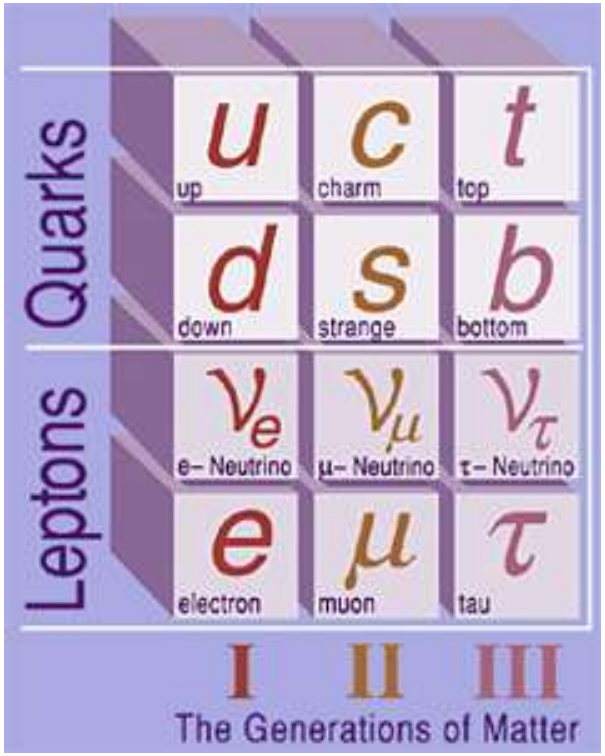
Searches for FCNC Decays $B_{s(d)} \rightarrow \mu^+\mu^-$

- Motivation
- Tevatron and CDF
- Analysis Method
- Results
- Conclusion

Matthew Herndon, February 2005
Johns Hopkins University
University of Minnesota High Energy Physics Seminar

The Standard Model

- Successes of the Standard Model
  - Simple comprehensive theory
    - Explains the hundreds of common particles: atoms, protons, neutrons, electrons
    - Explains the interactions between them
  - Basic building blocs
    - 6 quarks: up, down...
    - 6 leptons: electrons...
    - Force carrier particles: photon...



- All common matter particles are composites of the quarks & leptons which interact by the exchange of force carrier particles

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

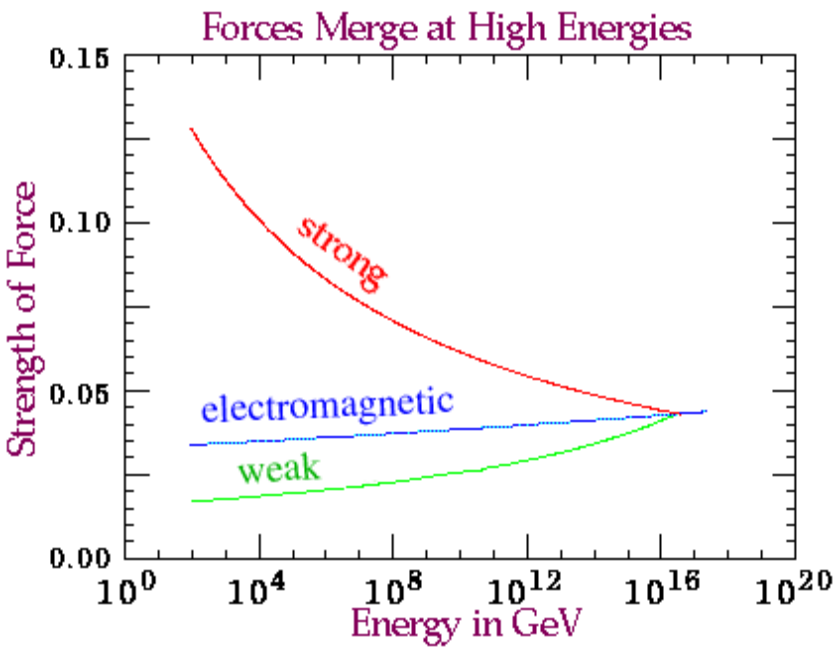
Predictions of the Standard Model have been verified to high precision

Beyond the Standard Model

- Why look for physics beyond the Standard Model

Standard Model fails to answer many fundamental questions

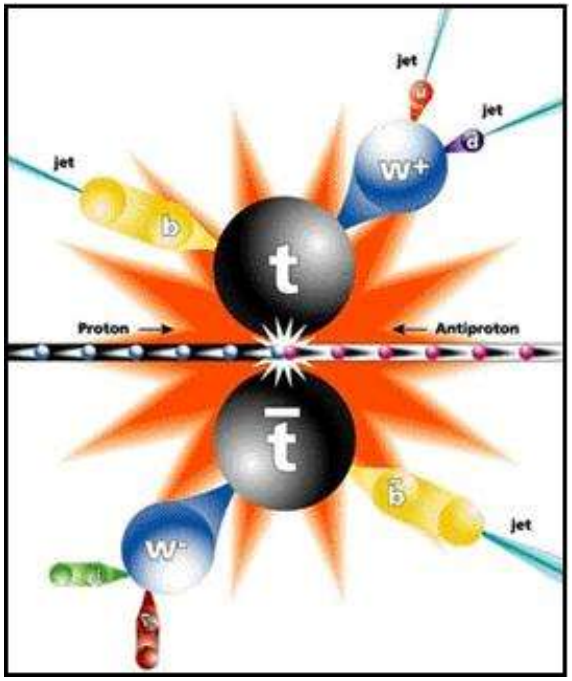
- Gravity not a part of the SM
- What is the very high energy behavior?
  - At the beginning of the universe?
  - Grand unification of forces?
- Antimatter?
  - Why is the observed universe mostly matter?
- Dark Matter?
  - Astronomical observations of gravitational effects indicate that there is more matter than we see



Look for new physics that would explain these mysteries:
SUSY, Extra Dimensions ...

Searches For New Physics

- How do you search for new physics at a collider?
  - Direct searches for production of new particles
    - Particle-antipartical annihilation
    - Example: the top quark
  - Indirect searches for evidence of new particles
    - Within a complex decay new particles can occur virtually



- Tevatron is at the energy frontier and a data volume frontier
  - So much data that we can look for some very unusual decays
- Where to look
  - Many weak decays of *B* and charm hadrons are very low probability
  - Look for contributions from other low probability processes – Non Standard Model

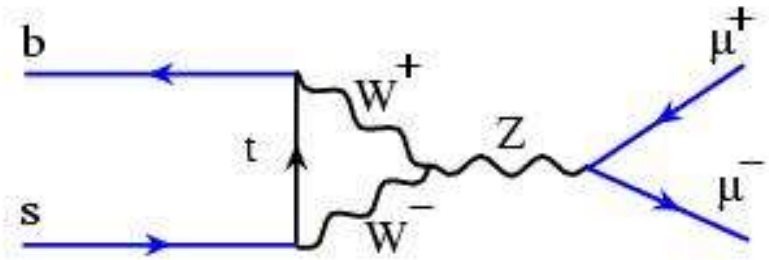
A unique window of opportunity to find new physics before the LHC

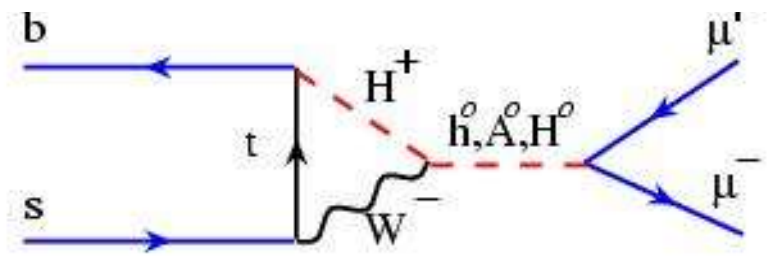
$B_s \rightarrow \mu\mu$: Beyond the SM

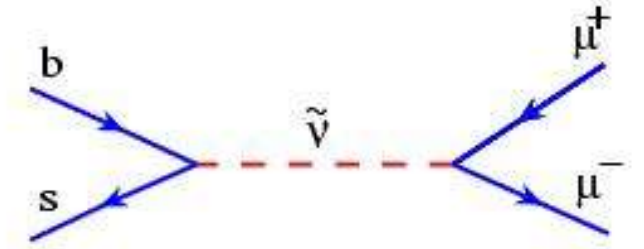
- Look at decays that are suppressed in the Standard Model: $B_{s(d)} \rightarrow \mu^+\mu^-$
  - Flavor changing neutral currents(FCNC) to leptons
    - No tree level decay in SM
    - Loop level transitions: suppressed
    - CKM , GIM and helicity(m_l/m_b): suppressed
    - SM: $BF(B_{s(d)} \rightarrow \mu^+\mu^-) = 3.5\times10^{-9}(1.0\times10^{-10})$

      G. Buchalla, A. Buras, Nucl. Phys. B398,285
- New physics possibilities
  - Loop: MSSM: mSugra, Higgs Doublet
    - 3 orders of magnitude enhancement
    - Rate $\propto \tan^6\beta/(M_A)^4$

      Babu and Kolda, Phys. Rev. Lett. 84, 228
  - Tree: R-Parity violating SUSY



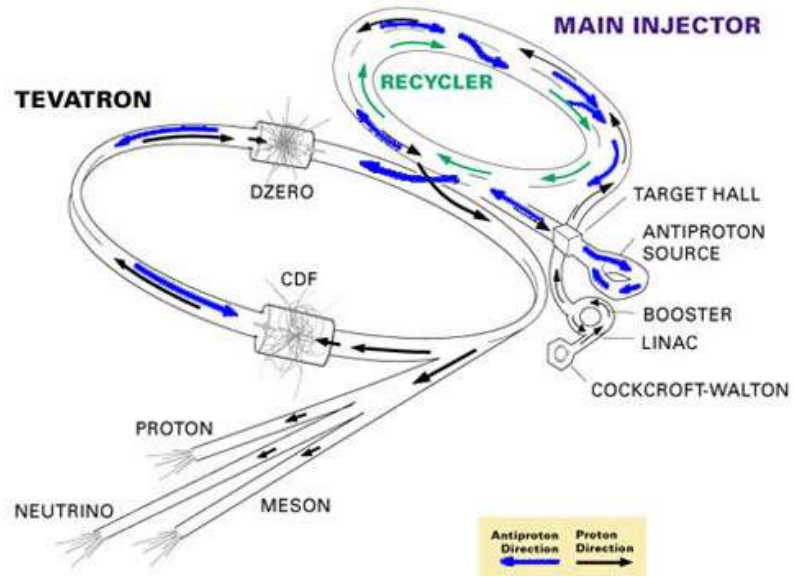


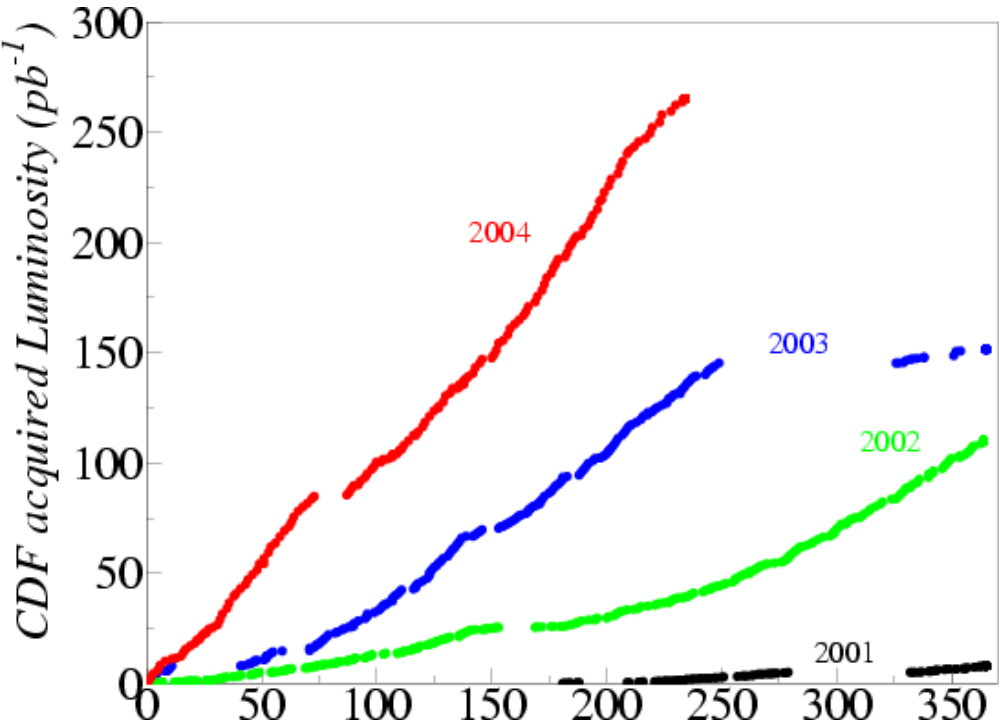


One of the best indirect search channels at the Tevatron

CDF and the Tevatron

- 1.96TeV $p\bar{p}$ collider
  - Performance substantially improving each year
  - Record peak luminosity in 2004: $1\times10^{32}\text{sec}^{-1}\text{cm}^{-2}$, 2x peak in 2003
  - Expect 2x in 2005, 4-9fb^{-1} by 2009



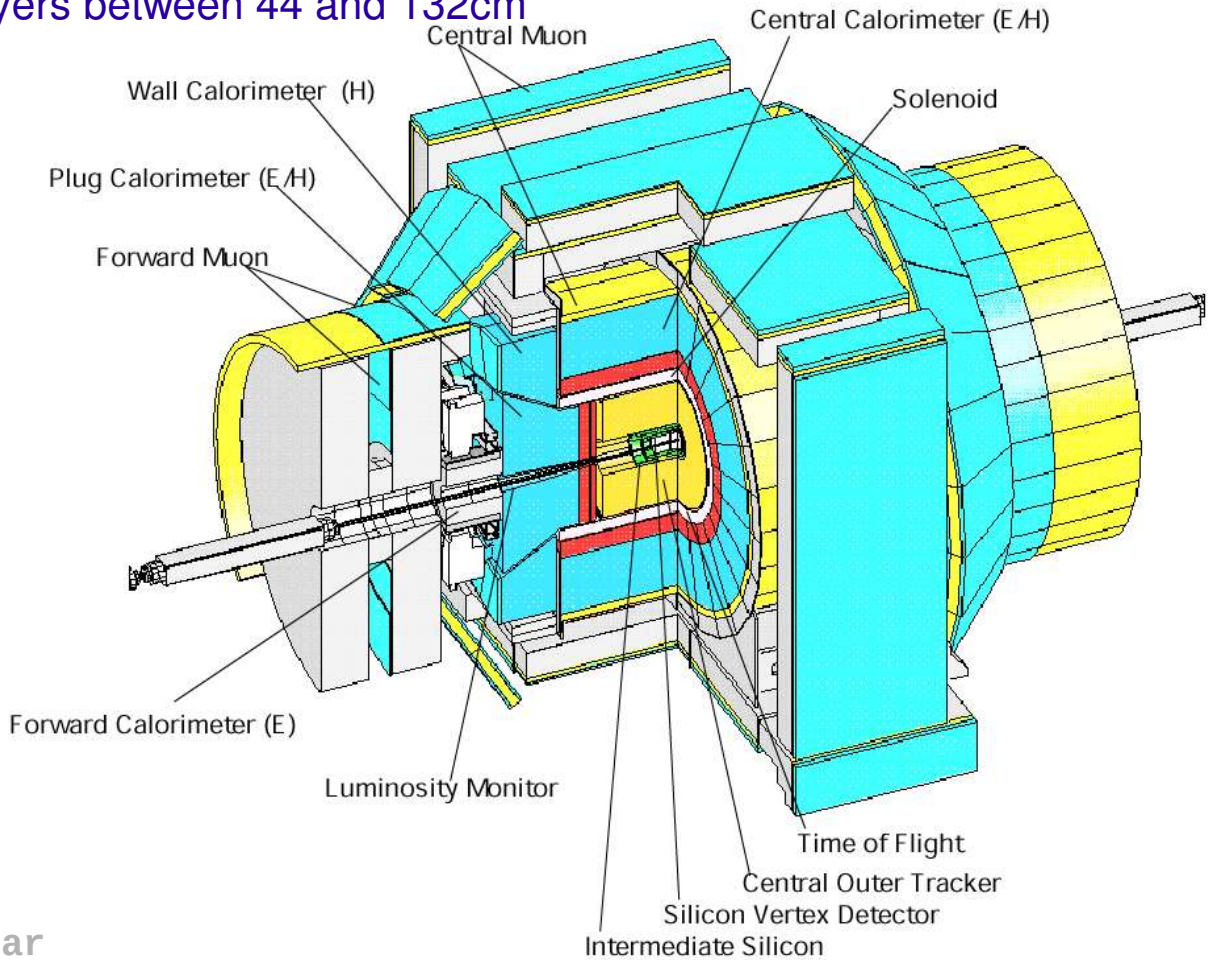


- CDF Integrated Luminosity
  - ~364pb^{-1} with good run requirements
    - All critical systems operating including silicon
  - Analyses presented here use 171pb^{-1} and 364pb^{-1}
  - Acquiring new data quickly in 2005

$B_{s(d)} \rightarrow \mu^+\mu^-$ benefits from new data

CDF Detector

- Silicon Tracker **EXCELLENT TRACKING**
  - $|\eta|<2$, 90cm long, r_{L00} =1.3 - 1.6cm
- Drift Chamber(COT)
  - 96 layers between 44 and 132cm
- Muon coverage
  - $|\eta|<1.5$
  - Triggered to $|\eta|<1.0$
  - Outer chambers: high purity muons



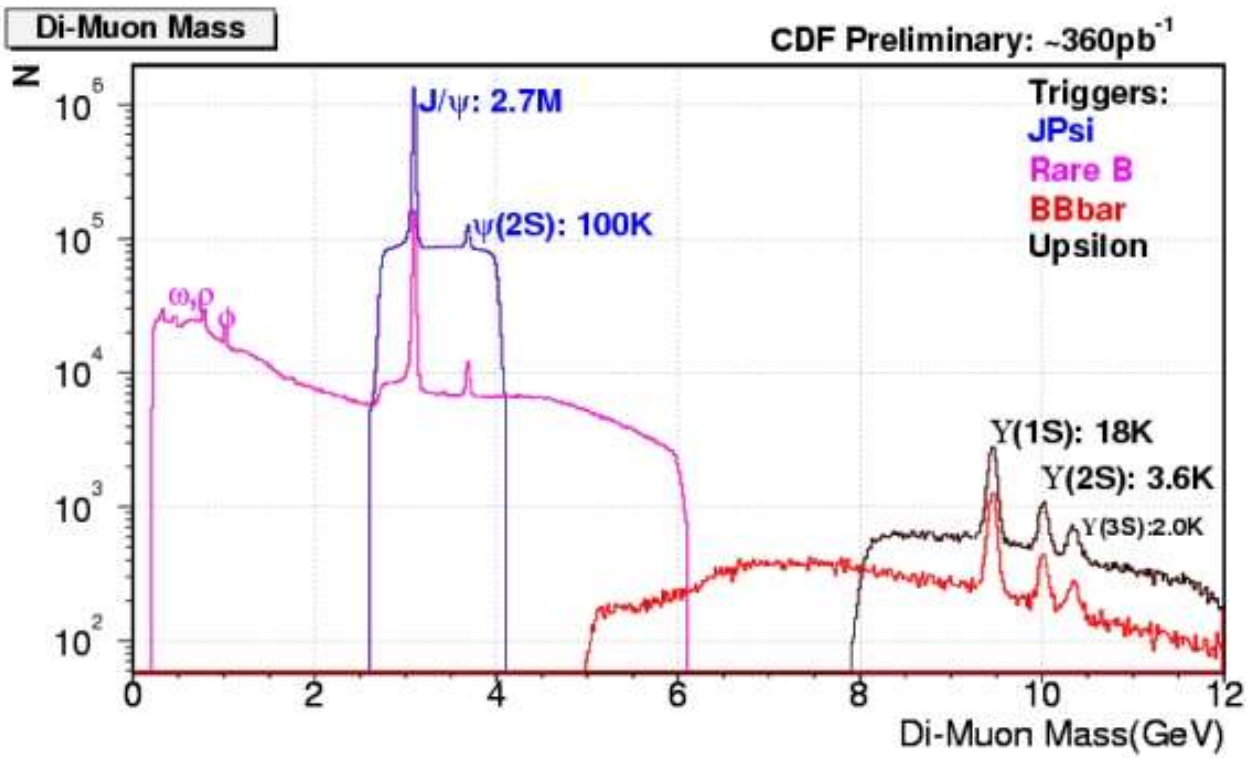
Rare *B* Decay Physics & Triggers

- Large production rates
  - $\sigma(p\bar{p} \rightarrow bX, |y| < 1.0, p_T(B) > 6.0\text{GeV/c}) = \sim 30\mu b, \sim 10\mu b$
- All heavy *b* states produced
  - $B^0, B^+, B_s, B_c, \Lambda_b, \Xi_b$
- Backgrounds: >3 orders of magnitude higher
  - Inelastic cross section ~100 mb
  - Challenge is to pick one *B* decay from $>10^3$ other QCD events
- Di-muon trigger
  - $p_T(\mu) > \sim 1.5$ GeV/c, $|\eta| < \sim 1.0$
  - *B* yields 2x Run I (lowered p_T threshold, increased acceptance)
- Di-muon triggers for rare decay physics
  - $B_{s(d)} \rightarrow \mu^+\mu^-$, $B^+ \rightarrow \mu^+\mu^- K^+$, $B^0 \rightarrow \mu^+\mu^- K^{*0}$, $B_s \rightarrow \mu^+\mu^- \phi$, $\Lambda_b \rightarrow \mu^+\mu^- \Lambda$
  - Trigger on di-muon masses from near 0GeV/c^2 to the above B_s mass
  - Reduce rate by requiring outer muon chamber hits: $p_T(\mu) > \sim 3.0$ GeV/c or $\Sigma p_{T\mu} > 5.0$GeV/c

100s of Millions of B Hadrons

TRIGGERS ARE CRITICAL

$B_s \rightarrow \mu\mu$: Experimental Challenge



- Primary problem is large background at hadron colliders
  - Analysis and trigger cuts must effectively reduce the large background around $m_{Bs} = 5.37 GeV/c^2$ to find a possible handful of events
- Key elements of the analysis are determining the efficiency and rejection of the discriminating variables and estimating the background level

Analysis Method

$$BF(B_s \to \mu^+\mu^-) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \epsilon_{total} \cdot 2 \cdot \sigma_{B_s} \cdot \int Ldt}$$

- Performing this measurement requires that we
  - Demonstrate an understanding of the background
  - Optimize the cuts to reduce the background
  - Accurately estimate α and ε: for triggers, reconstruction and selection cuts
- SM predicts 0 events, this is essentially a search
  - Emphasis on accurately predicting the N_{bg} and performing an unbiased optimization
- Employed a blind analysis method
  - Blind ourselves to the signal region
  - Estimate background from sidebands and test background predictions in orthogonal samples

Data Sample

- Start the with di-muon trigger
  - 2 CMU muons: $p_T(\mu) > \sim 1.5$ GeV/c, $|\eta| < \sim 0.6$ with $\Sigma p_{T\mu} > 5.0$GeV/c
  - 1 CMUP muon: $p_T(\mu) > \sim 3.0$ GeV/c and 1 CMU muon

76K Events

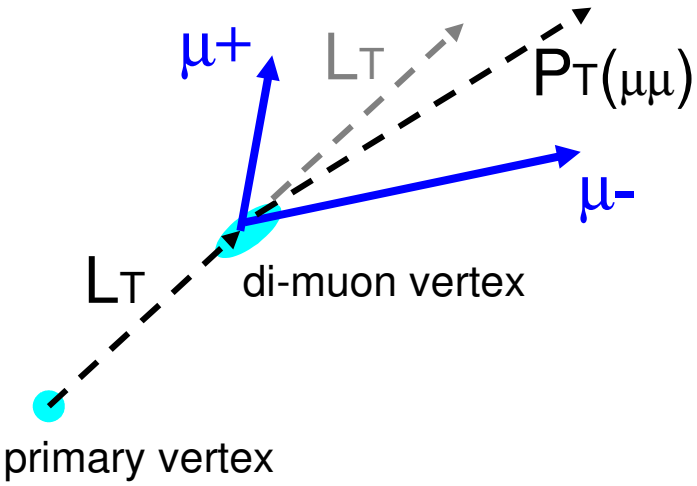
- Apply basic quality cuts
  - Track quality cuts: numbers of hits in our tracking system
  - Good match between tracks and the hits in the muon system: $\chi^2 < 9$
  - In the mass region around the B_s: $4.669 < M_{\mu\mu} < 5.969$ GeV/c^2
    - Blind region: $4\sigma(M_{\mu\mu})$, $5.169 < M_{\mu\mu} < 5.469$ GeV/c^2
    - Sideband region 0.5 GeV/c^2 on either side of the blinded region
  - Vertex quality cuts
  - $P_T(\mu^+\mu^-) > 6.0$ GeV/c
  - Rejects 96% of the background

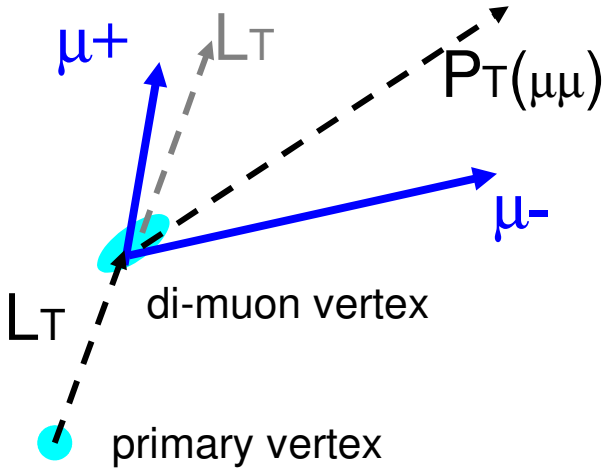
2984 Events

- Sample still background dominated
  - Expect < 15 $B_{s(d)} \rightarrow \mu^+\mu^-$ events to pass these cuts: based on the run 1 limit

Signal vs. Background

- Need to discriminate signal from background
  - Reduce background by a factor of > 1000
- Signal characteristics
  - Final state fully reconstructed
  - B_s is long lived ($c\tau$ = 438 μm)
  - B fragmentation is hard: few additional tracks
- Background contributions and characteristics
  - Sequential semi-leptonic decay: $b \to c\mu^- X \to \mu^+\mu^- X$
  - Double semileptonic decay: $b\bar{b} \to \mu^+\mu^- X$
  - Continuum $\mu^+\mu^-$, μ + fake, fake+fake
    - Note: $B \to hh$ background negligible: 1×10^{-9}
  - Partially reconstructed, short lived, has additional tracks

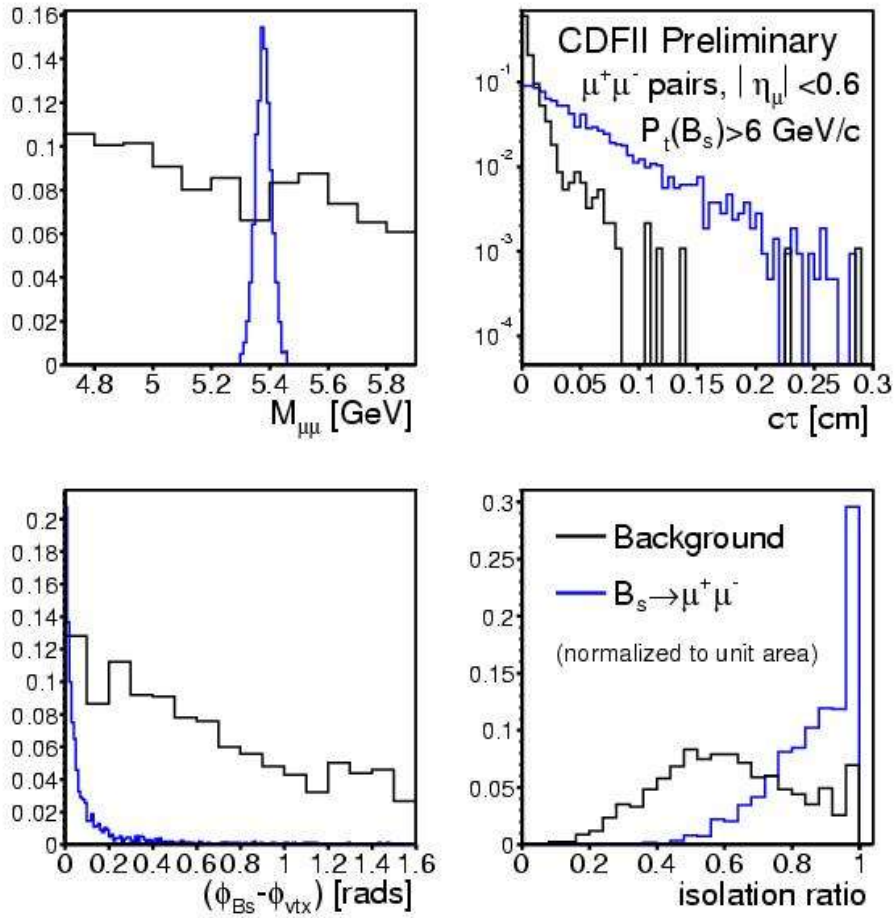




Cut on mass, lifetime, how well p_T points to the vertex and isolation

Discriminating Variables

- 4 primary discriminating variables



- Mass M
  - choose 3σ window: σ = 27MeV/c²
- $c\tau$: $L_{xy} \times M/p_{TB}$
- $\Delta\Phi$: $|\phi_B - \phi_{vtx}|$
- Isolation: $p_{TB}/(\Sigma trk + p_{TB})$
- Optimization
  - Unbiased optimization
  - Use simulated signal and data sidebands
  - Optimize based on likely physics result
    - *a priori* expected BF limit

$$<BF(B_s \to \mu^+\mu^-)> = \frac{<N_{signal}^{90\%CL}>}{\alpha \cdot \epsilon_{total} \cdot 2 \cdot \sigma_{B_s} \cdot \int Ldt}$$

$$<N_{signal}^{90\%CL}> = \sum_{n_{obs}=0}^{\infty} P(n_{obs}|n_{bg}) \cdot N_{signal}^{90\%CL}(n_{bg}, \Delta_{bg}, \Delta_{\alpha,\epsilon})$$

Background Estimate

- Estimate the background for any given set of requirements
  - Typical method: apply all cuts at see how many sideband events pass
    - Optimal cuts may be chosen to reject 1-2 unusual events
  - Factorize: Look at each cut separately: more statistics with other cuts not applied

$$n_{bg} = n_{sb}(c\tau, \Delta\Phi) \cdot f_{iso} \cdot f_M$$

n_{sb}: number of events passing a set of $c\tau$ and $\Delta\Phi$ cuts

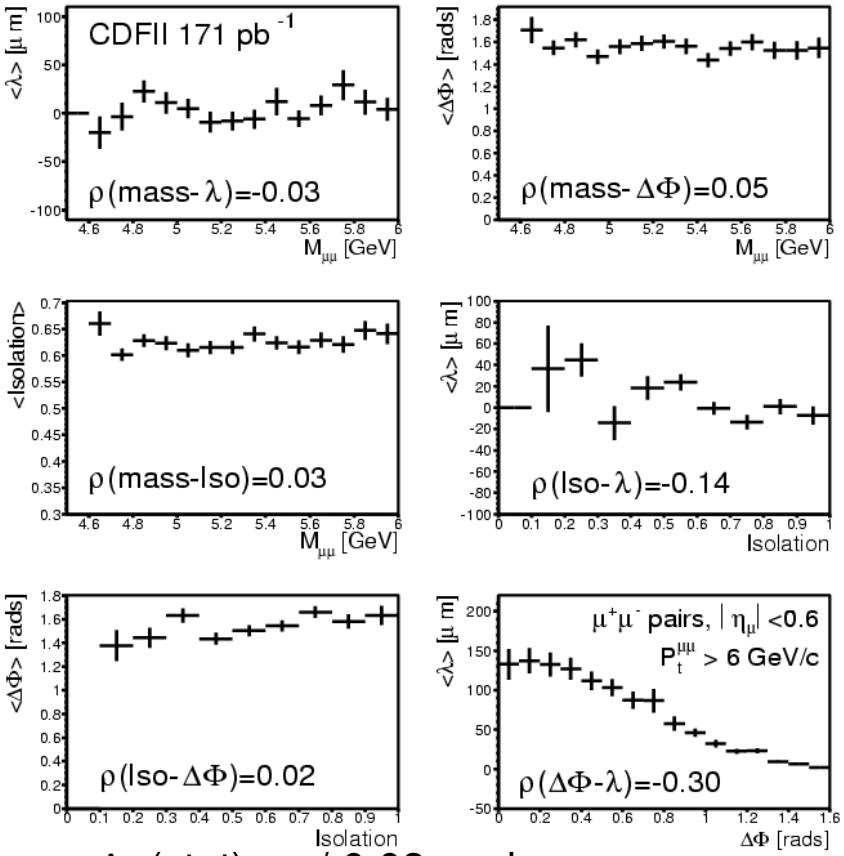
f_{iso}: fraction of events passing an isolation cut

f_M: ratio of events in signal and sideband regions

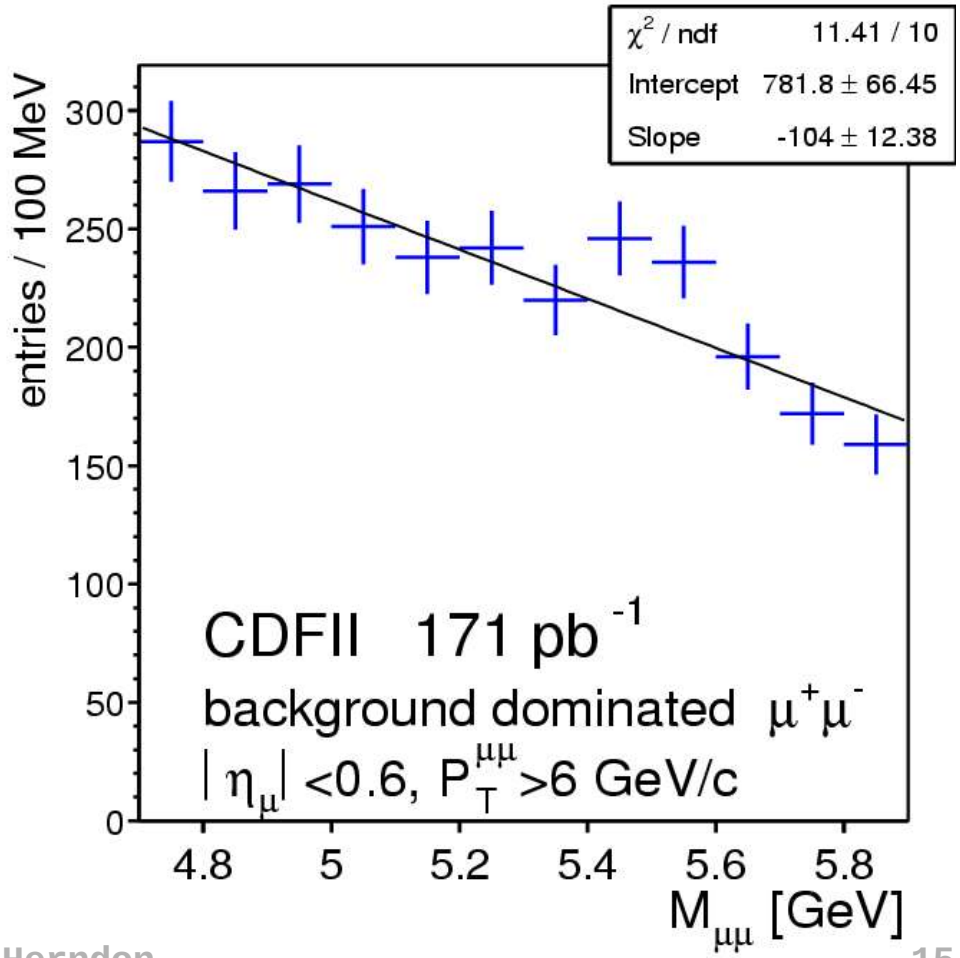
- Need to show that independent sets of cuts are uncorrelated
- Need to show that mass is linear

Correlations and Mass

- Using our background dominated data sample
  - Calculate linear coefficients of correlation for each pair of selection variables: good
  - Examine linearity of mass plot: whole region: good



Δρ(stat) = +/-0.03 each

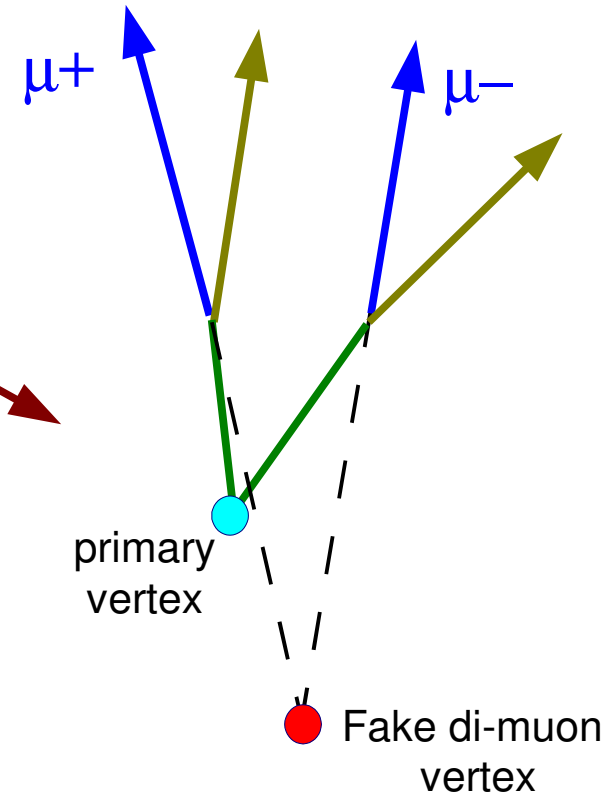


Background Cross-Checks

- Demonstrate accuracy of the factorization method

Analysis dependent on an accurate background estimate

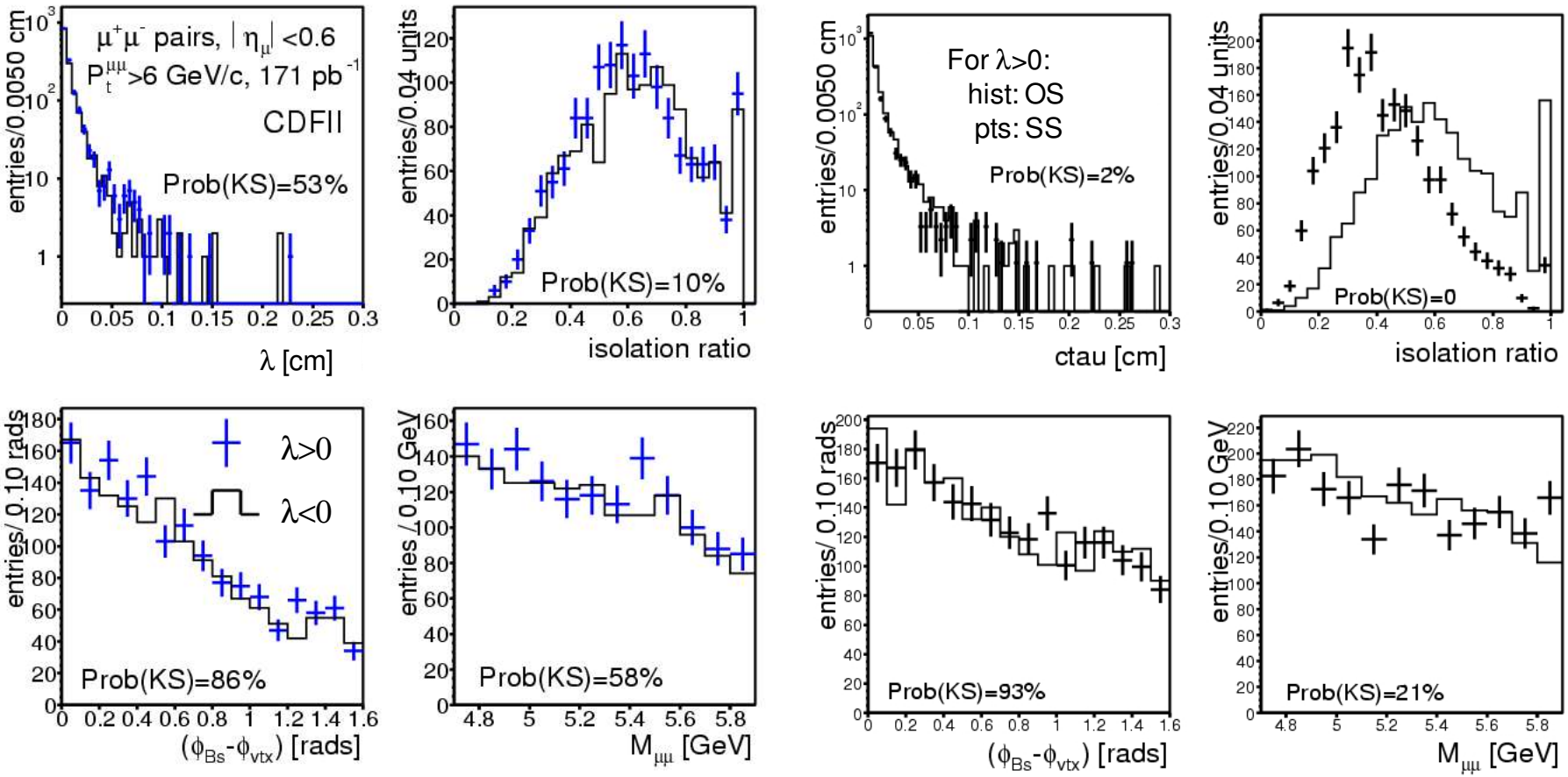
- Use independent data samples to test
  - OS-: opposite sign muons, negative lifetime (signal sample is OS+)
  - SS+ and SS-: same sign muons, positive and negative lifetime
  - OS- and OS+ fake μ enhanced, one μ fails the muon reconstruction quality cuts
- Compare predicted vs. observed # of bg. events: 3 sets of cuts
  - A: $c\tau > 100\mu m$, $\Delta\Phi < 0.2$ rad, Iso > 0.6
  - B: $c\tau > 150\mu m$, $\Delta\Phi < 0.2$ rad, Iso > 0.7: Near optimal cuts
  - C: $c\tau > 200\mu m$, $\Delta\Phi < 0.1$ rad, Iso > 0.8



Bg. Cross-Checks Cont.

OS+ vs. OS-

OS+ vs. SS+



- OS- Excellent control sample:
- SS could represent some $b\bar{b}$ backgrounds

Bg. Cross-Check Results

	Sample	#predicted	#obsvd	P(>=obs|pred)
A	OS-	10.43 +/- 1.89	16	4%
	SS+	5.80 +/- 0.98	4	83%
	SS-	6.72 +/- 1.10	7	51%
	Sum	22.94 +/- 3.14	27	
B	OS-	3.69 +/- 0.80	6	17%
	SS+	1.83 +/- 0.35	1	84%
	SS-	2.32 +/- 0.42	4	20%
	Sum	7.84 +/- 1.19	11	
C	OS-	0.64 +/- 0.22	1	47%
	SS+	0.29 +/- 0.08	0	75%
	SS-	0.27 +/- 0.08	1	24%
	Sum	1.21 +/- 0.27	2	

- For all samples and all cuts the predictions are consistent with the obs. #s

More Cross-Check Results

- Fake μ enhanced sample
  - Reduces signal efficiency by a factor of 50
  - Increases background by a factor of 3

fake enhanced sample

		#predicted	#obsvd
A	$c\tau > 0$	20.52 +/- 3.17	17
	$c\tau < 0$	22.33 +/- 3.41	22
B	$c\tau > 0$	6.52 +/- 1.15	4
	$c\tau < 0$	7.33 +/- 1.25	11
C	$c\tau > 0$	0.83 +/- 0.23	1
	$c\tau < 0$	0.97 +/- 0.25	1

- Fake μ cross-checks: predictions consistent with obs. #s
- All tests of background estimates all look good!

Acceptance & Efficiencies

$$\alpha \cdot \epsilon_{total} = \alpha \cdot \epsilon_{trig} \cdot \epsilon_{reco} \cdot \epsilon_{final}$$

From MC

$$\epsilon_{trig} = \epsilon_{L1} \cdot \epsilon_{L3}$$

From Data

$$\epsilon_{final} = \epsilon_{c\tau} \cdot \epsilon_{\Delta\Phi} \cdot \epsilon_{Iso} \cdot \epsilon_{mass}$$

From MC: Checked with Data

$$\epsilon_{reco} = \epsilon_{\cot} \cdot \epsilon_{muon} \cdot \epsilon_{svx} \cdot \epsilon_{vtx}$$

From Data

Second critical part of the analysis is estimating the efficiencies

- ε: efficiency - from data where possible
  - Using $J/\psi \rightarrow \mu^+\mu^-$ and $B^+ \rightarrow J/\psi K^+$ data and special unbiased J/ψ triggers

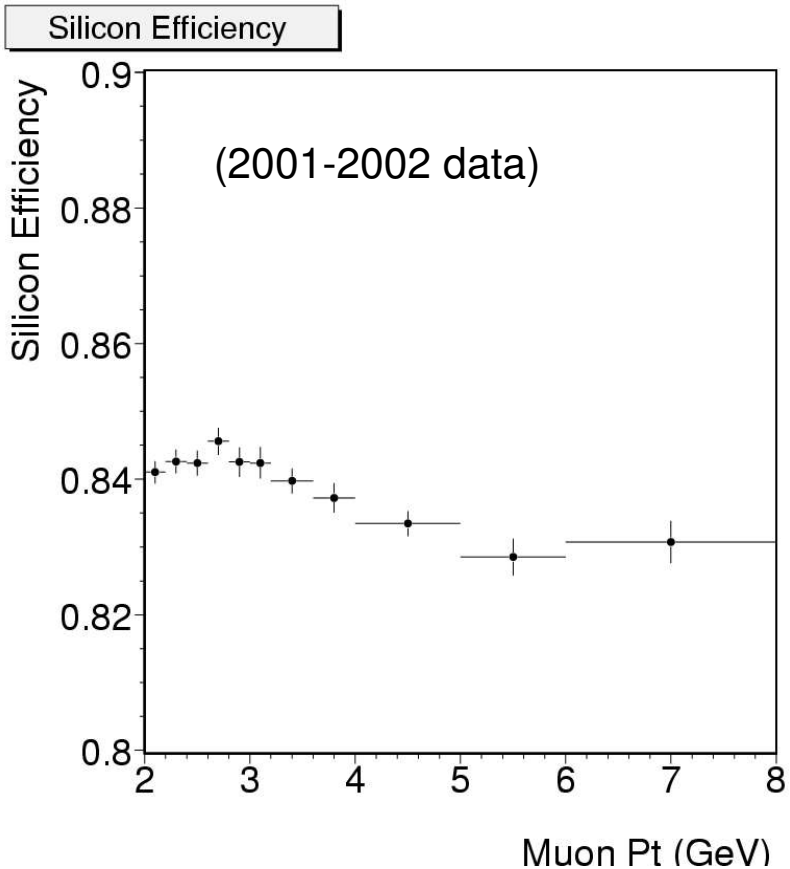
Acceptance

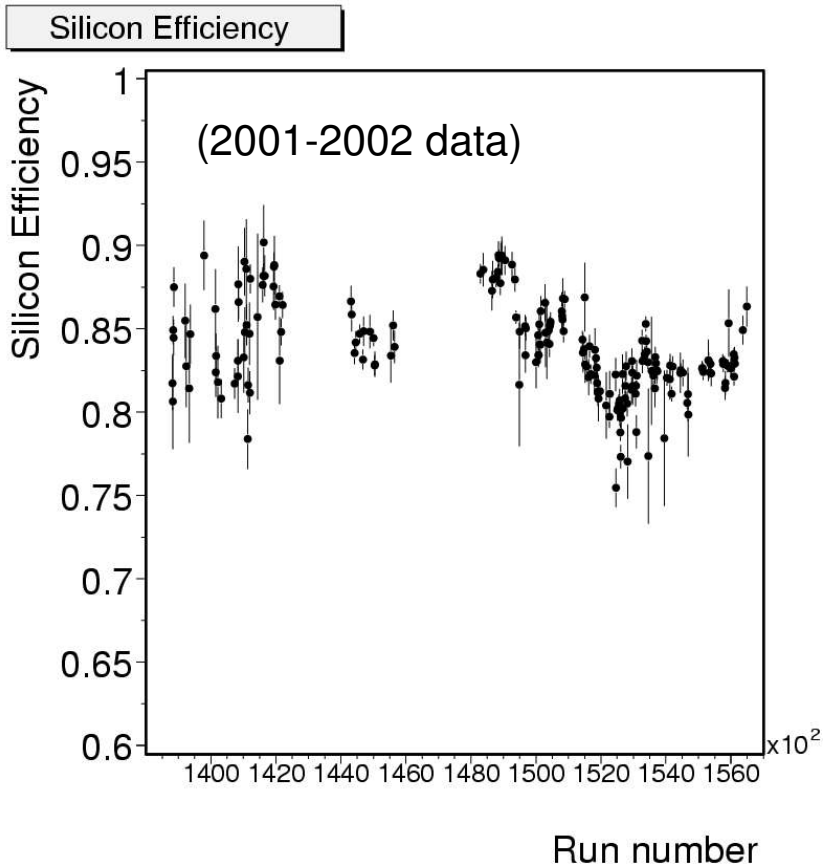
- α : Acceptance
  - Events which fall within the geometric acceptance of the detector
  - Satisfy the kinematic requirements of the trigger
  - Relative to $p_T(B) > 6.0$ GeV/c and $|y(B)|<1.0$
    - Allows normalization to Run 1 cross section measurement
- Evaluated using Pythia MC

	acceptance
α(CMU-CMU)	0.64%
α(CMUP-CMU)	0.02%
α(CMU-CMU && CMUP-CMU)	5.90%
α(CMU-CMU || CMUP-CMU)	(6.56 +/- 0.45)%

SVX Efficiency

- Measurement of the efficiency of adding silicon hits to COT tracks
  - Use $J/\psi \rightarrow \mu^+\mu^-$ data

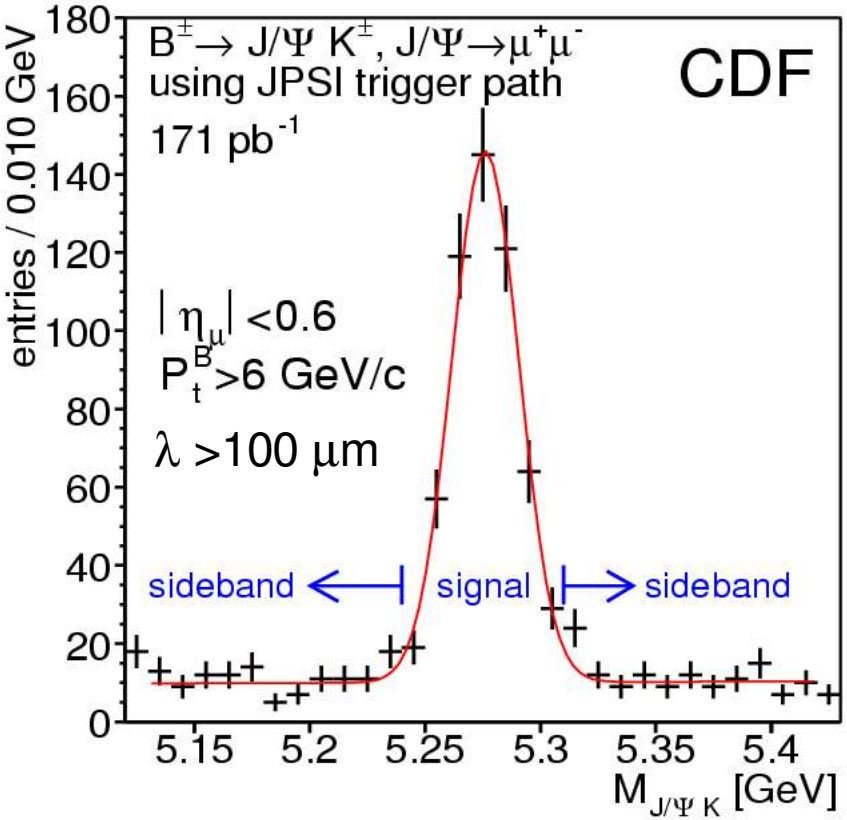




- $\varepsilon_{SVX} = 74.5 \pm 0.3(\text{stat}) \pm 2.2(\text{sys})\%$(2001-2003 data)
  - Average efficiency for adding silicon to two tracks

Selection Cut Efficiency

- Efficiencies determined using realistic MC
  - MC efficiencies compared with data using $B^+ \rightarrow J/\psi K^+$ and $J/\psi \rightarrow \mu^+\mu^-$ samples



- Lifetime selection cut
  - Normalized to cτ > 50 μm

	Data(obsvd)	MC(pred)
cτ>100 μm	473 +/- 15	451 +/- 3
cτ>150 μm	415 +/- 13	408 +/- 4
cτ>200 μm	378 +/- 12	369 +/- 4

- Agreement good
  - Selection cut made at cτ > 150-200 μm

Selection Cut Efficiency Cont.

- Isolation and Pointing Angle cuts

		Data	MC	(Data/MC)
	Iso > 0.6	(95 +/- 2)%	(97 +/- 1)%	0.98 +/- 0.02
	Iso > 0.7	(88 +/- 2)%	(92 +/- 1)%	0.96 +/- 0.03
	Iso > 0.8	(68 +/- 2)%	(79 +/- 2)%	0.87 +/- 0.04
$\lambda > 100\mu m$	$\Delta\Phi < 0.2$	(98 +/- 2)%	(97 +/- 1)%	1.00 +/- 0.02
	$\Delta\Phi < 0.1$	(89 +/- 3)%	(89 +/- 1)%	0.99 +/- 0.03
$\lambda > 150\mu m$	$\Delta\Phi < 0.2$	(99 +/- 1)%	(99 +/- 1)%	1.00 +/- 0.01
	$\Delta\Phi < 0.1$	(92 +/- 2)%	(93 +/- 1)%	0.99 +/- 0.02

- In general agrees to better than 5%: Assign +-5% relative systematic
  - Note: Isolation cuts made around 0.65

Time to Optimize!

Optimization Results

- Tried >100 sets of ($M_{\mu\mu}$, $c\tau$, $\Delta\Phi$, Iso)

Opt for 500 pb^{-1}

- Mass $M_{\mu\mu}$:3σ window: $\sigma = 27 MeV/c^2$
- $c\tau$: $L_{xy} \times M/p_{TB} > 200\mu m$
- $\Delta\Phi$: $|\phi_B - \phi_{vtx}| < 0.10 rad$
- Iso: $p_{TB}/(\Sigma trk + p_{TB}) > 0.65$

- Efficiencies
  - Acceptance: 6.6%
  - ε_{Trig}: 85%, ε_{Reco}: 67%
  - ε_{Final}: 54%

Selection cut eff. high

- $\alpha \times \varepsilon = 2.03 \pm 0.21\%$
- Expected background

  $B_{s(d)}$: $1.05 \pm 0.30 (1.07 \pm 0.31)$

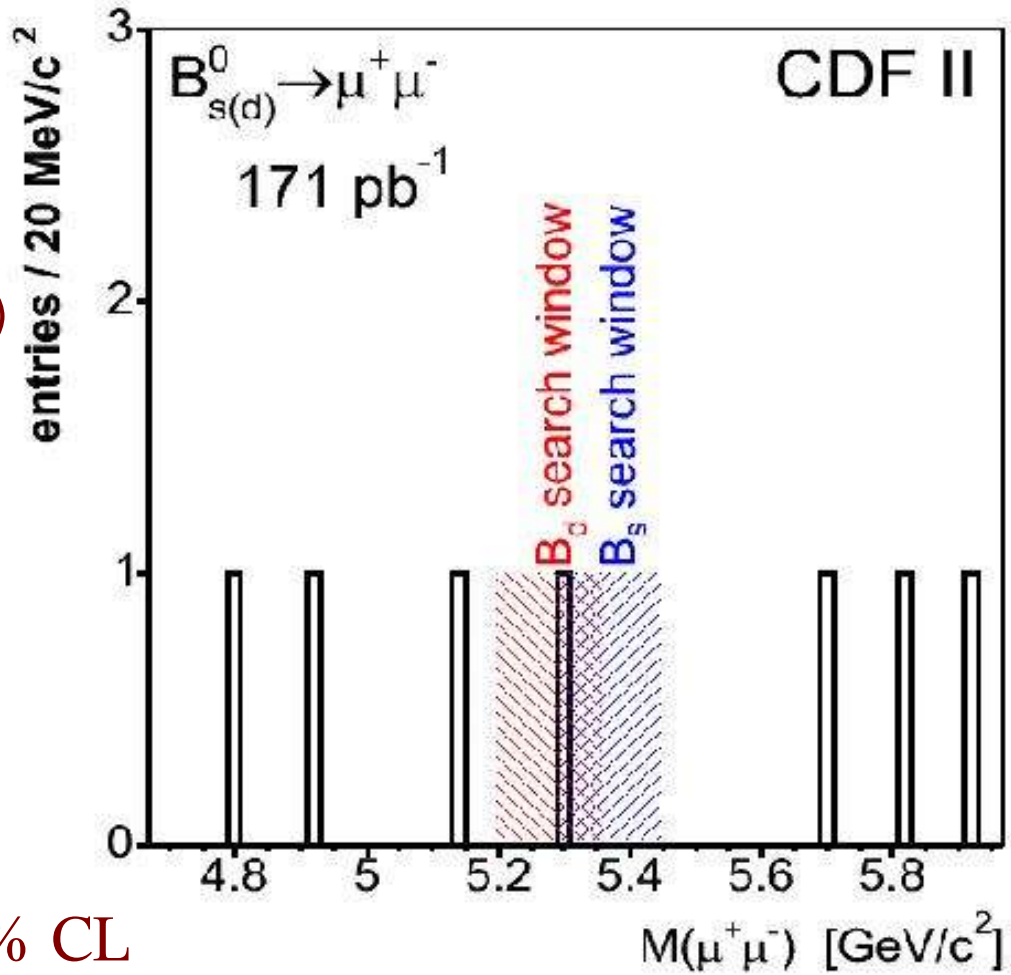
Low background

- Systematic uncertainties
  - Bg. estimation: 29%
    - Statistical error of Bg. pred.
  - Sensitivity: 21%
    - Run 1 cross section and f_s/f_u

a priori limit: 5.9×10^{-7} 90% CL: Time to open the box!

$B_{s(d)} \rightarrow \mu^+\mu^-$ Results

- CDF $B_{s(d)} \rightarrow \mu^+\mu^-$ results
  - $\alpha \times \varepsilon = 2.03 \pm 0.21\%$
  - Expected background $B_{s(d)}$: $1.05 \pm 0.30 (1.07 \pm 0.31)$
  - Expected limit: 5.9×10^{-7}
  - Observe 1 common event in the 3σ $B_{s(d)}$ mass windows



World's best limits(early 2004)

$$BF(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

$$BF(B_d \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-7}\ 90\%\ \mathrm{CL}$$ (4x more B_d produced than B_s)

D. Acosta et al., PRL 93, 032001 2004

$B_{s(d)} \rightarrow \mu^+\mu^-$ Compared

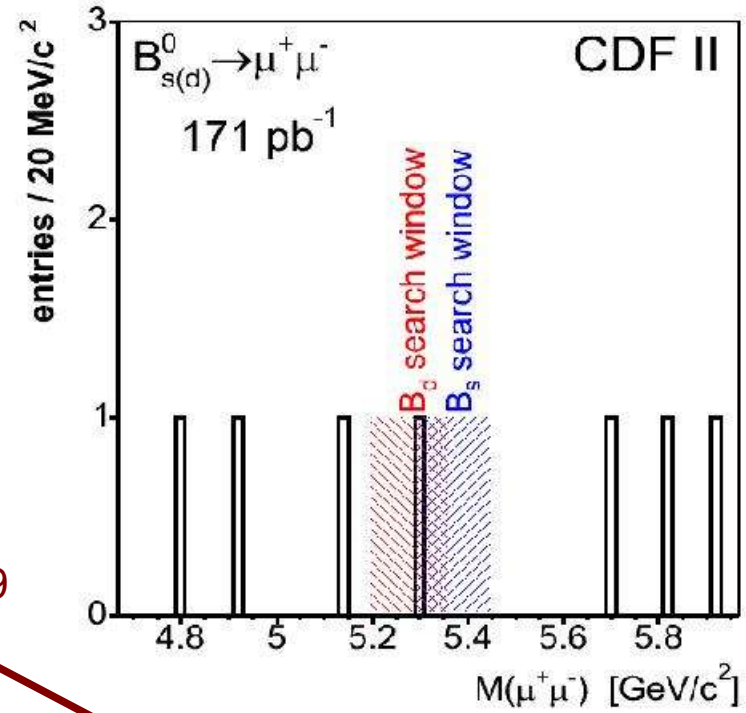
- CDF $B_{s(d)} \rightarrow \mu^+\mu^-$ results: 171pb^{-1}

$$BF(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

$$BF(B_d \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

D. Acosta et al., PRL 93, 032001 2004

- Less than 1/3 of previous CDF limit: 20.0×10^{-7} 90% CL



- D0 B_s result: 240pb^{-1} 4.1×10^{-7} hep-ex/0410039
- BaBar B_d result: 8.3×10^{-8} hep-ex/0408096
- Combined CDF/D0 limit:

  Bayesian approach with a flat prior. Systematic error on fs correlated.

$$BF(B_s \rightarrow \mu^+\mu^-) < 2.9 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

Some work to do – see next!

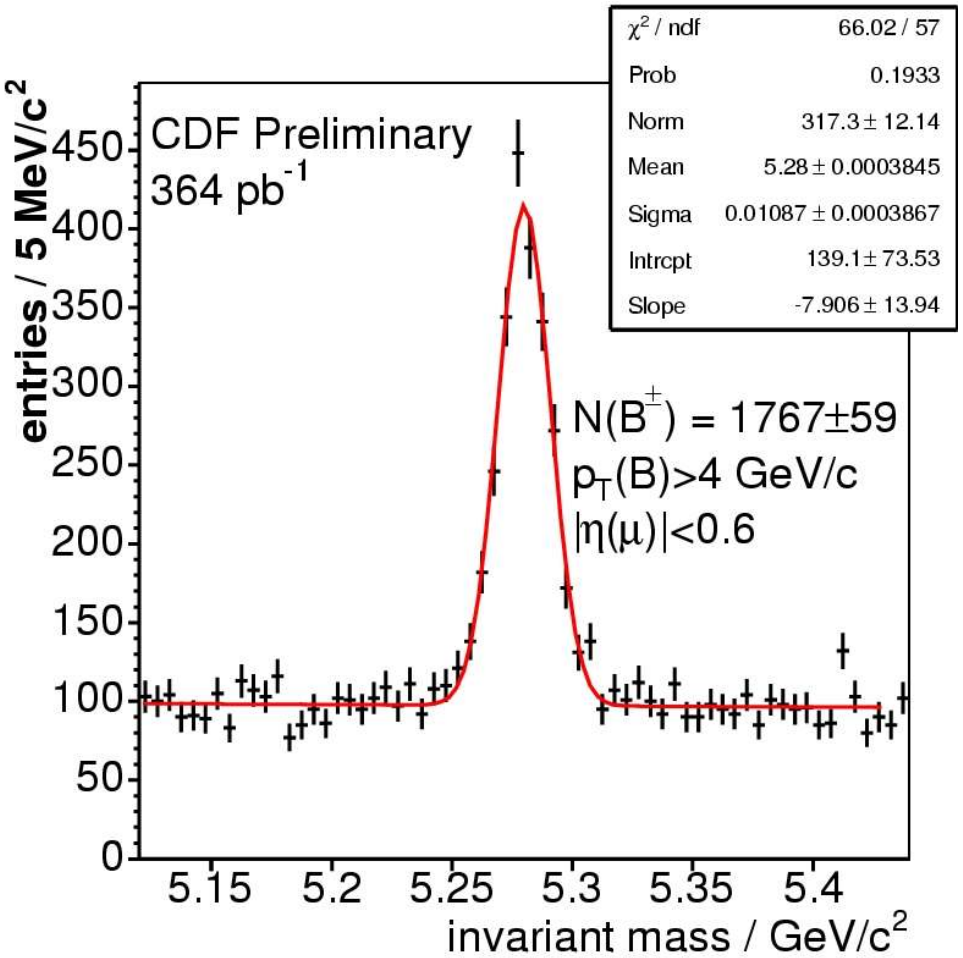
CDF Strikes Back

- Some work to do to improve on the limits of D0 and BaBar

- Expect we can considerably improve our sensitivity
  - More data: 171pb^{-1} → 364pb^{-1}
  - Multivariate discriminate
  - Relative normalization to $B^+ \to J/\psi K^+$

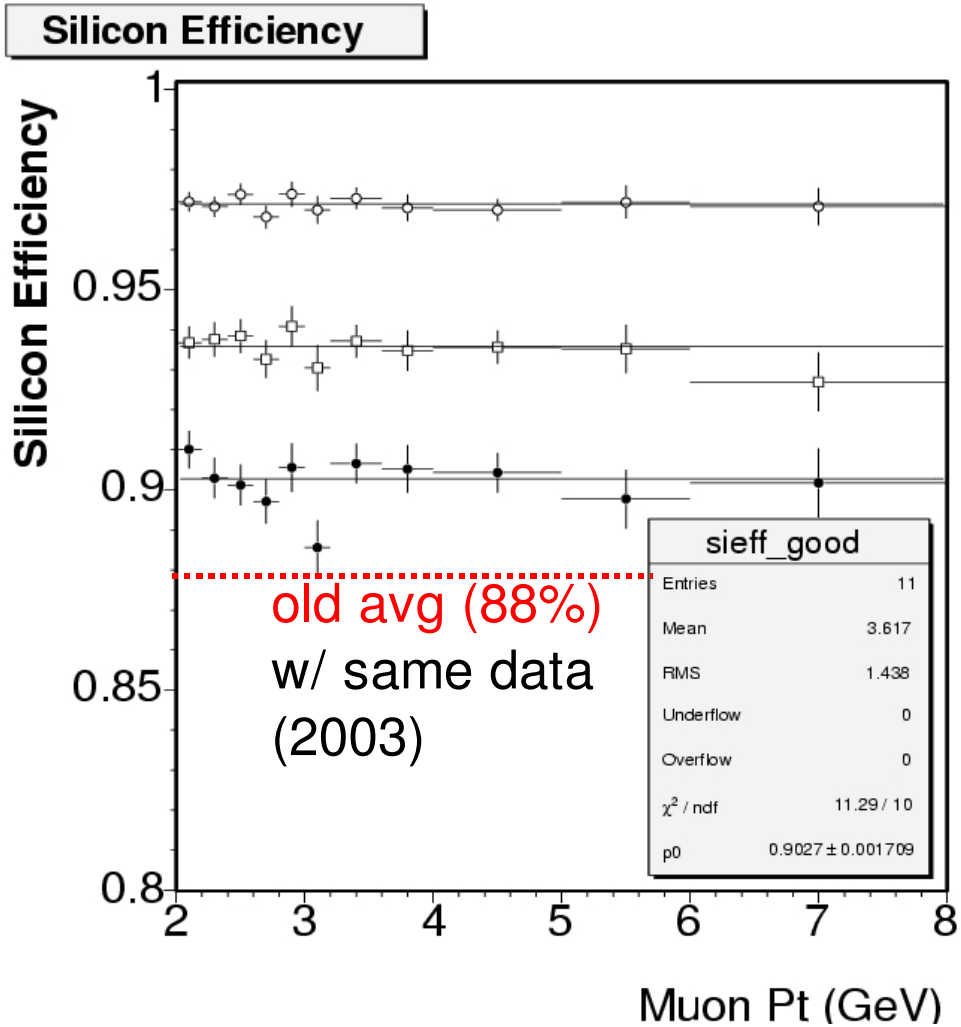
    Eliminates many systematic errors.

    Also allows a lower $p_T(B_s)$ cut
  - Use CMX(~0.6 < |η| < ~1.0)
  - Perform analysis in 3D using pointing angle to primary vertex
  - Improvements in efficiency from new software processing version



New SVX Efficiency

- Improved silicon pattern recognition code and detector performance



traverse >=3 active layers
(unchanged)

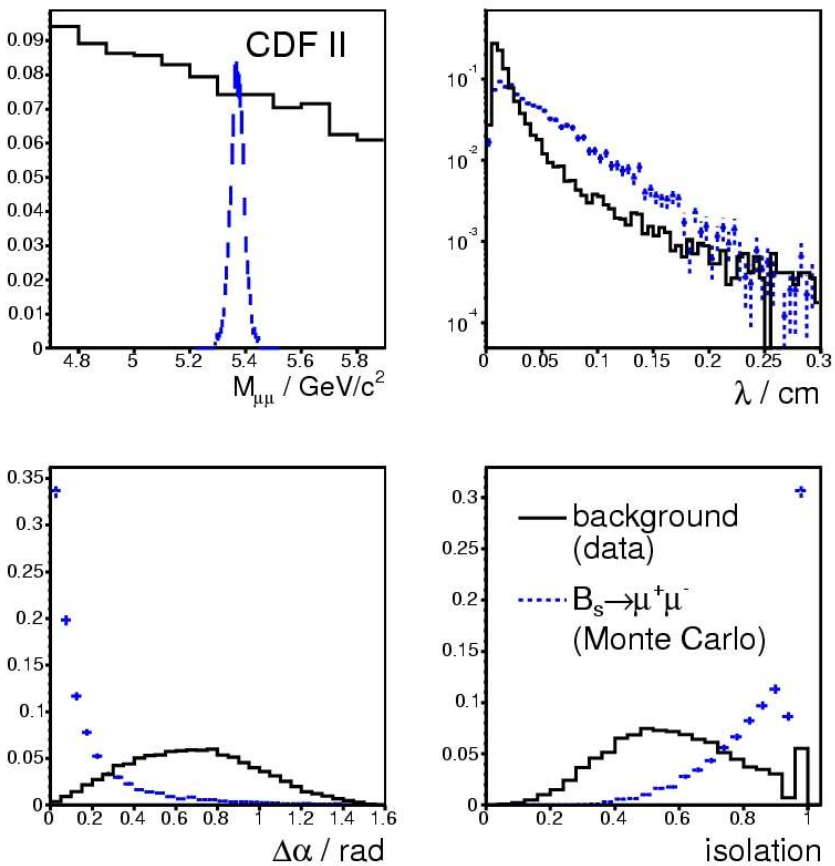
associate >=3 rϕ hits
(+3% absolute, few wrong hits used)

our more stringent requirements
(+2% absolute and flat)

ε_{SVX} = 74.5% → 88.5%

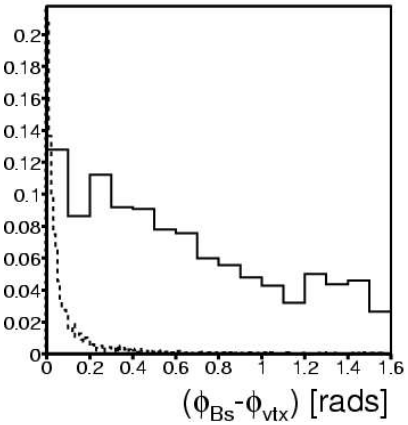
2001-2003 → 2001-2004 data

New Discriminating Variables



$$LH = \frac{\Pi_i P_s(x_i)}{\Pi_i P_s(x_i) + \Pi_i P_b(x_i)}$$

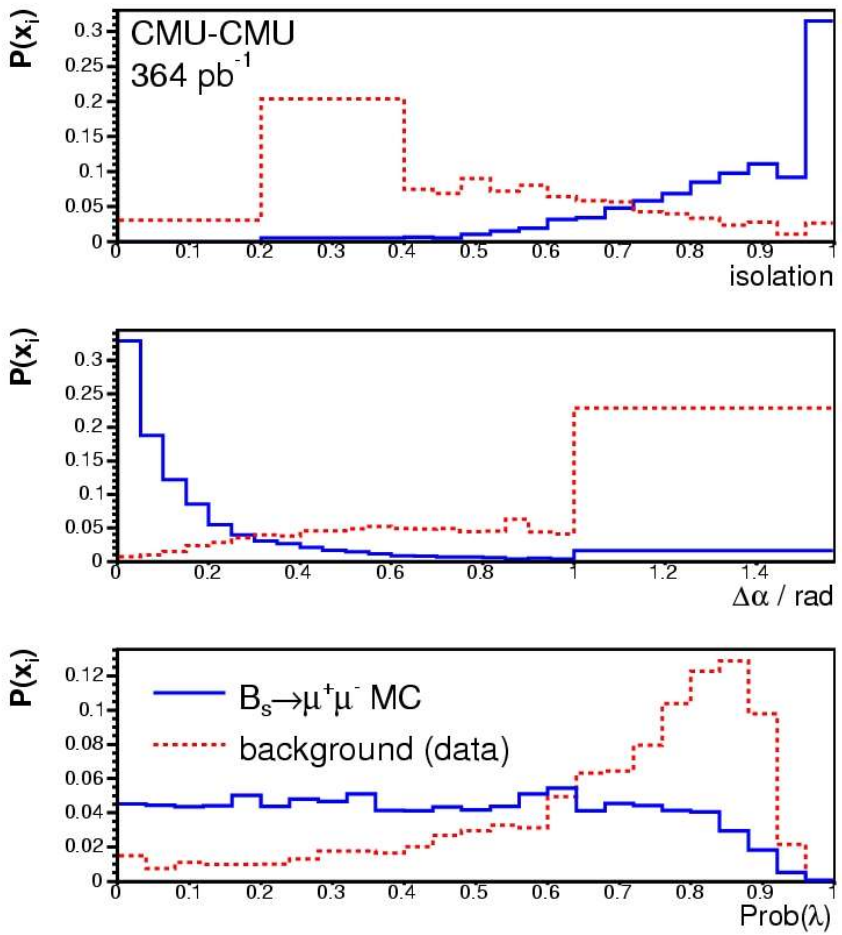
- Mass M
  - choose 2.5σ window: $\sigma = 25 MeV/c^2$
- $\exp(\lambda = c\tau / c\tau_{Bs})$
- $\Delta\alpha$: $|\phi_B - \phi_{vtx}|$ now in 3D
- Isolation: $p_{TB}/(\Sigma trk + p_{TB})$
- Optimization
  - Use selection variables in likelihood ratio

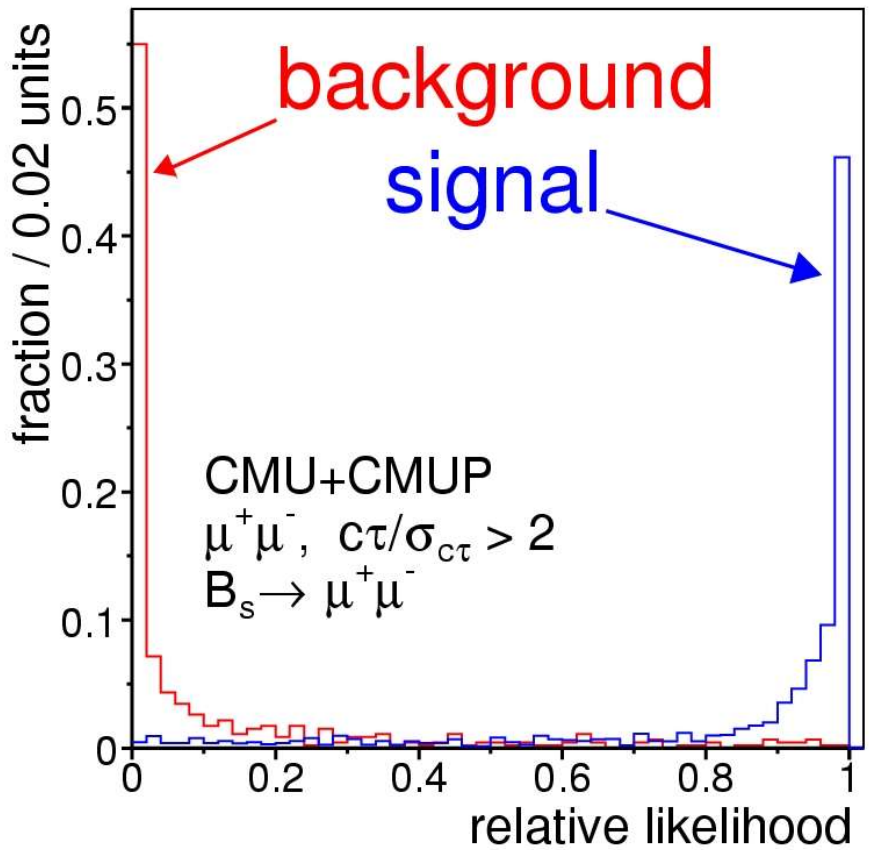


- 2D $\Delta\Phi$ from previous analysis

Likelihood Ratio

- Probability distributions used to construction the likelihood ratio
  - Use binned histograms to estimate the probabilities





- Resulting likelihood with signal MC and data sidebands

New Background Estimates

- Estimating Bg. using likelihood ratio difficult
- Background estimated using toy MC method
  - Throw random numbers for each of the likelihood variables and extract a set of ($\exp(c\tau/\sigma c\tau)$, $\Delta\alpha$, Iso) based on the distributions

As before: analysis dependent on an accurate background estimate

- Test toy MC Bg. estimations using independent data samples
- OS- and Fake μ samples
  - SS+,SS-: expect and find 0 events

OS-LHCut	Pred	Obs
0.50	54 +/- 1	55
0.90	8.8 +/- 0.3	5
0.99	0.9 +/- 0.1	0

FM+LHCut	Pred	Obs
0.50	14.7 +/- 0.6	11
0.90	2.9 +/- 0.2	1
0.99	0.3 +/- 0.1	0

New Optimization Results

- Tried Likelihood ratios from 0.9-0.99: LH Cut 0.99 **Opt for 1fb^{-1}**

- NB^{+}_{CMU}: 1767 ± 59
- NB^{+}_{CMX}: 721 ± 39
- ε_{LH}: 47% **Prev eff. 53%**
- Expected background
  - N_{bgCMU}~0.3, N_{bgCMX}~2.0

<1/2 Bg. in Prev Ana(CMU only)

- Systematic uncertainties
  - Bg. estimation: 22%
    - Bg statistical error
  - Sensitivity: 21%
    - from f_s/f_u
- In Progress
  - Tracking ε for Kaons: Used 100%
    Will improve result

a priori limits: CMU 2.4x10^{-7}, CMX 5.5x10^{-7} 90% CL

a priori limit combined: 1.8x10^{-7}

Prev. CDF result 5.8x10^{-7}

$B_s \rightarrow \mu\mu$: Physics Reach

Combined CDF/D0 limit:

$$BF(B_s \rightarrow \mu^+\mu^-) < 2.9 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

Expected limit of new CDF Analysis:

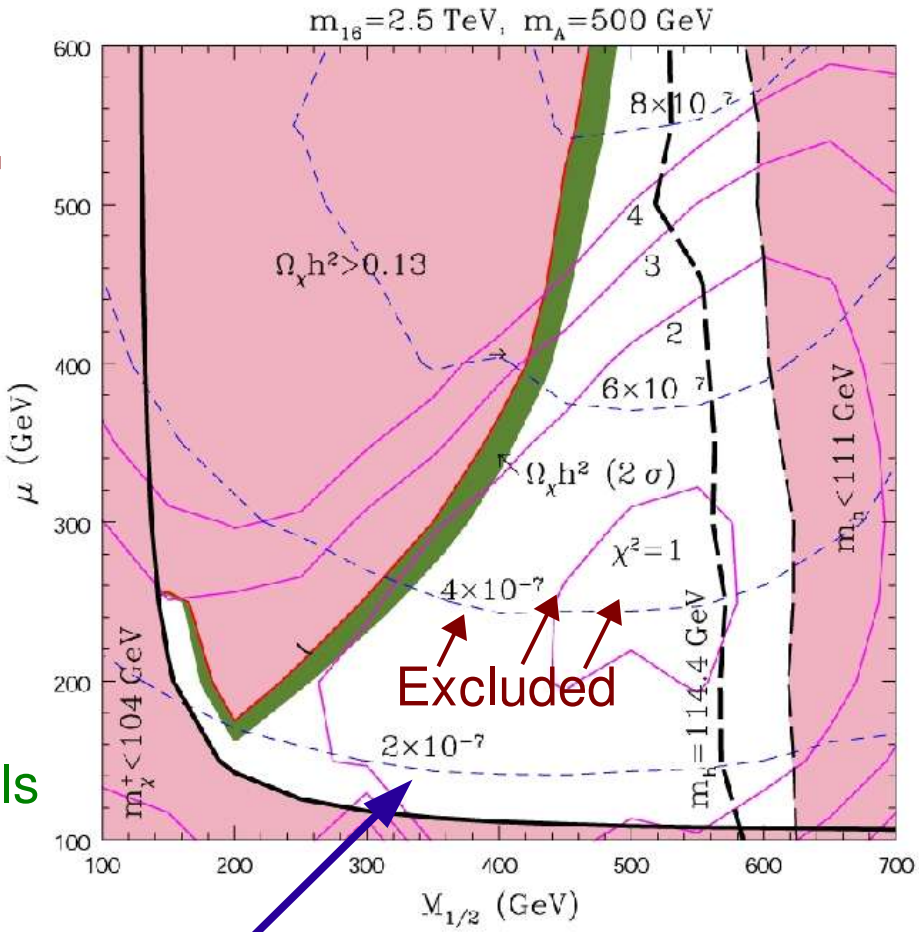
$$BF(B_s \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

- SM predictions:

$BF(B_{s(d)} \rightarrow \mu^+\mu^-)$: 3.5×10^{-9} (1.0×10^{-10})

  - No sensitivity for SM decay rate

- BSM predictions: Limiting many models
- Example SUSY S0(10)
  - Allows for massive neutrino
  - Accounts for relic density of cold dark matter



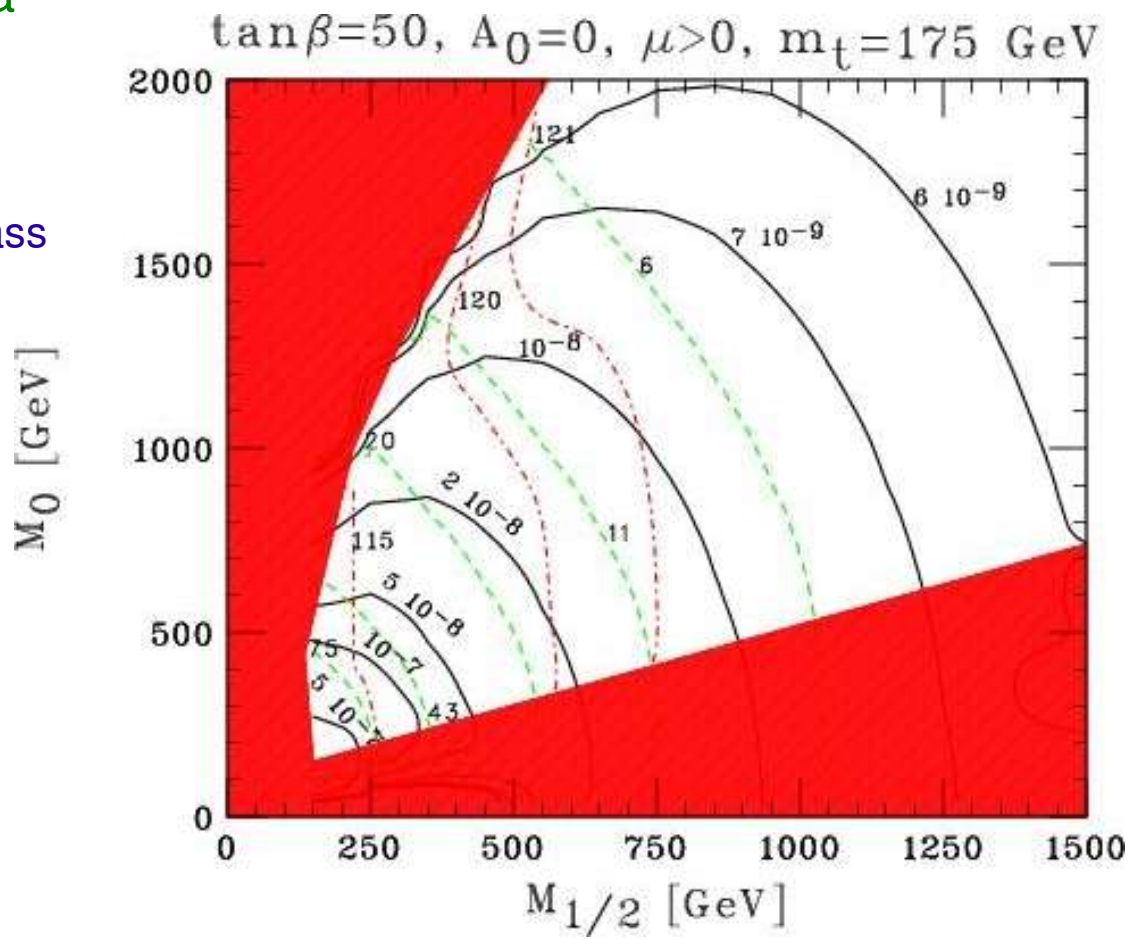
$BF\ B_s \rightarrow \mu^+\mu^-$: Dashed blue

Excludes scenarios where M_A is light and tanβ ~ 50: $M_A > 450\mathrm{GeV}/c^2$

R. Dermisek hep-ph/0304101,2003

$B_s \rightarrow \mu\mu$: Physics Reach

- In addition to limiting S0(10) models – starting to impact standard MSSM scenarios: mSugra
  - Solid black: $BF(B_s \rightarrow \mu^+\mu^-)$
  - Dashed green: $a_\mu = (g\text{-}2)_\mu/2$
  - Dashed red: Light Higgs Mass
  - Red areas: excluded



Combined CDF/D0 limit:

$$BF(B_s \rightarrow \mu^+\mu^-) < 2.9 \times 10^{-7}\ 90\%\ \text{CL}$$

New CDF Analysis:

$$< 1.8 \times 10^{-7}\ 90\%\ \text{CL}$$

Limit starting to intersect 115GeV Higgs contour

Conclusions

CDF $B_{(s,d)} \rightarrow \mu^+\mu^-$ results

$$BF(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

$$BF(B_d \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

Combined w/D0:

$$BF(B_s \rightarrow \mu^+\mu^-) < 2.9 \times 10^{-7}\ 90\%\ \mathrm{CL}$$

- Next version of the CDF analysis will again set the world's best limit on the decays $B_{(s,d)} \rightarrow \mu^+\mu^-$: (ready for winter conferences)
- We expect: $BF(B_s \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-7}\ 90\%\ \mathrm{CL}$
- Results on light B_d competitive with the B factories
- Limit excludes part of parameter space allowed by SO(10) models
- Expanding sensitivity to interesting areas of mSugra parameter space
  - CDF experiment integrating large amounts of new data
  - Multivariate technique for primary analysis cuts very powerful for reducing background
  - This analysis will only get better!

Backup: Limits

D0 $B_{(s,d)} \rightarrow \mu^+\mu^-$ result: 240pb^{-1} Old limit

$$BF(B_s \rightarrow \mu^+\mu^-) < 3.8\times10^{-7}\ 90\%\ \mathrm{CL}, \quad 4.6\times10^{-7}\ 95\%\ \mathrm{CL}$$

CDF $B_{(s,d)} \rightarrow \mu^+\mu^-$ results: 171pb^{-1}

$$BF(B_s \rightarrow \mu^+\mu^-) < 5.8\times10^{-7}\ 90\%\ \mathrm{CL}, \quad 7.5\times10^{-7}\ 95\%\ \mathrm{CL}$$

$$BF(B_d \rightarrow \mu^+\mu^-) < 1.5\times10^{-7}\ 90\%\ \mathrm{CL}, \quad 1.9\times10^{-7}\ 95\%\ \mathrm{CL}$$

CDF $B_{(s,d)} \rightarrow \mu^+\mu^-$ results: using updated f_s (used by D0)

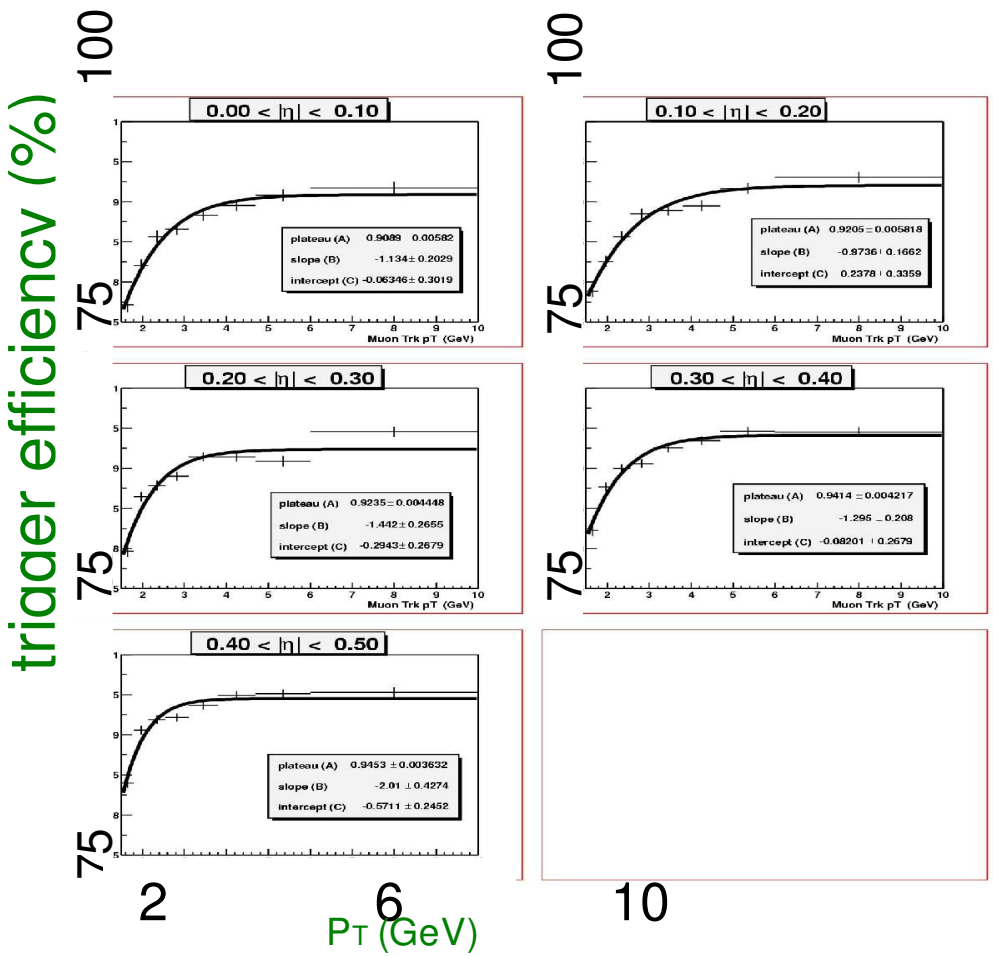
$$BF(B_s \rightarrow \mu^+\mu^-) < 5.4\times10^{-7}\ 90\%\ \mathrm{CL}, \quad 7.1\times10^{-7}\ 95\%\ \mathrm{CL}$$

Combined using updated f_s: Old Limits

$$BF(B_s \rightarrow \mu^+\mu^-) < 2.7\times10^{-7}\ 90\%\ \mathrm{CL}, \quad 3.4\times10^{-7}\ 95\%\ \mathrm{CL}$$

Muon & Trigger Efficiencies

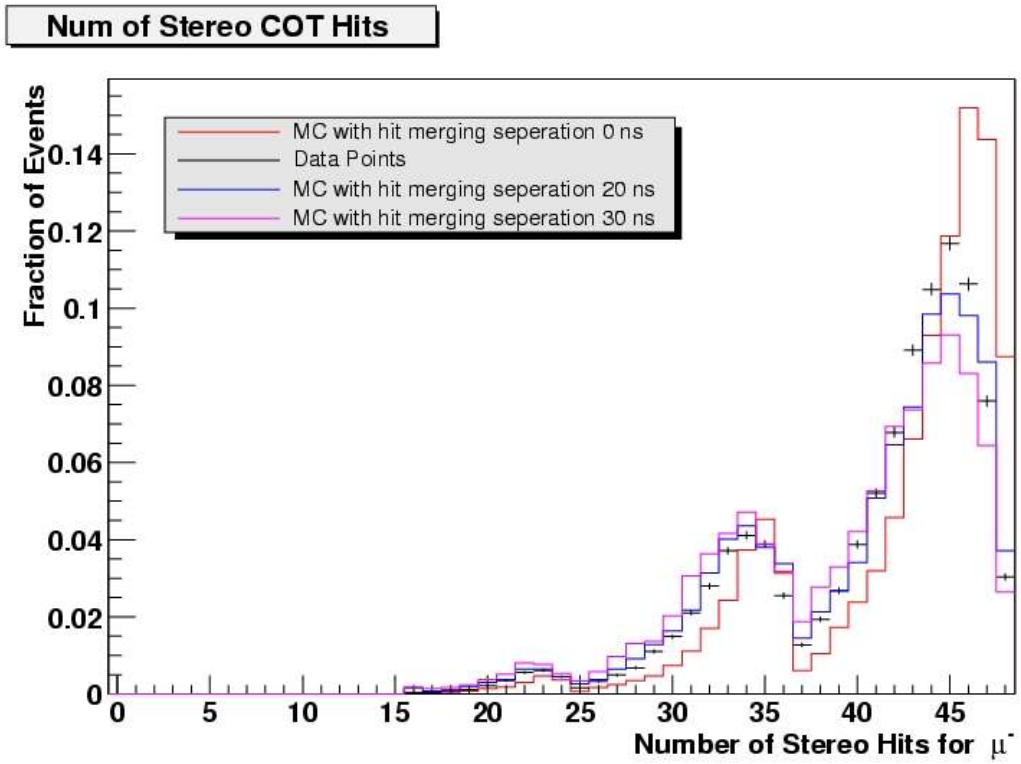
- L1 eff: Use $J/\psi \rightarrow \mu^+\mu^-$ trigger that only requires one muon
- L3 eff: Use autoexcept trigger



- L1 Muon L1(p_T,η), L3 1 number
  - Convolute ε_{L1} for each muon and ε_{L3}
- Systematic errors L1 and L3:
  - Kinematic difference between $J/\psi \rightarrow \mu^+\mu^-$ and $B_{s(d)} \rightarrow \mu^+\mu^-$
  - 2-Track correlations
  - Sample statistics
- $\varepsilon_{trig} = 85 \pm 3\%$
- Offline muon reconstruction
  - From $J/\psi \rightarrow \mu^+\mu^-$ L1 trigger with one muon found
  - Systematic from comparison to Z
- $\varepsilon_{muon} = 95.9 \pm 1.3(stat) \pm 0.6(sys)\%$

COT Efficiency

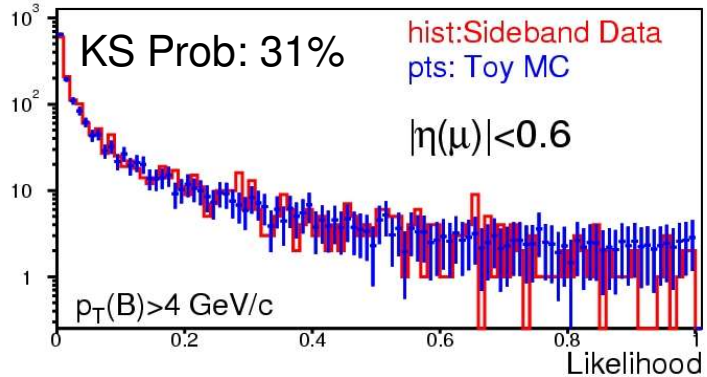
- Estimated by embedding COT hits from MC muons in real data
  - Occupancy effects correctly accounted for
  - Efficiency driven by loss of hits when hit density is high
  - Demonstrate agreement between hit usage in data and MC
  - Tunable parameters can lower or raise the hit usage and the efficiency to bracket the data

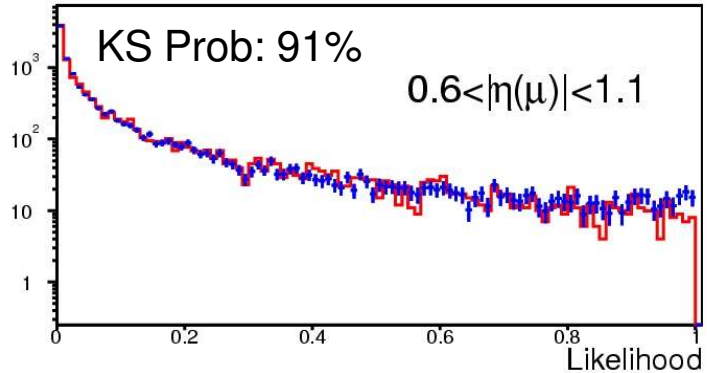


- ε_{COT} = 99.62 ± 0.02%
- Systematic errors
  - Isolation dependence dominant systematic
  - Pt dependence
  - 2-track correlations
  - Varying the simulation tuning
  - Error: +0.34 -0.91
- Consistent with true tracking eff. using high pt elections identified in the calorimeter

New Background Estimates

- Background estimated using toy MC method
  - Throw random numbers for each of the likelihood variables and extract a set of (exp(cτ/σcτ), ΔΦ, Iso) based on the distributions
  - Check that toy method predicts the likelihood distribution for sideband data events





- Statistical errors: 3%-10% for LH cuts 0.9-0.99
- Check in OS- and Fake μ samples
  - SS+,SS-: expect and find 0 events

OS-LHCut	Pred	Obs
0.50	54 +/- 1	55
0.90	8.8 +/- 0.3	5
0.99	0.9 +/- 0.1	0

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