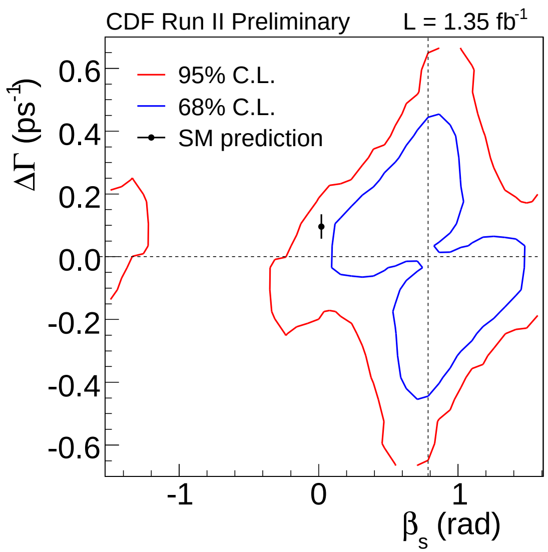
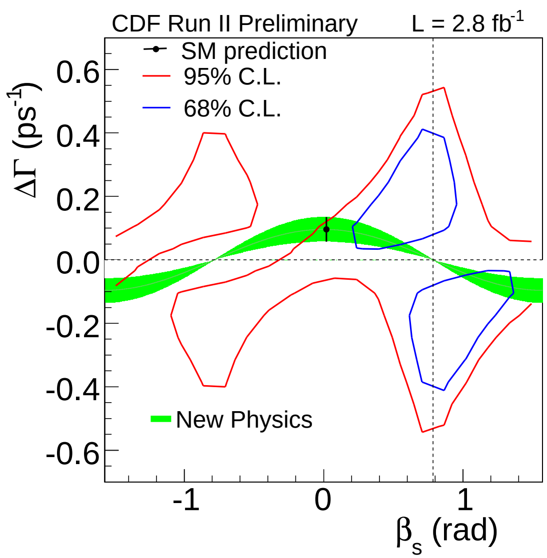
Measurement of CP Violation in $B_s \to J/\psi\phi$ at CDF

Michal Kreps for the CDF collaboration

Physics Department



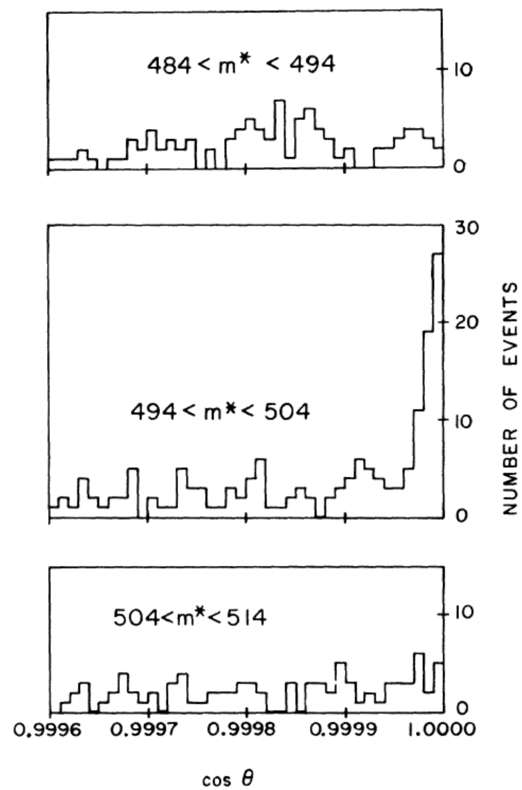
$\Rightarrow$

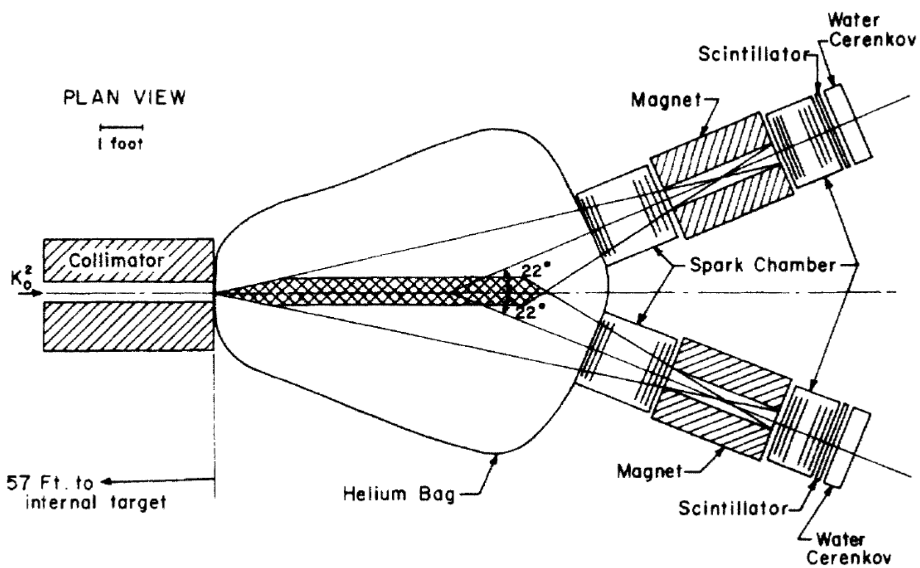


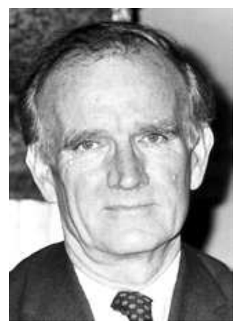
$\Rightarrow$?

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 3 π
- Observation of $K_2 \to \pi^+\pi^-$ in 1964 by Cronin and Fitch $\Leftrightarrow$ CP is not conserved







Explaining CP violation

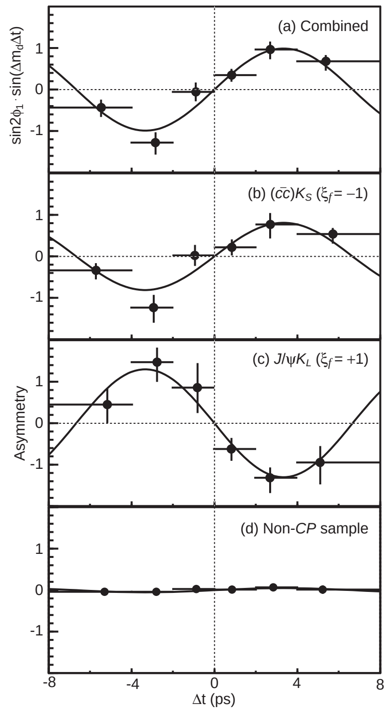
- Observation by Cronin and Fitch requires $\approx 10^{-3}$ admixture of wrong CP state in wave function
- In 1973 Kobayashi and Maskawa concludes that
  - No reasonable way to include CP violation in model with 4 quarks
  - Introduction of CP violation needs new particles
  - One of the suggested ways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

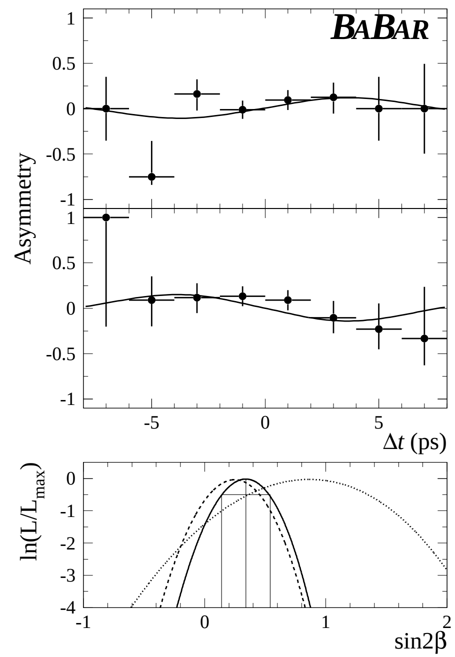
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Nobel prize in 2008


Implications

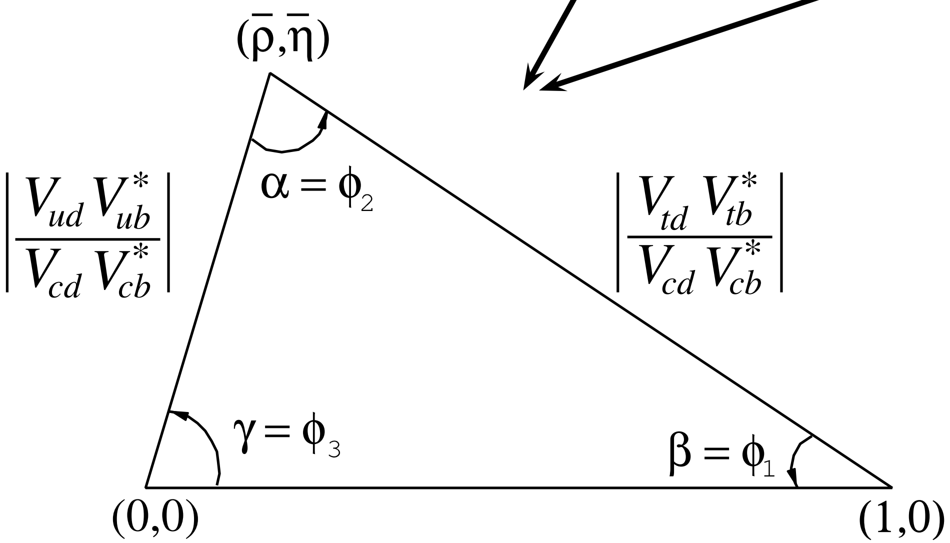
- When Kobayashi and Maskawa proposed their explanations, only 3 quarks were known
- The six quark model had several implications:
  - Existence of another 3 quarks to be seen by experiment
  - In 1980/1981 several people predicted large CP violation in *B* system
- Start of dedicated *B* physics experiments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

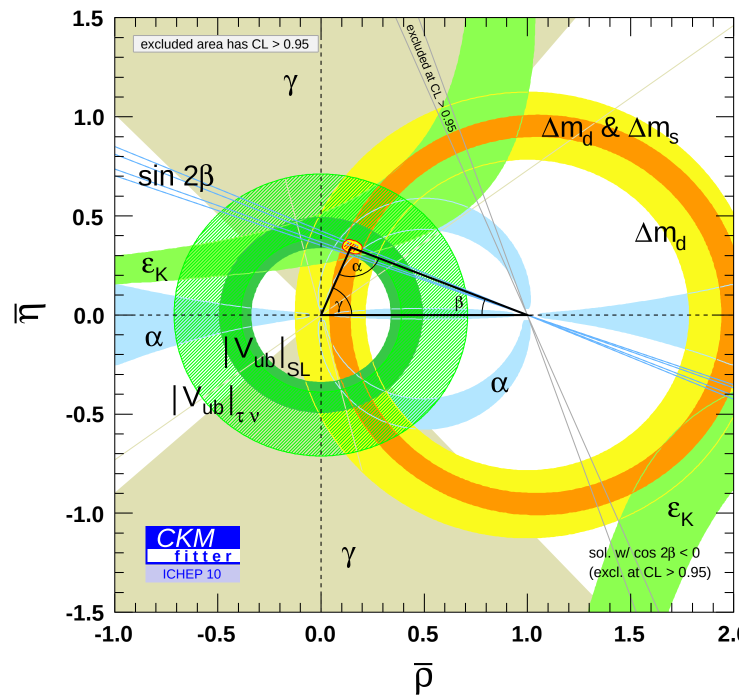




Global status

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





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

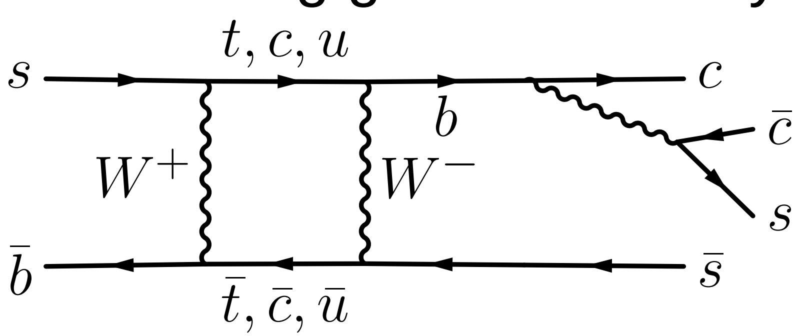
$$\begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

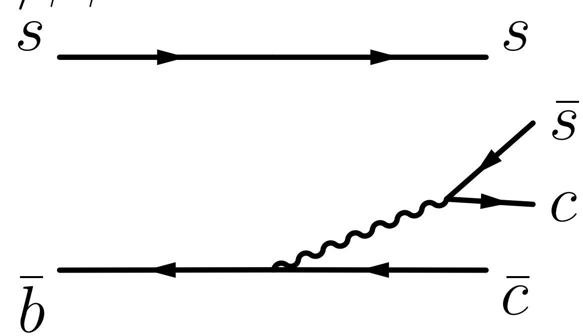
- Looking for indirect effects of new physics to discover it
- If new physics is discovered, understand which model is right one

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

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

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





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

Sidenote on phases

- B_s system is described by equation

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

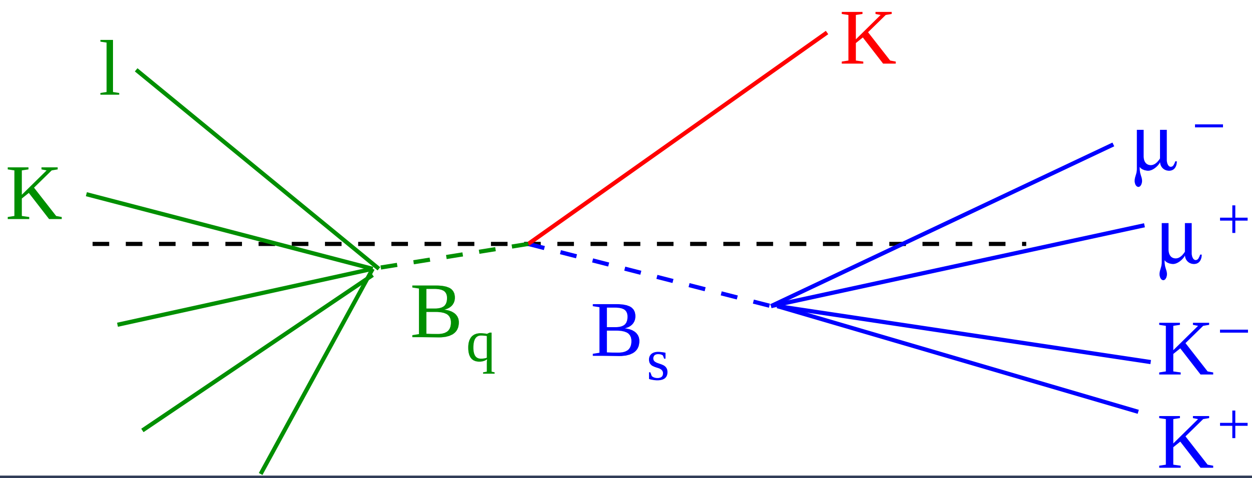
- Box diagram of mixing give rise to M_{12} and Γ_{12}
- Interesting quantities and relation to observables:
  - $\Delta M_s = 2|M_{12,s}^{\mathrm{SM}}|\cdot|\Delta_s|$
  - $\phi_s = \arg(-M_{12}/\Gamma_{12}) = \phi_s^{\mathrm{SM}} + \phi_s^{\Delta}$, in SM $\phi_s = (4.2 \pm 1.4)\cdot 10^{-3}$
  - $\Delta\Gamma_s = 2|\Gamma_{12,s}|\cdot\cos\left(\phi_s^{\mathrm{SM}} + \phi_s^{\Delta}\right)$
- CP Violation in $B_s \to J/\psi\phi$ measures
  - $\phi_s^{J/\Psi\phi} = -2\beta_s + \phi_s^{\Delta} + \delta_{\mathrm{Peng.}}^{\mathrm{SM}} + \delta_{\mathrm{Peng.}}^{\mathrm{NP}}$
    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

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

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



Likelihood anatomy

- Signal PDF for single tag

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

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

Likelihood anatomy

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

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

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

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

Issue of s-wave

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

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

  - Best upper bound from Belle $B(B_s \to J/\psi f_0(980))B(f_0(980) \to \pi\pi) < 1.63 \cdot 10^{-4}$ 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

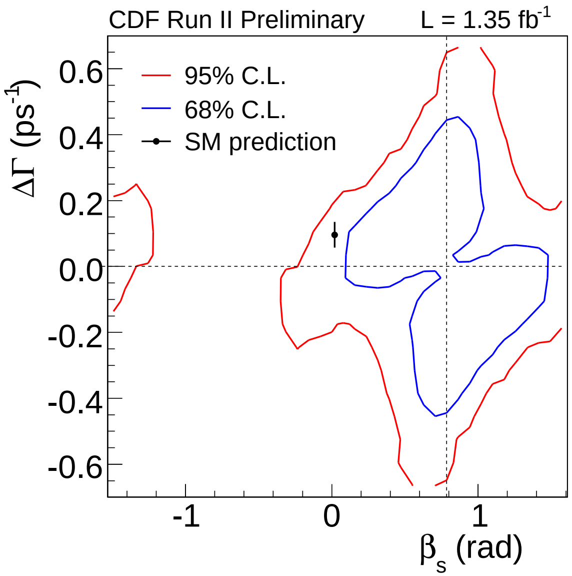
$\Rightarrow$ Account for it in the likelihood

Treatment of s-wave

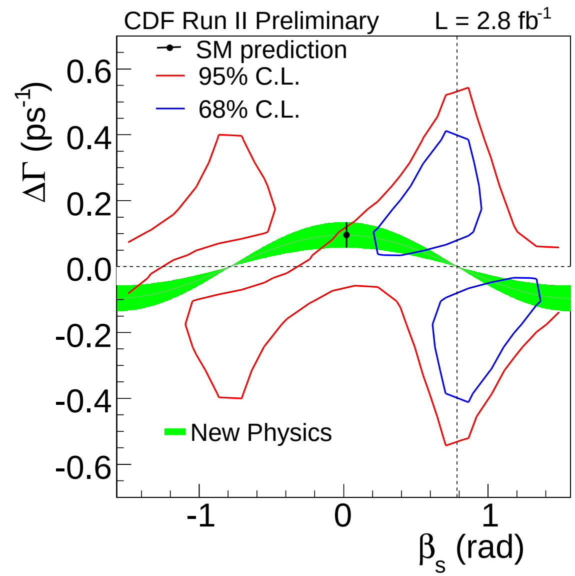
- Add amplitude for s-wave $\Leftrightarrow$ four angular terms (amplitude^2 + 3 interference terms)
- S-wave amplitude is pure CP-odd eigenstate with its own angular dependence
- Strong phases vary over resonance

$\Rightarrow$ 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

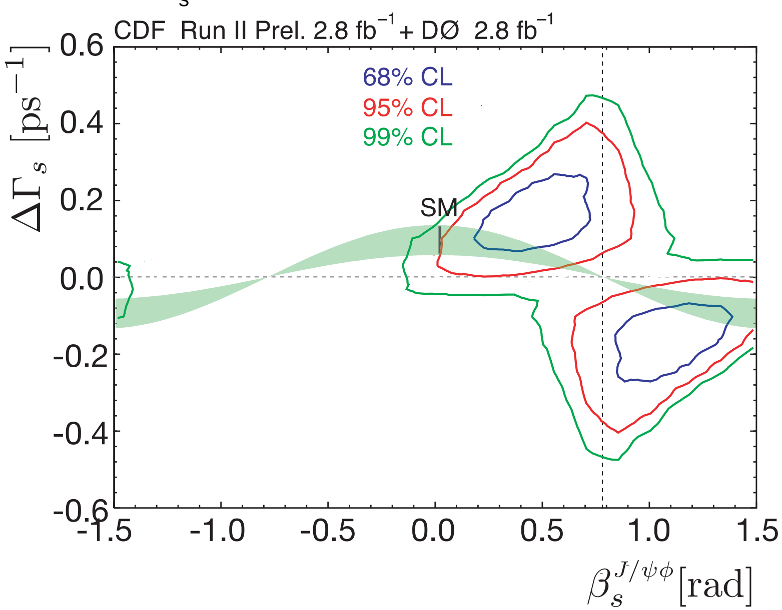
Previous results



CDF 1.35 fb^{-1}
p-value = 15%



CDF 2.8 fb^{-1}
p-value = 7%

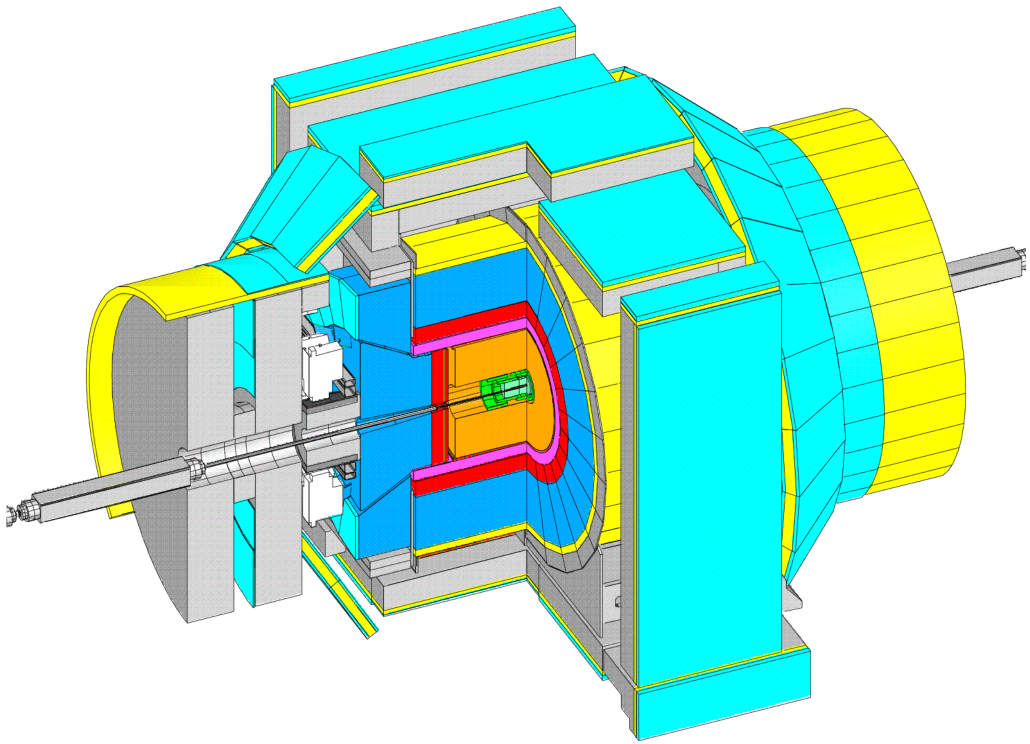


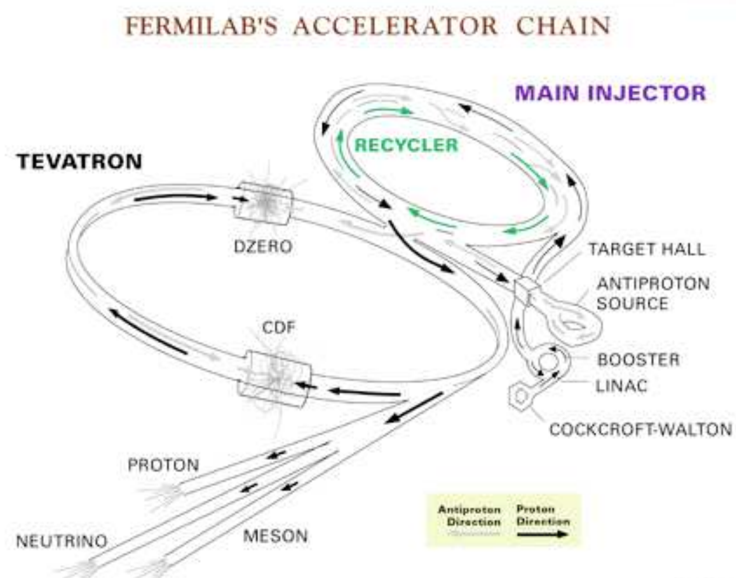
CDF 2.8 fb^{-1} + DØ 2.8 fb^{-1}
p-value = 3.4%

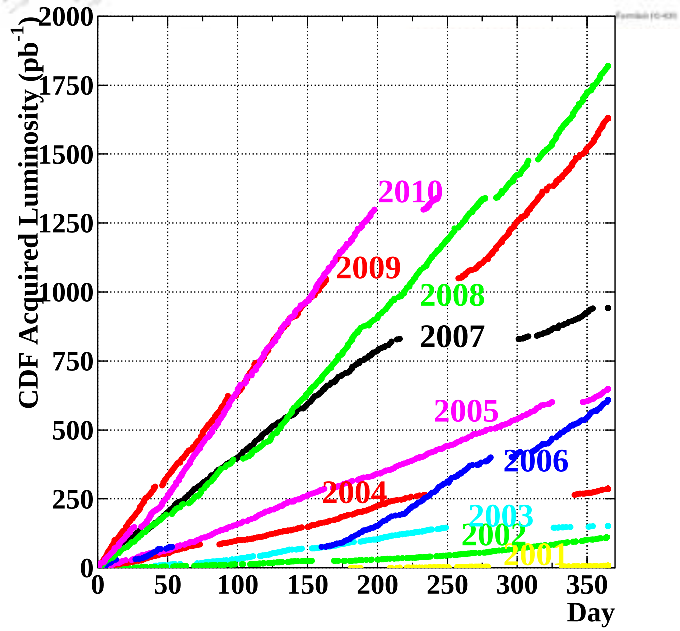
What next?

Tevatron and CDF experiment

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

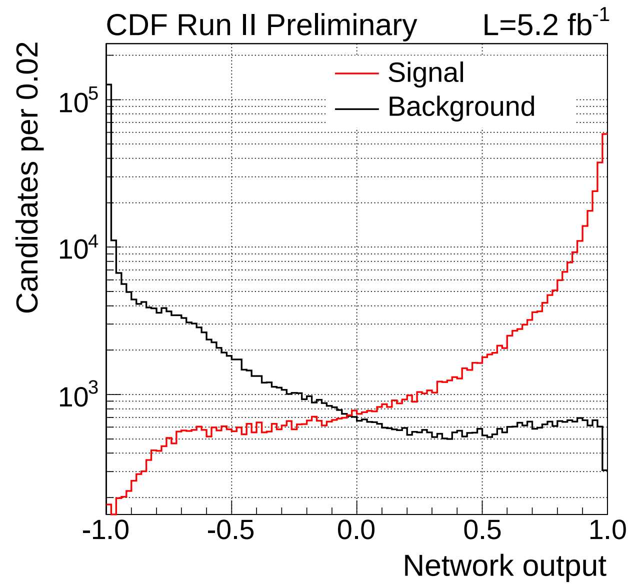


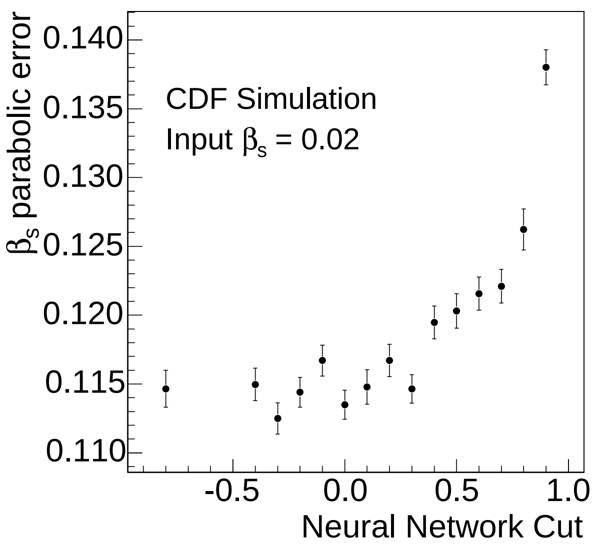


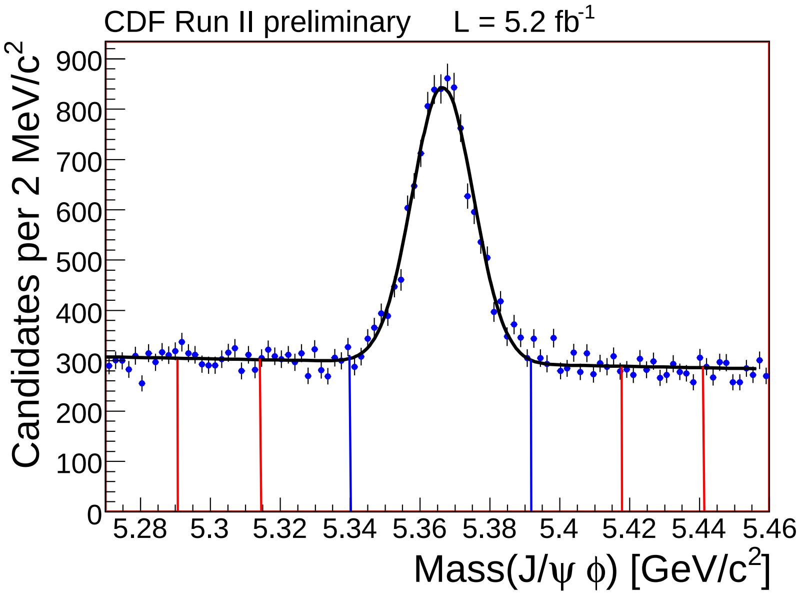


Selection

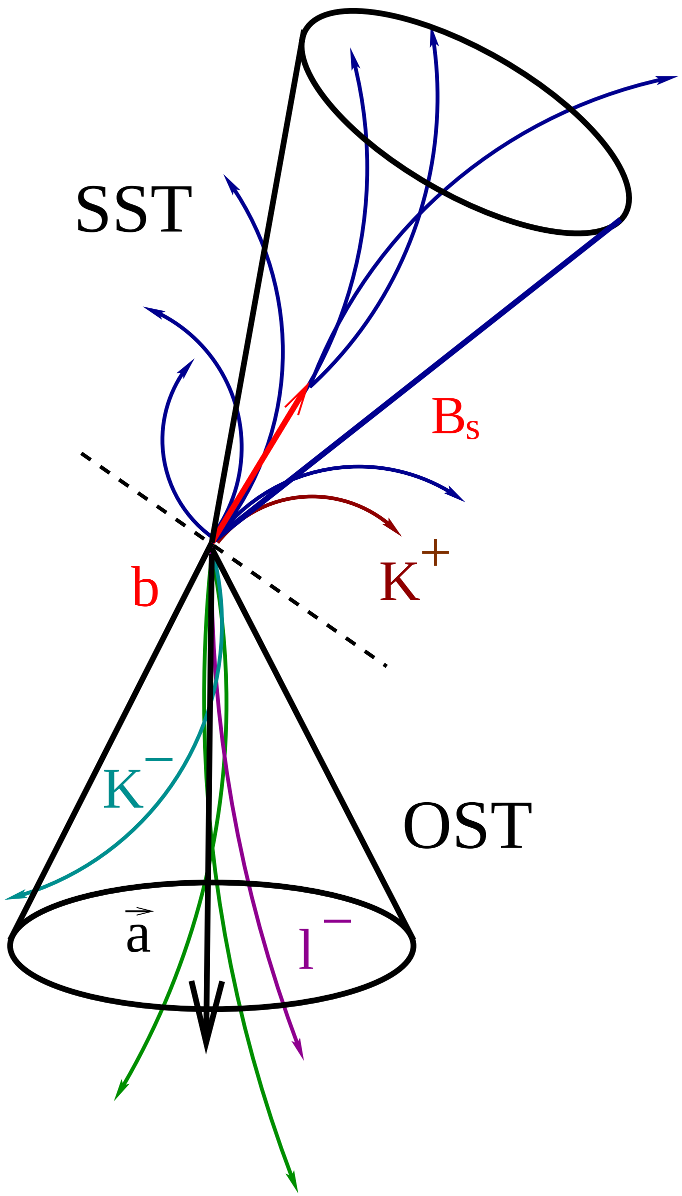
- Latest analysis uses 5.2 fb^{-1}
- Events selected using dimuon trigger
- Typical event has few dozens tracks $\Rightarrow$ lot of background
- Neural network to select interesting events
- Select $\approx$ 6500 $B_s \to J/\psi\phi$ decays

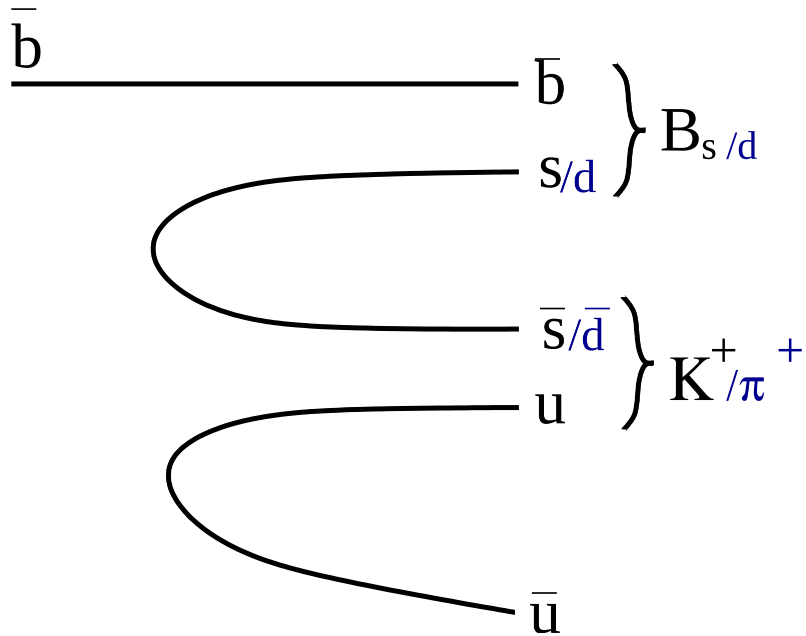






Flavor tagging

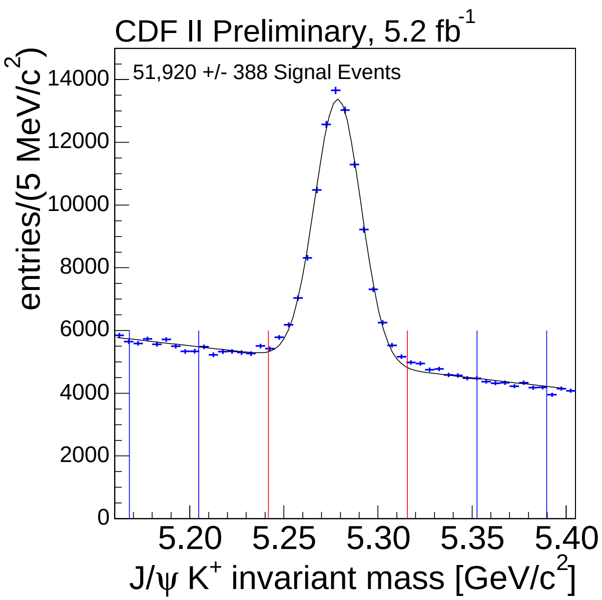


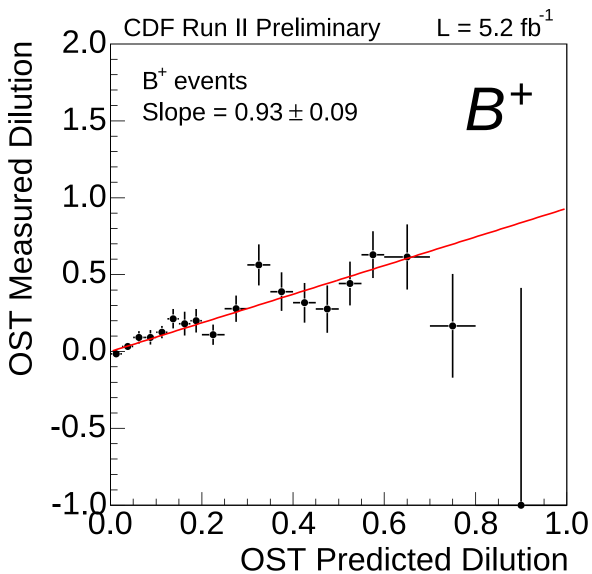


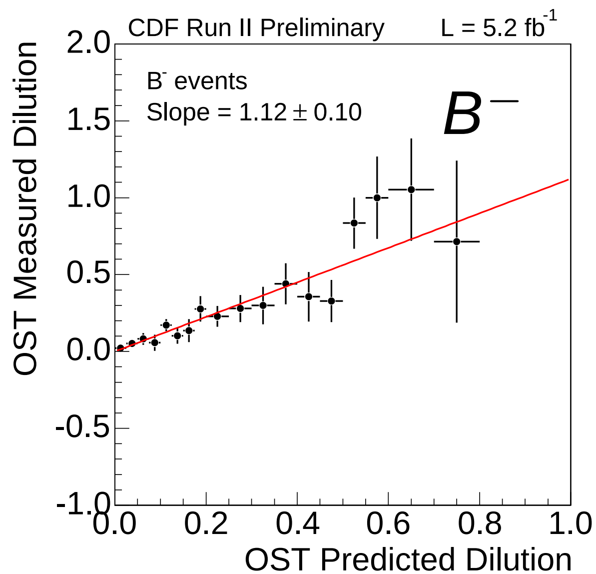
- Determination of the flavor at production time
- Difficult task due to large number of tracks
- Benefits from PID
- Calibrated with data

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 $\epsilon D^2 = 1.2\%$







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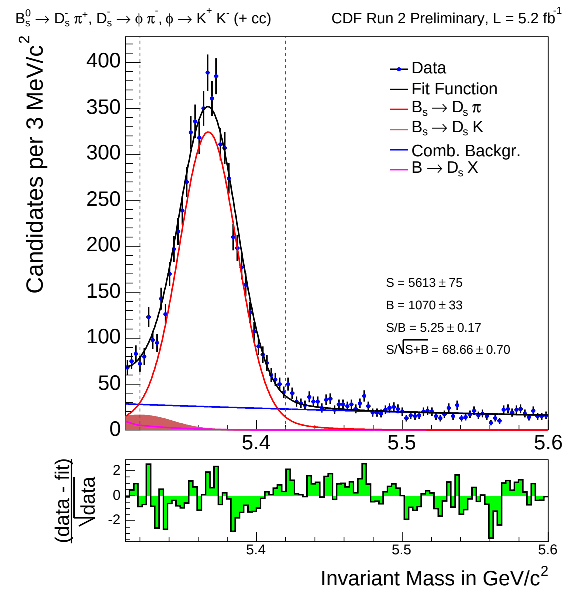
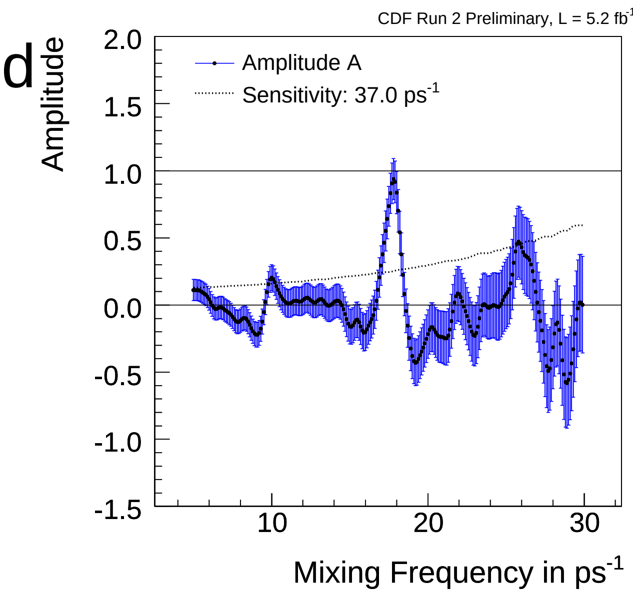
SSKT Calibration

- 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

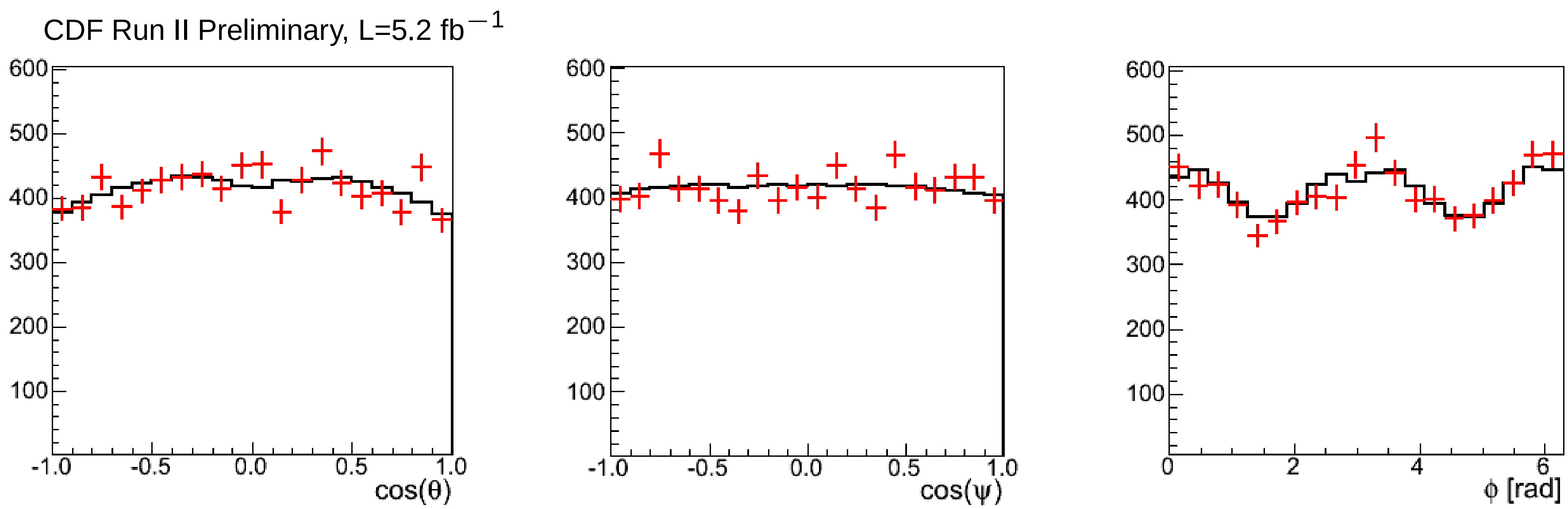
  $$A = \frac{N_{mix} - N_{unmix}}{N_{mix} + N_{unmix}} = A \cdot D \cos(\Delta m t)$$
- Use decays:
  - $B_s \to D_s\pi$ with $D_s \to \phi\pi$, $D_s \to K^*K$ and $D_s \to \pi\pi\pi$
  - $B_s \to D_s\pi\pi\pi$ with $D_s \to \phi\pi$
- In total $\approx$ 12900 signal events
- Total tagging power $\epsilon D^2 = 3.2 \pm 1.4\%$
- $\Delta m_s = 17.79 \pm 0.07(\mathrm{stat})$





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

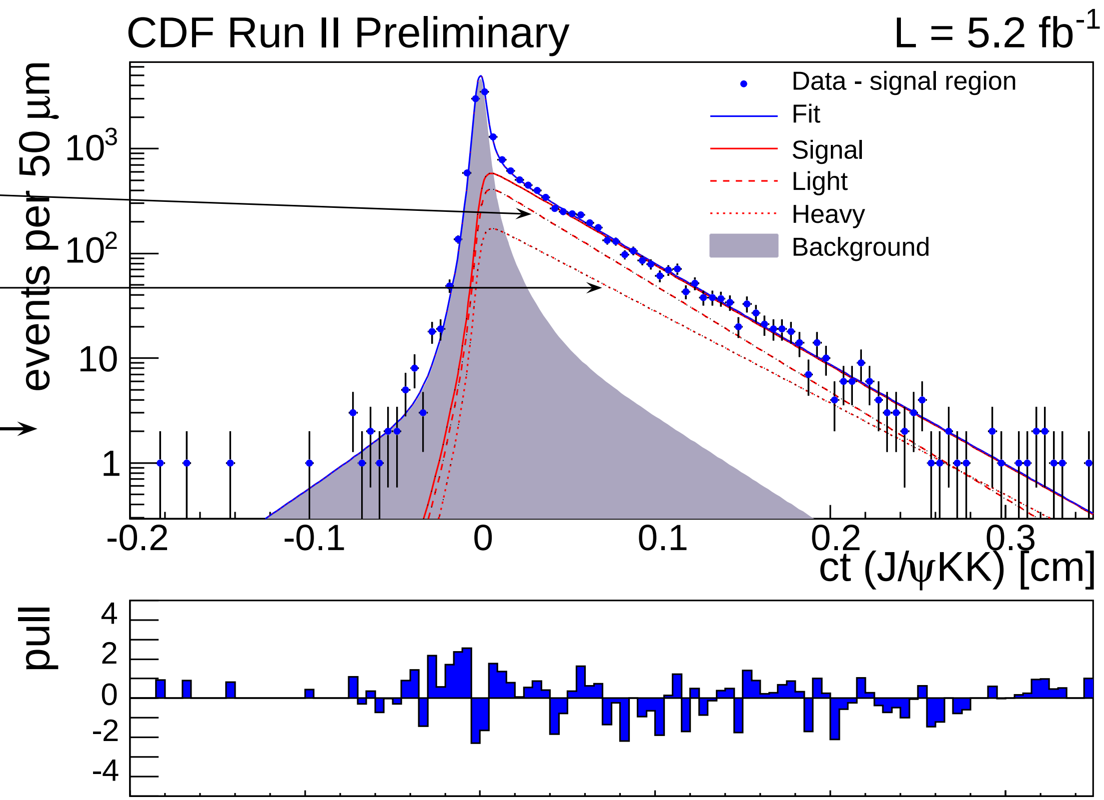


Lifetime and width difference

Distribution for B_{sL}

Distribution for B_{sH}

Signal mass region



Under SM assumption (β_s = 0) we measure:

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

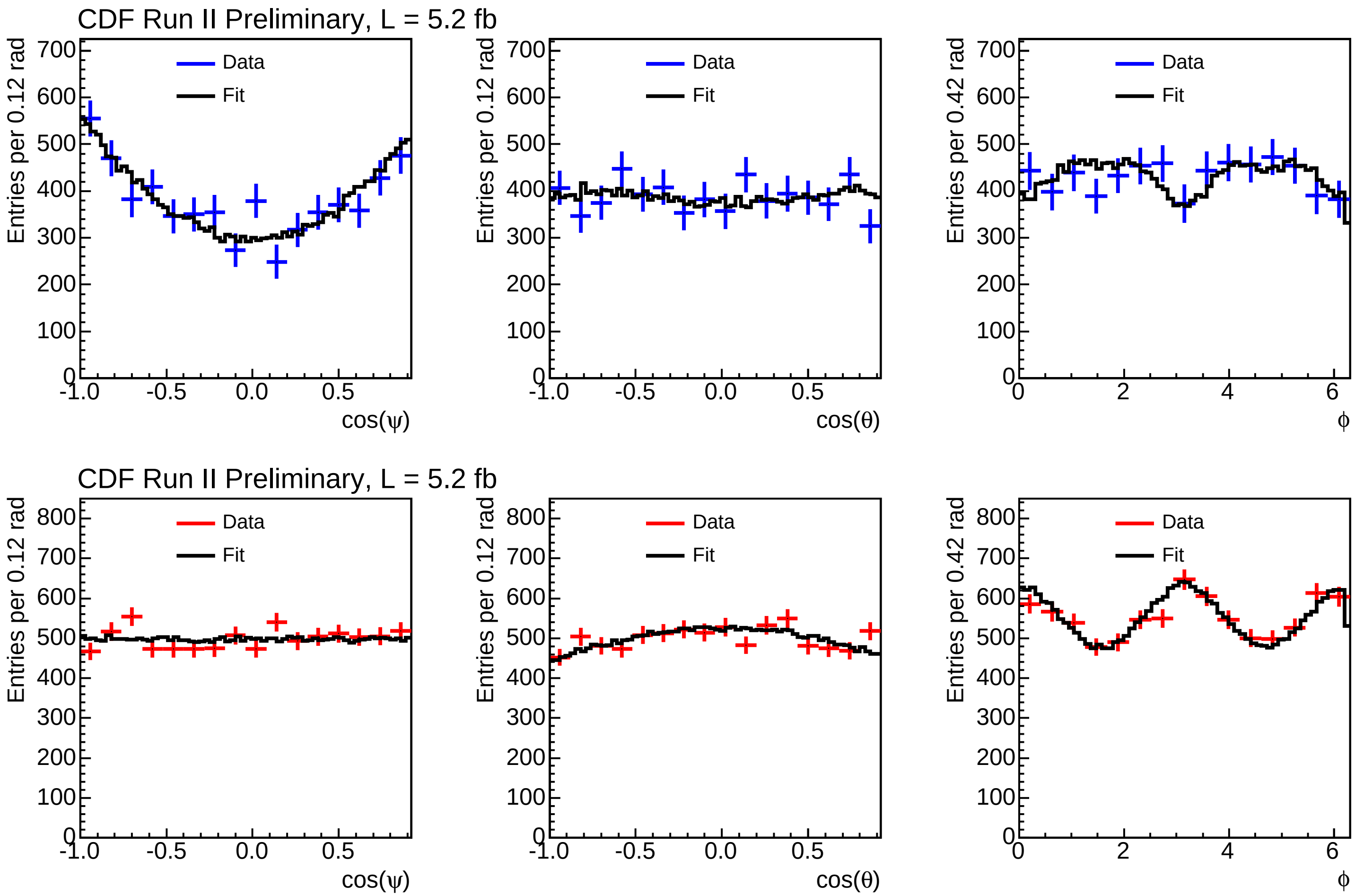
$$\Delta\Gamma_s = 0.075 \pm 0.035(\text{stat}) \pm 0.01(\text{syst})\,ps^{-1}$$

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

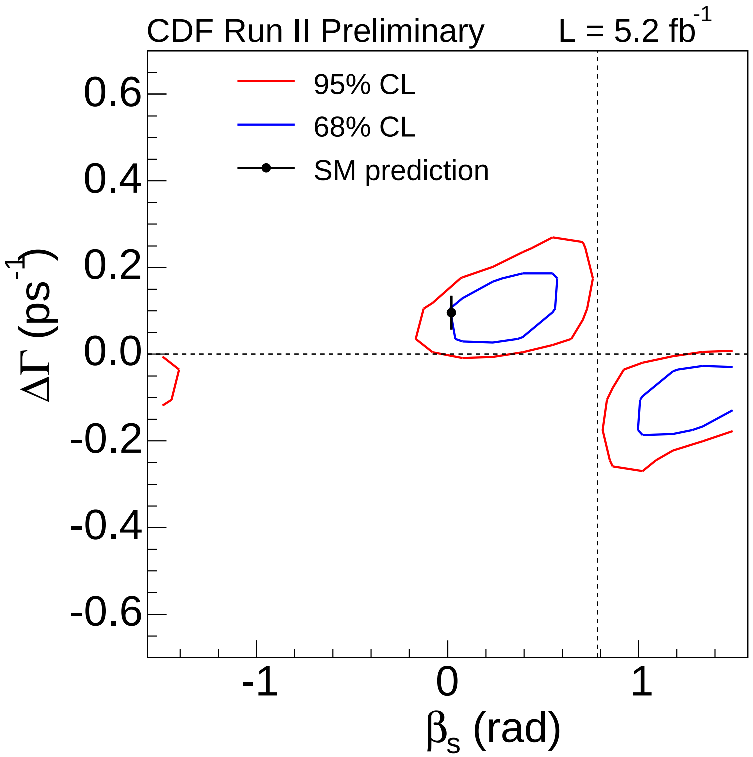
Background

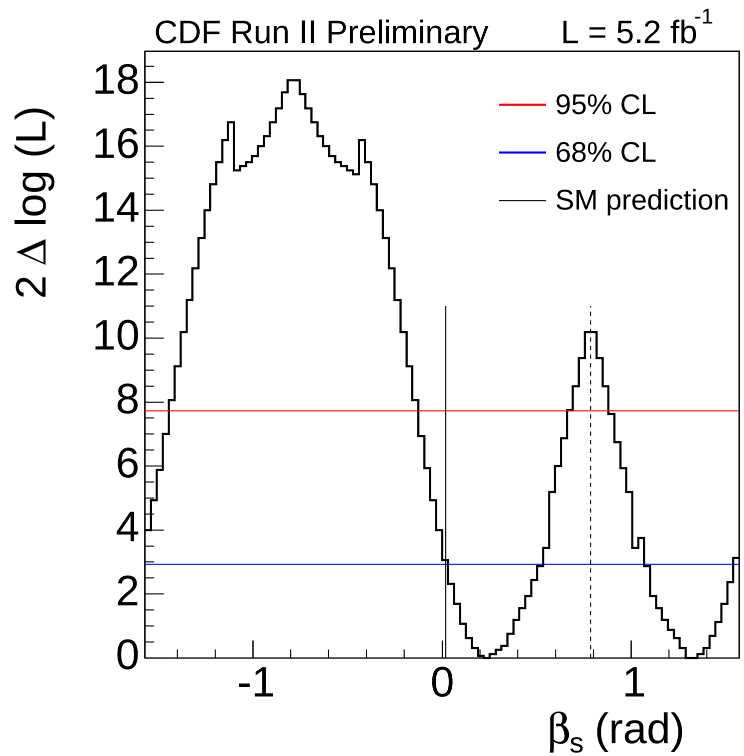


CP Violation

- 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.





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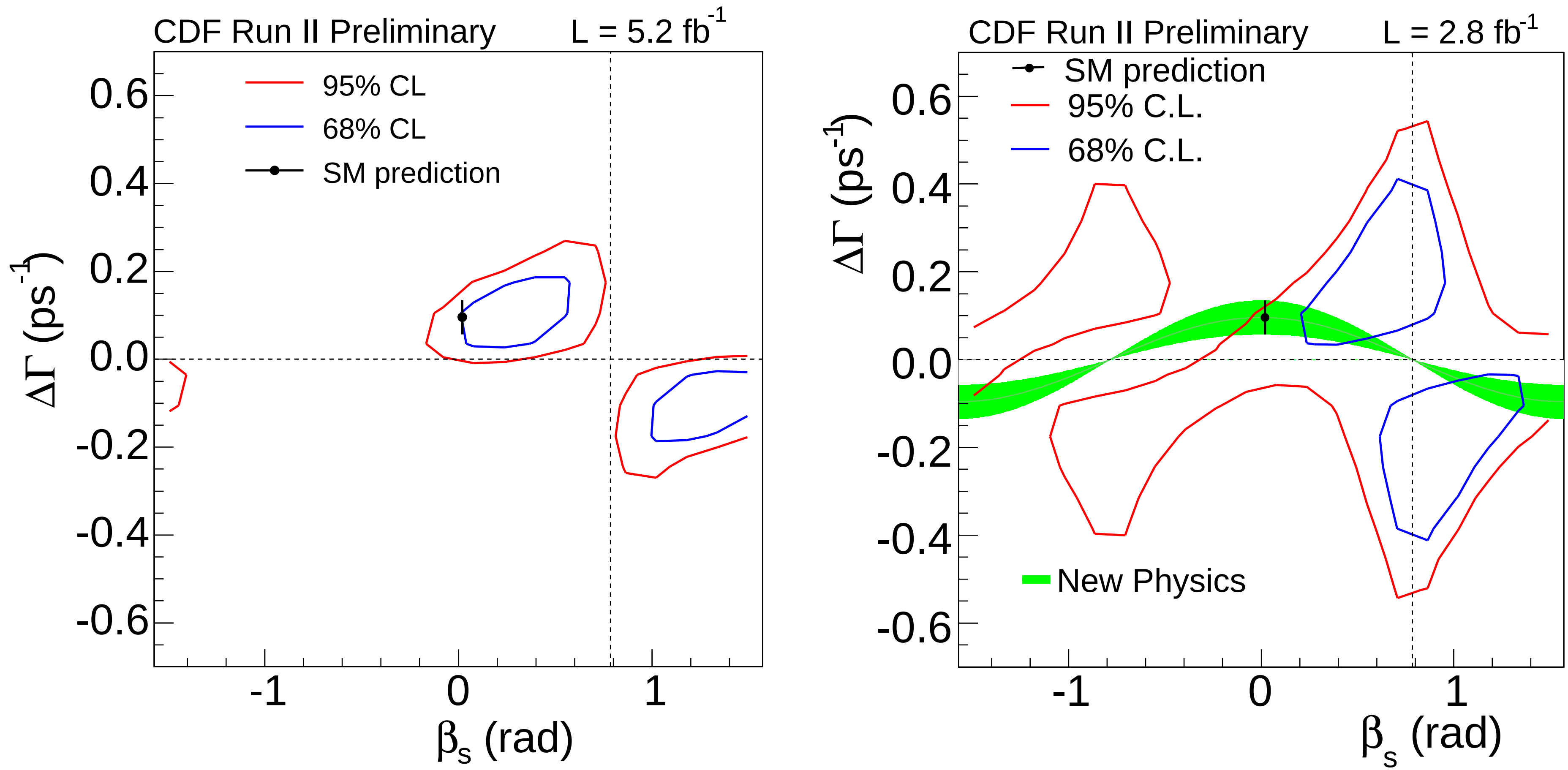
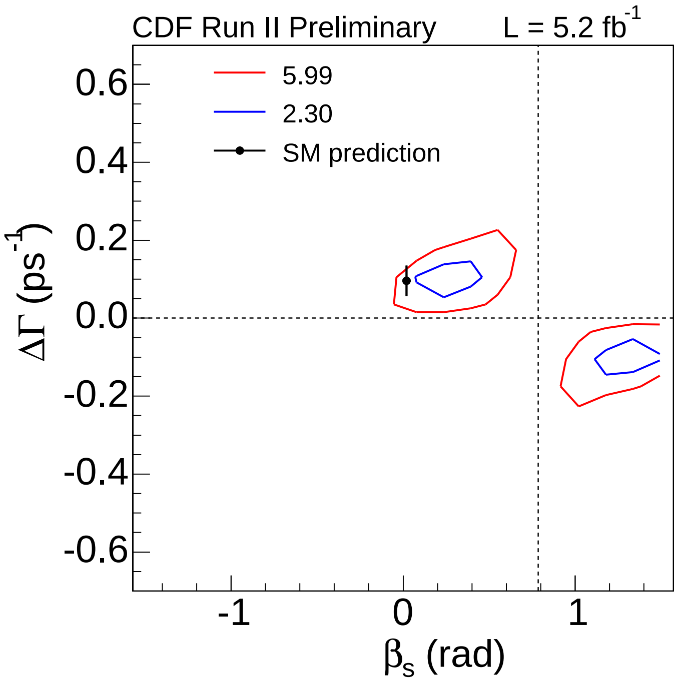
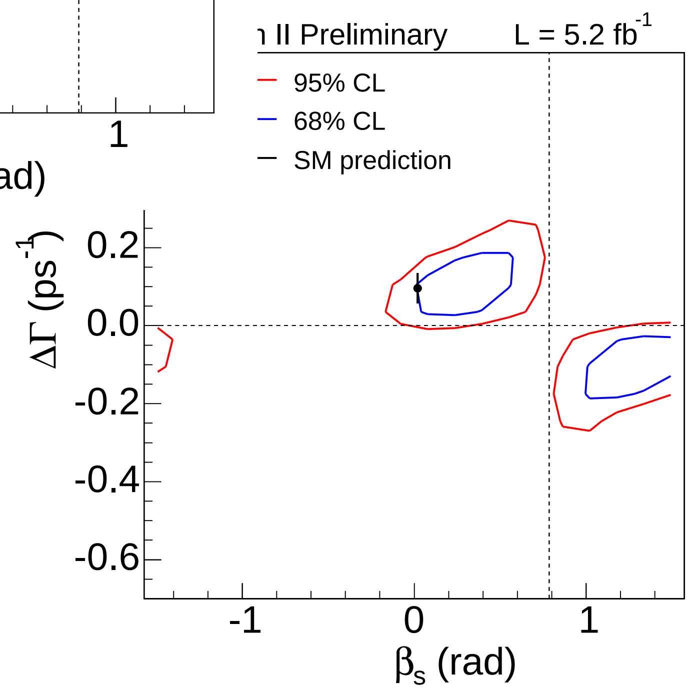
Comparison to previous result

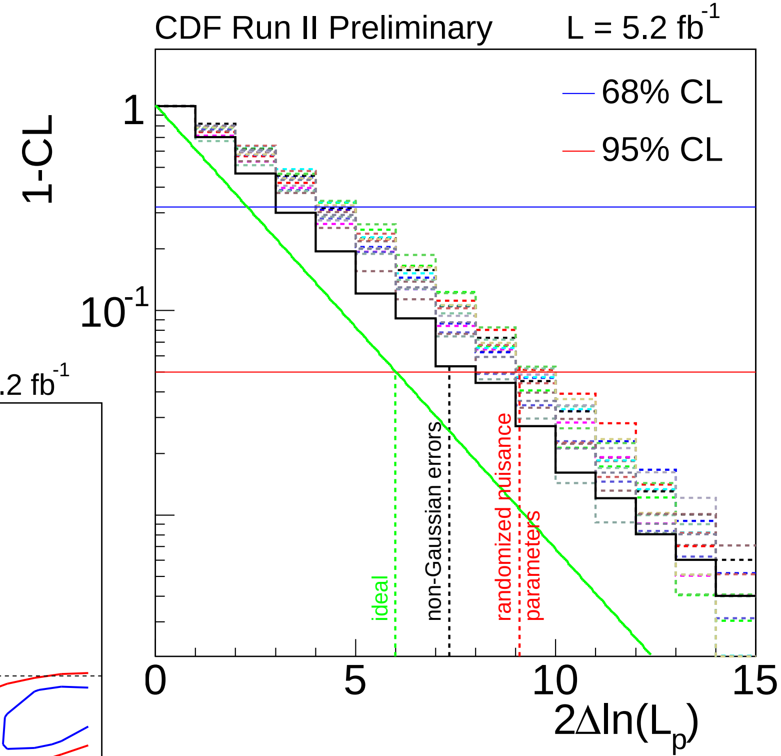


- Concentrate on size of the allowed region
- Significant improvement compared to our previous result

Size of the adjustment







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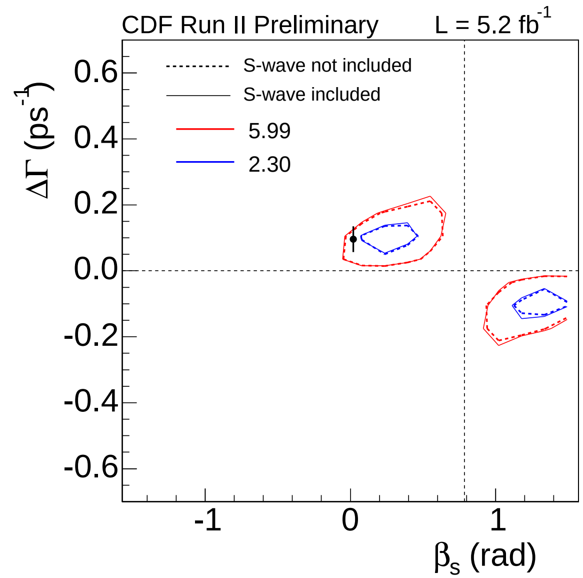
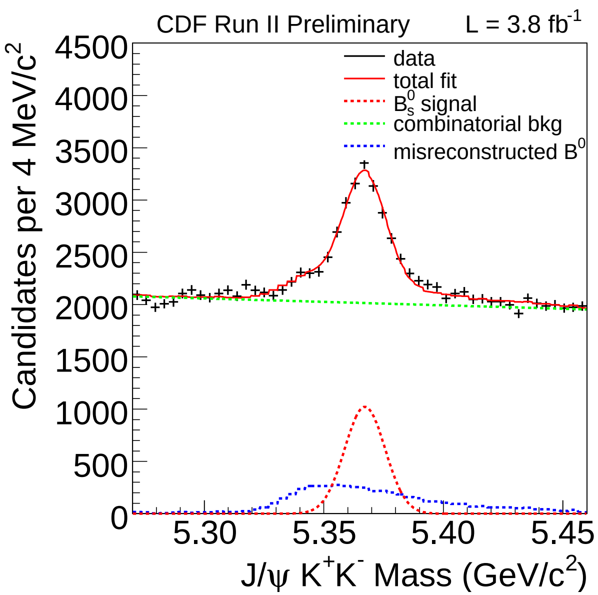
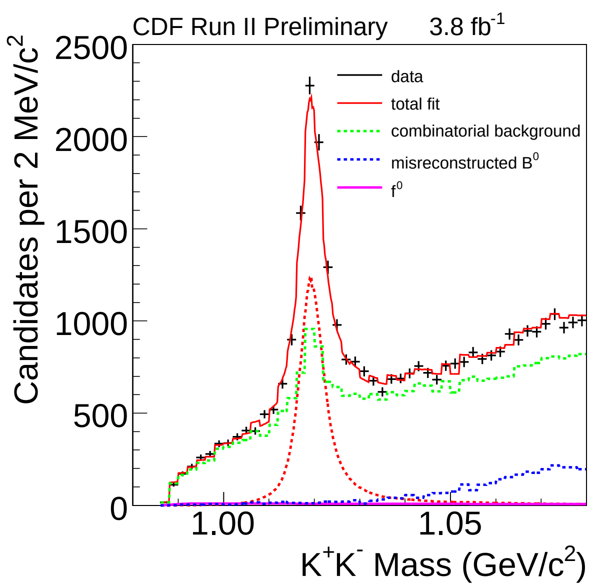
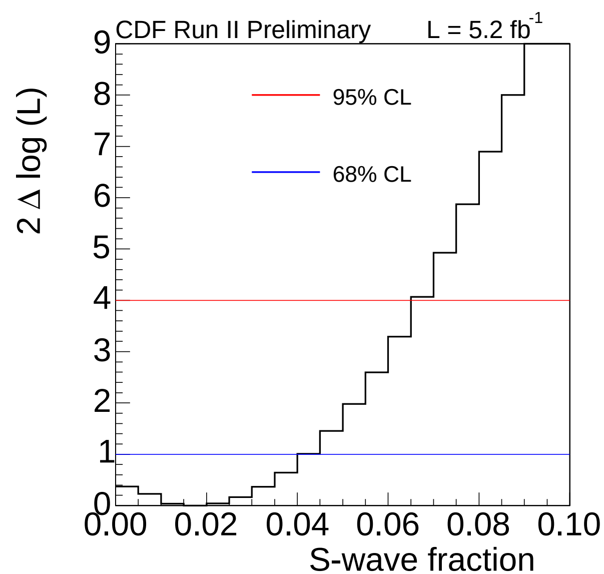
S-wave check

- 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









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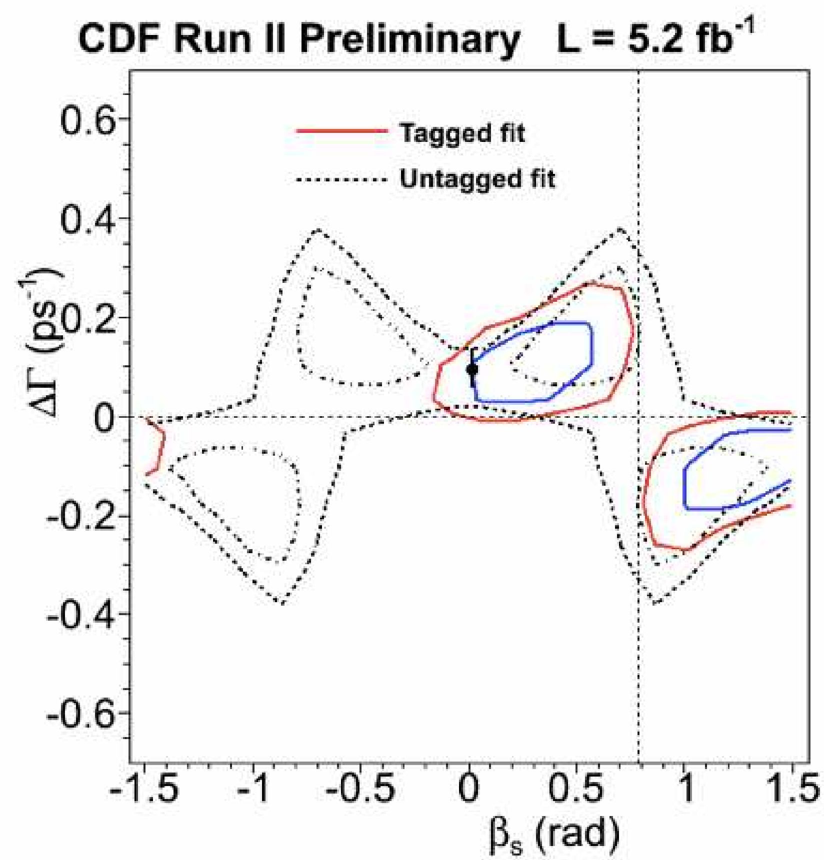
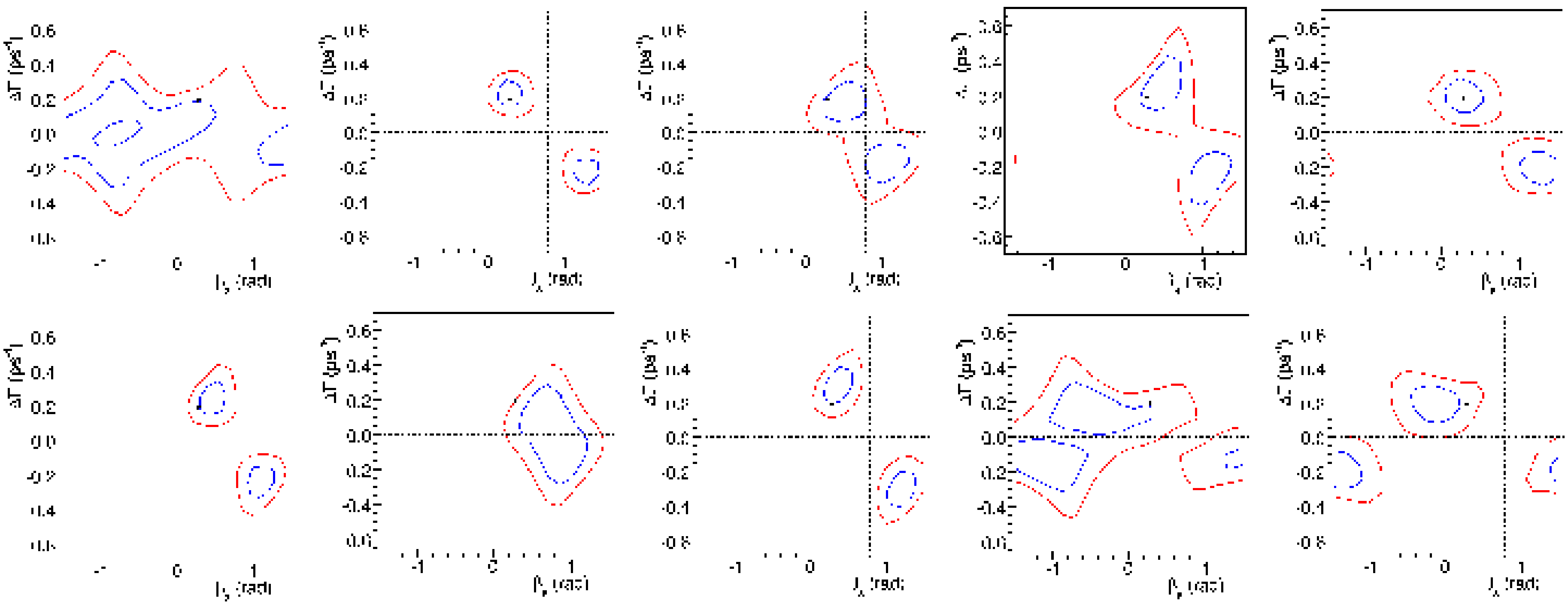
Effect of flavor tagging

- 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
  - $2\beta_s \to -2\beta_s$
    $\delta_\perp \to \delta_\perp + \pi$
  - $\Delta\Gamma \to -\Delta\Gamma$
    $2\beta_s \to 2\beta_s - \pi$
- Tagged symmetry
  - $2\beta_s \to \pi - 2\beta_s$
    $\Delta\Gamma \to -\Delta\Gamma$
    $\delta_{||} \to 2\pi - \delta_{||}$
    $\delta_\perp \to \pi - \delta_\perp$



Different parts of data



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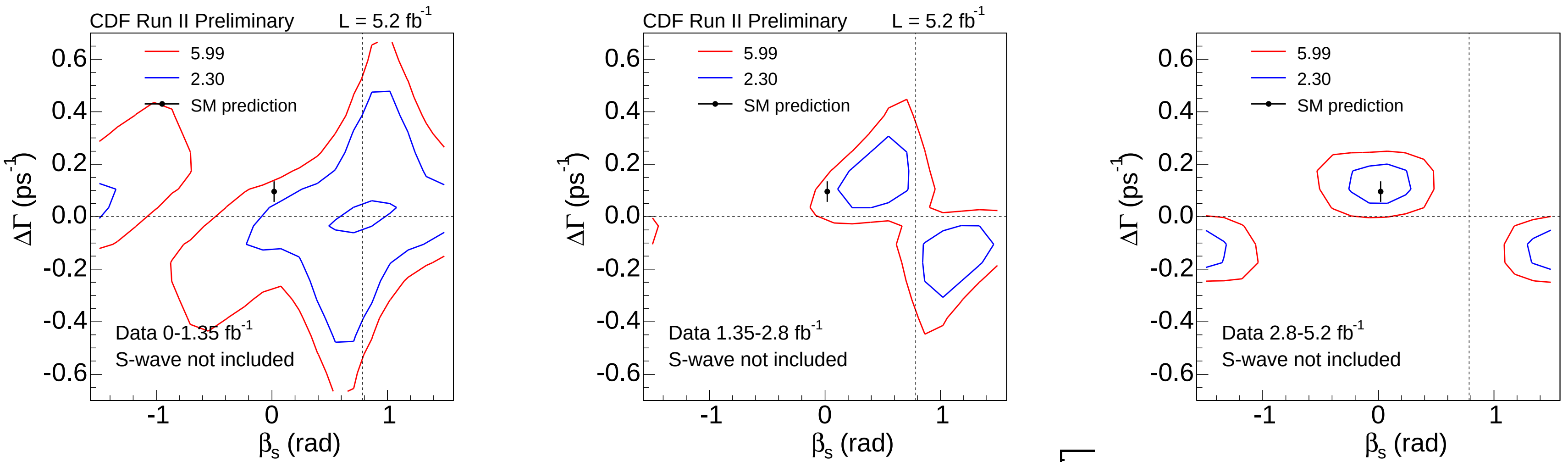
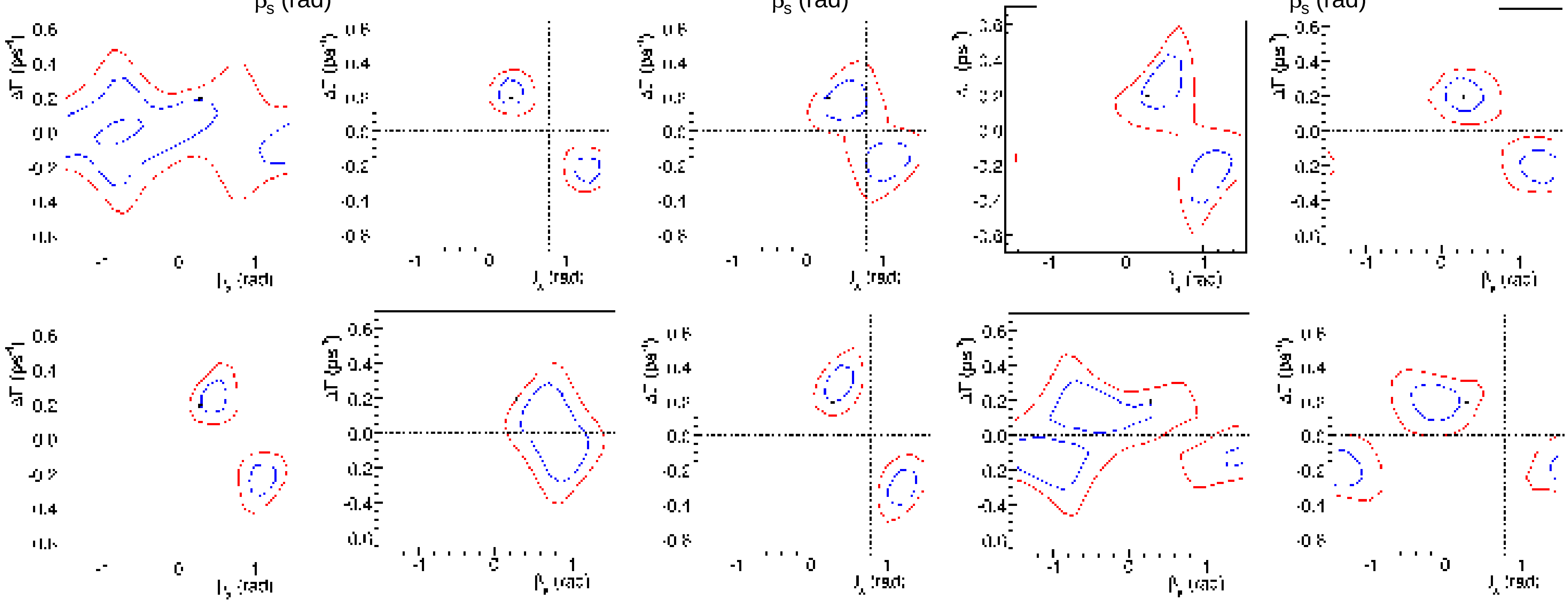
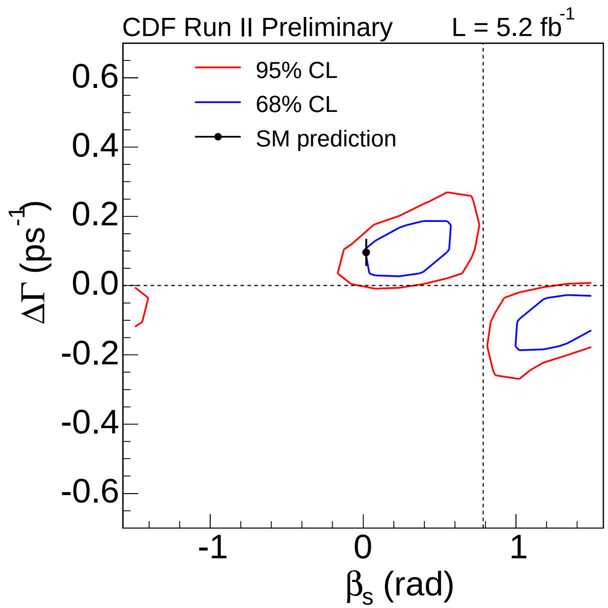
Different parts of data





Conclusions

- Significantly improved measurement of the CPV in $B_s \to J/\psi\phi$
  $\beta_s \in [0.02, 0.52] \cup [1.08, 1.55]$ @ 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 $B_s \to \psi(2S)\phi$
  - Look for $B_s \to J/\psi f_0(980)$ with $f_0(980) \to \pi^+\pi^-$
  - Add K^+K- mass as fit variable - helps in ambiguity resolution
- Still collecting data, expect to have $\approx$ 2 times more by the end of 2011
- Extension of running by 3 years under discussion