Analysis at a Hadron Collider

Lecture 2: Searches

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- Lecture 1: Introduction
- Lecture 2: Searches
- Lecture 3: Measurements

Review

- Yesterday's lecture covered three main things
  - Phenomenology of Hadron Collider Physics and the implications for detector design
  - Main features of hadron collider detectors, the typical resolutions achieved and the pursuant analysis challenges
  - Analysis design strategy to meet those challenges

Review: HCP Implications

- Initial state largely unconstrained
  - Only know that initial state $p_T = 0$
  - Often work in the transverse plane
  - Usually choose B-field parallel with beam line
- Cross sections large, many processes contribute
  - Broad physics program possible – must choose which evts to keep
  - Drives design of Trigger and DAQ
  - Backgrounds often large and varied - particle ID important
- Each event has contributions beyond the hard sctr
  - Underlying event (always; from proton remnants)
  - Multiple interactions (only when lumi high enough)
  - Precision vertexing and fine segmentation helpful

Review: Analysis Challenges

- In parent trigger sample, for most all analyses, Background orders of magnitude > Signal
  - Necessary to employ particle ID to suppress Bgd
  - Necessary to demonstrate thorough understanding of the Bgd using control samples

- Choice of trigger path affects sample composition
  - Takes time to characterize triggered sample
  - Custom Monte Carlo samples often required
  - Extrapolations from control samples uncertain

Review: Analysis Challenges

- *a priori* uncertainties arise from pdfs
  - Introduce uncertainty in theory predictions
  - Introduce uncertainty in experimental acceptances
- *a priori* uncertainties arise from “other” contributions in the events
  - Must account for underlying event
  - Must discriminate and correct multiple interactions
- A complete analysis requires a range of expertise (e.g. theory, detector hardware, analysis software)
  - No one has expertise across *all* of these things

Review: Analysis Rules of Thumb

- Look before you leap (LBYL)
  - Plan your analysis strategy carefully
- Trust but verify (TBV)
  - Always ask yourself, “Does this make sense?”
- A stitch in time saves nine (ASTS)
  - Sweat the (relevant) details, it will save time in the long run

Analysis Basics

- Basic inputs to all analyses essentially the same
  - Estimate of signal acceptance after all requirements
  - Estimate of number of expected background events surviving all selection requirements
  - Statistical and systematic uncertainties for each
- Basic types of analyses
  - Counting experiments (cross sections, BR)
  - Determining properties (mass, lifetime)
  - Search for something new (small SM σ*BR, NP)

In Practice

- Let's try to make some of this more concrete by discussing some specific examples from CDF
- As mentioned yesterday, specifics depend on type of analysis being pursued
- Following specific example will hopefully provide
  - A useful illustration of the analysis guidelines in practice
  - An introduction to several important experimental techniques

B2$\mu\mu$ Introduction

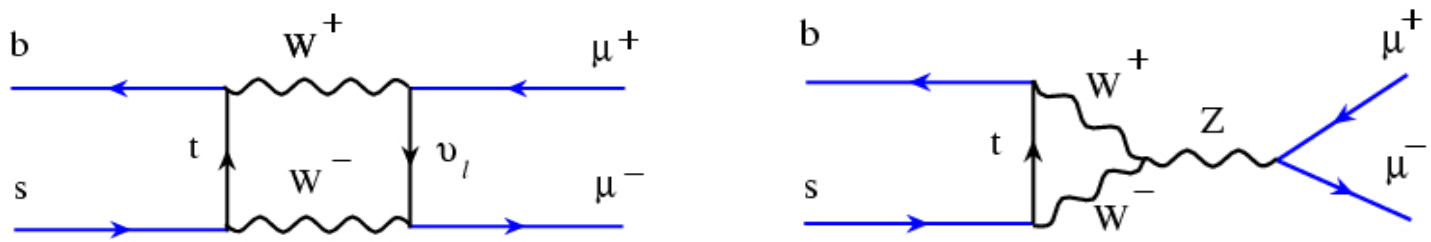
- We'll start with a Search analysis

  "Search for the Flavor Changing Neutral Current Decay $B_s \rightarrow \mu^+\mu^-$"

- Why?
  - Simple analysis with simple final state
  - One of first Run2 publications… some nice examples of early problems confronted
  - Anticipated to be among first analyses from Atlas/ CMS/LHCb in the coming year or so

B2μμ Motivation

- In the Standard Model the FCNC $B_s \rightarrow \mu^+\mu^-$ decay highly suppressed



- SM Predicts (M.Blanke, et al, JHEP 0610 (2006) 003)

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.4 \pm 0.4) \times 10^{-9}$$

- Many NP models predict a BR 10-1000 times larger
  - Observation of BR significantly larger than SM would be unambiguous evidence of NP

Getting Started

- How did we start this analysis? Where did we begin?
  - Wrote down the expression we'd have to use to measure (or limit) the branching ratio
    - Use this to itemize necessary inputs
    - Use this to help steer sensitivity studies
  - Considered the characteristics of the signal
    - Use this to help identify features which can be exploited to discriminate signal from background

Getting Started

- The number of signal events observed after all selection criteria is given by:

$$N^{B \rightarrow \mu\mu}_{\text{observed}} = \alpha \cdot \varepsilon_{\text{total}} \cdot N^{B \rightarrow \mu\mu}_{\text{produced}}$$

- The number of candidate events in the data which survive all selection criteria is given by:

$$N_{\text{candidate}} = N^{B \rightarrow \mu\mu}_{\text{observed}} + N_{\text{bg}}$$

- The Branching Ratio is defined as:

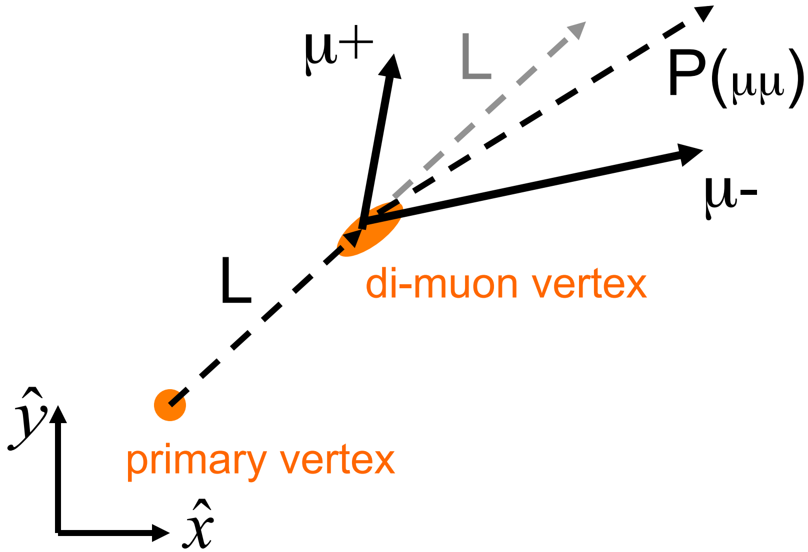
$$BR\left(B_s \rightarrow \mu^+ \mu^-\right) = \frac{N^{B \rightarrow \mu\mu}_{\text{produced}}}{N^{p\bar{p} \rightarrow B_s}_{\text{produced}}} = \frac{N^{B \rightarrow \mu\mu}_{\text{produced}}}{\sigma_{p\bar{p} \rightarrow B_s} \int L dt}$$

Getting Started: Expression

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

- This measurement requires that we:
  - Accurately estimate signal acceptance: $\alpha\varepsilon$
  - Accurately estimate background: N_{bg}
  - Intelligently optimize selection requirements
- Since it's a search we need to
  - Rigorously verify N_{bg} estimate
  - Ensure we perform an unbiased optimization

Getting Started: Signal Characteristics



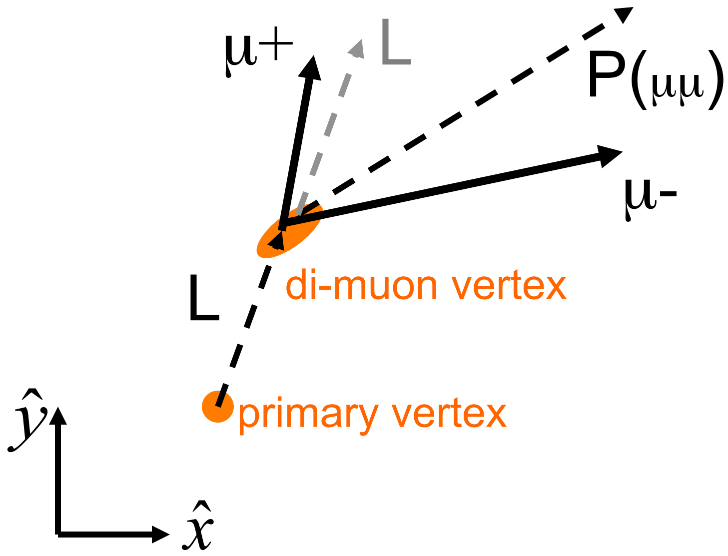
Signal Characteristics

- final state is fully reconstructed
- B_s has long lifetime ($c\tau$ = 440 μm)
- B fragmentation is hard

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

- $M_{\mu\mu} = M(B_s)$
- $\lambda = cL\, M_{\mu\mu}/P(\mu\mu)$ to be large
- L and P(μμ) to be co-linear
- few additional tracks (ie. should be isolated)

Getting Started: Background Characteristics



Contributing Backgrounds

– sequential semi-leptonic decay, $b \to \mu^- cX \to \mu^+\mu^- X$

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

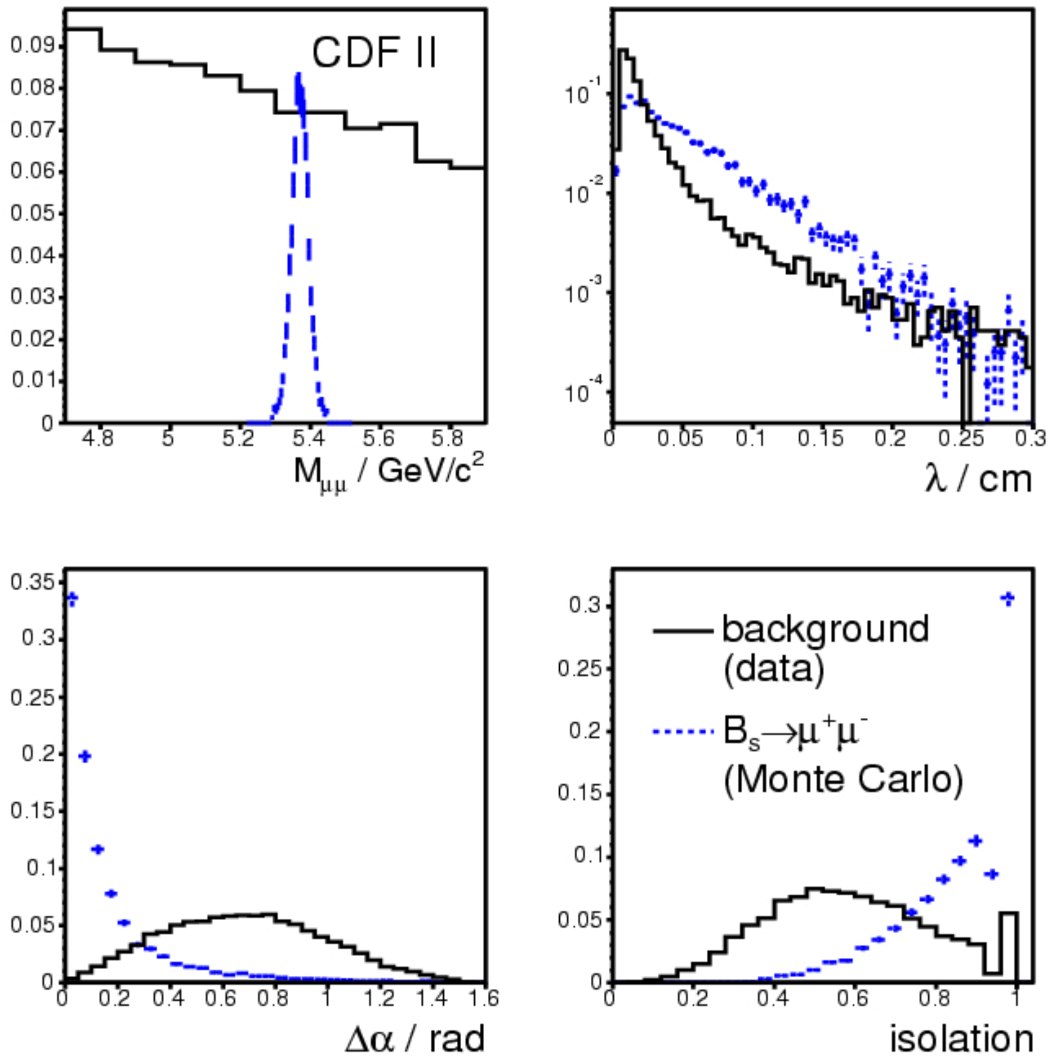
– continuum $\mu^+\mu^-$, μ + fake fake+fake

In general:

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

- L and P($\mu\mu$) will not be co-linear
- more additional tracks

Getting Started: Discriminating Variables



Discriminating Variables

- Invariant mass, $M_{\mu\mu}$
- Decay Length
  $\lambda = cL\, M_{\mu\mu}/P(\mu\mu)$
- $\Delta\alpha$: $\alpha(\vec{P}(\mu\mu)) - \alpha(\vec{L})$
- Isolation
  $= P_T(\mu\mu)/(\Sigma trk + P_T(\mu\mu))$

LBYL: Developing a Plan

Next, we developed a plan:

a) First, spend some time understanding how your sensitivity depends on the various inputs

The goal is to

- Identify priorities, which inputs are most important
- Set the scale

  (ie. how hard do you have to work at each piece… is +/-10% good enough? or is +/- 1% needed?

LBYL: Developing a Plan

Next, we developed a plan:

b) With a) in hand write something down

- Outline of thesis or publication manuscript
- List of plots, tables, figures you'll need

and for each piece think about

- What dataset and trigger you'll use
- What MC samples you'll need
- Caveats or concerns you'll need to address

Sensitivity Studies

- You first need to choose a “figure-of-merit” (FOM)
- Obvious for measurements
  - FOM = minimize the expected uncertainty on the quantity being measured
- For searches, a choice needs to be made
  - Standard FOM are
    - Maximize $S^2/(S+B)$
    - Minimize expected limit, <Limit>
    - Minimize necessary luminosity to achieve a given level of “discovery”, $L_{5\sigma}$

B2μμ Sensitivity Studies

- We chose to use the expected limit
  - No need to assume a BR(B→μμ)
  - Can easily include effects of systematic uncertainties
  - Can gauge whether or not sensitivity is significant by comparing to NP theory predictions

B2μμ Sensitivity Studies

- We varied n_{bg}, δ_{bg}, $\delta_{\alpha\varepsilon}$ in the expression

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

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

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

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

21

B2$\mu\mu$ Sensitivity Studies

- We learned that
  - Can tolerate large uncertainties on background prediction as long as $\delta_{bg} < \text{sqrt}(n_{bg})$
  - Expected limit degrades in proportion to $\delta_{\alpha\varepsilon}$ (ie. if $\delta_{\alpha\varepsilon}/\alpha\varepsilon = 10\%$, <Limit> 10% worse relative to $\delta_{\alpha\varepsilon} = 0$)
  - Can tolerate a larger n_{bg} as long as it is accompanied by a large gain in signal acceptance

Aside about "expected bgd"

- When somebody tells you their expected background is (n_{bg} +/- δn_{bg}) they're telling you that…
  - The *mean* expected background is n_{bg} events
  - The uncertainty on that mean is δn_{bg}
    - Neither n_{bg} nor δn_{bg} are required to be integer
- The number of background events you'll actually observe is (of course) integer
  - It follows the Poisson distribution $P(n_{obs}|\mu=n_{bg})$
  - The uncertainty on the mean, δn_{bg}, is accounted for by Gaussian smearing the Poisson mean

B2$\mu\mu$ Sensitivity Studies

- Can also use simplified MC studies to gain some insight into important physics and detector effects
- For B→$\mu\mu$ you find:
  - Perfect detector (MC truth): no backgrounds
  - Hadrons faking muons: B→KK, $\pi\pi$, πK bgds
  - Mass and d_0 resolutions: combinatoric bgds
- Background dominated by instrumental effects
  - Prudent to use data driven techniques whenever possible

B2$\mu\mu$ Analysis Plan

- Using the above studies, we developed this plan
  - Signal/search data set: DiMuons
  - Samples to measure signal efficiencies: use $J/\psi \rightarrow \mu\mu$ collected on same or similar DiMuon triggers
  - Samples to measure trigger efficiency: unbiased, inclusive, single-leg muon triggers (use tag-and-probe methods)
  - Sample to estimate combinatoric background: mass sidebands in DiMuon data set

B2$\mu\mu$ Analysis Plan

- Clean HF control sample for checks in signal efficiency: $B \rightarrow J/\psi\ K$
- Luminosity accounting: from DB for an absolute normalization, or from a relative normalization: $B \rightarrow J/\psi\ K$
- Bgnd xchecks: sidebands in same trigger? jet triggers?
- Clean sample of K and π to measure μ fake rates
- MC: $B \rightarrow \mu\mu$, $B \rightarrow hh$, $B \rightarrow J/\psi\ K$, generic b-bbar production +decay

All that's left is to implement the plan!

The suite of B2$\mu\mu$ studies

- The analysis note: cdf-6397 (42 pages)
  - Optimization, bgd estimates+xchecks, answer
- The additional notes required as inputs:
  - cdf-6104 Geo+Kinematic Acceptance (16 pgs)
  - cdf-7314 Di-muon Trigger efficiencies (226 pgs)
  - cdf-6347, 6114, 6835 Muon Reco (53 pgs)
  - cdf-6394 Tracking efficiency (54)
  - cdf-6318 Silicon efficiency (18)
  - cdf-6331 Primary vertex efficiency (4)
  - cdf-6273 Hadrons faking muons (44)

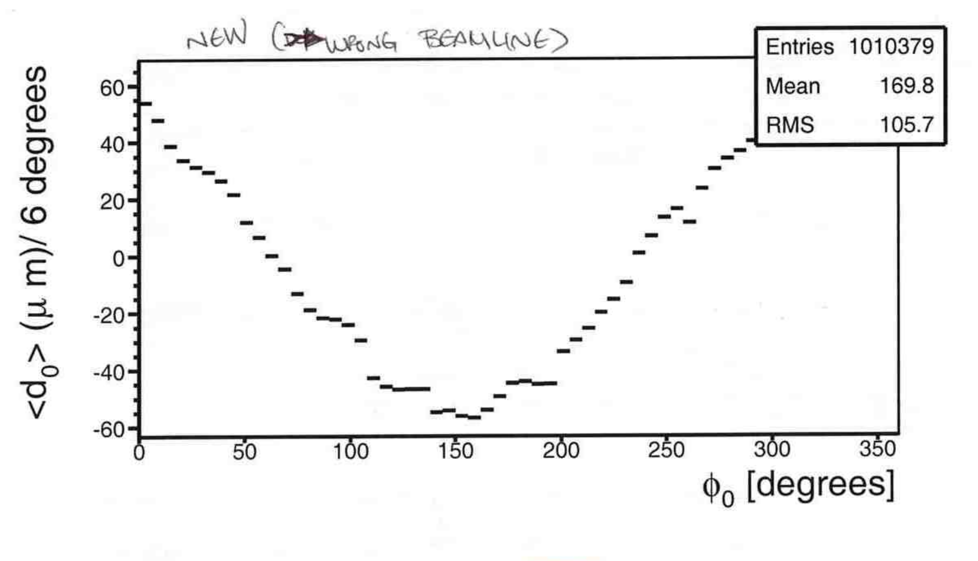
>400 pages of Supporting documentation

TBV: Pulling the Pieces Together

- For each input, begin by assembling necessary datasets and MC samples
- Verify that these samples look as expected
  - Sanity checks: d_0 vs ϕ_0, MET vs ϕ_0, muon p_T, etc.
  - MC validation: does it model those variables most important to your analysis?
- ASTS – do these things early and often
  - Once a problem is spotted, determine whether or not it's of a scale that will affect your analysis
  - If so, stop and fix it

B2μμ Data Validation

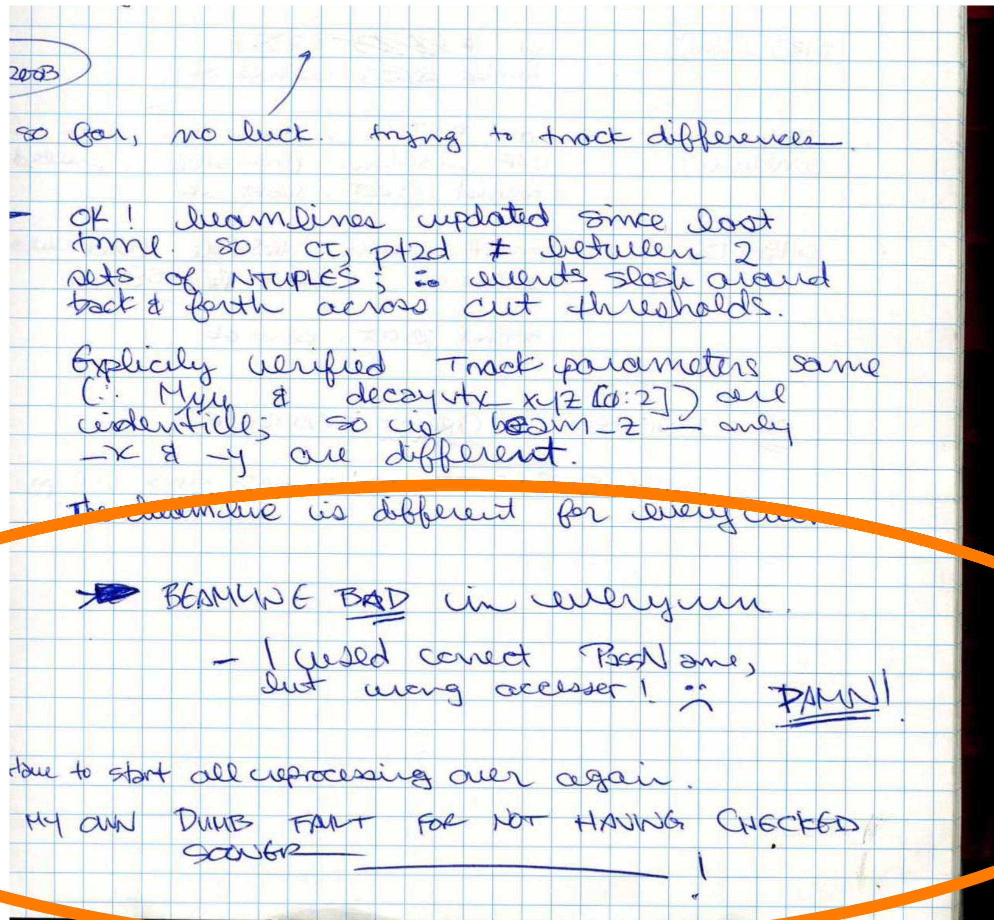
- TBV important because between the raw data and your plots, lots of opportunity for mistakes



- are you calculating d_0 wrt the actual beamline?
- are you specifying a consistent set of beamline and tracker alignments?
- did your executable pick-up the alignments and beamlines you intended it to?
- given the status of the tracker alignment, what variations should you expect?
- does it matter if this is data or MC?

B2μμ Data Validation

- In this case I had messed up… but caught it early so not too much time was wasted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so far, no luck. trying to track differences.

OK! beamlines updated since last time. so ct, pt2d ≠ between 2 sets of NTUPLES ; ∴ events slosh around back & forth across cut thresholds.

Explicitly verified Track parameters same (∴ Mμμ & decayvtx_xyz[0:2]) are identical; so is beam_z — only _x & _y are different.

The beamline is different for every run.

BEAMLINE BAD in everyrun.

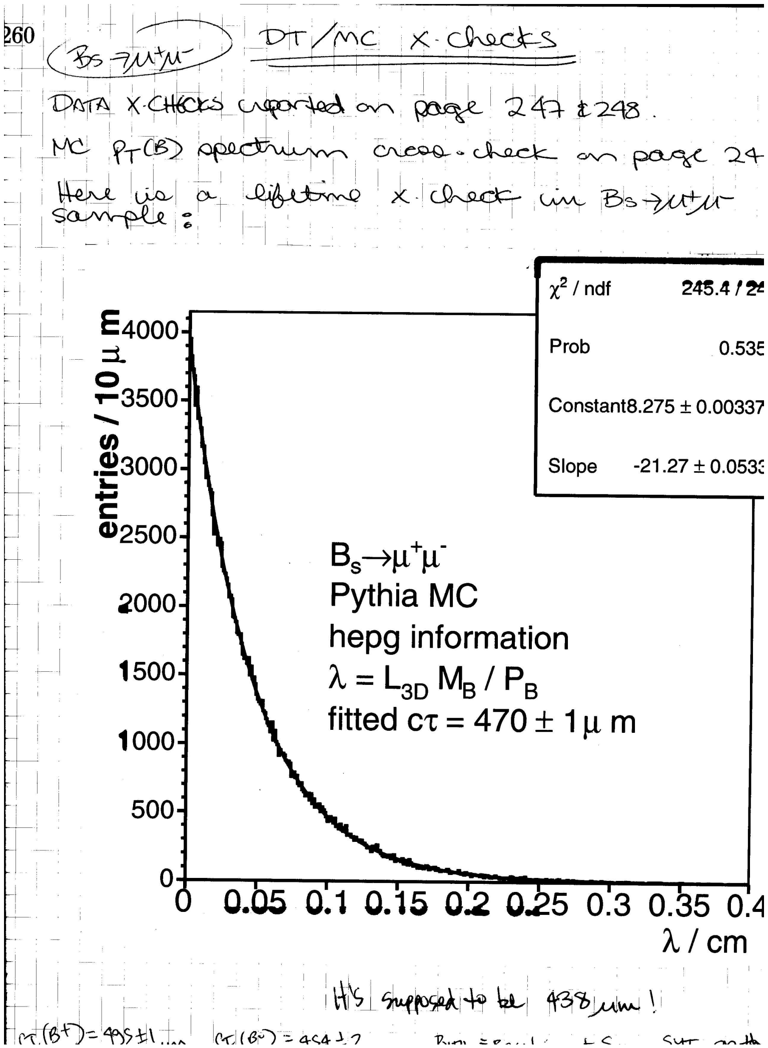
– I used correct PassName, but wrong accessor! :(DAMN!

Have to start all reprocessing over again.

MY OWN DUMB FAULT FOR NOT HAVING CHECKED SOONER!

B2μμ MC Validation

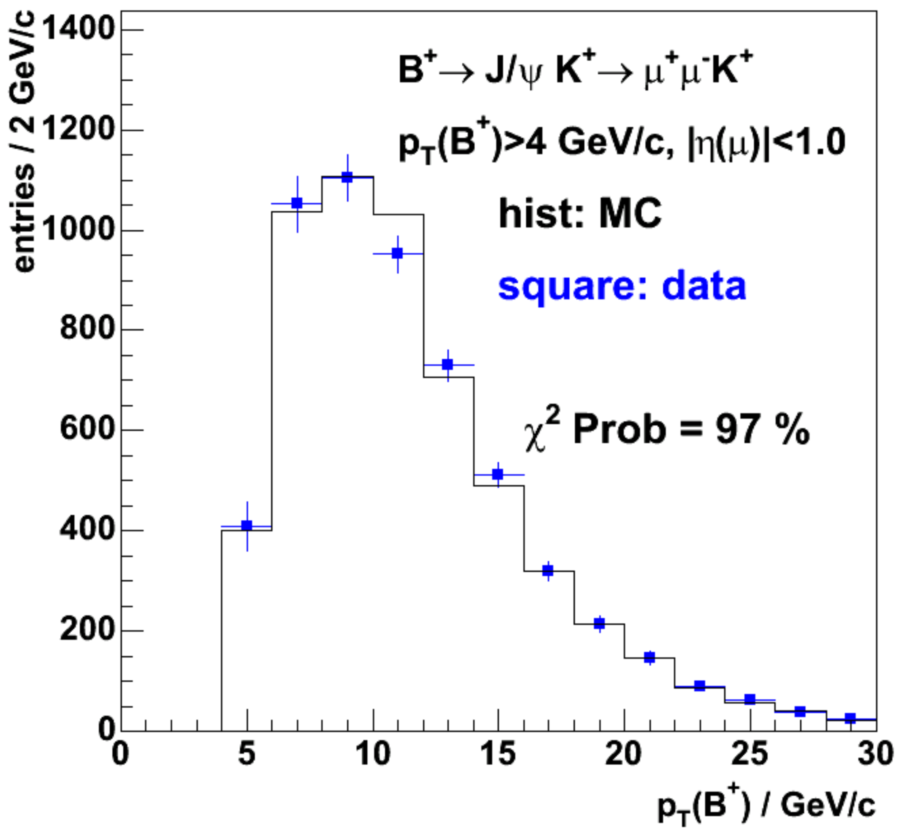
- Is the MC generated the way you need it to be?



- Are the masses, lifetimes, and branching fractions of those particles most important to your analysis generated the way you need them to be?
- Some of this likely verified by the Simulations Group, some of it maybe not… prudent to double check some things (TBV!)

B2μμ MC Validation

- Is the MC generated the way you need it to be?

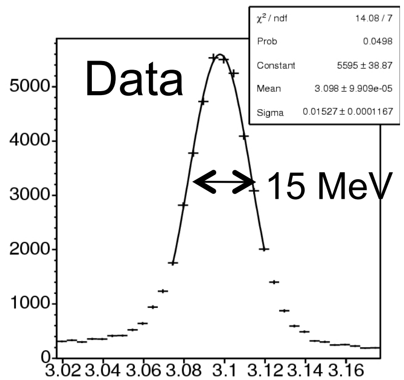


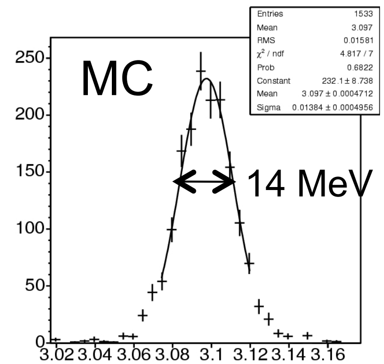
using $B^+ \to J/\psi\ K^+$ events

- MC can only be trusted to the extent that it accurately models the data.
- Detailed comparisons necessary for *each* analysis.
  - p_T spectra?
  - luminosity profile?
  - center-of-mass energy?
  - detector resolutions, and occupancies?

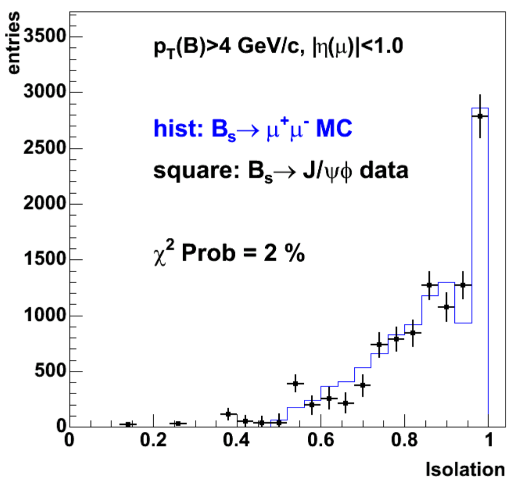
B2$\mu\mu$ MC Validation

- Is the MC generated the way you need it to be?





using $J/\psi \rightarrow \mu^+\mu^-$ from $B^+ \rightarrow J/\psi K^+$



using $B_s \rightarrow J/\psi\ \phi$ events

- MC can only be trusted to the extent that it accurately models the data.
- In this case
  - Small mis-modeling of mass resolution OK since the signal window wide (+/-3σ)
  - Isolation mis-modeling resolved by weighting MC to match data

B2μμ Validation

- Bottom line of last few slides…
  - Validation of Data and MC samples for CDF $B_s \rightarrow \mu\mu$ analysis spotted a few problems
  - Problems spotted early and fixed
- TBV is a continuous process… we'll come back to more of this later when we talk about estimating our backgrounds

ASTS: Filling in the numbers…

- The inputs for any given analysis are typically derived from
  – A variety of different studies undertaken in
  – A variety of different samples using
  – A variety of different methodologies
- Worth spending some time up front to think
  – Minimize potential sources of systematic uncertainty which can arise from differences in sample composition, kinematics, topology, (ie. “caveats”) etc.
  – Ensure things are consistently defined across studies so they “fit together” in the end

ASTS: Analysis Plan Caveats

- Using the above studies, we developed this plan
  - Signal/search data set: DiMuons
  - Samples to measure signal efficiencies: use $J/\psi \rightarrow \mu\mu$ collected on same or similar DiMuon triggers (p_T spectrum?)
  - Samples to measure trigger efficiency: unbiased, inclusive, single-leg muon triggers (use tag-and-probe, double leg correlations? If prescaled, lumi correlations?)
  - Sample to estimate combinatoric background: mass sidebands in DiMuon data set (correlations between dimuon mass and other discriminating variables? functional form?)

ASTS: Analysis Plan Caveats

- Clean HF control sample for checks in signal efficiency: $B \rightarrow J/\psi\ K$ (3-track vs 2-track vtx? kinematics different?)
- Luminosity accounting: from DB (accounting specific to your trigger? Any missing events?) from relative normalization: $B \rightarrow J/\psi\ K$ (which trigger?)
- Bgnd xchecks: sidebands in same trigger (which sidebands best? Correlations?) jet triggers? (trigger biases? sample composition?)
- MC: $B \rightarrow \mu\mu$, $B \rightarrow hh$, $B \rightarrow J/\psi\ K$, generic b-bbar production +decay (pT spectrum? Occupancies? Resolutions? All faithful models of the data?)

Each question is a potential source of Systematic Uncertainty

Efficiencies

B2$\mu\mu$ Efficiency

- We factorized the efficiency into several components
  - Used data-driven determinations of efficiency whenever possible
  - Allows some of the work to benefit other analyses since many of the efficiencies then independent of a specific analysis
  - Requires some forethought to ensure pieces each consistently defined

B2μμ Efficiency

- Here's how we factorized the efficiency

$$\alpha \cdot \varepsilon_{\text{total}} = \alpha \cdot \varepsilon_{\text{Tracking}} \cdot \varepsilon_{\text{Silicon}} \cdot \varepsilon_{\mu-\text{Reco}} \cdot \varepsilon_{\text{L1-Trig}} \cdot \varepsilon_{\text{L2-Trig}} \cdot \varepsilon_{\text{L3-Trig}} \cdot \varepsilon_{\text{vertex}} \cdot \varepsilon_{\text{analysis}}$$

α= geometric and kinematic acceptance of trigger paths used defined relative to B mesons with p_T> 4 GeV/c, |y(B)|<1

$\varepsilon_{\text{Tracking}}$ = efficiency to reconstruct the tracks in the drift chamber

$\varepsilon_{\text{Silicon}}$ = efficiency to attach silicon hits to drift chamber tracks

$\varepsilon_{\mu-\text{Reco}}$ = efficiency to reconstruct the muons

$\varepsilon_{\text{L1-Trig}}$ = efficiency of L1 trigger requirements

$\varepsilon_{\text{L2-Trig}}$ = efficiency of L2 trigger requirements

$\varepsilon_{\text{L3-Trig}}$ = efficiency of L3 trigger requirements

$\varepsilon_{\text{vertex}}$ = efficiency of vertex quality criteria

$\varepsilon_{\text{analysis}}$ = efficiency of analysis selection requirements

B2$\mu\mu$ Efficiency

- Here's how we determine those pieces

α : from MC truth information

$\varepsilon_{Tracking}$: embed MC tracks in data events

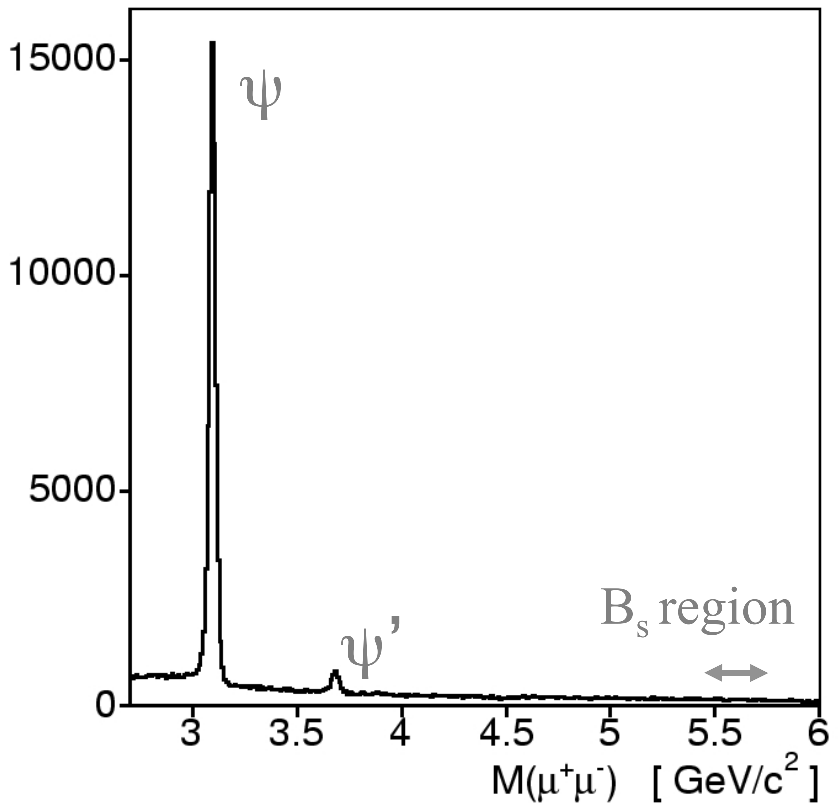
$\varepsilon_{Silicon}$: from J/ψ $\rightarrow\mu\mu$ events in signal sample

$\varepsilon_{\mu-Reco}$: from J/ψ $\rightarrow\mu\mu$ events using tag-and-probe method
$\varepsilon_{L1\text{-}Trig}$: from J/ψ $\rightarrow\mu\mu$ events using tag-and-probe method
$\varepsilon_{L2\text{-}Trig}$: from J/ψ $\rightarrow\mu\mu$ events using tag-and-probe method
$\varepsilon_{L3\text{-}Trig}$: from J/ψ $\rightarrow\mu\mu$ events using tag-and-probe method

ε_{vertex} : from B$\rightarrow\mu\mu$ MC; cross-check using B$\rightarrow$J/ψK data/MC
$\varepsilon_{analysis}$: from B$\rightarrow\mu\mu$ MC; cross-check using B$\rightarrow$J/ψK data/MC

Inclusive Trigger

- Helped that the trigger was defined to accept $J/\psi \rightarrow \mu^+\mu^-$ events as well as $B \rightarrow \mu^+\mu^-$ candidates



$\mu\mu$ mass distribution for events passing our RAREB trigger, muon quality and track quality criteria

B2μμ Efficieny

- Obtaining a self-consistent set of acceptances and efficiencies requires some forethought (ASTS):

```
* ============================================================
* --- DEFINITIONS RELEVANT FOR TOTAL ACCEPTANCE*EFFICIENCY
* ============================================================

We define our acceptance and efficiency like this for Bs-->mumu:

             #(pass L1,L3,offline reconstruction,quality and analysis cuts)
alpha*eff = ---------------------------------------------------------------,
                          #(Bs-->mumu in our kinematic box)

where the kinematic box is defined as Bs with  pt>6GeV and |rapidity|<1.
This is the same kinematic box to which runI measurements of B cross-
sections
are normalized.



The acceptance is defined as:

           #(Bs-->mumu within trigger, muon, COT, and SVX fiducial region)
 alpha = -------------------------------------------------------------------.
                        #(Bs-->mumu in our kinematic box)

The muon, COT and SVX fiducuality are driven by detector geometry.  The
trigger "fiduciality" additionally requires the muons from the Bs->MuMu
decay to satisfy the kinematic requirements of >=1 of the RAREB_DIMUON
triggers we use.  Details are available in CDF-6204.  The fiduciality
requirements are discussed in more detail below.
```

```
The total efficiency can be broken up into the following pieces:

 eff = eff(COT)*eff(SVX)*eff(muon)*eff(analysis cuts)*eff(L1)*eff(L3).

We have checked to make sure that the pieces of the efficiency
are measured in a consistent way.  The various efficiencies are measured
relative to offline quantities.  Only the COT reconstruction efficiency
is an absolute measurement.  The full expression is given below:

alpha*eff = alpha*eff(COT)*eff(muon)*eff(SVX)
                 *eff(L1)*eff(L3)*eff(analysis cuts).


       #(fiducial)      #(COT)       #(muon,COT)   #(SVX,muon,COT)
     = ----------- * ------------- * ----------- * --------------
       #(kin. box)     #(fiducial)      #(COT)        #(muon,COT)

                      #(L1,muon,SVX,COT)   #(L3,L1,muon,SVX,COT)
                    * ------------------ * ---------------------
                       #(muon,SVX,COT)       #(L1,muon,SVX,COT)

                      #(cuts,L3,L1,muon,SVX,COT)
                    * --------------------------
                        #(L3,L1,muon,SVX,COT)


       #(cuts,L3,L1,muon,SVX,COT)
     = --------------------------
             #(kin. box)
```

ASITSN: B2μμ Example

- Obtaining a self-consistent set of acceptances and efficiencies requires some forethought (ASTS):

```
* ==============================================================
* --- DETAILS REGARDING FIDUCIALITY
* ==============================================================

A charged particle is taken to be "COT fiducial" if its helix satisfies

                 |z_track(r=r_max_cot)| < |z_max_cot|,

or, more specifically,

                 |z_track(r=136cm)| < 155 cm.

The choices for exit radius and z threshold are driven by the XFT
requirements
in the trigger.  Since the XFT demands 11-of-12 hits in all four axial SL,
our fiducial requirements demand a track to traverse all four axial SL.



A COT track (passing our COT quality cuts, which are the same as the
DefTrack
requirements) is taken to be "SVX fiducial" if it extrapolates through at
least 3 layers of the SVX.  This is only a geometric requirement.   Three
layers is the minimum number of layers a track can traverse and still
possibly
satisfy our SVX quality cuts.  Our SVX quality cuts are:

            ( #SVX rphi hits >= 3 )
         && ( #SVX-rphi hits >= (#active-SVX-layers-traversed - 1) ).

These criteria were selected to eliminate those classes of tracks which
anamolously contribute to the negative tails of the signed-impact-parameter
distribution.  Note that, due to the lower bound imposed by our fiducial
requirements, #active-SVX-layers-traversed is a number between 3-5.
```

```
For the muon fiducial definition, we impose the same requirement as offline
CMU reconstruction and require both muon tracks to register >=3 hits in the
CMU chamber.  Note: the acceptance is computed from MC, which has 100%
efficient CMU chambers (muon reconstruction efficiency is taken from
the data).  Furthermore, since  we demand a track with 3/4 hits, any track
that scatters into the chamber cracks is not included in the numerator
of the acceptance (eg. a track that would be flagged as fiducial by
the muon fiducial tool but actually scattered into the gap between CMU
chambers).

The muon reconstruction efficiency (CDF-6347) was measured requiring the
track
to be at least 10cm away from the edge of the CMU chamber.  This cut was NOT
imposed to avoid the edge effect of the CMU chamber but to avoid the effect
of multiple scattering (cf. first paragraph of section 4 on page 4).  We
have
already accounted for the effect of multiple scattering in our acceptance
measurement.  If a track that scatters into the crack is also counted as
muon
reconstruction inefficiency, then we would be double counting the multiple
scattering effect.  Now, what about the issue of the CMU chamber edge
effect?
This point was also addressed in CDF-6347.  They have measured the CMU
reconstruction efficiency using high pT muon tracks from Z0 decays without
the 10cm cut.  The resulting efficiency is consistent with the measurement
using the J/psi sample.  From that, one concludes that the edge effect is
negligible.  Still, the difference is included in the systematic
uncertainty.
```

B2μμ Trigger Efficiency

- The $B_s \rightarrow \mu\mu$ analysis used two trigger paths
  - RAREB_CMUCMU (two central μ)
  - RAREB_CMUCMX (one central, one “forward” μ)
  - both are di-muon paths, with p_T , opposite charge, and opening angle requirements made
- CDF employs a three level trigger to collect events. The $B_s \rightarrow \mu\mu$ trigger efficiency is thus defined:

$$\begin{aligned}
\varepsilon_{\text{Trigger}} &= \varepsilon_{\text{L1}} \cdot \varepsilon_{\text{L2}} \cdot \varepsilon_{\text{L3}} \\
&= \varepsilon_{\text{L1}}\left(\text{L1} \mid \text{real-}\mu\right) \cdot \varepsilon_{\text{L2}}\left(\text{L2,L1} \mid \text{L1, real-}\mu\right) \cdot \varepsilon_{\text{L3}}\left(\text{L3,L2,L1} \mid \text{L2, L1, real-}\mu\right) \\
&= \varepsilon\left(\text{L3,L2,L1} \mid \text{real-}\mu\right)
\end{aligned}$$

B2$\mu\mu$ Trigger Efficiency

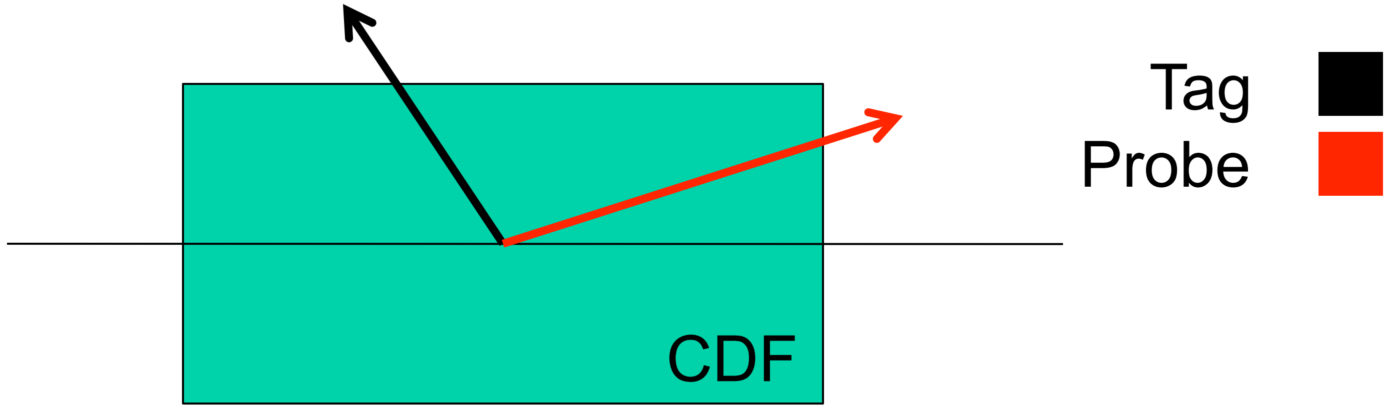
- Let's discuss in some detail the L1 efficiency work
  - Dominates the trigger inefficiency
  - Employs a lot of nice experimental techniques
- Methodology: Use a "tag-and-probe" method
  - Identify a single-leg muon trigger
  - Select a sample of $J/\psi \rightarrow \mu\mu$ events
  - Trigger muon is the "tag", the other leg is unbiased by the trigger and is the "probe"
  - Assumes di-muon efficiency is product of two single-muon efficiencies

B2μμ Trigger Efficiency

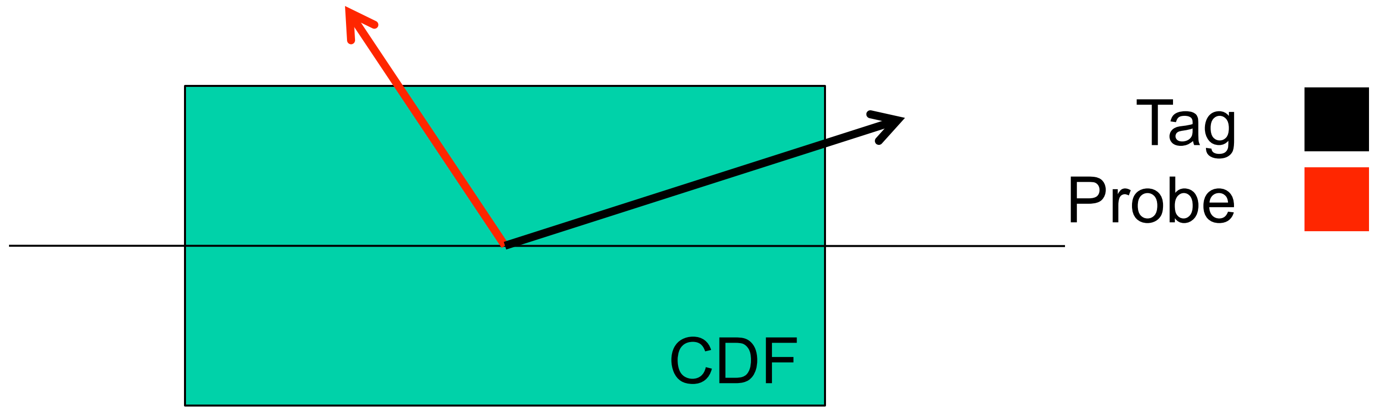
- To measure the L1 efficiency using "tag-and-probe" easiest to have two back-up trigger paths defined
  - CMU_PT4 (1 central μ; used to measure CMX ε)
  - CMX_PT4 (1 forward μ; used to measure CMU ε)
- For example, the L1 CMU efficiency can be estimated from the CMX_PT4 trigger like this:

$$\frac{\text{N(good J/}\psi\text{ satisfying L1CMU reqrments \&\& CMU}_{L1}\text{\&\&CMX}_{L1}\text{)}}{\text{N(good J/}\psi\text{ satisfying L1CMU reqrments \&\& CMX}_{L1}\text{)}}$$

Tag-and-Probe



- Use these to determine efficiency for triggering on forward μ



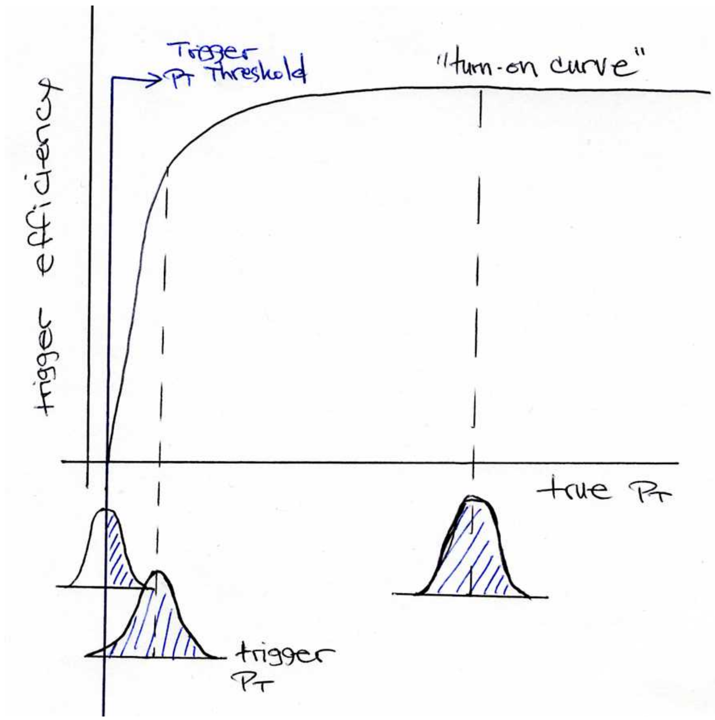
- Use these to determine efficiency for triggering on central μ

B2$\mu\mu$ Trigger Efficiency

- We can use the J/ψ resonance to identify a clean sample of muons
  - Remove small residual background using sideband subtraction
- Since p_T resolution at L1 not great ($\delta p_T/p_T$~1%), expect efficiency to be a function of true p_T
  - In other words, some μ which should have passed the trigger fail b/c their p_T is underestimated
  - True p_T approximated using full offline reconstruction, which for CDF has $\delta p_T/p_T$~0.10%
  - Resulting curve called the "turn-on curve"

Aside: Turn-on Curve

- The turn-on is basically an artifact of the limited resolution of the trigger… dominated by L1 since the resolution is the worst there

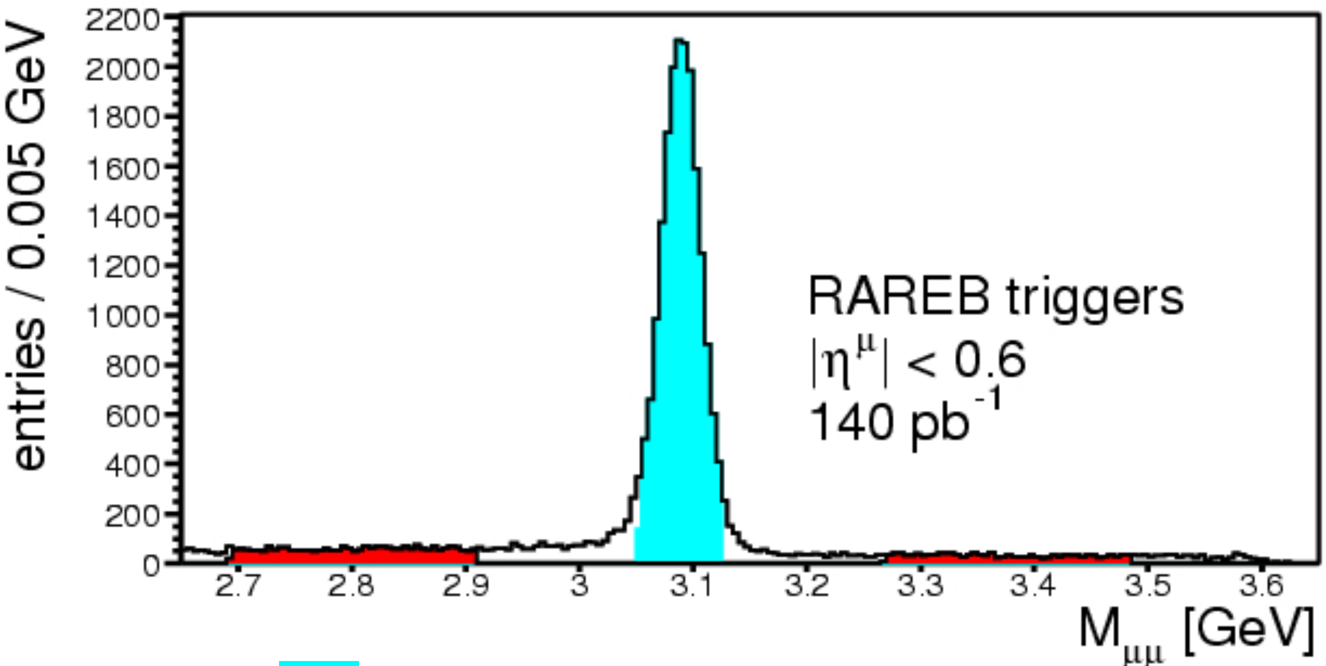


Aside: Sideband Subtraction

- Very common methodology for removing effects of background from a sample
  - Most straightforward application (discussed here) requires that background is well described by a linear function
  - Assumes that distribution you're exploring is independent of variable you're using to perform the subtraction
  - Most common use involves invariant mass distributions of resonances

Aside: Sideband Subtraction

- Some definitions



Signal region of width $\Delta M_{\text{signal-region}}$

Sideband region of width ΔM_{SB}

Aside: Sideband Subtraction

- #bgd-in-signal-region:

$$N^{b}_{\text{signal-region}} = \left(N^{b}_{\text{Left SB}} + N^{b}_{\text{Right SB}}\right) \cdot \left(\frac{\Delta M_{\text{signal-region}}}{\Delta M_{\text{LSB}} + \Delta M_{\text{RSB}}}\right)$$

- Can correct shape of other variables for background

$$f(x)^{\text{signal}}_{\text{signal-region}} = f(x)^{\text{all events}}_{\text{signal-region}} - f(x)^{\text{all events}}_{\text{LSB+RSB}} \cdot \left(\frac{\Delta M_{\text{signal-region}}}{\Delta M_{\text{LSB}} + \Delta M_{\text{RSB}}}\right)$$

(only works if variable x is uncorrelated with M)

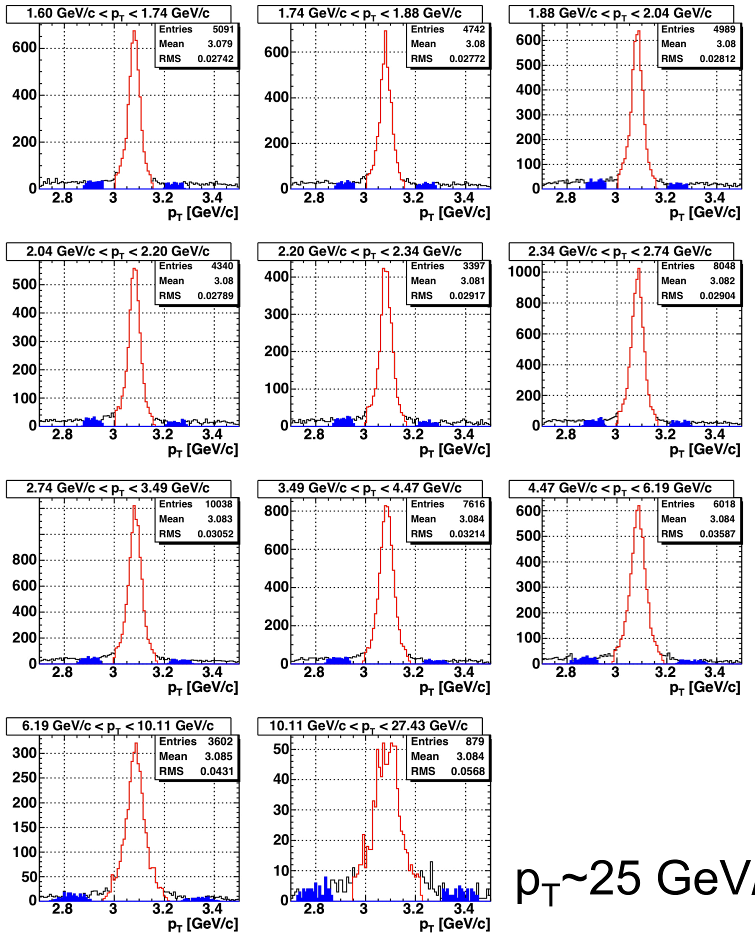
- SBs don't have to be in terms M, but most common

Details…

- So, to get the turn-on curve we're going to bin the "probe" muons by p_T
- In each bin we're going to remove the effects of background by using SB subtraction
- Recall though that $\delta p_T / p_T = \alpha p_T + \beta$
  - So mass resolution will change across p_T bins
  - Important to account for that… definition of "signal region" and "sideband regions" changes with p_T

Details…

p_T~1.6 GeV/c



p_T~25 GeV/c

signal

sidebands

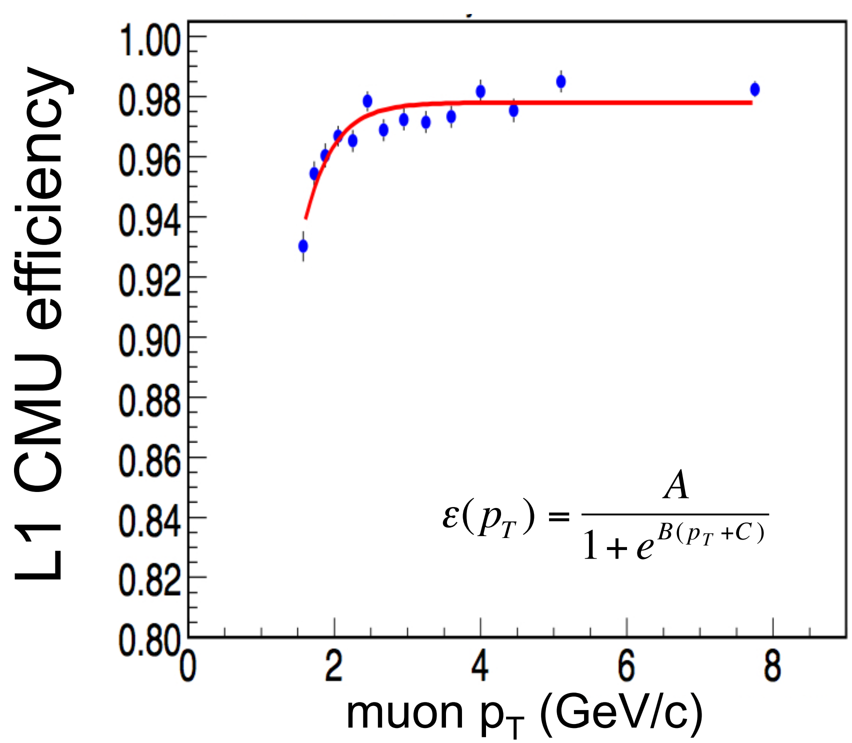
- Easy enough to deal with… just more book keeping

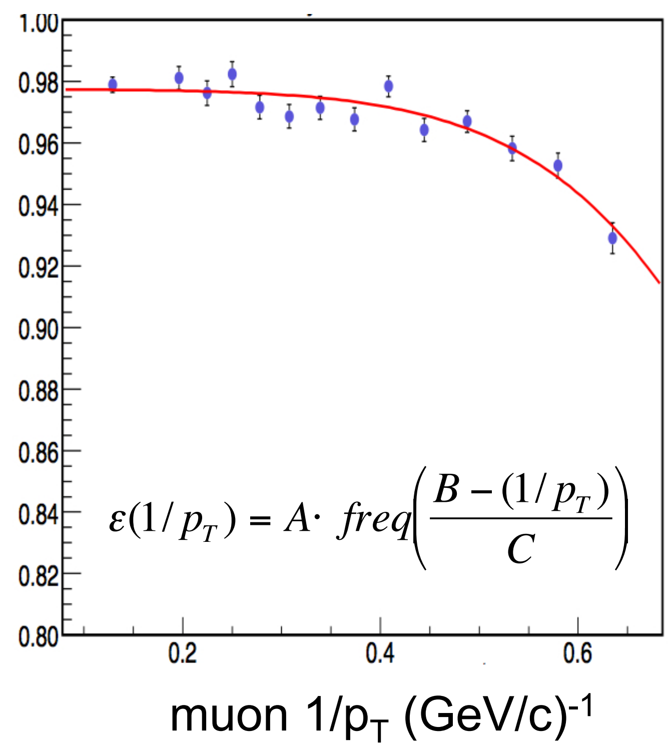
Details…

- The turn-on is important to characterize because the efficiency is, by definition, changing quickly there
- Before you fit your efficiency points to a functional form, you need to decide where along the x-axis (in this case the true p_T) to put each point
- Rule-of-thumb: if the distribution is changing quickly across a given bin, you should use the mean-x in each bin and *not* the bin-centered-x in order to get the correct functional form when fitting
  - Important for trigger turn-on curves
  - Important for some differential cross sections too

B2μμ Trigger Efficiency

- Our mind thinks in terms of p_T, but detector resolution actually gaussian only in $1/p_T$





B2μμ Trigger Efficiency

run numbers in several ranges is taken away by selecting a version of the trigger table.

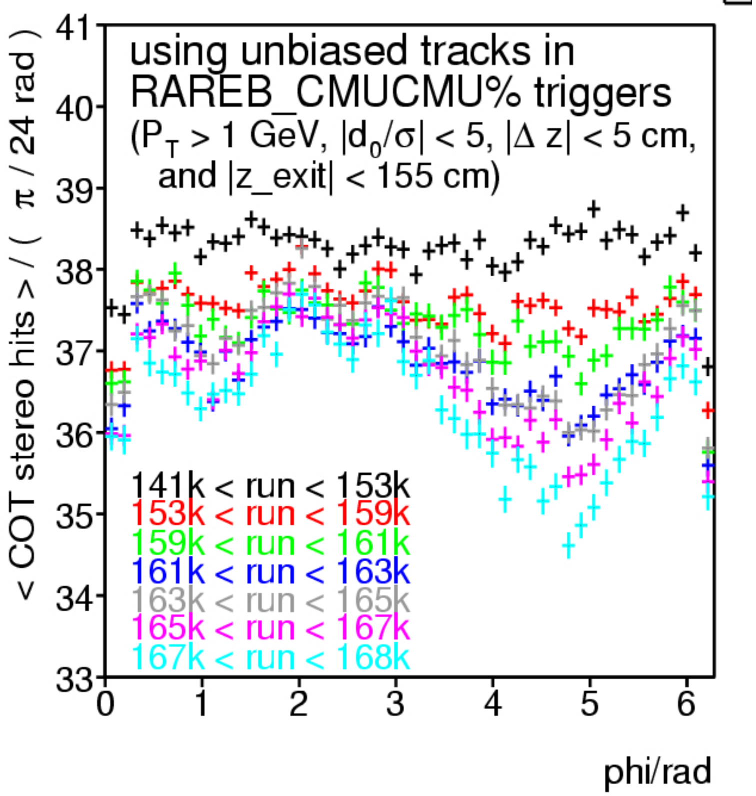
#	Range	$\mathcal{L}$, pb^{-1}	comment
1	138425 to 150144	18.2	(RAREB starts at 140885, 1 pb^{-1} later) CMU only, 2-miss XFT, bad mbx #8.
2	150145 to 152635	15.0	CMU (good mbx #8), CMX: 2-miss XFT.
3	152636 to 161324	60.2	1-miss XFT, no ϕ-dependence, have η-dependence; CMX starts with 152946.
4	161325 to 165499	59.6	1-miss, some ϕ-dependence, have η-dependence ($\sin\phi > -0.5$ and $\sin\phi > -0.5$ considered separately).
5	165500 to 168889	50.5	significant ϕ-dependence, ditto.
6	174778 to 179056	46.4	large ϕ-dependence, minor η-dependence.
7	182843 to 184061	32.1	ditto, L2 measurement starts; L3 runs 5.1.3. Also includes runs 180954-181190 and 182629-182697.
8	184228 to 186600	84.5	good COT, no ϕ-dependence, no η-dependence
9	190697 to 194632	100	Similar to #8, start of 0h data
10	194633 to 202817	311	XFT bins 0, 1, and 2 (of 288) are ≈ 20% low (through #15)
11	202818 to 203799	42	Prescale changes in L2. End of 0h data.
12	203800 to 205647	40	Start of 0i data.
13	205648 to 208790	85	Prescale changes in L2 and L3.
14	208791 to 210011	78	XTRP bin 99 (of 288) is bad (this range only).
15	210012 to 212133	48	Up to shutdown in 2006.
16	217990 to 219232	24	L3 ends running 5.1.3.
17	219237 to 222426	170	PHYSICS_4_00_v3,4
18	222184 to 223189	75	PHYSICS_4_00_v6
19	223190 to 226193	58	MT triggers added; low eff in XTRP bin(s) near $\phi \approx \pi$.
20	226194 to 227554	20	MT triggers switch to LUMI-enable.
21	227704 to 229761	93	PHYSICS_4_01_v1; fix to CMX MSKT in L2.
22	229686 to 232841	200	PHYSICS_4_01_v2
23	233028 to 233111	16	Fix to num. of COT hits in L3. End of p. 10.
24	233112 to 236255	120	PHYSICS_4_01 v1-v4
25	235389 to 237795	120	PHYSICS_4_01 v5 and 4_02_v2. End of p. 11.
26	237850 to 241674	140	Up to PHYSICS_4_02 v4. End of p. 12.
27	240802 to 243675	150	PHYSICS_4_02 v5 and v6.
28	243711 to 246231	180	PHYSICS_4_02 v7 to v12. End of p. 13. Shutdown begins.
29	252836 to 256824	220	Periods 14 and 15.
30	256840 to 258787	320	Periods 16 and 17

- Carefully kept track of important changes to
  - Detector
  - Trigger hardware
  - Trigger algorithm
  - Trigger definition
- To describe all of this required 4D

  $\varepsilon(p_T, \eta, \phi, \text{run\#})$

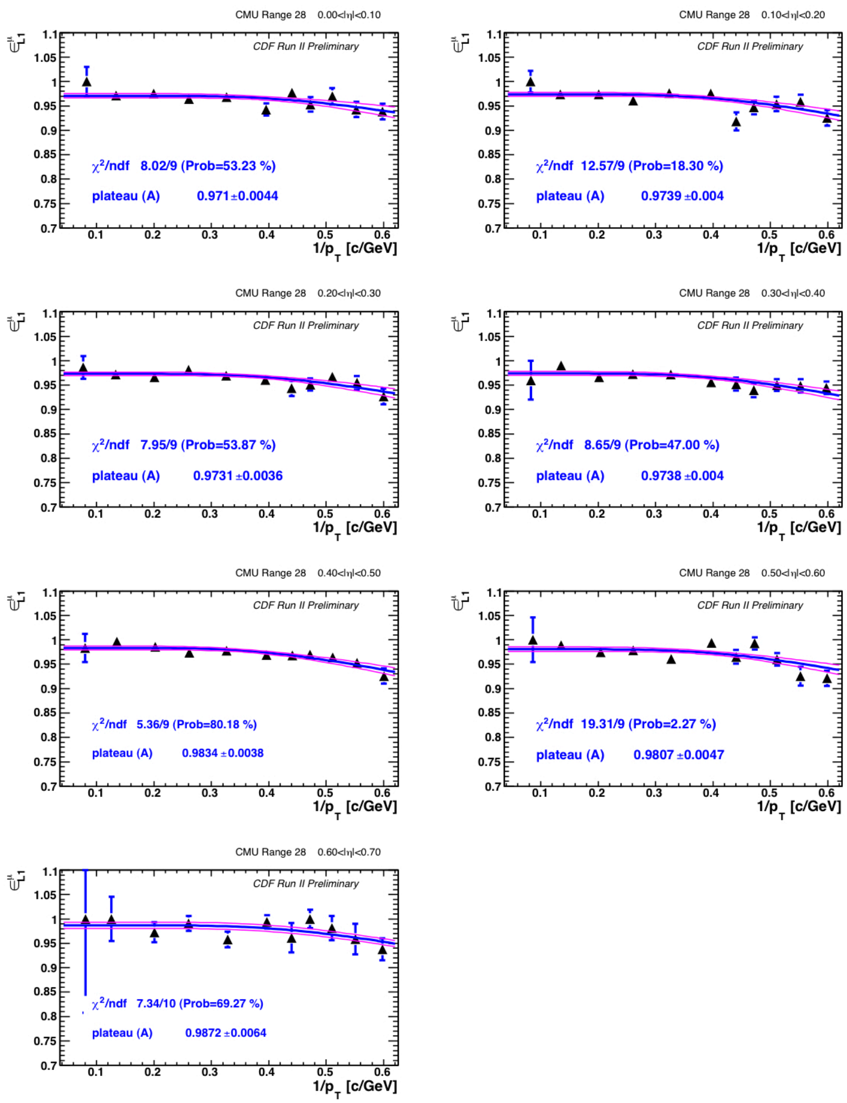
B2μμ Trigger Efficiency

- Early problems with pre-mature aging effects in the tracking chamber introduced a steep ϕ dependence



  - Affected all track based triggers and introduced geometric correlations for multi-track final states
  - Later understood, gain recovered to “like new”, and measures taken to prevent it from happening again
  - This introduced a ϕ and time (run) dependence into the trigger efficiency

B2μμ Trigger Efficiency

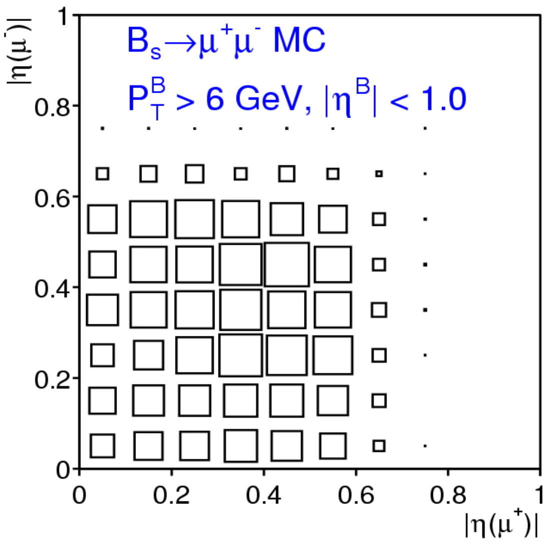


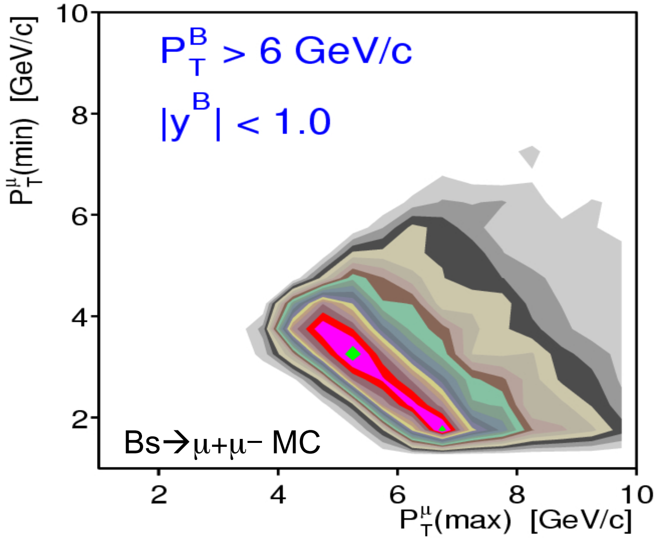
- Some L1 CMU fits vs $1/p_T$ in bins of η for a particular ϕ slice
  - Repeat in bins of ϕ
  - For each run range
- Repeat whole thing separately for L1 CMX

B2μμ Trigger Efficiency

- To get the L1 dimuon trigger efficiency relevant to the B→μμ analysis, need to convolute ε_{L1} with the expected di-muon (p_T,η,ϕ) distributions

$\varepsilon_{trig}(p_T,\eta,\phi) \otimes$





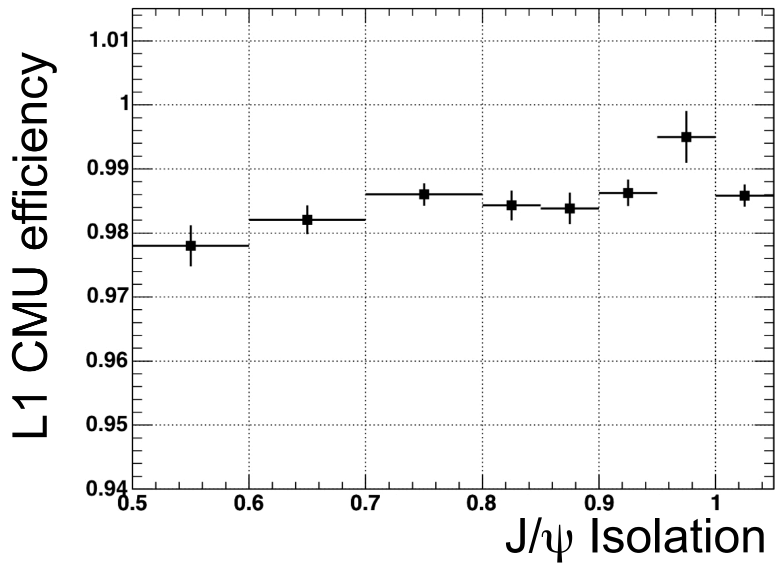
- Separately for each run range
- Average over all run ranges using luminosity weights
- Separately for CMUCMU CMUCMX
- Average CMU/X weighted by acceptance

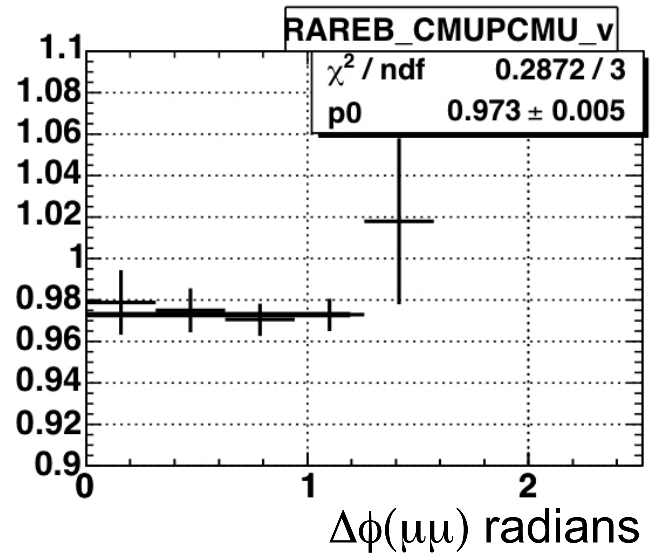
ε_{L1}=(85 +/- 3)% (this is a double leg efficiency)

B2$\mu\mu$ Trigger Efficiency

- Systematic Uncertainties
  - Several, but want to mention just two because they illustrate features common to most analyses
  - Differences in kinematics between sample used to measure trigger eff and signal sample (e.g. the $J/\psi \rightarrow \mu\mu$ sample and $B_s \rightarrow \mu\mu$ signal)
  - Back-up triggers used to measure trigger efficiency in an unbiased way usually pre-scaled (ie. luminosity profile != signal sample)

B2μμ Trigger Efficiency





- In general we found effects to be ~few%, fine for our purposes (recall we want to know $\alpha\varepsilon_{total}$ to ~10%)

B2$\mu\mu$ Trigger Efficiency

- Luckily L2 and L3 easier since resolutions and algorithms better… essentially flat across all relevant p_T and independent of (η,ϕ)

- To measure L2(L3) trigger requires a back-up trigger with L2_AUTO_ACCEPT (L3_AUTO_ACCEPT)

- For CDF's B$\rightarrow\mu\mu$: ε(L2)=99%, ε(L3)>99%

B2μμ Total Acceptance

- In general, repeated similar studies for all pieces of the expression given some while back

$$\alpha \cdot \varepsilon_{\text{total}} = \alpha \cdot \varepsilon_{\text{Tracking}} \cdot \varepsilon_{\mu\text{-Reco}} \cdot \varepsilon_{\text{Silicon}} \cdot \varepsilon_{\text{L1-Trig}} \cdot \varepsilon_{\text{L2-Trig}} \cdot \varepsilon_{\text{L3-Trig}} \cdot \varepsilon_{\text{vertex}} \cdot \varepsilon_{\text{analysis}}$$

From MC: 6.6% 55%

From Data: >99% 96% 83% 85% 99% >99% 95%

Efficiency for both muons combined

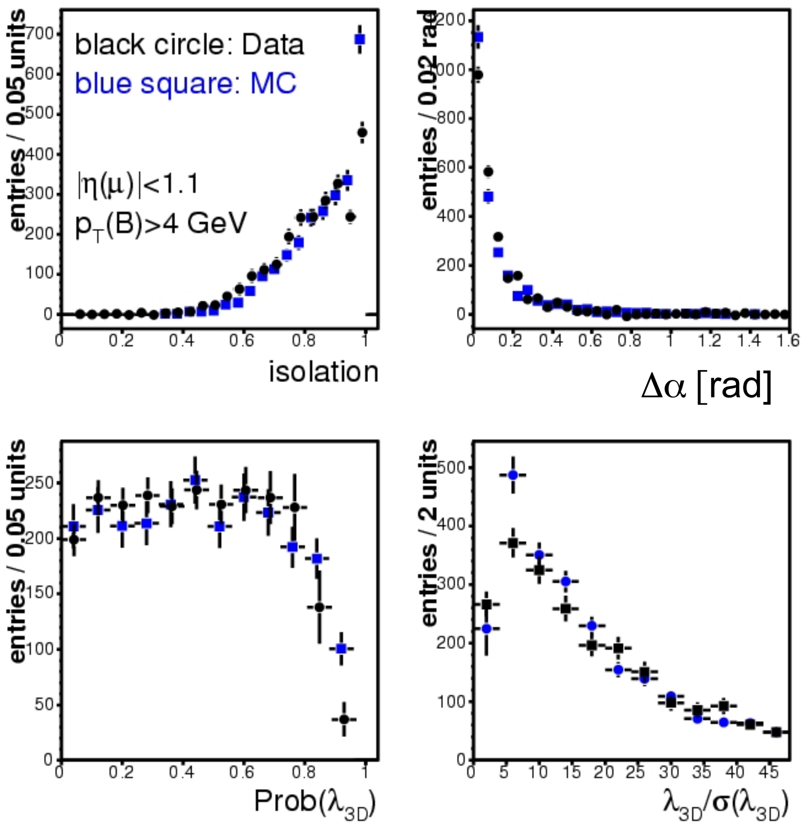
B2$\mu\mu$ Total Acceptance

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)

Validating Signal Modeling



Comparison of data to MC using $B^+ \rightarrow J/\psi K^+$ events.

Differences used to assign +/-5% (relative) systematic uncert.

- For searches, can’t isolate a clean signal sample in the data to validate MC signal modeling… typically use an intelligently constructed control sample instead

Background

ASTS: Background Estimate

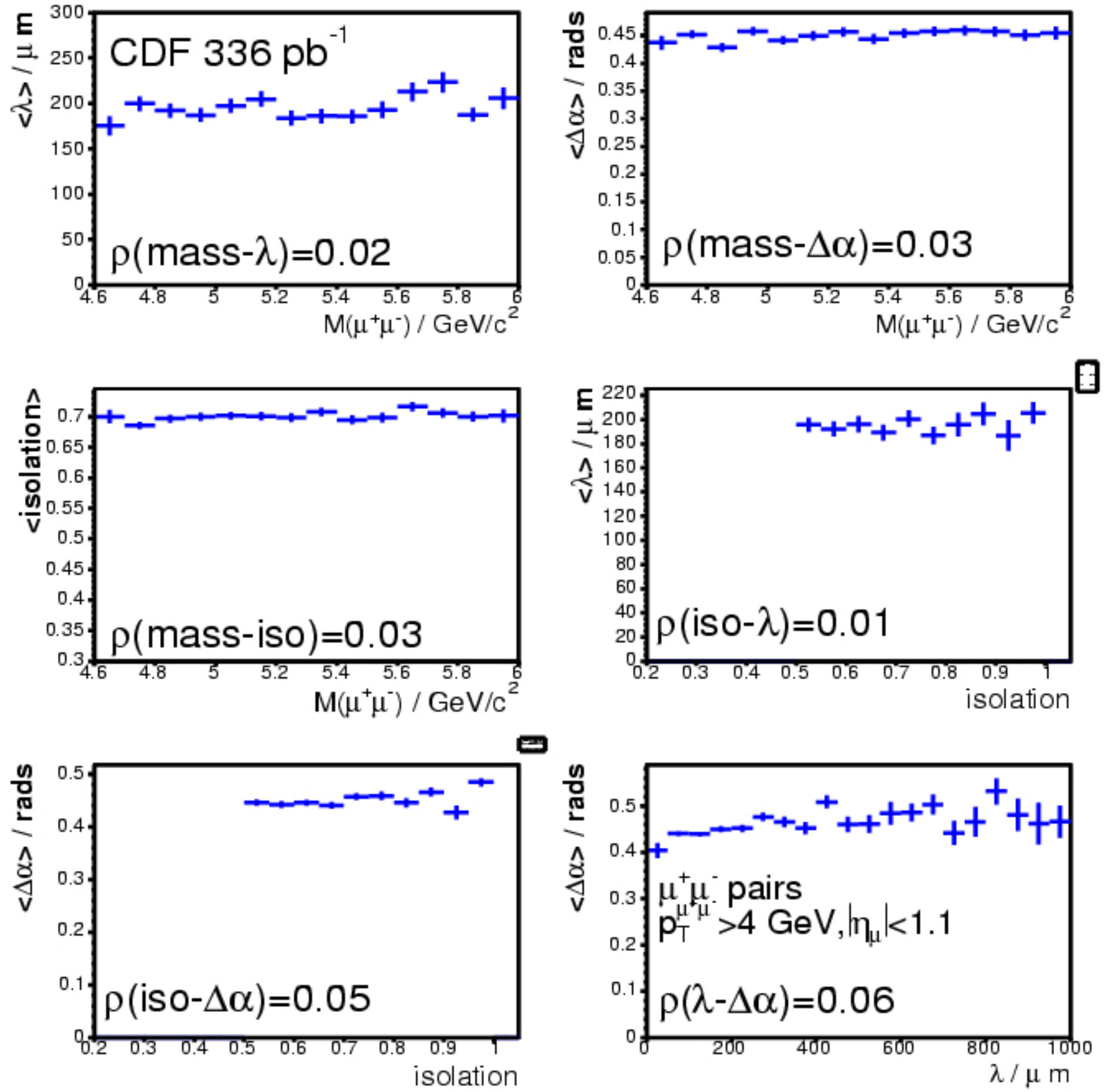
- Worth having a well thought-out plan for estimating your background
  - Try to delineate contributing processes *a priori*
  - Develop methods to estimate the various contributions
  - Likely will require multiple methods to account for all sources
  - Take care not to double count
- Verify your methodology on control samples before “opening the box” and looking in signal region (TBV)

B2$\mu\mu$ Background Estimate

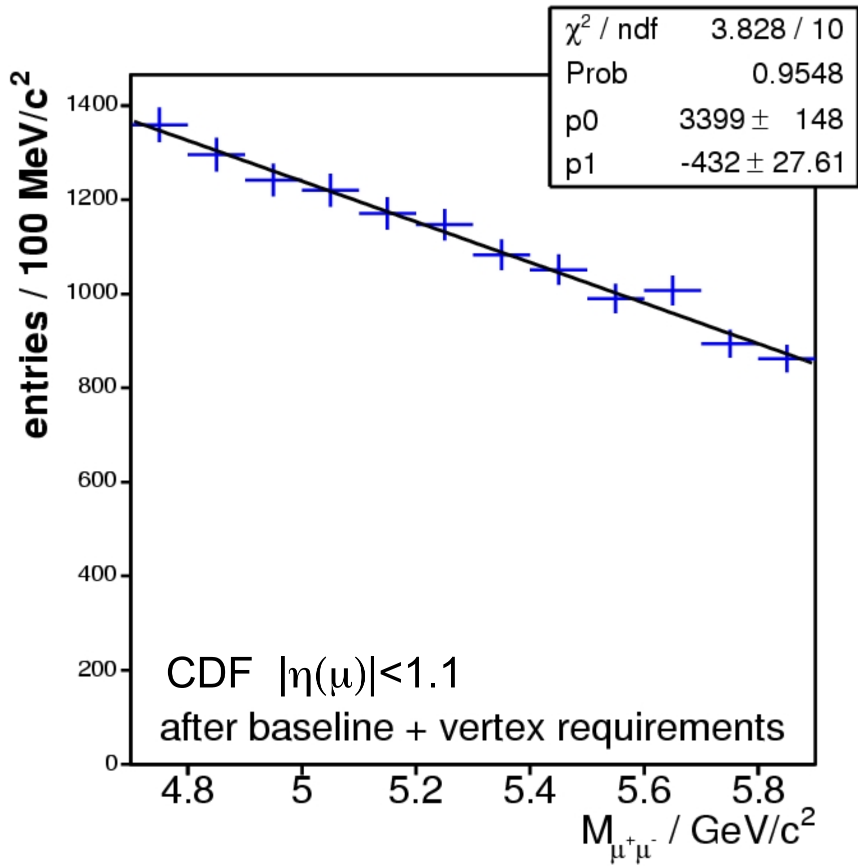
- Most backgrounds can be estimated using sideband subtraction after all other analysis requirements
  - Only works if mass uncorrelated with other discriminating variables and bgd linear in mass
- Above assumption untrue only for B→KK, Kπ, $\pi\pi$
  - These will populate the signal sample only when both hadrons are mis-identified as muons
  - Determine hadron→μ fake-rates using data
  - Convolute those probabilities with B→hh MC
  - Take remaining efficiencies from pg 62

B2μμ Background Estimate

- For combinatoric background, mass uncorrelated with the remaining discriminating variables



B2μμ Background Estimate



- Combinatoric backgrounds linear in mass

B2μμ Background Estimate

- So our assumptions hold and we can estimate our combinatoric backgrounds as

$$n_{bg}^{combinatoric} = \left(n_{obs}^{left\ \mathrm{SB}} + n_{obs}^{right\ \mathrm{SB}}\right)\left(\frac{\Delta \mathrm{M}_{\text{signal region}}}{2\Delta \mathrm{M}_{\text{SB region}}}\right)$$

where

n_{bg}^{comb} = number of expected combinatoric bg events in the signal region

n_{bg}^{SB} = number of observed events in the sidebands

ΔM_{signal} = 120 MeV/c^2

ΔM_{SB} = 500 MeV/c^2

B2$\mu\mu$ Background Estimate

For two-body B→hh (h=K or π):

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}

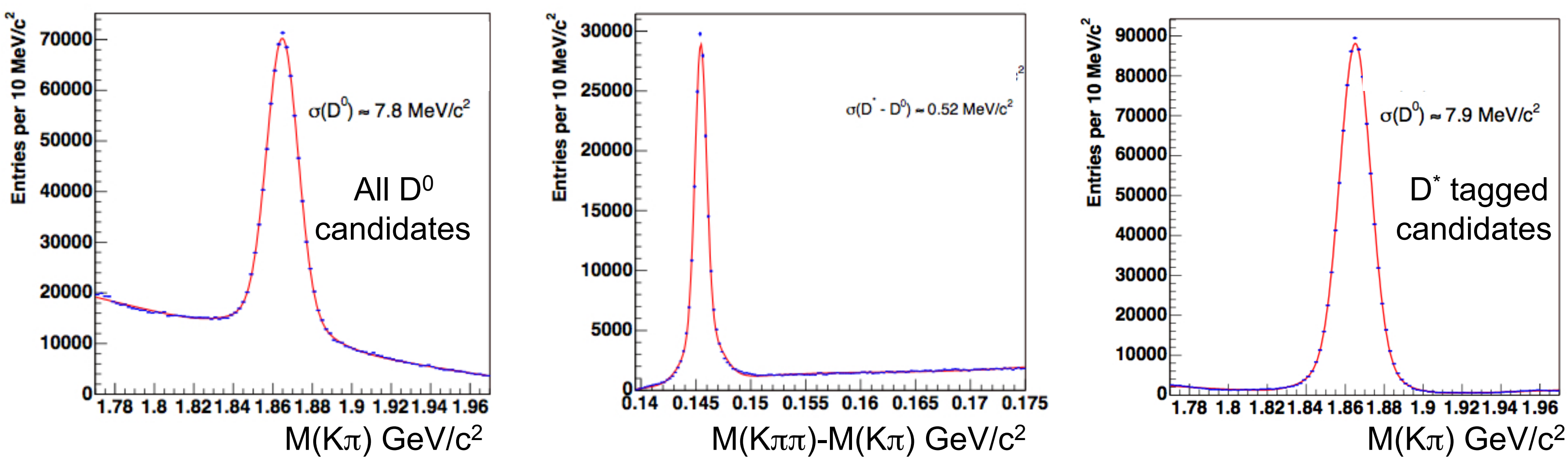
Yields estimates of <1 event for 4 fb^{-1} of data

Aside: D* tagged Samples

- Can identify a really clean sample of K and π using

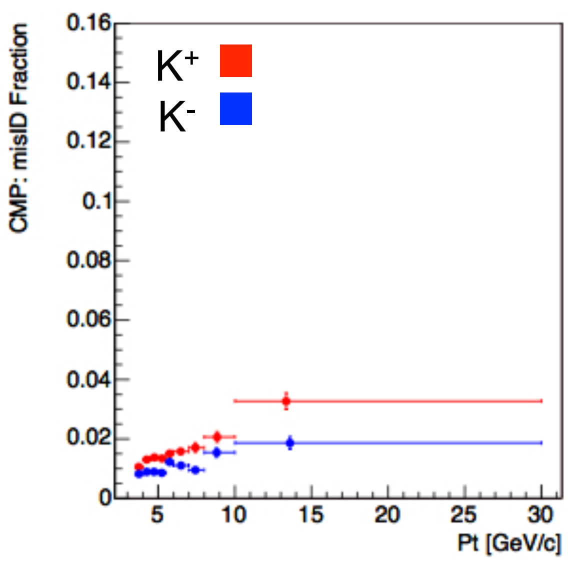
$$D^{*+} \rightarrow D^0\pi^+ \rightarrow \left(K^-\pi^+\right)\pi^+$$

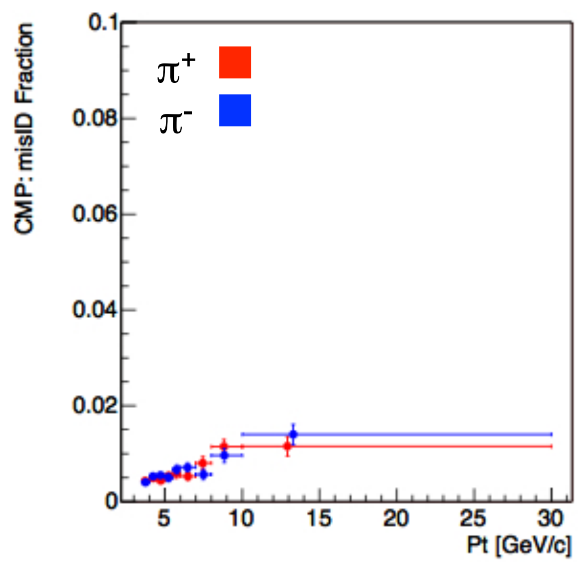
  – Use charge correlations to ID the K^- and π^+ in an unbiased manner



Aside: muon fake rates using D*

- Can use this clean sample to
  - Determine probability that K/π fake a muon
  - Determine the efficiency for PID algorithms
- Methodology same as $J/\psi \to \mu\mu$: employ sideband subtraction in bins of p_T





B2$\mu\mu$ Background Cross Checks

- We think we have a complete background estimate at this point
- Let's verify it can accurately estimate the number of observed events in control samples
  - Choose control samples in which you expect your background methodology to work
  - Choose control samples that have background compositions similar to signal sample
  - Demonstrate robustness of estimate by making comparisons for a variety of selection requirements

B2$\mu\mu$ Background Cross Checks

	Sample	N(expctd)	N(obsrvd)	$\mathcal{P}$(>=obs|exp)
Loose cuts	OS-	8.09 +/- 1.57	12	12%
	SS+	3.64 +/- 0.69	3	86%
	SS-	4.79 +/- 0.85	3	70%
	Sum	16.52 +/- 2.56	18	
Default cuts	OS-	3.03 +/- 0.70	5	19%
	SS+	1.22 +/- 0.27	1	81%
	SS-	1.64 +/- 0.33	1	70%
	Sum	5.89 +/- 1.02	7	
Tight cuts	OS-	0.64 +/- 0.22	1	47%
	SS+	0.27 +/- 0.08	0	76%
	SS-	0.20 +/- 0.07	0	82%
	Sum	1.11 +/- 0.27	1	

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

End Game

B2$\mu\mu$ Optimization

- At this stage we have all the pieces to optimize our final selection criteria
  - Reliable estimate of our signal acceptance
  - Methodology for estimating our background
- Choose figure-of-merit and vary final selection criteria to optimize
  - For B→$\mu\mu$ we used the expected limit as FOM
  - We considered over 100 different combinations of requirements on (M, λ, $\Delta\alpha$, Isolation)
- Avoid looking at signal region in data until done here

B2$\mu\mu$ (Old) Answer

- The first generation analysis used 171 pb^{-1} of data
  - Single-event-sensitivity = 1.6×10^{-7}

    (corresponds to the BR on pg 13 assuming N_s=1)

    (sets scale for experimental sensitivity)

    (caveat: tells you nothing about background)

  - Expected background: 1.1 +/- 0.3 events
  - Observed: 1 event
  - BR($B_s \rightarrow \mu\mu$) < 5.8×10^{-7} @ 90% CL

    (factor of >3 improvement over previous world's best)

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

B2$\mu\mu$ (Latest) Answer

- Latest generation analysis uses 3.7 fb^{-1} of data
  - Single-event-sensitivity = 3.2×10^{-9}

    (using 22 times as much data, achieve factor of 50 better sensitivity)

    (many improvements since first analysis: NN discriminator, fit for S+B in two dimensional plane of NN vs Mass, increased trigger acceptance, exploit full set of CDF particle ID to suppress B→hh, etc)
  - Expected background: 7 +/- 1 events
  - Observed: 7 events

    (projecting onto Mass axis in one NN slice)
  - $BR(B_s \rightarrow \mu\mu) < 3.6 \times 10^{-8}$ @ 90% CL

    (World's best. CDF Public Note 9892. Preliminary.)

Concluding Remarks

- Today we
  - Had a short review of yesterday's material
  - Used CDF's $B_s \rightarrow \mu\mu$ analysis
    - As a specific example of a search-type analysis
    - To highlight some of the analysis "guidelines" in action
    - To introduce several important experimental techniques
- Tomorrow we'll
  - Use CDF's t-tbar analyses as specific examples of measurement type-analyses

- Inv mass plots