Study of CP violation in $B_s \to J/\psi\phi$ decays at CDF

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Search for New Physics in transitions
$\longrightarrow$ Measurement of the properties of oscillating particles:

$$K^0 \qquad B^0 \qquad D^0 \qquad B_s^0$$

Motivation

Search for New Physics in transitions
$\longrightarrow$ Measurement of the properties of oscillating particles:

$$K^0 \qquad B^0 \qquad D^0 \qquad B_s^0$$

- B^0 and K^0 are well explored by other experiments

Search for New Physics in transitions
→ Measurement of the properties of oscillating particles:

$$K^0 \qquad B^0 \qquad D^0 \qquad B_s^0$$

- Evidence for $D^0 - \bar{D}^0$ Mixing, also at CDF [1]

[1] http://www-cdf.fnal.gov/physics/new/bottom/070809.blessed-CharmMixing/dmix_pubnote.pdf

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- B_s^0 sector still partially unexplored.

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- **Now: Measurement of the mixing phase β_s**

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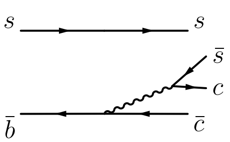
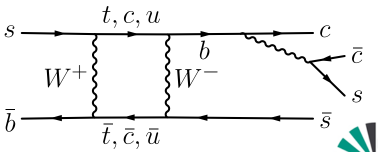
- 2006: **Mixing frequency** Δm_s of the B_s^0 measured by CDF and D∅
- **Now: Measurement of the mixing phase** β_s
- Accessible through interference of decays with and without mixing

$$B_s \longrightarrow J/\Psi(\rightarrow \mu^+\mu^-)\ \phi(\rightarrow K^+K^-)$$





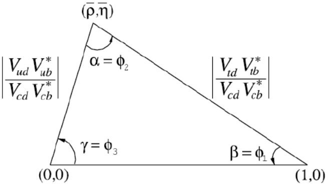
The CKM Matrix

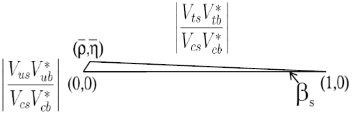
- The Cabibbo-Kobayashi-Maskawa matrix connects mass and weak quark eigenstates

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- To conserve probability, CKM matrix must be unitary.
- Unitary relations can be represented as unitarity triangles.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad\qquad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$





- Subject of this measurement $\boxed{\beta_s^{SM} = arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})}$

Flavor eigenstates of the B_s meson differ from mass eigenstates and mass eigenvalues are different. $\longrightarrow$ B_s oscillates with frequency

$$\Delta m_s = m_H - m_L = (17.77 \pm 0.12) ps^{-1}$$

Mass eigenstates have different decay widths:

$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| cos(\phi_s) \text{ with } \boxed{\phi_s = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)}$$

Standard Model expectation values:

$$\phi_s^{SM} = 4 \cdot 10^{-3} \qquad and \qquad \beta_s^{SM} = 0.02$$

New Physics affects both phases by **same** quantity [1]:

$$2\beta_s^{J/\Psi\phi} = 2\beta_s^{SM} - \phi_s^{NP} \quad \text{and} \quad \phi_s^{J/\Psi\phi} = \phi_s^{SM} + \phi_s^{NP}$$

If the new physics phase ϕ_s^{NP} dominates over the SM phases $2\beta_s^{SM}$ and ϕ_s^{SM} $\longrightarrow$ neglect SM phases and obtain:

$$2\beta_s^{J/\Psi\phi} = -\phi_s^{NP} = -\phi_s^{J/\Psi\phi}$$

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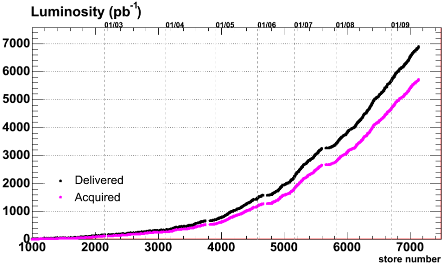
[1] arxiv:0705.3802v2

The Tevatron

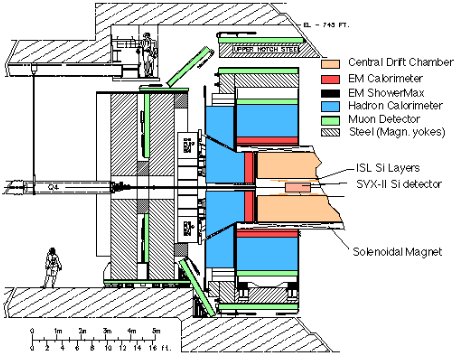
- Tevatron: circular particle accelerator at the Fermilab (near Chicago, Illinois)
- Proton-Antiproton collisions
- $\sqrt{s} = 1.96$ TeV
- Two detectors: CDF and D∅



Luminosity / Experiment:

Int. Lumi.	fb^{-1}
delivered	≈ 7.0
on tape	≈ 5.8
this analysis	≈ 2.8

The CDF Detector



Multi purpose detector featuring ...

- Tracking system contained inside a solenoid
- Electromagnetic and hadronic calorimeters
- Muon detectors ($|\eta| < 2$)
- Particle identification (dE/dx and TOF)

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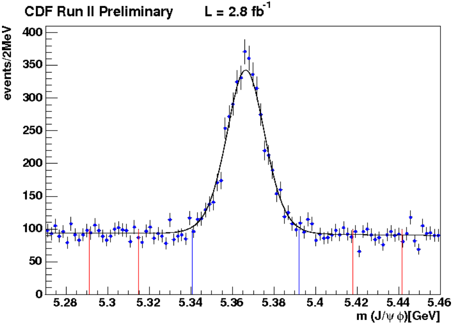
Signal Sample

Mixing phase β_s and decay width difference $\Delta\Gamma$ are extracted using an unbinned maximum likelihood fit in

- **Mass**
- Transversity angles and Proper decay time
- Tagging information



$\approx$ 3200 events

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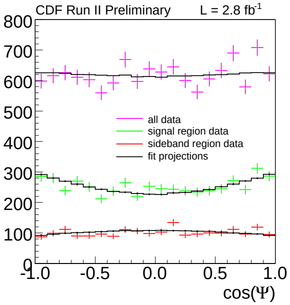

An angular analysis is performed to disentangle **CP even** and **CP odd** components. $\rightarrow$ increase sensitivity on β_s

$\vec{\rho} = (\Psi_T, \theta_T, \phi_T)$ are angles given in the transversity basis[a]

[a] hep-ph/9511363

Proper Decay Time

Mixing phase β_s and decay width difference $\Delta\Gamma$ are extracted using an unbinned maximum likelihood fit in

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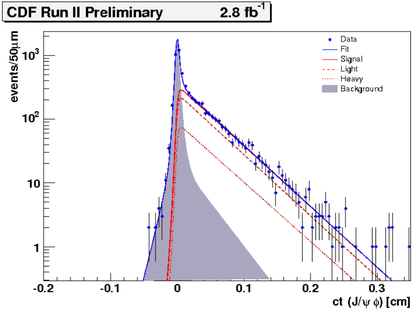

Mean lifetime assuming no CP violation ($\beta_s^{J/\Psi\phi} = 0$):

$$\tau(B_s) = (1.53 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.}))\ \text{ps}$$

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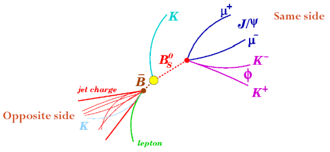
Flavour Tagging

Mixing phase β_s and decay width difference $\Delta\Gamma$ are extracted using an unbinned maximum likelihood fit in

- Mass
- Transversity angels and Proper decay time
- **Tagging information**



Tagging used to increase the sensitivity on the parameters.

Approach:

- **OST:** exploits decay products of other b-hadron in the event ($\epsilon D^2 \approx$ 1.2 %)
- **SST:** exploits the correlations with particles produced in fragmentation ($\epsilon D^2 \approx$ 3.6 %, used in this analysis only in $\mathcal{L}_{int} < 1.4$ fb^{-1})

Output: Decision (b or $\bar{b}$) and probability of being correct

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Breaking News: First CDF amplitude scan after the 2006 observation paper!

Performance of the flavour tagger can be determined **on data** by measuring the **amplitude of the oscillation**.

Decay channel:

$$B_s^0 \to D_s^-(\to \phi(\to K^+K^-)\pi^-)\pi^+$$

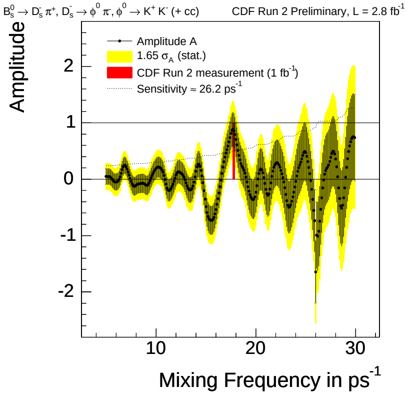
Tagger:

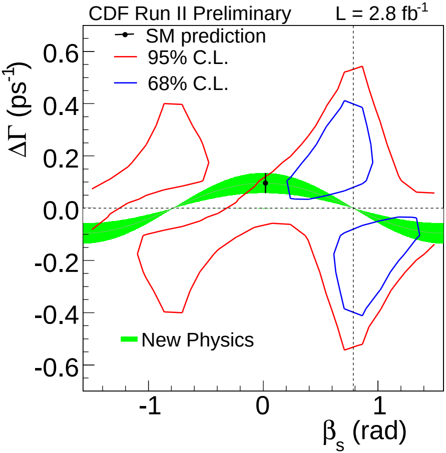
SSKT

Amplitude Interpretation:

$A < 1.0$: tagger overestimates itself

$A > 1.0$: tagger underestimates itself



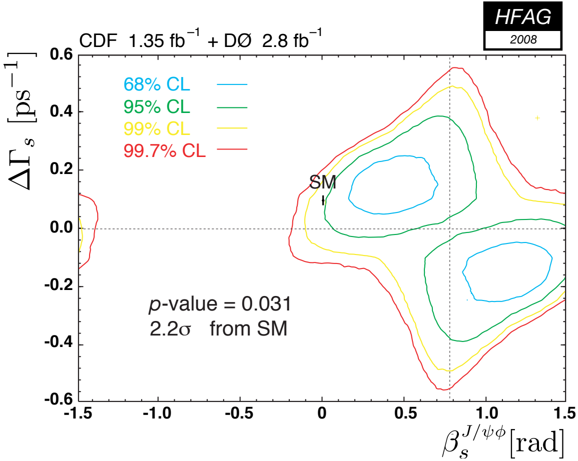


- Errors of β_s and $\Delta\Gamma$ are not Gaussian $\longrightarrow$ study confidence region
- $p - value = 7\%$
- 1.8 σ from SM

[2] http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

[3] arXiv:0712.2397v1 [hep-ex]

Combination of the up-to-date DØ measurement with the previous CDF measurement [4]:



$$p - value = 3.1\%$$
$$2.2\ \sigma \text{ from SM}$$

[4] arXiv:0808.1297v3 [hep-ex]

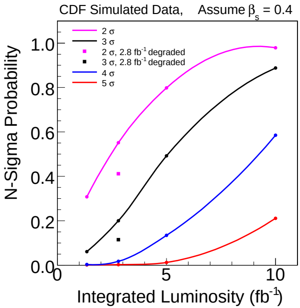
Evolution in the Past and Future Possibilities

Evolution of the deviation from the SM:

Date	Analysis	Deviation
Dec 2007	CDF (1.35/fb)	1.5 σ
Mar 2008	D∅ (2.8/fb)	1.7 σ
Jul 2008	CDF (2.8/fb)	1.8 σ
Jul 2008	Combination	2.2 σ

Fluctuations? Maybe! But the coherent pattern is interesting!

Probability to observe a non-SM β_s at CDF:



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Future Plans:

- Collect more data, perhaps even in 2011
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- Improvements in Tagging and PID
- Add other decay channels, e.g. $B_s \to J/\psi f_0$

Thanks for your Attention

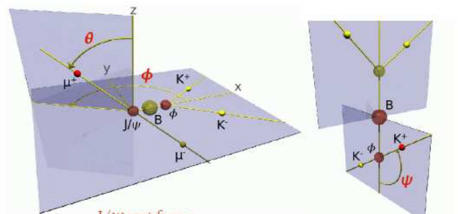
and

Stay tuned for Updates!

$$\begin{array}{cccc} B_s & \longrightarrow & J/\Psi\ (\rightarrow \mu^+\mu^-) & \phi\ (\rightarrow K^+K^-) \\ \text{(spin=0)} & & \text{(spin=1)} & \text{(spin=1)} \end{array}$$

Conservation of angular momentum lead to three different final states:

L = 0, 2	(s-wave),(d-wave)	CP even
L = 1	(p-wave)	CP odd



J/ψ rest frame φ rest frame

Choice of basis:

Transversity basis[a] with corresponding decay amplitudes:

$A_\perp$	CP odd
A_0	CP even
$A_\parallel$	CP even

and angles

$$\vec{\rho} = (\Psi_T, \theta_T, \phi_T)$$

[a] hep-ph/9511363

Time evolution of B_s **flavor eigenstates** described by Schrödinger equation:

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

Diagonalize mass (M) and decay matrices (Γ) → **mass eigenstates**:

$$\begin{aligned}|B_s^H(t)> &= p|B_s^0(t)> - q|\bar{B}_s^0(t)> \\ |B_s^L(t)> &= p|B_s^0(t)> + q|\bar{B}_s^0(t)>\end{aligned}$$

Flavor eigenstates differ from mass eigenstates and mass eigenvalues are different. B_s oscillates with frequency $\Delta m_s = m_H - m_L \approx 2|M_{12}|$

$$\Delta m_s = (17.77 \pm 0.12)ps^{-1}$$

Mass eigenstates have different decay widths:

$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|cos(\phi_s)$ with $\boxed{\phi_s = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)}$

The different phases and their SM expectation value:

$$\phi_s^{SM} = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4 \cdot 10^{-3} \qquad and \qquad \beta_s^{SM} = arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = 0.02$$

New Physics affects both phases by **same** quantity [5]:

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If the new physics phase ϕ_s^{NP} dominates over the SM phases $2\beta_s^{SM}$ and ϕ_s^{SM}
$\rightarrow$ neglect SM phases and obtain:

$$2\beta_s^{J/\Psi\phi} = -\phi_s^{NP} = -\phi_s^{J/\Psi\phi}$$

[5] arxiv:0705.3802v2

Time and angular probability for B_s^0:

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

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

$$\mathcal{U}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2) + \eta\cos(\Delta m_s t)\ \sin(\delta_\perp - \delta_{||}) - \eta \sin(\Delta m_s t)\ \cos(\delta_\perp - \delta_{||})\ \cos(2\beta_s)\right]$$

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Time and angular probability for B_s^0:

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Explanation

- Angular functions

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

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Lifetime and Transversity Angels

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Explanation

- Angular functions
- Polarization amplitudes
- Time evolution
- Strong phases
  $\delta_\perp = arg(A_\perp A_0^*)$
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$$+ |A_\perp|^2 f_3(\vec{\rho})\mathcal{T}_-(t) + |A_0||A_{||}| f_5(\vec{\rho}) \cos(\delta_{||})\mathcal{T}_+(t)$$
$$+ |A_{||}||A_\perp| f_4(\vec{\rho})\mathcal{U}(t) + |A_0||A_\perp| f_6(\vec{\rho})\mathcal{V}(t)$$

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

$$\mathcal{U}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2) + \eta\cos(\Delta m_s t)\ \sin(\delta_\perp - \delta_{||}) - \eta\sin(\Delta m_s t)\ \cos(\delta_\perp - \delta_{||})\ \cos(2\beta_s)\right]$$

$$\mathcal{V}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2) + \eta\cos(\Delta m_s t)\ \sin(\delta_\perp) - \eta\sin(\Delta m_s t)\ \cos(\delta_\perp)\ \cos(2\beta_s)\right]$$

Explanation

- Angular functions
- Polarization amplitudes
- Time evolution
- Strong phases
  $\delta_\perp = arg(A_\perp A_0^*)$
  $\delta_{||} = arg(A_{||} A_0^*)$
- Decay width difference

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Lifetime and Transversity Angels

Time and angular probability for B_s^0:

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

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

$$\mathcal{U}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2) + \eta\cos(\Delta m_s t)\ \sin(\delta_\perp - \delta_{||}) - \eta\sin(\Delta m_s t)\ \cos(\delta_\perp - \delta_{||})\ \cos(2\beta_s)\right]$$

$$\mathcal{V}(t) = e^{-\Gamma t}\left[\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2) + \eta\cos(\Delta m_s t)\ \sin(\delta_\perp) - \eta\sin(\Delta m_s t)\ \cos(\delta_\perp)\ \cos(2\beta_s)\right]$$

Explanation

- Angular functions
- Polarization amplitudes
- Time evolution
- Strong phases $\delta_\perp = arg(A_\perp A_0^*)$ $\delta_\parallel = arg(A_\parallel A_0^*)$
- Decay width difference
- CPV Phase

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Angular Functions

$$
\begin{aligned}
f_1(\vec{\rho}) &= 2cos^2\Psi_T(1 - sin^2\theta_T cos^2\phi_T) \\
f_2(\vec{\rho}) &= sin^2\Psi_T(1 - sin^2\theta_T sin^2\phi_T) \\
f_3(\vec{\rho}) &= sin^2\Psi_T sin^2\theta_T \\
f_4(\vec{\rho}) &= -sin^2\Psi_T sin2\theta_T sin\phi_T \\
f_5(\vec{\rho}) &= 1/\sqrt{2} sin2\Psi_T sin^2\theta_T sin2\phi_T \\
f_6(\vec{\rho}) &= 1/\sqrt{2} sin2\Psi_T sin2\theta_T cos\phi_T
\end{aligned}
$$

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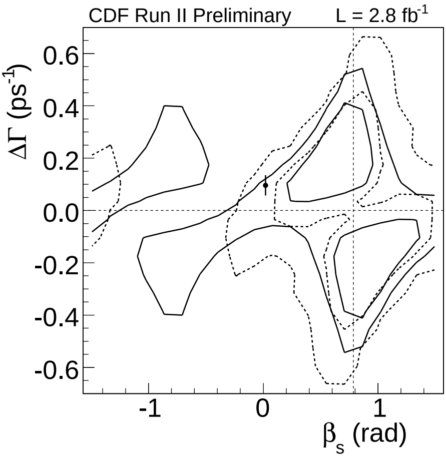
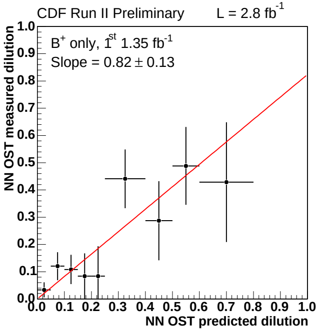
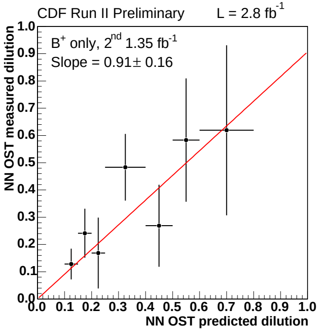
2D likelihood profile comparison with published result

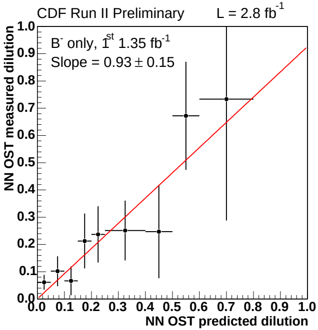


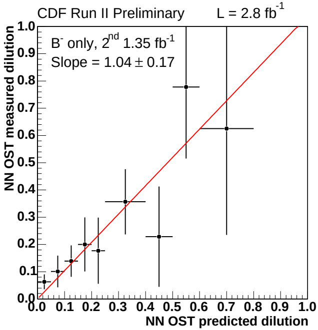
OST in B^+


CDF Run II Preliminary
L = 2.8 fb^-1
B+ only, 1st 1.35 fb^-1
Slope = 0.82 ± 0.13
NN OST measured dilution
NN OST predicted dilution


CDF Run II Preliminary
L = 2.8 fb^-1
B+ only, 2nd 1.35 fb^-1
Slope = 0.91± 0.16
NN OST measured dilution
NN OST predicted dilution

OST in B^-





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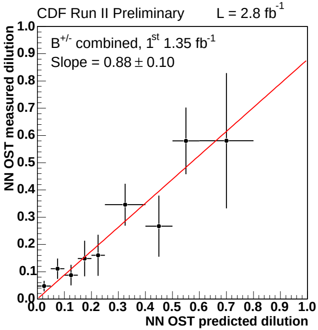
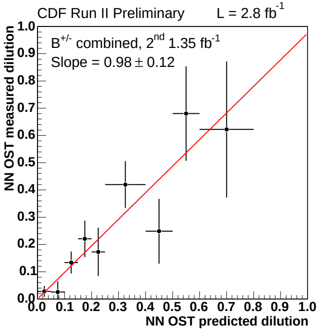
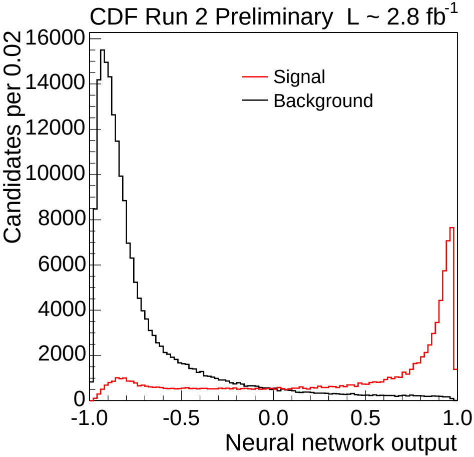
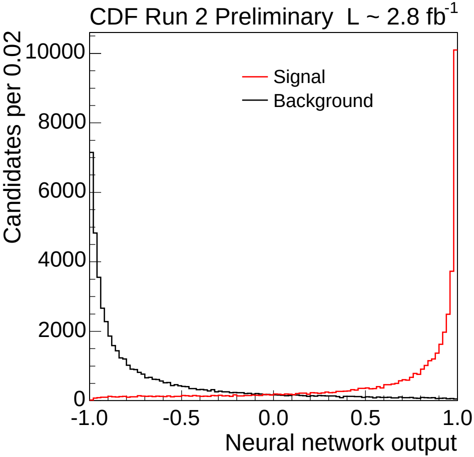
OST in $B^{\pm}$


CDF Run II Preliminary
L = 2.8 fb-1
B+/- combined, 1st 1.35 fb-1
Slope = 0.88 ± 0.10
NN OST measured dilution
NN OST predicted dilution

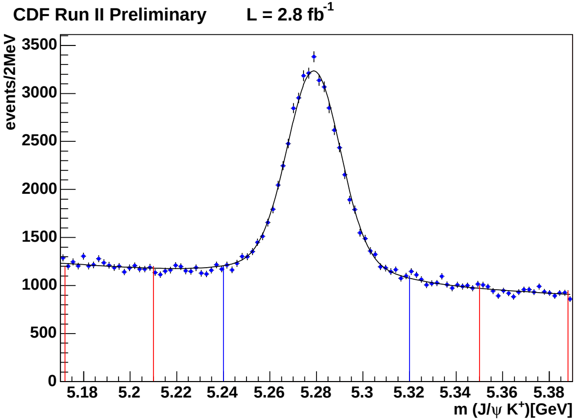

CDF Run II Preliminary
L = 2.8 fb-1
B+/- combined, 2nd 1.35 fb-1
Slope = 0.98 ± 0.12
NN OST measured dilution
NN OST predicted dilution

Neural Network for $B^{\pm}$




CDF Run 2 Preliminary L ~ 2.8 fb-1
Candidates per 0.02
10000
8000
6000
4000
2000
0
-1.0
-0.5
0.0
0.5
1.0
Neural network output
Signal
Background

Invariant Mass of B^+



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