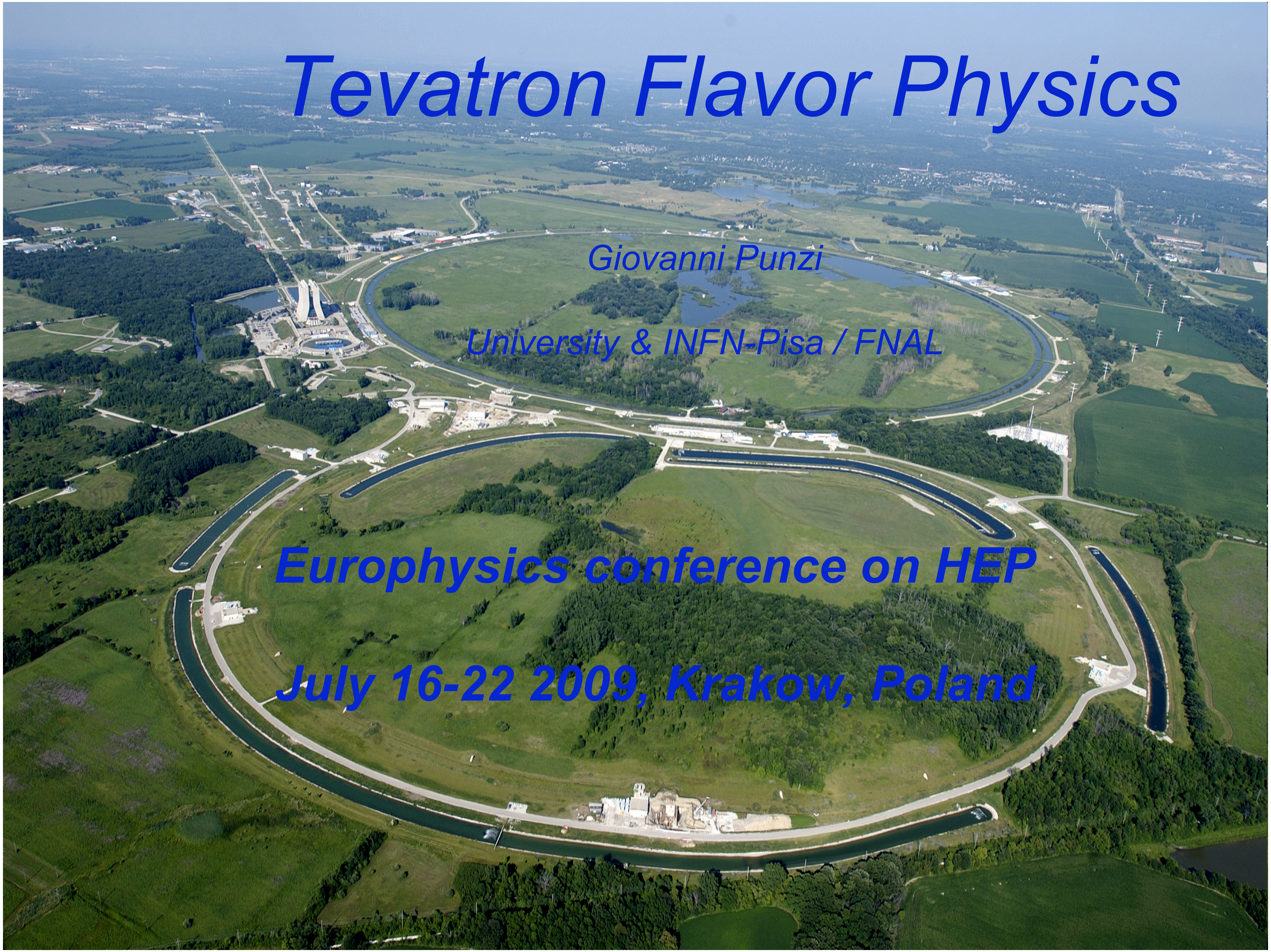


Tevatron Flavor Physics

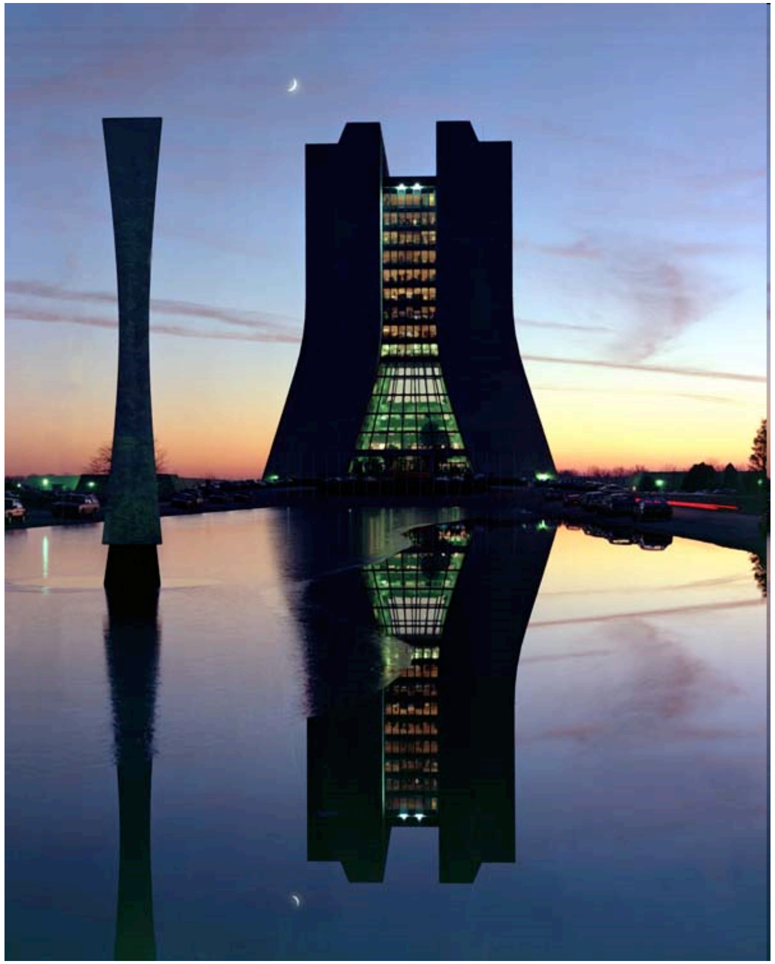
Giovanni Punzi

University & INFN-Pisa / FNAL

Europhysics conference on HEP

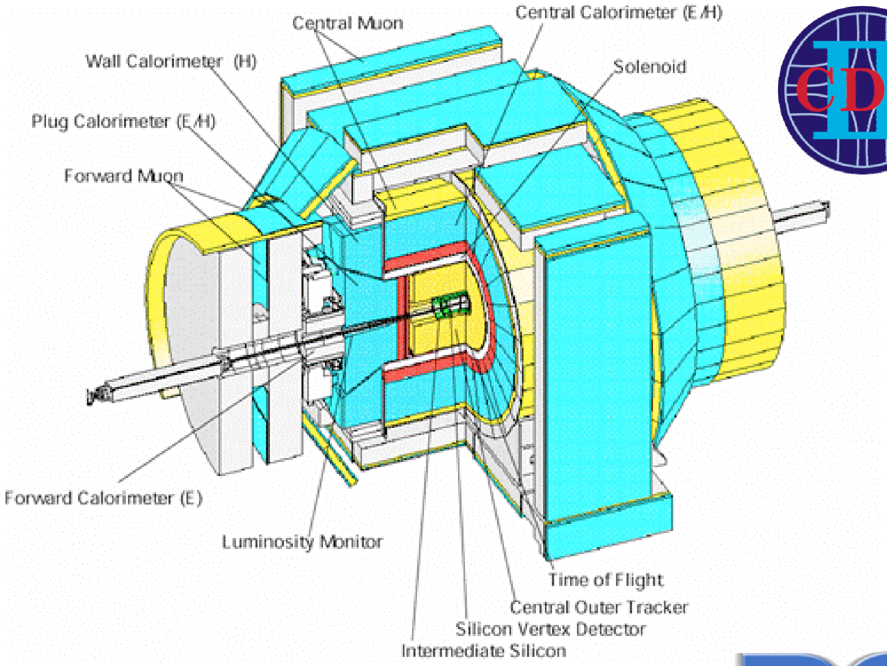
July 16-22 2009, Krakow, Poland

Outline



- CDF and D0 status
- Hadron properties
- Exotics
- FCNC
- B_s mixing
- A look at the future

Tevatron Detectors and FP

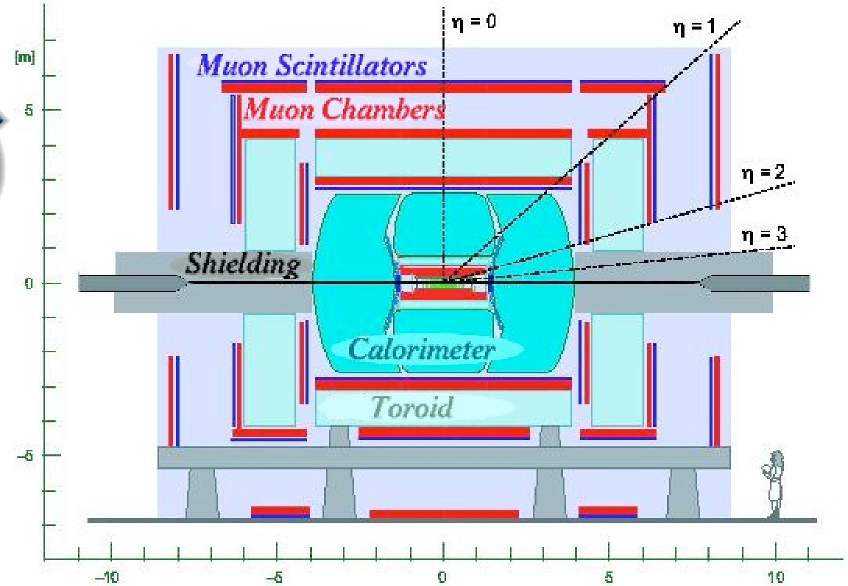


CDF II Detector

- Tracker: - **Silicon Vertex Detectors**
  - Precision Drift Chamber
- **Excellent Momentum Resolution**
- **Trigger on long-lived particles**
- **Particle ID**: TOF and dE/dx
- Triggered Muon Coverage $|\eta|<1$

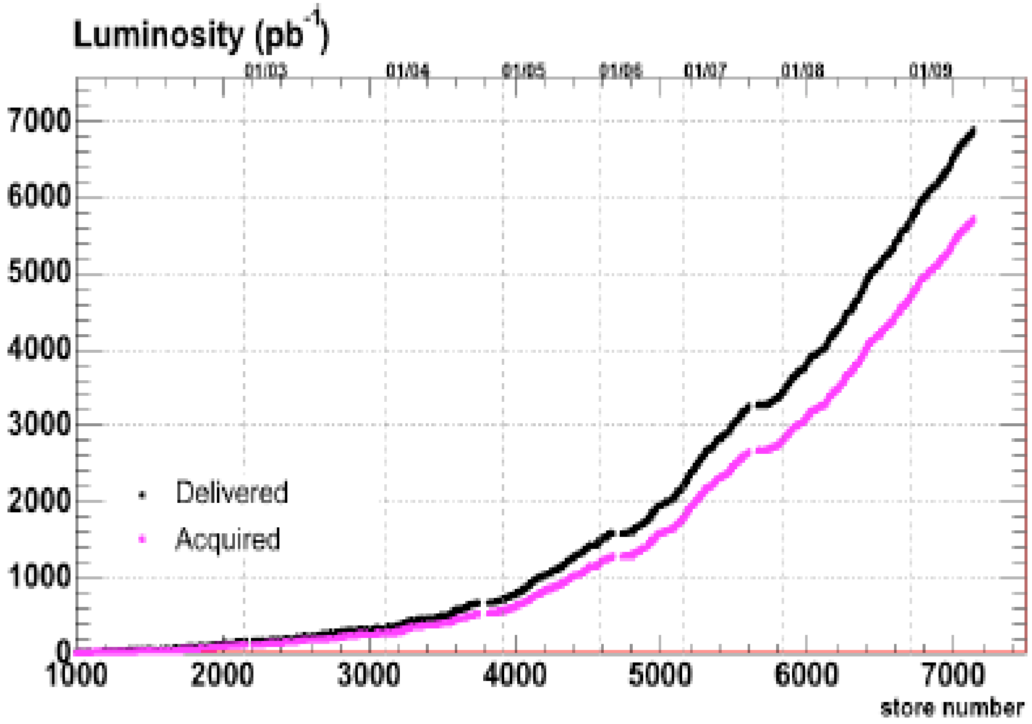
DØ Detector

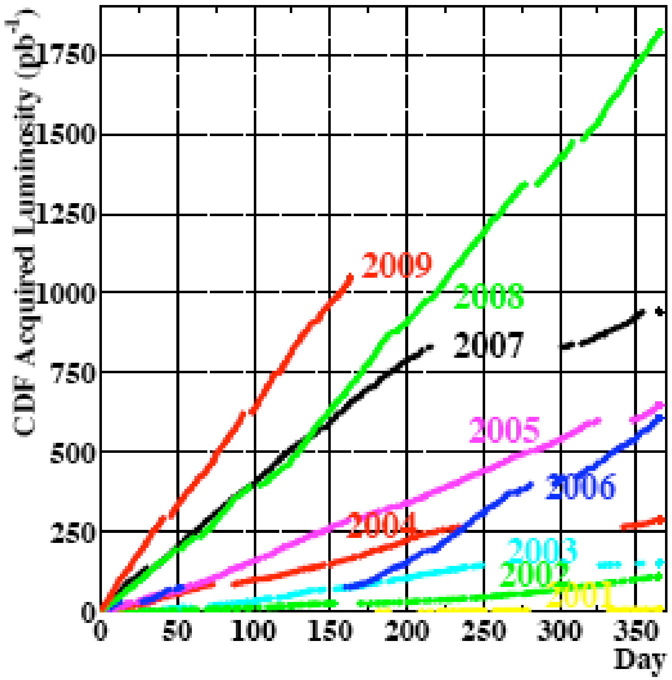
- **Large triggered Muon Coverage** $|\eta|<2.2$
- **Silicon Detectors - New L00** installed in 2006.
- Solenoid: 2T, polarity reversed weekly
- Excellent Calorimetry and electron ID



Tevatron data

(CDF shown, D0 is similar)

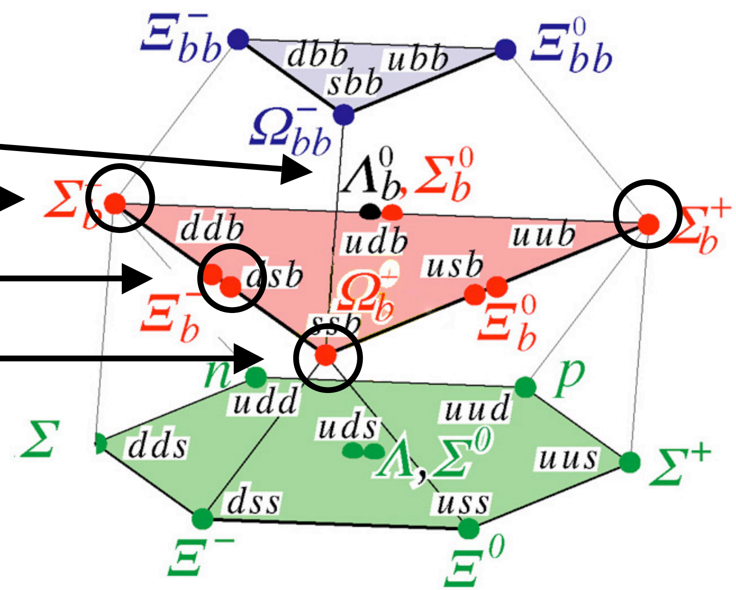




- Ever-increasing luminosity - current ~2fb^{-1}/year/experim.
- Current sample 6 fb^{-1} (Expect FY 2010: 9fb^{-1} , FY 2011: 12fb^{-1})
- Most flavor physics analyses use 1 fb^{-1} -- 5 fb^{-1}
- Large QCD backrounds, trigger is key, complex analyses.
- Enough energy to produce and study all *b* and *c* hadrons

Bottom Baryon States

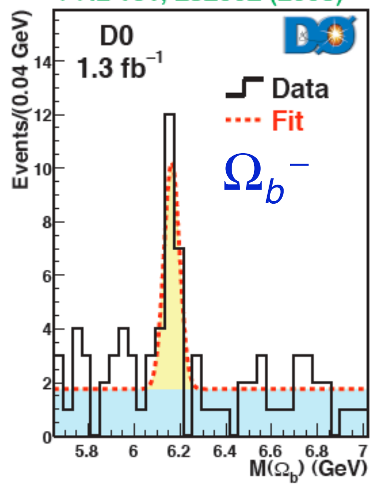
- Our knowledge of *b*-baryons has greatly expanded in the last ~3 years
- This is totally a Tevatron field
  - World's largest samples of Λ_b
  - $\Sigma_b^{(*)+}$ and $\Sigma_b^{(*)-}$ observed by CDF in 2007
  - Ξ_b^-, observed by D0 & CDF in 2007
  - Ω_b^- , observed by D0 in 2008, CDF 2009
- Will mention only the latest results, which are about Ξ_b^- (*usb*) and Ω_b (*ssb*). Both are weakly-decaying as the Λ_b and can be fully reconstructed in J/ψ modes by both experiments.



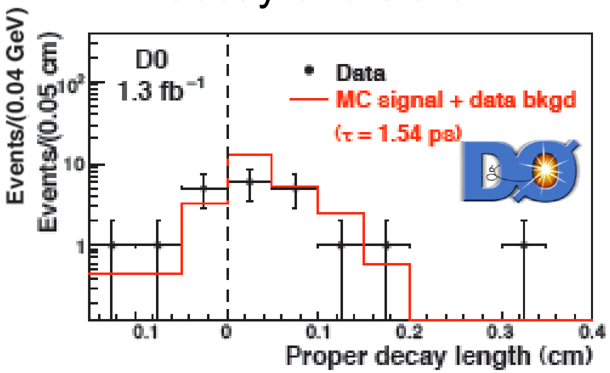
Ω_b / Ξ_b results

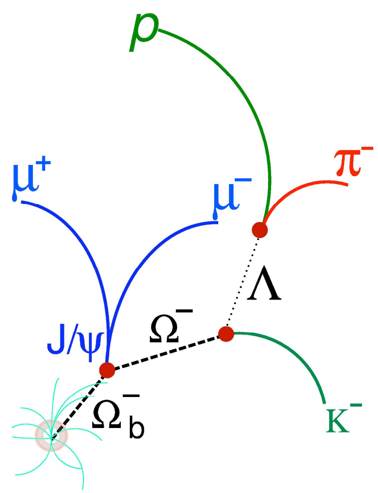
[*see talks by P.Lukens and J.Orduna*]

PRL **101**, 232002 (2008)

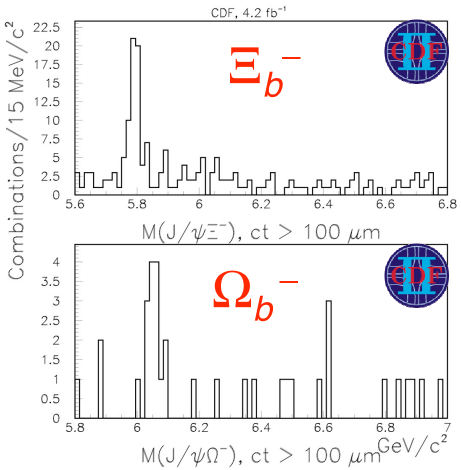


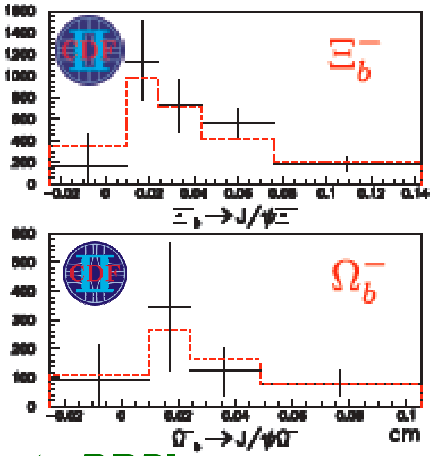
Distribution consistent with weak decay of *b*-state





$m(\Omega_b)$ = 6165 ±10 ±13 MeV/c^2





$$m(\Xi_b^-) = 5790.9 \pm 2.6 \pm 0.9\,\mathrm{MeV}$$
$$\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25} \pm 0.02\,\mathrm{ps}$$

└ First exclusive Ξ_b^- lifetime!

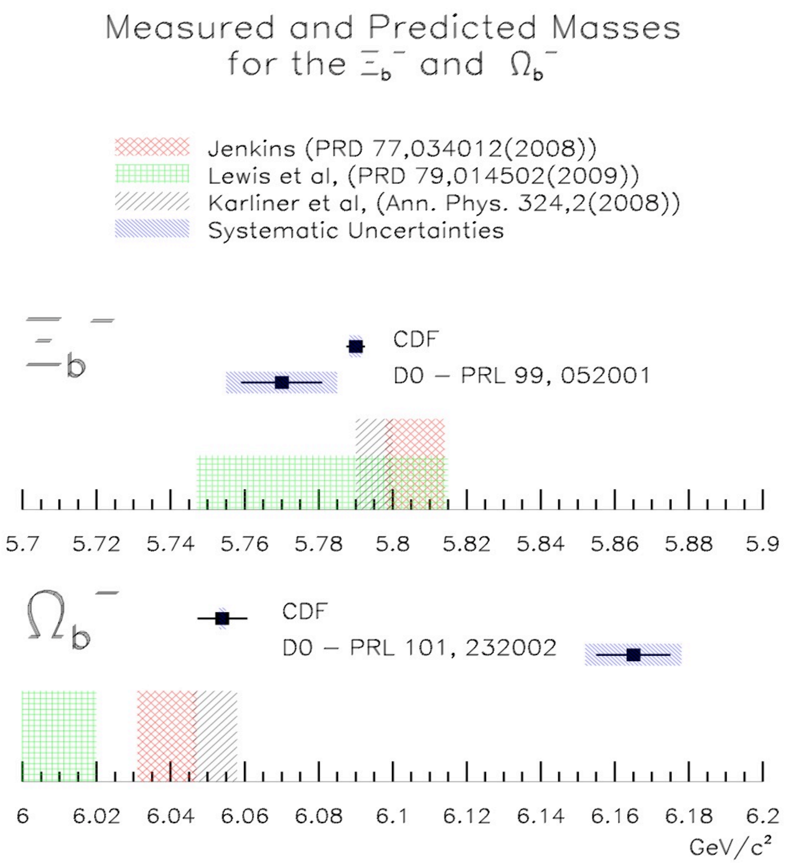
$$m(\Omega_b^-) = 6054.4 \pm 6.8 \pm 0.9\,\mathrm{MeV}$$
$$\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40} \pm 0.02\,\mathrm{ps}$$

└ First ever!

[*arXiv:0905.3123, subm. to PRD*]

CDF - D0 discrepancy on Ω_b

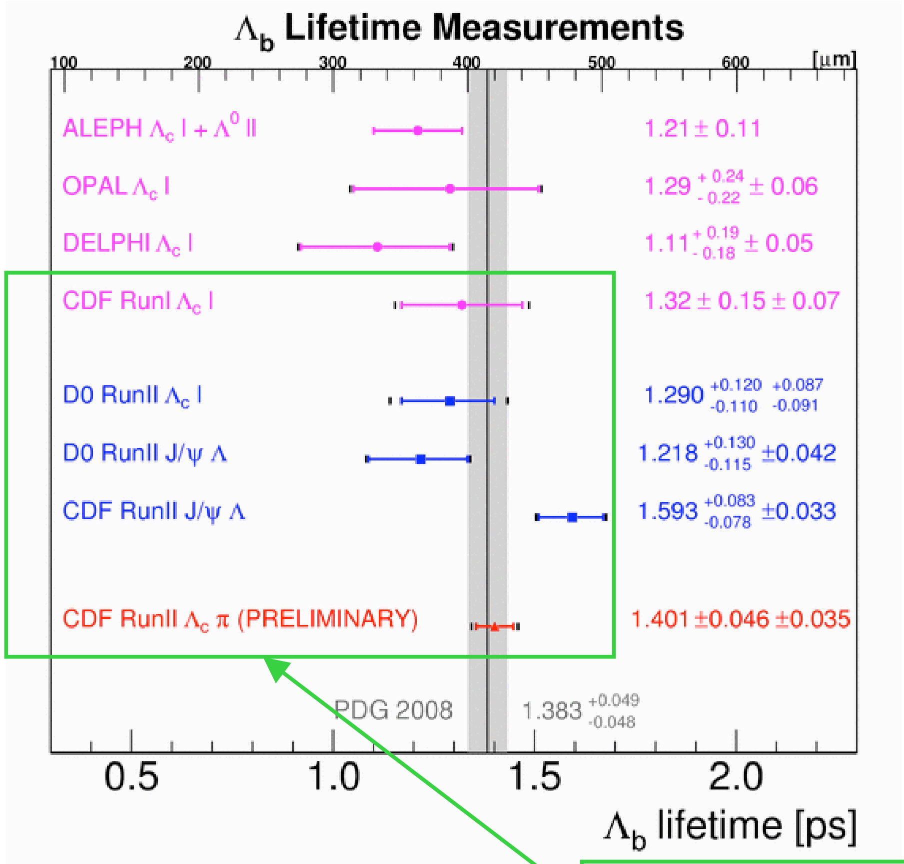
- $M(\Omega_b)_{D0} - M(\Omega_b)_{CDF} = 111 \pm 12 \pm 14$ MeV/c^2
  - Significant disagreement (6-sigma)
  - Agreement on Ξ_b^- : not a scale problem
  - Rates differ, but uncertainty large
  - Both signals >5σ
- Important to solve:
  - predictions exist for all heavy baryons
  - current resolutions allow significant progress in discriminating between (sub-)models. Sensitive even to different choice of potential.
- Both results look convincing: solution of the “doubly-strange” baryon puzzle can only come from more measurements.
  D0 working at update to full 6fb^{-1} sample.

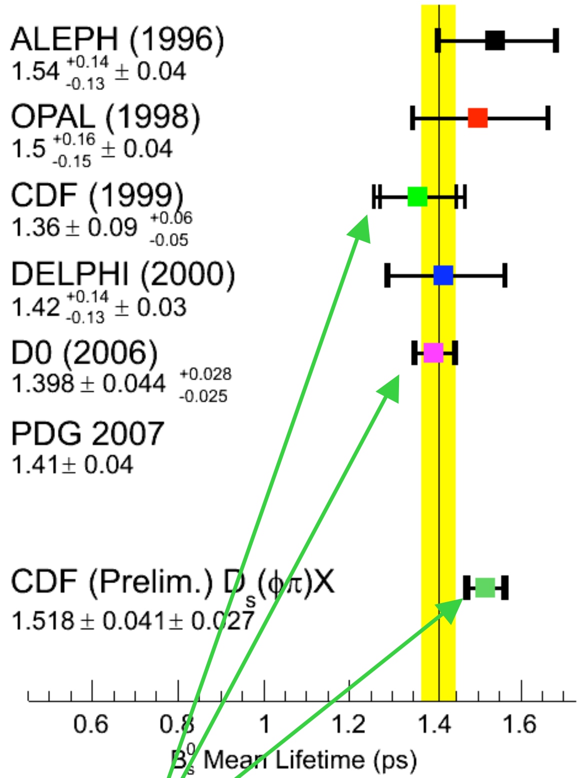


Reminds us of the importance of always having several experiments doing the same measurements

Other lifetimes: Λ_b and B_s

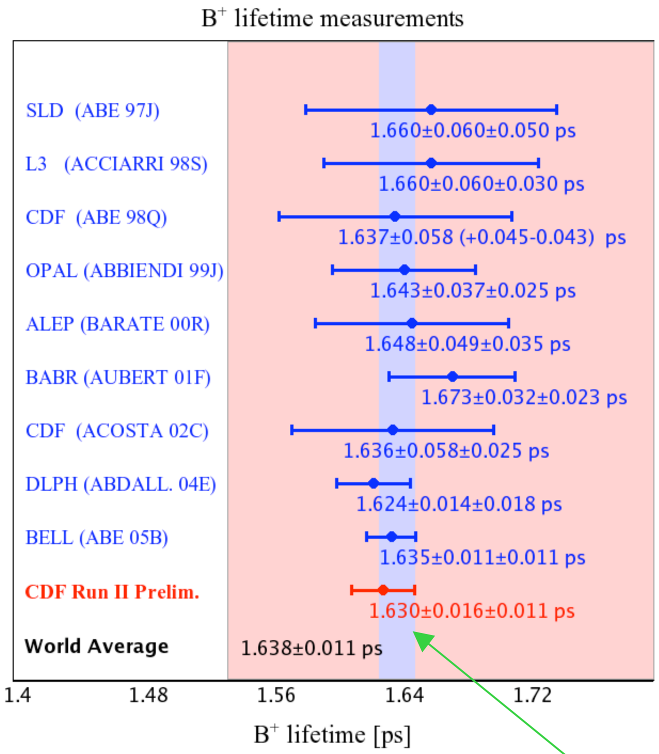
[*see talk by Fernandez*]

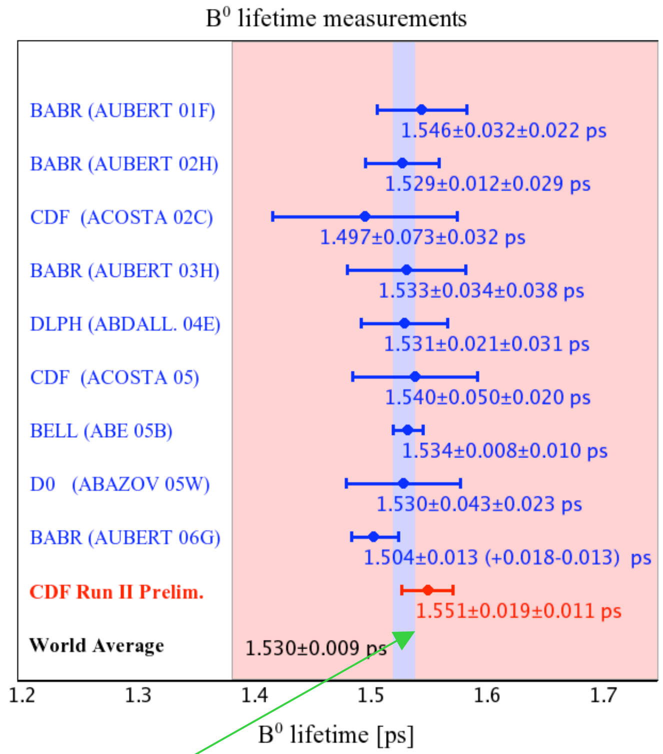




Tevatron measurements dominate averages

Entering the B^0/B^+ lifetimes business





1fb-1 measurements

With 5fb-1 expect single most precise measurements

EXOTICS: X(3872)

[arXiv:0906.5218 Subm. to PRL, 29 Jun 2009]

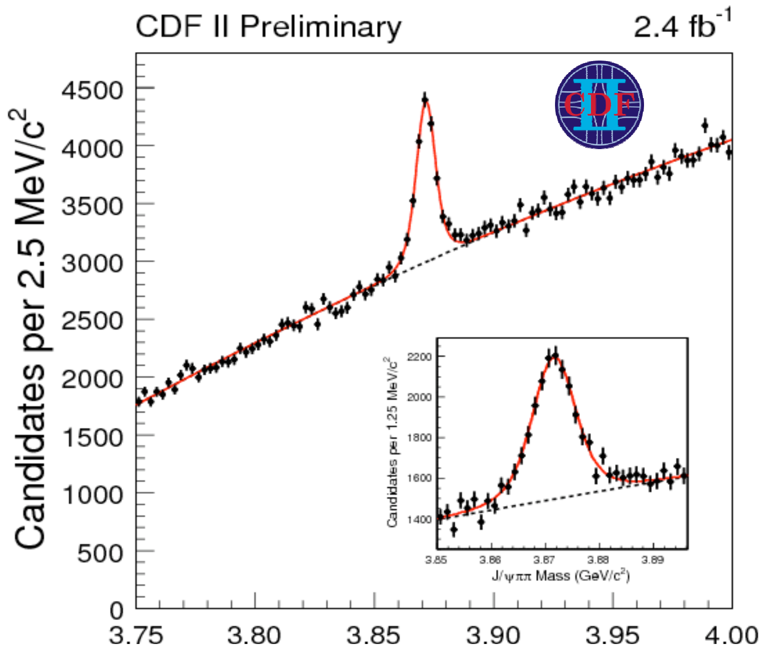
- Tevatron a great place to study exotic states.
- Largest X(3872) yields (6,000 events)
- Limit on two-state separation <3.2 MeV/c^2

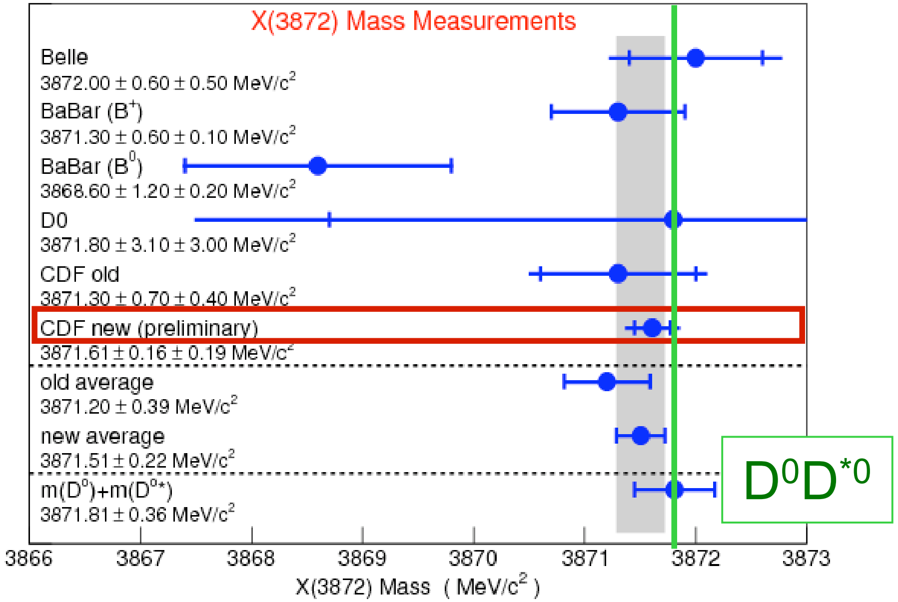
  Disfavor predictions of two-state system
- Best mass resolution:

  M = 3871.61 $\pm$ 0.16 $\pm$ 0.19 MeV/c^2

  Compatible with molecular model.
- But production cross-section disfavors it. *[s Piccinini in QCD session].*

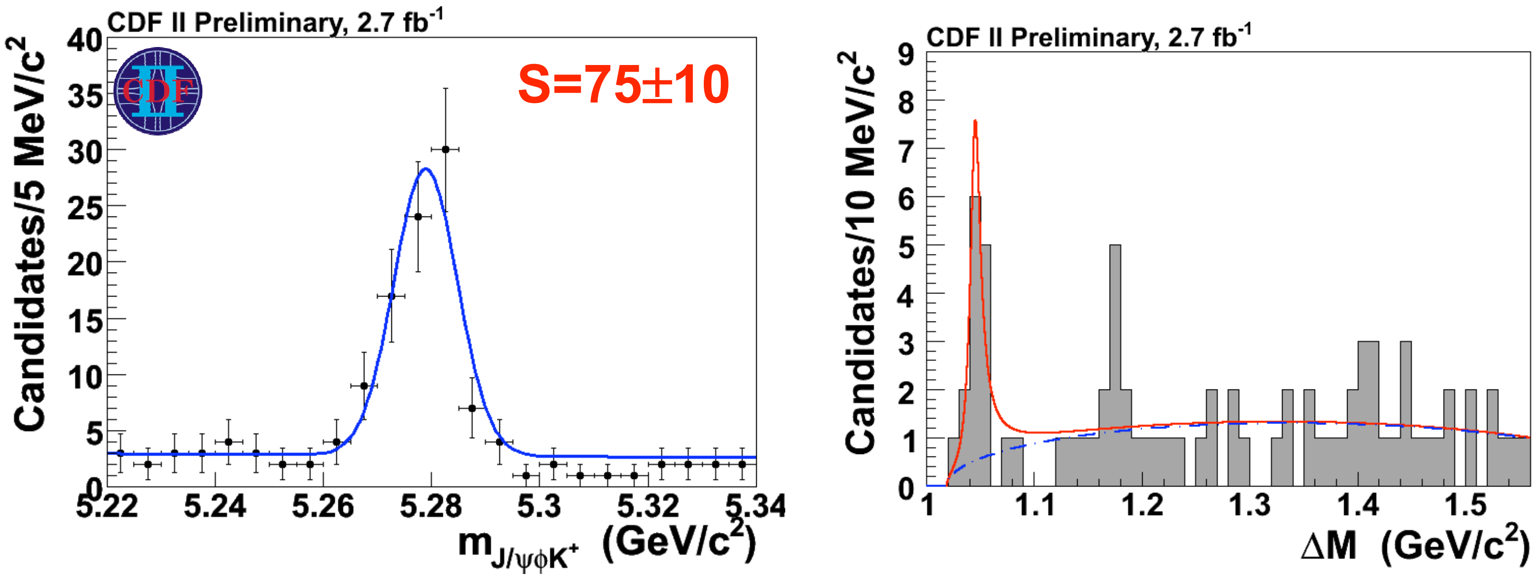
- Still need more studies to understand





EXOTICS: new resonance Y(4140)

[Phys.Rev.Lett.102:242002,2009]



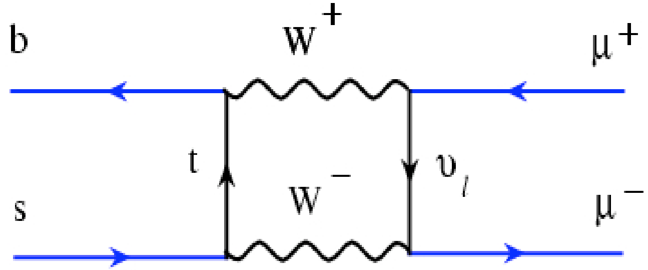
- First J/ψ-φ state, found in *world's largest sample* of $B^+ \to J/\psi\varphi K^+$. PID important for kaon identification.
- Yield 14 ± 5. Significance 3.8 σ.
- M=4143.0 ± 2.9 ± 1.2 MeV/c^2; Γ= $11.7^{+8.3}_{-5.0} \pm 3.7$ MeV/c^2 (≠0 @3.4σ)
- Suggest strong decay. Unclear nature, possible 4-quark or hybrid.
- Have more data in hand, will help clarify and make further progress.

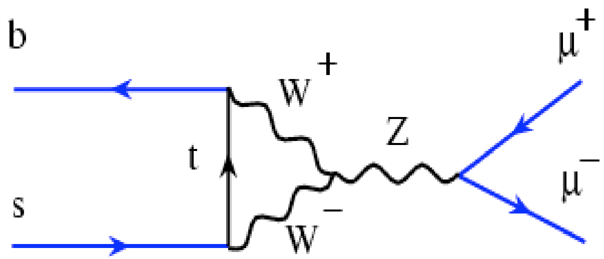
Rare modes

FCNC/LFV

- Rare in the SM, but can be significantly enhanced by several BSM processes.
- Require large production and large rejection - strong points of Tevatron experiments. Data collected from either dimuon trigger (Pt>1.5 GeV) or (remarkably) track trigger (Pt>2 GeV with impact parameter).
- Modes studied:
  - $B^0 \to K^{0*} l^+l^-$, $B^+ \to K^+ l^+l^-$, $B_s \to \varphi\, l^+l^-$
    - In progress, expect similar resolution to B-factories. Confirm hints of deviation ? *[see talk by T.Hurth*]
  - $D^0 \to \mu\mu$
    - BR <5.3 10^{-7} (0.36fb^{-1}). Best limit until recently.
  - $B_s /B_d \to ee, e\mu$
    Best Pati-Salam leptoquark limits: >48/60 TeV respectively [Phys.Rev.Lett.102:201801,2009]
  - $B_d \to \mu\mu$, $B_s \to \mu\mu$

$B_s/B_d \rightarrow \mu\mu$





A.J. Buras arXiv:0904.4917v1

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$$
$$BR(B_d \rightarrow \mu^+\mu^-) = (1.1 \pm 0.1) \times 10^{-10}$$

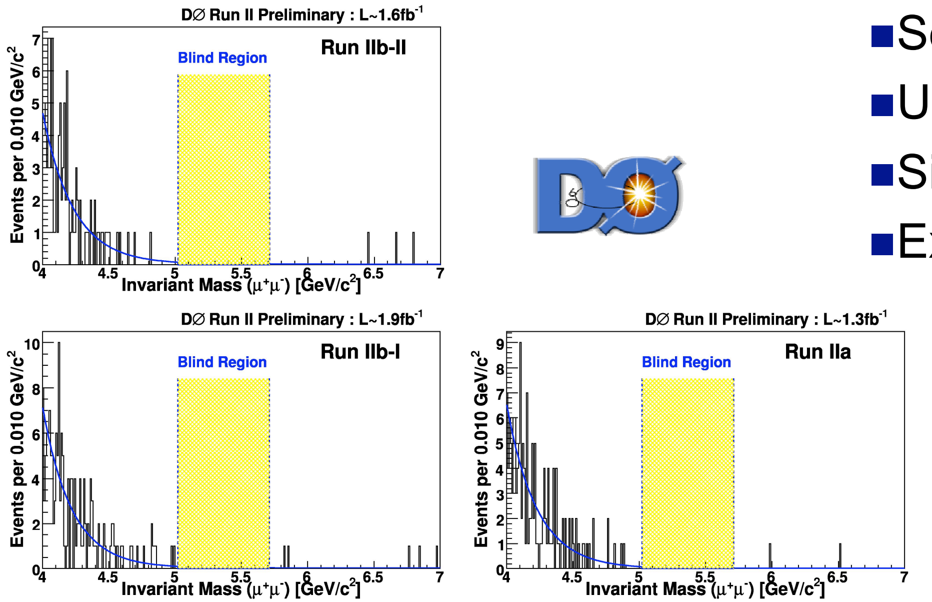
- Current best limits at 90(95%)CL:

(units 10^{-8})	Bd	Bs
CDF ($2fb^{-1}$)	1.5(1.8)	4.7(5.8)
D0($2fb^{-1}$)	-	7.5(9.3)

Unofficial Tevatron combination:
$BR(B_s \rightarrow \mu\mu) < 4.5*10^{-8}$ @ 95%CL
(13xSM)

- MFV predicts the same proportion to hold in BSM enhancements. Observing an excess in B_d without the B_s would point to MFV violation
- Possible New Physics contributions:
  - MSSM ~$\tan^6(\beta)$, for large $\tan(\beta)$
  - SUSY with R-parity violation (RPV)
  - Z' with off diagonal couplings
  - Almost any heavy object...

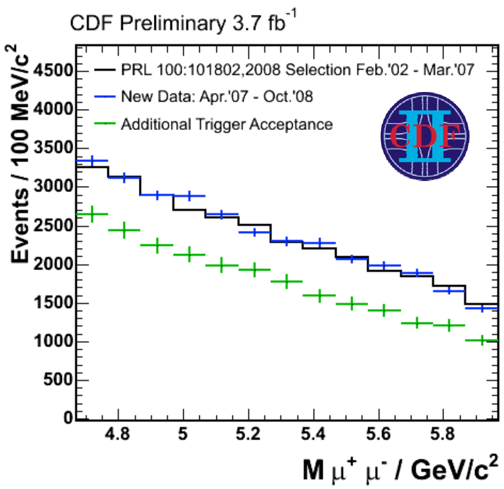
B→μμ updates in progress



- Separate data in different periods, ~5fb^{-1}
- Use BDT for selection, optimize on sCL
- Signal region still blind, show sidebands
- Expected limit:

4.3(5.3)10^{-8} @90(95)%

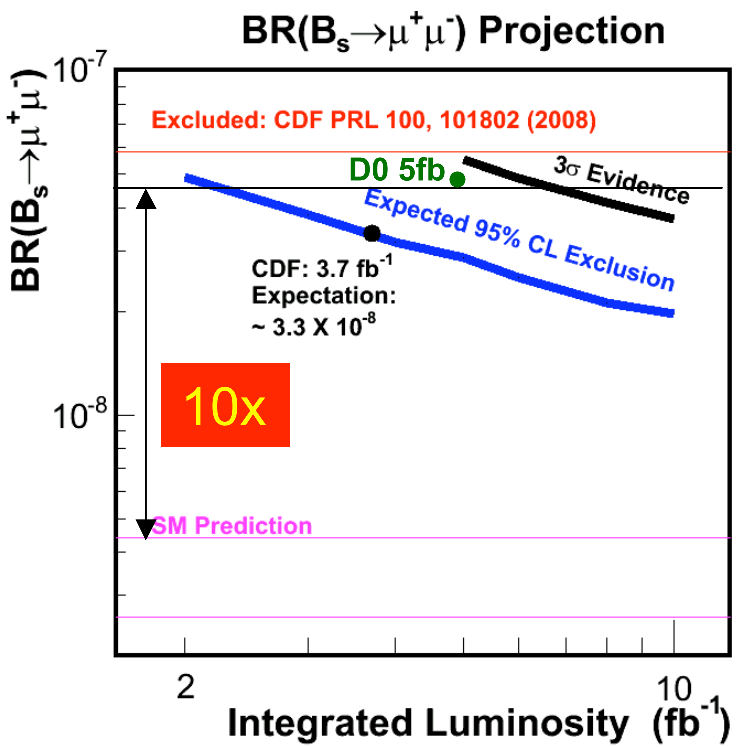
[see talk by Ripp-Baudot]



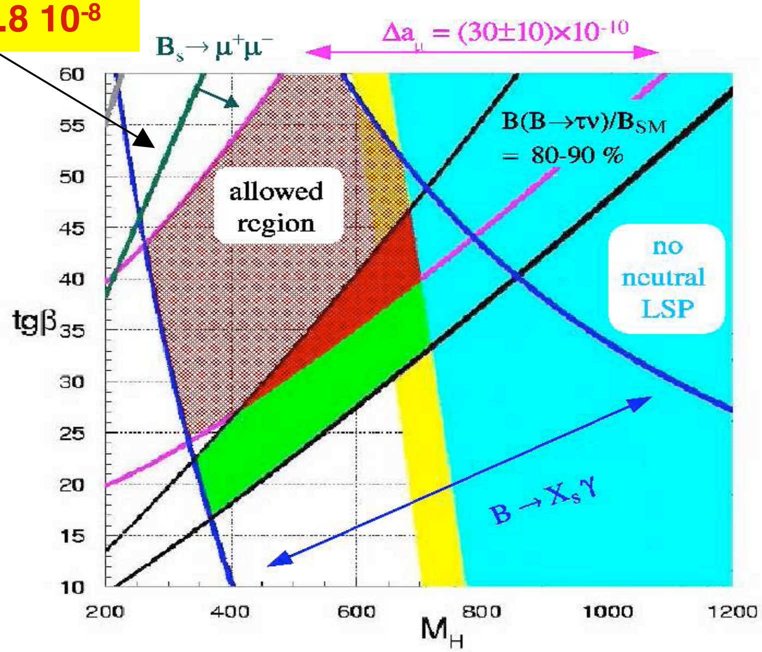
- NEW: CDF currently working on 3.7fb^{-1} Soon to be followed by 5fb^{-1}
- Added trigger acceptance by including further geometrical regions.
- Use a NN selection on similar variables as D0. Optimized on sCL limit.
- Expect limit improve almost **2x**: **3.3*10^{-8}** @95%CL

B → μμ summary

- Making a dent in the final factor of ***10*** from the SM !
- CDF and D0 expect ~2 SM $B_s \rightarrow \mu\mu$ events in their sample at this time - the game is now one of background reduction
- Both CDF and D0 aggressively trying to improve their analyses
- Start having serious implications for NP models.



Old limit: 5.8 10^{-8}



[MSSM model, heavy squarks, Isidori et al. arxiv:0801.303; PRD 75, 115019(2007)]

$B_s - \overline{B}_s$ system

B_s oscillation parameters

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

Diagonalize

CP Eigenstates: $|B_s^{odd}\rangle = |B_s^0\rangle + |\bar{B}_s^0\rangle$ $\quad |B_s^{even}\rangle = |B_s^0\rangle - |\bar{B}_s^0\rangle$

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

Heavy Light

If CP conserved in mixing, $p=q$

observables

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \qquad \Gamma_s = \frac{(\Gamma_L + \Gamma_H)}{2}$$
$$\Delta M_s = M_H - M_L$$

$$a^s_{fs} = \frac{\Gamma(\bar{B}_s(t) \to f) - \Gamma(B_s(t) \to \bar{f})}{\Gamma(\bar{B}_s(t) \to f) + \Gamma(B_s(t) \to \bar{f})}$$

$$\Delta M_s = 2|M_{12,s}^{\rm SM}| \cdot |\Delta_s|$$
$$\Delta\Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^{\Delta}\right)$$
$$\frac{\Delta\Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^{\Delta}\right)}{|\Delta_s|}$$
$$a^s_{fs} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^{\Delta}\right)}{|\Delta_s|} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan(\phi_s^{SM} + \phi_s^{\Delta})$$
$$\sin(\phi_s^{\rm SM}) \approx 1/240$$

Sensitive to a lot of possible New Physics:
SUSY, 4th generation, GUT, Extended Higgs, MFV, unparticle, …
Really attractive hunting ground - if you don't find NP here, where will you look ?

Status of mixing parameters

- All measurements Tevatron-dominated
- Δm_s - (CDF dominated) agree with SM.

  $$\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}$$

  - precision below theory uncertainties - done with for some time
- $\Delta\Gamma_s$ - HFAG 09: $\Delta\Gamma_s = 0.062^{+0.034}_{-0.037}$ but assumes no CPV. More interesting is combined determination with phase ϕ_s
- ϕ_s - hottest item, in progress. Measured in decays into CP eigenstates: use $B_s \to J/\psi\varphi$ with angular analysis. Today a joint CDF-D0 result for the first time.
- a_{fs} - recent measurement of A_{SL}

B_s semileptonic asymmetry

$$\mathcal{A}_{\rm SL}^{s} = \frac{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) - N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)}{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) + N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)} = \frac{|p/q|_s^2 - |q/p|_s^2}{|p/q|_s^2 + |q/p|_s^2}$$

$$|q/p|^2 \neq 1$$

CP violation in mixing

Experimentally, fit to:

Separate by flavor tag

Unmixed

$$\left.\begin{array}{l}\Gamma(B_s^0 \to \mu^+ X) \\ \Gamma(\bar{B}_s^0 \to \mu^- X)\end{array}\right\} \propto \exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) + \cos(\Delta m_s t)]$$

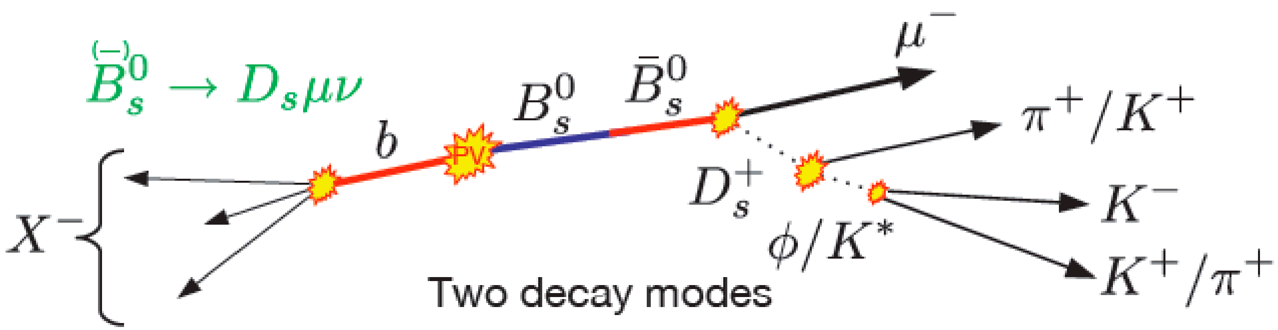
Mixed

$$\Gamma(\bar{B}_s^0 \to \mu^+ X) \propto (1 + \mathcal{A}_{\rm SL}^{s}) \exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)]$$

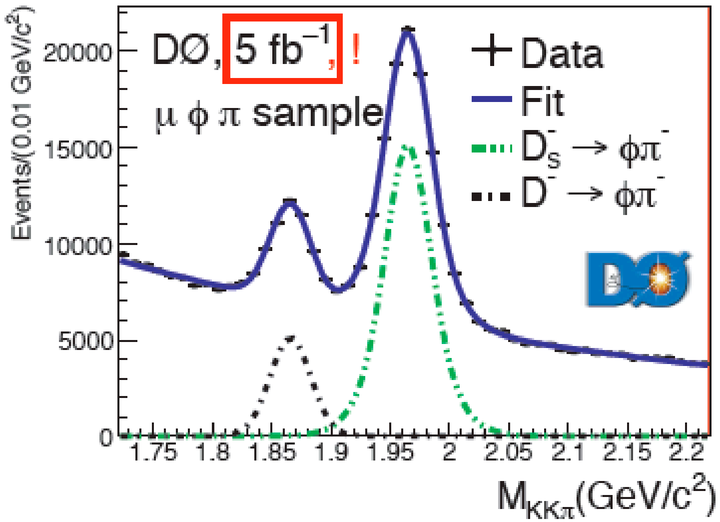
$$\Gamma(B_s^0 \to \mu^- X) \propto (1 - \mathcal{A}_{\rm SL}^{s}) \exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)]$$

$\overset{(-)}{B}{}_s^0 \to D_s \mu \nu$

Flavor tag

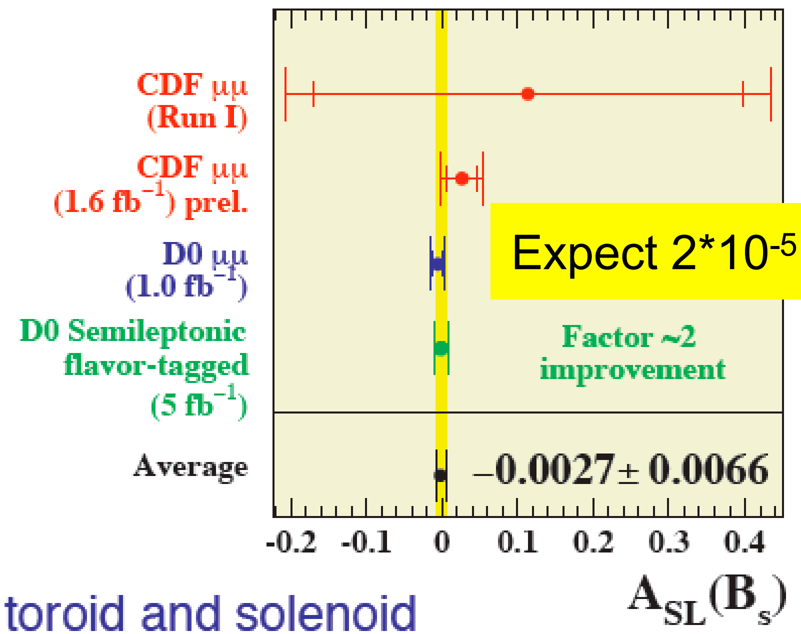


B_s semileptonic asymmetry



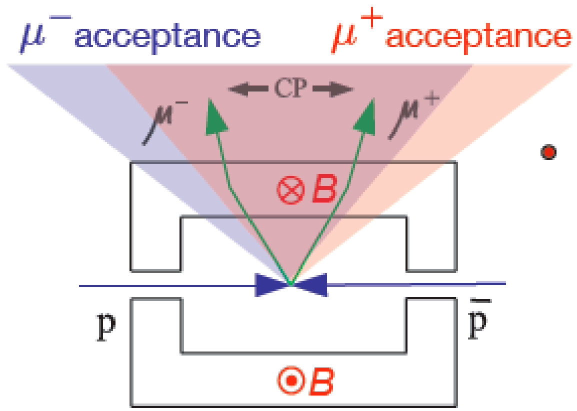
arXiv:0904.3907, sub. to PRL

$$\boxed{\mathcal{A}_{SL}^{s} = -0.0017 \pm 0.0091^{+0.0012}_{-0.0023}}$$



Expect $2*10^{-5}$ in SM

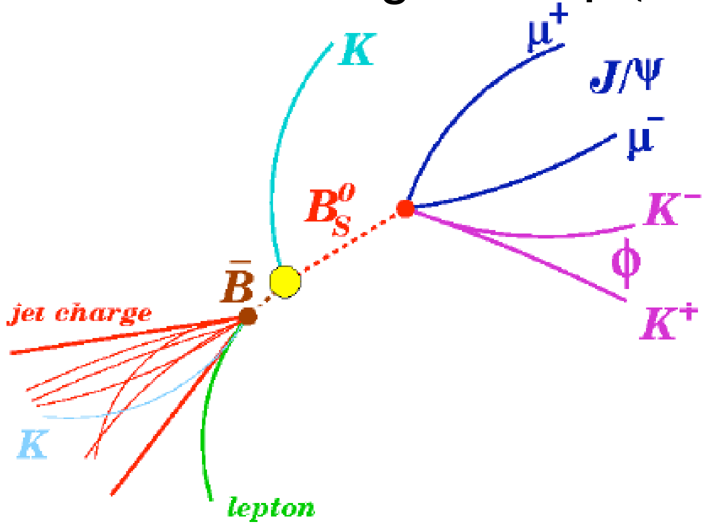
- ~115k total $\overset{(-)}{B}{}_s^0 \to D_s\mu\nu$ decays



- DØ toroid and solenoid polarities flipped regularly; control & measure detector asymmetries (and then correct, some as large as 3%)

Measuring mixing parameters with $B_s \to J/\psi\phi$

1. Reconstruct decays from stable products:
   - $B_s \to J/\Psi[\mu^+\mu^-]\ \Phi[K^+K^-]$
   - $B_d \to J/\Psi[\mu^+\mu^-]\ K^{*0}[K^+\pi^-]$ (control sample)



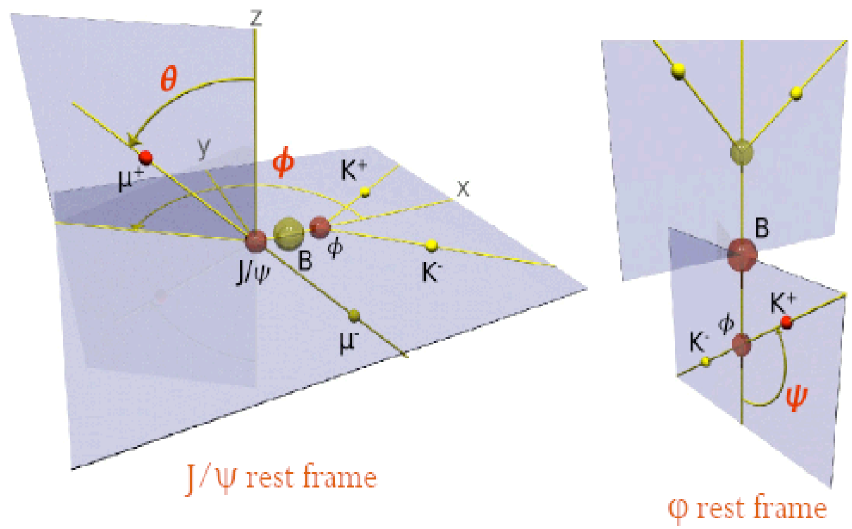
2. Measure lifetime $ct = m_B * L_{xy}/p_T$
   - Proper time resolution essential to resolve oscillations

3. Measure decay angles in transversity base:

$$\vec{w} = (\vartheta, \phi, \psi)$$

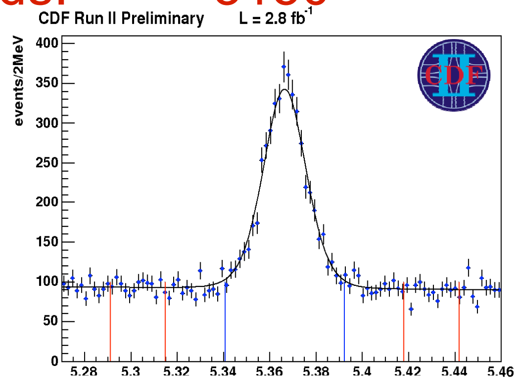
4. Identify Bs flavor at production time:
   - Flavor Tagging (Tag decision ξ)

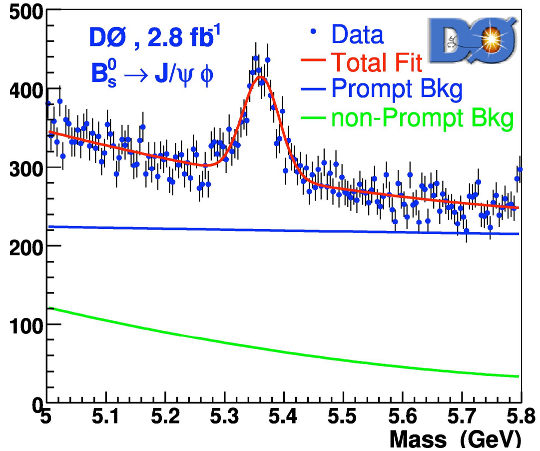
5. Perform maximum likelihood fit:
   - Likelihood in m, ct, w , ξ



$\phi_s^{J/\psi\phi} \equiv -2\beta_s^{J/\psi\phi}$ results (2.8fb^{-1}/exp.)

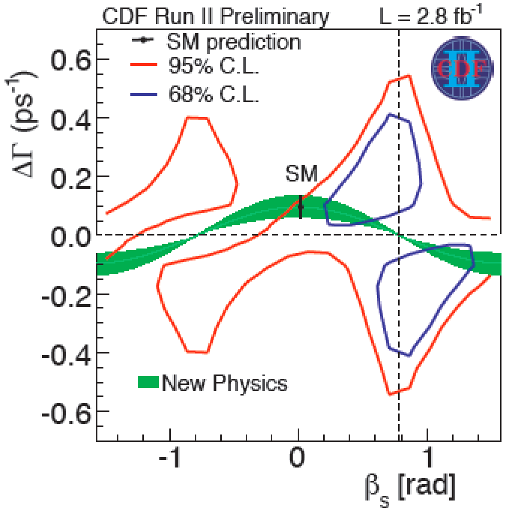
Yields: 3150 2000



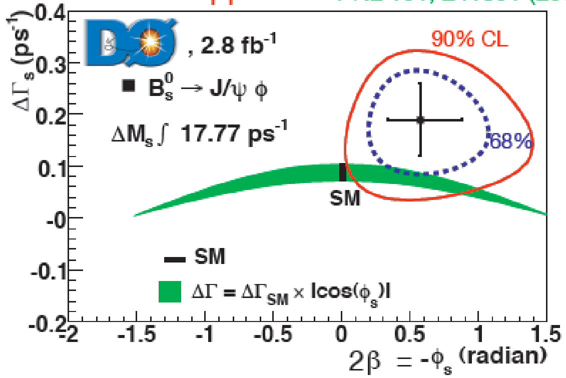


[see talks by
P. Gutierrez, J. Morlock]

CDF



DØ "Flipped" PRL 101, 241801 (2008)



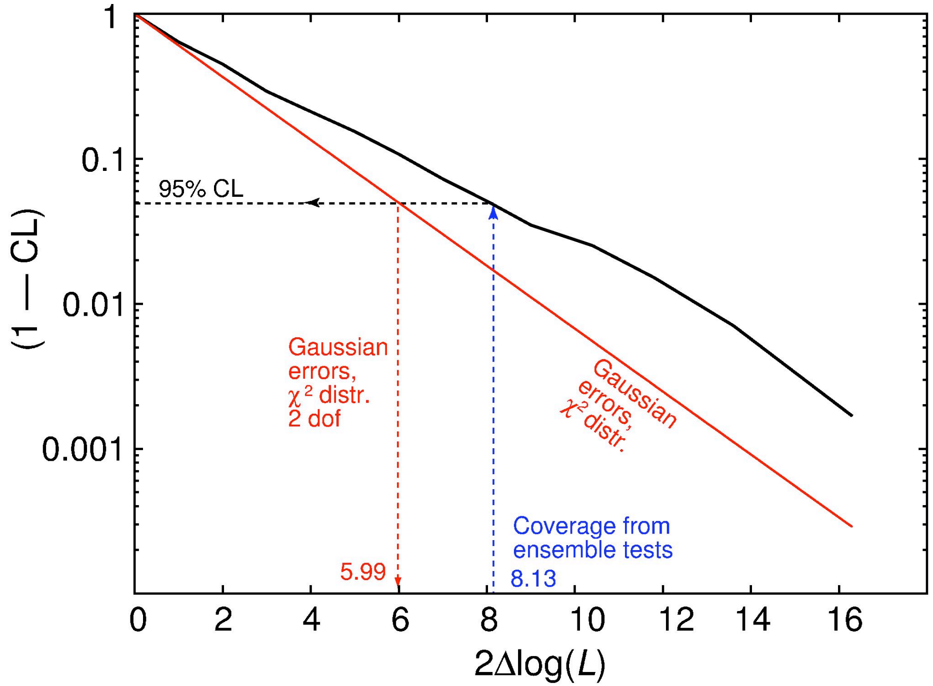
SM p-value: 0.07(~1.8σ) 0.066(~1.8σ)

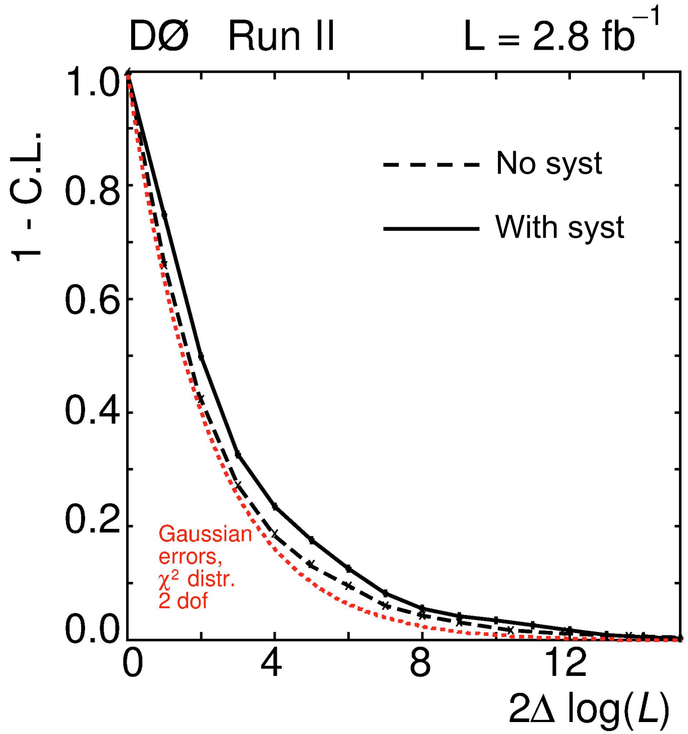
(with strong phase constraint)

- Tantalizing: small deviations in the same direction

The making of a Tevatron average

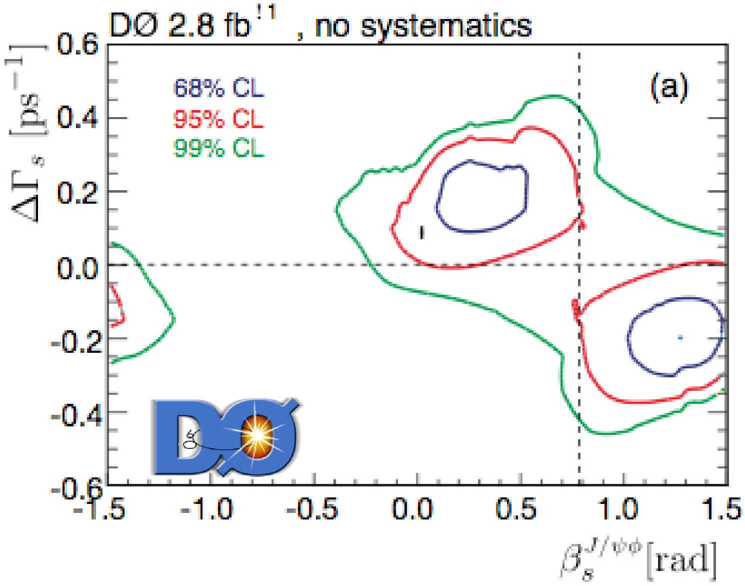
- Obviously want to combine CDF and D0, but not trivial.
- Substantial work to bring CDF and D0 to common standards.
- Account for non-asymptotic statistical behavior - important not to underestimate the effect of tails, due to limited statistics !

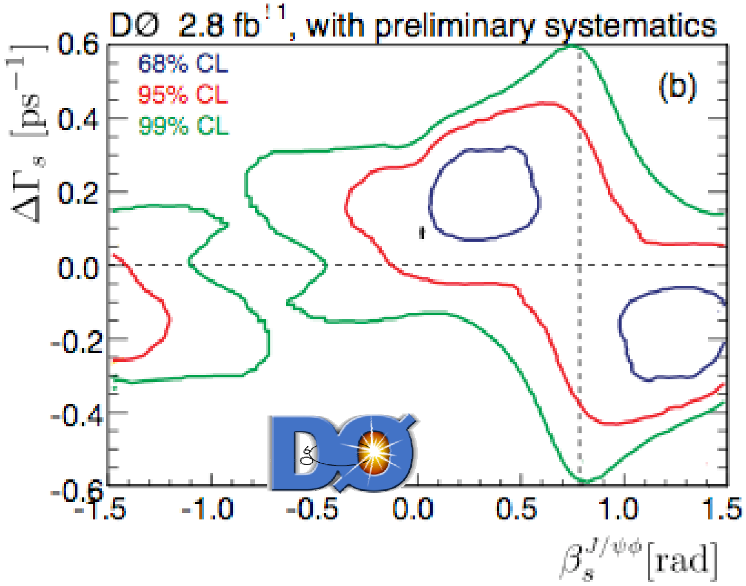




Updated D0 results

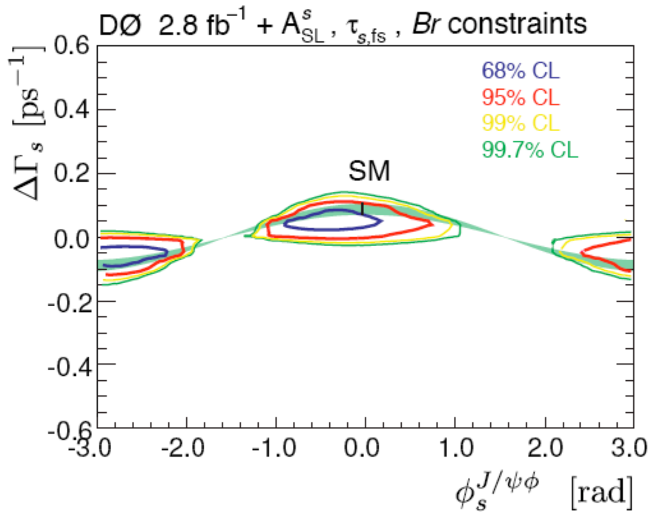
[D0 conf. note 5933]



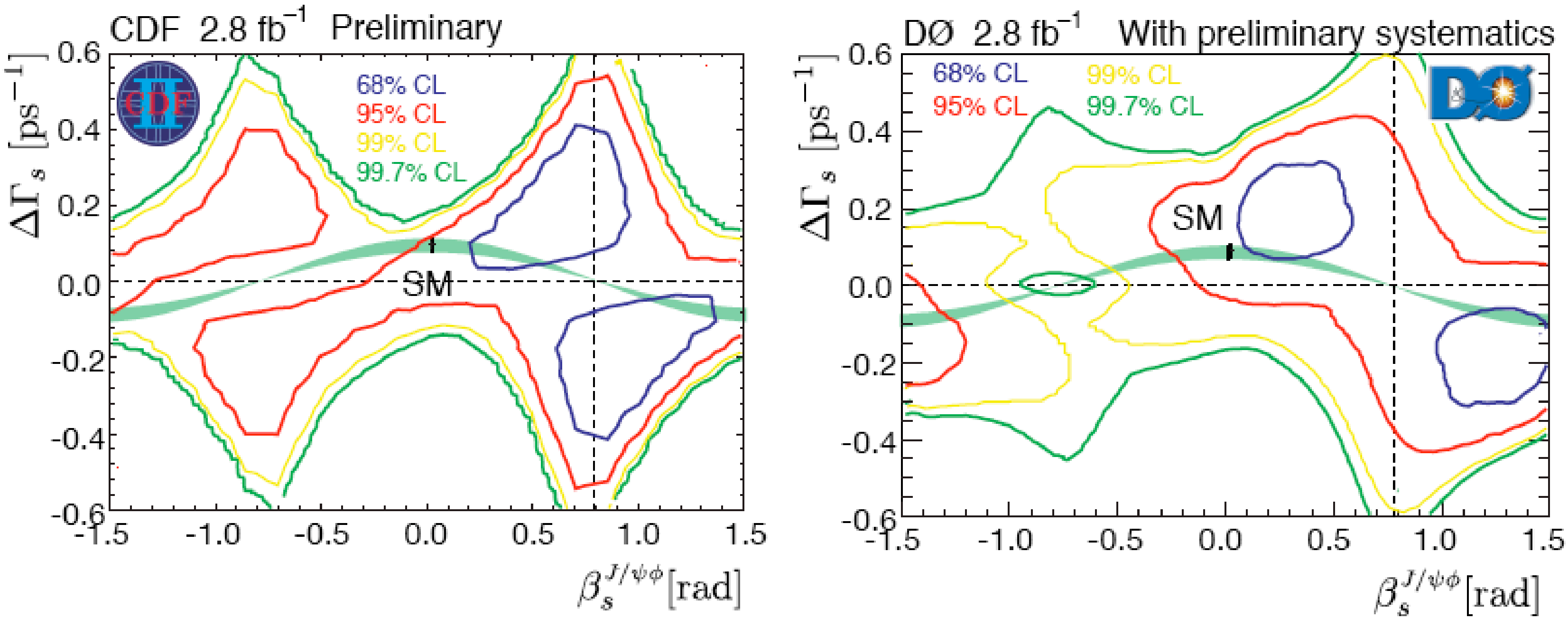


- Including constraints from some further measurements (mostly from D0):
  - A_{SL}
  - $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$ (constrains $|\Gamma_{12}|$)
  - Flavor-specific B_s lifetime (constrains $\Delta\Gamma_s$)

Obtains SM p-value 10%



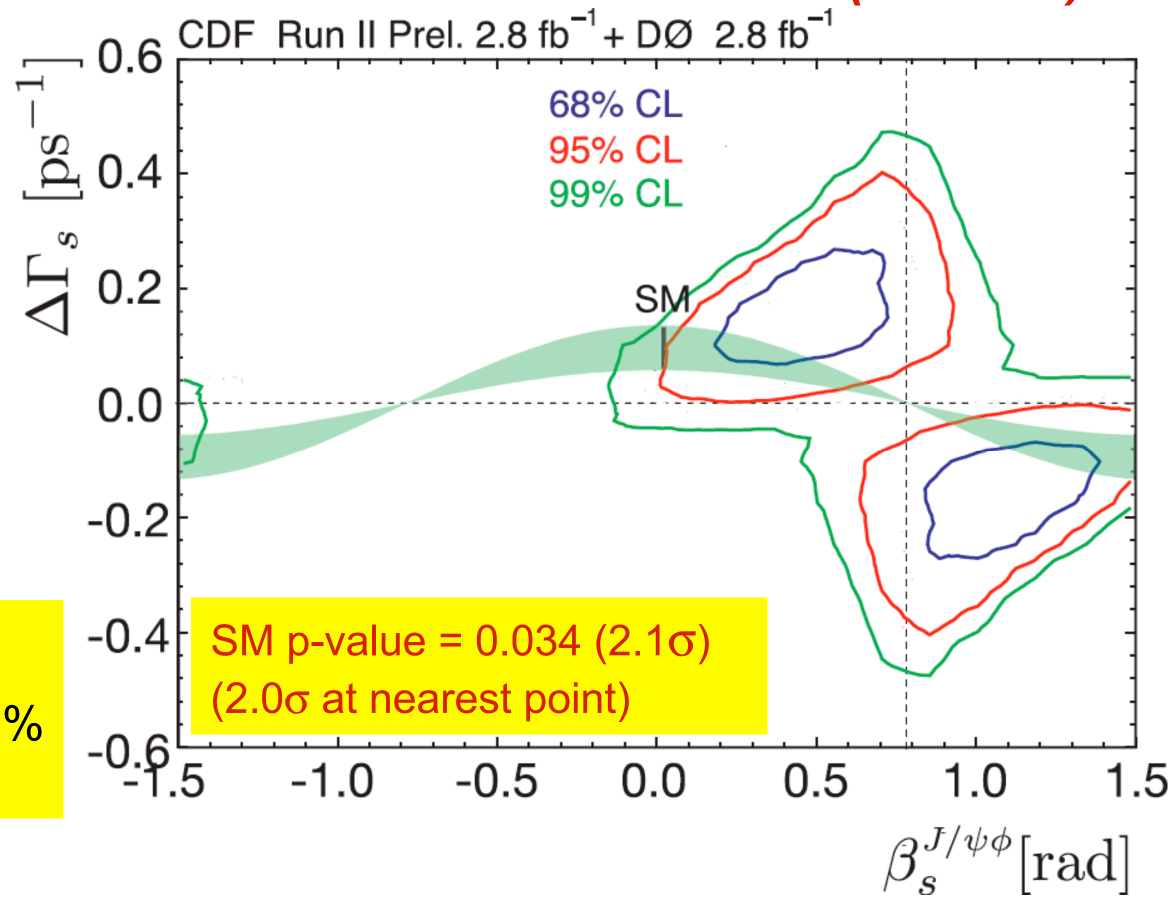
D0 and CDF brought to the same grounds (unconstrained)



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

Combined Tevatron result *(NEW)*

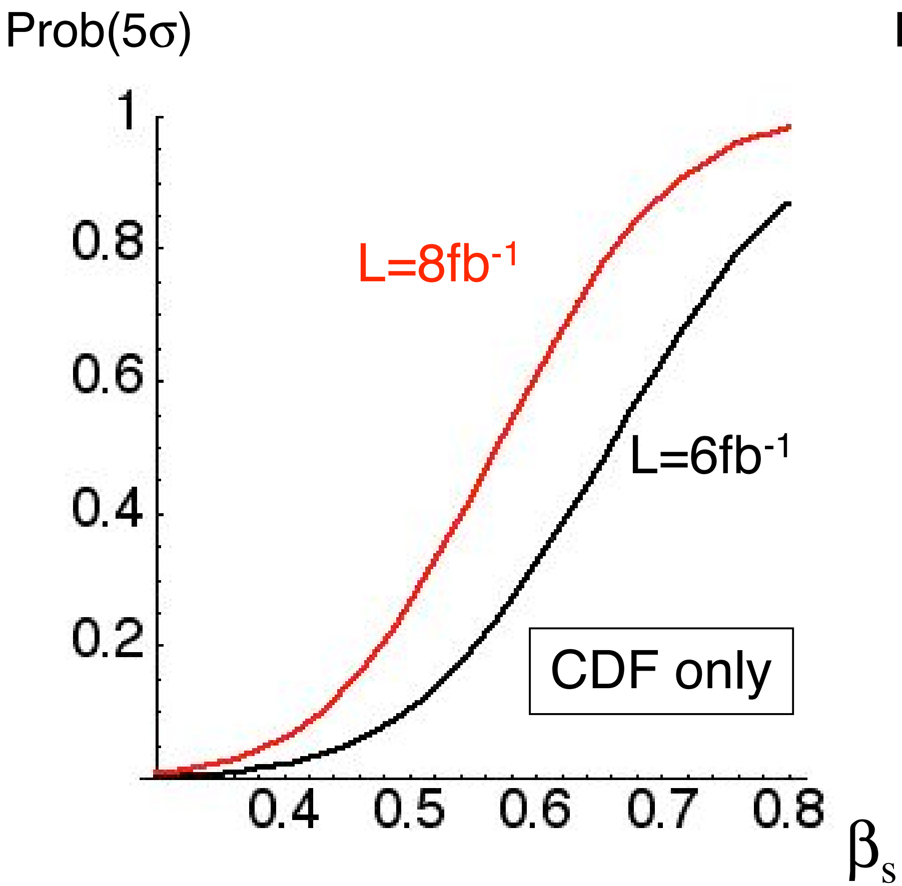
- Full inclusion of systematics and non-Gaussian effects
- No constraints. Make available to combination groups.

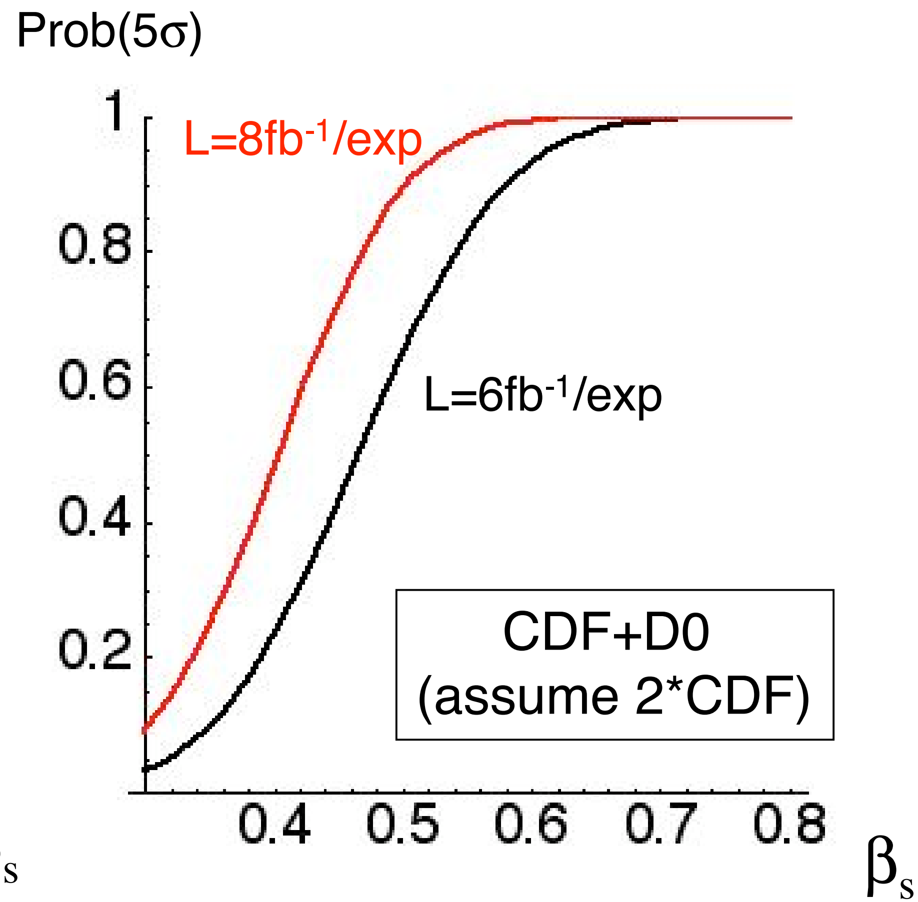


$\beta_s^{J/\psi\phi}$ range:
[0.27,0.59] U [0.97,1.30] @68%
[0.10,1.42] @95%

- Compared to HFAG 2008:
  Larger CDF sample + Better accounting for tails ⇒ same level of SM agreement.
- Both CDF and D0 currently working on **2x** samples.
- Expect improved precision by ***simultaneous fit*** of CDF and D0 samples.

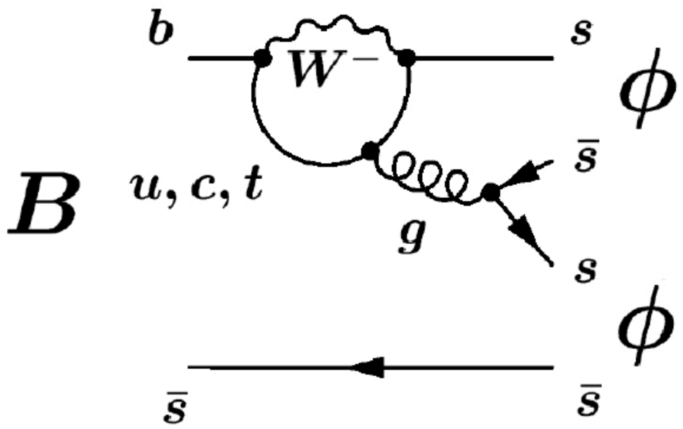
High probabity of 5σ discovery in interesting β_s range





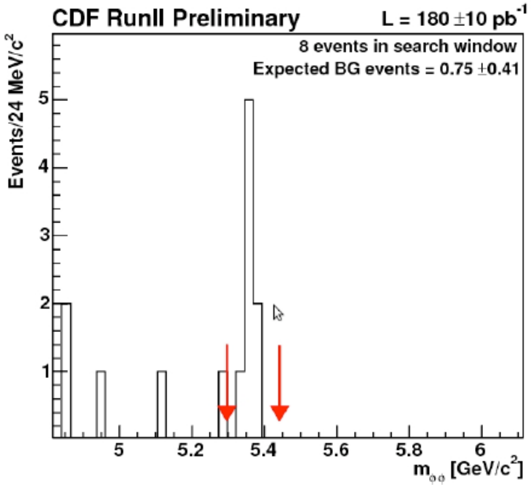
- Assumes constant data taking efficiency and no analysis improvements
- No external constraint or additional information (e.g. ASL)
- NP expectations $\beta_s = 0.3 \div 0.7$ [Hou at al., Phys.Rev.D76:016004,2007]

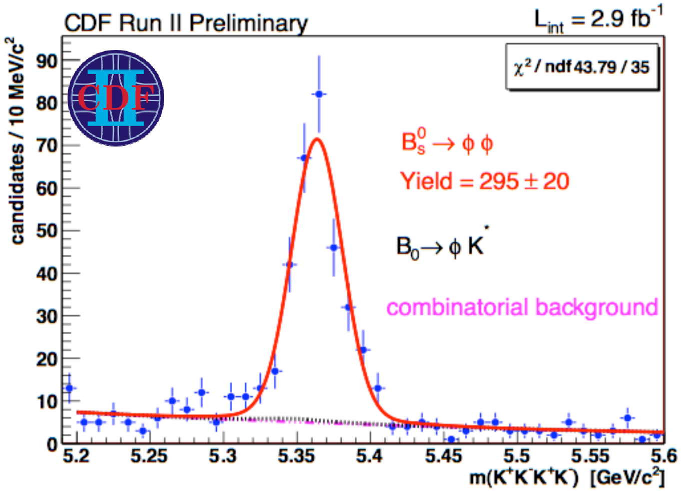
Further VV modes: $B_s \rightarrow \varphi\varphi$



- B $\rightarrow$ *sss* penguin process.
  Has shown interesting "features" in the past.
- Possible candidate for deviations:
  - BR
  - Polarization [see polarization puzzle, later in Bevan's talk]
  - CP violation (can enter in both mixing and decay)

$B_s \rightarrow \varphi\varphi$ results *(new)* *[see talk by D.Horn]*





- From initial observation of 8 events (0.2fb^{-1}) to ~300 events (2.9fb^{-1})
- More than just luminosity increase: improved selection/usage of multiple trigger selections (some more can still be added)

Relative BR: $\boxed{\frac{\mathcal{B}[B_s \rightarrow \phi\phi]}{\mathcal{B}[B_s \rightarrow J/\psi\phi]} = [1.78 \pm 0.14(stat) \pm 0.20(syst)] \cdot 10^{-2}}$

Translate to: $\mathcal{B}[B_s \rightarrow \phi\phi] = [2.40 \pm 0.21(stat) \pm 0.27(syst) \pm 0.82(BR)] \cdot 10^{-5}$

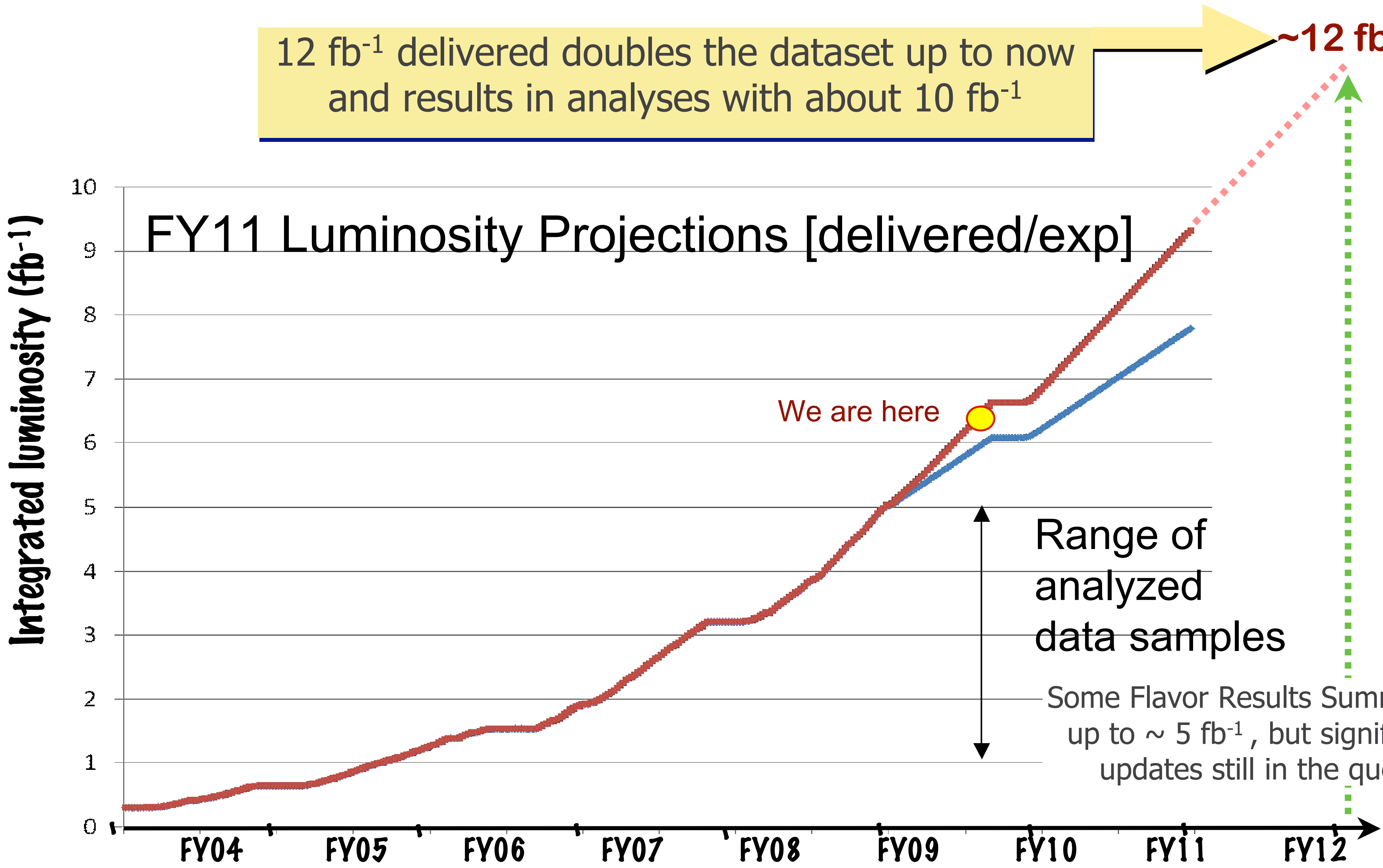
Predicted [Beneke 06] $\mathcal{B}[B_s \rightarrow \phi\phi] = [2.18^{+0.11+3.04}_{-0.11-1.7}] \cdot 10^{-5}$

Comparison dominated by theoretical and BR uncertainties.

Expect polarization measurement soon with precision 10%, eventually CPV

What is coming next ?

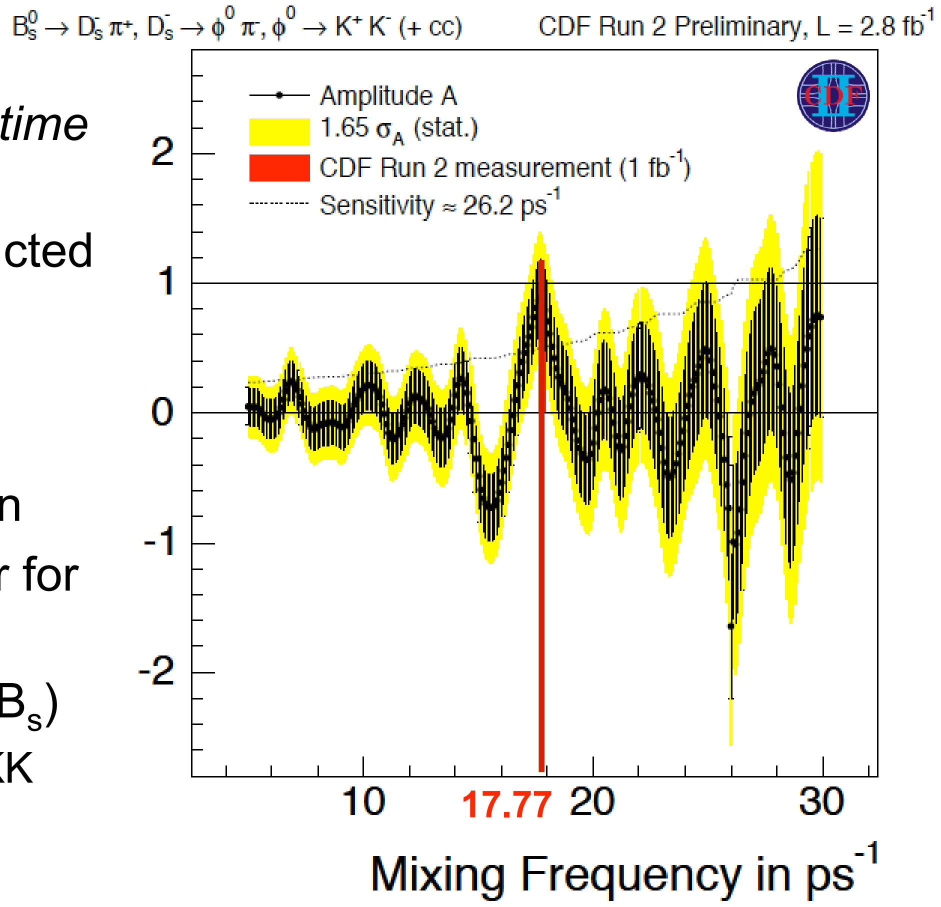
12 fb^{-1} delivered doubles the dataset up to now and results in analyses with about 10 fb^{-1}



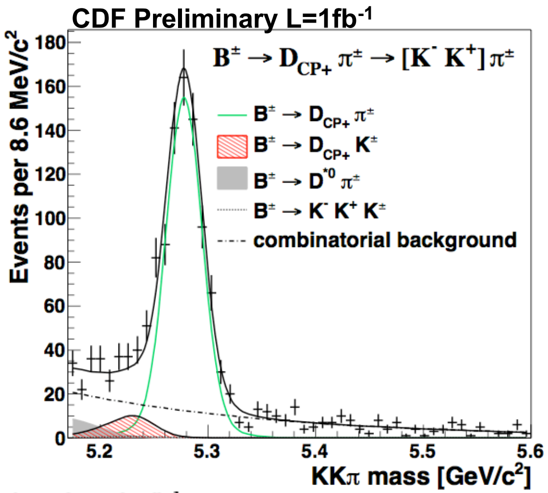
B_s oscillations are back !

[see talk by J.Morlock]

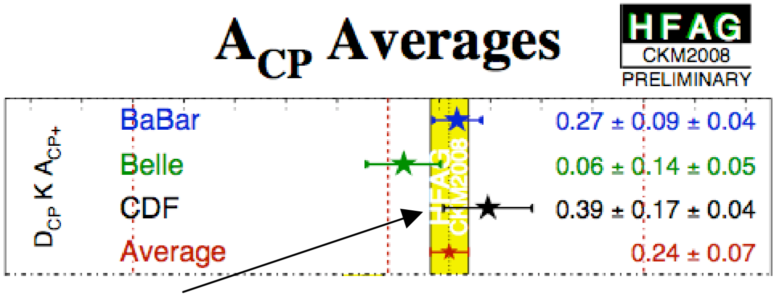
- CDF oscillation signal in 2.8 fb^{-1} (*first time* after 2006 discovery on 1fb^{-1}).
- This time from a single fully reconstructed mode, and a single tagger (SST).
- Performance of the tagger stayed the same despite higher luminosity
- Have enough data to calibrate Dilution
- Developing a NN-based global tagger for optimum performance.
- Open the era of time-dependent $A_{CP}(B_s)$
  - E.g. $B_s \to D_sK$ (CKM angle γ), $B_s \to KK$



Angle γ from $B^+ \to D^0K^+$

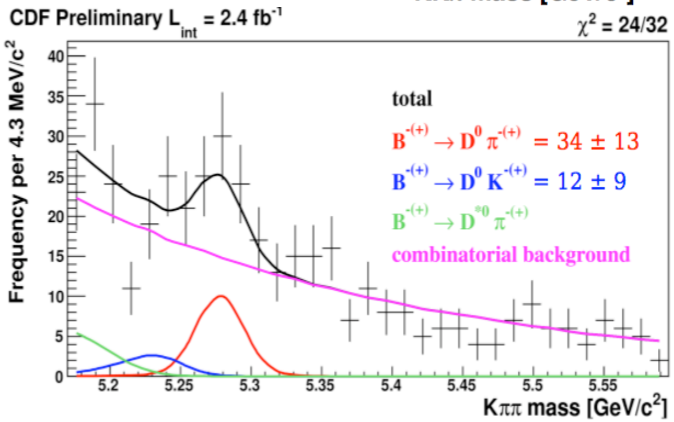


GLW method, $D^0 \to KK, \pi\pi$:



1fb^{-1} CDF $\equiv$ ~350fb^{-1} @B-factory

10fb^{-1} CDF $\equiv$ ~3.5ab^{-1} @B-factory



ADS method, $B^+ \to D\pi, K$:

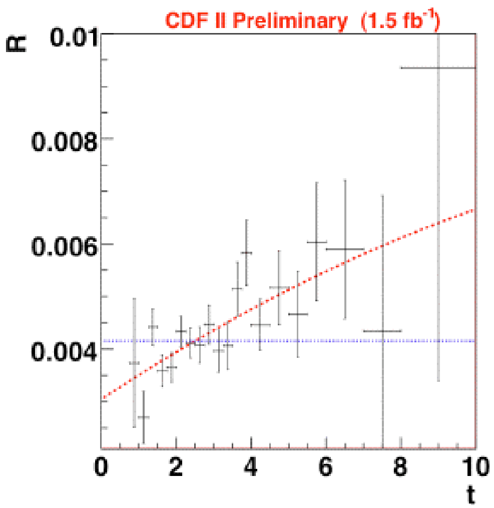
$$B \to D_{DCS}\pi \quad \text{yield } 34 \pm 13 \;/2.4\text{fb}^{-1}$$

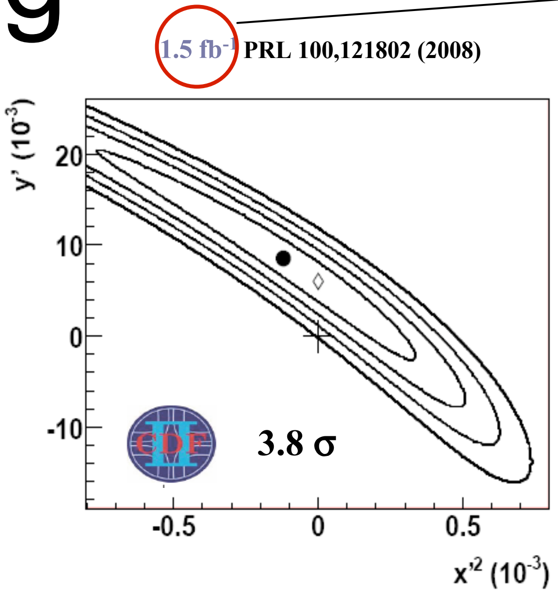
$$\sqrt{-2\Delta \ \log L} = 3.8\sigma$$

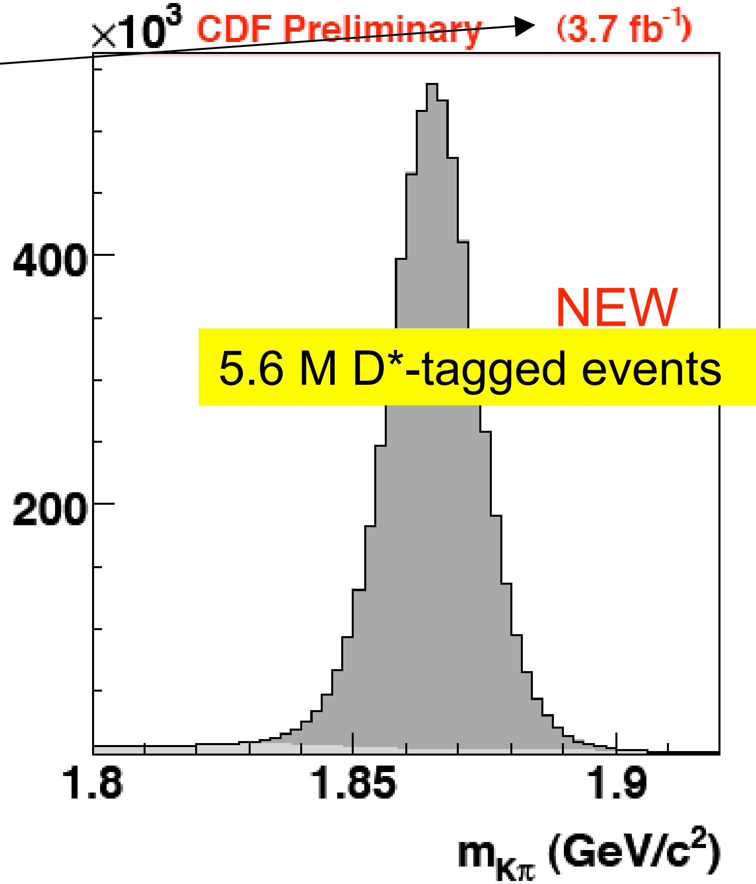
ACP resolution 30%

B mode	D mode	method	Yield / 5 fb^{-1}
$B \to D\pi$	$K\pi$ DCS	ADS	70
$B \to DK$	KK, $\pi\pi$	GLW	450

D^0 mixing







- Babar and CDF very similar results and significances for $D^0 \to K\pi$ mixing ($3.9\sigma/3.8\sigma$). (Belle disagrees).
- Globally strong evidence for D0 mixing, but no single experiment $>5\sigma$
- Current CDF sample 4x larger than this $\to$ if mixing is real, should be $>5\sigma$
- Large *ct* lever-arm helps determine parameters

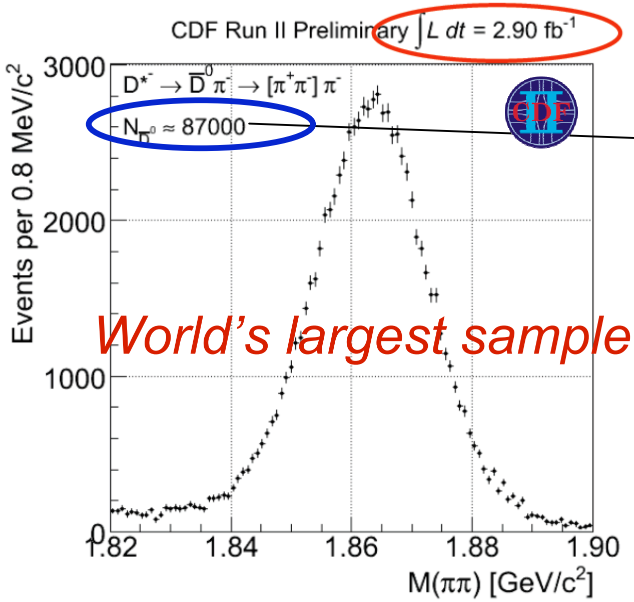
Currently accumulating

~4M/year (~**10x***Belle*)

CPV in Cabibbo-Suppressed modes

CPV in D^0 is unambiguos sign of NP (SM~10^{-4}). CS modes are likely to show NP effects of O(1%). [Grossmann et al., Phys.Rev.D75:036008,2007]

Mode	D^0	$\overline{D^0}$	Total
$K\pi$	$88,310 \pm 330$	$92,600 \pm 340$	$180,910 \pm 480$
KK	$8,190 \pm 140$	$8,030 \pm 140$	$16,220 \pm 200$
$\pi\pi$	$3,660 \pm 69$	$3,674 \pm 68$	$7,334 \pm 97$



PDG 2008 (Babar/Belle/CDF)

$A_{CP}(D^0 \to \pi\pi) = 0.2 \pm 0.4\%$

includes CDF 2005 (0.13fb^{-1})

$\sigma(A_{CP}) = 1.3\%$

(New) Analysis in progress:
$\sigma(A_{CP}) = 0.24\%$

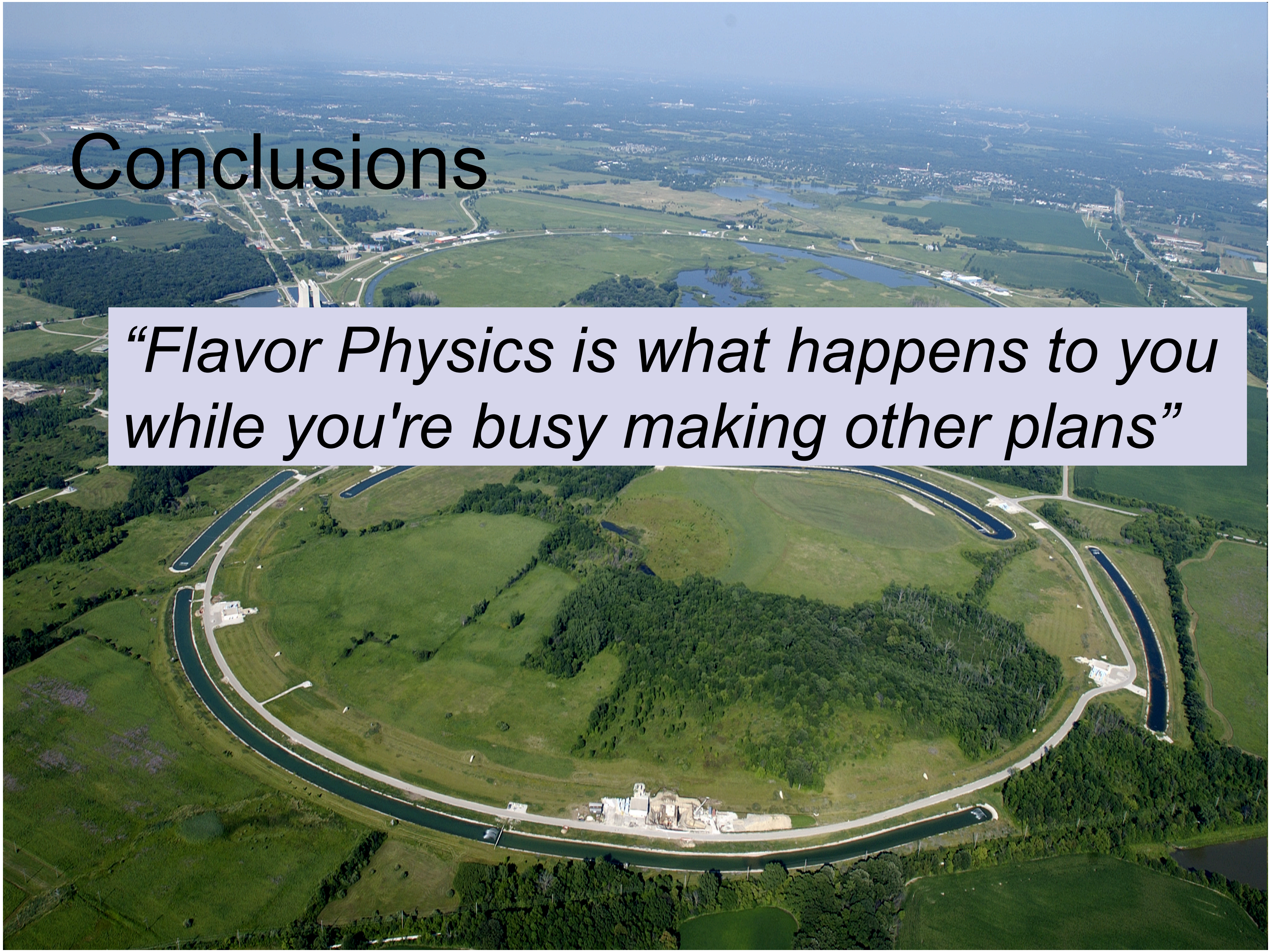
On tape (6 fb^{-1})
$\sigma(A_{CP}) = 0.17\%$

By 2011 (12 fb^{-1})
$\sigma(A_{CP}) = 0.12\%$

If an effect is there to be seen, the Tevatron is going to see it.

Conclusions

Conclusions



“Flavor Physics is what happens to you while you're busy making other plans”

Conclusions

"Flavor Physics is what happens to you while you're busy making other plans"

Expect many more results from Tevatron !