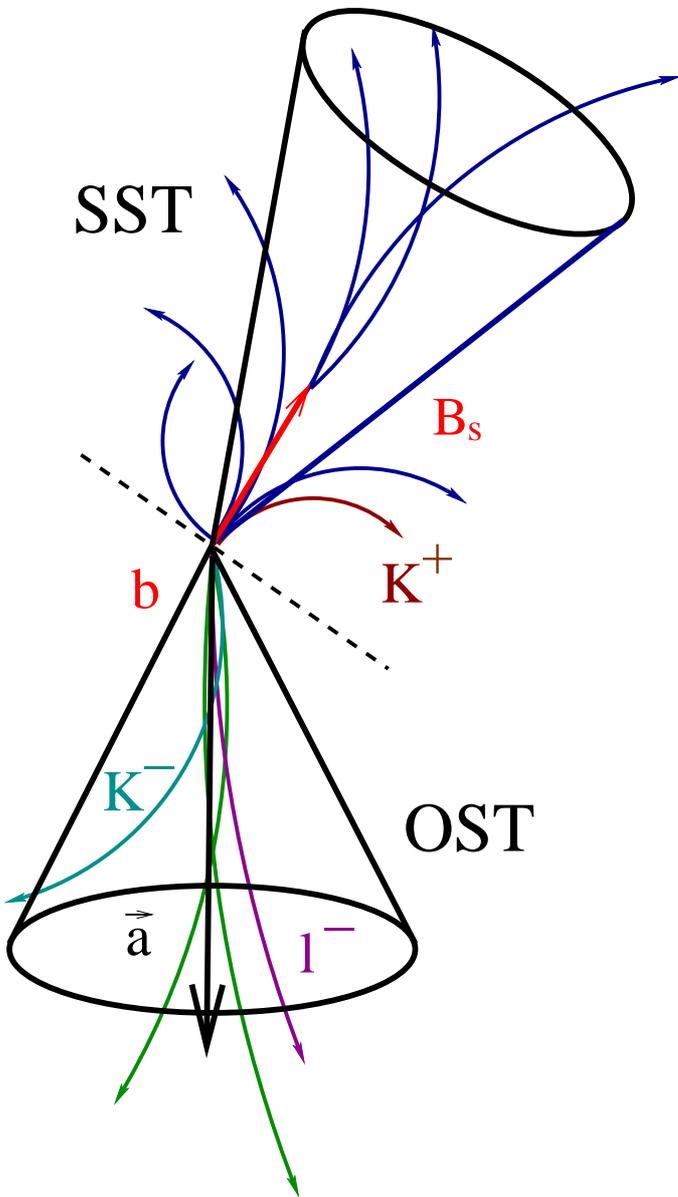


Selection

- Latest analysis uses 5.2 fb^{-1}
- Events selected using dimuon trigger
- Typical event has few dozens tracks \Rightarrow lot of background
- Neural network to select interesting events
- Select $\approx 6500 B_s \rightarrow J/\psi \phi$ decays



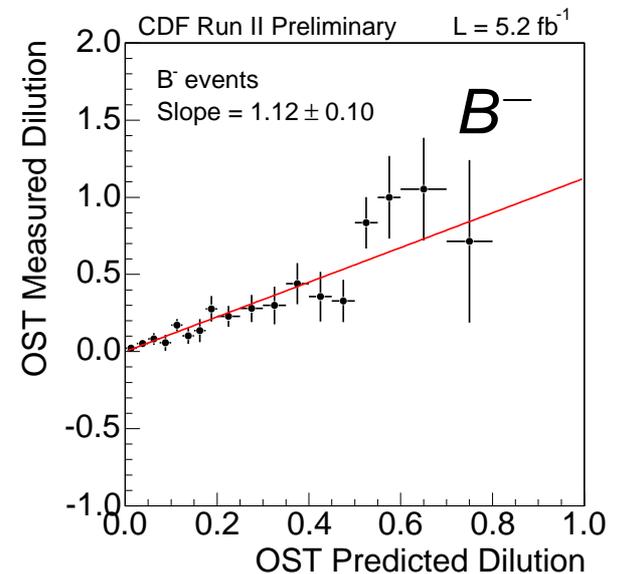
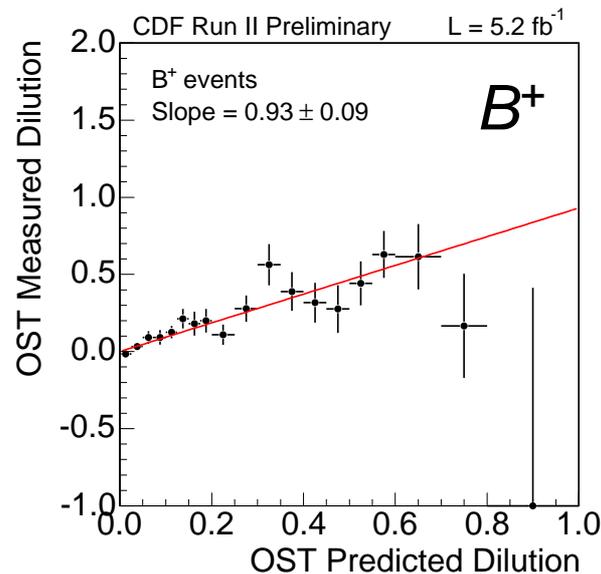
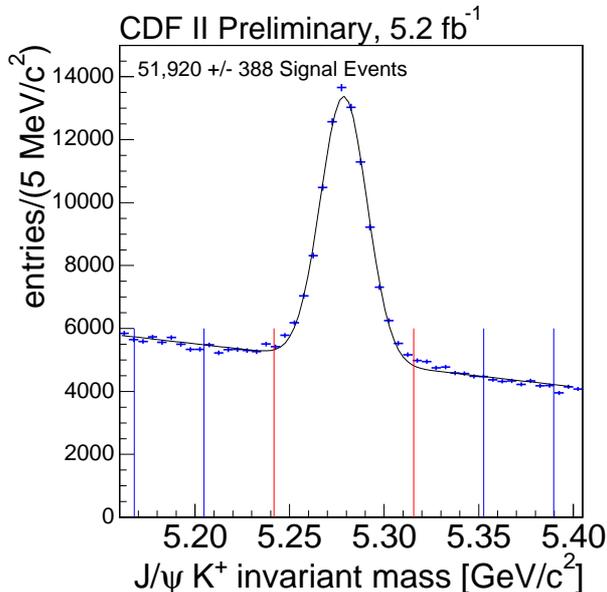
Flavor tagging



- Determination of the flavor at production time
- Difficult task due to large number of tracks
- Benefits from PID
- Calibrated with data

OST Calibration

- Flavor tagging algorithm is characterized by
 - Efficiency ϵ
 - Dilution $D = 2 \cdot P - 1$
- Quantity ϵD^2 defines effective statistics
- Opposite side tagging is independent of studied hadron
- Effective power of OST is $\epsilon D^2 = 1.2\%$



SSKT Calibration

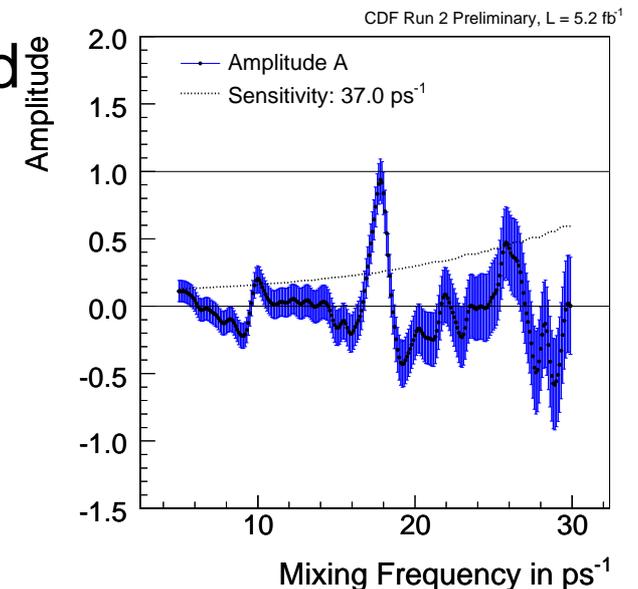
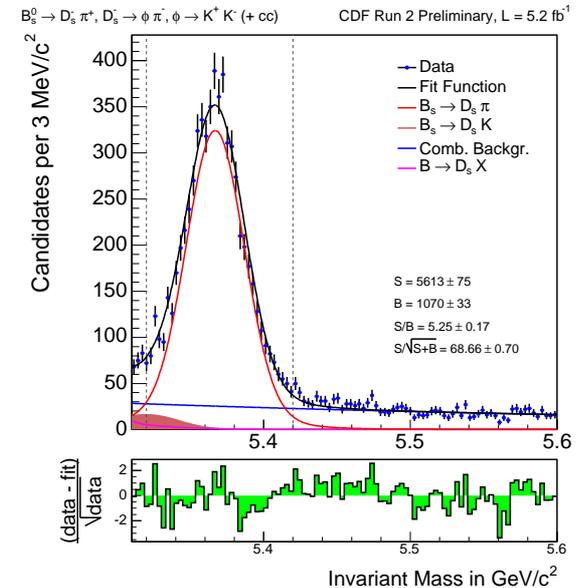
- SSKT depends on the meson we study
- Only way to calibrate is to use B_S itself
- Fortunately B_S oscillation is sensitive to quality of tagging

Principle

$$A = \frac{N_{mix} - N_{unmix}}{N_{mix} + N_{unmix}} = A \cdot D \cos(\Delta mt)$$

Use decays:

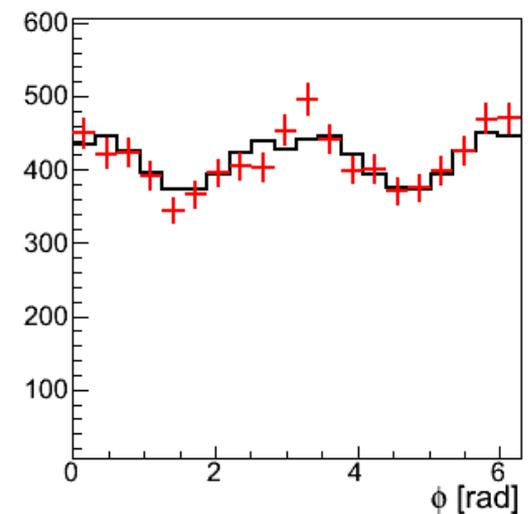
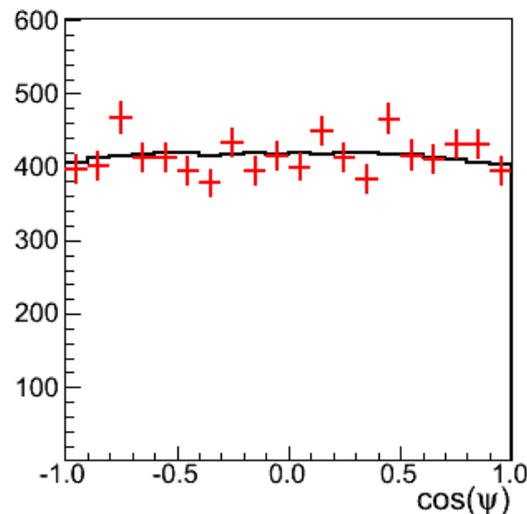
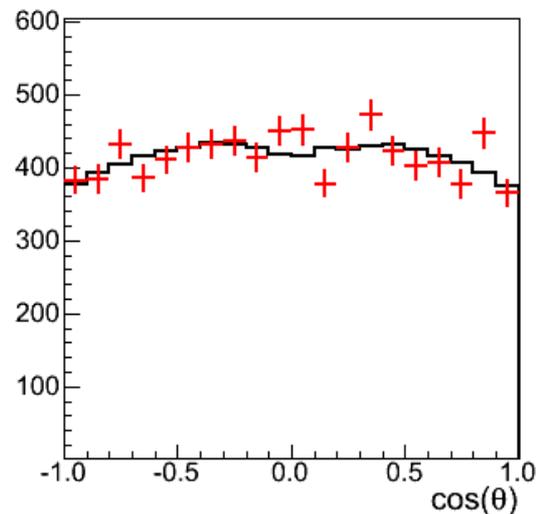
- $B_S \rightarrow D_S \pi$ with $D_S \rightarrow \phi \pi$, $D_S \rightarrow K^* K$ and $D_S \rightarrow \pi \pi \pi$
- $B_S \rightarrow D_S \pi \pi \pi$ with $D_S \rightarrow \phi \pi$
- In total ≈ 12900 signal events
- Total tagging power $\epsilon D^2 = 3.2 \pm 1.4\%$
- $\Delta m_S = 17.79 \pm 0.07(\text{stat})$



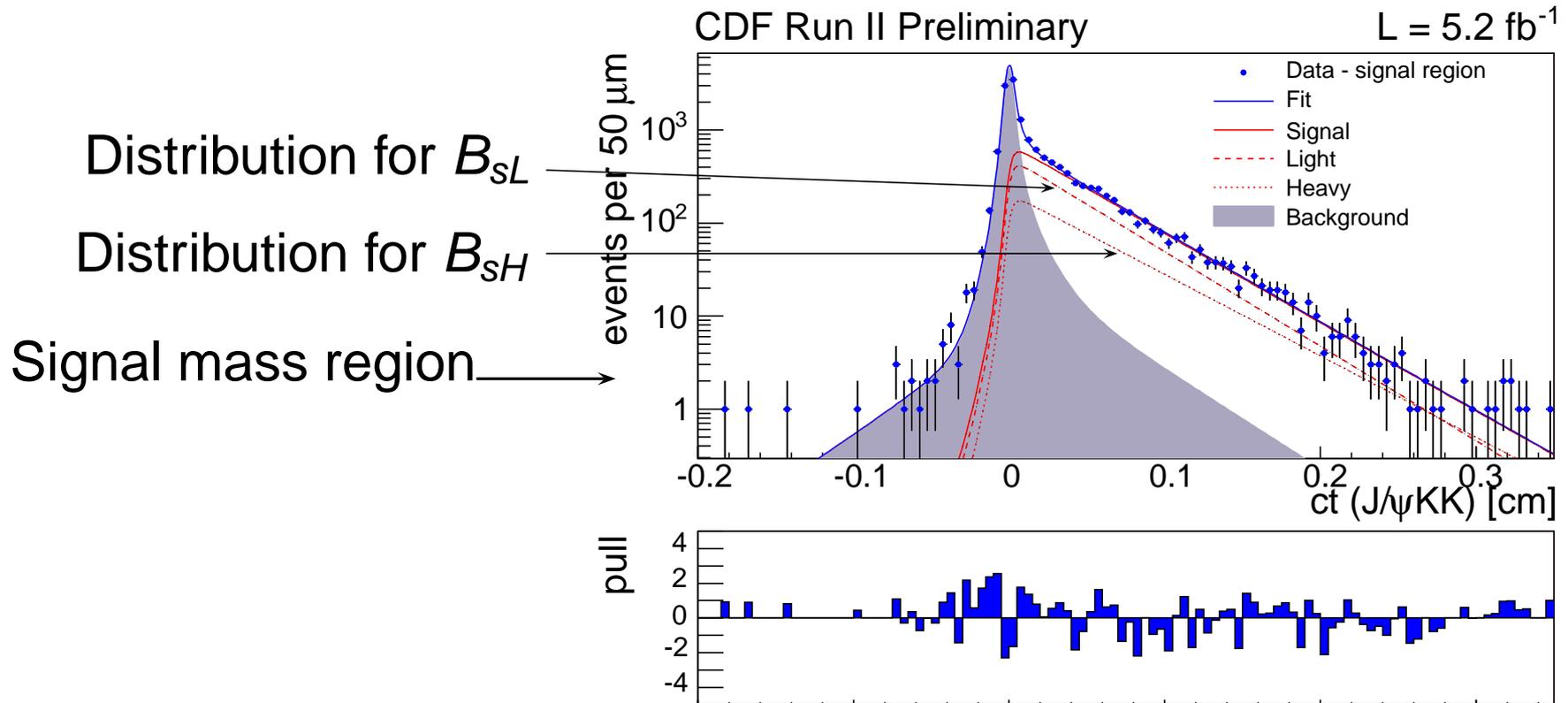
Angular efficiencies

- Derived from large statistics MC
- Parameterized in three dimensions
- CP Violation relatively insensitive to exact details
- Efficiency compares well with angular distributions of combinatorial background

CDF Run II Preliminary, $L=5.2 \text{ fb}^{-1}$



Lifetime and width difference



Under SM assumption ($\beta_s = 0$) we measure:

$$c\tau = \frac{2}{\Gamma_H + \Gamma_L} = 1.529 \pm 0.025(\text{stat}) \pm 0.012(\text{syst}) \text{ ps}$$

$$\Delta\Gamma_s = 0.075 \pm 0.035(\text{stat}) \pm 0.01(\text{syst}) \text{ ps}^{-1}$$

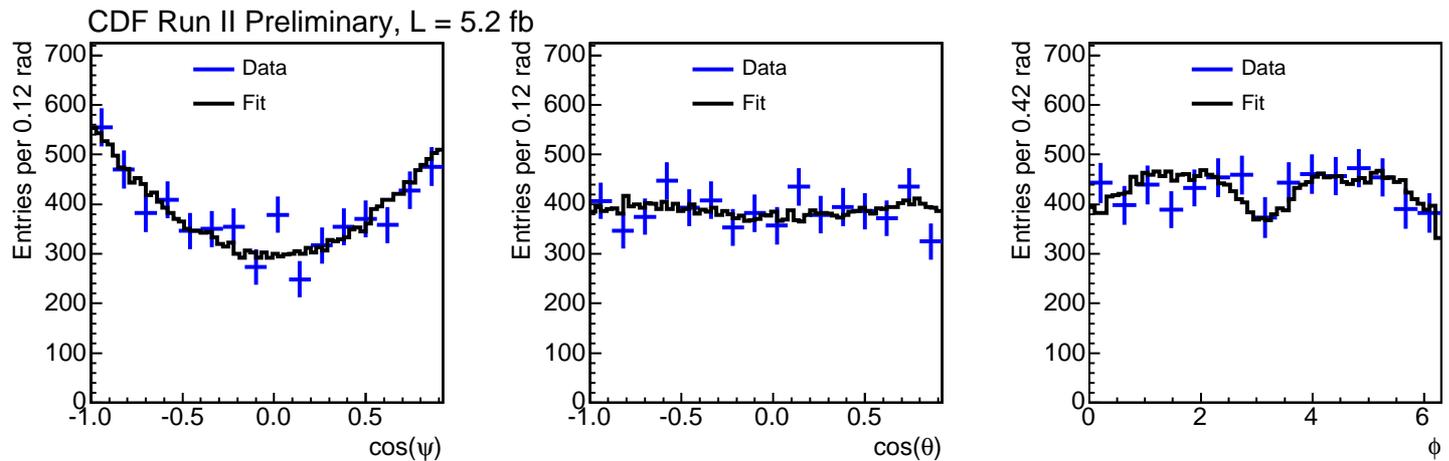
Polarization amplitudes

$$|A_{||}|^2 = 0.231 \pm 0.014(\text{stat}) \pm 0.015(\text{syst})$$

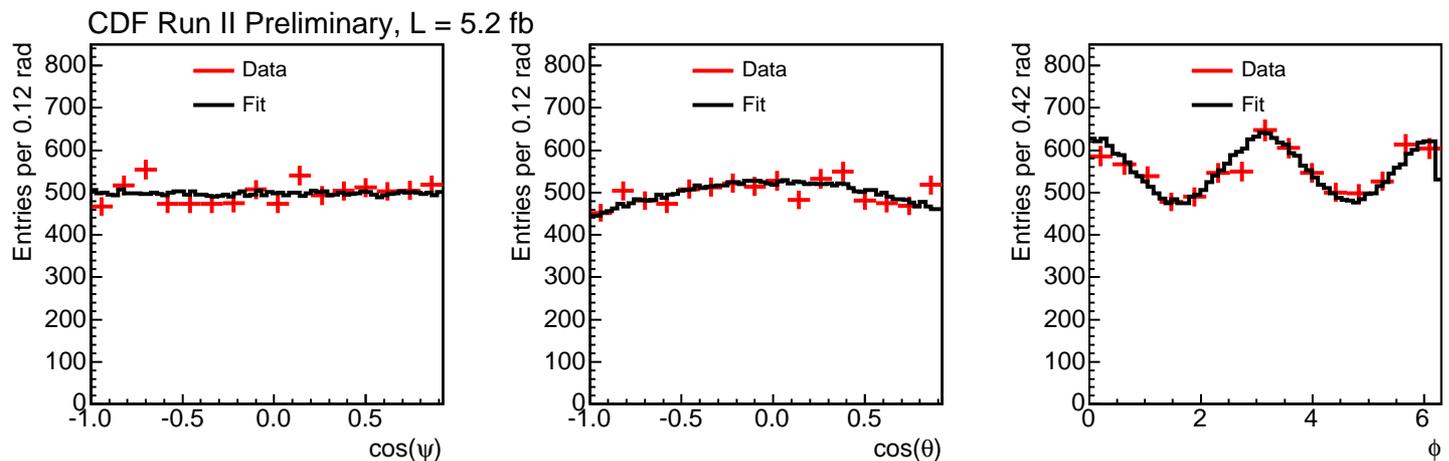
$$|A_0|^2 = 0.524 \pm 0.013(\text{stat}) \pm 0.015(\text{syst})$$

$$\phi_{\perp} = 2.95 \pm 0.64(\text{stat}) \pm 0.07(\text{syst})$$

Signal



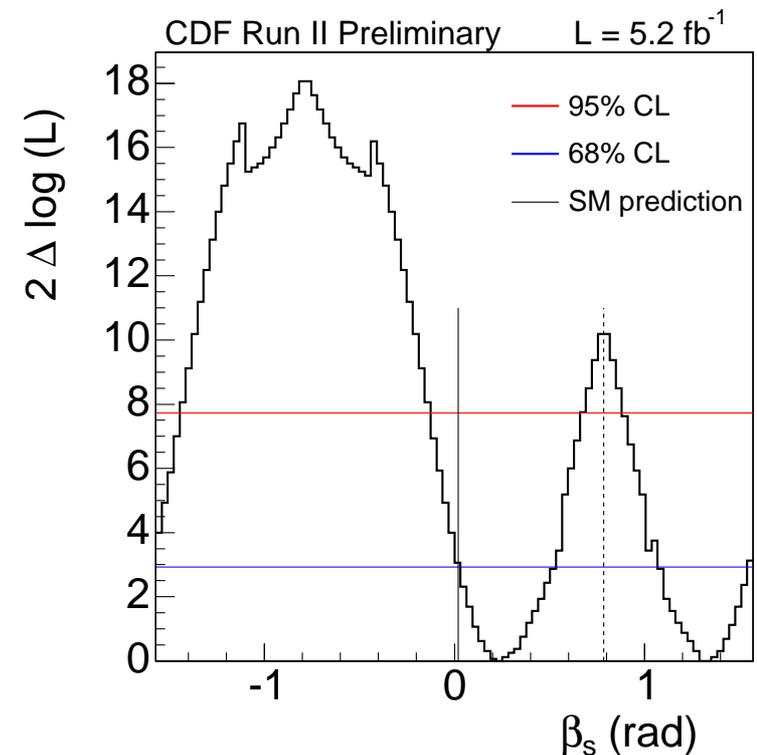
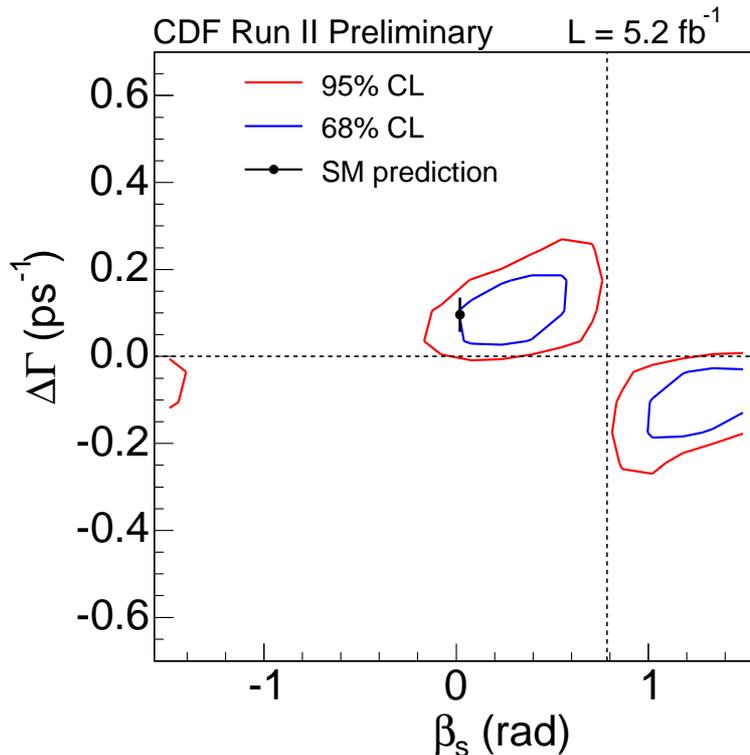
Background



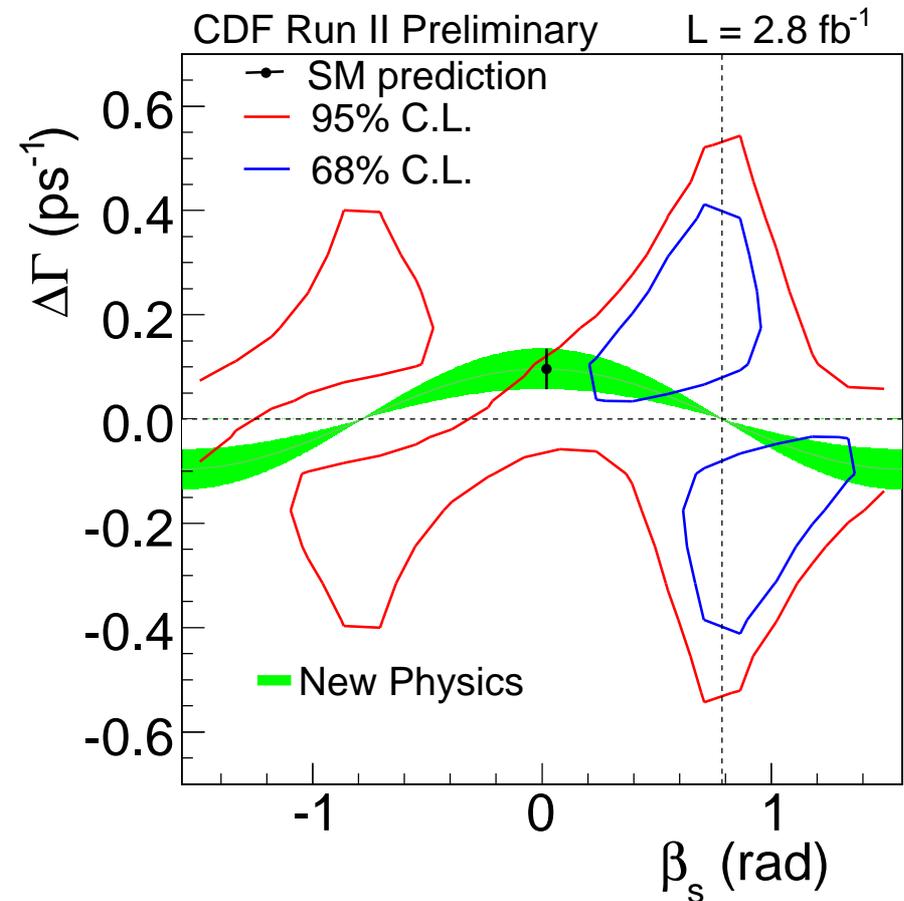
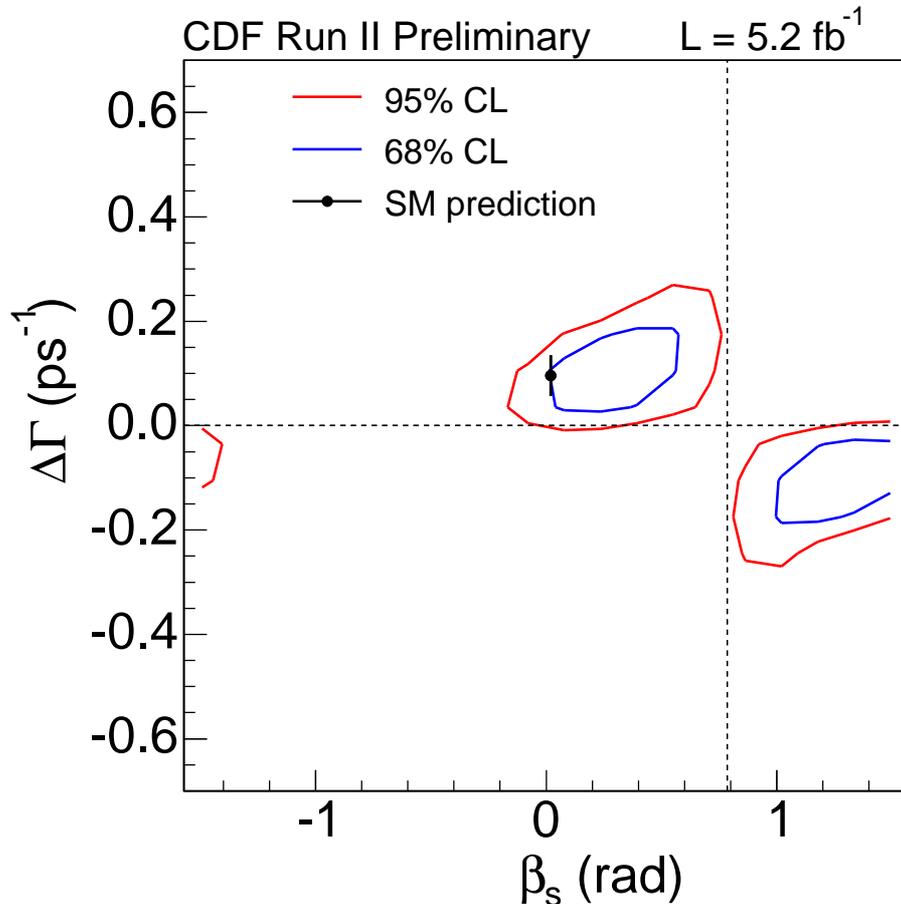
CP Violation

- SM p-value is 44%
- Corresponds to 0.8σ
- Significant improvement
- Strong phases free

- SM p-value is 31%
- Comparable to 2D case $\Leftrightarrow \Delta\Gamma$ consistent with SM
- $\beta_s \in [0.02, 0.52] \cup [1.08, 1.55]$ @ 68% C.L.

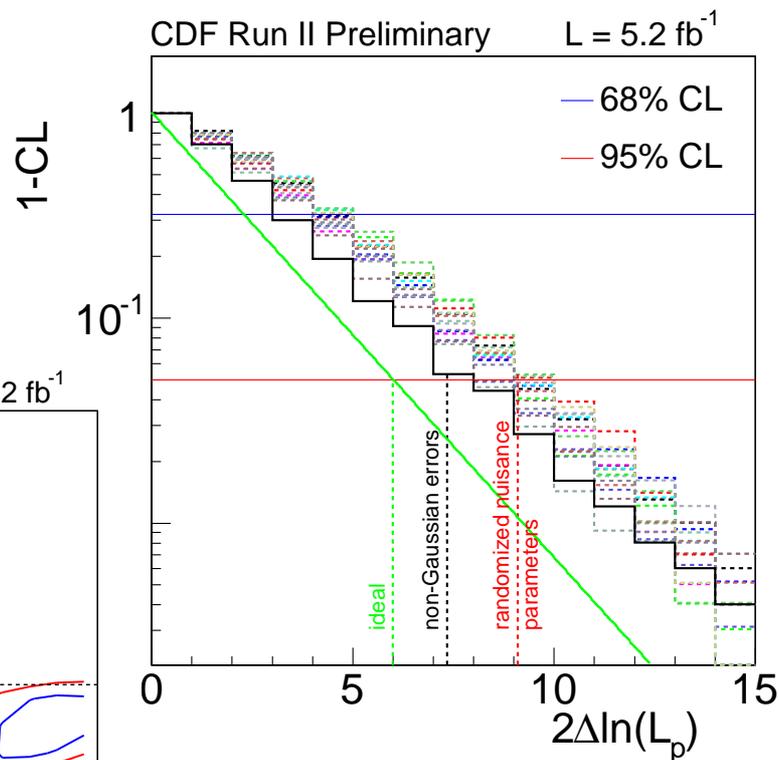
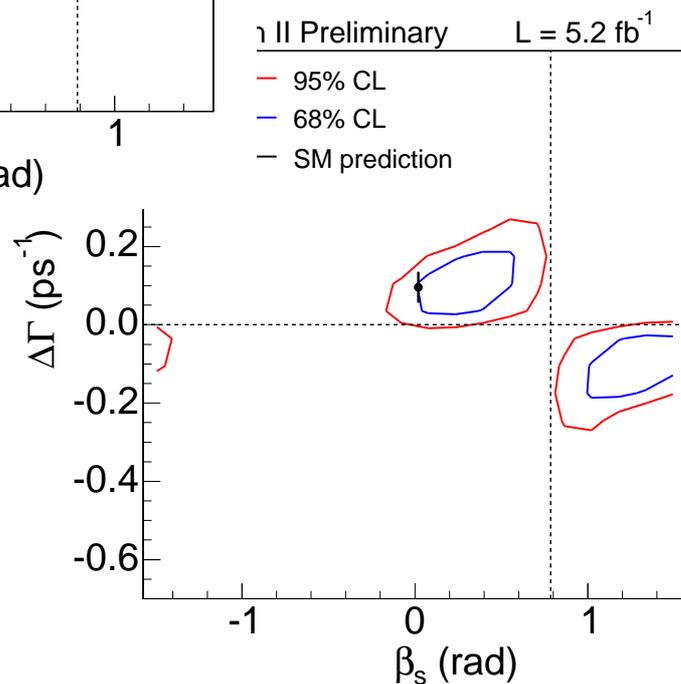
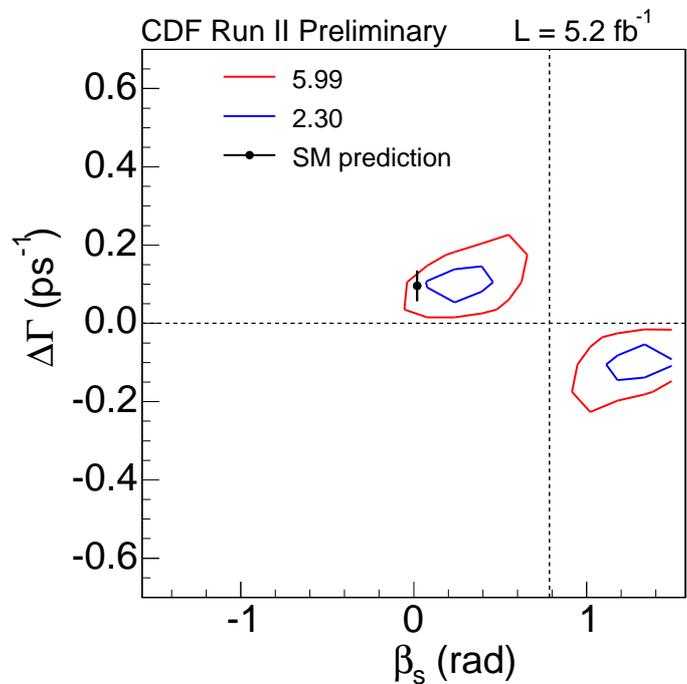


Comparison to previous result



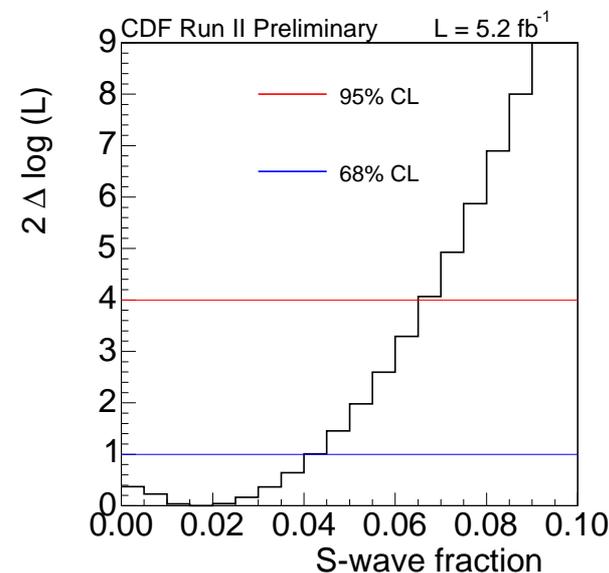
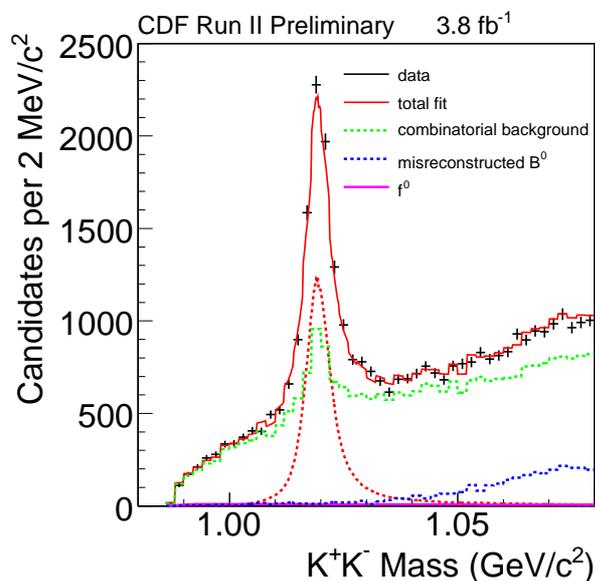
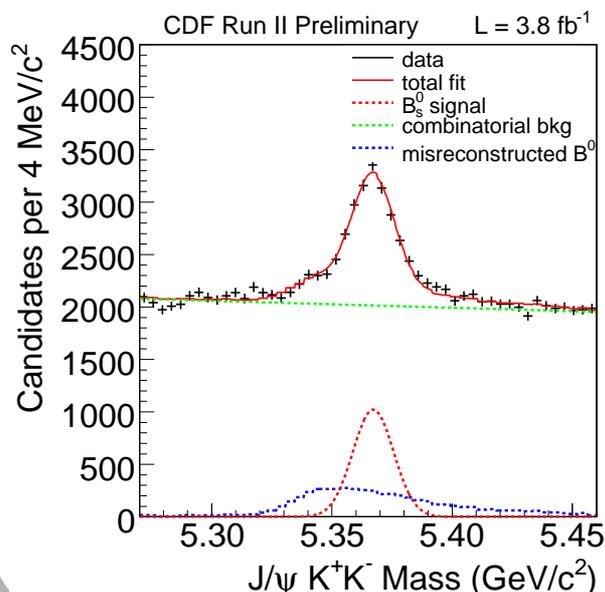
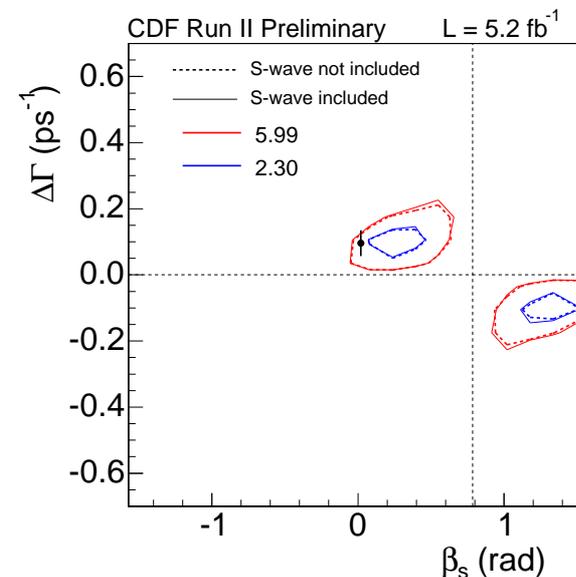
- Concentrate on size of the allowed region
- Significant improvement compared to our previous result

Size of the adjustment



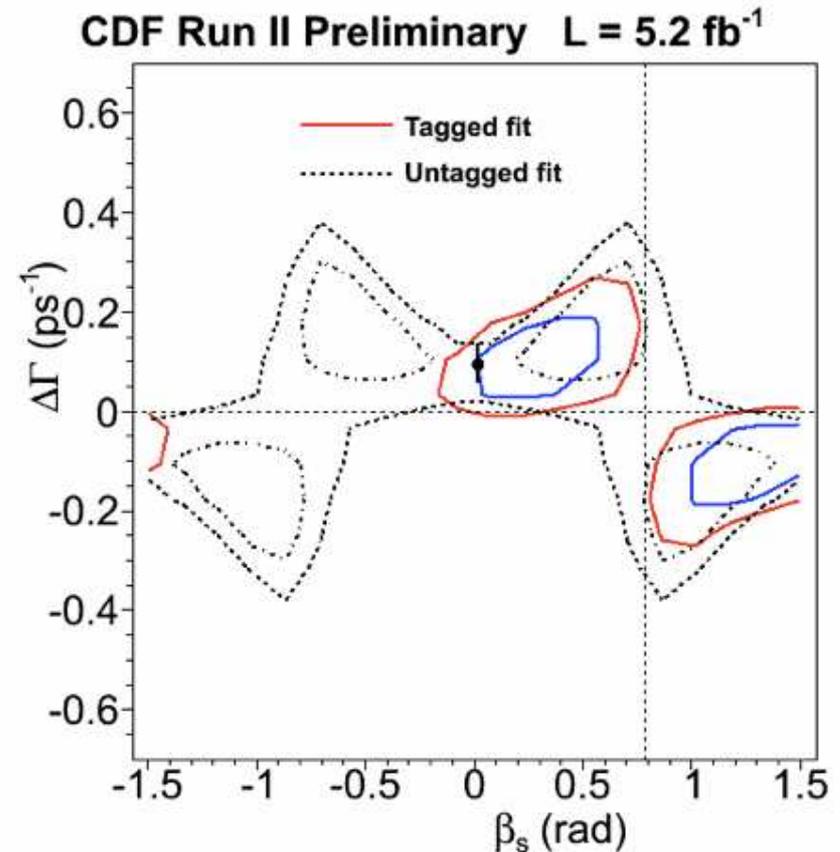
S-wave check

- Q: Is change since last time due to previously omitted s-wave?
- A: No, likelihood almost same with s-wave fixed to zero
- Q: Is the K^+K^- mass consistent with our fit model?
- A: Yes it is

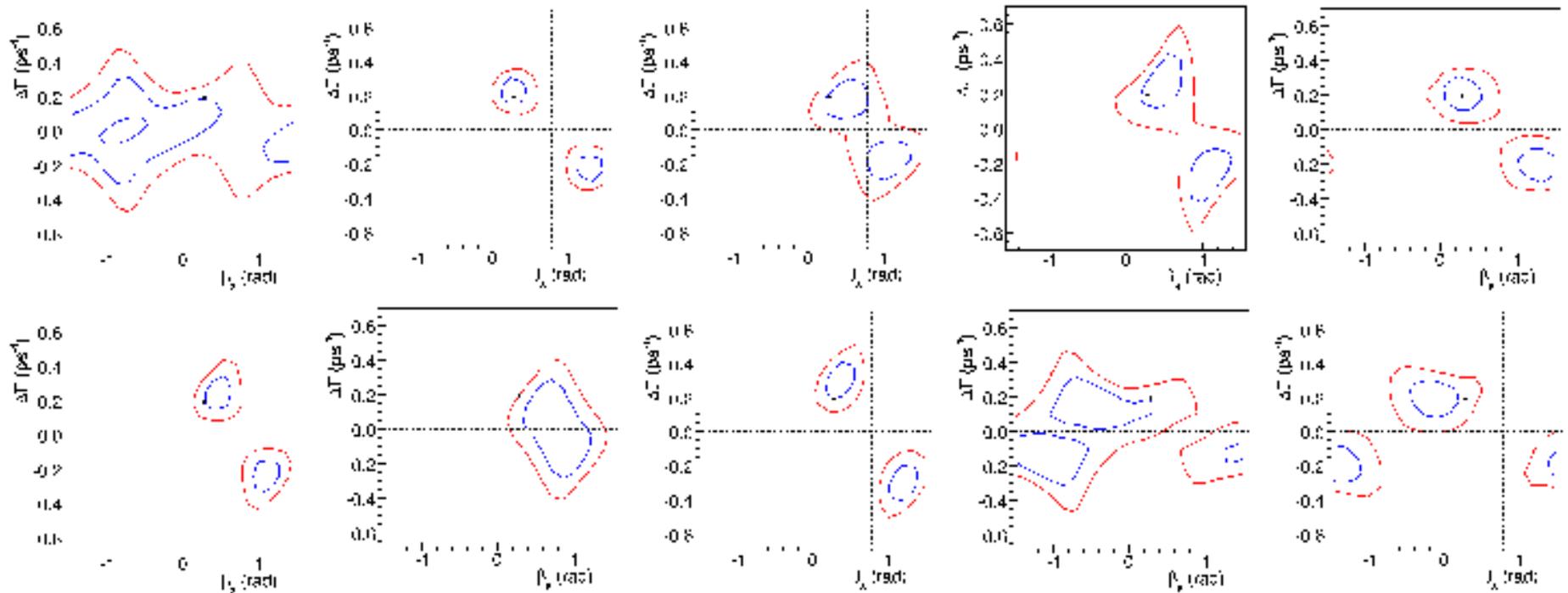


Effect of flavor tagging

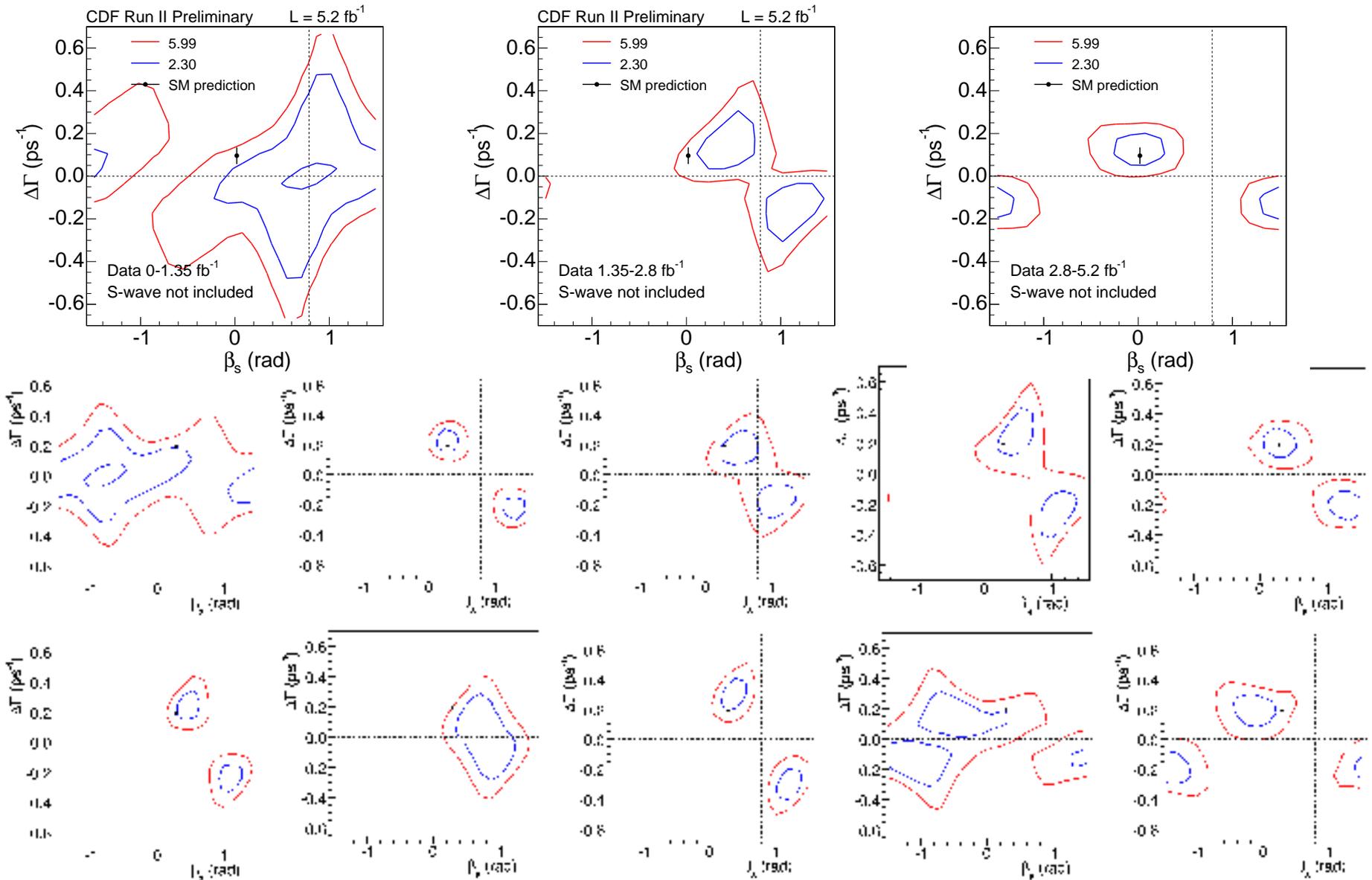
- With tagging of $\epsilon D^2 \approx 5\%$ we don't gain lot in precision
- Main effect in reducing ambiguities
- Untagged case symmetric under each
 - $2\beta_s \rightarrow -2\beta_s$
 $\delta_{\perp} \rightarrow \delta_{\perp} + \pi$
 - $\Delta\Gamma \rightarrow -\Delta\Gamma$
 $2\beta_s \rightarrow 2\beta_s - \pi$
- Tagged symmetry
 - $2\beta_s \rightarrow \pi - 2\beta_s$
 $\Delta\Gamma \rightarrow -\Delta\Gamma$
 $\delta_{\parallel} \rightarrow 2\pi - \delta_{\parallel}$
 $\delta_{\perp} \rightarrow \pi - \delta_{\perp}$



Different parts of data

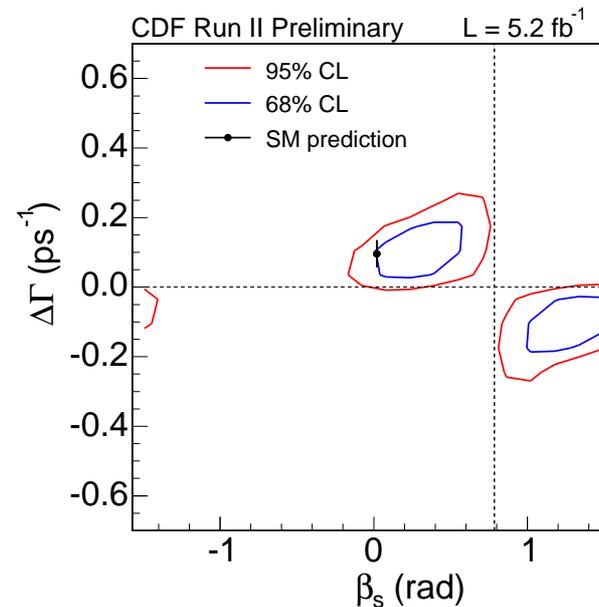


Different parts of data



Conclusions

- Significantly improved measurement of the CPV in $B_s \rightarrow J/\psi\phi$
 $\beta_s \in [0.02, 0.52] \cup [1.08, 1.55]$ @ 68% C.L.
- CDF data now agree on the $\approx 1\sigma$ level with SM
- Best measurement of
 - Mean lifetime
 - Width difference between mass eigenstates
 - Polarization amplitudes



Prospects

- Couple of improvements possible beyond collecting data
 - Include other triggers gives $\approx 25\%$ more statistics
 - Add $B_s \rightarrow \psi(2S)\phi$
 - Look for $B_s \rightarrow J/\psi f_0(980)$ with $f_0(980) \rightarrow \pi^+ \pi^-$
 - Add $K^+ K^-$ mass as fit variable - helps in ambiguity resolution
- Still collecting data, expect to have ≈ 2 times more by the end of 2011
- Extension of running by 3 years under discussion

