Study of Multimuon Events at CDF

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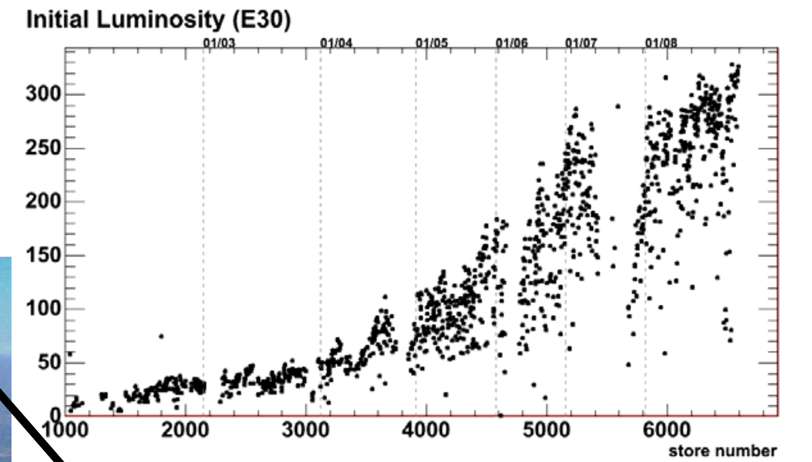
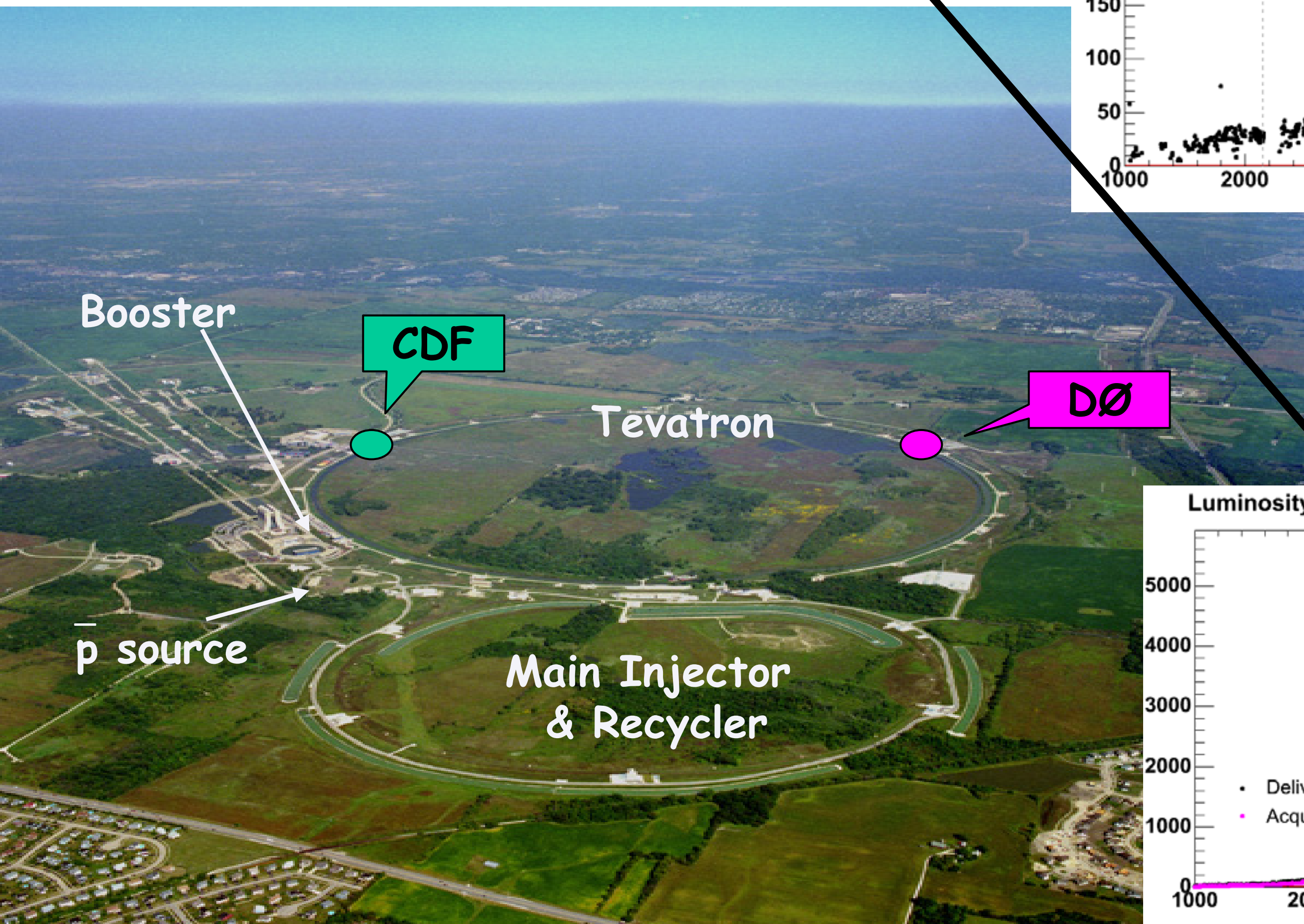
Outline

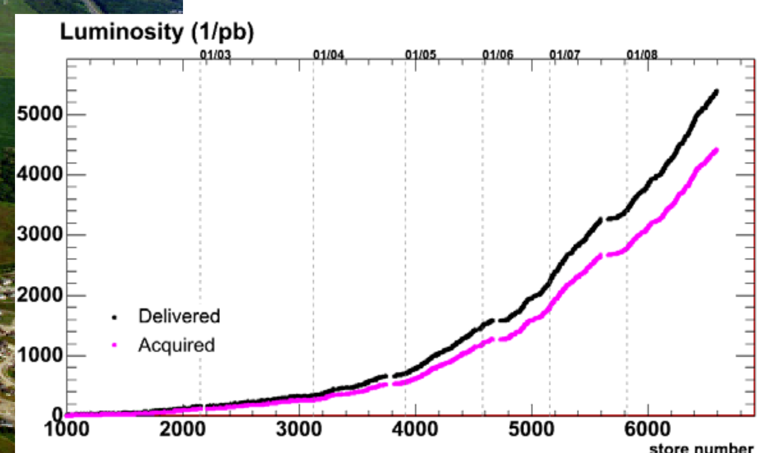
- Introduction
- History: *b* production and decay puzzles from the 1990s
- Recent results
  - Inclusive *B* cross sections
  - $b\bar{b}$ cross section
- New study of multimuon events

Fermilab Tevatron

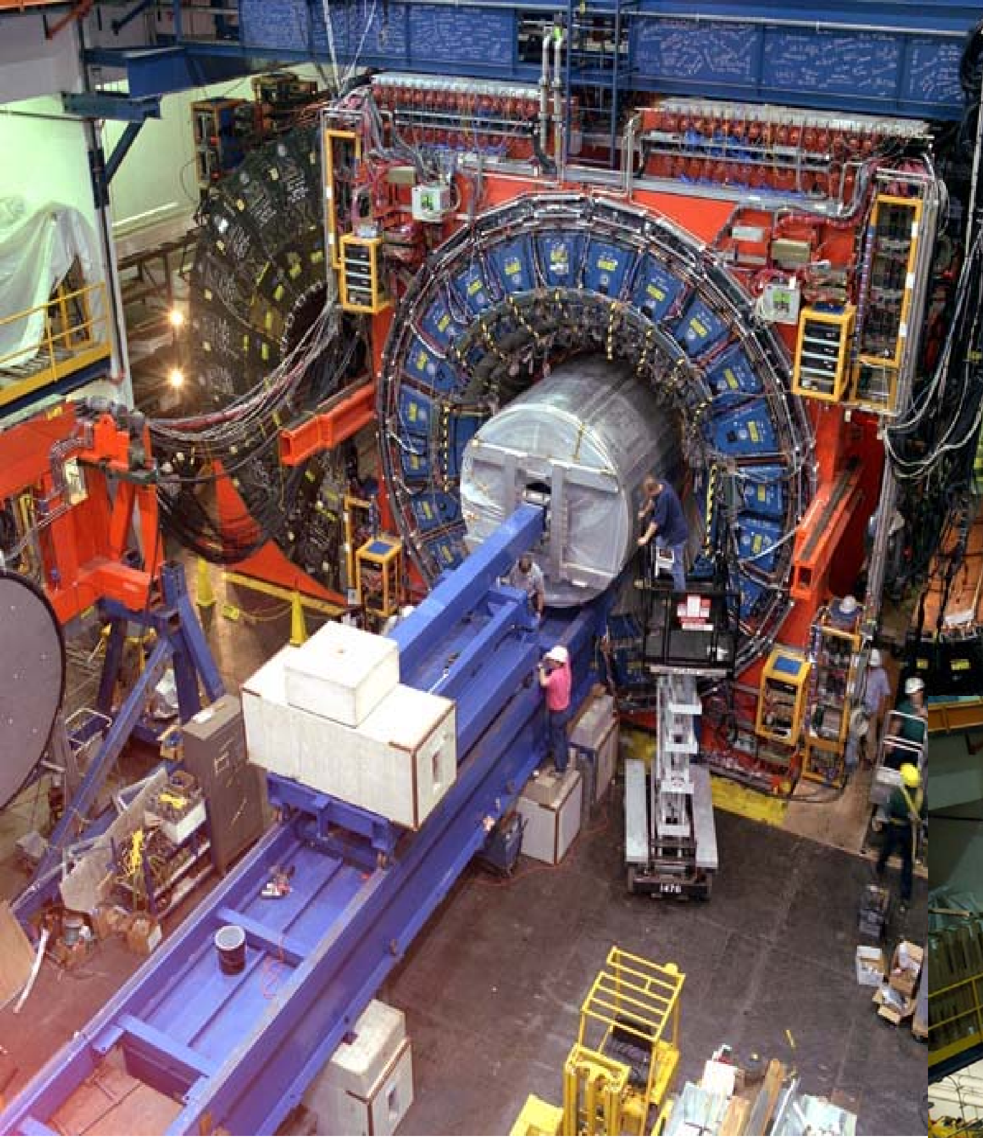
- $p\bar{p}$ collisions at high energy
  - Run I 1992-1996 sqrt(s)=1.8 TeV
  - Run II 2002-present sqrt(s)=1.96 TeV



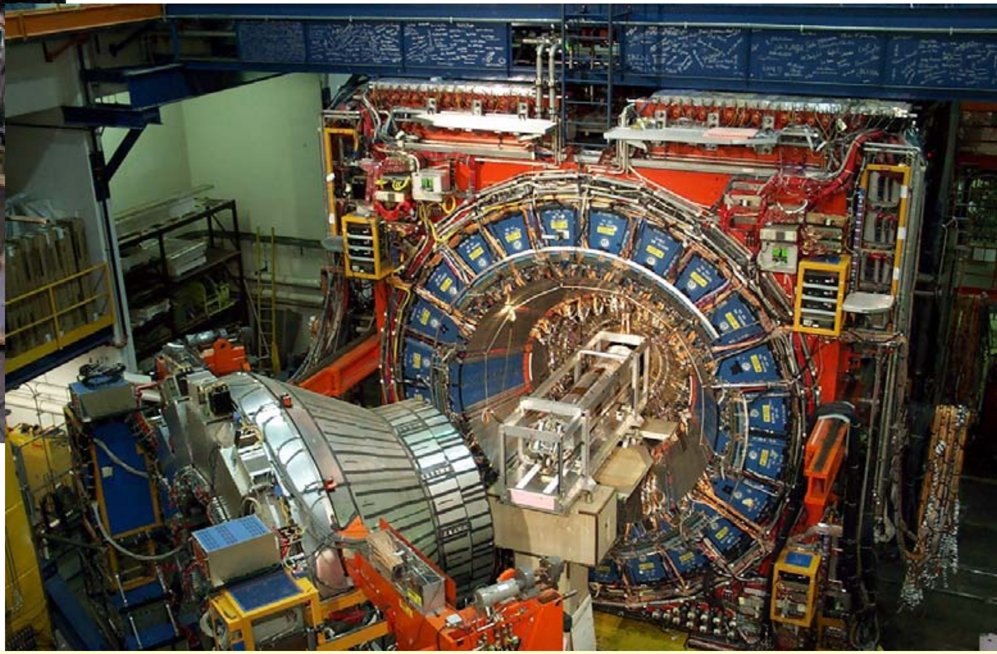




CDF Detector



- Central tracking
- Silicon vertex detector
- Good lepton identification
- Particle ID (TOF and dE/dx)
- High rate trigger/DAQ system



CDF silicon detector installation

- For the analyses discussed today, Run I and Run II detectors similar
  - Differences in microvertex detectors discussed later.

Puzzles from the 1990's

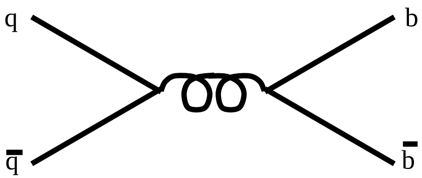
Three results related to *b* production and decay from Tevatron run I (1992-1996).

1. $\sigma(pp \to b\bar{b}X)$ larger than expected from NLO QCD
2. Time-integrated mixing measured at Tevatron larger than LEP average

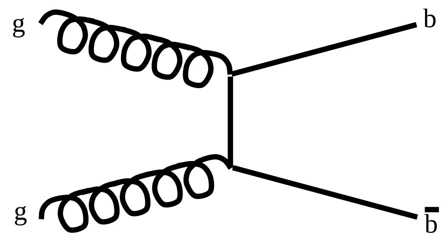
$$\bar{\chi} = \frac{\Gamma\left(B^0 \to \bar{B}^0 \to l^+ X\right)}{\Gamma\left(B \to l^\pm X\right)} = \frac{\text{"}same\ sign\text{"}}{\text{"}total\text{"}},\ B^0 = B_d^0\ or\ B_s^0$$

3. low mass dilepton spectrum inconsistent with expectations from heavy flavor.

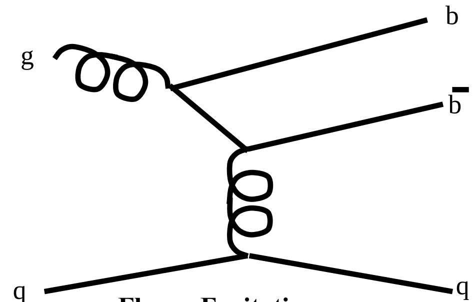
I. B Cross Sections



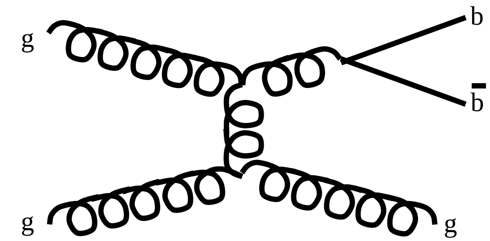
Flavor Creation (annihilation)



Flavor Creation (gluon fusion)



Flavor Excitation

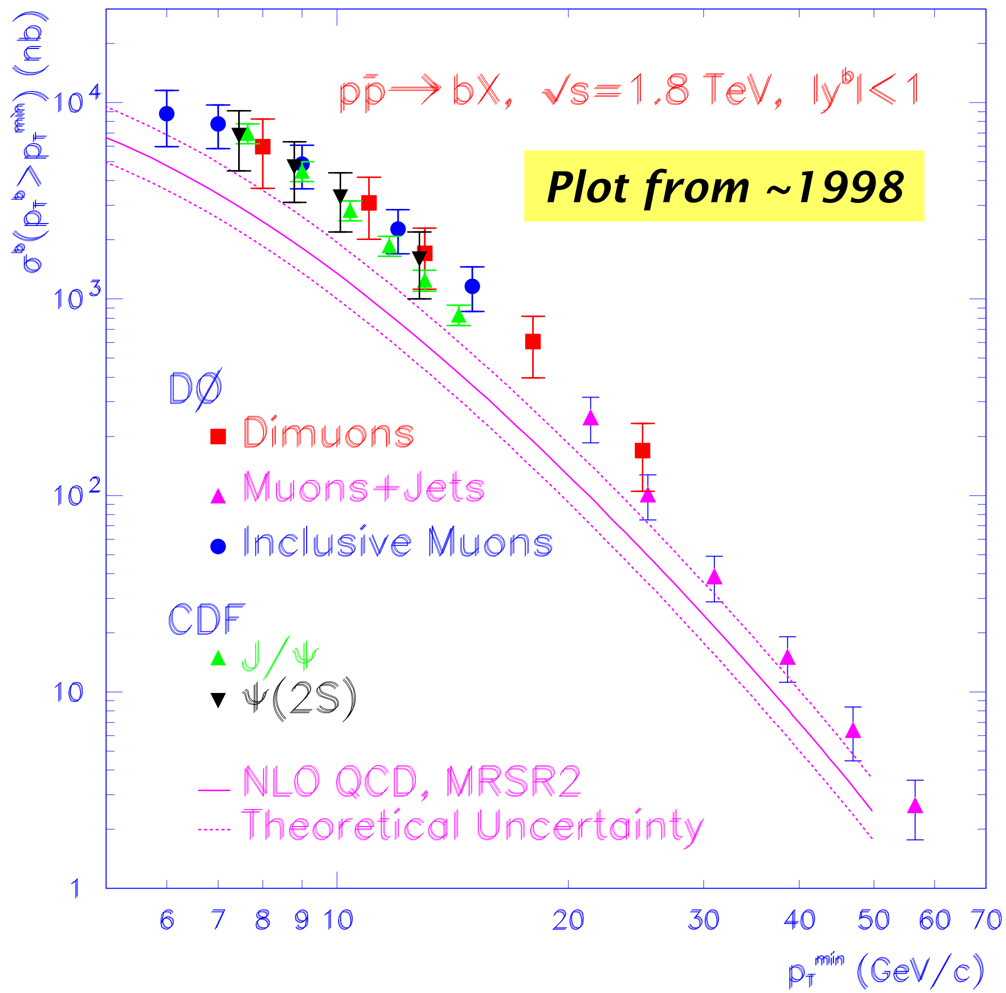


Gluon Splitting

- **Two types of cross section measurements:**
  - "Inclusive" = "single B"
    - Only require one reconstructed *B*
    - Experimentally: high yield, can use clean, exclusive states,
      - e.g. $B^+ \rightarrow J/\psi K^+$ or $B^0 \rightarrow \mu D^0 X$
    - Theoretically: significant uncertainty from higher order contributions, fragmentation, structure functions
  - "Correlated $b\bar{b}$" = "two *B*"
    - Both *B*'s must be central with sufficient p_T
    - Experimentally: BR*efficiency for exclusive states too low, must use more inclusive techniques (vertex tagging, inclusive lepton tagging)
    - Theoretically: smaller uncertainty because Born term dominates

Inclusive σ_b

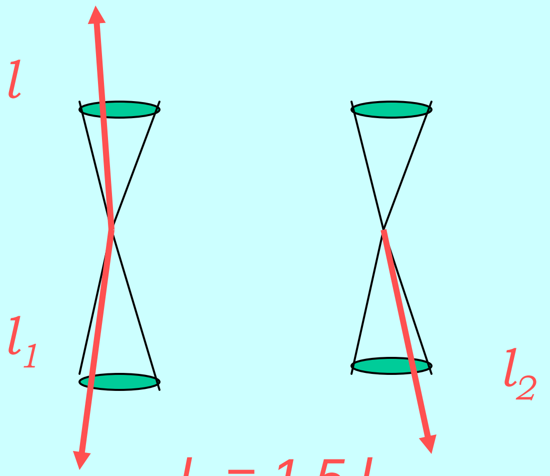
- **Tevatron Run I (1992-1996): Inclusive cross sections systematically higher than NLO theory**



Correlated σ_{bb}

- **Measurement techniques**
  - Vertex tagging
  - Lepton tagging

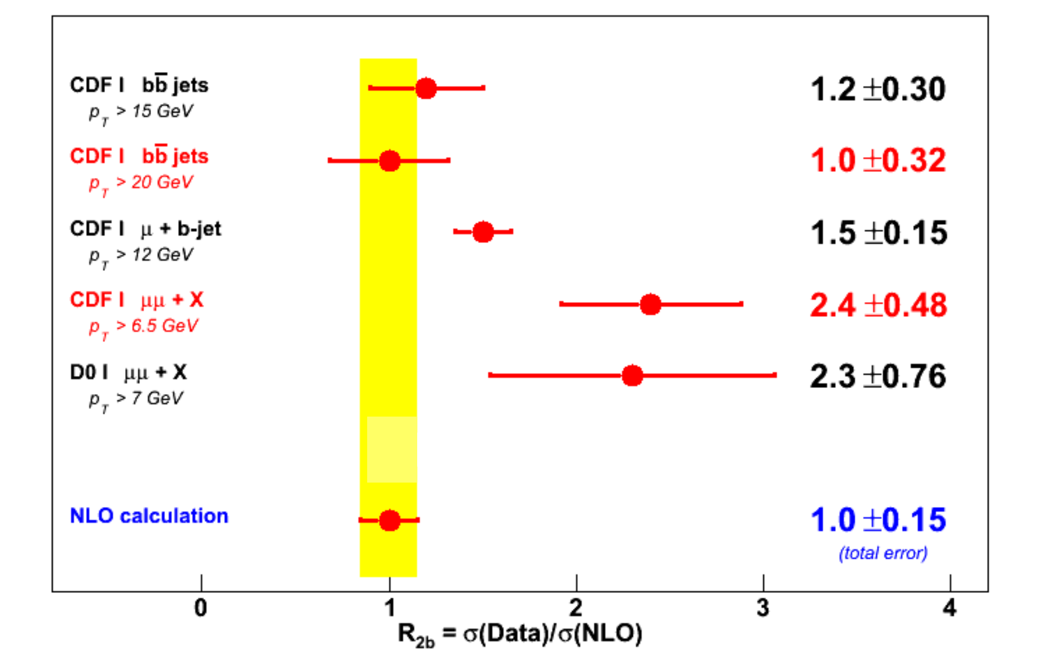
- **"per jet" lepton rate also showed high relative rate**



$l_1 = 1.5\ l_2$

PRD 69, 072004 (2004)

- **Run I σ_{bb} measurements.**
  - Plot shows $R_{2b}=\sigma_{bb}$(measured)/σ_{bb} (NLO)
    - Vertex tag analyses consistent with $R_{2b}=1$
    - Analyses using muons have $R_{2b}>1$.



II. Time Integrated Mixing

$$\bar{\chi} = \frac{\Gamma\left(B^0 \to \bar{B}^0 \to l^+ X\right)}{\Gamma\left(B \to l^\pm X\right)} = \frac{\text{"same sign"}}{\text{"total"}}, \quad B^0 = B_d^0 \text{ or } B_s^0$$

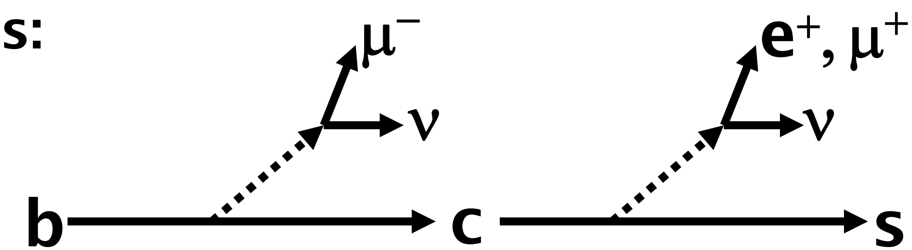
- **Since B_d and B_s both oscillate:** $\bar{\chi} = f_s \chi_s + f_d \chi_d$
  - f_d and f_s are fraction of b quarks that fragment into B_d and B_s
  - χ_d and χ_s are time integrated mixing parameters.

$$\chi_d = \frac{x_d^2}{2\left(1+x_d^2\right)}, \qquad \chi_s = \frac{x_s^2}{2\left(1+x_s^2\right)}$$

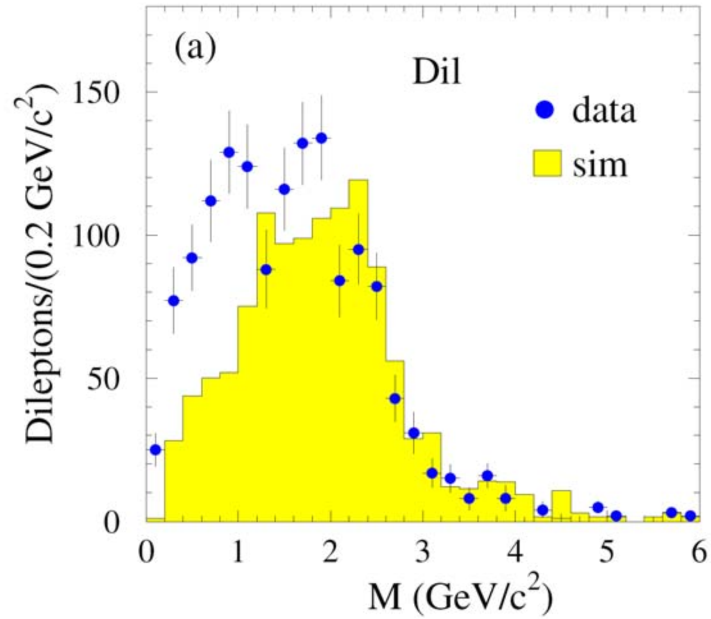
  - Since x_d and x_s well measured, measure of χ constrains production fractions.
  - Expect same production fractions at Tevatron and LEP, since $q^2 >> m_{u,d,s}^2$
  - CDF Run I result (0.152±0.013) [PRD 69, 012002 (2004)] larger than LEP average (0.126 ±0.004)
    - Different production fractions at high energy?

III. Low mass dileptons

- **Identify sample enriched in *B* decays.**
- **Look at "low mass" dileptons**
  - **Expect to be dominated by sequential semileptonic decays:**



  - **Should be well-modeled by simulation**
  - **See poor agreement for $m_{\mu\mu}$<2 GeV**



PRD 72, 072002 (2005)

Puzzles from the 1990's

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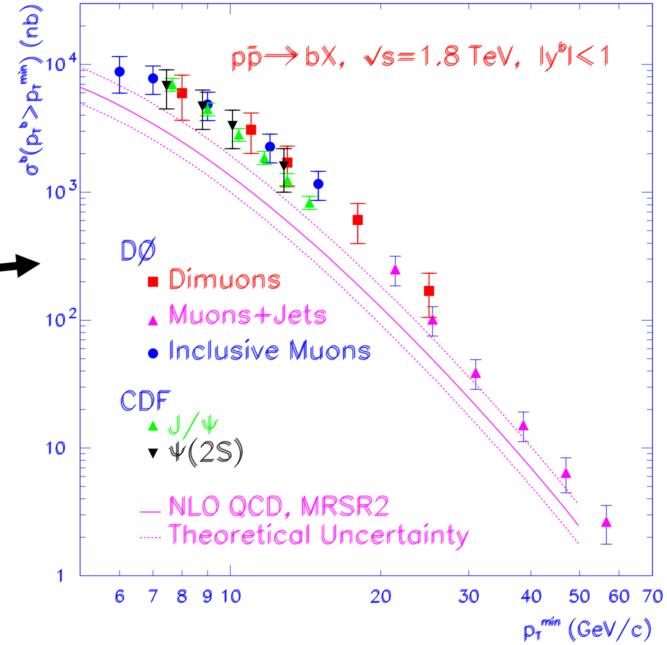
3. low mass dilepton spectrum inconsistent with expectations from heavy flavor.

None of these are "showstoppers", but it is interesting to ask whether they are experimental or theoretical effects.

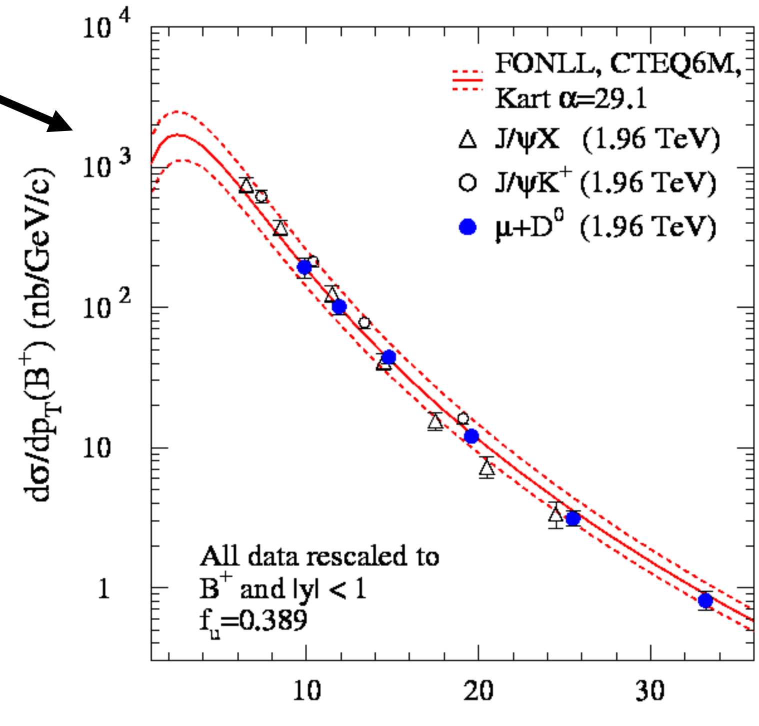
Step 0: Inclusive σ_b

- **Tevatron Run I (1992-1996): Inclusive cross sections systematically higher than NLO theory**

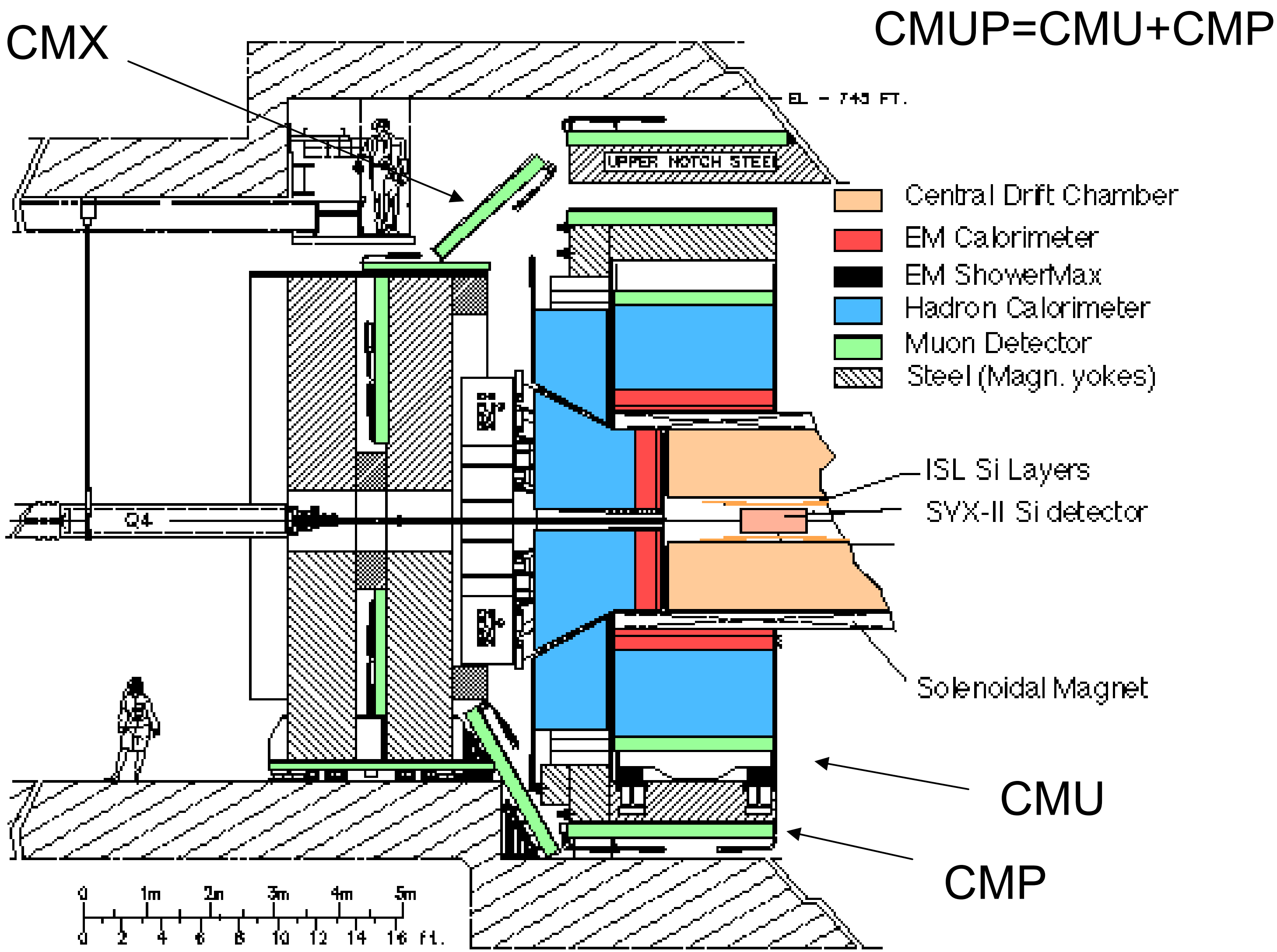


- **Tevatron Run II: Remeasure inclusive cross sections in Tevatron Run 2**
  - **Better acceptance**
  - **Higher statistics**
  - **Smaller uncertainties**

- **See better agreement with theory now, but in fact data is consistent with Run I results.**
  - **Improved agreement primarily from theoretical improvements.**

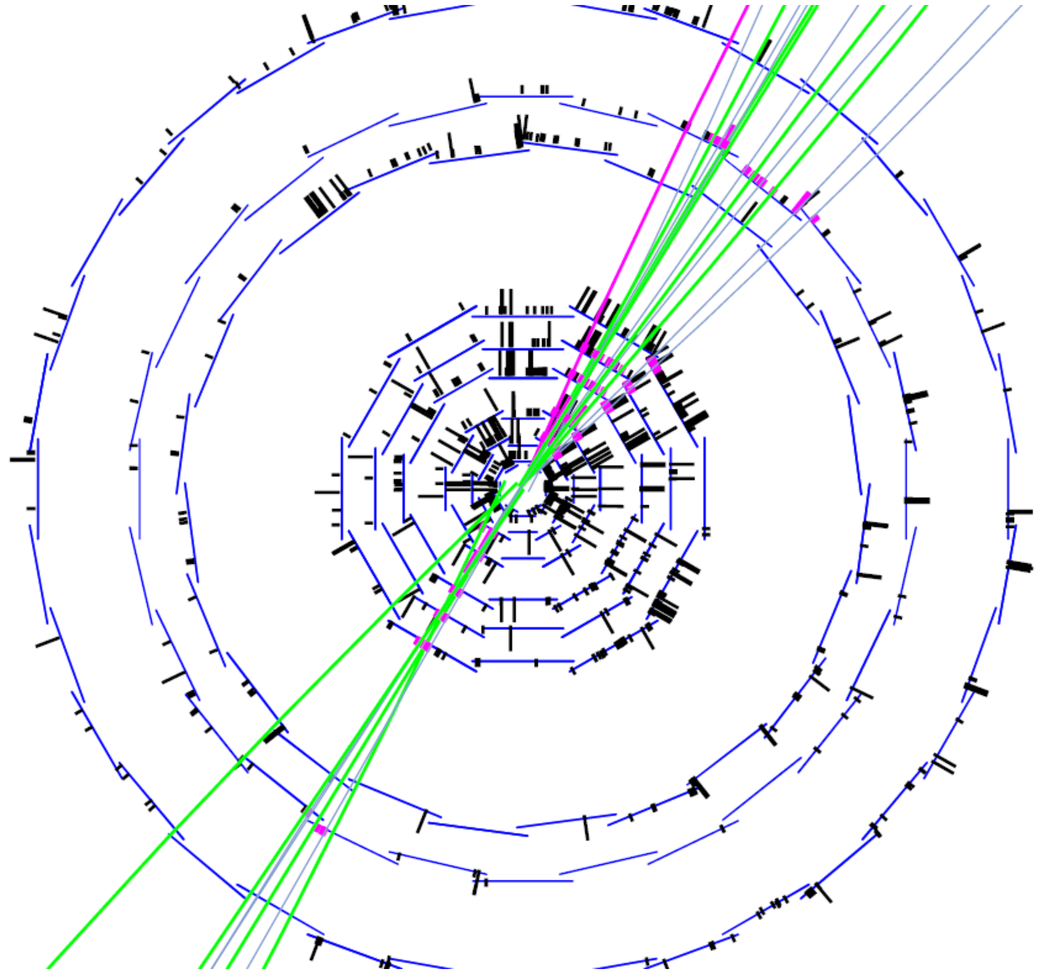


CDF detector

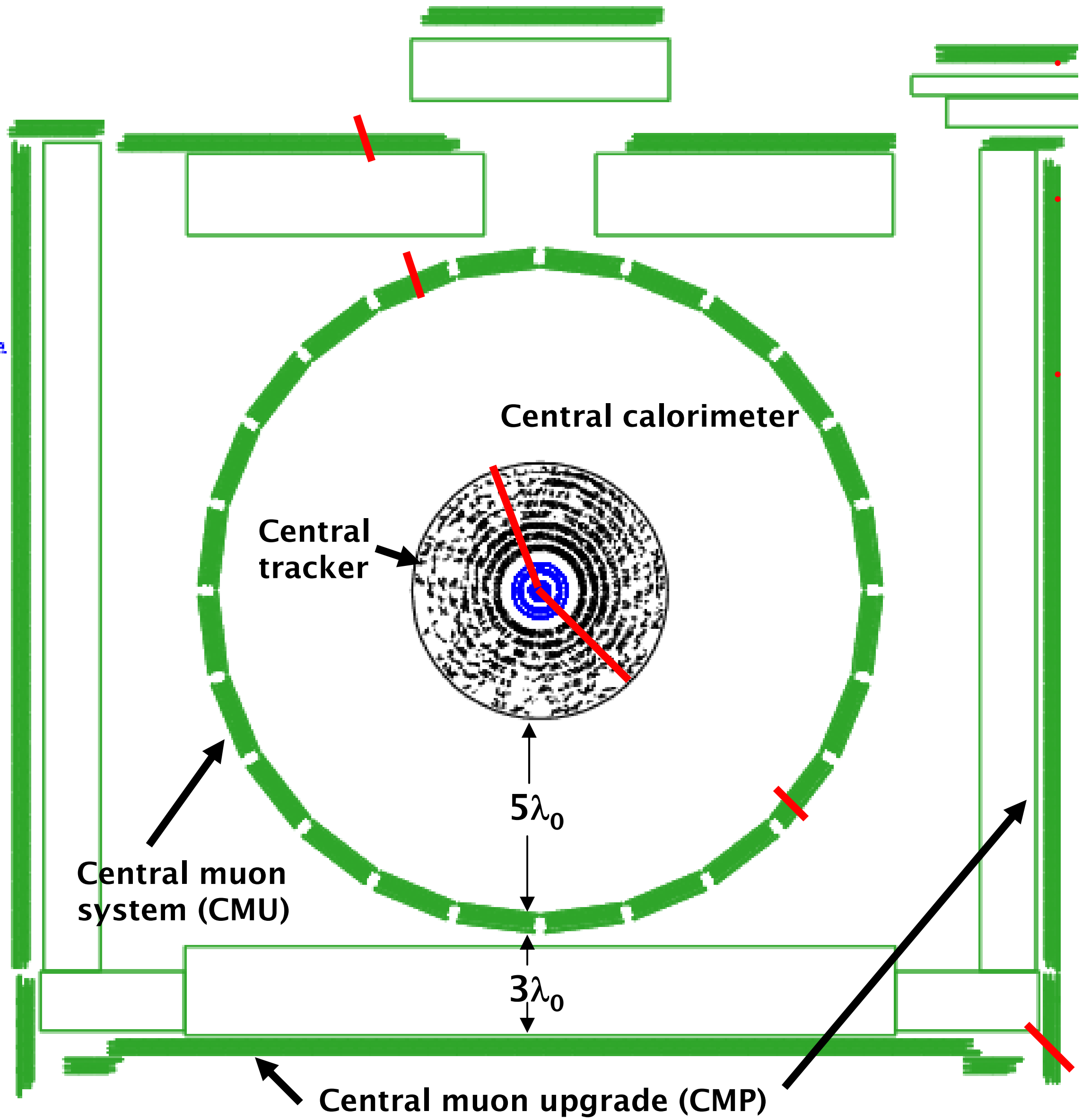


CDF microvertex detector

- **silicon layer radii**
  - L00 1.6cm (on beampipe)
  - L0 2.5cm
  - L1 4.1cm
  - …
- **Impact parameter resolution:**
  - 230 μm (COT without Si)
  - 30 μm (COT with ≥3 Si hits)



Dimuon Triggered Sample

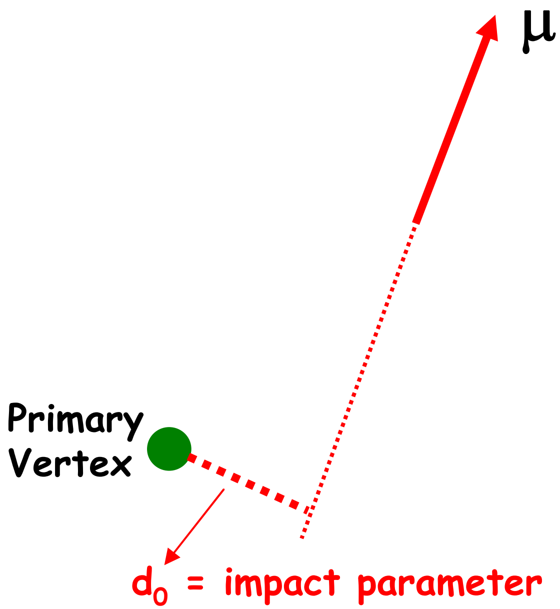


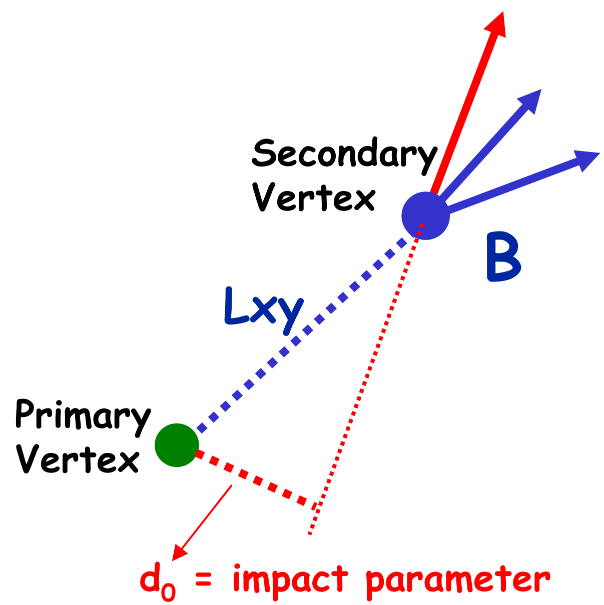
- **Data sample defined by a dimuon trigger.**
- **Each muon:**
  - Central track, p_T>3 GeV
  - Match to stub in CMU
  - Match to stub in CMP
- **Dimuon pair**
  - $m_{\mu\mu}$> 5 GeV to get rid of sequential ($b \to c\mu$ with $c \to \mu s$) decays

Impact parameter and decay length

- **Impact parameter (d_0) is the distance of closest approach of a track to the primary ($p\bar{p}$) collision vertex**
  - **We will be looking at $d_0(\mu)$ quite a bit**
  - **Impact parameter is a property of each track, do not need to reconstruct a secondary vertex.**

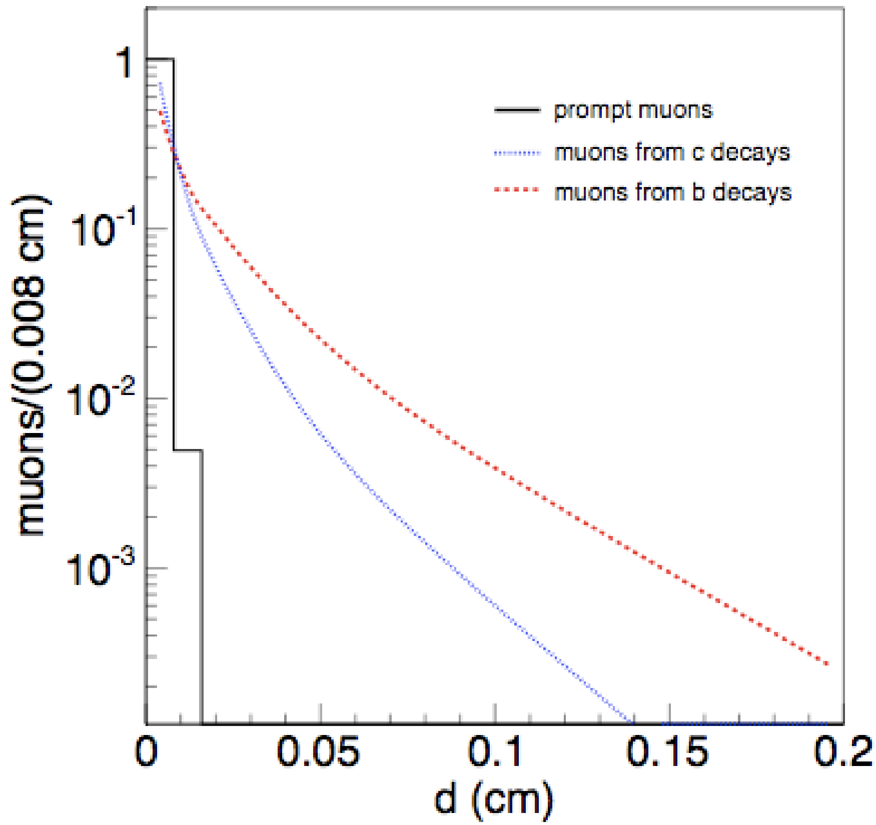
- **Decay length (L or L_{xy}) is the flight distance between primay $p\bar{p}$ collision vertex and secondary vertex.**





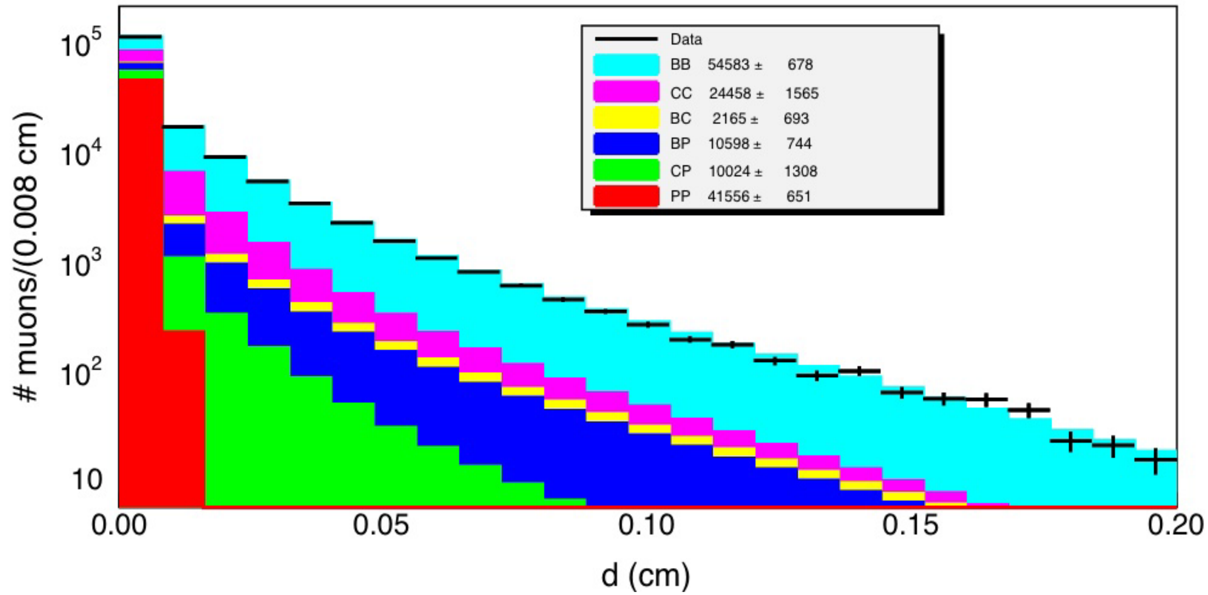
Step 1, re-measure $\sigma(p\bar{p} \rightarrow b\bar{b}X)$

- **Known sources of real dimuons**
  - $b \rightarrow \mu$ ($c\tau$ = 470 μm)
  - $c \rightarrow \mu$ ($c\tau$ = 210 μm)
  - Prompt (Y, Drell-Yan).
- **Known sources of fake muons**
  - Hadrons punching through calorimeter
  - Hadrons that decay-in-flight
    - $K \rightarrow \mu$, $\pi \rightarrow \mu$
  - Fakes can be from prompt or heavy flavor sources.
- **Procedure**
  - Develop d_0 templates for
    - Heavy flavor (from MC)
    - Prompt sources (from data)
  - Fit (in 2D) the $d_0(\mu_1)$ versus $d_0(\mu_2)$ distribution to extract contributions.
  - Require our highest tracking precision to separate out prompt and charm backgrounds.
    - Both μ have hits on two innermost Si layers (L00 and L0)
  - Correct for fake muon contribution to extract $\sigma(pp \rightarrow bbX)$

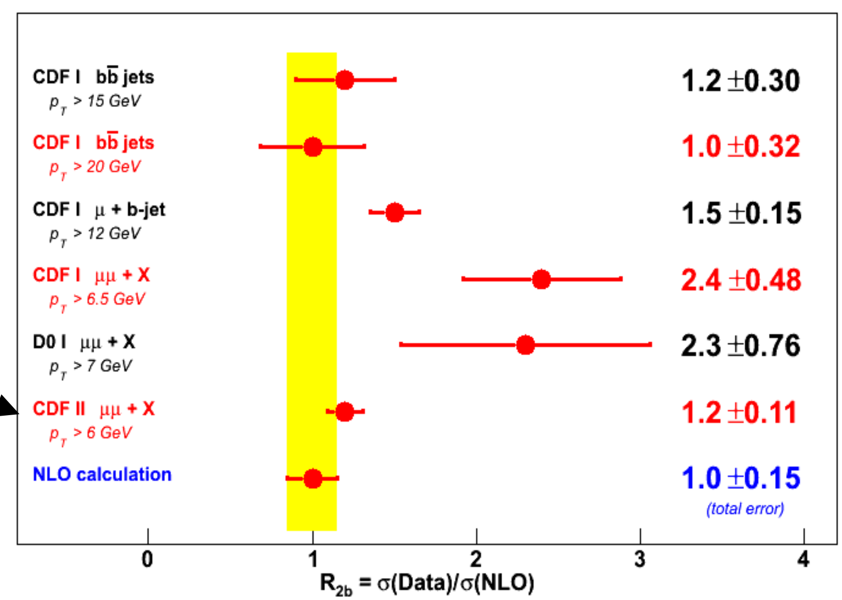


- 1d projection of 2d templates
- Full fit includes all dimuon combinations
  - bb, bc, cc, b+prompt, c+prompt, prompt+prompt

Step 1, re-measure $\sigma(p\bar{p}\rightarrow b\bar{b}X)$



- **d_0 fit is 2D, plot is projection**
- **Sample**
  - **742 pb^{-1}**
  - **Well modeled by templates**
  - **High purity: ~40% *bb***
- **Result**
  - **Measurement accuracy 10%**
  - **Good agreement with theory**

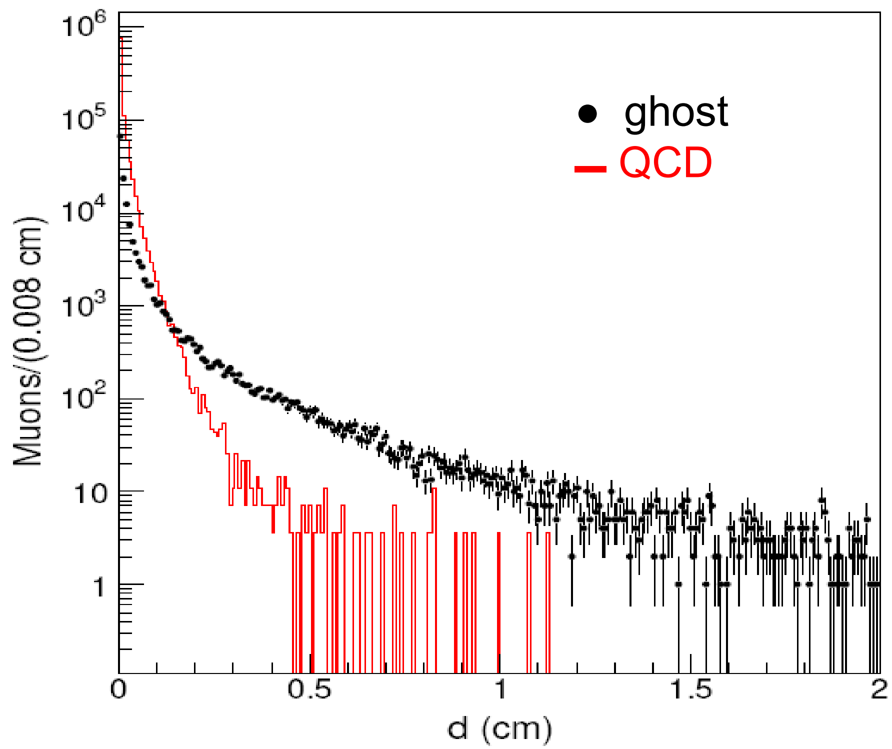


PRD 77, 072004 (2008)

Next, investigate "other" dimuons

- **observe many more events rejected by the tight selection than expected.**
  - Recall: tight selection requires muons have hits on two innermost silicon layers.
  - Implications
    - more background than expected in total sample
    - background removed by tight selection
  - Much of this background was not removed because it appears at large impact parameter.
- **Sample definitions**
  - QCD = sum of contributions measured in $b\bar{b}$ cross section analysis (prompt, c and b)
  - Ghost = the excess after accounting for tight selection efficiency

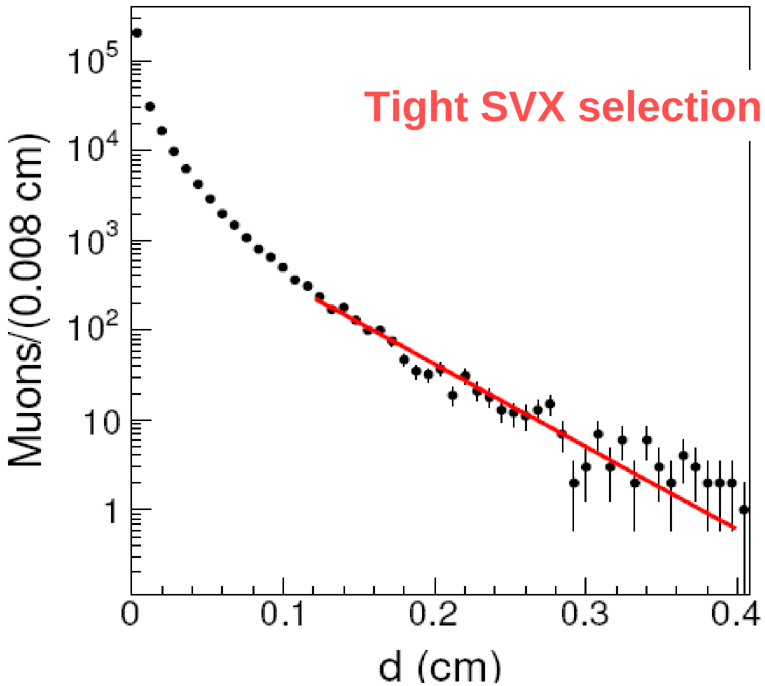
    Ghost = all events – (QCD/efficiency)



- **QCD sources (includes heavy flavor) have $d_0(\mu)$<0.5cm**
- **"Ghost" events have much larger impact parameter!**

Tight Selection

- Charm contribution minimal for d>0.12cm
- Fit d_0 distribution for muons with $0.12<d_0<0.4$cm
  Measure $c\tau=469.7 \pm 1.3$ μm (stat. error only)
  PDG average b lifetime: $c\tau=470.1 \pm 2.7$ μm



- Conclude:
  - Sample selected with tight cuts not appreciably affected by additional background.
  - *b* contribution almost fully exhausted for $d_0>0.5$cm

Yields in 742 pb^{-1}

Type	No SVX	Tight SVX	Loose SVX
All	743006	143743	590970
All OS		98218	392020
All SS		45525	198950
QCD	589111 ± 4829	143743	518417 ± 7264
QCD OS		98218	354228 ± 4963
QCD SS		45525	164188 ± 2301
Ghost	153895 ± 4829	0	72553 ± 7264
Ghost OS		0	37792 ± 4963
Ghost SS		0	34762 ± 2301

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Assume same as "ALL tight"

Assume zero

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Extrapolate from tight SVX yields using measured tight/loose efficiency

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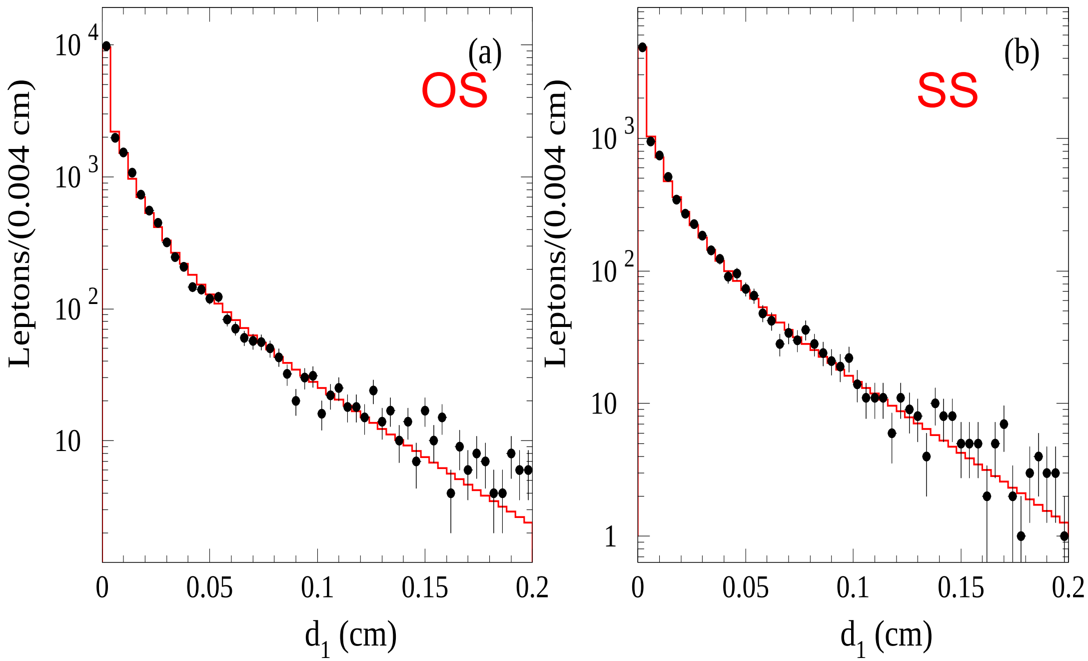
"All" – "QCD" = ghost

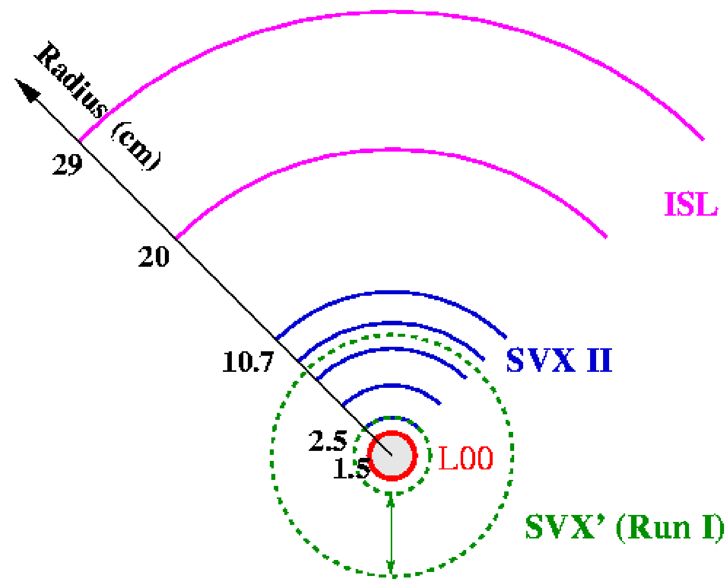
- 221564±11615 bb events with no SVX [194976 ± 10458 with loose requirements]
- Ghost contribution to entire sample (154k) comparable to bb contribution (222k)!

What about $\overline{\chi}$?

- Traditionally CDF measurements use **loose SVX** requirements (3 out of 8 silicon layers)
  - muons could originate as far as10.6 cm from the beam line
- CDF Run I analyses selected muons originating from distances as large as 5.7 cm from the beam line



Run I $\overline{\chi}$ measurement



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- **Run I measurements used selection closer to "loose SVX"**
- **Recall χ = (same sign)/total**
- **Ghost sample ~50/50 in OS/SS $\Rightarrow$ high value for $\overline{\chi}$**

Where are we so far?

- Have a identified a source of background that was not previously considered.

- It is plausible that this background explains:
  - Run I $\sigma(p\overline{p} \to bbX)$ larger than expected from NLO QCD
    - Run II measurement with tight cuts agrees with prediction
  - Time-integrated mixing ($\overline{\chi}$) measured at Tevatron larger than LEP average.
    - Ghost contribution definitely affecting SS/OS ratio.

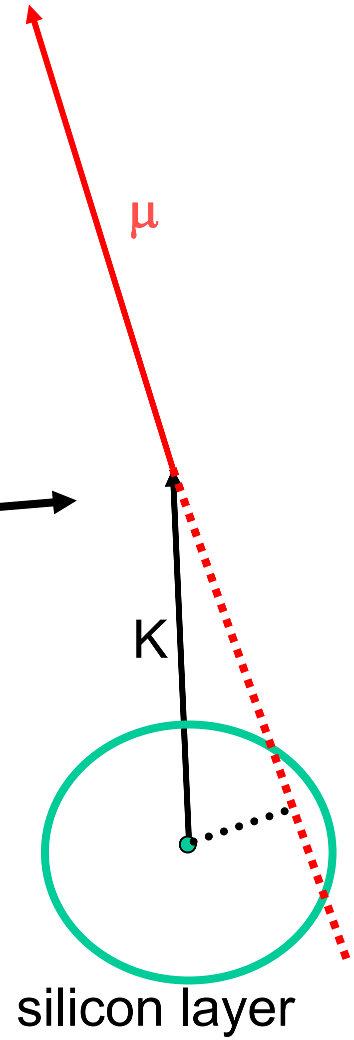
- This does not (yet) explain
  - low mass dilepton spectrum inconsistent with expectations from heavy flavor.

- And we have not yet explained the source of this background.

Sources of Ghost Events

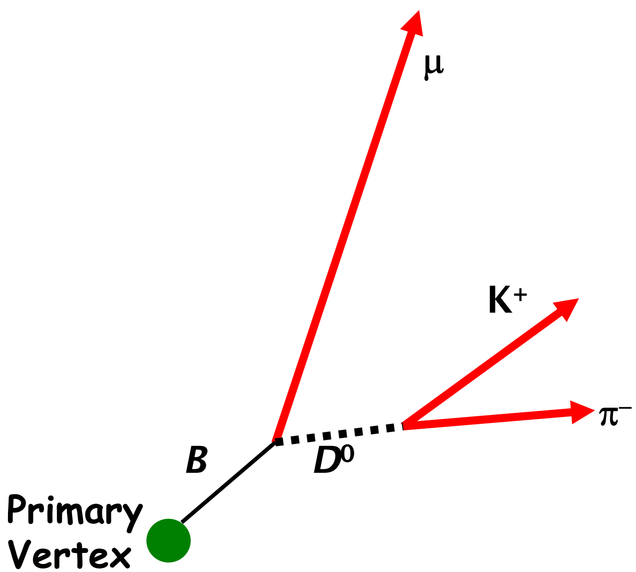
What could give rise to real or fake muons at large d_0 which preferentially miss inner silicon layers?

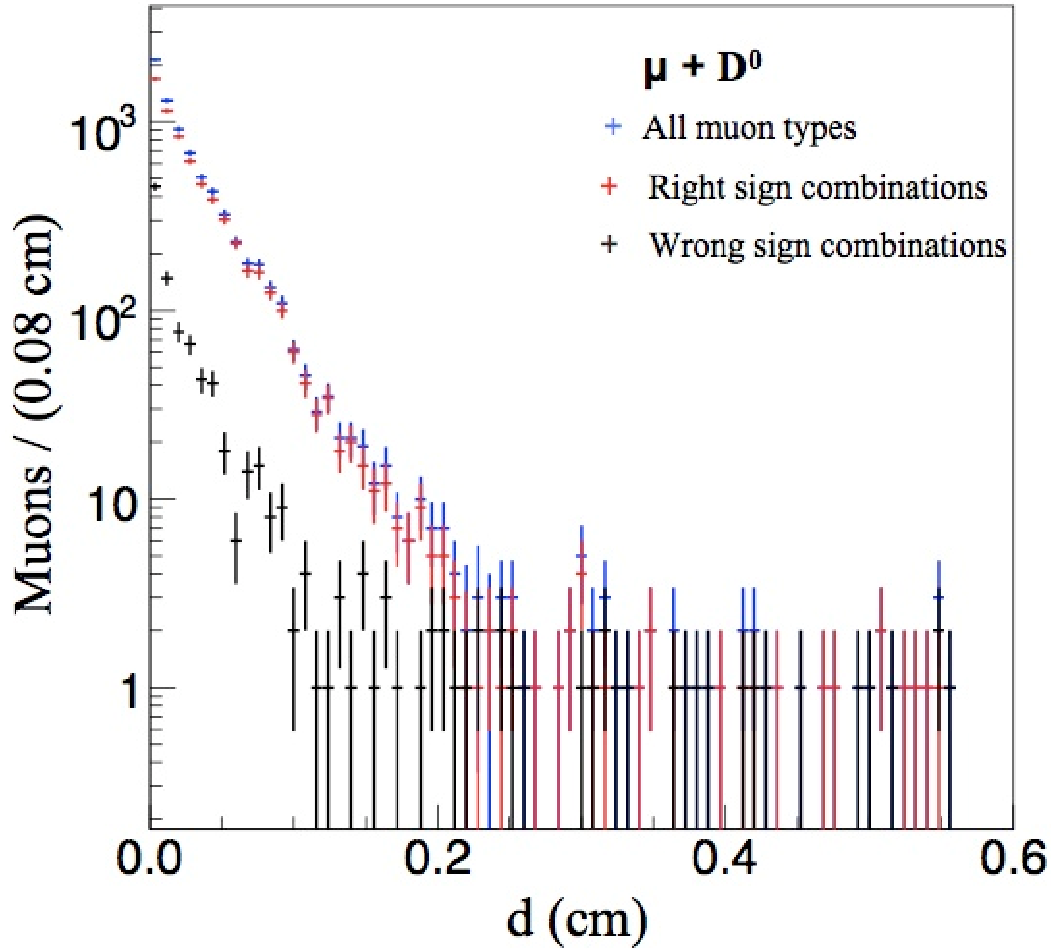
- **Mismeasured tracks**
- **In-flight decays of kaons and pions**
  - $K^{\pm} \rightarrow \mu\nu_{\mu}$ **and** $\pi^{\pm} \rightarrow \mu\nu_{\mu}$
- **Long lived particles (K_S, hyperons)**
- **Secondary interactions in detector material**
  - **e.g. hadron interacts in silicon produces secondaries with large d_0**



Mismeasurement?

- Look at μ+D^0 events
  - dominantly come from $b\bar{b}$ (and a bit of $c\bar{c}$)



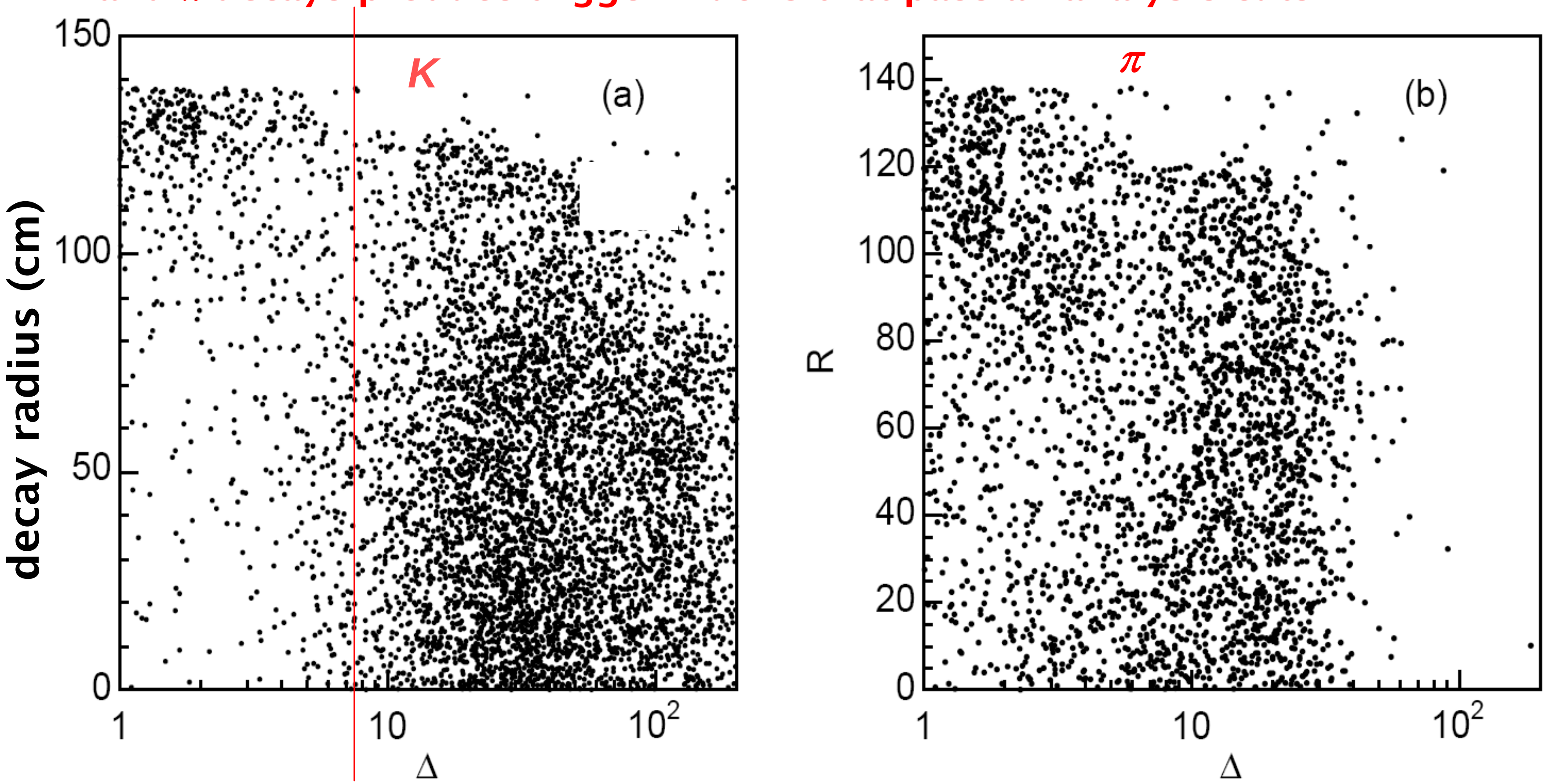


- Additional studies of track quality and other control modes indicate tracking is ok.

- $d_0(\mu)$ consistent with coming from *B* decays
- no evidence of long tail

In-flight decays

- **Use a heavy flavor simulation (HERWIG) to measure the probabilty that *K* and π decays produce trigger muons that pass all analysis cuts**



Δ is a χ^2/NDOF based on the difference between the hadron at generator level and the reconstructed track in the η, ϕ, p_T space

In-flight decays

- Probability per track that a hadron yields a trigger muon:

  0.07% pion   and 0.34% kaon

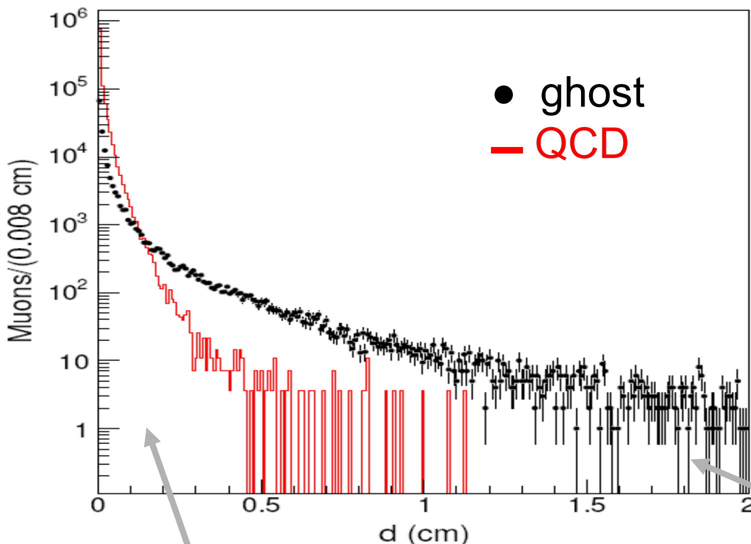
- Normalize this rate from Herwig MC to measured $b\bar{b}$ cross section

- prediction: 57000 ghost events from DIF
  - Recall: total ghost sample is: 154000 ±4800

- Large uncertainty on the prediction coming from
  - total cross section, $b\bar{b}$ cross section, particle fractions (π/K ratio), momentum spectra, acceptance…

- In terms of total yield, in-flight decays could easily account for entire ghost sample.

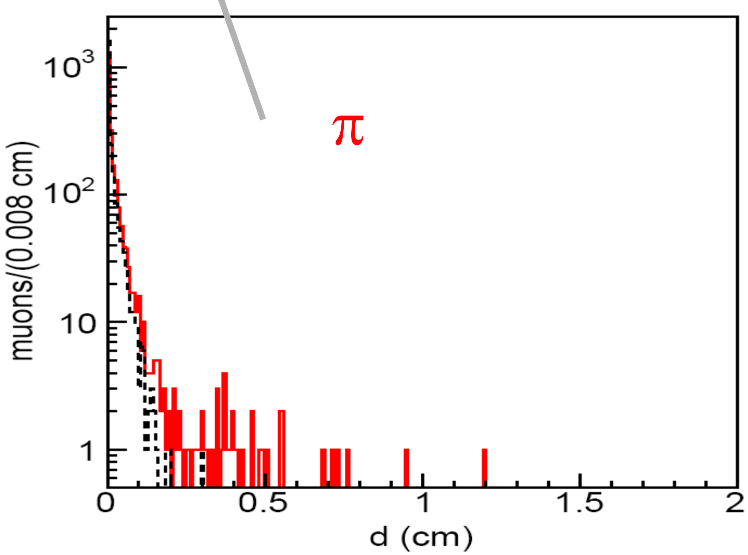
In-flight decays

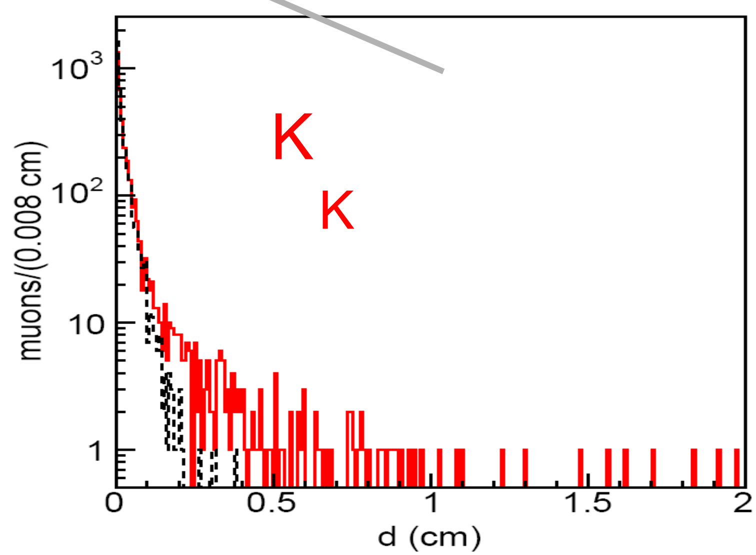


IFD prediction explains 35% of the ghost events, but only 10% of the events with d>0.5 cm

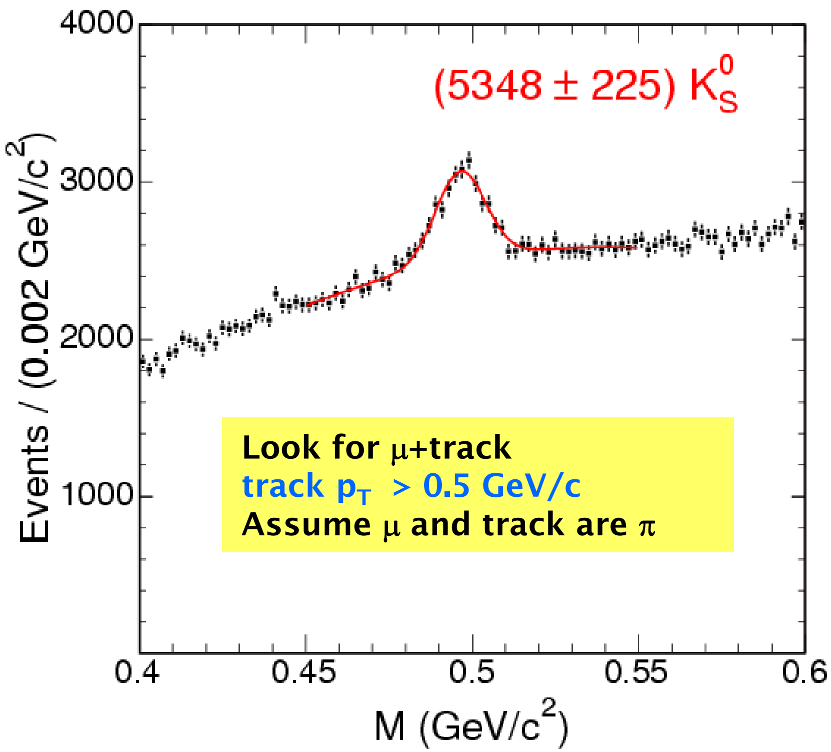
X 5

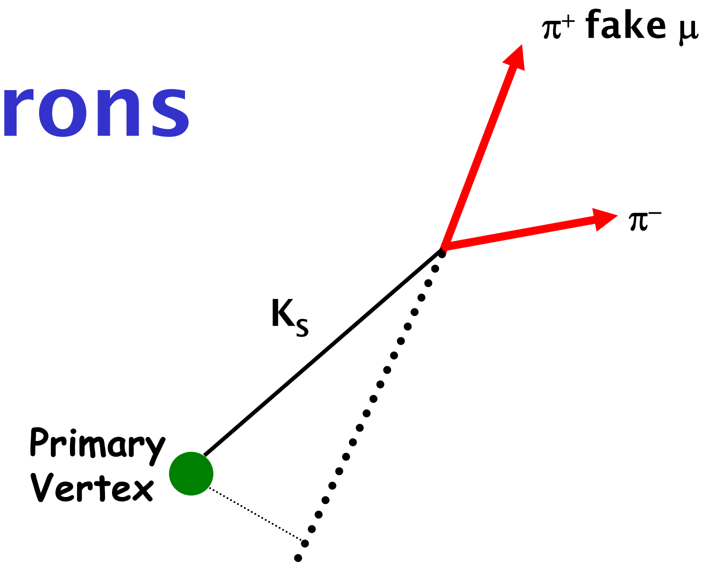
X 5

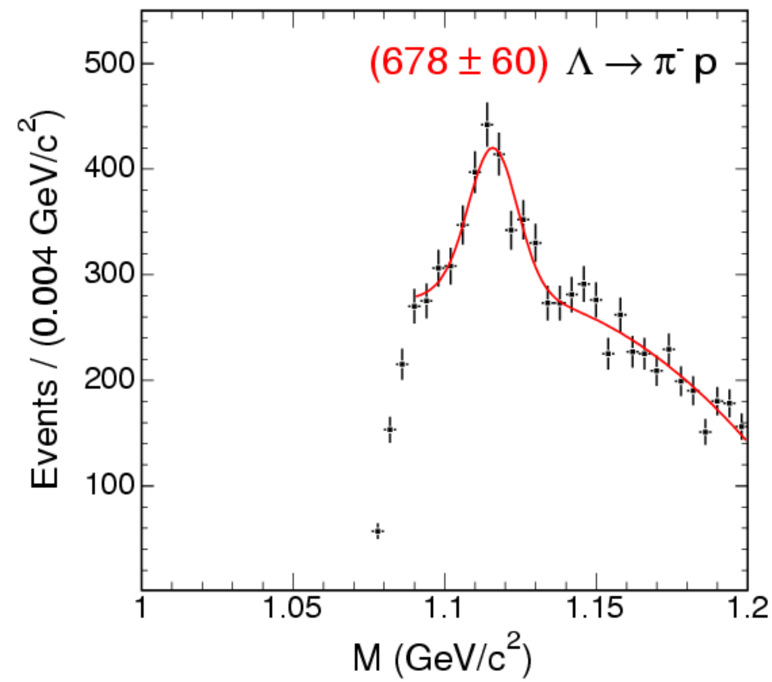




K_S and hyperons



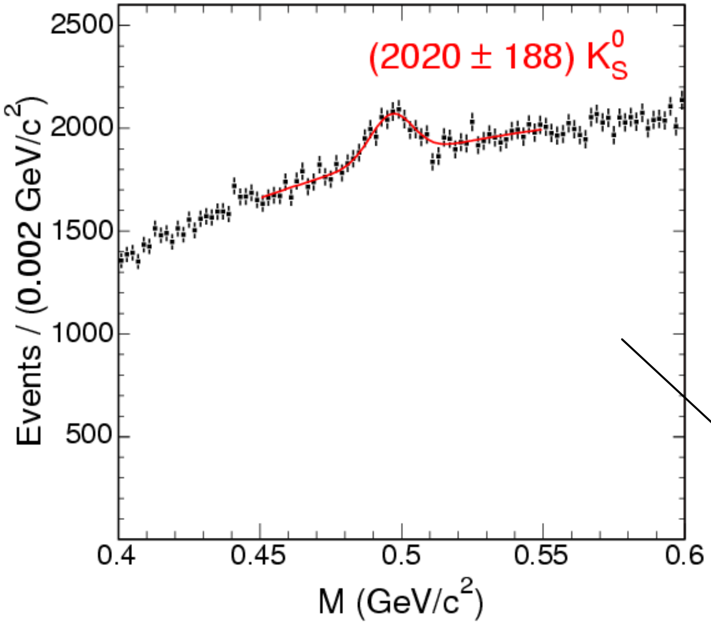




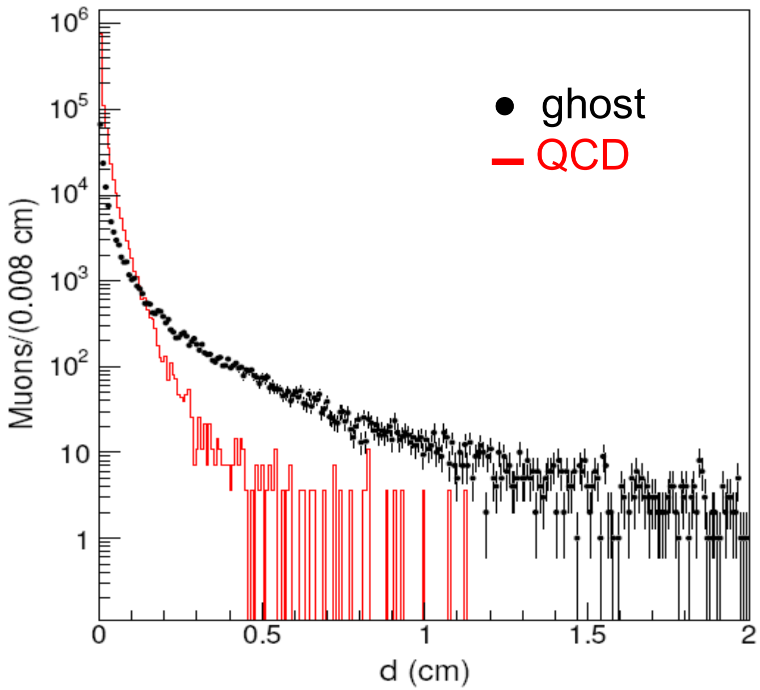
Kinematic acceptance times reconstruction efficiency ~ 50%

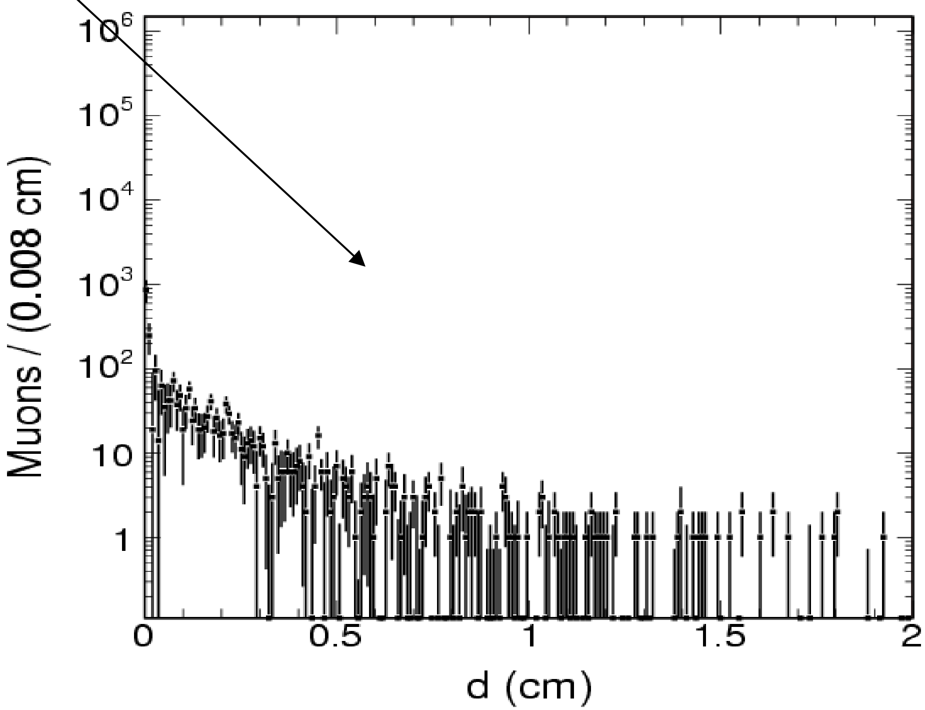
These decays account for about 12000 ghost events

K_S

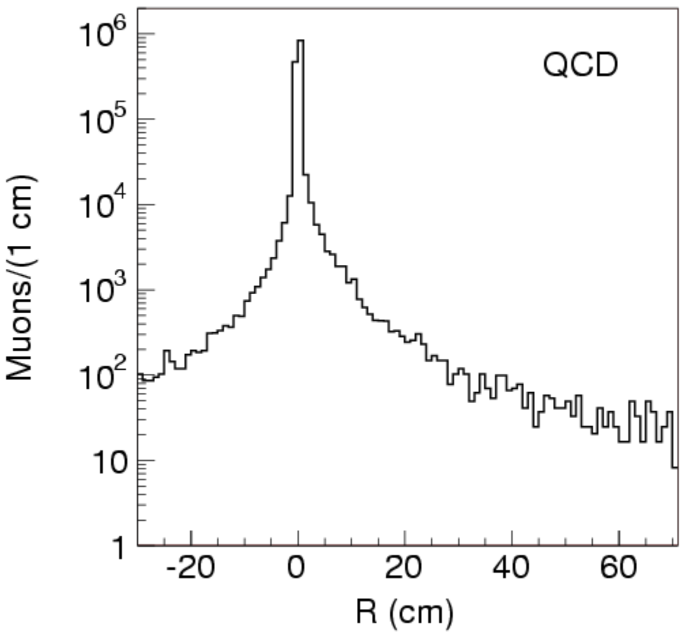


- **Loose SVX selection**
- **K_S populate higher d_0**

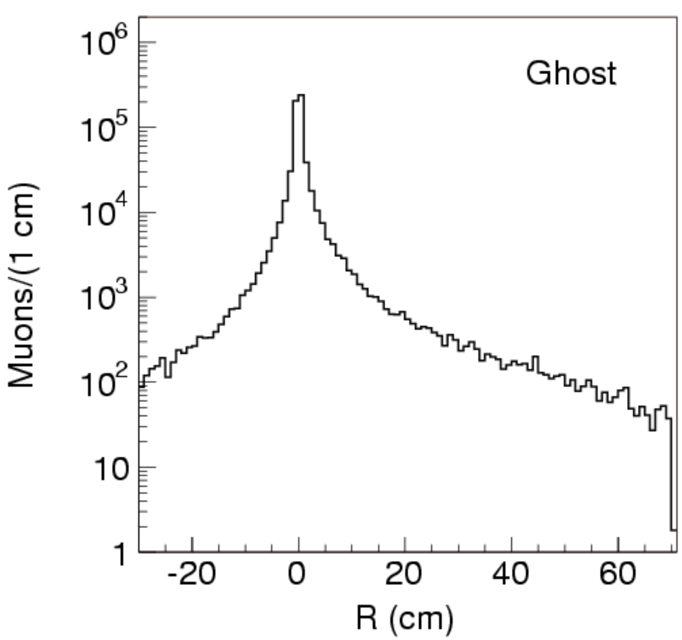


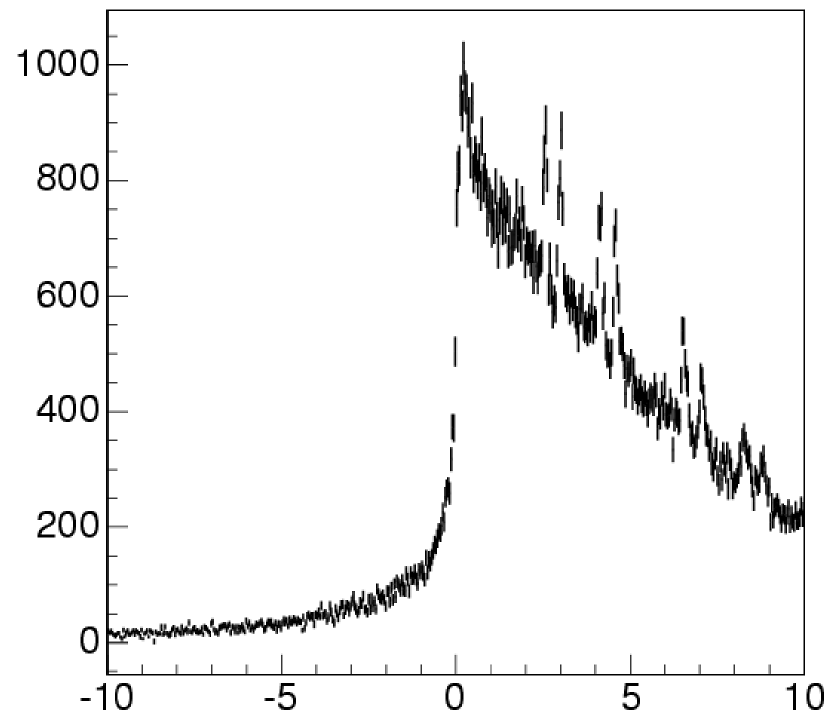


Secondary interactions



- Combine initial muons with tracks with p_T > 1 GeV/c in a 40° cone





Simulation – tracks, not muons

Sources of ghost events

- **Our prediction accounts for approximately 50% of observed number of ghost events (70000 out 150000 events)**
  - **uncertainty on the in-flight decay rate is large**
  - **cannot rule out a contribution from quasi-elastic secondary nuclear interactions**

- **At this point it appears that ghost events can be fully accounted for by a combination of in-flight and long-lived decays.**

Search for Additional Muons

- **Interesting for several reasons:**
  - Ghost events may be related to the excess of low mass dileptons
  - Events due to secondary interactions or fake muons are not expected to contain many additional muons
  - If ghosts events were normal QCD events with mismeasured initial muons, the rate of additional muons should be similar to that of QCD

- **Search for additional muons with p_T > 2 GeV/c and $|\eta| < 1.1$ around each initial muon – require invariant mass smaller than 5 GeV/c^2**

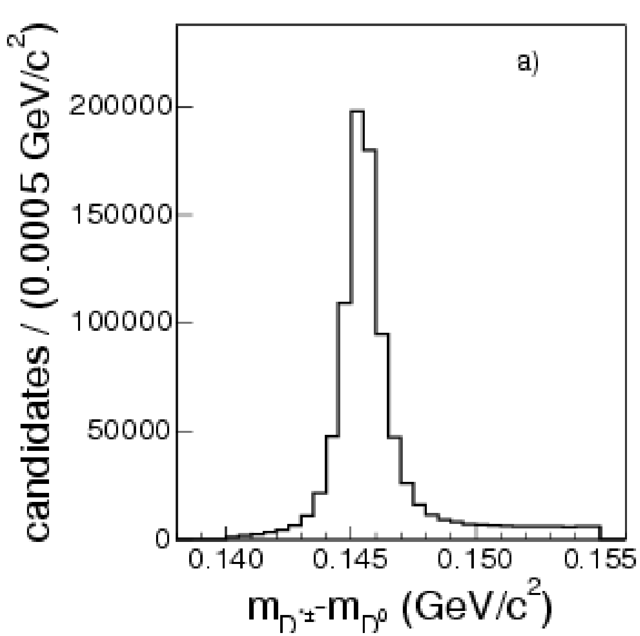
- **Expectation:**
  - the main source of real additional muons are sequential decays of *b* quarks
  - a sizable contribution of muons mimicked by hadrons.

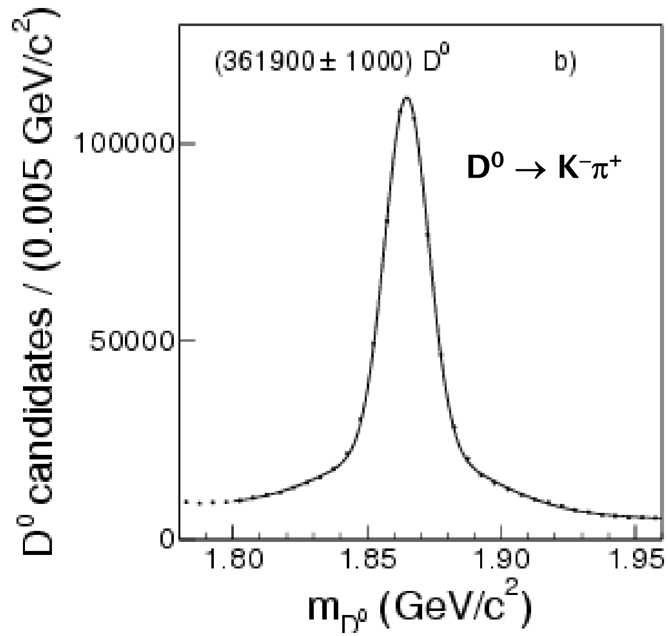
- **Analysis strategy:**
  - perform loose muon selection to get maximal acceptance
  - take higher fake muon rate, correct for it by precisely assessing fakes.

Muon Fake Rate

- **Measure the probability per track that a pion or kaon will "punch through" the calorimeter and fake a muon.**

- **Technique:**
  - **Reconstruct $D^{*+} \to D^0\pi^+$ decays with a $D^0 \to K^-\pi^+$**
  - **D^* tag uniquely identifies π and K**
  - **Reconstruction by tracking only, then ask at what rate were the hadrons found as muons?**

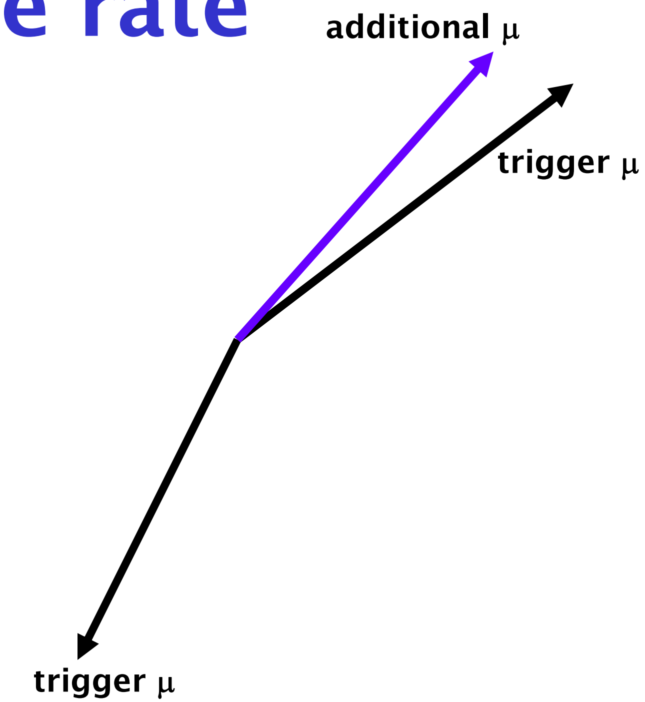


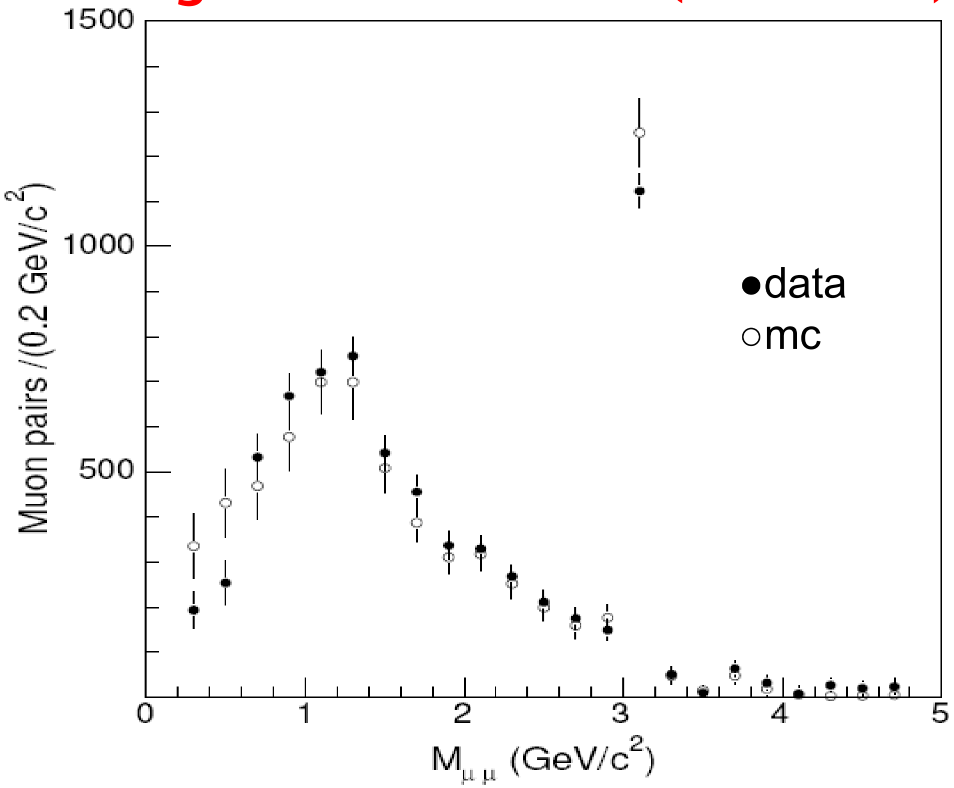


Verifying the fake rate

- Compare data to heavy flavor simulation which includes fake prediction.

- Tight SVX selection (no Ghost)



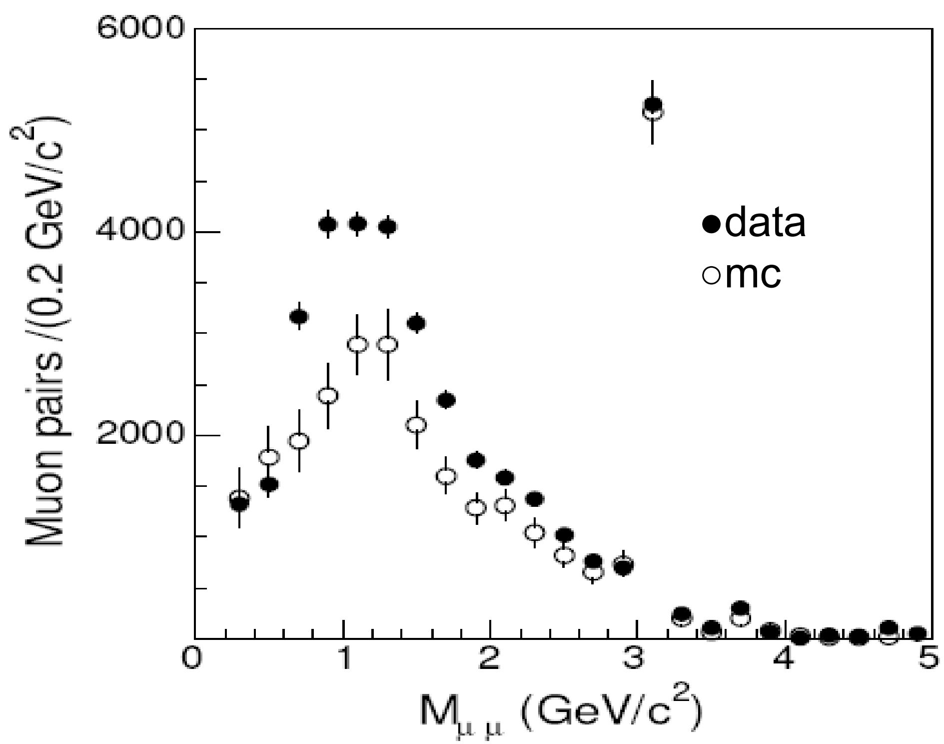


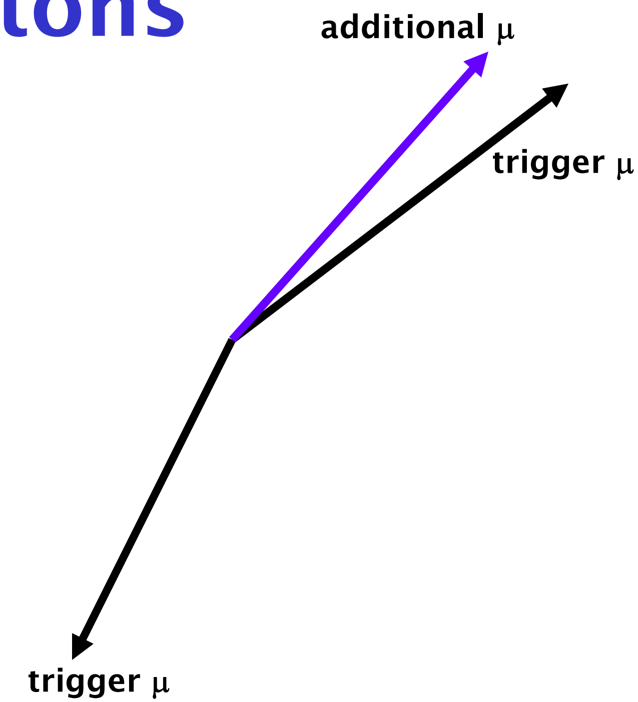
- 6935±154 in the data and 6998±293 predicted
- We understand the heavy flavor simulation and the fake muon background

Low mass dileptons

- **Compare data to heavy flavor simulation which includes fake prediction.**

- **Total sample:**





- ***J/ψ* yield correctly modeled**
- **See a clear excess at low mass.**
  - Tight SVX sample didn't show this
  - Excess coming from ghost sample
- **Same as the low mass dilepton puzzle from Run I.**

Multiplicities

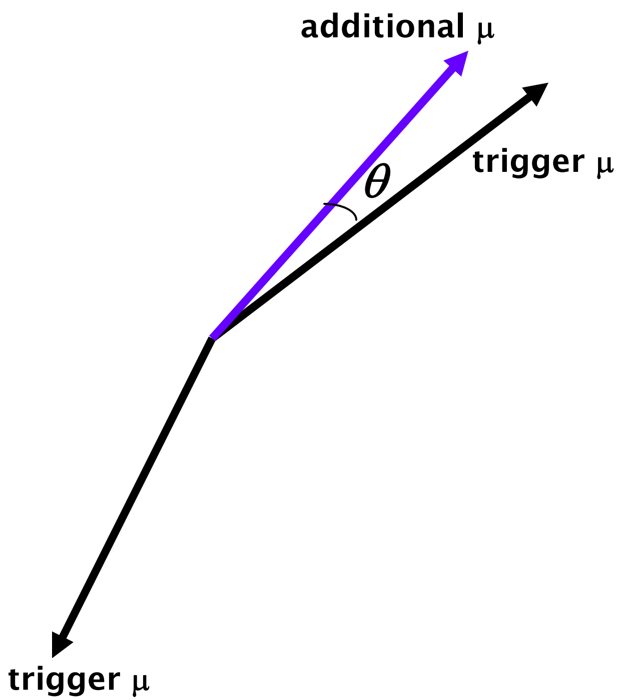
- QCD sample well understood
- Ghost sample less well understood, but appears to be mostly QCD-like, with muons from in-flight and long-lived decays .

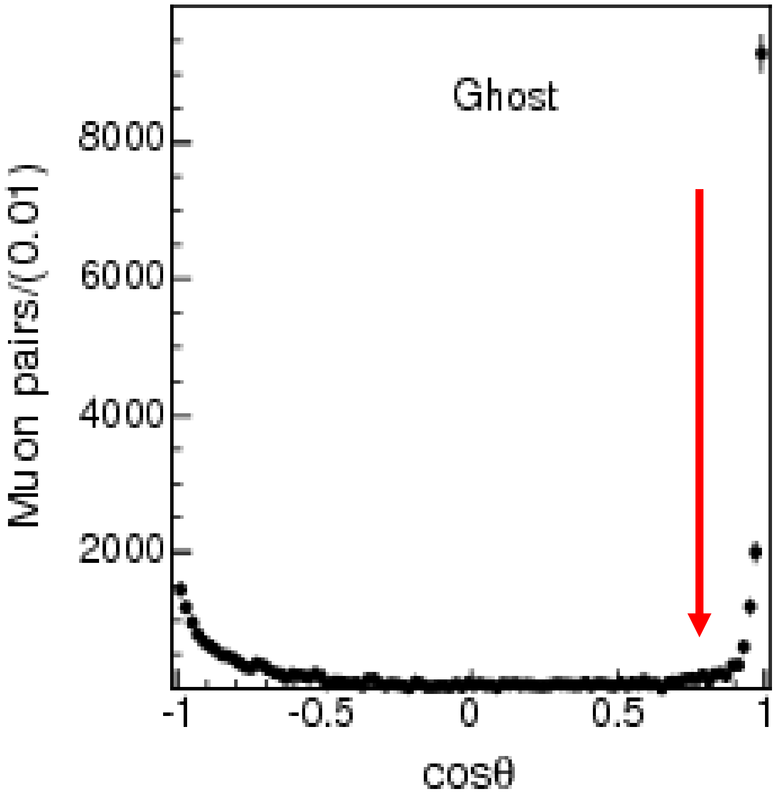
Compare ghost to QCD:

1. After correcting for fakes, the rate of additional muons in Ghost sample 4x larger than QCD
   - If mostly DIF, expect additional muon contribution to be suppressed, not enhanced.
2. Number of charged tracks (p_T>2GeV) in Ghost sample 2x larger than QCD

Additional muons

- **Additional muons very close to trigger muon**
- **Virtually all μ have cosθ>0.8 with respect to nearest trigger μ**
- **Evaluate additional muons within a cone of cosθ>0.8 around initial muon**



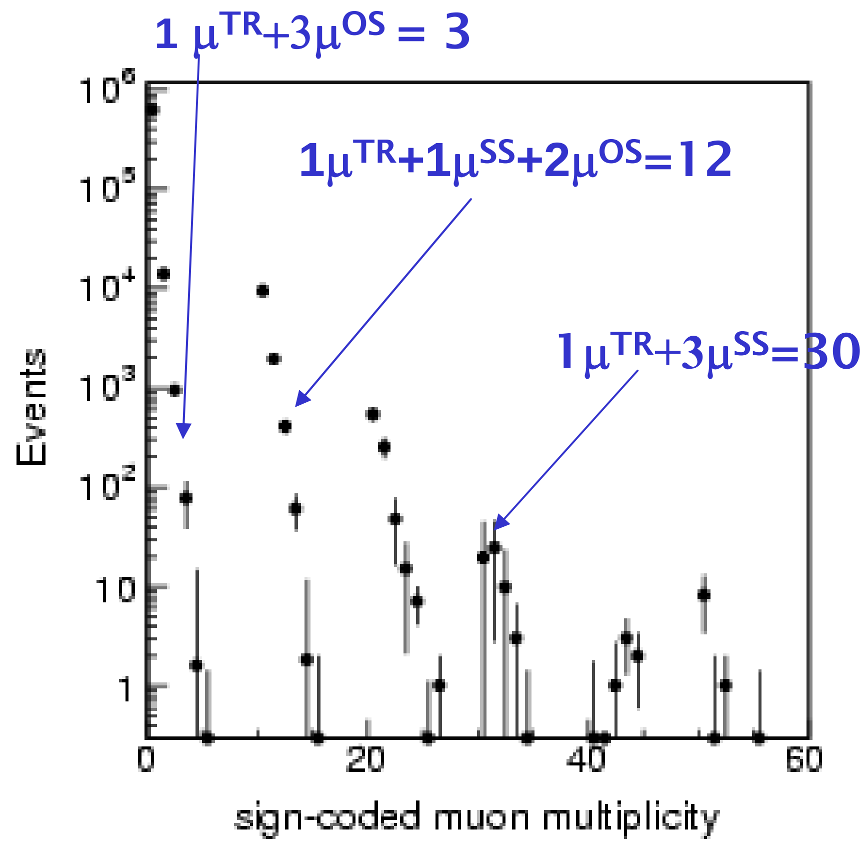


additional muon multiplicity

- **Plot is muons in a single cone in Ghost sample.**
  - **after fake correction**

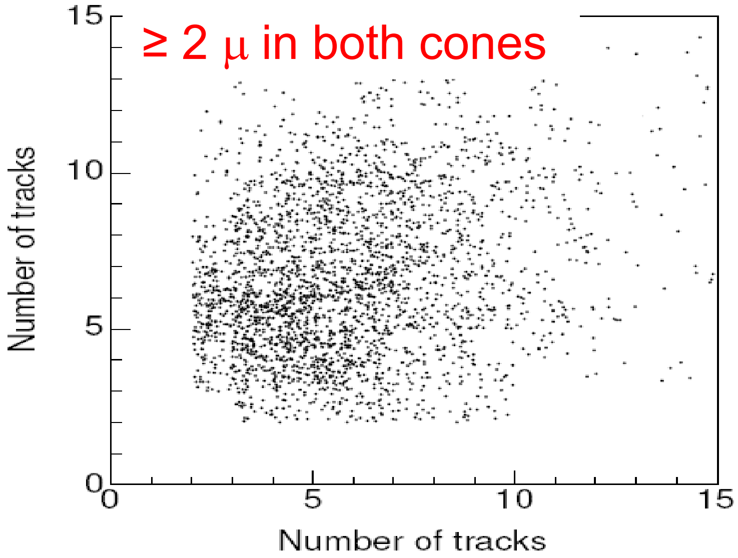
  counting additional muons (not trigger muon) in a single cone.

- **Relative to trigger μ**
  - **OS μ: +1**
  - **SS μ: +10**
- **Example:**
  - **Trigger μ^+, find 2 μ^+ and $1\mu^-$ in cone: plot in bin 21**



On average, a multiplicity increase of one unit corresponds to a population decrease of 7

Cone correlations



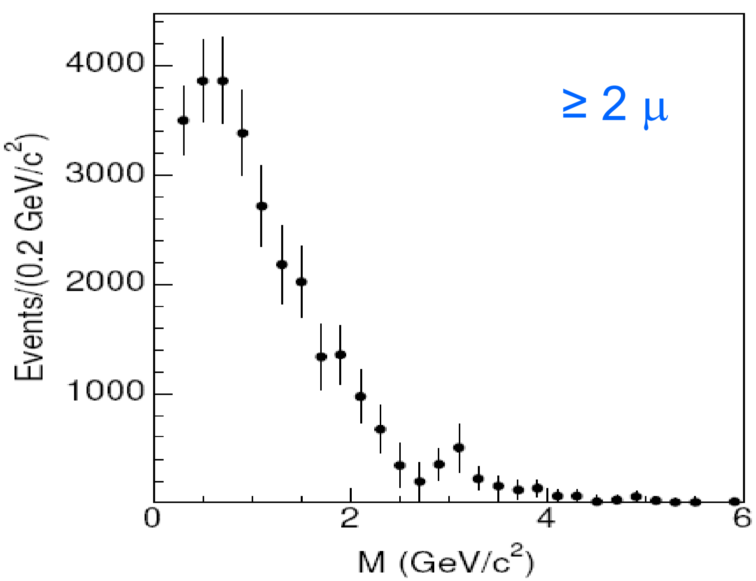
Ghost events

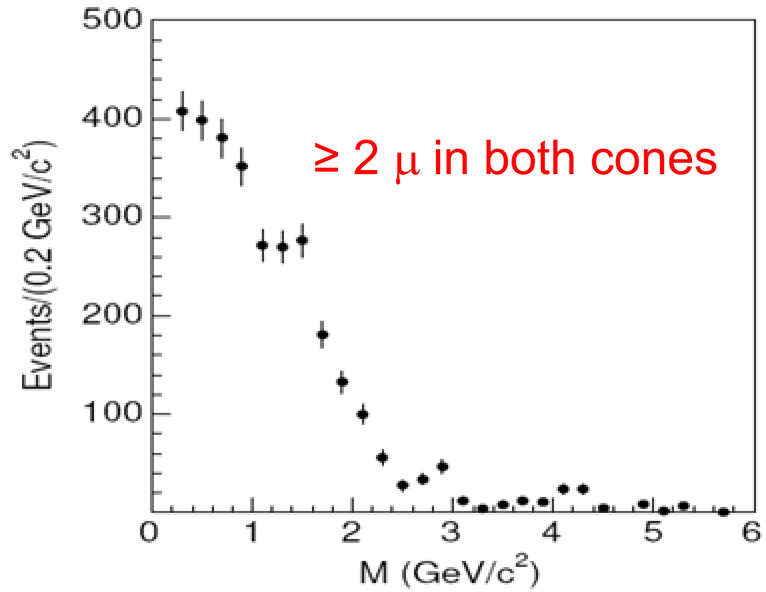
27790±761 cones with ≥ 2 μ (a)

4133±263 cones with ≥ 3 μ

3016 with ≥ 2 μ in both cones (b)

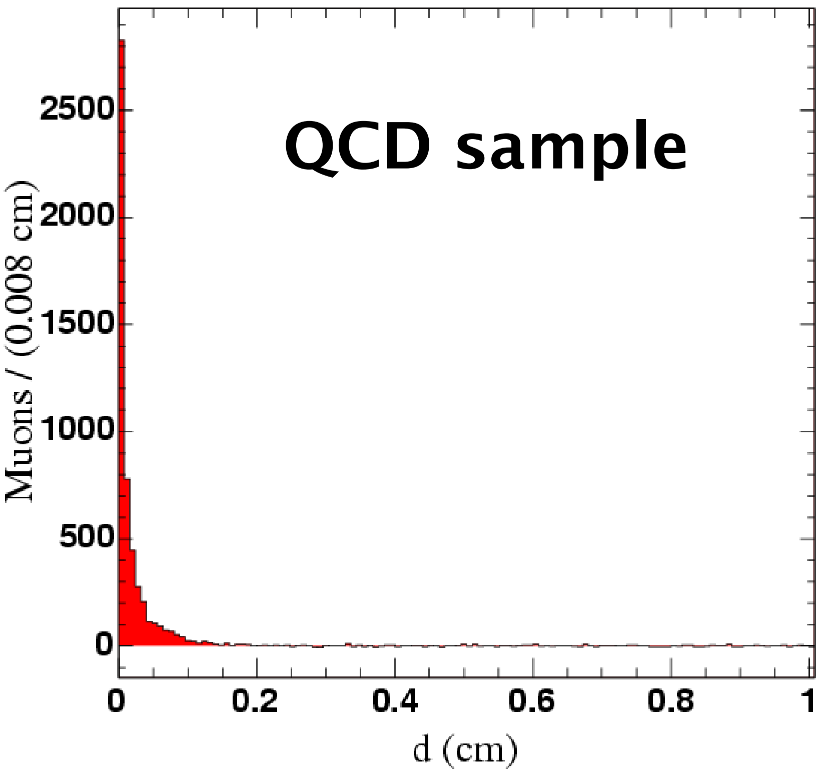
Ratio (b)/(a) = 0.11 is quite large. Events triggered by a central jet, the fraction of events containing another central jet is 10-15%

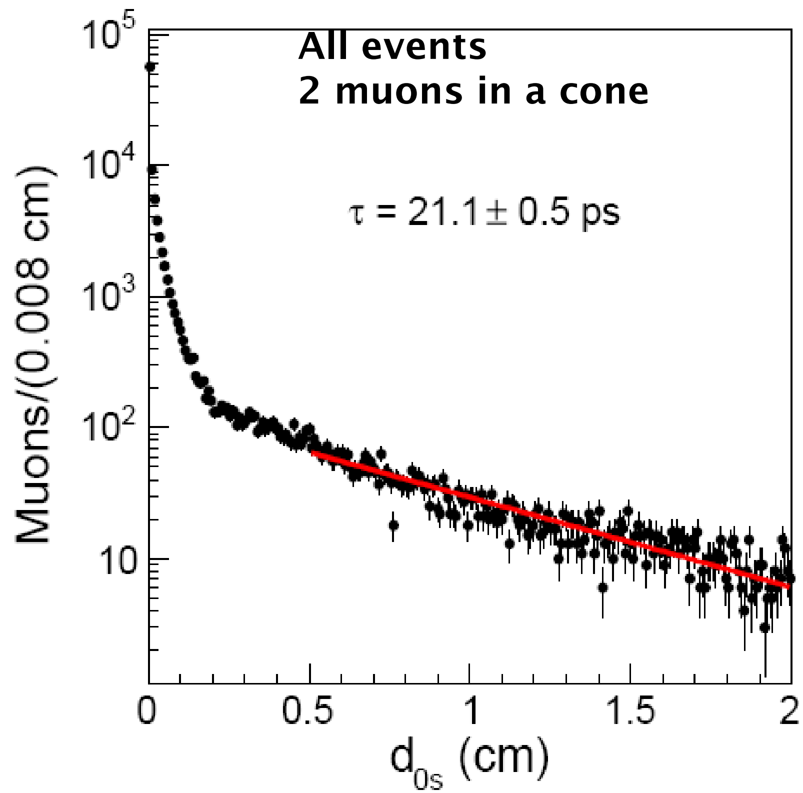




Impact parameter

- **Look at impact parameter of additional muons**
  - **Additional muons not biased by trigger**





Where are we now?

1. After correcting for fakes, the rate of additional muons in Ghost sample 4x larger than QCD sample
   - If mostly DIF, expect additional muon contribution to be suppressed, not enhanced.

2. Some events have very large muon multiplicities (3 or 4 muons in a cone)

3. Number of charged tracks (p_T>2GeV) in Ghost sample 2x larger than QCD sample

4. Impact parameter of additional muons extends well beyond that of QCD sample

Back to the Puzzles

Three results related to *b* production and decay from Tevatron run I (1992-1996).

1. $\sigma(pp \rightarrow bb\bar{X})$ larger than expected from NLO QCD
2. **Time-integrated mixing measured at Tevatron larger than LEP average**

$$\bar{\chi} = \frac{\Gamma\left(B^0 \rightarrow \bar{B}^0 \rightarrow l^+ X\right)}{\Gamma\left(B \rightarrow l^\pm X\right)} = \frac{\text{"same sign"}}{\text{"total"}}, \quad B^0 = B_d^0 \text{ or } B_s^0$$

3. **low mass dilepton spectrum inconsistent with expectations from heavy flavor.**

These puzzles all appear to be plausibly explained by the new background we have identified…but what is the background?

On the Ghost Sample

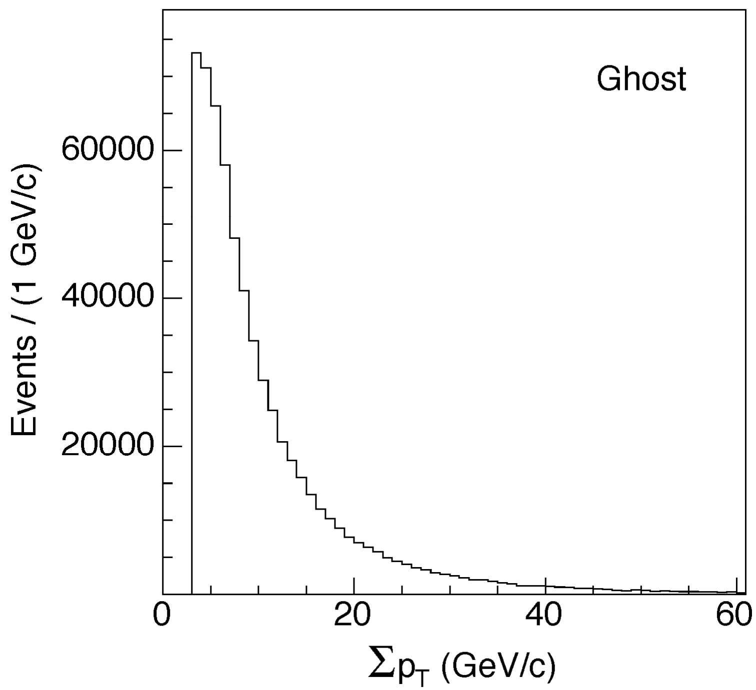
- The QCD sample is well explained by our understanding of the detector, reconstruction and the physics.
- We have identified a large background sample that was unexpected.
  - Its size is comparable to $b\bar{b}$ production.
- Much of the background can be explained by in-flight decays along with K_S and hyperons
- Another piece of this background is puzzling, it seems inconsistent with any of our expectations.
  - This component of the background shows high muon and charged track multipliticy

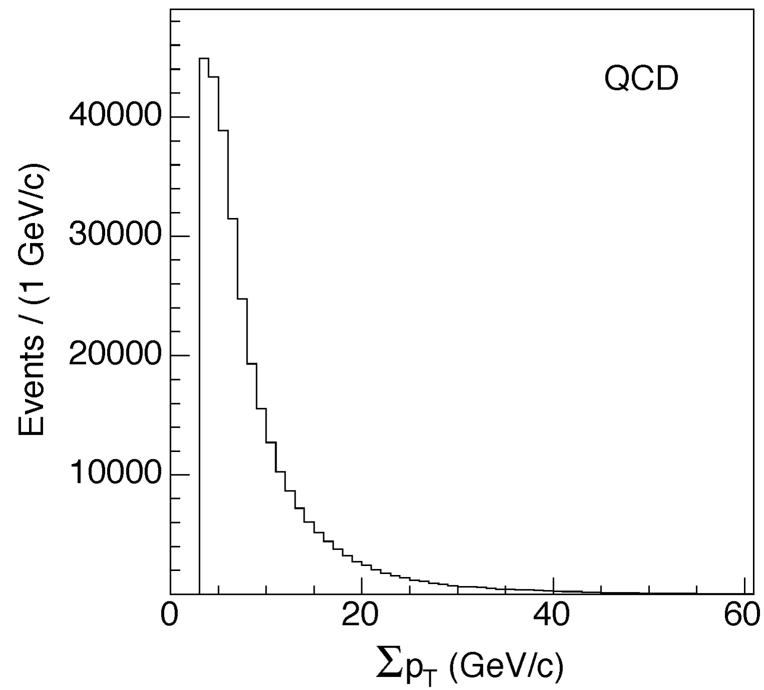
Comment on fake rates

- Our "per track" fake probability assumes that fake muons are uncorrelated.
- Probably not completely true
  - high energy jet $\Rightarrow$ large leakage $\Rightarrow$ lots of activity in muon chambers $\Rightarrow$ lots of fake muons
- We don't posses any calibration sample that allows us to directly probe this effect.
- Requiring tighter muon selection and higher purity muons do not affect the salient features of the ghost sample.
- If the high multiplicity events are caused by correlated fakes, why don't we see it in the QCD sample?
- Calling all high multiplicity events as "fake" only removes 1/3 of the excess over QCD.

QCD vs. Ghost

- **If the high multiplicity events are caused by correlated fakes, why don't we see it in the QCD sample?**
- **Correlated fake muons not seen to be a problem in other analyses, e.g. soft lepton tagging for top decays.**





- **Total charged momentum spectrum, Σp_T, is similar between Ghost and QCD samples.**
  - **Ghost sample slightly harder in Σp_T**

Summary

- Through the study of multimuon events, we believe we have found a plausible explanation for a number of puzzles which have been around for a decade.
- We have identified a sample of events which appear to have some very unique properties.
- We currently cannot explain these events, and we have not ruled out known processes.