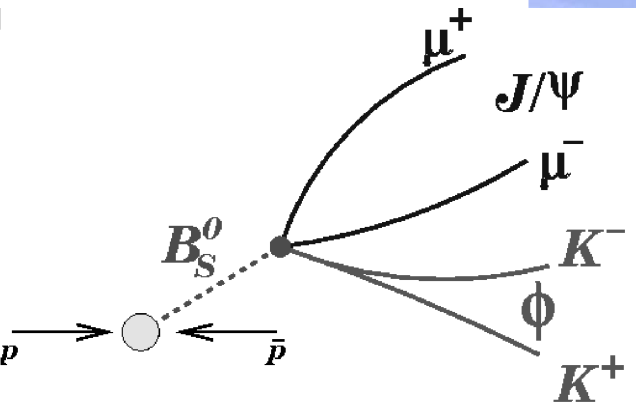
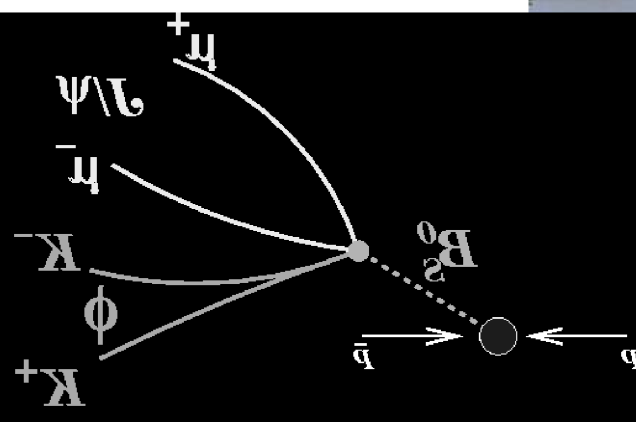
Study of CP violation in $B_s^0 \rightarrow J/\Psi\ \Phi$ at CDF





Ignatio Redondo
on behalf of the
CDF Collaboration

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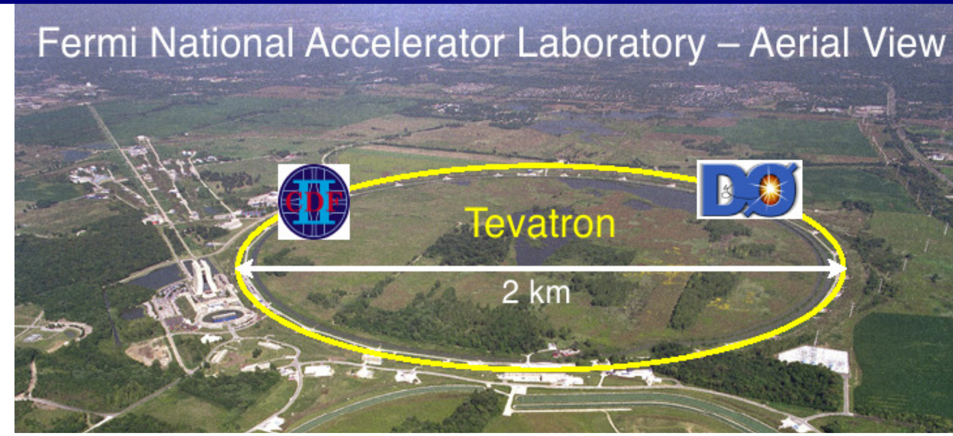
Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

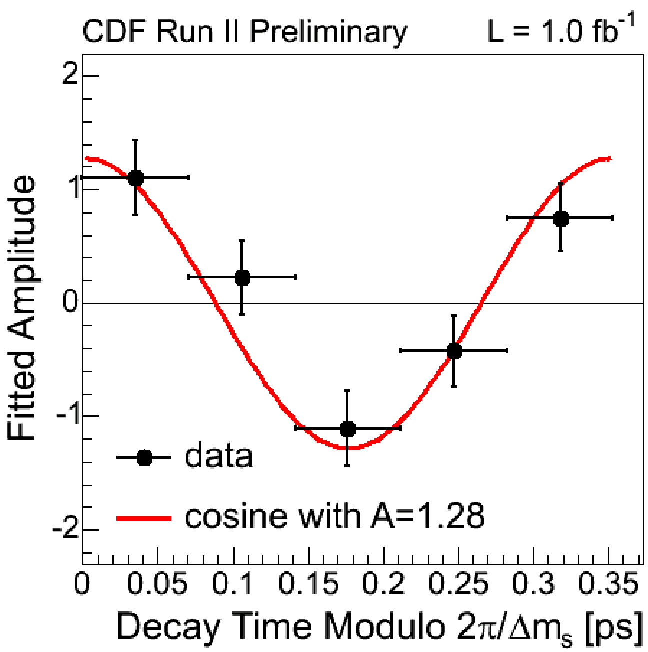
Intro



- Proton-Antiproton Collider
- 1.96 TeV Center of Mass
- Huge b xsec at Tevatron

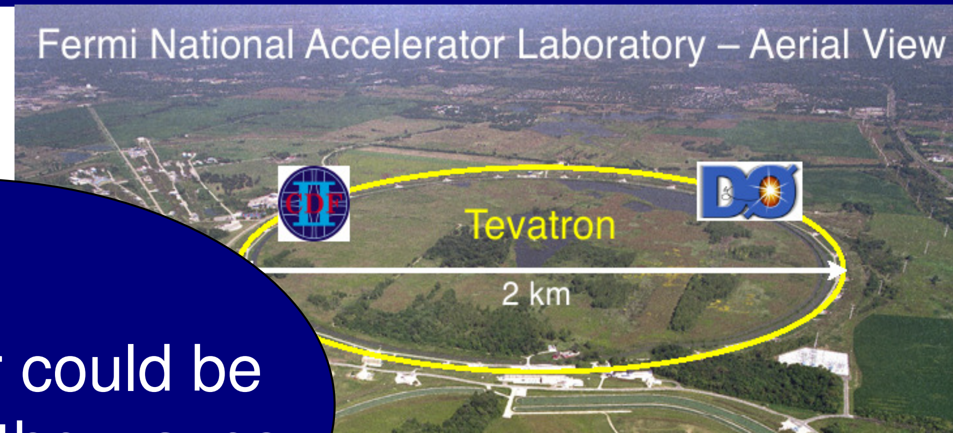
17.6 ± 0.4(stat) + 2.5 -2.3 (syst) μb(CDF)

- 2.8 fb^{-1} used in this analysis
- ~6 fb^{-1} delivered so far
- Expect ~10 fb^{-1} by end of 2011



- B_s^0 system do oscillate into its antiparticle.
- CDF Observation was big news in 2006 (PRL 97, 242003 2006)
- Negligible CP violation in the B_s^0 system is a firm SM prediction
- A sizeable observation of CPV in the **J/Ψ Φ** final state is a strong indication of physics beyond the SM

Intro



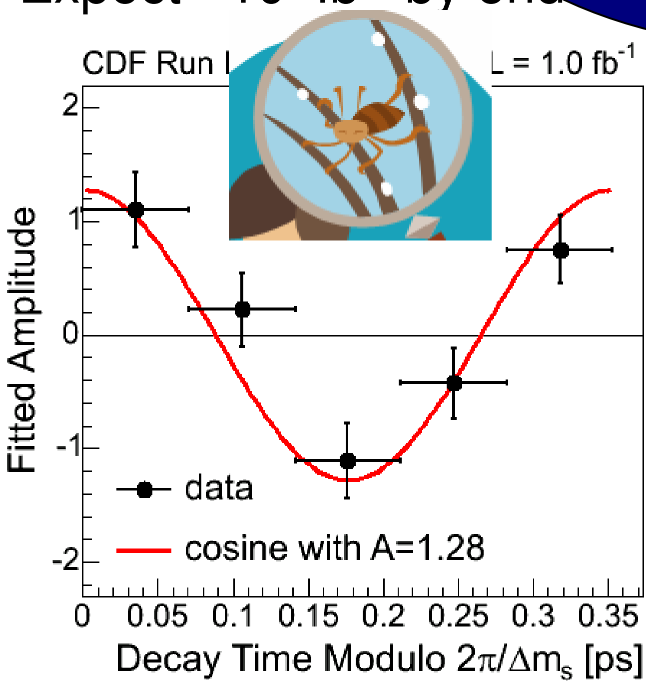
- Proton-Antiproton Collider
- 1.96 TeV Center of Mass
- Huge b xsec at Teva

17.6 ± 0.4(stat) + 2.5 -2

- $2.8 fb^{-1}$ used in thi
- $\sim 5\ fb^{-1}$ delivered so
- Expect $\sim 10\ fb^{-1}$ by end

Any monster could be hiding under the waves

em do oscillate into its
particle.



- CDF Observation was big news in 2006 (PRL 97, 242003 2006)
- Negligible CP violation in the B_s^0 system is a firm SM prediction
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CDF is probing the SM flavour sector by searching CPV in B_s^0 oscillations

β_s Phase and the CKM Matrix

- CKM matrix connects mass and weak quark eigenstates
- Expand CKM matrix in $\lambda = \sin(\theta_{Cabibbo}) \approx 0.23$

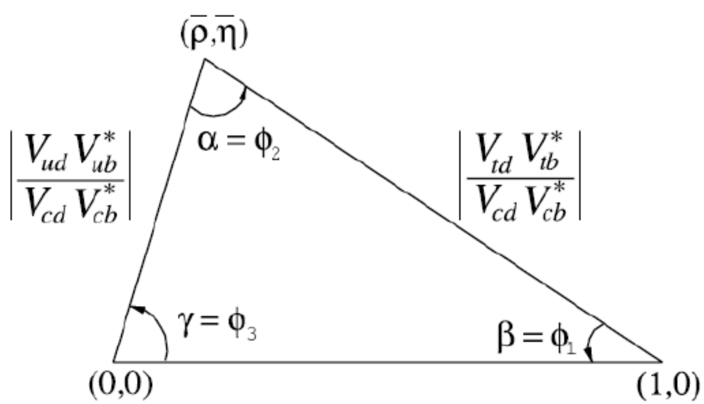
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

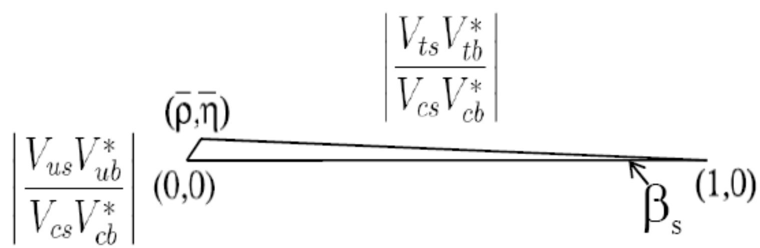
- To conserve probability CKM matrix must be unitary
  → Unitary relations can be represented as “unitarity triangles”

unitarity relations:

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

unitarity triangles:





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$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} O(1) & O(\lambda) & O(\lambda^3) \\ O(\lambda) & O(1) & O(\lambda^2) \\ O(\lambda^3) & O(\lambda^2) & O(1) \end{pmatrix}$$

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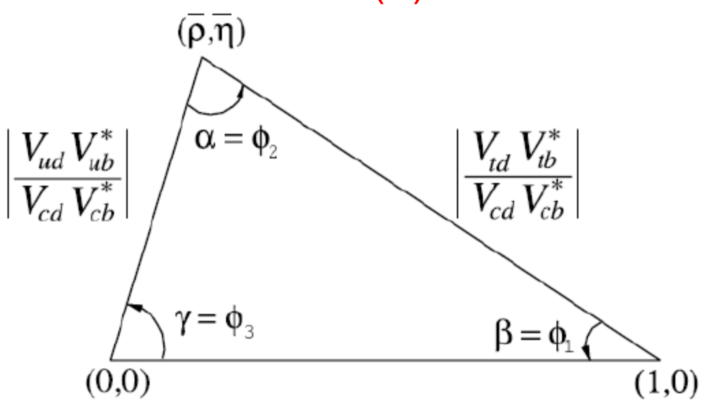
unitarity relations:

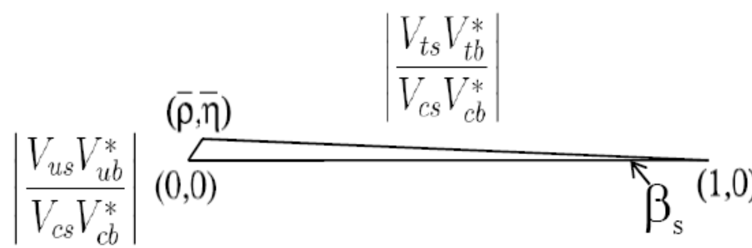
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

All sides ~O(1)

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

unitarity triangles:





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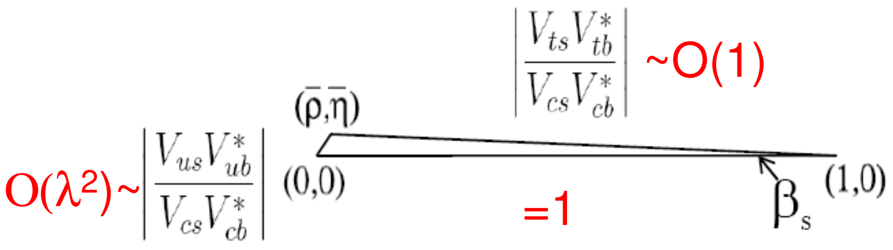
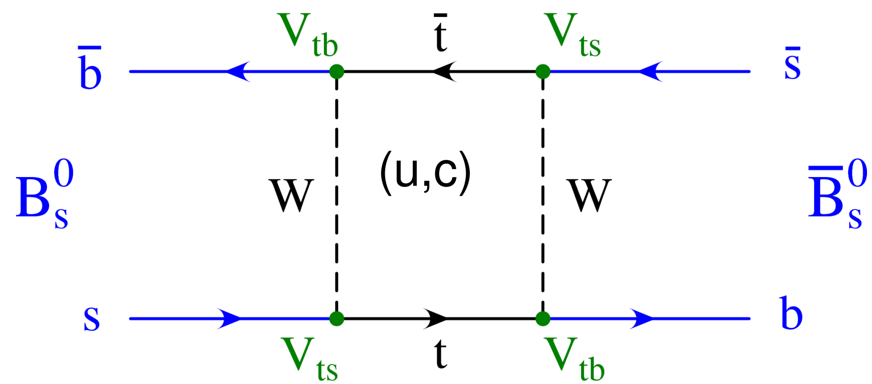
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



Very small CPV phase β_s of O(λ^2)

$$\beta_s = \arg\left(-V_{tb}V_{ts}^*/V_{cb}V_{cs}^*\right) \overset{SM}{\approx} 0.02$$

$$\beta_s = \arg\left(-V_{tb}V_{ts}^{*}/V_{cb}V_{cs}^{*}\right) \overset{SM}{\approx} 0.02$$



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

- Time evolution of B_s^0 flavor eigenstates described by Schrodinger equation:
- Diagonalize mass (M) and decay (Γ) matrices
- Eigenstates have different mass *and* width eigenvalues:

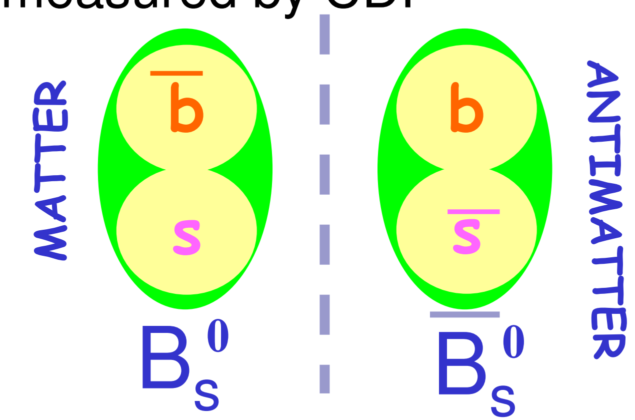
$\Delta m_s = m_H - m_L \approx 2|M_{12}|$ $\Delta\Gamma = \Gamma_L - \Gamma_H = 2\,\Gamma_{12}\cos(\Phi)$ $\Phi = \arg(-M_{12}/\Gamma_{12})$

- SM expectation (A.Lenz &U Nierste hep-ph/0612167)

$\Delta m_s = (19.3 \pm 6.7)\ ps^{-1}$ $\Delta\Gamma_s = (0.096 \pm 0.039)\ ps^{-1}$ $\Phi = (4.2 \pm 1.4)10^{-3}$

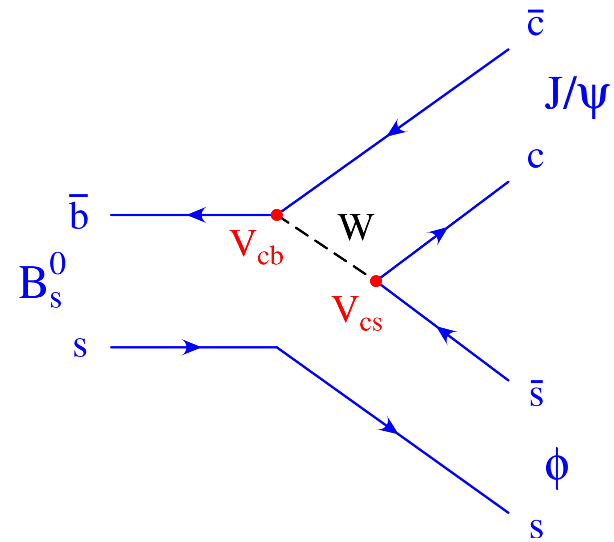
→ B_s^0 oscillates fast with frequency Δm_s precisely measured by CDF

$\Delta m_s(B_s^0)$ =	(17.77 ± 0.12)	ps^{-1}
$\Delta m(B^0)$ ~	0.5	ps^{-1}
$\Delta m(D^0)$ ~	0.02	ps^{-1}
$\Delta m(K^0)$ ~	0.005	ps^{-1}



$B_s^0 \rightarrow J/\Psi\Phi$

- $V_{cb}V_{cs}^*$ accesible through the $b \rightarrow c\bar{c}s$ decay
- Tree level: decay dominated by SM

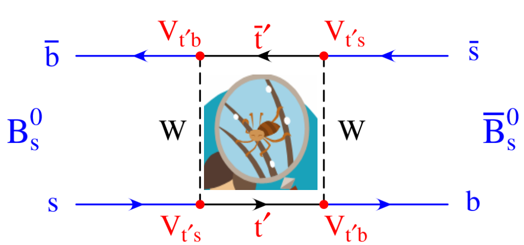


- The interference between mixing and $b \rightarrow c\bar{c}s$

(**J/Ψ Φ** decay in particular) is sensitive to β_s

- New Physics would contribute to the CP violating phase

$$2\beta_s = -\phi_s^{\mathrm{NP}} = -\phi_s$$



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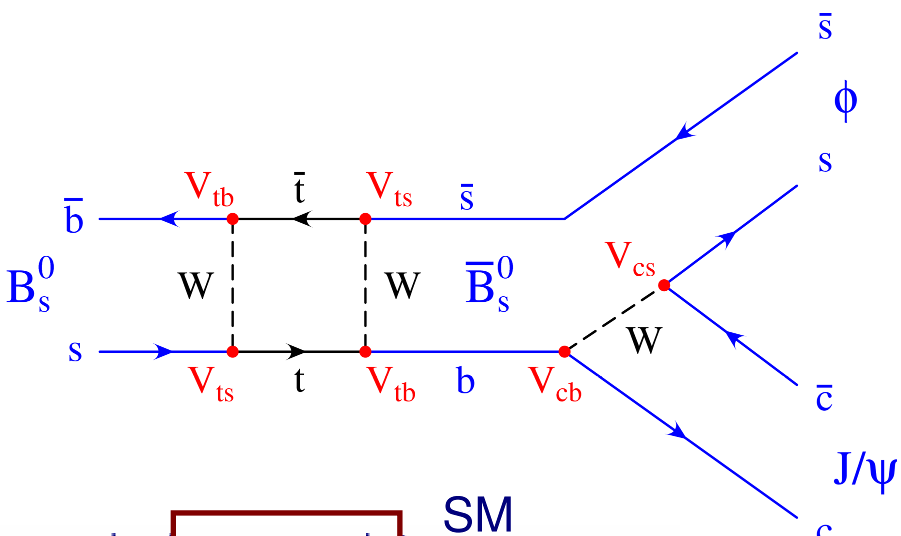


$$\beta_s = \arg\left(-V_{tb}V_{ts}^* / \boxed{V_{cb}V_{cs}^*}\right) \overset{\text{SM}}{\approx} 0.02$$

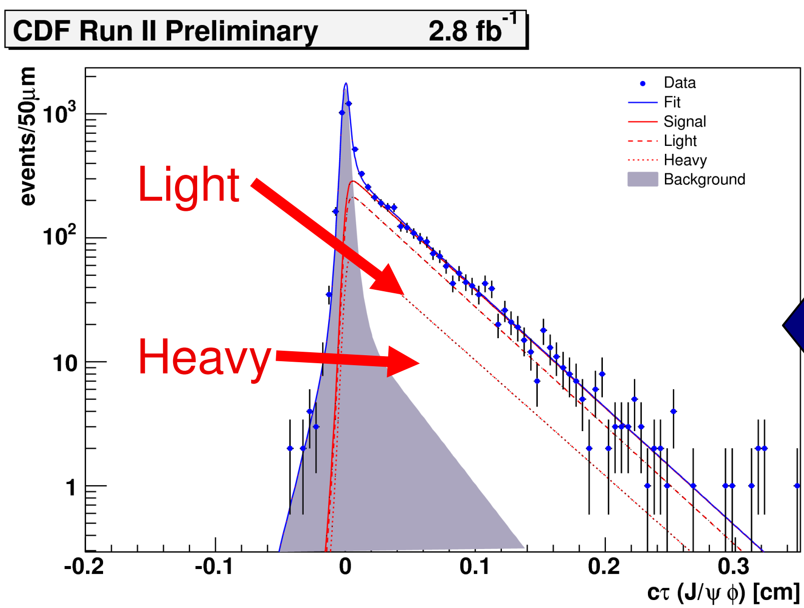
CP violation in $B_s \to J/\Psi\Phi$?

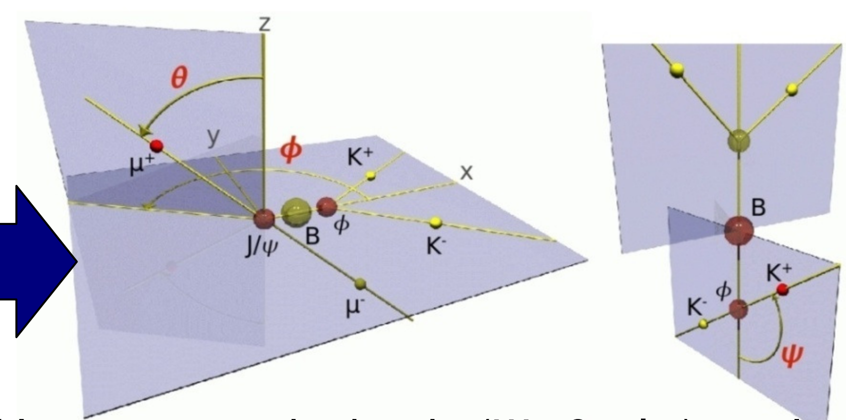
- Decay of B_s^0 (spin 0) to J/Ψ(spin 1) Φ(spin 1) akin to $B^0 \to J/\Psi$(spin 1) K_0^*(spin 1)
- Three different CP/angular momentum final states: $CP|\mathbf{J/\Psi\ \Phi}\rangle = (-1)^L$, L=0,1,2

  L = 0 (s-wave), 2 (d-wave) → CP even

  L = 1 (p-wave) → CP odd
- If CP is conserved → $|B_{sL}\rangle = |B_{s\,CP+}\rangle \qquad |B_{sH}\rangle = |B_{s\,CP-}\rangle$
  - Light, short lived state should follow L=0,2 angular distributions and
  - Heavy long lived one should follow L=1 angular distributions

Infer CP state from time dependent angular distributions





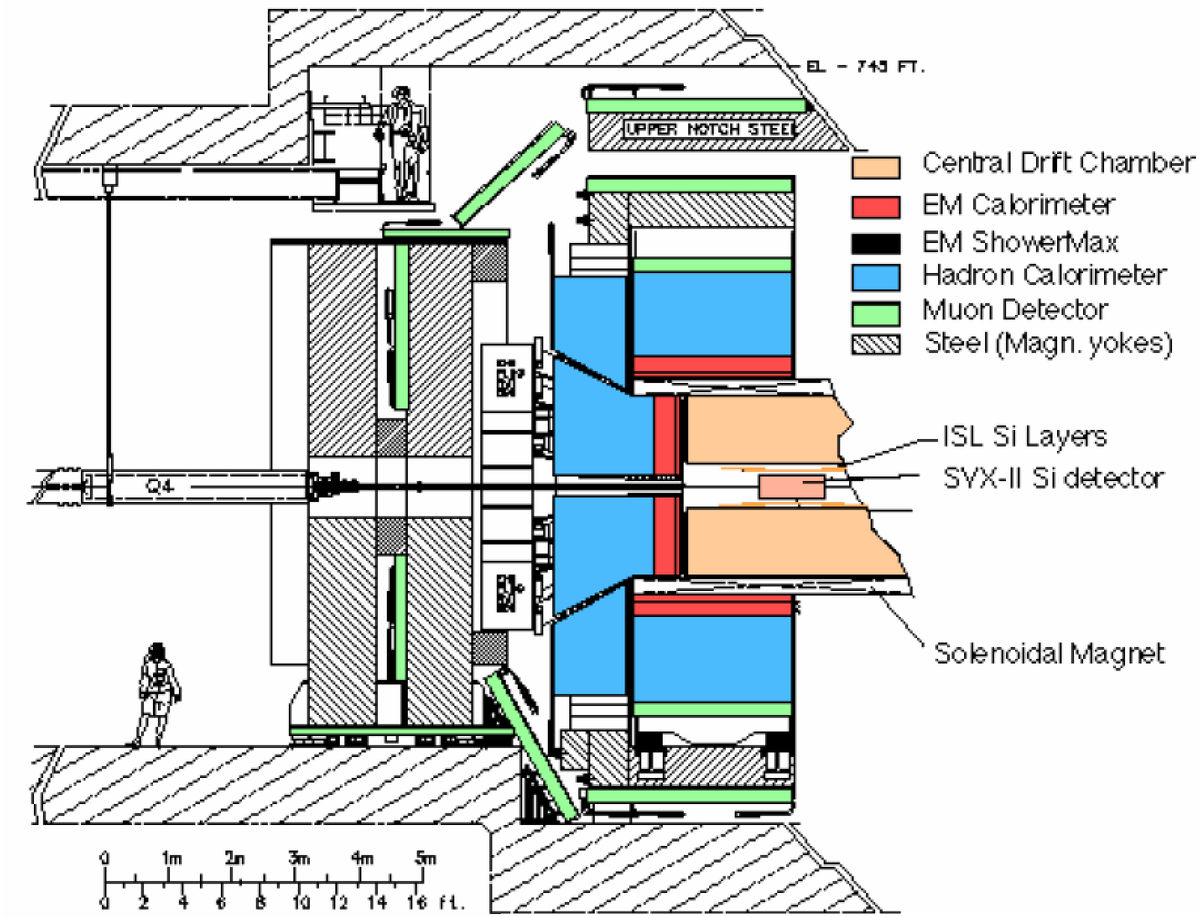
Use transversity basis (Ψ_T,θ_T,Φ_T) angles (hep-ph/951163)

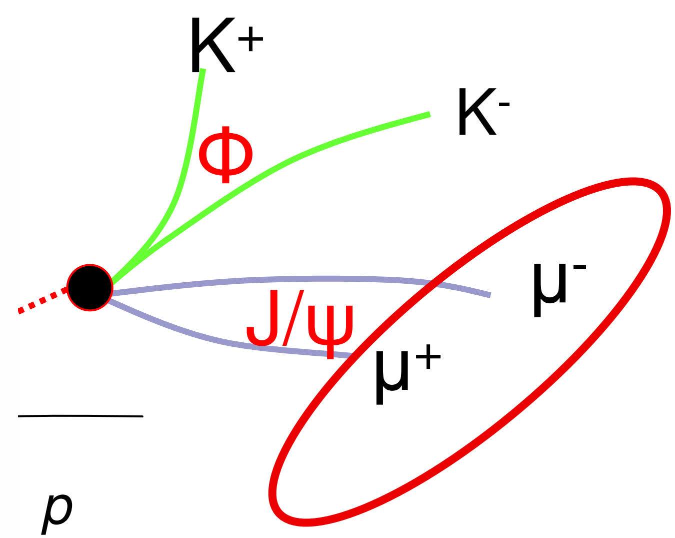
Knowing initial flavour enhances sensitivity

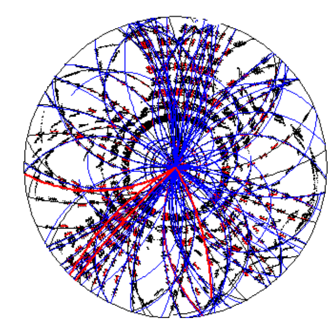
A flavor-tagged analysis of time dependent angular distributions

Measuring: 0-Trigger on dimuons

- Muon system is a combination of wire chambers and scintillator
- Trigger efficiently in dimuons pt(mu)>1.5 GeV |η| <1.15
- Efficiency flat ~0.87 above 2 GeV
- No trigger bias in time distributions



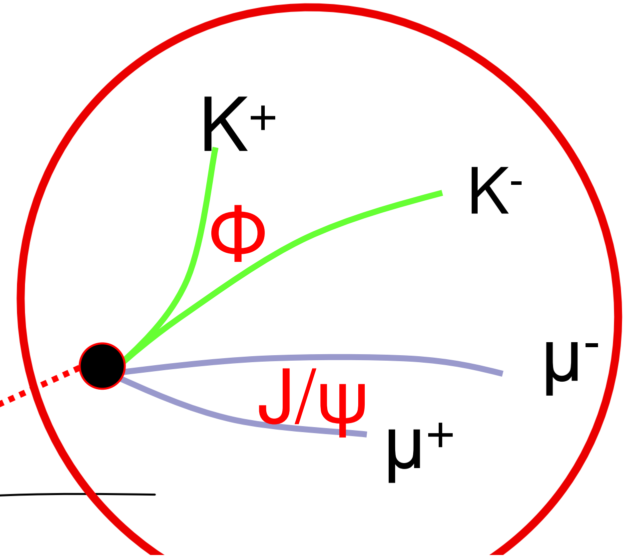




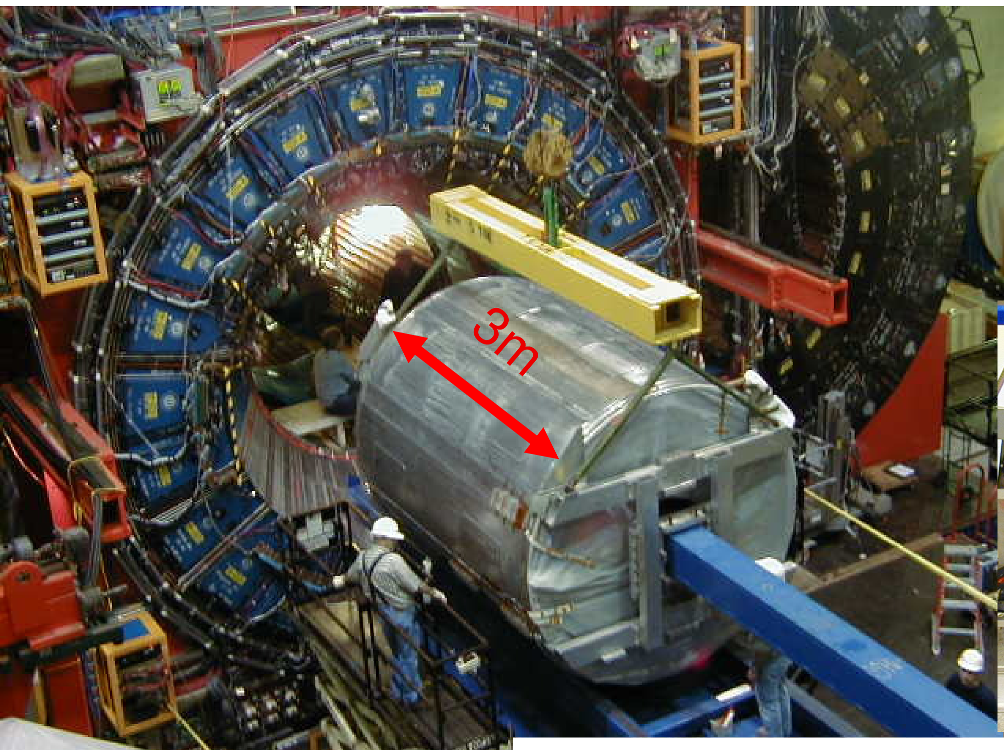
Measuring: 1- Tracking reconstruction

- Find **J/Ψ Φ** Resonances
- B_s^0 mass (**J/Ψ Φ**)
- Angular distributions to infer CP state
- Correct detector acceptance bias

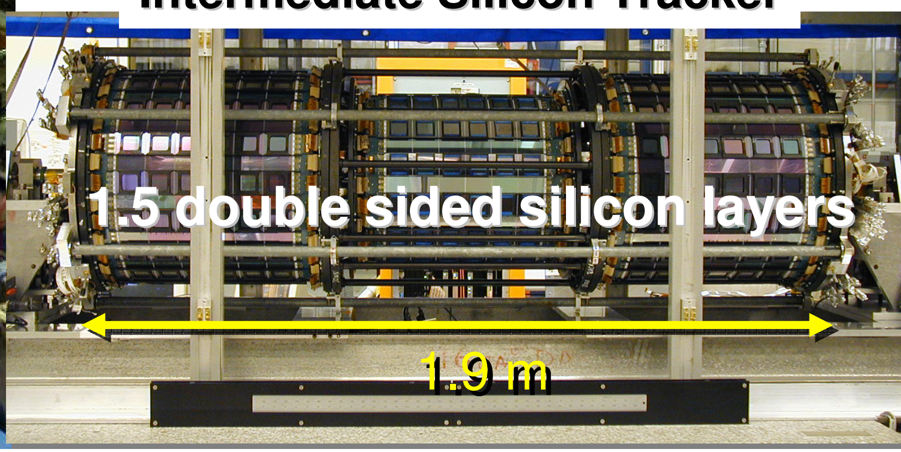
- CDF has excellent tracking/mass resolution: $\sigma(p_T)/p_T \sim 0.1\%\ p_T$/GeV



COT: 96 layer drift chamber r=44-132 cm

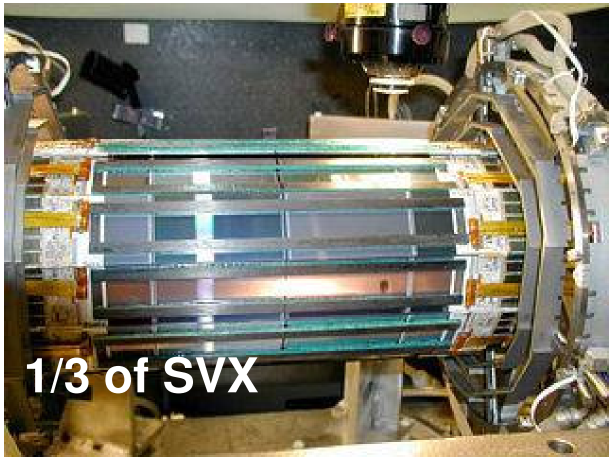


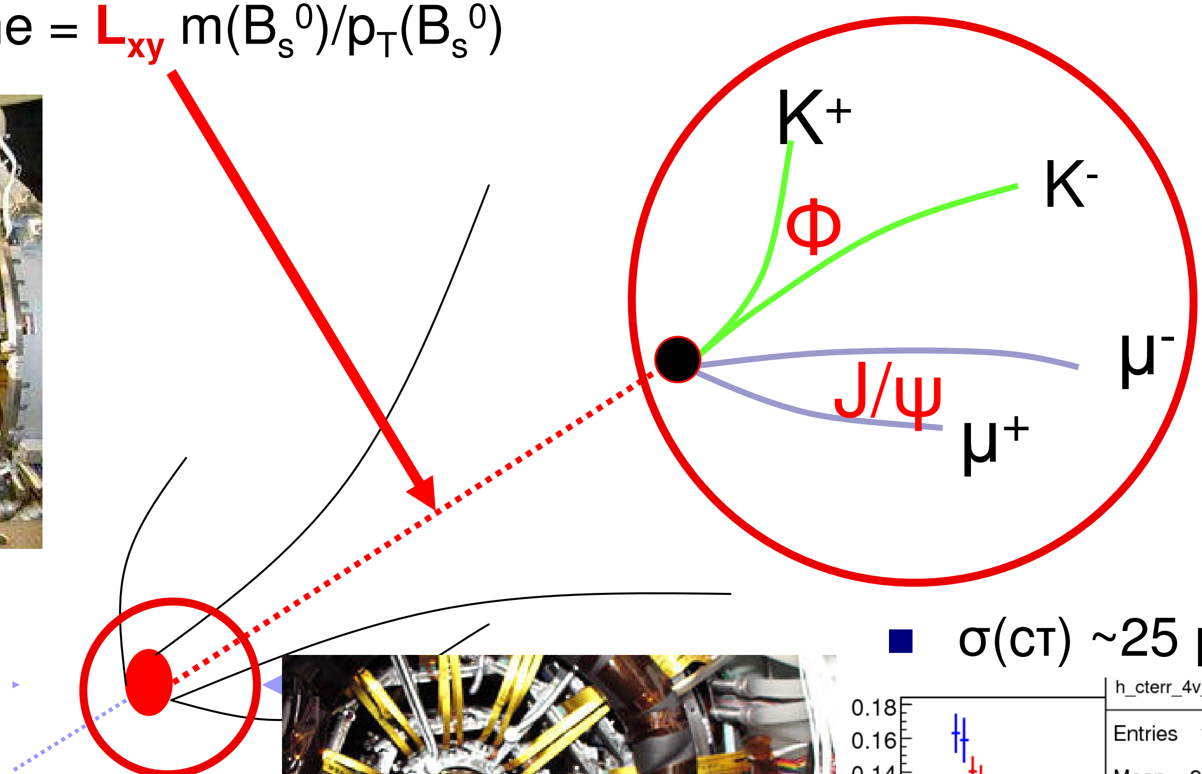
Intermediate Silicon Tracker



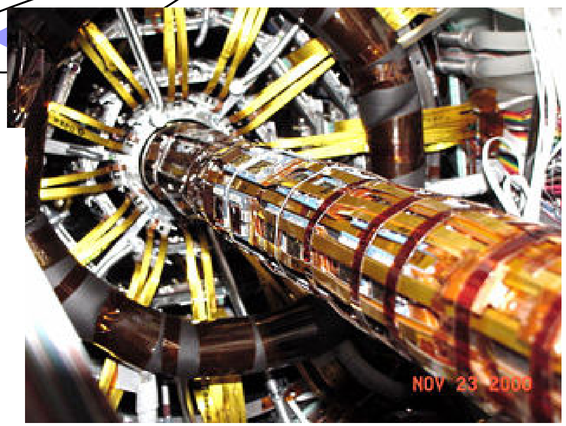
A flavor-tagged analysis of time dependent angular distributions

- SVX and L00 microstrip silicon detectors provide secondary vertexing
- B_s^0 Proper decay time = $L_{xy}\, m(B_s^0)/p_T(B_s^0)$

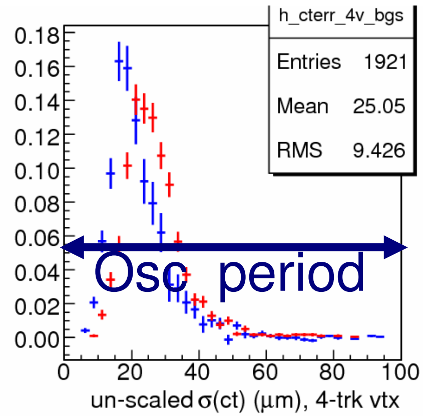




- SVX:5 layers of double-sided silicon r=2.5-25 cm
- L00 is glued on top of beam pipe, 1.35 cm from IP
- Single sided CMS type silicon
- Improves σ(cτ) by 20 %



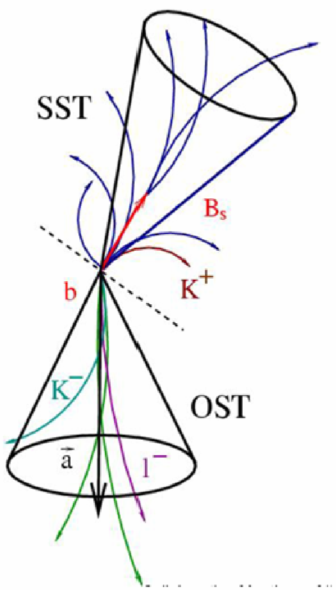
- σ(cτ) ~25 μm

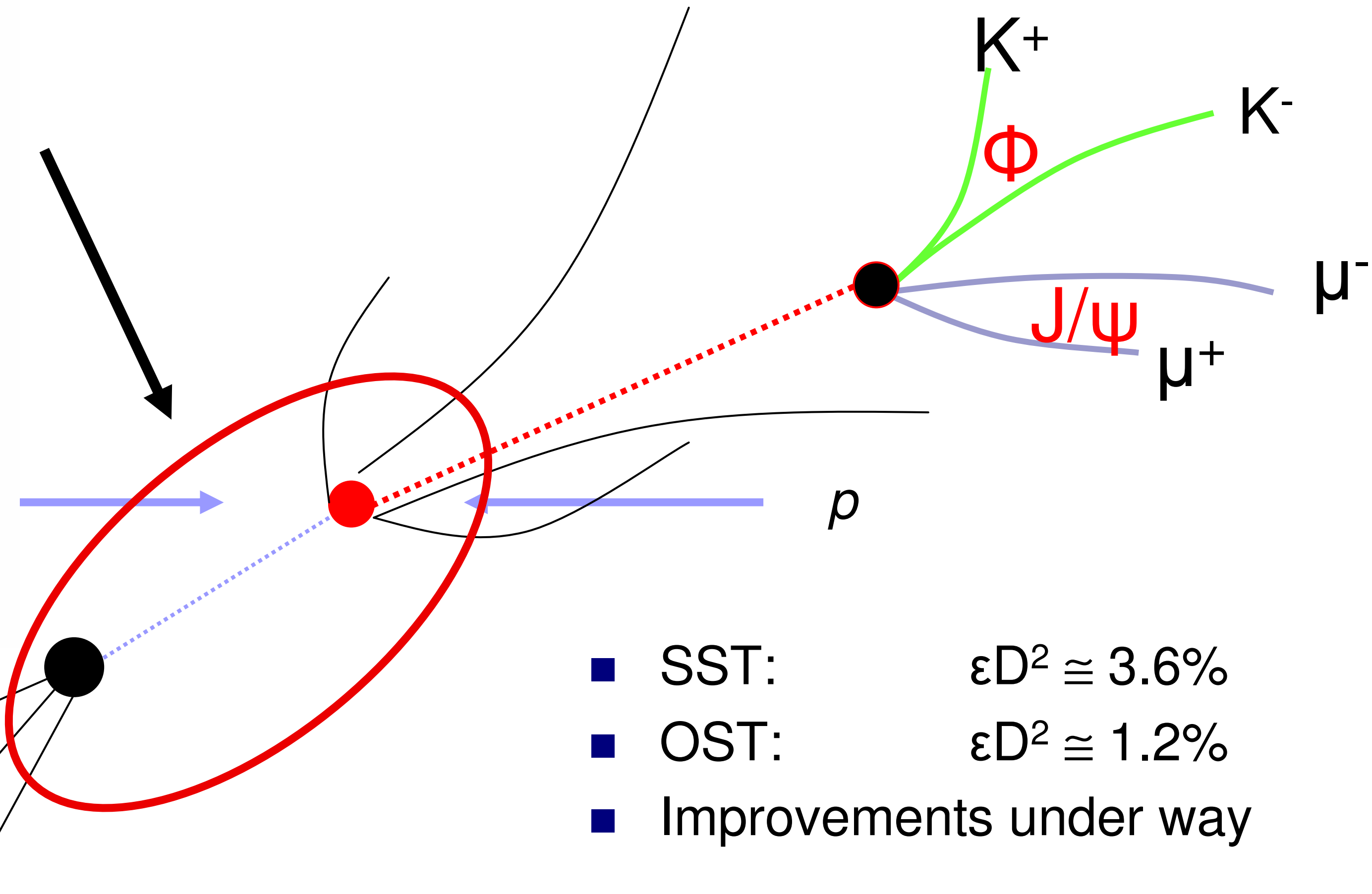


A flavor-tagged analysis of time dependent angular distributions

Measuring: 2 –Reconstruct flavour

- Particle identification capability from COT dE/dX and TOF scintillator system (not calibrated yet)
- Same Side Tagger and Opposite Side Tagger algorithms





- SST: $\varepsilon D^2 \cong 3.6\%$
- OST: $\varepsilon D^2 \cong 1.2\%$
- Improvements under way

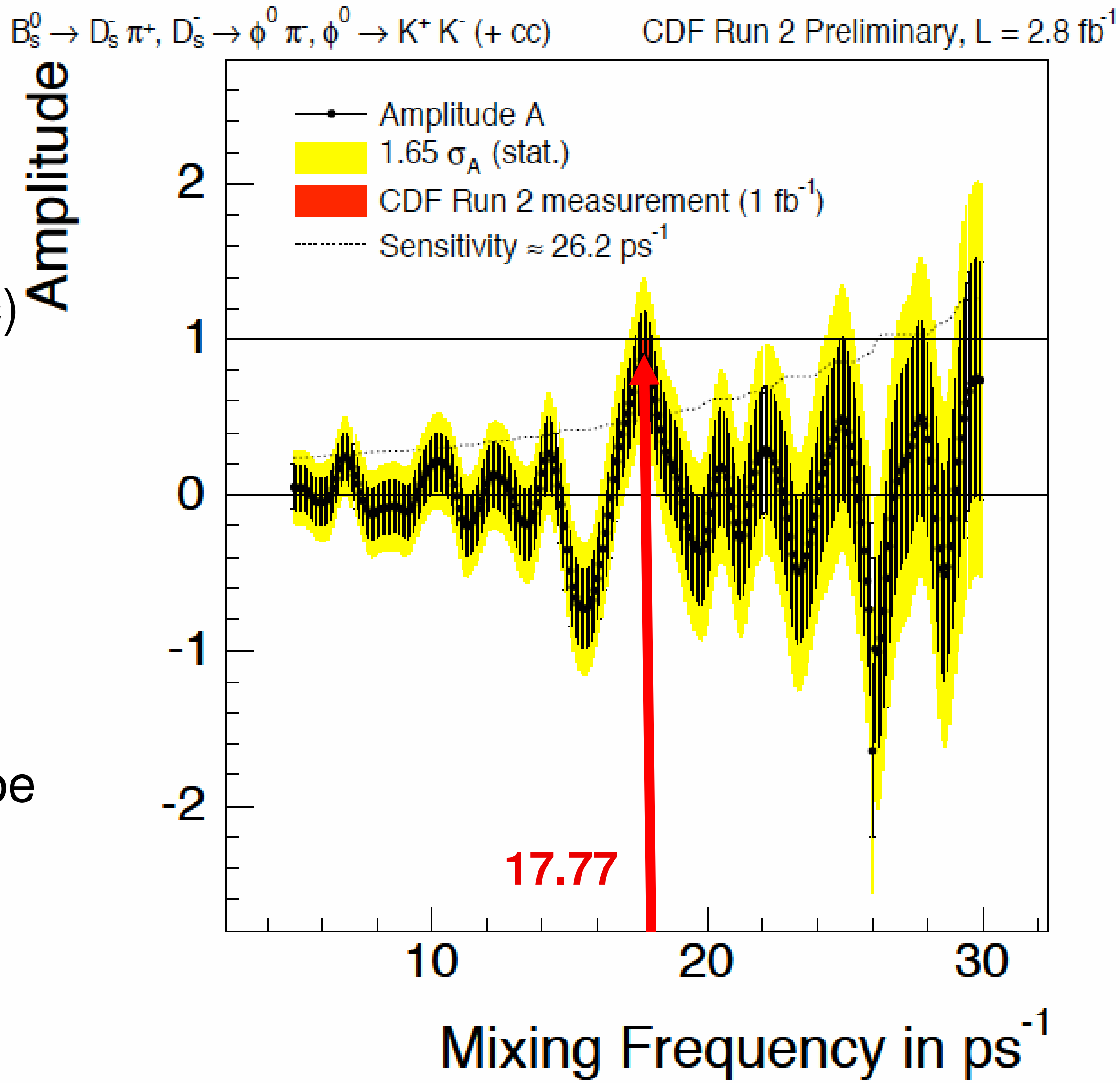
A flavor-tagged analysis of time dependent angular distributions

Flavour tagging improvents

- Revisit Δm_s using 2.8 fb^{-1} (vs.1 fb^{-1} at discovery)
- Use Single decay mode

$B^0_s \rightarrow D_s^- \pi^+; D_s^- \rightarrow \Phi\pi^-$(+c.c)

- SST performace independent of instantaneous luminosity

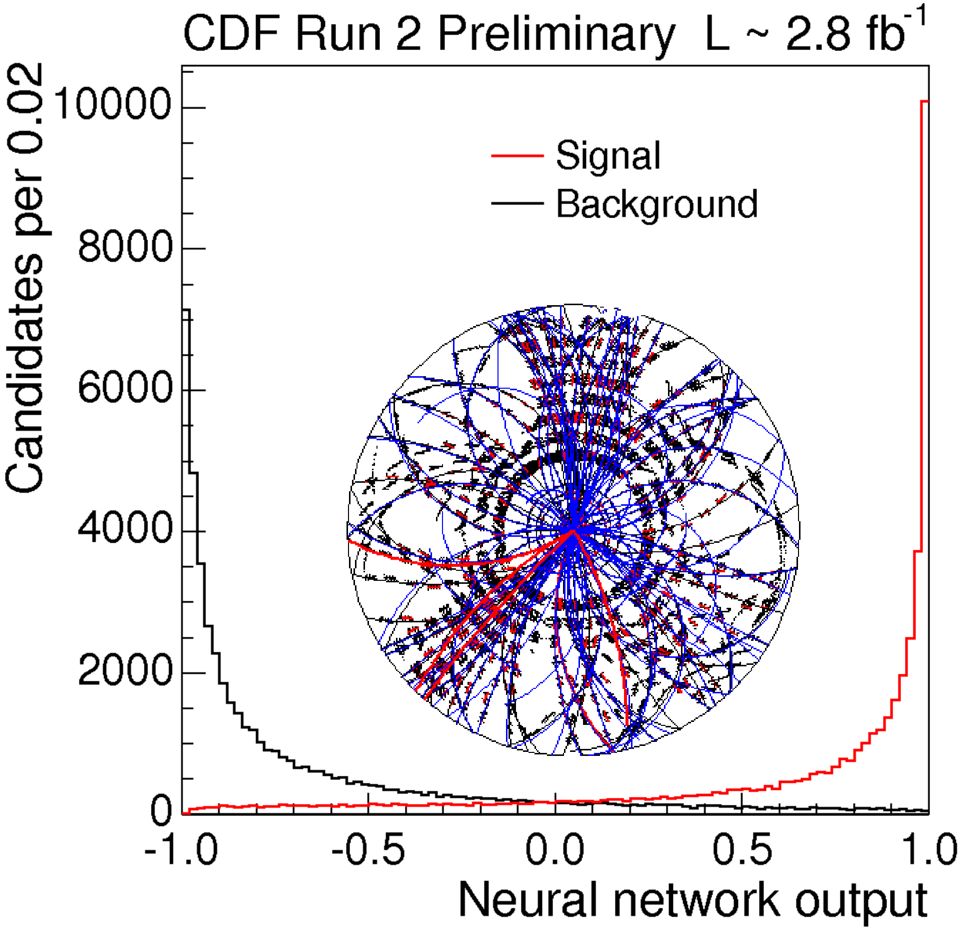


- Developing global NN-based tagger which will be calibrated against Δm_s

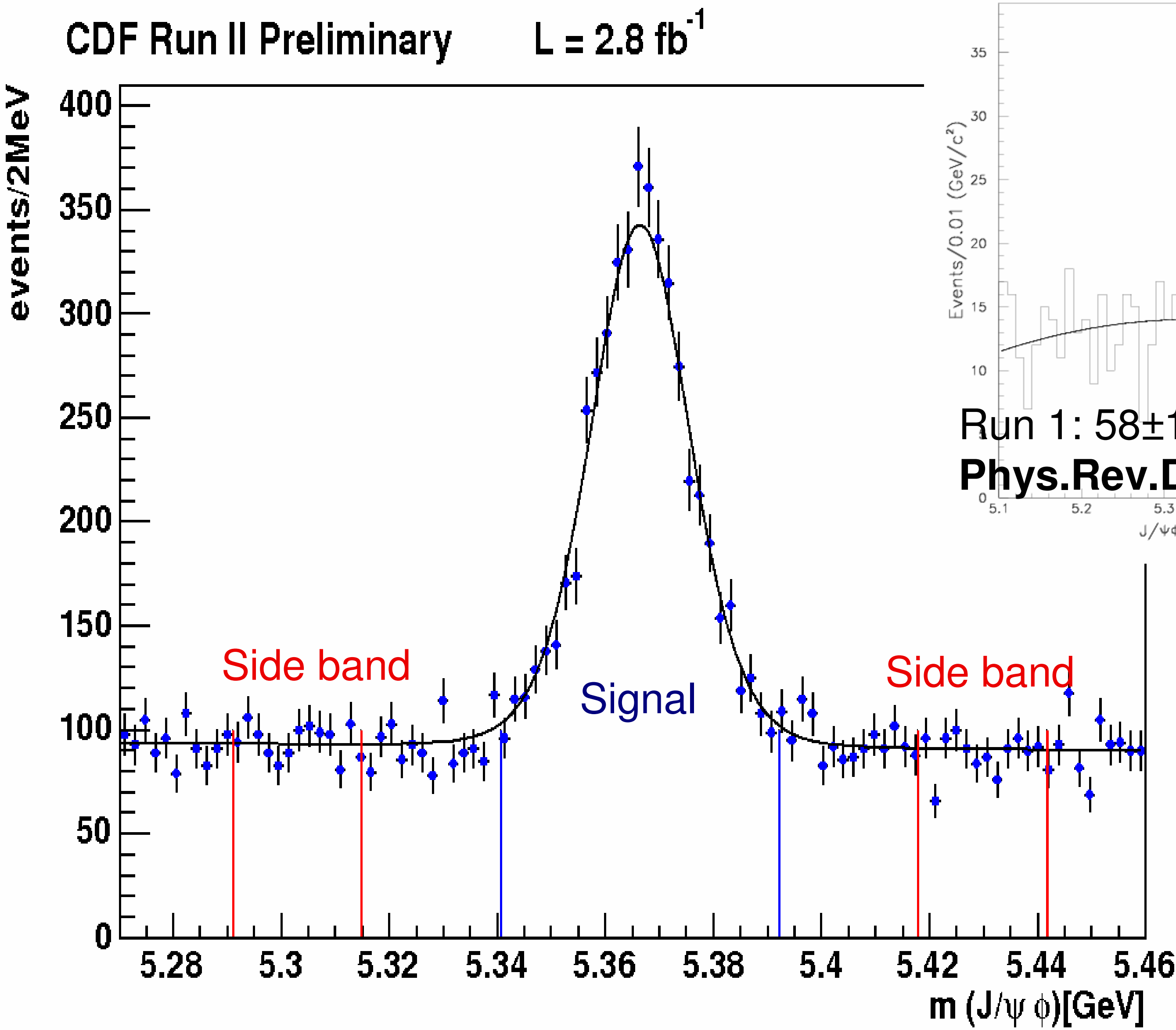
Measuring : 3- Selection

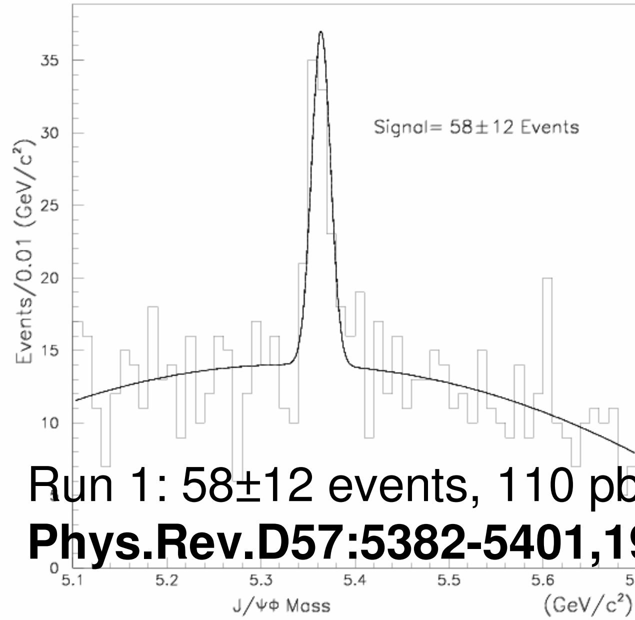
- Use Neural Network to amass large B_s^0 sample
- Optimized on S/sqrt(S+B) where S is MC and B comes from side bands
- 15 variables

Index	Variable	Rank
1	training target	-
2	$\chi^2_{r-\phi}(B_s)$	9
3	$p_T(B_s^0)$	10
4	$Prob(\chi^2)(B_s^0)$	4
5	$p_T(\phi)$	14
6	$Prob(\chi^2)(\phi)$	11
7	$\lvert m_{K^+K^-} \rvert$	2
8	$p_T(K_1)$	3
9	$p_t(K_2)$	1
10	$p_T(J/\psi)$	6
11	$Prob(\chi^2)(J/\psi)$	15
12	$\lvert m_{\mu^+\mu^-} - m_{J/\psi}^{PDG} \rvert$	12
13	$\max(\mathrm{lh}(\mu^+), \mathrm{lh}(\mu^-))$	13
14	$\min(\mathrm{lh}(\mu^+), \mathrm{lh}(\mu^-))$	5
15	$\max(p_T(\mu^+), p_T(\mu^-))$	7
16	$\min(p_T(\mu^+), p_T(\mu^-))$	8



~3200 $B_s^0 \to J/\psi(\to\mu^+\mu^-)\Phi(\to K^+K^-)$ in 2.8 fb^{-1}

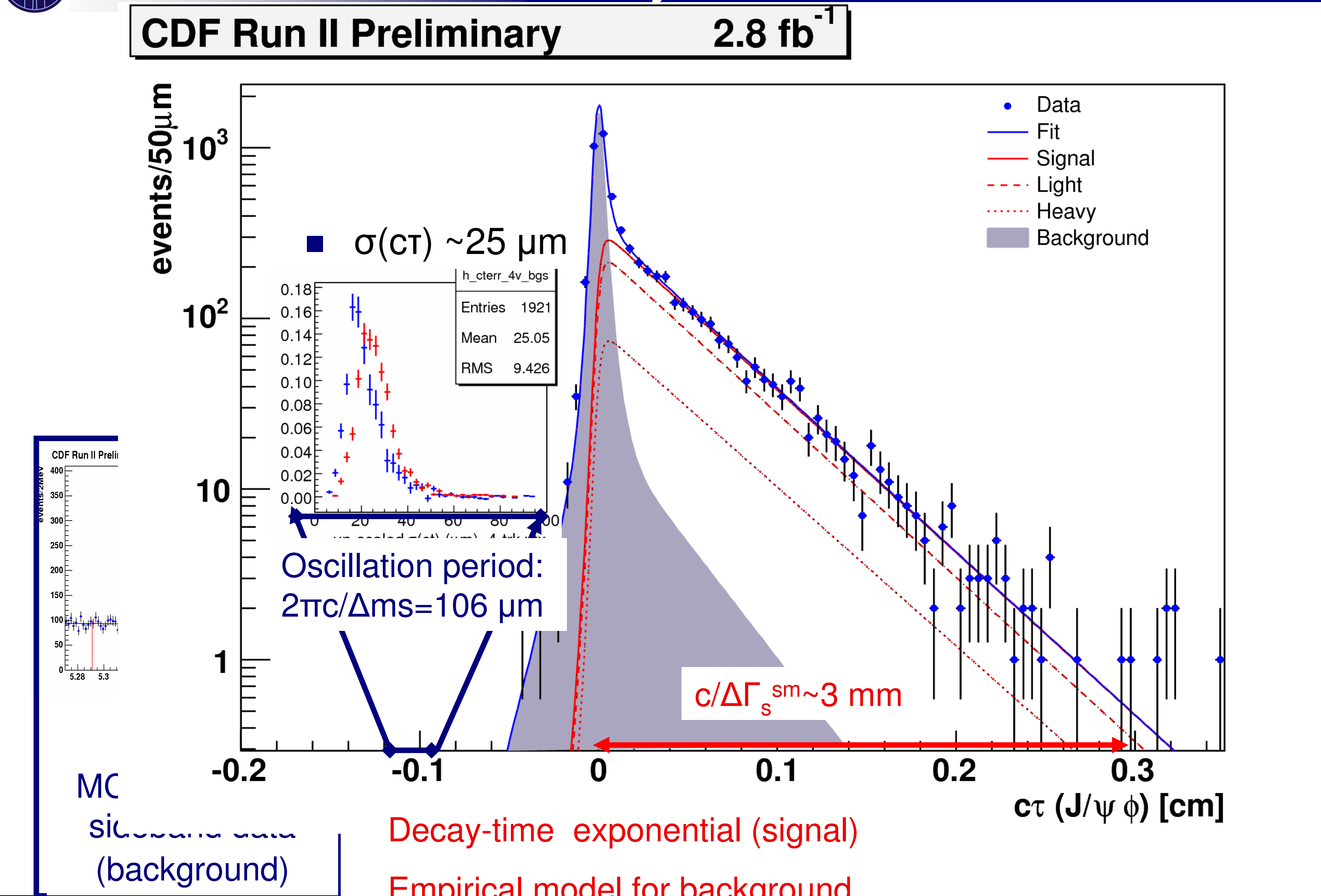




Run 1: 58±12 events, 110 pb^{-1}

Phys.Rev.D57:5382-5401,1998.

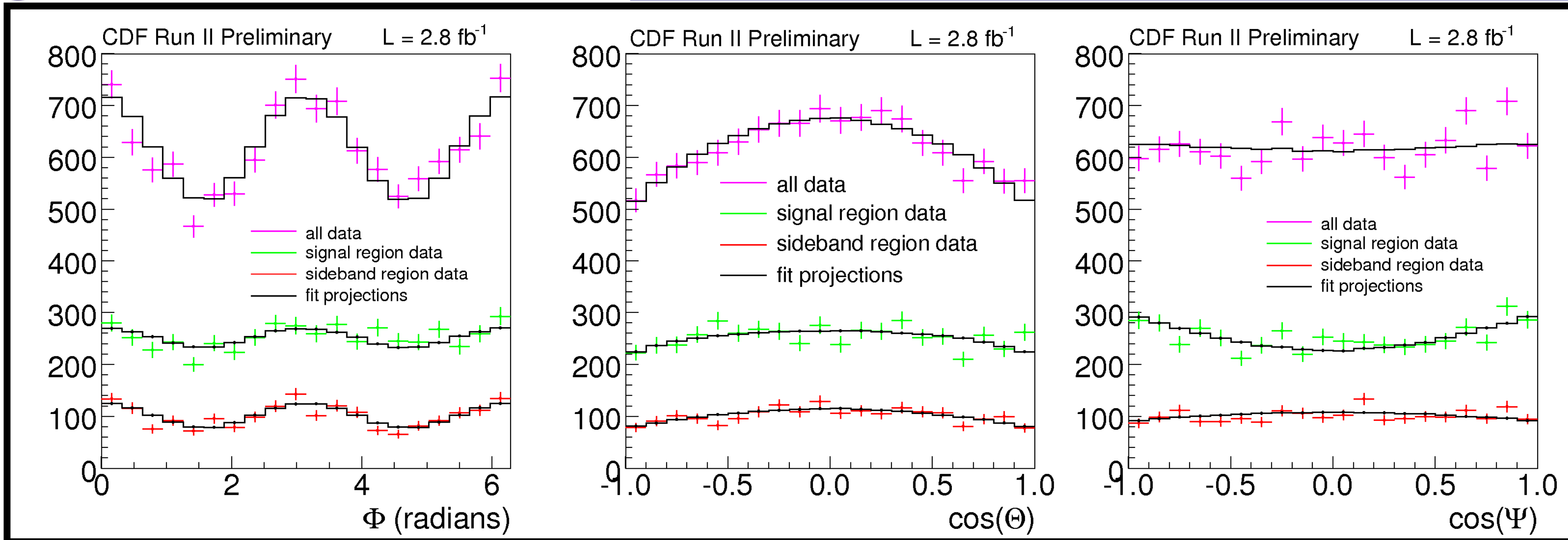
Decay time distribution

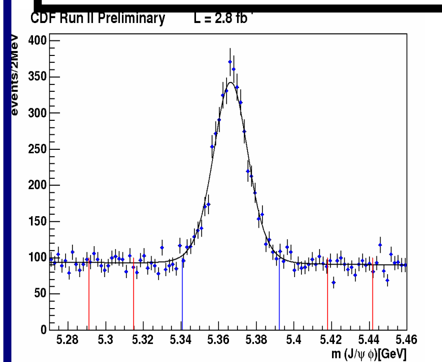


Decay-time exponential (signal)

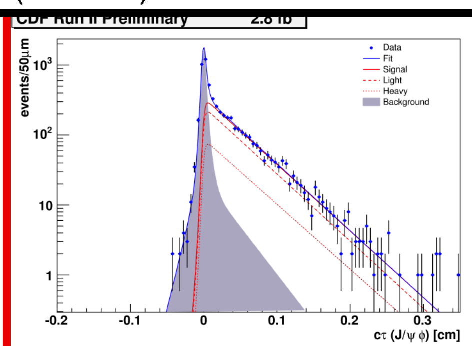
Empirical model for background

Angular distributions, Tagging





Mass
MC (signal) and
sideband data
(background)



Decay-time
exponential
(signal) empirical
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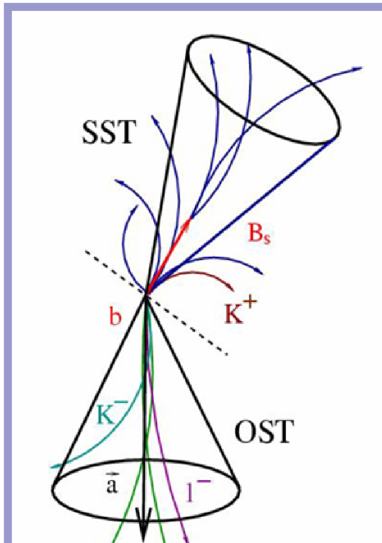
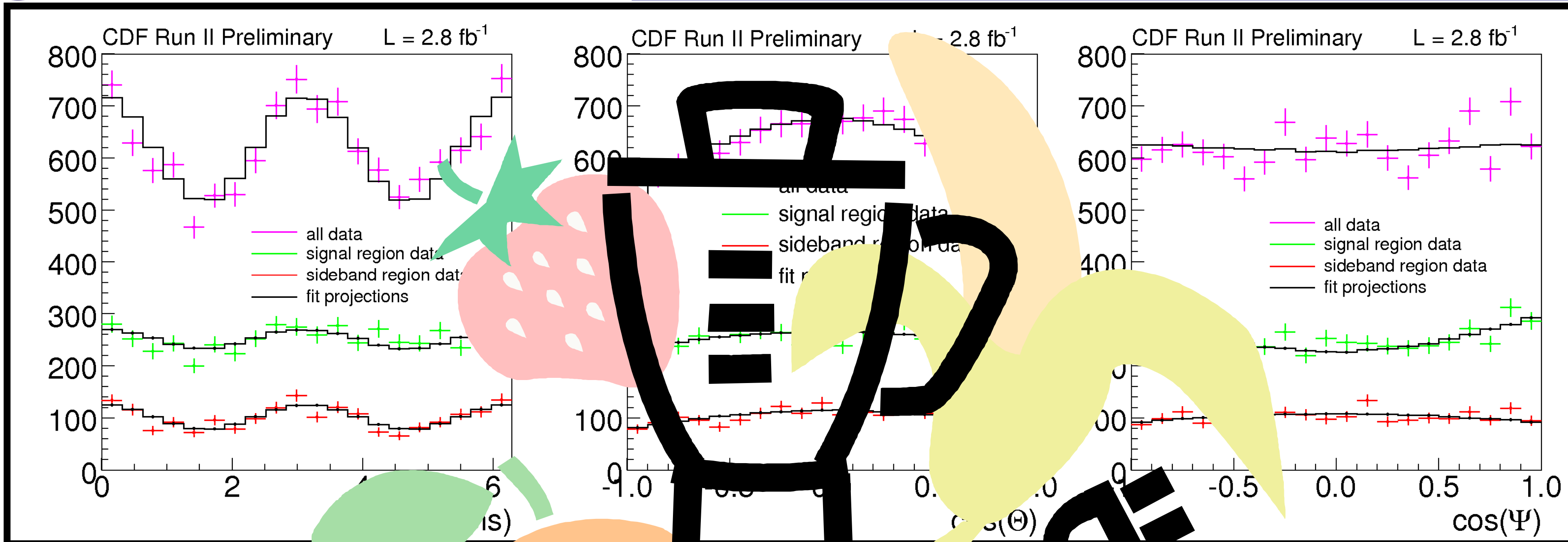
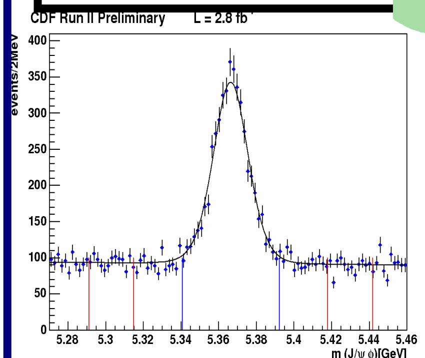
background



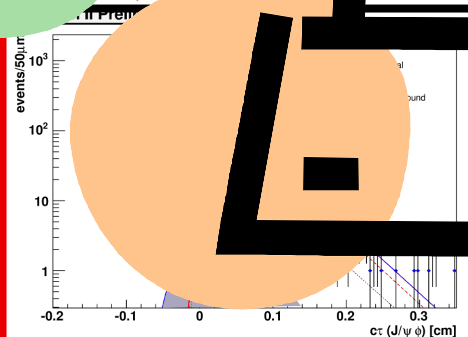
Tagging
dilution

Fit them all!

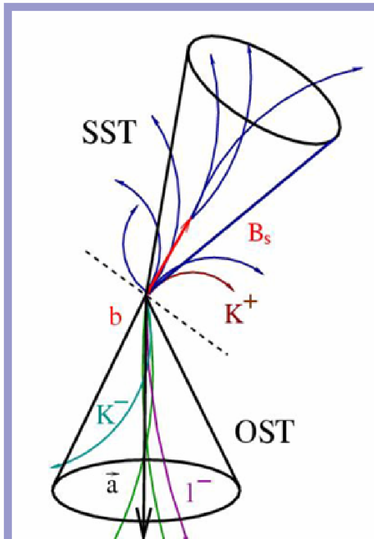




Mass MC (signal) and sideband data (background)



Decay-time exponential (signal) empirical model for background

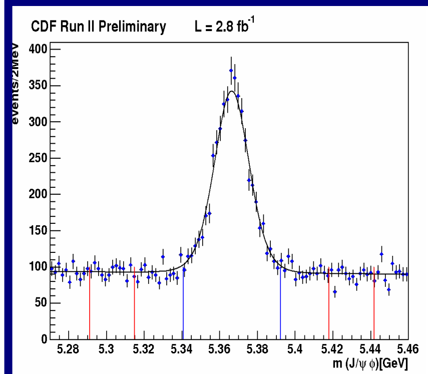


Tagging dillution

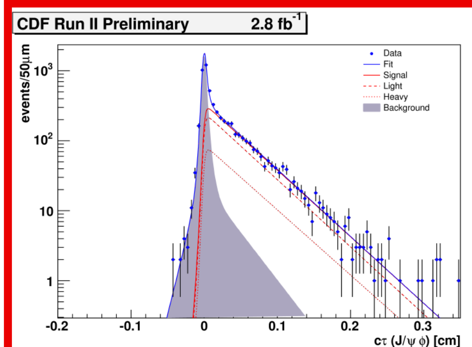
Un-binned likelihood fit

- Likelihood constructed from 9 measured variables for signal and background

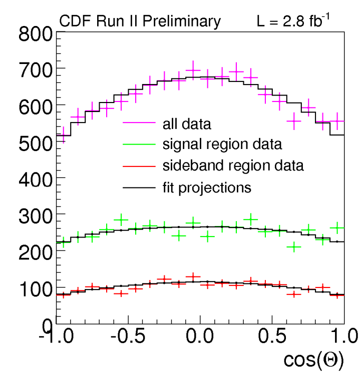
$$f_s P_s(m|\sigma_m)\, P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t)\, P_s(\sigma_t)\, P_s(\mathcal{D})$$



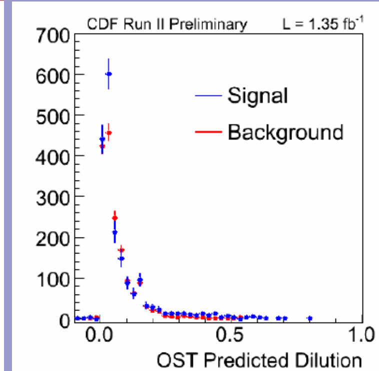
Mass
MC (signal) and sideband data (background)



Decay-time & σ_t
Exponential (signal) empirical model for background



3 Angles
MC and data (signal), sidebands (background)



Tagging dillution

Fit Output

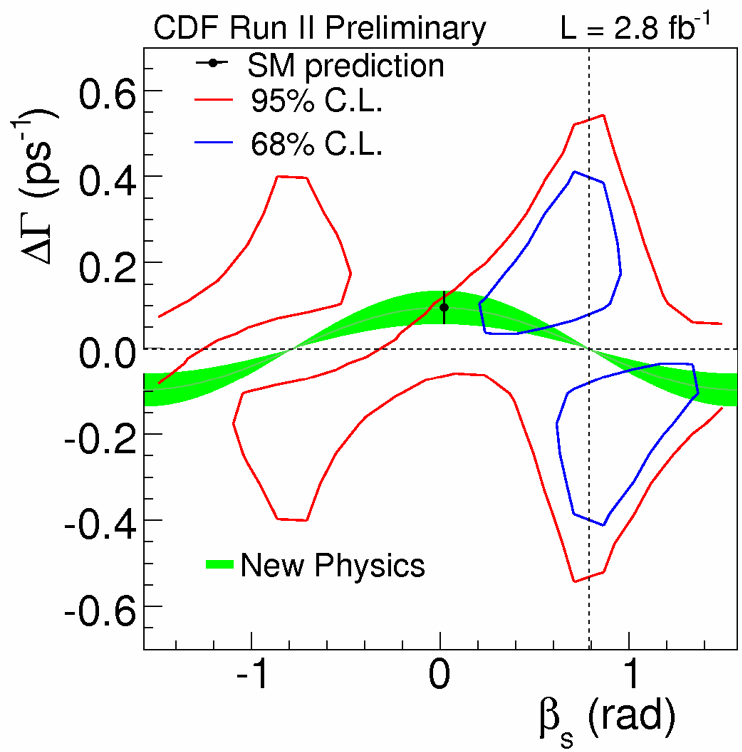
$$f_s P_s(m|\sigma_m) P_s(t, \vec{\rho}, \vec{\xi}|\vec{\mathcal{D}}, \sigma_t) P_s(\sigma_t) P_s(\mathcal{D})$$
$$+(1-f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\vec{\mathcal{D}})$$

- Likelihood depends on 36 parameters
- First, assuming no CPV (β_s=0), measure relevant nuisance parameters:
  - Width difference = 0.02 ± 0.05 (stat.) ± 0.01 (syst.) μm
  - Average lifetime = 459 ± 12 (stat.) ± 3 (syst.) μm
    - PDG: cτ (B^0) = 459 ±0.027 μm
    - HQET: cτ(B_s^0) = (1.00±0.01) cτ(B^0)

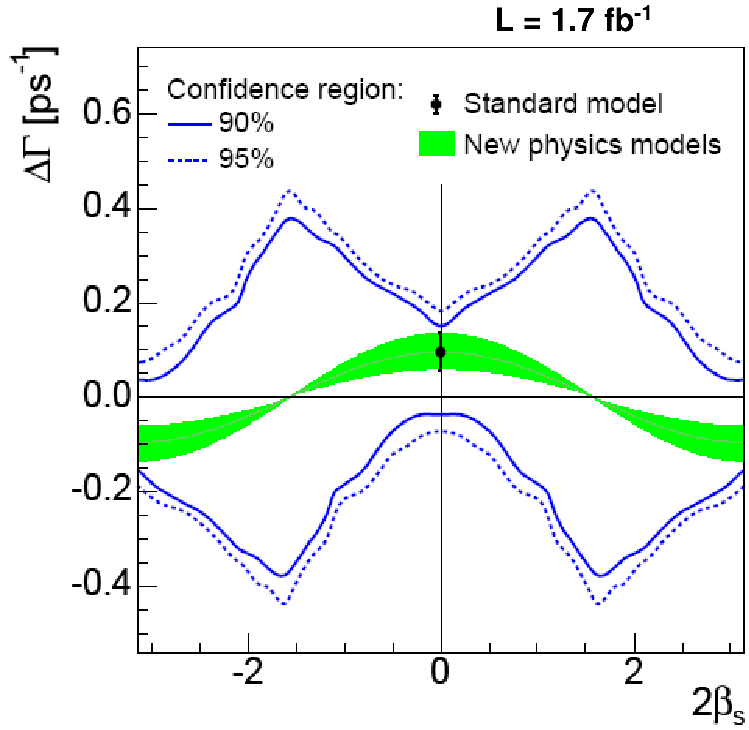
$|A_{||}(t=0)|^2$ = 0.241 ± 0.019 (stat) ± 0.007 (syst)
$|A_0(t=0)|^2$ = 0.508 ± 0.024 (stat) ± 0.008 (syst)
} CP even

- Then, adjust confidence region contours in the ΔΓ- β_s plane from the p-value distribution obtained from pseudo-experiments.
- Include systematics by recalculating p-value distribution over a 5 sigma range in the nuisance parameters and choosing worst case to define the confidence limit region.

Tagged & Untagged Results



PRL 100,161802 (2008)



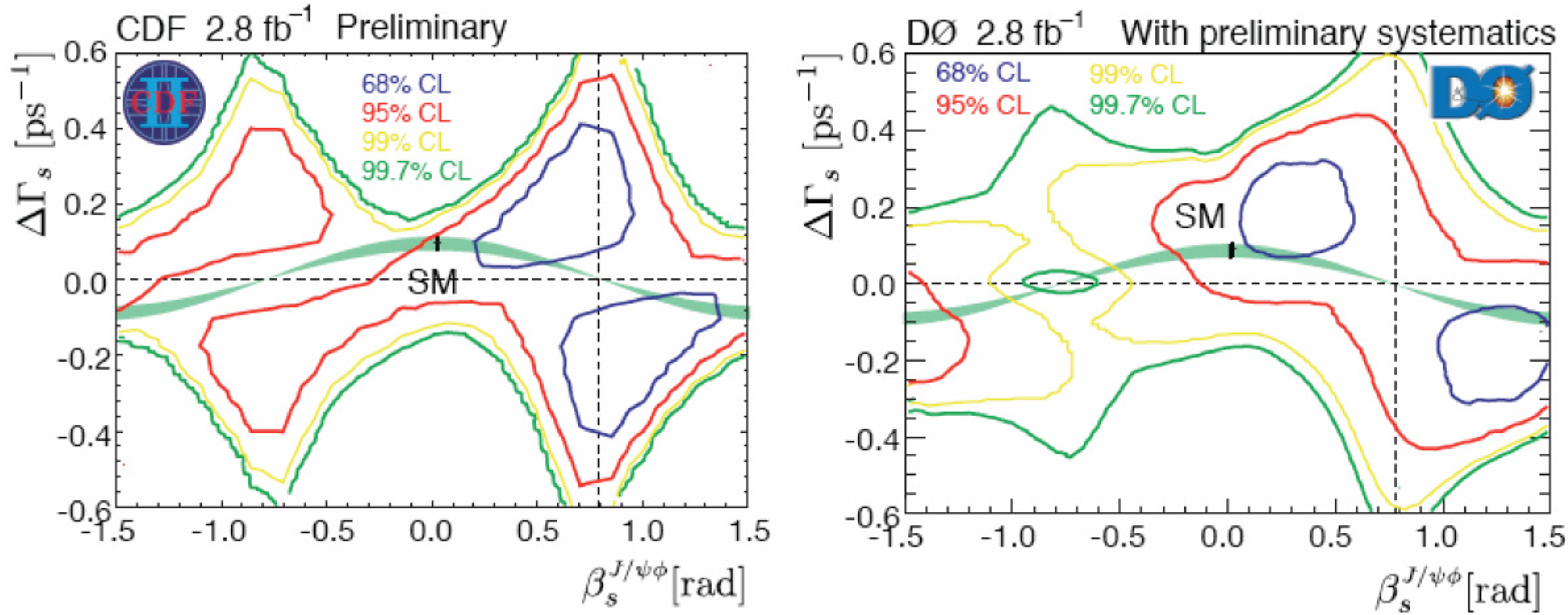
- Flavour tagging suppresses negative β_s reducing significantly the allowed parameter space
- β_s in [0.28,1.29] @ 68% CL.

The significance of CPV is 1.7σ (p-value=7%)

- Remaining symmetry can be broken using strong phases from other measurements

$$\begin{aligned} \beta_s &\rightarrow \frac{\pi}{2} - \beta_s, \\ \Delta\Gamma &\rightarrow -\Delta\Gamma, \\ \delta_{\parallel} &\rightarrow 2\pi - \delta_{\parallel}, \\ \delta_{\perp} &\rightarrow \pi - \delta_{\perp}. \end{aligned}$$

- Comparable CDF and D0 results.
  - Without external constraints in strong phases
  - With systematics



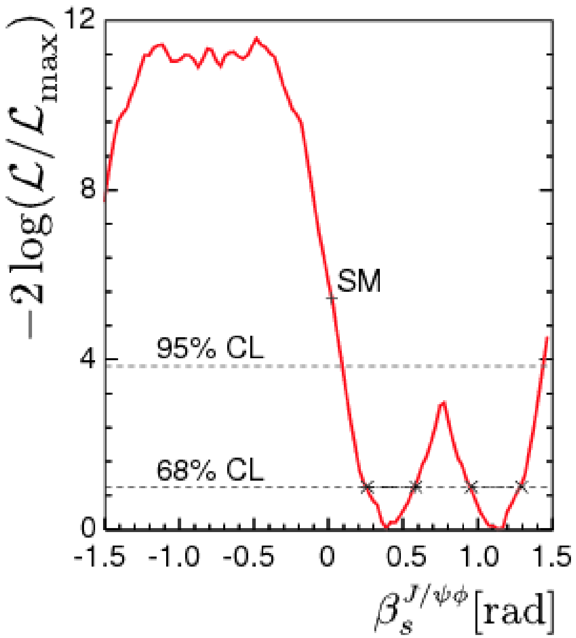
From publication: PRL 101, 241801 (2008);
DØ Note 5933-CONF

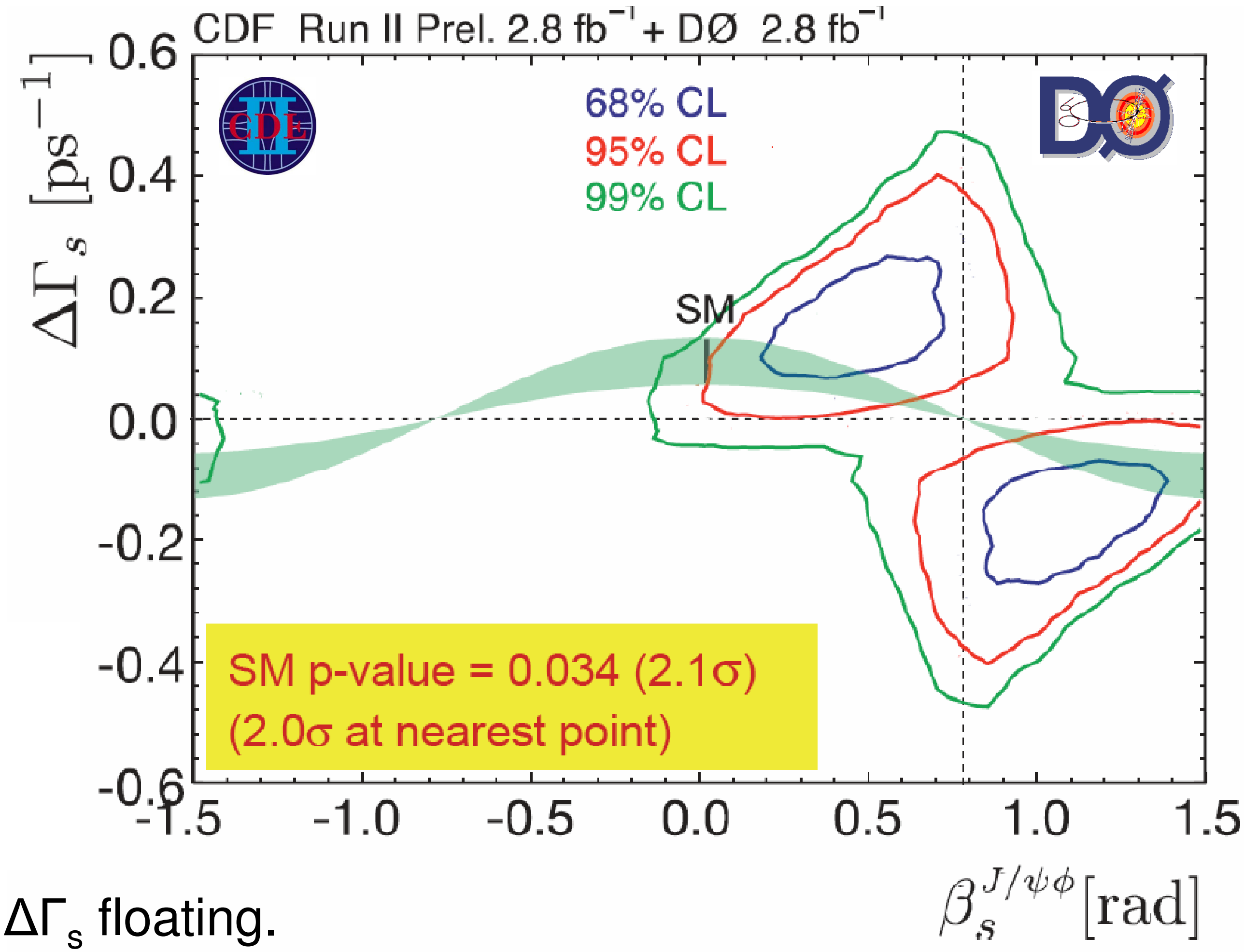
- Combination in the $\Delta\Gamma_s$-β_s 2d slice of the n-dimension likelihoods
- Result could improve if simultaneous fit performed in all dimensions

CDF/D0 $\Delta\Gamma_s$,β_s Combination Working Group:
Common CDF/D0 note CDF/PHYS/BOTTOM/CDFR/9787 - D0 Note 5928-CONF

Tevatron combination II

- Full inclusion of systematics and non Gaussian effects
- No constraints:





- 1d βs range with $\Delta\Gamma_s$ floating.
- [0.10,1.42] @ 95 % → p-value for the SM point is 2.0% or 2.33 σ
  [0.27,0.59] U [0.97,1.30] @ 68 %

CDF/D0 $\Delta\Gamma_s$,β_s Combination Working Group:
Common CDF/D0 note CDF/PHYS/BOTTOM/CDFR/9787 - D0 Note 5928-CONF

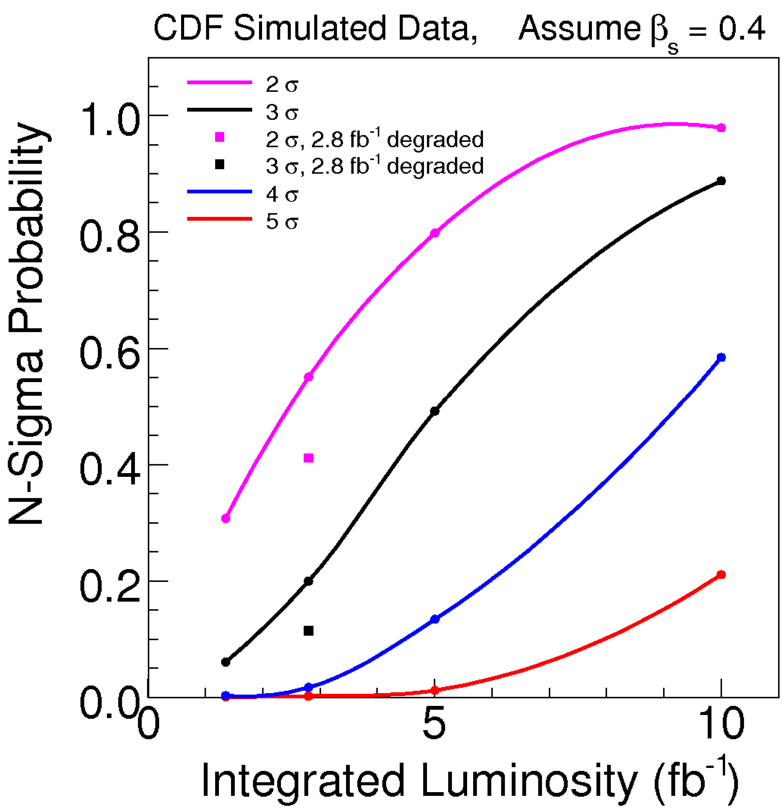
Prospects

- Intriguing 2σ effect, has not gone away:

Dec 2007	CDF(0.35 fb^{-1})	1.35 σ
Mar 2008	D0 (2.8 fb^{-1})	1.7 σ
Jul 2008	Ext. Combo	2.2 σ
Jul 2008	CDF(2.8 fb^{-1})	1.8 σ
Jul 2009	CDF/D0 combo	2.12 σ

- Assume constant efficiency, no analysis improvements
- Assume βs = 0.4.

Reasonnable for t´ (Hou PRD76 16004, 2007)



<u>Improvements in the pipeline</u>

- Incorporate PID, improved tagging
- Factor ~3-4 in luminosity
- Simultaneous CDF/D0 fit

At the end of Run 2 there is a chance for 5 sigma sensitivity to large CPV in B_s^0 oscillations

THE END

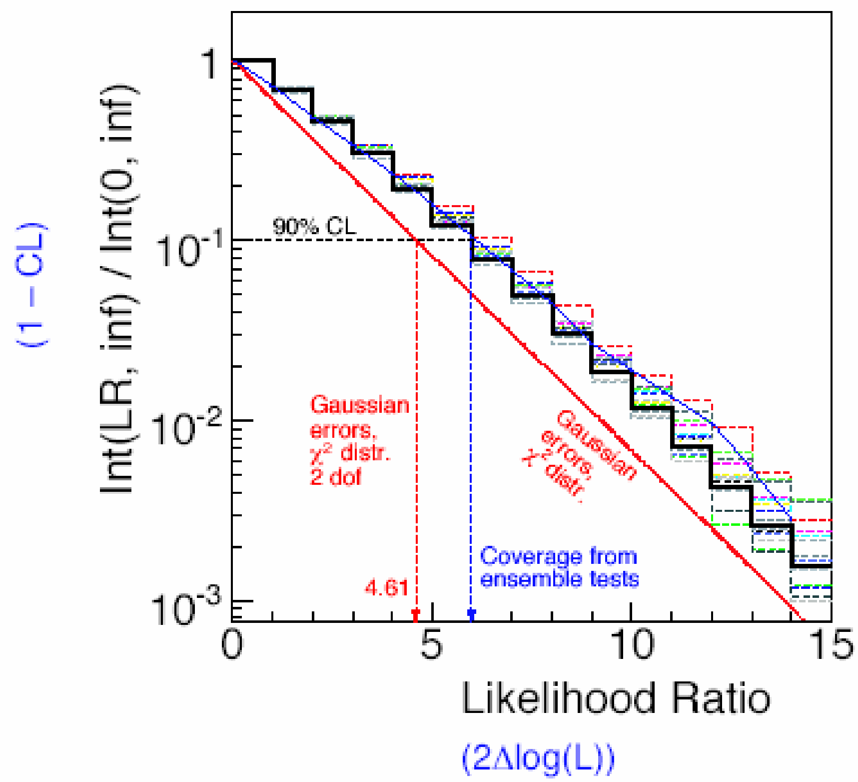
Ensuring coverage

$$R(\Delta\Gamma_s,\beta_s) = \log\frac{L(\Delta\hat{\Gamma}_s,\hat{\beta}_s,\hat{\theta})}{L(\Delta\Gamma_s,\beta_s,\hat{\theta}')}$$

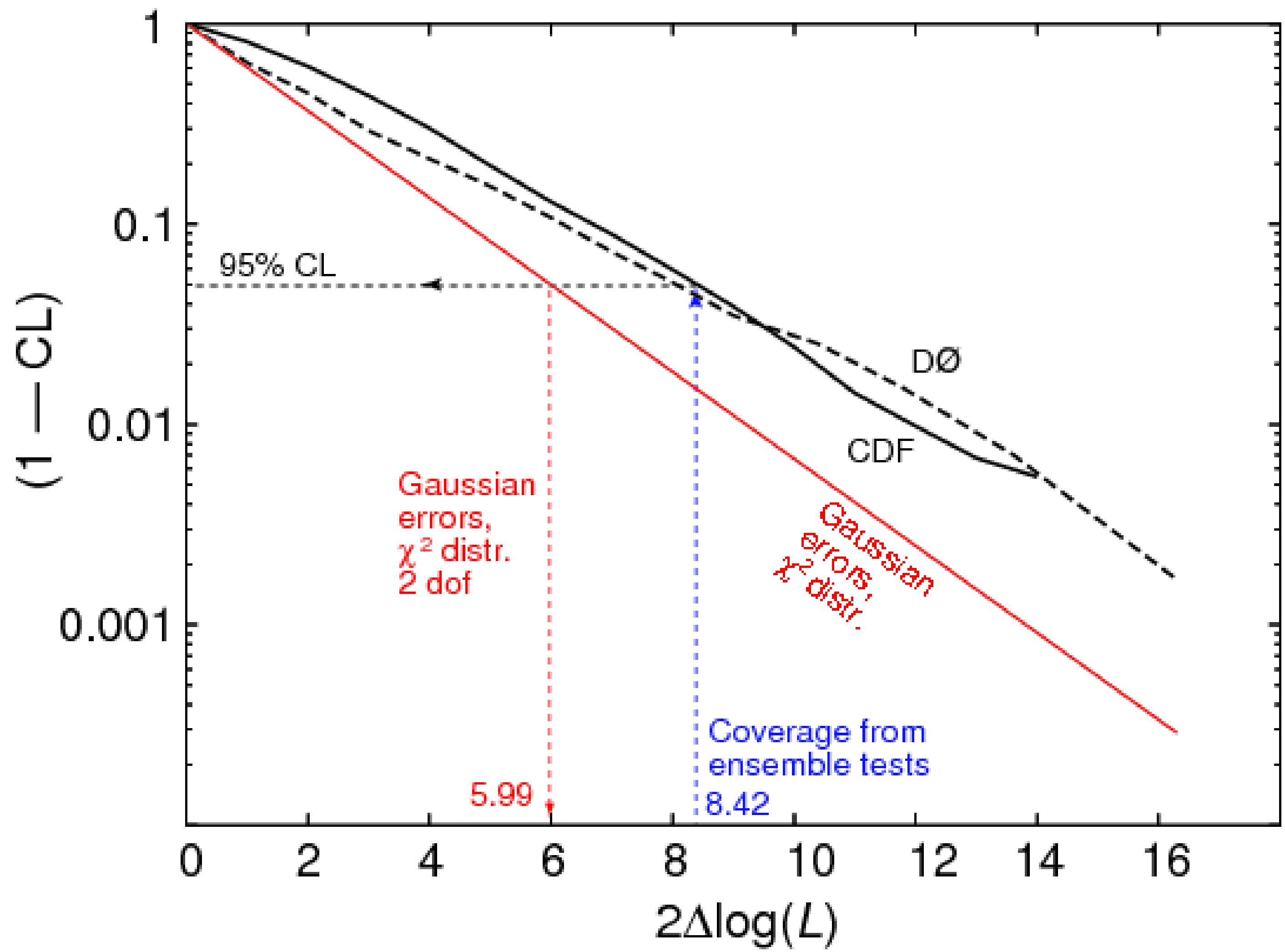
^ = parameters that maximize likelihood L

θ' = nuisance parameters that maximize L at fixed $\Delta\Gamma_s,\beta_s$

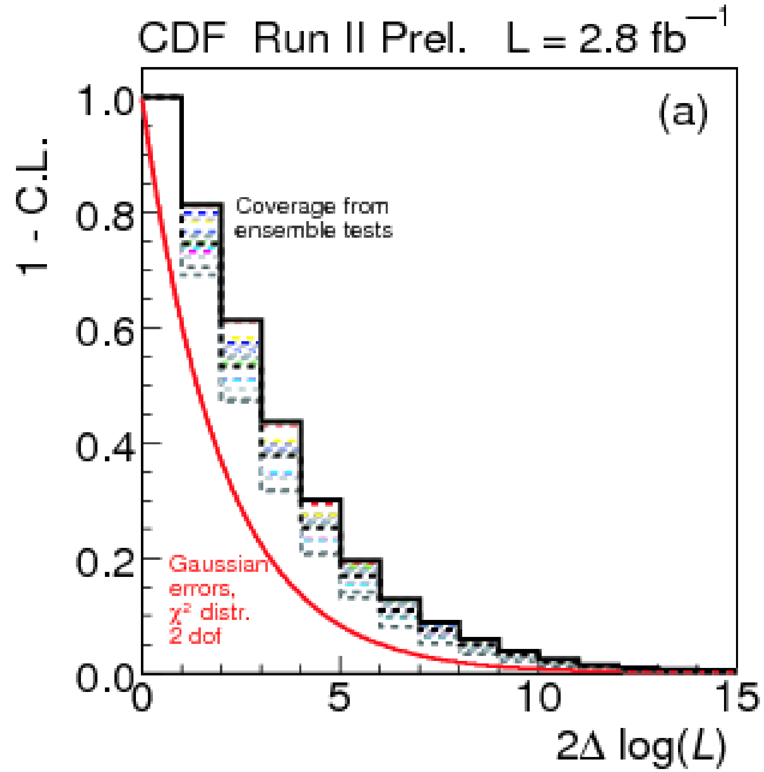
Guarantees coverage at quoted C.L. Accounts for non-asymptotic behaviour of likelihood, i.e. log(L) non-parabolic, and possible large fluctuations of L shape from experiment-to-experiment

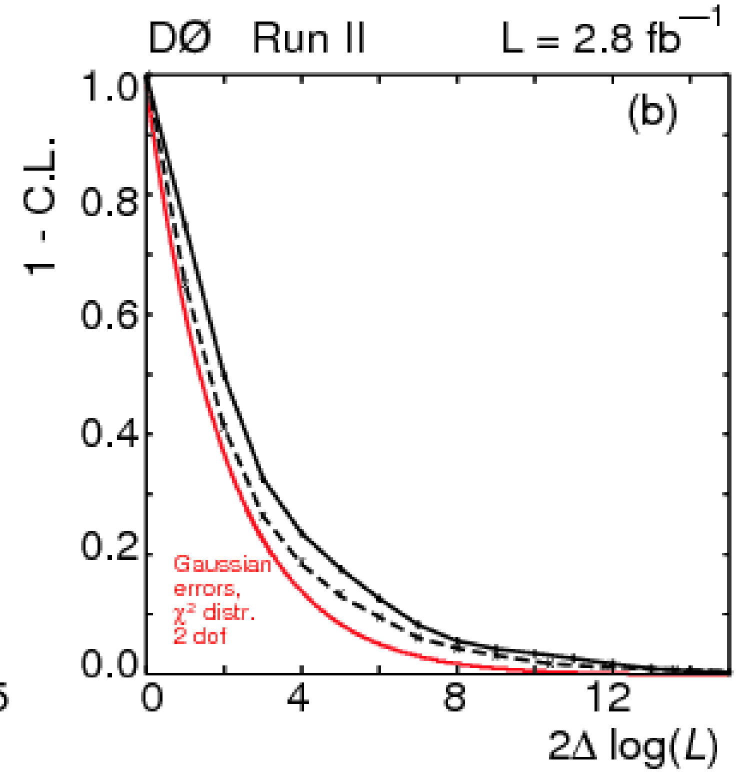


Include systematics by varying nuisance parameters within 5sigma of their estimates on data and choosing worst case to define the region


1
0.1
0.01
0.001
(1 — CL)
95% CL
DØ
CDF
Gaussian
errors,
χ² distr.
2 dof
Gaussian
errors,
χ² distr.
Coverage from
ensemble tests
5.99
8.42
0
2
4
6
8
10
12
14
16
2Δlog(L)

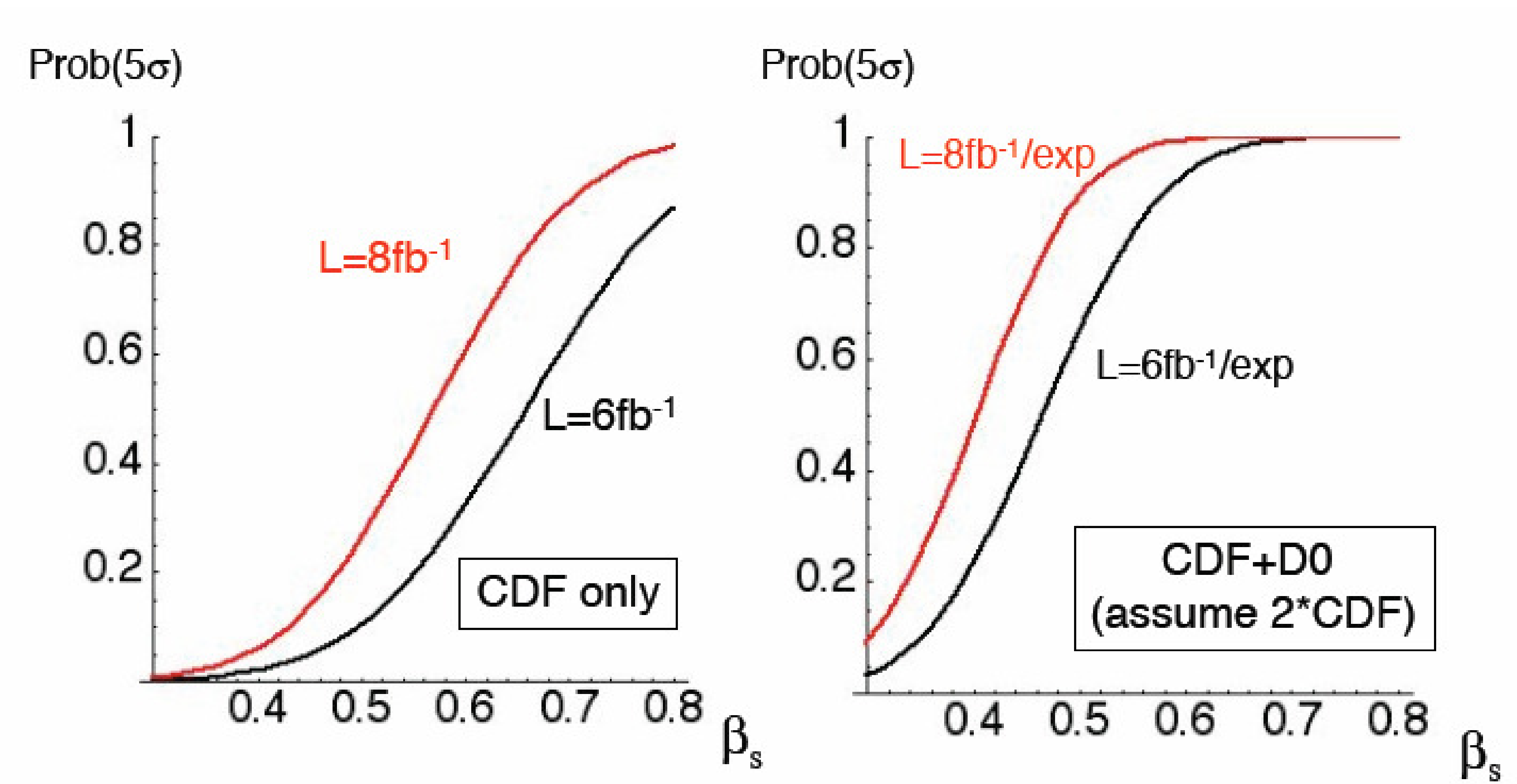
CDF/D0 combo CL distributions





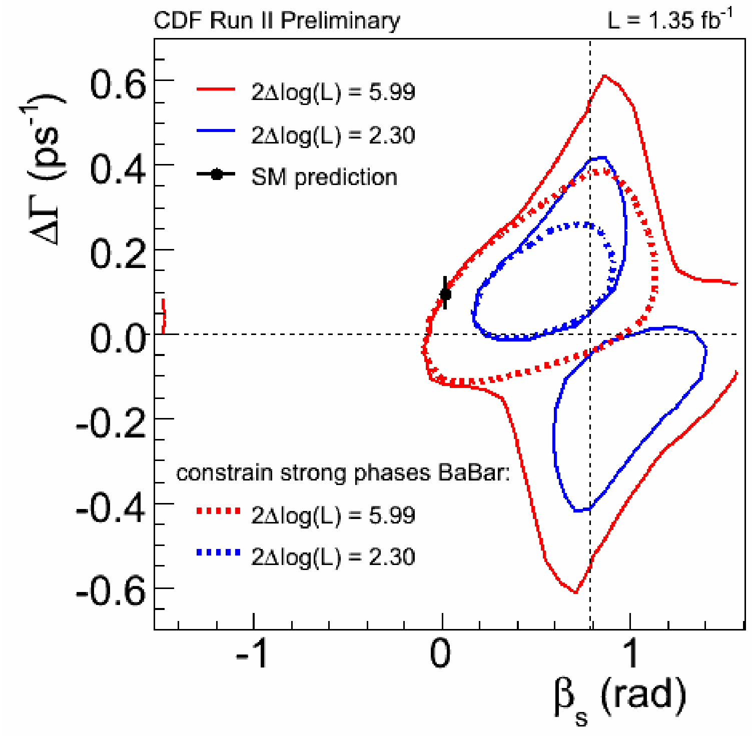
Future

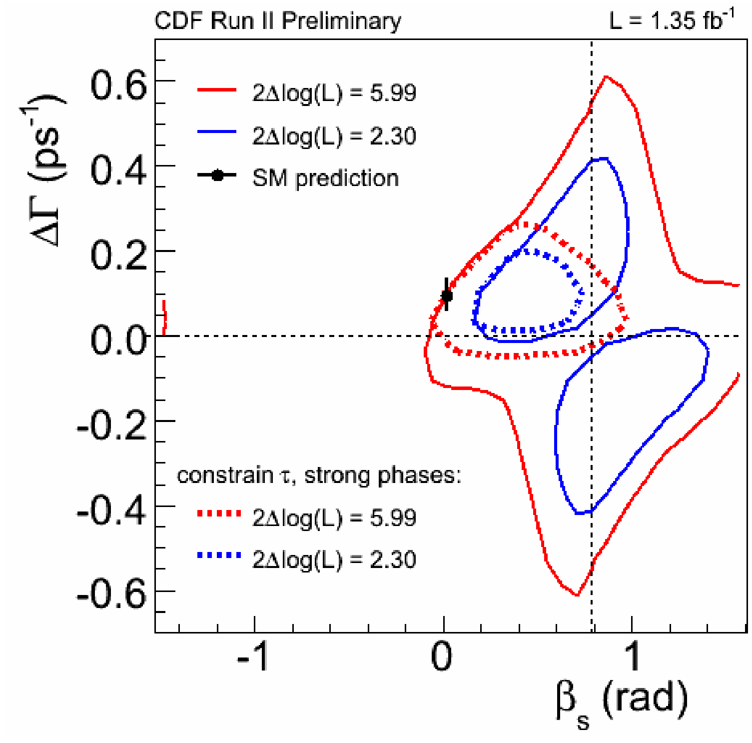
- Assume constant efficiency, no analysis improvements
- βs ~ 0.3 for t´ Hou PRD76 16004, 2007



- Spectator model of B mesons suggests that B_s and B^0 have similar lifetimes and strong phases
- Likelihood profiles with external constraints from B factories:

constrain strong phases: constrain lifetime and strong phases:





- External constraints on strong phases remove residual 2-fold ambiguity

β_s vs. ϕ_s

- Up to now, introduced two different phases:

$\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4x10^{-3}$ and $\beta_s^{\rm SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$

- New Physics affects both phases by same quantity $\phi_s^{\rm NP}$ (arxiv:0705.3802v2):

$$2\beta_s = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}$$

$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}$$

- If the new physics phase $\phi_s^{\rm NP}$ dominates over the SM phases $2\beta_s^{\rm SM}$ and $\phi_s^{\rm SM}$
→ neglect SM phases and obtain:

$$2\beta_s = -\phi_s^{\rm NP} = -\phi_s$$

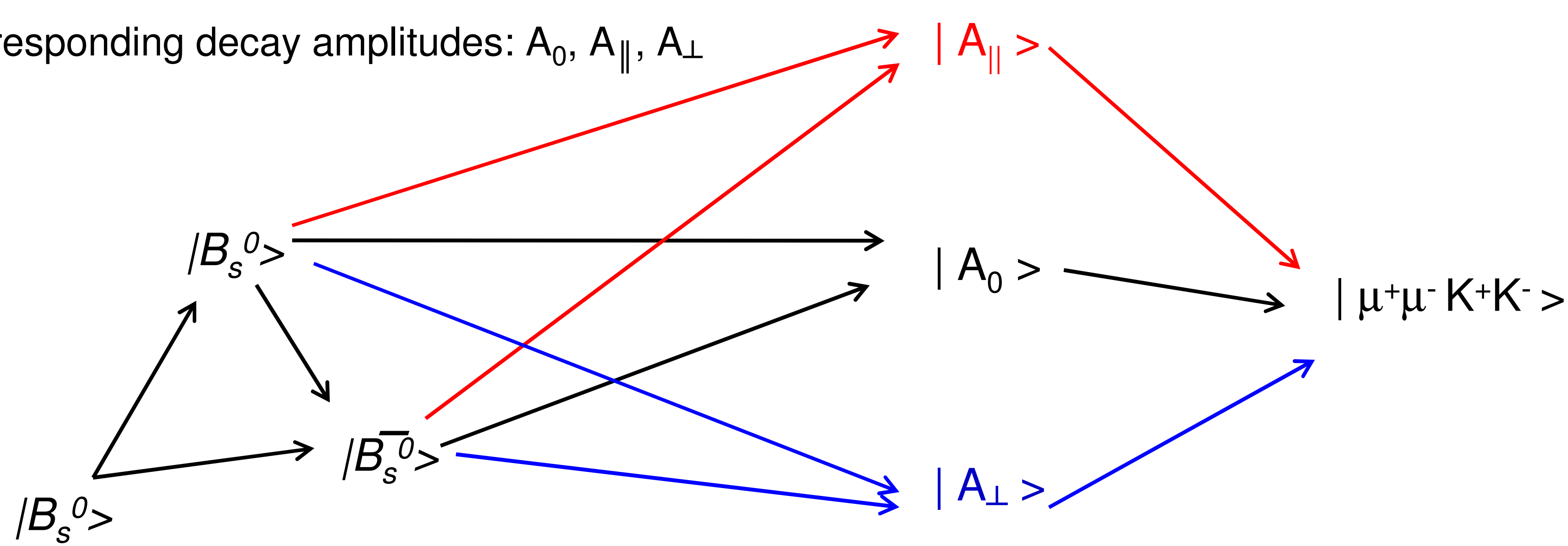
$B_s \to J/\Psi\Phi$ transversity axis

- Three angular momentum states form a basis for the final J/ΨΦ state

- Use alternative “transversity basis” in which the vector meson polarizations w.r.t. direction of motion are either (Phys. Lett. B 369, 144 (1996), 184 hep-ph/9511363):

  - transverse ($\perp$ perpendicular to each other) → CP odd
  - transverse ($\parallel$ parallel to each other) → CP even
  - longitudinal (0) → CP even

- Corresponding decay amplitudes: A_0, $A_\parallel$, $A_\perp$



$B_s \to J/\Psi\Phi$ Decay Rate

Measurement is a flavor-tagged analysis of time-dependent angular distributions

- $B_s \to J/\Psi\Phi$ decay rate as function of time, decay angles and initial B_s flavor:

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

time dependence terms

angular dependence terms

terms with β_s dependence

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

terms with Δm_s dependence present if initial state of B meson (B vs anti-B) is determined (flavor tagged)

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

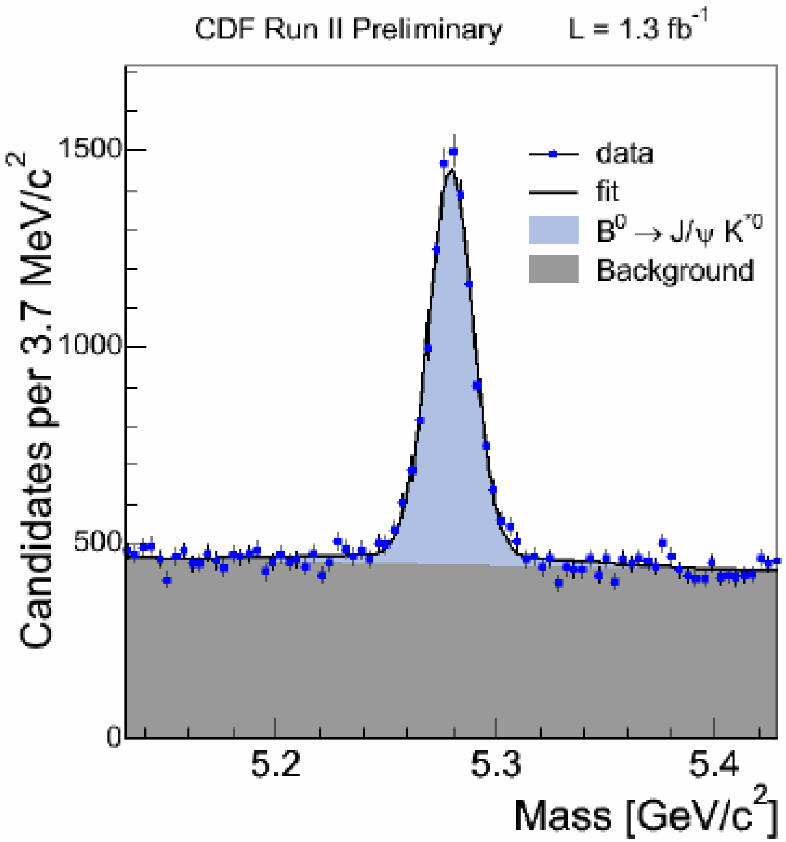
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)].$$

'strong' phases:

$$\delta_\parallel \equiv \mathrm{Arg}(A_\parallel(0)A_0^*(0))$$
$$\delta_\perp \equiv \mathrm{Arg}(A_\perp(0)A_0^*(0))$$

Identification of B flavor at production (flavor tagging) → better sensitivity to β_s

Measure polarization of $B_0 \rightarrow \psi K^*$



$$c\tau = 456 \pm 6\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$$

$$|A_0(0)|^2 = 0.569 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$$

$$|A_\parallel(0)|^2 = 0.211 \pm 0.012\ (\text{stat}) \pm 0.006\ (\text{syst})$$

$$\delta_\parallel = -2.96 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$$

$$\delta_\perp = \ \ 2.97 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$$

Consistent and competitive with B-factories