

# Study of multi-muon events at CDF

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on behalf of the CDF collaboration

Le Rencontres de Physique de la Vallée d'Aoste  
March 6<sup>th</sup>, 2009

# Outlook

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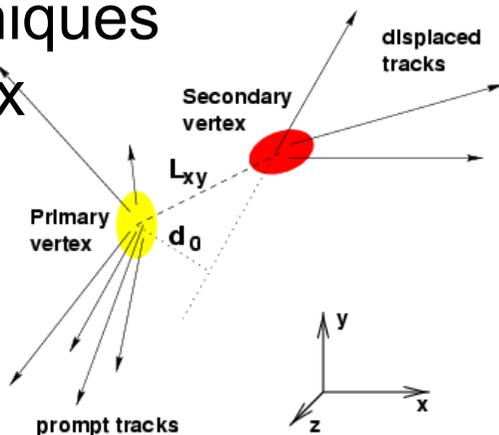
- Physics motivation:
  - puzzles in  $b$  production and decays from the previous century
    - Correlated  $bb$  production,  $\sigma_{bb}$ , higher than Standard Model
    - Dilepton invariant mass spectrum of  $b$  cascade decays
- Recent results:
  - new and very precise measurement of  $\sigma_{bb}$  agrees with the prediction [\[PRD 77,072004 \(2008\)\]](#)
- Study of the multi-muon events responsible for the differences between the old and the new  $\sigma_{bb}$  measurements [arXiv:0810.5357\[hep-ex\]](#)

# Correlated $b\bar{b}$ cross section

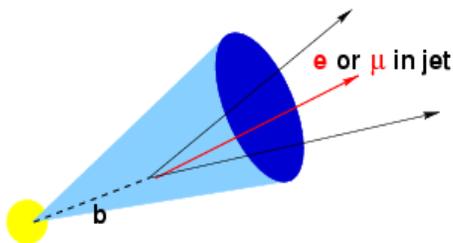
Two central  $b$ 's with enough  $p_T$ . Small theoretical uncertainty (15%), LO diagrams dominate

- Measurement techniques

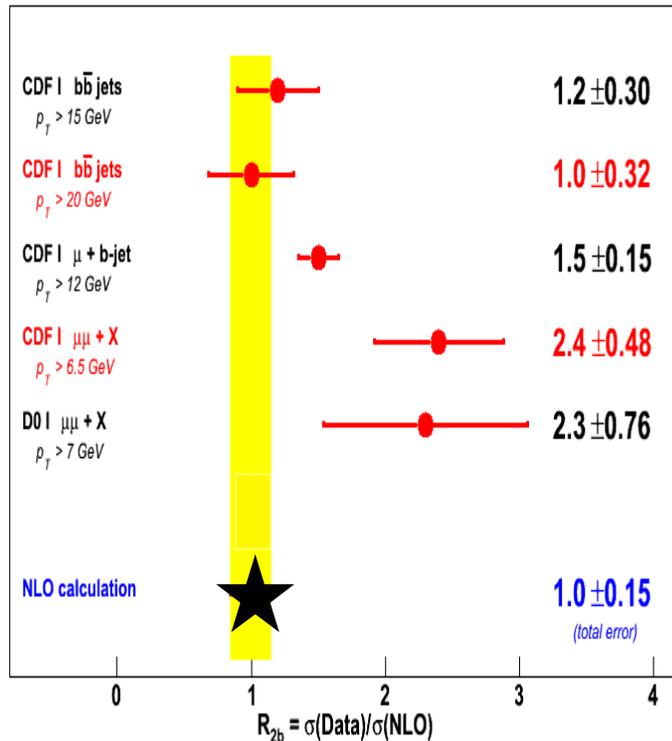
- secondary vertex tagging



- muon tagging



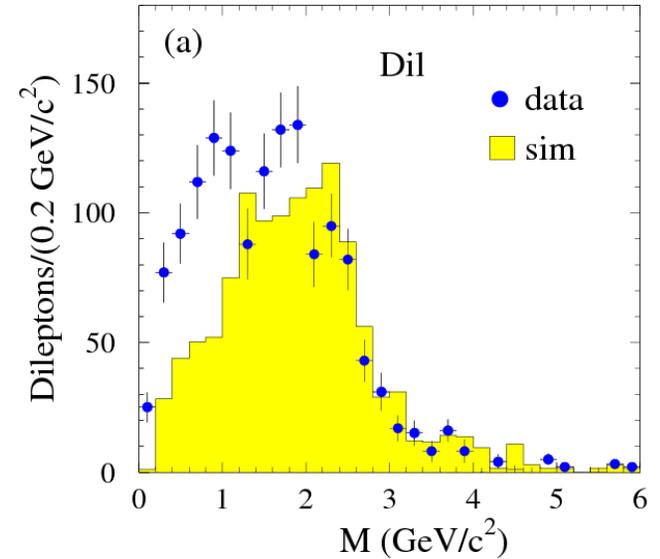
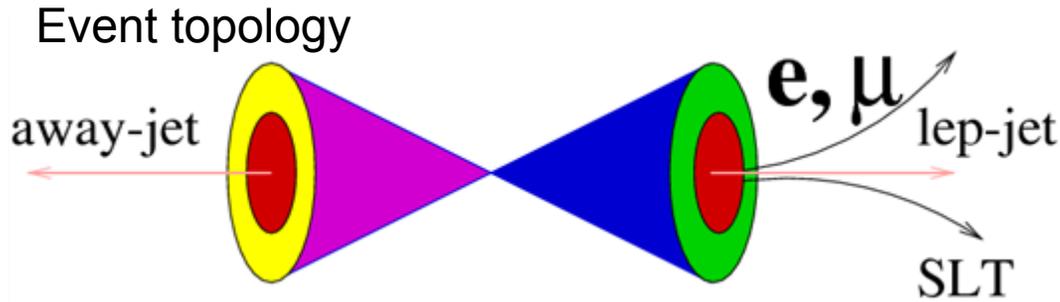
- $R_{2b} = \sigma_{bb}(\text{measured})/\sigma_{bb}(\text{NLO})$ 
  - Vertex tag analyses  $\rightarrow R_{2b} = 1$
  - Analyses using muon tags  $\rightarrow R_{2b} > 1$



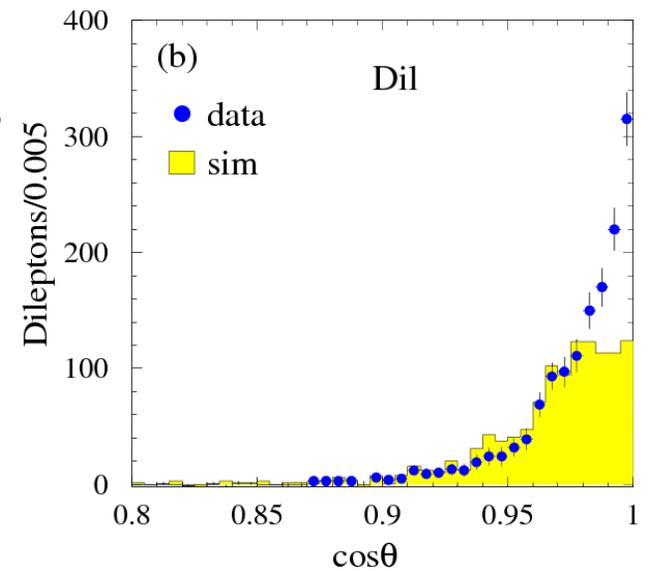
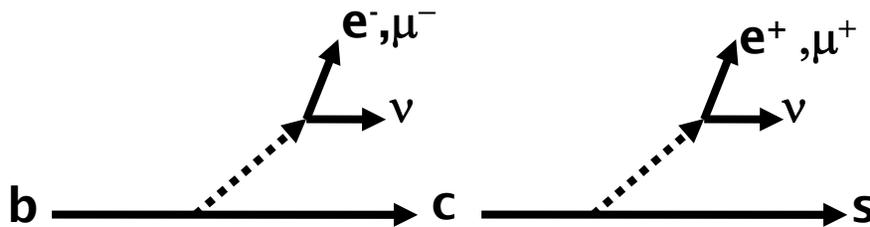
$$\sigma(p\bar{p} \rightarrow b\bar{b} \rightarrow llX)$$

larger than NLO  $\propto N(\mu)$

# low mass dileptons



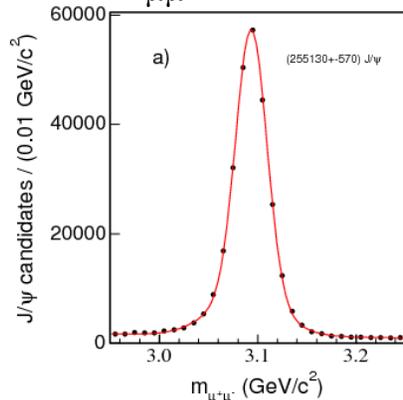
- $B$  enriched sample:  
the low mass di-lepton invariant mass is not well modeled by sequential semi-leptonic decays of single  $b$  quarks



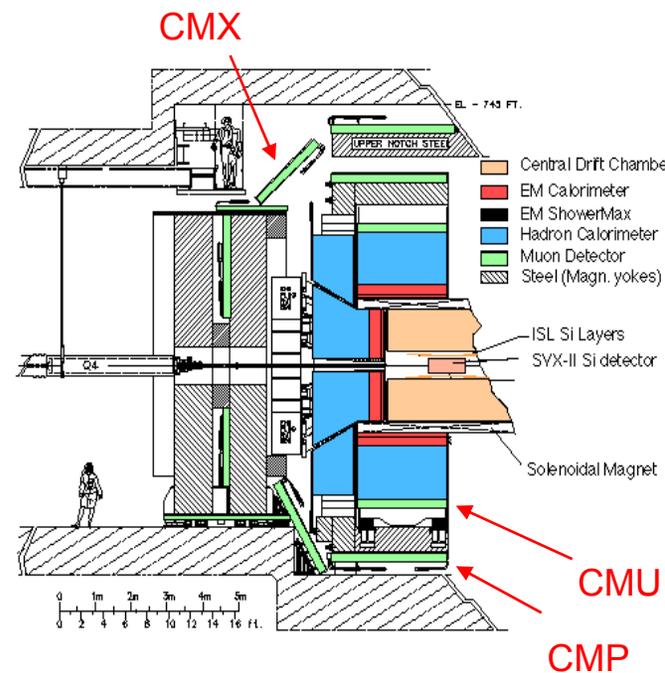
- Simulation: HERWIG+EVTGEN

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

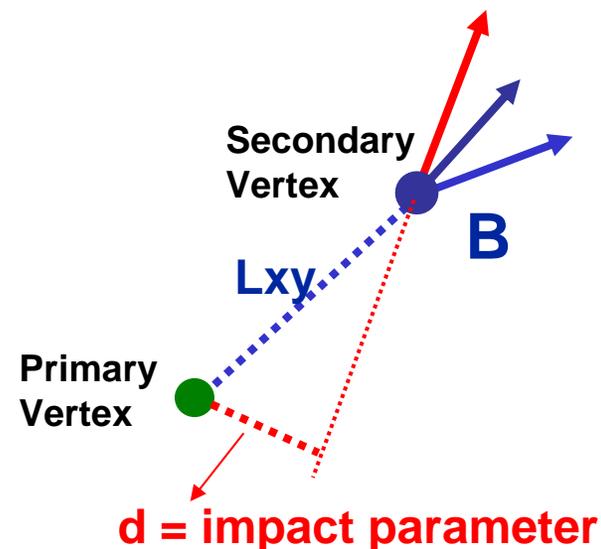
- Data sample used in this analysis ( $\sim 750\text{pb}^{-1}$ ) defined by a trigger requiring 2 muons with:
  - Central track with  $p_T > 3 \text{ GeV}$ ,  $|\eta| < 0.7$
  - Match to stub in CMU and CMP (CMUP)
  - $5 < M_{\mu\mu} < 80 \text{ GeV}$  ( no  $Z$ 's,  $J/\psi$ ,  $b \rightarrow c\mu \rightarrow \mu\mu X$  )



→  $J/\psi$ :  
muons purity

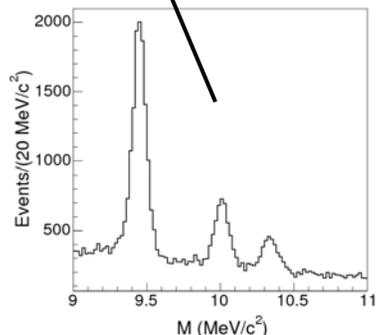
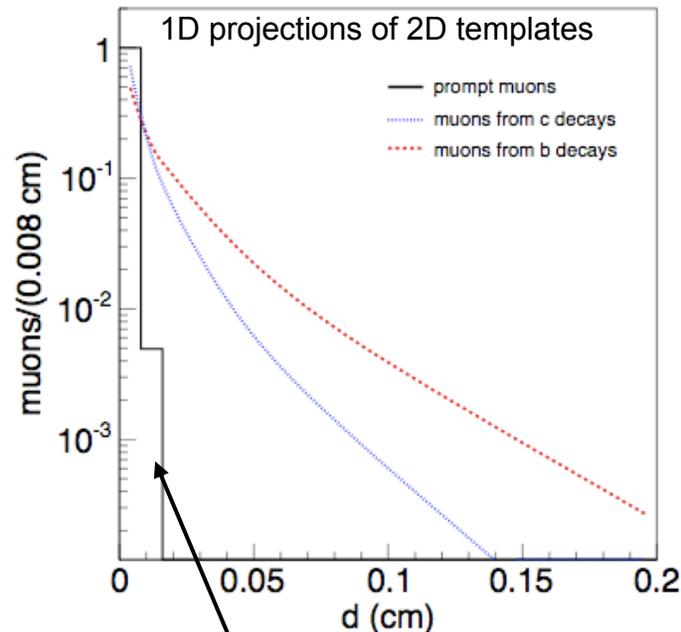


- Known sources of real muons are:
  - $b \rightarrow \mu$  ( $c\tau = 470 \mu\text{m}$ ),  $c \rightarrow \mu$  ( $c\tau = 210 \mu\text{m}$ )
  - Prompt muons ( $\Upsilon$ , Drell-Yan)
- Known sources of fake muons include:
  - Hadrons punching through calorimeter
  - Decays in flight ( $K_S \rightarrow \mu$ ,  $\pi \rightarrow \mu$ )
  - Fake muons can be from prompt or h.f. decays

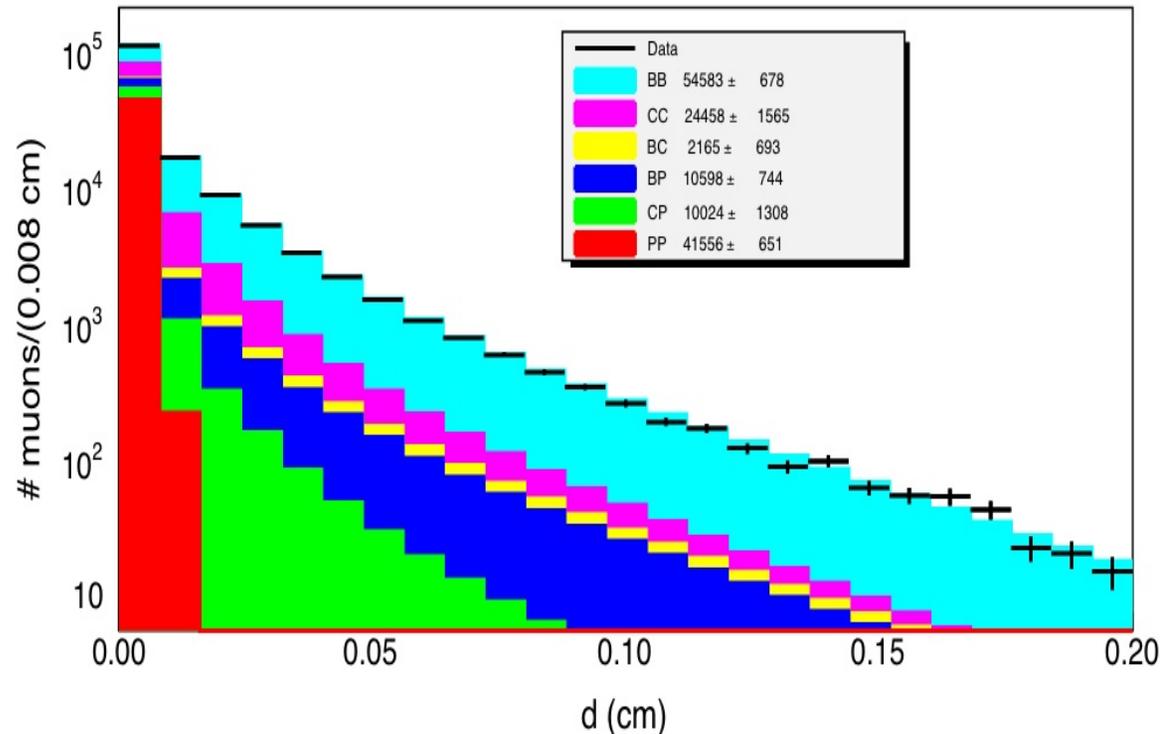


# New measurement of $\sigma_{bb}$ : experimental method

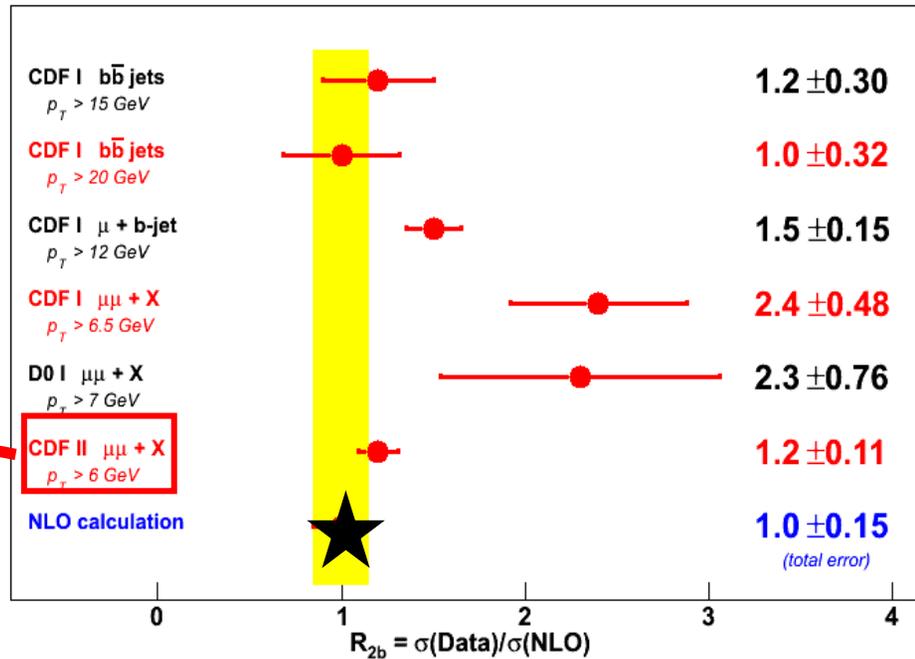
- Extract the sample composition by fitting the observed  $d_0$  distribution of the muons [2D fit -  $d_0(\mu_1)$  vs  $d_0(\mu_2)$ ] with the expected  $d_0$  distributions of muons from various sources and for all the combination ( $bb, cc, pp, bc, bp, cp$ )
- Derive templates for h.f (MC) and Prompt (Y from data)



Y



# New measurement of $\sigma_{bb}$ : results



- Very accurate
- Appreciably smaller than Run I results

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

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

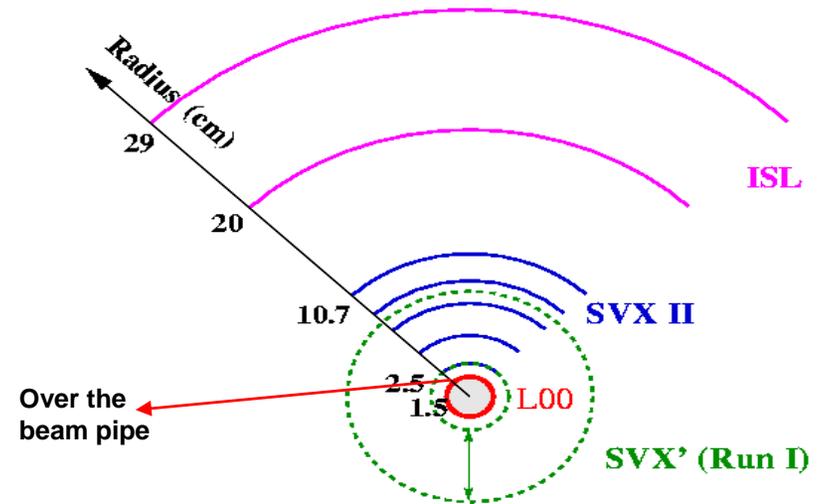
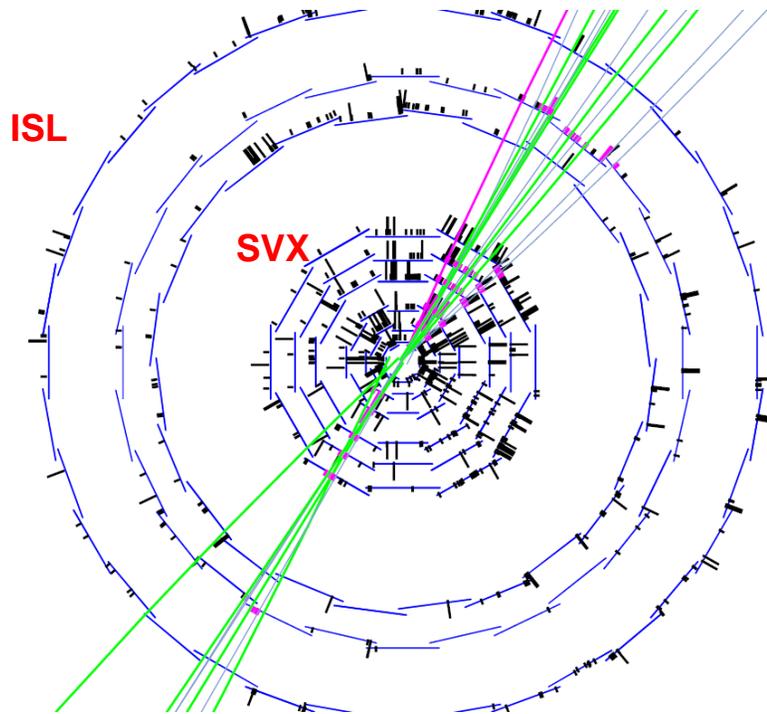
$$(p_T > 6 \text{ GeV} \quad |\eta| < 1.0)$$

WHY?

# Investigating the differences: tracking

The highest tracking precision is achieved using hits in the SVX II detector; in this way we can separate muons from  $b$ 's,  $c$ 's and prompt sources

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



Impact parameter resolution:

- 230  $\mu\text{m}$  (COT only tracks)
- 30  $\mu\text{m}$  (COT +  $\geq 3$  SVX hits)

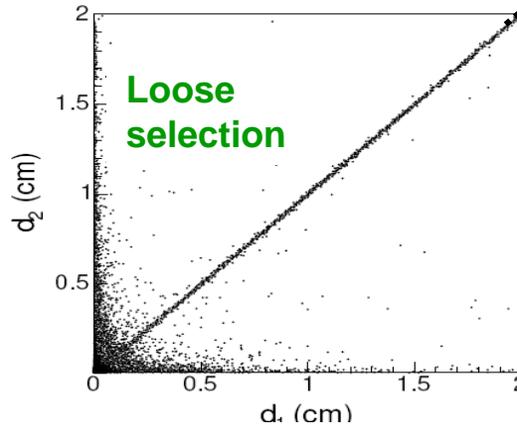
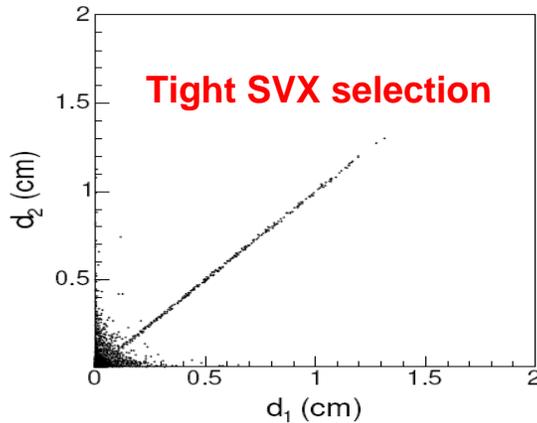
The excellent modeling of the 2 muons impact parameter distribution is obtained only using

- tight SVX requirements (hits in L0, L00 and two of the remaining L1-L4 layers)
- L0 and L00 are essential

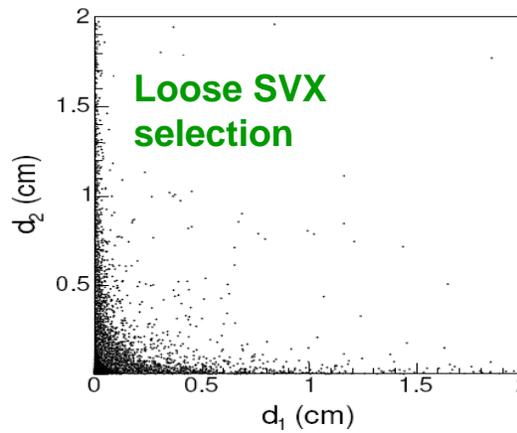
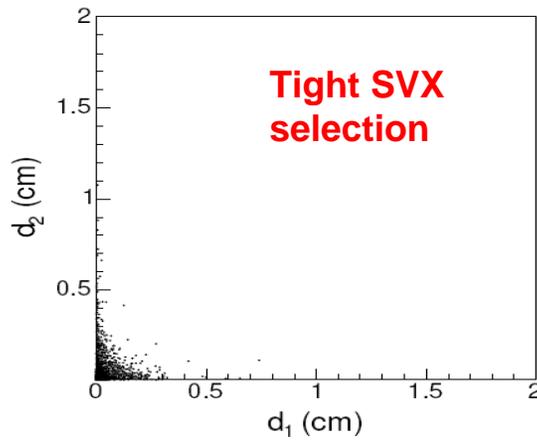
This selection requires that both muons originate inside the beam pipe

# Tracking differences

- Analyses in CDF use **loose SVX** requirements: 3/8(SVX+ISL) layers
  - Muons can originate as far as 10.8 cm from the beam line
  - According to simulation, 96% of QCD events have 2 muons originating inside the beam pipe
- Run I analyses selected muons originating from distances as large as 5.7 cm from the beam line



Cosmic rays overlapping  $p\bar{p}$  collisions:  
2 back to back muons  
clustering along the diagonal  
of  $d_0(\mu_1)$  vs  $d_0(\mu_2)$



After cosmic removal

$$\mathcal{G}_{\mu^-\mu^+} < 3.135 \text{ rad}$$

# Tight SVX efficiency

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- Evaluate efficiencies using control samples of data
  - Prompt:  $(25.7 \pm 0.4)\%$  using Y and Drell Yan
  - Heavy Flavor:  $(23.7 \pm 0.1)\%$  using
$$B \rightarrow J / \psi, B \rightarrow J / \psi K, B \rightarrow \mu D^0$$
- If the dimuon sample before the tight SVX had the composition determined by the fit, the average **efficiency of the tight SVX** requirement,  $\epsilon_{\text{tight SVX}}$ , would be  **$0.244 \pm 0.002$**  whereas it is measured to be  **$0.1930 \pm 0.0004$**
- such a difference means that there are many more events rejected by the tight SVX selection than expected:
  - more background in the total sample (before SVX requirements)
  - Background is removed with the tight SVX selection
  - Background is not removed with looser SVX selection since it appears at large  $d_0$

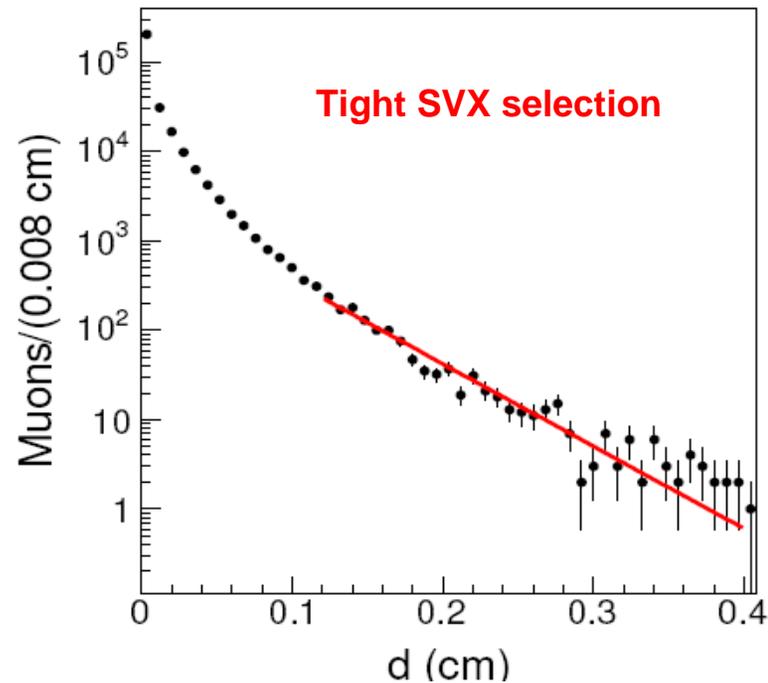
# QCD events

Assume that the tight SVX selection only isolates known sources of dimuon events that we call QCD

- Charm contribution minimal for  $d_0 > 0.12$  cm
- Fit  $d_0$  distribution for muons with  $0.12 < d_0 < 0.4$  cm
  - ✓ Measure  $c\tau = 469.7 \pm 1.3 \mu\text{m}$  (stat. error only)
  - ✓ PDG average  $b$  lifetime:  $c\tau = 470.1 \pm 2.7 \mu\text{m}$
  - ✓ Reasonable initial assumption

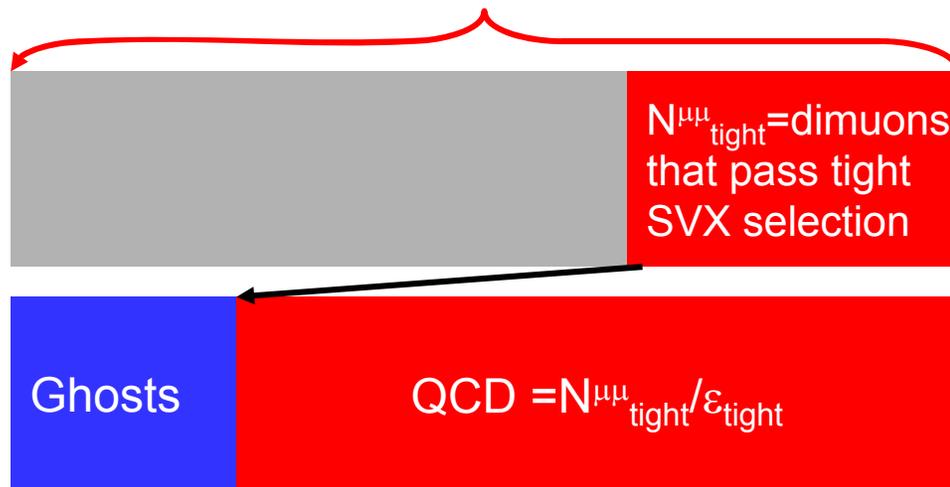
Conclude that:

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

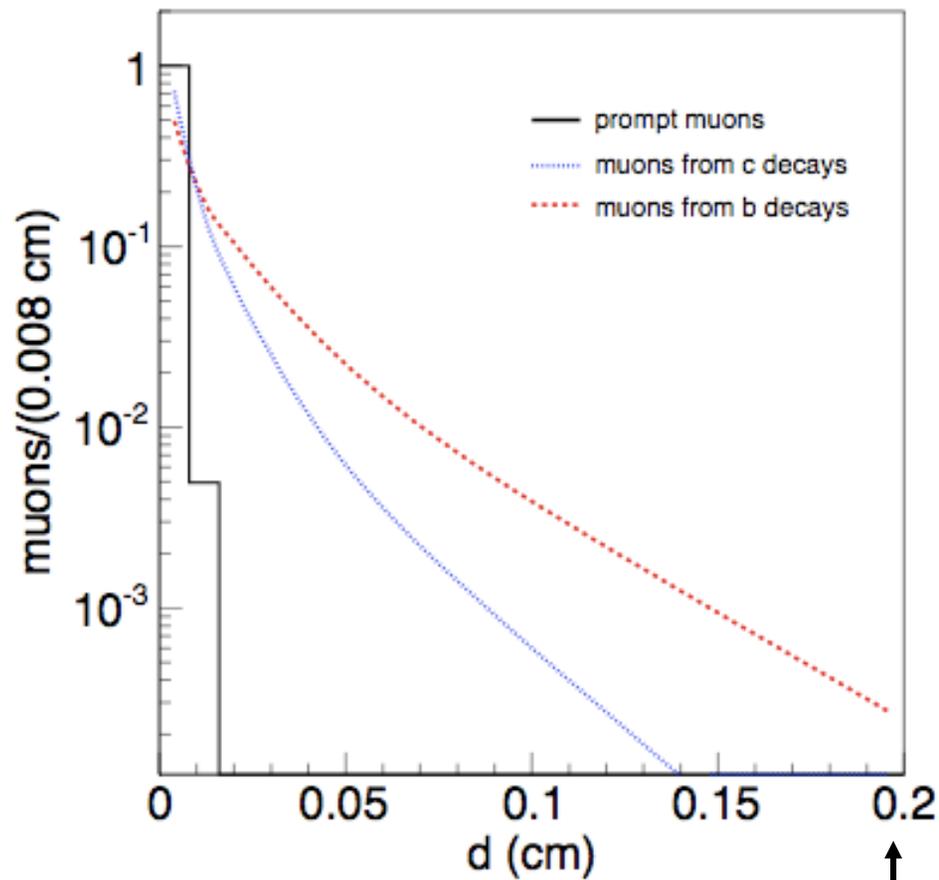
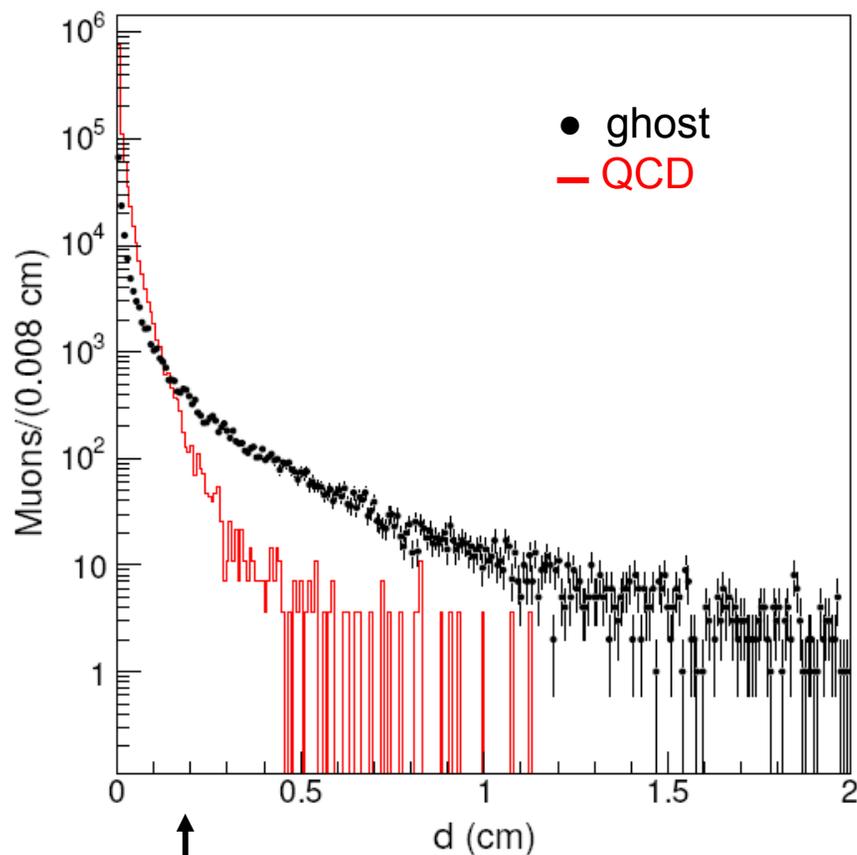


# Ghost events

- Start with the total sample of dimuons
- We call Ghost events the excess of events that escapes the tight SVX requirements after accounting for the tight SVX efficiency
  - Sample definition:
    - **QCD** = sum of contributions determined by the fit of the  $b\bar{b}$  cross section analysis [ $b$ ,  $c$ , prompts]
    - **GHOST** =  $\text{AllDimuons} - \text{QCD} / \epsilon_{\text{tight SVX}}$



# Impact parameter distribution of trigger muons in QCD and Ghost events



↑  
0.2 cm

- QCD sources of dimuons have  $d_0 < 0.5$  cm
- Ghost events have much larger impact parameters

# Counting events

From the tight SVX selection that we assume to be all QCD events, and using the known efficiencies estimate the QCD contribution in “All” and “loose SVX” sample  
 Ghost = ALL-QCD

Type	Total	Tight SVX	Loose SVX
All	743006	143743	590970
All OS	<i>event counting</i>	98218	392020
All SS		45525	198950
QCD		<i>assumption</i> 143743	518417 ± 7264 = 143743 * $\epsilon_{\text{loose}} / \epsilon_{\text{tight}}$
Ghost	153895 ± 4829	0	72553 ± 7264

In the whole dimuon sample: ghost = AllDimuons - QCD /  $\epsilon_{\text{tight}}$   
 QCD = dimuon events with tight SVX cuts

In loose SVX sample: ghost = AllDimuons - (QCD /  $\epsilon_{\text{tight}}$ ) \* ( $\epsilon_{\text{loose}} = .88$ )

# $\sigma_{bb}$ inconsistencies explanation

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Previous  $\sigma_{bb}$  measurements used selections:

- close to “loose SVX”: ghost  $\sim 73\text{K}$  events compared to bb of  $\sim 195\text{K}$   $\rightarrow R \sim 1.3$
- No SVX req's at all: ghost  $\sim$  bb  $\rightarrow R \sim 2$

The general observation is that:

$\sigma_{bb}$  measurements increase as SVX req's are made looser together with the increase of the ghost events contribution

# Possible sources of Ghost events

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We have investigated ordinary sources of events that could give rise to real or fake muons with large  $d_0$  and therefore missing the inner SVX layers.

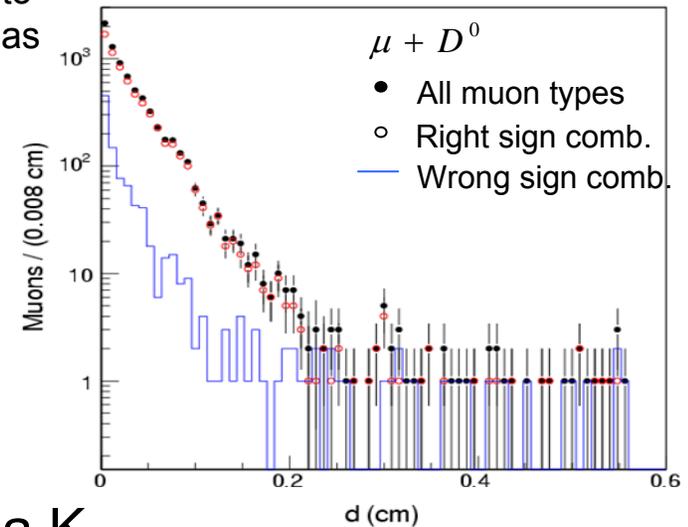
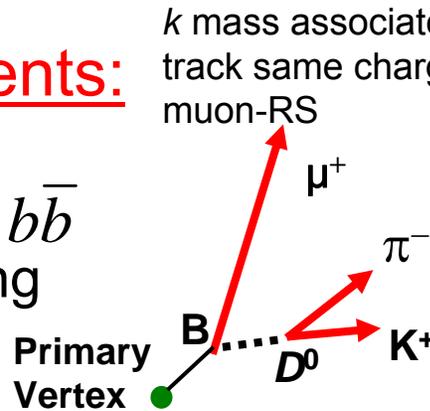
- Mis-measured tracks
  - Hadrons mimicking a muon (punch throughs)  
*evaluated using  $D^0 \rightarrow K\pi$  decays in data*
  - In flight decays of  $K^\pm, \pi^\pm \rightarrow \mu^\pm \nu_\mu$   
*evaluated using herwig Monte Carlo*
  - Long-lived hadrons ( $\Lambda \rightarrow p\pi^-, K_S^0 \rightarrow \pi^+\pi^-$ )  
*evaluated using data*
  - Secondary interactions of hadrons in the silicon that produce secondaries with large  $d_0$
- ~57000 evts
- ~12000 evts

We can explain 50% of the total ghost sample (153895 evts)

# Possible sources of ghost events

- Track mismeasurements:**

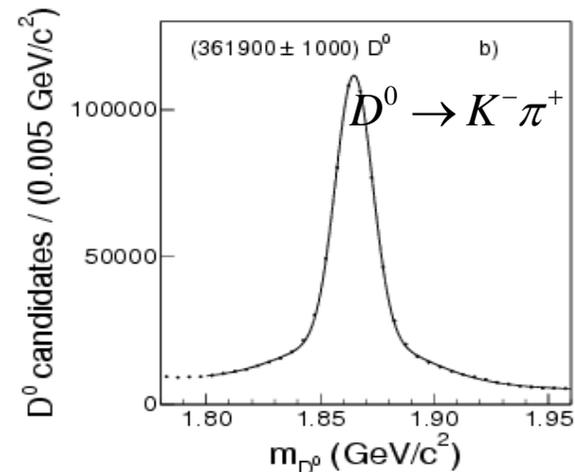
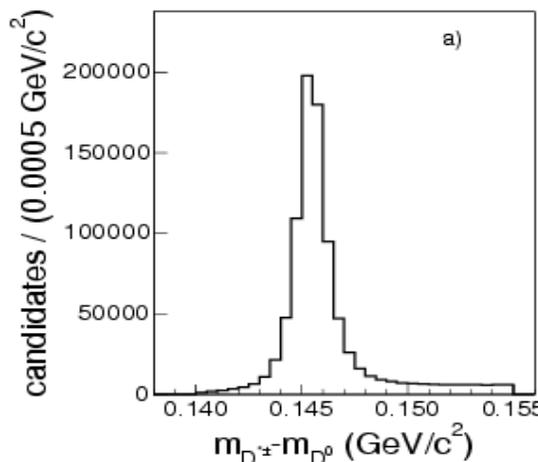
look at  $\mu + D^0$  events.  
 Most of them come from  $b\bar{b}$   
 $d_0(\mu)$  consistent as coming  
 from B's – no long tails



- Punch throughs:**

Measure the probability per track that a  $\pi$  or a K punches through the calorimeter and fakes a muon

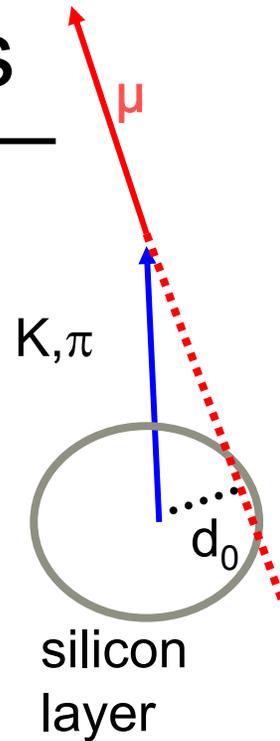
- Reconstruct  $D^{*+} \rightarrow D^0 \pi^+$  decays with  $D^0 \rightarrow K^- \pi^+$
- $D^{*+}$  uniquely identifies  $\pi$  and  $K$
- Ask at what rate hadrons are found as muons



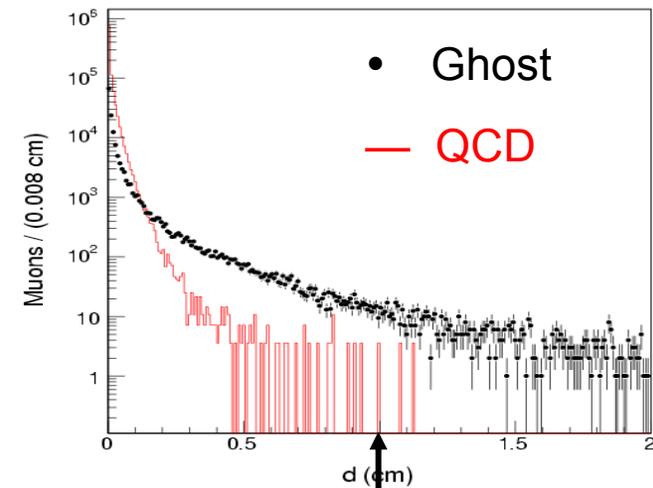
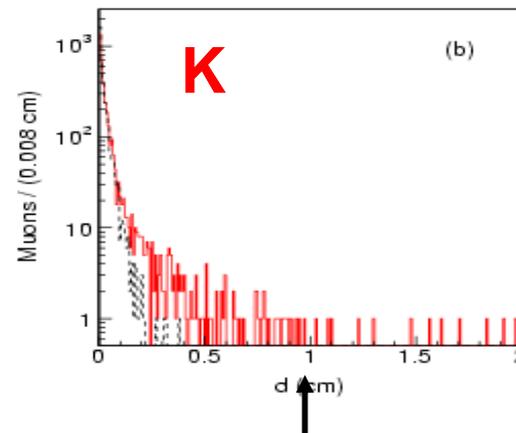
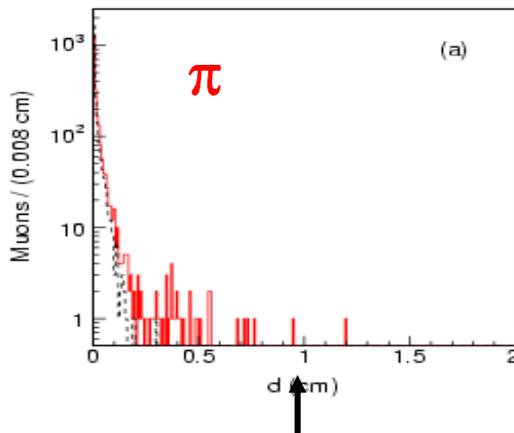
# Possible sources of ghost events

## Decays in flight:

- Measure the probability that K and  $\pi$  decays produce CMUP muons (trigger muons) and pass all analysis cuts. Use a heavy flavor simulation [HERWIG].
- Probability per track that a hadron yields a trigger muon is 0.07% for  $\pi$  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 decays in flight



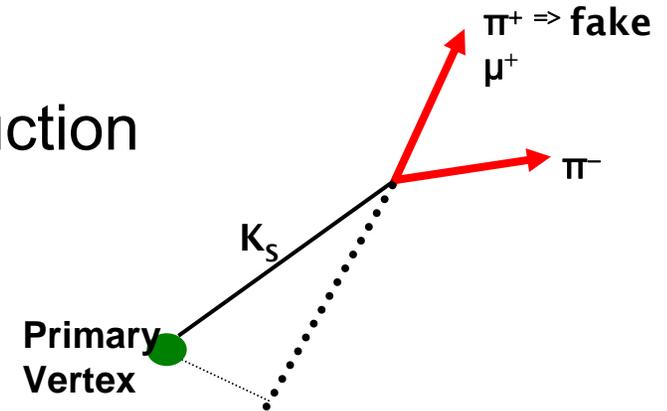
In-Flight decays prediction explains 35 % of the ghost events, but only 10% of the events with  $d_0 > 0.5$  cm.



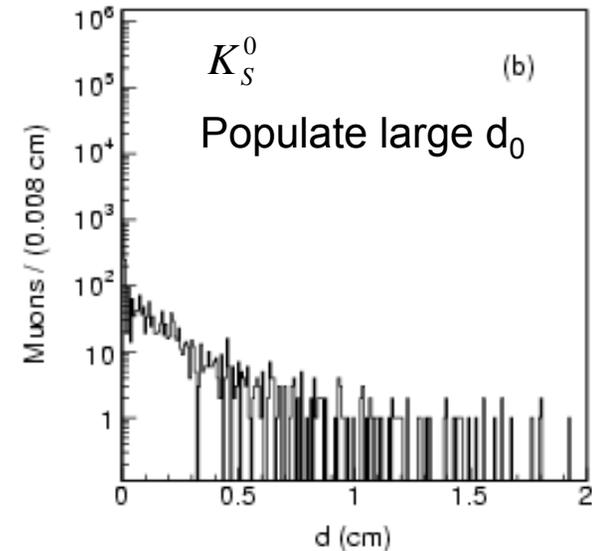
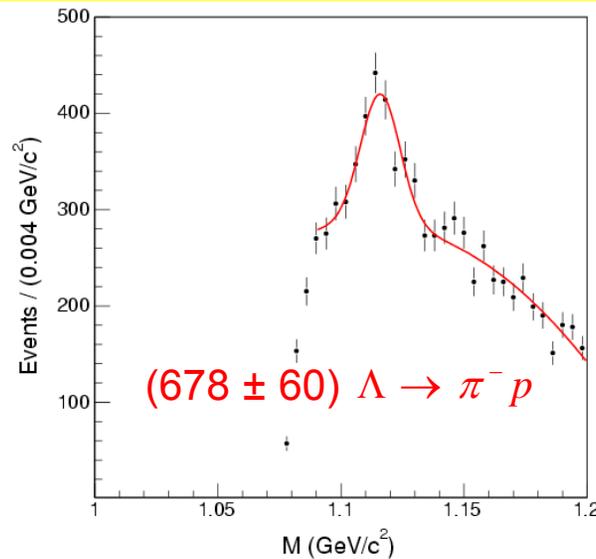
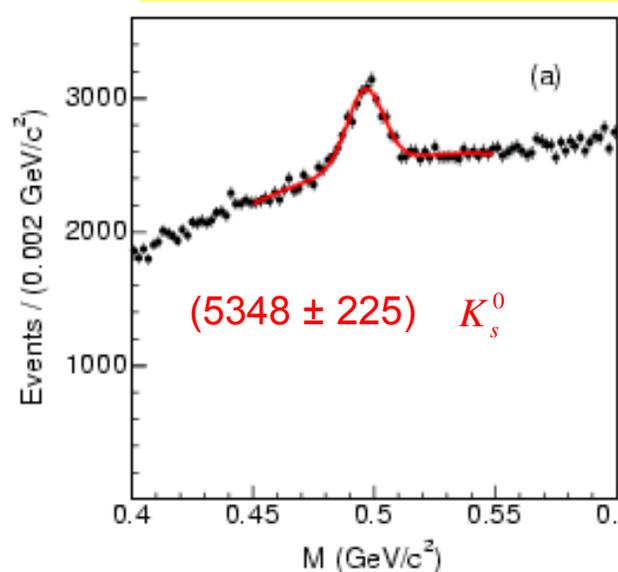
# Possible sources of ghost events

## $K_S^0$ and hyperons:

- Kinematic acceptance times reconstruction efficiency  $\sim 50\%$  (MC).
- Approximately 12000 ghost events are contributed by these decays.



Look for  $\mu^+$  track  $p_T > 0.5 \text{ GeV}/c$  Assume  $\mu$  and track are  $\pi$



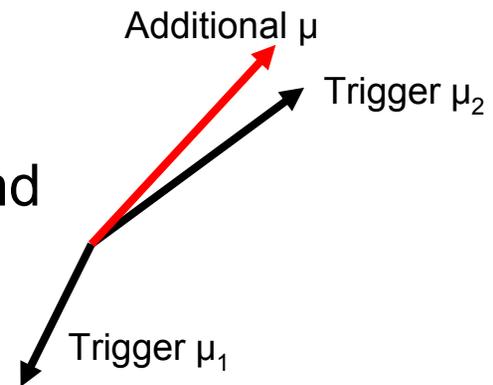
# Search for additional muons

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Interesting:

- If the Ghost events were all due to known sources of fake and real muons one would expect that the request of additional muon decreased the contribution of ghost with respect to QCD that contains also  $b$  sequential decays
- The request for an additional muon should select  $b$  quark sequential decays and depress all other contributions
  - (0.9% of  $Y$  contain an additional  $\mu$  – 1.7% of  $K_S^0$ )
- One would expect that  $\epsilon_{\text{tight svx}}$  rose from 0.193 towards 0.244  
→ 0.166 first surprise!
- Ghost events may be related to the excess of low mass dileptons – start with this study

Search for additional muons with  $p_T > 2 \text{ GeV}/c$  and  $|\eta| < 1.1$  around each initial muon;  $M_{\mu\mu} < 5 \text{ GeV}/c^2$  -  
Use CMU+CMF+CMX



# Low mass dimuons-sequential $b$ decays

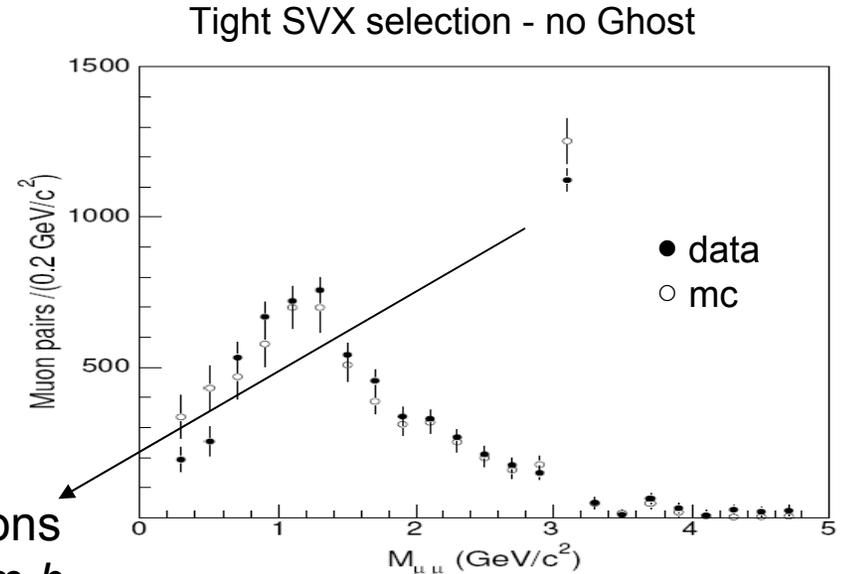
Compare invariant mass in data and simulation that includes fakes

Tight SVX :

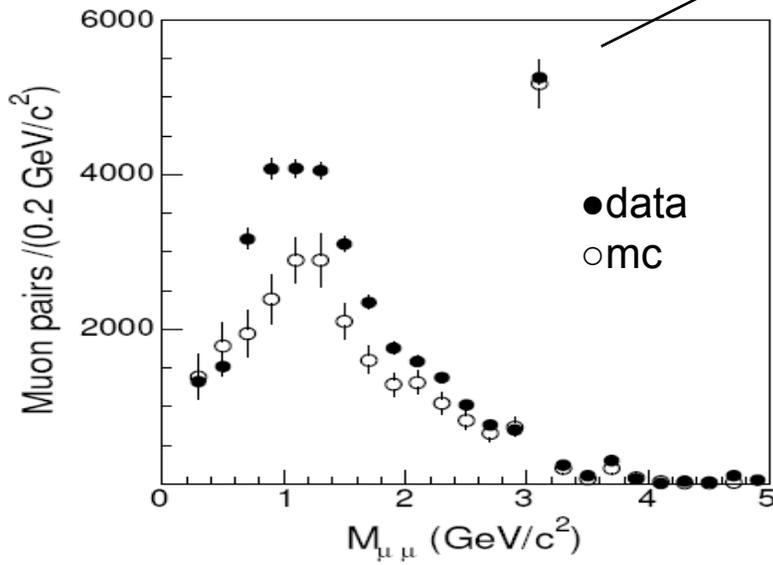
Data:  $6935 \pm 154$

MC:  $6998 \pm 239$

We conclude we understand  $\sigma_{bb}$ , the heavy flavor simulation and the fake muon bkg

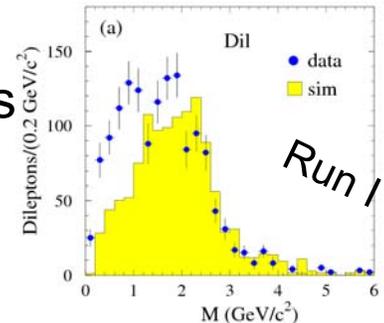


$J/\psi$  mesons arise from  $b$



Entire sample no SVX req's :

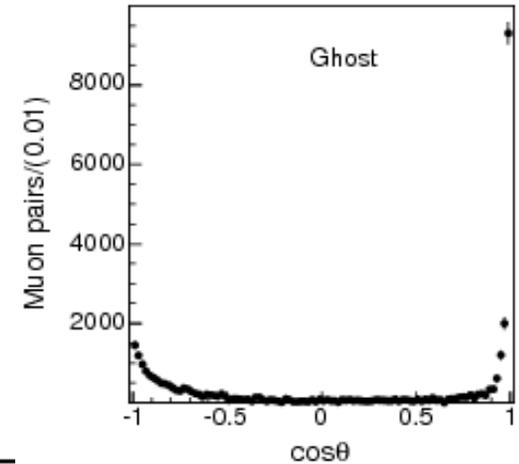
- ✓ Excellent agreement on the  $J/\psi$  prediction
- Clear excess at low mass not seen with tight SVX associated with ghost



# Extra muons/tracks in ghosts

We notice that in the ghost sample, many of the additional muons lie in a  $\cos\theta > 0.8$  cone around the trigger muons. Count muons inside cones.

# of additional muons in ghost



Topology	Observed	$F_K$	$F_\pi$
<i>OS</i>	$28692 \pm 447$	$15447 \pm 210$	$9649 \pm 131$
<i>SS</i>	$20180 \pm 246$	$10282 \pm 137$	$6427 \pm 81$

There are 295481 ghost events that contain approximately 28000 real muon combinations with SS or OS charge (9.4% )

- number of additional muons in ghosts is 4 times larger than in QCD (2.5%)
- Number of charged tracks ( $p_T > 2\text{GeV}$ ) in ghosts is 2 times larger than in QCD

# muon multiplicity in a $\cos\theta > 0.8$ cone

Plot shows the number of additional muons in a single cone (after fake sub.)

We count additional muons relative to the trigger muon:

$$\mathcal{M} = N_{OS} + 10N_{SS}$$

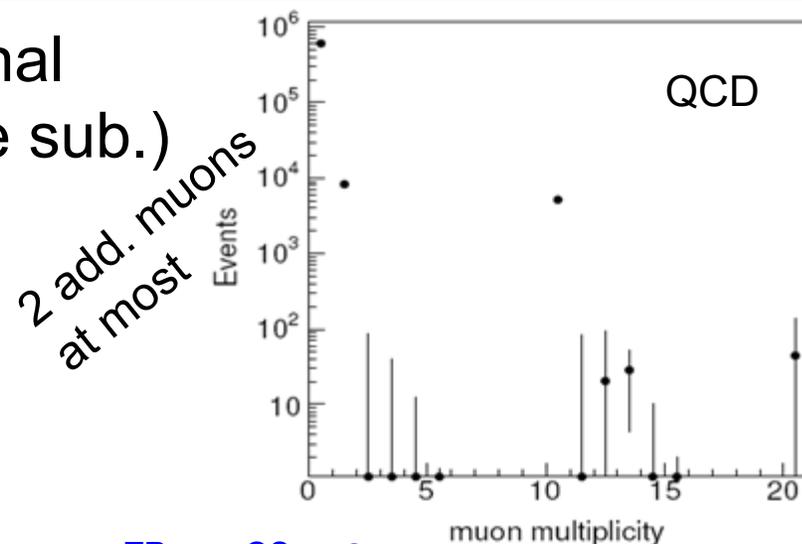
$$\nabla \text{ OS } \mu: \mathcal{M} = ++1$$

$$\nabla \text{ SS } \mu: \mathcal{M} = ++10$$

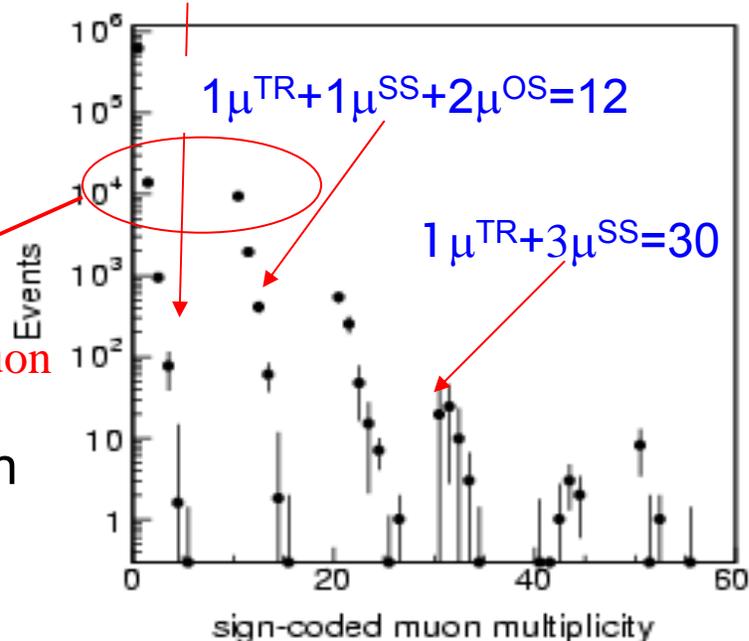
For example: in a cone of  $\mu^+$  we find  $2\mu^-$  and  $1\mu^+$ :  
It corresponds to bin 12

Some ghost events have very large muon multiplicities - 3 or 4 muons in a cone

**Second surprise!**

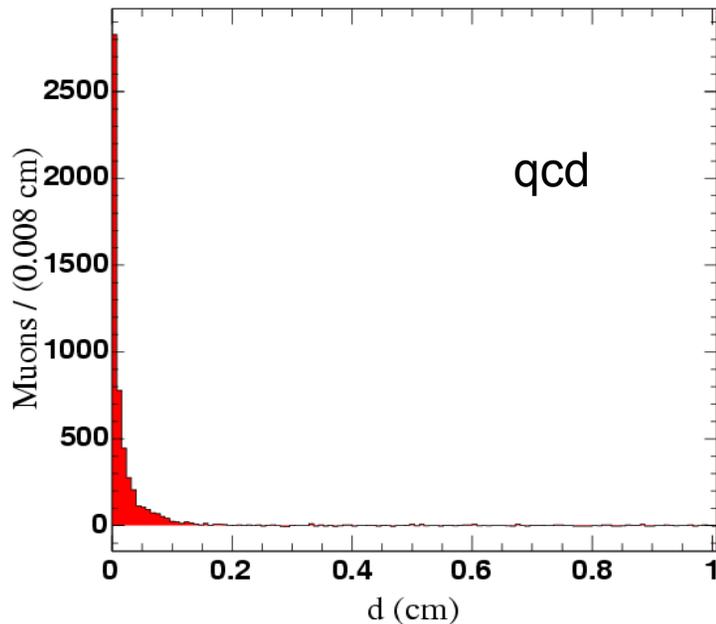


$$1\mu^{TR} + 3\mu^{OS} = 3$$

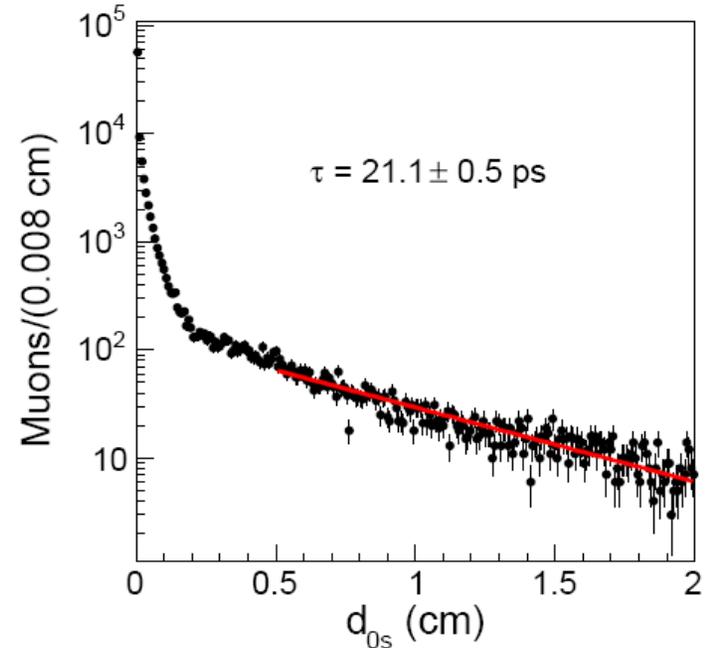


# additional muons' impact parameter

- The impact parameter of the additional muons is consistent with that of initial muons - large tail



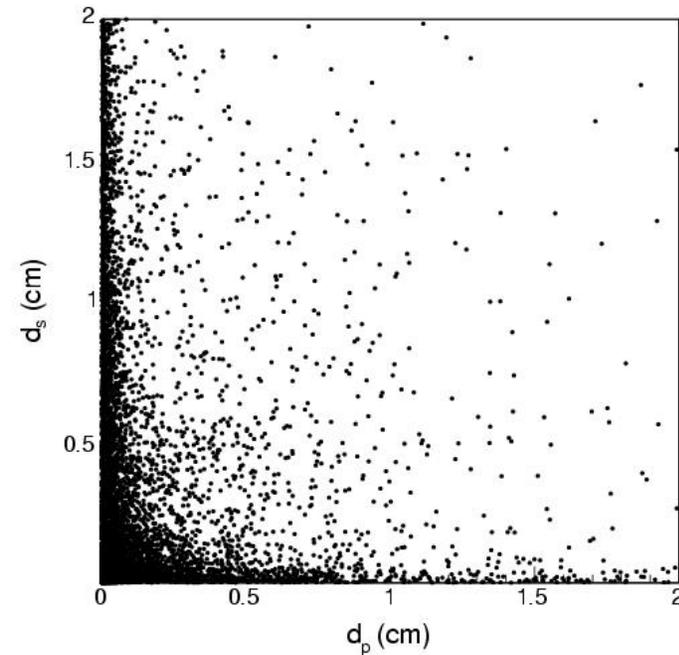
**Third surprise!**



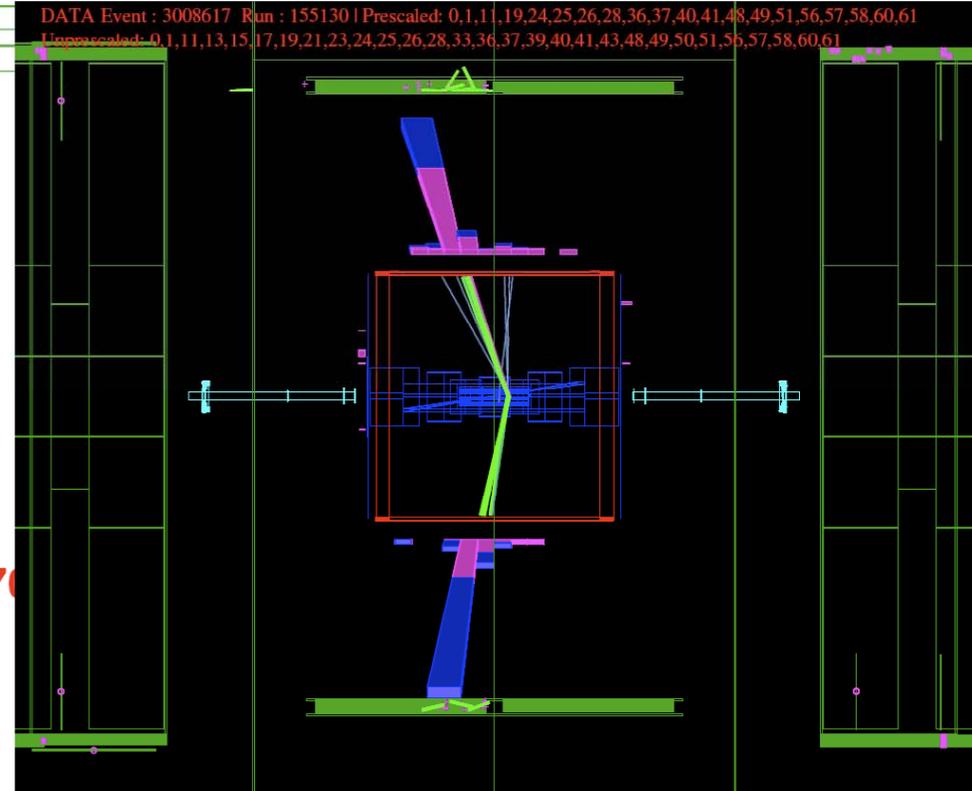
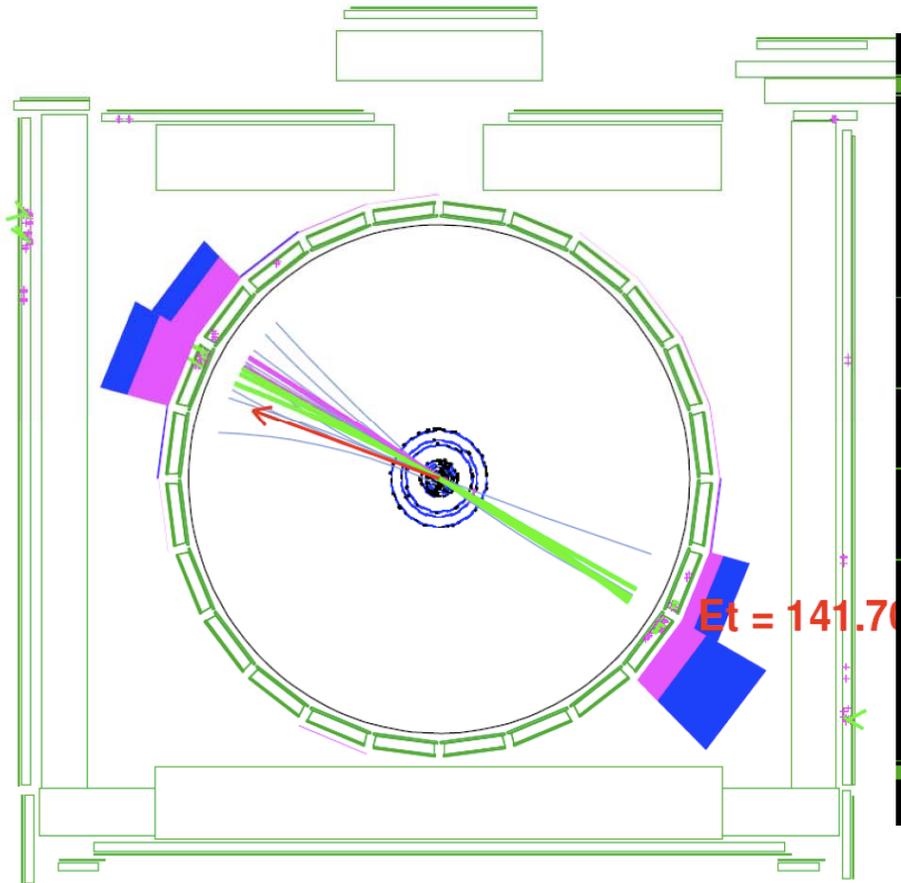
# Impact parameter of additional CMUP muons in ghost events

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- The salient features of ghost events, like additional track and muon multiplicity higher than that of QCD events, are there when requiring the additional muon to be CMUP (**very pure**)
- the large impact parameter distribution of additional muons is consistent with the trigger muons



# Event display



# conclusions

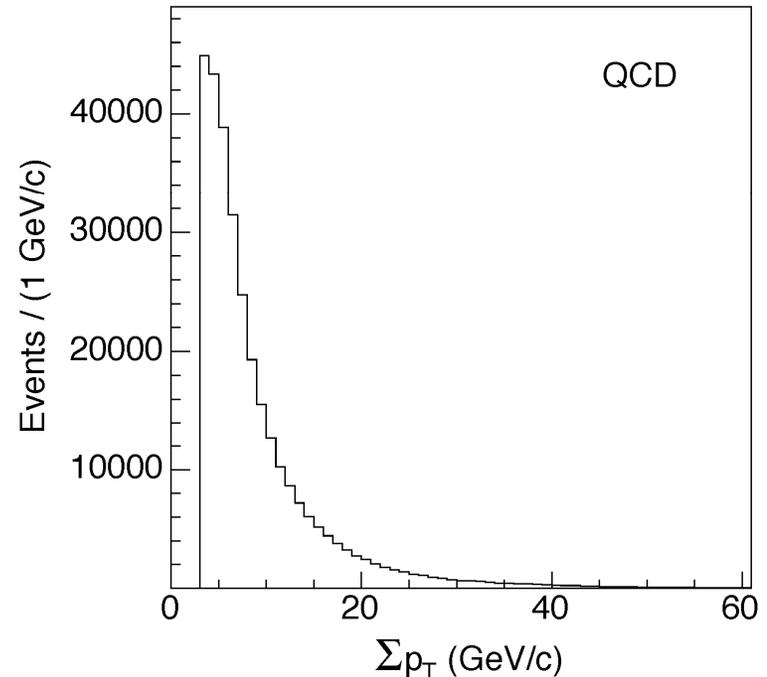
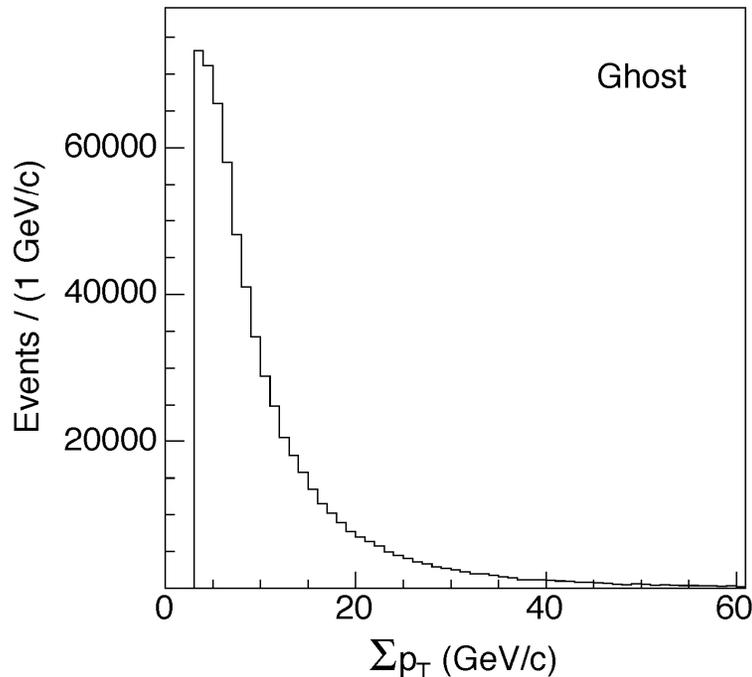
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- There is a significant number of events acquired with the CDF dimuon trigger we don't understand, called Ghosts
- The size is comparable to the  $bb$  contribution
- They are a plausible explanation of the  $\sigma_{bb}$  observed discrepancies with theory and for the dilepton invariant mass
- Ghost events contain high muon and track multiplicity
- The additional muons in the Ghost sample exhibit impact parameter distribution which extends well above the one of additional muons in the QCD sample
- We currently can not explain these events and we are not yet able to rule out known processes

# Correlated punch through

- Traditionally searches for soft muons performed by CDF estimate the fake muon contribution using a per-track probability. It has been argued that ghost events could be due to a breakdown of this method in presence of events with high  $E_T$  jets with many tracks not contained in the calorimeters. We would observed this effect also in the QCD control sample since the energy flow in the jet is similar:

Track  $p_T$  sum in  $\cos\theta > 0.8$  cones



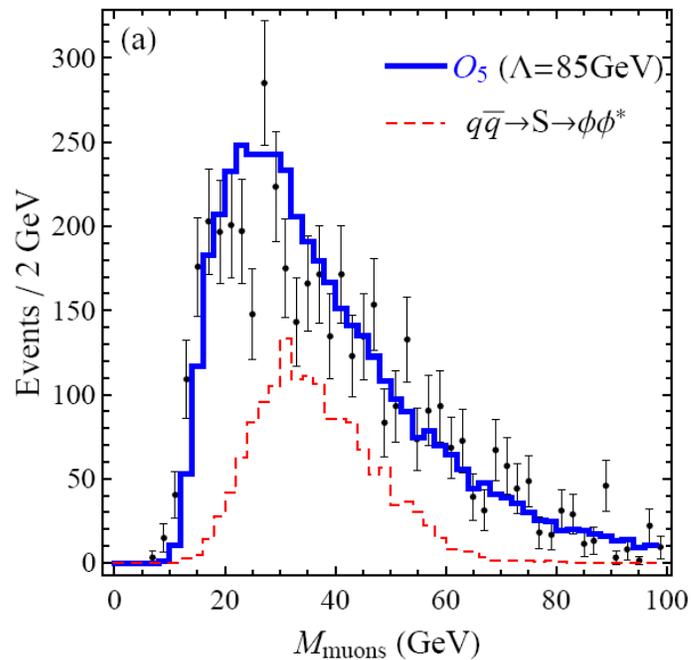
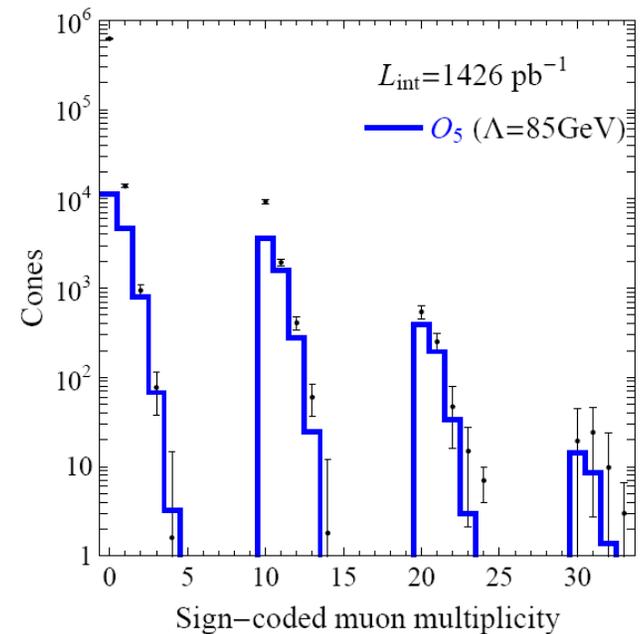
# Barbieri et al.

$$O_5 = \frac{1}{\Lambda} (\bar{q}q) |\phi|^2, \quad p\bar{p} \rightarrow \phi\phi$$

$$\phi \rightarrow 2 \phi_1 \rightarrow 4 \phi_2 \rightarrow 8 \tau$$

$$m_\phi = 15 \text{ GeV}$$

$$\phi_2 \rightarrow \tau\bar{\tau} \text{ with a long lifetime}$$



invariant mass of muons in a cone for events with 2 cones with at least 2 muons

