Probes for 4th generation at CDF: φ_s, $A_{FB}(Kll)$, D^0-mixing

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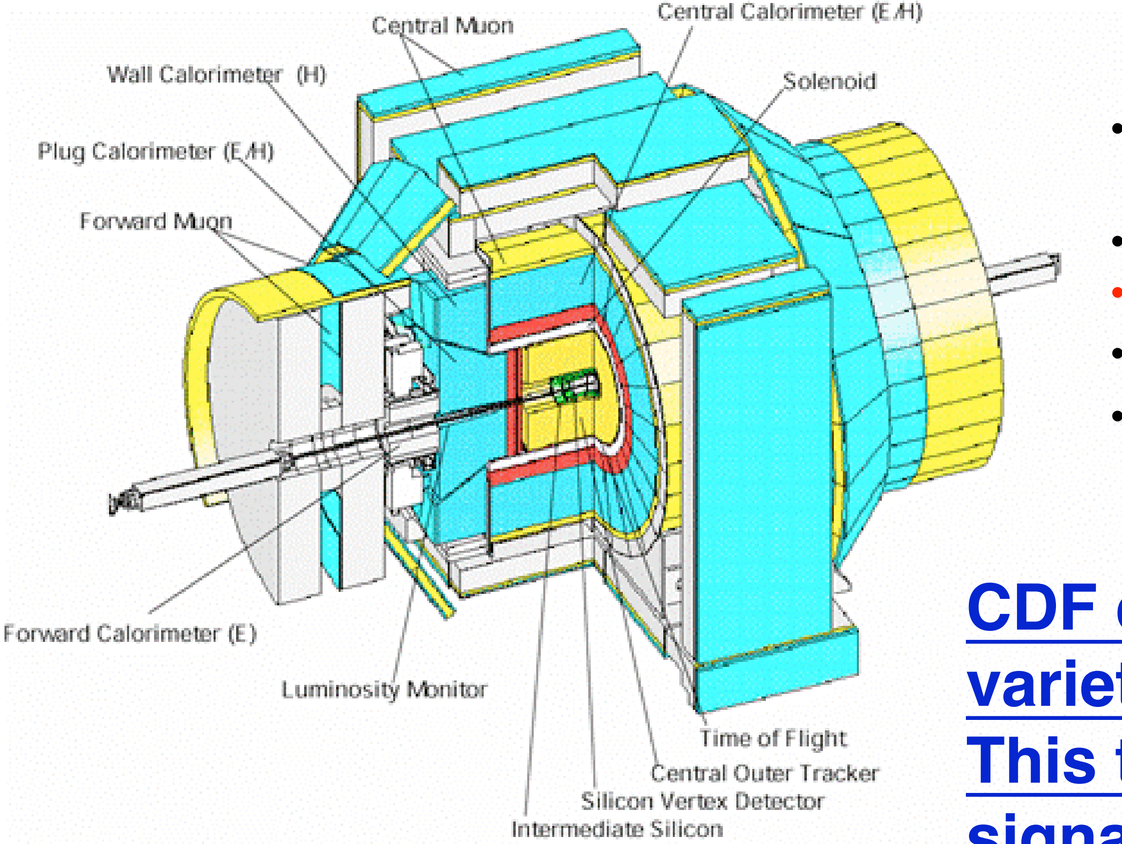
CDF and the 4th-generation



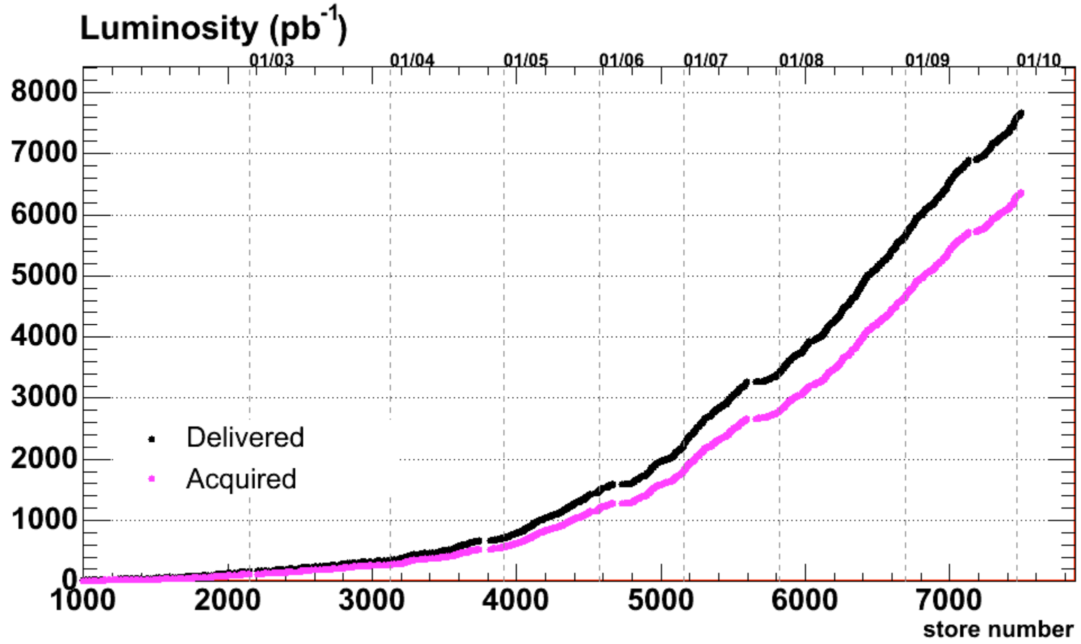
CDF II Detector

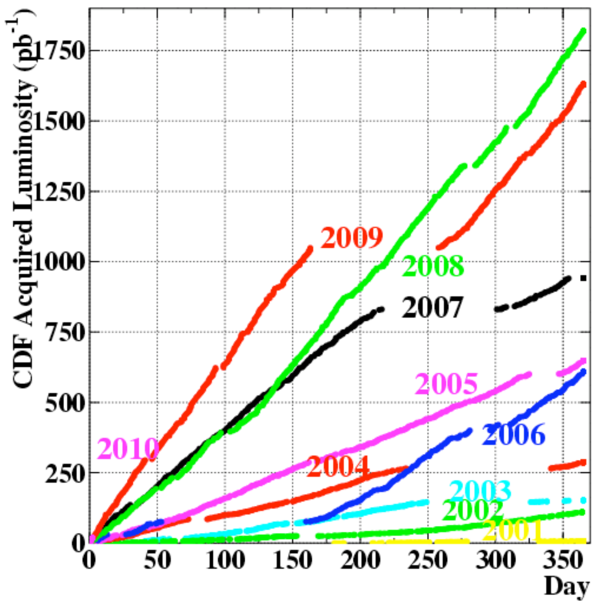
- Tracker: - **Silicon Vertex Detectors**
  - Precision Drift Chamber
- **Excellent Momentum Resolution**
- **Trigger on long-lived particles**
- **Particle ID**: TOF and dE/dx
- Triggered Muon Coverage $|\eta|<1$

CDF can access a wide variety of channels.
This talk is about “indirect” signatures in flavor physics

[see D. Whiteson talk in Sess.III for direct searches]

CDF data sample





- Ever-increasing luminosity - current ~2fb^{-1}/year/experim.
- Current sample ~6 fb^{-1}. Expect FY 2010: 8fb^{-1} , FY 2011: 10fb^{-1}
- Most flavor physics analyses currently use 1 fb^{-1} -- 5 fb^{-1} but many updates still in the queue ⇒ doubling of statistics by end of 2011

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, $p=q$

$$\Delta M_s = 2|M_{12,s}^{SM}| \cdot |\Delta_s|$$

$$\Delta\Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{SM} + \phi_s^{\Delta}\right)$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{SM}|} \cdot \frac{\cos\left(\phi_s^{SM} + \phi_s^{\Delta}\right)}{|\Delta_s|}$$

$$a_{fs}^s = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{SM}|} \cdot \frac{\sin\left(\phi_s^{SM} + \phi_s^{\Delta}\right)}{|\Delta_s|} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan(\phi_s^{SM} + \phi_s^{\Delta})$$

$$\sin(\phi_s^{SM}) \approx 1/240$$

observables

$$\Gamma_s = (\Gamma_L + \Gamma_H)/2$$

$$\Delta M_s = M_H - M_L$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$\phi_s \equiv -2\beta_s$$

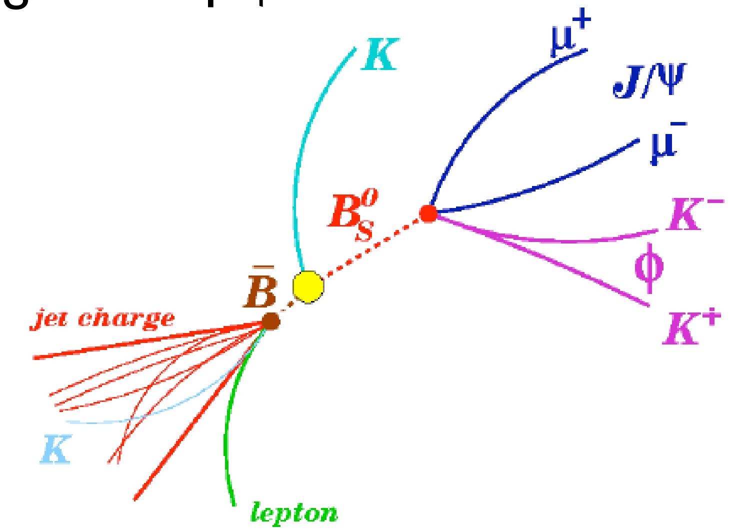
$$a_{fs}^s = \frac{\Gamma(\bar{B}_s(t) \to f) - \Gamma(B_s(t) \to \bar{f})}{\Gamma(\bar{B}_s(t) \to f) + \Gamma(B_s(t) \to \bar{f})}$$

ϕ and $\Delta\Gamma$ are the least known, and are sensitive to a lot of possible New Physics: SUSY, 4th generation, GUT, Extended Higgs, MFV, unparticle, …

Measuring β_s with $B_s \to J/\psi\phi$

1. Reconstruct decays from stable products:

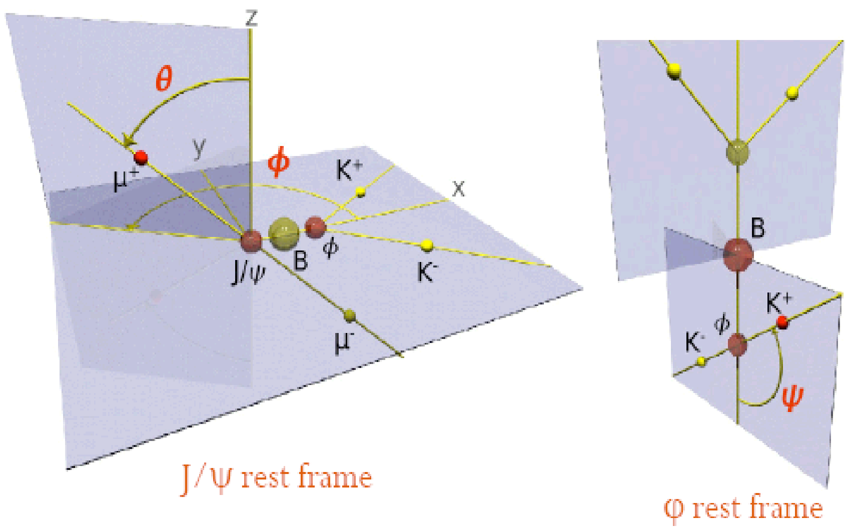
   - $B_s \to J/\Psi[\mu^+\mu^-]\ \Phi[K^+K^-]$
   - $B_d \to J/\Psi[\mu^+\mu^-]\ K^{*0}[K^+\pi^-]$ (control sample)



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:

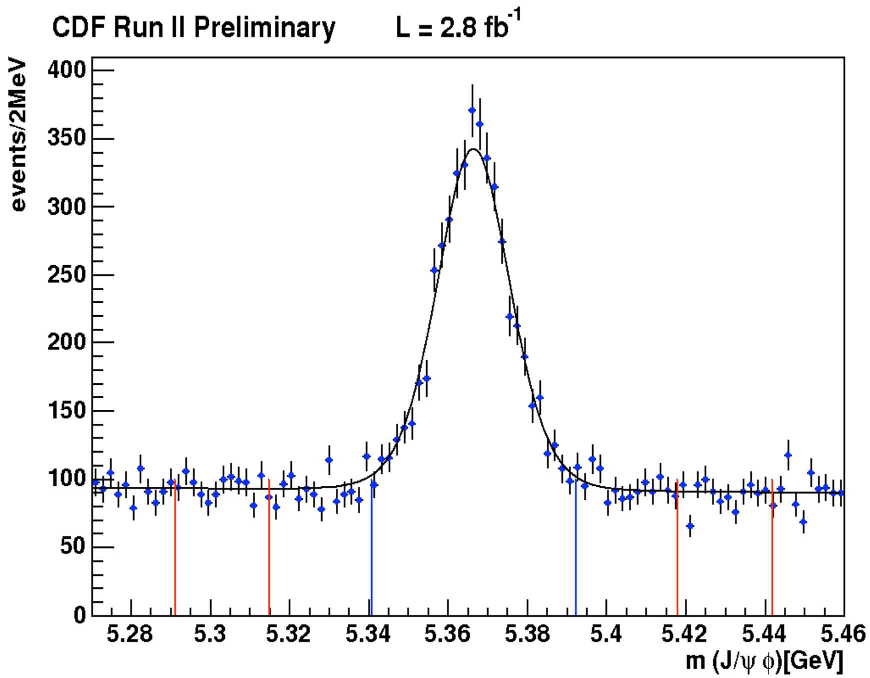
   - Flavor Tagging (Tag decision ξ)

5. Perform maximum likelihood fit:

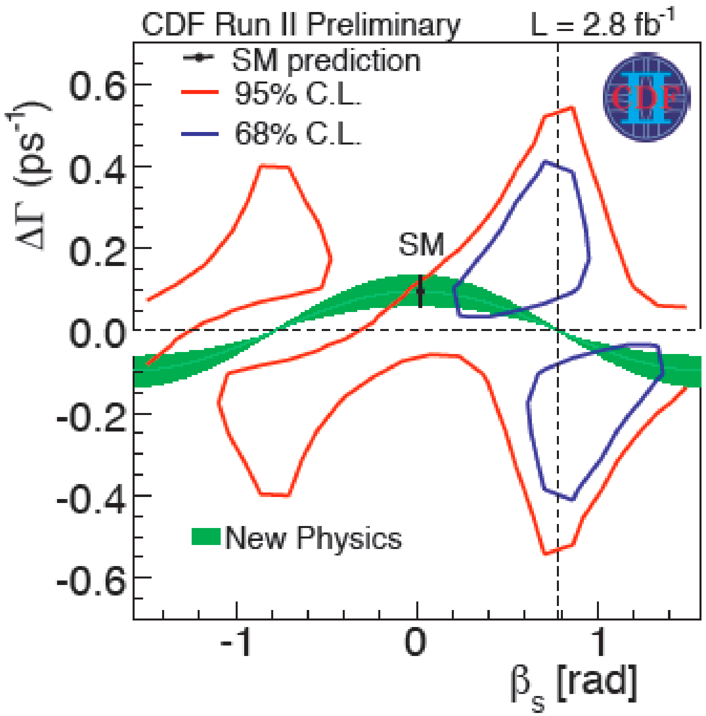
   - Likelihood in m, ct, w , ξ

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

Yield: 3150 events



CDF

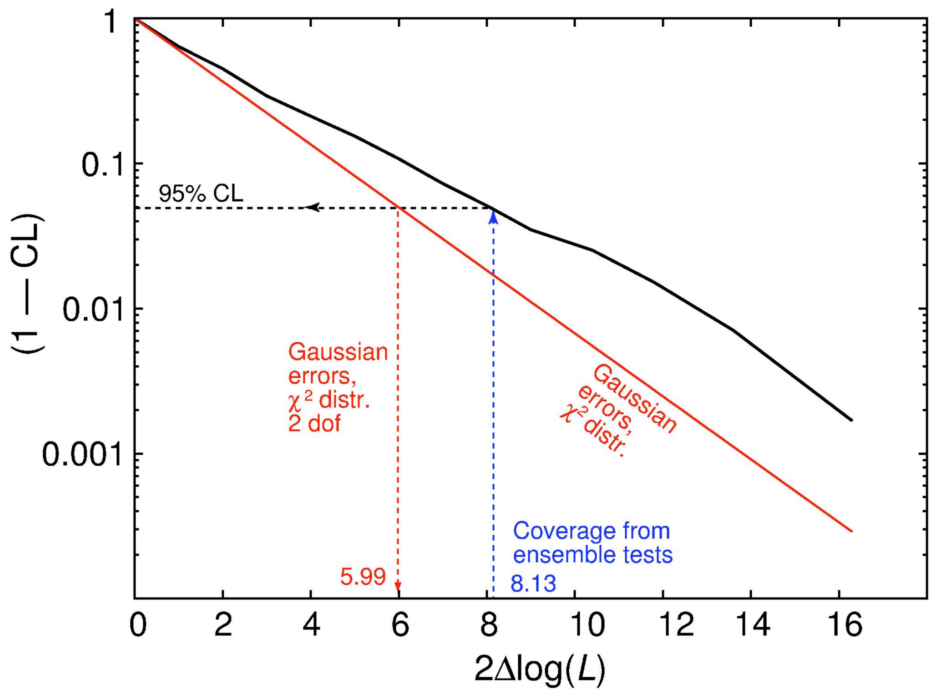


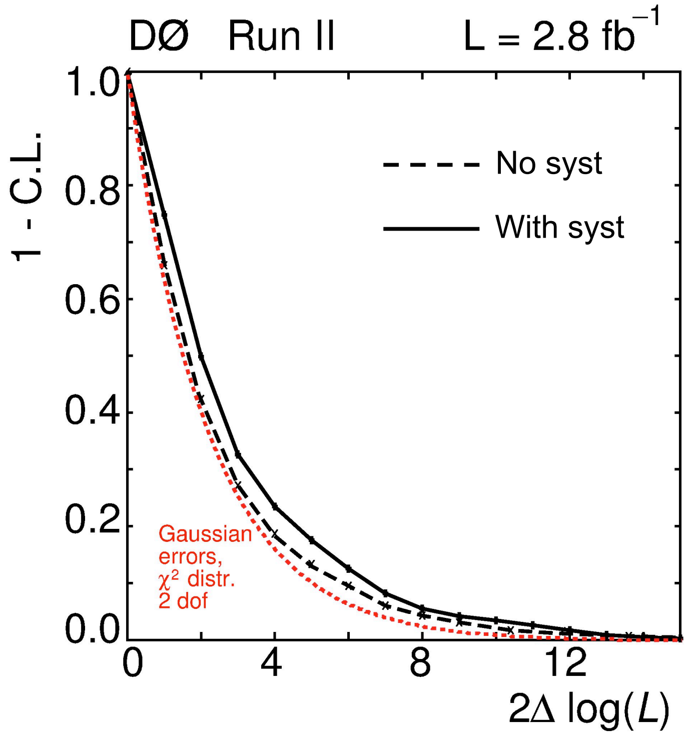
SM p-value: 0.07(~1.8σ)

- Tantalizing: small deviation in the same direction as D0

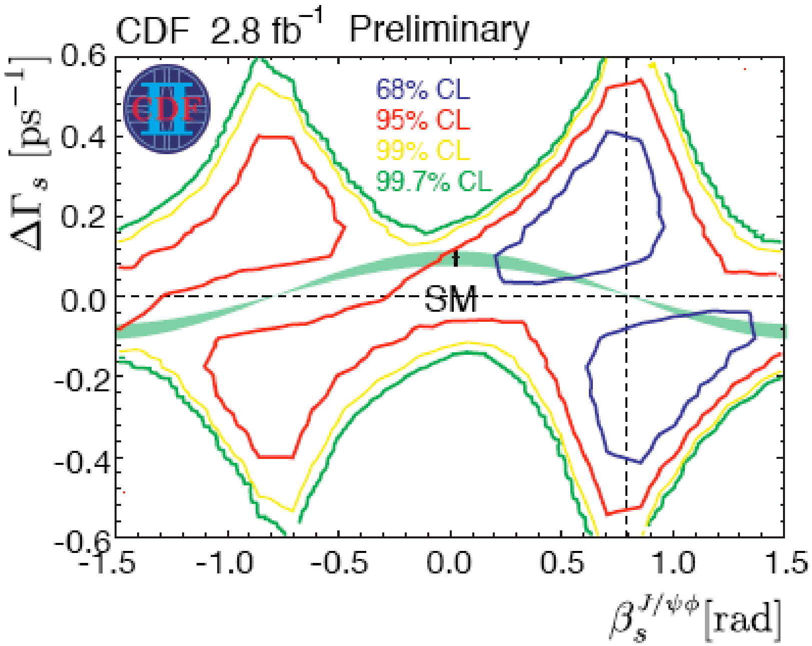
The making of a Tevatron average

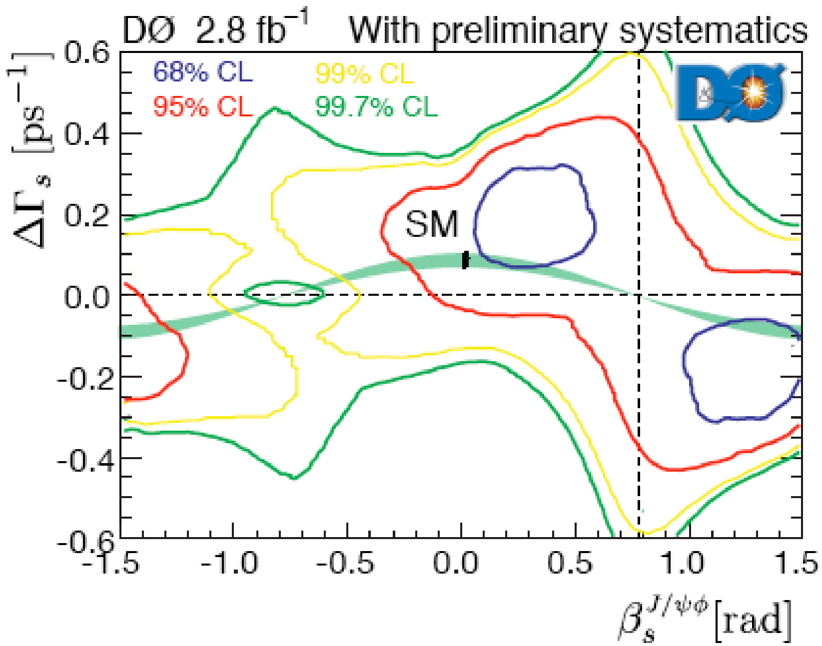
- Combining CDF and D0 is important although not trivial.
- Substantial work to bring CDF and D0 to common standards.
- Account for non-asymptotic statistical behavior - important not to underestimate the effect of tails, due to limited statistics !





D0 and CDF brought to the same grounds (unconstrained)

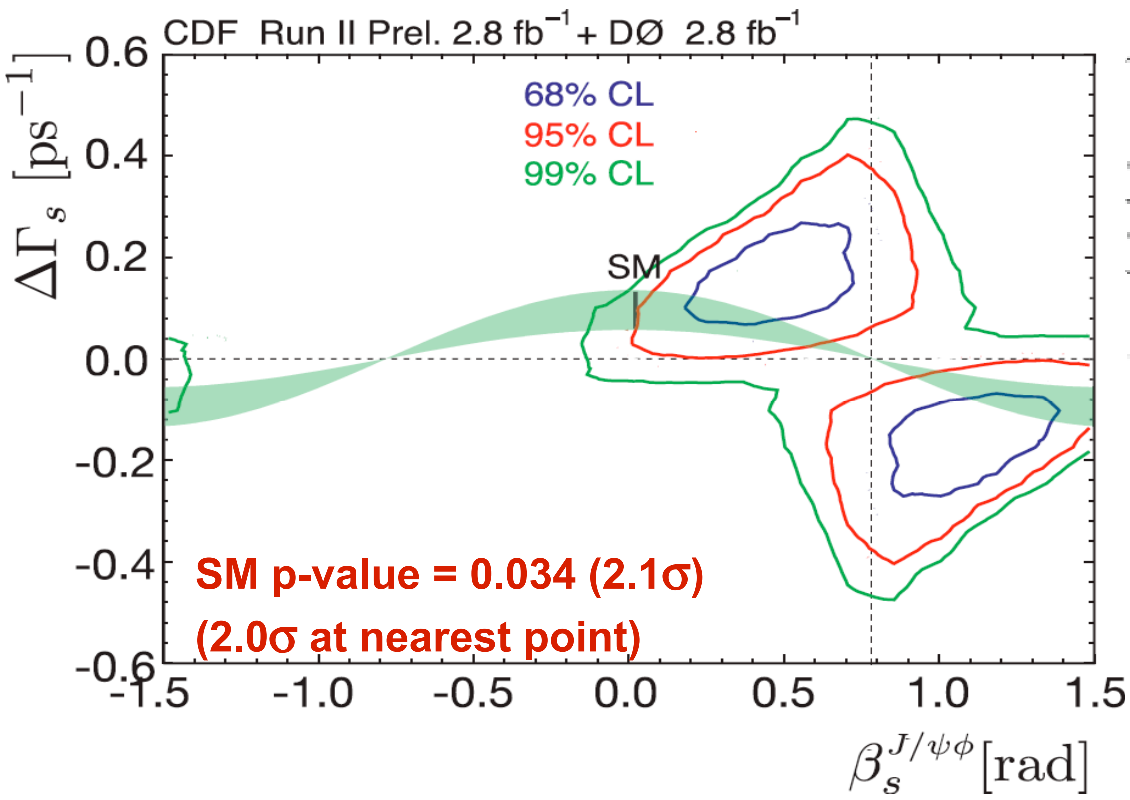


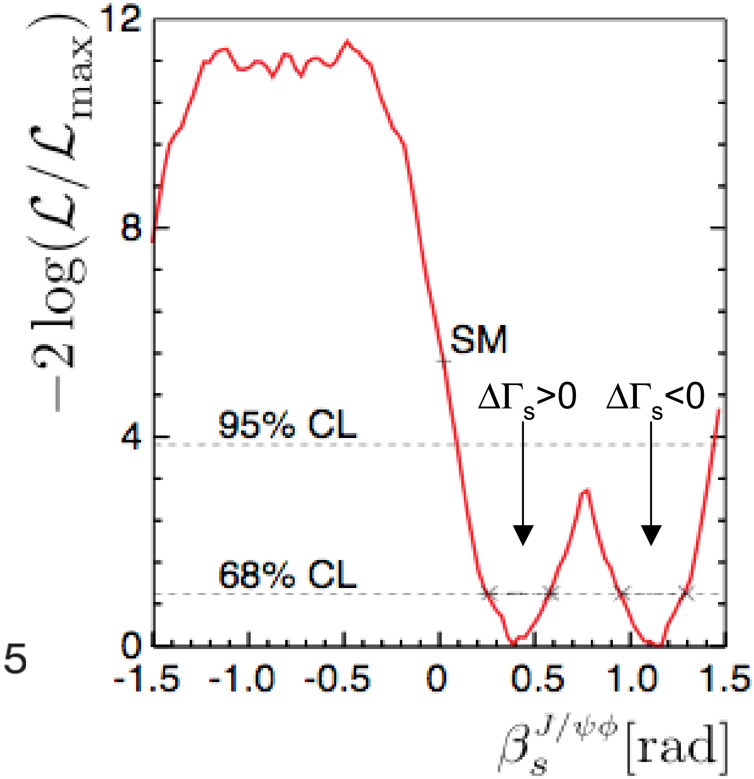


From publication: PRL 101, 241801 (2008);
DØ Note 5933-CONF

Combined Tevatron result

[http://tevbwg.fnal.gov]





- Full inclusion of systematics and non-Gaussian effects. No external constraints.
- Compared to HFAG 2008:
  Larger CDF sample + Better accounting for tails ⇒ same level of SM agreement.

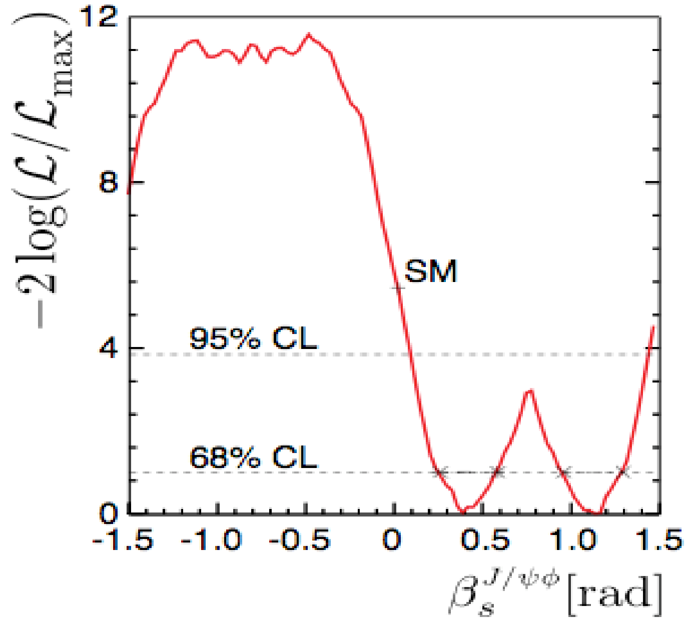
$\beta_s^{J/\psi\phi}$ range:

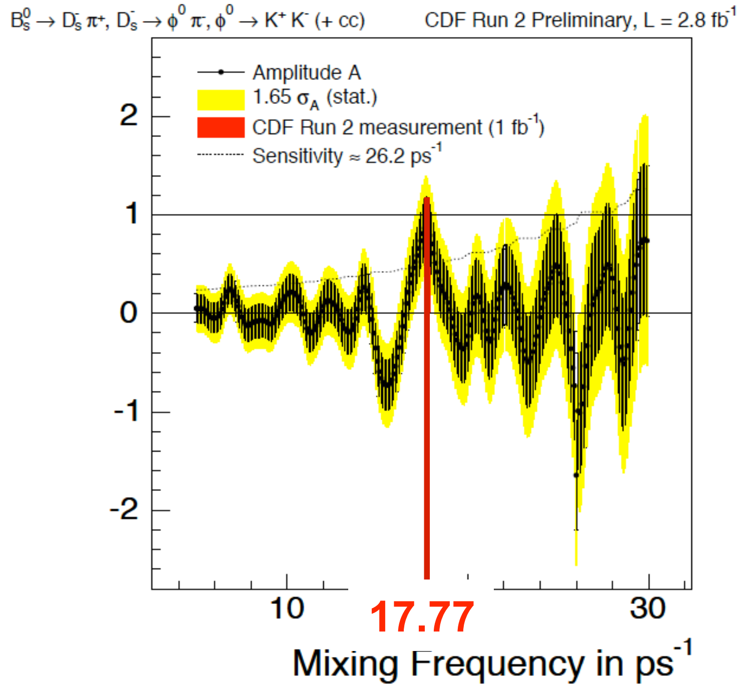
[0.27,0.59] U [0.97,1.30] @68%

[0.10,1.42] @95%

1-D p-value for SM= 0.020 (2.3σ)

Coming up next





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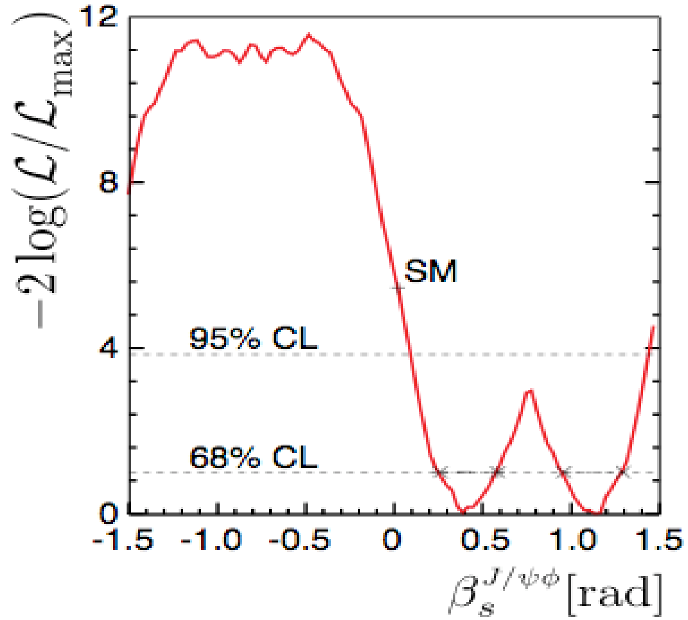

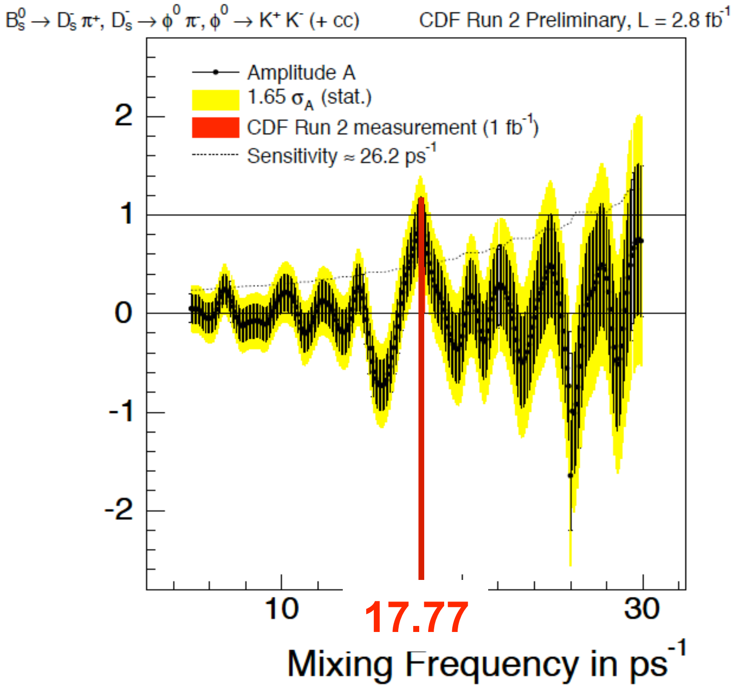

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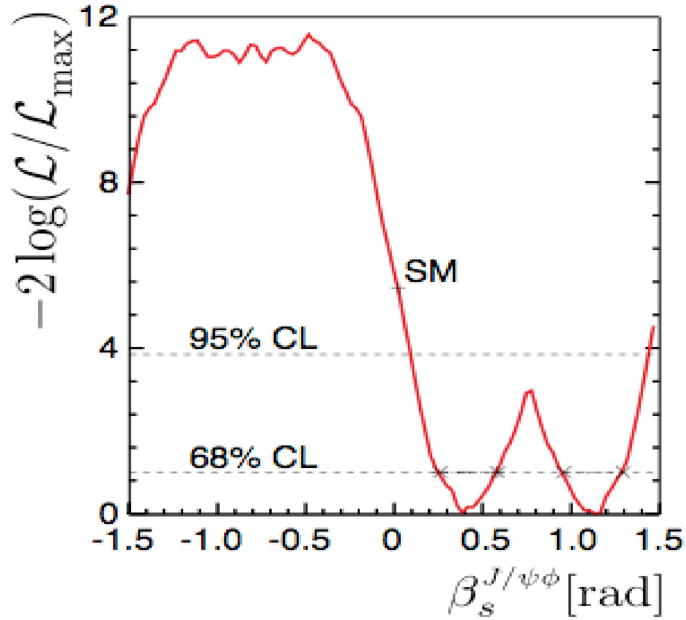

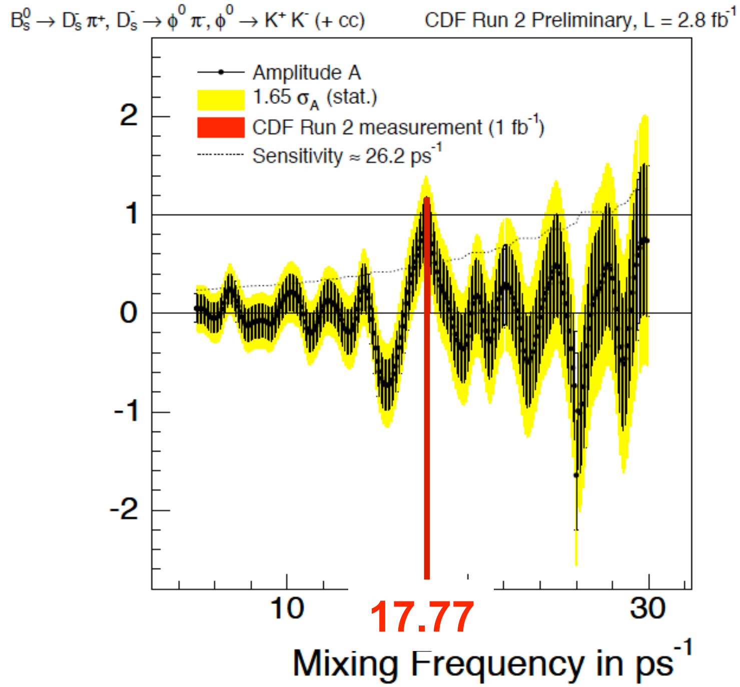

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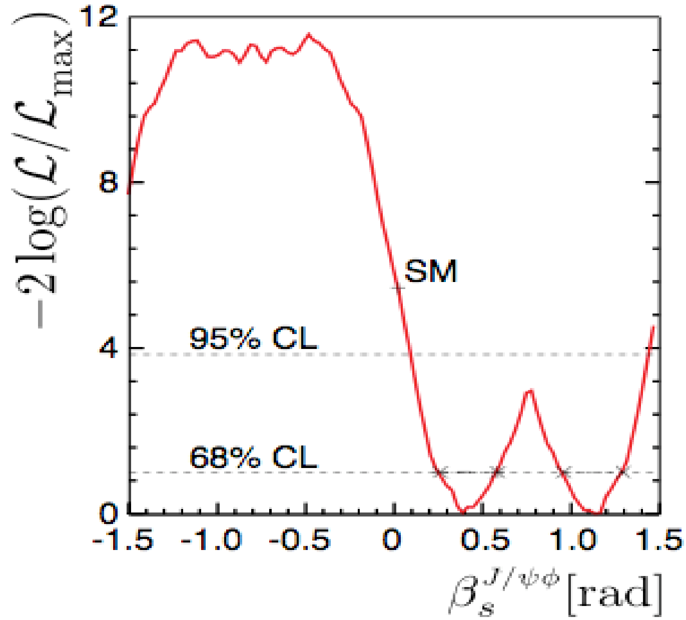

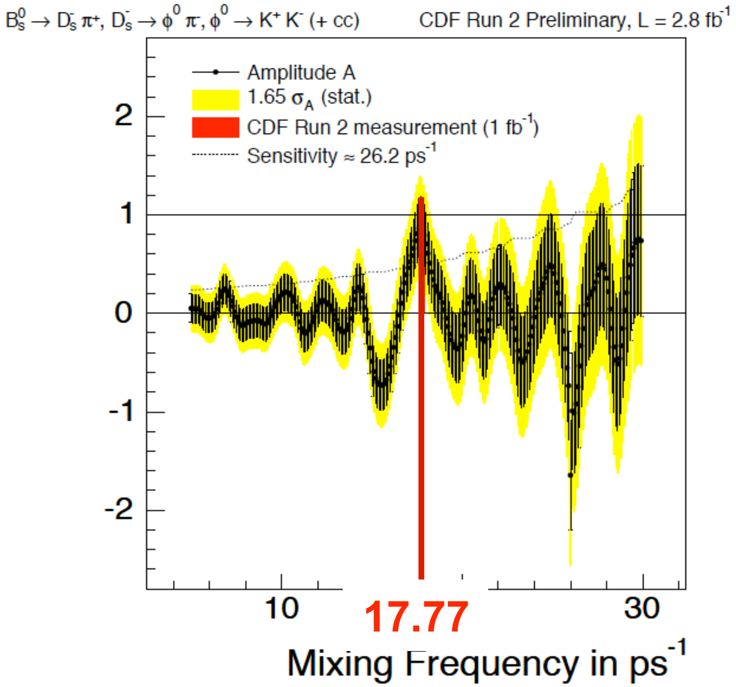

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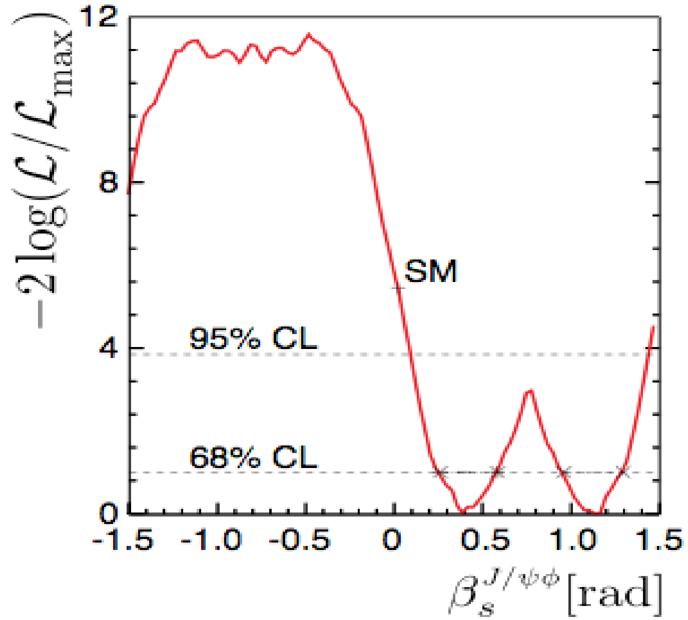

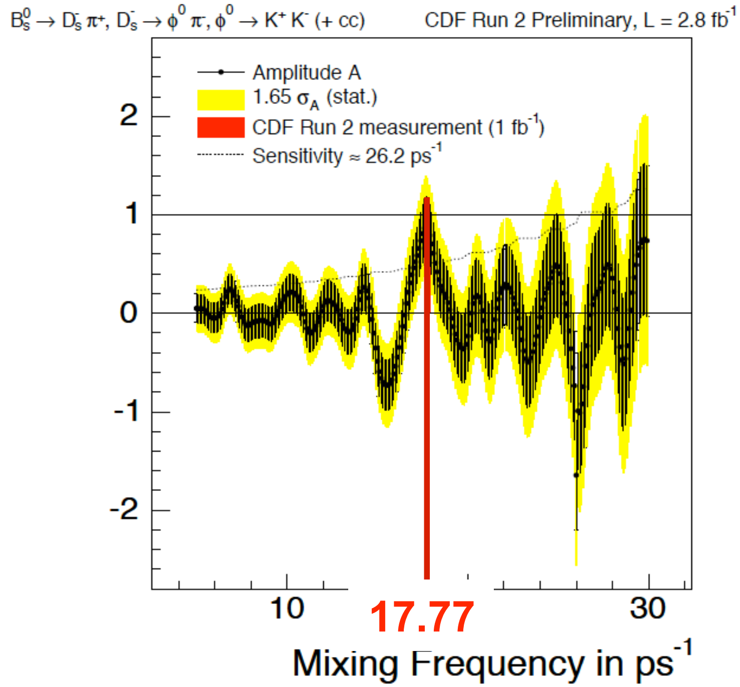

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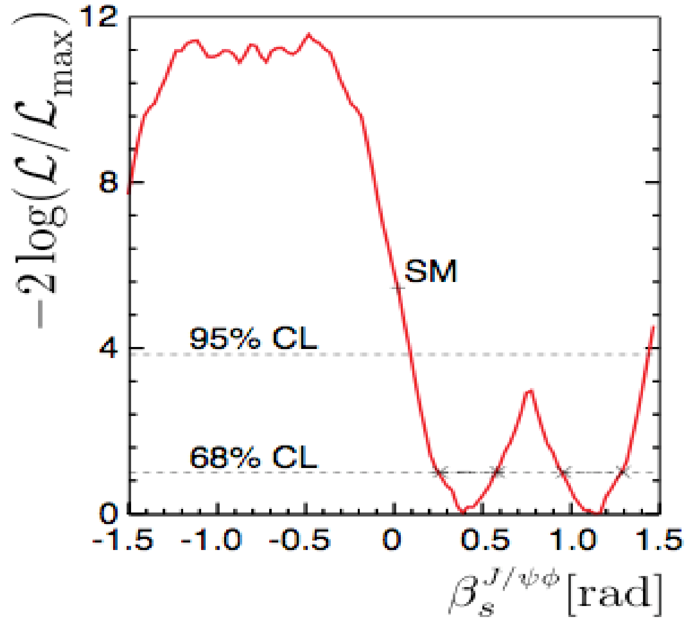

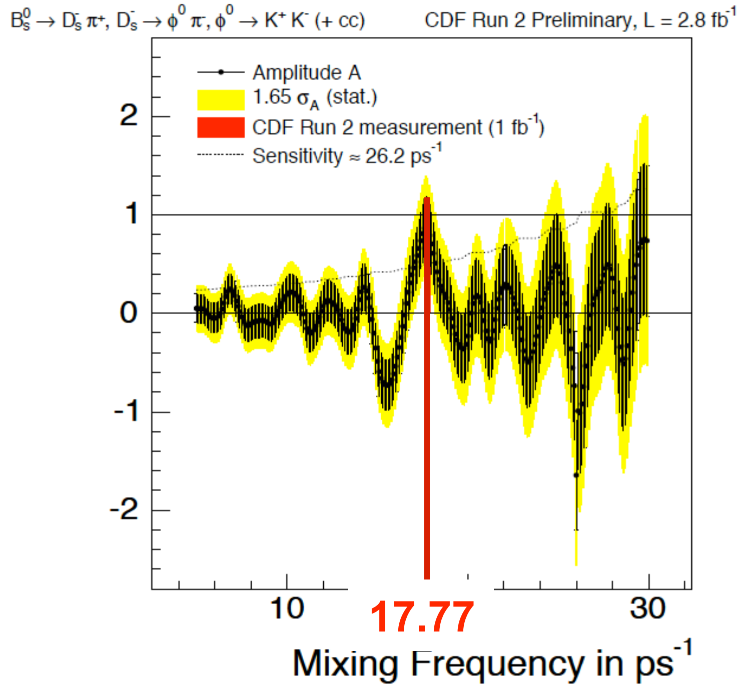

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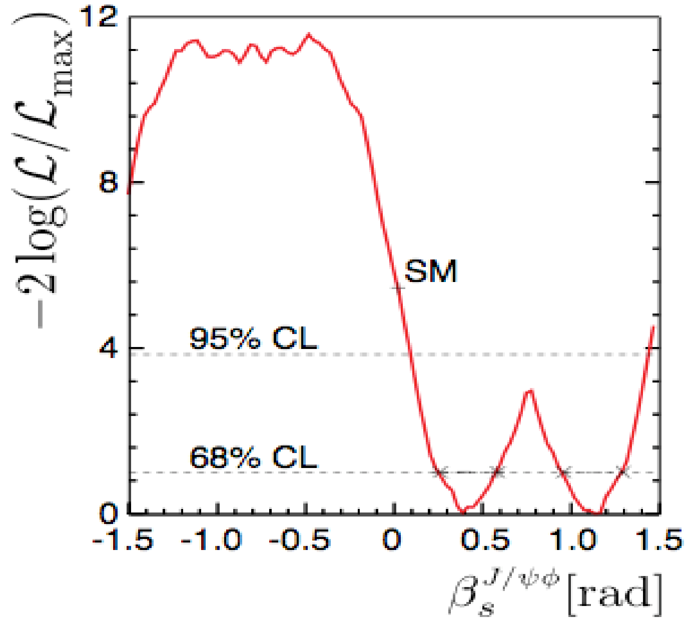

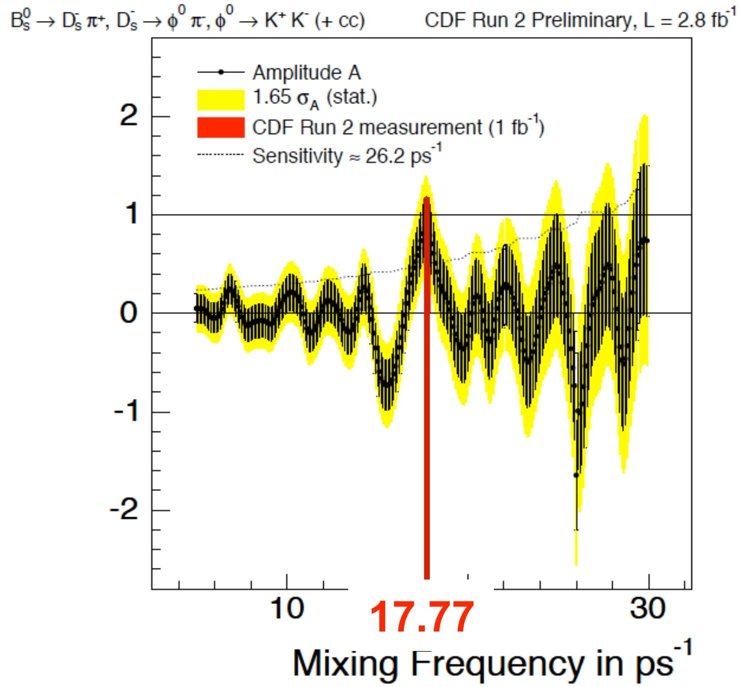

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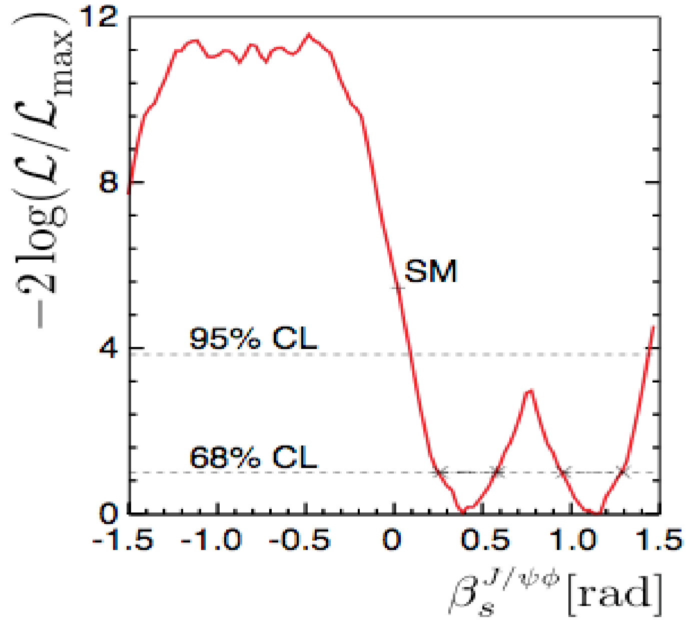
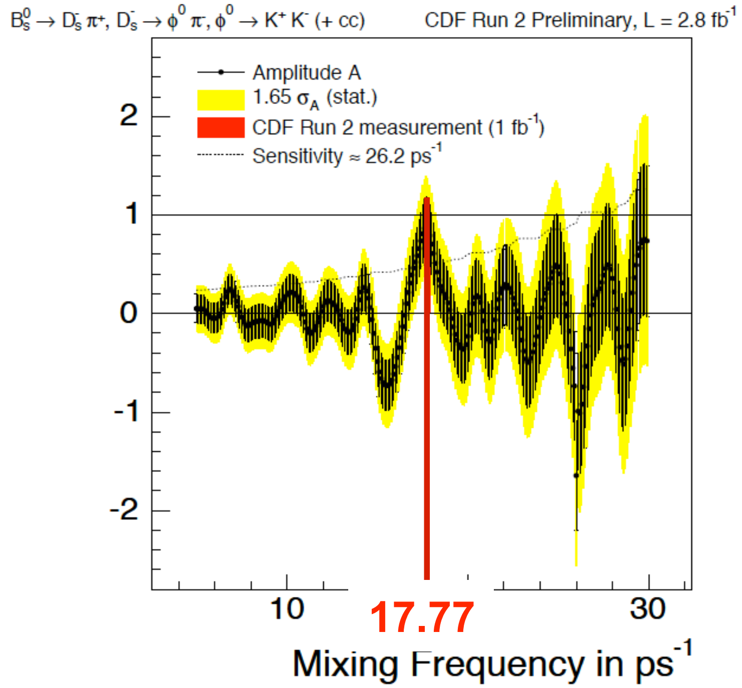
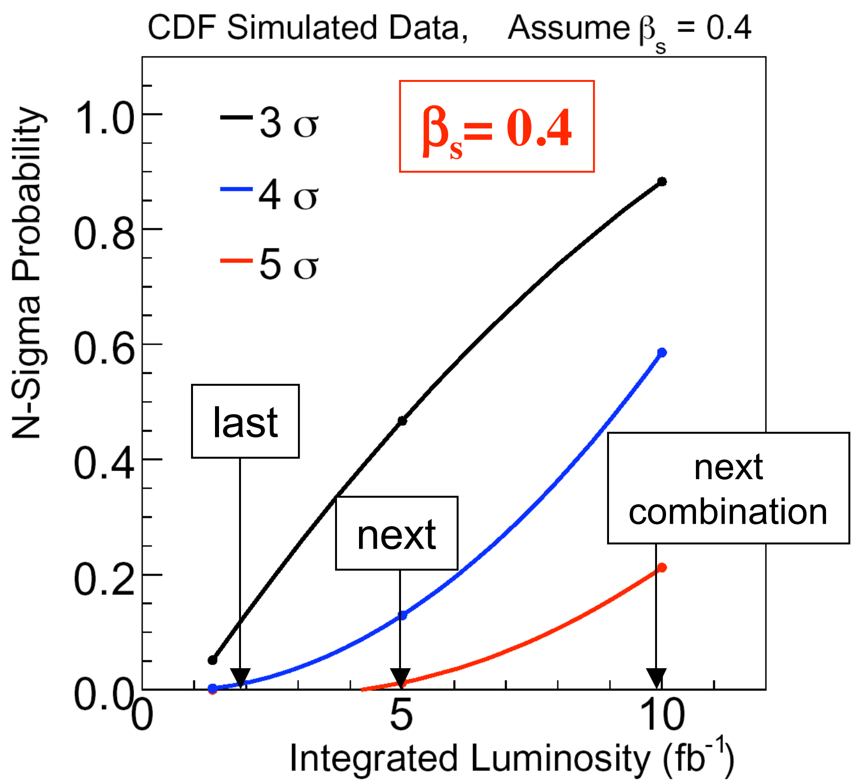
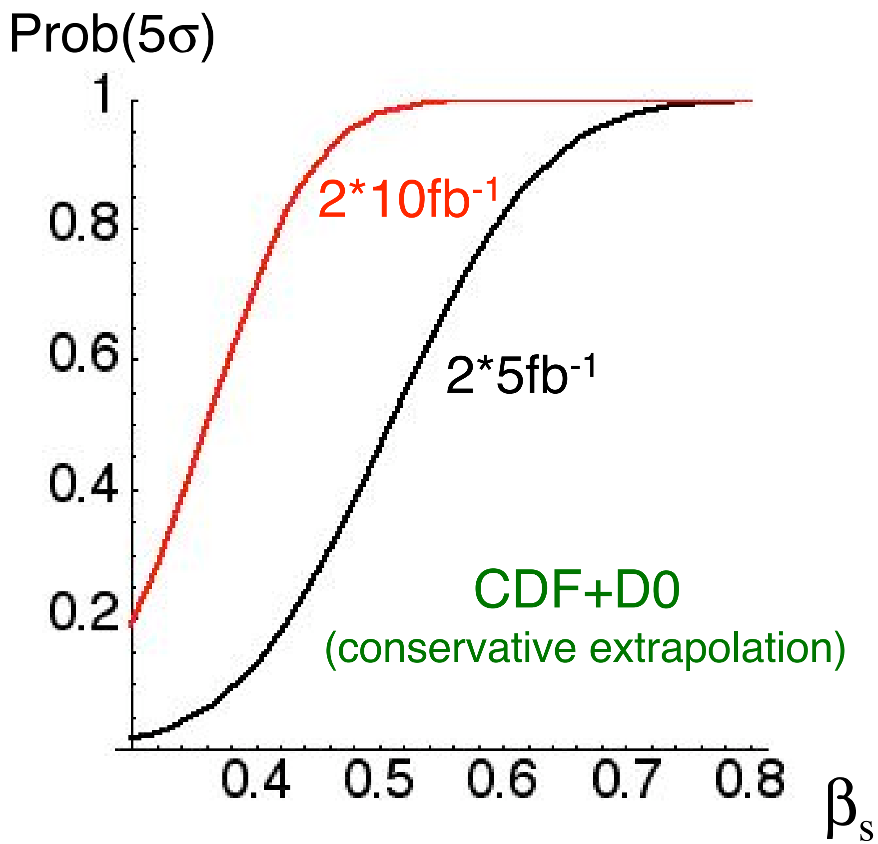
- Next step: possibility of improved precision of the combination by simultaneous fit of CDF and D0 samples.





Outlook



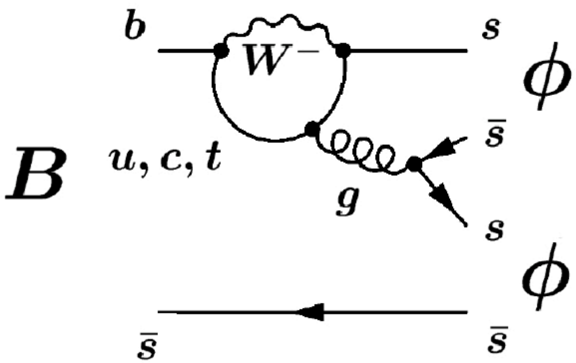


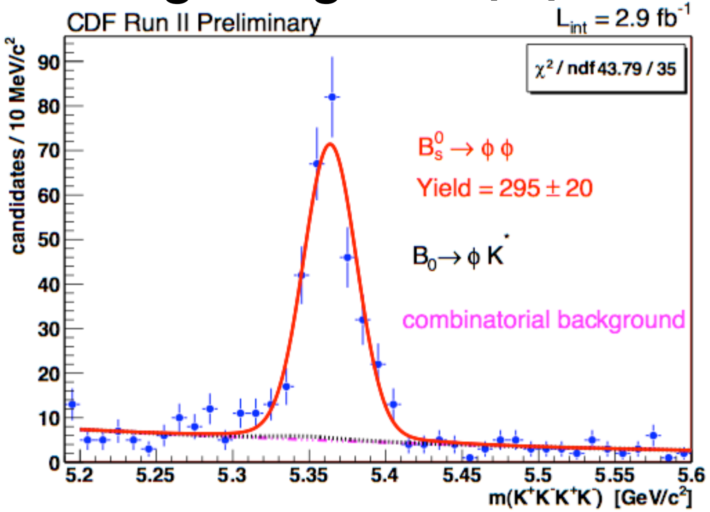
- High probabity of discovery for β_s above ~0.4

⇒ Implies high exclusion power if effect not found.

- Assumes constant data taking efficiency and no analysis improvements
- No external constraint or additional information (e.g. ASL)

More CPV in the B_s: $B_s \to \varphi\varphi$





- B $\to$ *sss* penguin process. CPV can enter in both mixing and decay. Possibility of deviations in BR and polarization (“polarization puzzle”).
- **Very clean !** Currently ~300 events/2.9fb^{-1} $\Rightarrow$ expect 1000 events by 2011. (Might still add some additional trigger paths)

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

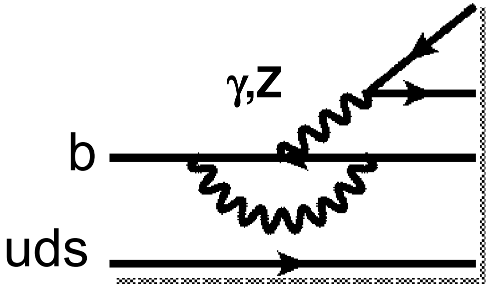
Translate to: $\mathcal{B}[B_s \to \phi\phi] = [2.40 \pm 0.21(stat) \pm 0.27(syst) \pm 0.82(BR)] \cdot 10^{-5}$

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

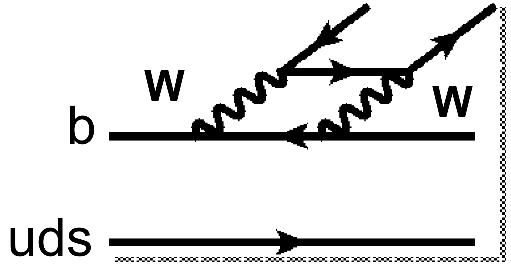
Comparison dominated by theoretical and BR uncertainties.

Expect polarization measurement soon with precision 10%, eventually CPV

B→Kll at CDF



EW penguin

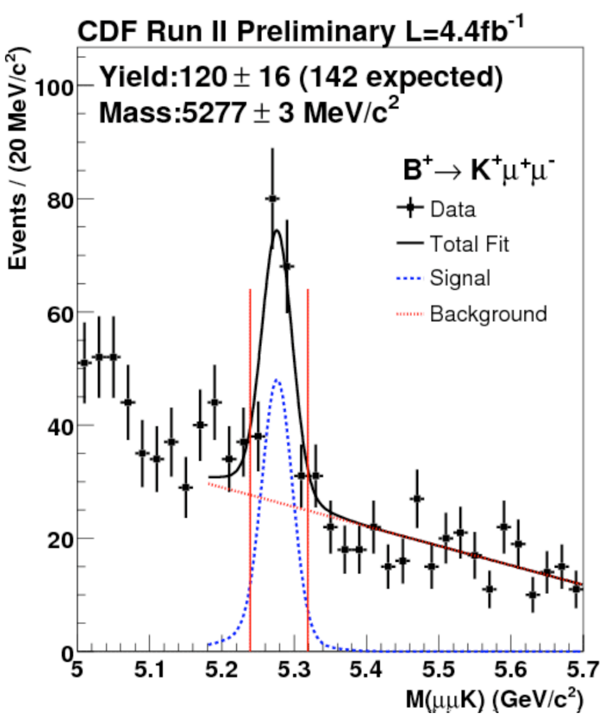


W-box

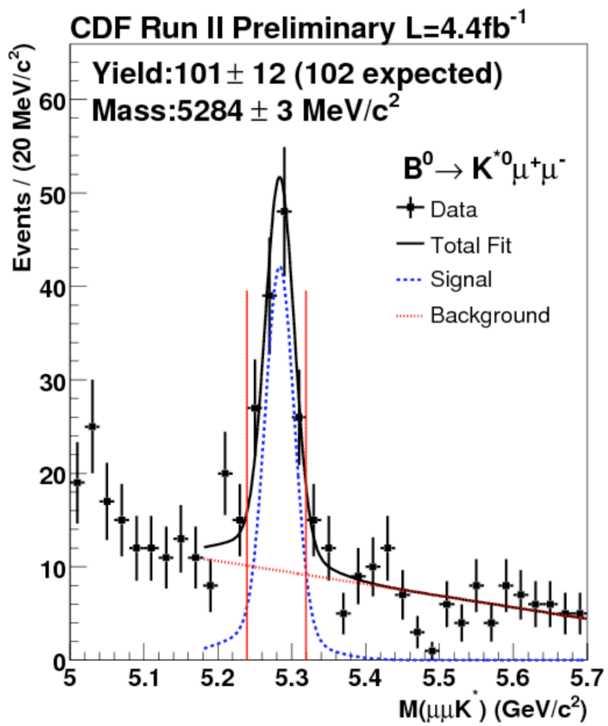
- Hints of deviations from SM in A_{FB} at the B-factories, possible 4th generation effect, but not enough data.
- CDF has reconstructed signals on $1fb^{-1}$, but not enough data for meaningful A_{FB} measurements [Phys.Rev.D79:011104,2009]
- ***New results*** with **4.4 fb^{-1}**

B→Kll at CDF (4.4fb^{-1})

- ✓ Use neural network to optimize event selection
- ✓ Currently use a single final state per decay channel
  - ✓ $B^+ \to K^+ \mu^+ \mu^-$
  - ✓ $B^0 \to K^{*0}(\to K^+ \pi^-)\ \mu^+ \mu^-$



Stat. significance ~9 σ



Stat. significance ~10 σ

Total BRs

(x10^{-6})

	BaBar (384M BB)	Belle (657M BB)	CDF (4.4fb^{-1})
$K^+\mu\mu$	$0.41^{+0.16}_{-0.15}$(stat)±0.02(syst)	$0.53^{+0.08}_{-0.07}$(stat)±0.03(syst)	0.38±0.05(stat)±0.03(syst)
$K^{*0}\mu\mu$	$1.35^{+0.40}_{-0.37}$(stat) ±0.10(syst)	$1.06^{+0.19}_{-0.14}$(stat) ±0.07(syst)	1.06±0.14(stat)±0.09(syst)
Kll	0.39±0.07(stat)±0.02(syst)	$0.48^{+0.05}_{-0.04}$(stat)±0.03(syst)	Same as $K^+\mu\mu$
K*ll	$1.11^{+0.19}_{-0.18}$(stat)±0.07(syst)	$1.07^{+0.11}_{-0.10}$(stat)±0.09(syst)	Same as $K^{*0}\mu\mu$

PRL102:091803 (2009) PRL103:171801 (2009)

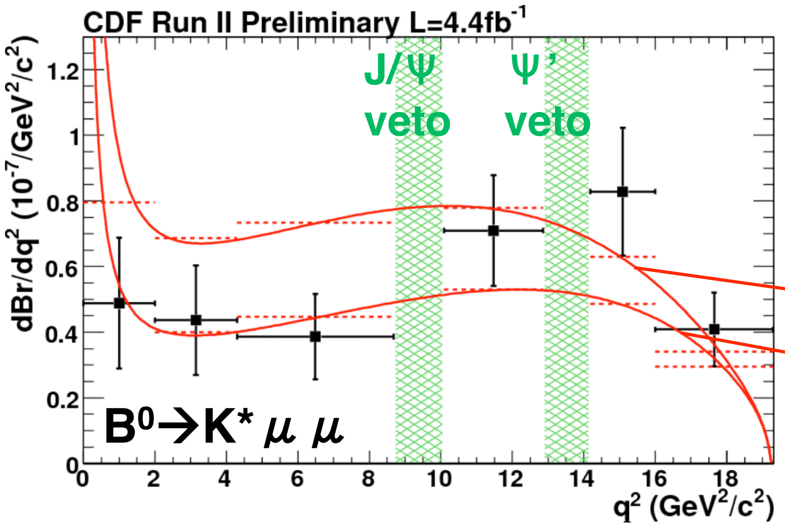
Best measurements for the given final state!

$\{K\pi, K_s\pi, K\pi^0\}^*\{ee, \mu\mu\}$

$\{K, K_s\}^*\{ee, \mu\mu\}$

- ✓ Compatible with previous measurements
- ✓ Best results for the given final state
- ✓ Other final states also accessible in principle at CDF using other trigger selections, but not yet studied how well.

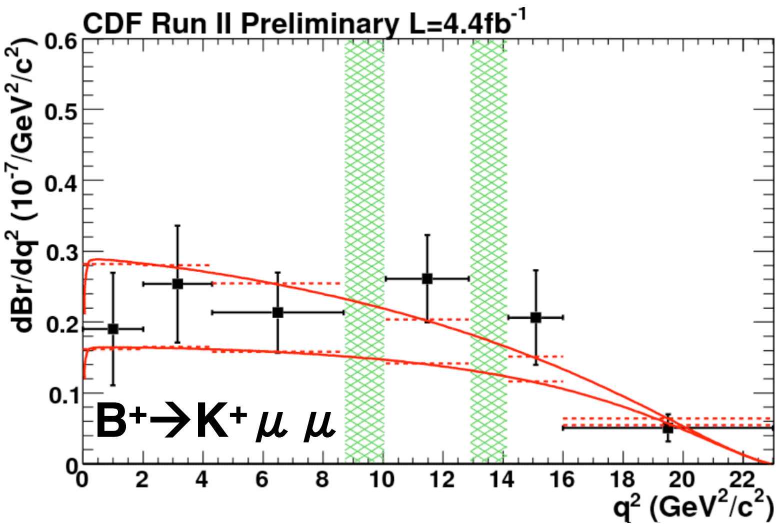
B→Kll at CDF: differential BR



BR wrt q^2, where $q^2=M_{\mu\mu}^2$

SM maximum allowed

SM minimum allowed



q^2 binning

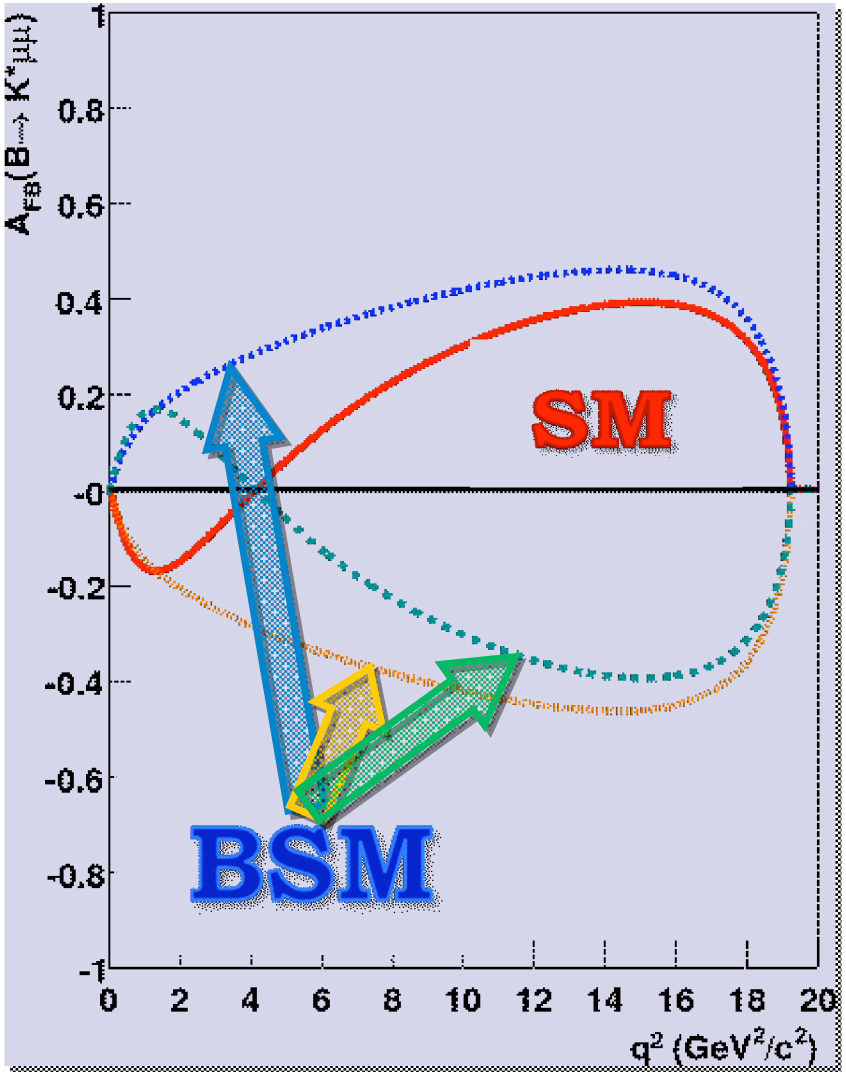
	$B^0 \to K^{*0}\mu^+\mu^-$	$B^+ \to K^+\mu^+\mu^-$
Bin#1	0.00-2.00	0.00-2.00
Bin#2	2.00-4.30	2.00-4.30
Bin#3	4.30-8.68	4.30-8.68
Bin#4	10.09-12.86	10.09-12.86
Bin#5	14.18-16.00	14.18-16.00
Bin#6	16.00-19.30	16.00-23.00

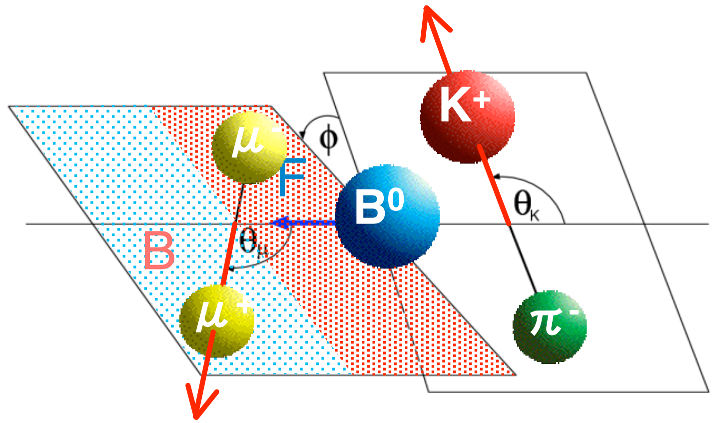
Same definition as Belle

Consistent with SM and previous measurements

- BaBar, PRL102:091803 (2009)
- Belle, PRL103:171801 (2009)

F_L and A_{FB}





$B^0 \to K^{*0} \mu\mu$ decay plane

Forward-Backward Asymmetry :

$$A_{FB}(q^2) \equiv \frac{\Gamma(q^2,\cos\theta_\mu > 0) - \Gamma(q^2,\cos\theta_\mu < 0)}{\Gamma(q^2,\cos\theta_\mu > 0) + \Gamma(q^2,\cos\theta_\mu < 0)}$$

where $q^2 = M_{\mu\mu}^2$

Expect A_{FB} ~0 and F_L=1 for $K\mu\mu$ mode

$$\frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

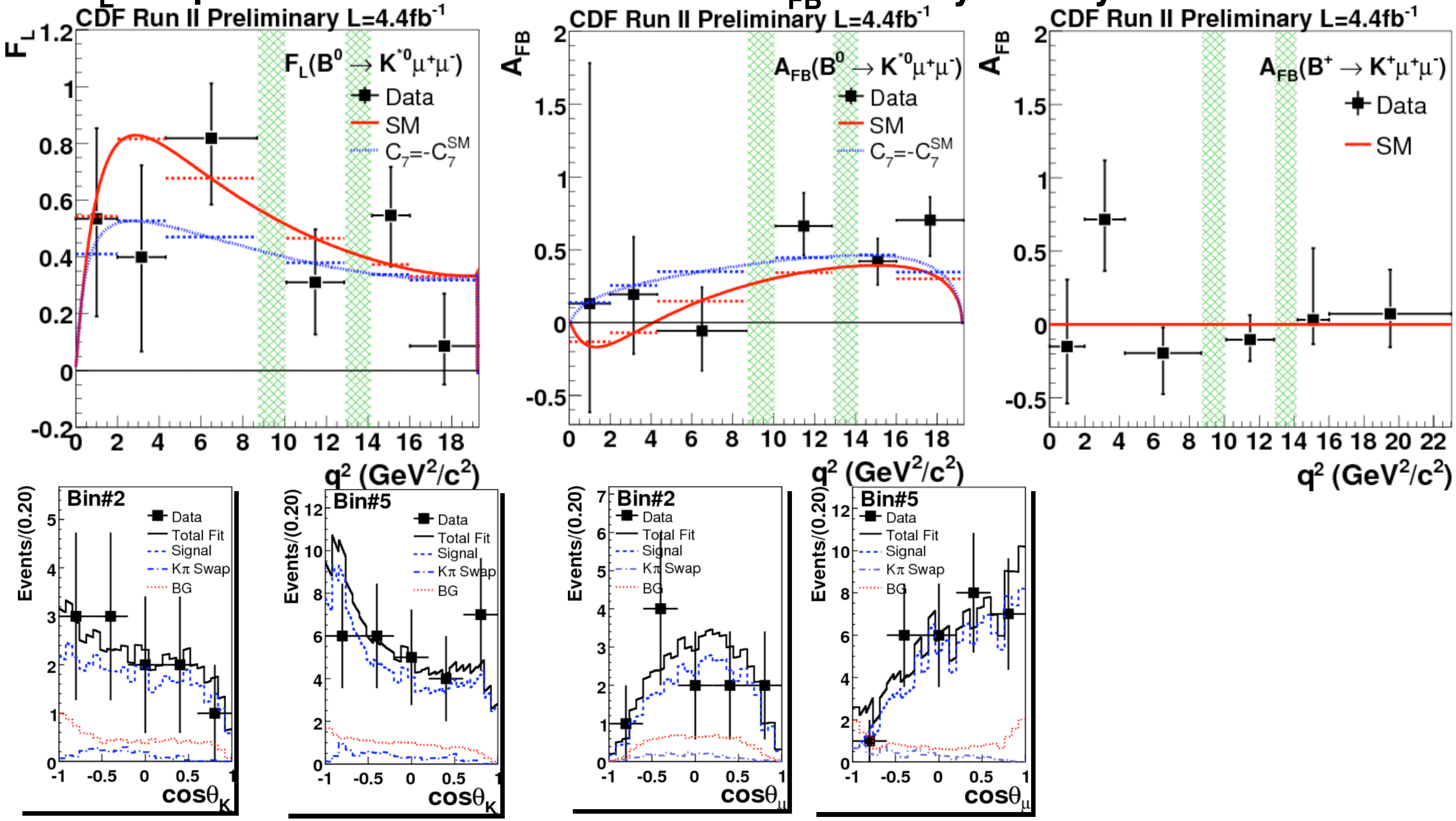
$$\frac{3}{4}F_L(1-\cos^2\theta_\mu)+\frac{3}{8}(1-F_L)(1+\cos^2\theta_\mu)+A_{FB}\cos\theta_\mu$$

Good probe for 4th gen

B→Kll at CDF: F_L and A_{FB} results

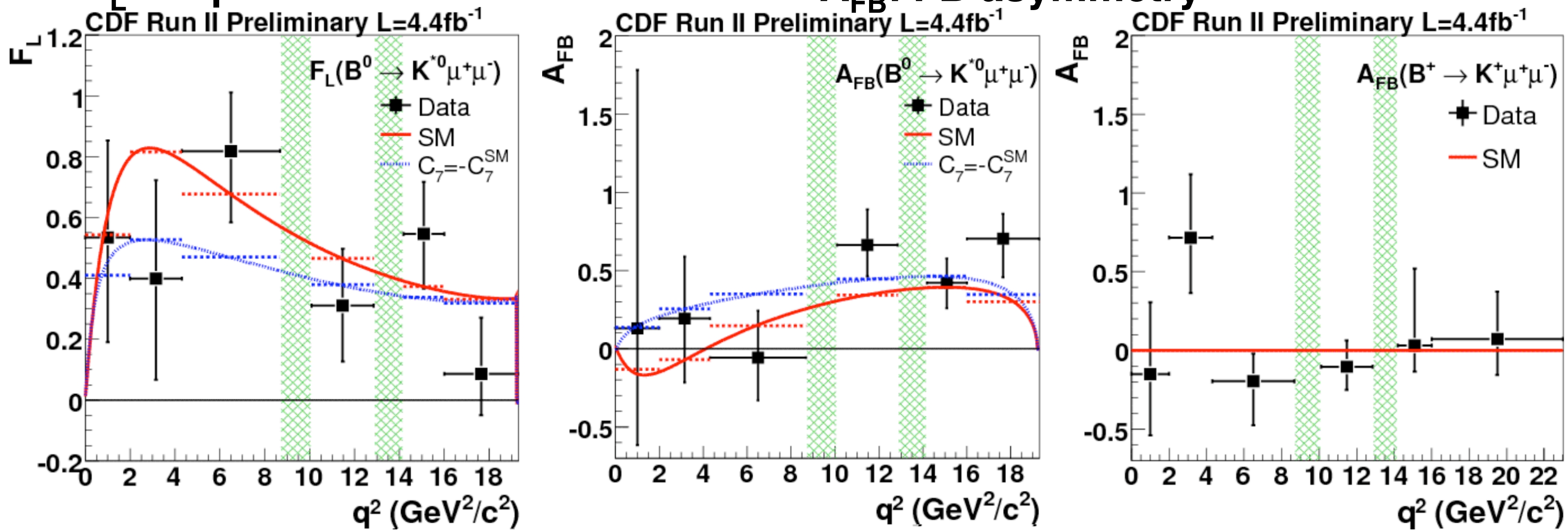
F_L: K* polarization

A_{FB}: FB asymmetry



B→Kll at CDF: F_L and A_{FB} results

F_L: K* polarization **A_{FB}: FB asymmetry**



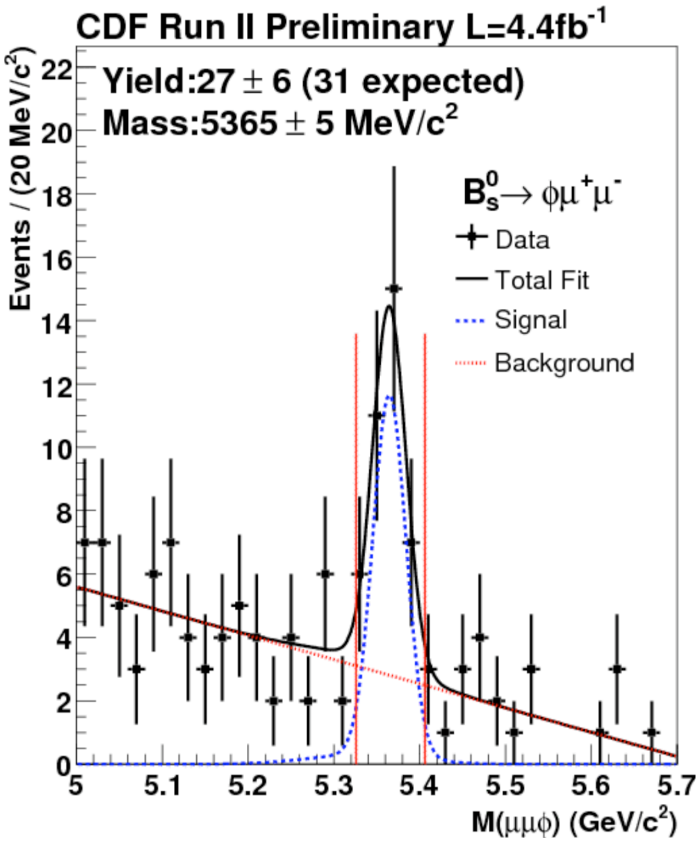
- Consistent with both SM and a BSM expectations: need more data.
- Consistent with B-factories measurements, shows a slight positive excess as well. Combination might be interesting.

  BaBar: PRD79,031102(R) (2009) Belle: PRL103,171801(2009)

- **Expect several further improvements:**
  - >2x data in 2010/2011 run
  - additional sub-decay channels and additional trigger paths

⇒ CDF will give important contribution to this measurement.

NEW: 1st Observation of $B_s \rightarrow \phi \mu^+ \mu^-$



Stat. significance ~6 σ

- ✓ Similar analysis as $B \rightarrow K^{(*)} \mu \mu$
- ✓ Obtain pretty clean signal
- ✓ First Measurement: $BR(B_s \rightarrow \phi \mu \mu)=$ $=[1.44 \pm 0.33(stat) \pm 0.46(syst)] \times 10^{-6}$

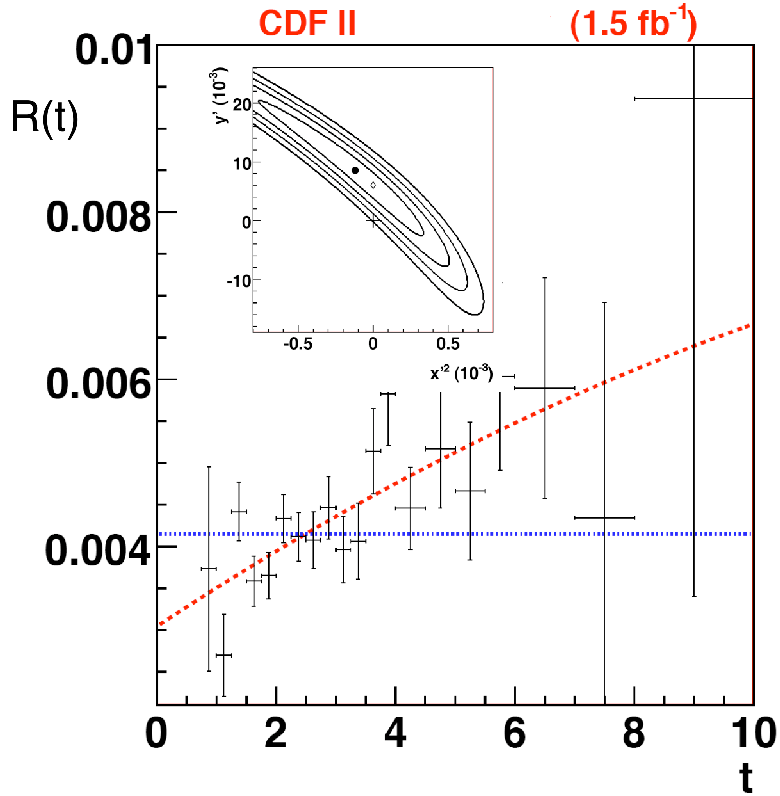
  Consistent with prediction $\sim 1.6 \times 10^{-6}$

  [curiosity: the rarest observed B_s decay]
- ✓ Next step: measure polarization F_L

Measurement of CP-asymmetries in $D^0 \to h^+h^-$

D^0-mixing at CDF

CDF observed evidence of mixing at 3.8σ with just 1.5 fb^{-1}[PRL 100,121802(2008)].
Data extends up to 10 lifetimes.
Next step is precision measurements.



Here we focus on CPV in CS modes ($D^0 \to \pi\pi$, $D^0 \to KK$)

$A_{CP}(t) \approx (x \sin\varphi - y\, \varepsilon \cos\varphi)\ (t/\tau)$

In SM: $\sin\varphi$, $\varepsilon < 10^{-3}$

NP can make them of O(1).

4th gen can be $\sin\varphi \sim 0.1\text{-}0.2$

[Hou, hep-ph/0611154]

⇒Look for $A_{CP}(t) \sim 10^{-3}(t/\tau)$ vs. SM $\sim 10^{-5}(t/\tau)$

This survives integration over time if incoherently produced, as in CDF

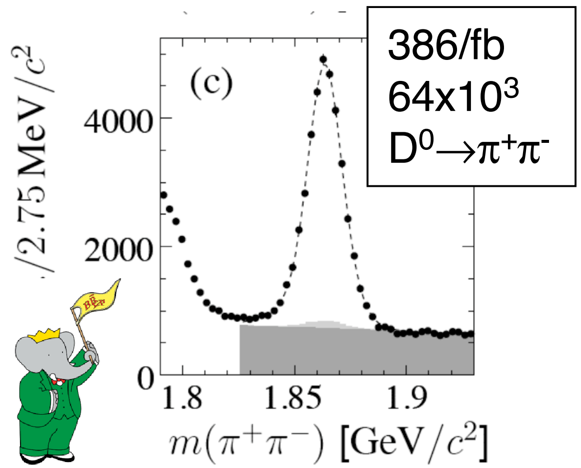
$A_{CP}(D^0 \rightarrow h^+h^-)$ current status

$$A_{CP}^{\pi\pi} = \frac{\Gamma(D^0 \rightarrow \pi^-\pi^+) - \Gamma(\overline{D}^0 \rightarrow \pi^+\pi^-)}{\Gamma(D^0 \rightarrow \pi^-\pi^+) + \Gamma(\overline{D}^0 \rightarrow \pi^+\pi^-)}$$

Tag the flavor of the D^0 by selecting decays $D^{*+} \rightarrow D^0\pi^+$

Note small sample

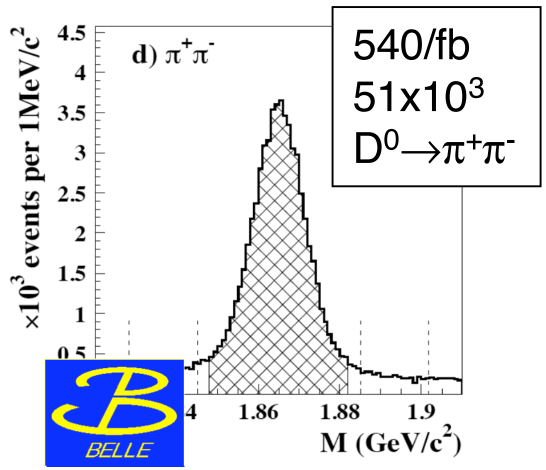
PRL100,061803(2008)



$$A_{CP}^{KK} = [+0.00 \pm 0.34 \pm 0.13]\%$$

$$A_{CP}^{\pi\pi} = [-0.24 \pm 0.52 \pm 0.22]\%$$

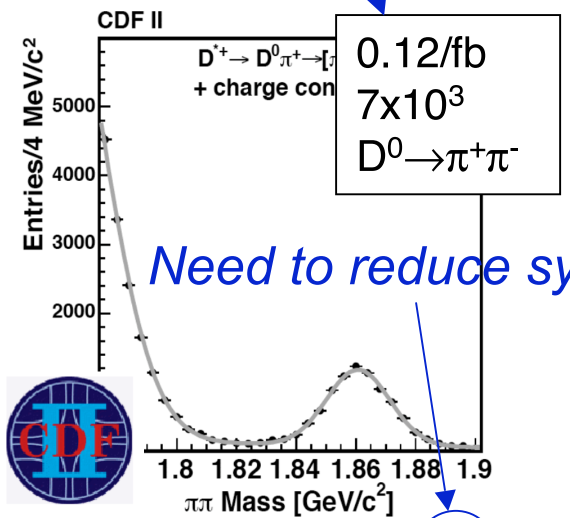
PLB670,190-195(2008)



$$A_{CP}^{KK} = [+0.43 \pm 0.30 \pm 0.11]\%$$

$$A_{CP}^{\pi\pi} = [+0.43 \pm 0.52 \pm 0.12]\%$$

PRL94,122001(2005)

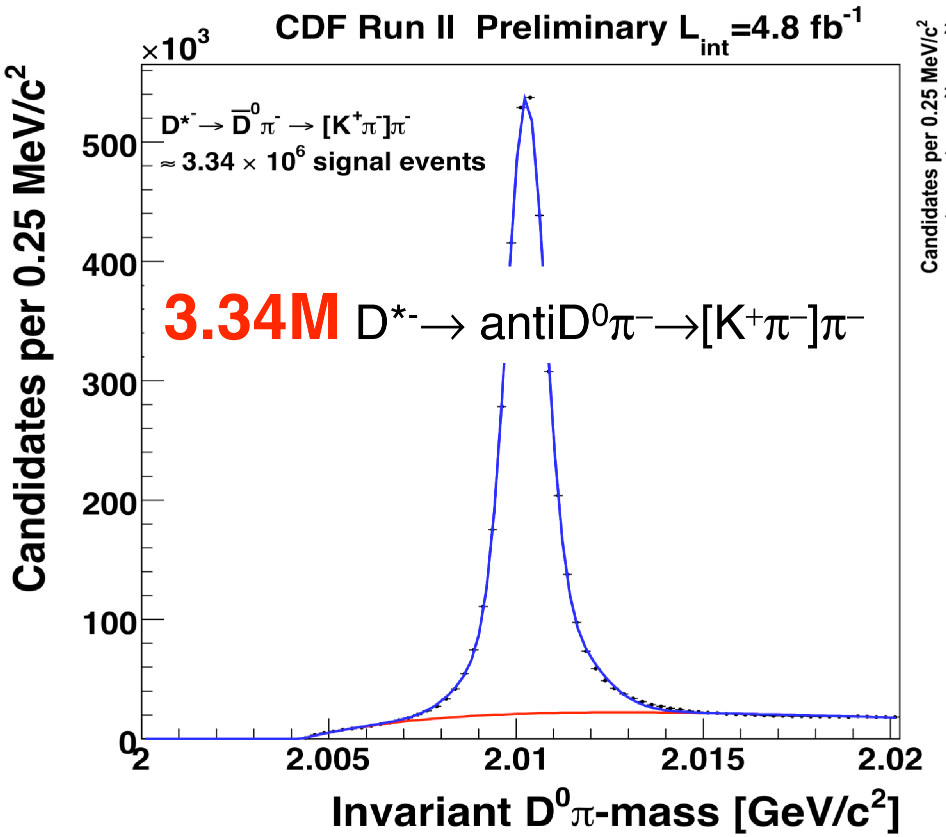


Need to reduce syst

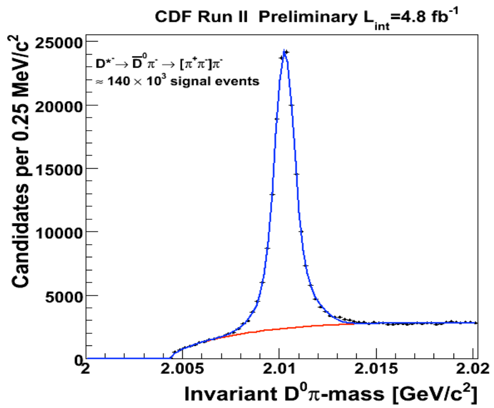
$$A_{CP}^{KK} = [+2.0 \pm 1.2 \pm 0.6]\%$$

$$A_{CP}^{\pi\pi} = [+1.0 \pm 1.3 \pm 0.6]\%$$

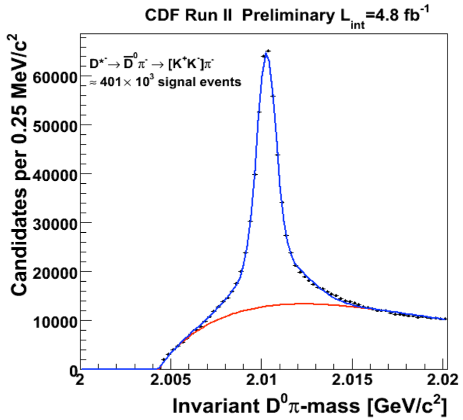
CDF now has world's largest samples



3.34M D*-→ antiD⁰π⁻→[K⁺π⁻]π⁻



140K $D^{*-} \to [\pi^+\pi^-]\pi^-$



401K $D^{*-} \to [K^+K^-]\pi^-$

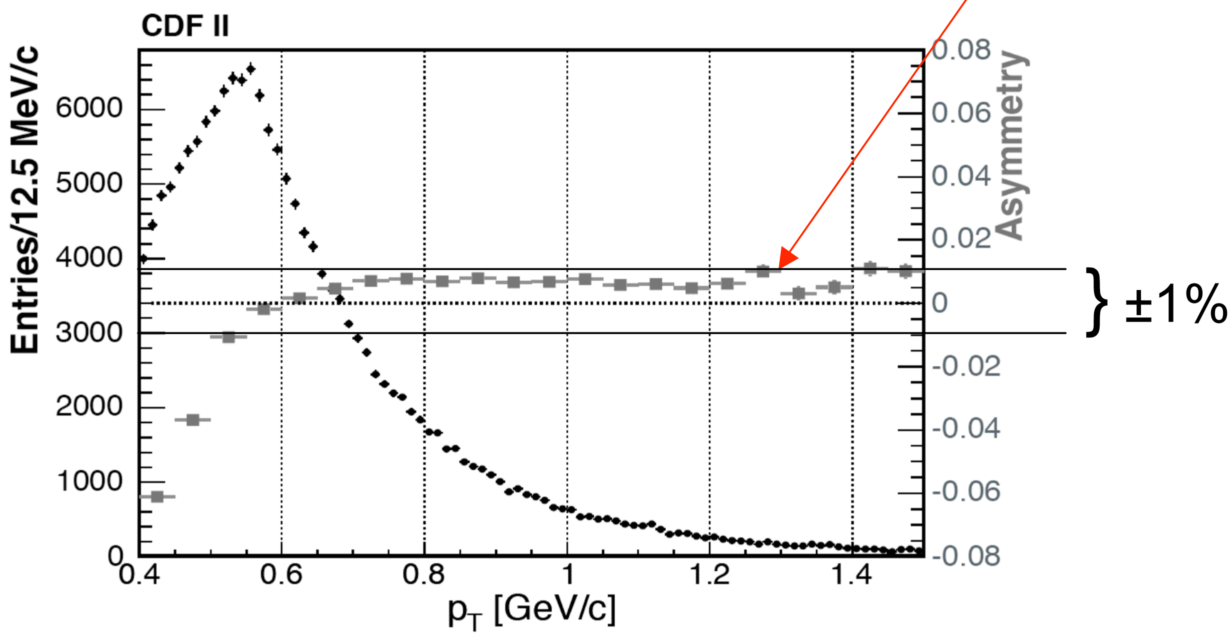
- Currently taking data at a rate **10x**Belle

CDF as a "Charm Decay Factory" ?

- Would be interesting to keep it up for a while

The issue with detector asymmetries

$$\frac{\Gamma(D^{*-} \rightarrow \overline{D}^0\pi_s^- \rightarrow [h^+h^-]\pi_s^-)}{\Gamma(D^{*+} \rightarrow D^0\pi_s^+ \rightarrow [h^+h^-]\pi_s^+)} = \frac{N_{h^+h^-\pi_s^-}}{N_{h^+h^-\pi_s^+}} \cdot \frac{\varepsilon_{h^+h^-}}{\varepsilon_{h^+h^-}} \cdot \frac{\varepsilon_{\pi_s^+}}{\varepsilon_{\pi^-}}$$



Need “very accurate” correction for charge asymmetries

Cancellation of detector asymmetries

$$\frac{\varepsilon_{\pi_s^+}}{\varepsilon_{\pi_s^-}} = \frac{N_{K^+\pi^-}}{N_{K^-\pi^+}} \cdot \cancel{\frac{\varepsilon_{K^-\pi^+}}{\varepsilon_{K^+\pi^-}}} \cdot \frac{N_{K^-\pi^+\pi_s^+}}{N_{K^+\pi^-\pi_s^-}} \cdot \cancel{\frac{\varepsilon_{K^+\pi^-}}{\varepsilon_{K^-\pi^+}}}$$

From untagged $D^0 \to K^-\pi^+$

From D*-tagged $D^0 \to K^-\pi^+$

Some *unique features* of CDF allow for cancellation of all detector-induced charge asymmetries. Totally data-driven technique, already used in $B \to hh$.
Exploits two points:

1) p-pbar production $\to$ same number of particle/antiparticle at production.
2) Detector symmetric in pseudo-rapidity (η) $\to$ cancellation of beam-drag effects.

NOTE Direct CPV in $D^0 \to K^-\pi^+$ *ALSO* cancels out

Work in progress, but expect cancellation works to the percent level,
$\Rightarrow$ expect systematics on A_{CP} *well below 0.1%*

Prospects for $A_{CP}(D^0 \to \pi^+\pi^-)$ on 4.8 fb^{-1}

Assuming: $\sigma_N \cong \sigma_{\overline{N}} \cong 1/\sqrt{N} \Rightarrow \sigma_{A_{CP}} = 1/\sqrt{N+\overline{N}}$

Experiment	N $(D^0 \to \pi^+\pi^-)$ CDF(4.8/fb)	Current Babar/Belle
$A_{CP}(D^0 \to \pi^+\pi^-)$ (%)	xxx ± 0.19(stat) ± xxx (syst)	0.5(stat)
$A_{CP}(D^0 \to K^+K^-)$ (%)	xxx ± 0.11(stat) ± xxx (syst)	0.3(stat)

- A good step forward in precision, further factor of 2 by end of 2011.
- For CPV in mixing, can combine $\pi^+\pi^-$ and K^+K^-. Precision 0.07%
- Potential to actually see an effect of few permille !
- Long lever arm in lifetime helps

Further CDF measurements

- $A_{CP}(J/\psi\ K^+)$

10 Kevents/fb^{-1} ⇒ 0.4% stat in 5fb^{-1}

systematics not determined yet.

Best B-factory result: Babar 1.4%

D0 published result 0.6% statistical

4th generation effect expected O(1%)
[Hou et al., PRL 95 (2005) 141601]

- $A_{CP}(K\pi)$

CDF will measure $A_{CP}(K^+\pi^-)$ to < 1%

World's largest sample (3k/fb^{-1}), most precise result.

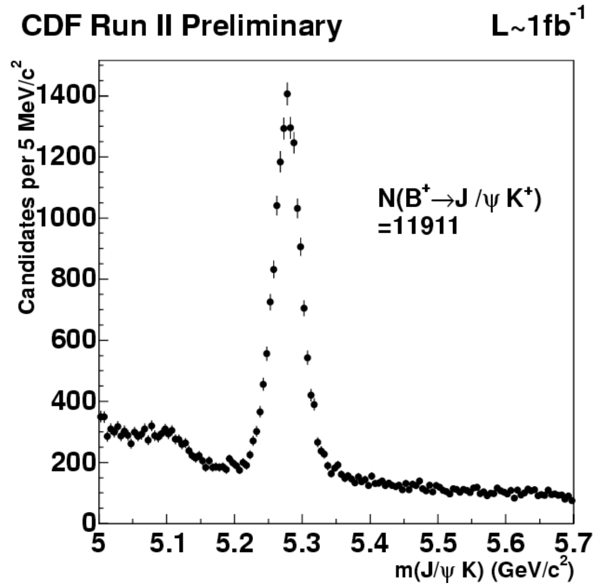
Cannot do much on $K^+\pi^0$ and $K_s\pi^0$ though.

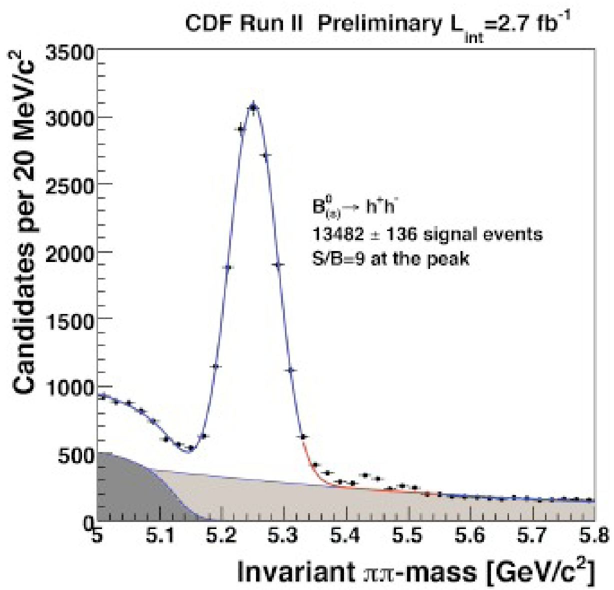
- BR($B_s \to \mu\mu$), BR($D^0 \to \mu\mu$)

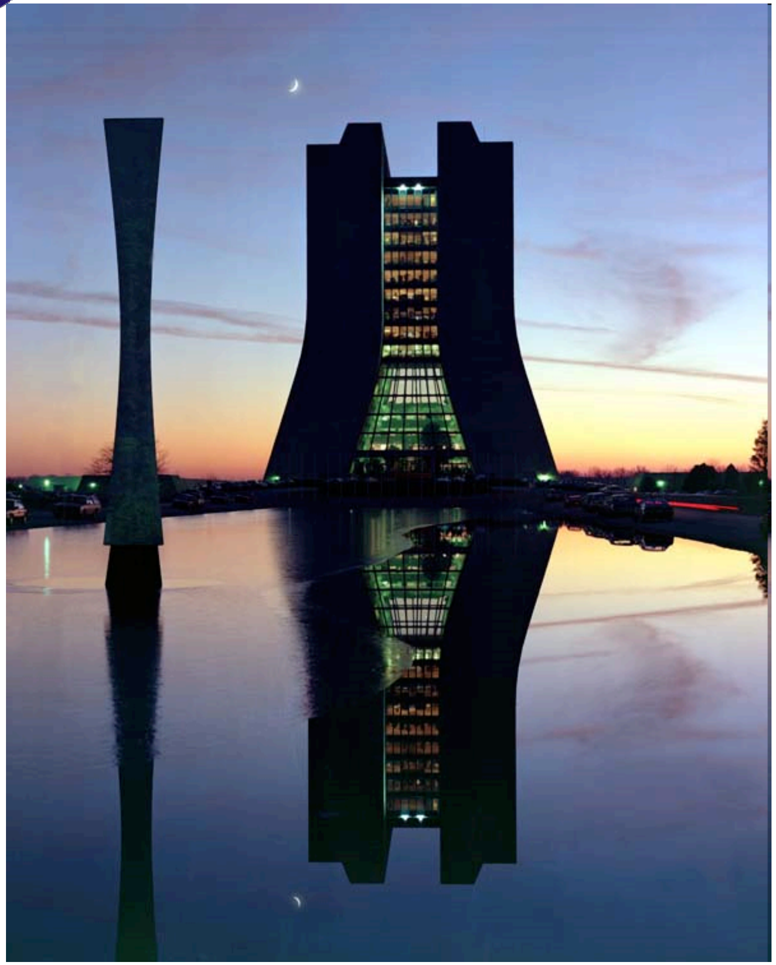
World's best measurements.

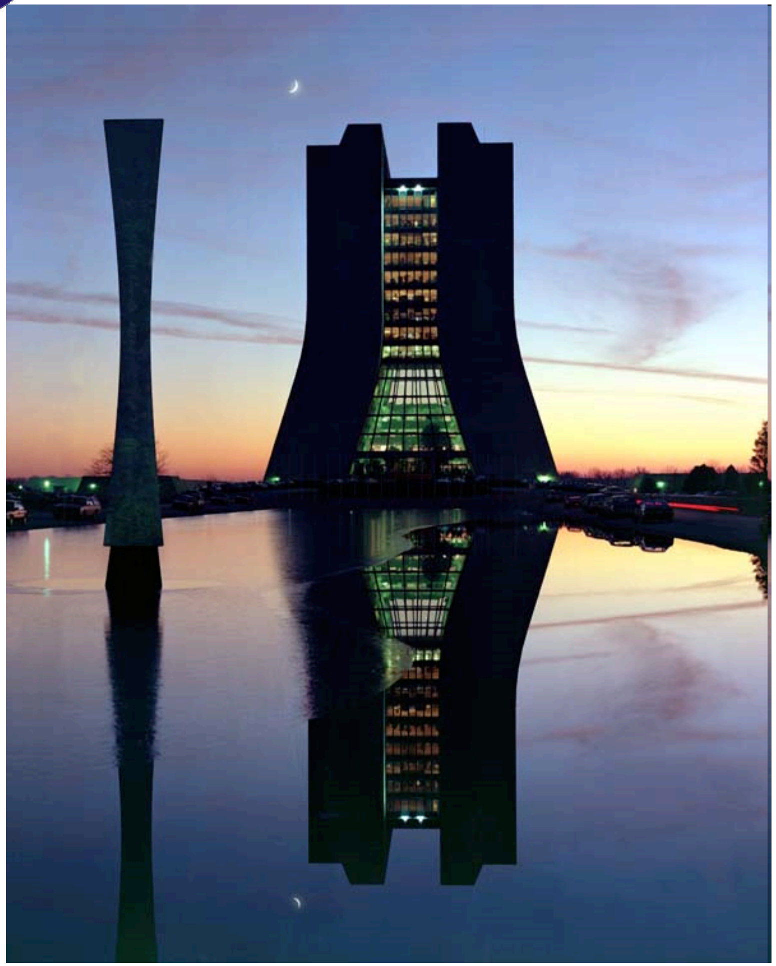
Both down to BR ~10^{-8}

- but 4th gen effects maybe too small ?

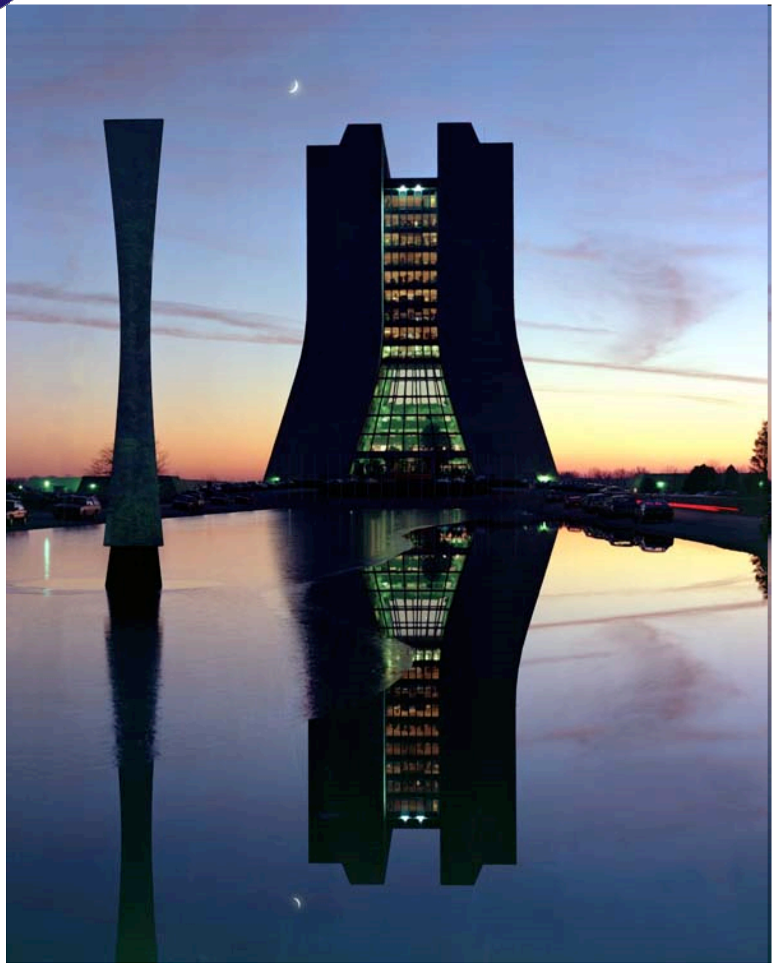








- CDF allows many crucial measurements sensitive to 4th generation, in addition to direct searches:
  - ϕs, Kll,ACP(D^0),DCPV…



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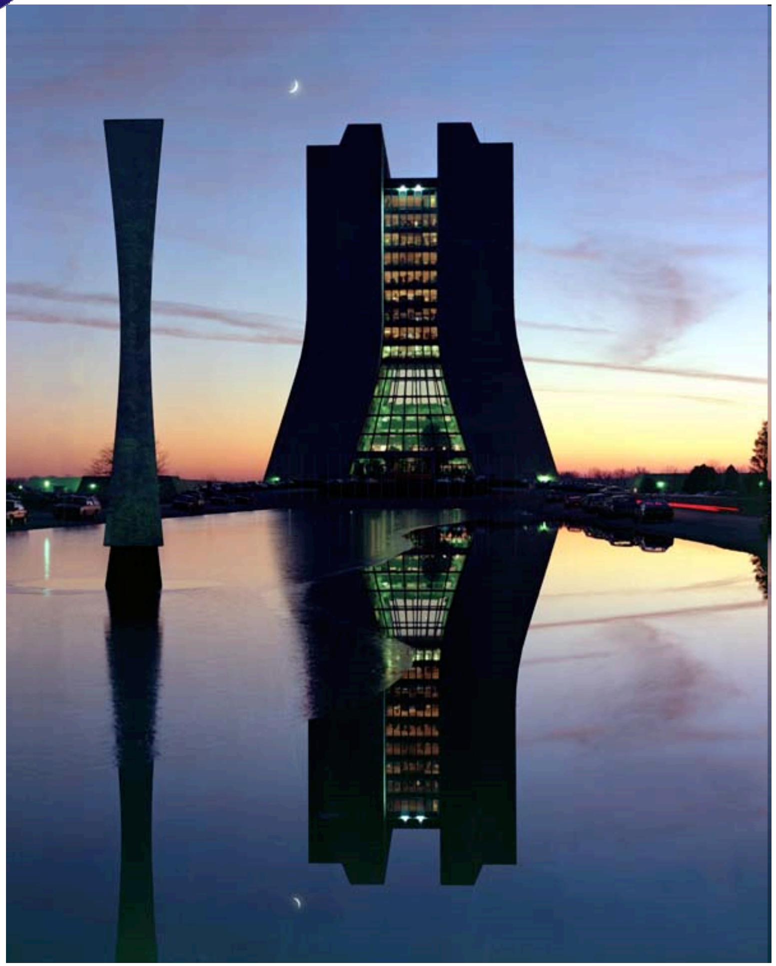

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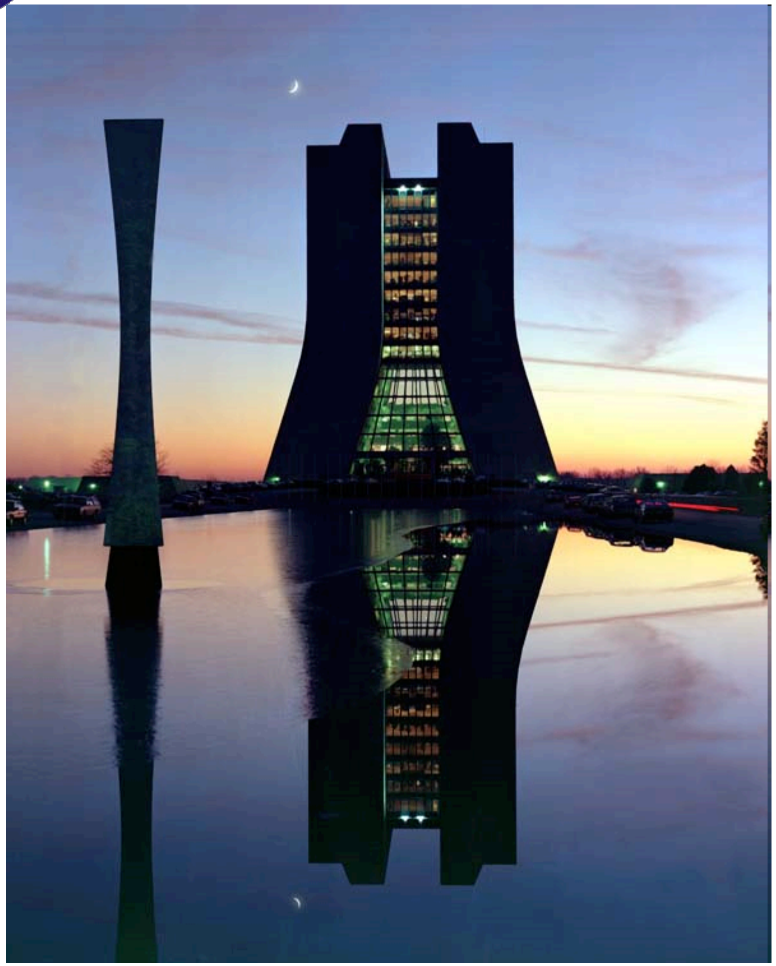

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The dawn of a new generation?