Study of multi-muon events produced in proton-antiproton collisions at 1.96 TeV

arXiv:0810.5357[hep-ex], arXiv:0810.5730[hep-ph]

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on behalf of the CDF collaboration

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Outline

- Physics motivation:

Analysis is motivated by long-standing/well-known inconsistencies in b production/decay measurements at the Tevatron (Run I):

  - Large $\sigma_{b\bar{b}}$ compared to NLO QCD expectation
  - Time integrated mixing probability larger at Tevatron than LEP
  - Low-mass dilepton spectrum inconsistent with QCD expectations from heavy flavor
- Some recent results (Run II)
  - Inclusive *B* cross sections
  - Correlated $b\bar{b}$ cross sections
- Study of multi-muon events
- Summary

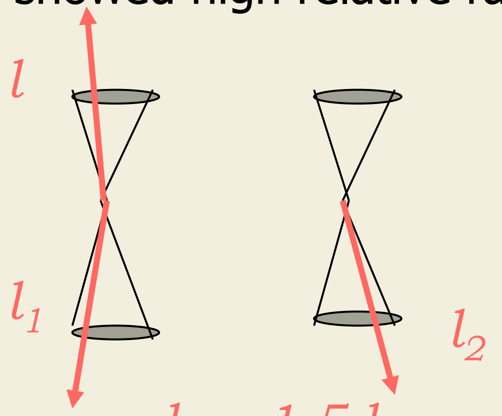
Correlated σ_{bb} [Inconsistency #1]

Two central b's, with sufficient p_T

Small theoretical uncertainty (~15%)
Born diagrams dominate

- Measurement techniques
  - Vertex tagging
  - Lepton tagging

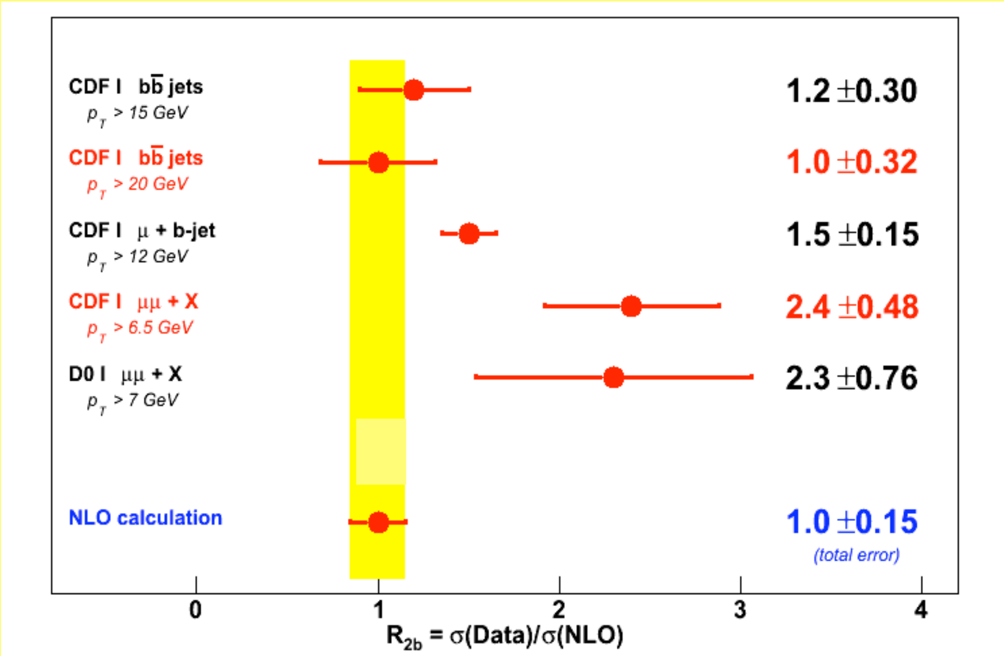
- "per jet" lepton rate also showed high relative rate



$l_1 = 1.5\, l_2$

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 $R_{2b}>1$.



$\sigma(p\bar{p}\rightarrow b\bar{b}X\rightarrow llX)$ larger than NLO QCD

Puzzles from Tevatron Run I

[Inconsistency #2]

PRD 69, 012002 (2004)

Average time-integrated mixing probability of *b* hadrons, $\bar{\chi}$ measured at the Tevatron is significantly larger than at LEP

0.152±0.013 vs 0.126±0.004

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

$$\bar{\chi} = \chi_d f_d + \chi_s f_s$$

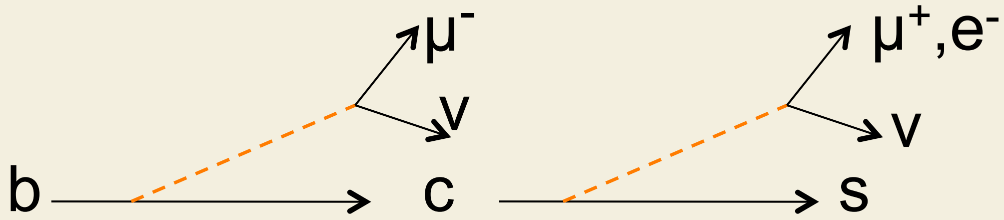
Time integrated mixing parameters χ_d and χ_s well measured

Measurement of $\bar{\chi}$ constraints the fractions, f_d and f_s, of b quark fragmenting into B_d and B_s

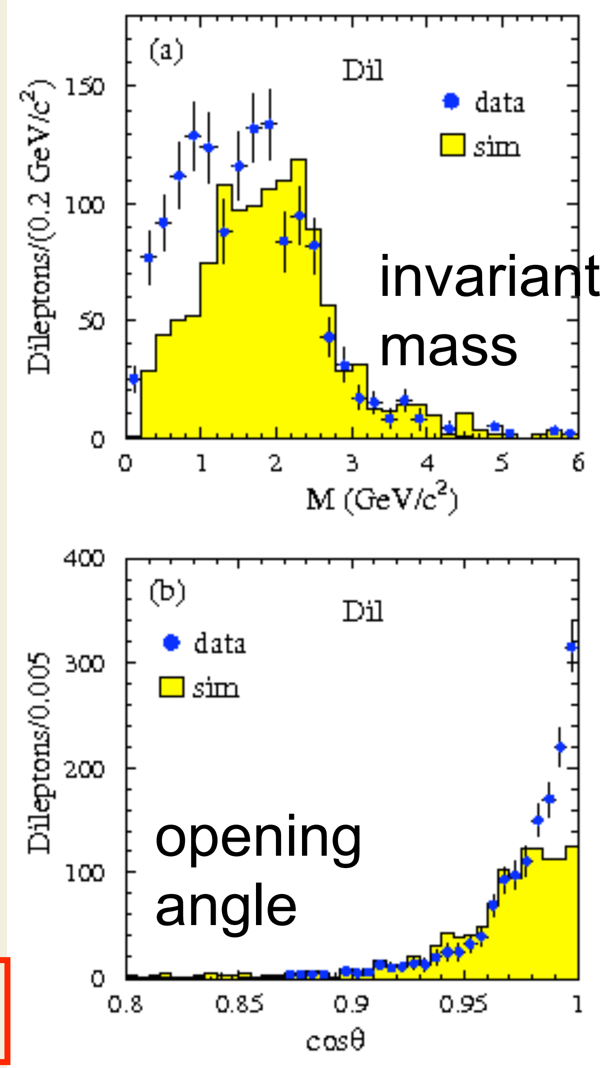
PDG concluded that the *b*-hadron mixtures must be different!

Puzzles from Tevatron Run [Inconsistency #3]

- Low mass di-lepton invariant mass spectrum in a B-enriched sample is not well modeled by sequential semi-leptonic decays of single *b* quarks.



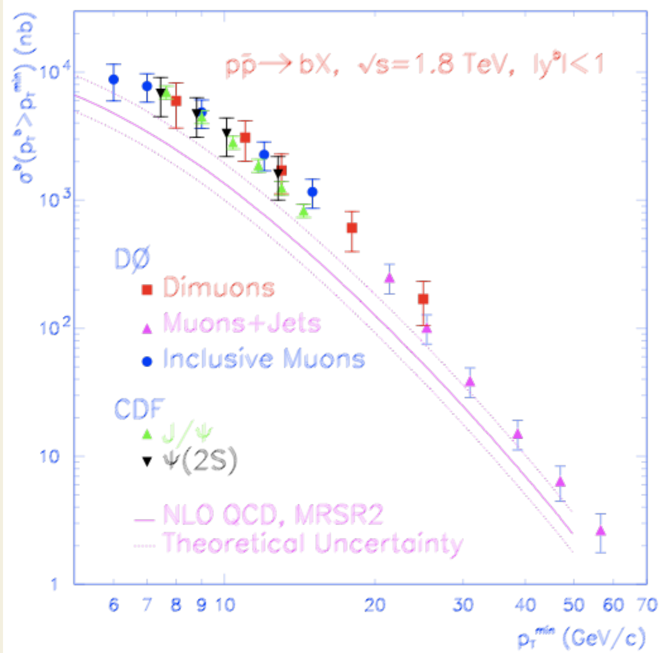
  - Simulation:
    HERWIG (PYTHIA)+EVTGEN (QQ)
  - Accurate measurement, mostly eμ



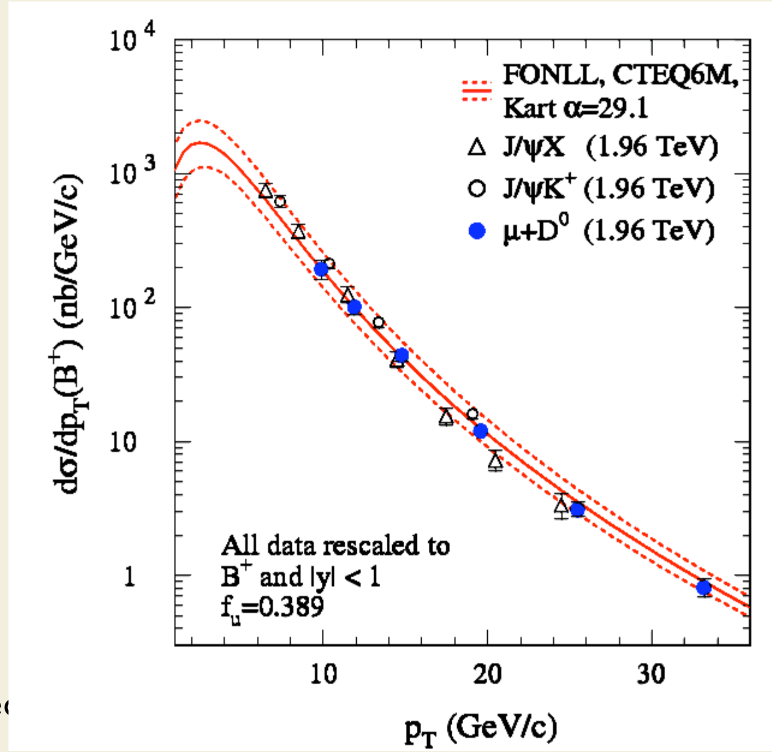
PRD 72, 072002 (2005)

Some Recent Result (Run II): σ_b

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



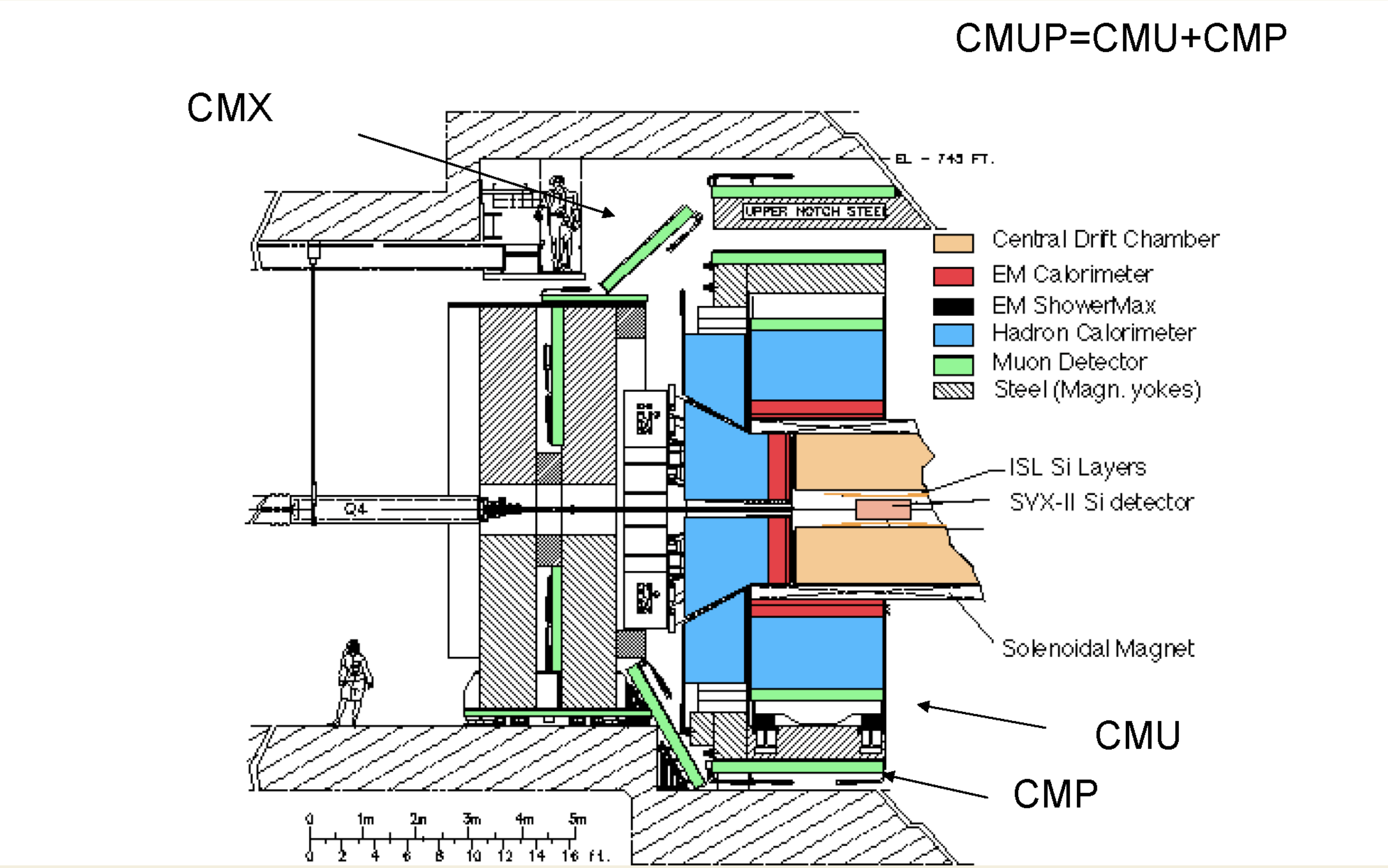
- Tevatron Run II: Re-measure inclusive cross sections
  - Better acceptance
  - Higher statistics
  - Smaller uncertainties



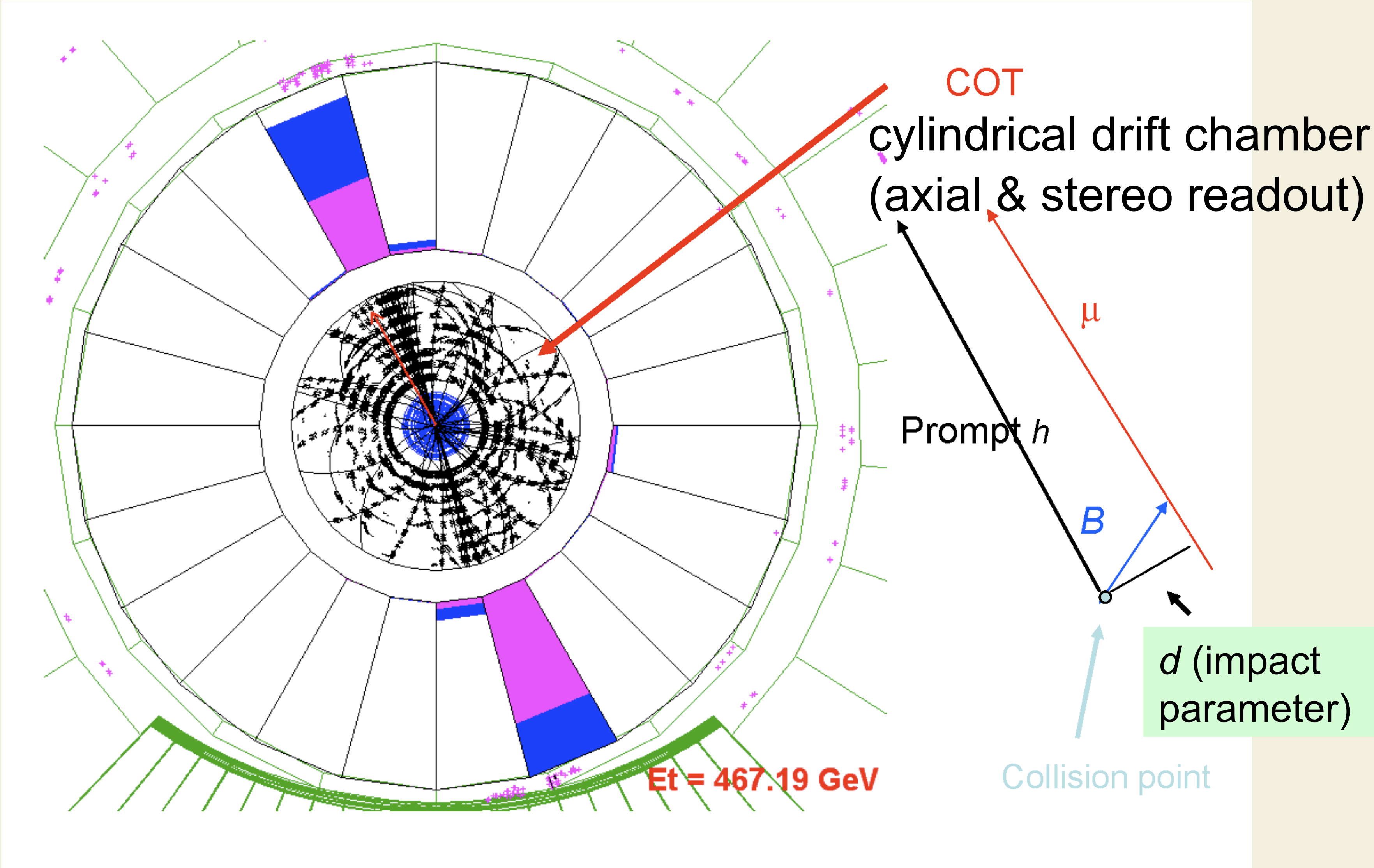
- See better agreement with theory now, but in fact data is consistent with Run I results.
  - Improved agreement primarily from theoretical improvements.

CDF II Detector

- Multi-purpose detector
  - Charged particle spectrometer
  - Finely segmented calorimeter



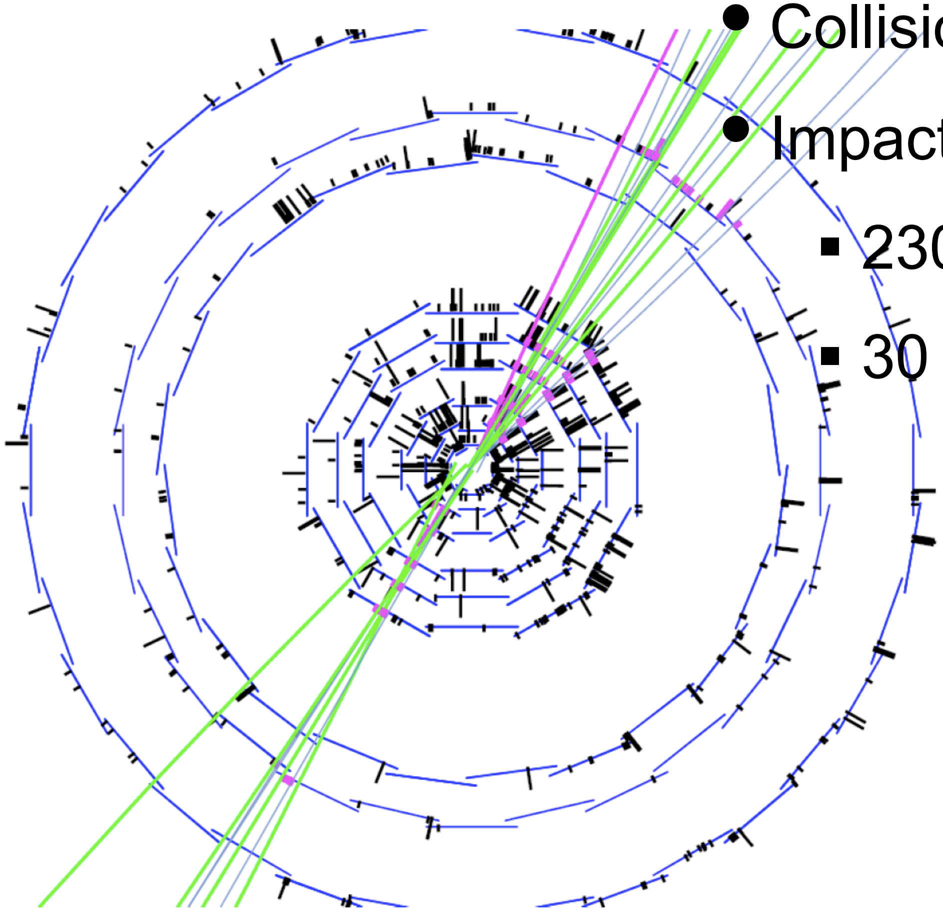
CDF II Detector (continue)

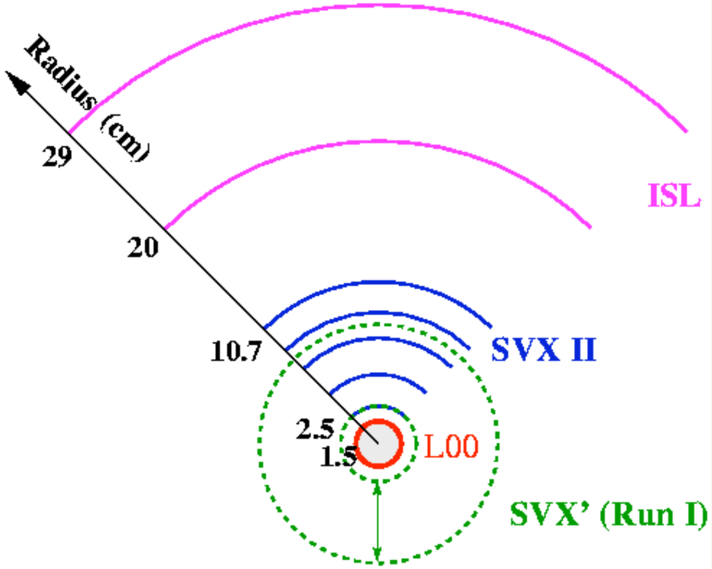


CDF II Detector (continue)

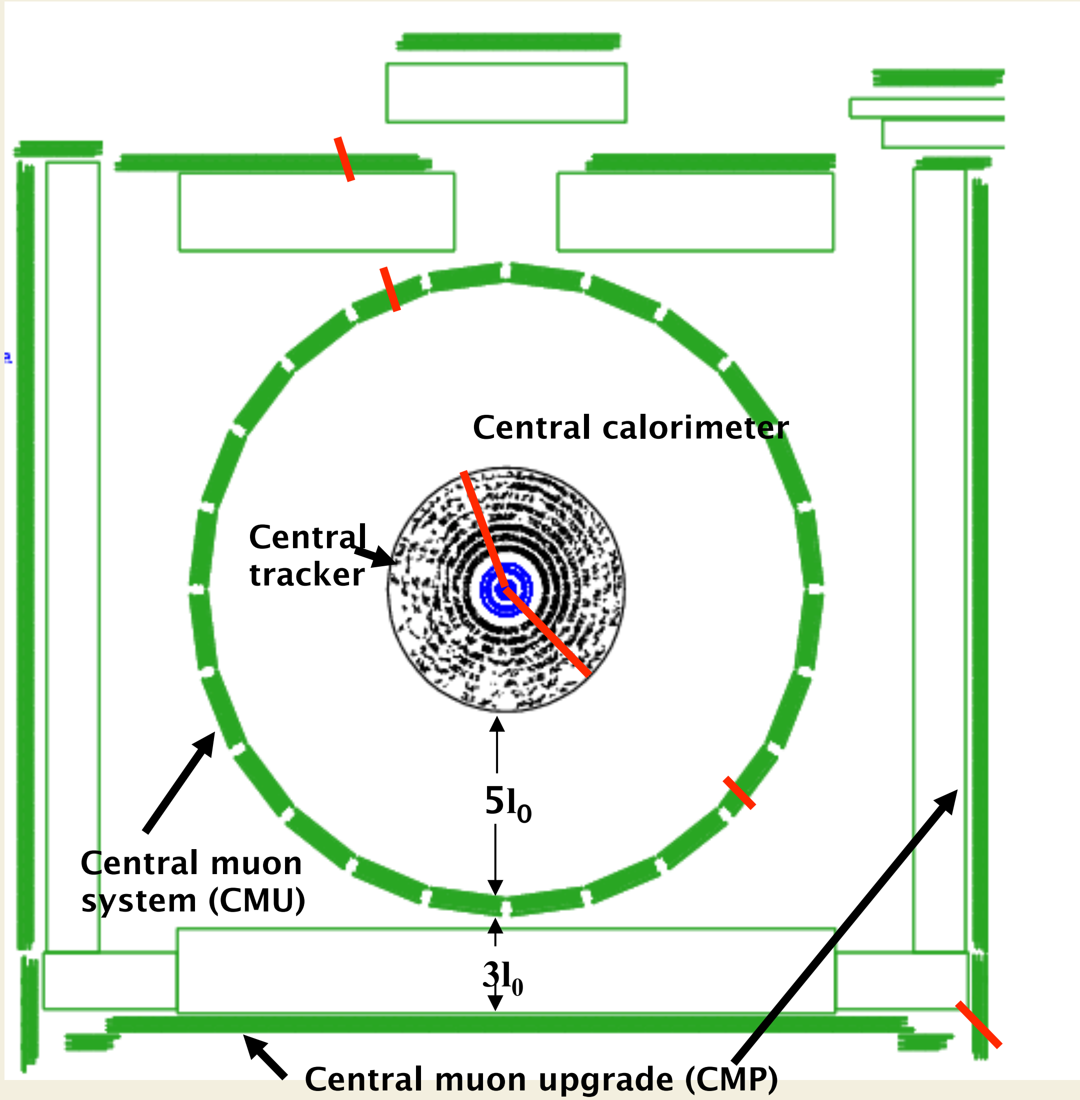
SVX II (L00, L0, L1, L2, L3, L4)

- Collision point (rms): 3 μm
- Impact parameter resolution (rms)
  - 230 μm (COT without silicon hits)
  - 30 μm (COT with ≥3 silicon hits)





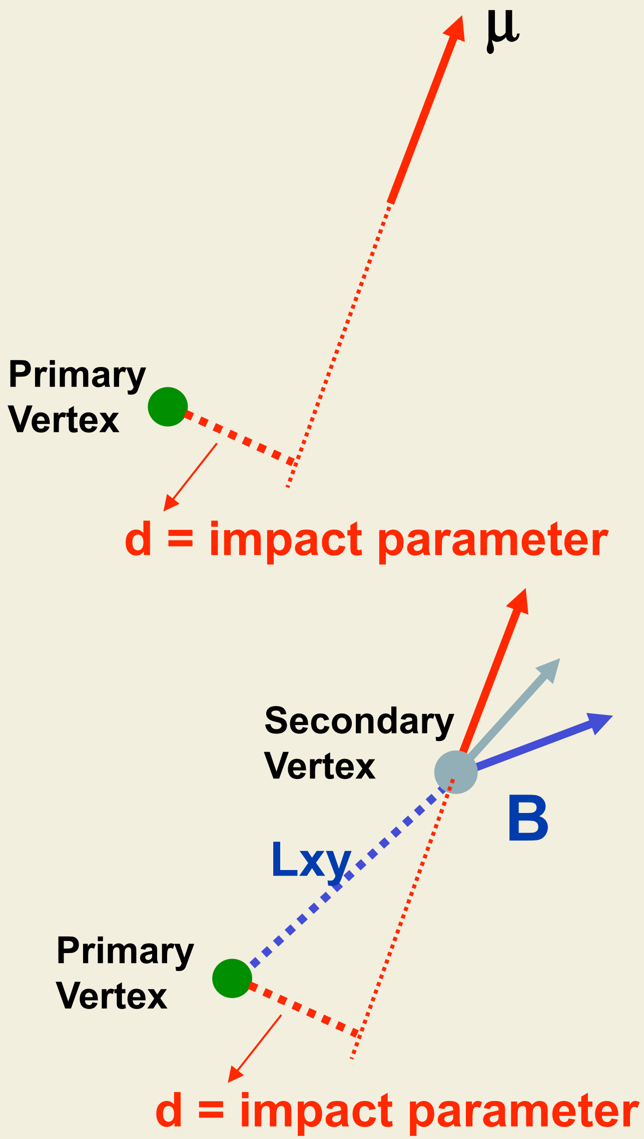
Data Sets: Dimuon Triggered Sample



- Data sample collected by a dedicated dimuon trigger.
- *L* = 2100 pb^{-1}
  (742, 1426, 2100 pb^{-1})
  → unprescaled
- At least 2 muons, each with:
  - Central track, $p_T > 3\ GeV$
  - Match to stub in CMU
  - Match to stub in CMP
    $|\eta| < 0.7$
- Mass of dimuon pair
  $$5 < M_{\mu\mu} < 80 GeV$$
  get rid of Z's and sequential decays $b \to \mu c \to \mu\mu X$

Impact parameter & decay length

- Impact parameter (d): distance of closest approach of a track to the primary ($p\bar{p}$) collision vertex
  - We look at d(μ) 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 primary $p\bar{p}$ collision vertex and secondary vertex.



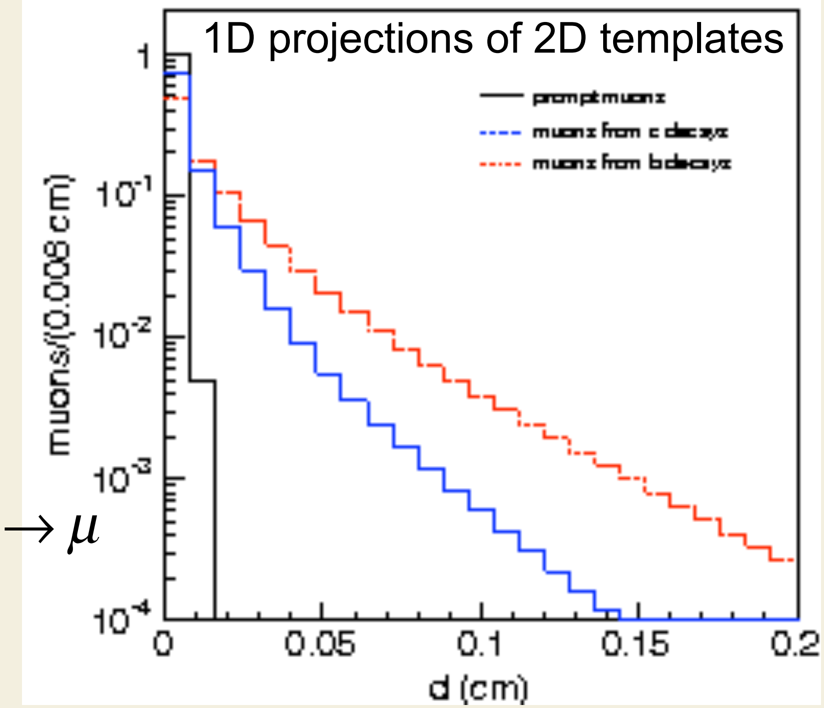
Calibration Samples

- μ-SVT: determine detector acceptance & reconstruction efficiency of muons
- CHARM: determine the probability that the punch-through of a charmonium mimics a muon signal using $D^0 \to K^- \pi^+$ decays.

Experimental Method

Sources of dimuons:

- Real muons:
  - $b\bar{b}$ $c\tau$= 470μm
  - $c\bar{c}$ $c\tau$= 210μm
  - Prompt (Y, Drell-Yan) processes
- Fake muons:
  - Hadronic punch through
  - Hadron decays in flight $K \to \mu, \;\; \pi \to \mu$
  - Fakes can be from prompt or heavy flavor sources

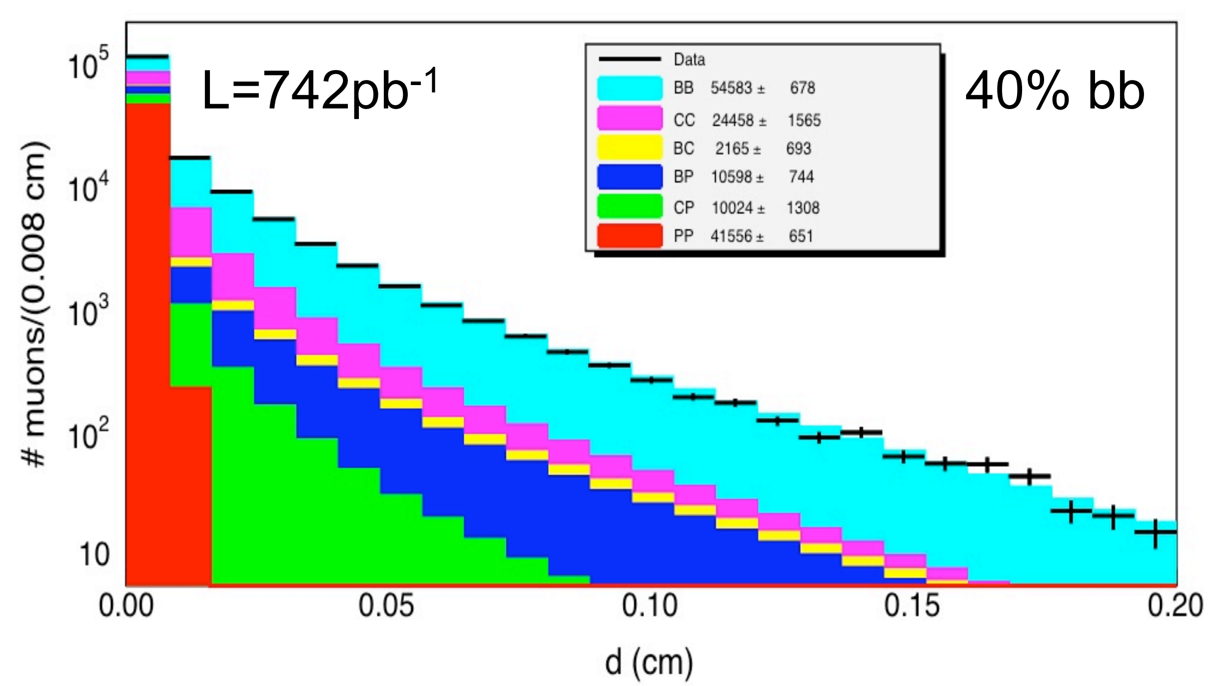


[idea] Extract the sample composition by fitting the observed d_0 distribution of the muons [2D fit – $d_0(\mu_1)$ vs $d_0(\mu_2)$] with the expected d_0 distributions of muons from various sources

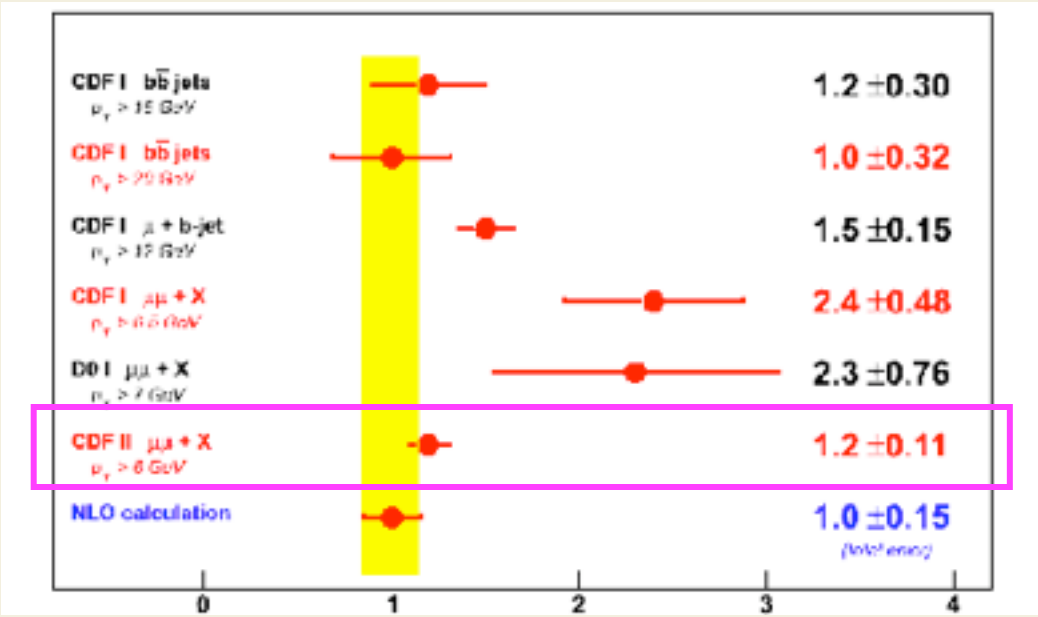
- Develop templates for (a) Heavy flavor (MC) (b) Prompt (data)

The Method [PRD 77,072004 (2008)]

- Require the highest tracking precision to separate b's from charm and prompt sources
  - Use tight SVX selection requirements (L00, L0 and 2 out of the remaining 4 layers)
  - Data could be modeled only by requiring the presence of hits in the first 2 layers – problematic when asking any 4 layers *
- Remove background from fake muons in h.f. decays
- Full fit includes all dimuon combinations: bb, cc, pp, bp, cp, bc



Extracted $\sigma_{b\bar{b}}$



$$R_{2b} = \sigma_{b\bar{b}}^{measured} / \sigma_{b\bar{b}}^{NLO}$$

PRD 77, 072004 (2008)

- Very accurate
- Appreciably smaller than Run I results

$$\sigma_{b\bar{b}} = 1328 \pm 209 nb \quad \text{NLO}$$

$$\sigma_{b\bar{b}} = 1618 \pm 148 nb \quad \text{Data}$$

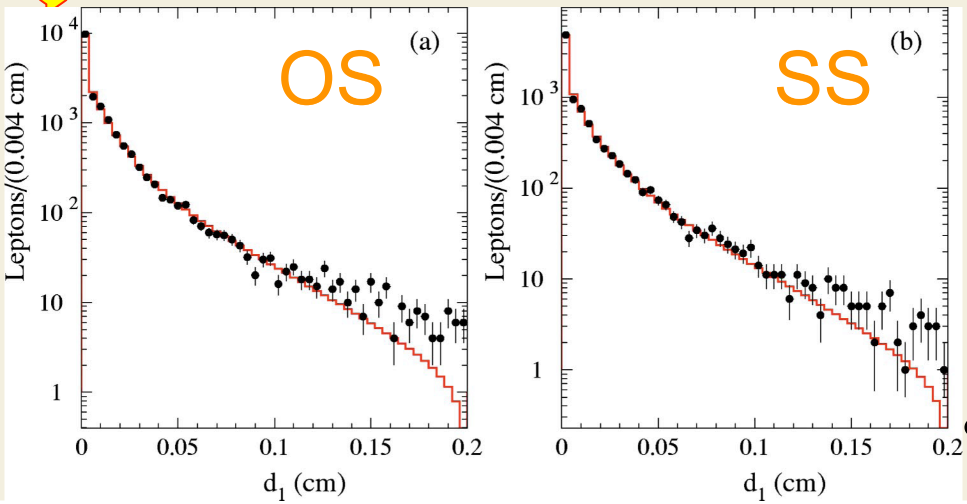
$$\left(p_T > 6 GeV \quad |\eta| < 1.0\right)$$

- New result agrees with NLO QCD prediction and measurements that use secondary vertex identification.

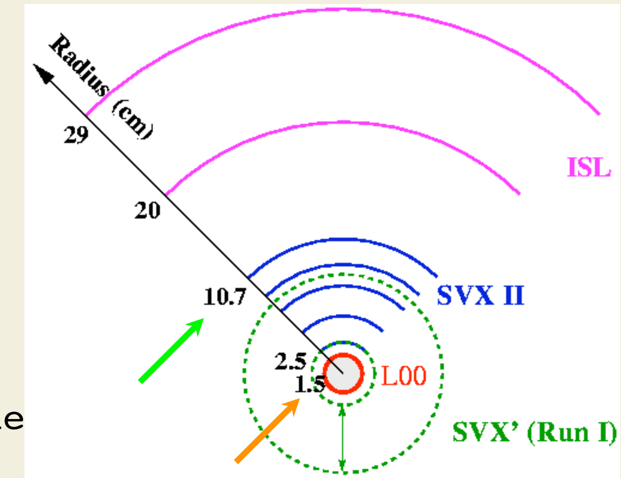
[resolve inconsistency #1]

Mysteries left over…

- Need tight SVX requirements to fit – realize that this selects muons originating from inside the beampipe
- Analyses in CDF use loose SVX requirements: 3/8 (SVX+ISL) layers - muons can originate as far as 10.8cm from the beam line
- Run I $\overline{\chi}$ measurement required ≥2/4 SVX layers and muons could originate as far as 5.4cm from the beam line
- We observe many more events which are rejected by the tight SVX selection than expected:
  - More background in the total sample (before Si requirements)
  - Background is removed with the tight SI selection
  - Background is not removed with looser Si selection - large d_0

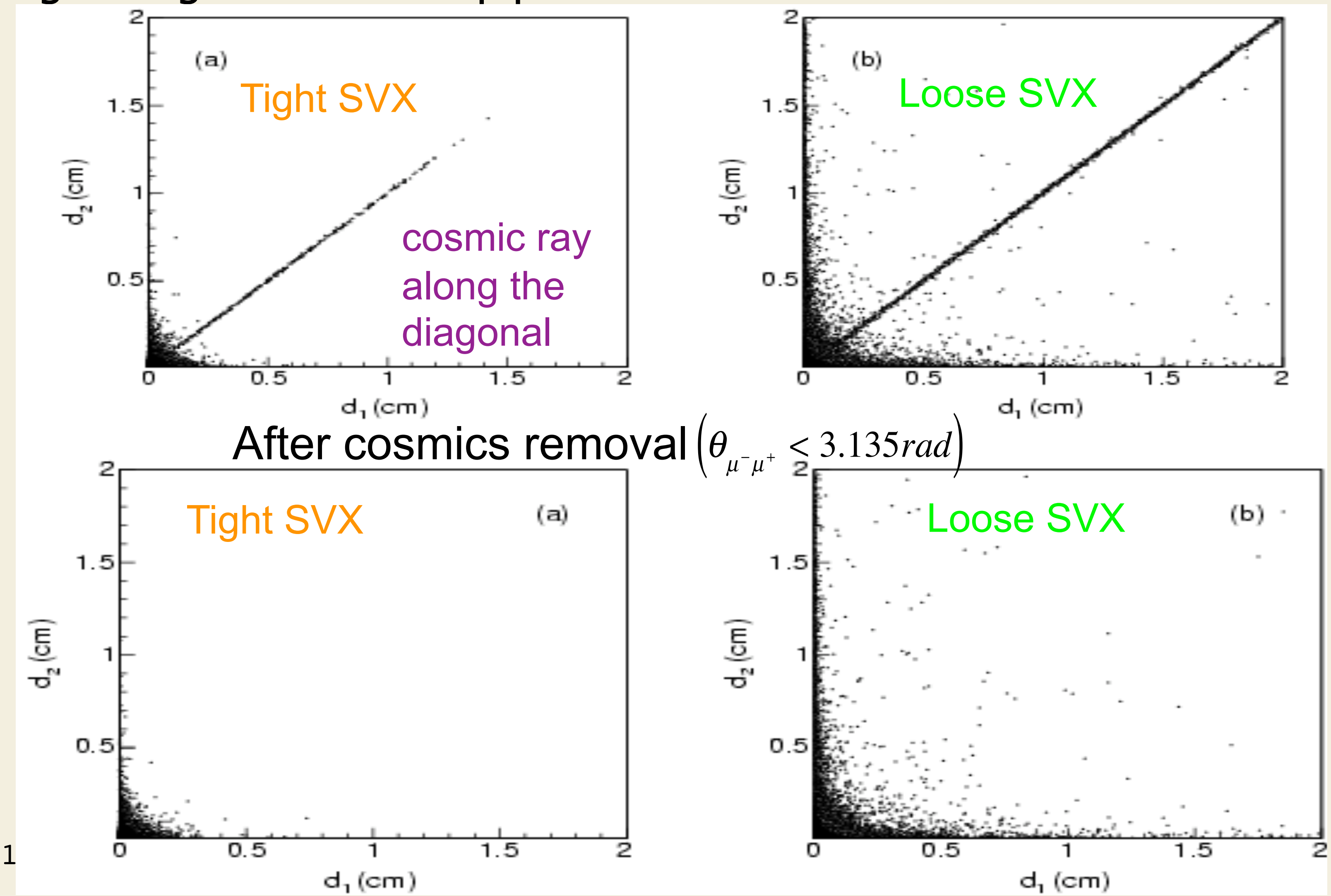


duced at the



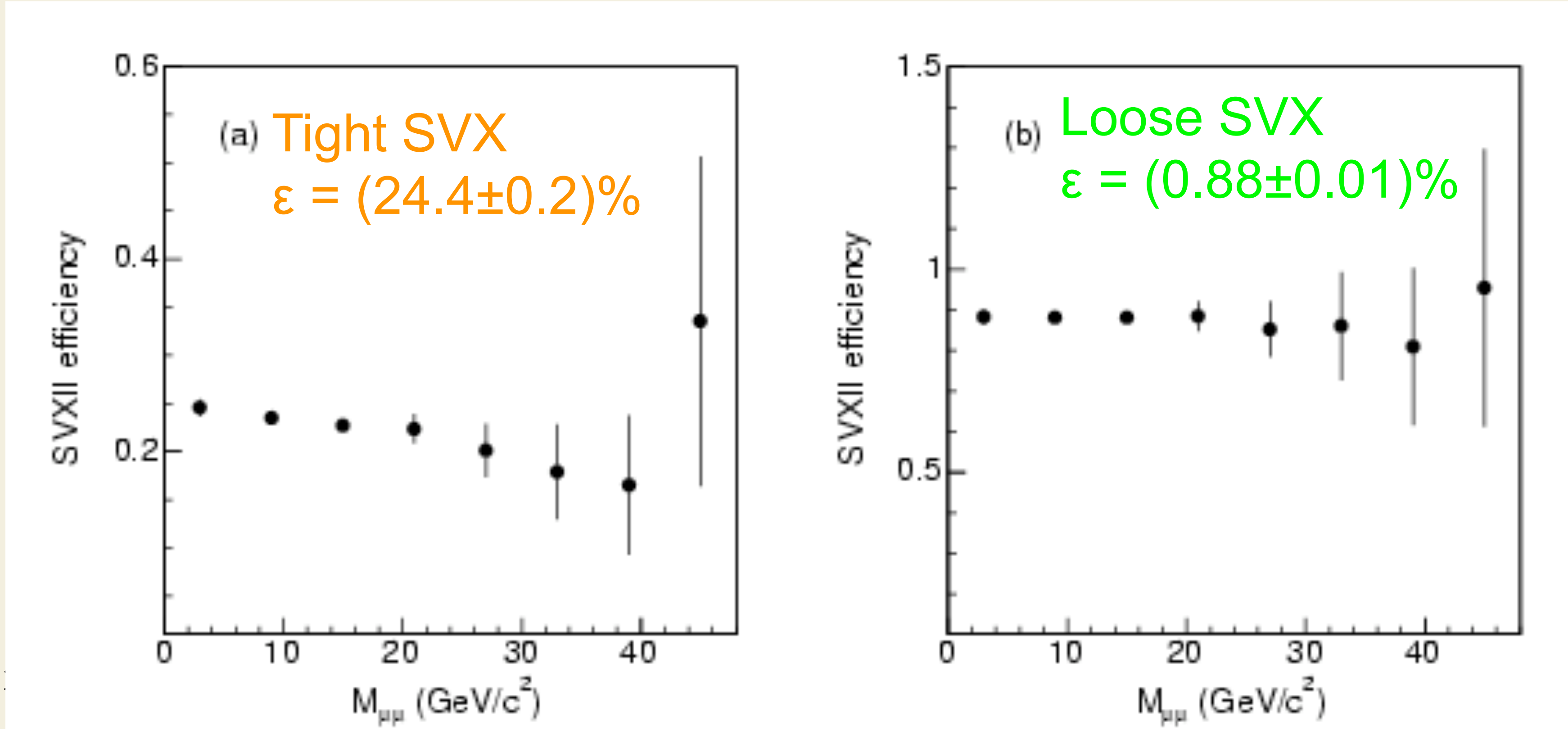
Cosmic rays and SVX Selection

- According to simulation, 96% of the QCD events have two muons originating inside beam pipe.



Efficiency of SVX Selection

- Evaluate efficiencies using control samples of data:
  - Prompt: (25.7±0.4)% use Υ and Drell-Yan
  - Heavy flavor: (23.7±0.1)% use $B \to J/\psi,\ B \to J/\psi K,\ B \to \mu D^0$
- Average efficiencies predicted using sample composition determined by impact parameter fit



Initial Mystery…

- The efficiency of the tight SVX selection of the dimuon data is measured to be ε=(19.3±0.04)%
- However it is expected to be ε=(24.4±0.2)% - Difference 79%
  - To see such a difference, the initial sample contains a large fraction of background events (ghost) that are suppressed by the tight SVX selection more than the QCD contributions

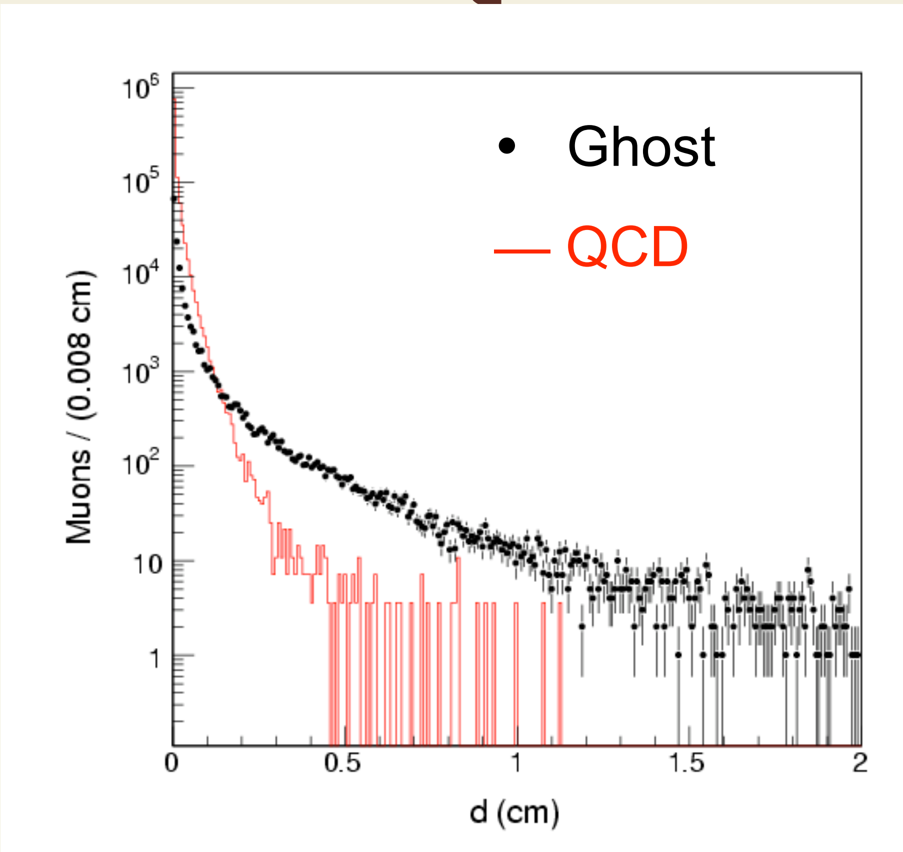
Sample Definitions/terminology:

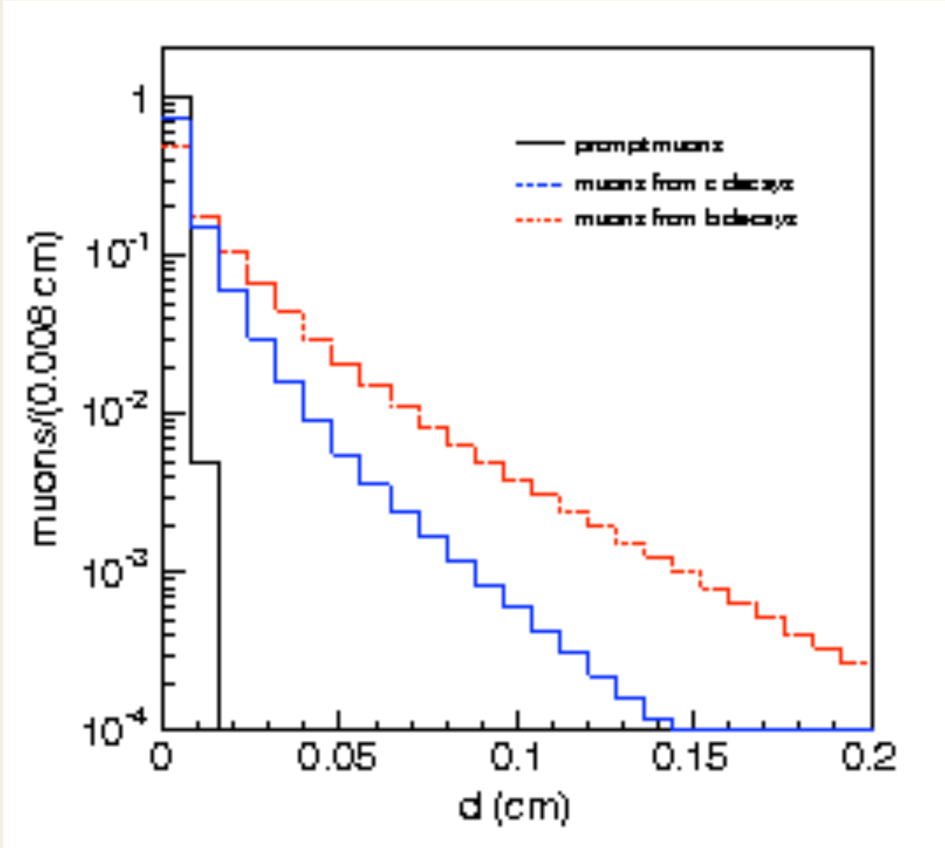
QCD = sum of contributions determined by the fit of the bb cross section analysis [b,c,prompt]

GHOST = The excess in the data after accounting for the efficiency of the tight SVX selection

$$Ghost = Data - (tight\ SVX)/\varepsilon_{tight\ \mathrm{SVX}}$$

Impact Parameter Distributions of QCD and Ghost Events

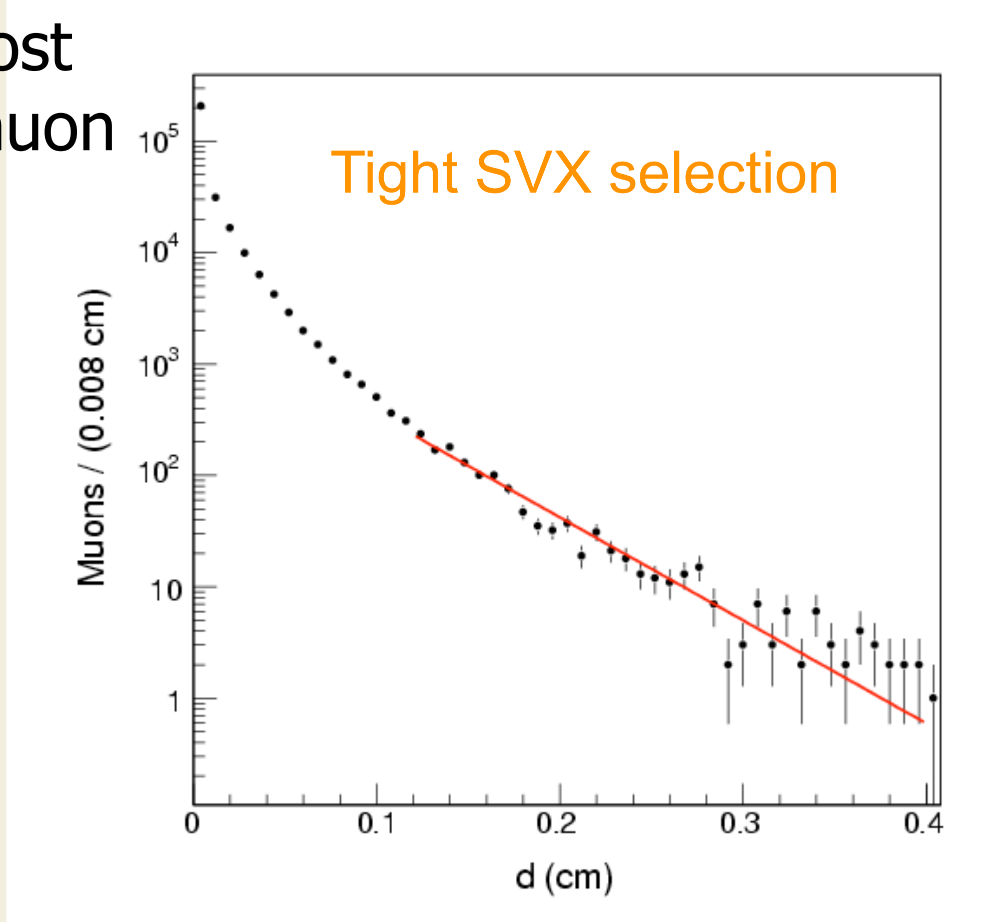




Events due to QCD processes have $d_0(\mu) < 0.5$ cm
Ghost events have large d_0 tail

Tight SVX sample

- Assume no presence of ghost events in the tight SVX dimuon sample – Reasonable
- Charm-quark contribution exhausts beyond 0.12 *cm*.
- Bottom-quark contribution exhausts beyond 0.5 *cm*.
  - Fit: $c\tau = 469.7 \pm 1.3\ \mu m$
  - PDG: $c\tau = 470.1 \pm 2.7\ \mu m$
- Bottom data are not appreciably contaminated by the ghost events.



Yields in 742 pb^{-1}

Type	Total	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

event counting

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assumption

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Extrapolated by tight/loose efficiency measured using MC

Yields in 742 pb^{-1}

Ghost = All − QCD

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[explain inconsistency #3]

bb sample consists of 221564±11615 events without SVX request (194976±10458 bb events with loose SVX) – Ghost events :154K!

Lessons learnt so far

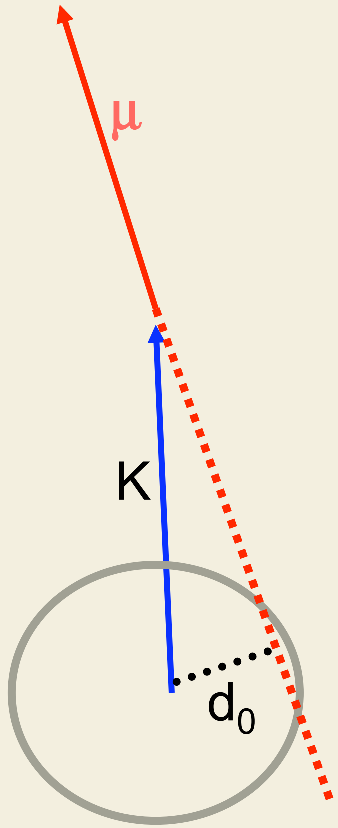
- We have observed a source of background that has not be considered in previous analyses
- Plausible this background explains previous inconsistencies:
  - bb cross section of Run I as measured from semileptonic decays
    - Run II measurement with tight SVX curs very close to NLO predictions
  - Time integrated mixing as measured at Tevatron larger than LEP
    - Ghost events definitely affect the SS/OS
- There is still an unexplored yet inconsistency:
  - The low mass dilepton spectrum observed in run I

Need to find an explanation for the source of the ghost events

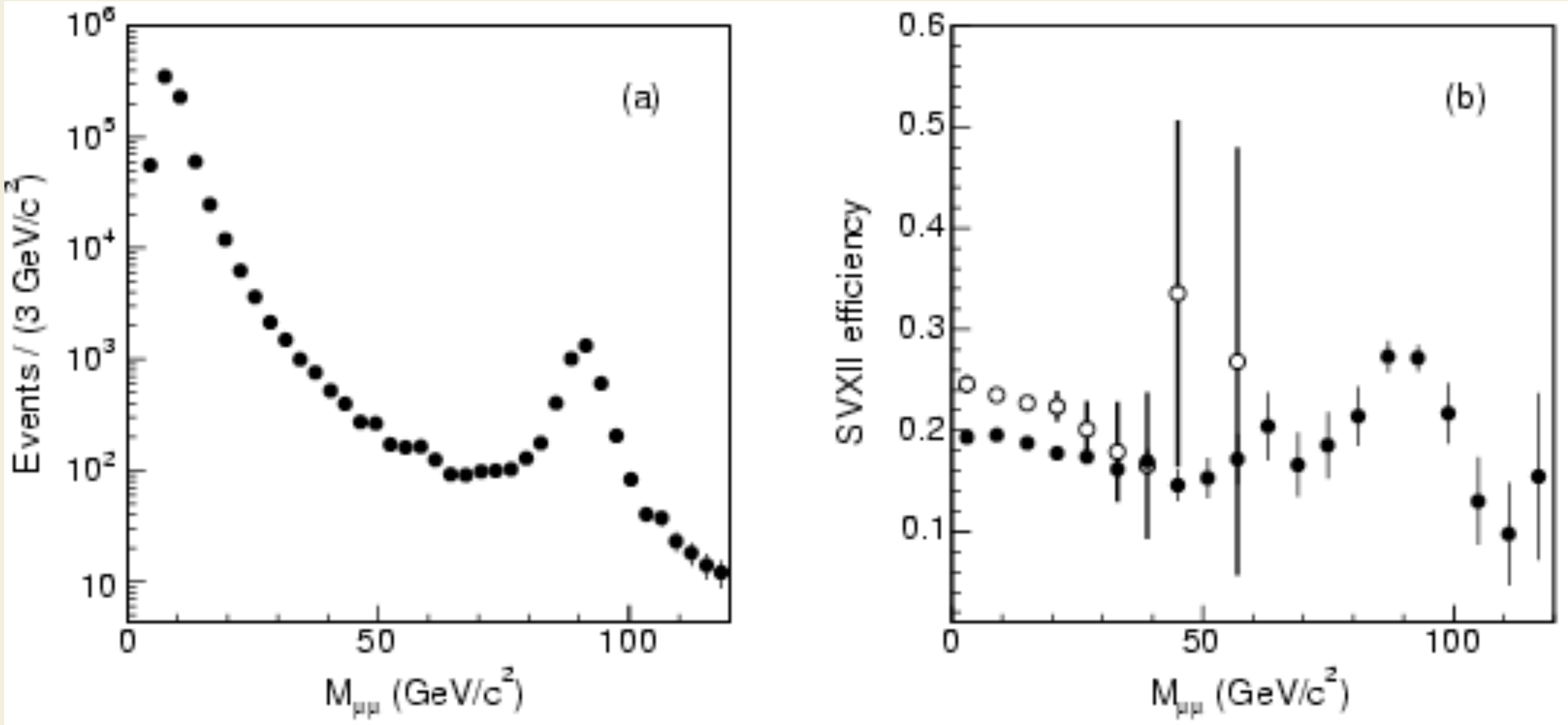
Possible sources of ghost events?

?? What could give rise to real or fake muons that have large d0 and miss the inner silicon layers??

- In flight decays of $K^{\pm} \to \mu^{\pm}\nu_{\mu}$ and $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$ (may result to mismeasured tracks that link to SVX with lower efficiency)
- Long-lived hyperons (Λ, K_S^0)
- Mismeasured tracks
- Secondary interactions of hadrons in the silicon produce secondaries with large d0
- Heavy flavor hadrons with unusual large Lorentz boost – inconsistent though with high d_0



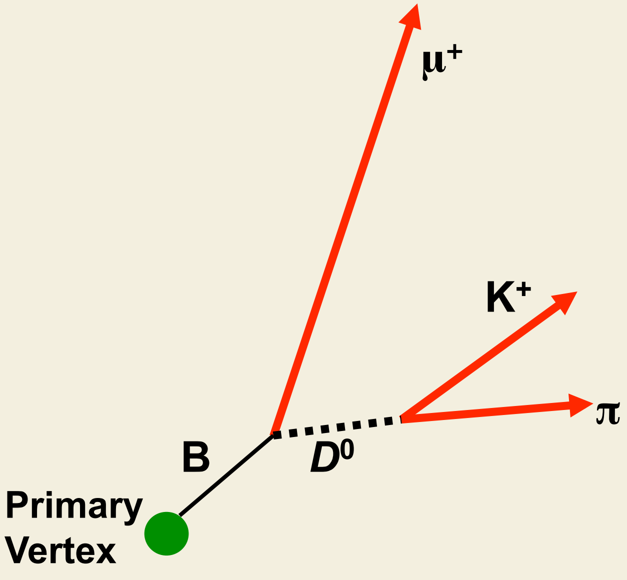
Lorentz Boost



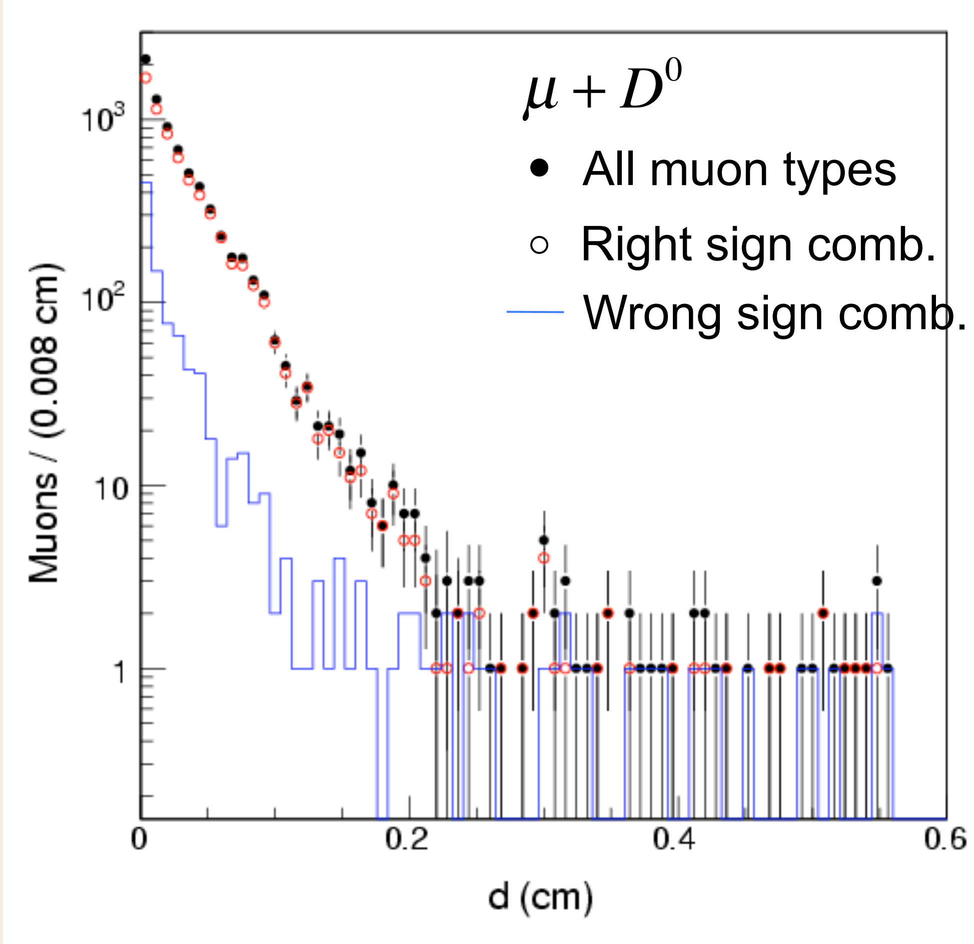
Track mismeasurement

Look at $\mu + D^0$ events

Most of them come from $b\bar{b}$ and a few from $c\bar{c}$



Additional studies of track quality and other control modes show no tracking problems



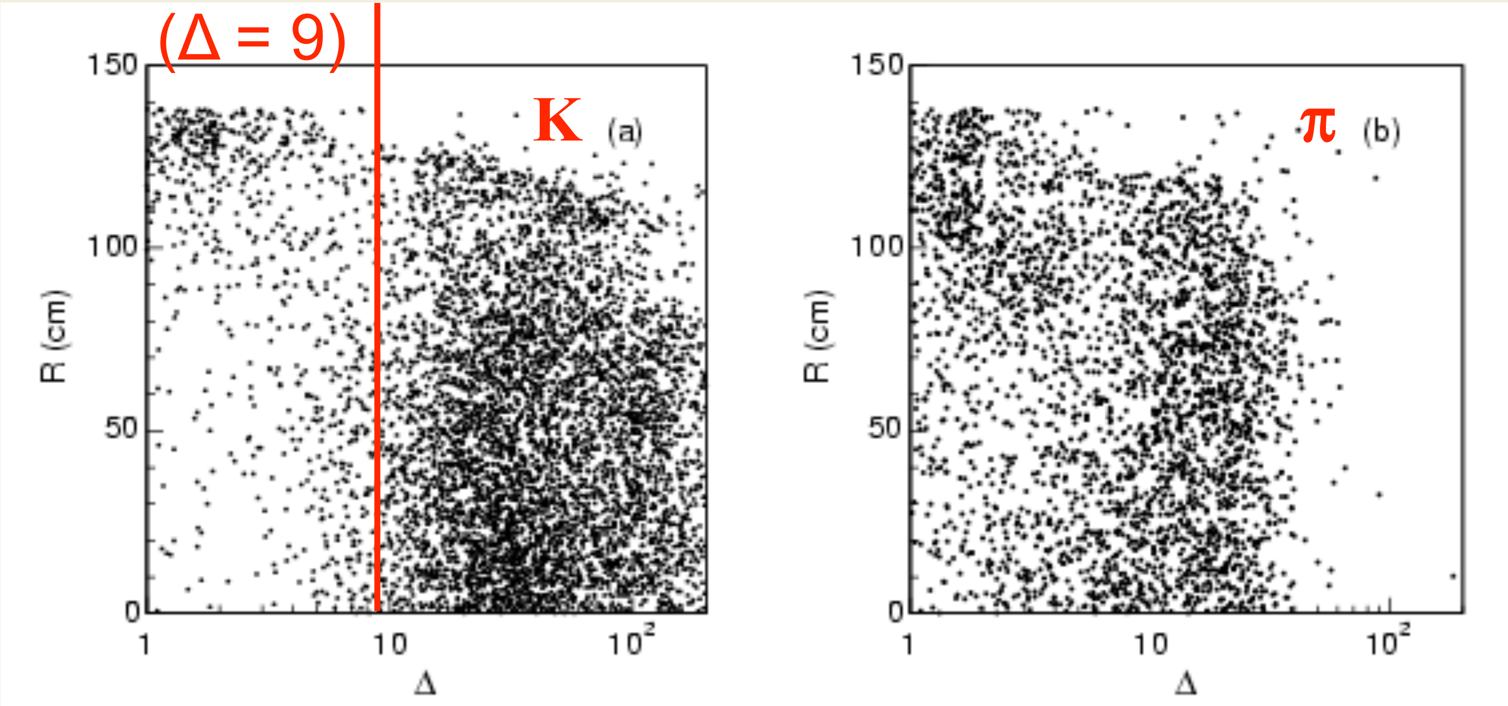
$d_0(\mu)$ consistent as coming from B's

No evidence of long tail

WS comb. show low level of fakes

In-Flight Decays

- Measure the probability that *K* and *π* decays produce CMUP muons (trigger muons) and pass all analysis cuts.
  Use a heavy flavor simulation [HERWIG].



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

In-Flight Decays (continue)

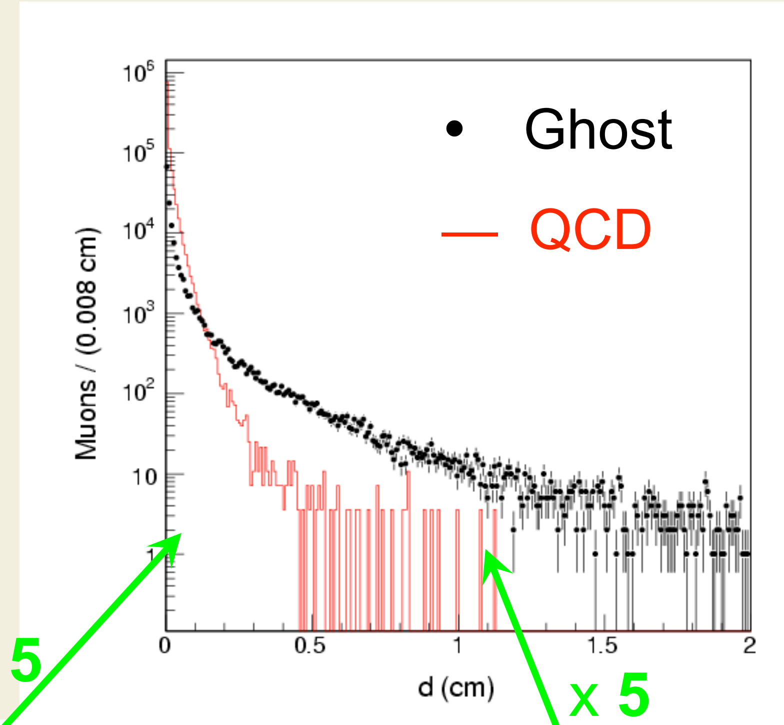
- Probability per track that a hadron yields a trigger muon is
  0.07% for π and 0.34% for K
- Normalize this rate from Herwig MC to measured bb cross section
- We predict 57000 events in ghost sample due to in-flight decays
- Large uncertainty on the prediction mainly due to:
  total cross section, bb cross section, π/K fractions, acceptance, momentum spectrum
- In-flight decays could account for total yield of ghost events

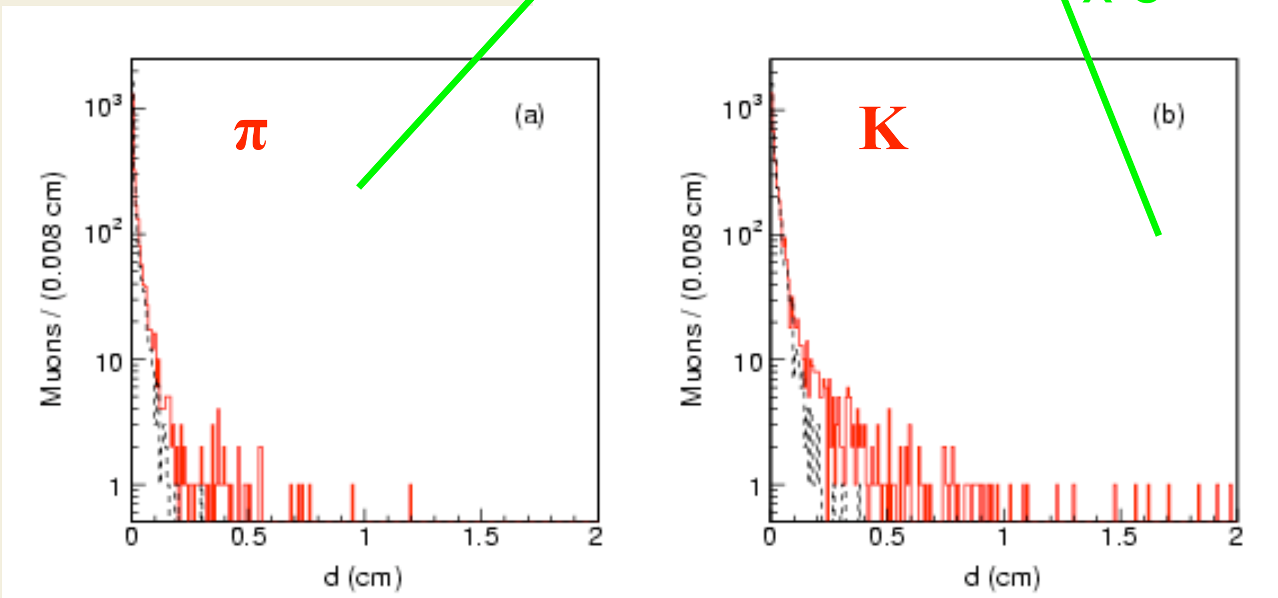
Selection	π (P = 0.07%)	K (P = 0.34%)
Tracks	2667199	1574610
In-flight-decays (Δ > 5)	14677	40561
CMUP + L1	1940	5430
Loose SVX	897	3032
Tight SVX	319	1135

Impact parameter of In-Flight Decays

- In-Flight decay prediction explains 35 % of the ghost events, but only 10% of the events with

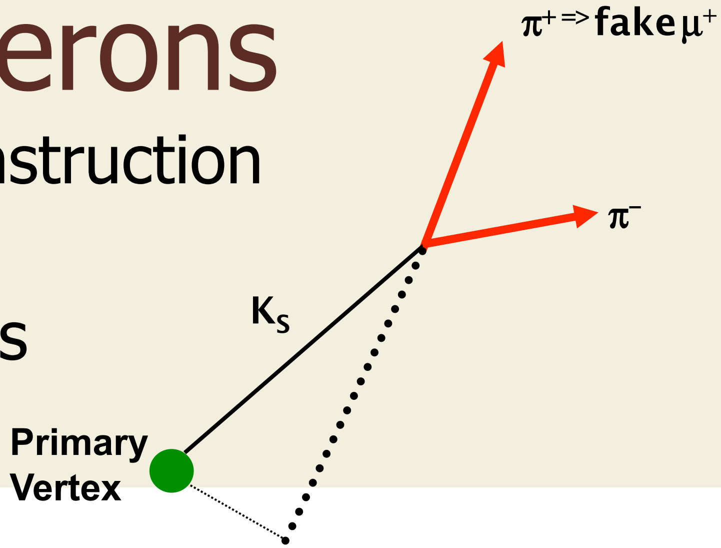
  d > 0.5 *cm.*

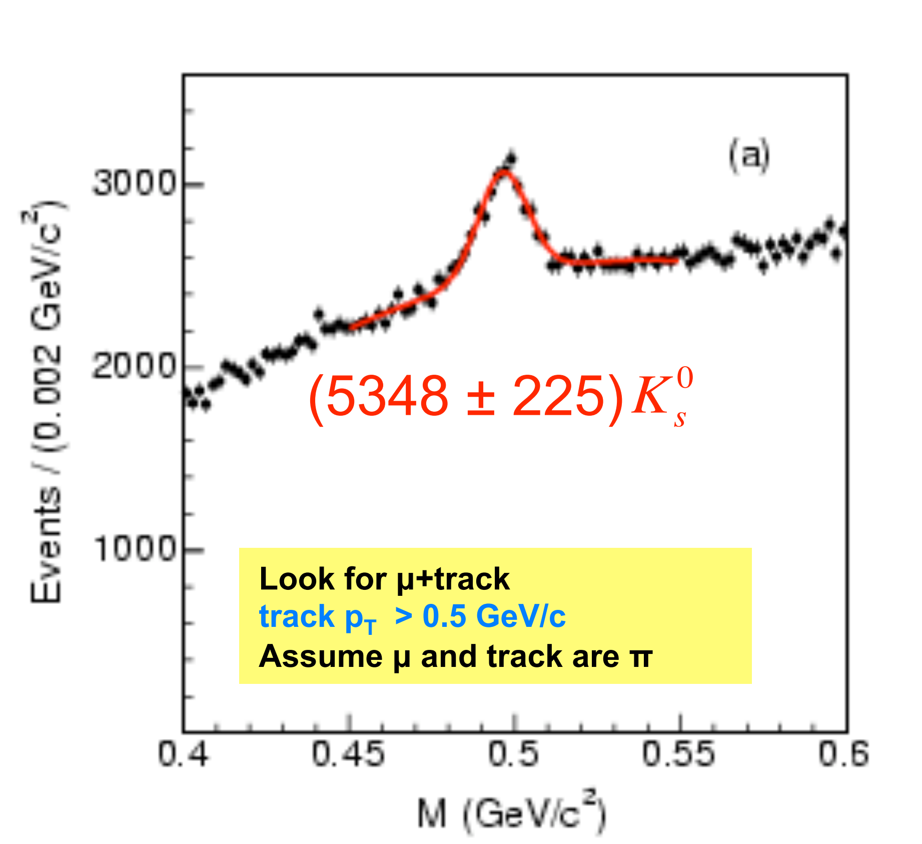


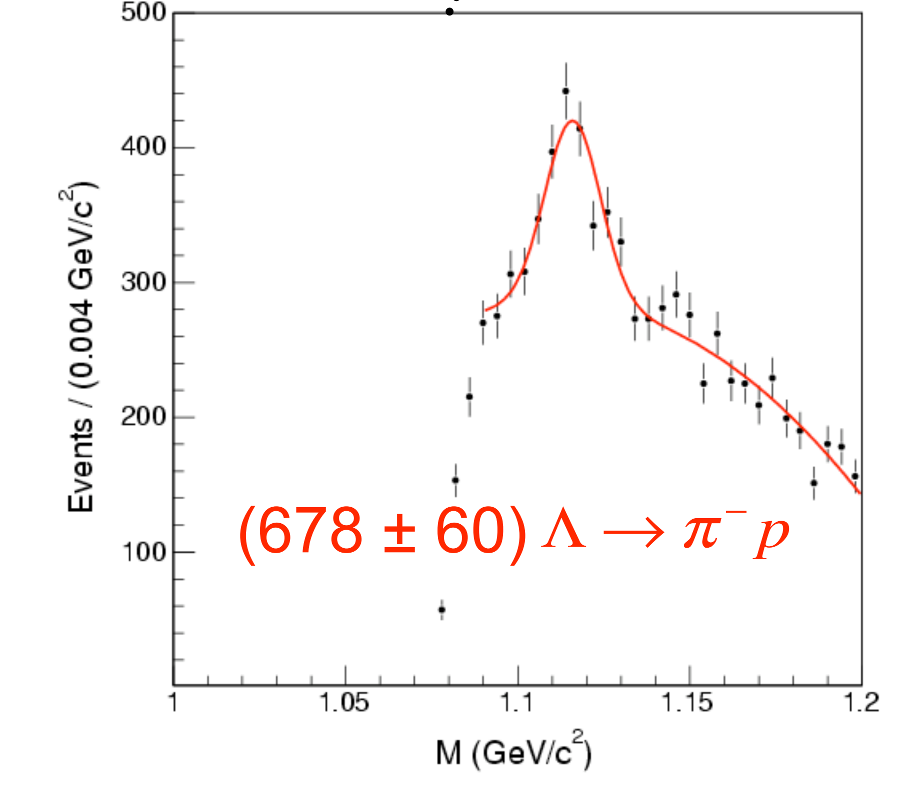


K^0_S and hyperons

- Kinematic acceptance times reconstruction efficiency ~ 50%.
- Approximately 12000 ghost events contributed by these decays.

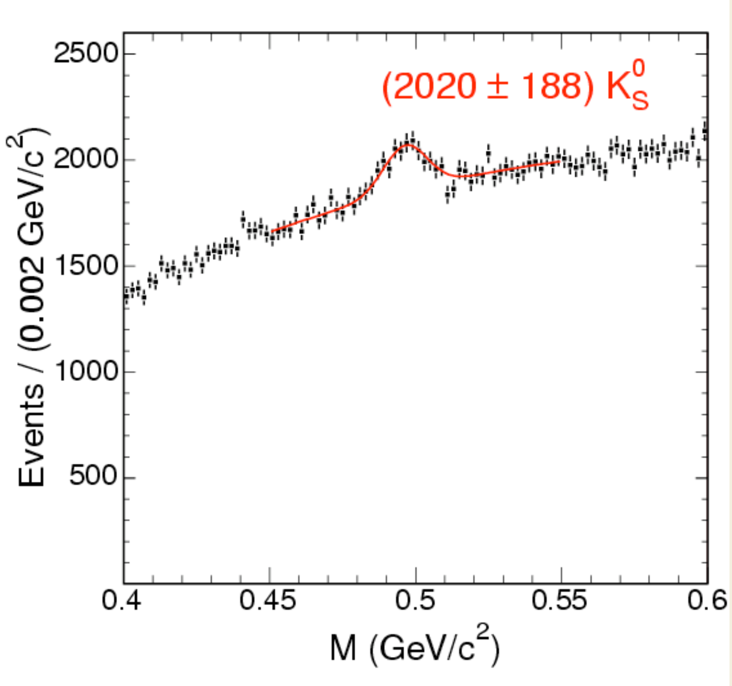


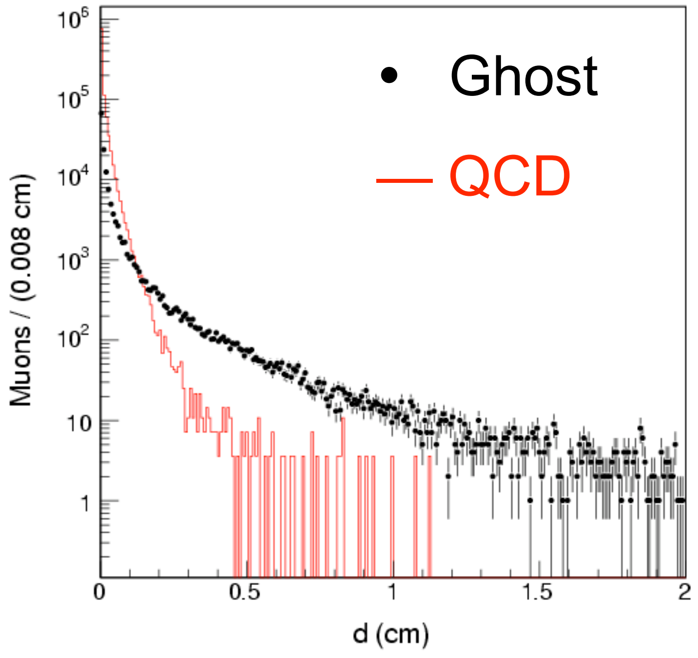


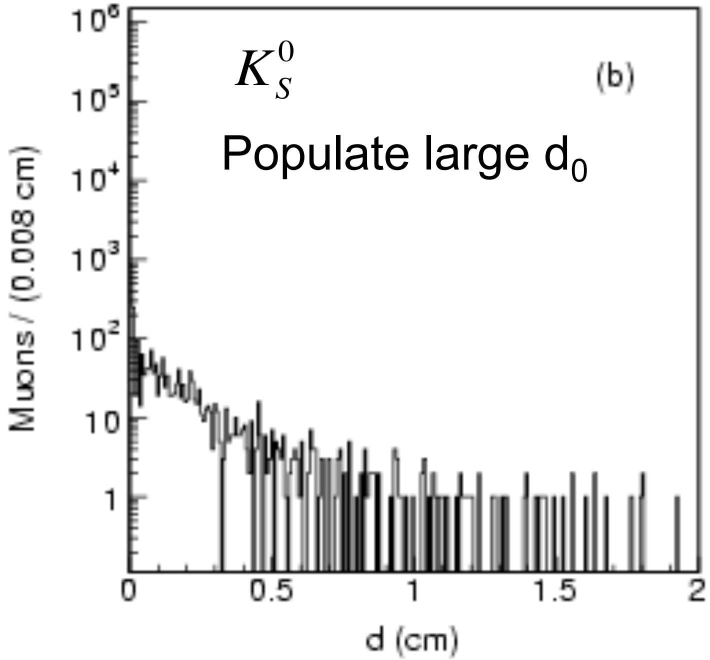


$K^0{}_S$

- Loose SVX selection



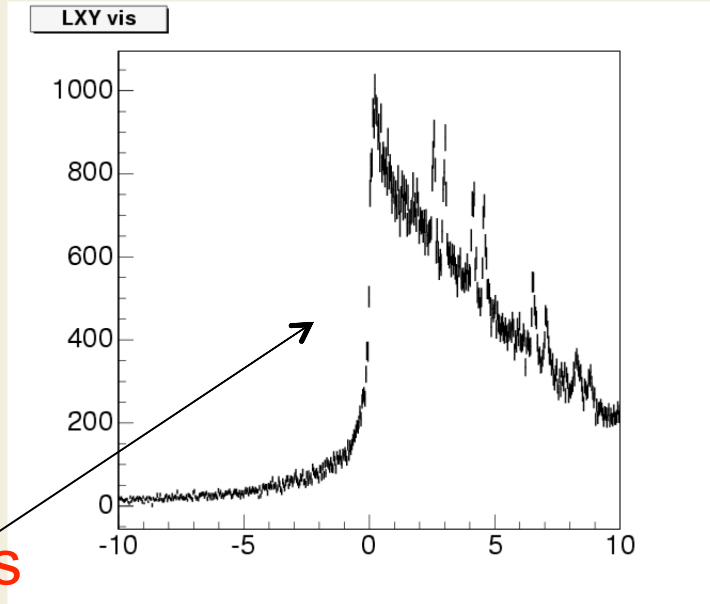


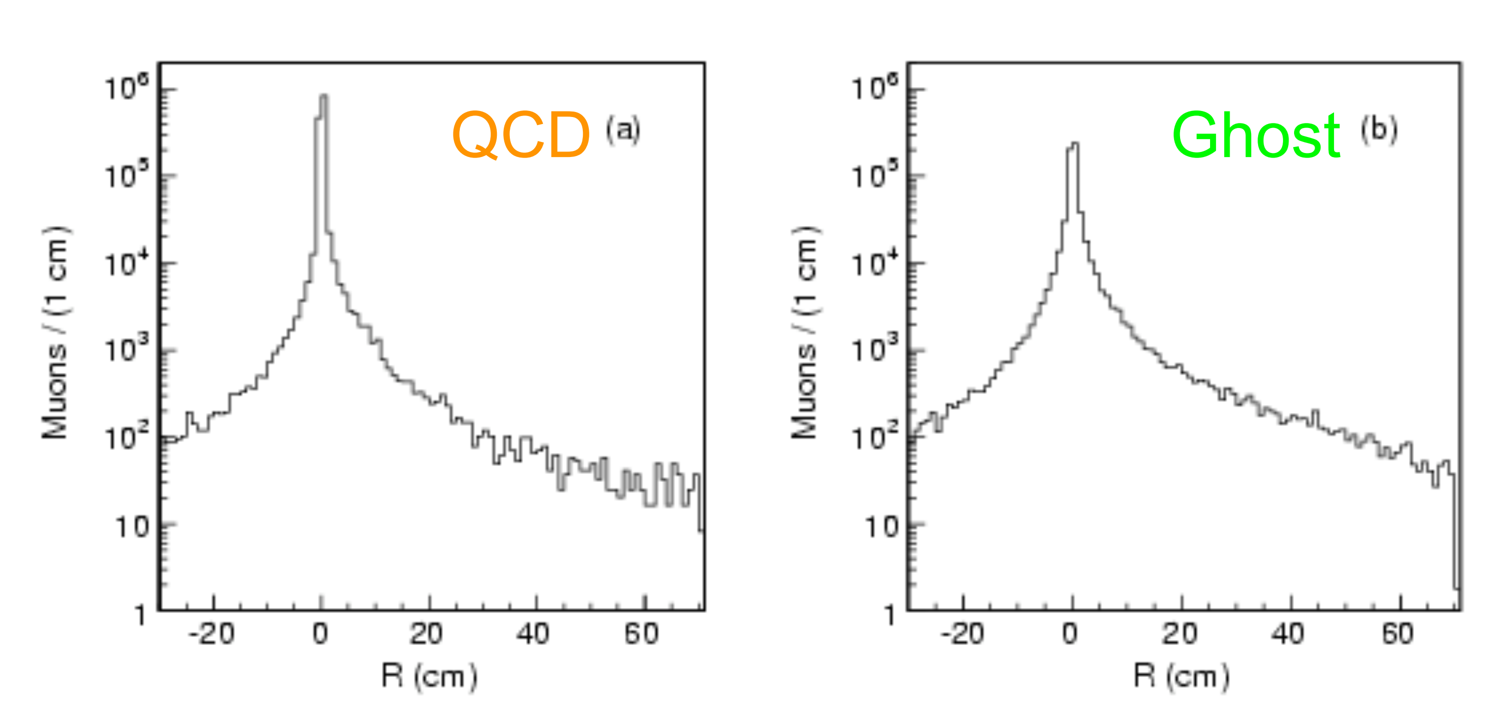


Secondary Interactions

- Combine initial muons with tracks with $p_T > 1$ GeV in a 40^o 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

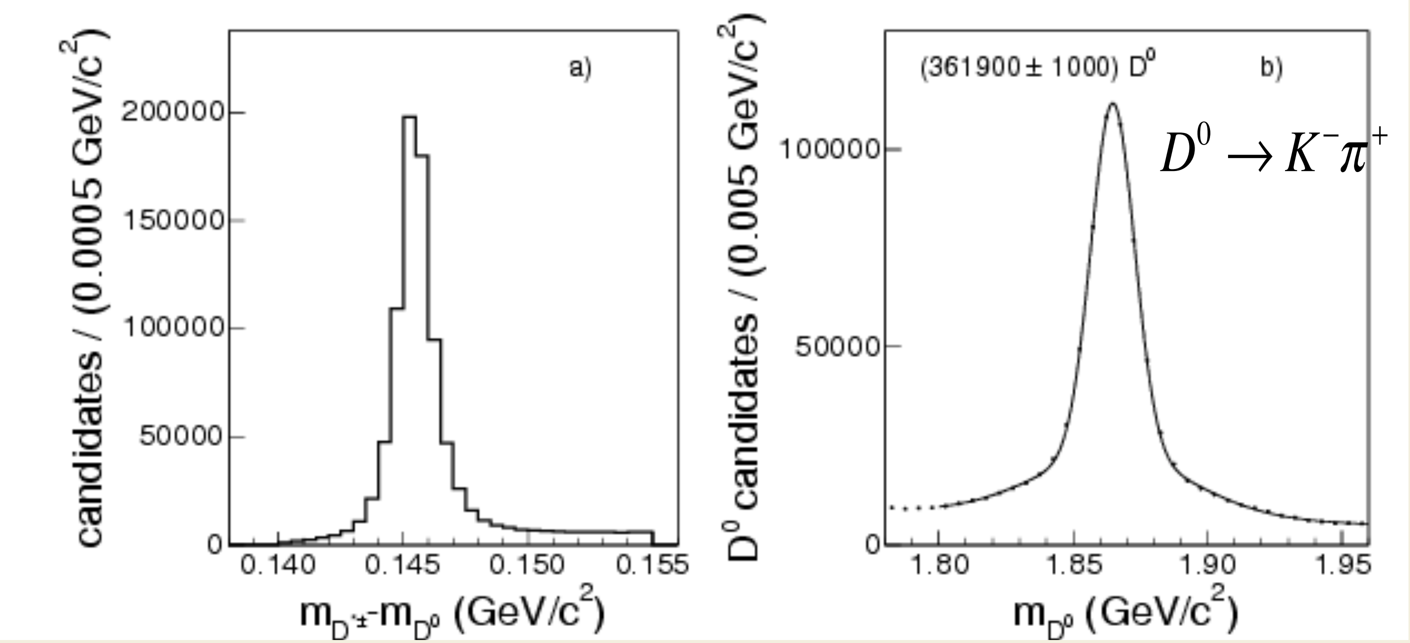
At this point it appears that ghost events can be fully accounted for by a combination of in-flight and long-lived decays.

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
- Look for additional muons with $p_T > 2$ GeV, $|\eta|<1.1$ around each initial muon and ask the invariant mass to be < 5 GeV
- Expectation:
  - Main source of real additional muons are b sequential decays
  - a sizable contribution of muons mimicked by hadrons
- Strategy:
  - Keep acceptance maximal using loose muon selection
  - Take higher muon fake rate but correct for it by precisely assessing the fakes

Muon fake rates

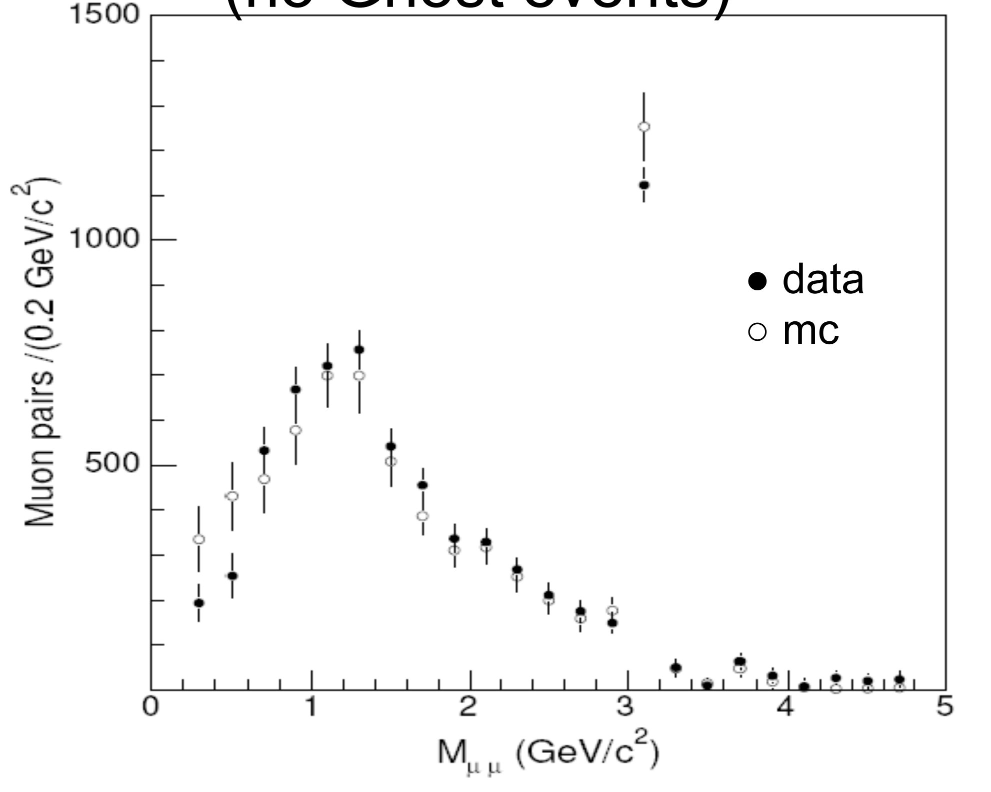
- Measure the probability per track that a π or a K will punch through the calorimeter and fake a muon
- Technique
  - Reconstruct $D^{*+} \to D^0\pi^+$ decays with $D^0 \to K^-\pi^+$
  - D^{*+} uniquely identifies π and K
  - Reconstruction by tracking only. Ask at what rate hadrons were found as muons

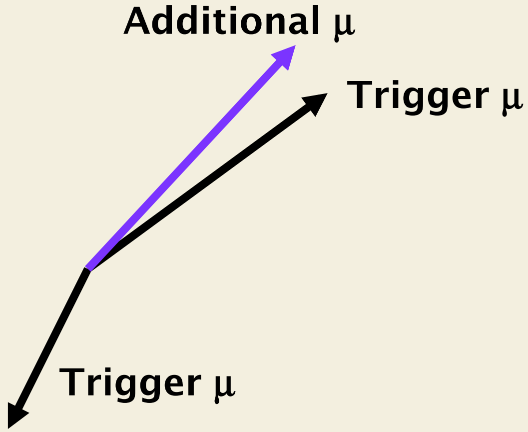


Verifying the fake rates

- Compare data to simulation that includes fake predictions

Tight SVX selection
(no Ghost events)





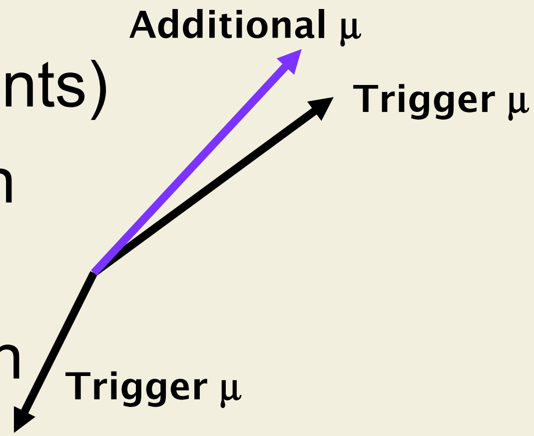
Observe:

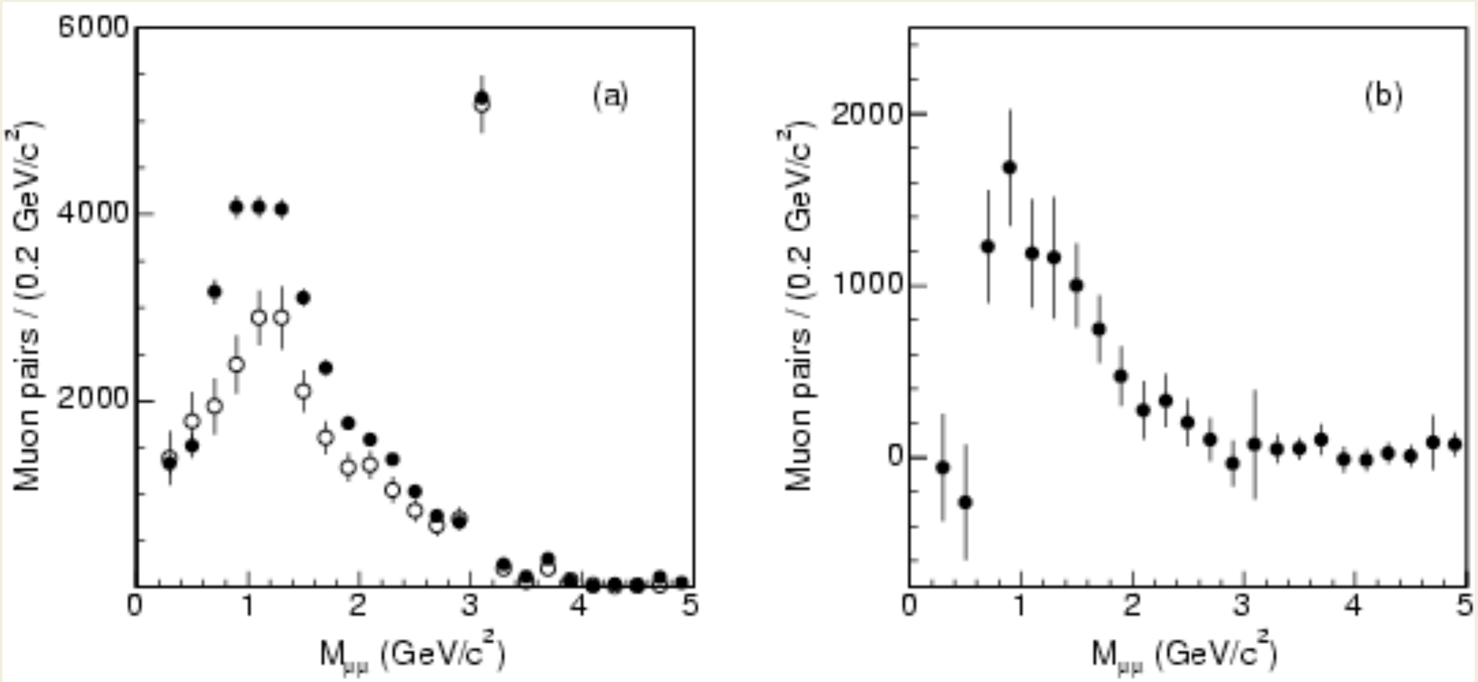
Data: 6935±154
MC: 6998±239

We conclude we understand the heavy flavor simulation and the fake muon bkg

Low mass dilepton

- ➢ Use the entire sample (no silicon requirements)
- ❑ Compare data to the heavy flavor simulation that includes fakes
  - ✓ Excellent agreement on the J/ψ prediction
  - ➢ Clear excess at low mass
    - – not seen with tight SVX – associated with ghost events





Same as the low mass excess of Run I

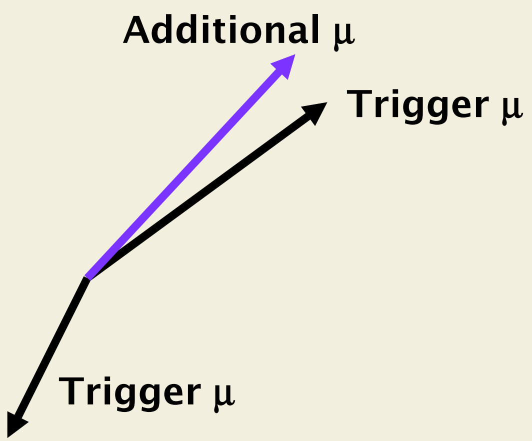
Multiplicities

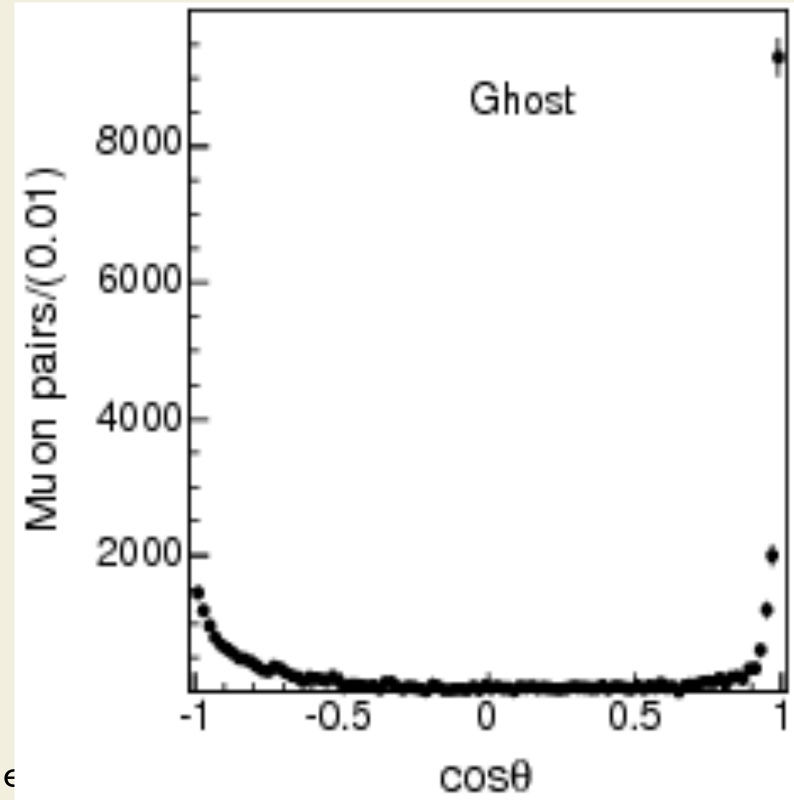
- QCD sample well understood
- Ghost sample less understood but appears to be mostly due to known processes with muons coming from decays in flight or decays of long lived hyperons

- Compare ghost to QCD
  - After correcting for fakes the rate of additional muons in the Ghost sample is 4 times that of QCD
  - ?? If there were due to in-flight decays we would expect the additional muon rate to be suppressed
  - Number of charged tracks (p_T>2GeV) is 2 times larger in ghost events than QCD

Additional muons

- Additional muons very close to trigger muons
- Almost all muons have cosθ>0.8 within the nearest trigger muon
- Evaluate additional muons within a cone of cosθ>0.8 around the trigger muon





Additional muon multiplicity

Plot shows additional muons in a single cone (after fake removal)

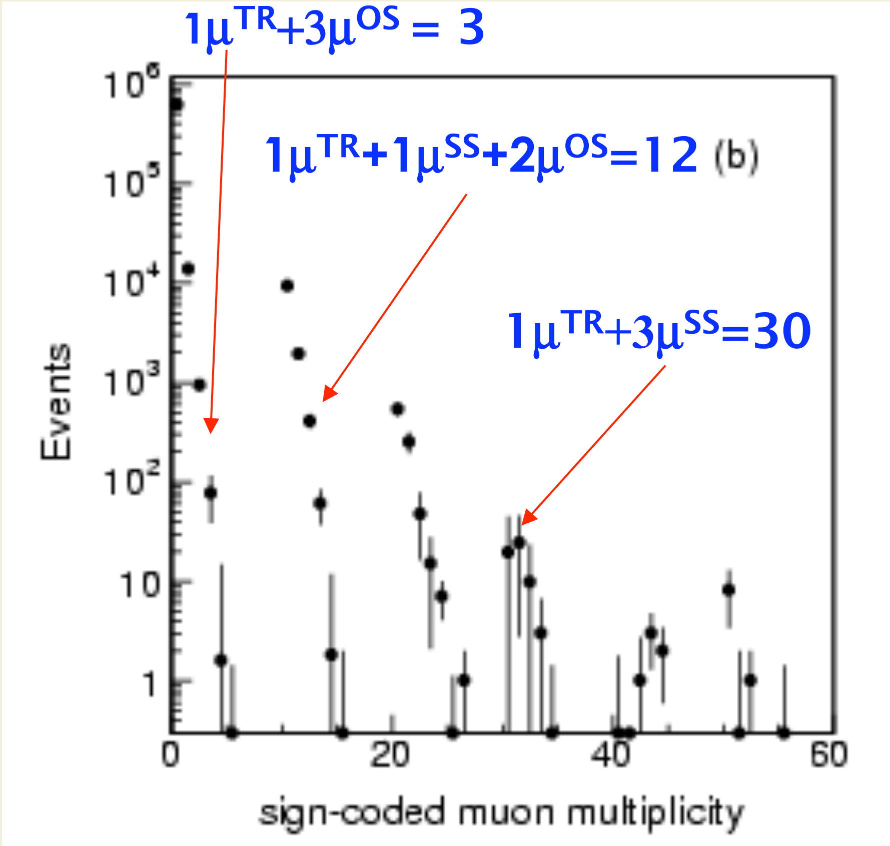
We count additional muons and not the trigger muon

Relative to trigger muon:

OS: μ+1

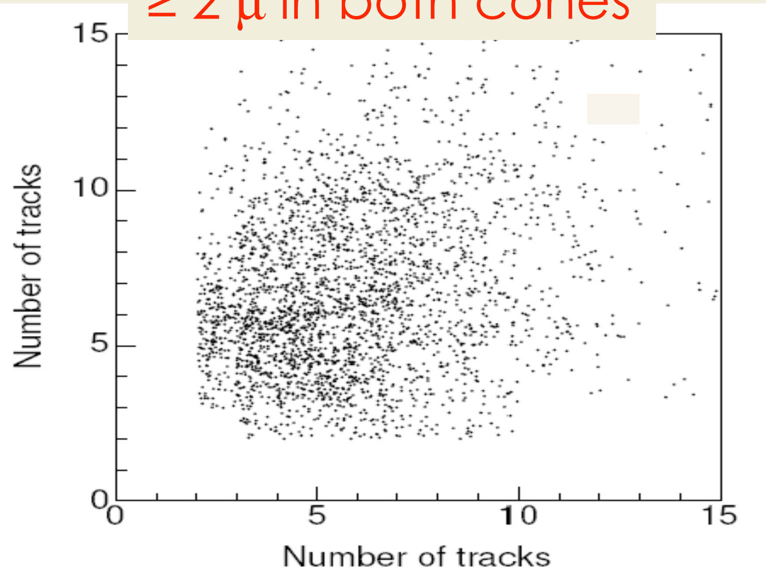
SS: μ+10

For example: in a cone of μ^+ we find $2\mu^-$ and $1\mu^+$:
It corresponds to bin 12



On average a multiplicity increase results in a population decrease of 7

Cone correlations



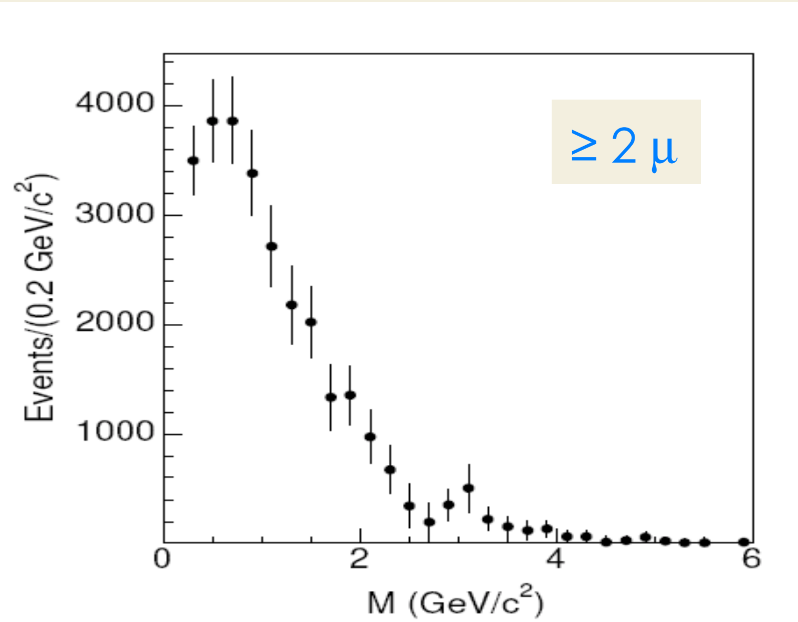
Ghost Events

27790±761 cones with ≥2μ (α)

4133±263 cones with ≥ 3μ

3016 with ≥2μ in both cones (b)

Ration of (b)/(a) =0.11 comparable to what expected for double parton production (jets)



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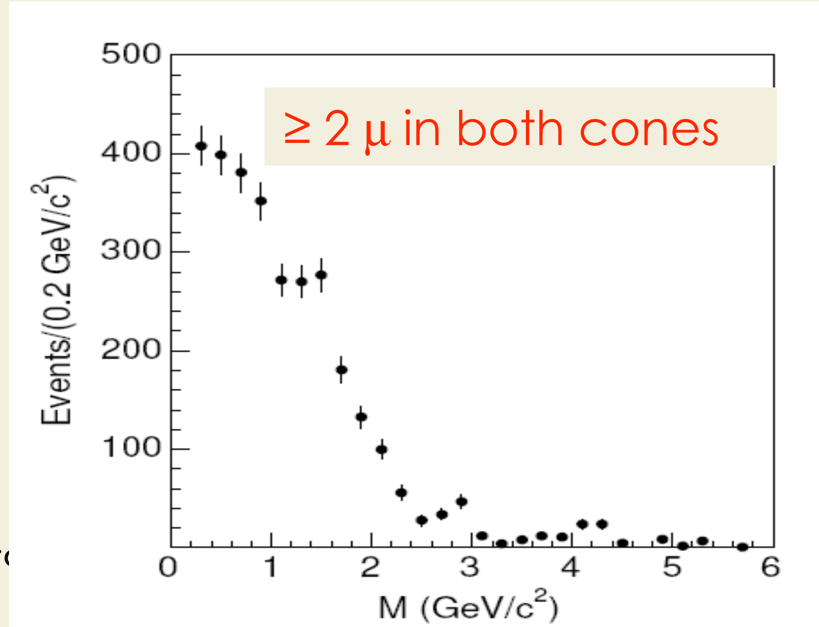
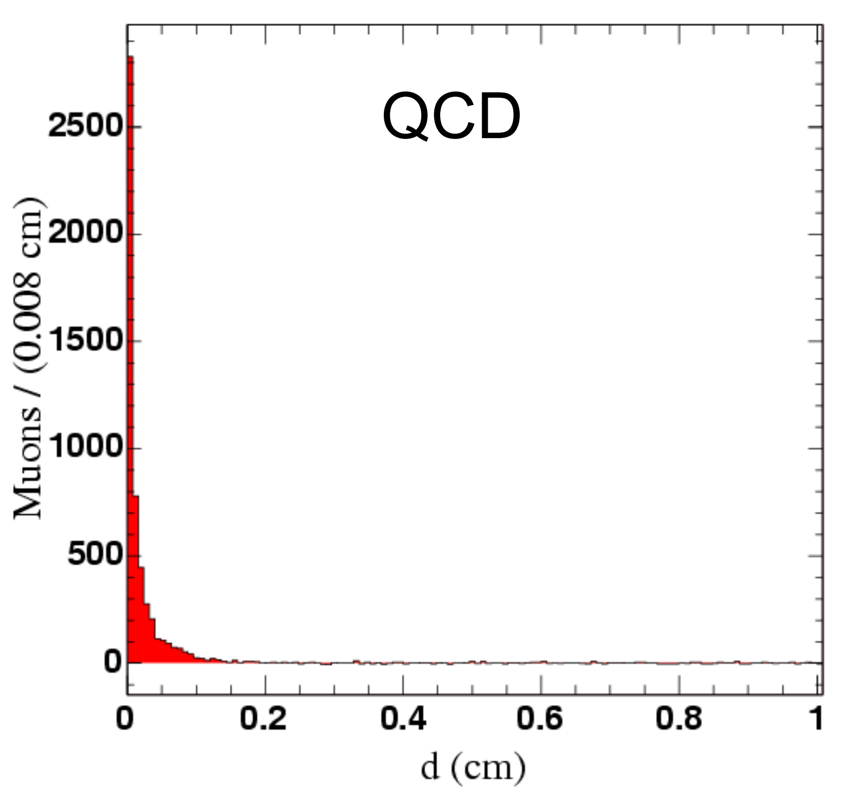
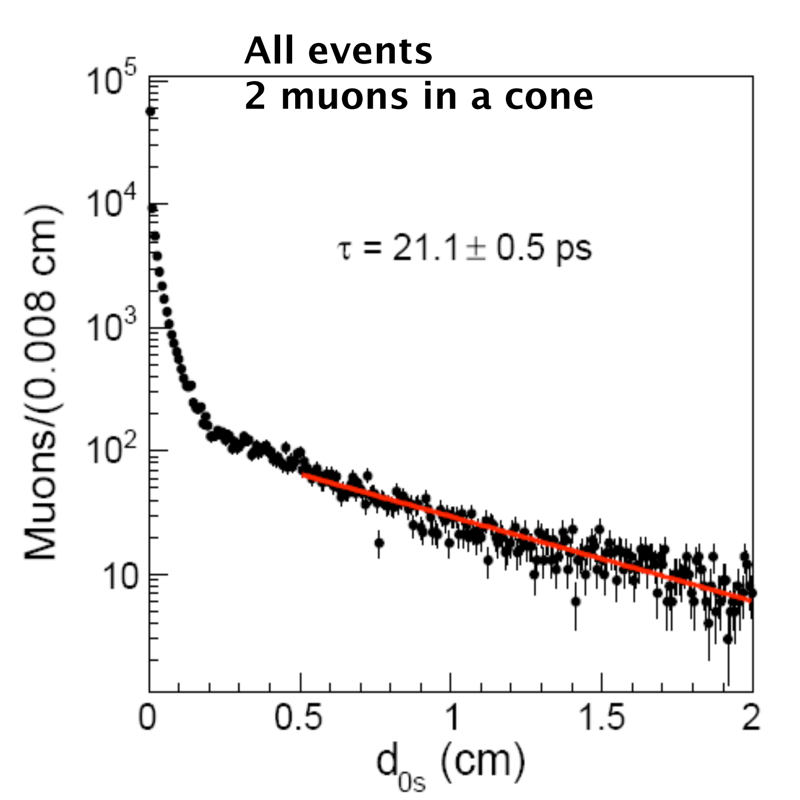


Impact parameter of additional muons

Look at the impact parameter of additional muons
It is not biased by the trigger requirement on the initial muons





Features of the Ghost sample

- After correcting for fakes the rate of additional muons in the Ghost sample is 4 times larger than in the QCD sample
  - If we had assumed that the initial Ghost sample is due to in-flight decays we wouldn’t expect to see an increased rate of additional muons
- We have observed events with muon multiplicity of 3 or 4 muons in a cone of 36.8^0 around the trigger muon
- The track multiplicity in the Ghost sample (tracks with p_T>2GeV) is 2 times larger than in the QCD sample
- The additional muons in the Ghost sample exhibit impact parameter distribution which extends well above the one of additional muons in the QCD sample

The Ghost sample

We have identified a background sample comparable in size to the sample from bb production.

Large fraction of the background can be identified in terms of known processes – decays in flight, K_S and hyperon decays

The background possesses some strange/unexplained piece and is inconsistent to our expectations

- This piece of the background contains high muon and track multiplicity.

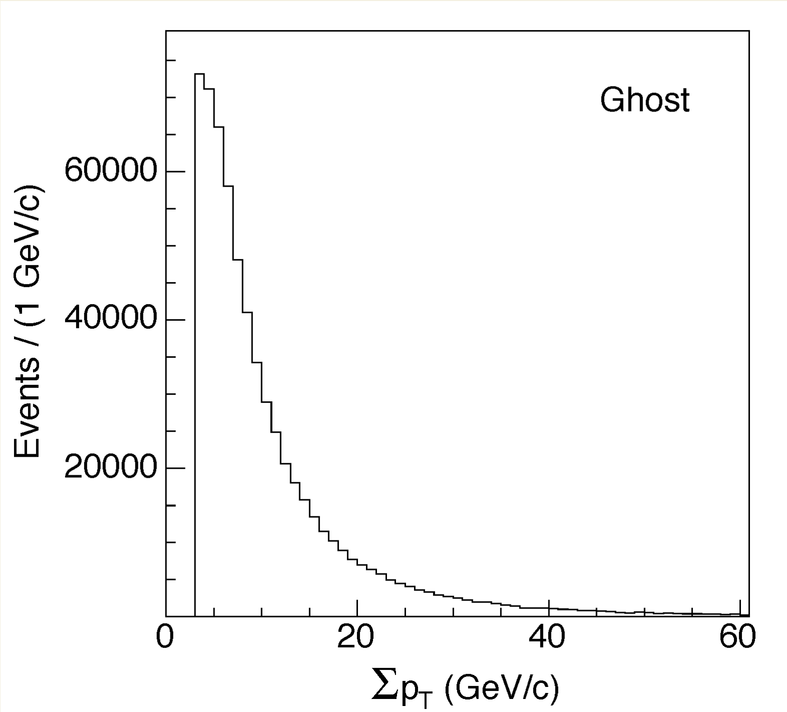
Contrary to this observations we understand very well the QCD sample in terms of detector, reconstruction and physics

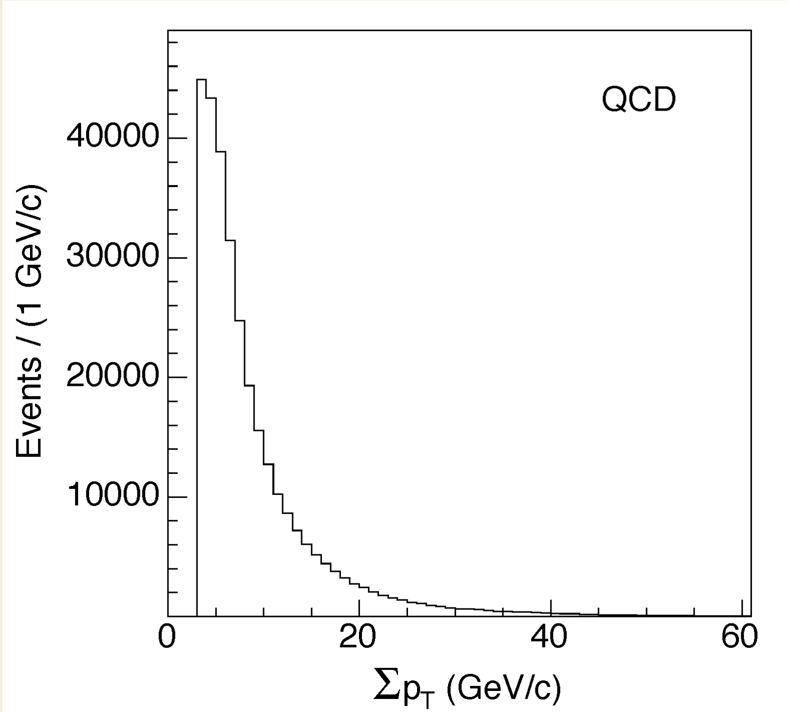
Comments on Fake rates

- Fake rates are derived on "per track" basis and it is assumed that fake muons are uncorrelated
- For high energy jets there might be leakage on the back of the calorimeter causing activity in the muon chambers and therefore fakes – So assumption may not be totally true
  - Lack of a control sample to study the effect
- However by tightening the muon selection criteria or asking high purity muons (CMUP) reduce the acceptance but do not alter the salient features of the data
- Assuming that all high multiplicity events are fakes we can remove only 1/3 of the excess above QCD events
- Even if the high multiplicity events were due to correlated fake muons we should have observed them in the QCD data

Correlated fakes?

- Other analysis deriving fake muon rates [SoftLeptonTagging for top events] do not observe any effects of correlated fakes
- Are Ghost events different than QCD in terms of energy flow?



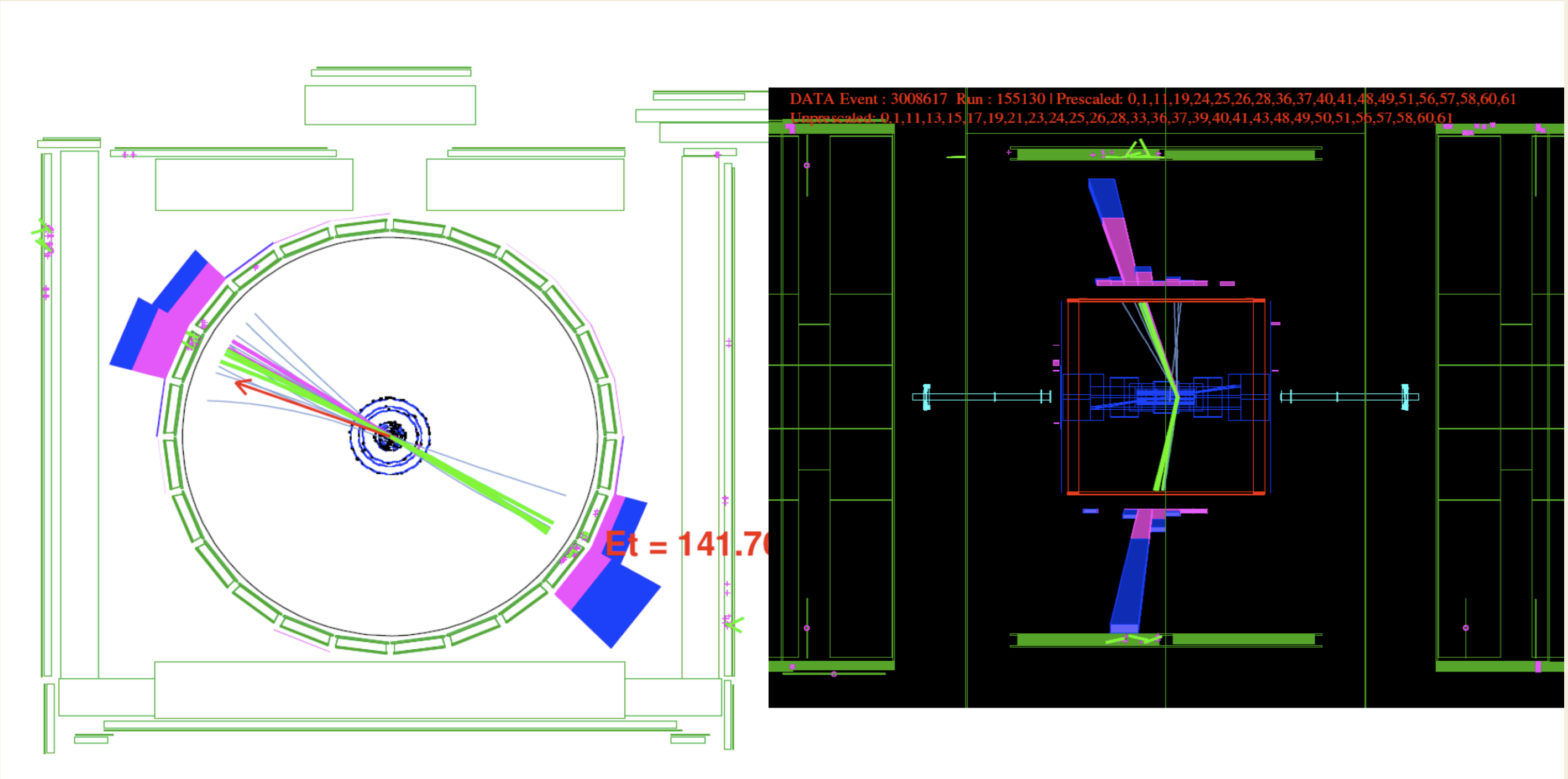


No dramatic differences in the total momentum spectrum of tracks with p_T>1GeV inside a cone of 36.8^o around a muon In QCD and Ghost - Ghost sample a bit harder in

Summary

- Through the study of multi-muon events acquired by CDF detector with a dedicated di-muon trigger, we believe we have found a plausible explanation for all inconsistencies and puzzles which have affected measurements of the *b*-quark production and decay at the Tevatron for a decade.
- We have identified a sample of events which appear to be special with some very unique properties.
- We currently cannot explain these events, and we have not ruled out known processes.

Event Display



Event Display (continue)