Search for $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$ Decays

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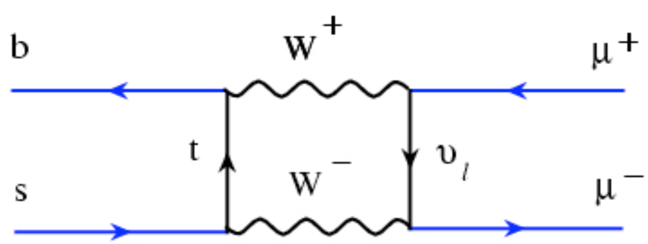
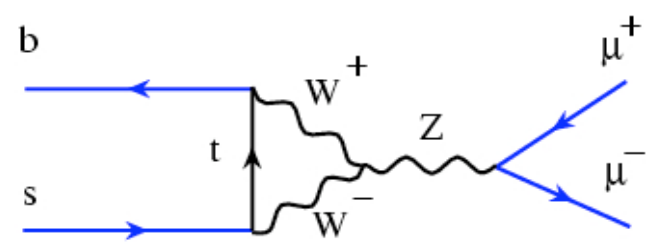
Outline
- Introduction
- CDF & Tevatron
- Method
- Results

Introduction

In the Standard Model B→μμ is a FCNC decay…

only possible at the loop level





$$BR(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

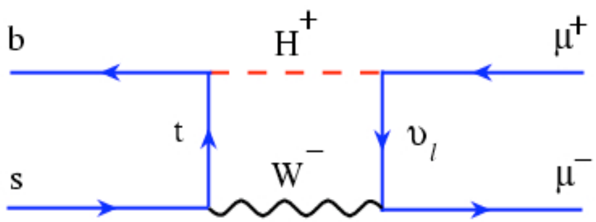
Not yet experimentally observed.

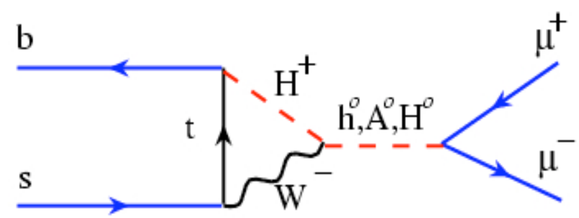
$$BR(B_s \to \mu^+\mu^-) < 2.0 \times 10^{-6} @ 90\% CL$$

(CDF, PRD 57 (1998) 3811R)

Introduction

Several extensions to SM allow for BR >> BR(SM)

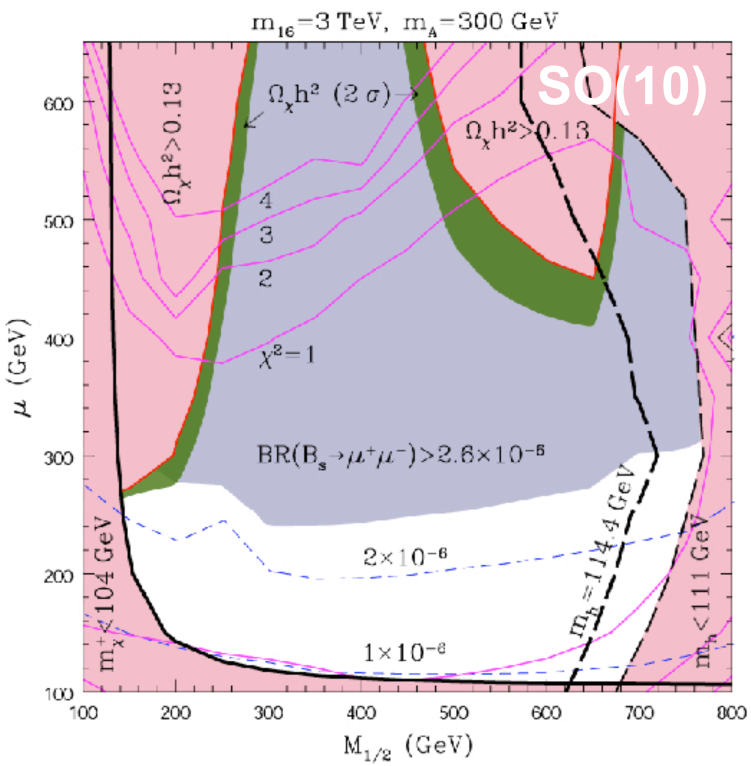




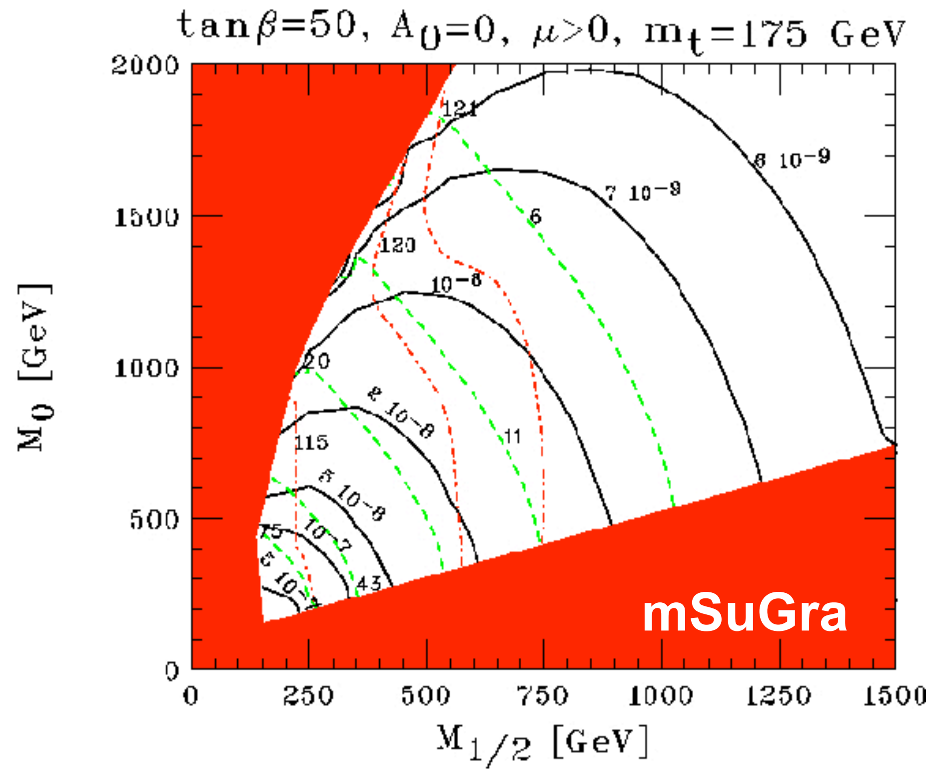
BR enhanced *10-1000

Observable in RunII.

Introduction



(R.Dermisek et al., JHEP 07 (2002) 050)



(Dedes, Dreiner, Nierste, PRL (2001) 251804)

Even modest improvements to limits can give interesting constraints on “relevant” models.

Introduction

B-hadron production cross-sections:

- PEPII : $\sigma(B)$~1 nb
- TevII : $\sigma(B)$~30000 nb

After trigger and reconstruction:

- 1 fb-1(B-factory) ~ 1 pb-1(Tevatron)

Center of mass energies at B-factories below B_s threshold, but at Tevatron: #$B^+ : B_d : B_s : \Lambda_b \sim 4 : 4 : 1 : 1$

This decay mode offers the Tevatron experiments a unique opportunity.

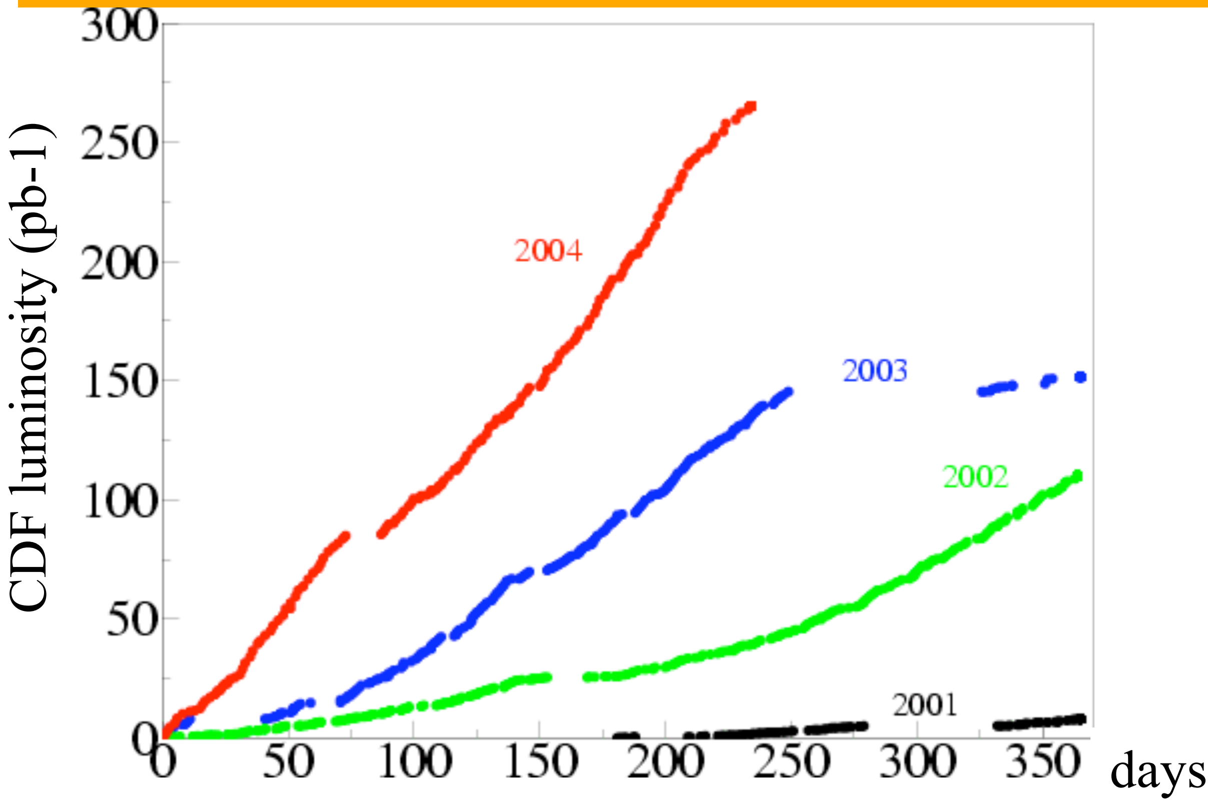
Tevatron

- World's highest energy $p\bar{p}$ collider

  E_{cm} = 2 TeV

- CDF and D0 significantly upgraded
- New data taking since Mar-2001
- Significant accelerator upgrades ongoing

Tevatron

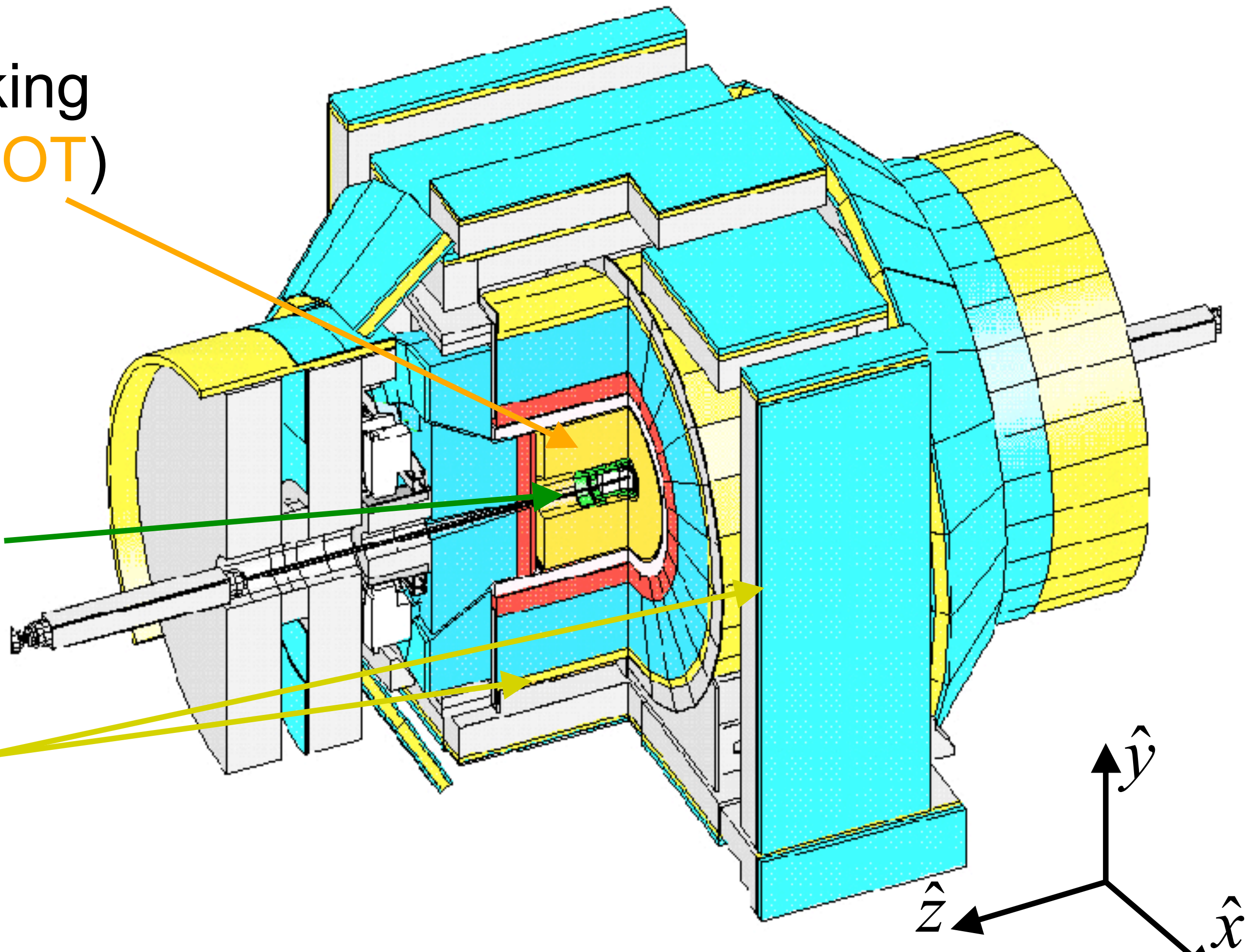


- Have ~500 pb-1 on tape
- this analysis based on 171 pb-1
- Tevatron doing well
- expect another >=400 pb-1 FY05

CDF:

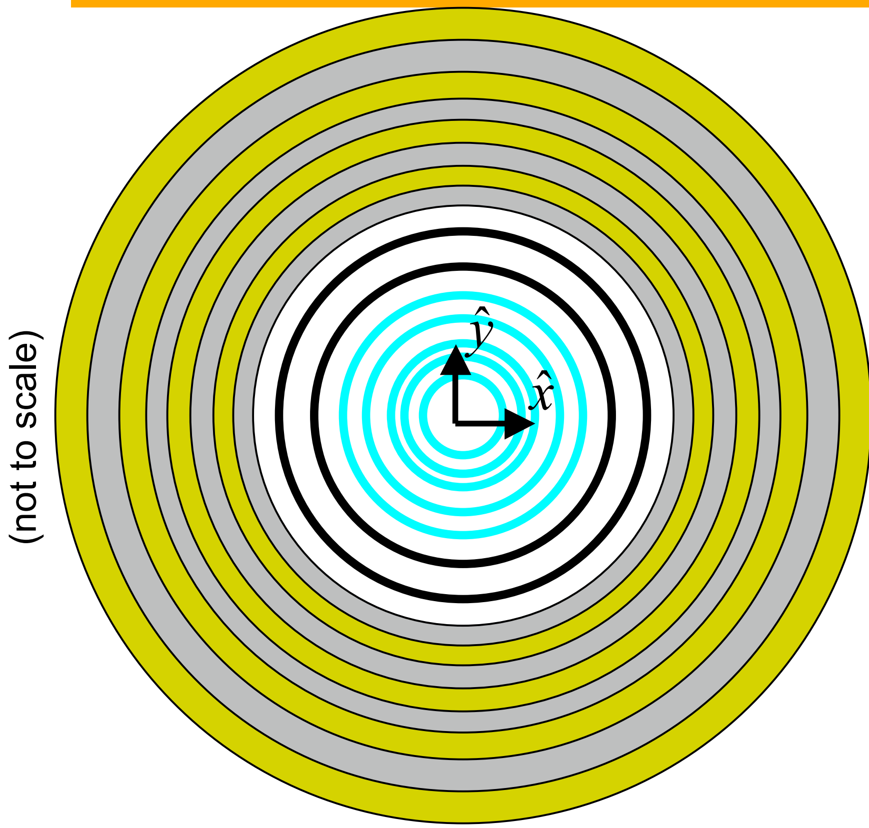
Features:

- large radius tracking wire chamber (COT)
- 1.4 T solenoid
- precision silicon vertexing (SVX)
- muon chambers (CMU & CMP, $|\eta| < 0.6$)



$$\eta = -\ln(\tan(\theta/2))$$

CDF



COT:

- 8 “Super Layers” (SL) of 12 sense wires each
- SL 1, 3, 5, 7 are stereo
- SL 2, 4, 6, 8 are axial
- Axial SL used in trigger
- $40 < r < 140$ cm

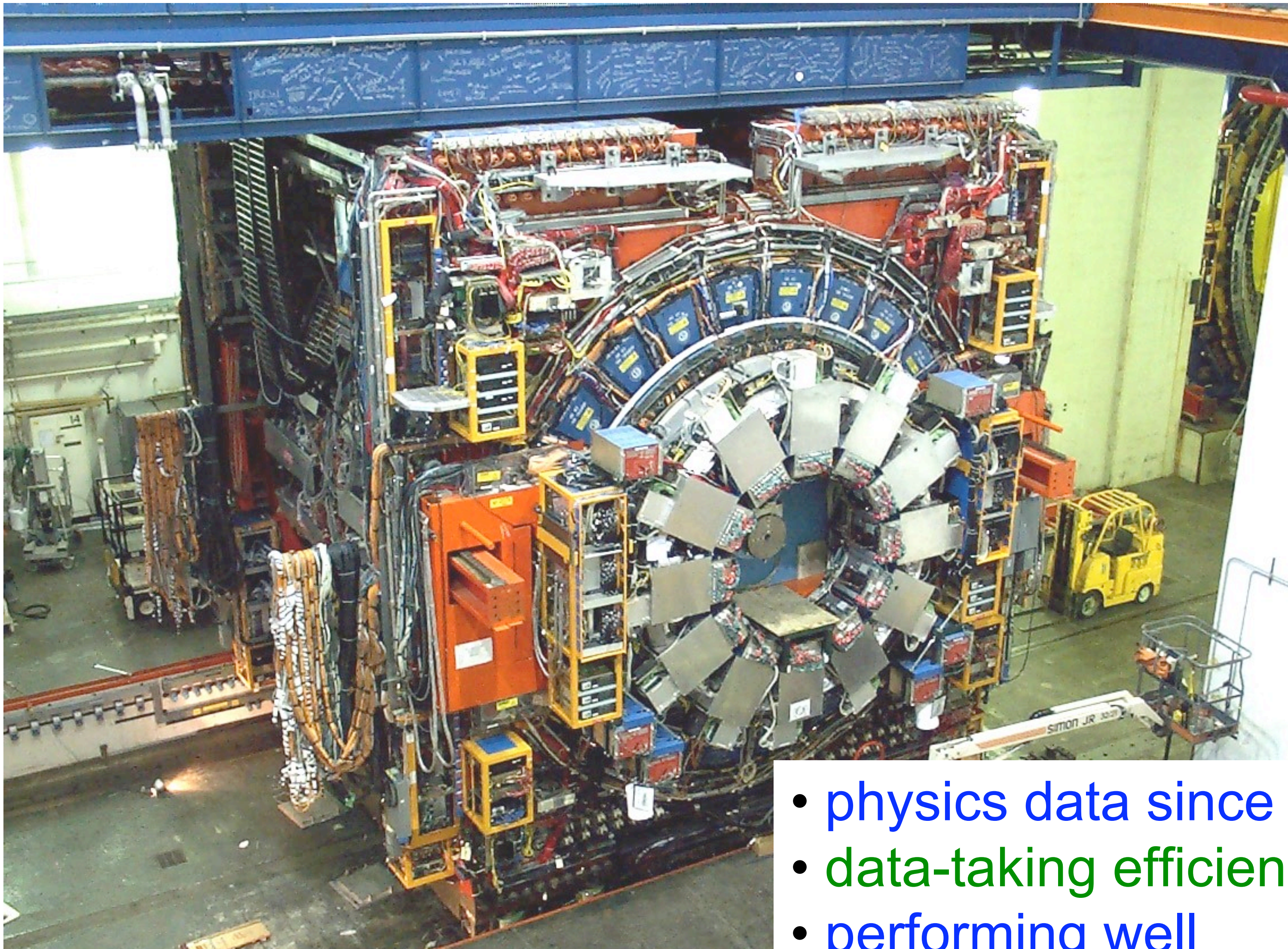
SVX:

- 5 layer silicon μ-strip
- $r\phi$ and rz readout
- used in trigger
  (but not for this analysis)
- $2.5 < r < 10$ cm

ISL:

- 2 layer silicon μ-strip
- $r\phi$ and rz readout
- $20 < r < 30$ cm

CDF



- physics data since Feb-2002
- data-taking efficiency >85%
- performing well

CDF

So far in RunII, CDF…

- Has published 6+1 papers in PRL+PRD
- Has submitted another 3+5 to PRL+PRD
- Has another 9 papers in final review
- Has another 28 papers in early review

Published+Submitted+Drafts:

17 from B Physics
13 from Top Physics
13 from Searches
7 from Electroweak
2 from QCD

Method

$$BR(B_s \to \mu^+\mu^-) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int L dt}$$

This measurement requires that we:

- demonstrate understanding of background, N_{bg}
- accurately estimate $\alpha\varepsilon$
- intelligently optimize cuts

Since SM predicts 0 events, this is really a "search"

- more rigorous about testing N_{bg} estimate
- emphasis on performing an unbiased optimization

Method

Collect sample using Di-Muon Triggers

↓ **150k events**

Make reconstruction requirements & Constrain to a common 3D vertex

↓ **2981 events**

Apply cuts to discriminate Signal from Background

↓ **? events**

Estimate BR using:

$$BR(B_s \to \mu^+\mu^-) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int Ldt}$$

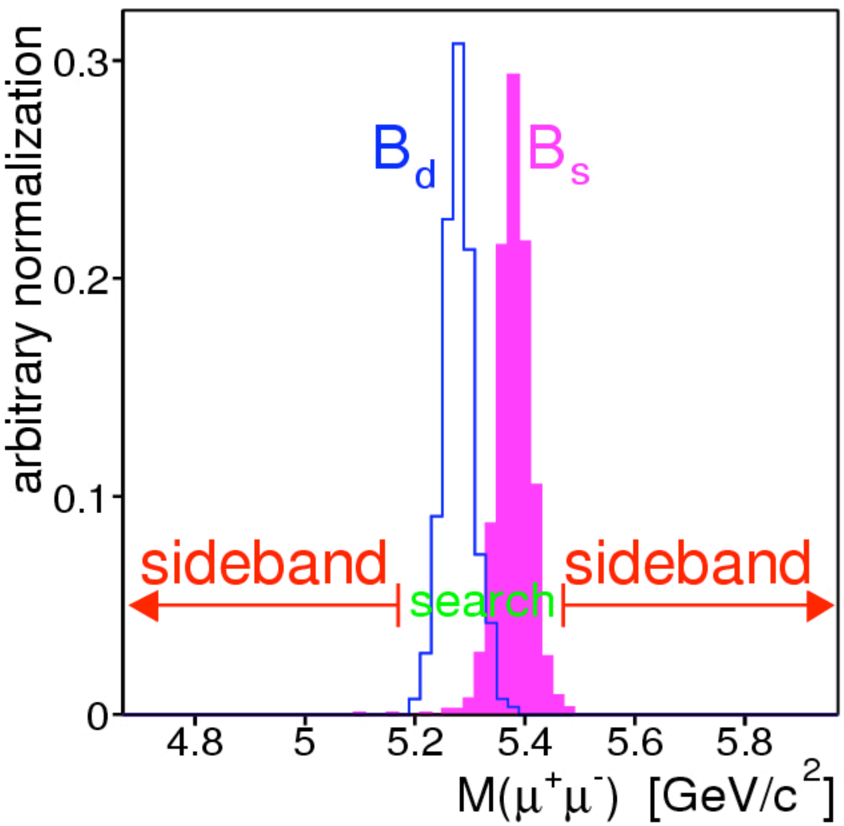
Strategy:

- "blind" ourselves to data in signal region
- use sideband data to understand background
- employ *a priori* optimiztn
- don't "open box" until expected sensitivity warrants (< 0.5 RunI)

➡ I'll talk about each piece in turn

Method: Unbiased Optimization

When optimizing the selection criteria, we "blinded" ourselves to the data in an extended search region.



Search Region:

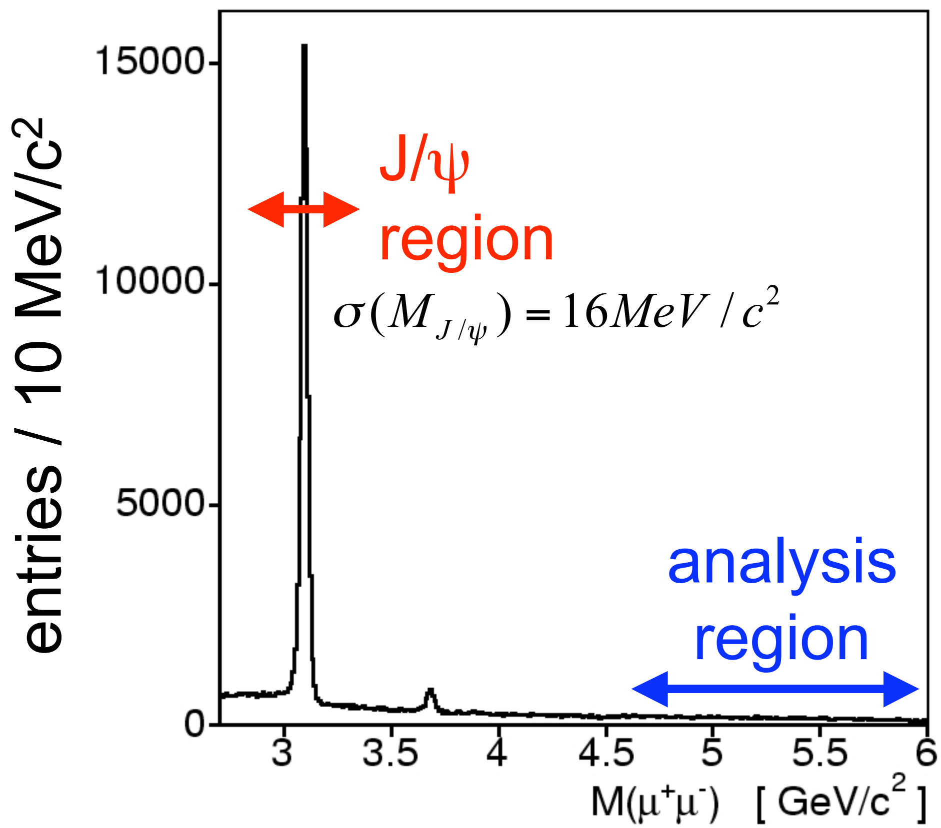
- $5.169 < M_{\mu\mu} < 5.469$ GeV
- corresponds to +/- $4\sigma(M_{\mu\mu})$
- width included in optimiztn

Sideband Regions:

- additional 0.5 GeV on either side of search region
- used to understand Bkgd

Method: Triggers

Collect sample using Di-Muon Triggers



- "CMU-CMU"
  - both muons in CMU
  - $P_T(\mu) > 1.5$ GeV
  - $2.7 < M_{\mu\mu} < 6.0$ GeV
  - $\Delta\phi(\mu\mu) < 2.25$ rad
  - $P_T(\mu+) + P_T(\mu-) > 5$ GeV
- "CMUP-CMU"
  - 1 muon in CMP, 1 in CMU
  - $P_T(\text{CMU-}\mu) > 1.5$ GeV
  - $P_T(\text{CMP-}\mu) > 3.0$ GeV
  - $2.7 < M_{\mu\mu} < 6.0$ GeV
  - $\Delta\phi(\mu\mu) < 2.25$ rad

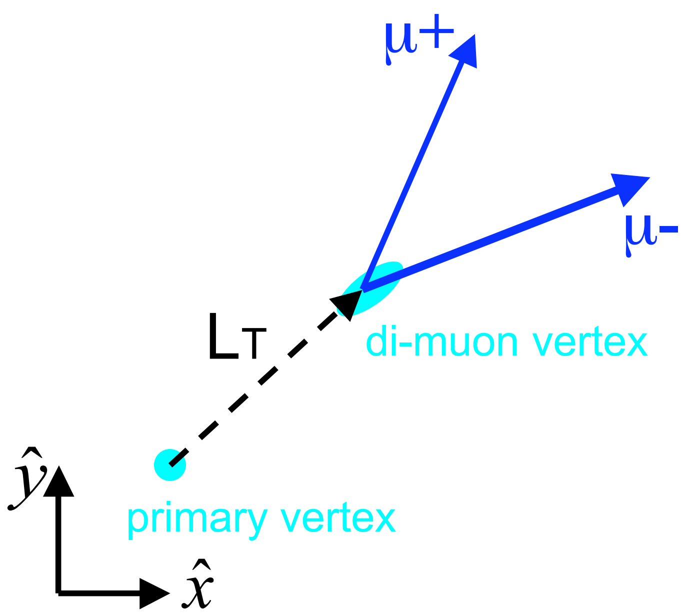
➡ 150k events satisfy trigger

Method: Reconstruction Requirements

Collect sample using Di-Muon Triggers

↓ **150k events**

Make reconstruction requirements & Constrain to a common 3D vertex

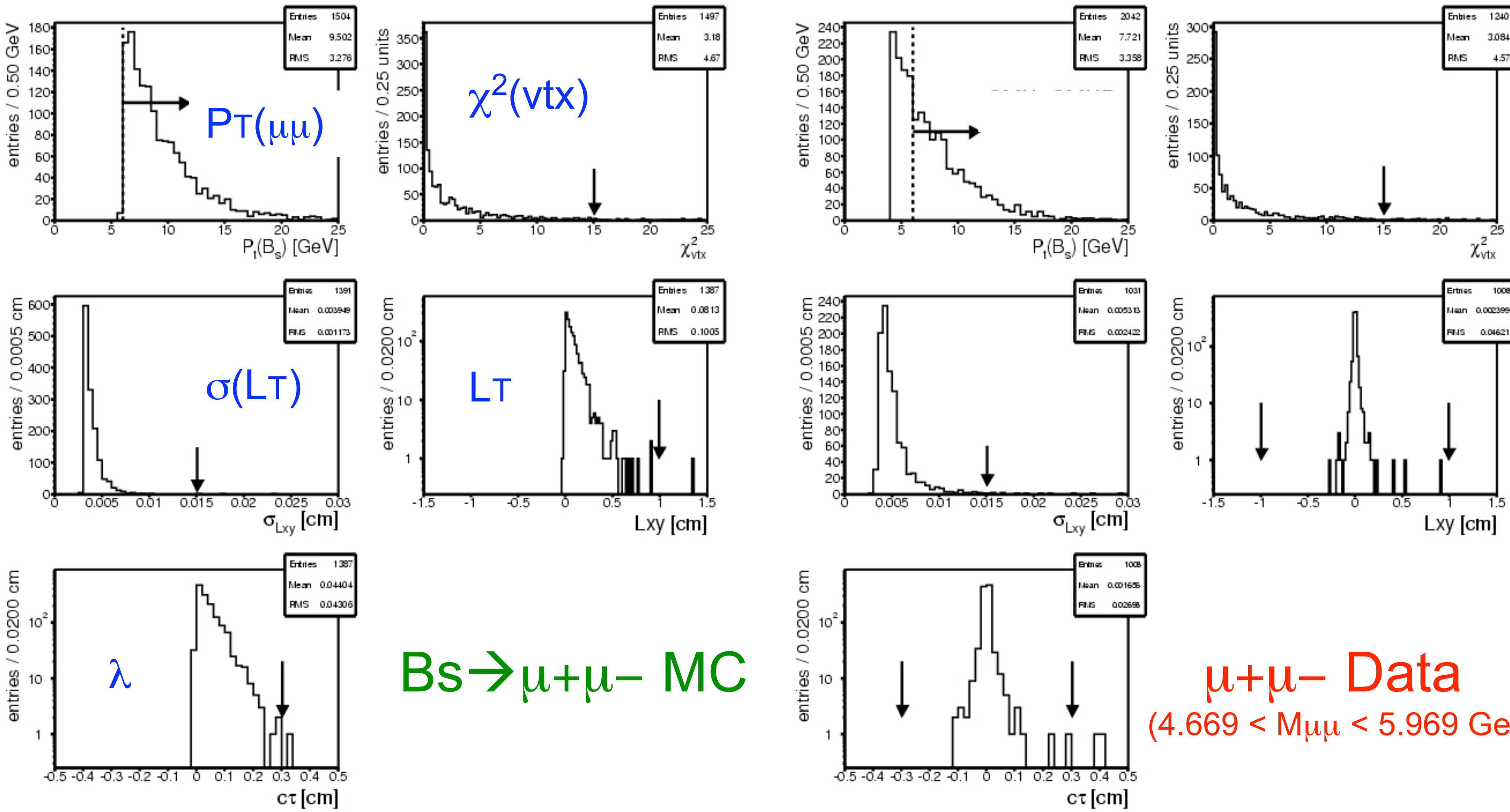


We Require:

- "good" COT tracks and CMU/P track-stubs
- >=4 SVX r-ϕ hits
- $4.669 < M_{\mu\mu} < 5.969$ GeV
- "good" vertex
  - $\sigma(L_T) < 150\ \mu m$
  - $\chi^2 < 15$
  - $L_T < 1$ cm
- $P_T(\mu\mu) > 6$ GeV

➡ 2984 events survive (expect <30 $B_s \to \mu^+\mu^-$… this is bkgd dominated)

Method: Reconstruction Requirements



Bs→μ+μ− MC

μ+μ− Data

(4.669 < Mμμ < 5.969 GeV)

$$\lambda = cL_T \cdot \frac{M_{\mu^+\mu^-}}{P_T^{\mu^+\mu^-}}$$

These requirements:

keep 92% of Bs→μ+μ−

reject 50% of the background.

Method: Discriminate Signal from Background

Collect sample using Di-Muon Triggers

↓ **150k events**

Make reconstruction requirements & Constrain to a common 3D vertex

↓ **2981 events**

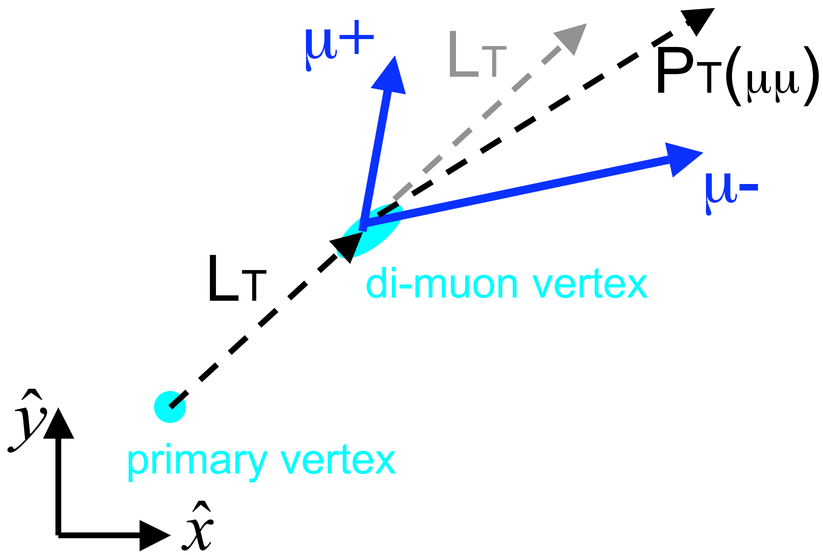
Apply cuts to discriminate Signal from Background

At this stage:

- sample is background dominated
- need to find variables that reduce background by a factor of >1000
- … and keep as much signal as possible

➡ let's think about signal & background characteristics…

Method: Discriminate Signal from Background



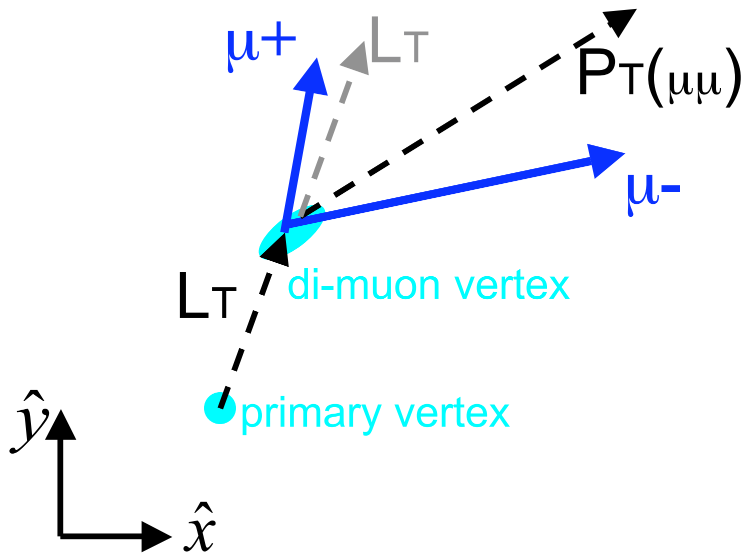
Signal Characteristics

- final state is fully reconstructed
- B_s has long lifetime ($c\tau$ = 438 μm)
- B fragmentation is hard

For real $B_s \rightarrow \mu^+\mu^-$ expect:

- $M_{\mu\mu} = M(B_s)$
- $\lambda = cL_T\, M_{\mu\mu}/P_T(\mu\mu)$ to be large
- L_T and $P_T(\mu\mu)$ to be co-linear
- few additional tracks

Method: Discriminate Signal from Background



Contributing Backgrounds

– sequencial semi-leptonic decay, $b \rightarrow \mu^- cX \rightarrow \mu^+\mu^- X$

– double semi-leptonic decay, $g \rightarrow b\bar{b} \rightarrow \mu^+\mu^- X$

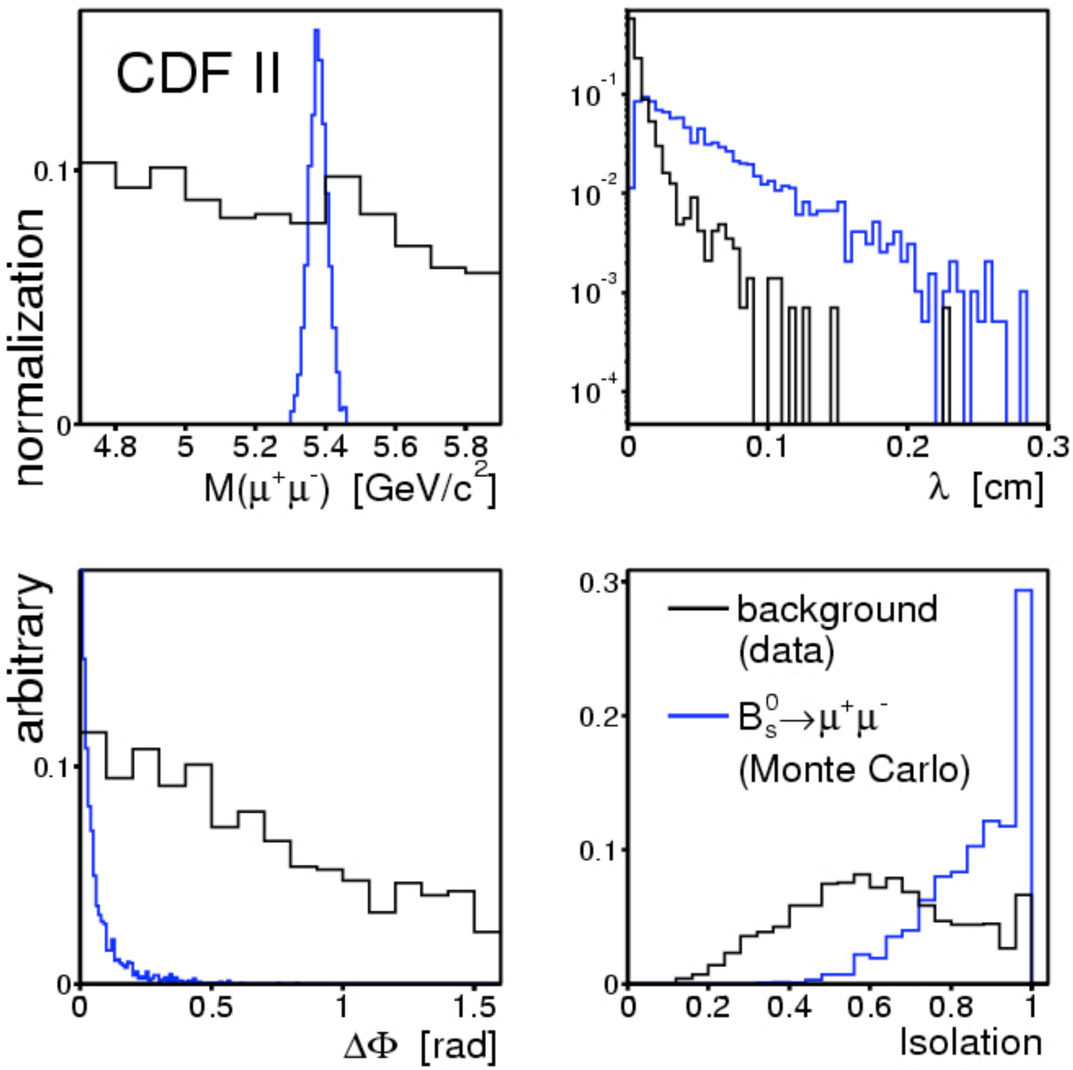
– continuum $\mu^+\mu^-$, μ + fake fake+fake

In general:

- $M_{\mu\mu} \neq M(B_s)$
- $\lambda = cL_T\, M_{\mu\mu}/P_T(\mu\mu)$ will be smaller

- L_T and $P_T(\mu\mu)$ will not be co-linear
- more additional tracks

Method: Discriminating Variables



Discriminating Variables

- Invariant mass, $M_{\mu\mu}$
- $\lambda = cL_T\, M_{\mu\mu}/P_T(\mu\mu)$
- $\Delta\Phi$: $\phi(\vec{P}_T(\mu\mu)) - \phi(\vec{L}_T)$
- Isolation
  $= P_T(\mu\mu)/(\Sigma_{trk} + P_T(\mu\mu))$

➡ need to determine optimal requirements

Method: Unbiased Optimization

We used the set of requirements which yielded the minimum *a priori* expected BR Limit:

$$\left\langle BR(B_s \to \mu^+\mu^-)\right\rangle = \frac{\left\langle N^{90\%CL}_{signal}\right\rangle}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{B_s} \int L dt}$$

where we've summed over all possible n_{obs}:

$$\left\langle N^{90\%CL}_{signal}\right\rangle = \sum_{n_{obs}=0}^{\infty} \mathrm{P}(n_{obs} \mid n_{bg}) \cdot N^{90\%CL}_{signal}(n_{bg}, \Delta_{bg}, \Delta_{\alpha\cdot\varepsilon})$$

Poisson prob of observing n_{obs} when expecting n_{bg}

90% CL UL on N_{signal} when expecting n_{bg} bkgd evts using Bayesian Method and including uncertainties

Method: Unbiased Optimization

The a priori expected BR limit is given by:

$$\left\langle BR(B_s \rightarrow \mu^+\mu^-)\right\rangle = \frac{\left\langle N^{90\%CL}_{signal}\right\rangle}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{B_s} \int L dt}$$

where:

$$\left\langle N^{90\%CL}_{signal}\right\rangle = \sum_{n_{obs}=0}^{\infty} \mathrm{P}(n_{obs} \mid n_{bg}) \cdot N^{90\%CL}_{signal}(n_{bg}, \Delta_{bg}, \Delta_{\alpha\cdot\varepsilon})$$

To perform the optimization we needed:

- background estimate, n_{bg} +/- Δ_{bg}
- total acceptance estimate, $\alpha\varepsilon_{total}$ +/- $\Delta_{\alpha\varepsilon}$

for each set of ($M_{\mu\mu}$,λ,$\Delta\Phi$,Isolation) requirements.

Method: Background Estimate

We estimate the background in the signal region using:

$$n_{bg} = n_{sb}(\lambda, \Delta\Phi) \cdot f_{Isol} \cdot f_M$$

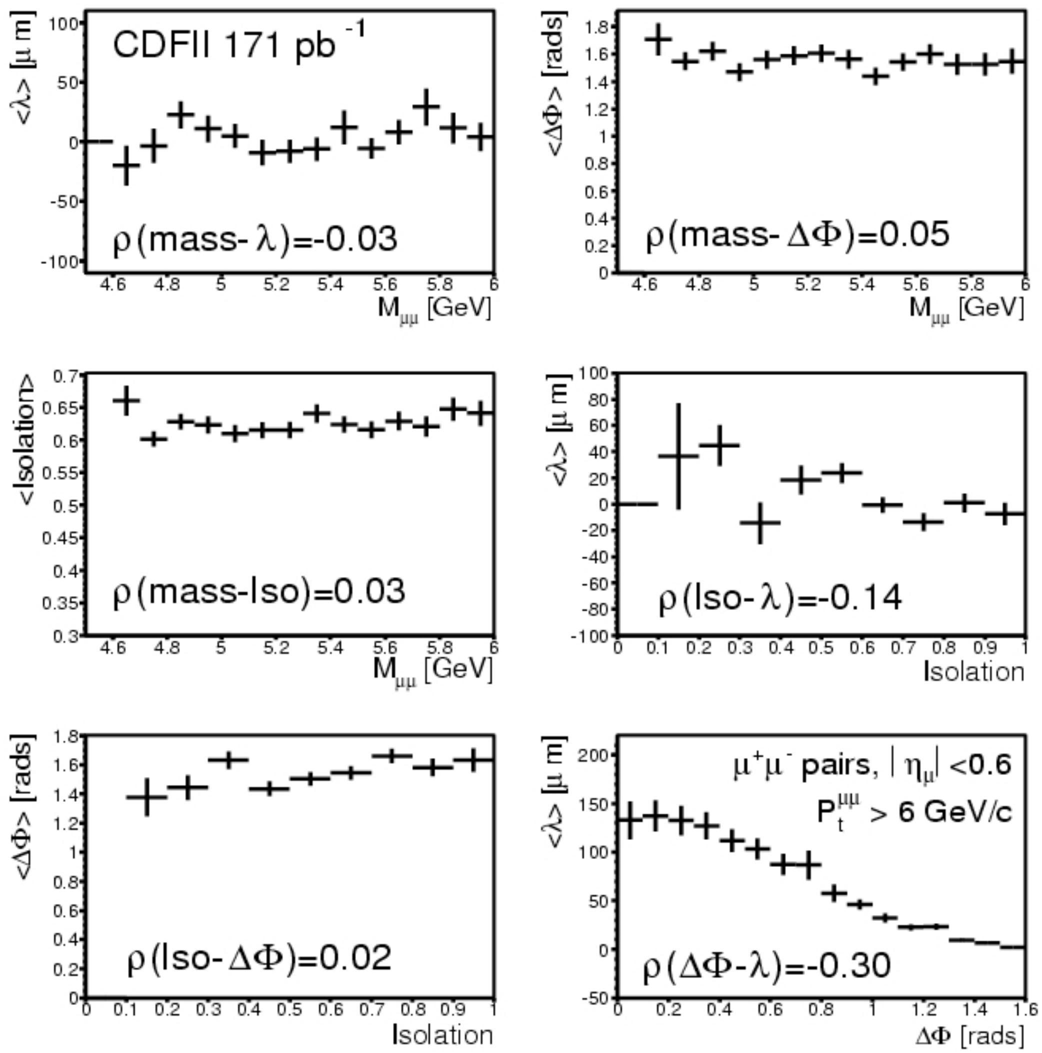
#sideband events surviving (λ,$\Delta\Phi$) requirements

fraction of background events expected to survive Isolation req'rmt

ratio of #events in signal region, given #evts in sidebands

- Isol and $M_{\mu\mu}$ need to be uncorrelated w/ other vars
- background $M_{\mu\mu}$ needs to be linear
- can determine f_{isol} and f_M on samples w/ loose (no) λ, $\Delta\Phi$ requirements… Δ_{bg} reduced

Method: Background Estimate



(Δρ(stat) = +/-0.03 each)

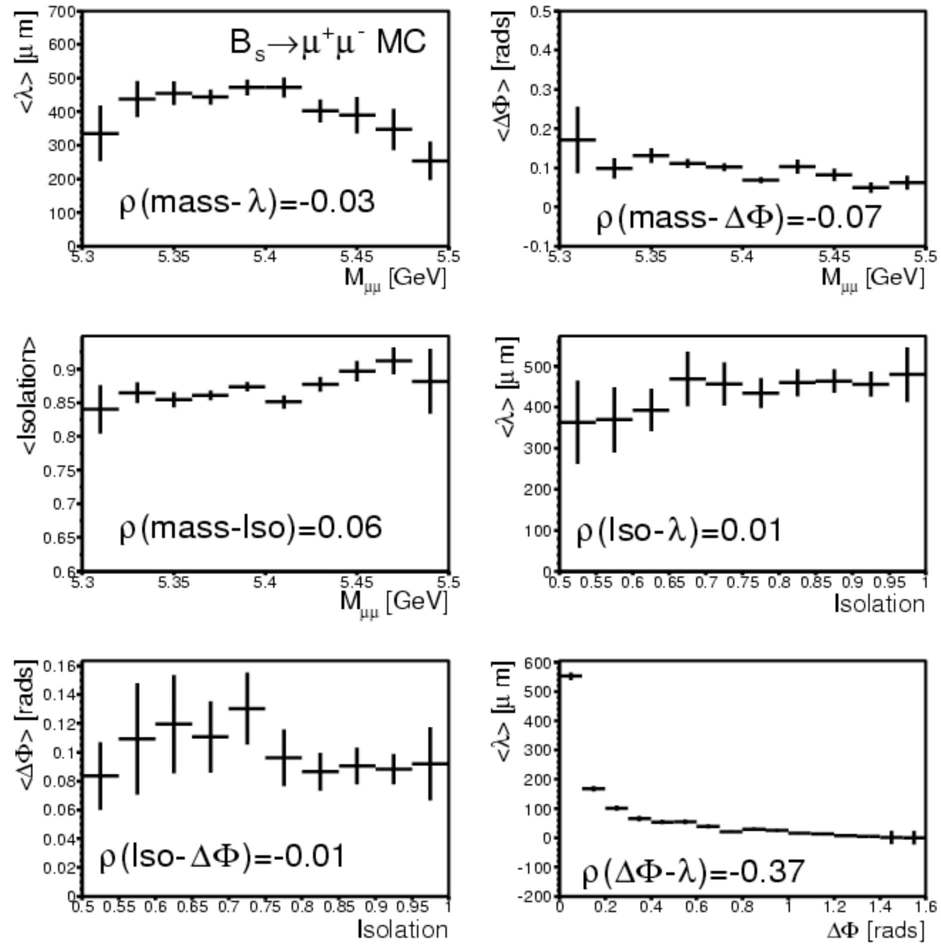
using our background dominated data sample…

estimate linear correlt'n coefficient for each combination of variables:

$$\rho_{xy} = \frac{1}{N-1} \cdot \frac{\sum_{i=1}^{N} (x_i - \hat{x})(y_i - \hat{y})}{\sigma_x \sigma_y}$$

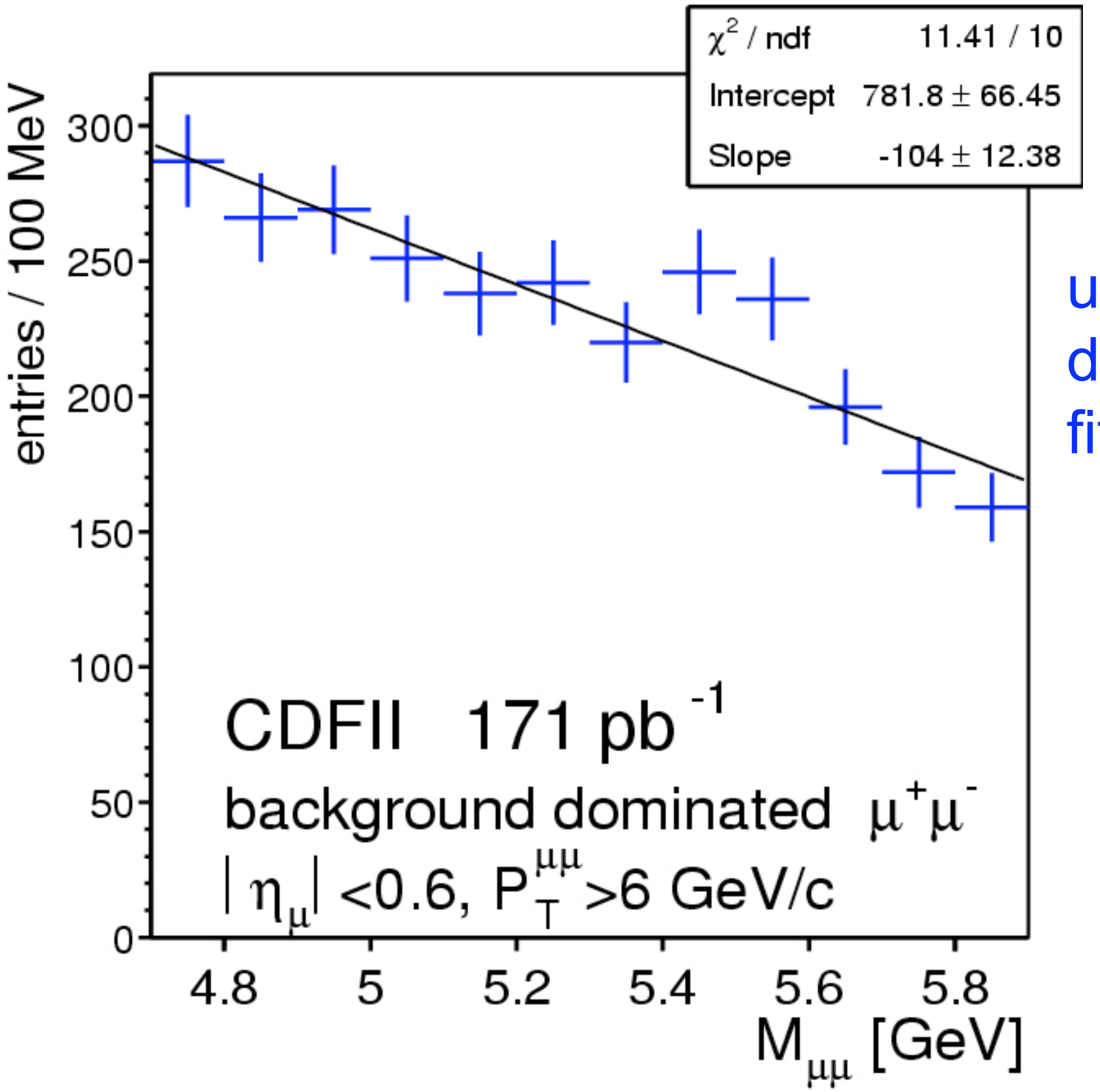
✓ Isol and $M_{\mu\mu}$ are uncorrelated with other variables

Method:



NOTE: $M_{\mu\mu}$ and Isolation are generally uncorrelated with other variables… even for signal.

<u>Method</u>: Background Estimate



using our background dominated data sample, fit $M_{\mu\mu}$

✓ background $M_{\mu\mu}$ is linear

Method: Background Estimate

Since assumptions satisfied, we can determine f_{iso} and f_M using background dominated sample:

$$f_{Iso} = \frac{\#\,evts(Iso > threshold)}{\#\,evts}$$

$$f_M = \frac{\#\,evts(signal)}{\#\,evts(sideband)}$$

threshold	f_{iso}
Iso>0.60	0.535 +/- 0.009
Iso>0.65	0.450 +/- 0.009
Iso>0.70	0.362 +/- 0.009
Iso>0.75	0.283 +/- 0.008
Iso>0.80	0.214 +/- 0.008
Iso>0.85	0.160 +/- 0.007

(variation in bins of λ and $M_{\mu\mu}$ yield a systematic uncertainty of +/- 5%)

Since background $M_{\mu\mu}$ is linear,

$$f_M = \frac{\Delta M(\text{signal})}{\Delta M(\text{sideband})}$$

<u>Aside</u>: Specific Background Sources

Let's pause here to consider some specific background sources:

1. Two-body B-decays
   - $B \rightarrow h^+h^-$ ($h = \pi$ or K)
   - $M_{\mu\mu}$ not linear
2. Generic $b\bar{b}$ events
   - $M_{\mu\mu}$ linear?
   - Surprises?

Aside: Specific Background Sources

For two-body B-decays, B→h+h- (h = π or K)…

Estimate contribution to signal region by:

1. Take acceptance, M_{hh} (assuming μ mass), $P_T(h)$ from MC samples
2. Convolute $P_T(h)$ with μ-fake rates derived from D* tagged K, π tracks
   - fake rates binned in P_T and charge
   - separately determined for π and K
   - yields double fake rates of 2-6 x 10^{-4}

B_d→h+h- : $\alpha \cdot \varepsilon_{total} \cdot BR < 4 \times 10^{-11}$

B_s→h+h- : $\alpha \cdot \varepsilon_{total} \cdot BR < 1 \times 10^{-9}$

…expected sensitivity in 10^{-7} range, can safely ignore these backgrounds

Aside: Specific Background Sources

For generic $b\bar{b}$ events…

Used $b\bar{b}$ MC sample to learn:

1. Mass and Isolation correlations small
2. $M_{\mu\mu}$ is linear

➡ Will be accurately accounted for

As a check, can use method described above to predict how many $b\bar{b}$ MC events will fall into signal region for a loose set of cuts:

n_{bg}	$\lambda>50\mu m$	$\lambda<50\mu m$
Predicted	3.1+/-0.7	8.8+/-1.3
Observed	2	6

<u>Aside</u>: Specific Background Sources

For generic $b\bar{b}$ events…

As a further check, can use a set of requirements that are near optimal (ie. tight) and look at (N-1) distributions:

Cut omitted	#survive	comment
Isolation	0	
λ	1	λ = 6 μm
$\Delta\Phi$	1	$\Delta\Phi$ = 0.91 rad
$M_{\mu\mu}$	1	$M_{\mu\mu}$ = 5.559 GeV

- only 3 events (of 1.2 x 10^9) fail a single cut and these are *far* from the cut thresholds

…no special treatment required.

<u>Aside</u>: Specific Background Sources

We paused to consider some specific background sources:

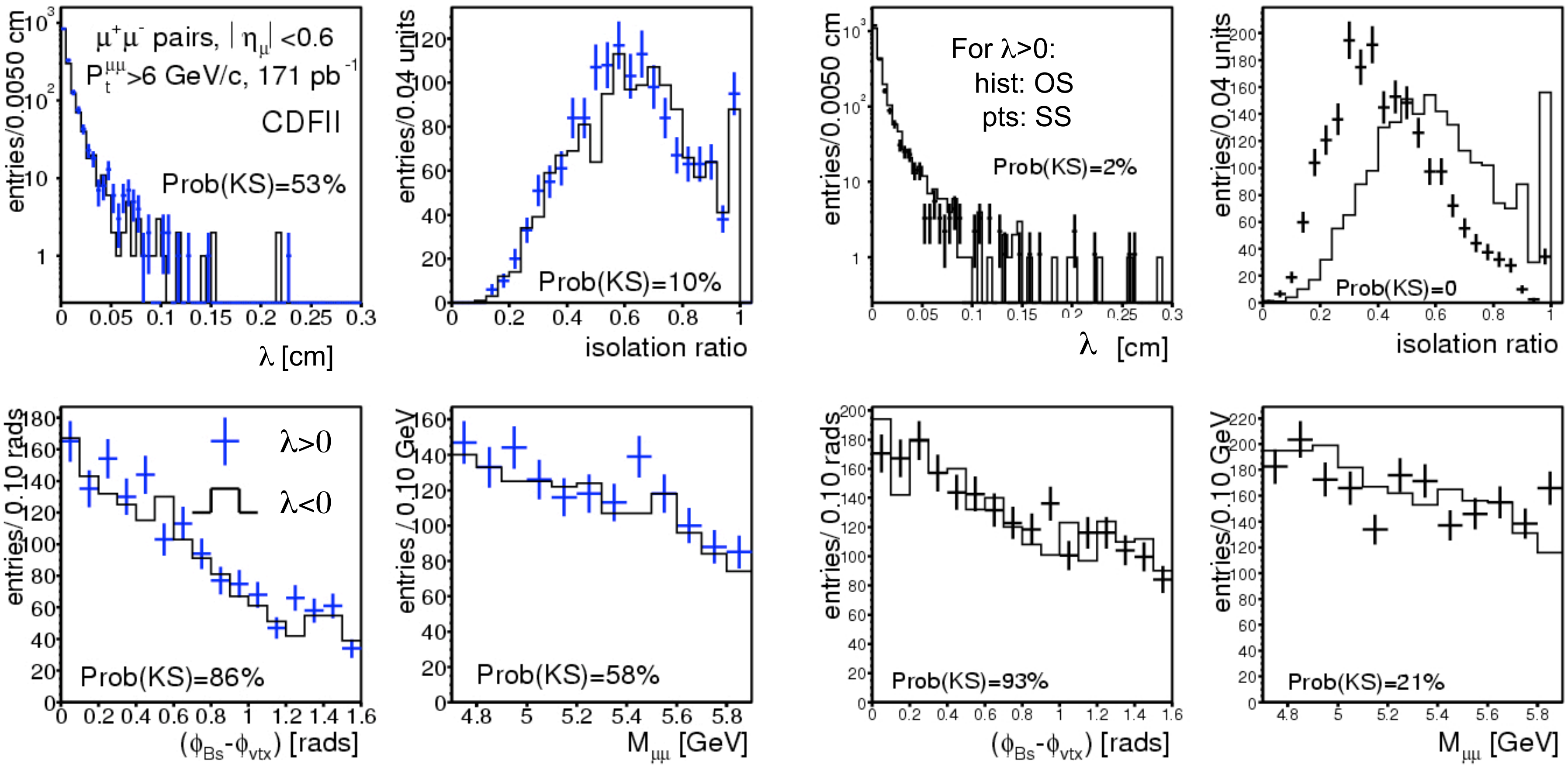
1. Two-body B-decays
   - negligible
2. Generic $b\bar{b}$ events
   - no special treatment required

Let's compare n_{bg} predictions to observations in control samples.

<u>Method</u>: Background Cross-checks

- Data Samples (statistically independent)
  - OS+ : opposite-sign muon pairs, $\lambda > 0$;
    the signal sample – not used for xchecks
  - OS- : opposite-sign muon pairs, $\lambda < 0$
  - SS+ : same-sign muon pairs, $\lambda > 0$
  - SS- : same-sign muon pairs, $\lambda < 0$
- OS samples pass the default reco+vertex cuts
- SS samples pass looser reco cuts
  - looser == remove trigger matching, and
    $P_T(\mu)>1.5$ and $P_T(\mu\mu)>4.0$ GeV

Method: Background Cross-checks



- OS- sample "ideal" control sample.
- SS sample not ideal but useful since some B-backgrounds there.

Method: Background Cross-checks

- Compare #predicted vs #observed for three sets of cuts
  - A : $(\lambda, \Delta\Phi, \mathrm{Iso}) = (>100\mu m, <0.20\ \mathrm{rad}, >0.60)$
  - B : $(\lambda, \Delta\Phi, \mathrm{Iso}) = (>150\mu m, <0.20\ \mathrm{rad}, >0.70)$
  - C : $(\lambda, \Delta\Phi, \mathrm{Iso}) = (>200\mu m, <0.10\ \mathrm{rad}, >0.80)$

- ''B'' corresponds to near optimal cuts, while A (C) correspond to looser (tighter) sets of cuts

- Note: C < B < A (ie. correlated for same sample), but OS-, SS+ and SS- stat. independent

Method: Background Cross-checks

	OS+	OS-	SS+	SS-
ρ(Iso-λ)	-0.14	-0.05	0.00	0.05
ρ(Iso-ΔΦ)	0.02	-0.08	-0.02	-0.02
ρ(Iso-M)	0.03	0.03	-0.02	-0.01
ρ(λ-M)	-0.03	-0.05	-0.02	-0.00
ρ(ΔΦ-M)	0.05	0.06	0.06	0.01
ρ(ΔΦ-λ)	-0.30	-0.21	-0.20	-0.20

(uncertainty is +/-0.03 and +/-0.02, per element, for OS and SS samples, respectively)

➡ ρ(mass-x), ρ(Iso-x) small for all samples

Method: Background Cross-checks

	Sample	#predicted	#obsrvd	$\mathcal{P}$(>=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	

where P(>=o|p) is the Poisson prob of observing >=o when expecting p; when 0 observed give P(0|p).

Method: Background Cross-checks

one last x-check in fake-μ enhanced sample

- require >=1 leg to fail μ quality cuts
- reduces signal efficiency by factor of 50, while increasing background by factor of about 3
- verify ρ(mass-x) and ρ(Iso-x) are small

fake-μ enhanced sample

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

➡ OK sufficient confidence in background prediction.

Let's consider efficiencies…

Method: Efficiency and Acceptance

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

where,

From Data

$$\varepsilon_{trig} = trigger$$

From Data

$$\varepsilon_{reco} = \varepsilon_{COT} \cdot \varepsilon_{muon} \cdot \varepsilon_{SVX} \cdot \varepsilon_{vtx}$$

From MC, Chkd w/ Data

$$\varepsilon_{final} = \varepsilon_{\lambda} \cdot \varepsilon_{\Delta\Phi} \cdot \varepsilon_{Iso} \cdot \varepsilon_{mass}$$

I'll briefly describe each.

For optimization, only ε_{final} varies.

Method: Efficiency and Acceptance

Acceptance = fraction of $B_s \rightarrow \mu^+\mu^-$ events that fall within the geometric acceptance of CDF and satisfy the kinematic requirements of the trigger used to collect the dataset.

Use Pythia MC to estimate:

	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)%

(relative to $P_T(B)$>6 GeV && $|y(B)|$<1.0)

Systematics include variations of $P_T(B)$ spectrum, detector material in simulation, and modeling of beam profile and offset.

Method: Efficiency

A quick summary of our efficiency estimates:

- determine trigger and reconstruction efficiencies from data (+/-10% syst associated w/ kinematic differences between data J/Ψ and signal B_s)
- use realistic MC to determine efficiency of cuts on discriminating variables
- cross-check MC modeling of above by comparing MC to Data in sample of B+ → J/ΨK+ (+/-5% syst)
- total uncertainty +/- 11% dominated by syst

(all uncertainties on this slide are relative uncertainties)

Method: Trigger Efficiency

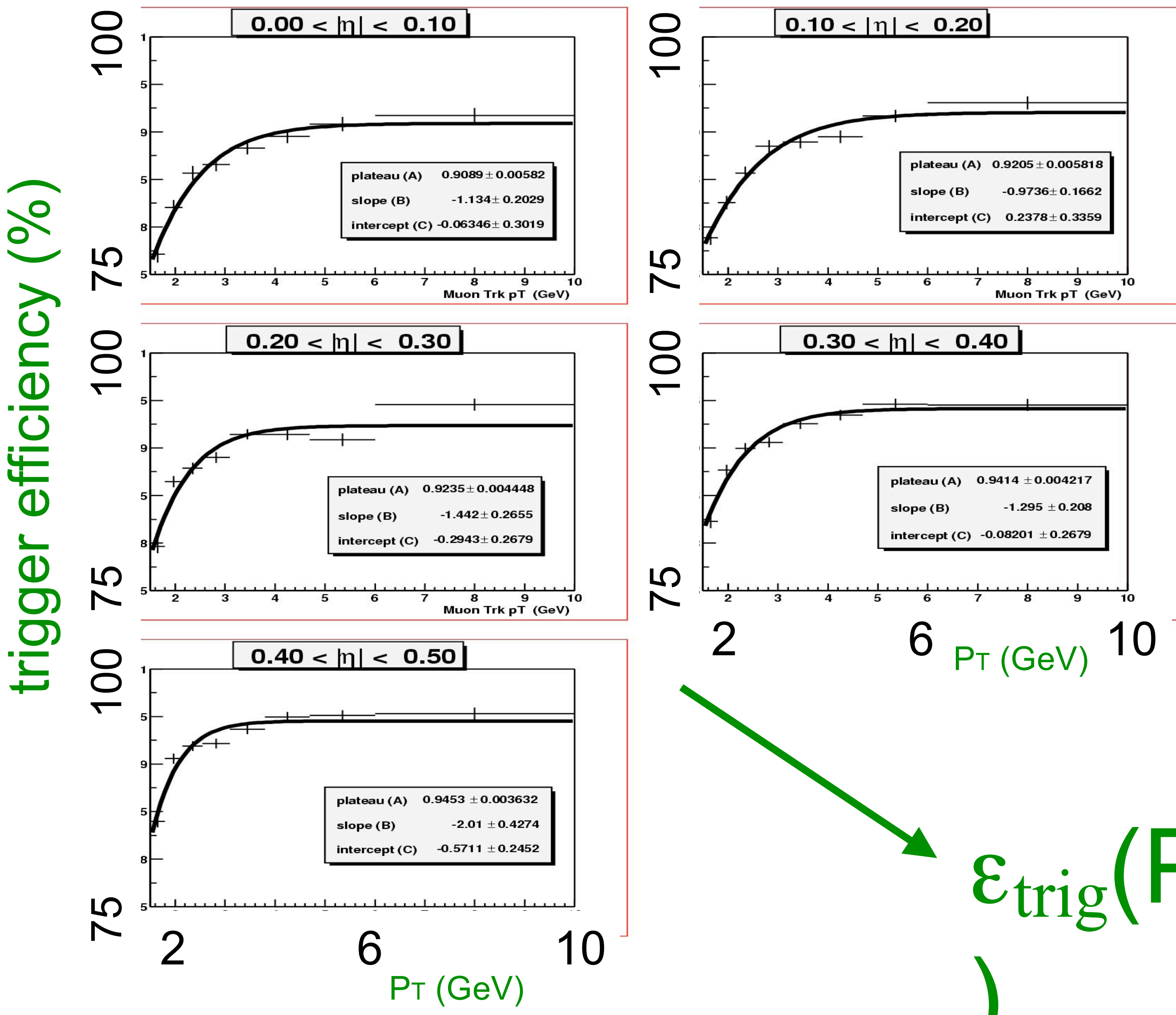
- use J/ψ→μ+μ− samples
  - use triggers that require only one muon
  - unbiased muon used to parameterize $\varepsilon_{trig}(P_t,\eta)$

$$\varepsilon_{trig}^{signal} = \varepsilon_{trig} \otimes \left(P_T^{\mu^+}, \eta^{\mu^+}, P_T^{\mu^-}, \eta^{\mu^-}\right)_{B_s \to \mu^+\mu^-}$$

= (85 +/- 3)%

  - uncertainty dominated by:
    syst differences J/ψ→μ+μ− and Bs→μ+μ−
  - uncertainty also includes:
    syst variations of parameterization, effects of 2-track correlations and statistics of sample

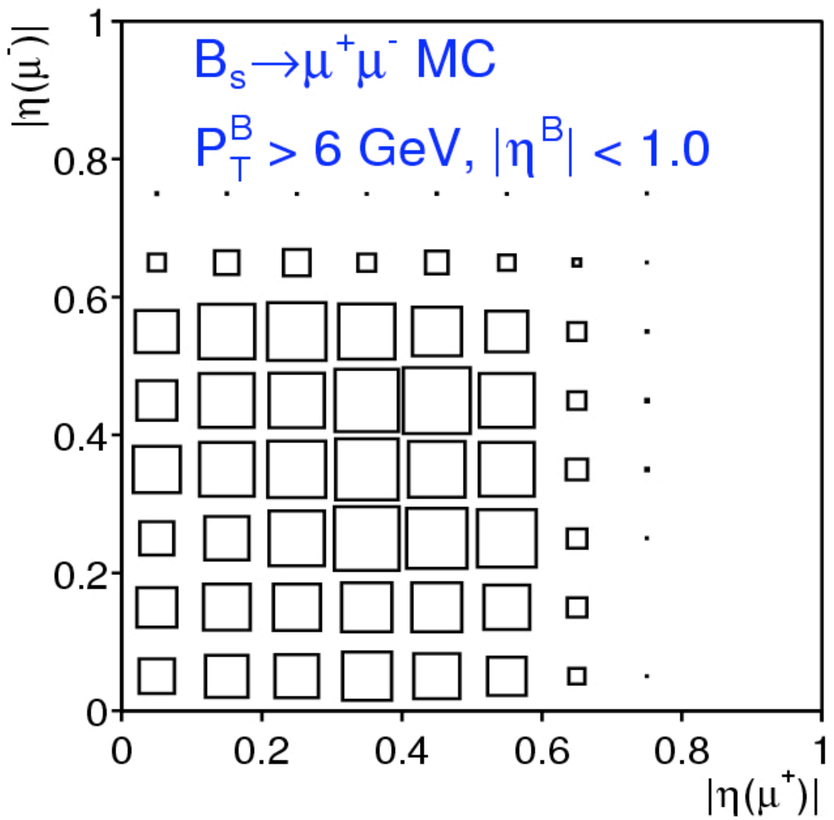
Method: Trigger Efficiency

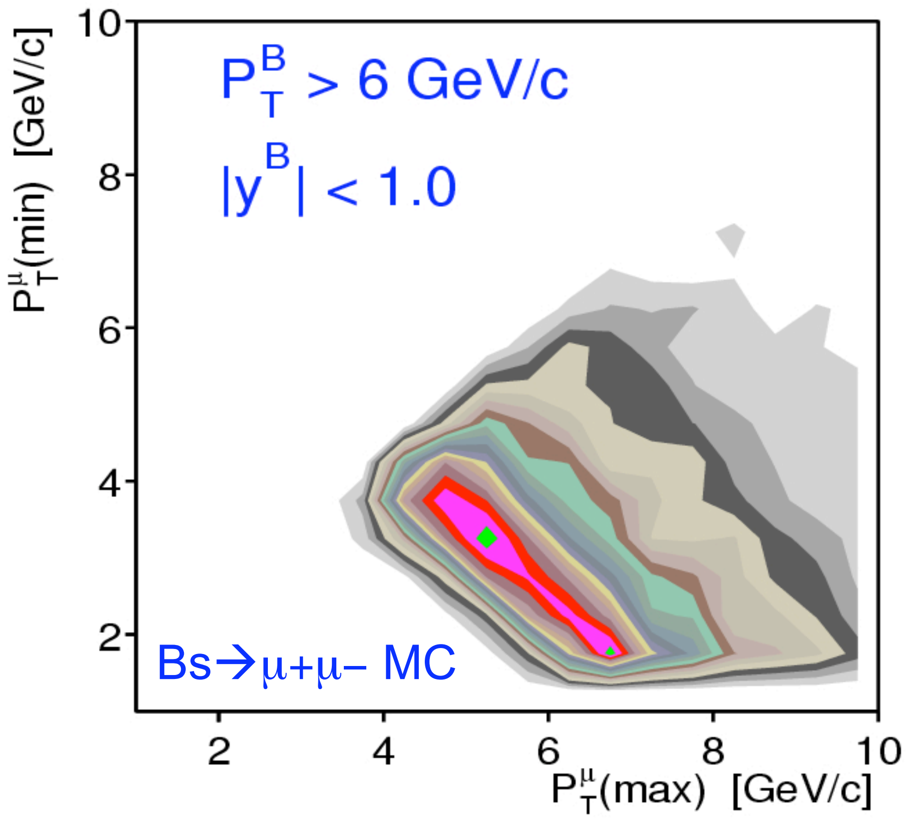


$\varepsilon_{trig}(P_T, \eta)$

Method: Trigger Efficiency

$\varepsilon_{trig}(Pt,\eta) \otimes$



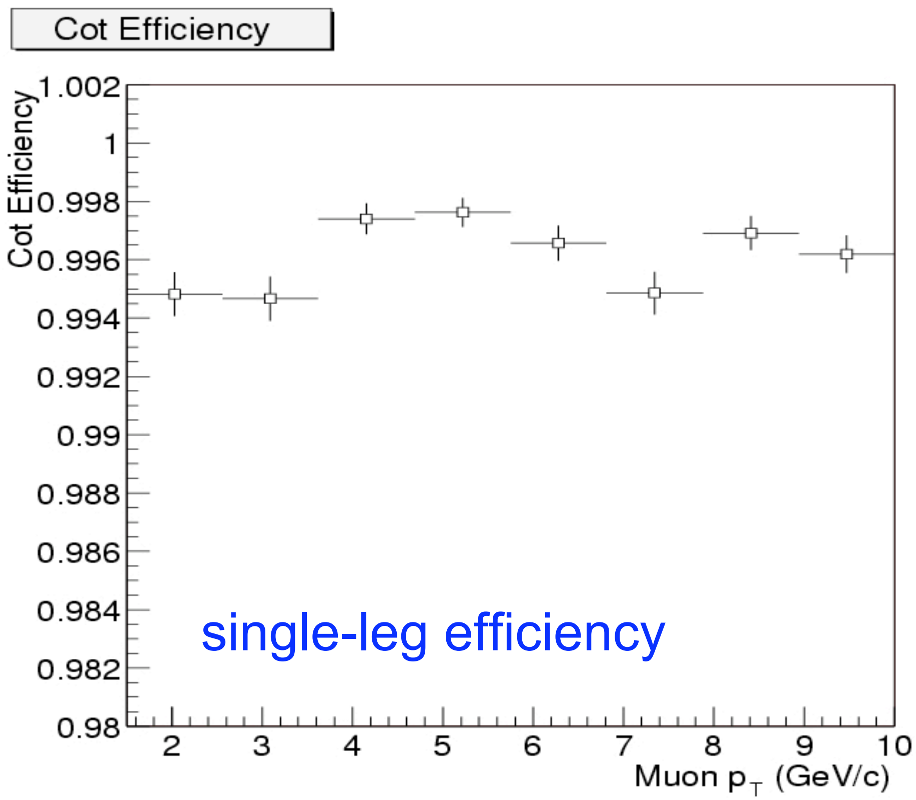


= (85 +/- 3)%

Method: COT Efficiency

COT Efficiency is estimated by embedding COT hits from MC muons into real data

- occupancy effects correctly accounted for
- need to tune COT hit simulation



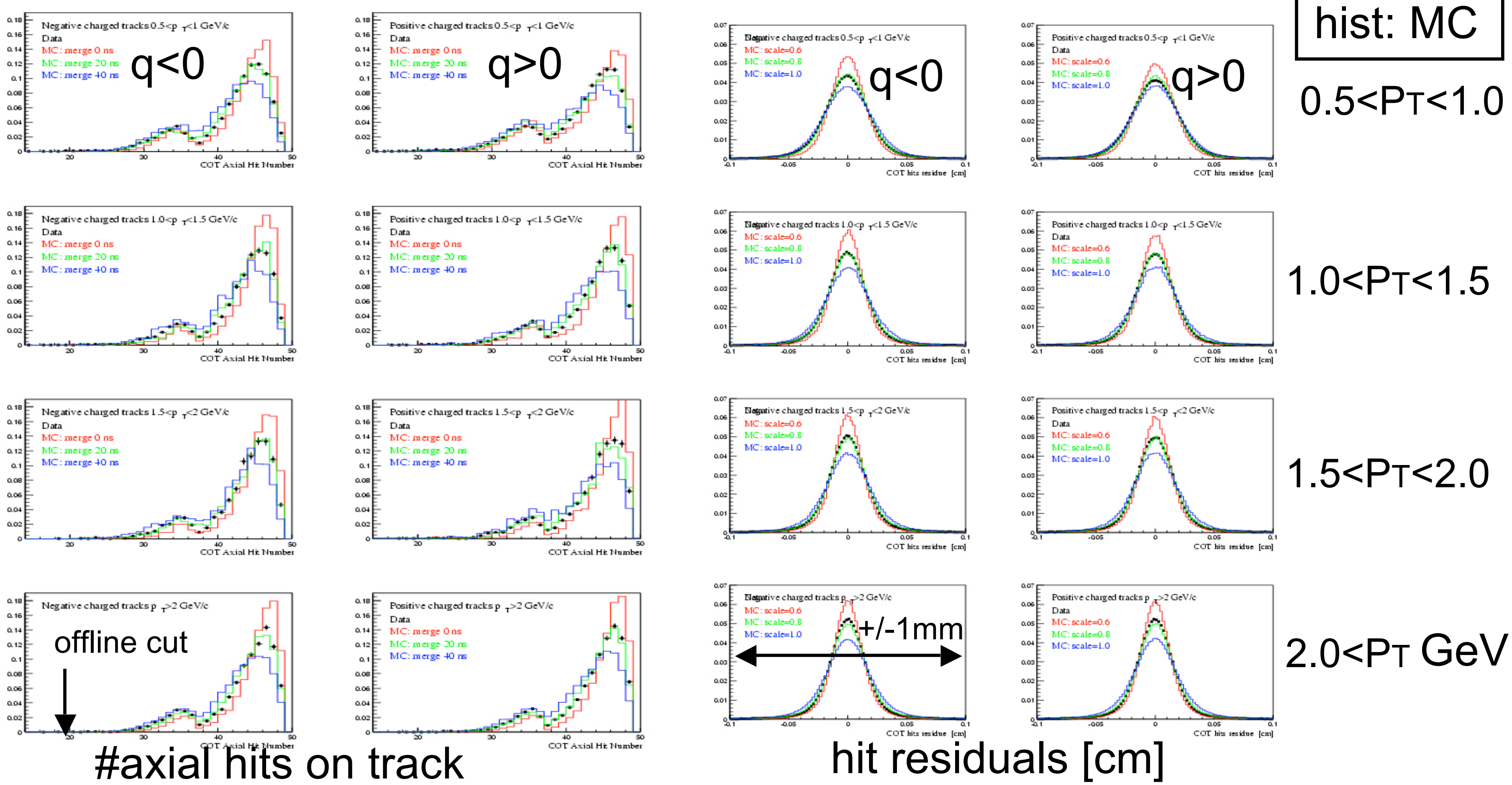
$$\varepsilon_{COT} = 99.22 \pm 0.01^{+0.68}_{-1.80}\%$$

(note: this is a double-leg efficiency)

Method: COT Efficiency

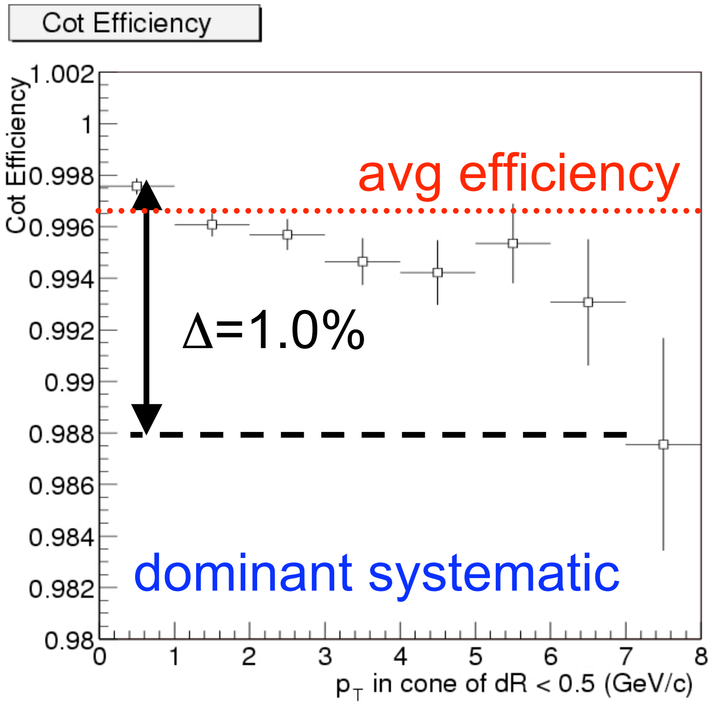
Need to tune COT hit simulation…

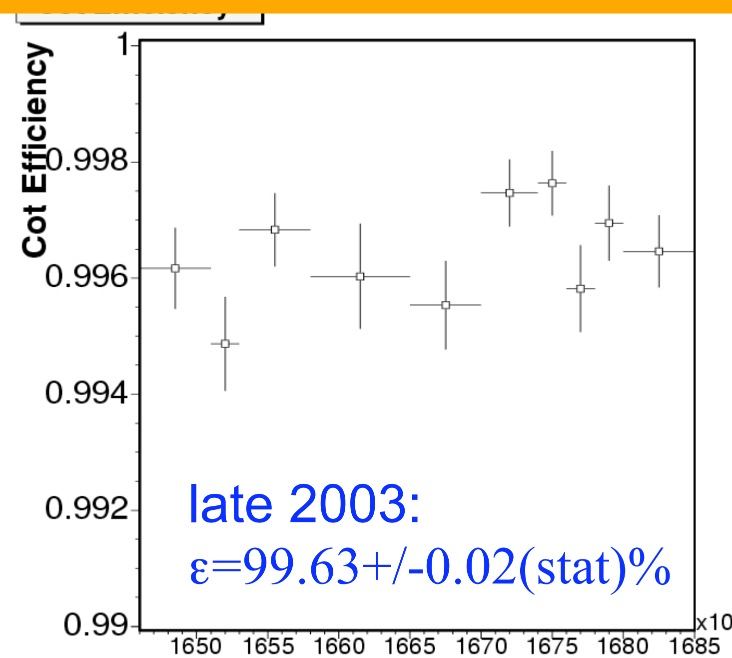
pts: data
hist: MC



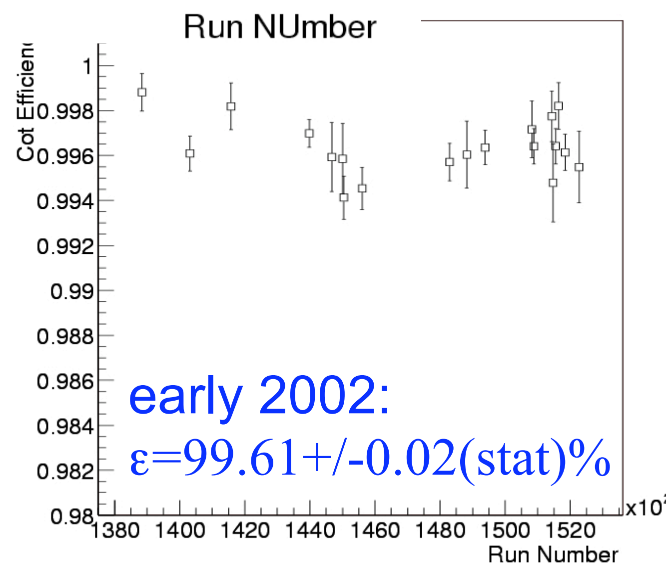
- reasonably well tuned at hit level
- have tunes which bracket data (for syst)

Method: COT Efficiency (this page is all single-leg efficiency)





occupancy effects negligible



Systematics

Isolation dependence: $^{+0.14}_{-0.86}\%$

Residual run/Pt depend: $\pm 0.29\%$

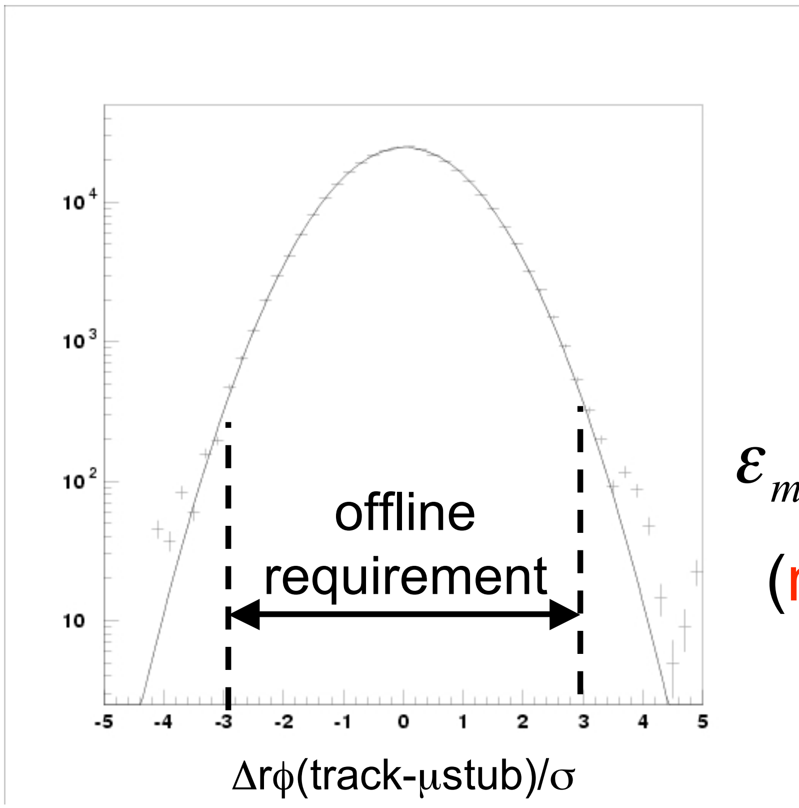
2 track correlations: -0.27%

Vary simulation tuning: $\pm 0.08\%$

<u>Method</u>: Muon Efficiency

Muon Efficiency is estimated using J/ψ→μ+μ– and Z→μ+μ– data events collected with triggers that only require 1 muon

- unbiased muon used to estimate μ reco efficiency
- can compare J/ψ and Z events



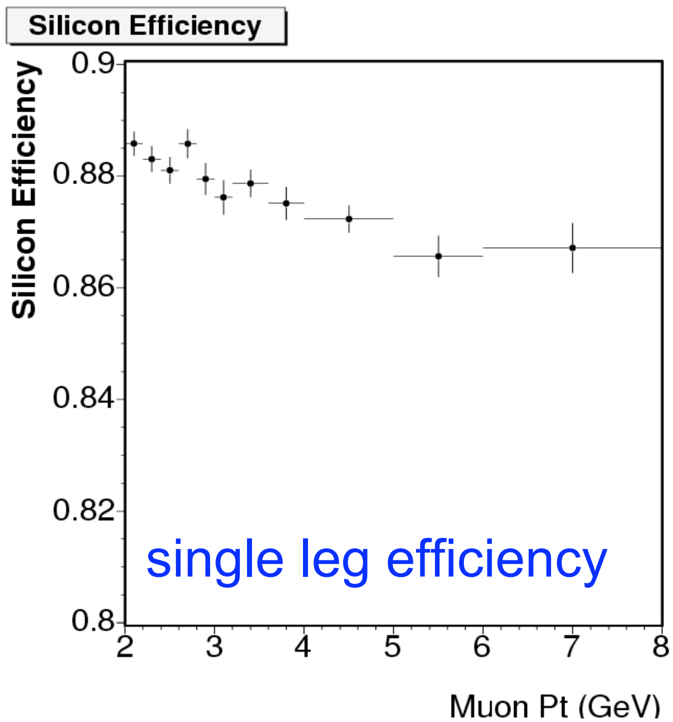
$$\varepsilon_{muon} = 95.9 \pm 1.3(stat) \pm 0.6(syst)\%$$

(note: this is a double-leg efficiency)

Method: SVX Efficiency

SVX Efficiency is estimated using $J/\psi \rightarrow \mu^+\mu^-$ data events

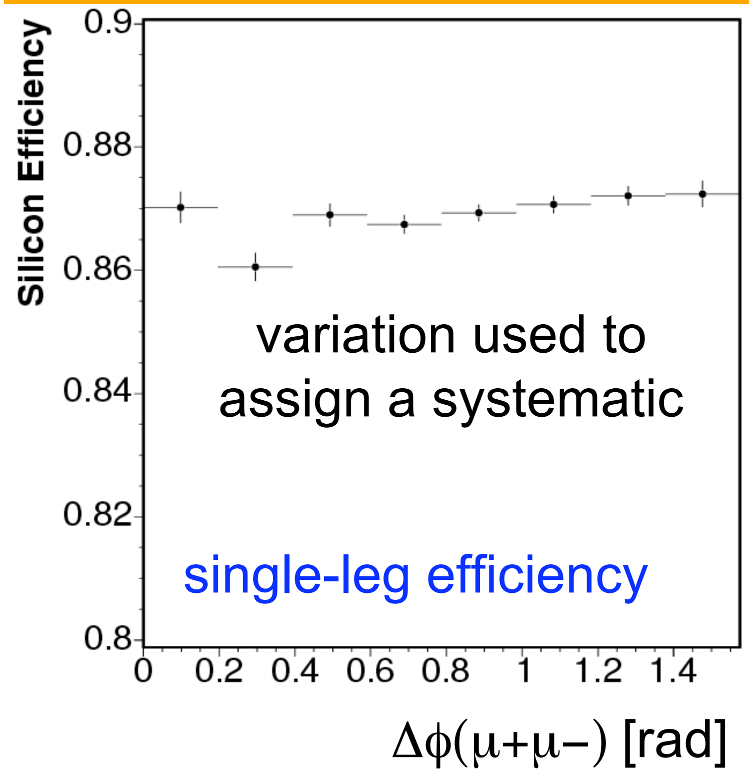
- no SVX requirements in our trigger path
- completely data determined



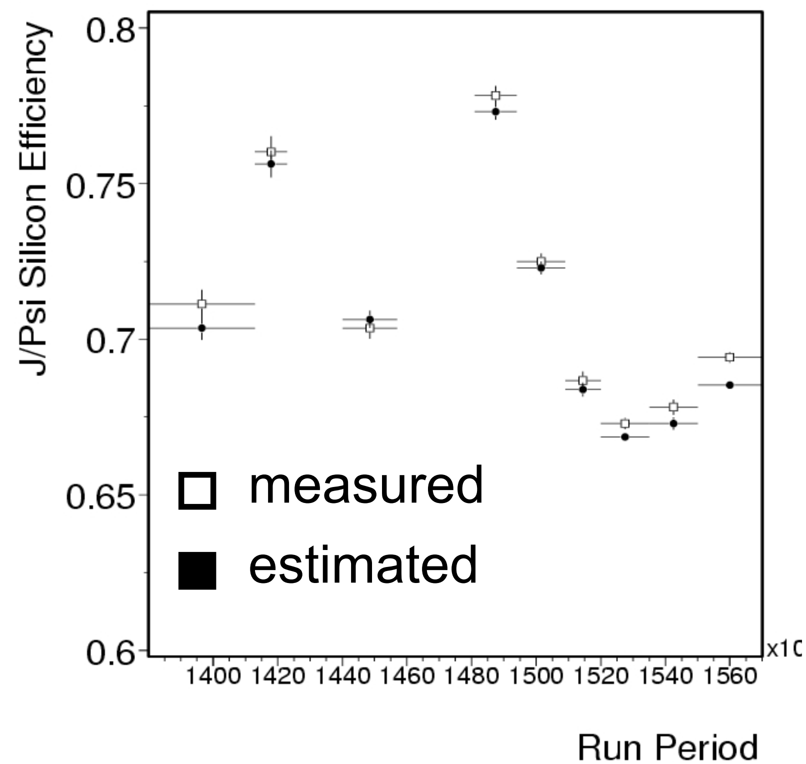
$$\varepsilon_{SVX} = 74.5 \pm 0.3(stat) \pm 2.2(syst)\%$$

(note: this is a double-leg efficiency)

Method: SVX Efficiency



cross-check double-leg efficiency



(spring/summer 2002)

Systematics

P_T dependence: $\pm 1.0\%$

2 track correlations: $\pm 0.7\%$

Run dependence: $\pm 0.4\%$

(single-leg uncertainties)

Method: SVX Efficiency

Double-leg SVX efficiency sounds low:

$$\varepsilon_{SVX} = 74.5 \pm 0.3(stat) \pm 2.2(syst)\%$$

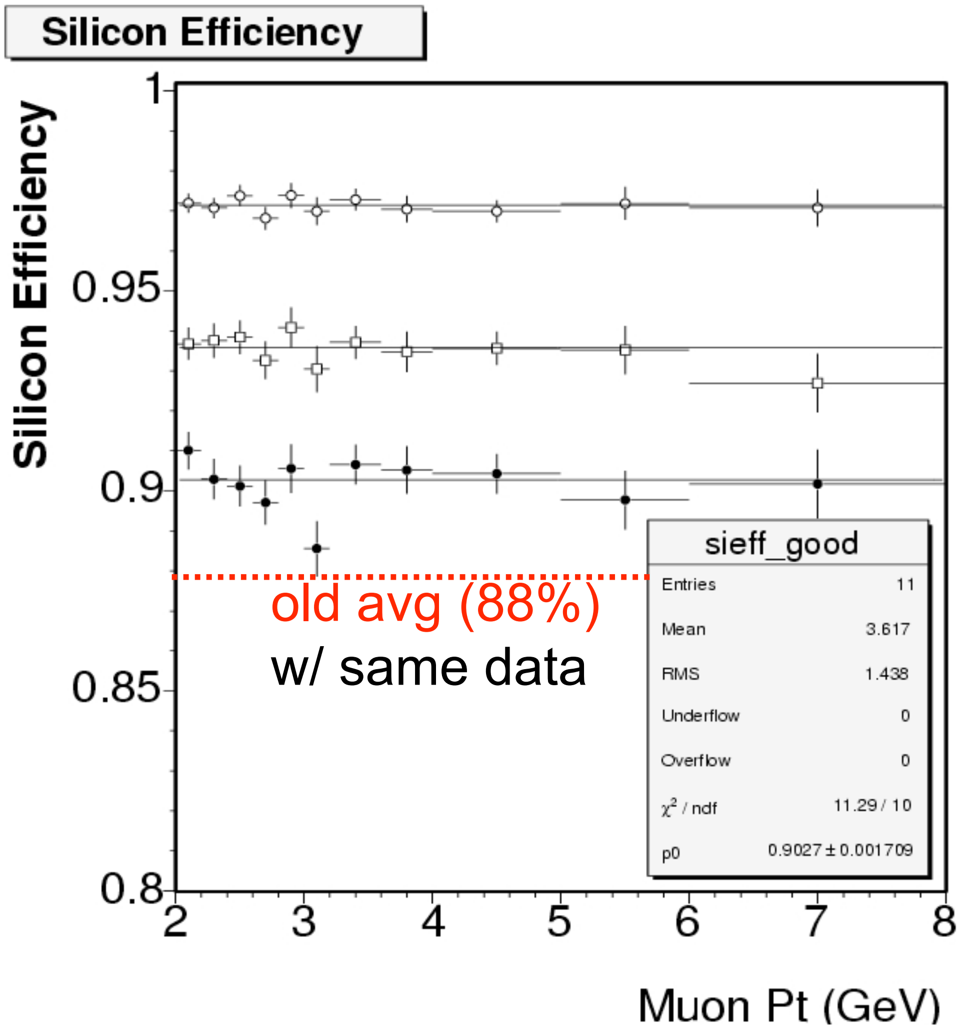
This corresponds to a single-leg efficiency of 86%.

The efficiency approximately breaks-down like this:

Single-leg SVX efficiency using 2003 data	
COT track traverses >=3 active SVX layers:	97%
has >=3 SVX rϕ hits associated:	91%
our more stringent requirements:	88%
average over full dataset:	86%

Method: SVX Efficiency

Have since improved pattern recognition so that:



traverse >=3 active layers
(unchanged)

associate >=3 rϕ hits
(+3% absolute)

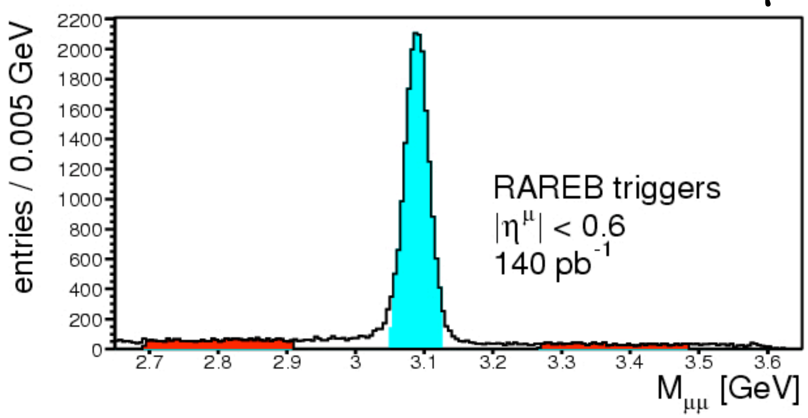
our more stringent requirements
(+2% absolute and flat)

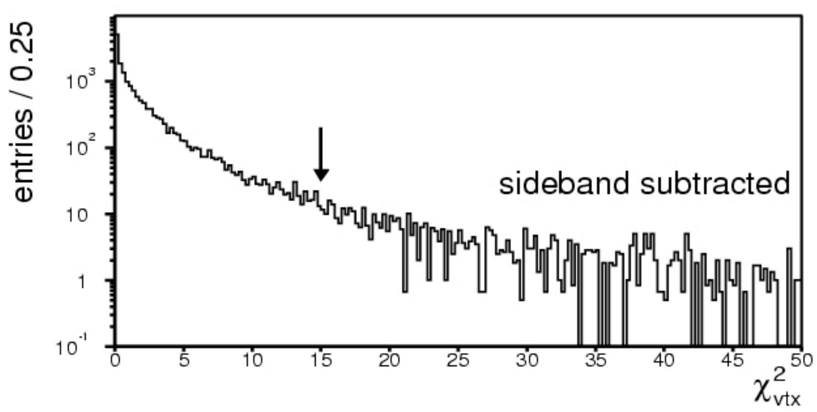
- next generation of this analysis will take advantage of these improvements

Method: Vertex Efficiency

Vertex Efficiency is estimated using J/ψ→μ+μ– data events collected with the same triggers as used for search

- data determined J/ψ→μ+μ– efficiency agrees w/i 2% MC determined B_s→μ+μ– efficiency



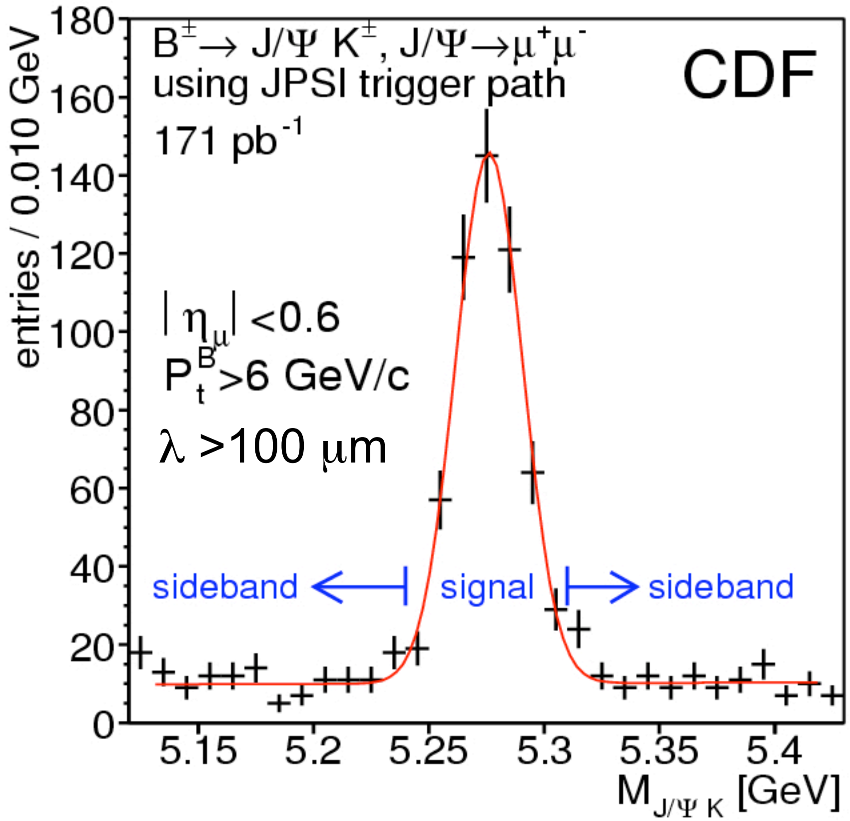


$$\varepsilon_{vtx} = 94.7 \pm 0.2(stat) \pm 1.9(syst)\%$$

<u>Method</u>: Efficiency of Final Selection Criteria

Determine efficiency of final selection criteria (M,λ,$\Delta\Phi$,Isol) using realistic MC simulation

- simulation tuned to detector (COT, SVX, etc.) hit level
- check modeling by comparing B+→J/ψK+ in data/MC



- compare 2-track (μ+μ–) and 3-track distributions
- momentum scale and invariant mass resolution well modeled in MC (ie. ε(M) OK)

<u>Method</u>: Efficiency of Final Selection Criteria

Compare relative efficiencies of Iso and $\Delta\Phi$ cuts:

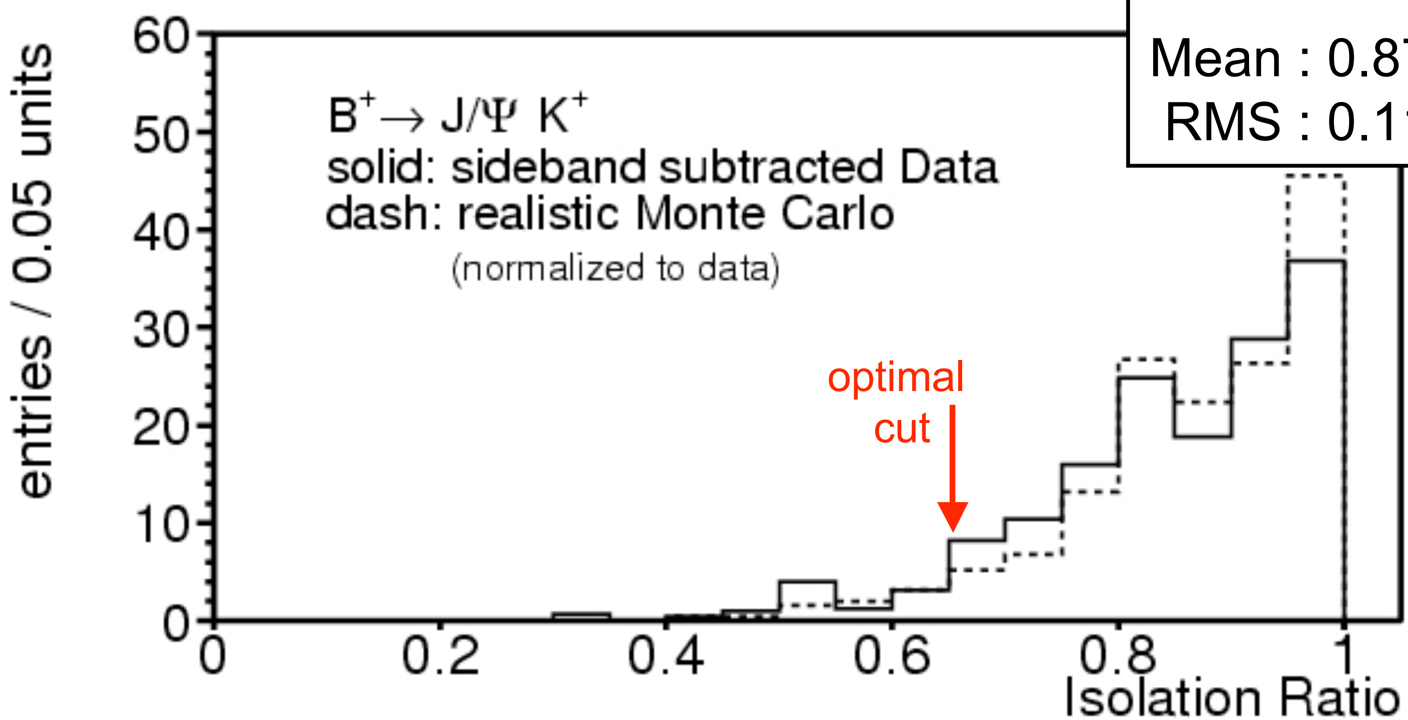
		Data	MC	(Data/MC)
	Iso > 0.6	(95 +/- 2)%	(97 +/- 1)%	0.98 +/- 0.02
	Iso > 0.7	(88 +/- 2)%	(92 +/- 1)%	0.96 +/- 0.03
	Iso > 0.8	(68 +/- 2)%	(79 +/- 2)%	0.87 +/- 0.04
$\lambda > 100\mu m$	$\Delta\Phi < 0.2$	(98 +/- 2)%	(97 +/- 1)%	1.00 +/- 0.02
	$\Delta\Phi < 0.1$	(89 +/- 3)%	(89 +/- 1)%	0.99 +/- 0.03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

For search, we make cut at Iso>0.65 $\Delta\Phi$<0.1:

- ✓ efficiencies agree well
- ✓ ε(Iso) and $\varepsilon(\Delta\Phi)$ OK

Method: Efficiency of Final Selection Criteria

Monte Carlo slightly more isolated than Data:



	MC	DT
Mean :	0.87	0.82
RMS :	0.11	0.16

- loose Isolation requirements OK, tighter requirements incur larger systematic

Method: Efficiency of Final Selection Criteria

Compare relative efficiencies of λ cuts:

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

prediction normalized to λ>50 μm requirement

For search, we make cut at λ>150-200 μm:

✓ relative efficiency agrees well

✓ $\varepsilon(\lambda)$ OK

In general, MC tracks data efficiencies to better than 5%.
Use MC determined ε_{final} with +/-5% (relative) systematic.

Method: Optimization

We now have in hand:

1. Background estimate
2. Estimate of total acceptance*efficiency
3. Their associated uncertainties

Let's Optimize!

Considered >100 different sets of ($M_{\mu\mu}$,λ,$\Delta\Phi$,Iso) requirements with ε_{final} = 28 - 78%:

- use set which minimized *a priori* expected limit,
- minima shallow,
 varying by <5% over wide range
- same results for integrated luminosities up to 400 pb-1
- same optimal selection criteria for $B_d \rightarrow \mu^+\mu^-$ search

Method: Efficiencies and Uncertainties

Using the optimal selection criteria…

Efficiencies

Acceptance :	6.6%
ε_{trig} :	85%
ε_{reco} :	71%
ε_{vtx} :	95%
ε_{final} :	54%
$\alpha^{*}\varepsilon_{total}$:	2.0%

(α is determined for $P_T(B)>6$ GeV && |y|<1)

Uncertainties

Background stat :	27%
syst :	5%
Total :	30%
Acceptance :	7%
ε_{trig} :	4%
$\varepsilon_{reco}{}^{*}\varepsilon_{vtx}$:	4%
ε_{final} :	5%
$\alpha^{*}\varepsilon_{total}$:	10%
Luminosity :	6%
Normalization :	17%
$\alpha^{*}\varepsilon_{totl}{}^{*}L^{*}\sigma_{Bs}$:	21%

(these are all relative uncertainties)

Method: Optimization Results

The optimal set of final selection criteria is:

$\Delta M_{\mu\mu}$ = +/- 80 MeV around $M(B_s)$=5.369 GeV

$\lambda > 200\ \mu m$

$\Delta\Phi < 0.10$ rad

Isolation > 0.65

which corresponds to:

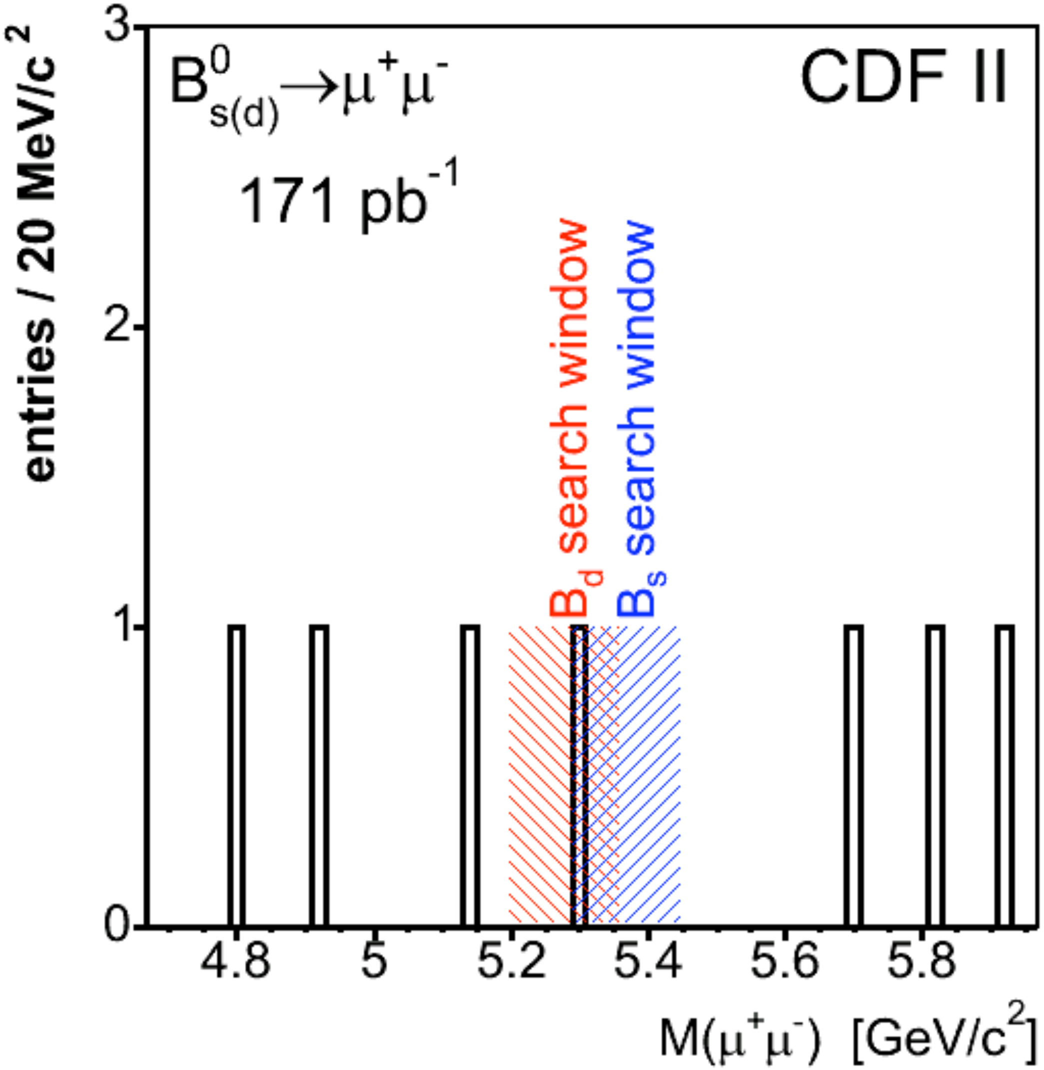
$\alpha * \varepsilon_{total}$ = (2.0 +/- 0.2)%

single event sensitivity = 1.6×10^{-7}

<Bgd> in 171 pb^{-1} = 1.1 +/- 0.3 events

($\alpha\varepsilon$ & Bgd are unchanged for mass window centered on 5.279 GeV for the $B_d \rightarrow \mu^+\mu^-$ search)

Results



At 90% CL:

$BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-7}$

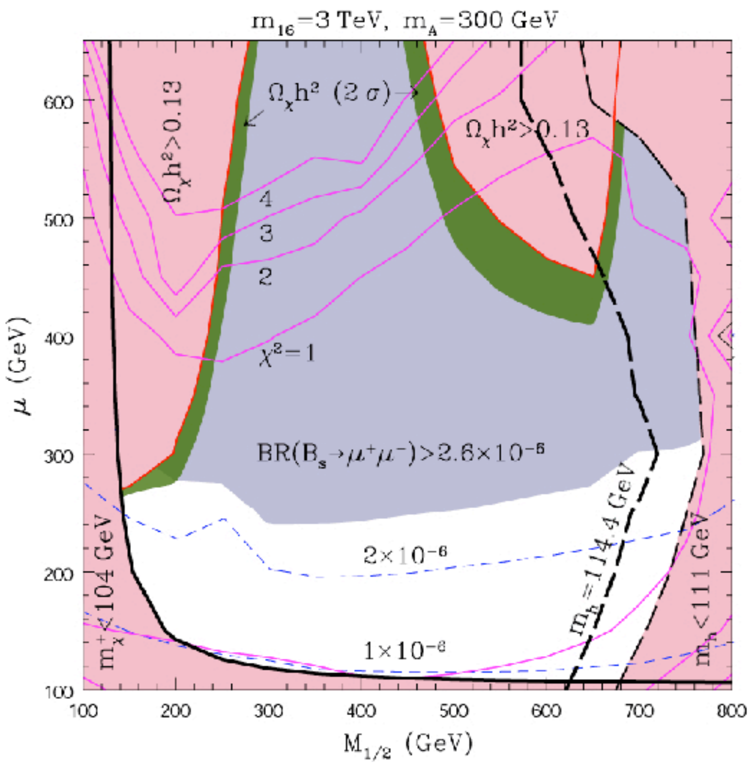
$BR(B_d \to \mu^+\mu^-) < 1.5 \times 10^{-7}$

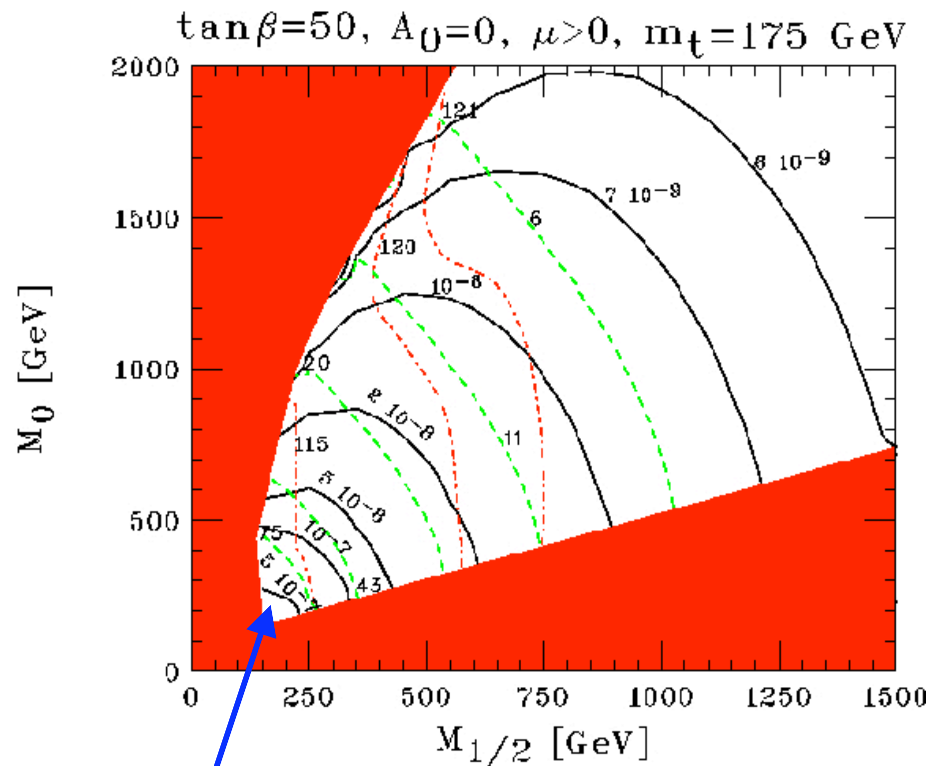
These are both the best published limits in the world for these decays.

Phys. Rev. Lett. **93**, *(2004)* 032001.

Results

This new limit...





Eliminates this entire plane

(raising MA to ~400 GeV opens it back up).

Just begins to eat into allowed parameter space in this plane.

Conclusions

- Have searched for $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ decays using 171 pb^{-1} of CDFII data.
- Observed 1 and expected 1.1 +/- 0.3 background events.
- Established these world best limits at 90 (95)% CL:

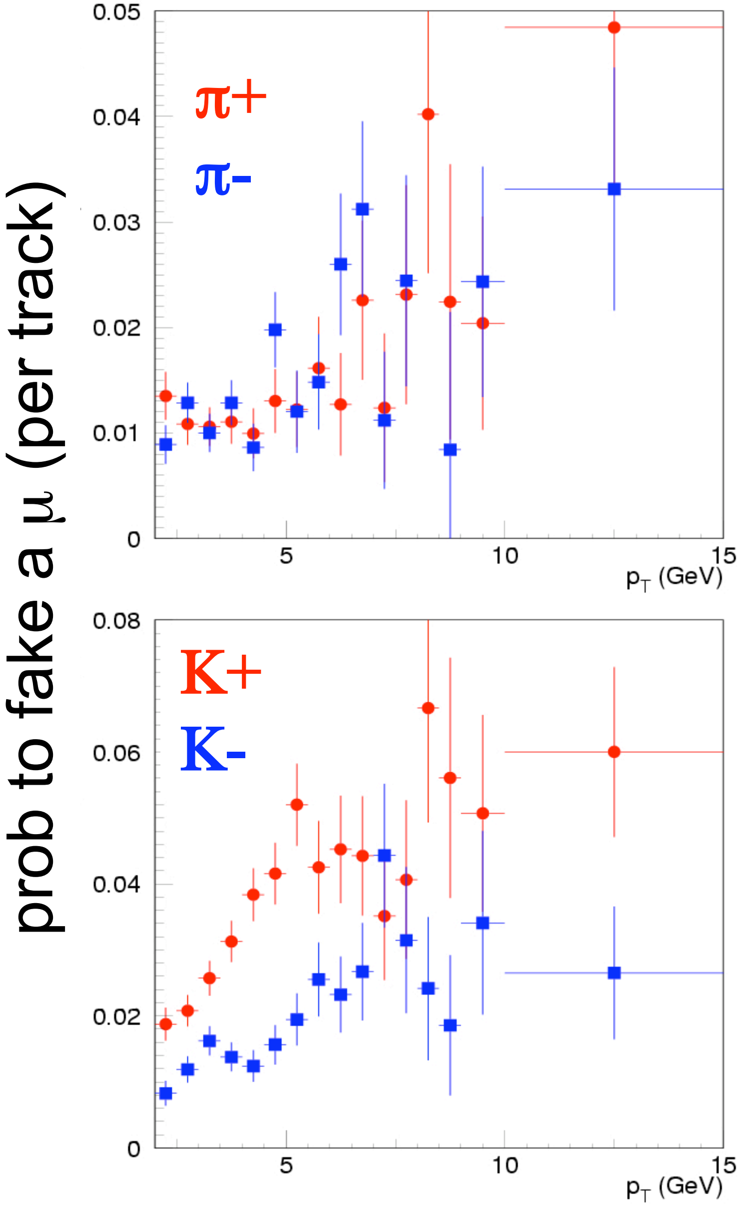
$$BR(B_s \to \mu^+\mu^-) < 5.8\ (7.5) \times 10^{-7}$$

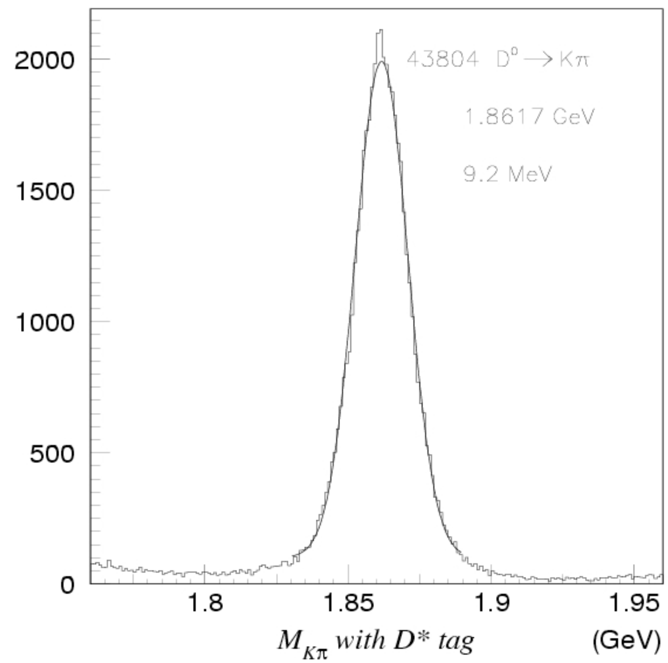
$$BR(B_d \to \mu^+\mu^-) < 1.5\ (1.9) \times 10^{-7}$$

(there exist preliminary Belle and D0 results that better both of these)

- Yields significant reduction in allowed parameter space of some models.
- Expect significant improvements with:
  - more data, more acceptance, more Bgd rejection

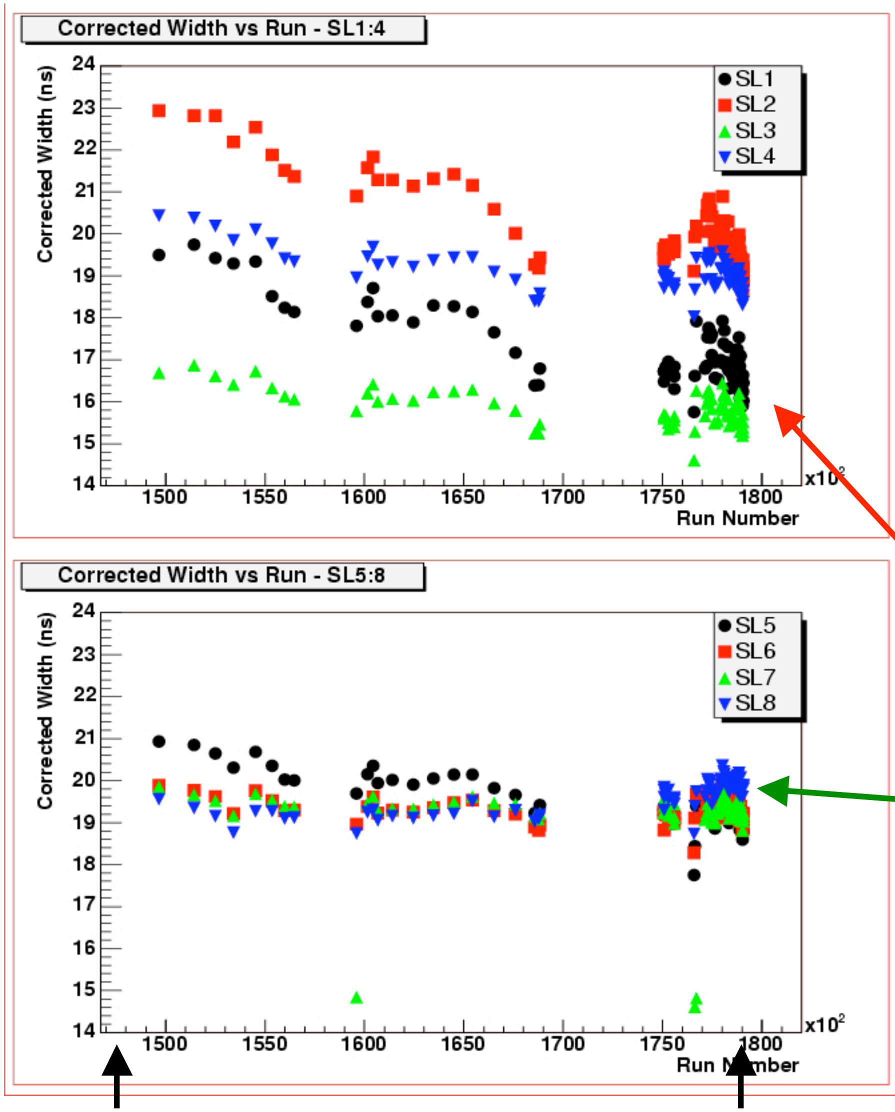
Backup: Probability for π or K to fake a μ





- use D*→Dπ→Kππ events to measure μ-fake rates for p+, p-, K+, K- separately as a function of pT
  - P(μ|π) ~ 1.2%
  - P(μ|K) ~ 2.5%
- convolute these functions w/ relevant pT spectra for B→h+h- decays

<u>Backup</u>: COT "Aging"



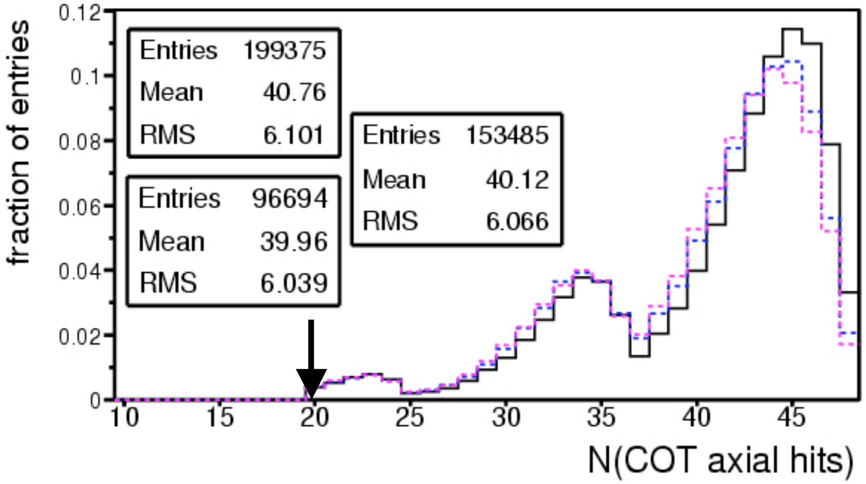
Summer 2002

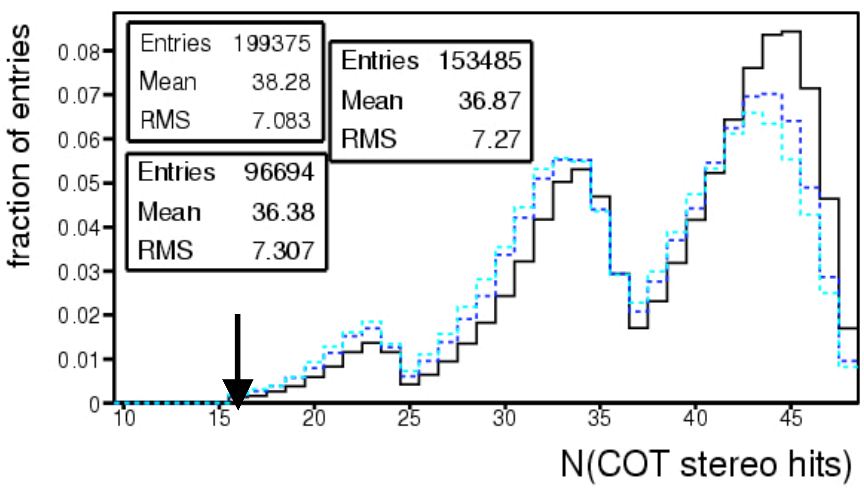
Spring 2004

- recall that COT geometry consists of 8 "Super Layers" (SL)
  - 12 sense wires in each SL
  - SL 1, 3, 5, 7 are stereo
  - SL 2, 4, 6, 8 are axial
  - axial SL used in L1 trigger
- unexpected reduction in gain on inner 4 SL
- outer 4 SL not significantly affected

how does this affect tracking?

Backup: COT "Aging"

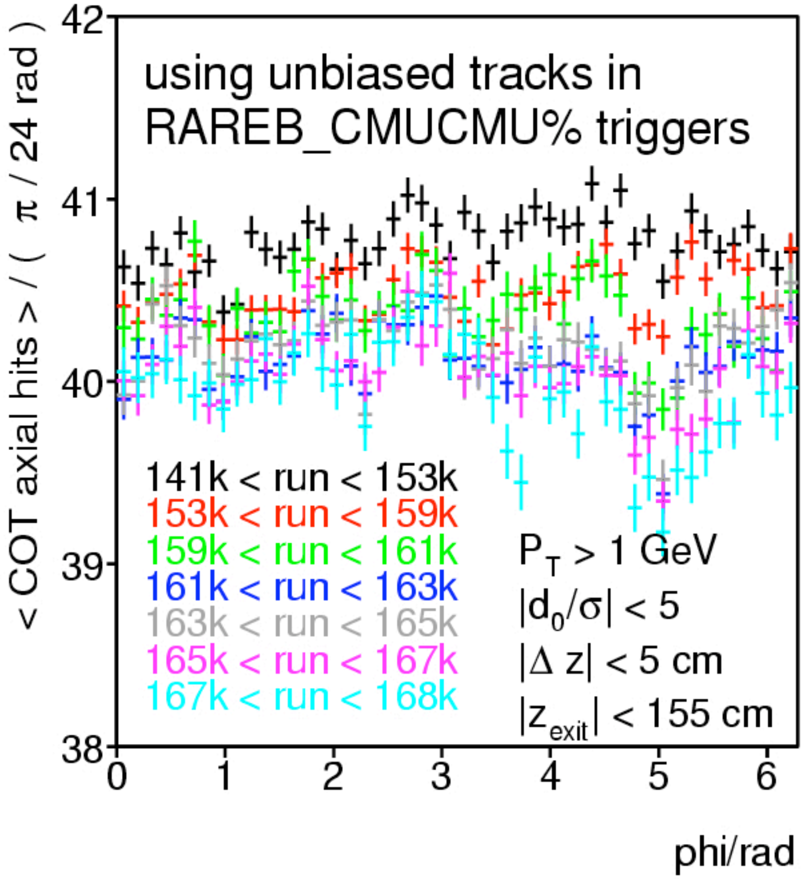


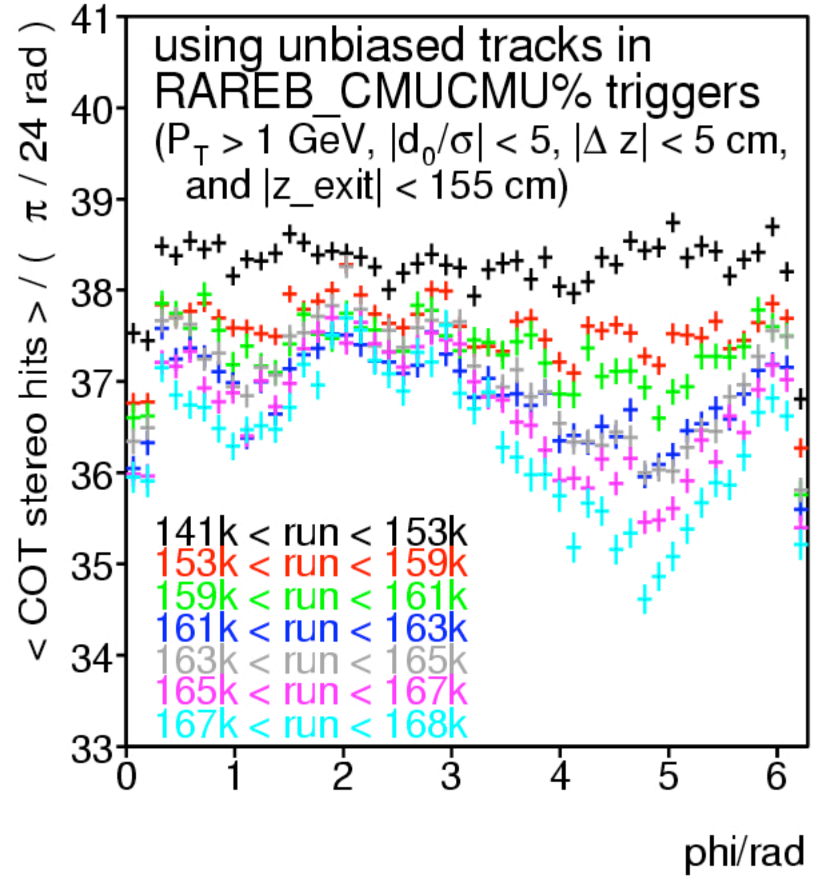


(↓ Indicate min # hits required offline)

- use RAREB triggered evts
- remove (XFT-trgd) muons
- look at tracks P_T>1 GeV
- divided into 7 run ranges of approximately 25/pb each
- 3 (early, middle, late) shown
- averaged over phi:
  - ✓<Nax> drops by 0.8 cnt
  - ✓<Nst> drops by 1.9 cnts
  - ✓Smaller than drops induced when varying simulation tune parameters to get syst for COT efficiency (< 0.1%)
  - ✓ concentrated on inner 3 layers

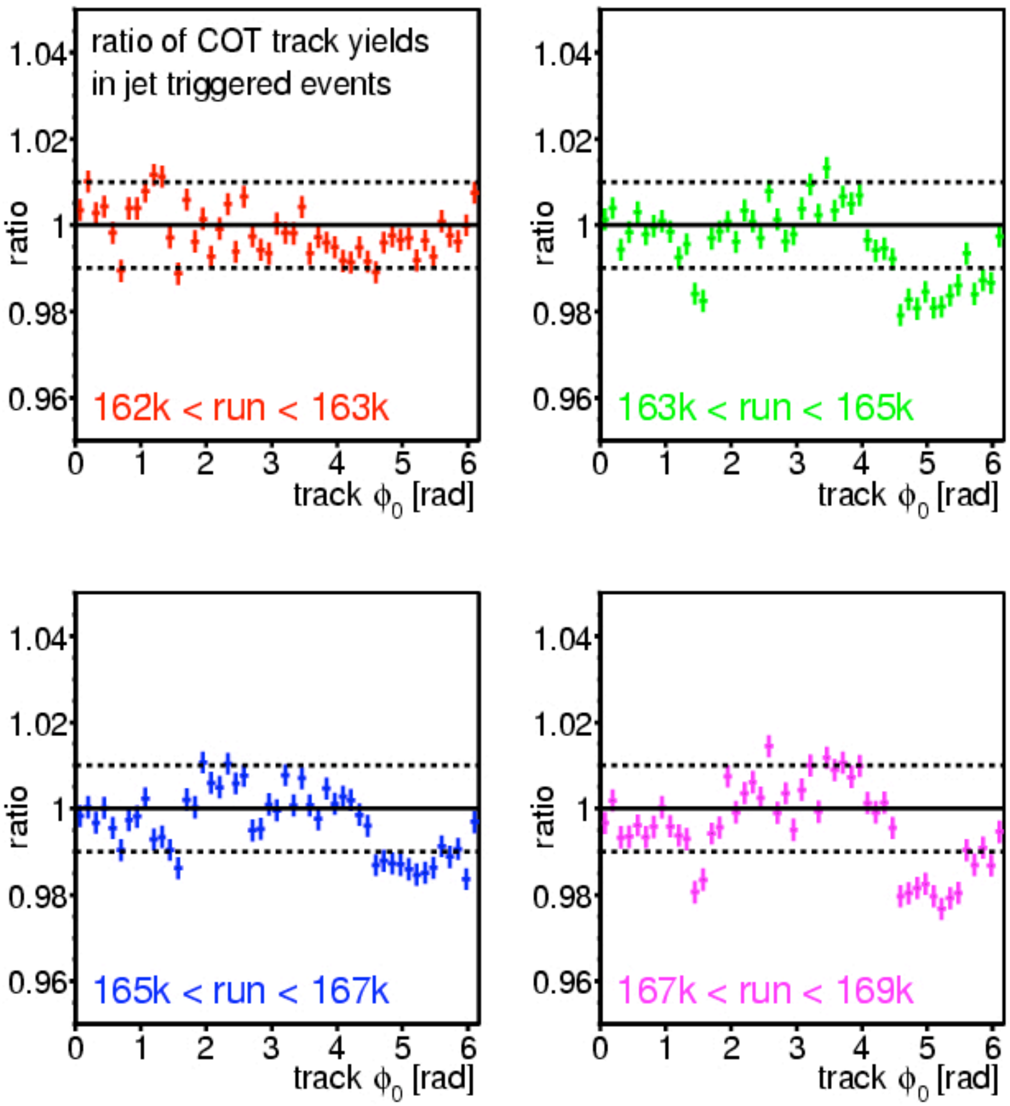
Backup: COT "Aging"





- same thing, binned in ϕ, all run ranges shown
- effect dominated by region around ϕ=4 rad
- multi-track (geometric) correlations important

<u>Backup</u>: COT "Aging"

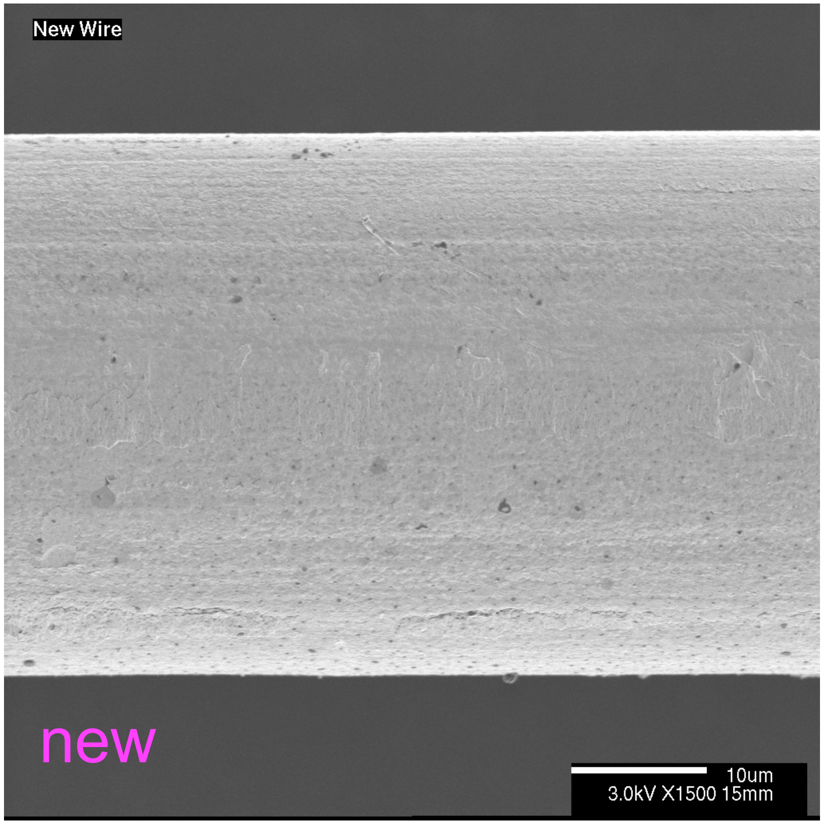


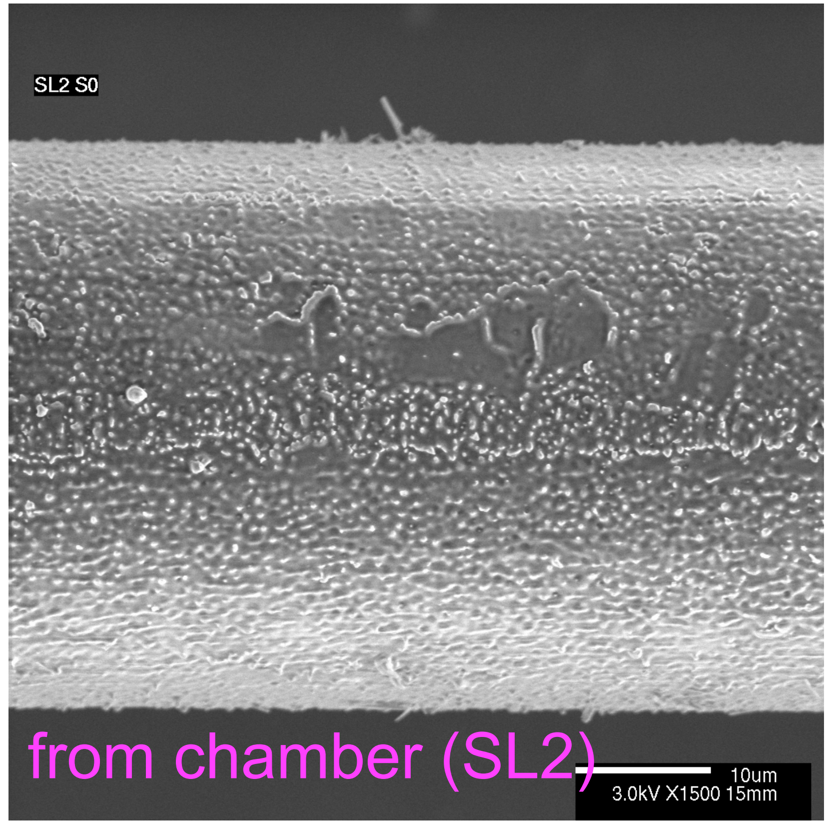
- generate relative efficiency in bins of ϕ using jet triggered events; also bin in run ranges, each corresponding to ~25pb-1
- fold Bs→μμ (ϕ,ϕ) spectrum with each of these curves
- lumi-weighted result:

0.9946

- difference w/ 1. assigned as additional systematic to the double-leg efficiency

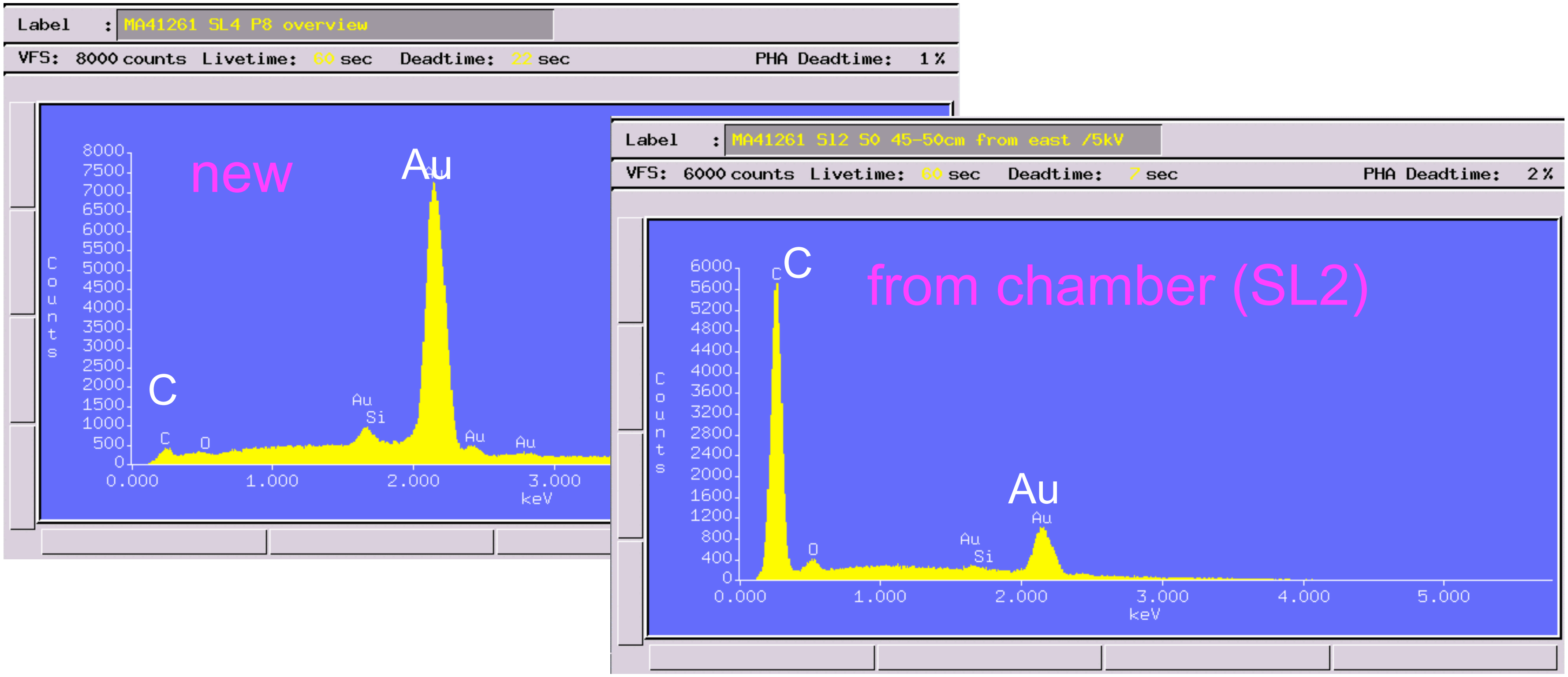
Backup: COT "Aging"





Recently swapped some wire planes out of chamber and had them analyzed. Visibly very different than an unused wire. Potential wire from same plane looked like new.

Backup: COT "Aging"



Further analysis reveals that there's ~300 nm of hydro-carbons on the affected sense wires. No evidence of silicas (ie. gas system is clean).

Backup: COT "Aging"

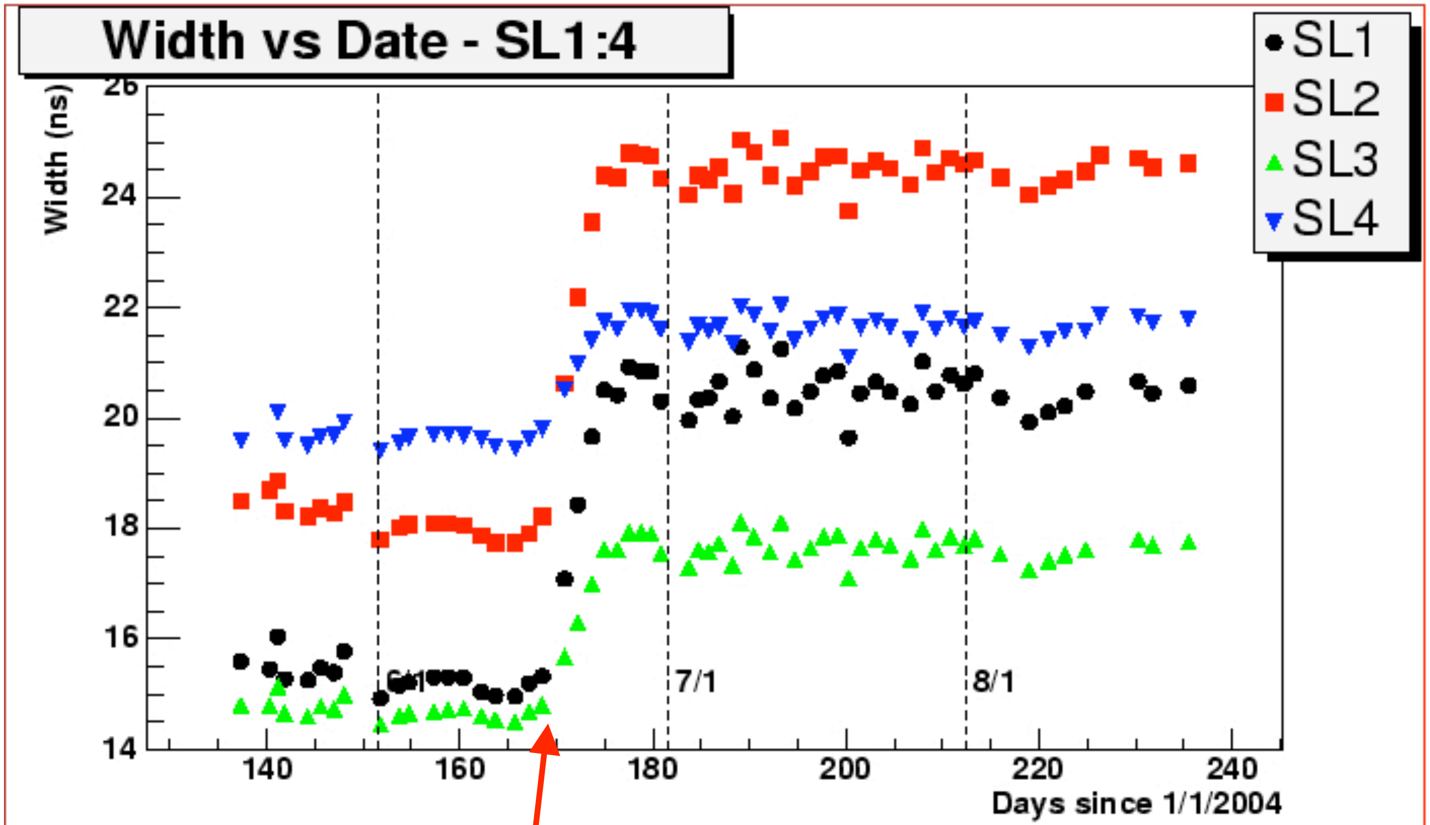
What did we do?

- reduced voltage on inner 4 SL while we investigated problem and possible solutions
- modified trigger to cope with the reduced gains on the inner axial SLs (more on next slide)
- assembled an international committee of experts
- increased gas flow by x20 and introduced small amount of O2 (~100 ppm) into system

gains fully recovered on all SL since Jun-04

- are further investigating the possibility of using a different gas in case needed at higher luminosities (using a pulled wire plane in a test chamber to study)

Backup: COT “Aging”



Spring 2004

Summer 2004

Increased flow &
Introduce 100 ppm of O_2

Backup: COT "Aging"

Is this data useful?

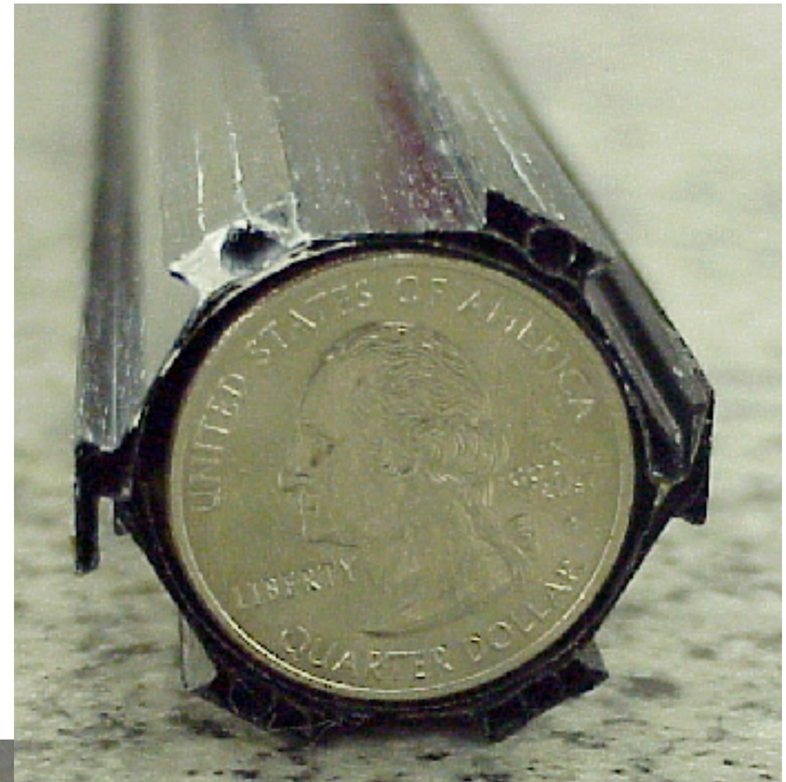
- track trigger modified to accommodate this (10-20% reduction in yields, depending on N_{track})
- COT track efficiency for leptons from W and Z unaffected and >99% (determined using missing energy triggers)
- track efficiency for pions and muons reduced 5-10% in P_T range 1-10 GeV (recall, we started with 99.6%)
- efficiency for adding SVX hits unchanged (thanks to ISL)
- with SVX hits attached, resolutions nearly unchanged
- 50 pb-1 of data like this so far
- this data usable for physics… will require dedicated simulation effort

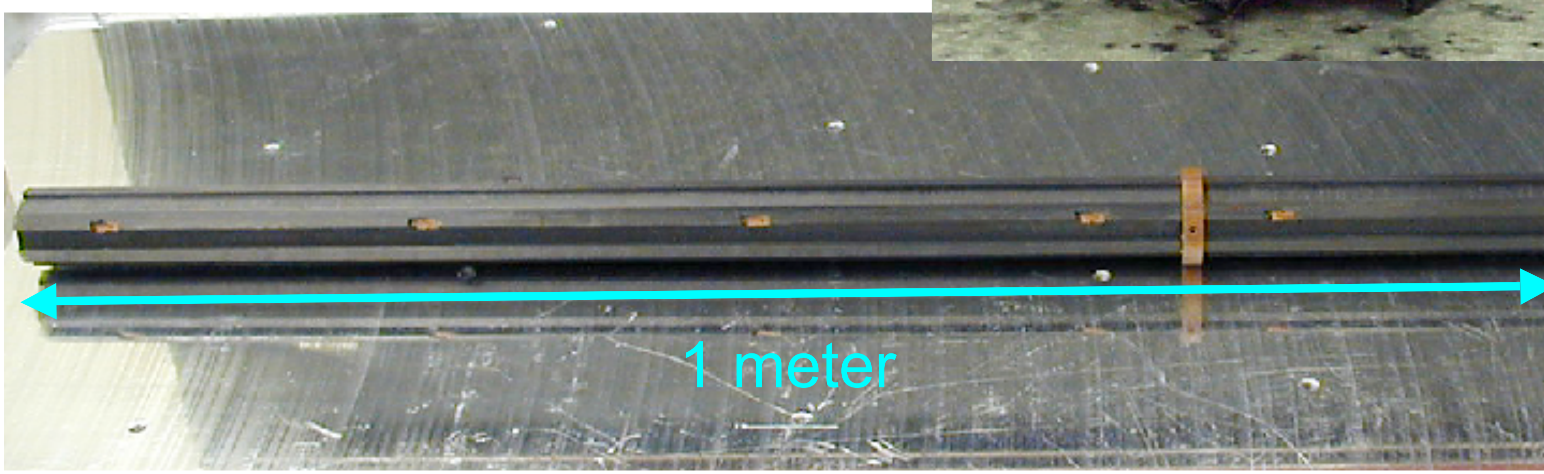
Backup: L00

What about L00?

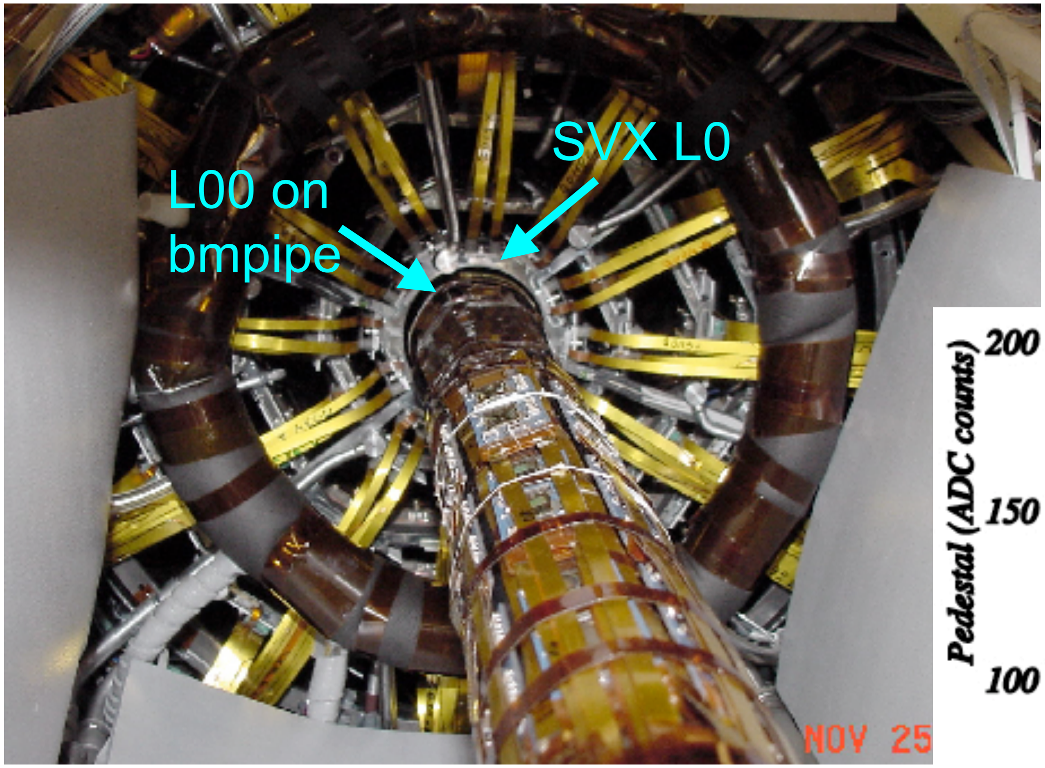
Recall…

- single-layer on beampipe
- rad-hard LHC silicon
- single-sided rϕ readout
- <1% X_0
- $1.3 < r < 1.5$ cm

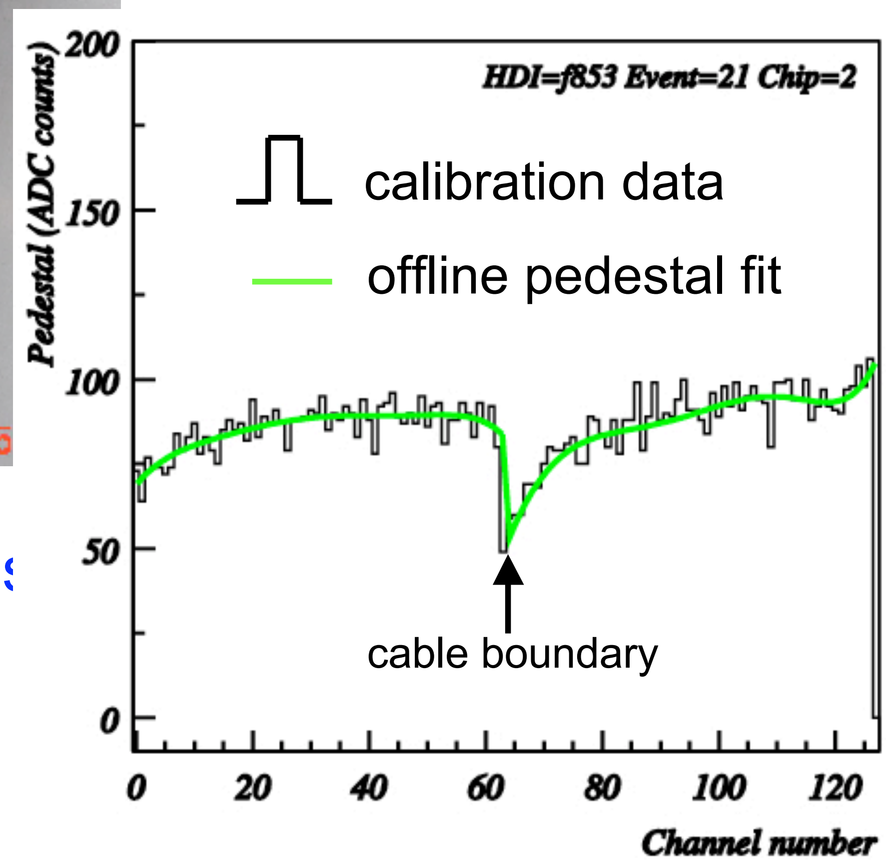




<u>Backup</u>: L00



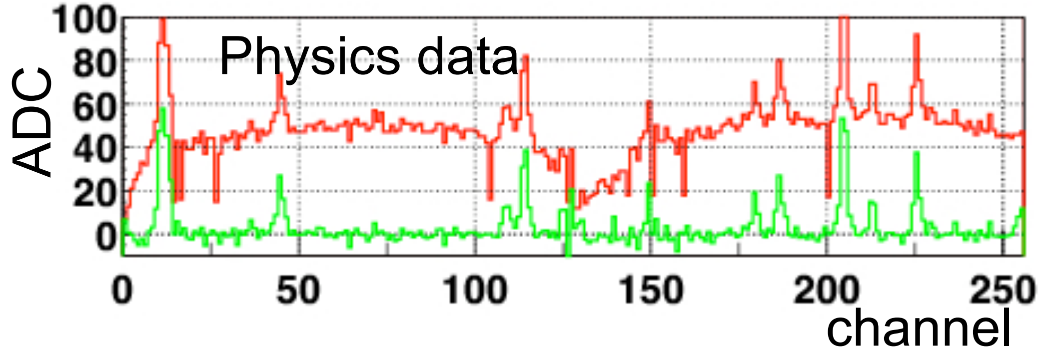
However: installation clearances very tight (300μm) – only limited shielding possible. Looked OK on bench top.



in situ, large pedestal fluctuations

- vary from event-to-event
- vary from chip-to-chip
- not uniform across a chip

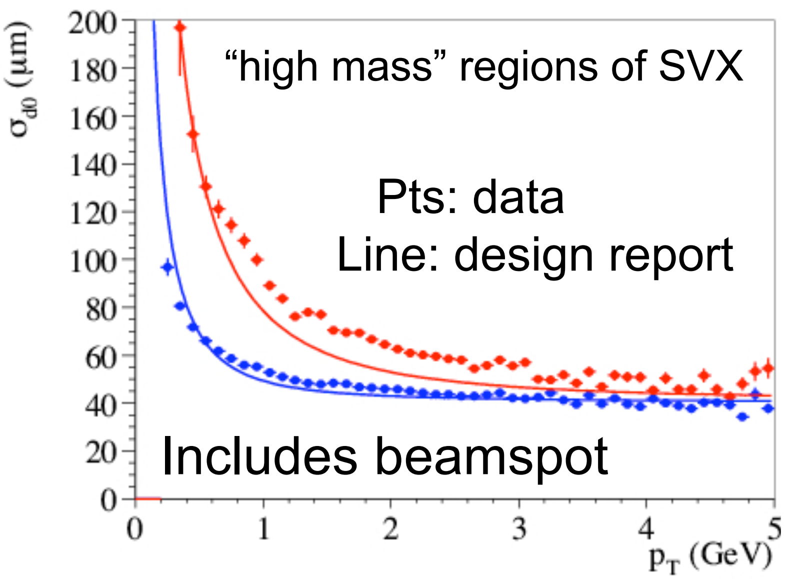
Backup: L00

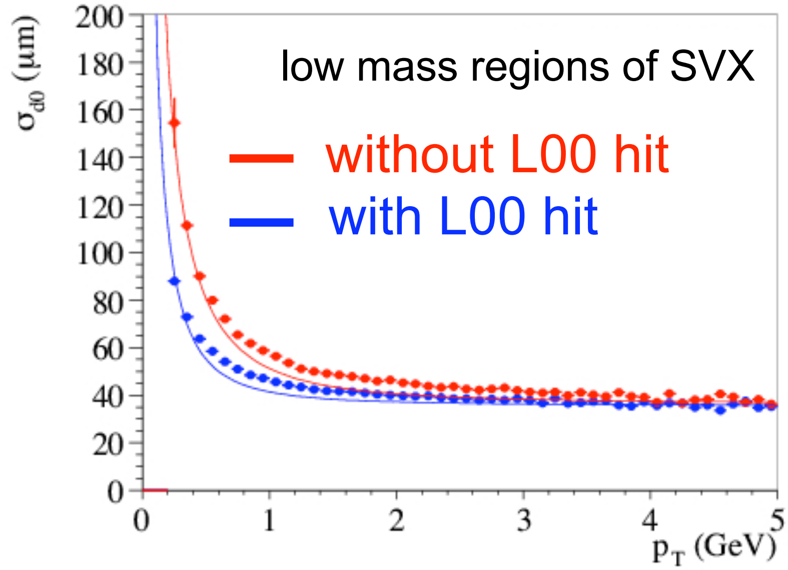


Employ offline fit evt-toevt for each chip to correct

Before pedestal fit

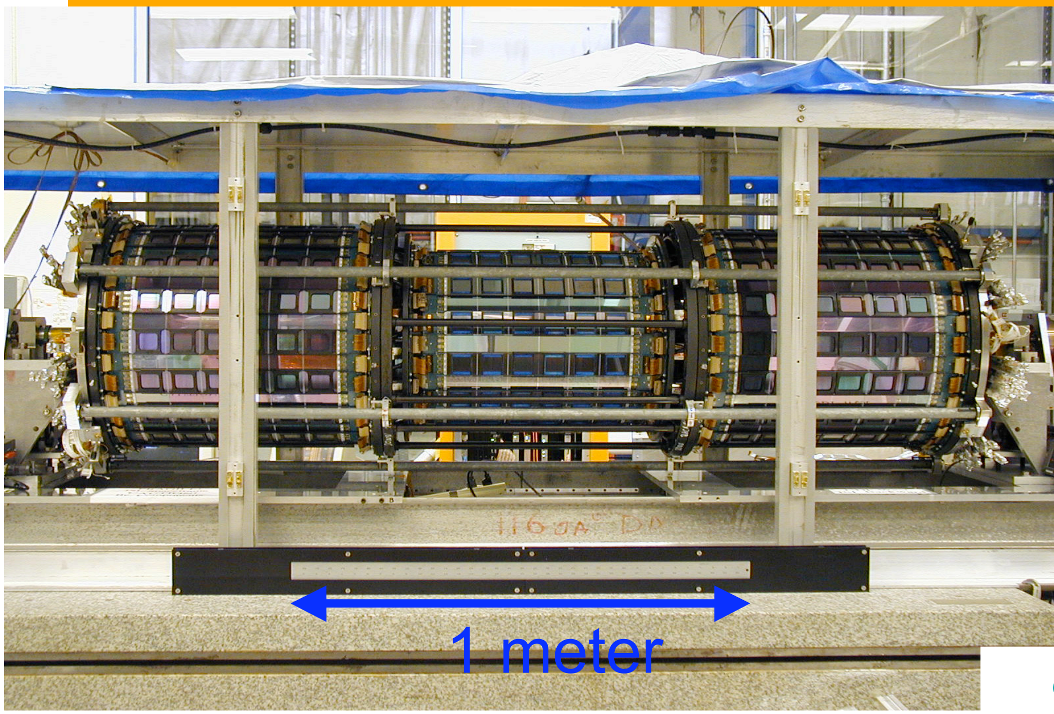
After pedestal fit



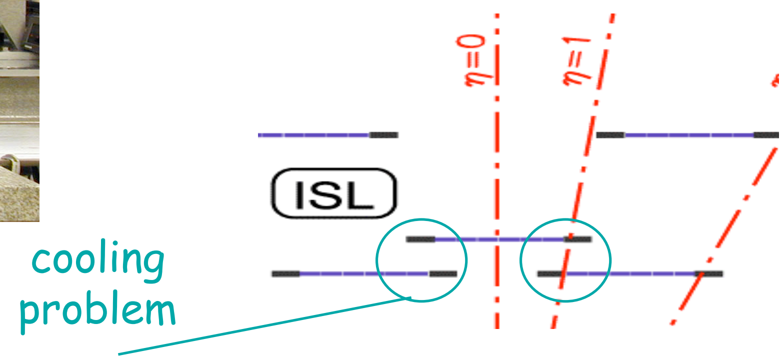


Recover offline, but forced to operate L00 unsparsified… cannot include in SVT trigger. Not yet used in analysis.

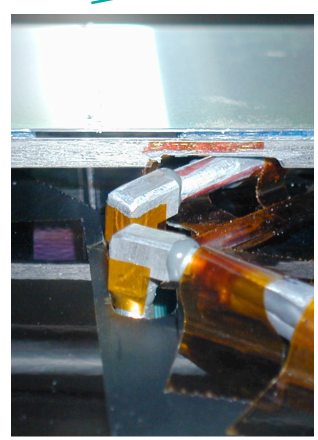
Backup: ISL

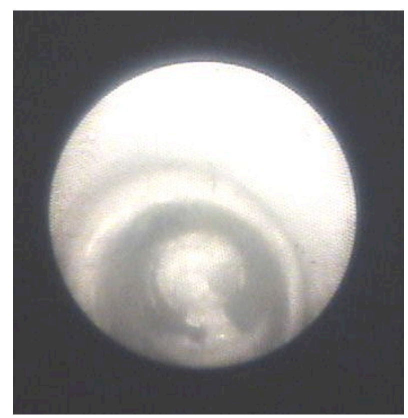


In Mar-01 found 12 (of 34) cooling lines with insufficient flow...
35% of ISL inoperable.



Used custom diagnostics to identify problem as epoxy blockages at elbows used to cool central portion of detector.

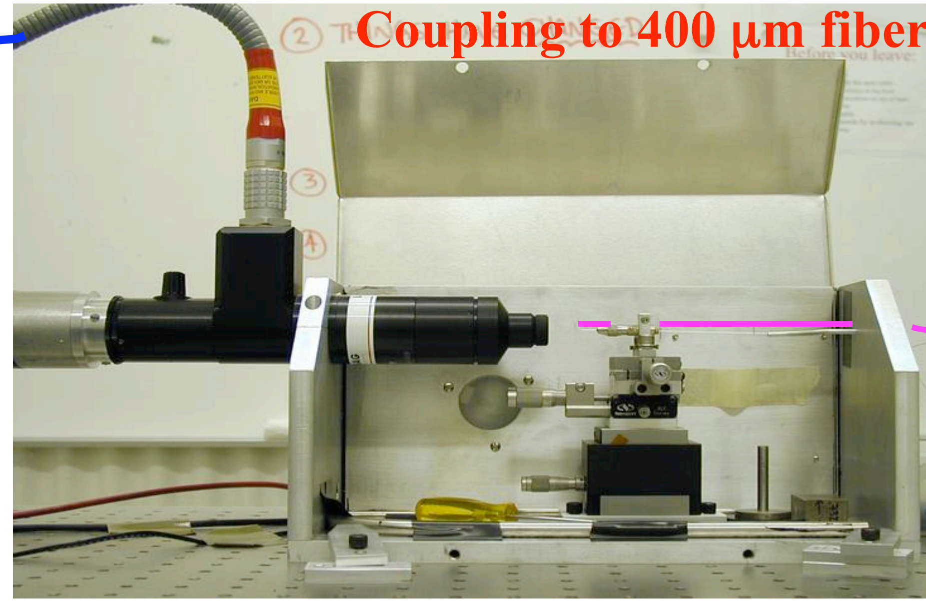


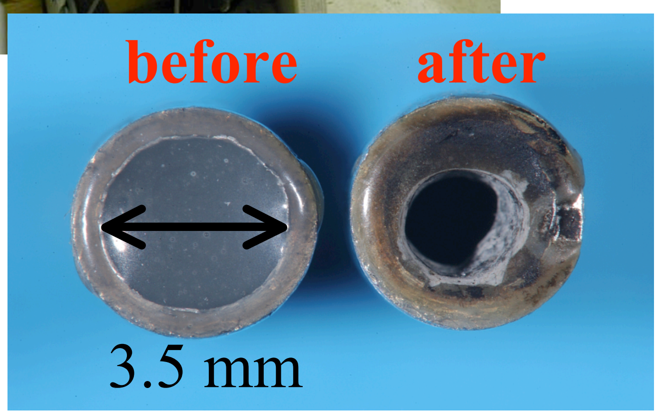


View of blockage w/ borescope

Backup: ISL


Laser+control laptop
SLS 200 C1
LASAG


Coupling to 400 μm fiber


before
after
3.5 mm


4 mm
LIBERTY
IN GOD WE TRUST
1995
coupling to prism

<u>Backup</u>: ISL

Developed Method to remove epoxy *in situ* using Nd:YAG laser

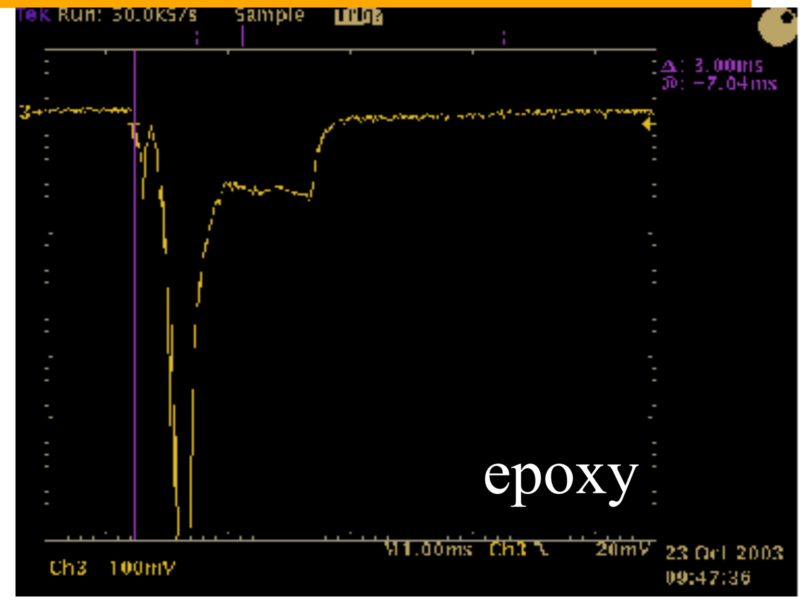
- use custom prisms to deliver laser around corner to epoxy

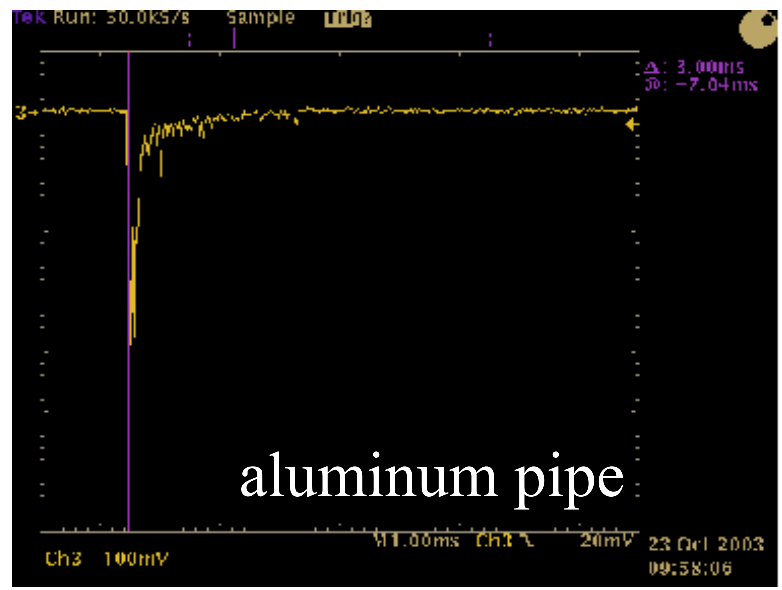
Are we pointed at Al. pipe? or epoxy?

- couple reflections back into PMT
- use scope to differentiate Al. /epoxy
- can do this at low energy, so no danger to Al. cooling pipes
- once on target, crank-up energy

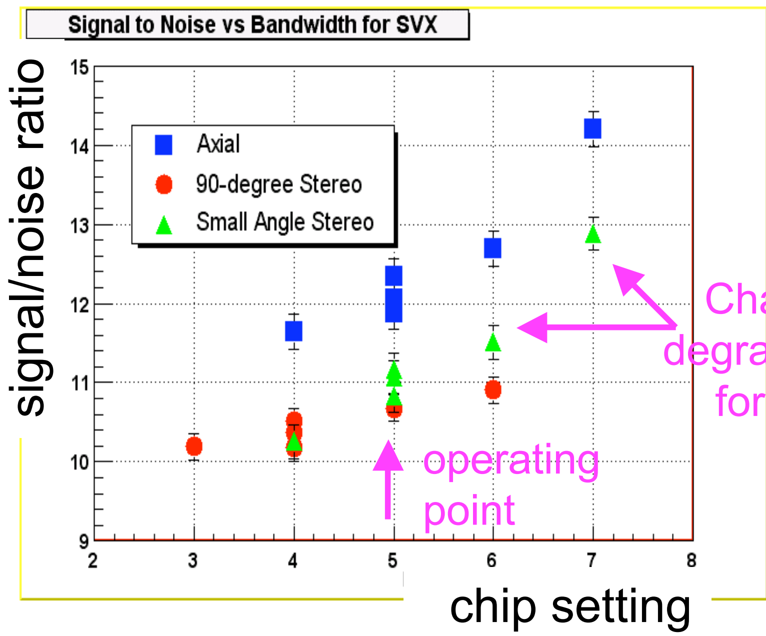
Have recovered 11/12 blocked lines

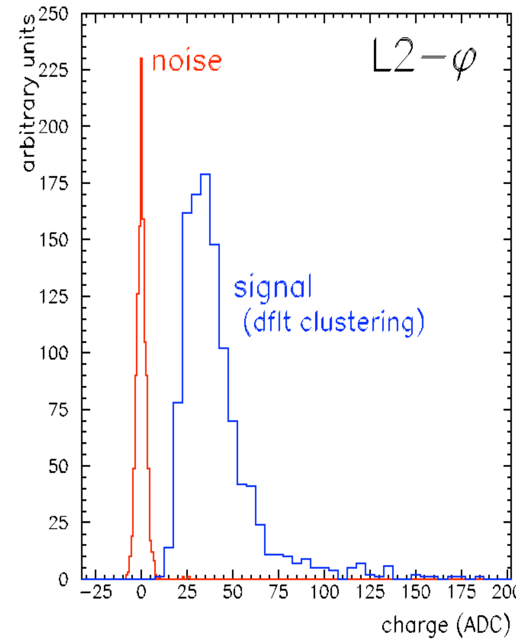
- taking high-quality data with the affected modules (look same as rest of ISL) since Jan-2003

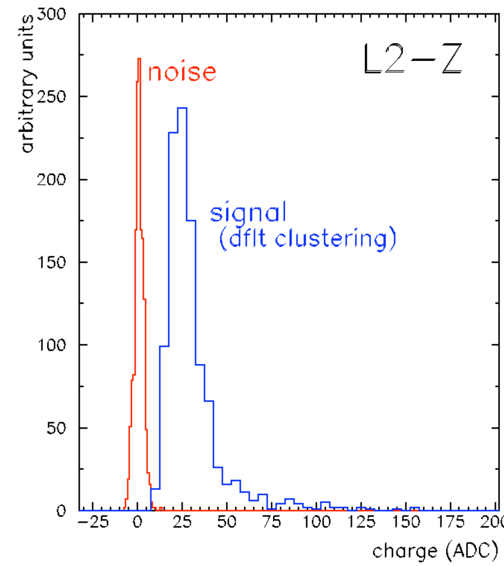




Backup: SVX







SVX and ISL performing as expected:

- S/N = 10-12 depending on layer/side
- single-hit efficiency >99%
- low noise occupancy 1-2%
- good 2-strip resolution (9 μm)

Backup: Momentum Scale

Absolute scale set by pinning M(J/ψ) to PDG.

Cross-check using other resonances:

	Measured (stat. only)	PDG (stat+sys)
$K_s \rightarrow \pi+\pi-$	497.36 ± 0.04	497.67 ± 0.03
$\Upsilon \rightarrow \mu+\mu-$	9461 ± 5	9460.30 ± 0.26
$D^0 \rightarrow K-\pi+$	1864.15 ± 0.10	1864.5 ± 0.5
$D^+ \rightarrow K\pi\pi$	1868.65 ± 0.07	1869.3 ± 0.5
$D^+ \rightarrow \phi\pi+$	1868.95 ± 0.37	1869.3 ± 0.5
$D^+_s \rightarrow \phi\pi+$	1968.20 ± 0.26	1968.6 ± 0.6
$B^+ \rightarrow J/\psi K+$	5278.2 ± 2.2	5279.0 ± 0.5

(all values in MeV/c^2; charge conjugation implied)

Backup: Normalization

$$BR(B_s \to \mu^+\mu^-) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int L dt}$$

We chose to use an absolute normalization.

$$\sigma_{B_s} = \frac{f_s}{f_u} \cdot \sigma_{B_d}$$

- σB_d measured from CDF PRD 65 (2002) 052005.
- straight forward (and same as RunI)
- with present statistics, contributes to total uncertainty at same level as relative normalization to $B^+ \rightarrow J/\psi K^+$