Study of Multimuon Events at CDF

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Outline

- 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

Puzzles from the 1990's

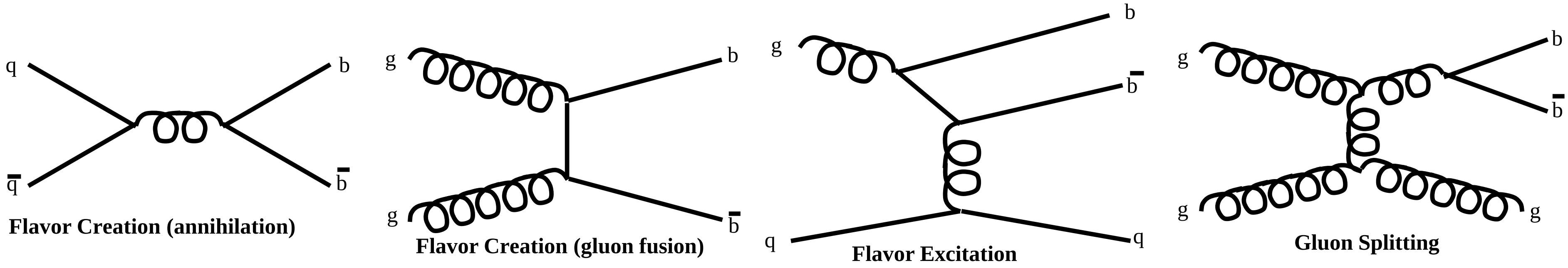
Three results related to *b* production and decay from Tevatron run I (1992-1996).

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

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

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

I. B Cross Sections

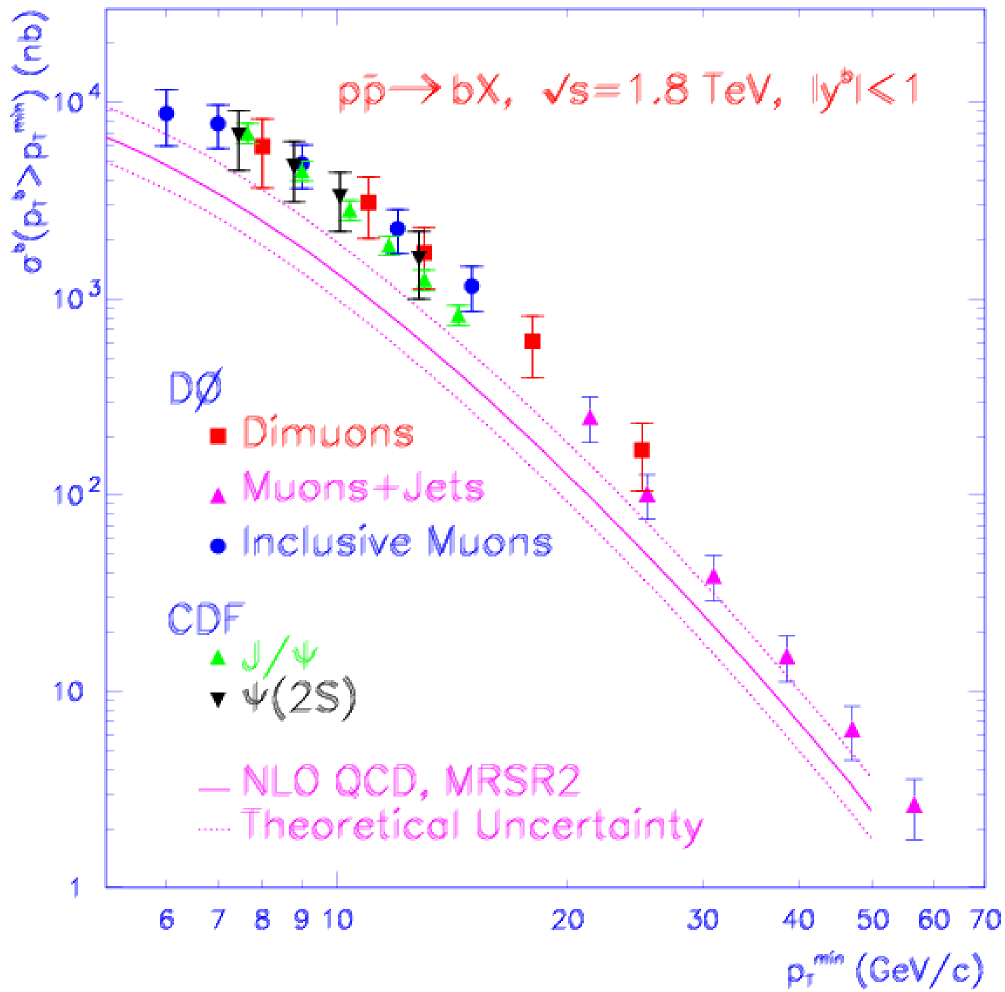


Flavor Creation (annihilation) — Flavor Creation (gluon fusion) — Flavor Excitation — Gluon Splitting

- **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

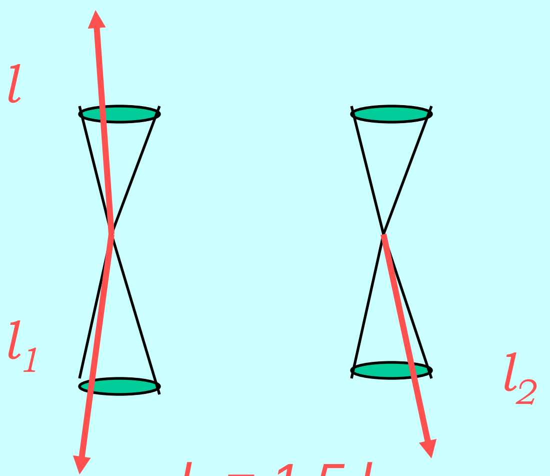
- **Tevatron Run I (1992-1996): Inclusive cross sections systematically higher than NLO theory**



Correlated σ_{bb}

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

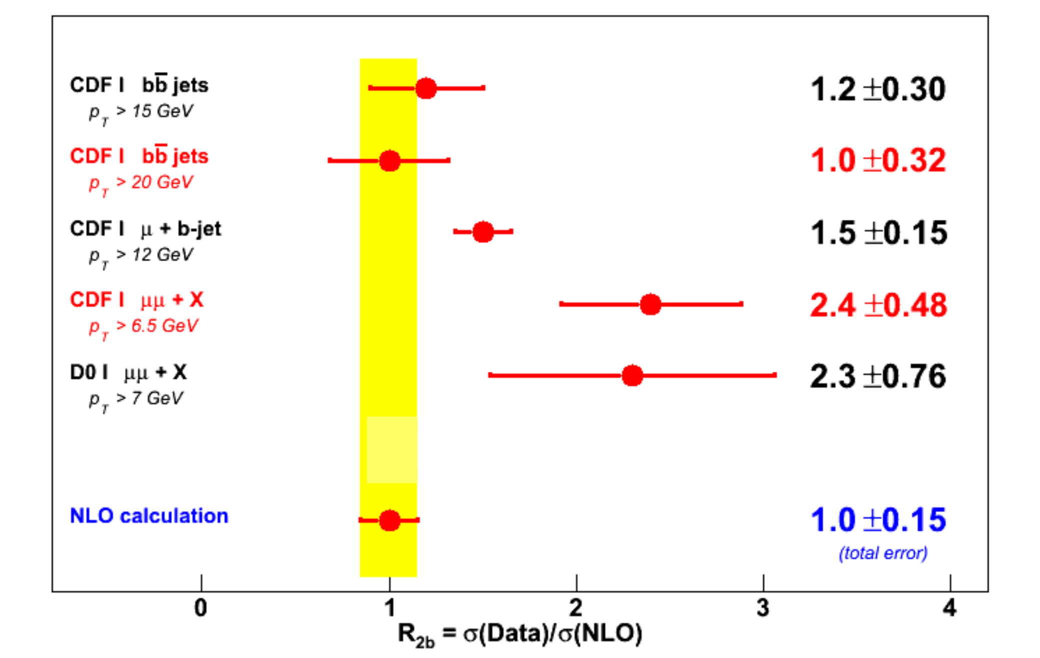
- **"per jet" lepton rate also showed high relative rate**



$l_1 = 1.5\, l_2$

PRD 69, 072004 (2004)

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



II. Time Integrated Mixing

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

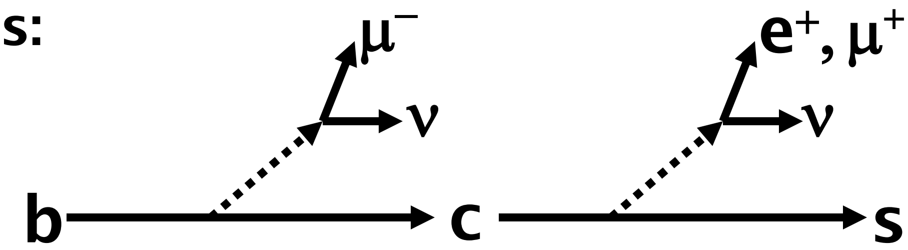
- **Since B_d and B_s both oscillate:** $\bar{\chi} = f_s \chi_s + f_d \chi_d$
  - **f_d and f_s are fraction of *b* quarks that fragment into B_d and B_s**
  - **χ_d and χ_s are time integrated mixing parameters.**

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

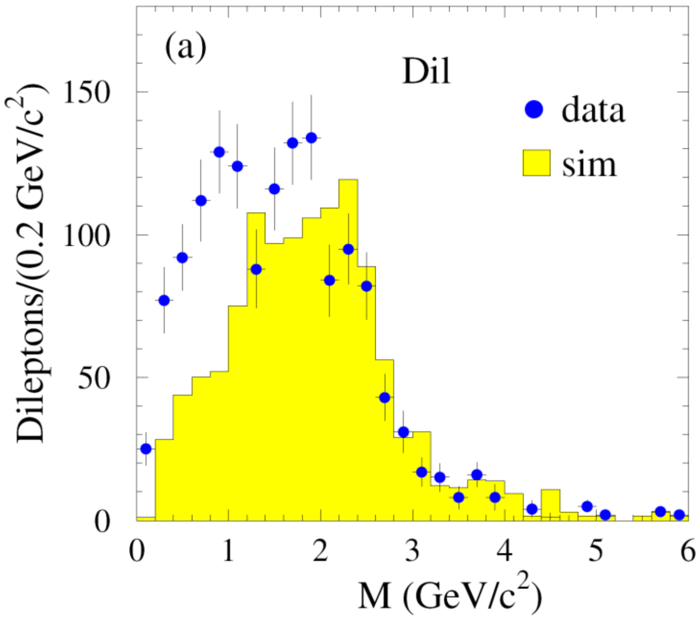
  - **Since x_d and x_s well measured, measure of χ constrains production fractions.**
  - **Expect same production fractions at Tevatron and LEP, since $q^2 >> m_{u,d,s}^2$**
  - **CDF Run I result (0.152±0.013)** [PRD 69, 012002 (2004)] **larger than LEP average (0.126 ±0.004)**
    - **Different production 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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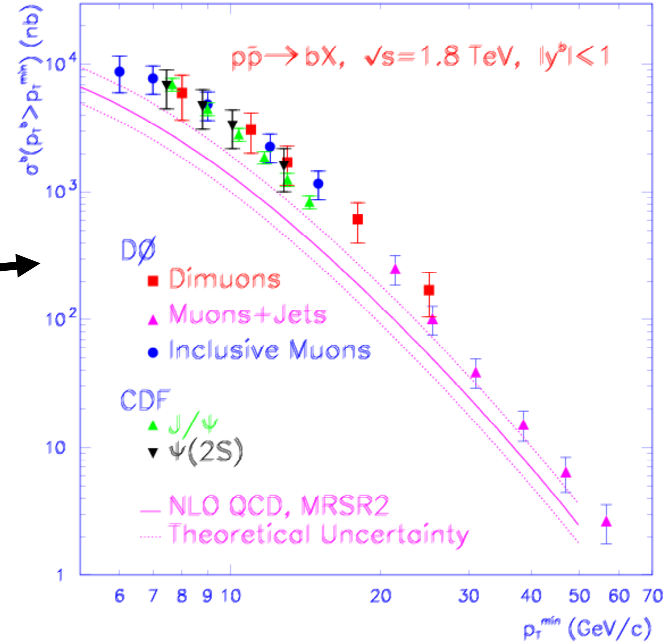
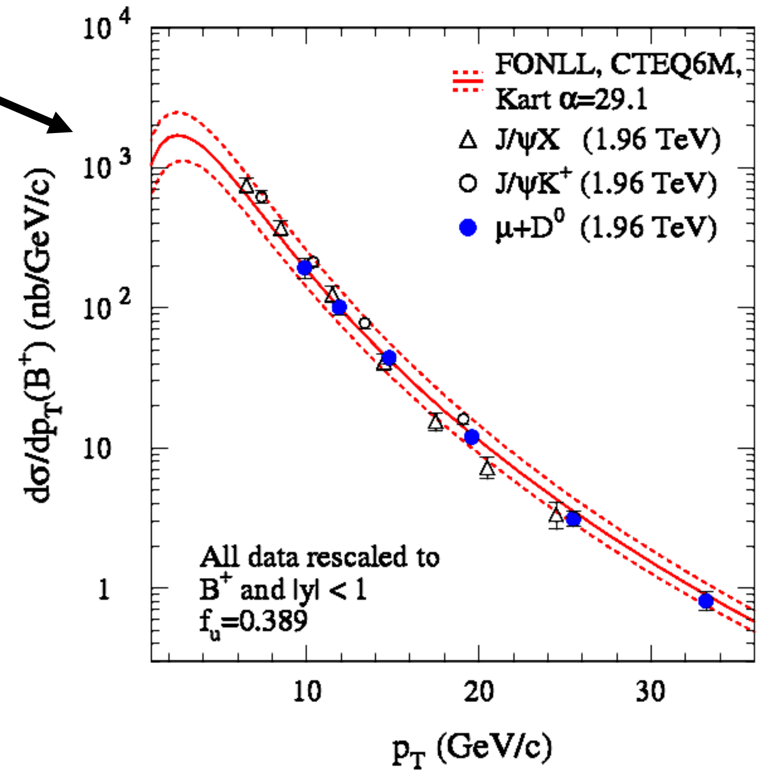
Step 0: Inclusive σ_b

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

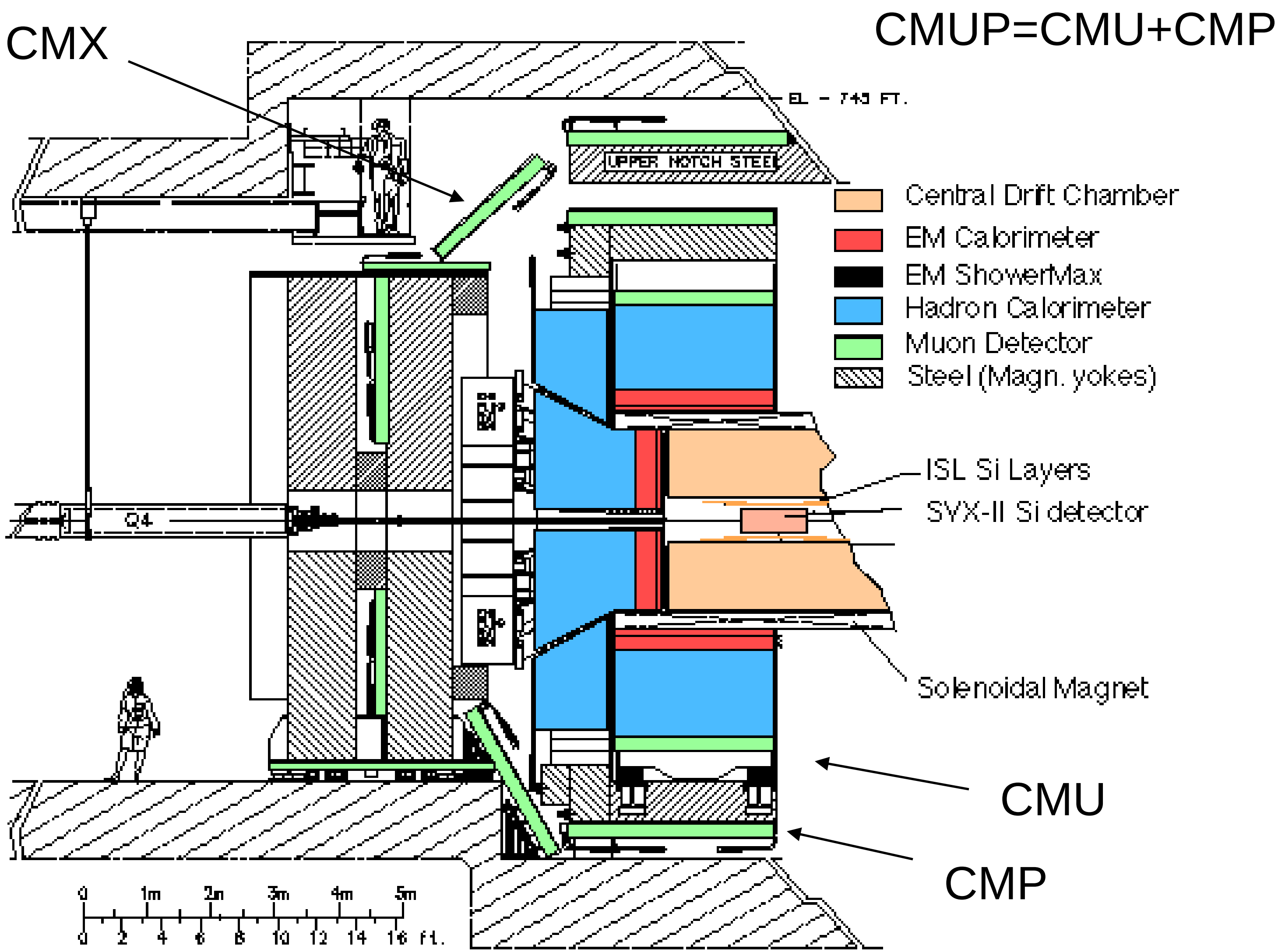


- **Tevatron Run II: Remeasure inclusive cross sections in Tevatron Run 2**
  - Better acceptance
  - Higher statistics
  - Smaller uncertainties

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

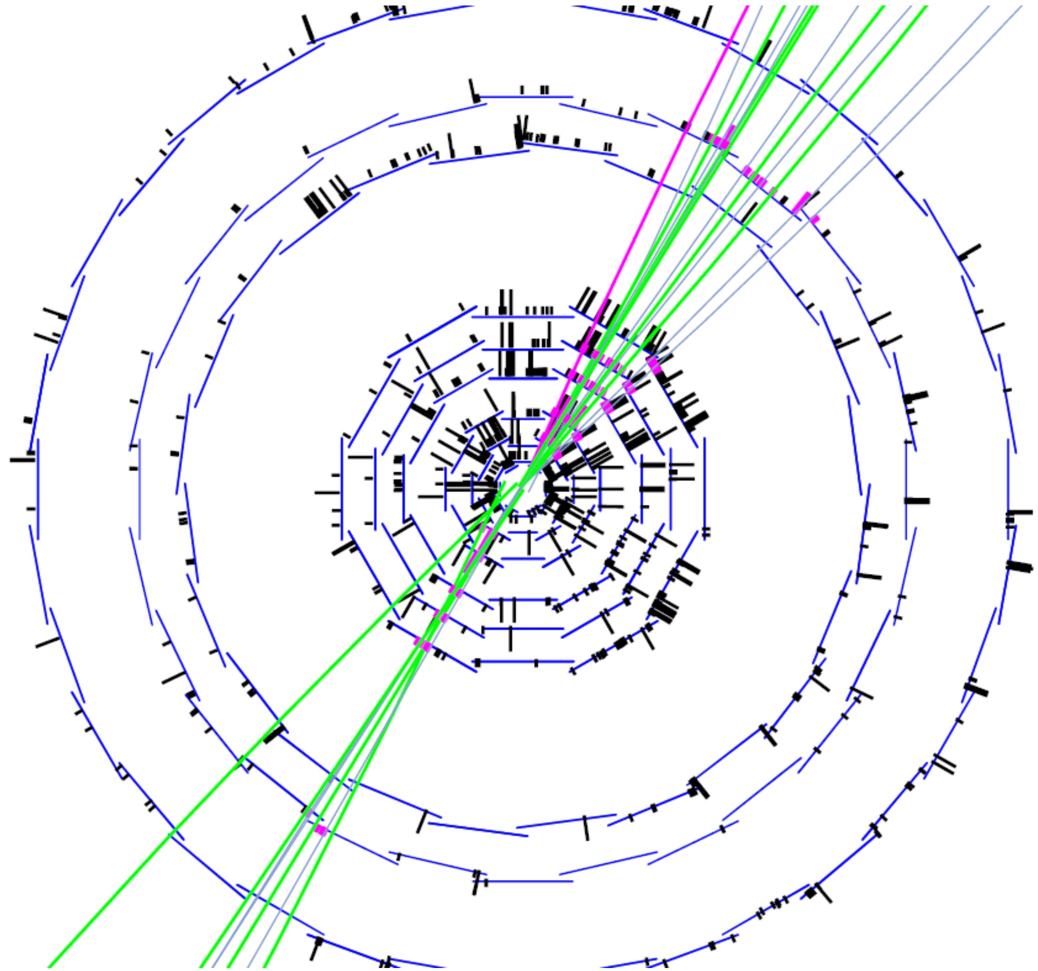


CDF detector

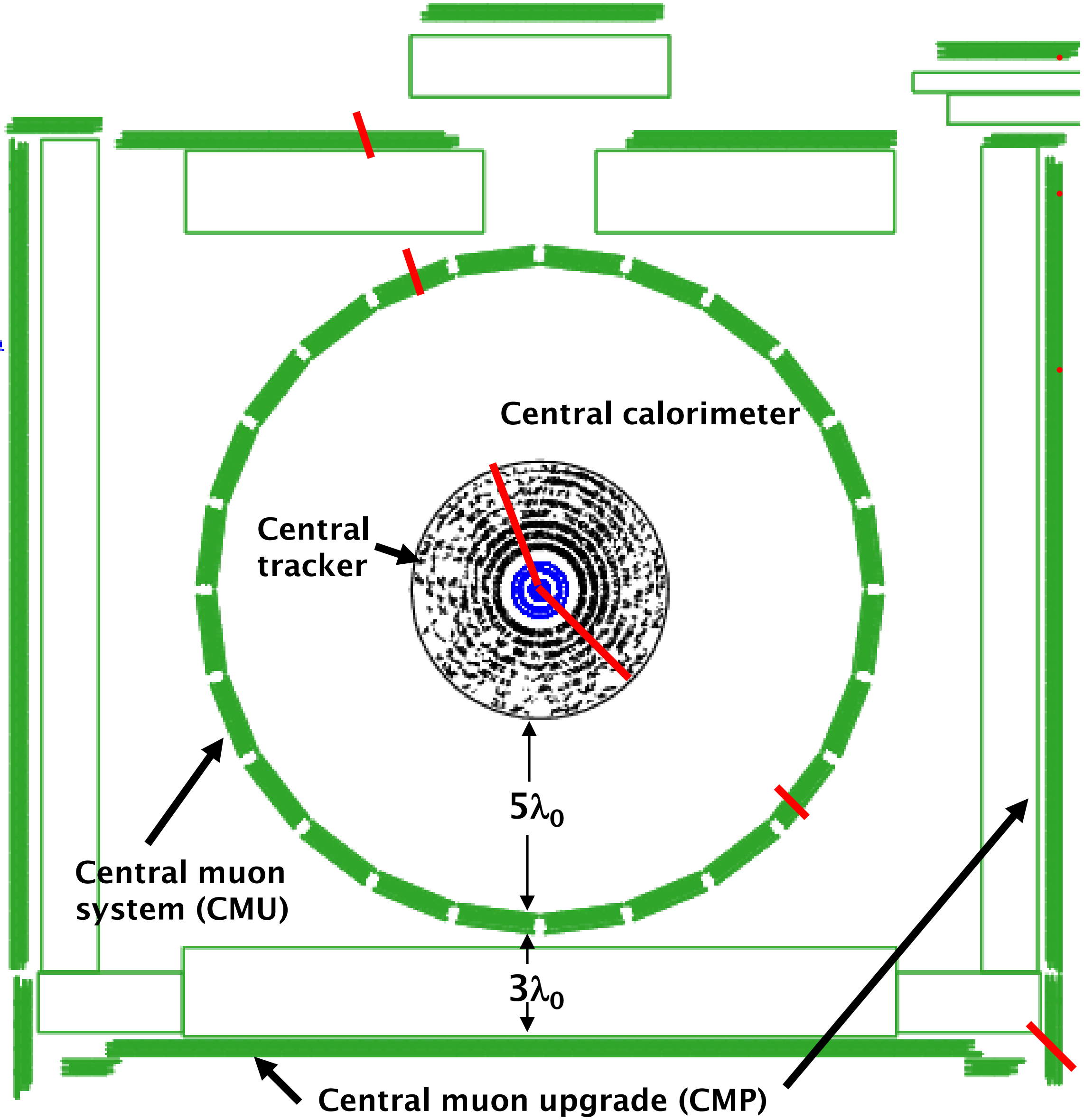


CDF microvertex detector

- **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

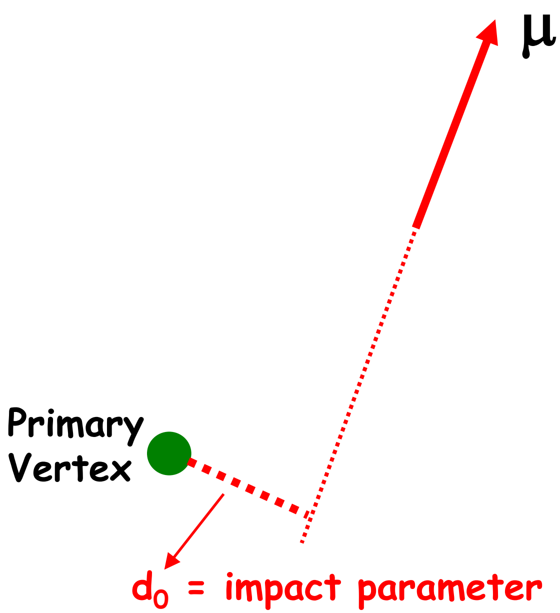


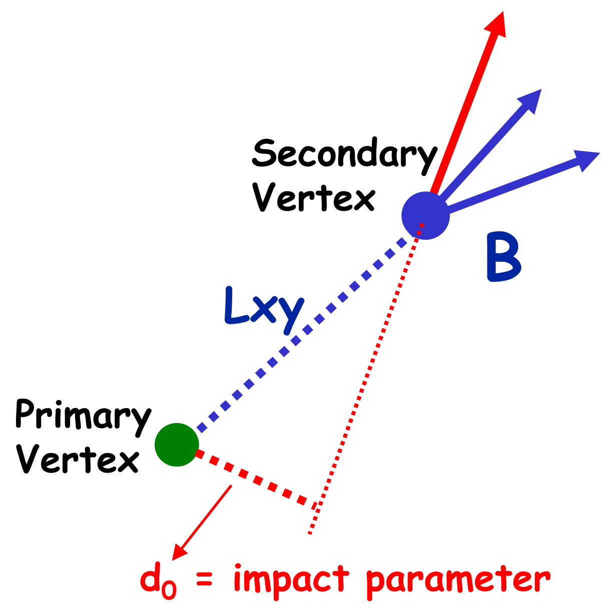
- **Data sample defined by a dimuon trigger.**
- **Each muon:**
  - Central track, p_T>3 GeV
  - Match to stub in CMU
  - Match to stub in CMP
- **Dimuon pair**
  - $m_{\mu\mu}$> 5 GeV to get rid of sequential ($b \rightarrow c\mu \rightarrow \mu$) decays

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.

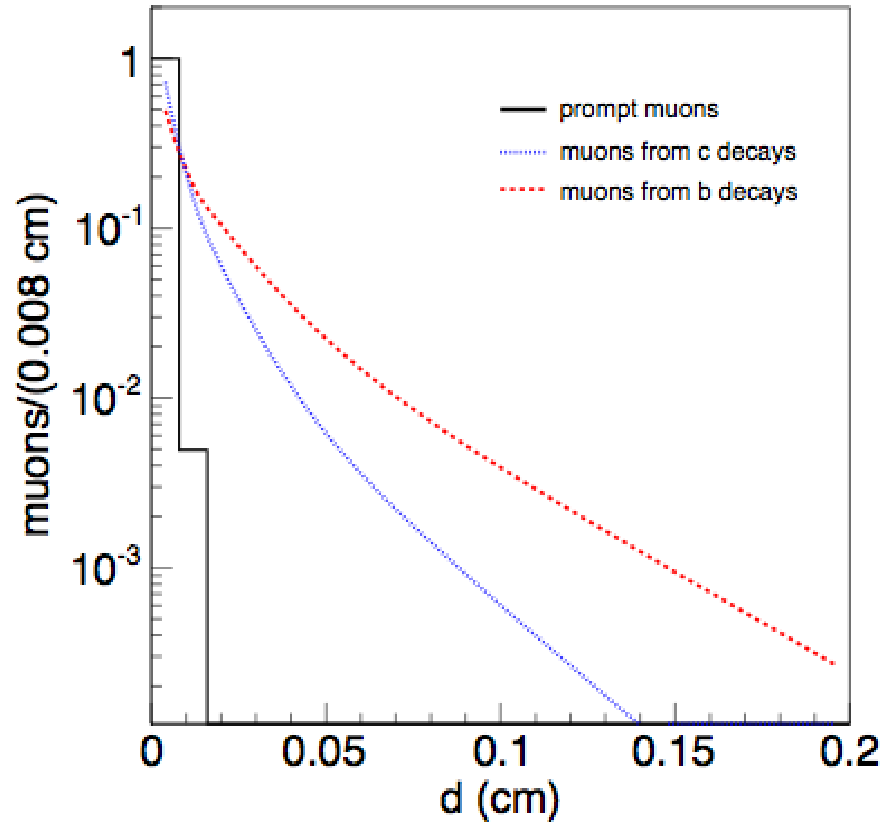
- **Decay length (L or L_{xy}) is the flight distance between primay $p\bar{p}$ collision vertex and secondary vertex.**





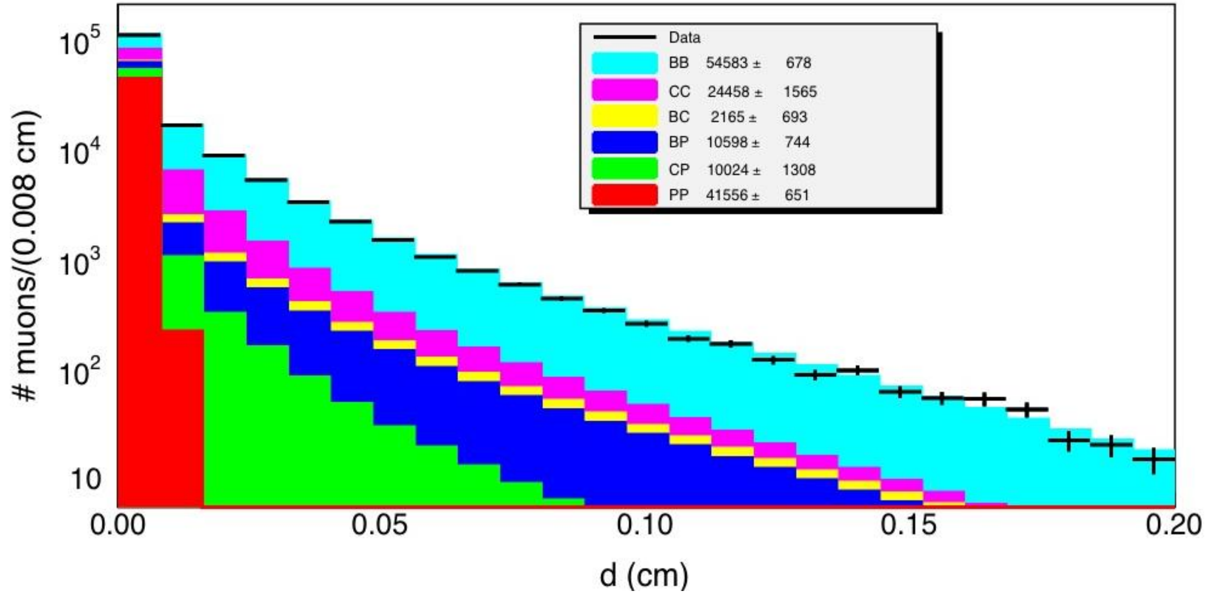
Step 1, re-measure $\sigma(pp \to bbX)$

- **Known sources of real dimuons**
  - $b \to \mu$ ($c\tau$ = 470 μm)
  - $c \to \mu$ ($c\tau$ = 210 μm)
  - Prompt (Υ, Drell-Yan).
- **Known sources of fake muons**
  - Hadrons punching through calorimeter
  - Hadrons that decay-in-flight
    - $K \to \mu$, $\pi \to \mu$
  - 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 $\sigma(pp \to bbX)$

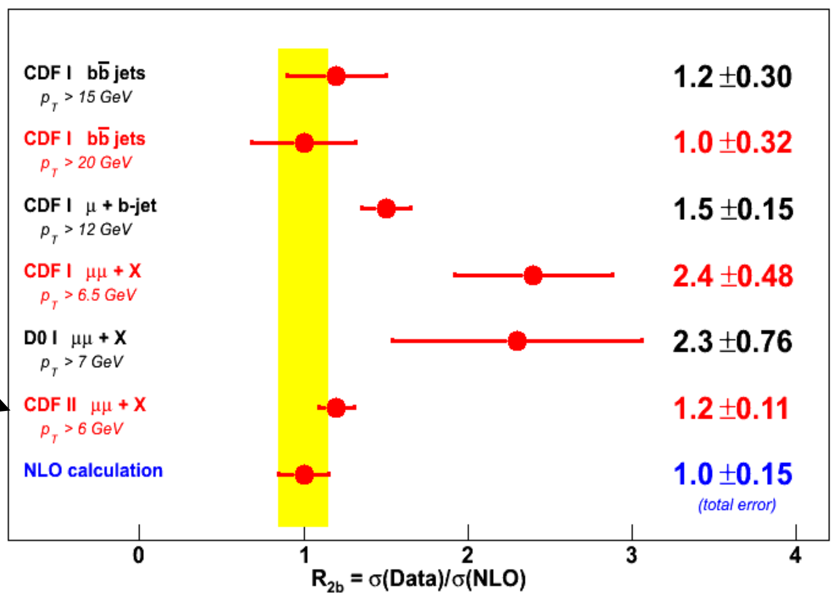


- 1d projection of 2d templates
- Full fit includes all dimuon combinations
  - bb, bc, cc, b+prompt, c+prompt, prompt+prompt

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



- 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



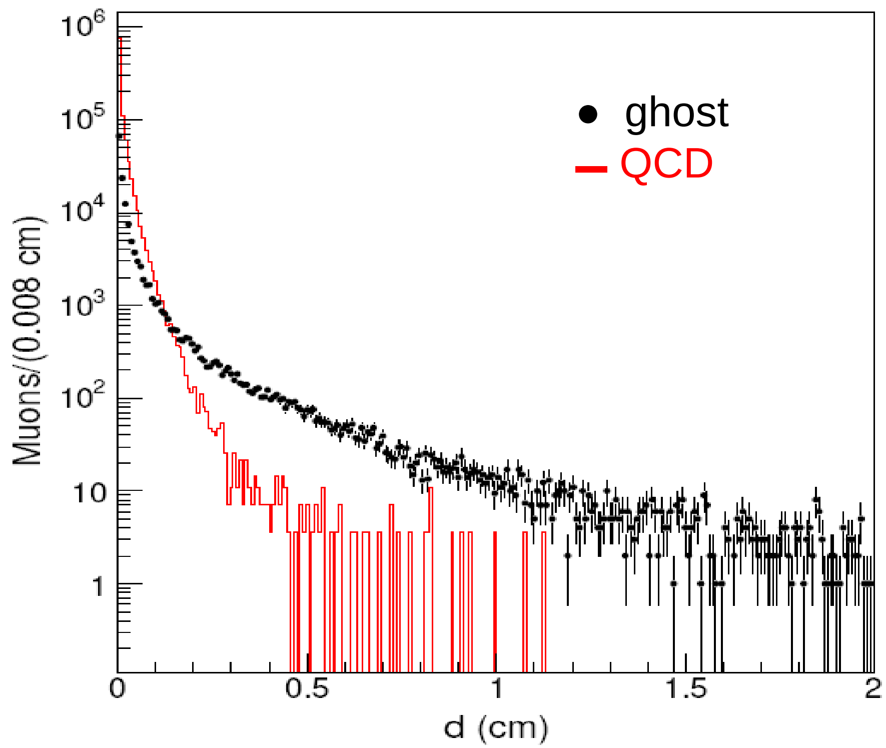
PRD 77, 072004 (2008)

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

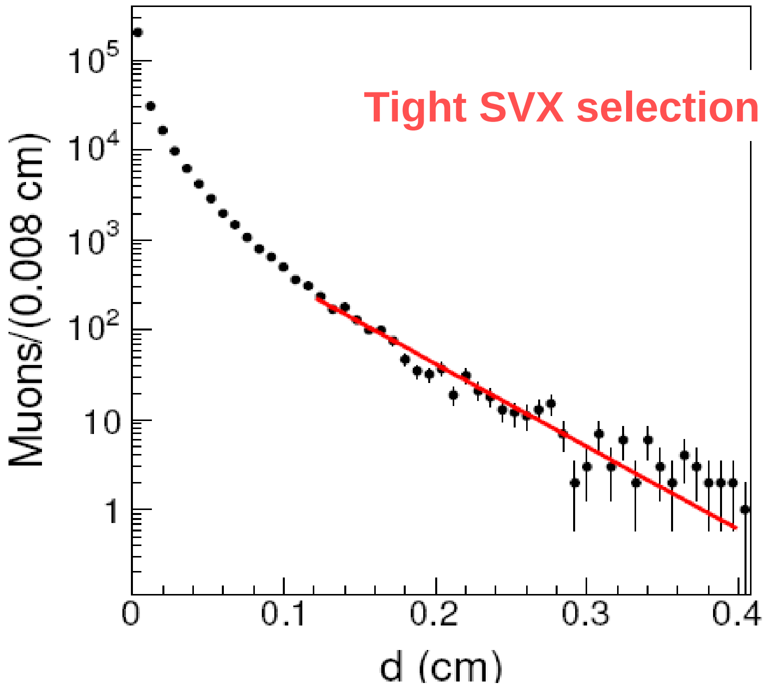
    Ghost = all events – (QCD/efficiency)



- **QCD sources (includes heavy flavor) have $d_0(\mu)<0.5$cm**
- **“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
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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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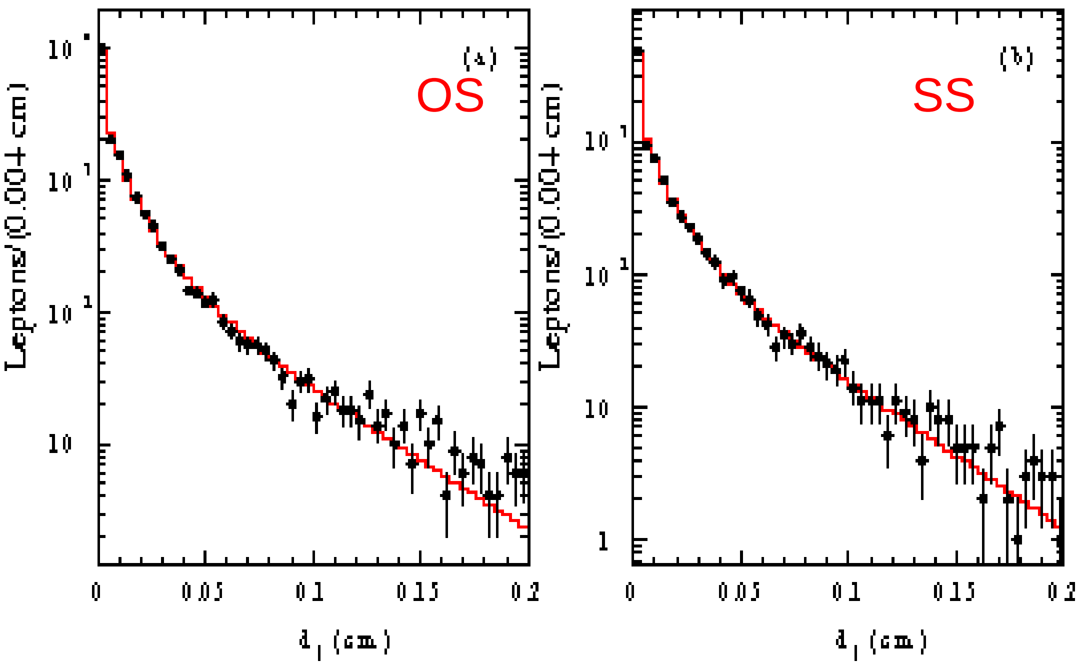
"All" – "QCD" = ghost

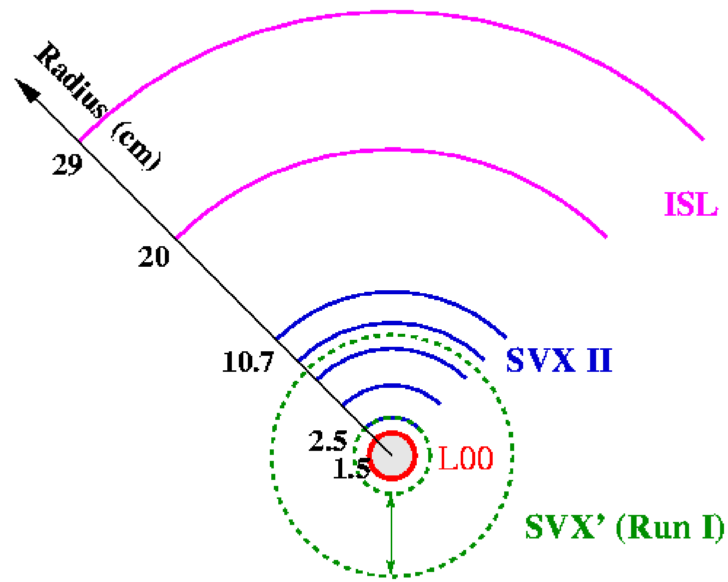
- 221564±11615 bb events with no SVX [194976 ± 10458 with loose requirements]
- Ghost contribution to entire sample (154k) comparable to bb contribution (222k)!

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 $\sigma(p\bar{p}\rightarrow b\bar{b}X)$ larger than expected from NLO QCD
    - Run II measurement with tight cuts agrees with prediction
  - Time-integrated mixing ($\bar{\chi}$) measured at Tevatron larger than LEP average.
    - Ghost contribution definitely affecting SS/OS ratio.

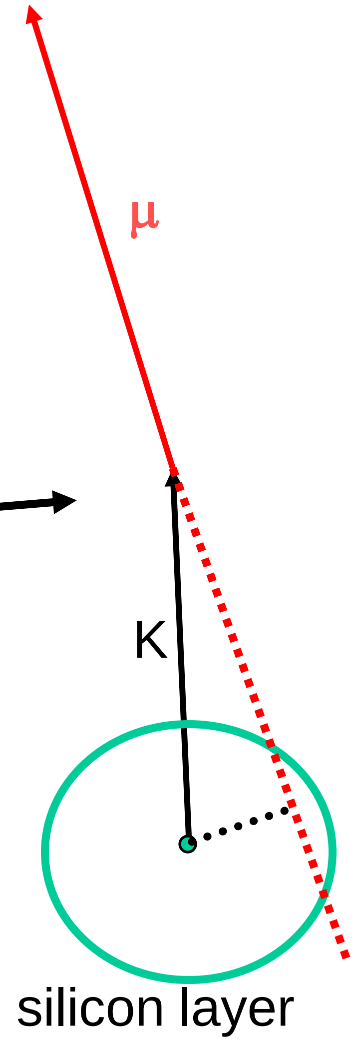
- This does not (yet) explain
  - low mass dilepton spectrum inconsistent with expectations from heavy flavor.

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

Sources of Ghost Events

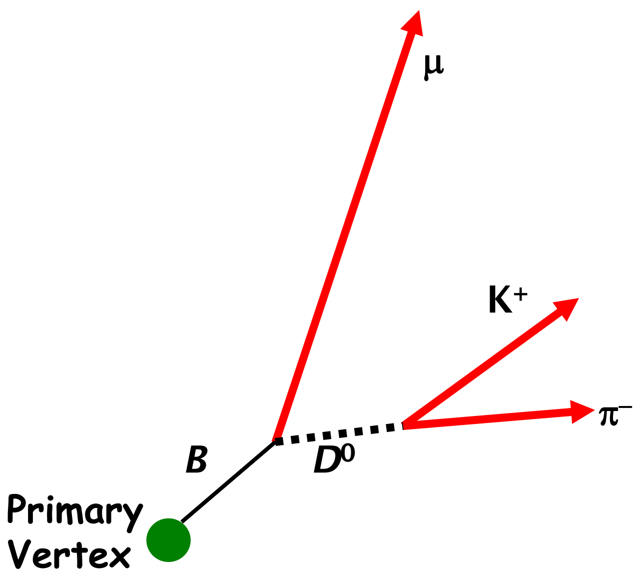
What could give rise to real or fake muons at large d_0 which preferentially miss inner silicon layers?

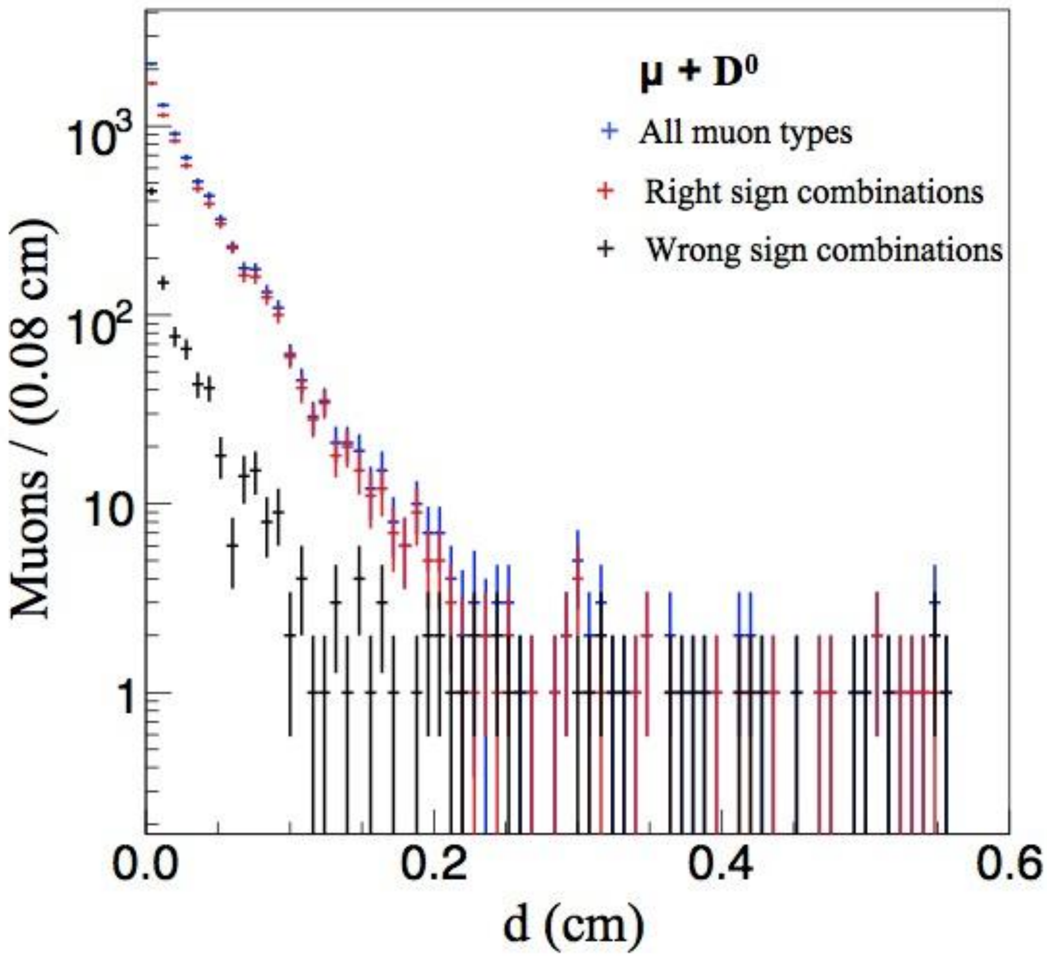
- Mismeasured tracks
- In-flight decays of kaons and pions
  - $K^{\pm} \to \mu\nu_{\mu}$ and $\pi^{\pm} \to \mu\nu_{\mu}$
- Long lived particles (K_S, hyperons)
- Secondary interactions in detector material
  - e.g. hadron interacts in silicon produces secondaries with large d_0



Mismeasurement?

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



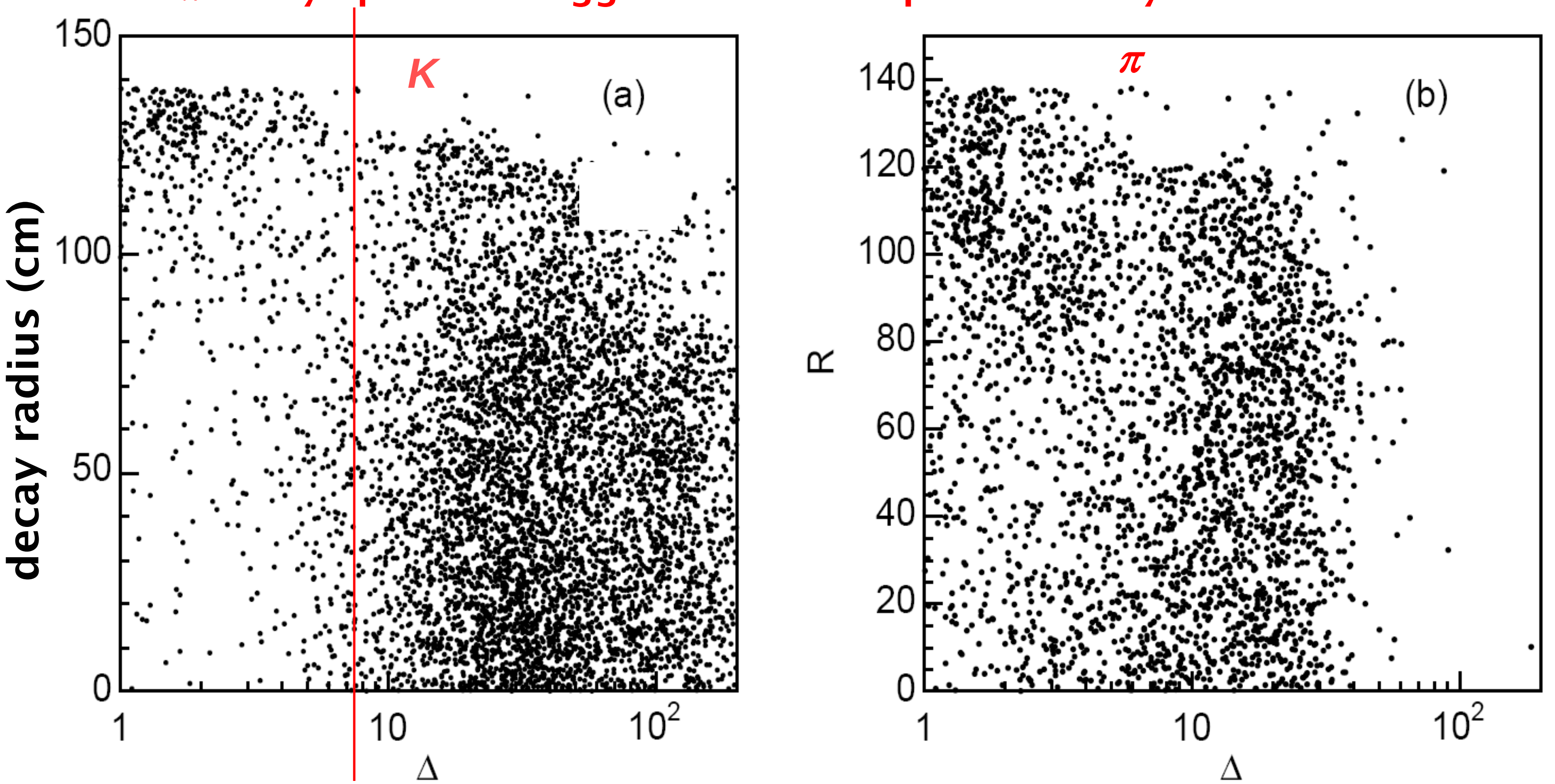


- Additional studies of track quality and other control modes indicate tracking is ok.

- $d_0(\mu)$ 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**

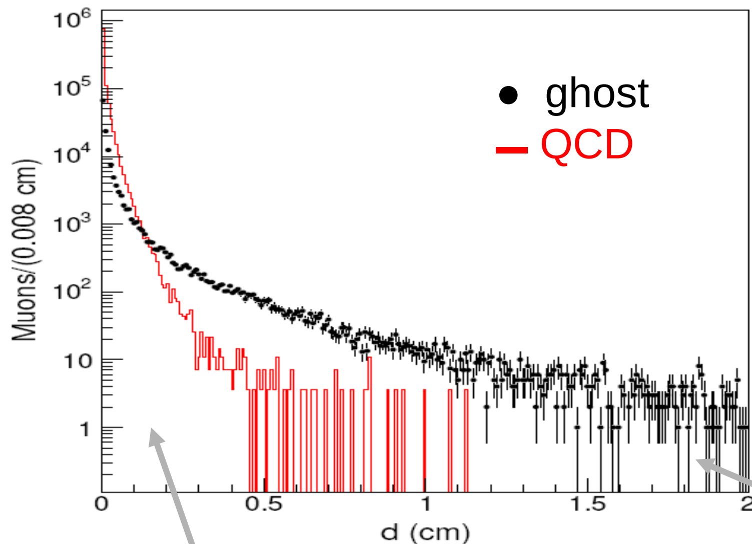


Δ is a χ^2/NDOF based on the difference between the hadron at generator level and the reconstructed track in the η, ϕ, p_T space

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.

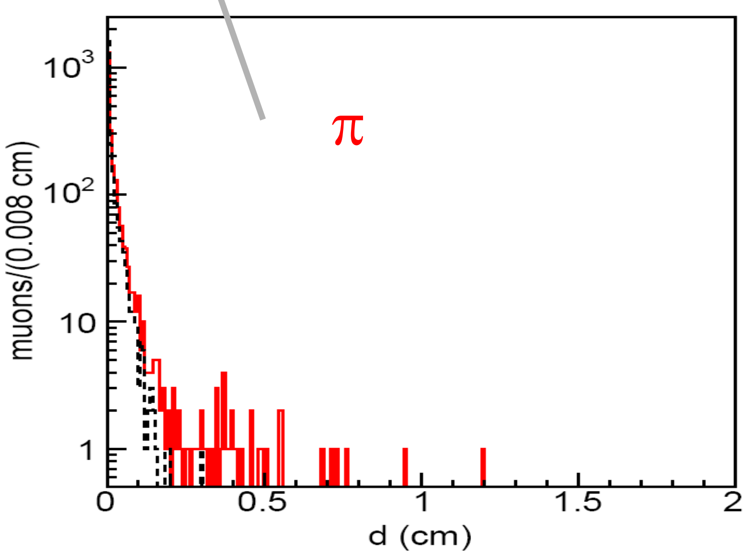
In-flight decays

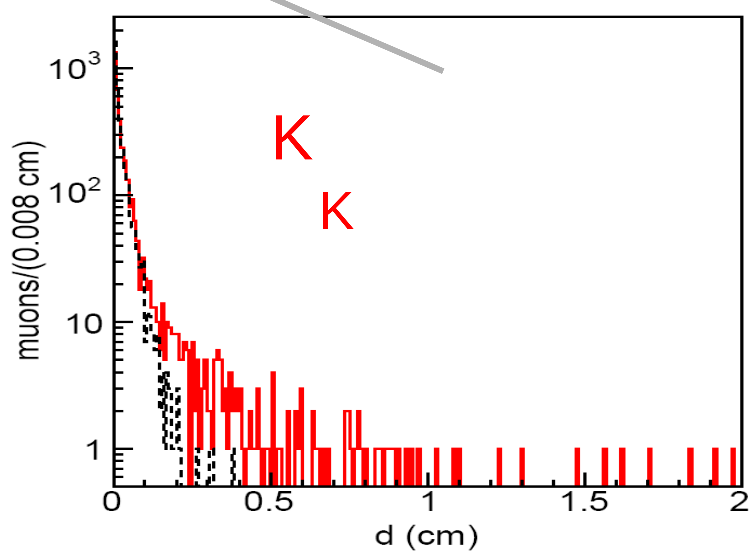


IFD prediction explains 35% of the ghost events, but only 10% of the events with d>0.5 cm

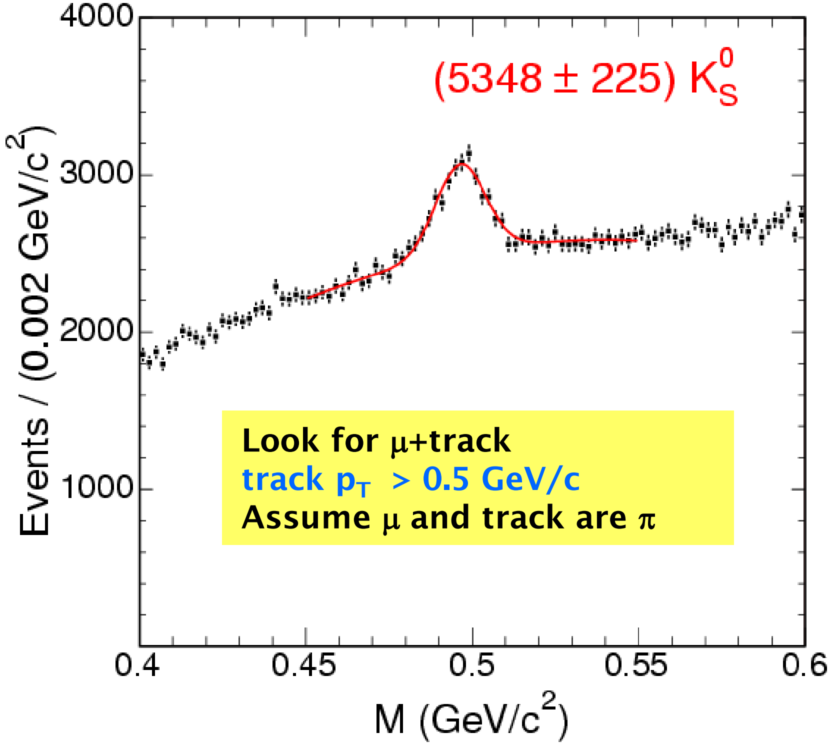
X 5

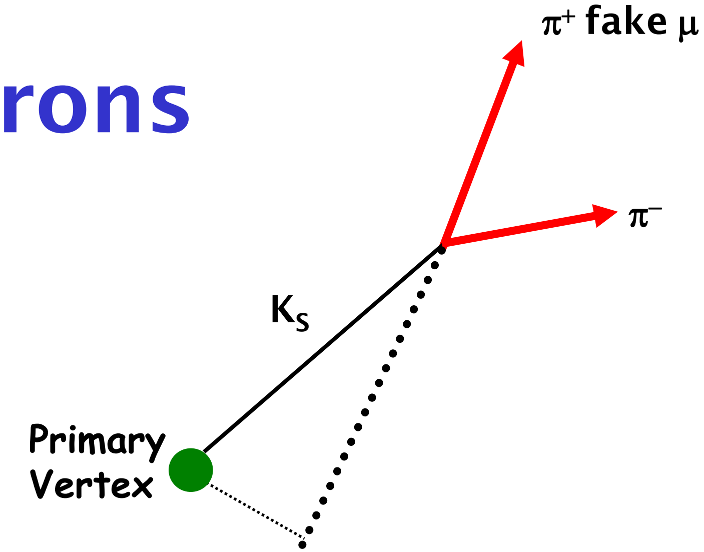
X 5

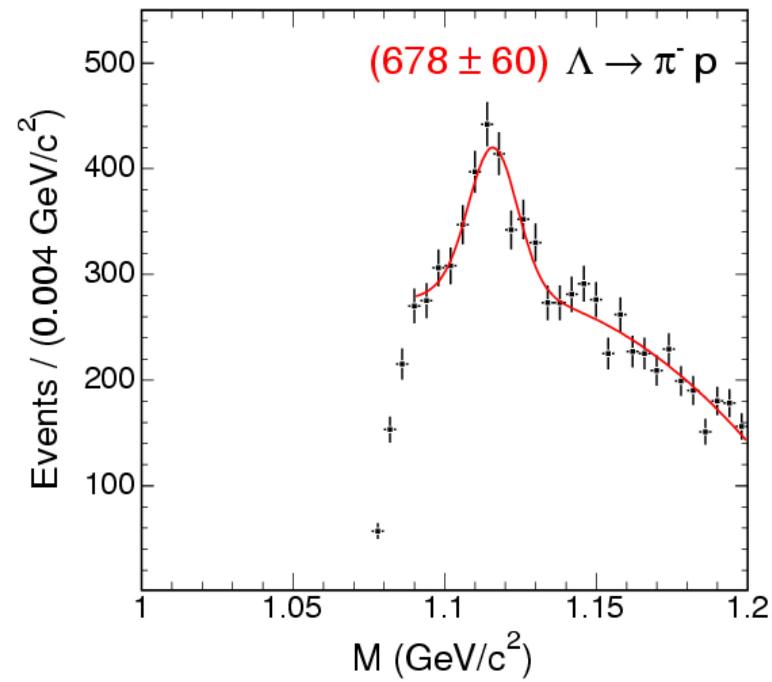




K_S and hyperons



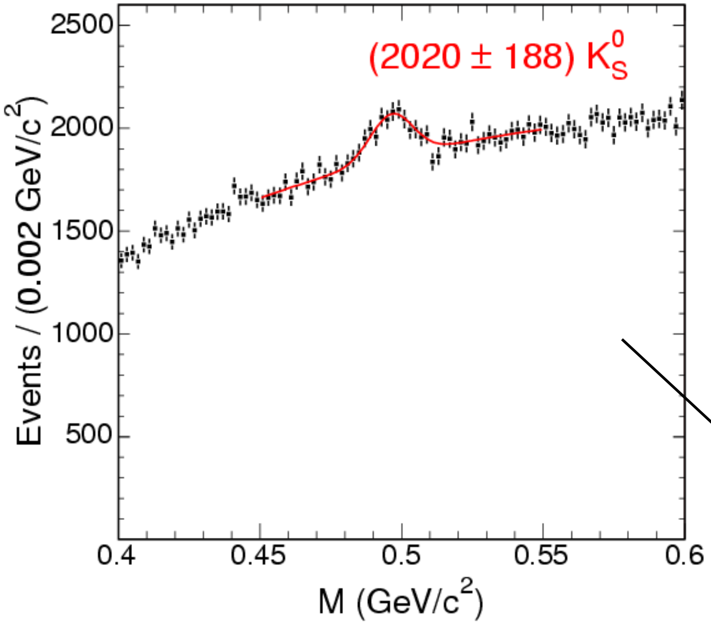




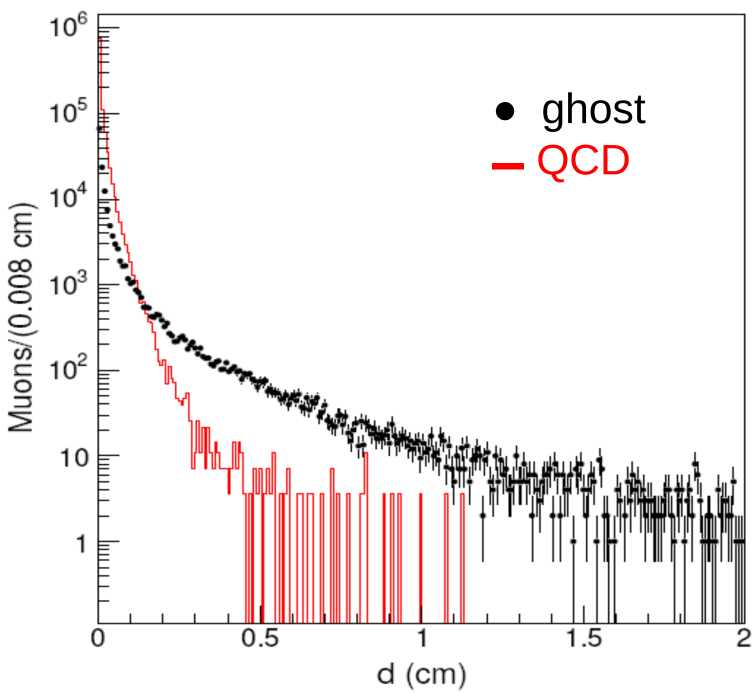
Kinematic acceptance times reconstruction efficiency ~ 50%

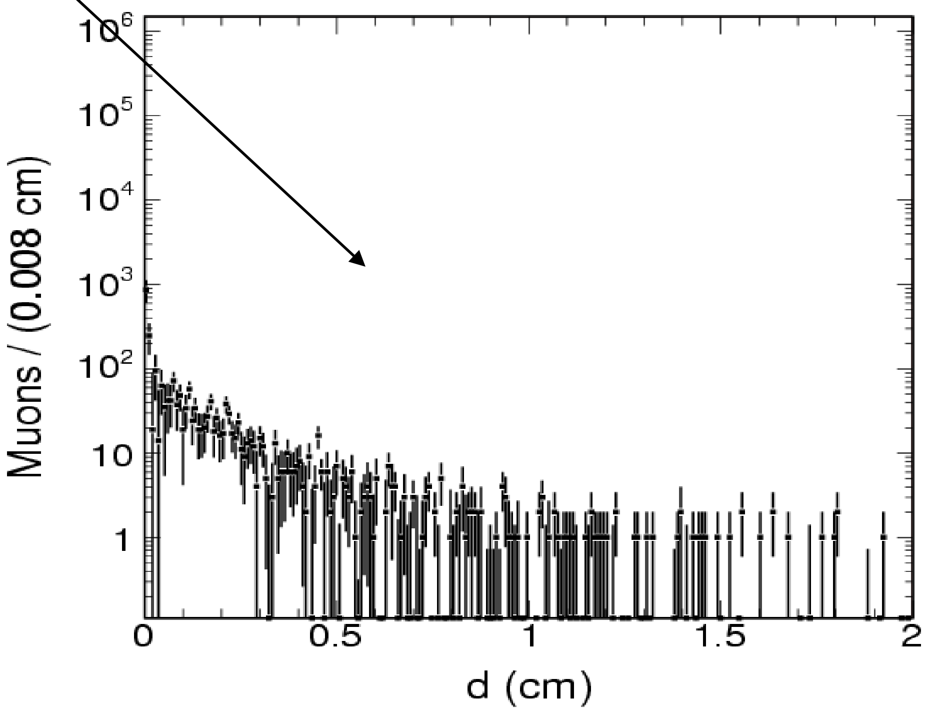
These decays account for about 12000 ghost events

K_S



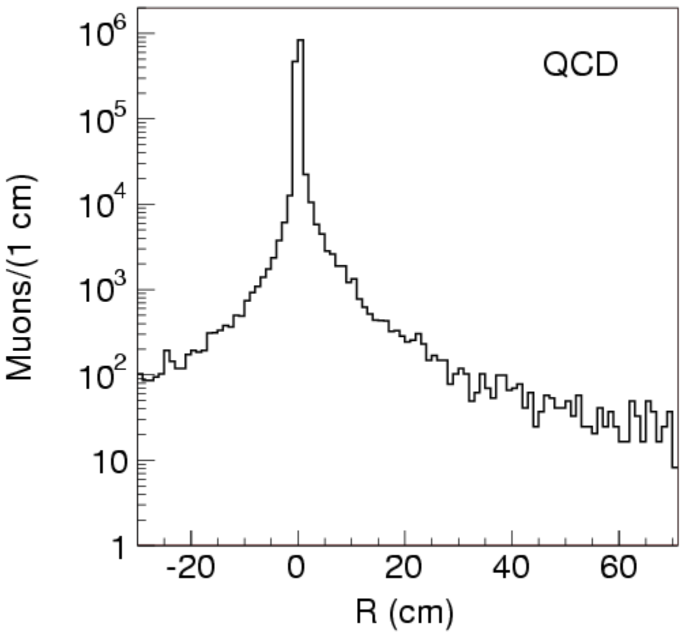
- **Loose SVX selection**
- **K_S populate higher d_0**

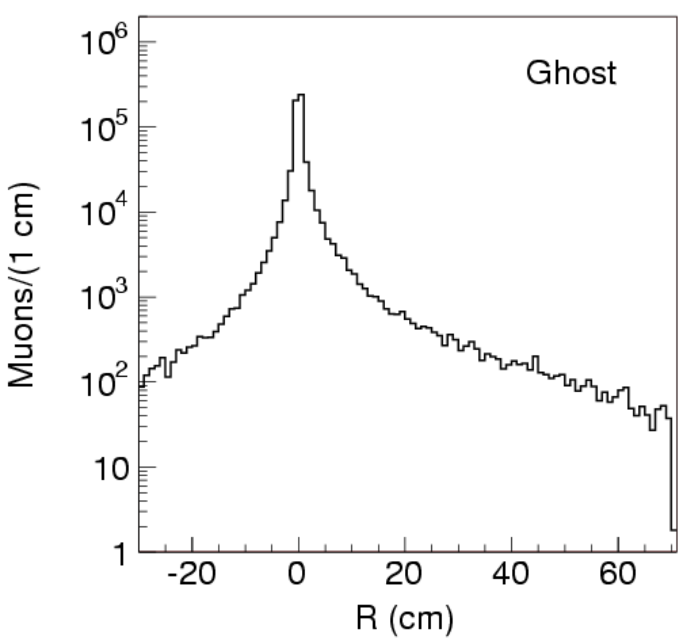


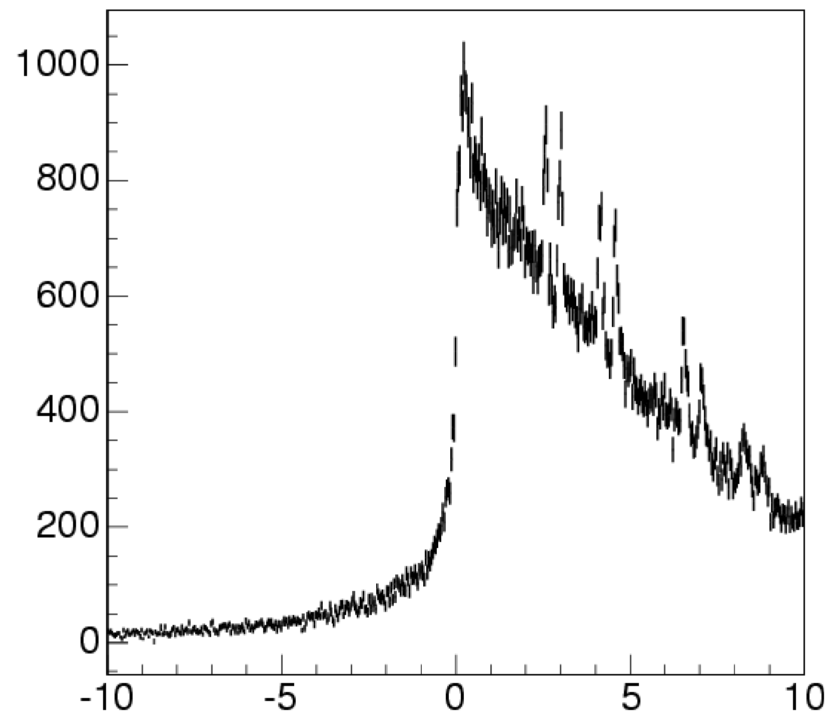


Secondary interactions

- 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

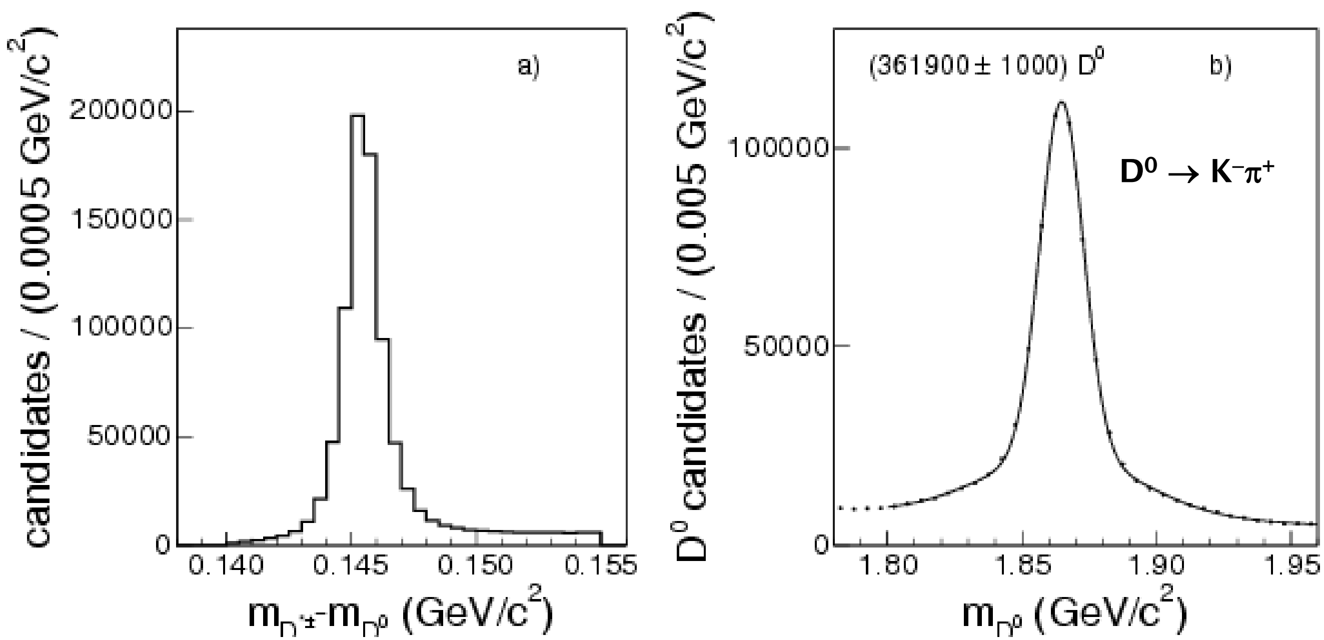
- **Search for additional muons with p_T > 2 GeV/c and $|\eta| < 1.1$ around each initial muon – require invariant mass smaller than 5 GeV/c^2**

- **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.

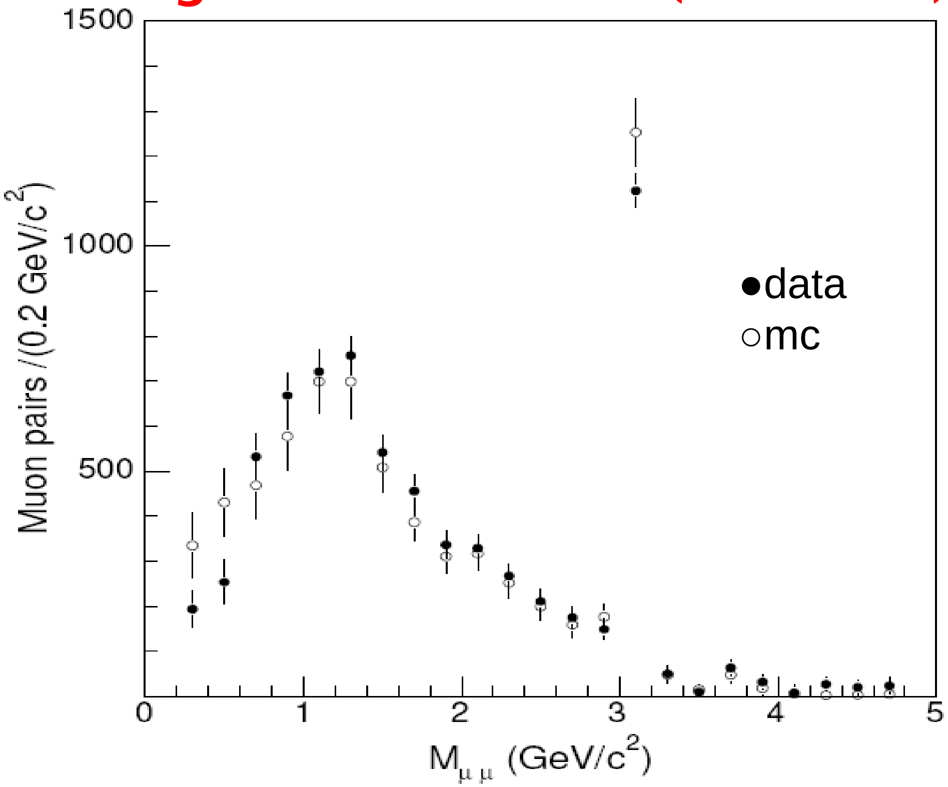
Muon Fake Rate

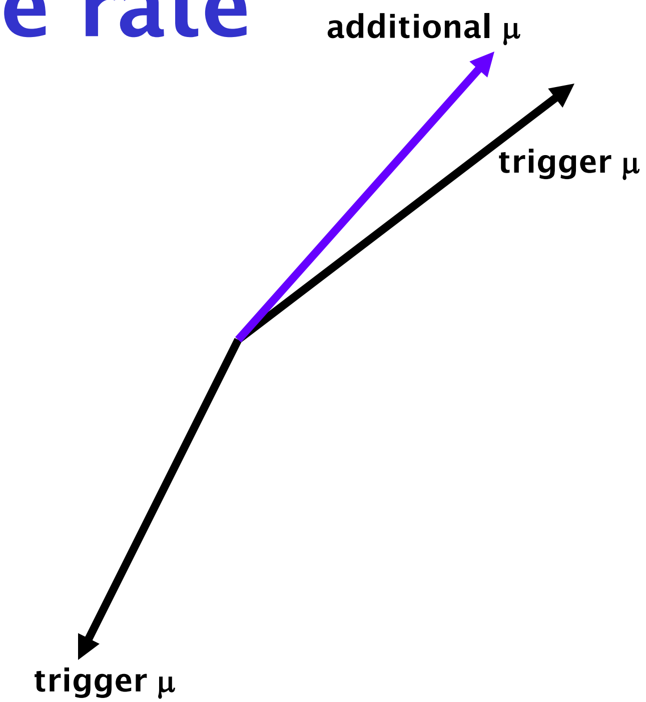
- **Measure the probability per track that a pion or kaon will "punch through" the calorimeter and fake a muon.**
- **Technique:**
  - Reconstruct $D^{*+} \rightarrow D^0\pi^+$ decays with a $D^0 \rightarrow K^-\pi^+$
  - D^* tag uniquely identifies π and K
  - Reconstruction by tracking only, then ask 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)



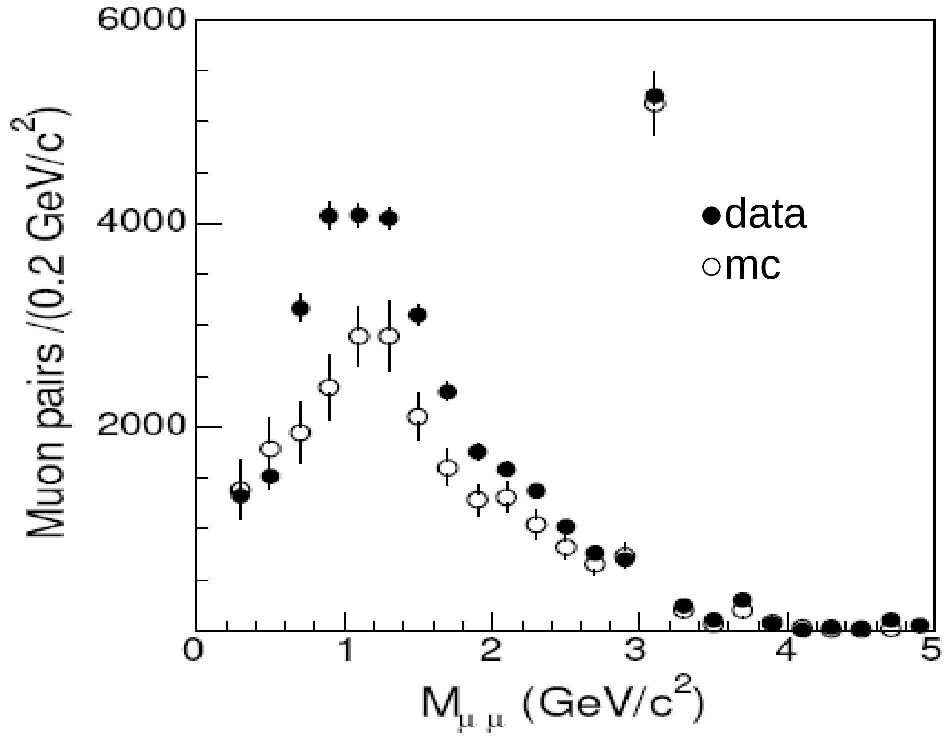


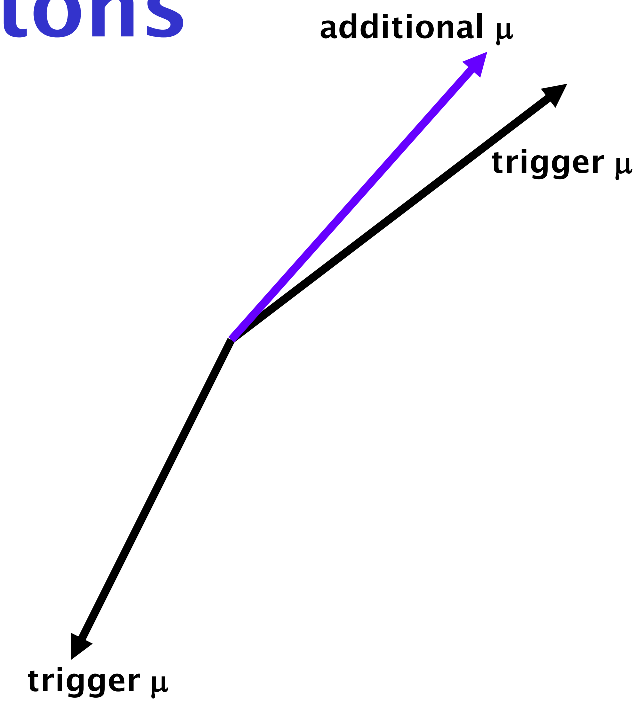
- 6935±154 in the data and 6998±293 predicted
- We understand the heavy flavor simulation and the fake muon background

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

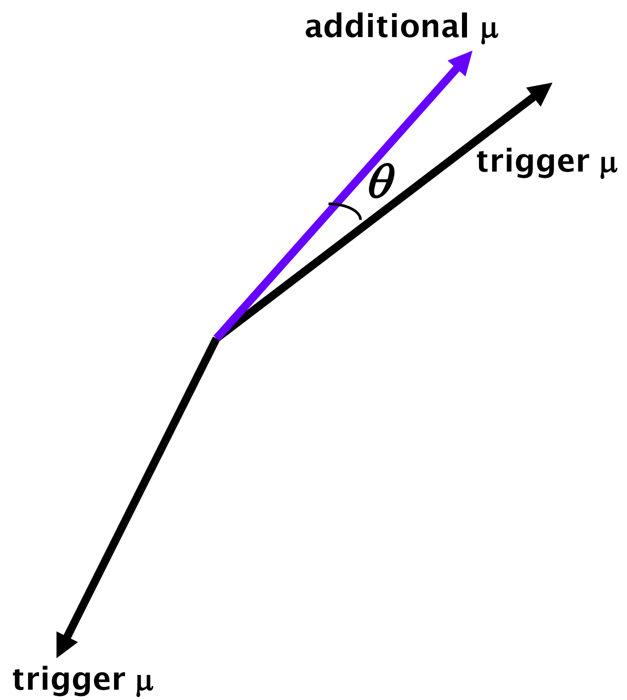
- QCD sample well understood
- Ghost sample less well understood, but appears to be mostly QCD-like, with muons from in-flight and long-lived decays .

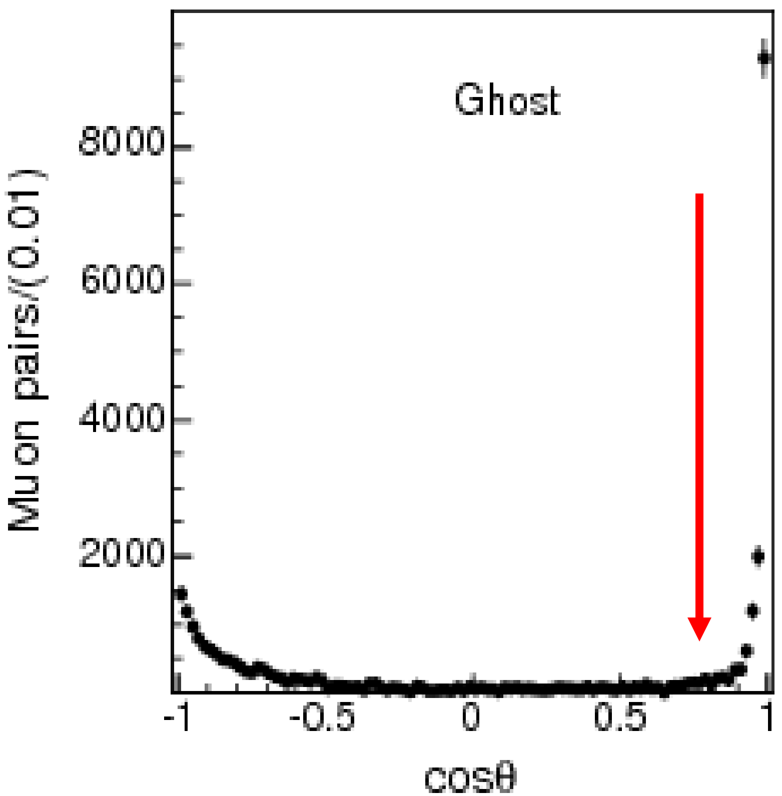
Compare ghost to QCD:

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



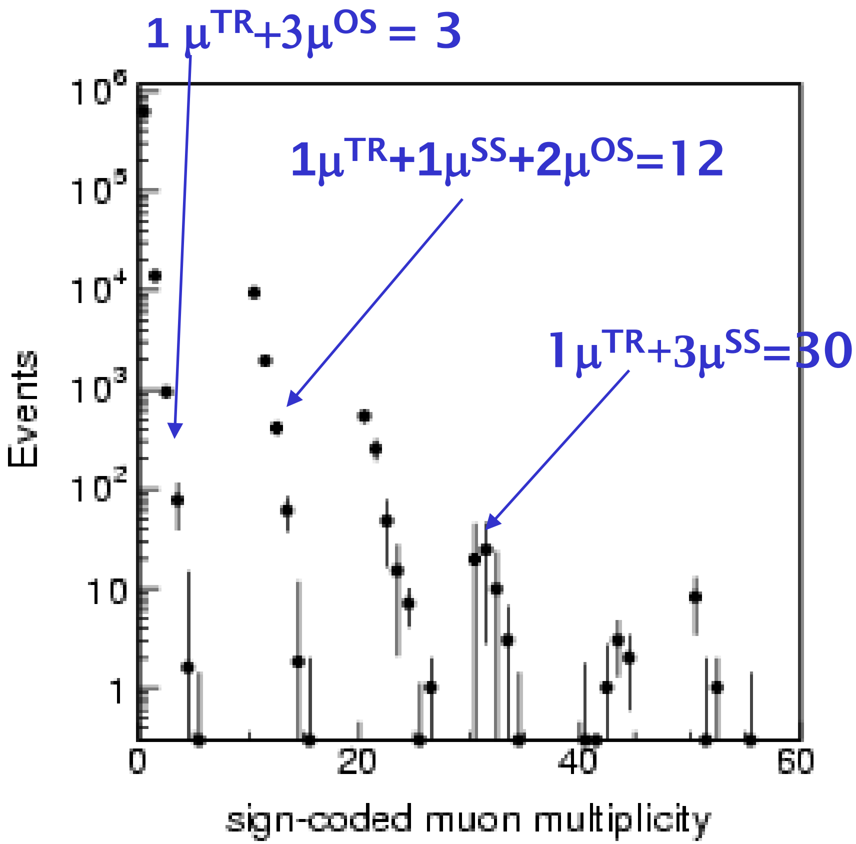


additional muon multiplicity

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

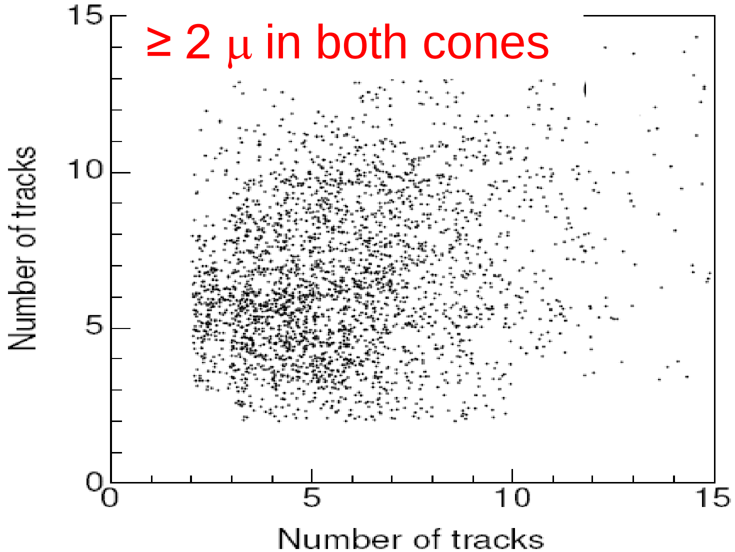
  counting additional muons (not trigger muon) in a single cone.

- **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



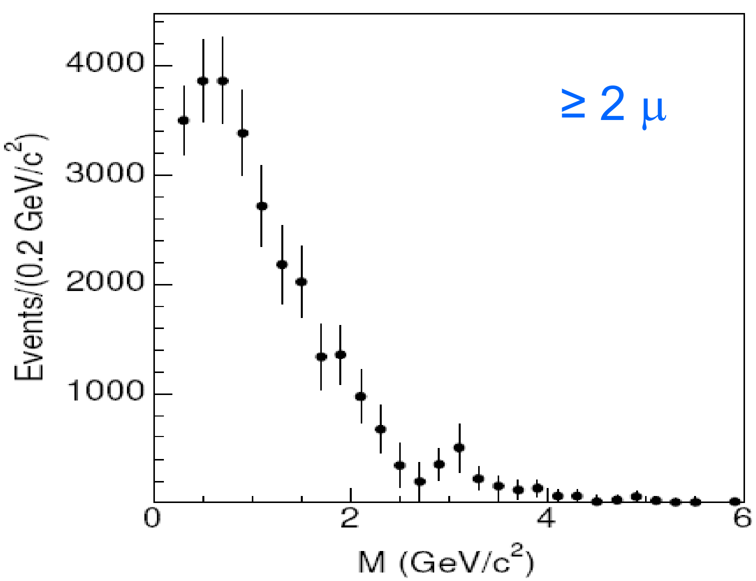
Ghost events

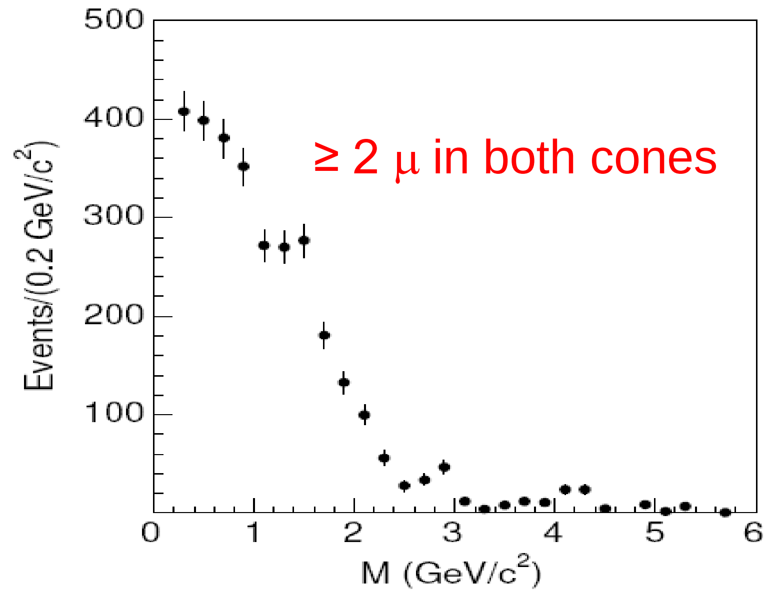
27790±761 cones with ≥ 2 μ (a)

4133±263 cones with ≥ 3 μ

3016 with ≥ 2 μ in both cones (b)

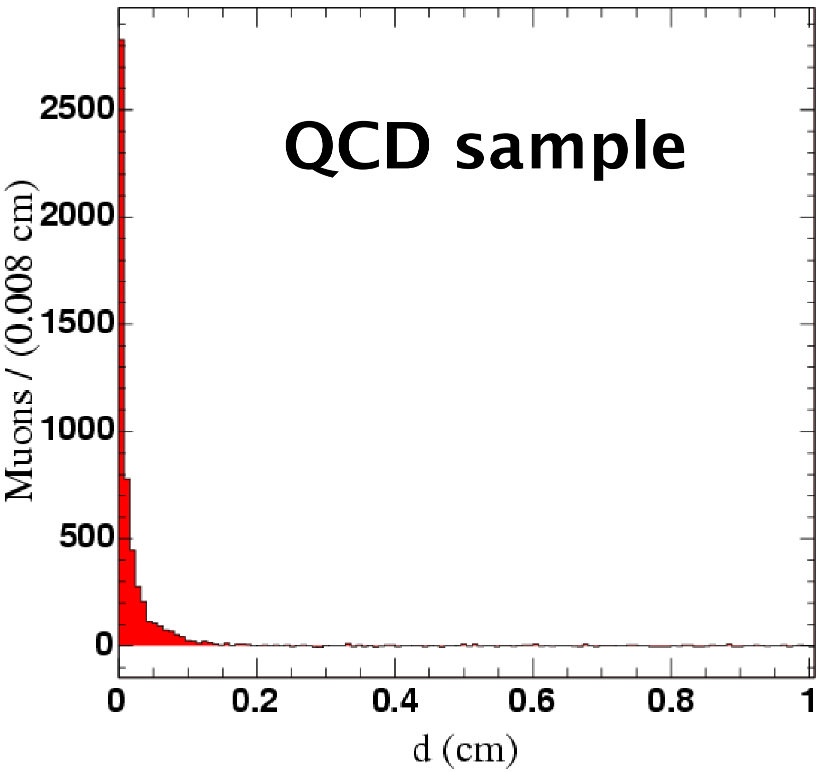
Ratio (b)/(a) = 0.11 is quite large. Events triggered by a central jet, the fraction of events containing another central jet is 10-15%

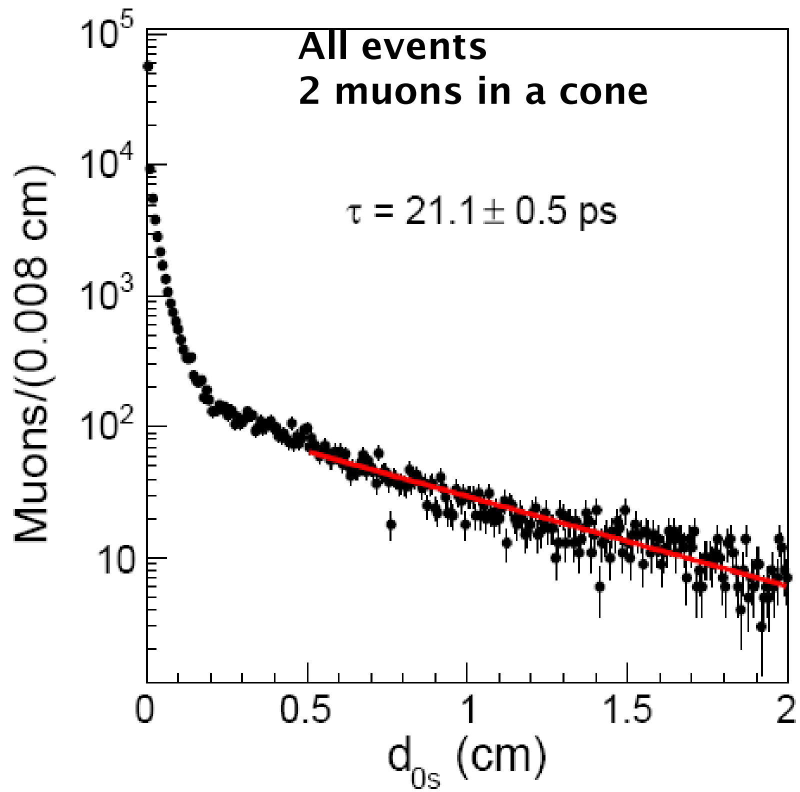




Impact parameter

- **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

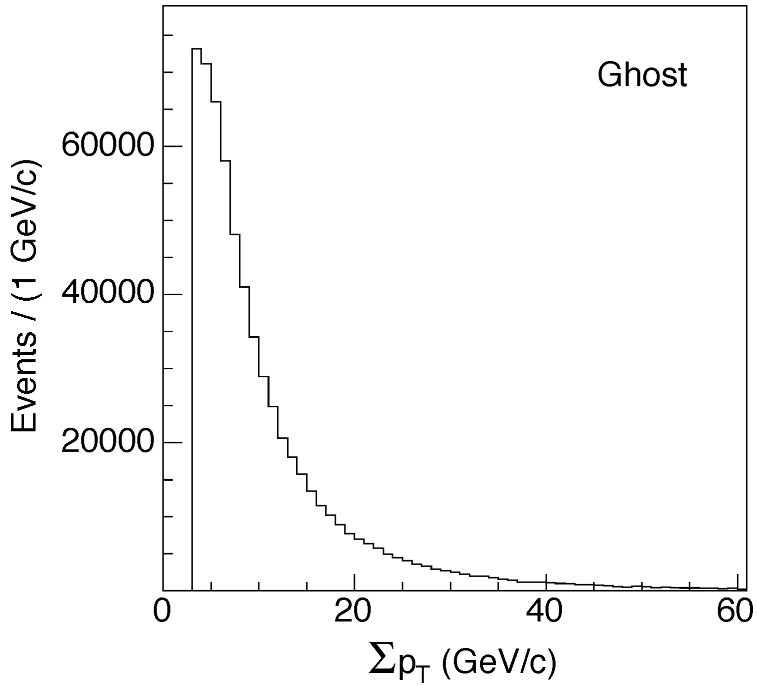
- Another piece of this background is puzzling, it seems inconsistent with any of our expectations.
  - This component of the background shows high muon and charged track multipliticy

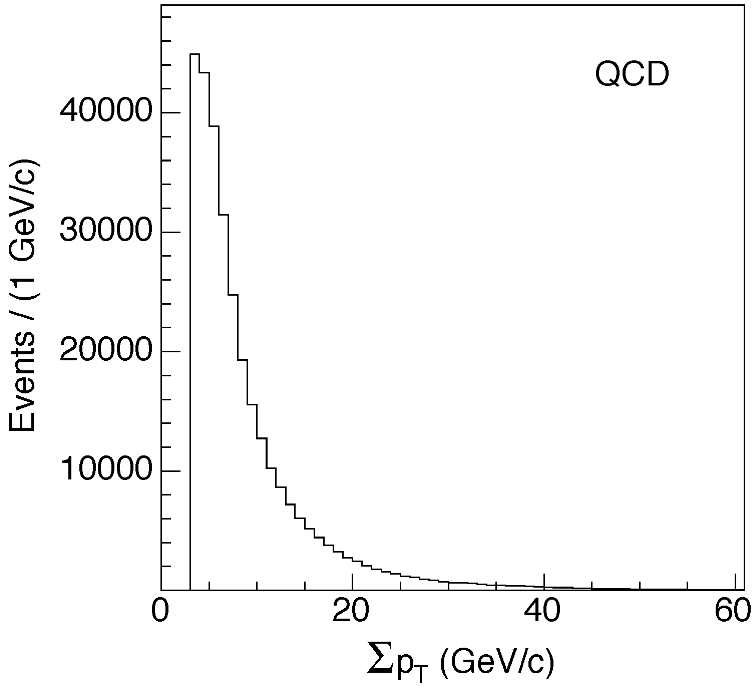
Comment on fake rates

- Our "per track" fake probability assumes that fake muons are uncorrelated.
- Probably not completely true
  - high energy jet ⇒ large leakage ⇒ lots of activity in muon chambers ⇒ 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.