Study of Multi-muon Events at CDF

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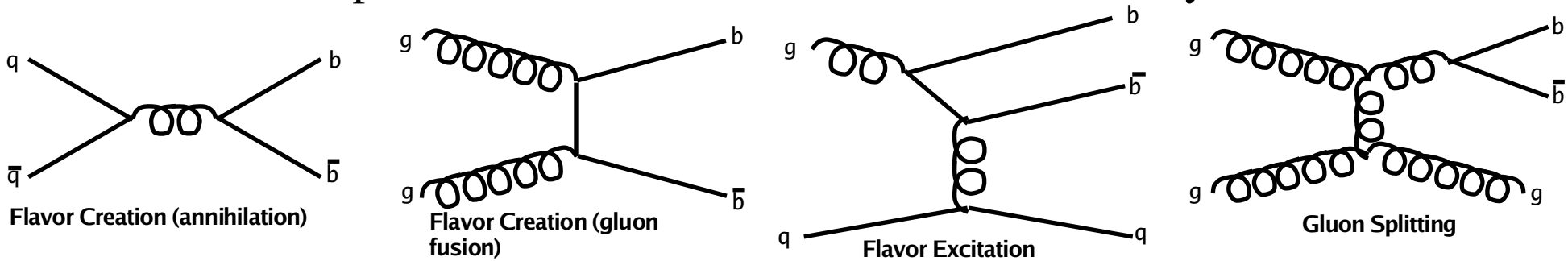
Outline

- History
  - Previous puzzles from b production and decay
    - Correlated bb production
    - Time integrated mixing
    - Dilepton invariant mass spectrum
- New study of Multi-muon events
  - Analysis leading to excess of multi-muon events
  - Possible sources of multi-muon excess
  - Additional properties of excess

- Acknowledgments: Paolo Giromini, Kevin Pitts

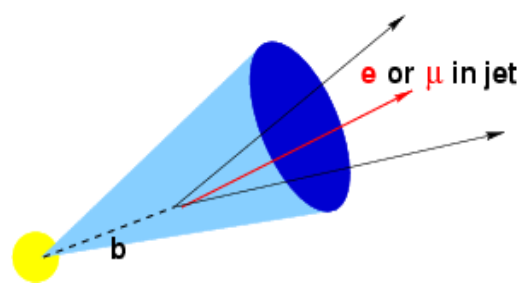
Introduction

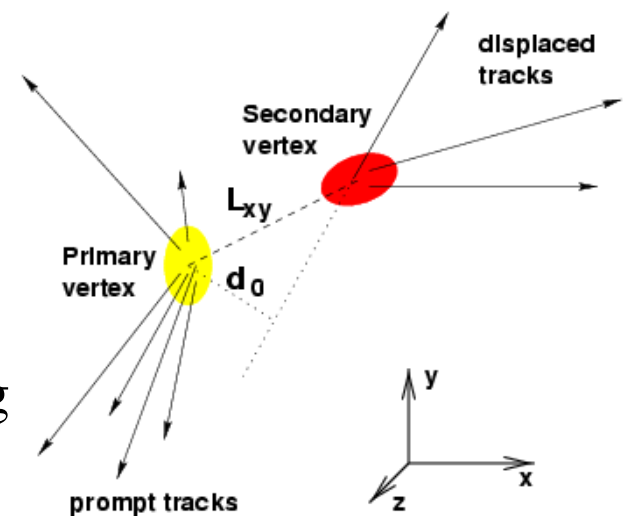
- This study starts from the measurement of the correlated bb cross-section, σ_{bb} , where bb can be produced at the Tevatron in a number of ways:



- B hadrons travel ~3mm before decaying and can be identified inclusively using secondary vertex (SVX) information, or identifying muons in the "b-jet", or by reconstructing exclusive states,

  e.g. $B^+ \rightarrow J/\psi K^+$ or $B^0 \rightarrow \mu D^0 X$

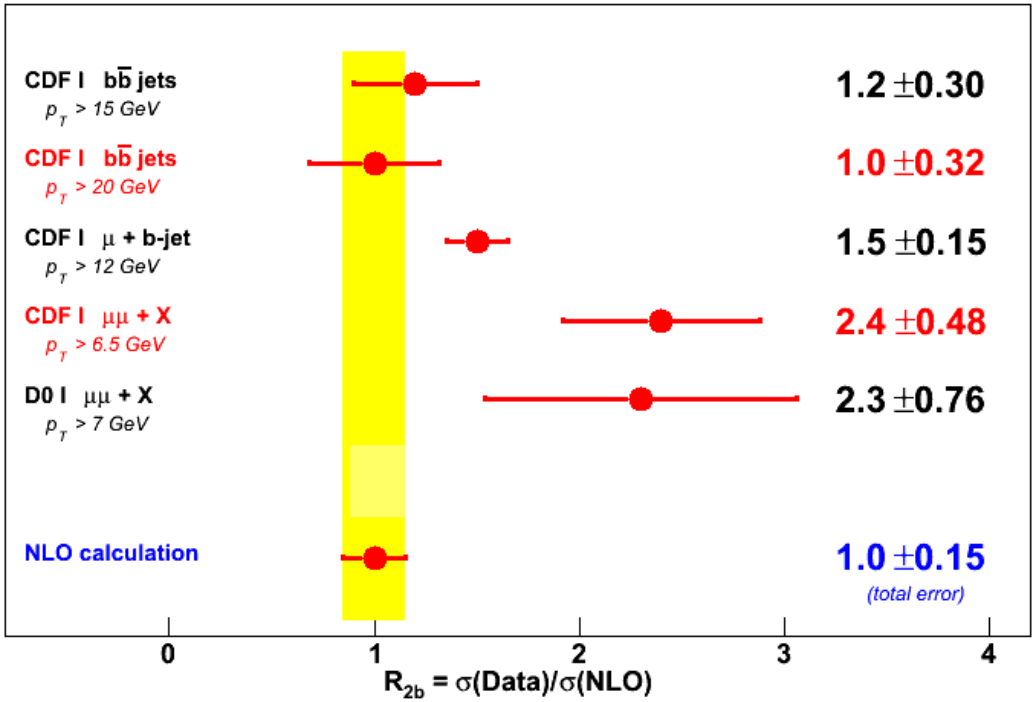


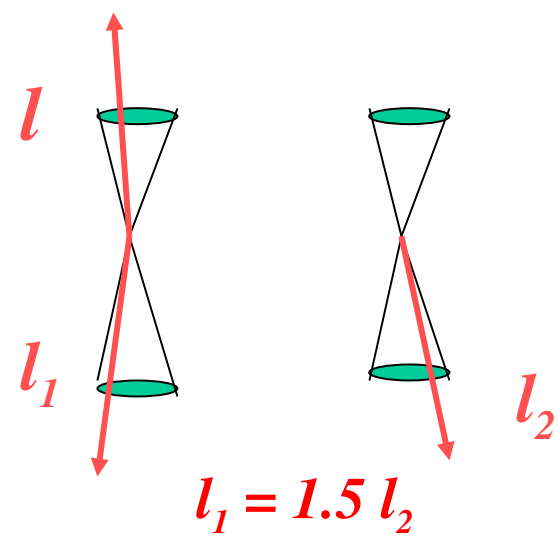


- The σ_{bb} measurement uses both vertex and muon tagging

Puzzle 1: Correlated σ_{bb} measurements

- From "Run 1" (1992-1996): ~100pb^{-1}
- B-jets both vertex tagged and lepton tagged (central muons typically with $P_T > 3$ GeV)
- Plotted is $R_{2b} = \sigma_{bb}(\text{measured})/\sigma_{bb}(\text{NLO})$
  - Vertex tag analyses consistent with $R_{2b} = 1$
  - Analyses using muon tags have $R_{2b} > 1$
- lepton rates per jet also showed high relative rates depending on whether "other" jet was vertex or muon tagged
  - PRD 69, 072004 (2004)
  - PRD 75, 014026 (2006)





Puzzle 2: Time Integrated Mixing

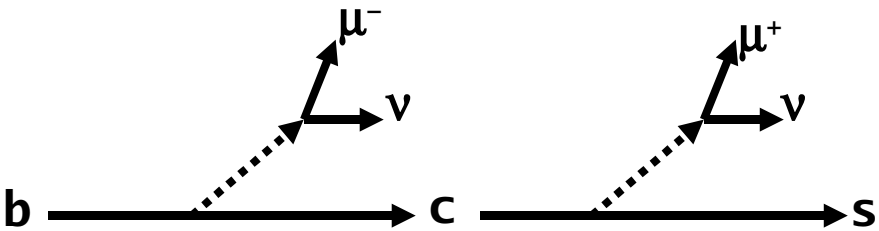
- Measured from the ratio of SS to OS dileptons:

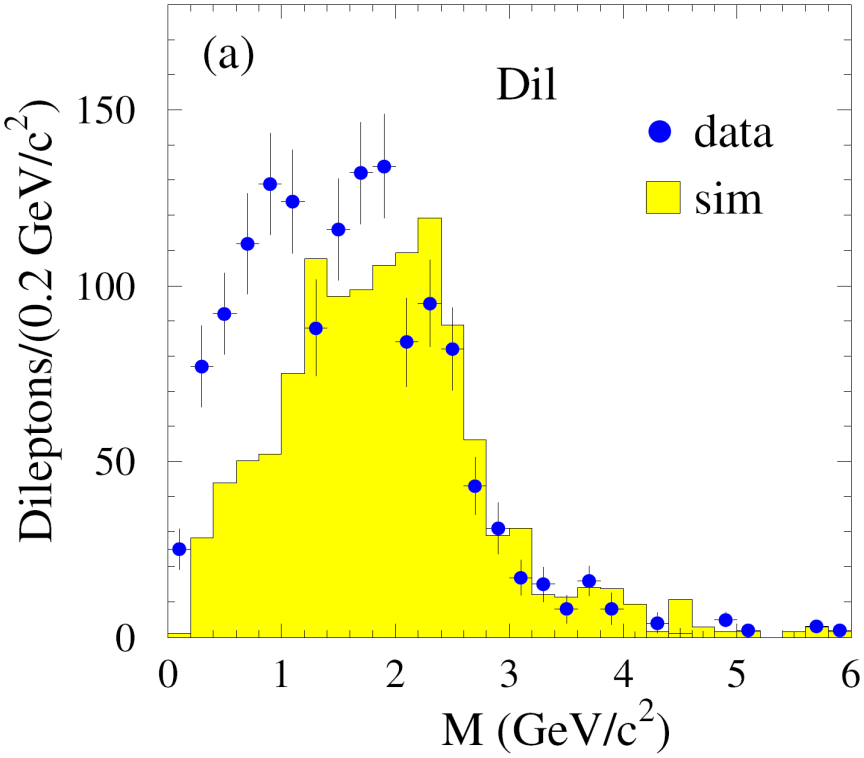
$$\bar{\chi} = \frac{\Gamma\left(B^0 \to \bar{B}^0 \to l^+ X\right)}{\Gamma\left(B \to l\ X\right)} = \frac{\text{"same sign"}}{\text{"total"}},\ B^0 = B_d^0 \text{ or } B_s^0$$

- B_d and B_s both oscillate $\Rightarrow$ $\bar{\chi} = f_s \chi_s + f_d \chi_d$
  - f_s and f_d are the fractions of b-quarks that fragment into B_s and B_d
  - χ_s and χ_d are the time integrated mixing parameters for B_s and B_d separately
  - Expect same production fractions at Tevatron and LEP since $q^2 \gg m_{u,d,s}^2$
  - The CDF Run 1 result (0.152 ± 0.013) is significantly higher than the combined LEP result (0.126 ± 0.004) : PRD 69, 012002 (2004)
    - Could it be due to different production fractions at higher energy (suggested by PDG) ?

Puzzle 3: low mass dileptons

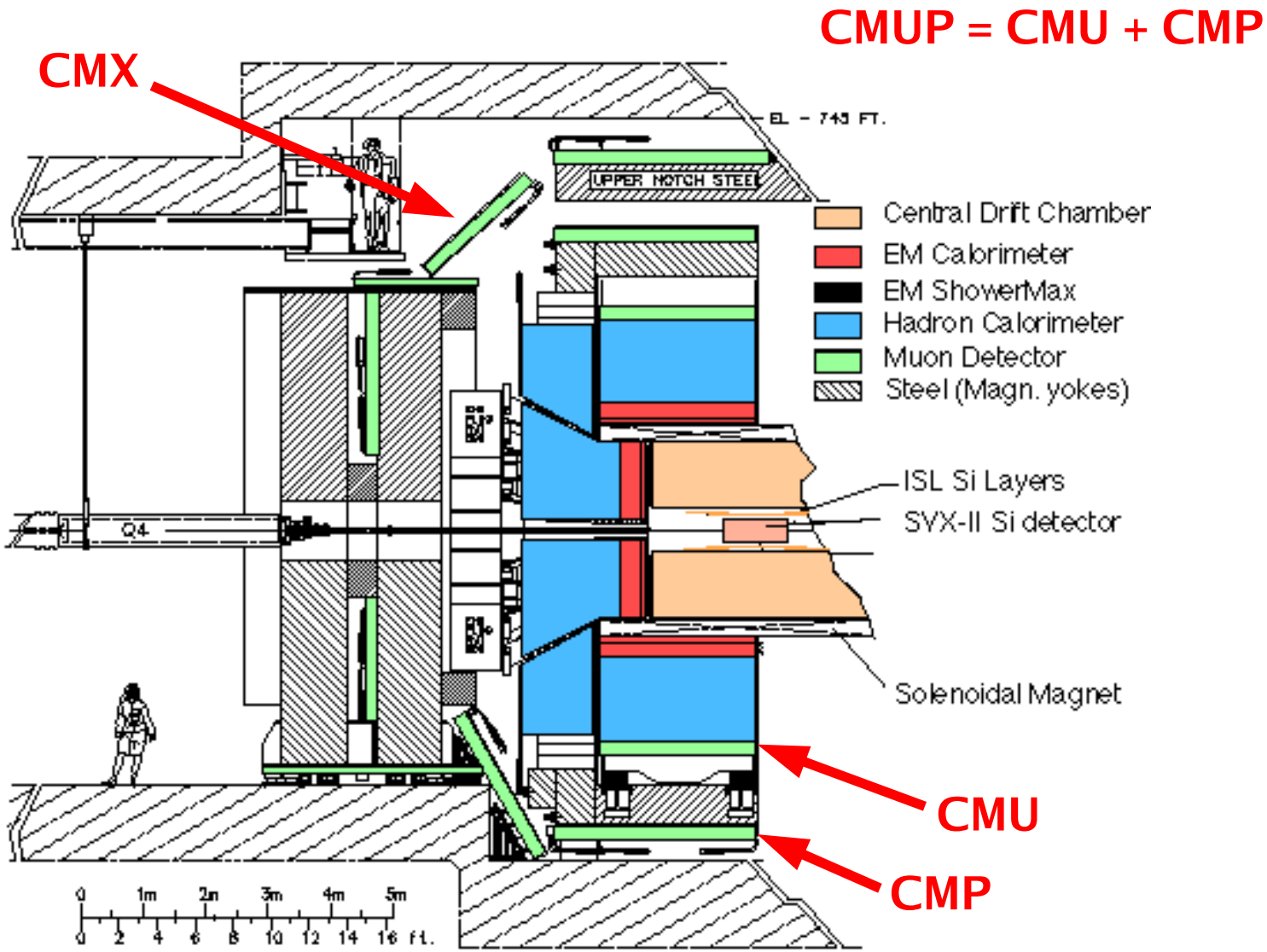
- In a B-enriched sample expect dimuon events to be dominated by:
- Expect to be well modeled by simulation
- Observe the cross-section of sequential semileptonic decays of single b-quarks to be underestimated with the disagreement being dominated by the $M_{\mu\mu} < 2$ GeV region





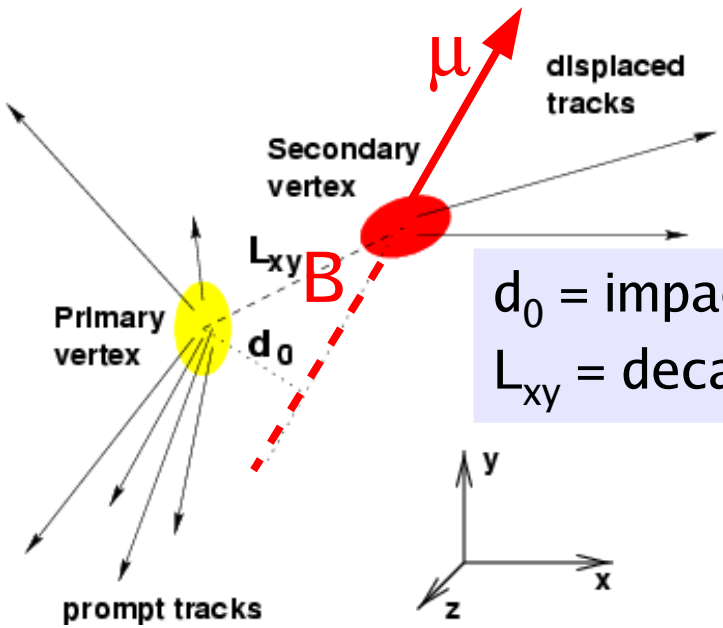
PRD 72, 072002 (2005)

The CDF Detector

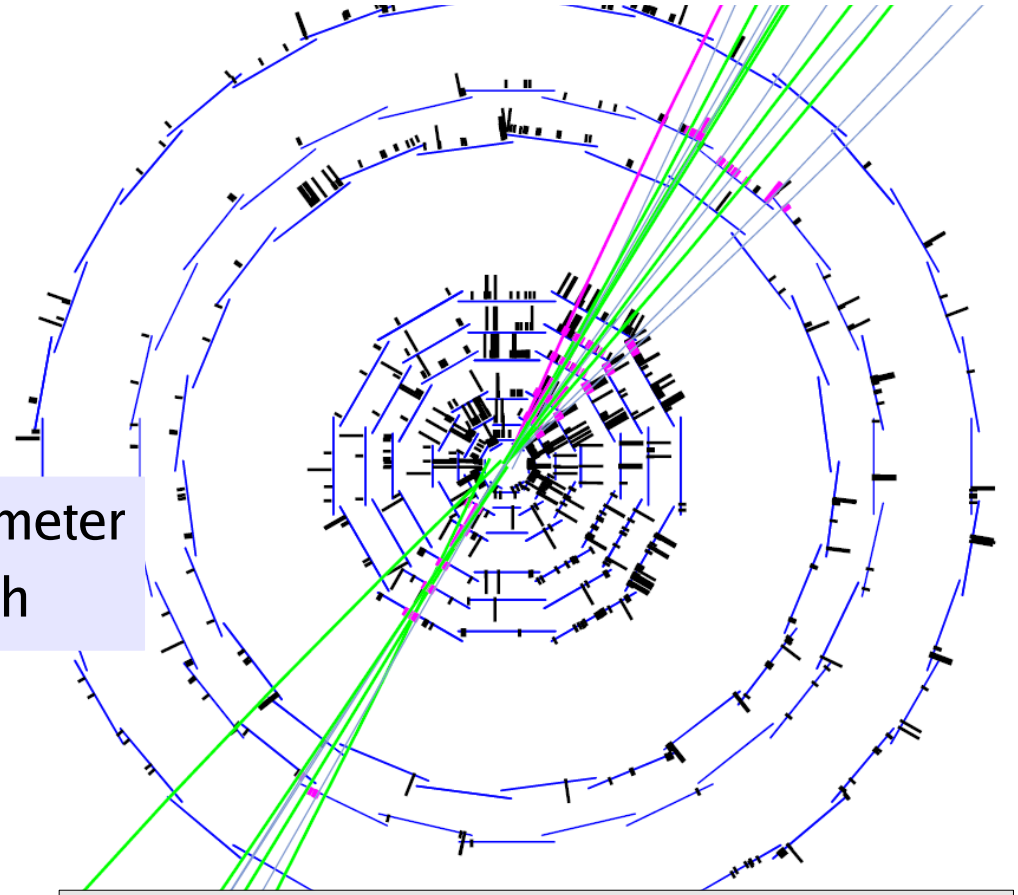


Silicon vertex detector (SVX)

- Used for precision tracking in reconstructing secondary vertices



d_0 = impact parameter
L_{xy} = decay length

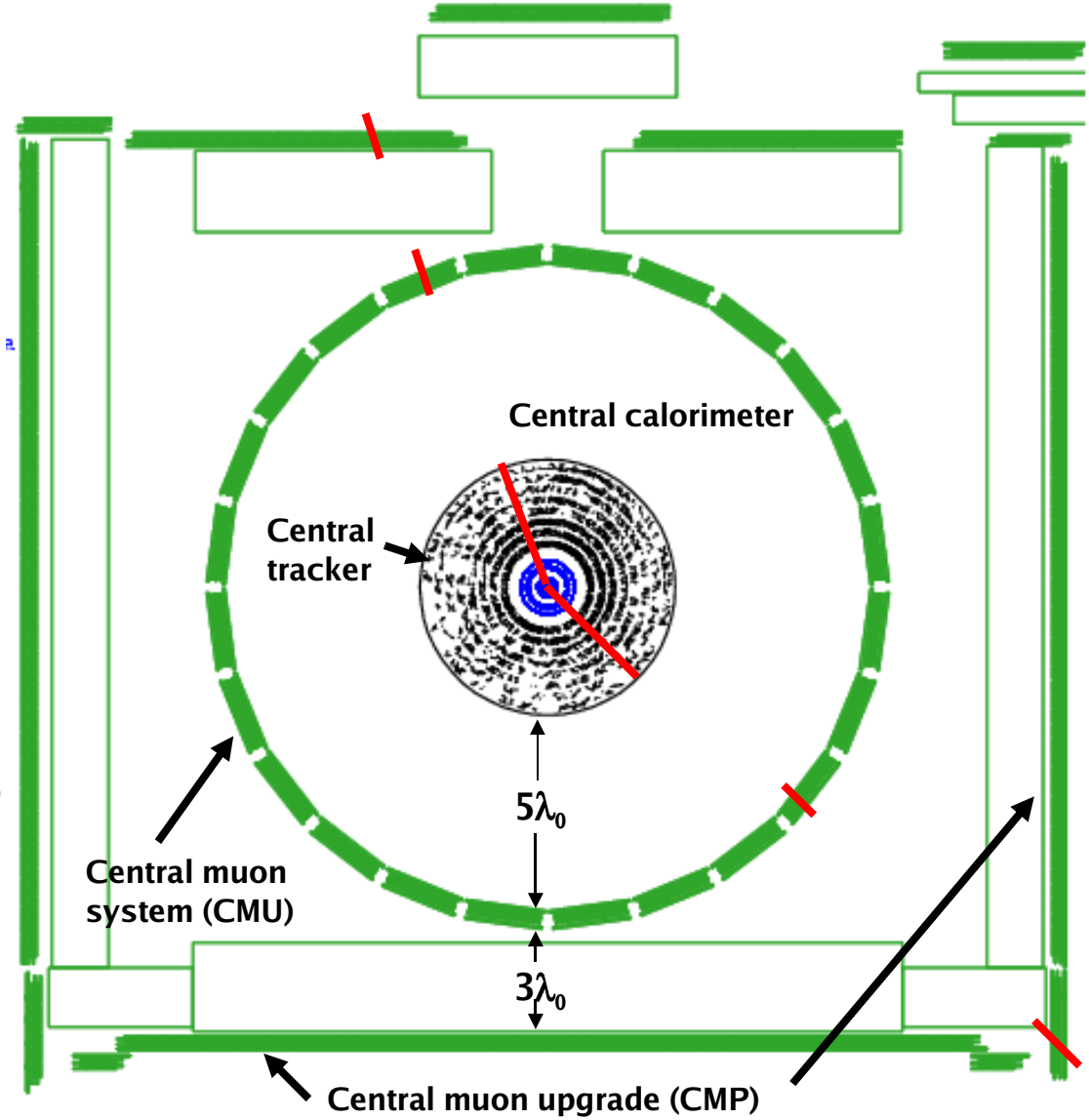


- Impact parameter resolution:
  - 230 μm (COT only tracks)
  - 30 μm (COT + ≥ 3 SVX hits)

- Silicon detector radii:
  - L00: 1.5 cm (on beampipe)
  - L0-L4 (SVX II): 2.4 – 10.6 cm
  - ISL: 20 – 30 cm

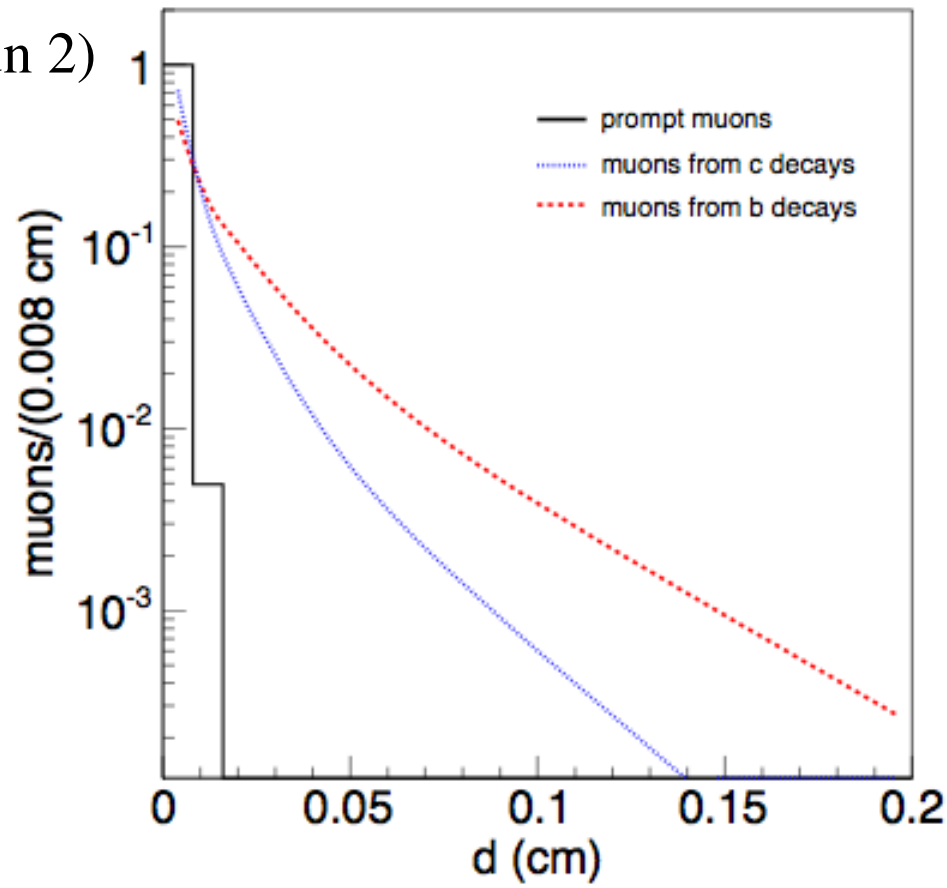
Dimuon triggered sample

- Data sample used in this analysis defined by a trigger requiring 2 muons with:
  - Central track with $P_T > 3$ GeV
  - Match to stub in CMU
  - Match to stub in CMP
  - $M_{\mu\mu} > 5$ GeV (to get rid of sequential $b \rightarrow c\mu \rightarrow \mu\mu$ decays)



New measurement of $\sigma(p\bar{p} \rightarrow b\bar{b}X)$

- Use dimuon triggered sample (~750pb^{-1} Run 2)
- Known sources of real dimuons include:
  - $b \rightarrow \mu$ ($c\tau = 470\ \mu m$)
  - $c \rightarrow \mu$ ($c\tau = 210\ \mu m$)
  - Prompt muons (Y , Drell-Yan)
- Known sources of fake muons include:
  - Hadrons punching through calorimeter
  - "Decays in flight" (e.g. $K_s \rightarrow \mu$, $\pi \rightarrow \mu$)
  - Fake muons can be from hadrons that are prompt or that arise from h.f. decays

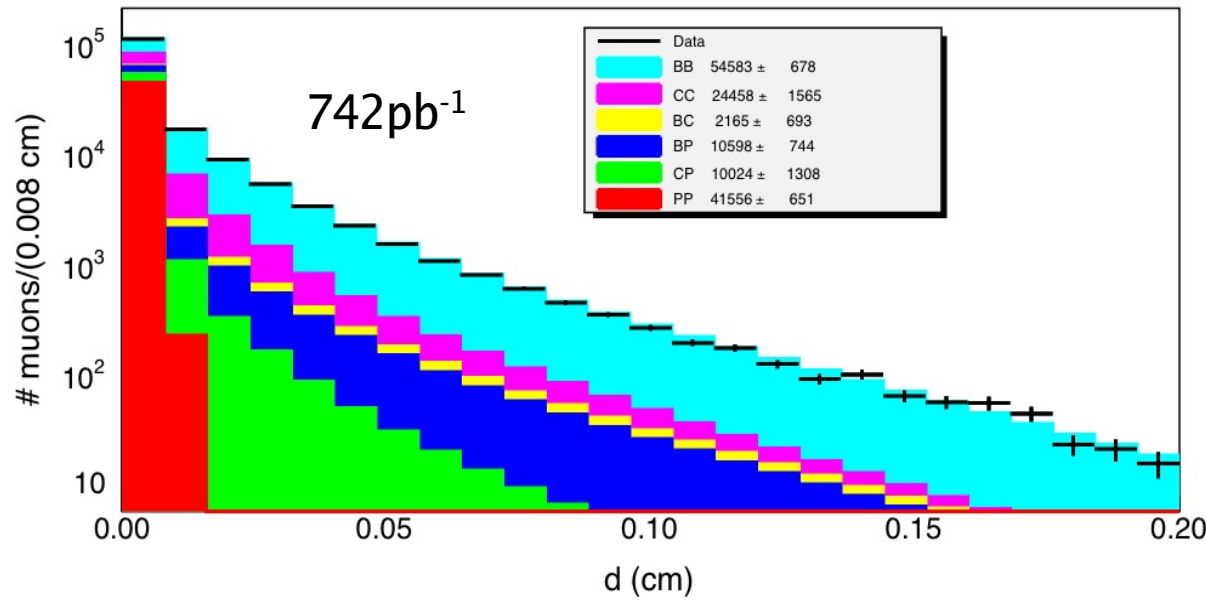


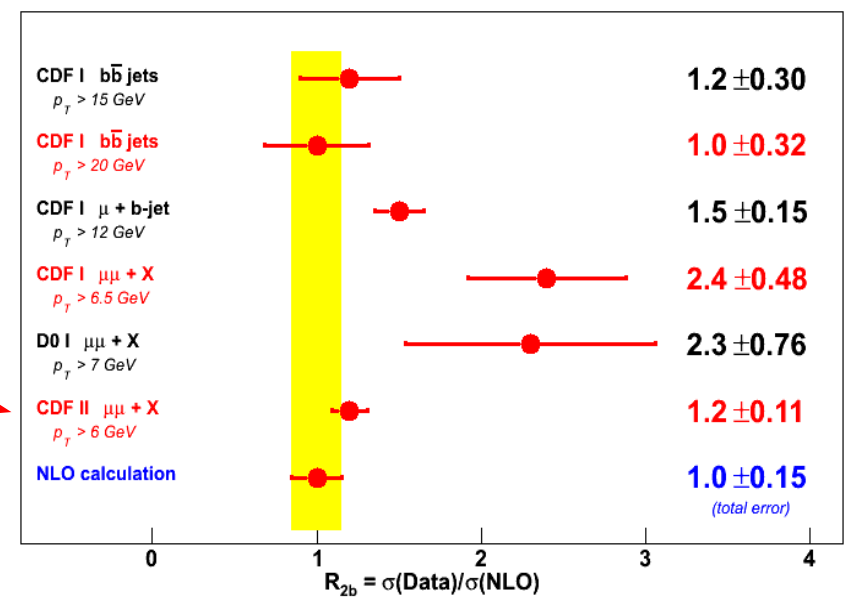
- Procedure: fit 2-D distribution of $d_0(\mu_1)$ vs. $d_0(\mu_2)$ with templates of the various components derived from MC (heavy flavour) or data (prompt), to extract σ_{bb}

New measurement of $\sigma(p\bar{p} \rightarrow b\bar{b}X)$

PRD 77, 072004 (2008)

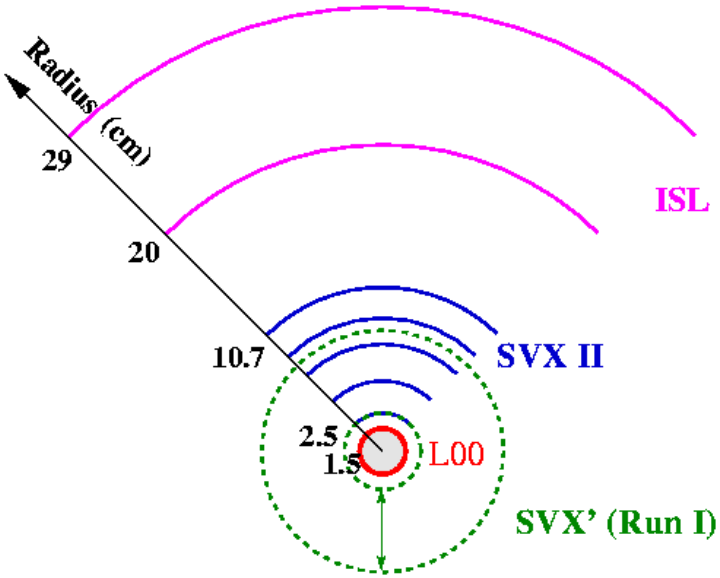
- Plot is projection of 2-D distributions
- Measurement uses "tight" SVX requirements: both muons must have hits on the 2 innermost silicon layers (L00 + L0) and on 2 of the remaining 4 SVXII layers
- Sample well modeled by templates with high bb purity (~40%)
- Result:
  - Measurement accuracy ~10%
  - Good agreement with theory





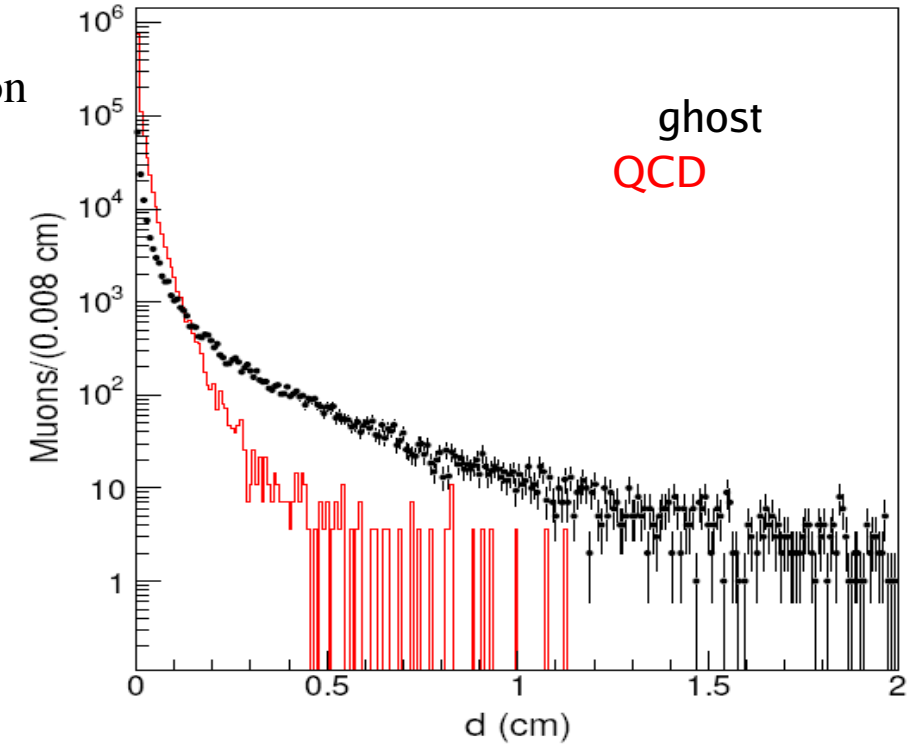
Immediate observations regarding new σ_{bb}

- The excellent modeling of the data at large impact parameter is only true when requiring the presence of L00 and L0 silicon hits (request of any 4 silicon layers destroys the agreement)
- This selection essentially requires that both muons originate inside the beam-pipe
- Traditionally CDF measurements use "loose SVX" requirements: 3 out of 8 SVX+ISL layers (muons could originate as far out as 10.7cm)
- Run 1 analyses selected muons originating as far as 5.7 cm from the beam pipe



Investigation of "lost" dimuons

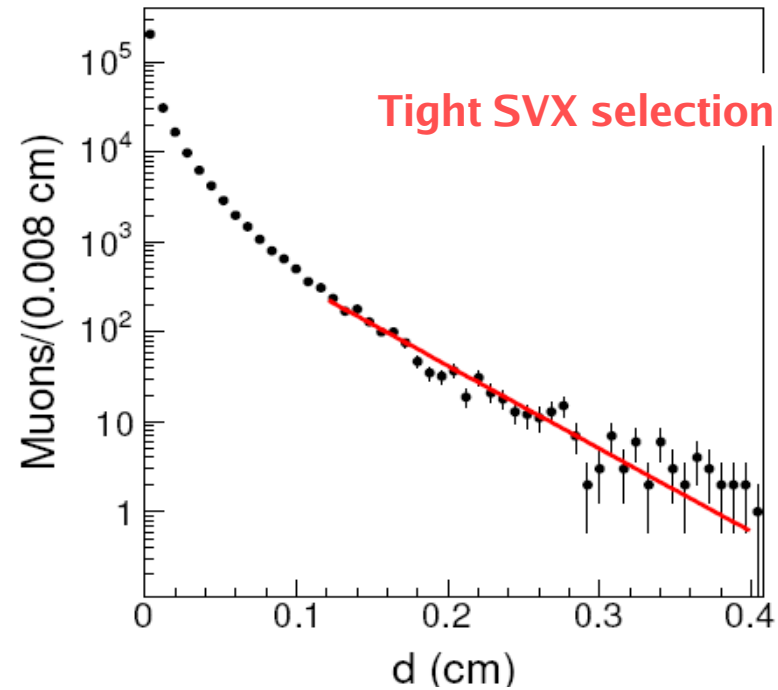
- Start with total sample of all dimuon pairs
- Observe many more events rejected by the tight SVX selection than expected
  - More background than expected in total sample
  - This background is removed by tight SVX selection
  - Much of this background is not removed by the loose SVX selection because it appears at large impact parameter
- Definitions:
  - **QCD** = sum of all contributions measured in σ_{bb} analysis (prompt, c, b)
  - **Ghost** = the excess after accounting for tight SVX efficiency: Ghost = all events – (QCD/efficiency)



- QCD sources of dimuons (includes bb, cc) have $d_0 < 0.5$ cm
- Ghost events have much larger impact parameters

More on the QCD sample after tight selection

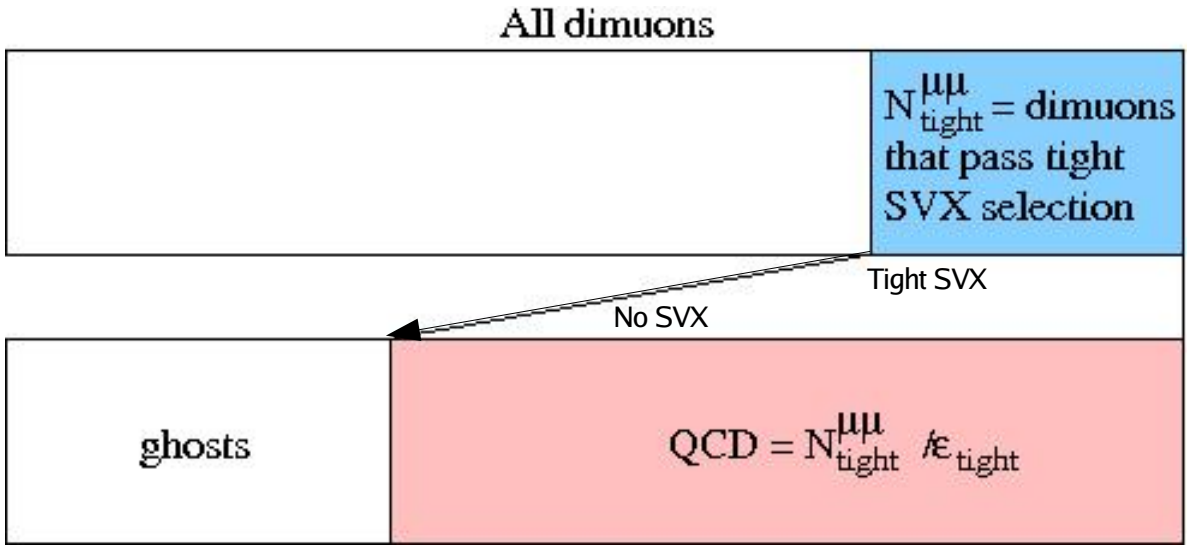
- Charm contribution minimal for $d_0 > 0.12$ cm
- Fit d_0 distribution for muons with $0.12 < d_0 < 0.4$ cm
  - Measure $c\tau = 469.7 \pm 1.3$ μm (stat. error only)
  - PDG average b lifetime: $c\tau = 470.1 \pm 2.7$ μm



- Conclude that:
  - QCD sample (selected with tight cuts) not significantly affected by additional background
  - b contribution almost fully exhausted for $d_0 > 0.5$ cm

More on the ghost sample

- Dimuon sample contains large background (ghost) that is suppressed more by the tight SVX requirements than the QCD contribution
  - Efficiency of tight SVX selection observed to be 0.1930 ± 0.0004 instead of the expected ε_{tight} = 0.244 ± 0.002 (verified in control samples)



- Size of ghost sample:
  - In all dimuons: ghost = data – $N^{\mu\mu}_{tight}$ / ε_{tight}
  - In loose SVX sample: ghost = data - ($N^{\mu\mu}_{tight}$ / ε_{tight}) * (ε_{loose} = 0.88 ± 0.01)

Yields in 742pb^{-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

$/\varepsilon_{tight}$ $*\varepsilon_{loose}/\varepsilon_{tight}$

Data (observed)

Assume after tight selection all QCD and no Ghost

From the tight selection QCD estimate QCD in "All" and "loose SVX" using the known efficiencies, then: **GHOST = ALL – QCD**

Find:

- (222 ±12)k bb events with no SVX [(195 ± 10)k with loose requirements]
- Ghost contribution to entire sample (154k) comparable to bb contribution (222k)

Plausible explanation of previous inconsistencies

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
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Ghost *SS*		0	34762 ± 2301

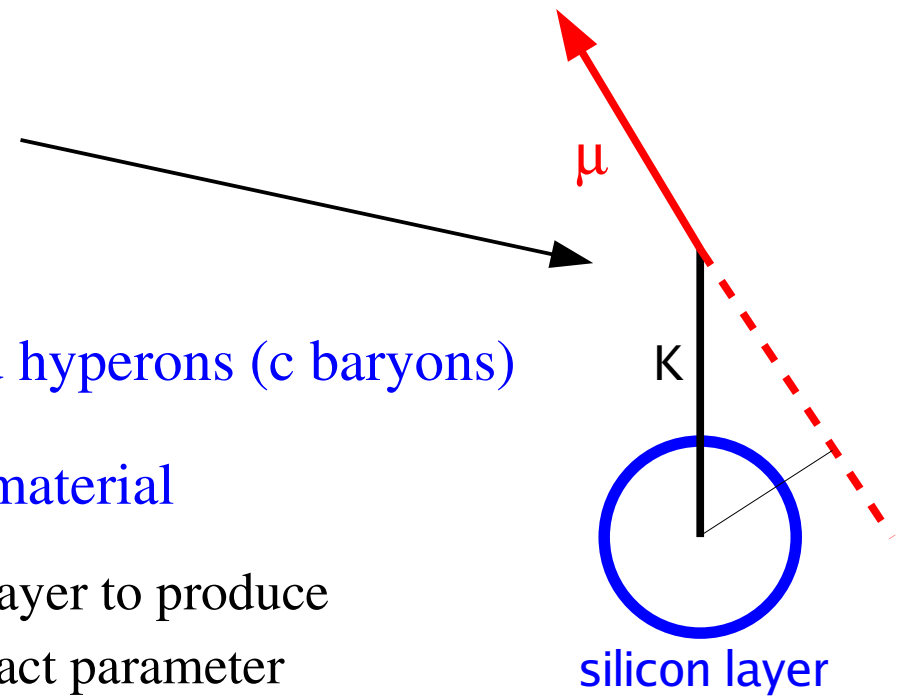
- σ_{bb} : Previous measurements used selection closer to "loose SVX"
  - Ghost contribution ~73k compared to bb of about 195k
- χ : Recall calculated from SS/total
  - Ghost about 50/50 SS/OS $\Rightarrow$ high χ measurement using loose SVX selection

Recap of where we are

- Have identified a possible source of background that was not previously considered and which is significantly reduced when requiring muons to originate from inside the beam pipe ("tight SVX" requirements)
- Offers a plausible explanation to inconsistencies between the recent CDF σ_{bb} measurement (which used "tight SVX" selection) and previous measurements (using "loose SVX") as well as inconistencies in the CDF χ measurement (which also used "loose SVX")
- This additional background (referred to as the ghost contribution) has a large impact parameter tail
- This does not (yet) explain the dilepton excess at low invariant mass
- We have not (yet) looked at other properties of the ghost contribution to see if it could simply be explained by a significant misunderstanding of, for example, the fake muon rate in the dimuon triggered sample

Possible sources of ghost events

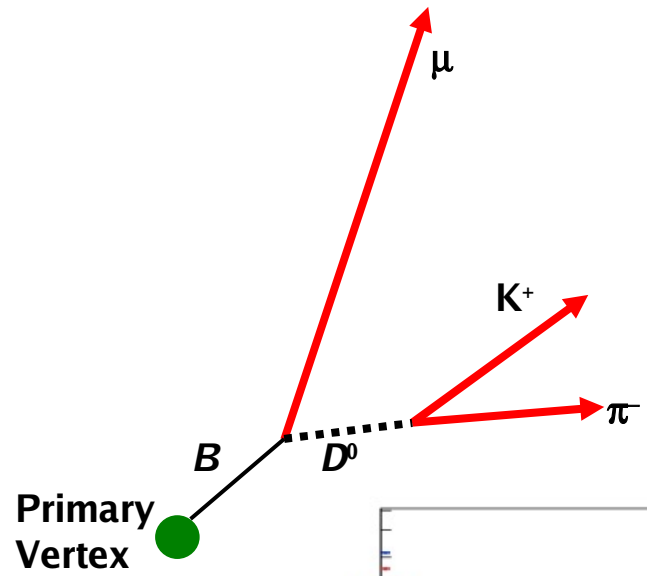
- What could give rise to real or fake muons with large impact parameters which preferentially miss the inner silicon layers?
  - Mismeasured tracks
  - In flight decays of kaons and pions
    - $K^{\pm} \rightarrow \mu\nu_{\mu}$, $\pi^{\pm} \rightarrow \mu\nu_{\mu}$
  - Long-lived particles such as K_S and hyperons (c baryons)
  - Secondary interactions in detector material
    - e.g. Hadron interacts with silicon layer to produce secondary particles with large impact parameter

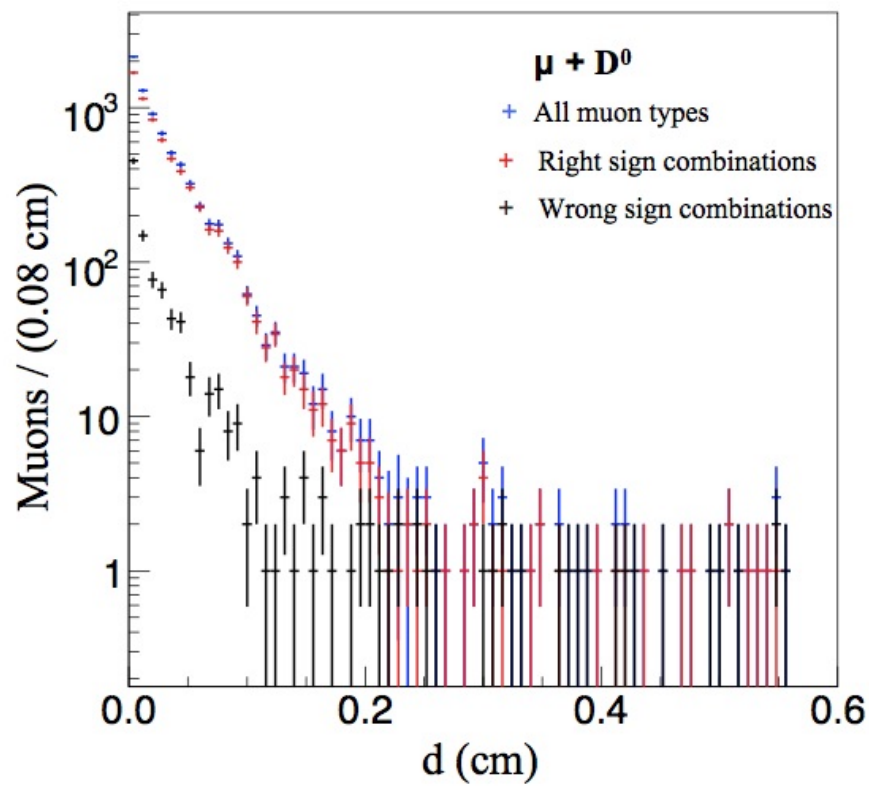


- Some of these sources we expect will contribute to the ghost rate

Mismeasured tracks

- One cross-check is to look at $\mu + D^0$ events (no SVX requirements)
  - dominantly from bb
- $d_0(\mu)$ distribution consistent with coming from B decays
- No evidence of a long tail





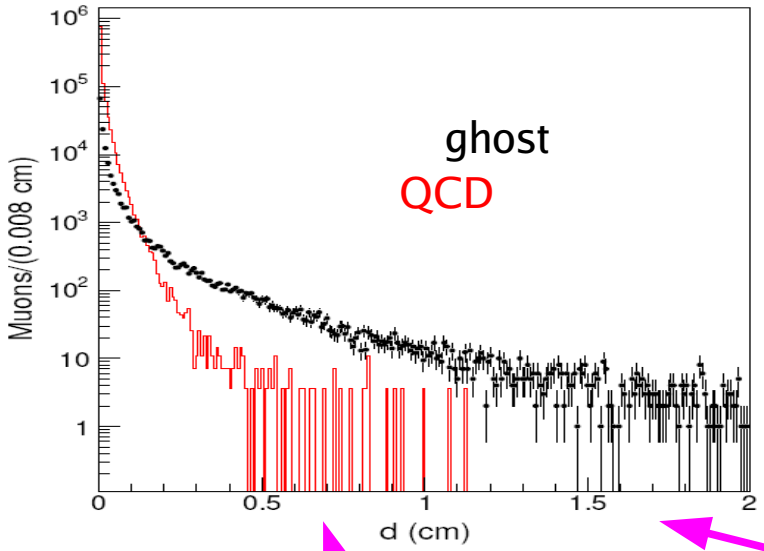
Decays in-flight

- Use a heavy flavor simulation (HERWIG) to measure the probability that K and π decays produce trigger muons that pass all analysis cuts
- Probability per track that a hadron yields a trigger muon:

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

- Normalize this rate from MC to the measured bb cross-section
  - Predict 57000 ghost events from DIF (recall total ghost sample is 154000 ± 5000)
  - Efficiency of tight and loose SVX requirements are 8% and 44% respectively
- Large uncertainty on prediction (from σ_{bb}, particle fractions, momenta spectra,....)
  - In terms of total yield, easily imaginable that DIF can account for entire ghost sample

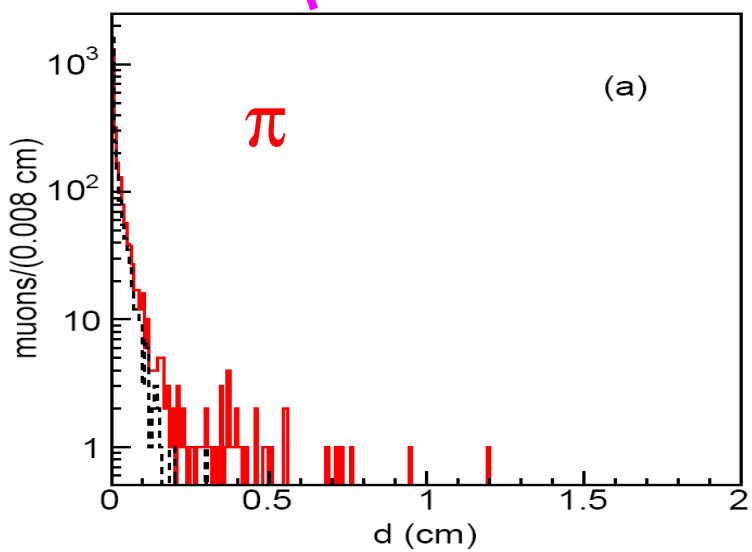
Decays in-flight

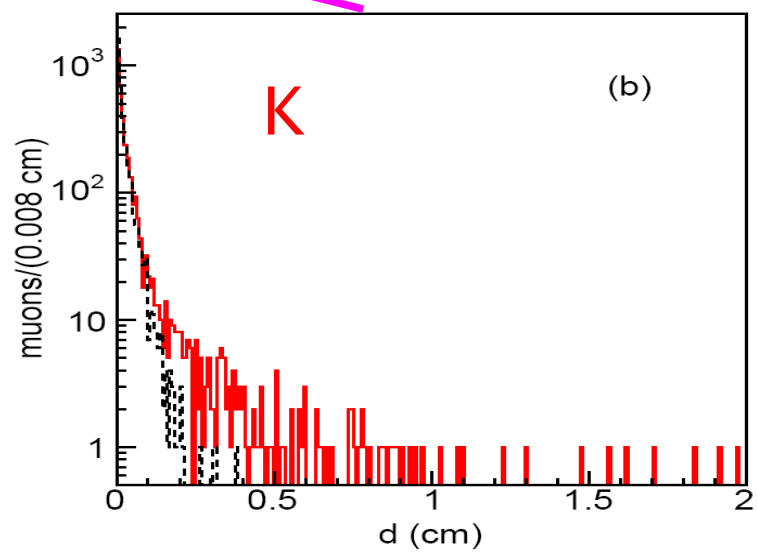


- DIF predicts ~35% of the ghost events but only about 10% of the events with $d_0 > 0.5$cm

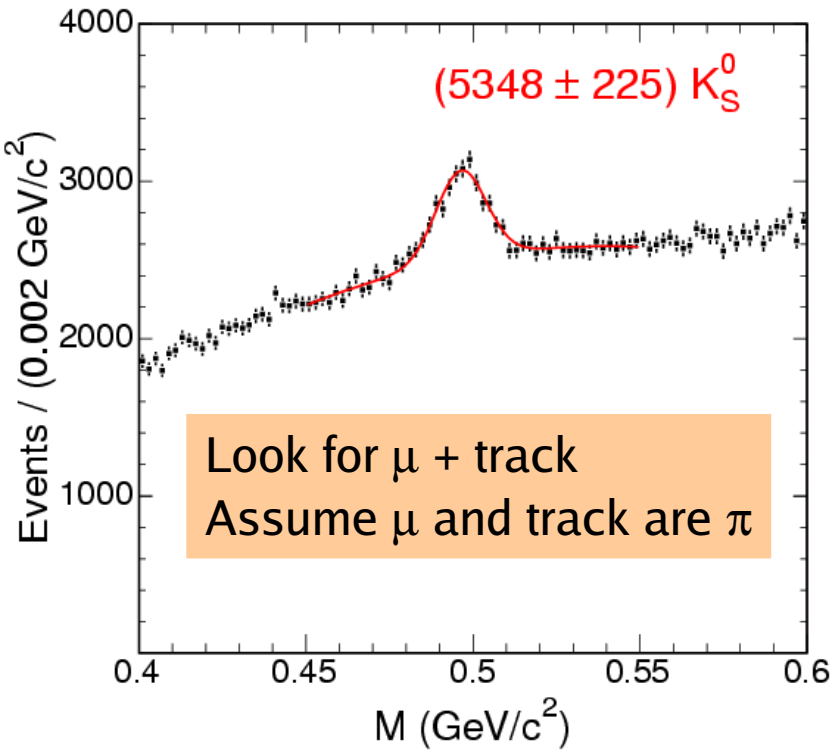
x 5

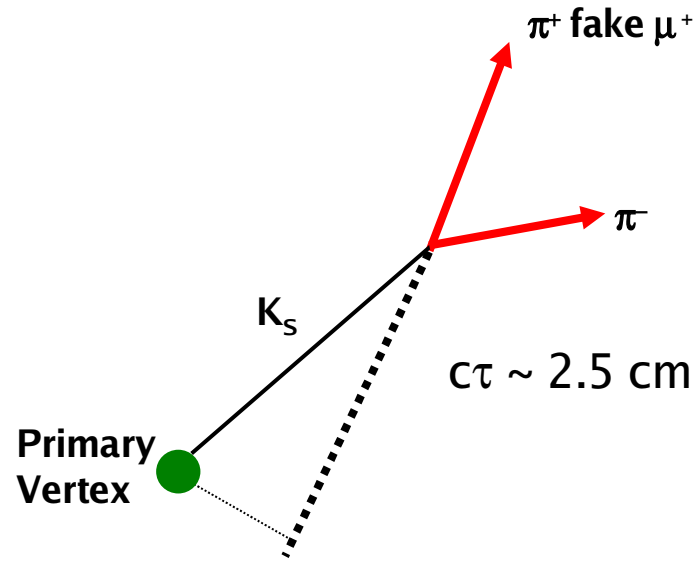
x 5

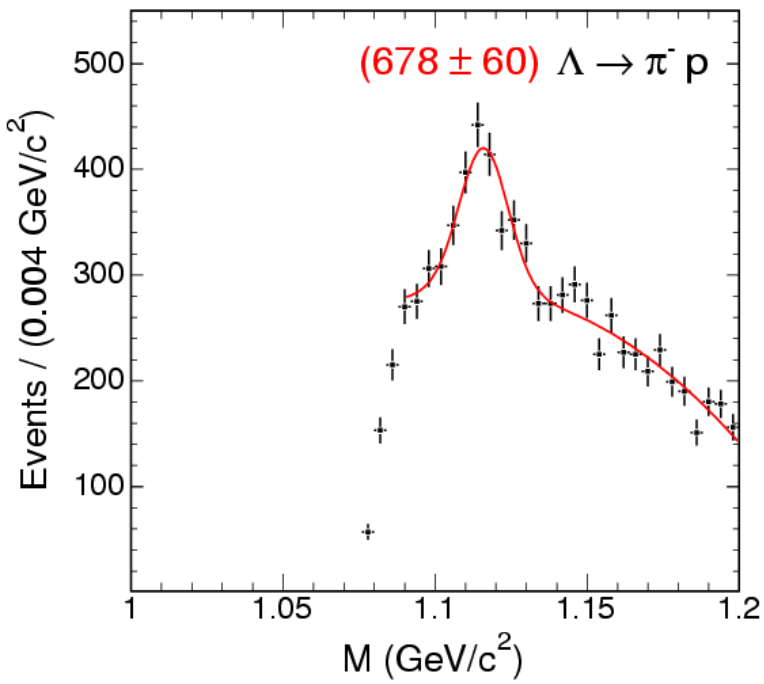




K_S and hyperons

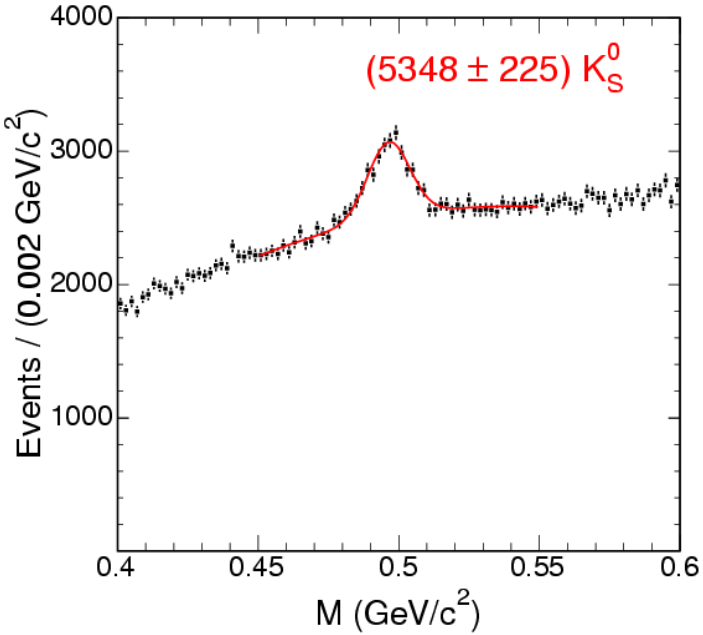




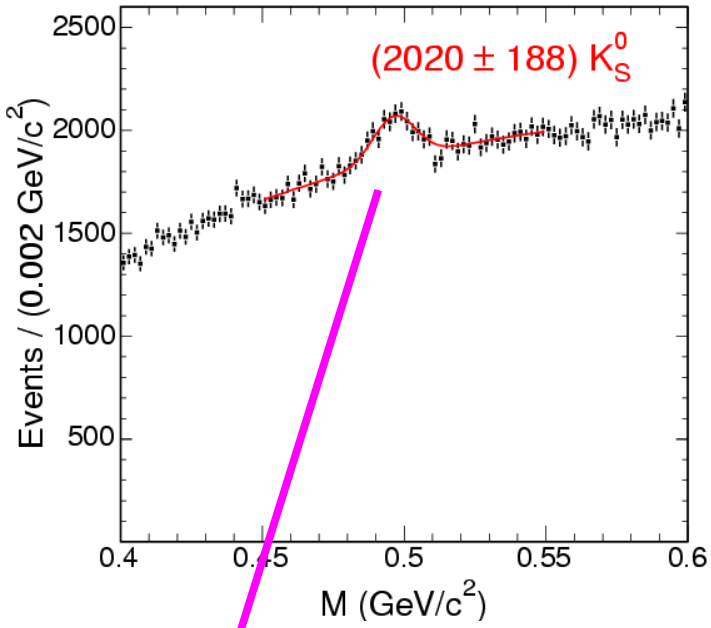


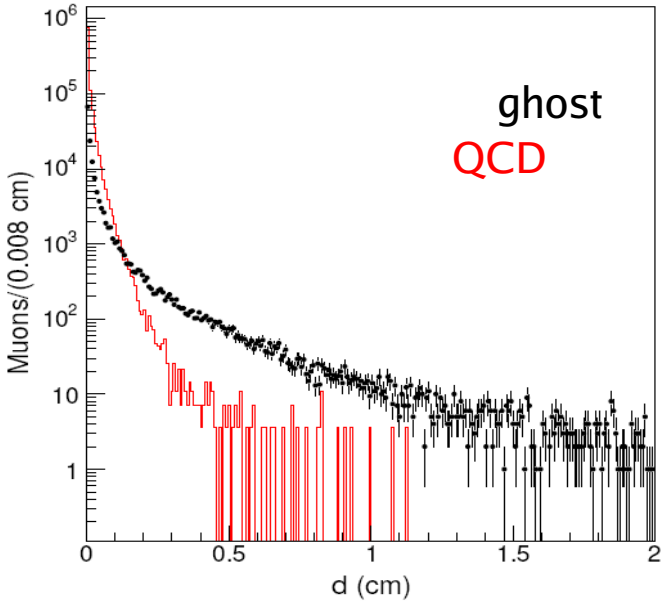
- Kinematic acceptance times reconstruction efficiency ~50%
- Accounts for about 12000 of the ghost events (~8%)

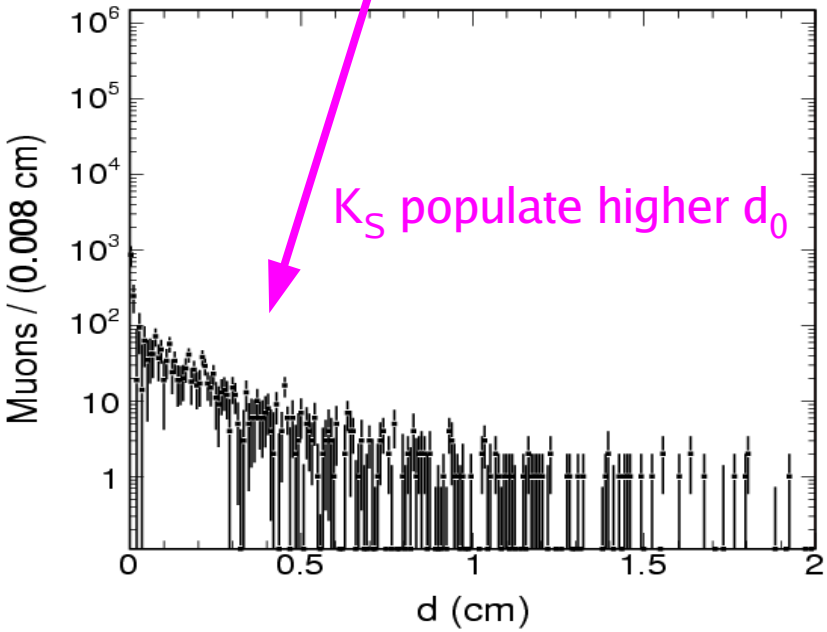
K_S



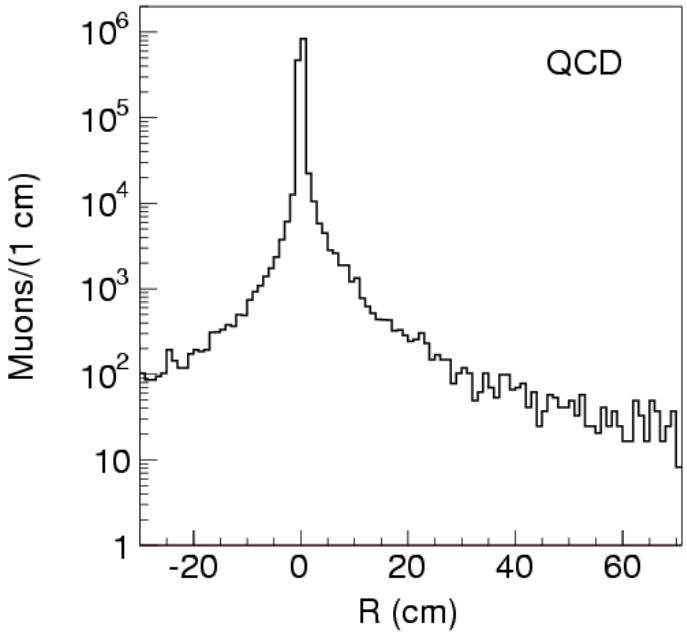
Loose SVX selection

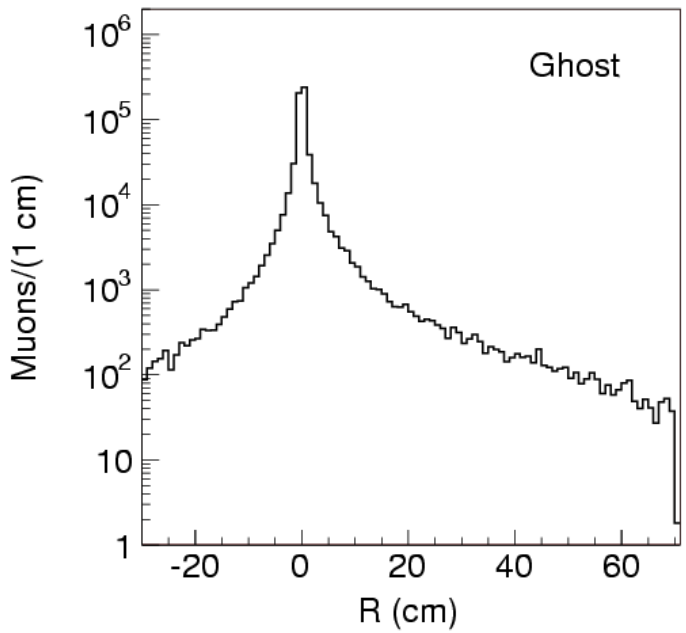




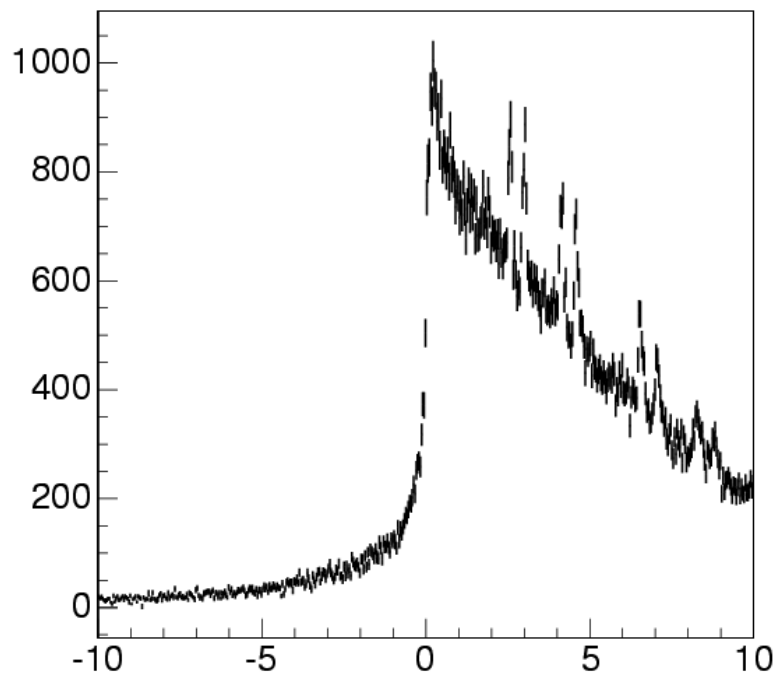


Secondary interactions





- Will occur at radii of detector material
- Combine initial muons with tracks with $P_T > 1$ GeV in a 40° cone
- Plot radius of intersection of tracks



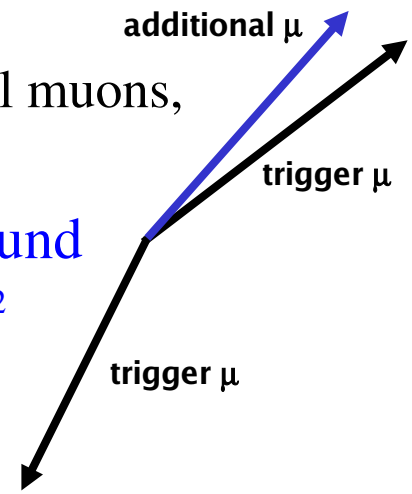
Simulation using tracks, NOT muons

SM sources of ghost events - summary

- Our prediction acounts for approximately 50% of the ghost events (70000 out of 150000)
  - Uncertainty in contribution from decays-in-flight might be large
  - Cannot rule out contribution from quasi-elastic nuclear interactions
- At this stage it is not unreasonable to postulate that the ghost events can be fully accounted for by a combination of the previously studied effects
- Now look at additional characteristics of ghost events

Search for additional muons

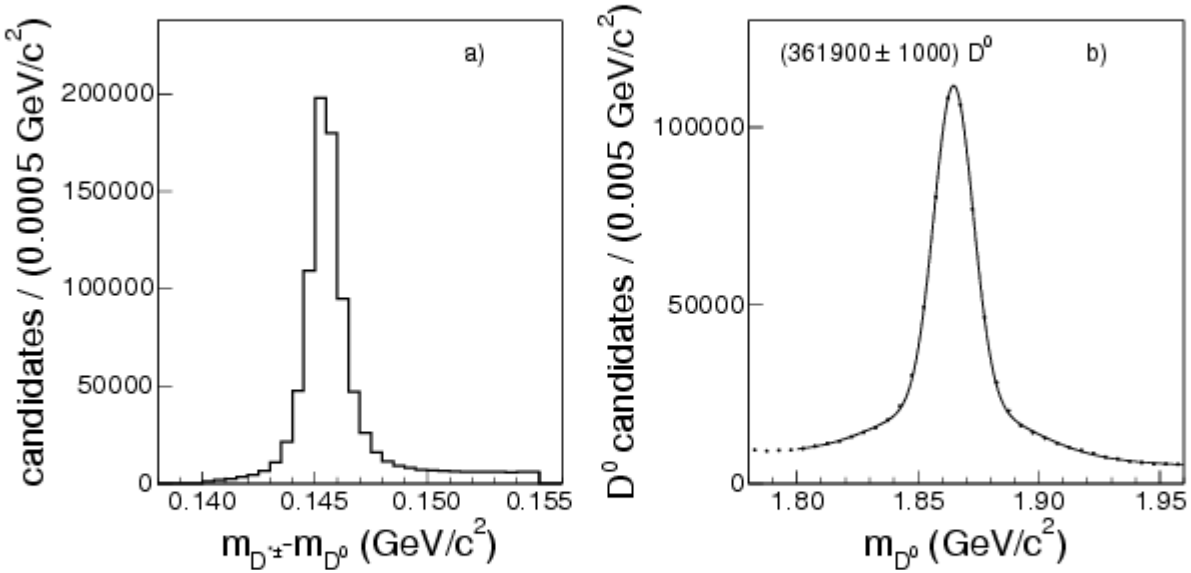
- Could be interesting for several reasons:
  - Ghost events may be related to the excess of low mass dileptons
  - Events due to secondary interactions or fake muons are not expected to contain many additional muons
  - If ghosts events were normal QCD events with mismeasured initial muons, the rate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



- Expect:
  - the main source of real additional muons are sequential decays of b quarks
  - a sizable contribution of muons mimicked by hadrons (evaluated using a fake probability per track derived from a large sample of $D^0 \to K\,\pi$ decays)
- Strategy:
  - Use loose muon selection for maximum acceptance and take correspondingly higher fake rate (also performed cross-checks using much tighter selection)

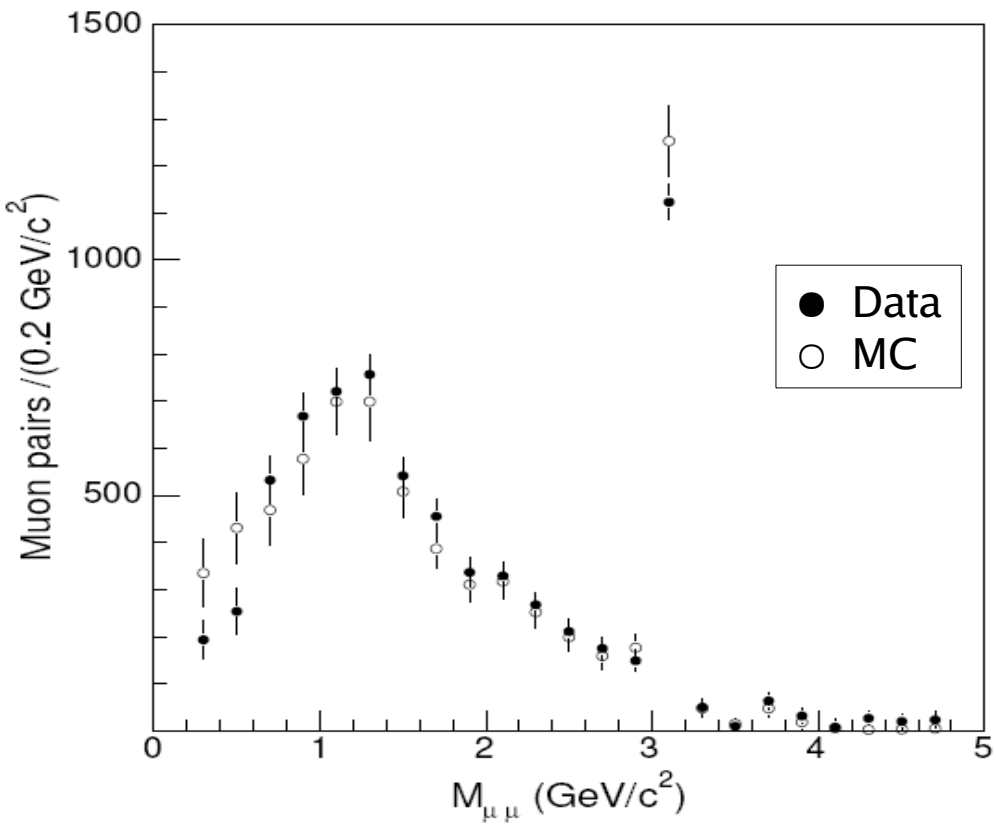
Muon fake rate

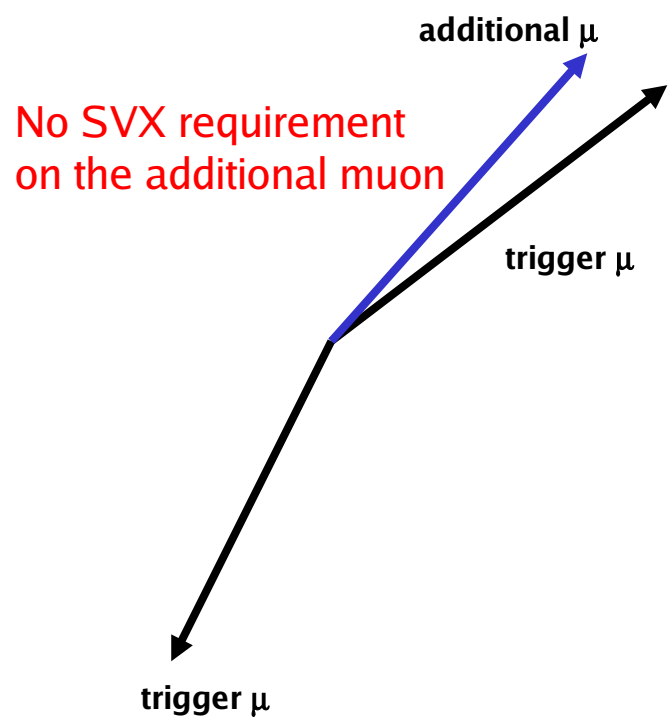
- Measure the probability per track that a pion or kaon will "punch through" the calorimeter and fake a muon
- Technique:
  - Reconstruct $D^{*+} \rightarrow D^0\pi^+$ decays with a $D^0 \rightarrow K^-\pi^+$
  - D* tag uniquely identifies π and K
  - Reconstruction by tracking only, then ask at what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



Verifying the muon fake rate

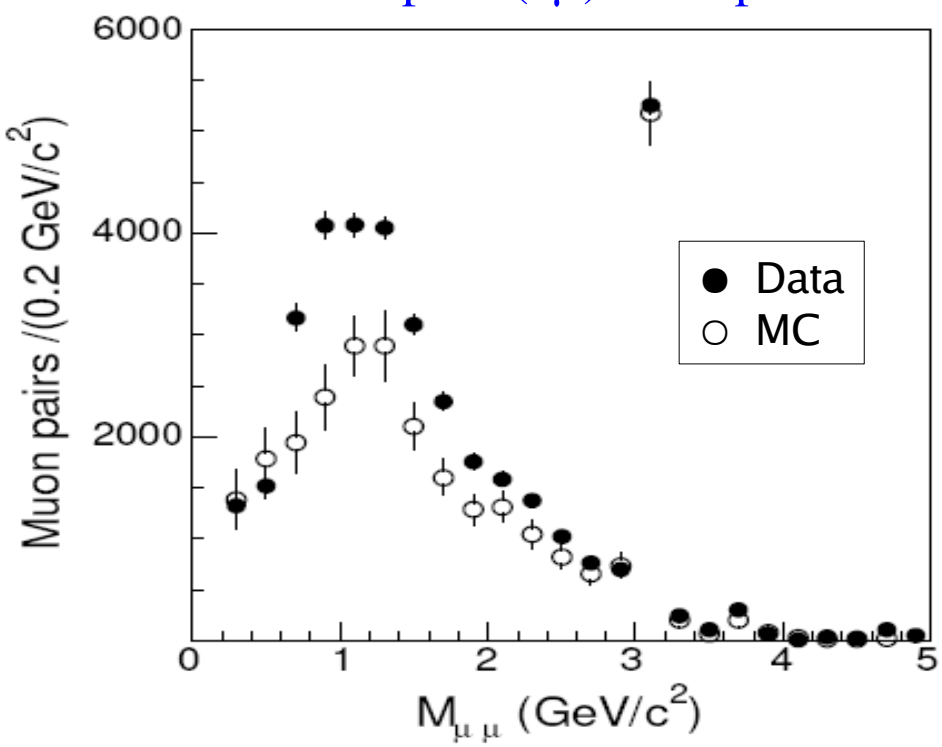
- Compare data to heavy flavor simulation which includes fake prediction
- Tight SVX selection (no ghosts)
  - 6935±154 in the data and 6998±293 predicted
  - We understand the heavy flavor simulation and the fake muon background

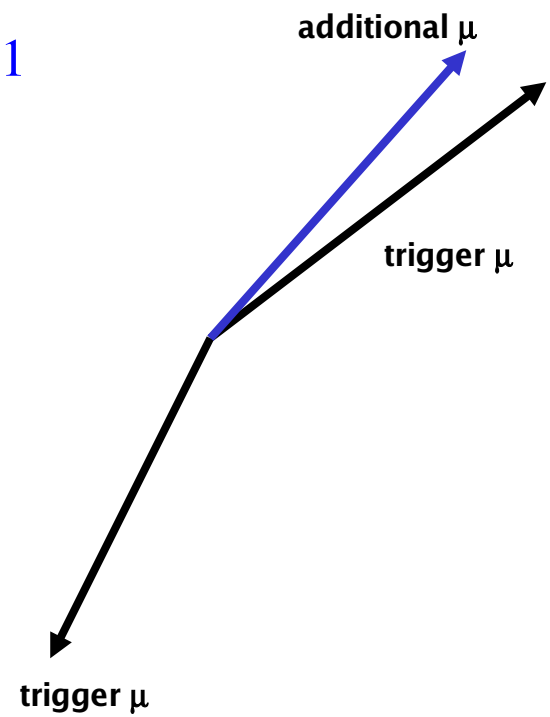




Low mass dileptons

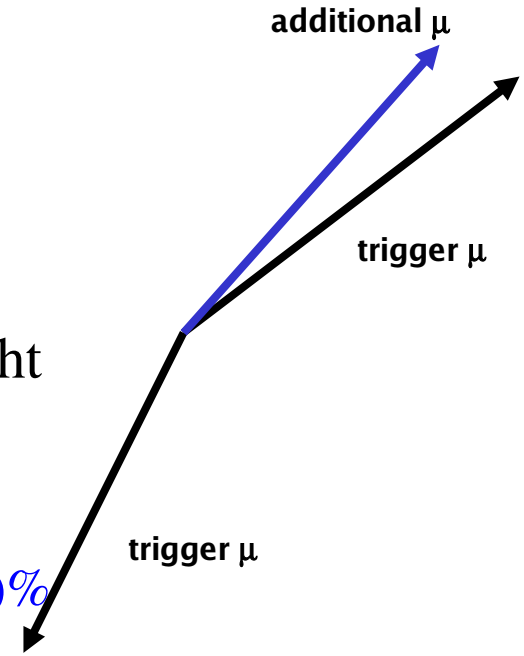
- Compare data to heavy flavor simulation which includes fake prediction
- All data (no SVX requirements)
  - J/ψ yield correctly modeled
  - Clear excess at low mass – not seen with tight SVX requirements
  - Excess coming from ghost sample
  - Same as the low dilepton (eμ) mass puzzle from Run 1

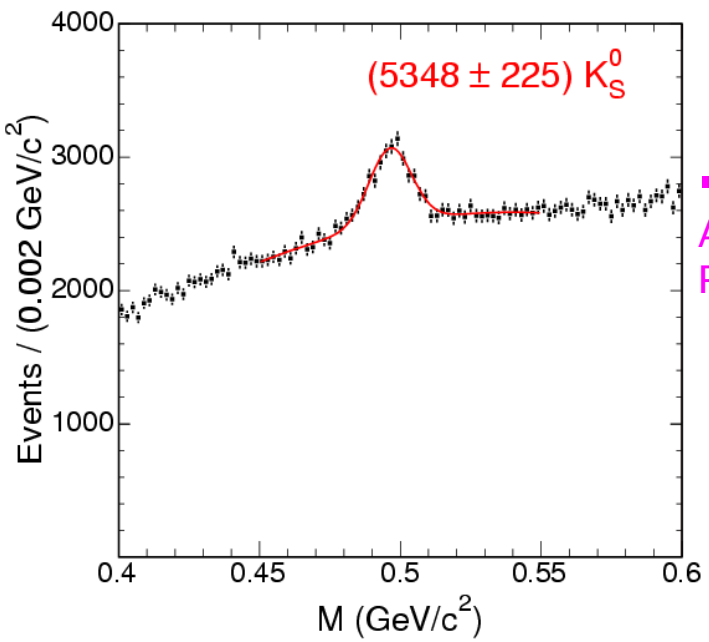




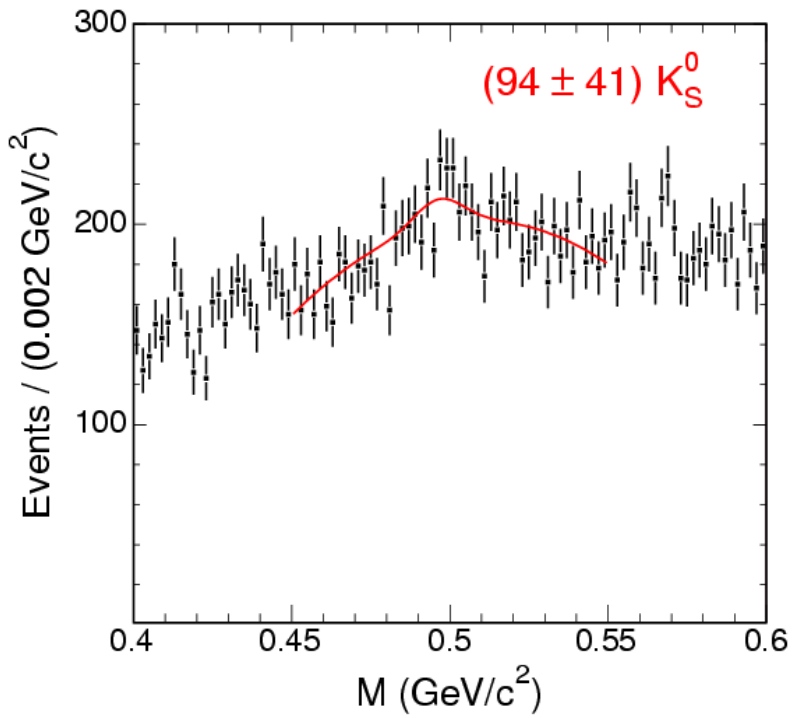
Additional muons

- Additional real muons mostly come from sequential b decays
- The request of additional muons depresses all other SM contributions such as Drell-Yan or events acquired via in-flight decays because they only contain fake additional muons, for example:
  - the fraction of additional (fake) muons in Y events is (0.9±0.1)%
  - (1.7±0.8)% of the events with a K_S contain an additional muon:





Additional muon with P_T>2GeV and |η|<1.1

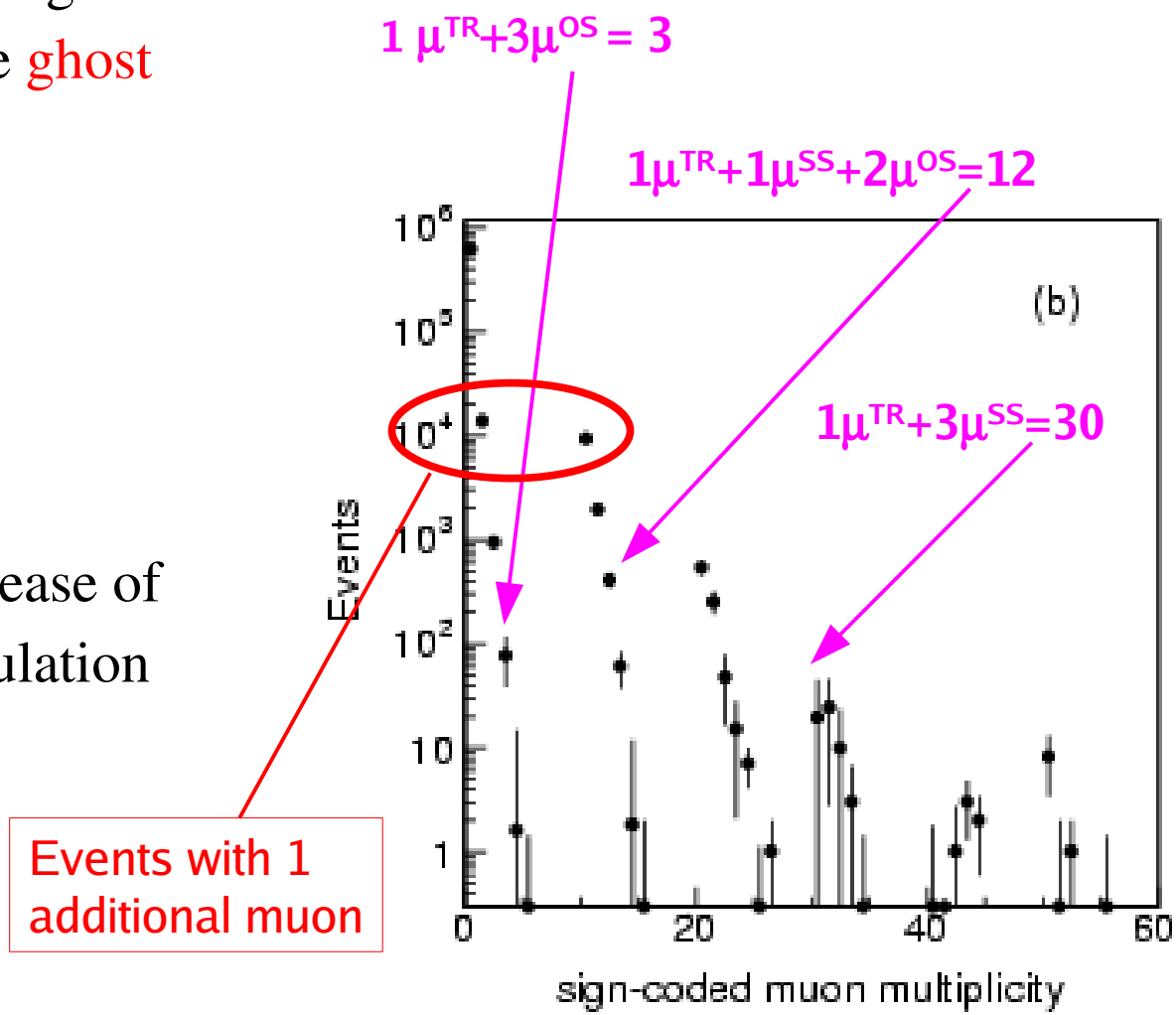


Additional muons

- QCD sample is well understood
- Ghost sample is less well understood but if we believe its mostly "QCD-like" with the dominant contributions from decays-in-flight and long-lived particles, then we can compare the effect of requesting an additional muon on ghosts and QCD
- After correcting for fakes, the rate of additional muons in the ghost sample is 4 times larger than in QCD
  - If mostly DIF or long-lived particles would expect additional muon contribution to be suppressed not enhanced!
  - Using our estimate of ~50% ghosts being DIF or long-lived particles where additional muons are less than in QCD, then a fraction of the ghost sample would appear to be rather special
  - Also find number of charged tracks ($P_T > 2$ GeV) in ghost sample to be 2 times larger than in QCD

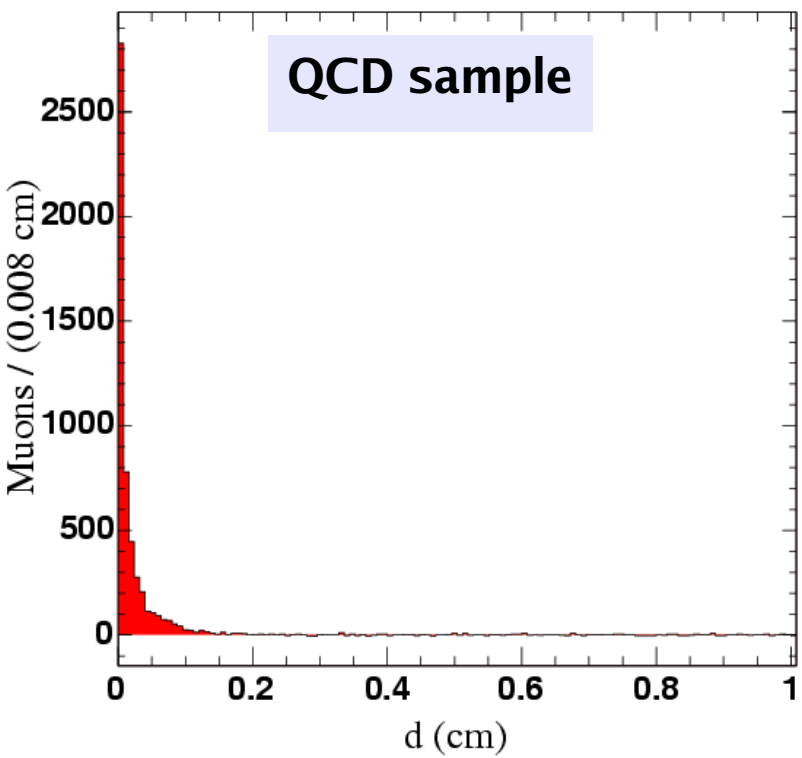
Additional muon multiplicity

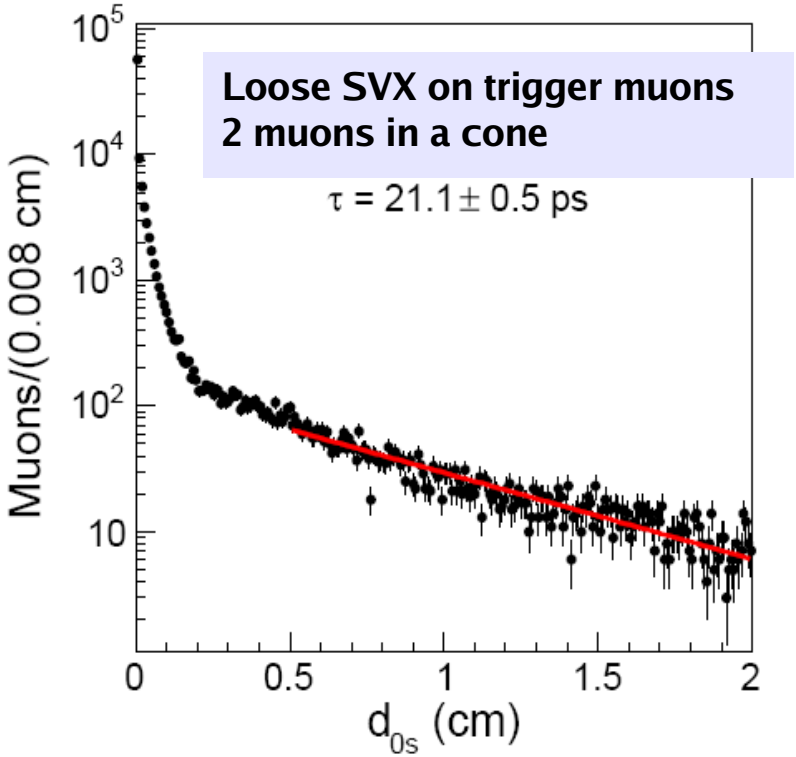
- Plot is additional muons in a single cone around the trigger muon in the ghost sample (after fake correction)
- Relative to the trigger muon:
  - +1 if additional muon if OS
  - +10 if SS
- On average a multiplicity increase of one unit correpsonds to a population decrease of 7



Impact parameter of additional muons

- Additional muons (in a cone around the trigger muon) not biased by the trigger
  - Loose SVX requirements on trigger muon, no SVX requirements on additional muon
- DIF and long-lived particles suppressed by multiple muon request
- If assume additional muons arise from decay of an object with a lifetime get a fit from the impact parameter distribution of: $\tau = 21.4 \pm 0.5$ ps (error statistical only)





Recap of where we are

- Several sources of ghost events were investigated that could account for about 50% of the ghost sample rate (predominantly DIF and long-lived particles), however, other characteristics of the ghost events are not what one would expect from these sources:
  - Rate of additional muons 4 times larger than in QCD (expect rate to be less if from DIF and long-lived particles)
  - Some ghost events have very large muon multiplicities (after correcting for fakes) – 3 or 4 muons in a cone
  - Number of charged tracks in ghost sample 2 times larger than in QCD
  - Impact parameter of additional muons extends well beyond that of QCD
  - (not discussed in this talk) Cone correlations – more than 10% of ghost events with at least one additional muon in one cone has at least one additional muon in the cone around the second trigger muon
- Strength of analysis is very good demonstrated understanding of control regions

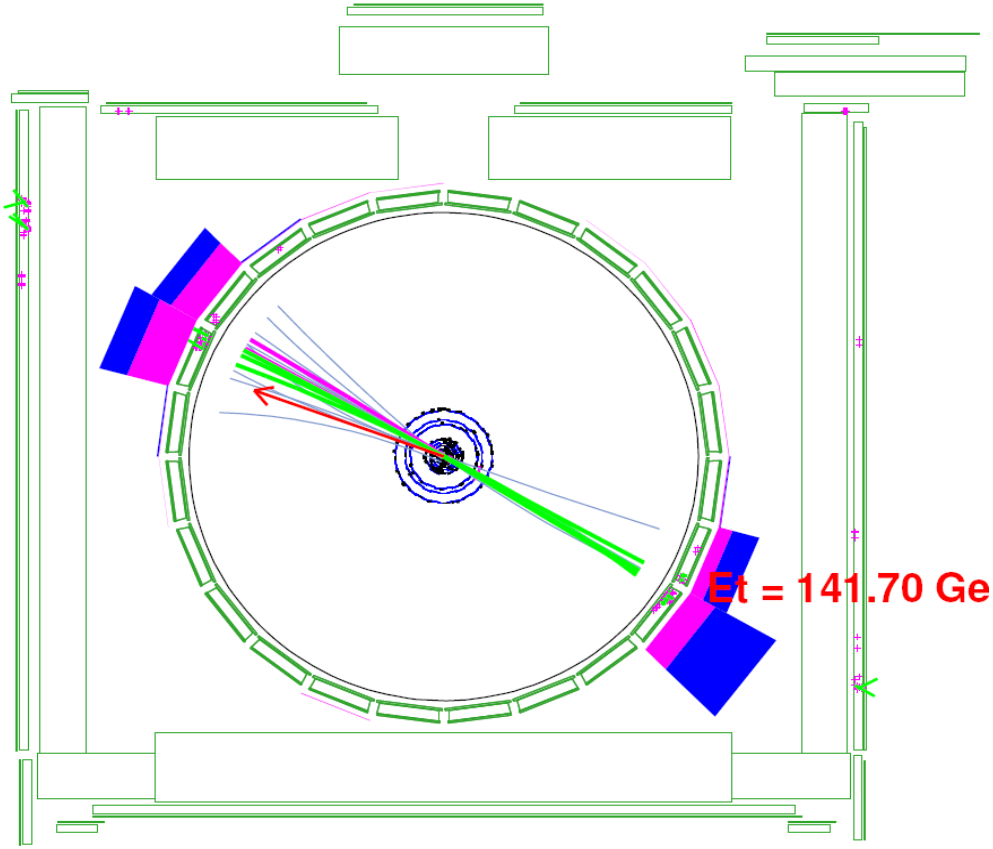
Correlated muon fake rates ?

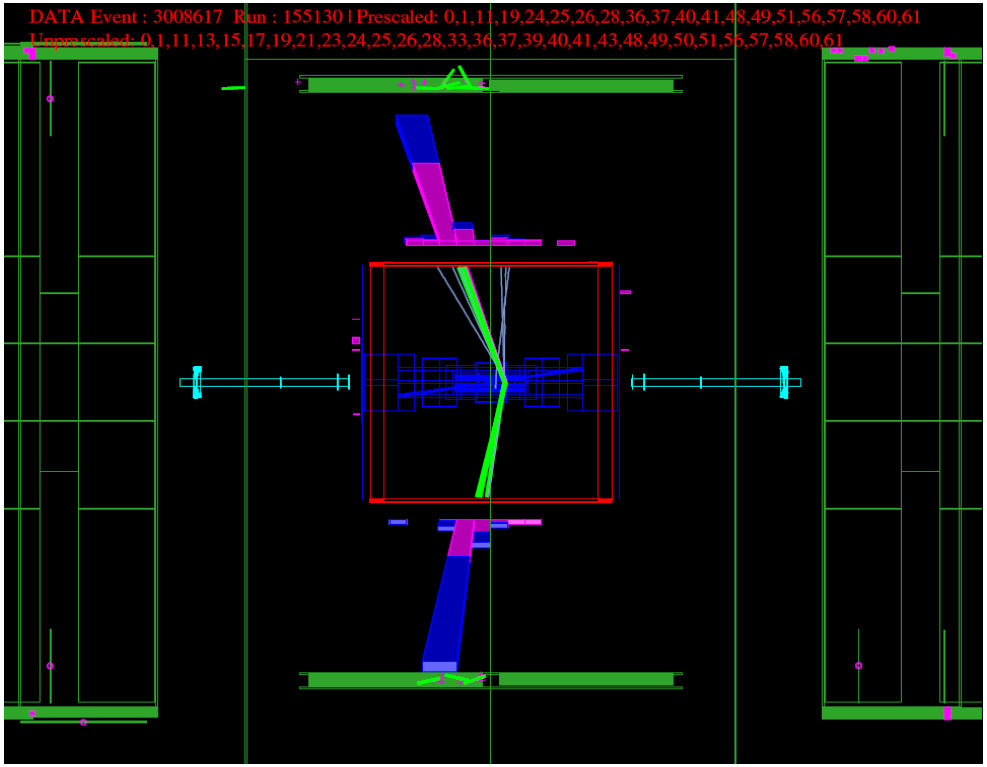
- Our per-track fake probability assumes that fake muons are uncorrelated
- Probably not entirely true:
  - high energy jet ⇒ large leakage ⇒ lots of activity in muon chambers ⇒ lots of fake muons
- There is no clear way to directly probe this effect (require a sample in which to calibrate any fake rate)
- However can reduce its effect by requiring tighter muon selection
  - Higher purity muons do not affect the salient features of this effect
- If the high muon multiplicity events in the ghost sample are caused by correlated fakes, we would still need to explain why we don't see it in the QCD sample
- At any rate, this remains an open issue, and is under further study

Conclusions

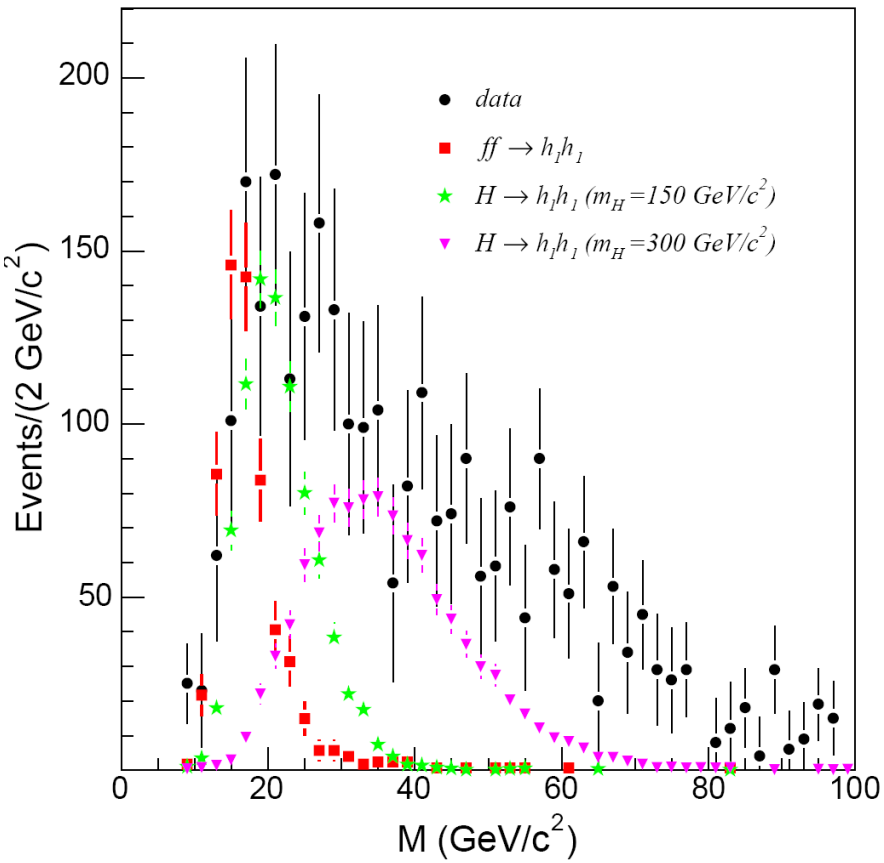
- There are a significant number of events acquired with the CDF dimuon trigger that we do not have a good understanding of (called ghost events)
- However, they offer a plausible explanation for a number of puzzles that have been around over the last decade
- A significant fraction of these events seem to have very unique properties
- We currently can not explain these events, and we can not rule out known processes – more work on a longer time scale is required for a better understanding of their source
- Perhaps a useful lesson though for the LHC: unexpected events can show up in ways not previously considered and in very difficult environments which requires a very careful line of attack, both in terms of physics, and politics!
- We hope to be able to shed more light on these events in the coming months

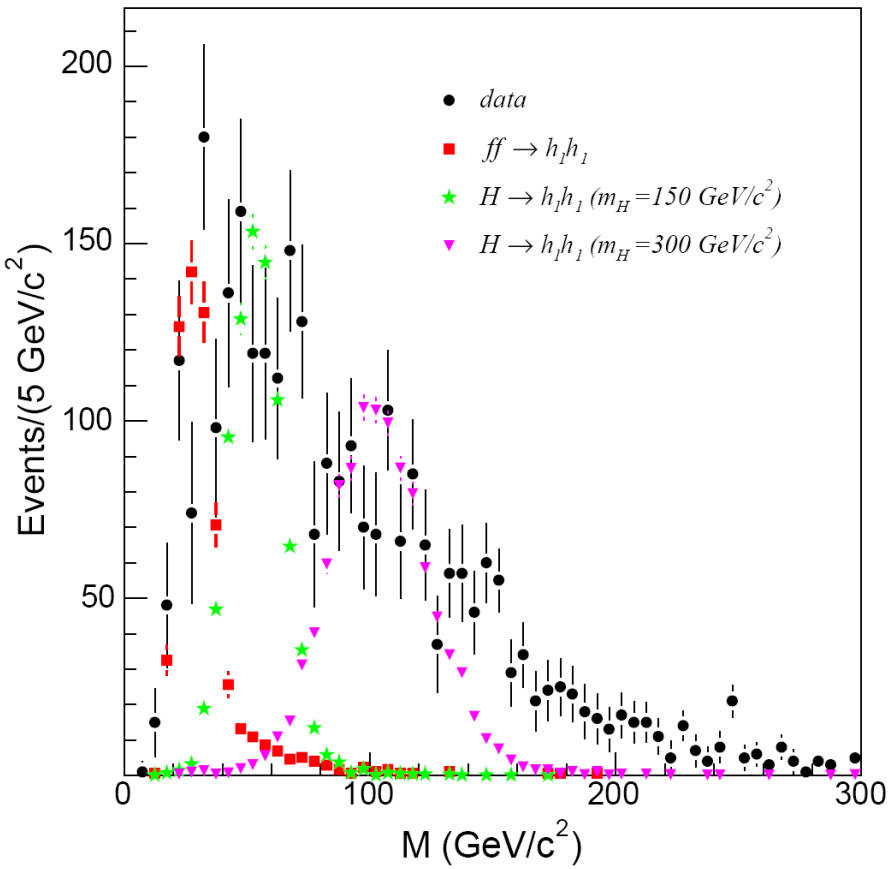
Backup plots





Green track = muon candidate





Invariant mass of all muons for events in which both cones contain at least two muons

σ= 3.4 nb

σ= 50 pb

σ= 35 pb

Invariant mass of all tracks for events in which both cones contain at least two muons

Cone correlations

Ghost events

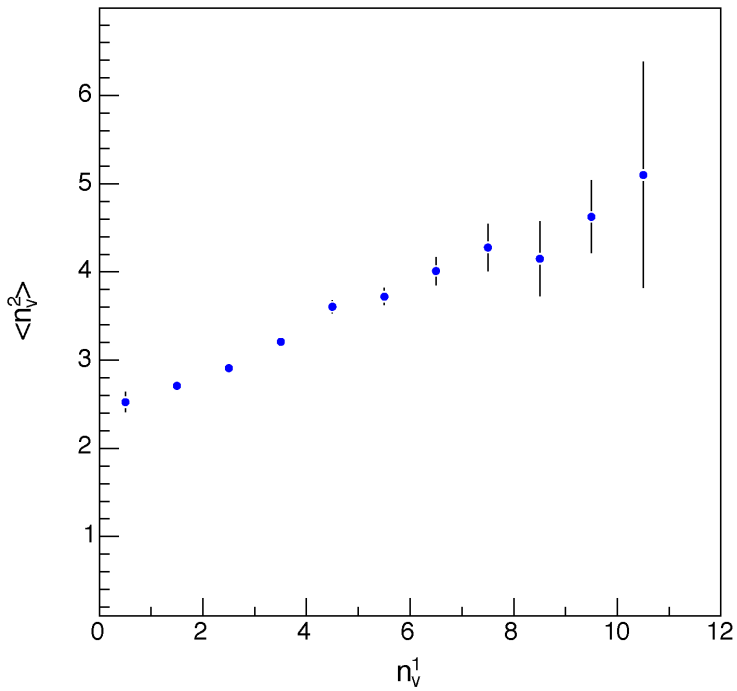
27790±761 cones with ≥ 2 μ (a)

4133±263 cones with ≥ 3 μ

3016 with ≥ 2 μ in both cones (b)

The ratio (a)/(b) = 0.11 is quite large - for comparison, in events triggered by a central jet, the fraction of events containing another central jet is 10-15% depending on the jet transverse energy

A simulation of the process ff->$h_n h_n$ yields the same ratio



Number of secondary vertices in one cone versus the other – both cones contain at least 2 muons