The Strange Beauty beyond the SM

CPPM seminar

Marseille
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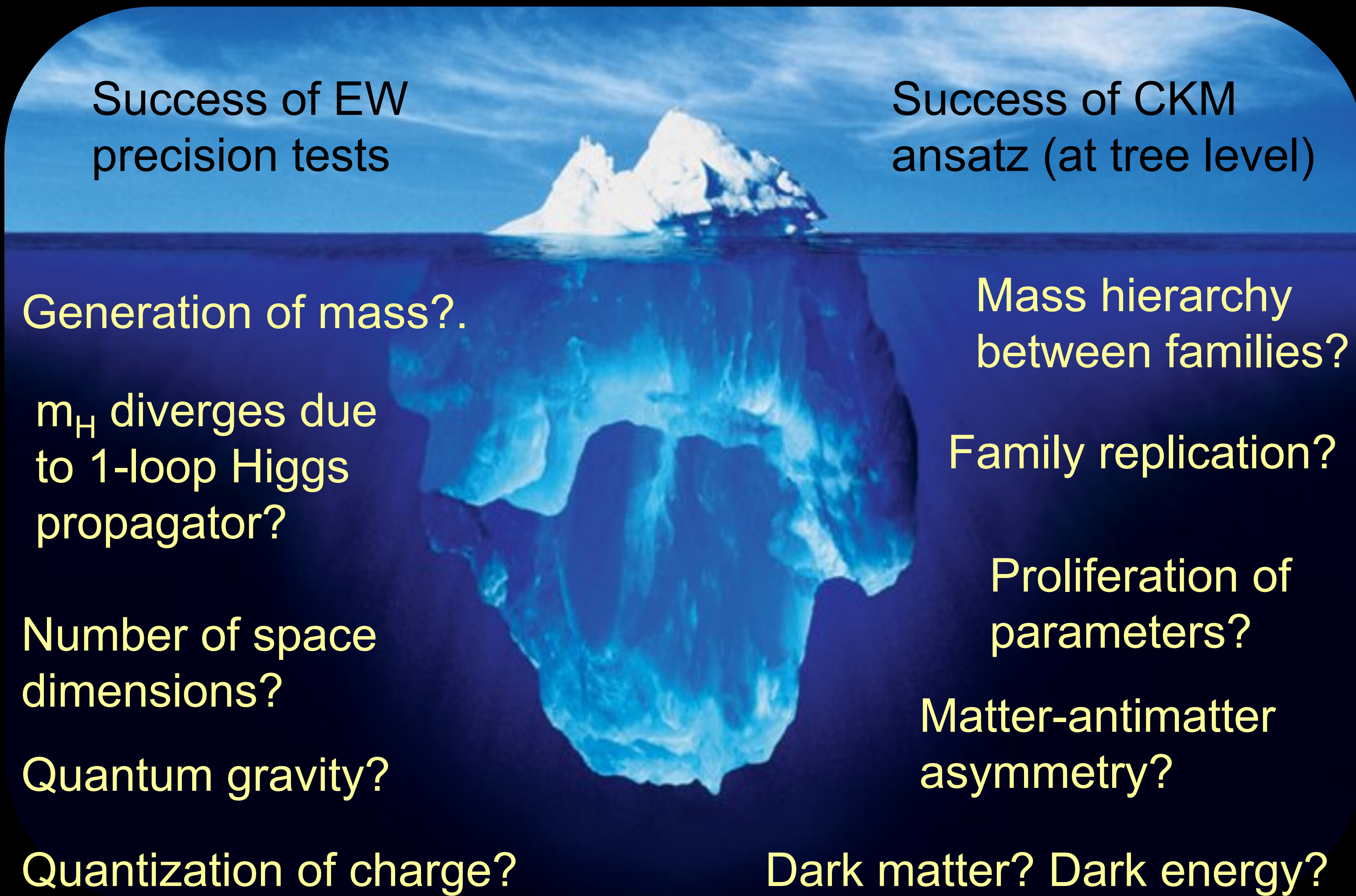
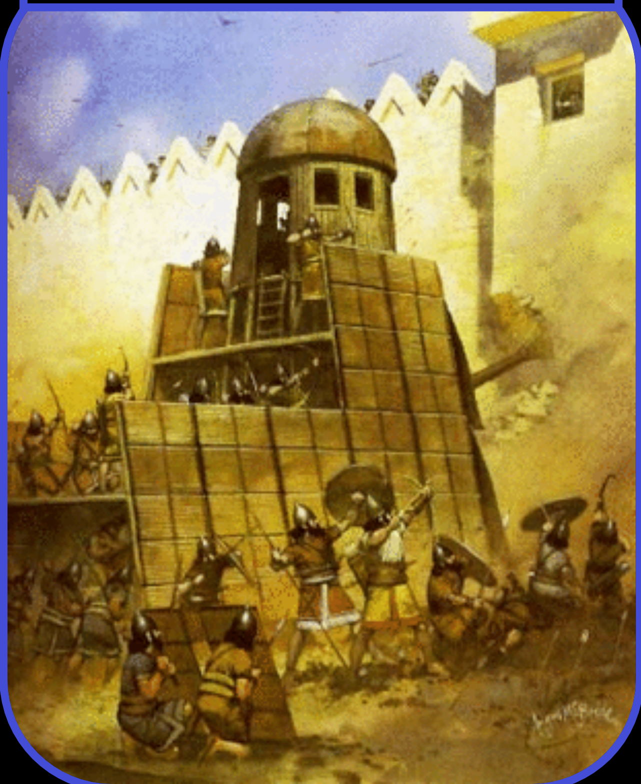
Fermilab

Where do the we stand?



Challenging the New Physics fortress

Direct (relativistic) way



Direct observation of on-shell new particles. Needs (very) high-energy.

Indirect (quantum) way

Presence of NP revealed by data-theory inconsistencies in low-energy quantities. Needs (very) high statistics.

"The flavor problem"

Kaon physics and *B* factories: SM picture of CP violation satisfactory at least at tree level in B^0 and B^+ decays. NP amplitudes < 10%, if any.

…the end of the story?

Success of the CKM picture rules out NP with generic flavor structure. To keep the NP-scale in the TeV range, physics beyond the SM should have a highly fine-tuned flavor structure

Why Strange Bottom mesons?

V On the Autonomy of B_s Dynamics

original paradigm: need B_d & B_s to determine all 3 angles

ϕ_2/α, ϕ_1/β from B_d vs. ϕ_3/γ from B_s

new paradigm: can get all angles from B_d

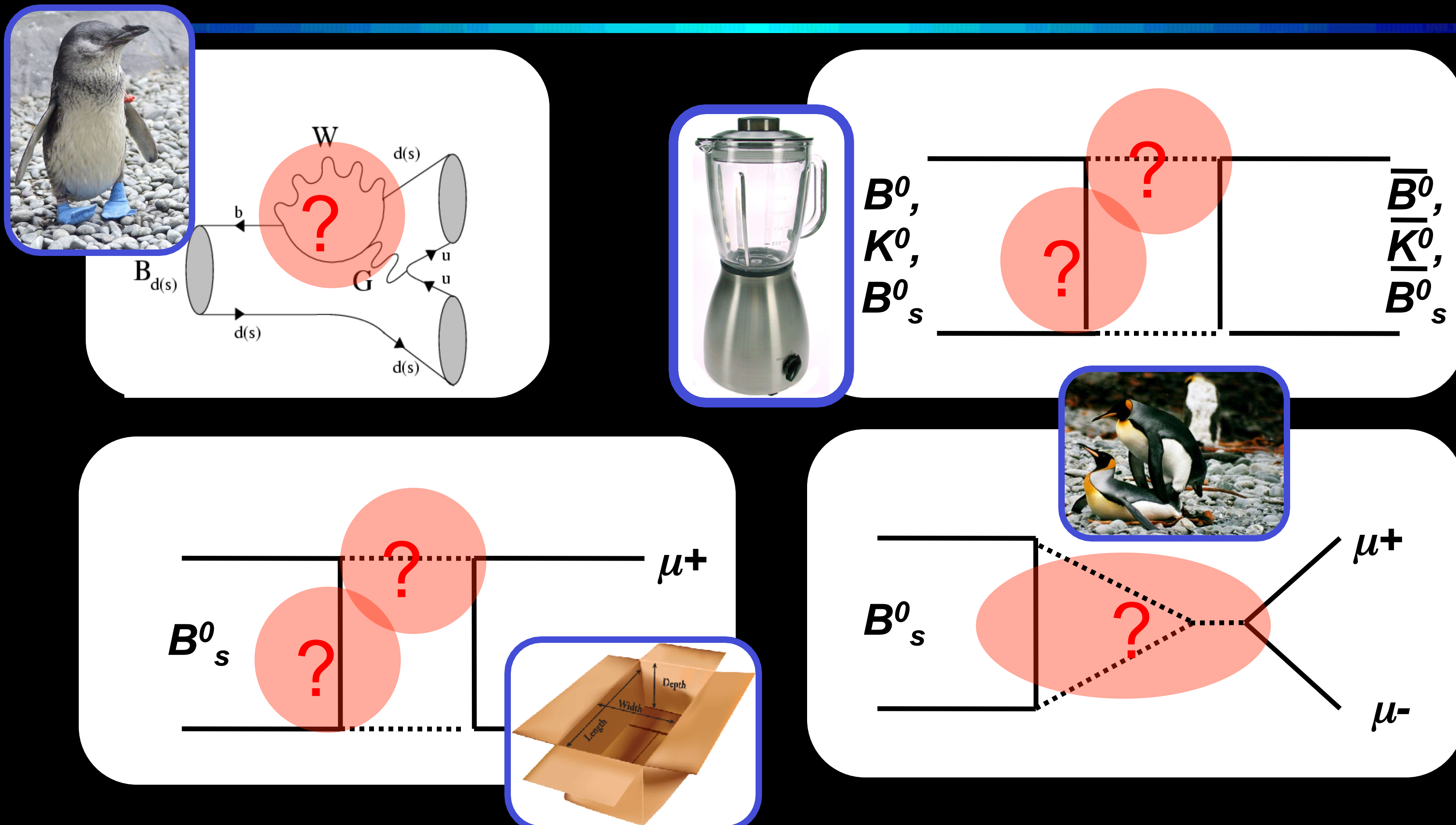
Furthermore NP in general will not obey SM relations between B and B_s decays

➡ B_s decays a priori independent chapter in nature's book on fundamental dynamics

$B_s(t) \rightarrow \psi\phi, \psi\eta, \phi\phi$ not a repetition of lessons from B_d & B_u decays!

stolen from I. Bigi, CERN Theory Institute, 26/5/2008

What’s left for New Physics?



New physics, if any, in suppressed processes. Need high statistics

The Tevatron

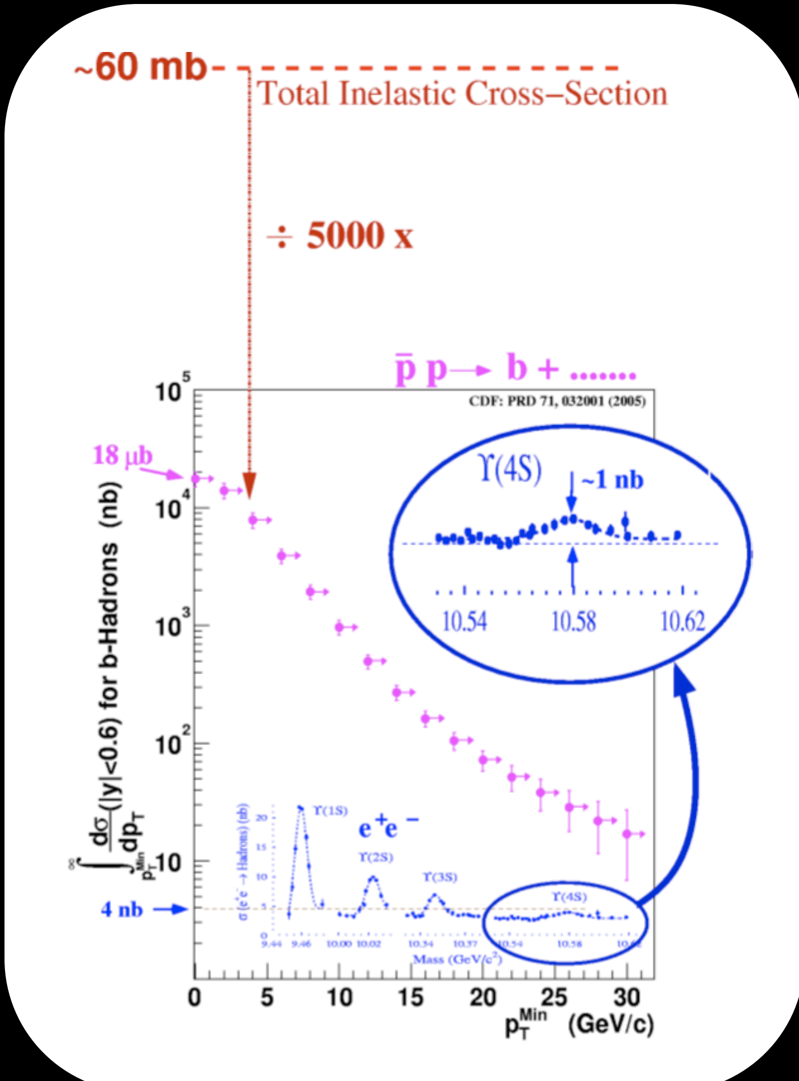
Superconducting proton-synchrotron: 36 (p)× 36 (pbar) bunches
collide every 396 ns at $\sqrt{s}$ = 1.96 TeV

interactions/bunch-crossing…………..$\langle N \rangle_{poisson}$ = 2 (at 10^{32} $cm^{-2}s^{-1}$)

Luminous region size……………………30 cm (beam) × 30 μm (transverse)
need long Si-vertex **small wrt ct(*B*) ~ 450 μm**

Luminosity………………………………..routinely starting at 3.5 × 10^{32} cm^{-2} s^{-1}
~ 50 pb^{-1} / week recorded on tape
>7 fb^{-1} on tape now.

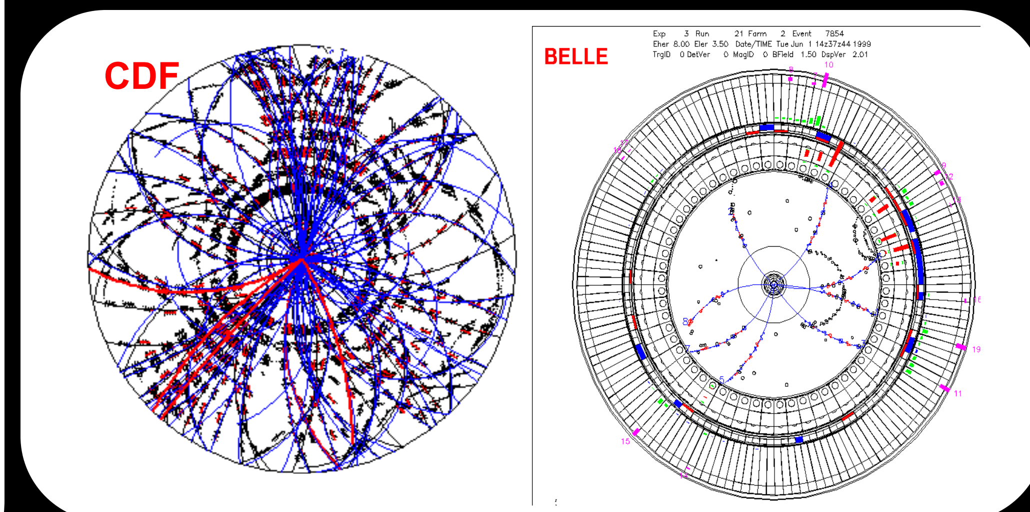
$p\bar{p}$ collisions: a challenge for *flavor* physics



Strong, incoherent production of all b-hadrons: ~2000 *B* per second within acceptance. Backgrounds 5×10^3 larger.

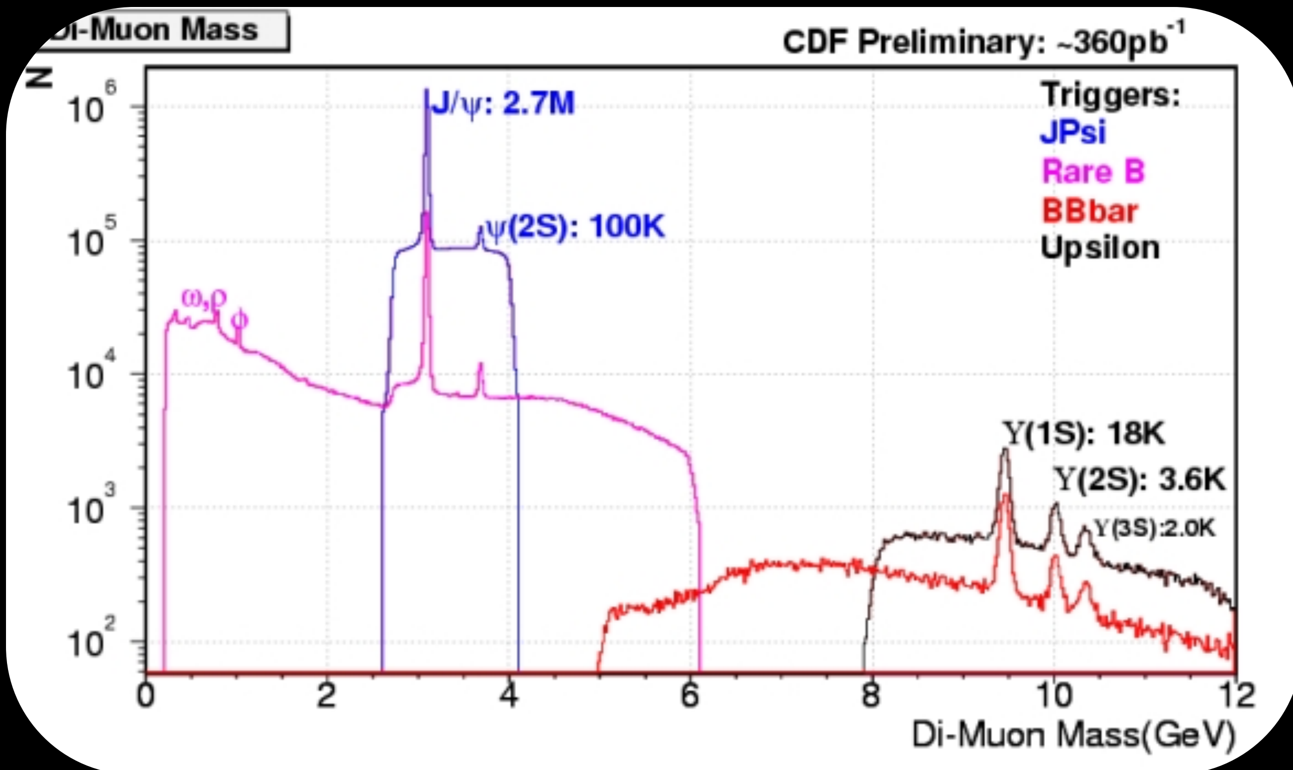
Lorentz-boosts $\beta\gamma$~2. Displaced vertices

Messy environment



Crucial role of highly-selective trigger

Old-school: di-muons



Clean signature and high rates. Each muon candidate with

$(|\eta|<0.6$ AND $p_T>1.5$ GeV/c) OR $(0.6<|\eta|<1.0$ AND $p_T>2.0$ GeV/c)

Revolutionary: displaced tracks

1.5 ps lifetime of *b*-hadrons: a powerful signature.

Sufficiently boosted *B* fly a path resolvable with vertex detectors before decaying.

CDF only experiment to have Si-track trigger

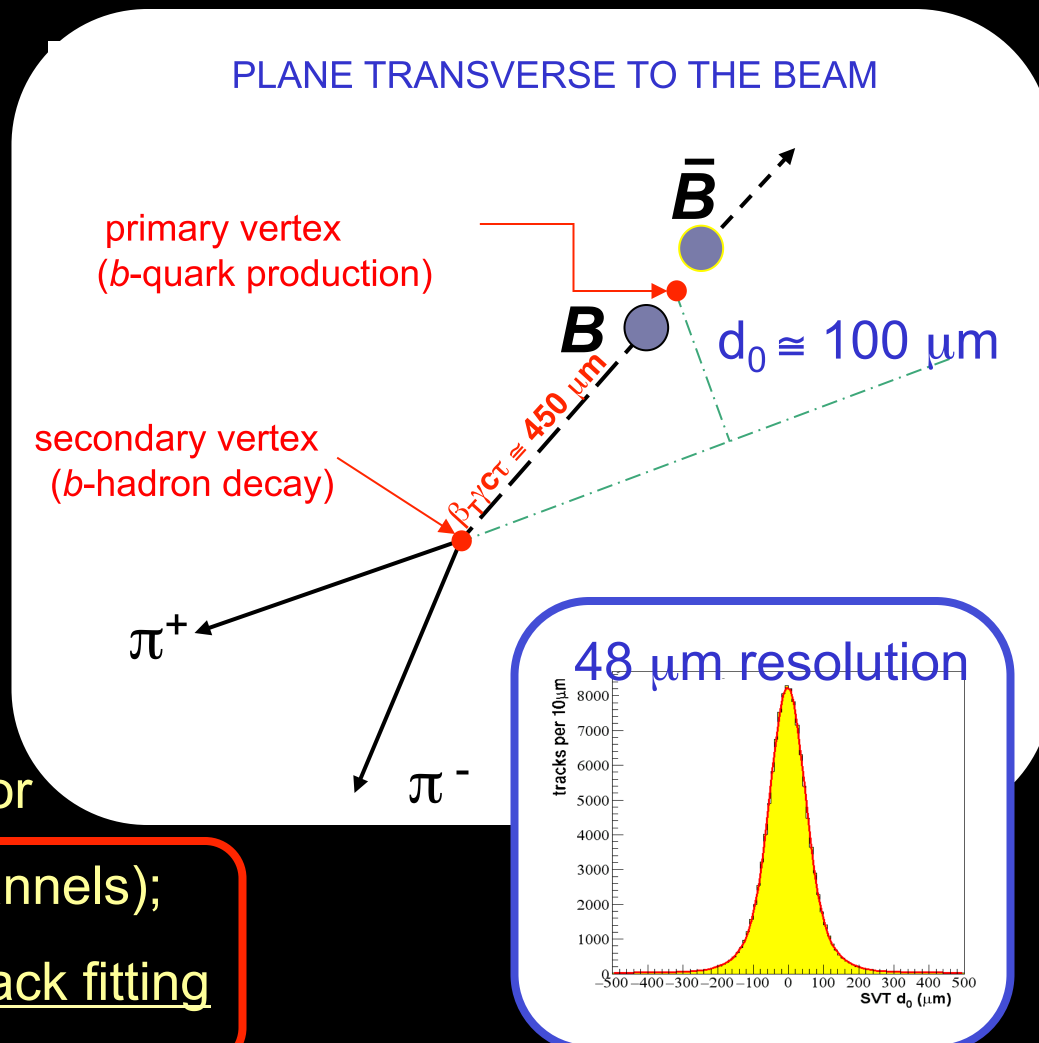
An experimental challenge that requires

(1) <u>high resolution</u> vertex detector

(2) <u>read out</u> silicon (212,000 channels);

(3) do <u>pattern recognition</u> and <u>track fitting</u>

within 25 μs



The result

The world's largest samples of heavy flavor decays. With 5 fb^{-1}

250K fully hadronic *B* decays

12K $B^0 \to K^+\pi^-$, 5.3K $B^0_s \to K^+K^-$

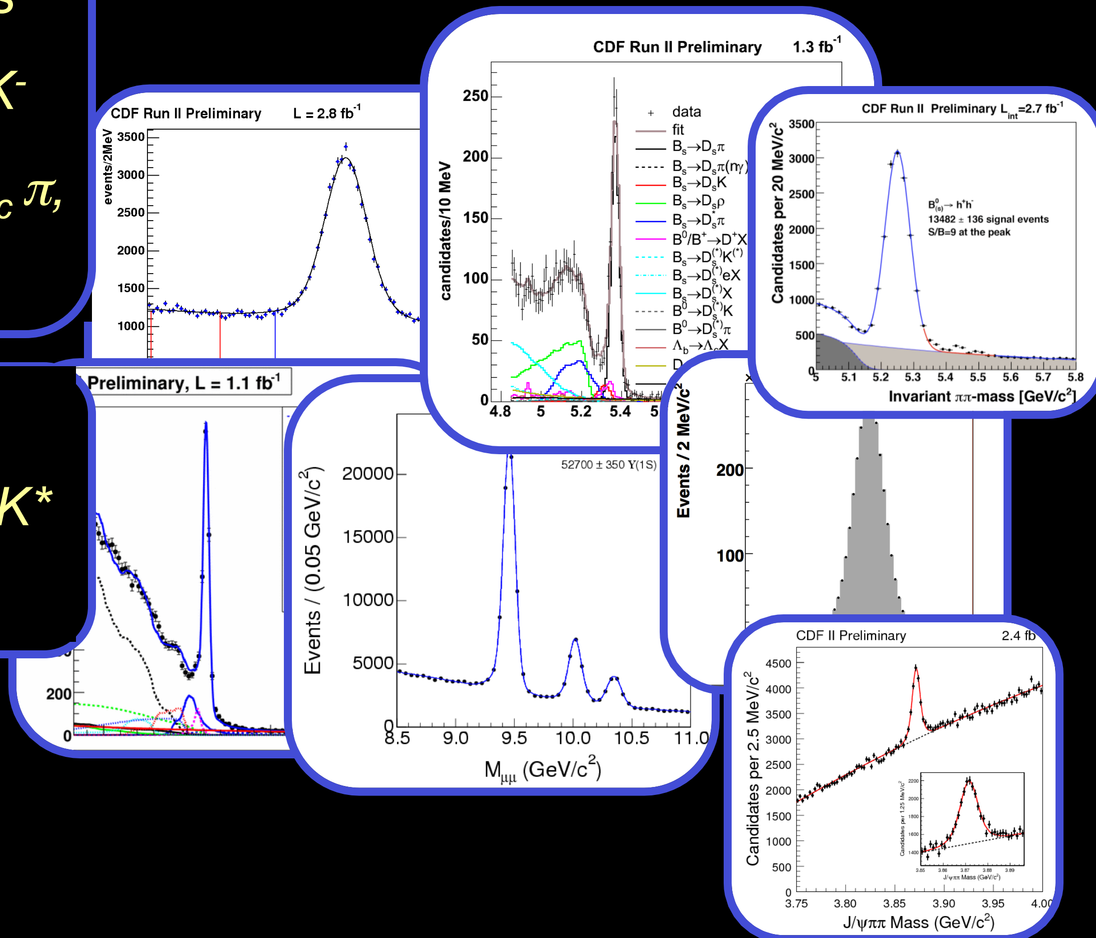
4K $B^0_s \to D_s\pi$, 11K $\Lambda^0_b \to \Lambda^+_c\pi$,

50M $D^0 \to K^-\pi^+$

40M J/ψ (~20% from *B*)

6K $B^0_s \to J/\psi\phi$, 32K $B^0 \to J/\psi K^*$

12K $X(3872) \to J/\psi\pi\pi$



Today: three CDF measurements involving B^0_s mesons that are particularly deadly in killing NP models.

(or, hopefully, effective in discovering them)

The Bad - $B^0_s \rightarrow \mu^+ \mu^-$

$B^0_s \rightarrow \mu^+\mu^-$ - trivia

GIM, CKM, and helicity suppressed in the SM.

All leptonic decay. Robust SM prediction
Br = $(3.42 \pm 0.54)\times10^{-9}$.

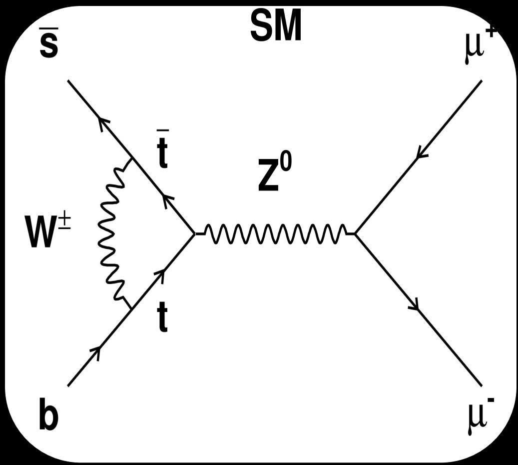
NP can enhance rate up to 100×.

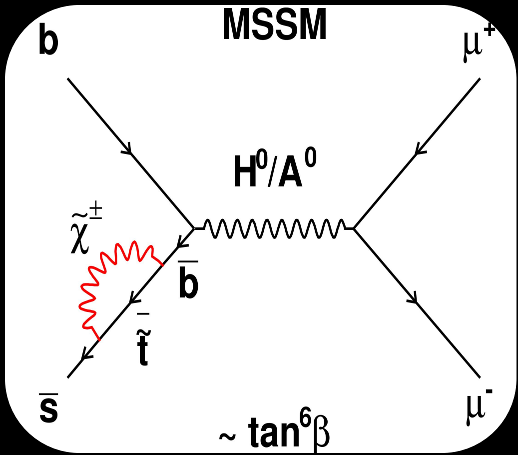
MSSM: Br $\propto \tan^6(\beta)$.

RPV SUSY enhances also at low $\tan(\beta)$.

Sensitive to a broad class of NP models, complementary to many TeV/LEP direct searches.

Either observation or null result provides crucial information





$B^0_s \to \mu^+\mu^-$ - the measurement

Latest result (summer 2009) uses 3.7 fb^{-1} (half of current sample)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{\boxed{N_s}}{\boxed{N_+}} \cdot \boxed{\frac{\alpha_+}{\alpha_s}} \cdot \boxed{\frac{\epsilon_+}{\epsilon_s}} \cdot \frac{1}{\boxed{\epsilon_N}} \cdot \boxed{\frac{f_u}{f_s} \cdot \mathcal{B}(B^+)},$$ PDG08

Signal decays at 95%CL to be measured

Trigger acceptance ratio from MC approx. 0.2-0.3

Rec. efficiency ratio from MC/DATA approx 0.8

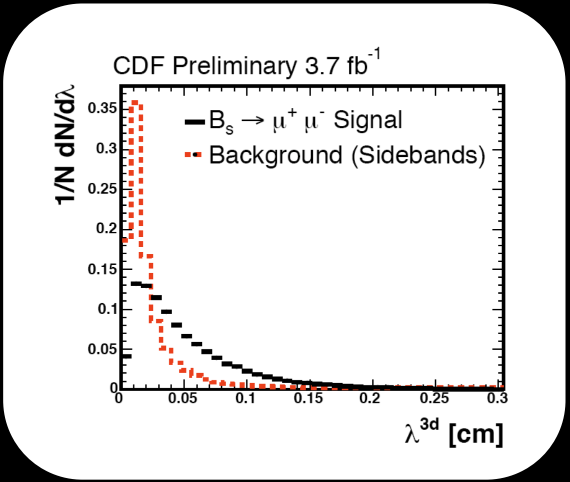
$B^+ \to J/\psi K^+$ decays from data approx. 20K

Efficiency of NN requirement from MC, approx 80-20% (cut-dependent)

The challenge: reject 10^6 background while keeping signal efficiency high.

$B^0_s \rightarrow \mu^+ \mu^-$ - selection

Discriminants: mass, life, p_T (obvious), B isolation and pointing to $p\bar{p}$ vertex



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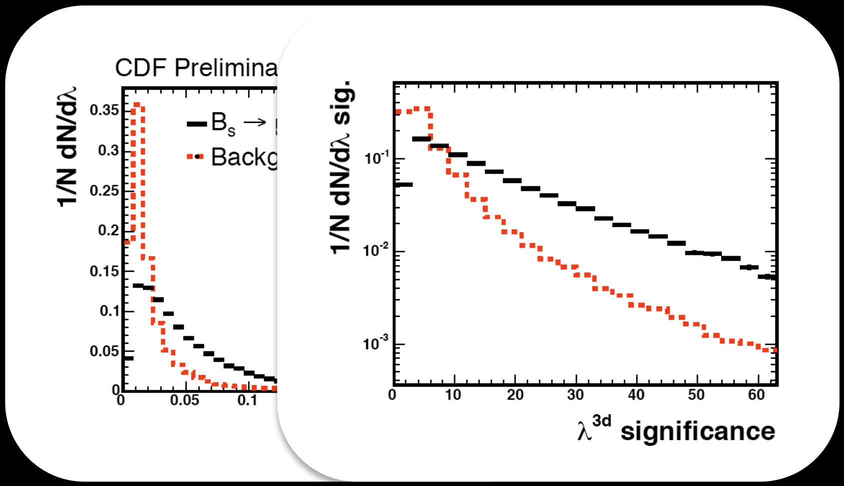

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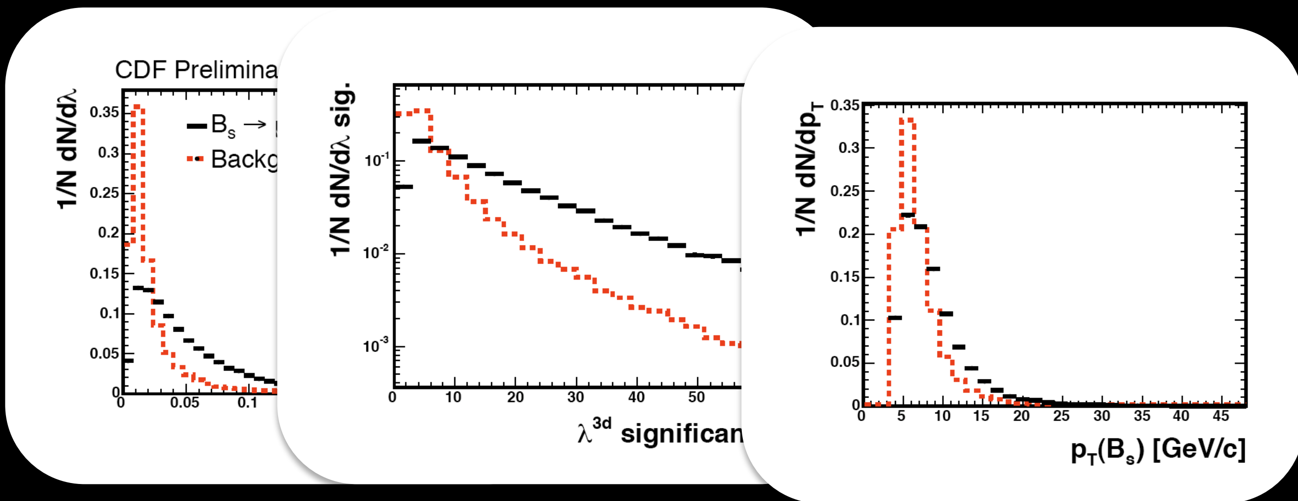

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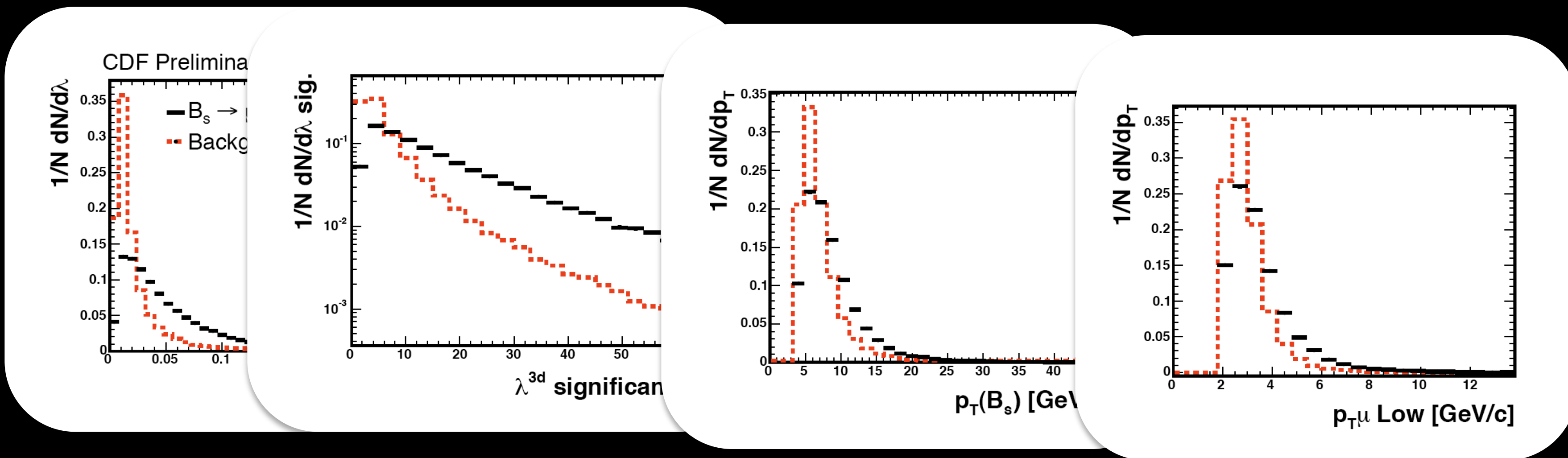

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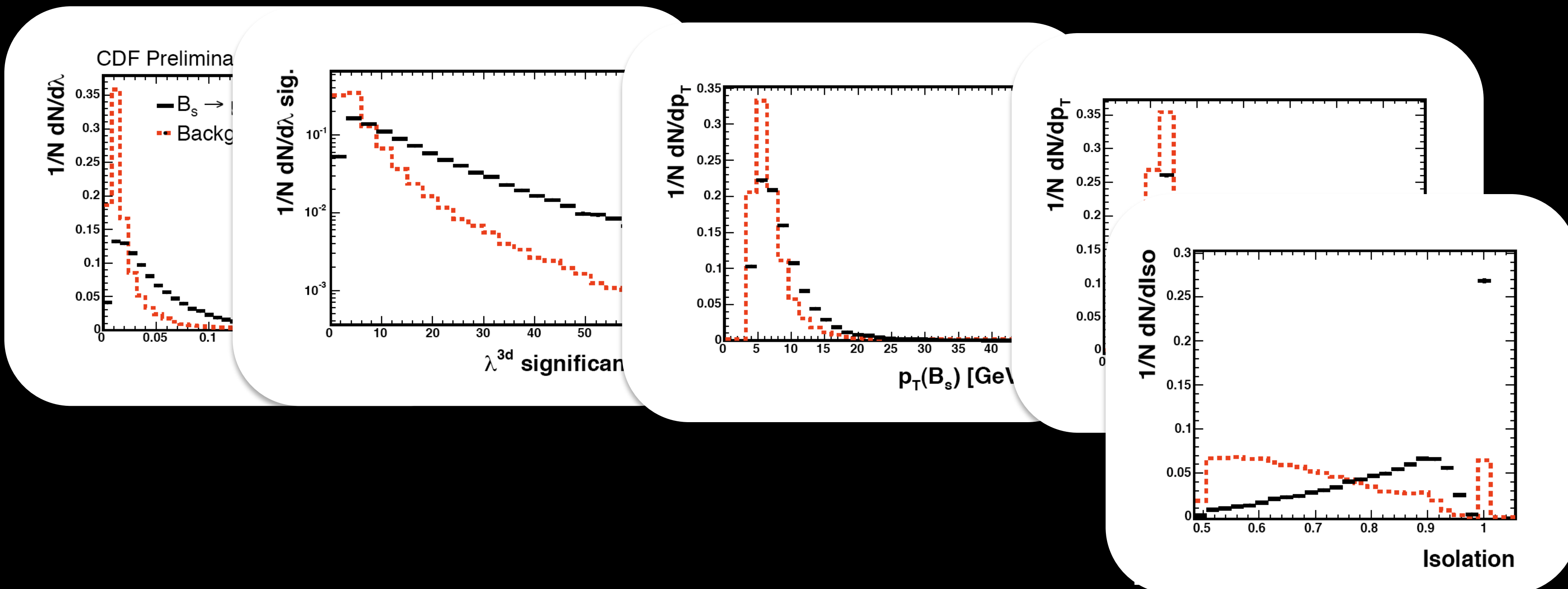

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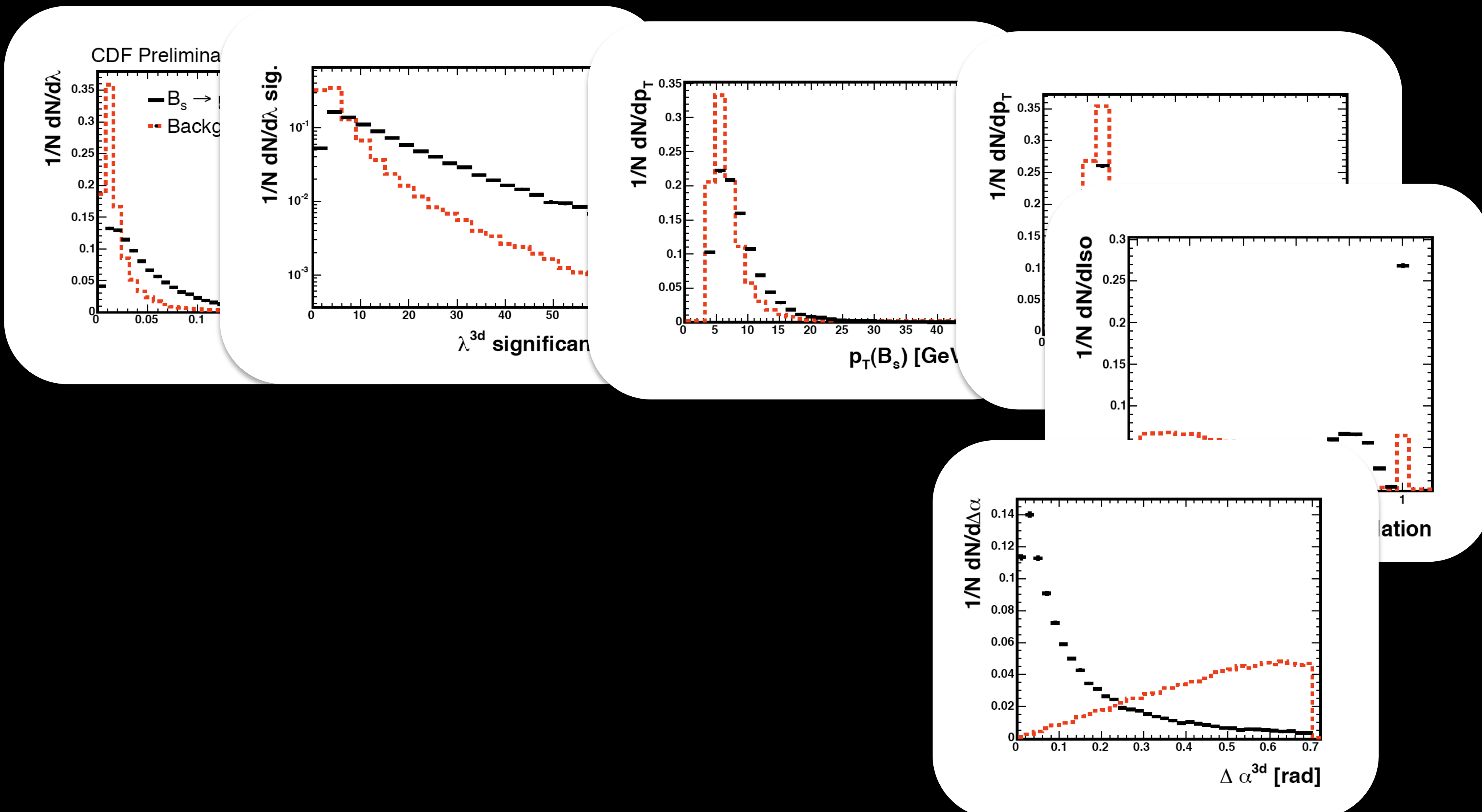

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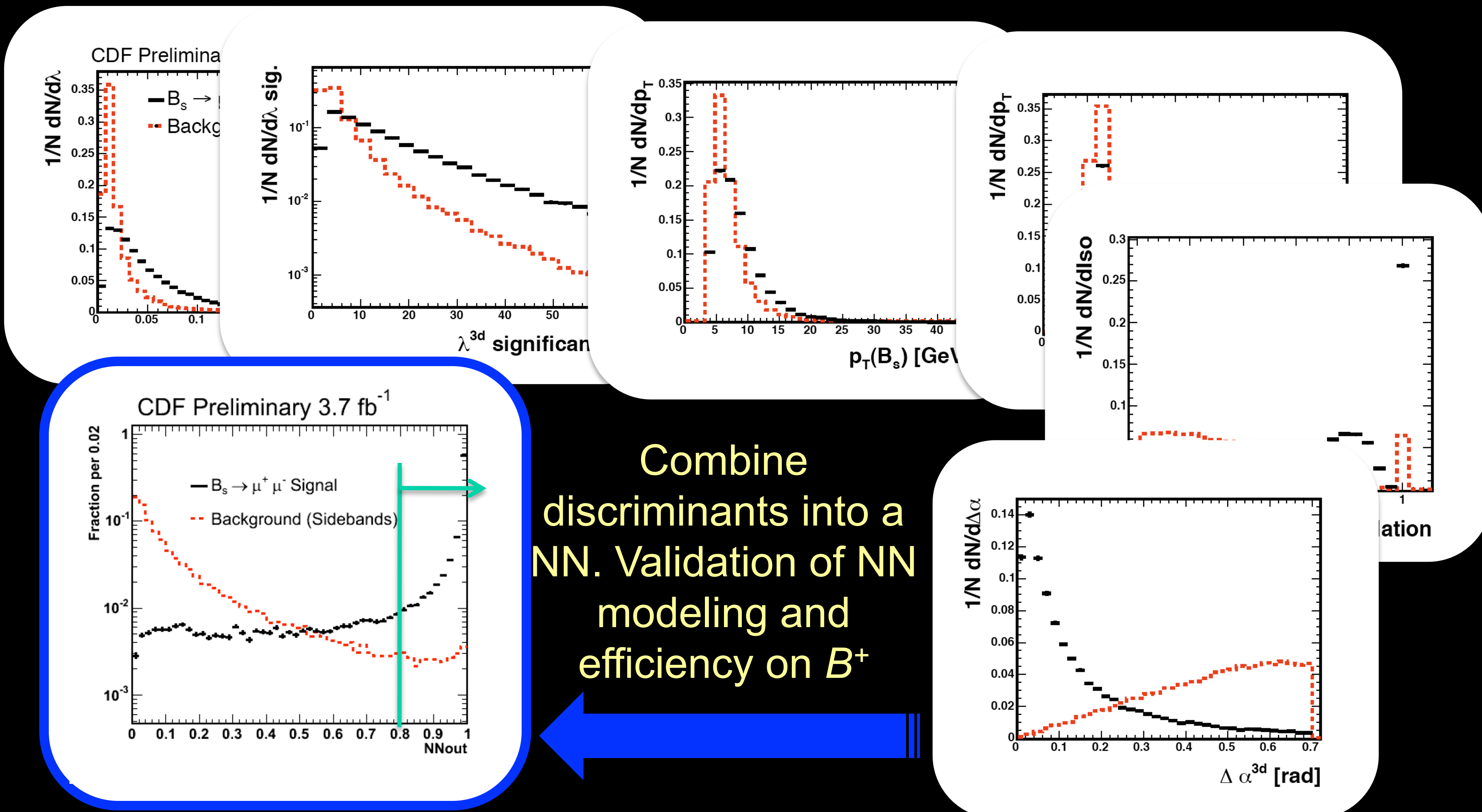
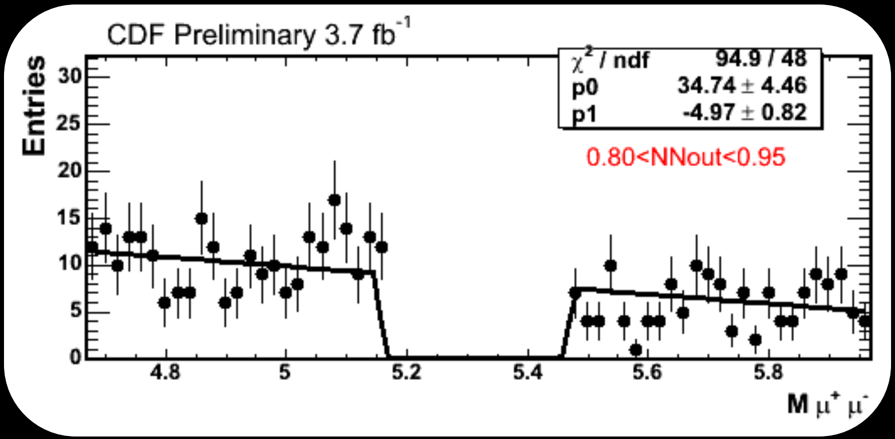


Combine discriminants into a NN. Validation of NN modeling and efficiency on B^+

$B^0_s \to \mu^+\mu^-$ - backgrounds

Possible offenders:

- ✓ continuum $\mu\mu$ from Drell-Yan
- ✓ sequential $b \to c\mu X \to \mu\mu s$ semilept.
- ✓ double semileptonic $b\bar{b} \to \mu\mu + X$
- ✓ $b/c \to \mu$ + fake
- ✓ fake + fake (dominated by peaking *B → hh component*)



Suppress fakes: calorimeter, dE/dx, muon-track matching. All calibrated on $J/\psi \to \mu\mu$, $D^0 \to K\pi$, $\Lambda \to ph$ decays in data.

Combinatorial: extrapolate from sidebands into signal region

Extensive checks with background-enriched control samples: same-sign dimuons, dimuons with <0 decay-length, dimuons failing fake veto

$B^0_s \to \mu^+\mu^-$ - results

	$\mathcal{B}(B_s \to \mu^+\mu^-)$ 90%	95%	$\mathcal{B}(B_d \to \mu^+\mu^-)$ 90%	95%
Expected $\mathcal{B}$	2.7×10^{-8}	3.3×10^{-8}	7.2×10^{-9}	9.1×10^{-9}
Observed $\mathcal{B}$	3.6×10^{-8}	4.3×10^{-8}	6.0×10^{-9}	7.6×10^{-9}

World-leading result. 10*SM with 3.7 fb^{-1}.

40x improvement with respect to Run I (world best in 2001).

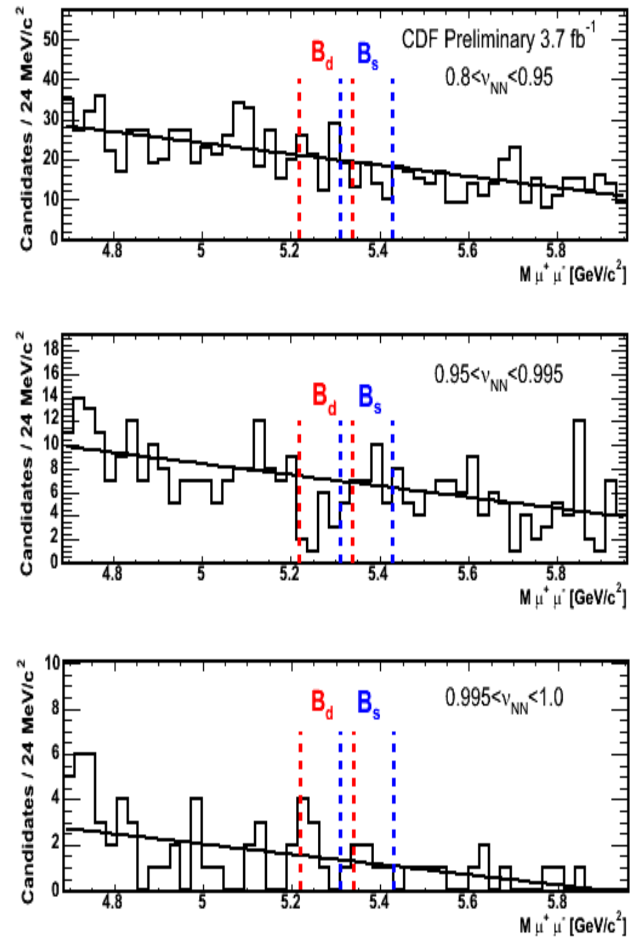
Plenty of NP models already excluded.

This result CDF Note 9892,

2 fb^{-1} PRL100, 101802 (2008) topcite100+

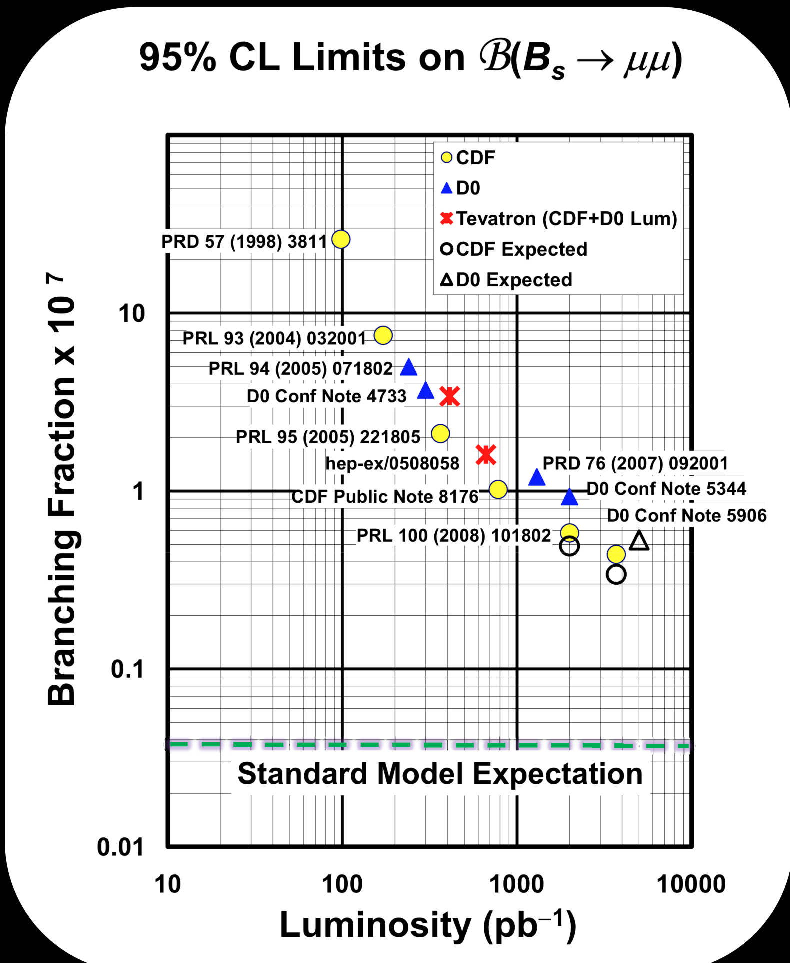
0.78 fb^{-1} PRL93, 032001 (2008) topcite50+

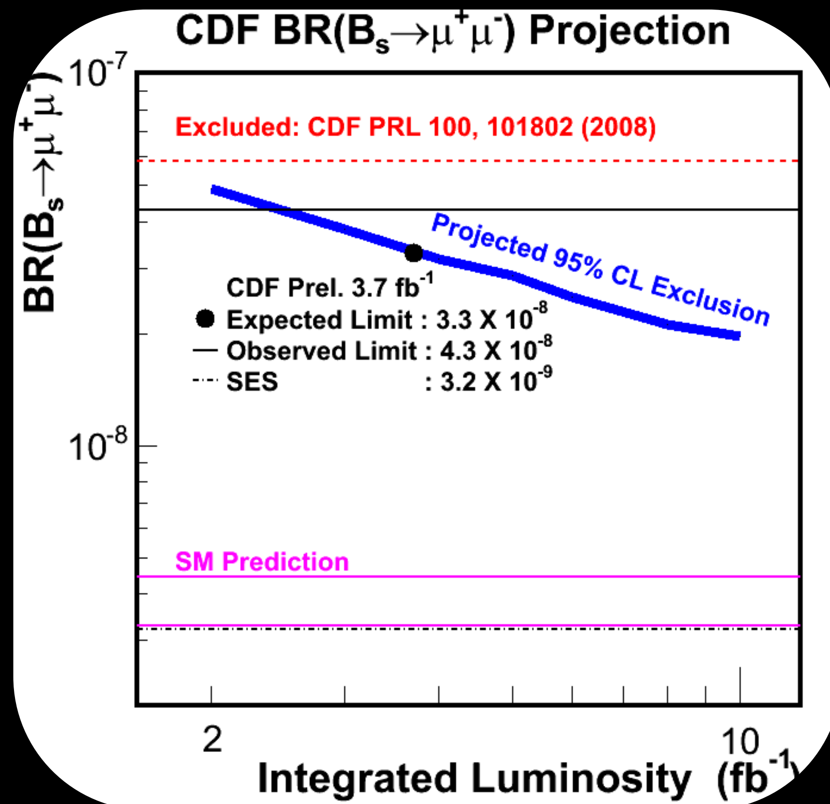
Three slices of NN output



6 bckg expected, 7 evts observed

$B^0_s \to \mu^+\mu$ - past and future





$<2\times10^{-8}$ (6×SM) at 10 fb^{-1} (~year 2011). Combined with DØ may reach 4×SM

The Ugly – $B^0_s \rightarrow h^+h'^-$

$B^0_{(s)} \rightarrow h^+h'^-$ - motivation

Decays of B^0 and B^0_s mesons into pairs of charged kaons and pions (KK, $K\pi$, $\pi\,\pi$)

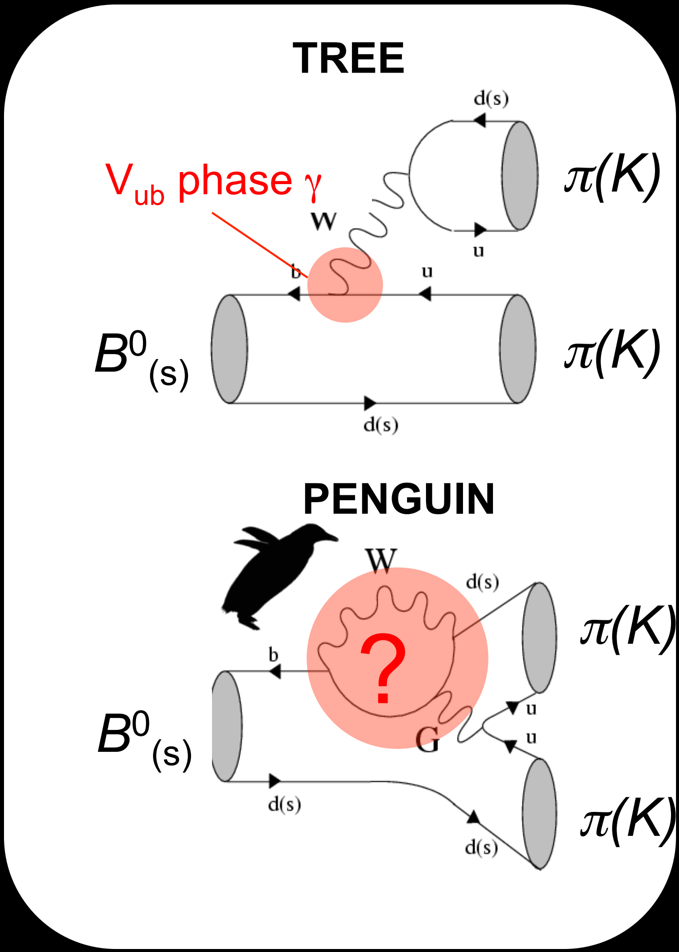
Multiple decays related by flavor-symmetries (cancel some theory-uncertainties) and similar final states (cancel some systematics):

Measurements of Br and CP-violation

Probe presence of NP in “penguins”.

Sensitive to CKM angle γ through penguins

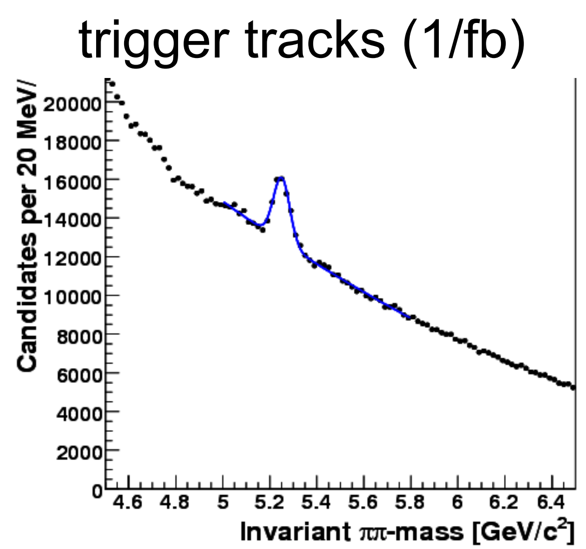
Test low-energy QCD effective models.



$B^0_{(s)} \to h^+h'^-$ - *the first challenge*

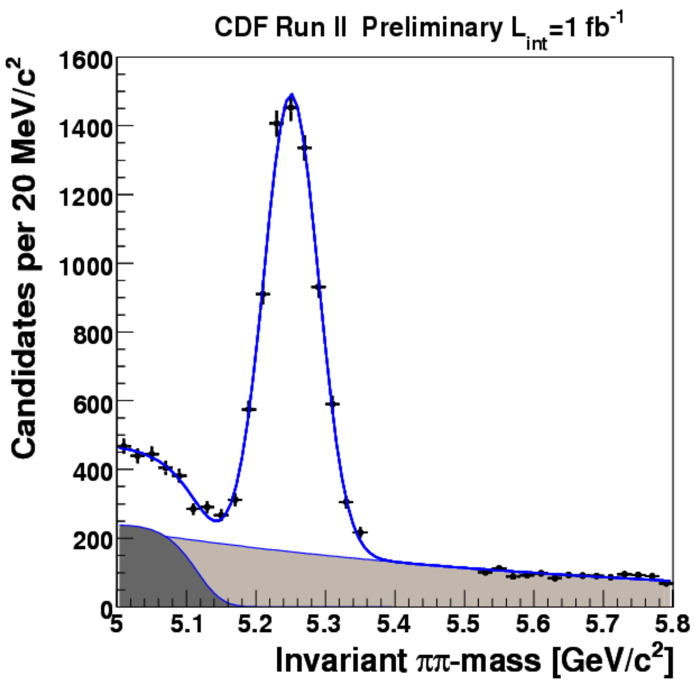
S/B at production is 10^{-9}. Very “common” signatures (no intermediate resonances, just π or K – as background). Yet in 2000 few believed that a *signal would have ever been seen*.

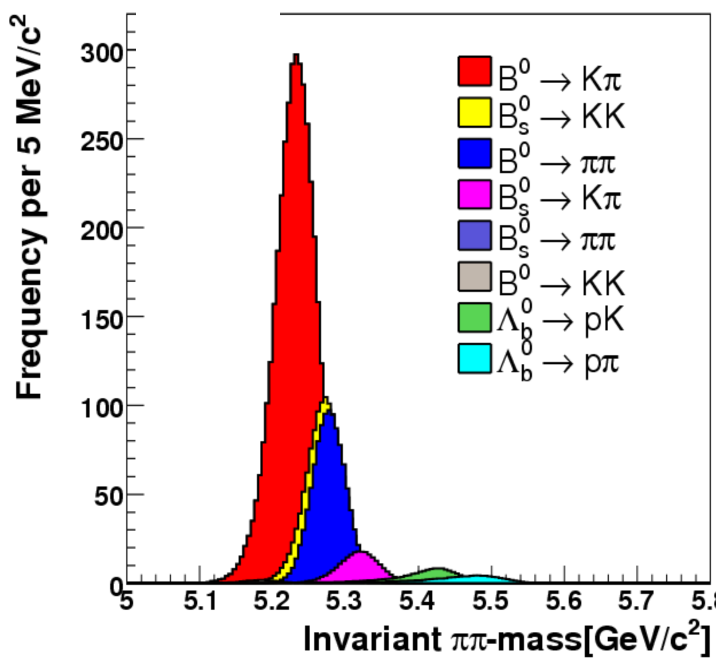
The trigger on displaced tracks



CDF has today the world’s largest samples of charm-less B decays.

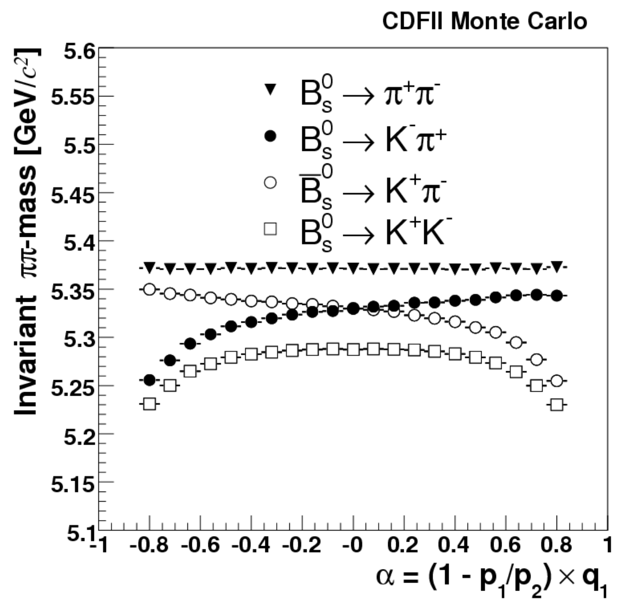
$B^0_{(s)} \rightarrow h^+h'^-$ - the second challenge



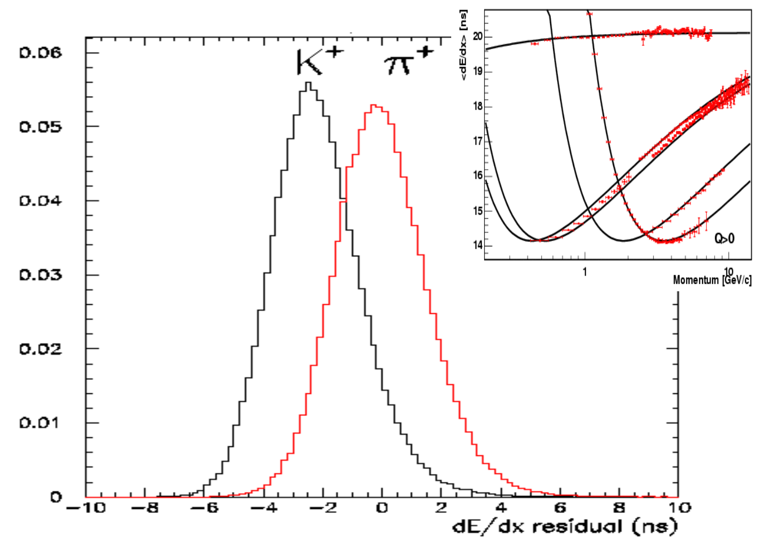


Insufficient mass and PID resolution to discriminate decay modes on a per-event basis

$B^0_{(s)} \rightarrow h^+h'^-$ - depuzzling sample composition



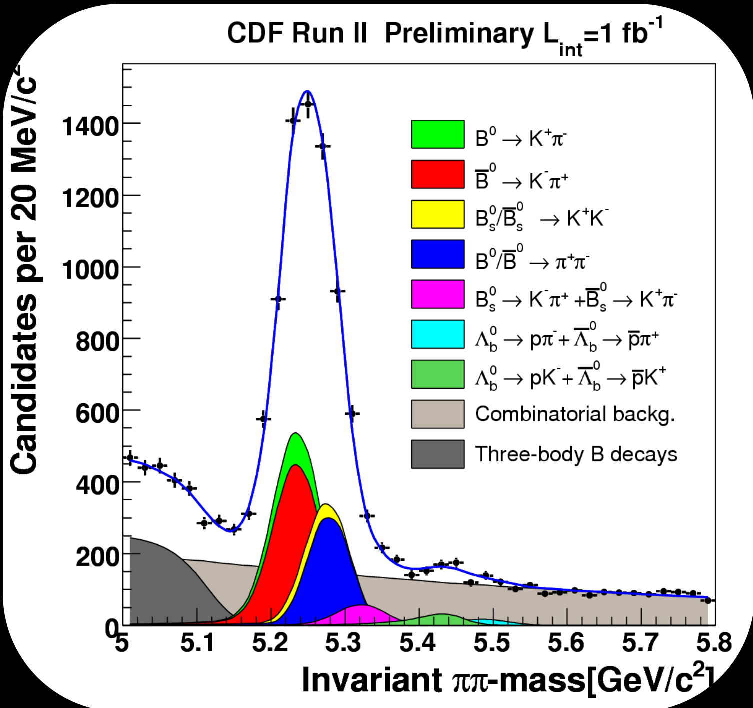
Correlation between any (arbitrary) mass assignment and momentum imbalance



Output pulse-width of 96 COT samplings $\propto$ log(Q). 1.5σ K/π separation at p>2 GeV/c

Statistical separation using kinematics and PID folded in a 5-dimensional ML fit.

$B^0_{(s)} \rightarrow h^+h'^-$ - results



Four new decay modes observed (2 B^0_s and 2 Λ^0_b).

Access to DCPV asymmetries in B^0_s decays. DCPV asymmetries in B^0 decays competitive with *B*-factories

$$\frac{f_s}{f_d} \times \frac{BR(B_s^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} = 0.347 \pm 0.020(stat.) \pm 0.021(syst.)$$

$$BR(B_s^0 \to K^-\pi^+) = (5.0 \pm 0.7(stat.) \pm 0.8(syst.)) \times 10^{-6}$$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.086 \pm 0.023(stat.) \pm 0.09(syst.)$$

4000 $B^0 \rightarrow K^+\pi^-$

1300 $B^0_s \rightarrow K^+K^-$ per fb^{-1}

A plethora of measurements

1 fb^{-1} PRL103, 031801 (2009) , CDF Notes 8579, 9092

0.18 fb^{-1} PRL97, 211802 (2006) topcite50+

$B^0_{(s)} \to h^+h'^-$ - a model independent NP test

Unitarity of CKM matrix:

$$\mathrm{Im}(V_{ub}^* V_{us} V_{cb} V_{cs}^*) = -\mathrm{Im}(V_{ub}^* V_{ud} V_{cb} V_{cd}^*) \ ,$$

implies a relation between differences of CP-rates that is valid only in the SM. Unambiguous check if DCPV is induced by NP or by SM amplitudes.

$$\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-) = \Gamma(B_s^0 \to K^-\pi^+) - \Gamma(\overline{B}_s^0 \to K^+\pi^-)$$

We measure:

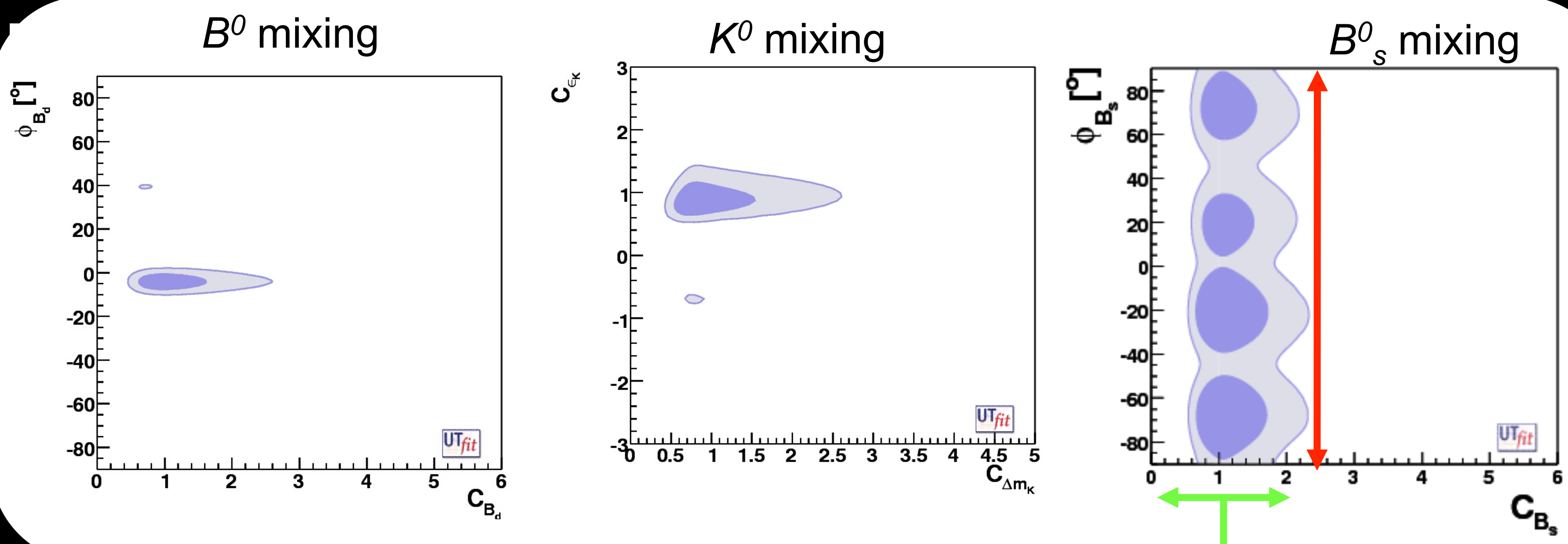
$$\frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}_s^0 \to K^+\pi^-) - \Gamma(B_s^0 \to K^-\pi^+)} = -0.83 \pm 0.41(stat.) \pm 0.12(syst.)$$

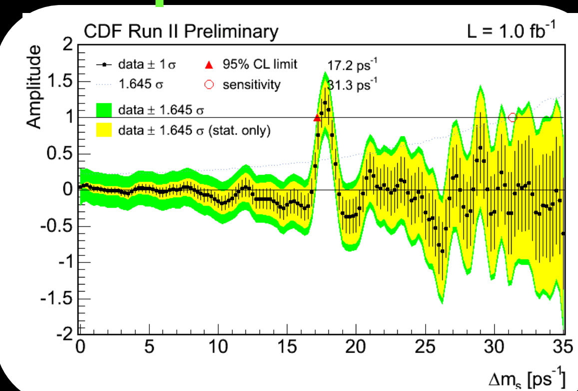
(-1 in the SM)

Still limited by statistics. Now, with ~5x data on tape, may have real chance to probe NP in these decays.

The Good – $B^0_s \rightarrow J/\psi\phi$

Mixing phase - *experimental picture*



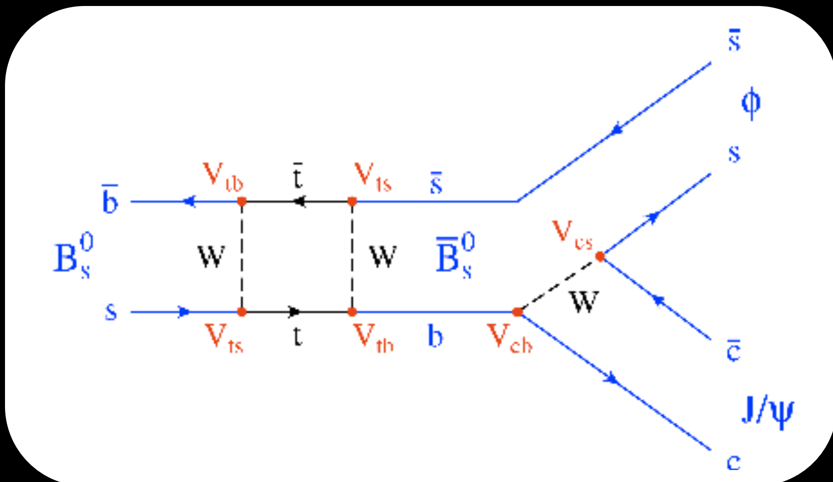


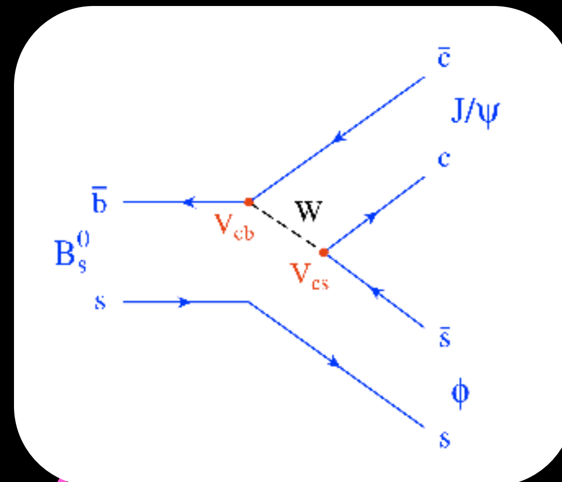
Lattice-QCD dominated uncertainty

$$\frac{\langle M|H_{\mathrm{eff}}^{\mathrm{full}}|\bar{M}\rangle}{\langle M|H_{\mathrm{eff}}^{\mathrm{SM}}|\bar{M}\rangle} = C_M e^{2i\phi_M}$$

Experimentally-dominated uncertainty.

Mixing phase - *role of $b \to \bar{c}cs$ transitions*





Mixing phase sensitive to NP

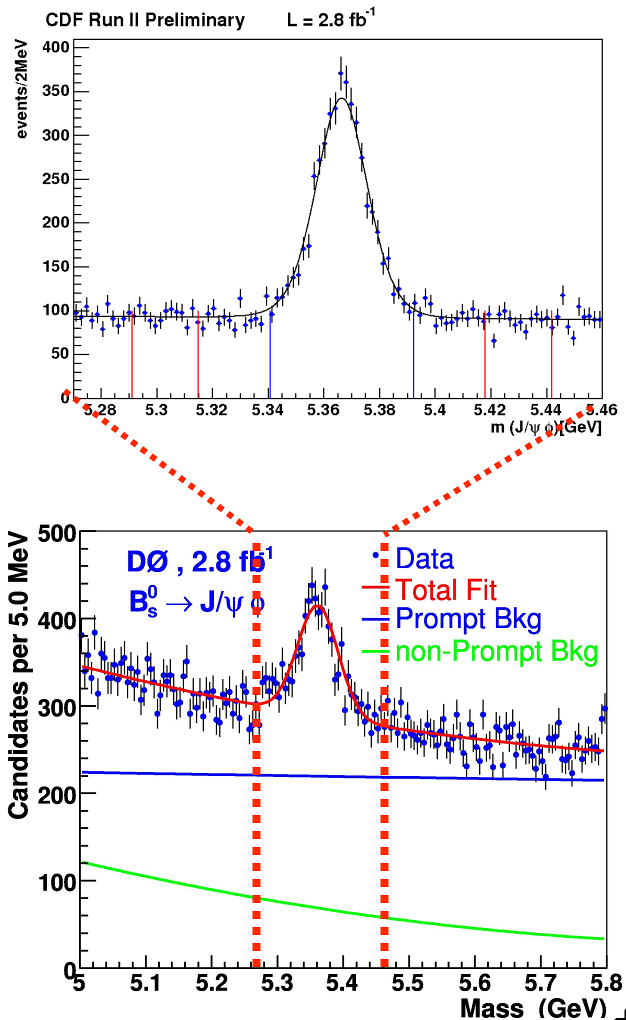
Tree *b→ccs* phase ≈ 0

Time-evolution:

$$2\beta_s = -\arg[\overbrace{(V_{tb}V_{ts}^*)}^{}{}^2/\overbrace{(V_{cb}V_{cs}^*)}^{}{}^2]$$

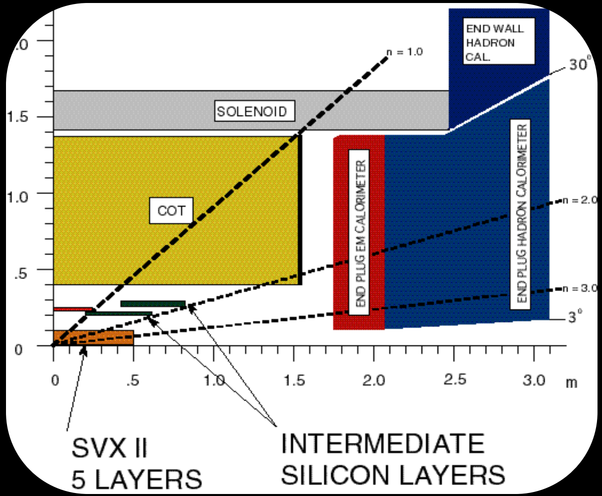
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3\left[1-(1-\frac{1}{2}\lambda^2)(1-\rho-i\eta)\right] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

Mixing phase - *signal extraction*

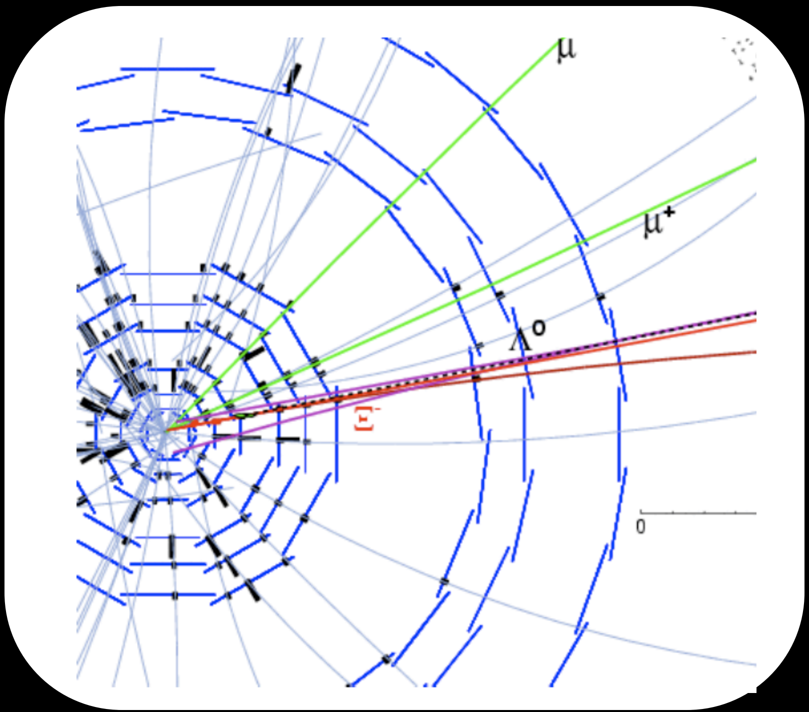


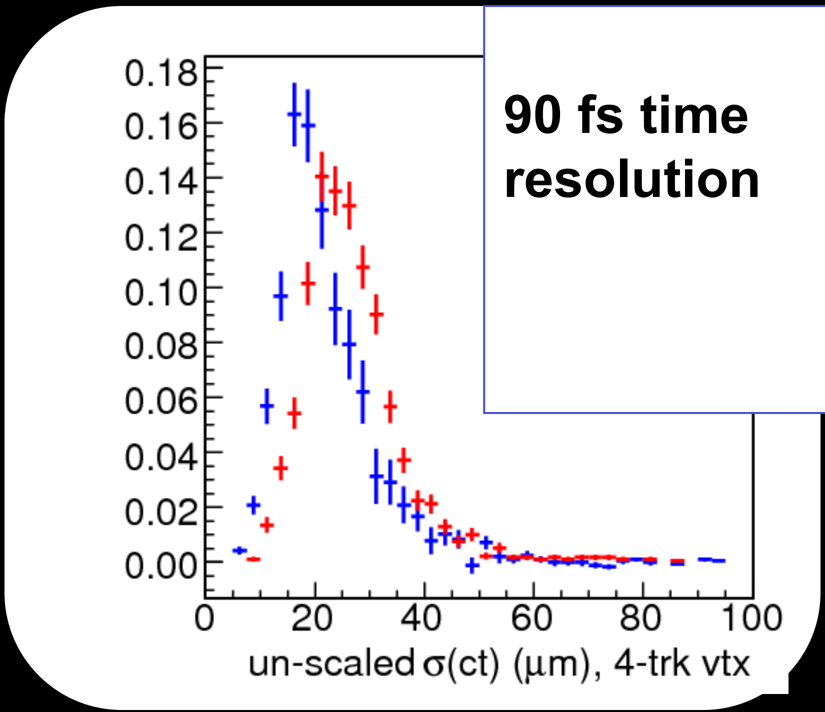
Selection based on ANN ~3200 signal decays with S/B~2 in 2.8 fb^{-1}

CDF tracker:
1.4T in 132 cm lever-arm with 96 drift chamber + 6 Silicon samplings



Mixing phase - *vertex resolution*



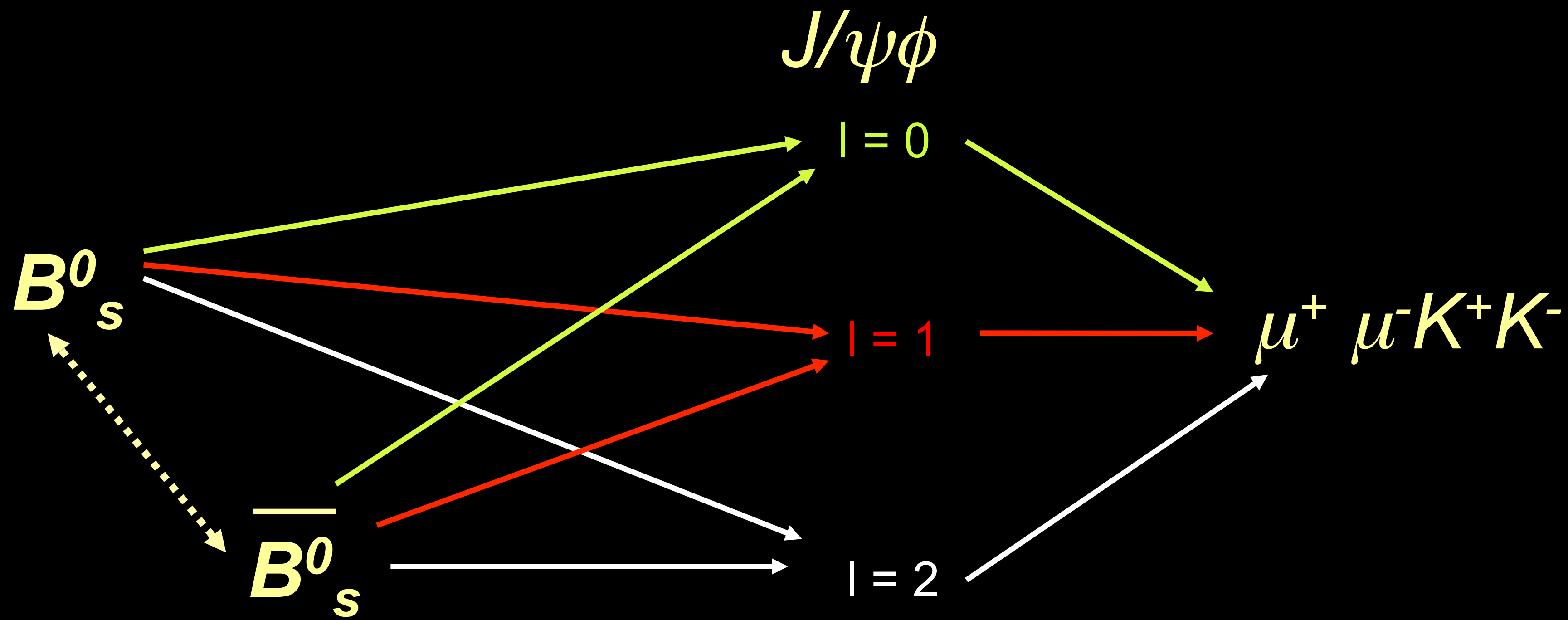


90 fs time resolution

CDF tracker - 1 silicon layer at 1.5 cm from the beam plus 5 double-sided sensors at 2.5--10 cm.

Mixing phase - *CP composition*

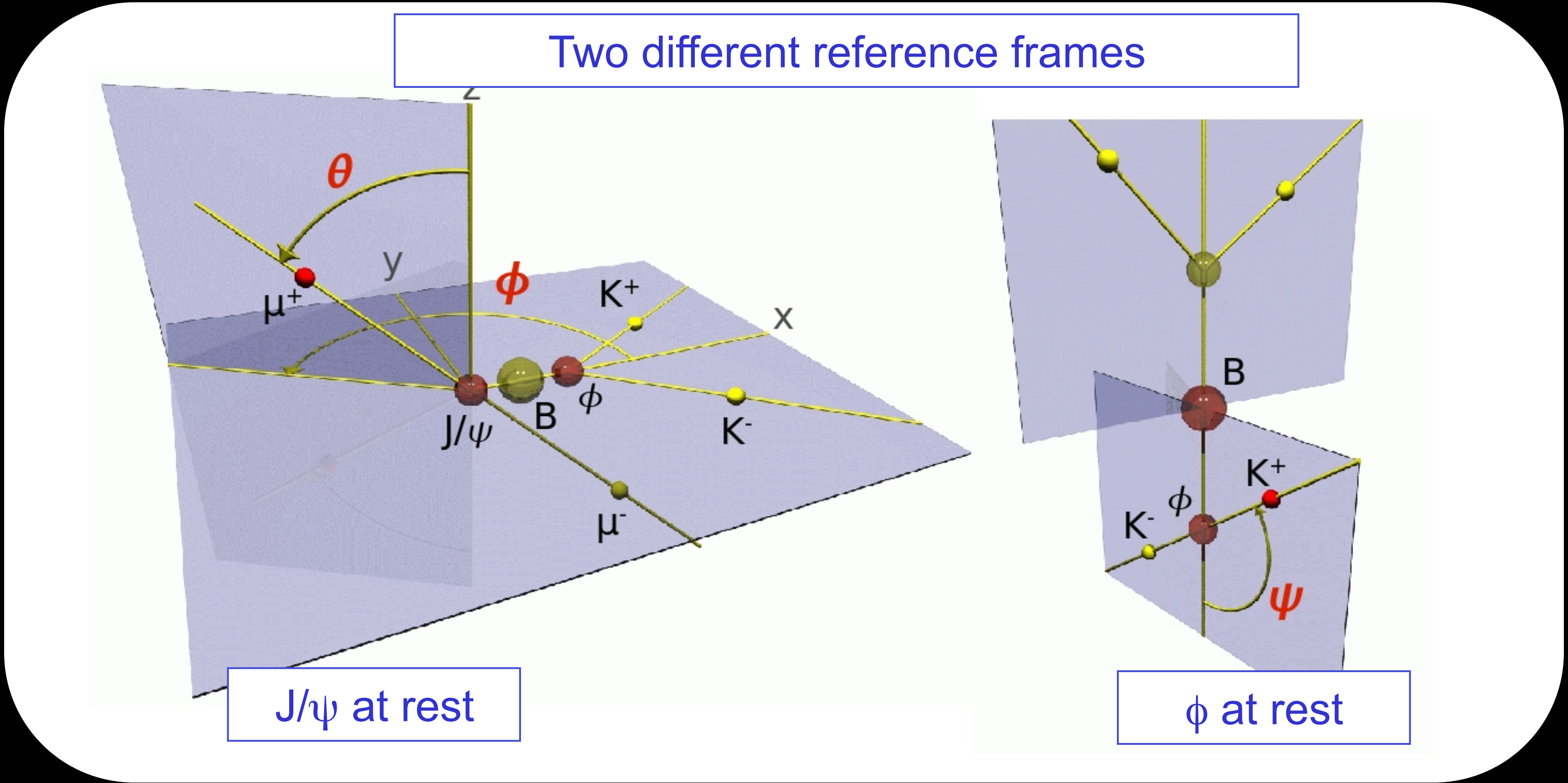
B^0_s (pseudoscalar) $\rightarrow J/\psi$(vector) ϕ (vector). Final states CP-even (S- or D-wave, short-lived and light) and CP-odd (P-wave, long-lived, heavy).



Exploit different dependence on phase between *CP*-even *and CP*-odd

Angular correlations in decay products ➔ separation of CP-components.

Mixing phase - *"Transversity" basis*



State at time *t* decomposed in: polarizations longitudinal to direction of motion (CP-even), polarizations transverse and ⊥ each other (CP-even), polarizations transverse and // each other (CP-odd). PLB 369, 144 (1996)

Mixing-phase - *production-flavor*

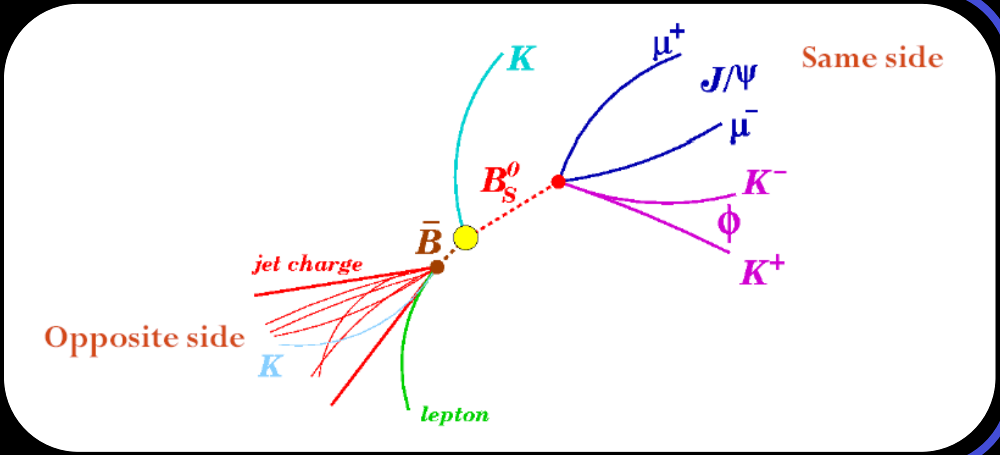
Flavor-tagging inherited from mixing-frequency measurement

b-quarks mainly produced in $b\bar{b}$-pairs at the Tevatron

Opposite Side: looks at decay of the ‘other’ *b*-hadron in the event

Same Side: exploits the charge/species correlations with associated particles produced in hadronization of reconstructed B^0_s meson

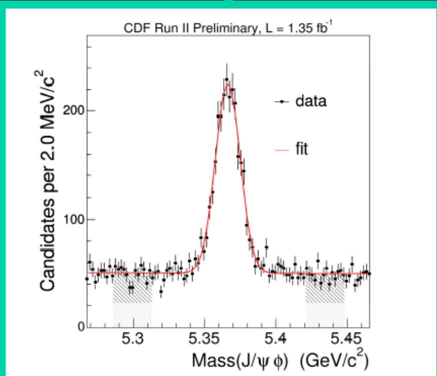
Total $\varepsilon D^2 \sim 4\%$



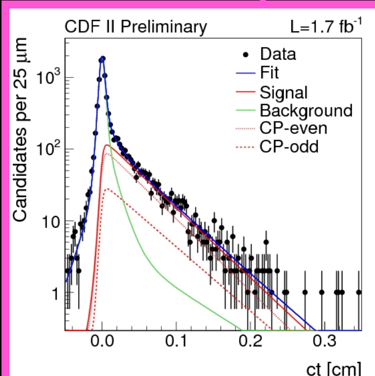
Output: decision (*b*-quark or $\bar{b}$-quark) and probability of being correct

Mixing phase - *fit overview*

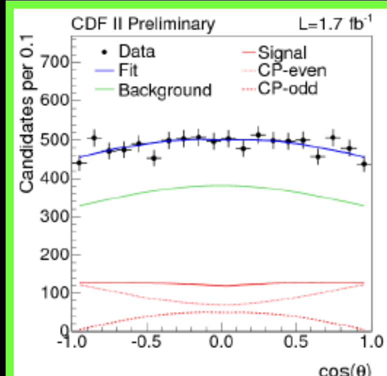
$$f_s P_s(m|\sigma_m) P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t) P_s(\sigma_t) P_s(\mathcal{D})$$



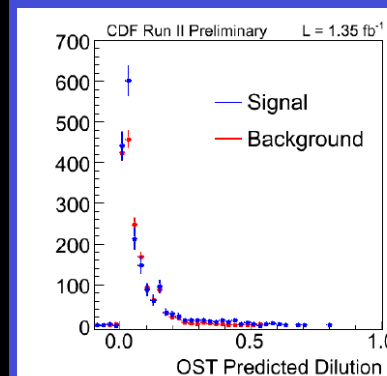
Mass
discriminate signal against background



Decay-time
Determine lifetime of each CP and flavor state



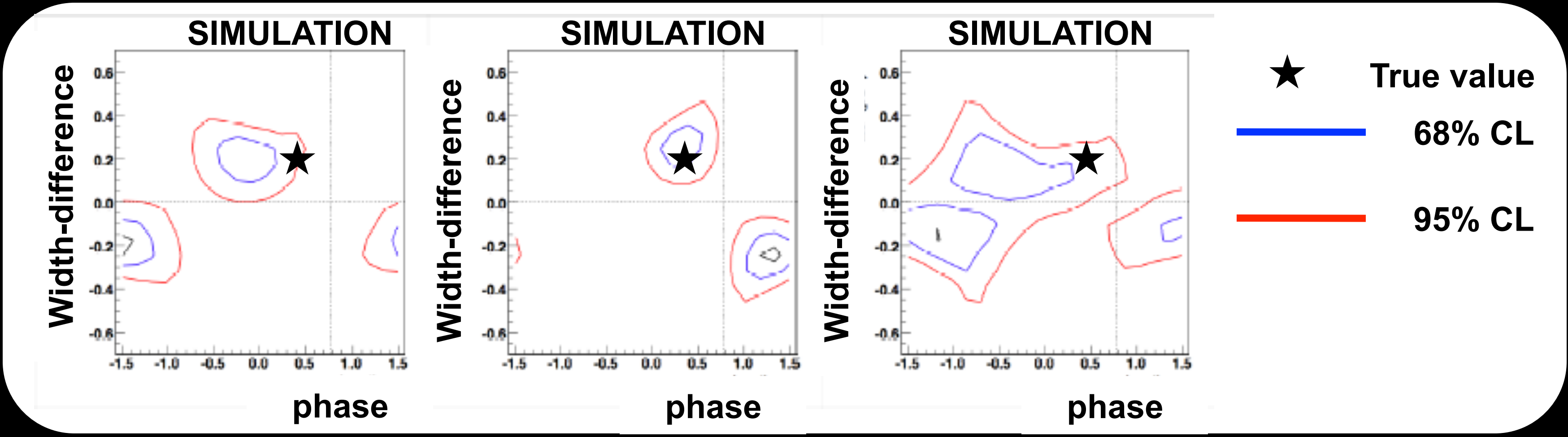
Angles
Separate CP-even from CP-odd final states



Tagging
Determines flavor of initial state

Mixing phase - *Likelihood features*

1σ and 2σ Likelihood contours in the (ΔΓ, βs) plane.

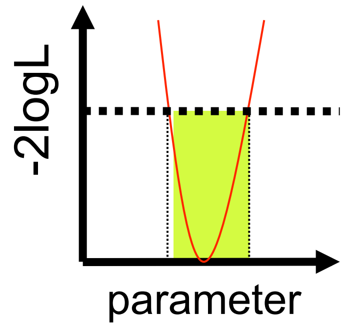


Wild fluctuations. Likelihood has two minima – strongly non-Gaussian

Not reporting central values and their uncertainties. Use interval estimation (confidence regions) instead.

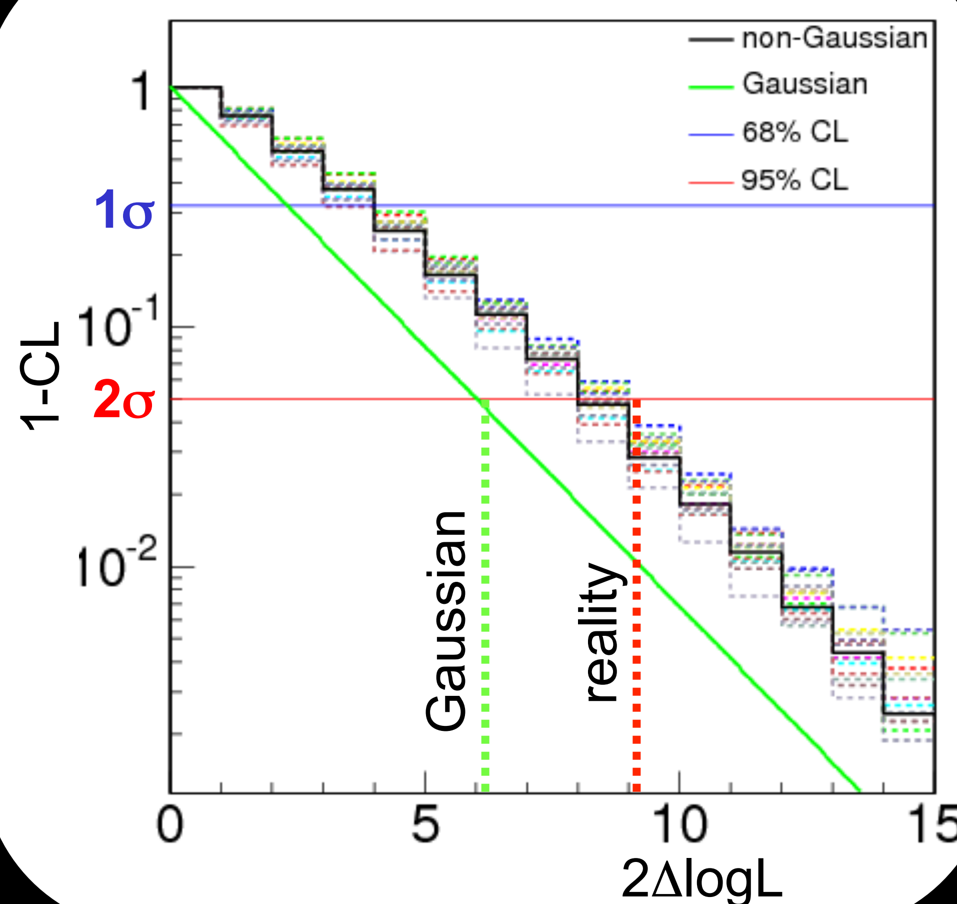
Mixing phase - *Enforcing coverage*

Standard likelihood ratio method fails



Remap observed 2ΔlogL distribution to get coverage. Account for non-Gaussian Likelihood. E.g. to get the 95.5% CL, 2ΔlogL~9 units (as opposed to 5.99 asymptotic)

Include systematics: vary nuisance parameters within 5σ of their estimates on data.
Use worst case.

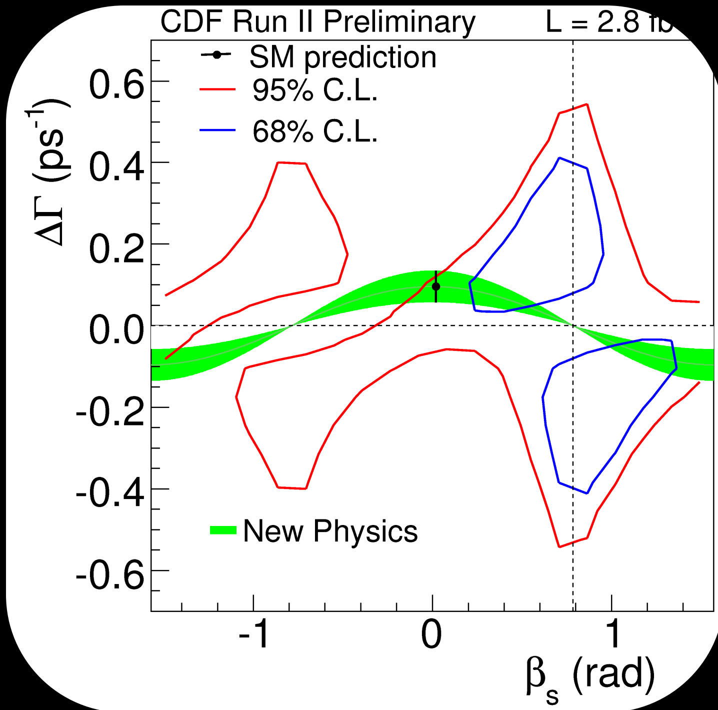


arXiv:0810.3229

Mixing phase – *2.8 fb^{-1} results*

2D projection of the confidence region from the space of all fit parameters.

A specific value of $\Delta\Gamma$ and βs is excluded only if it can be excluded *for any* assumed values of nuisance parameters (within 5σ from observed values). PRL100, 161802(2008) topcite100+



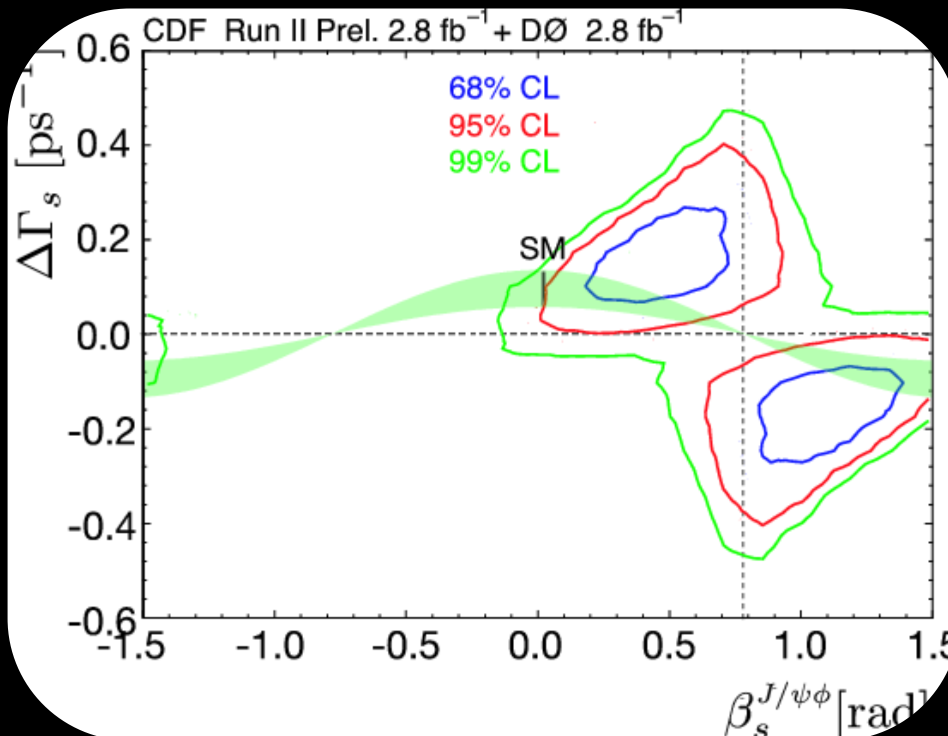
1.8σ from SM. Probability of observing a fluctuation as large or larger than observed in data is 7%

One dimensional: 0.28 < βs < 1.29 at 68% CL

www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

Mixing phase: *Tevatron combination*

DØ observed a fluctuation consistent with CDF (same direction, same signifcance)



2.1σ from SM. One-dimensional ranges:

0.27 < βs < 0.59 OR 0.97 < βs < 1.30 at 68% CL

http://tevbwg.fnal.gov/results/Summer2009_betas/

..some excitement…

If large phase confirmed - not only unambiguous signal of physics beyond SM, but also beyond MFV. Several speculations: non-abelian flavor symmetries, SUSY GUT, CKM non-unitarity….

Fourth family a nice example: SM *t'* quark with 0.3 - 1 TeV/c^2 mass

PRL **95,** 141601 (2005) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2005

Difference in B^+ and B^0 Direct CP Asymmetry as an Effect of a Fourth Generation

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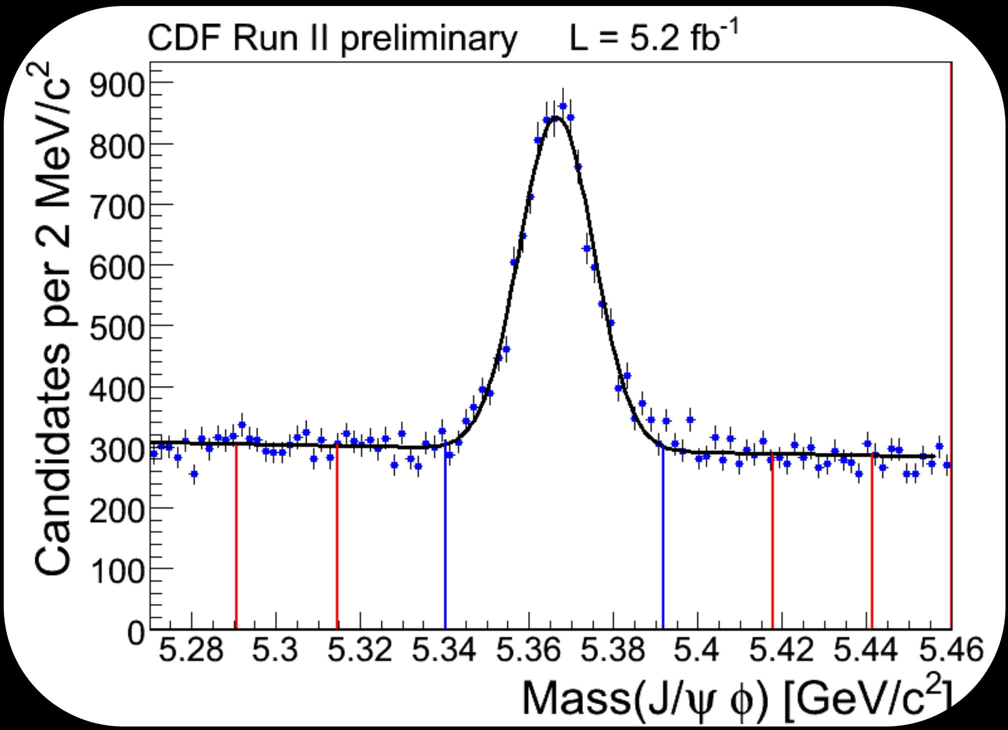
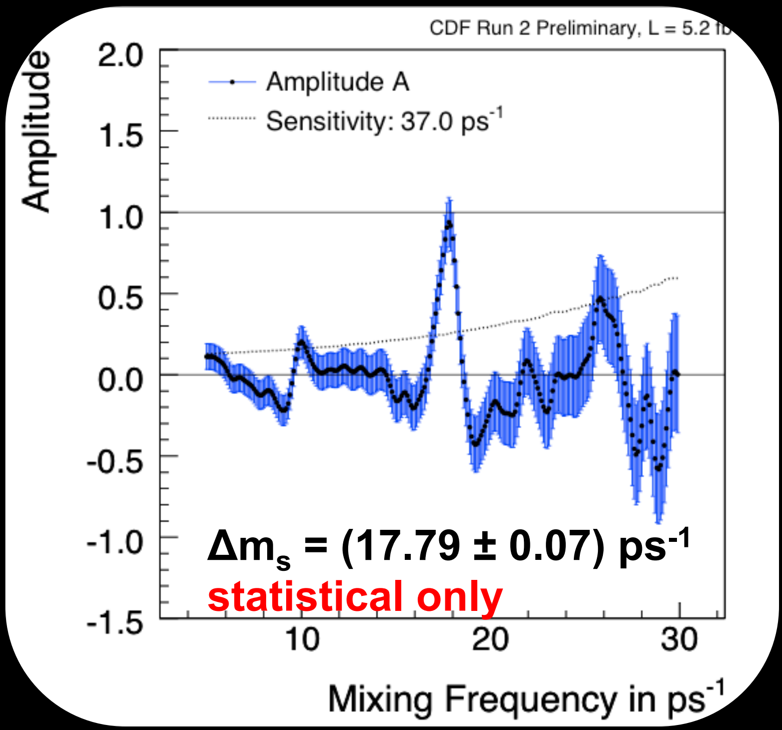
(Received 8 March 2005; revised manuscript received 20 June 2005; published 30 September 2005)

Direct CP violation in $B^0 \to K^+\pi^-$ decay has emerged at the -10% level, but the asymmetry in $B^+ \to K^+\pi^0$ mode is consistent with zero. This difference points towards possible new physics in the electroweak penguin operator. We point out that a sequential fourth generation, with sizable $V_{t's}^* V_{t'b}$ and near maximal phase, could be a natural cause. We use the perturbative QCD factorization approach for $B \to K\pi$ amplitudes. While the $B^0 \to K^+\pi^-$ mode is insensitive to t', we critically compare t' effects on direct CP violation in $B^+ \to K^+\pi^0$ with $b \to s\ell^+\ell^-$ and B_s mixing. If the $K^+\pi^0 - K^+\pi^-$ asymmetry difference persists, we predict $\boxed{\sin 2\Phi_{B_s} \text{ to be negative.}}$

Mixing phase – *5 fb^{-1} update coming soon*





Improved optimization of selection: maximize the expected average resolution on betas

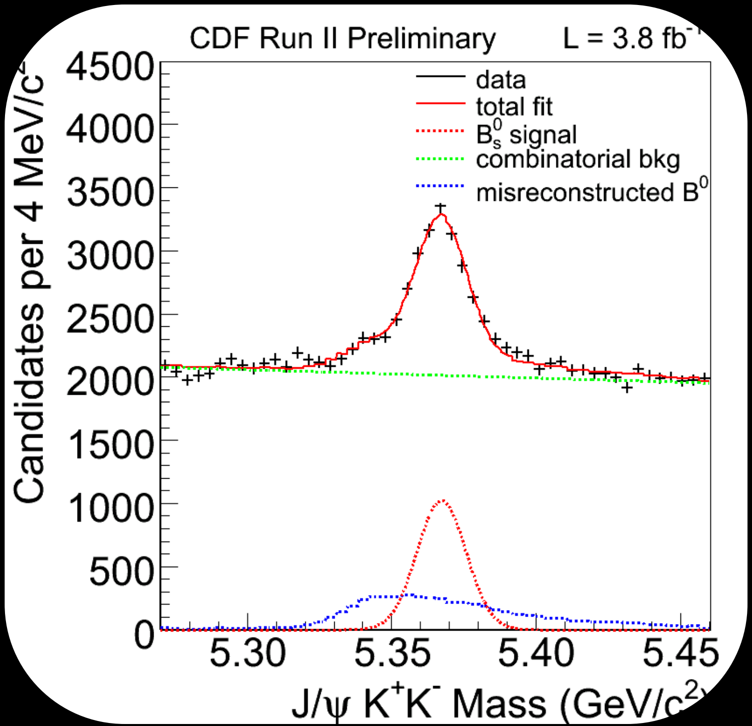
New mixing measurement for SSKT calibration

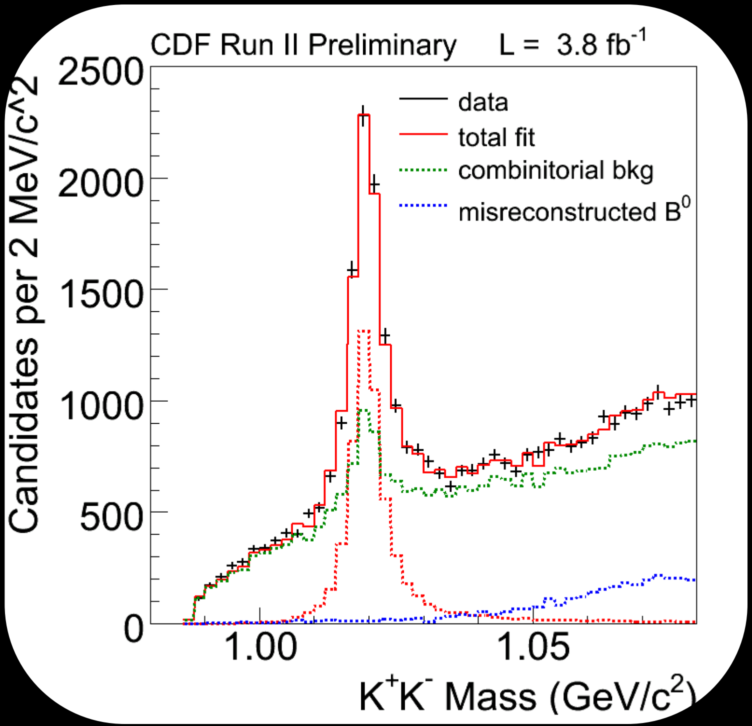
A = 0.94 ± 0.15 ± 0.13

εD^2 ~ 3.2%

Mixing phase – *upcoming update*

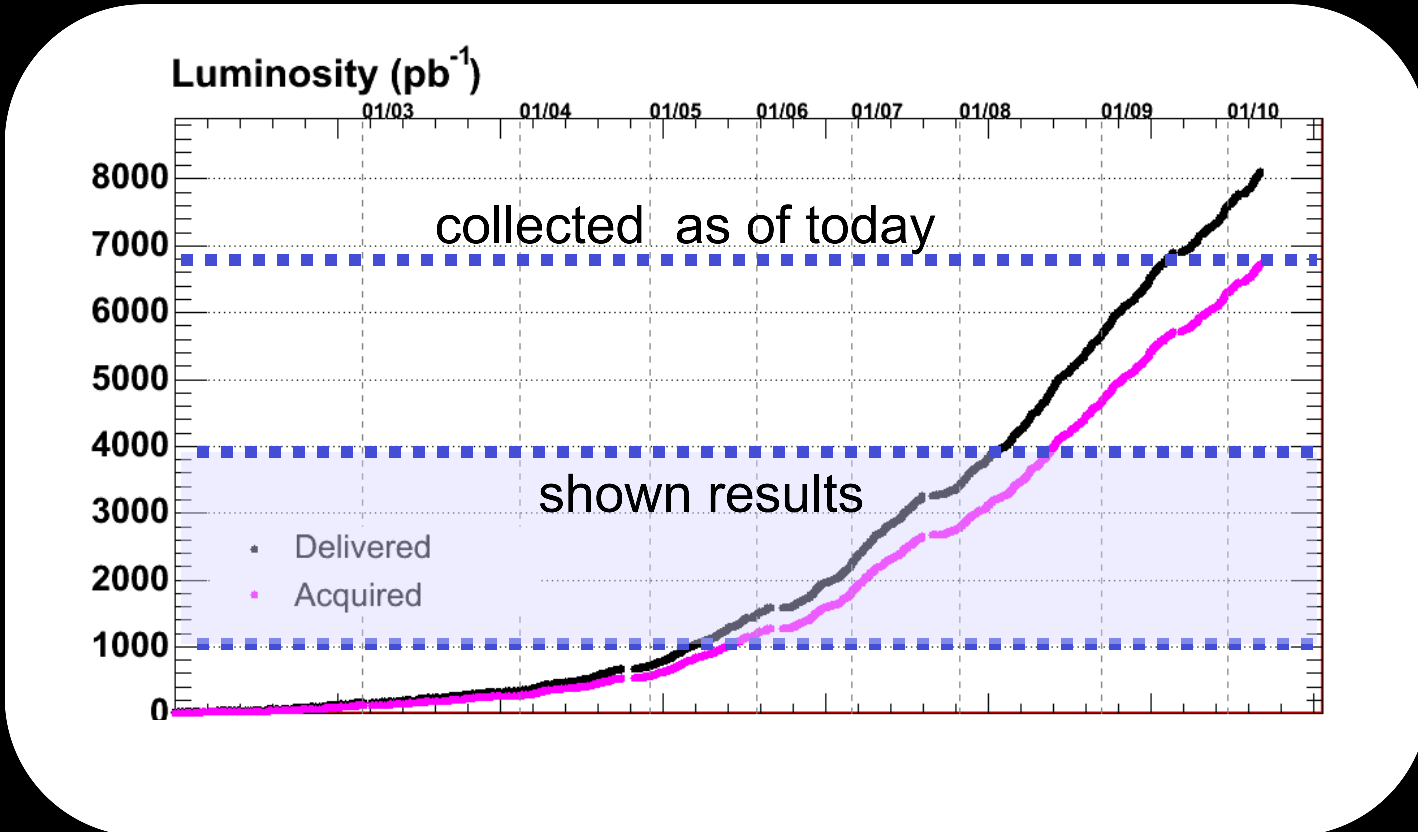
Up to a 15% non-ϕ KK component possible. May spoil βs result.





Open up *KK* window. Fit $B^0{}_s$ mass to extract shape and size of combinatorial and B^0 reflection. Fix them in a fit of the KK-mass where the ϕ and any non-ϕ contribution float. No indication of significant non-ϕ contributions.

What next?



More than 10 fb^{-1} of physics-quality data on tape by end of 2011, corresponding to 2.5-10x wrt what shown today

Concluding remarks

Strange-bottom mesons: our last chance to circumvent flavor problem.

CDF at full steam with 3rd-generation analyses. Ultimate impact in B^0_s .

$B^0_s \to \mu\mu$ keeps shrinking NP-allowed space.

Charmless B^0_s decays - a plethora of measurements and a model-independent test for non-SM physics.

Search for NP in B^0_s mixing phase. Allowed space halved . Tantalizing fluctuation to large, non-SM values. Still modest (~2.2σ) but stays there.

Only 10-40% of data expected by end of 2011 shown. Analyses continuously improved. Psychological advantage: lots of data, complex analyses already set up, all pressure is on CERN.

We are sitting on a goldmine of data. Doing our best to give hard time to LHC experiments for the next few years.

Collider Detector at Fermilab

www-cdf.fnal.gov

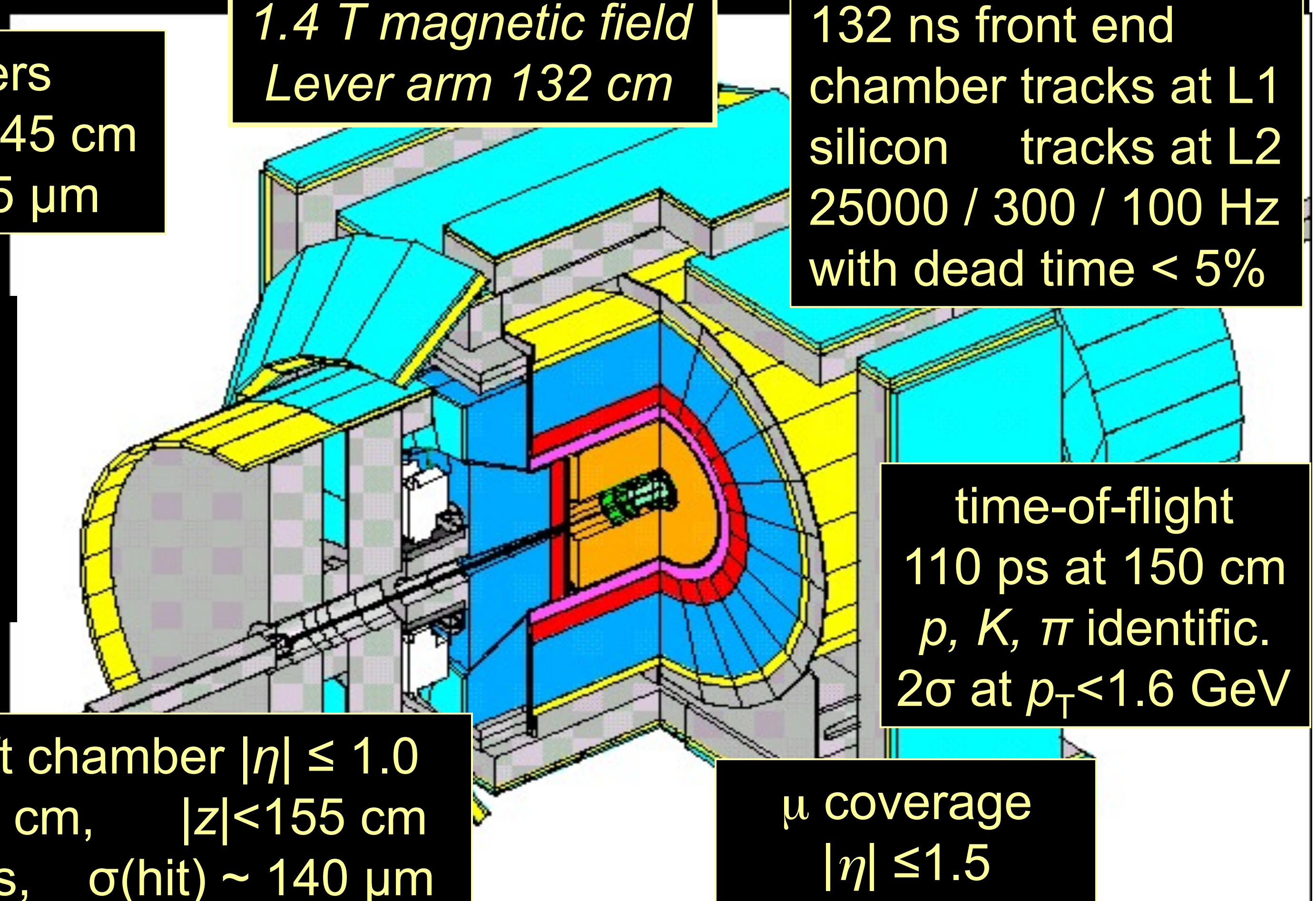
The CDF II detector

7 to 8 silicon layers
$1.6 < r < 28$ cm, $|z|<45$ cm
$|\eta| \leq 2.0$ σ(hit) ~ 15 μm

1.4 T magnetic field
Lever arm 132 cm

132 ns front end
chamber tracks at L1
silicon tracks at L2
25000 / 300 / 100 Hz
with dead time < 5%

Some resolutions:
p_T~0.15% p_T (c/GeV)
J/Ψ mass ~14 MeV
IP~ 40 μm
(includes beam spot)



time-of-flight
110 ps at 150 cm
p, K, π identific.
2σ at p_T<1.6 GeV

96 layer drift chamber $|\eta| \leq 1.0$
$44 < r < 132$ cm, $|z|<155$ cm
30k channels, σ(hit) ~ 140 μm
dE/dx for *p, K, π* identification

μ coverage
$|\eta| \leq 1.5$
84% in φ

Mixing phase - *outlook*

% of CDF clones that would observe a 5σ-effect, as a function of βs

<u>Assumptions</u>

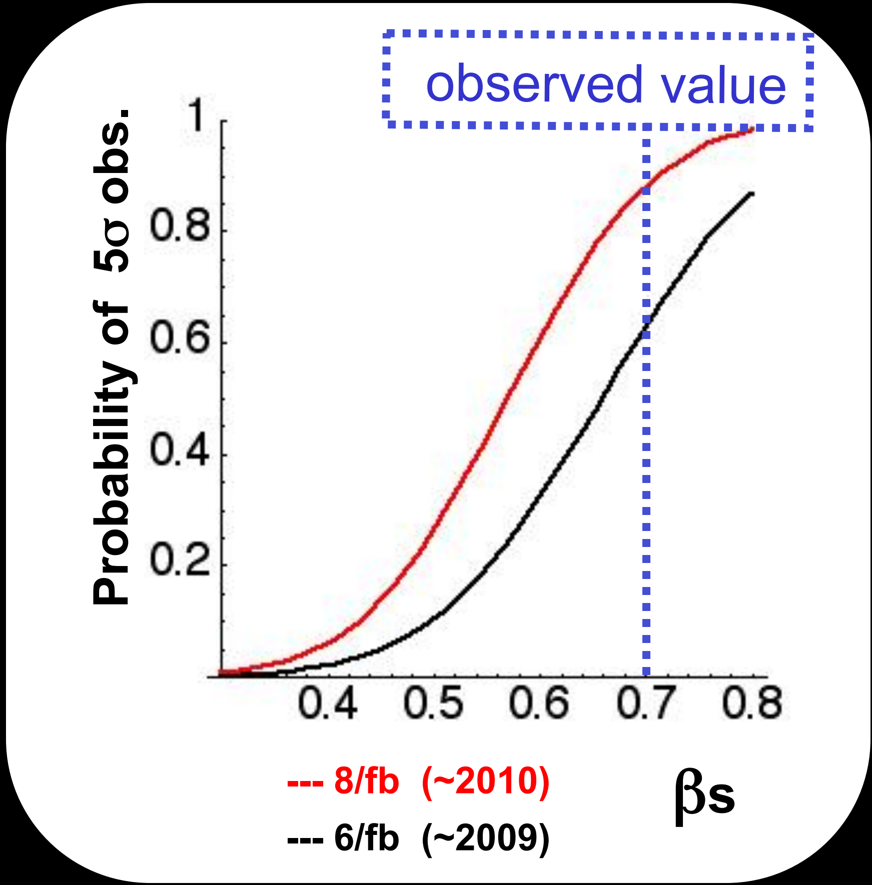
✓ $\Delta\Gamma_s = 0.1\ ps^{-1}$

✓ Constant data-taking efficiency

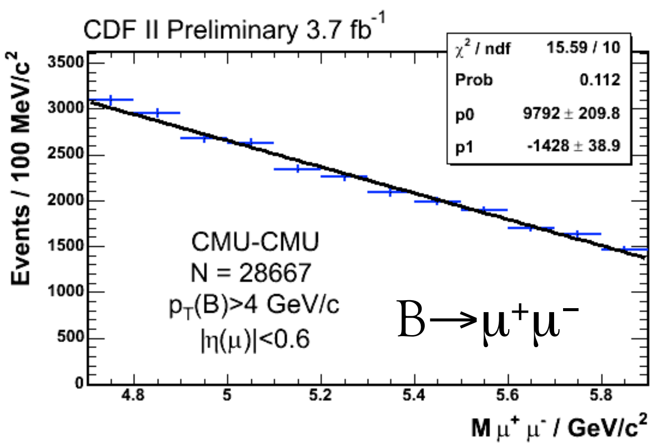
✓ No analysis improvements.

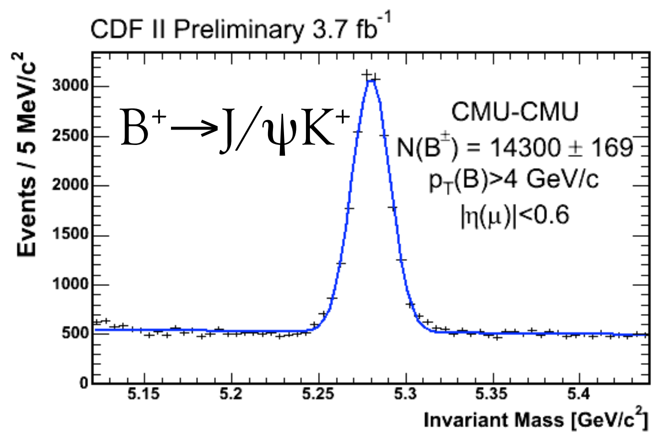
✓ No external constraints (A_{SL}, lifetimes) used.

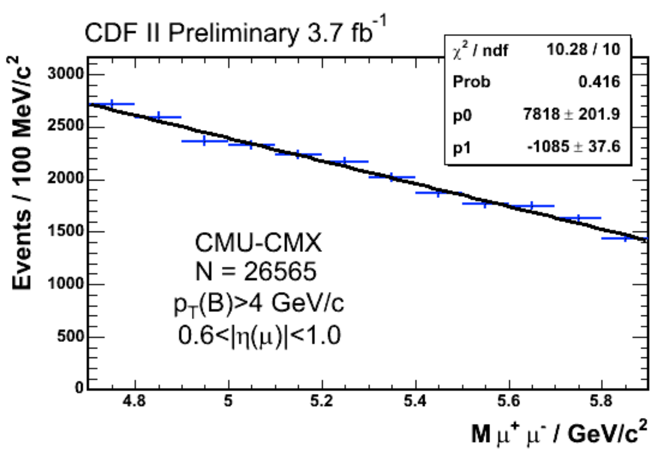
CDF next future will probably be better than that.

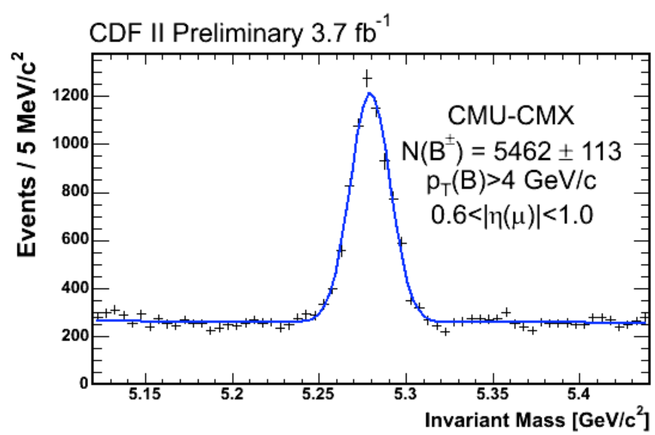


$B \to \mu^+\mu^-$ – *pre-selection*









$B \to \mu^+\mu^-$ – *Selection*

Selection based on following kinematics discriminating variables:

Transverse momentum of candidate $p_T^{\mu+\mu-}$ (>4GeV)

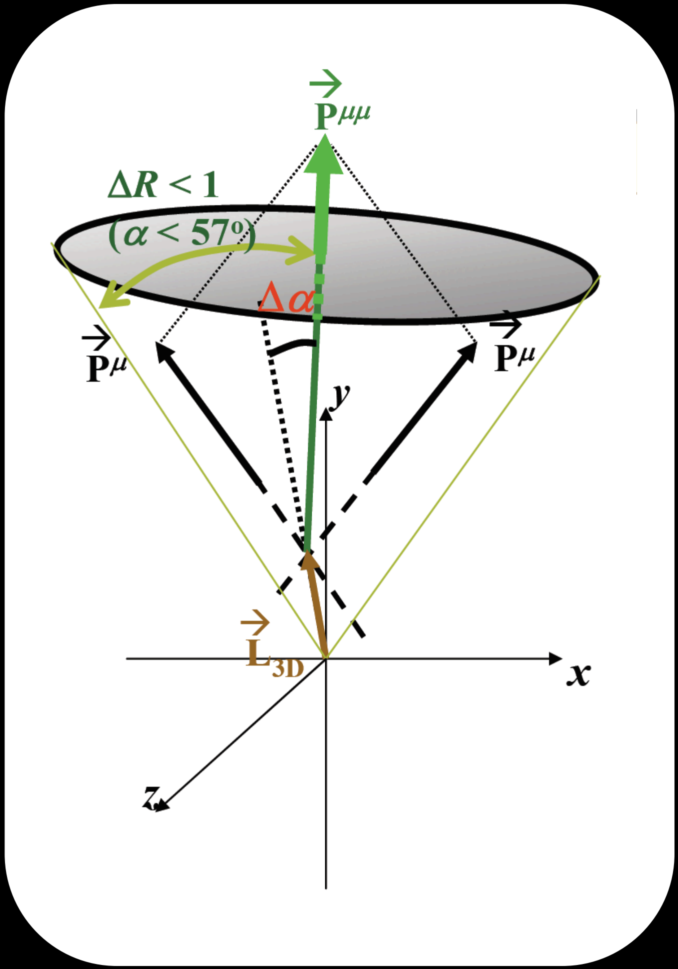
Transverse lower momentum of muon track p_T

Proper decay time $\lambda = L_{3D} \times M_{\mu\mu} / |p^{\mu+\mu-}|$

Significance of proper decay time λ/σ_λ (>2)

3D opening angle $\Delta\alpha$ (<0.7 rad)

Isolation of B candidate I (>0.5)

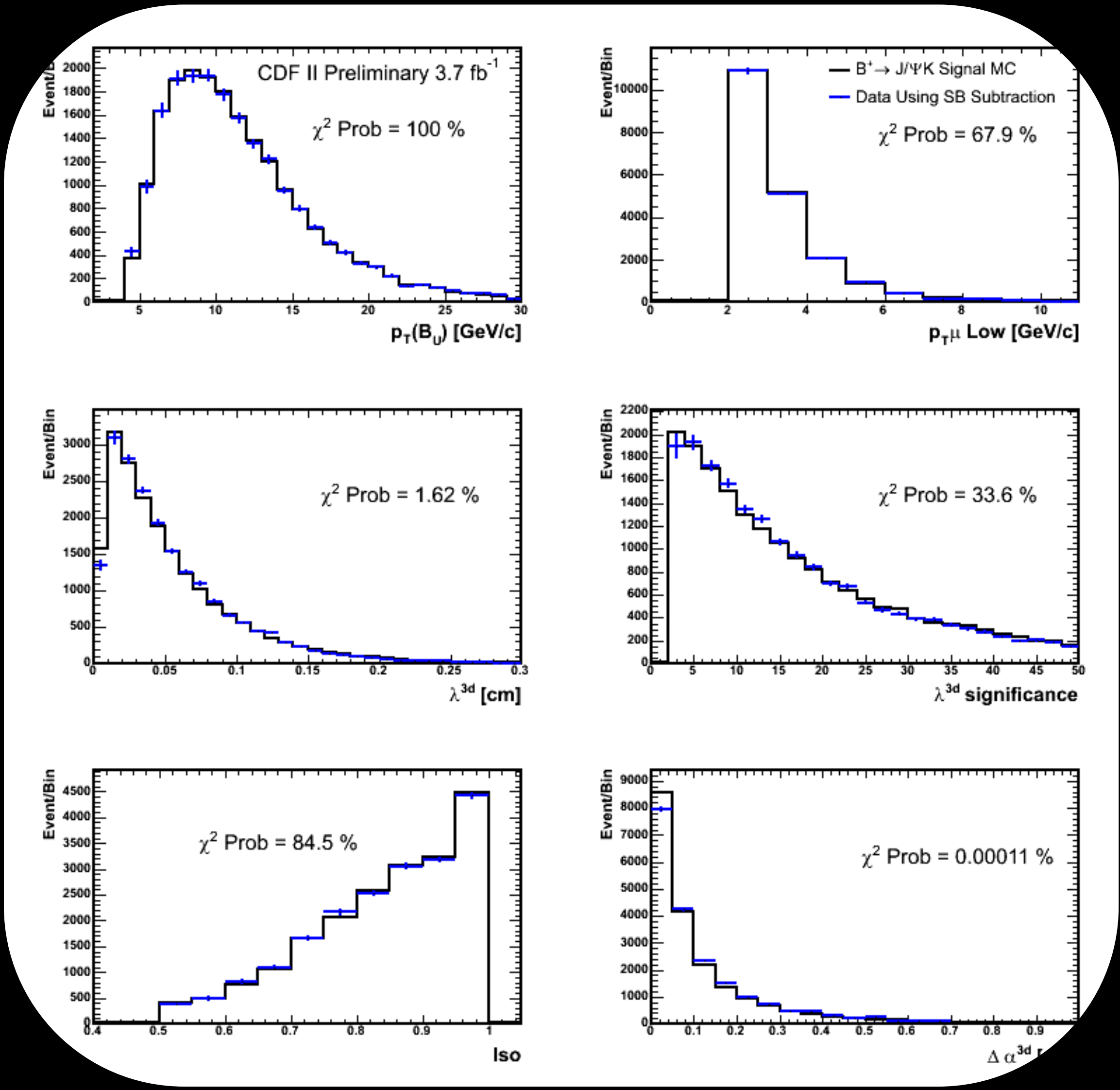


$B \rightarrow \mu^+\mu^-$ – *NN validation*

Detailed MC-data validation using control mode.

Need for isolation and momentum reweighing.

< 4% residual discrepancies

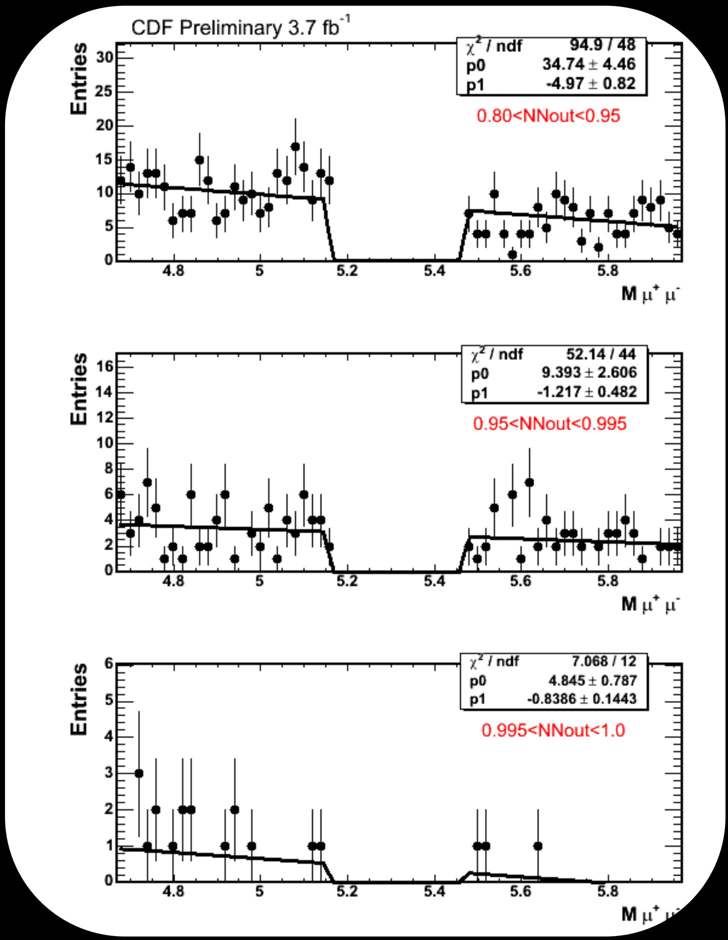


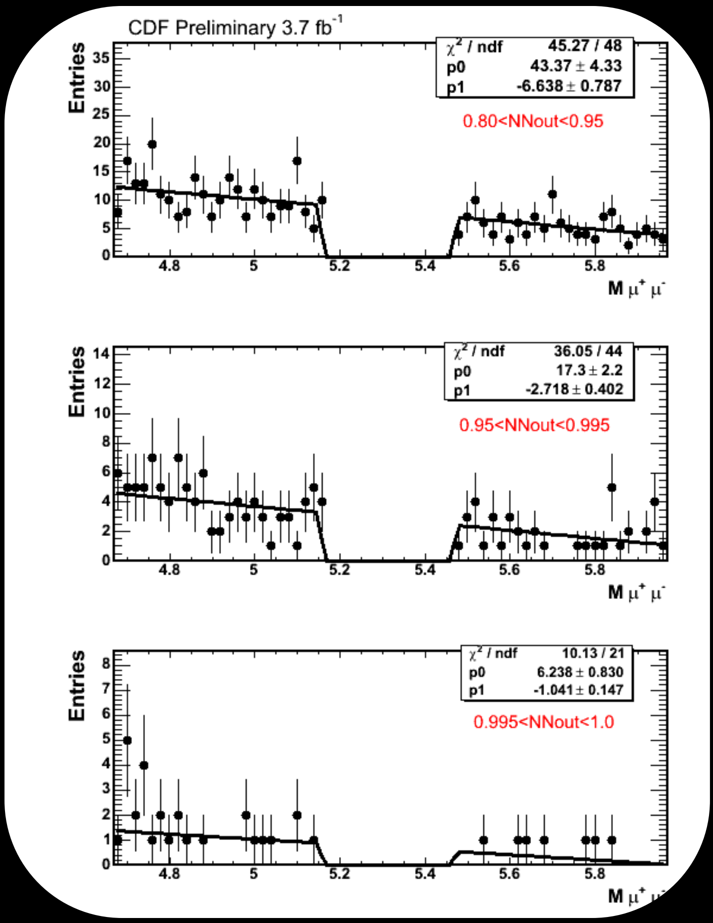
$B \rightarrow \mu^+\mu^-$ – *background control*

		CMU-CMU			CMU-CMX		
sample	NN cut	pred	obsv	prob(%)	pred	obsv	prob(%)
OS-	$0.80 < \nu_{NN} < 0.95$	$275 \pm (9)$	287	26	$310 \pm (10)$	304	39
	$0.95 < \nu_{NN} < 0.995$	$122 \pm (6)$	121	46	$124 \pm (6)$	148	3.2
	$0.995 < \nu_{NN} < 1.0$	$44 \pm (4)$	41	36	$31 \pm (3)$	50	0.4
SS+	$0.80 < \nu_{NN} < 0.95$	$2.7 \pm (0.9)$	1	29	$2.7 \pm (0.9)$	0	10
	$0.95 < \nu_{NN} < 0.995$	$1.2 \pm (0.6)$	0	34	$1.2 \pm (0.6)$	1	66
	$0.995 < \nu_{NN} < 1.0$	$0.6 \pm (0.4)$	0	55	$0.0 \pm (0.0)$	0	-
SS-	$0.80 < \nu_{NN} < 0.95$	$8.7 \pm (1.6)$	9	49	$5.7 \pm (1.6)$	2	11
	$0.95 < \nu_{NN} < 0.995$	$3.0 \pm (1.0)$	4	36	$3.6 \pm (1.0)$	2	34
	$0.995 < \nu_{NN} < 1.0$	$0.9 \pm (0.5)$	0	43	$0.3 \pm (0.3)$	0	70
FM+	$0.80 < \nu_{NN} < 0.95$	$169 \pm (7)$	169	50	$73 \pm (5)$	64	19
	$0.95 < \nu_{NN} < 0.995$	$55 \pm (4)$	43	9	$19 \pm (2)$	18	49
	$0.995 < \nu_{NN} < 1.0$	$20 \pm (2)$	20	48	$3.6 \pm (1.0)$	3	53

Predicted vs observed backgrounds in 4 control sample for 3 different NN cuts: 24 independent checks of bckg estimation method.

$B \to \mu^+\mu^-$ – *background control*





Combinatorics from linear fit to sidebands. Use exp for systematics.

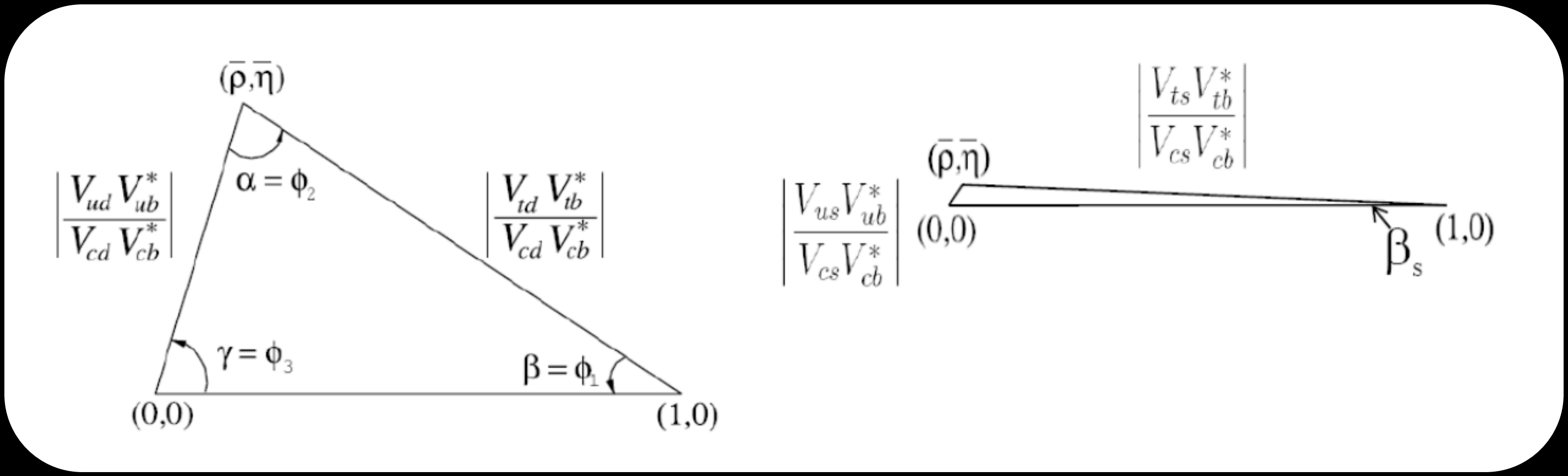
$B \to \mu^+\mu^-$ – *results*

	Mass Bin (GeV)	5.310-5.334	5.334-5.358	5.358-5.382	5.382-5.406	5.406-5.430	Total
UU NN bin 0.80-0.95	Exp Bkg	9.66 ± 0.47	9.46 ± 0.46	9.27 ± 0.46	9.08 ± 0.46	8.88 ± 0.45	46.3 ± 2.4
	Obs	7	5	10	5	5	32
UU NN bin 0.95-0.995	Exp Bkg	3.42 ± 0.27	3.33 ± 0.27	3.25 ± 0.27	3.17 ± 0.26	3.09 ± 0.26	16.2 ± 1.4
	Obs	2	3	4	3	5	17
UU NN bin 0.995-1.0	Exp Bkg	0.869 ± 0.17	0.821 ± 0.18	0.783 ± 0.19	0.75 ± 0.19	0.717 ± 0.21	4.0 ± 1.0
	Obs	0	1	2	0	0	3
UX NN bin 0.80-0.95	Exp Bkg	9.94 ± 0.48	9.8 ± 0.48	9.66 ± 0.48	9.51 ± 0.47	9.37 ± 0.47	48.3 ± 2.4
	Obs	12	8	9	9	5	43
UX NN bin 0.95-0.995	Exp Bkg	3.5 ± 0.29	3.47 ± 0.29	3.43 ± 0.29	3.39 ± 0.29	3.36 ± 0.29	17.2 ± 1.4
	Obs	3	4	3	7	0	17
UX NN bin 0.995-1.0	Exp Bkg	0.467 ± 0.14	0.438 ± 0.15	0.412 ± 0.15	0.387 ± 0.16	0.362 ± 0.16	2.08 ± 0.78
	Obs	1	1	0	1	1	4

Table 10: B_s signal window for CMU-CMU(top) and CMU-CMX(bottom): Expected backgrounds, including $B \to hh$, and number of observed events

Mixing phase - *B^0 analogy*

$B^0_s \rightarrow J/\psi\phi$ for sin(2βs) $\Leftrightarrow$ $B^0 \rightarrow J/\psi K^0_S$ for sin(2β)



Additional experimental complications:

- ✓ $J/\psi\phi$: a mix of CP-even and CP-odd eigenstates, treat them separately;
- ✓ B^0_s oscillates ~35 times faster than B^0;
- ✓ sin(2β)~ 0.7, sin(2βs) expected x20 smaller.

Mixing phase - *an example of synergy*

If large phase confirmed - not only unambiguous signal of physics beyond SM, but also beyond MFV. Several speculations: non-abelian flavor symmetries, SUSY GUT, CKM non-unitarity….

Fourth family a nice example: SM *t'* quark with 0.3 - 1 TeV/c^2 mass

PRL **95,** 141601 (2005) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2005

Difference in B^+ and B^0 Direct CP Asymmetry as an Effect of a Fourth Generation

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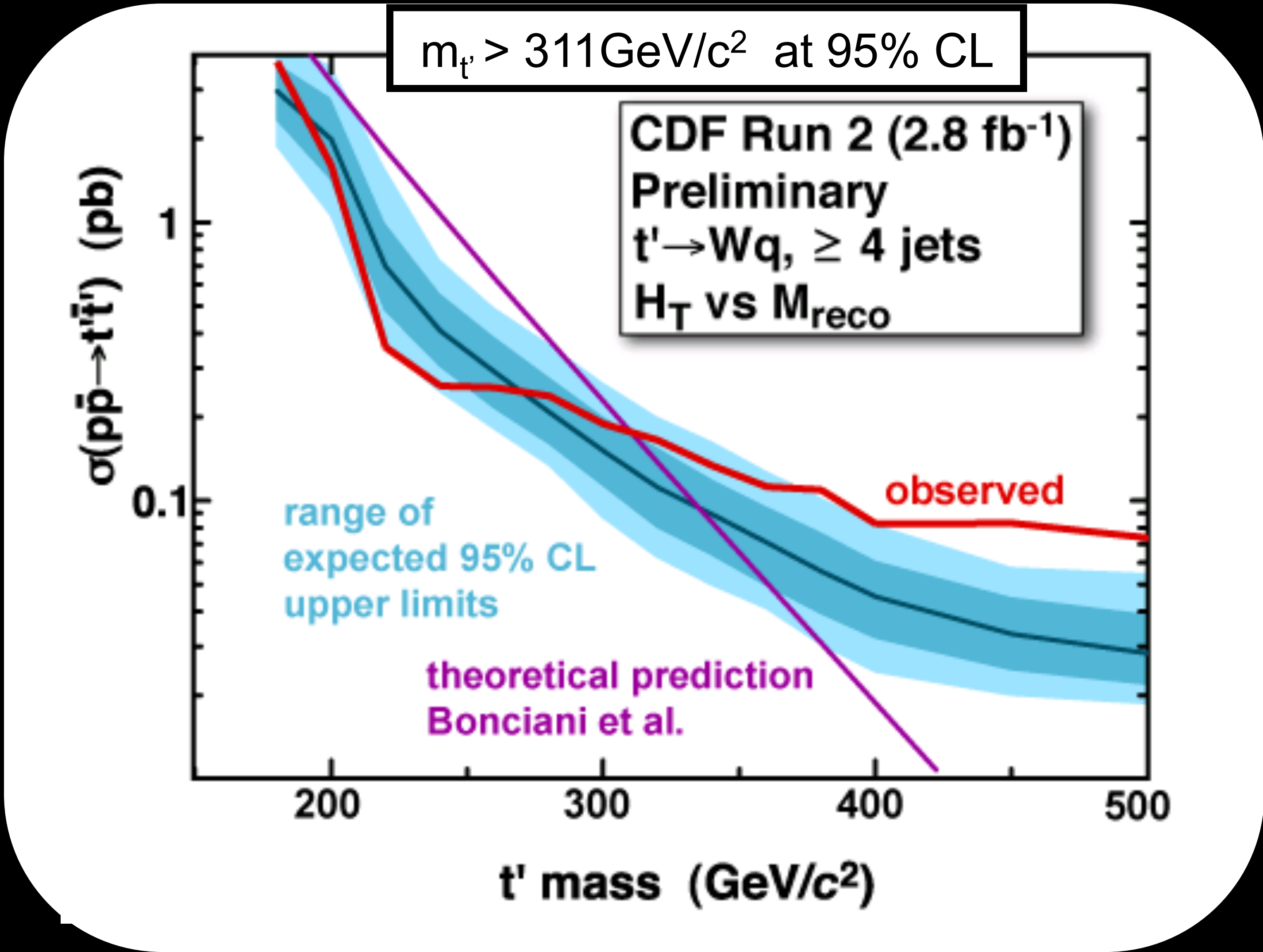
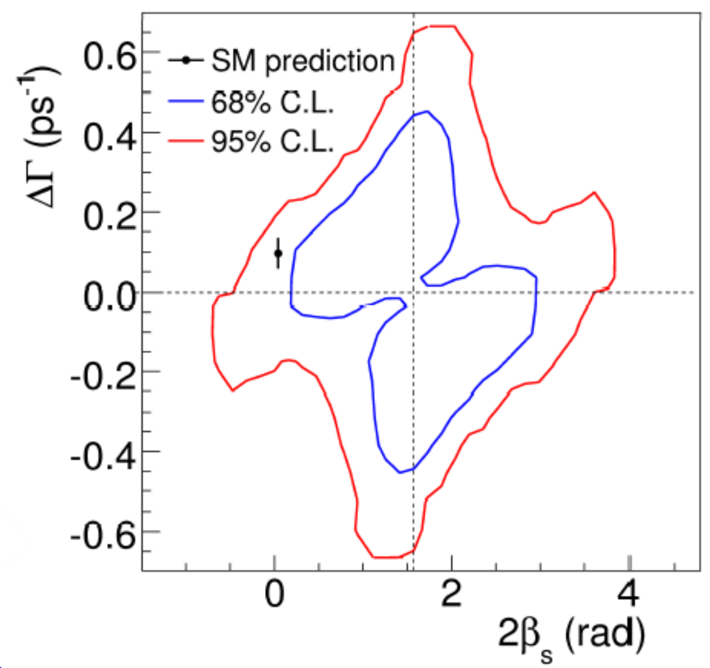
Mixing phase - *complementary to searches*



Mixing phase – *other results*

Assuming the SM, the probability of observing a fluctuation as large or larger than observed in data is 15% (1.5σ)

One-dim: $0.16 < \beta s < 1.41$ at 68% CL



Untagged CDF results (2.8/fb)

$\tau(B_s^0)$ = 1.53 ± 0.04 (stat) ± 0.01 (syst) ps

$\Delta\Gamma$ = 0.02 ± 0.05 (stat) ± 0.01 (syst) ps^{-1}

$B^0_{(s)} \rightarrow h^+h'^-$ Next

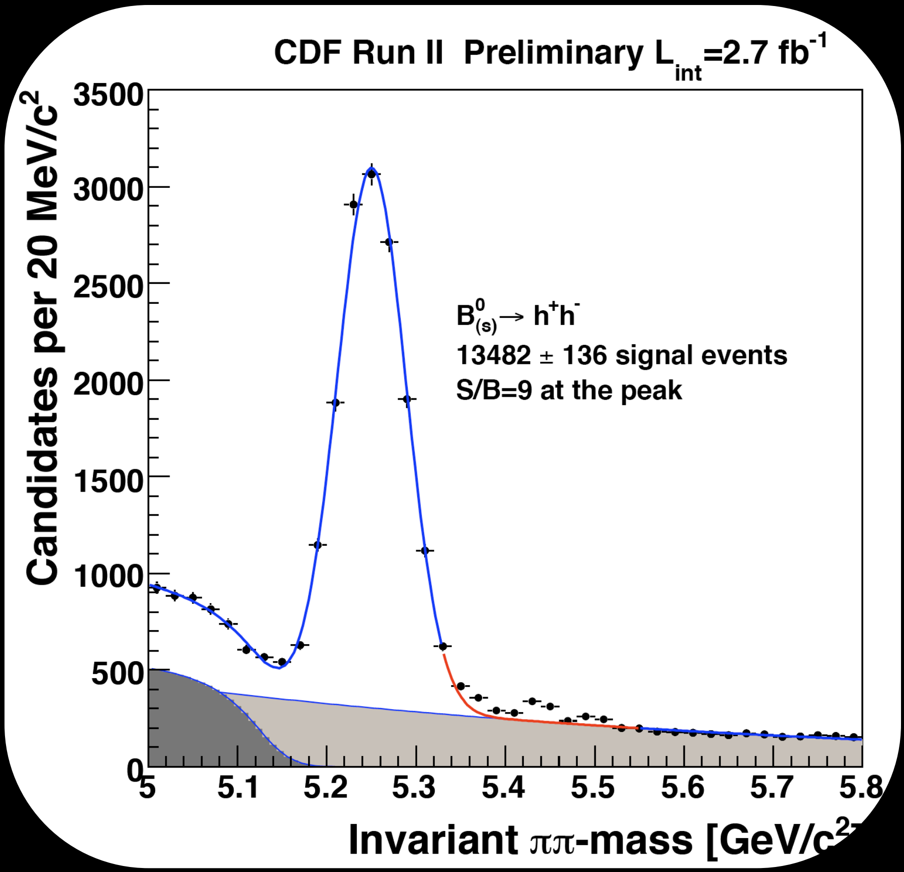
5 fb^{-1} analysis in progress

✓ Observation of DCPV in B^0_s ?

✓DCPV in B^0 competitive with Belle.

✓ Precision Br of rare modes.

✓ Observe $B^0_s \rightarrow \pi^+\pi^-$?

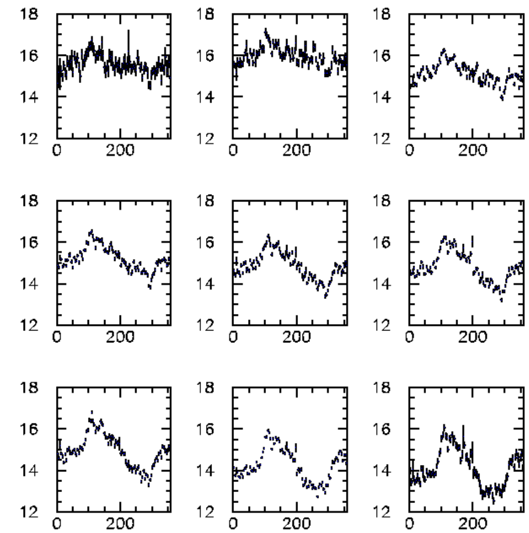


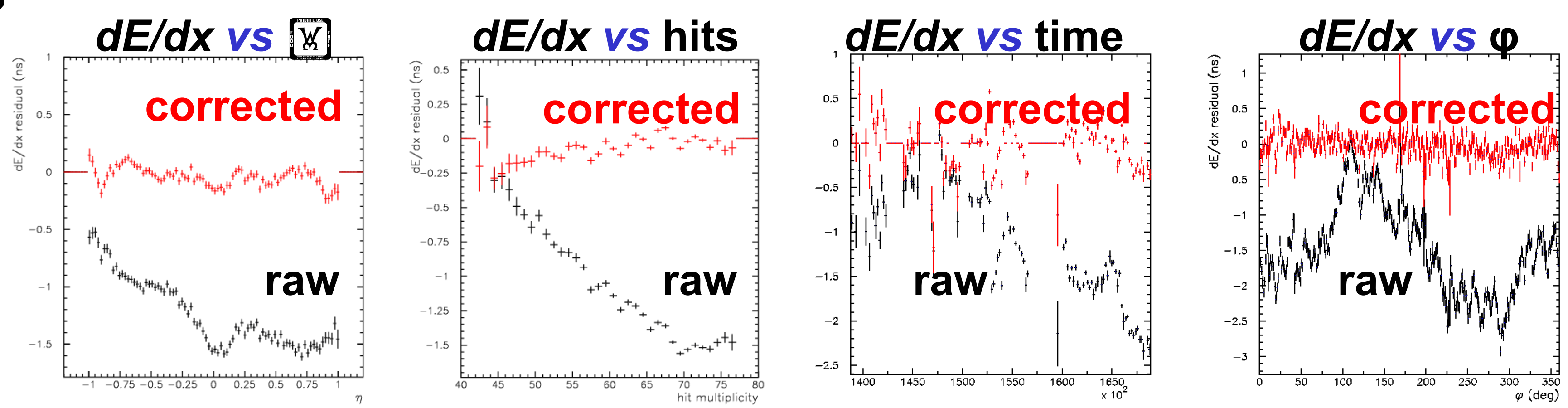
$B^0_{(s)} \to h^+ h'^-$ - PID calibration

dE/dx response needs accurate equalization over tracking volume and time.

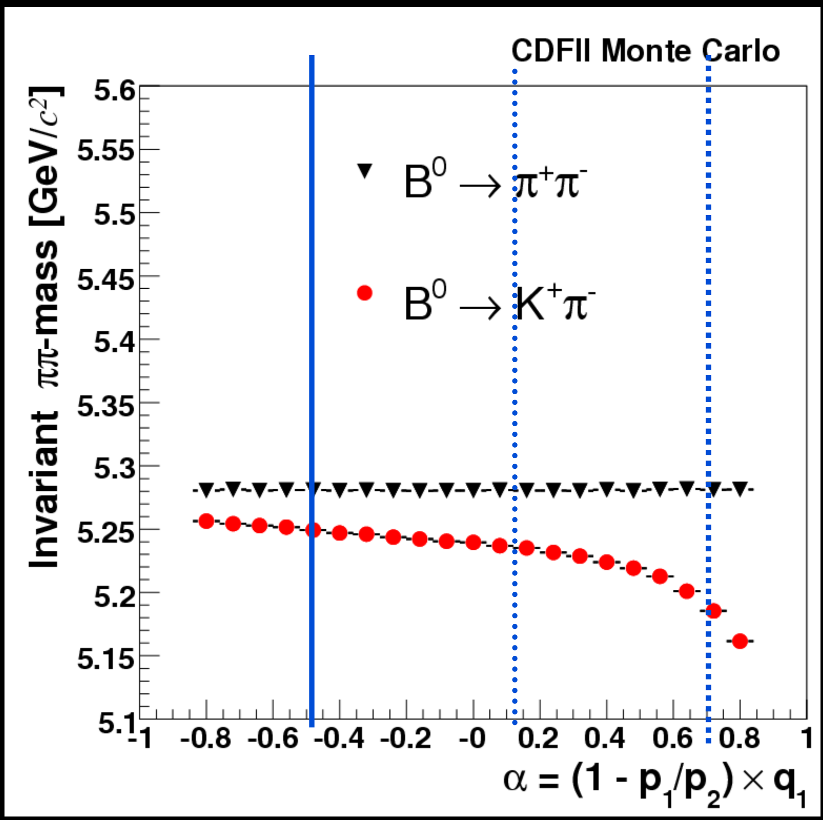
Systematic variations are of same order as K/π separation

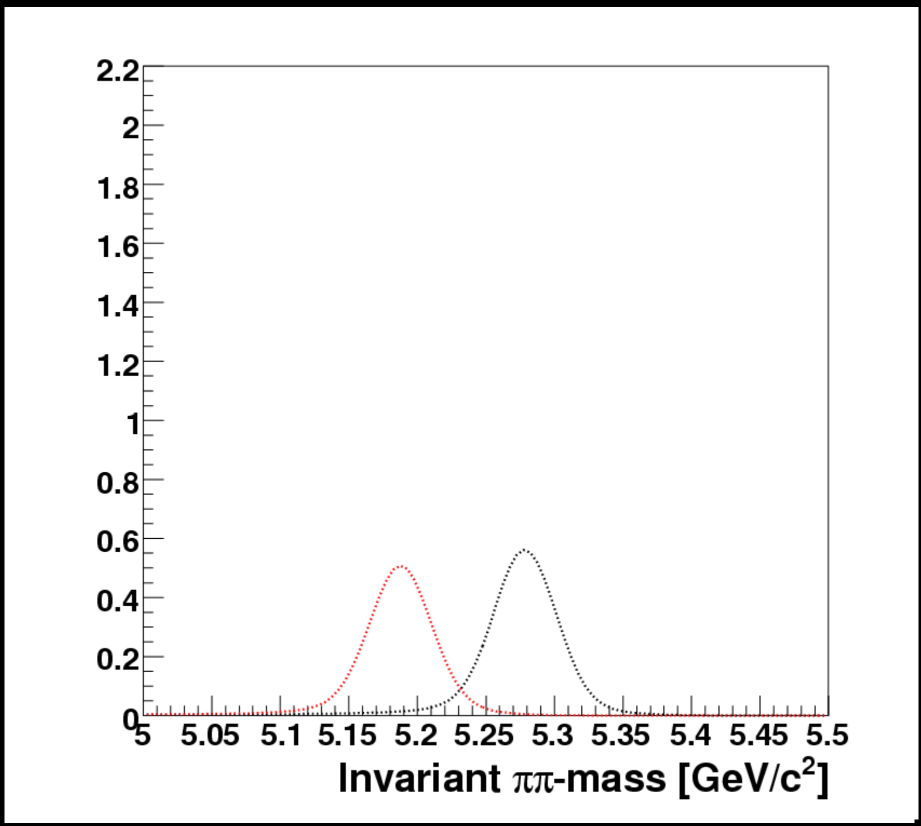
Not easy: many intercorrelated effects. Use D* tagged $D^0 \to K\pi$ decays.





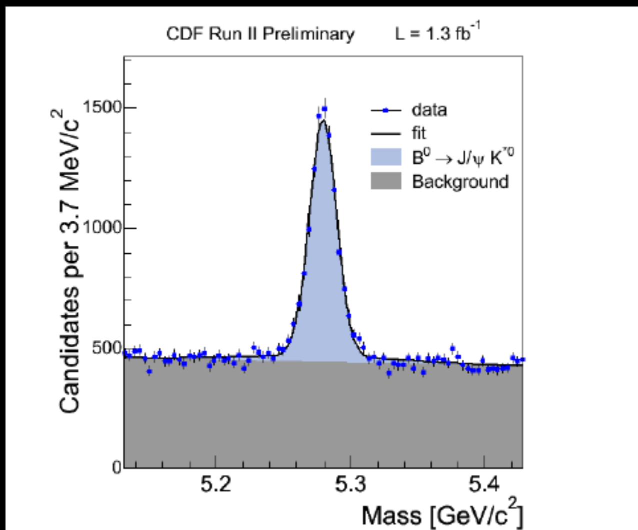
Kinematics at work





Data-driven checks

Angles



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

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

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

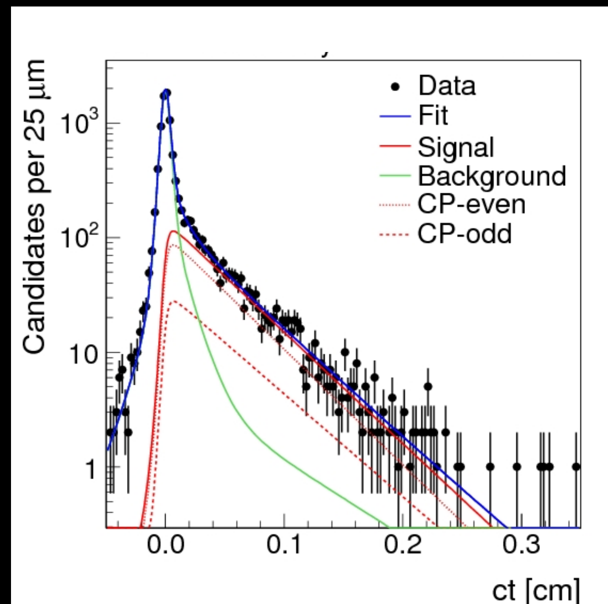
$\delta_\parallel = -2.96 \pm 0.08 \text{ (stat)} \pm 0.03 \text{ (syst)}$

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

Polarization of $B^0 \to \psi K^*$: consistent w/ B-factories

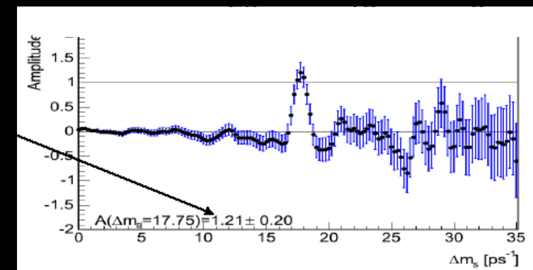
www-cdf.fnal.gov/physics/new/bottom/070830.blessed-BdPsiKS/

Mass-lifetime



Measurement w/o flavor tagging: ΔΓs and τs

Flavor tagging



OST tuned on B^+

SST tuned on MC, checked on mixing measurement *a posteriori*

Neutral flavored mesons

Extremely rich phenomenology. (Approximated) time-evolution

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} = H \begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} \equiv \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}}\Bigg]\begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix}$$

$$B^0_{s,H} \sim B^0_s - \overline{B}^0_s$$

$$B^0_{s,L} \sim B^0_s + \overline{B}^0_s$$

Hamiltonian eigenstates (definite mass and lifetime) are mixtures of flavor eigenstates

Experimentally accessible quantities

$\Delta m_s = m_H - m_L \approx 2\lvert M_{12}\rvert$	Oscillation frequency	measured ~18 ps-1
$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2\lvert\Gamma_{12}\rvert\cos(\phi_s)$	Decay-width difference	measured ~5-15% x Γ
$\phi_s = \arg[-M_{12}/\Gamma_{12}]$	CP-violating phase	???

Φs and βs are <u>not</u> the same phase

β_s = arg [- $V_{tb}V^*_{ts}/V_{cb}V^*_{cs}$] ~ 2.2° (SM)

phase of *b→ccs* transition that accounts for decay and mixing+decay.

Φ_s = arg[$-M_{12}/\Gamma_{12}$] ~ 0.24° (SM)

arg[M_{12}]=arg$(V_{tb}V_{ts}^*)^2$ matrix element that connects matter to antimatter through oscillation.

arg[Γ_{12}] = arg[$(V_{cb}V^*_{cs})^2 + V_{cb}V^*_{cs}V_{ub}V^*_{us} + (V_{ub}V^*_{us})^2$] width of matter and antimatter into common final states.

Both SM values are experimentally unaccessible by current experiments (assumed zero).
If NP occurs in mixing:

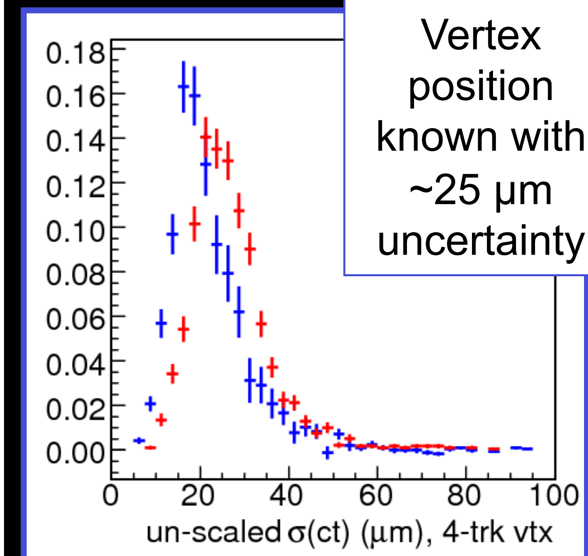
$$\Phi_s = \Phi_s^{SM} + \Phi_s^{NP}$$

$$2\beta s = 2\beta_s^{SM} - \Phi_s^{NP}$$

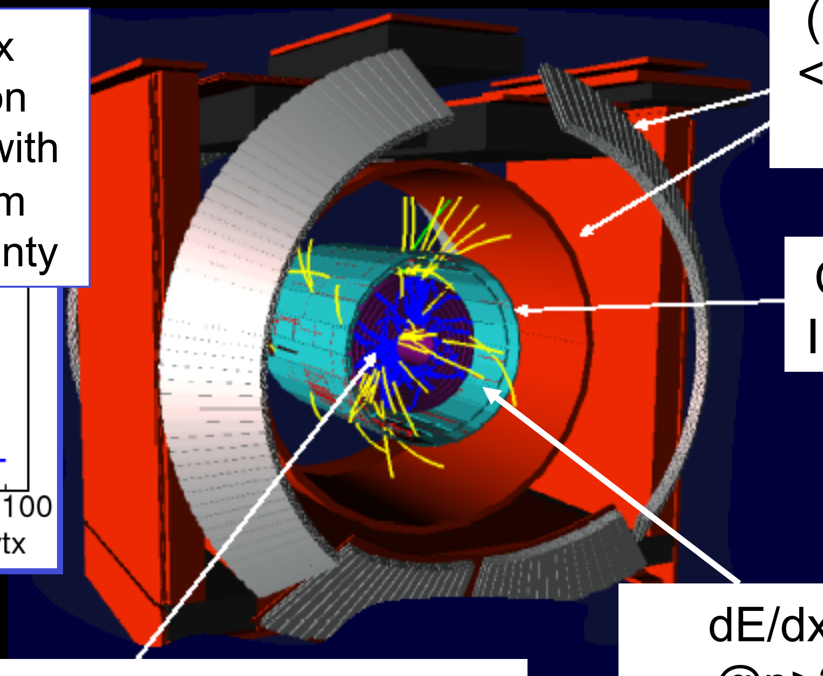
➔ standard approximation: $\Phi_s = -2\beta_s$

Experimental requirements

CDF strengths.



Vertex position known with ~25 μm uncertainty



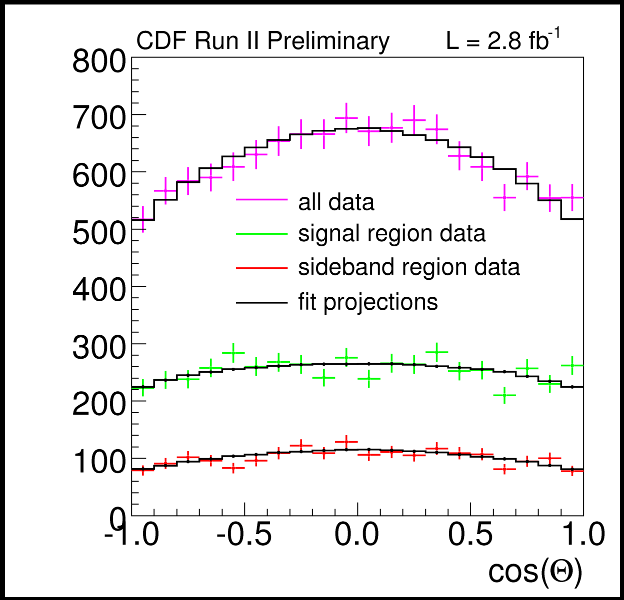
High muon acceptance (84% azimuthal at |eta| <1.5) and precise muon ID

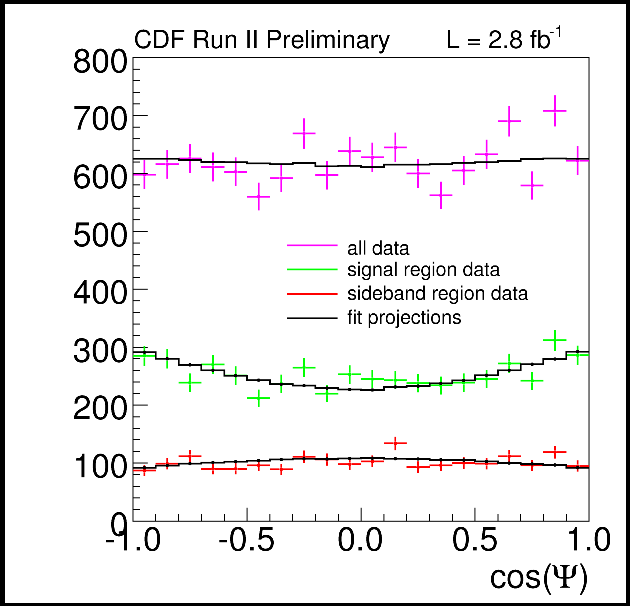
Calorimeter for electron ID used in flavor tagging

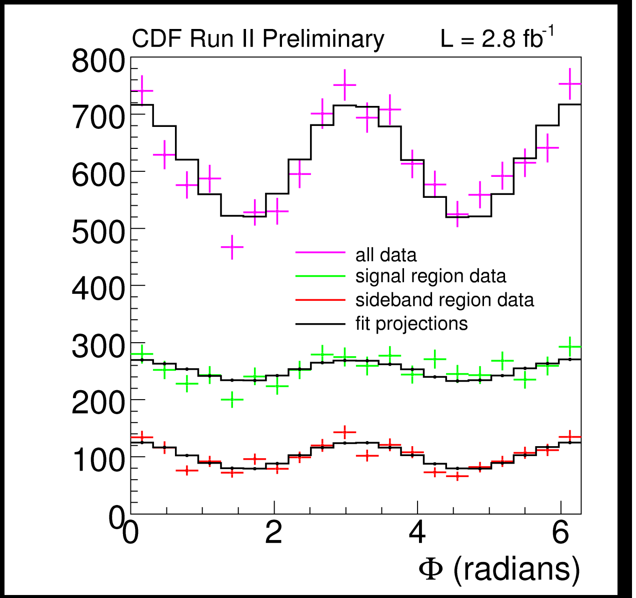
dE/dx in drift chamber (1.5σ @p>2 GeV/c) and TOF (2σ @p<1.6 GeV/c) provide pion/kaon ID crucial in flavor tagging

Excellent vertexing to resolve fast oscillations (silicon detector) and momentum resolution for improving S/B (large radius drift chamber) immersed in 1.4 T B field.

Quality of the angular fit





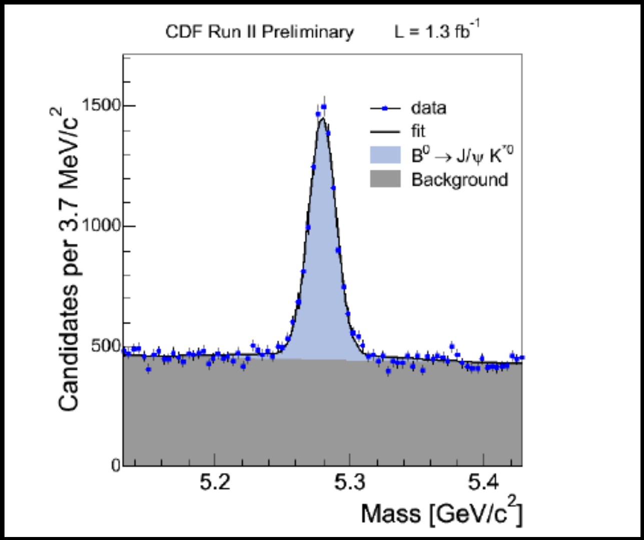


Cross-check sample

$B^0 \to J/\psi K^{*0}$: high-statistics test of angular efficiencies and fitter

ANN removes *K^{*0}* mis-reconstructed with swapped *$K\pi$* assignment

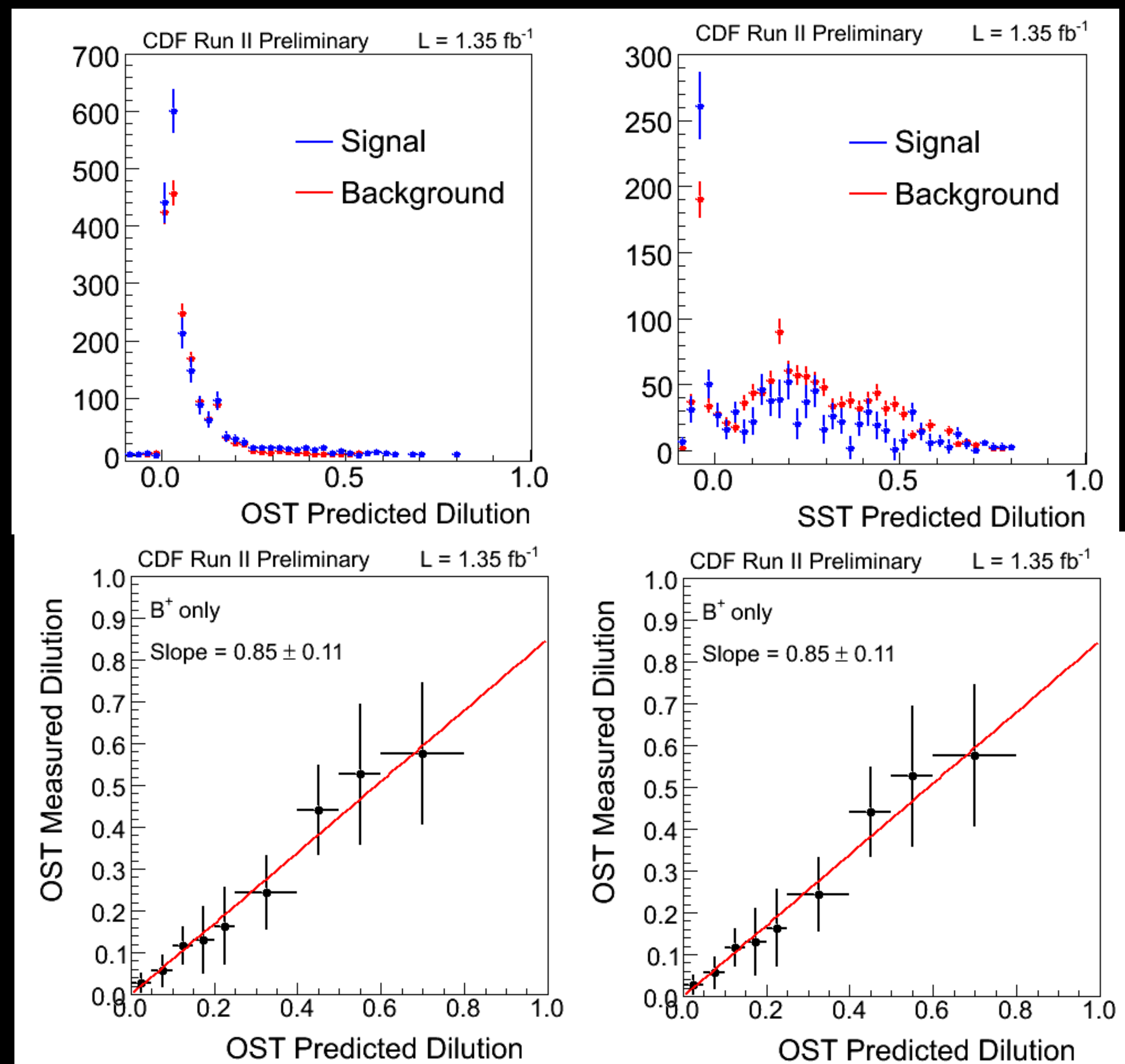
$$c\tau = 456 \pm 6\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$$
$$|A_0(0)|^2 = 0.569 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$$
$$|A_\parallel(0)|^2 = 0.211 \pm 0.012\ (\text{stat}) \pm 0.006\ (\text{syst})$$
$$\delta_\parallel = -2.96 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$$
$$\delta_\perp = 2.97 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$$



Agrees with latest Babar results. PRD 76,031102 (2007)
Actually…competitive ;-)

$$|A_0(0)|^2 = 0.556 \pm 0.009\ (\text{stat}) \pm 0.010\ (\text{syst})$$
$$|A_\parallel(0)|^2 = 0.211 \pm 0.010\ (\text{stat}) \pm 0.006\ (\text{syst})$$
$$\delta_\parallel = -2.93 \pm 0.08\ (\text{stat}) \pm 0.04\ (\text{syst})$$
$$\delta_\perp = 2.91 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$$

Tagging calibration and performance



More on SST

Most Powerful Tagger:

Fragmentation Track

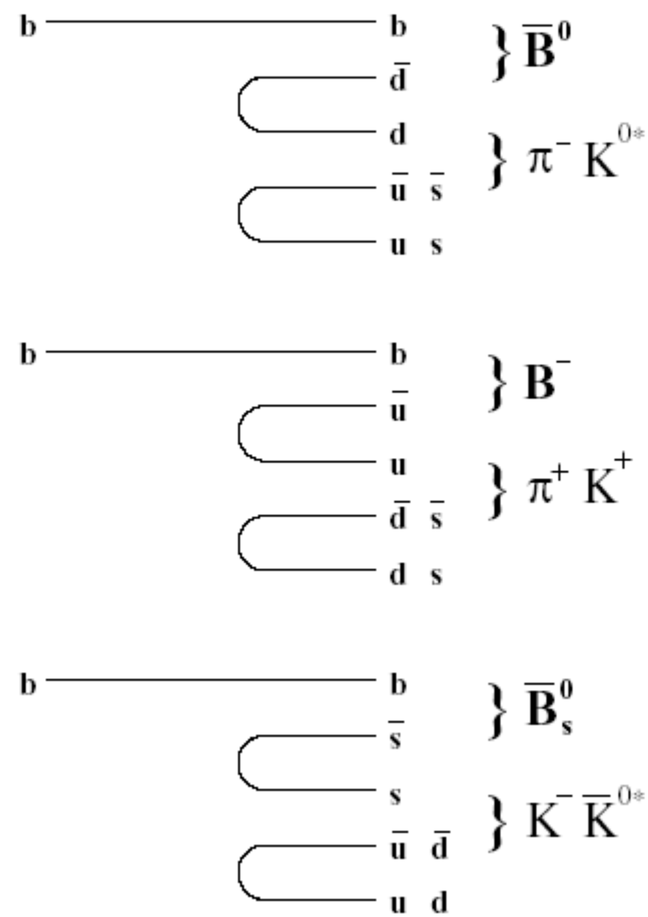
- Look for Kaon assoc. w/ B_s^0 production
- Use TOF & COT for $\pi - K$ separation

Calib using Monte Carlo

- B_s^0, B_d^0, B^+ different
- Use PYTHIA simulation

Performance

- Efficiency: $\varepsilon = 0.50 \pm 0.01$
- Avg Dilution: $\mathcal{D} = 0.27 \pm 0.04$



More on OST

Exclusive algorithms:

Soft Lepton Tagger

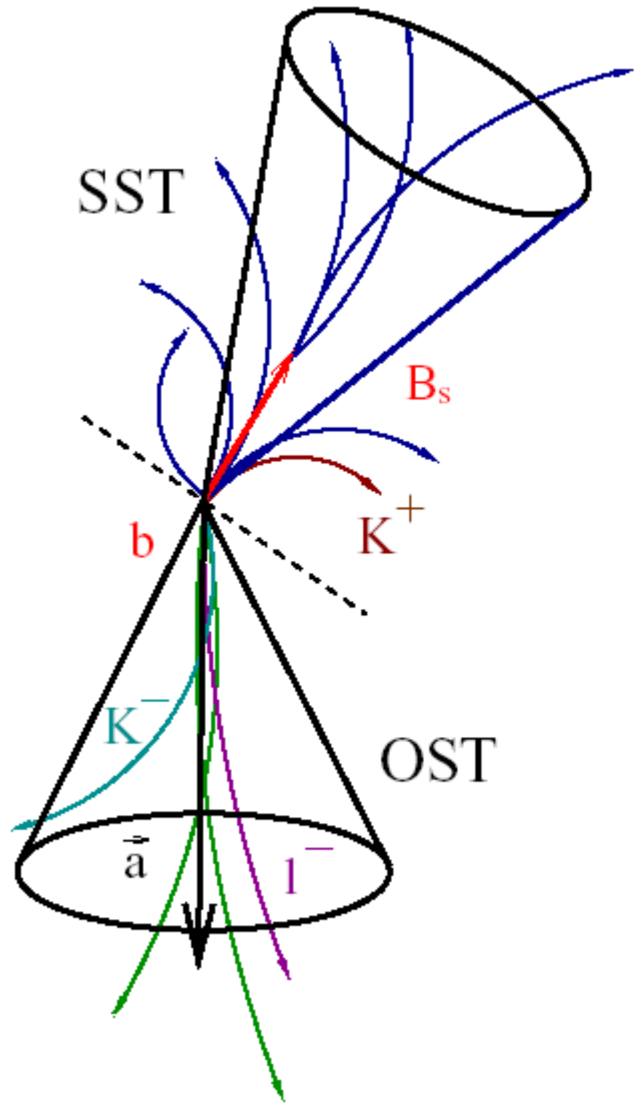
- look for semileptonic B decay on OS
- lepton charge indicates *b*-flavor
- μ, *e* tagger

Jet Charge Tagger

- look for jet or secondary vertex on OS
- jet charge indicates *b*-flavor

Performance

- Efficiency: $\varepsilon = 0.96 \pm 0.01$
- Avg Dilution: $\mathcal{D} = 0.11 \pm 0.02$

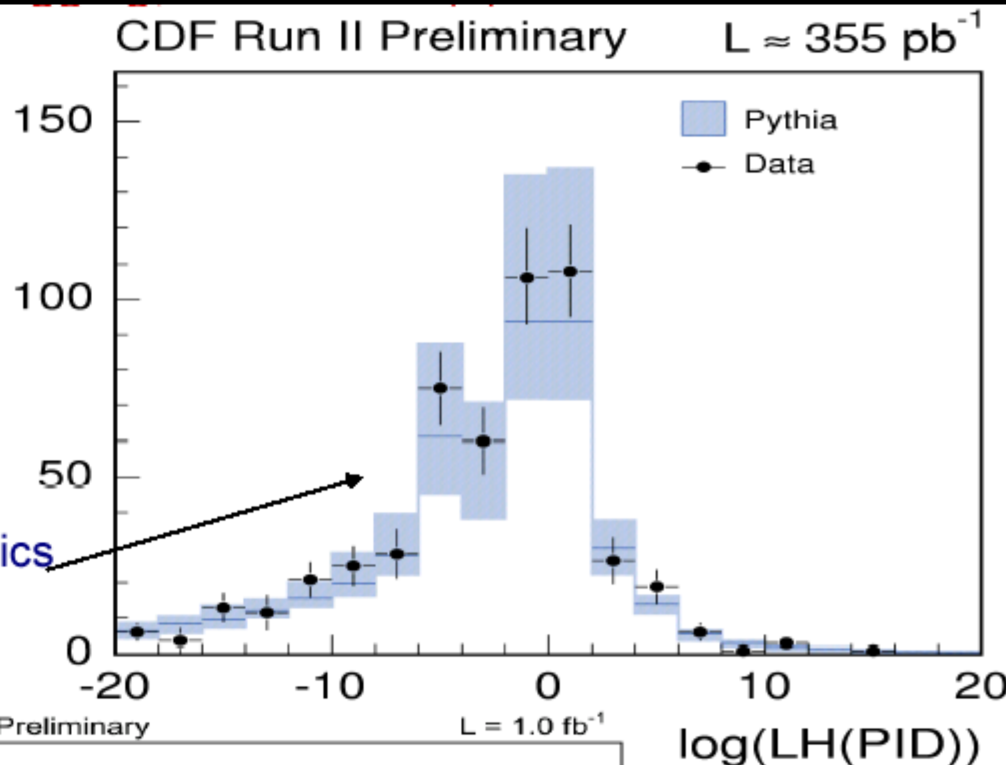


SST calibration

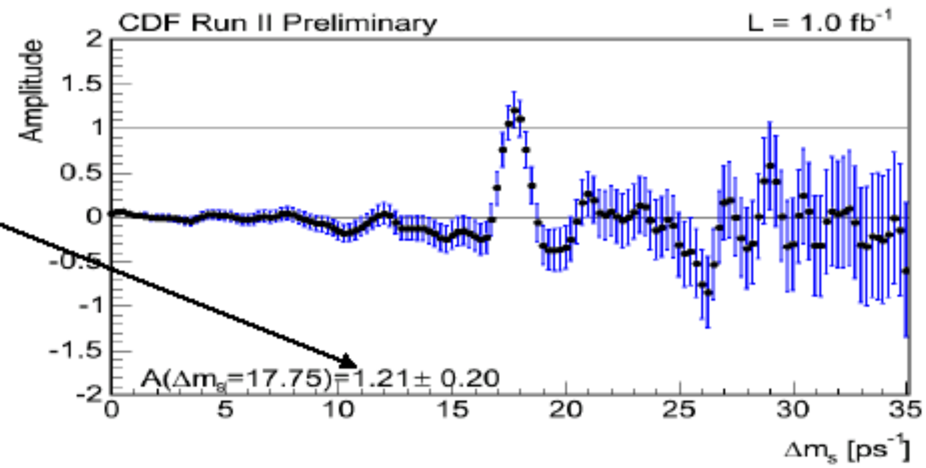
Systematic studies:

- Fragmentation Model
- bb Production Mechanisms
- B** content
- Detector/PID resolution
- Multiple interactions
- PID content around B
- Data/MC agreement

discrepancies covered by systematics

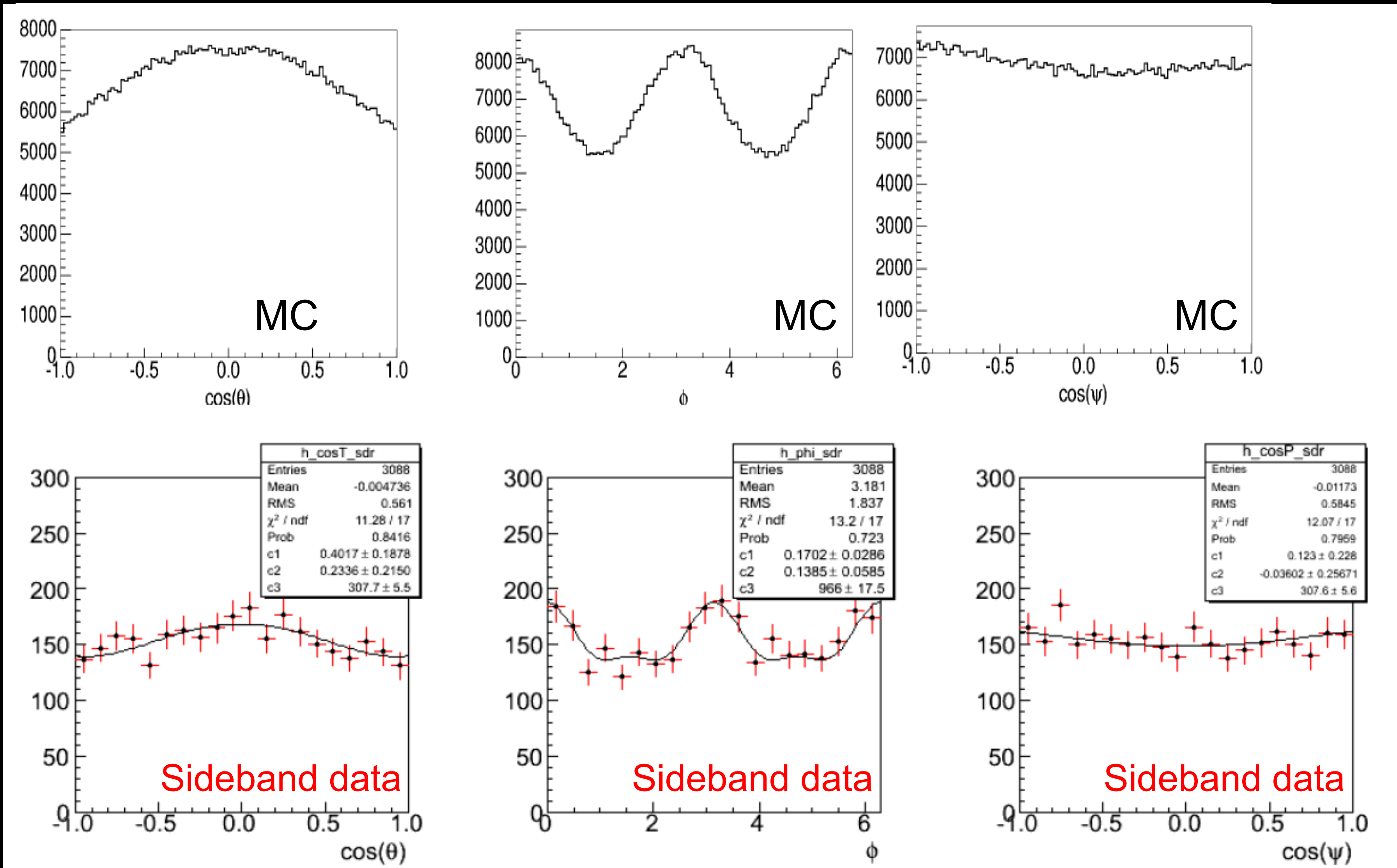


Correct calibration was confirmed later



20

Angular model cross-check



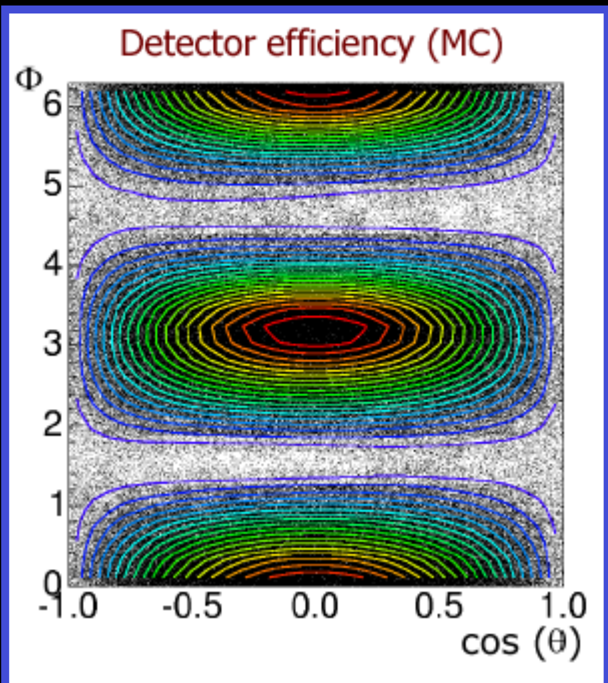
Signal probability density

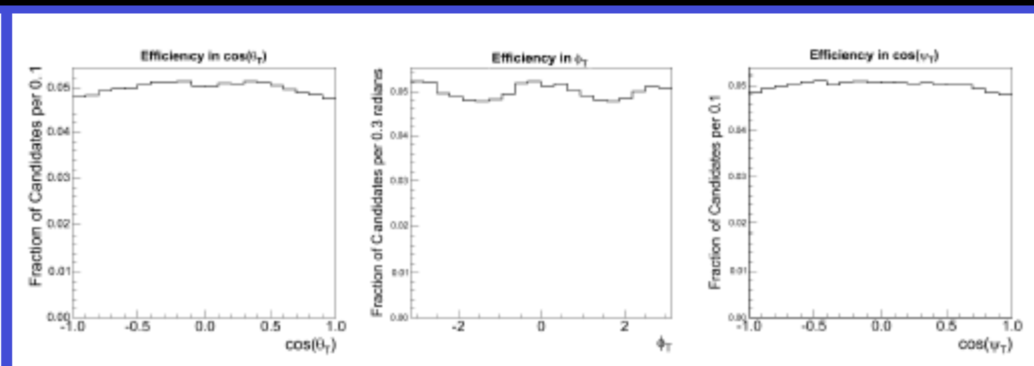
$$P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) = \frac{1+\xi\mathcal{D}}{2} P(t, \vec{\rho}|\sigma_t)\epsilon(\vec{\rho}) + \frac{1-\xi\mathcal{D}}{2} \bar{P}(t, \vec{\rho}|\sigma_t)\epsilon(\vec{\rho}),$$

Flavor tagging

B^0_s term

anti-B^0_s term





Angular sculpting from MC. Deviations from flat indicate detector effects.

Cross-checked in data (more later)

Flavor-specific time evolutions

B^0_s term

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

A_0, $A_\parallel$, $A_\perp$: transition amplitudes in a given polarization state

anti-B^0_s

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

f(ρ): angular distribution for a given polarization state

CP-violating terms

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

$$\begin{aligned}\mathcal{U}_{\pm} = \pm e^{-\Gamma t} \times & \left[\sin(\delta_\perp - \delta_\parallel)\cos(\underline{\Delta m_s} t)\right. \\ & - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\underline{\Delta m_s} t) \\ & \left.\pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right],\end{aligned}$$

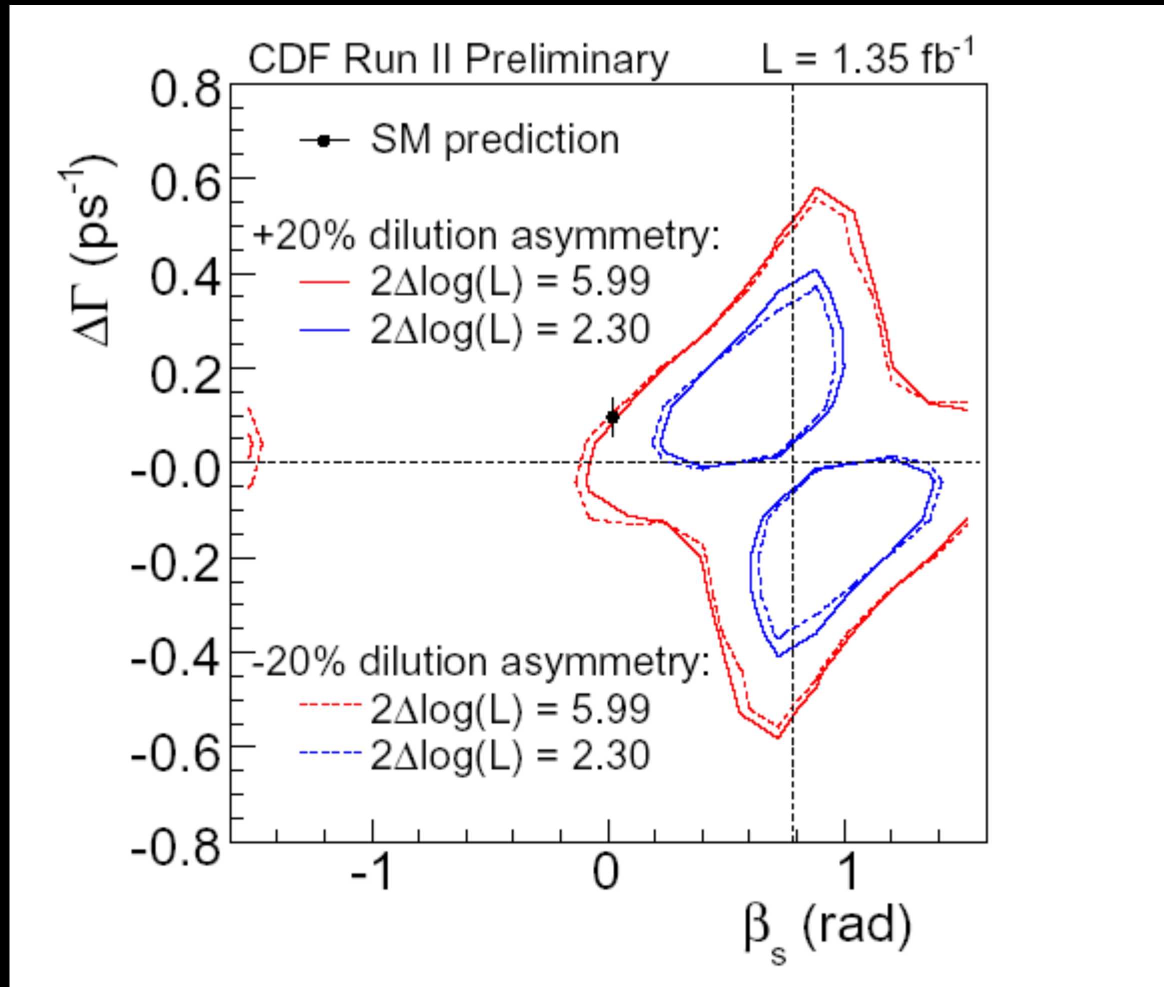
$$\begin{aligned}\mathcal{V}_{\pm} = \pm e^{-\Gamma t} \times & \left[\sin(\delta_\perp)\cos(\underline{\Delta m_s} t)\right. \\ & - \cos(\delta_\perp)\cos(2\beta_s)\sin(\underline{\Delta m_s} t) \\ & \left.\pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right].\end{aligned}$$

Knowledge of B^0_s mixing frequency needed

"Strong" phases: $\delta_\perp = \arg[A_\perp{}^*A_0]$, $\delta_\parallel = \arg[A_\parallel{}^*A_0]$,

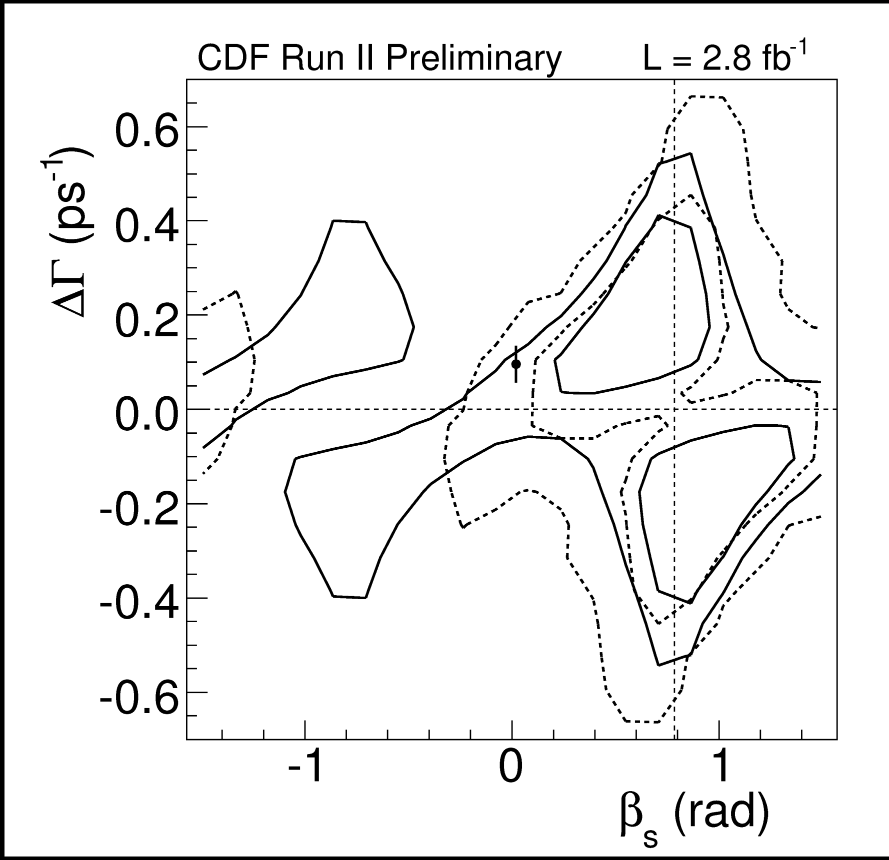
Dilution asymmetries

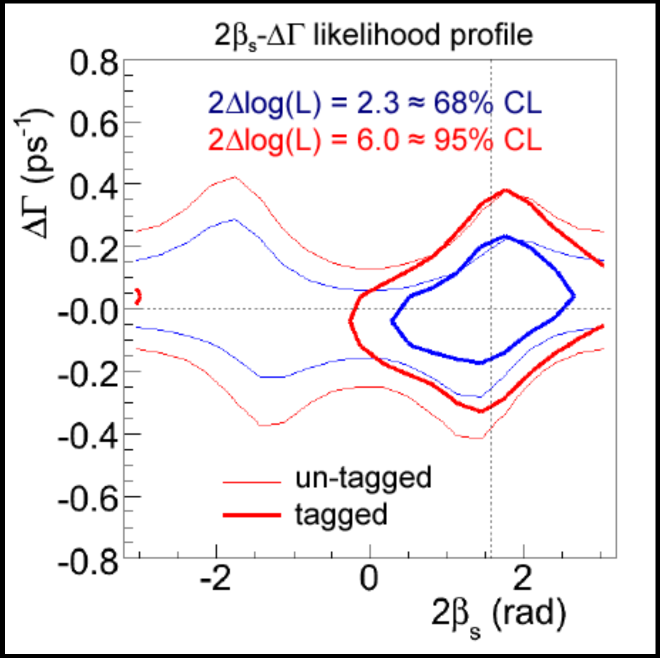
Insert an artificial 20% asymmetry in dilution between matter and antimatter and check the effect on confidence region



Contours: New vs "Old"

w/o tagging Likelihood gets sensitive to $|\sin 2\beta_{s|}$ instead of $\sin 2\beta s$. Solutions increase 2→4 due to additional likelihood symmetries.





Global fit

FIRST EVIDENCE OF NEW PHYSICS IN b $\leftrightarrow$ s TRANSITIONS

(UT*fit* Collaboration)

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

Arxiv:0803.0658v1[hep-ex]
March, 5, 2008

Some caveats:

Do not account for non-Gaussian tails.

Some 'guesswork' to remove from D0 results the assumptions they put in.

I do not believe the 3σ significance figure is rigorously derived.