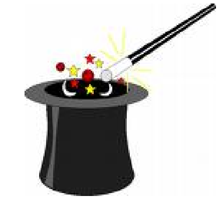
Study of multi-muon events at CDF

arXiv:0810.5357, sub to PRD (the CDF collaboration)

→ arXiv:0810.5730, sub to PRD

P. Giromini, Fnal 11/11/08

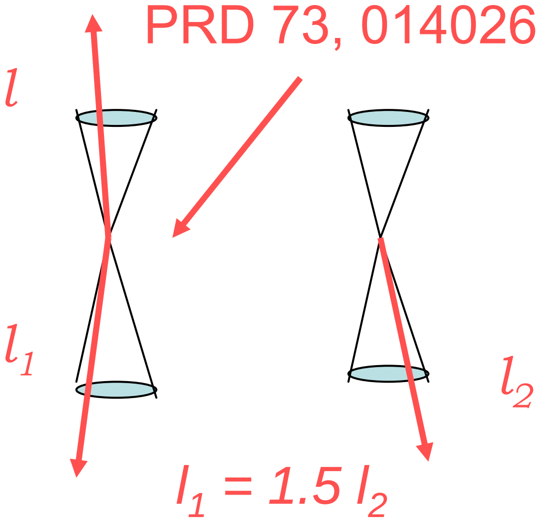
Analysis motivated by long-standing and well known inconsistencies related to the $b\bar{b}$ production and decay

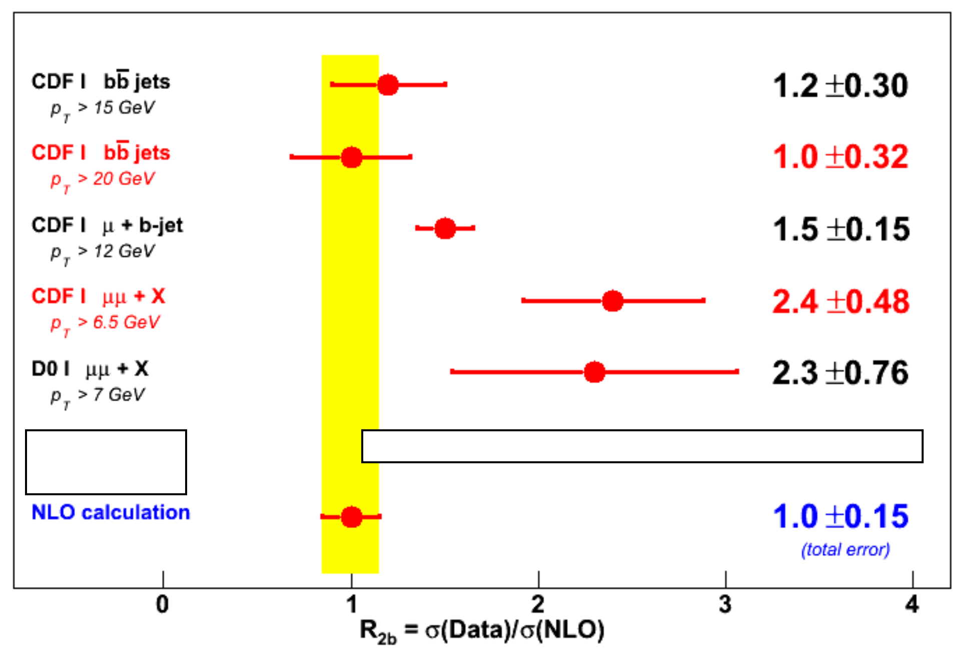


- First inconsistency - Arkani-Hamed did not notice
- The correlated *bb* production cross section when heavy flavors are identified via their semileptonic decays
- Typical analyses, as the present one, use events acquired with 2 muons with p_T > 3 GeV/c, $|\eta|<0.7$. Several CDF, D0, and UA1 measurements
- σ_{bb} is measured to be much larger than the NLO prediction and the corresponding measurements that select b quarks with secondary vertex identification – measurements with leptons are old and not as precise as those with secondary vertices

PRD 69, 072004 (2004)

PRD 73, 014026 (2006)





Ed Berger went wild

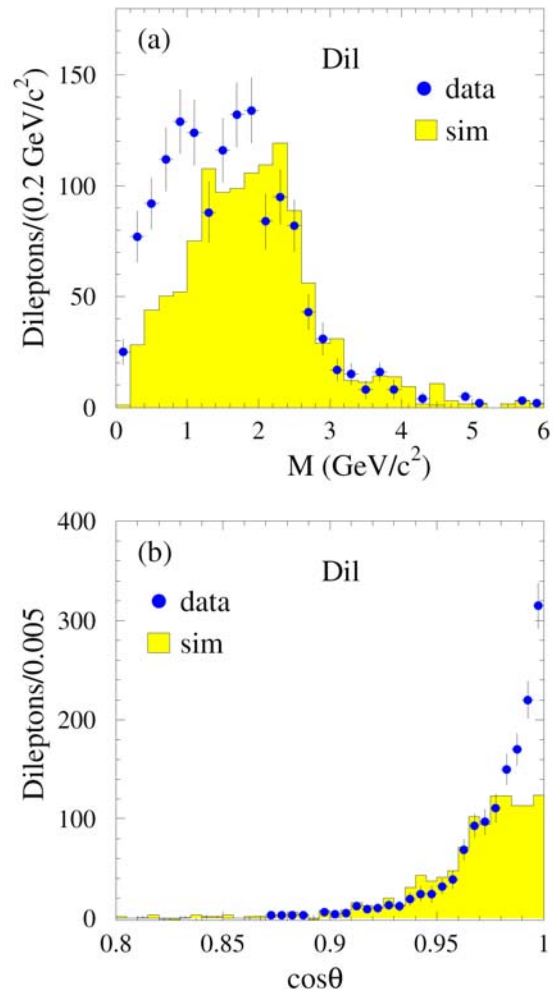
- Second inconsistency
- $\bar{\chi}$, the integrated mixing probability of the b-hadron mixture, is measured to be higher at hadron colliders than at LEP (0.15 vs 0.12)
- Measured from the ratio of SS/OS dileptons
- the CDF measurement is as precise as the LEP measurements combined

PRD 69, 012002 (2004)

The PDG conclusion is that the b-hadron mixtures must be different !

G. Kane did not notice

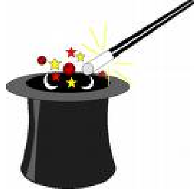
- Third inconsistency
- The cross section of sequential semileptonic decays of single b quarks is underestimated by the theoretical prediction. In the data, the opening angle and invariant mass distributions are different from what predicted by the standard HERWIG (PYTHIA) + EVTGEN (QQ) simulations
- Accurate measurement



Mostly e μ

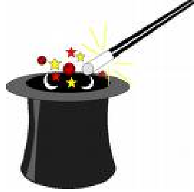
PRD 72, 072002 (2005)

Not on the top 10 list of the P5 or HEPAP



- Run I CDF and D0 measurements of the single b quark production cross section were also inconsistent between themselves, but also not extremely accurate - PRD 73,014026 (2006)
- Which inconsistencies are not experimental mistakes and worth investigating?
- All of them. Many new measurements:
  J/psi   PRD 7103201   (2005)
  J/psi K   PRD 052001   (2007)
  μ D^0 submitted for publication
- All the new measurements have 10% accuracy –
  All inconsistencies in the single b quark cross section are gone

Connecting the dots



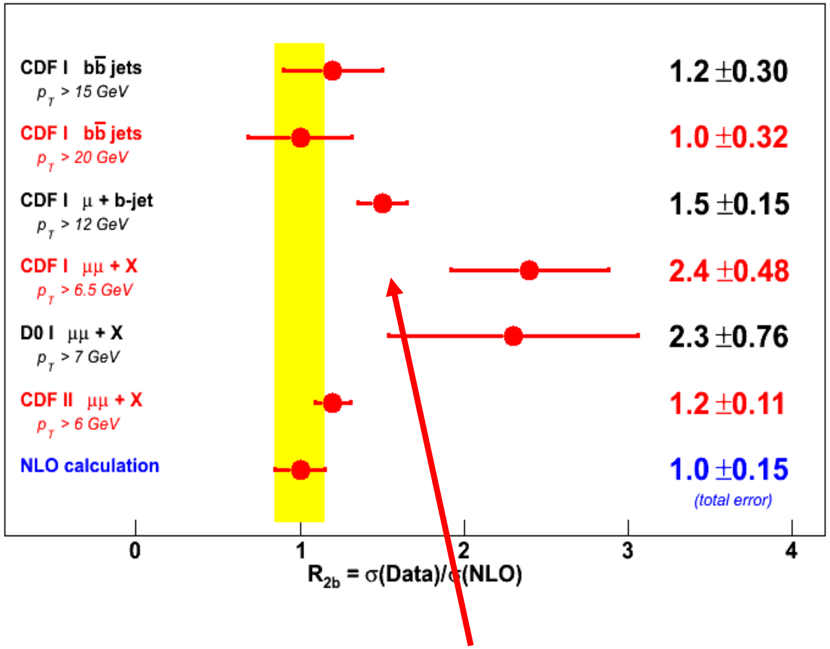
- PRD 77, 072004 (2008) – a new CDF measurement of σ_{bb} using a dimuon data set. We use events which contain at least 2 CMUP muons with $p_T > 3$ GeV/c, $|\eta|<0.7$

- The measurement makes use of the precision tracking provided by the silicon microvertex detector

- The new measurement is very accurate

- The new cross section value agrees with the NLO prediction and measurements that use secondary vertex identification

- The new cross section value is appreciable smaller than previous results

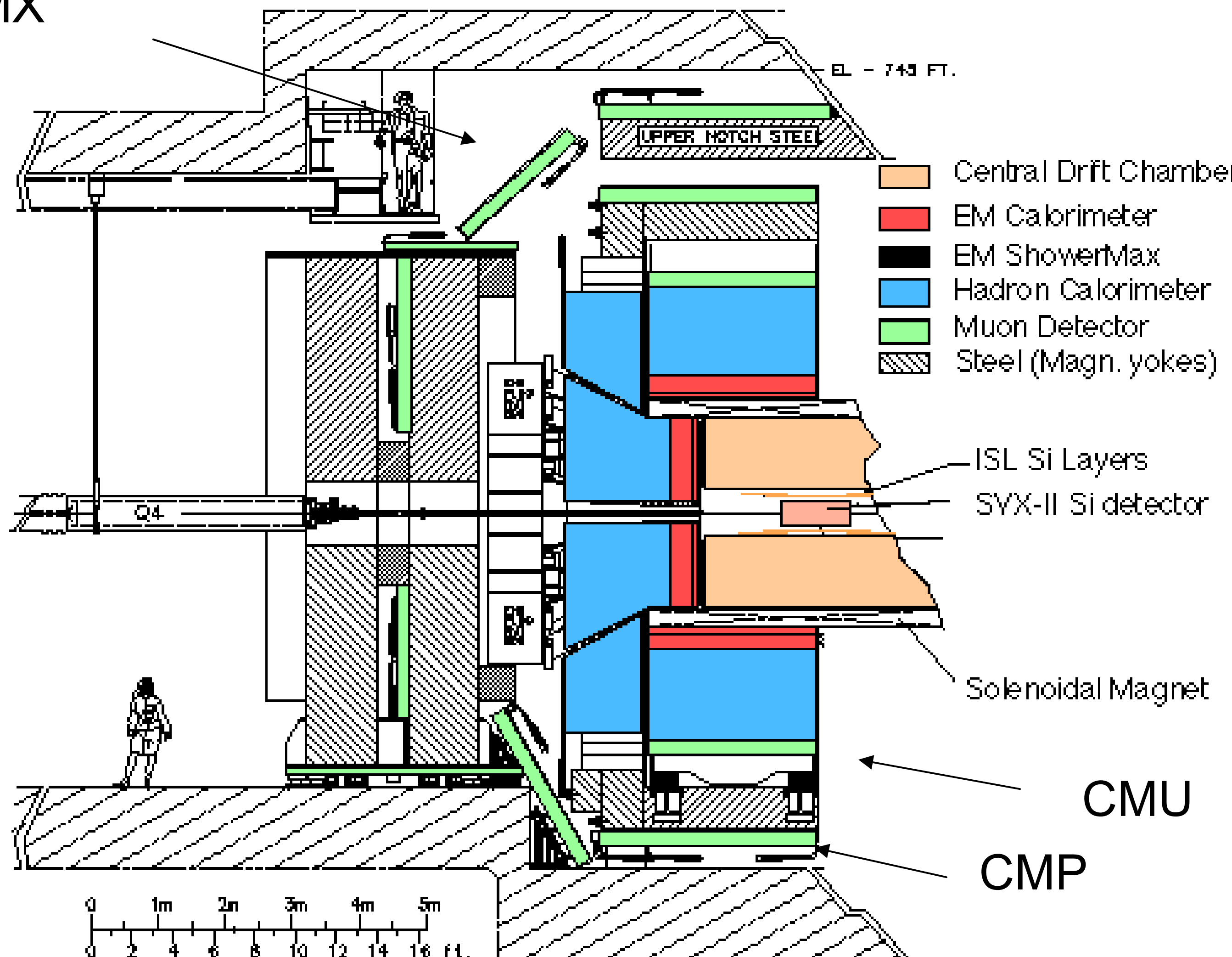


e.c.:1.7 ± 0.35

Da CDF detector

CMUP=CMU+CMP

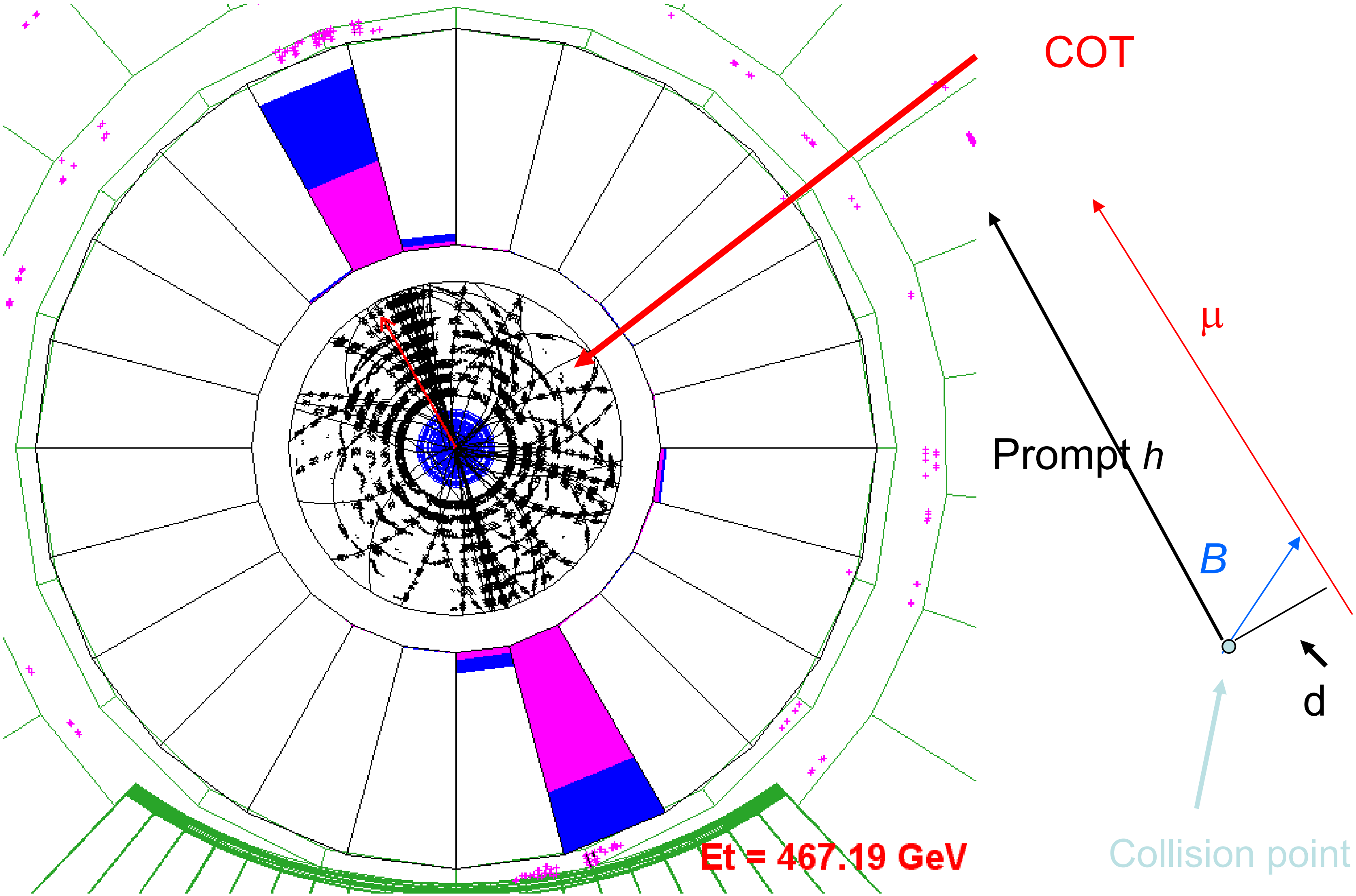
CMX



CMU

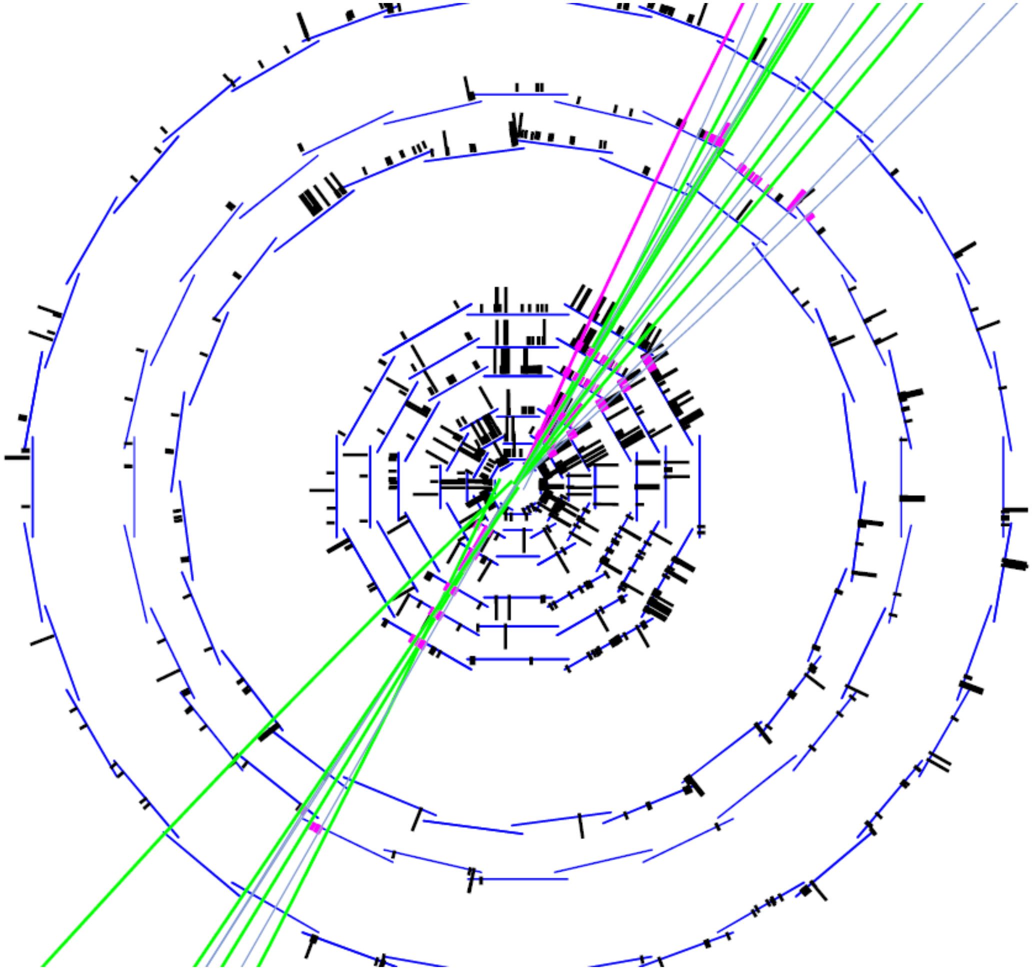
CMP

Da CDF detector



Da CDF detector

SVX



Collision point rms 3 μm

d rms

COT 230 μm

COT+ ≥ 3 SVX hits 30 μm

L00

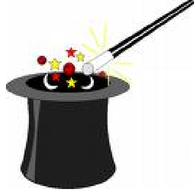
LO

L1

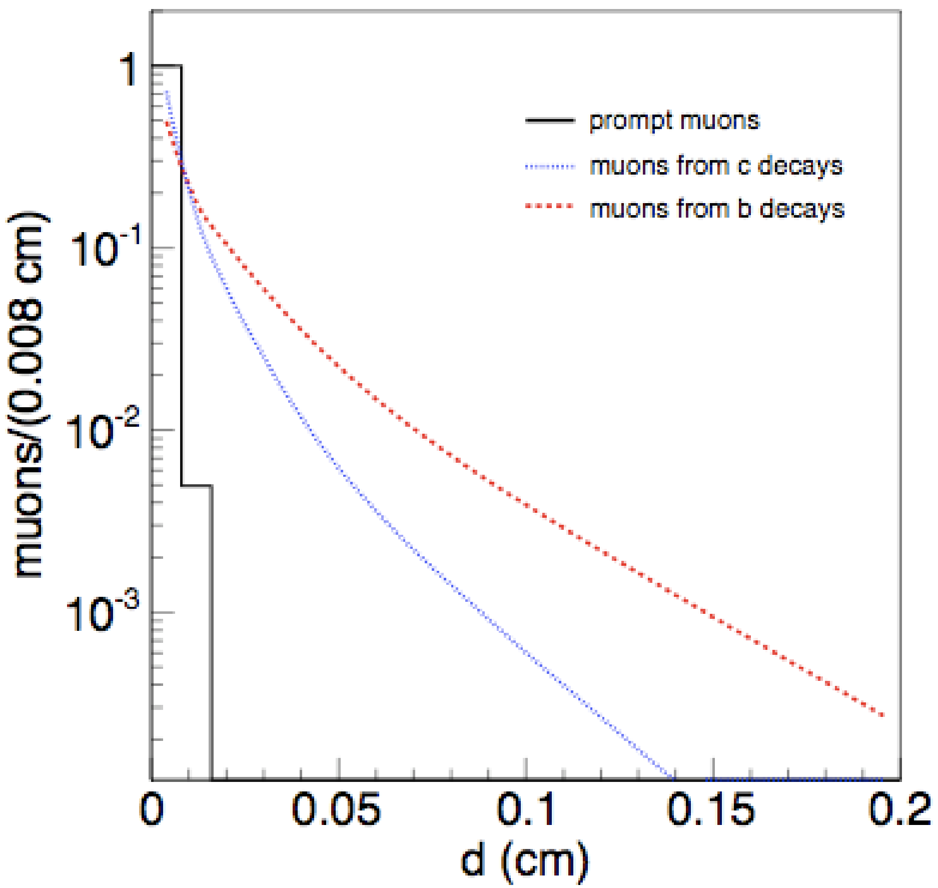
L2

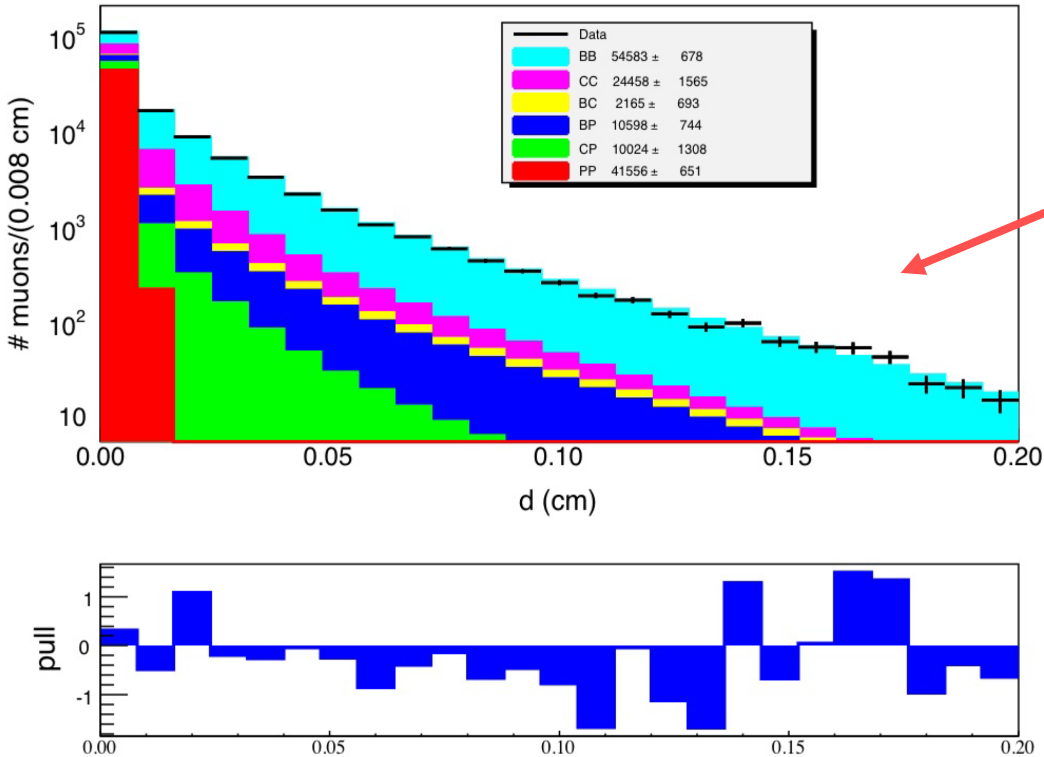
………

Experimental method

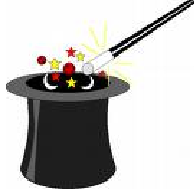


- Known sources of dimuons are semileptonic decays of b ($c\tau$ = 470 μm) and c ($c\tau$ = 210 μm) quarks + prompt muons (Υ, Drell-Yan). In addition, there is a contribution of muons mimicked by hadrons that are prompt or arise from h.f. decays.
- The procedure to extract σ_{bb} is to fit the two-dimensional distribution of the muon impact parameters with templates for the different components derived from data or heavy flavor simulations





QCD contribution

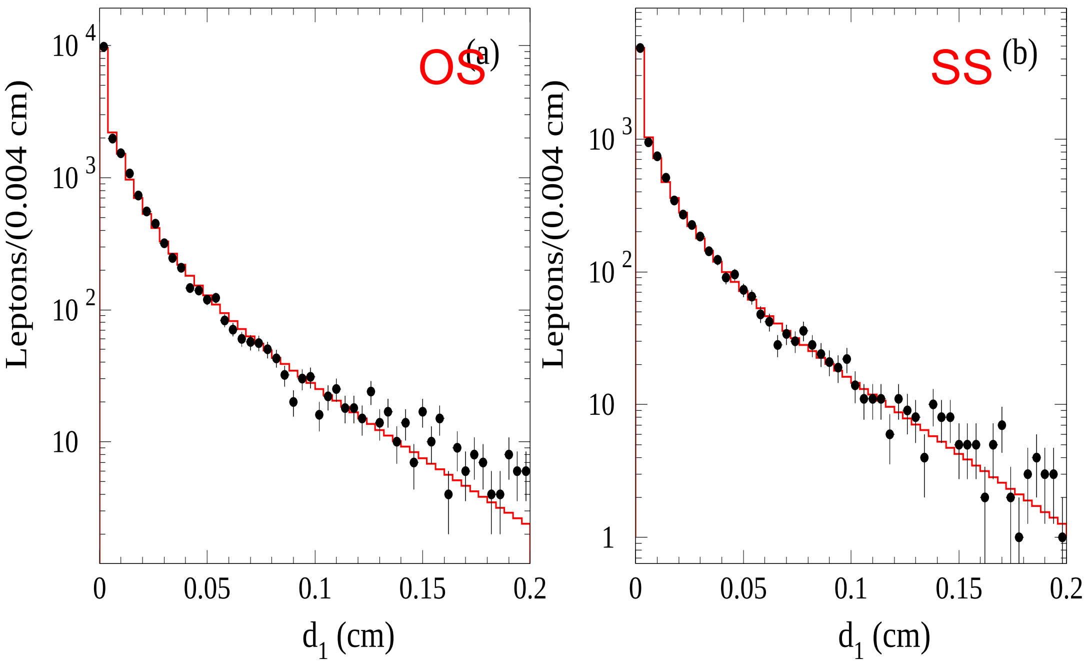


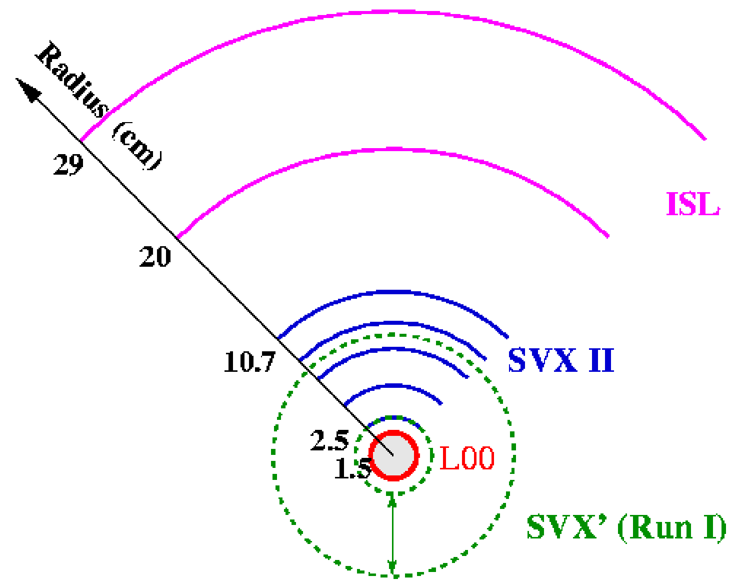
PRD 77, 072004 (2008)

742 pb^{-1}

- The new measurement uses tight SVX requirements (L00, L0, and 2 out of the remaining 4 SVX layers)
- Ad hoc selection chosen to fit the data with the templates from various sources
- We could model the data at large impact parameters only by requiring the presence of L00 and L0 – the request of any 4 layers was not good enough
- A bit of a mystery at the beginning, until we realized that the tight SVX selection requires that both muons originate inside the beam pipe

- Traditionally CDF measurements use loose SVX requirements (3 out of 8 SVX+ISL layers) – they use muons originating from distances as large as 10.6 cm from the beam line
- Run I analyses selected muons originating from distances as large as 5.7 cm from the beam line

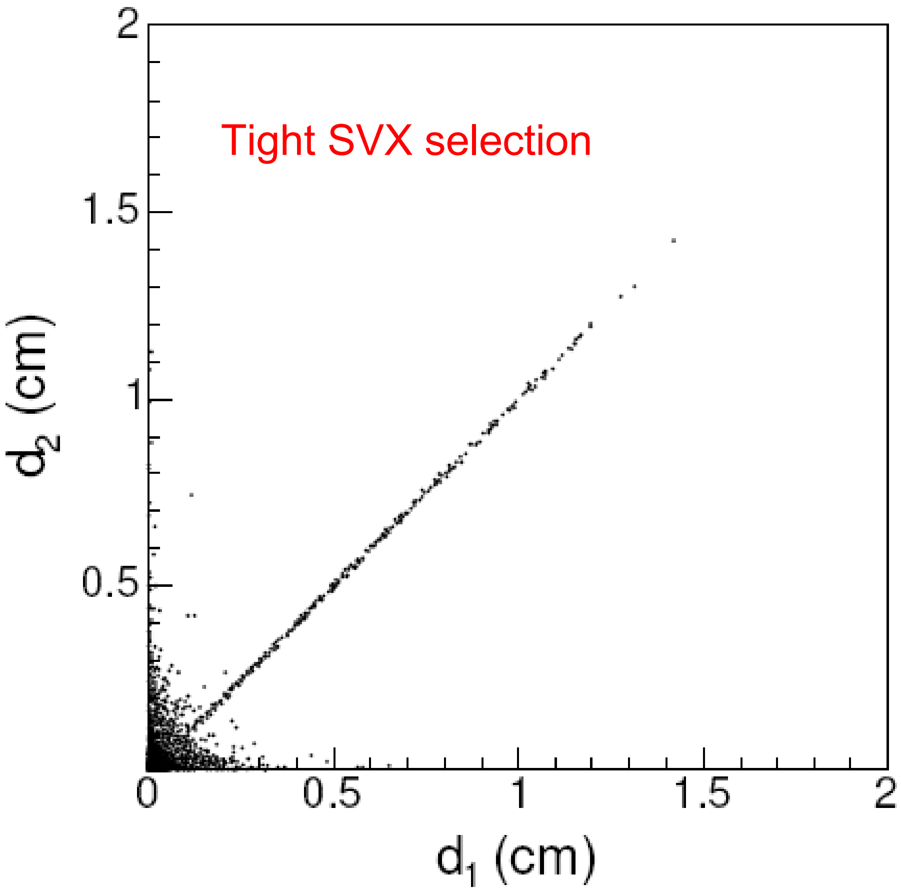


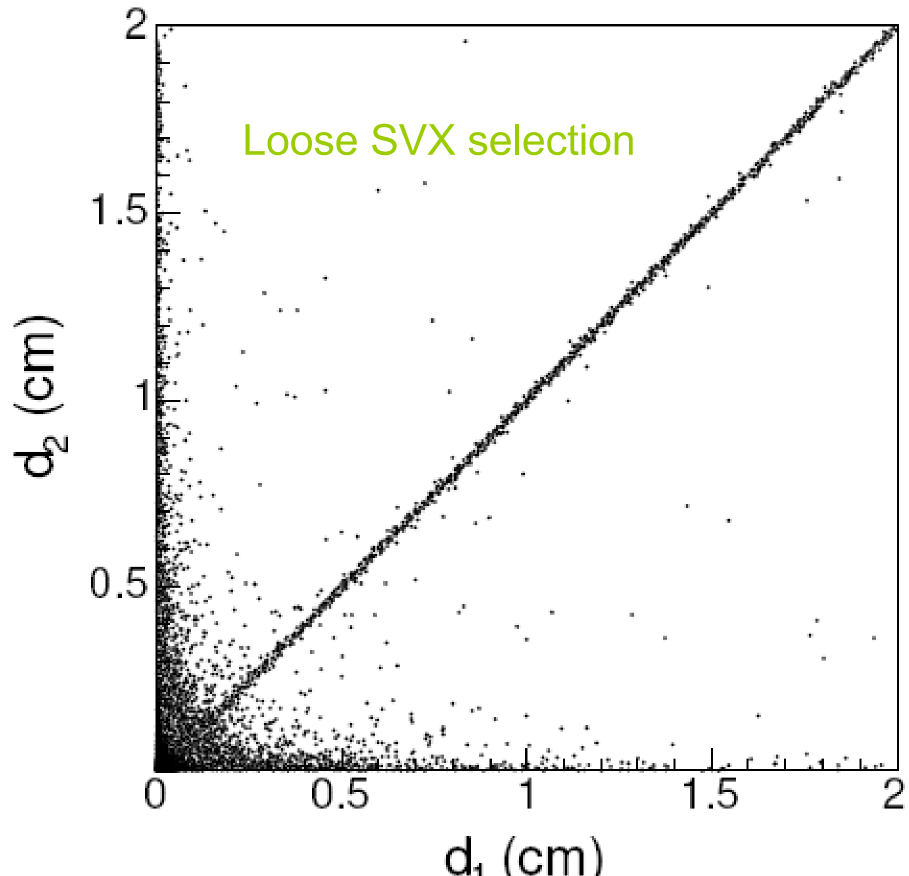


Run I $\bar{\chi}$ measurement

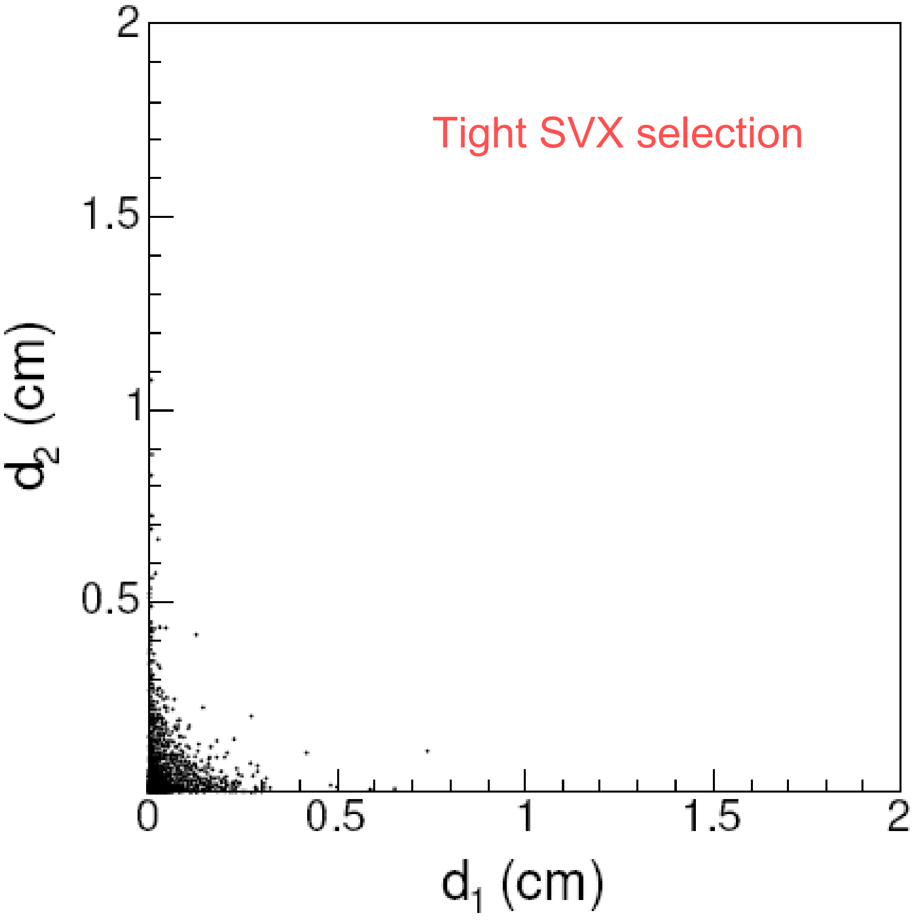
Cosmic rays overlapping $p\bar{p}$ interactions

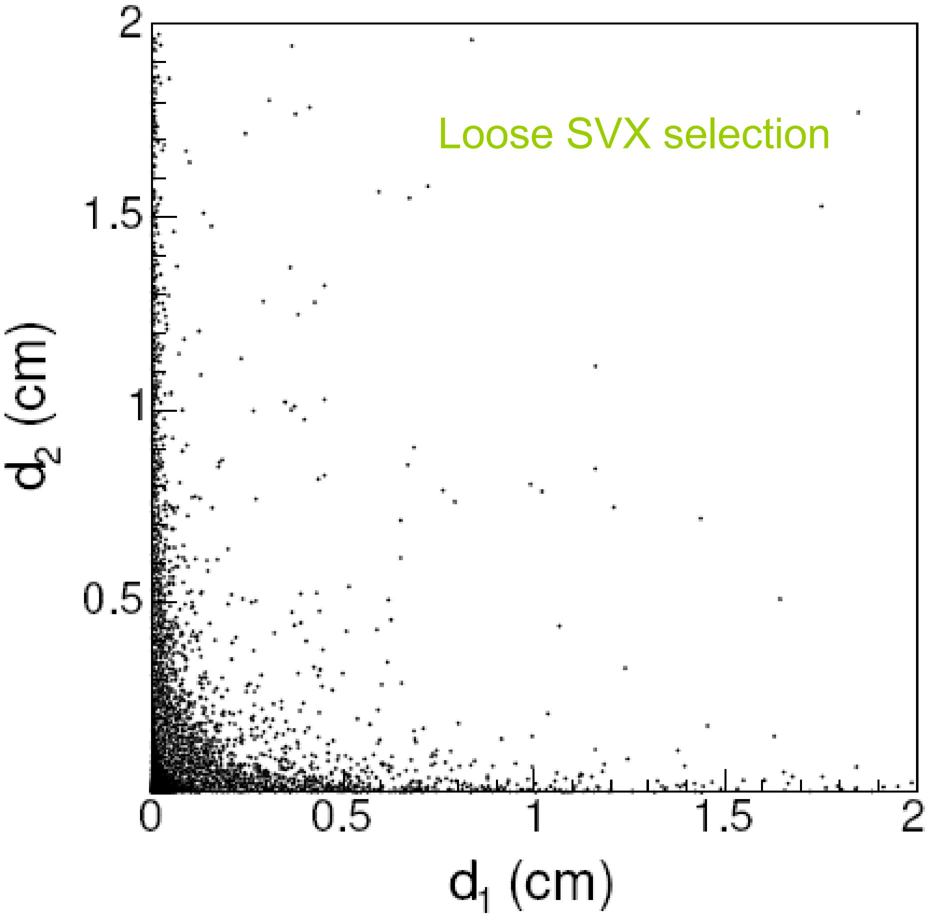
According to the simulation, 96% of the QCD events have two muons originating inside the beam pipe





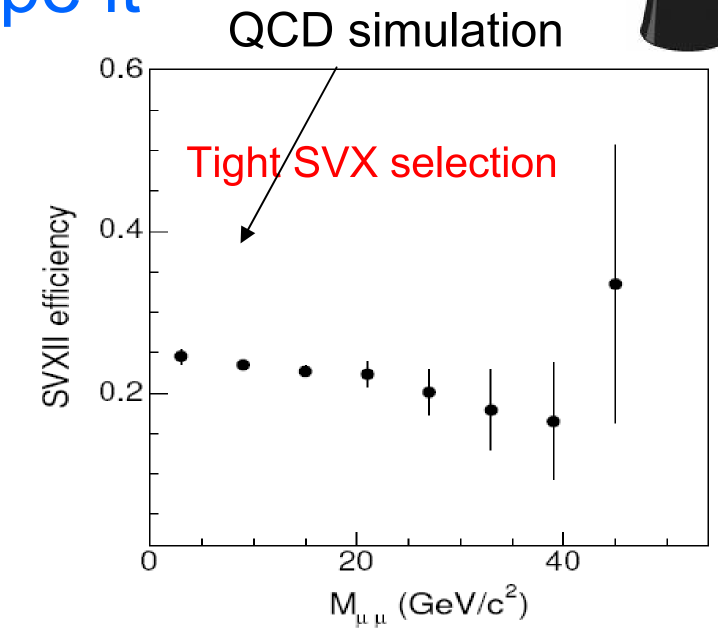
Result of the different SVX requirements on the dimuon sample

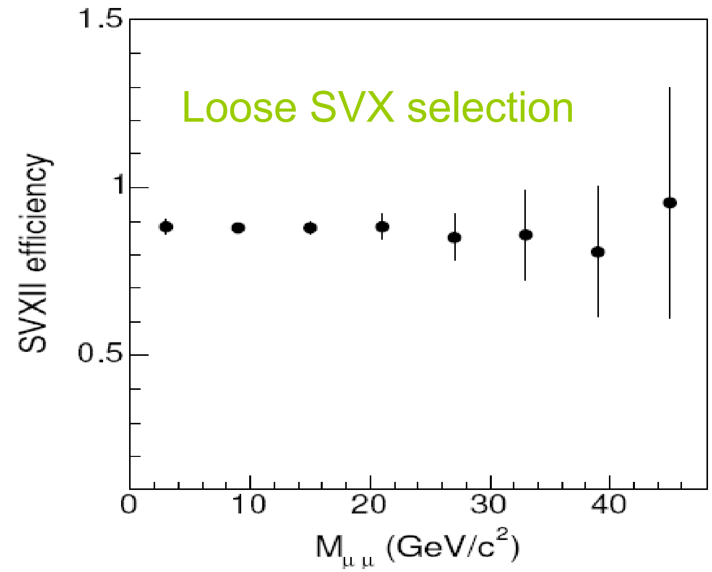




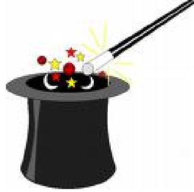
Efficiency of the tight SVX selection and how many events escape it

- We can evaluate the efficiency of the tight SVX selection by using control samples of data
- The efficiency of the tight SVX selection for prompt muons (Y, D-Y) is geometrical $\varepsilon = 0.257 \pm 0.004$
- For heavy flavor the efficiency is $\varepsilon = 0.237 \pm 0.001$ (high p_T h.f. hadrons) – verified with J/ψ mesons from B decays, J/ψ K, and muons accompanied by D^0 mesons
- Using the sample composition determined by the IP fit, one predicts that the average efficiency in this data set is $\varepsilon = 0.244 \pm 0.002$
- The efficiency of the loose SVX selection is $\varepsilon = 0.88 \pm 0.01$



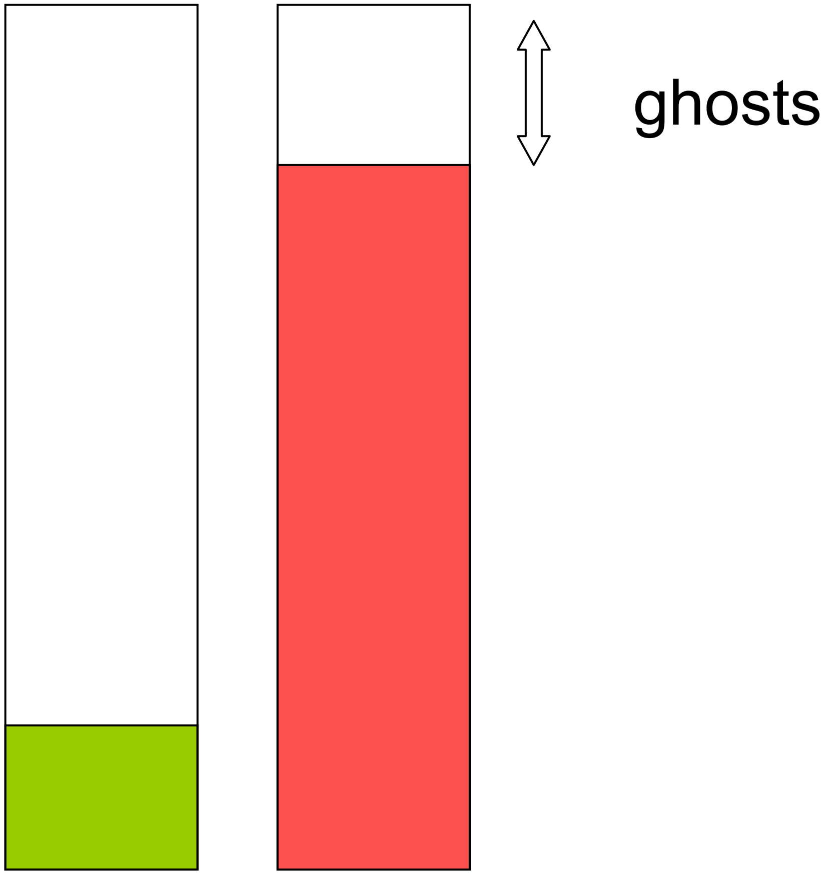


Number of ghost events

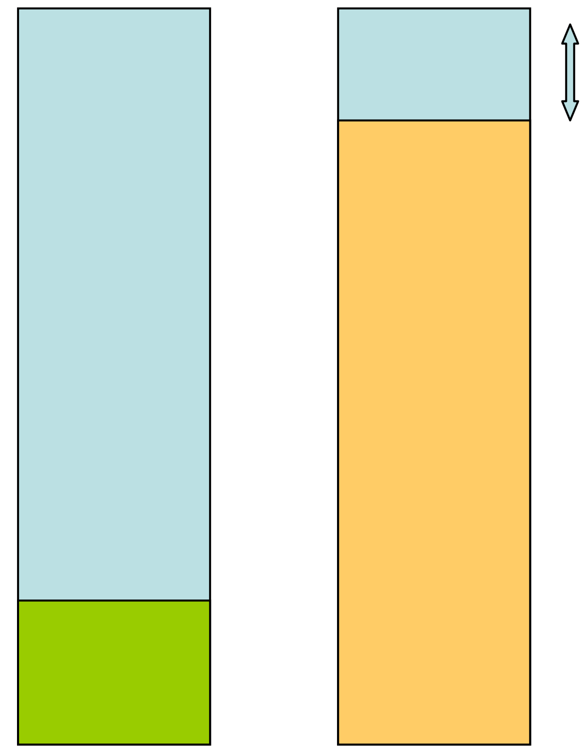


- The efficiency of the tight SVX selection in the dimuon data set is $\varepsilon=0.1930\pm0.0004$ instead of expected $\varepsilon=0.244\pm0.002$ (79%)
- The dimuon sample contains a large background (ghost) that is suppressed by the tight SVX selection more than the QCD contribution.
- Start by assuming that ghost events are totally removed by the tight SVX selection
- Size of the ghosts : Data - SVX/($\varepsilon=0.244\pm0.002$) , where SVX is the QCD contribution passing the tight SVX selection
- The size of ghost events that eventually pass the loose SVX selection: Data - SVX/($\varepsilon=0.244\pm0.002$) * ($\varepsilon=0.88\pm0.01$)

All dimuons



Dimuons that pass loose SVX selection

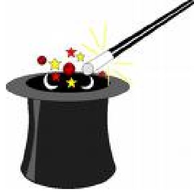


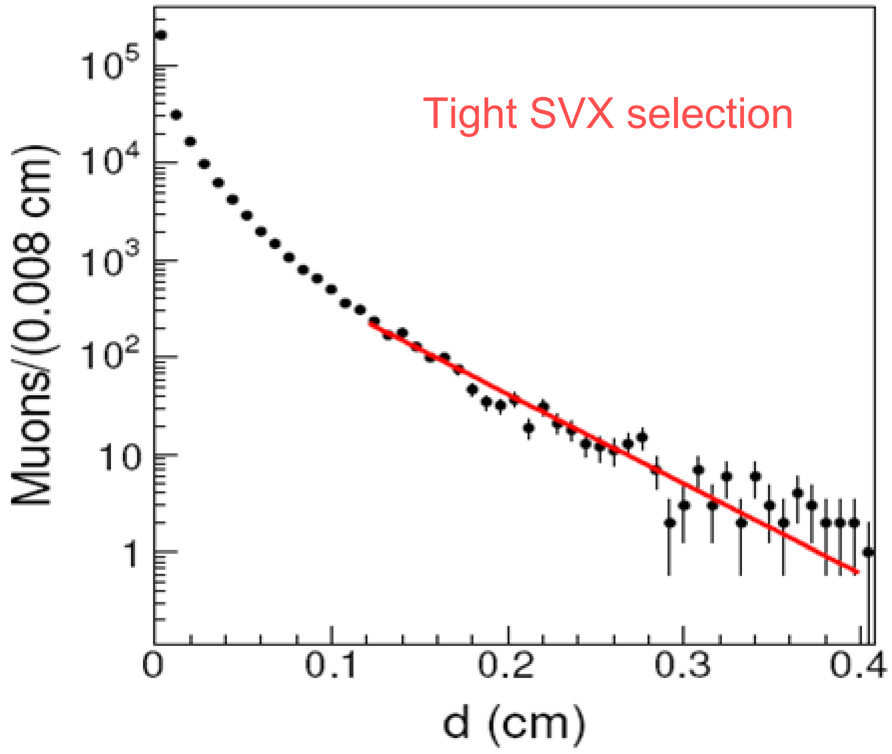
Dimuons that pass tight SVX selection

QCD= /ε=0.244

QCD= /ε=0.244*e= 0.88

Reasonable assumption





$c\tau$ = 469.7 ± 1.3 μm

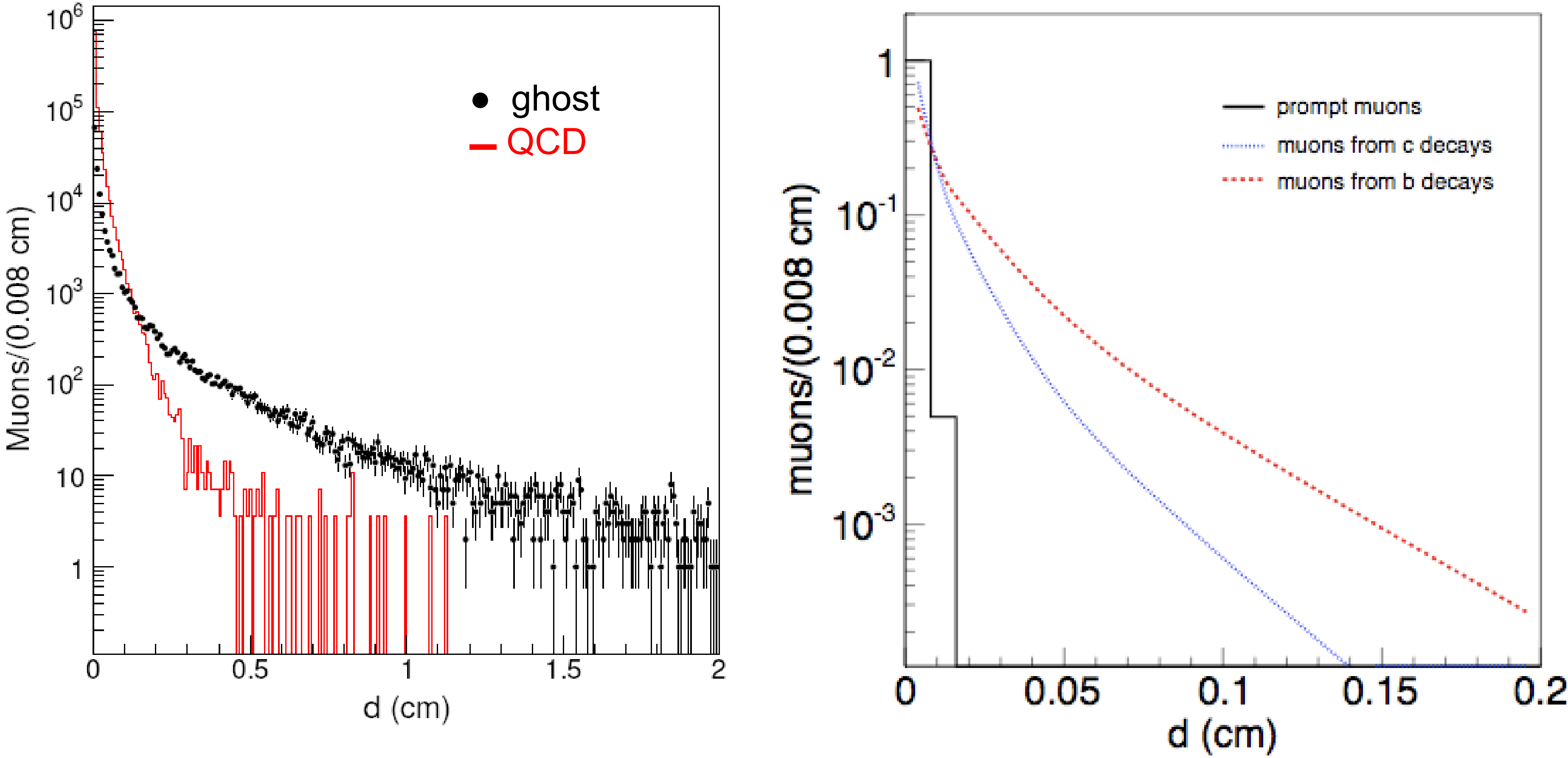
PDG: 470.1 ± 2.7

Bottom data are not appreciably contaminated by the ghost events

Charmed quark contribution exhausted beyond 0.12 cm

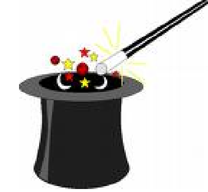
Bottom contribution exhausted beyond 0.5 cm

IP distribution in QCD and ghost events



Loose SVX selection

Plausible explanation for previous inconsistencies of b cross section and integrated mixing measurements

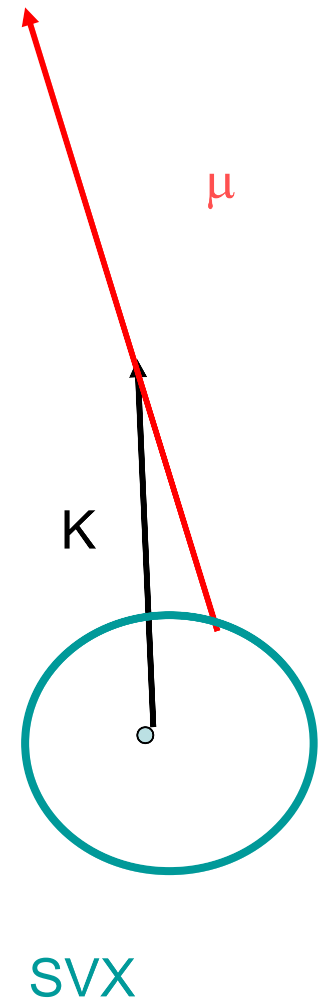


Type	No SVX	Tight SVX	Loose SVX
All	743006	143743	590970
All OS		98218	392020
All SS		45525	198950
QCD	589111 ± 4829	143743	518417 ± 7264
QCD OS		98218	354228 ± 4963
QCD SS		45525	164188 ± 2301
Ghost	153895 ± 4829	0	72553 ± 7264
Ghost OS		0	37792 ± 4963
Ghost SS		0	34762 ± 2301

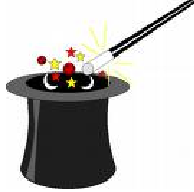
742 pb^{-1}, 221564 ± 11615 $b\bar{b}$ events with no SVX and 194976 ± 10458 with loose SVX requirements

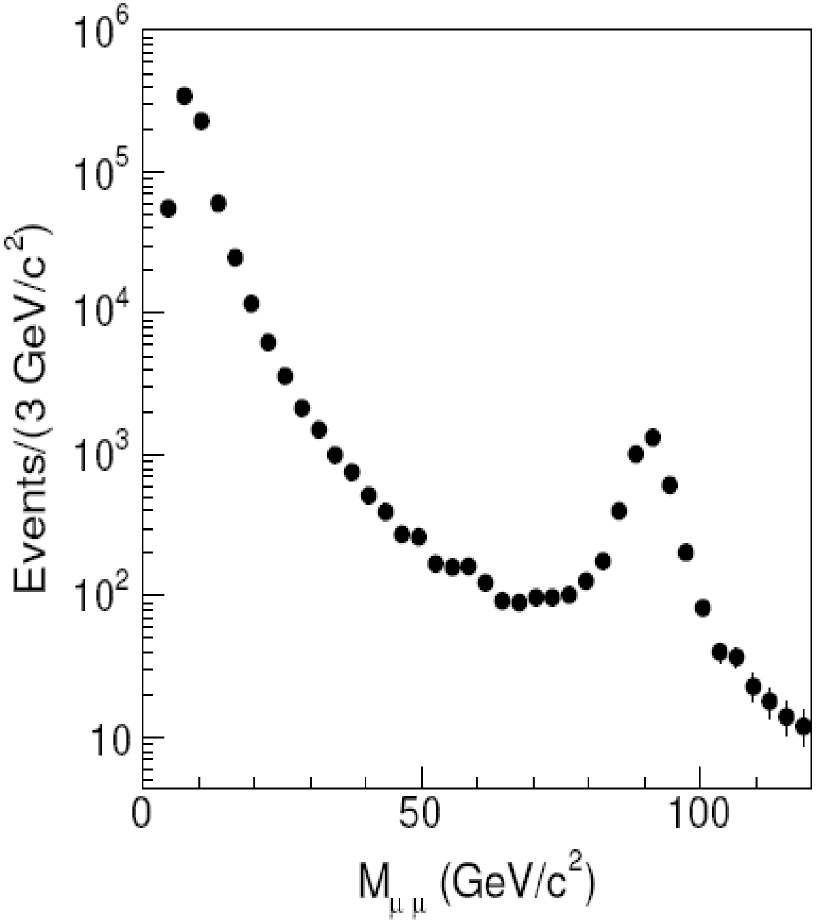
Revisiting our ignorance

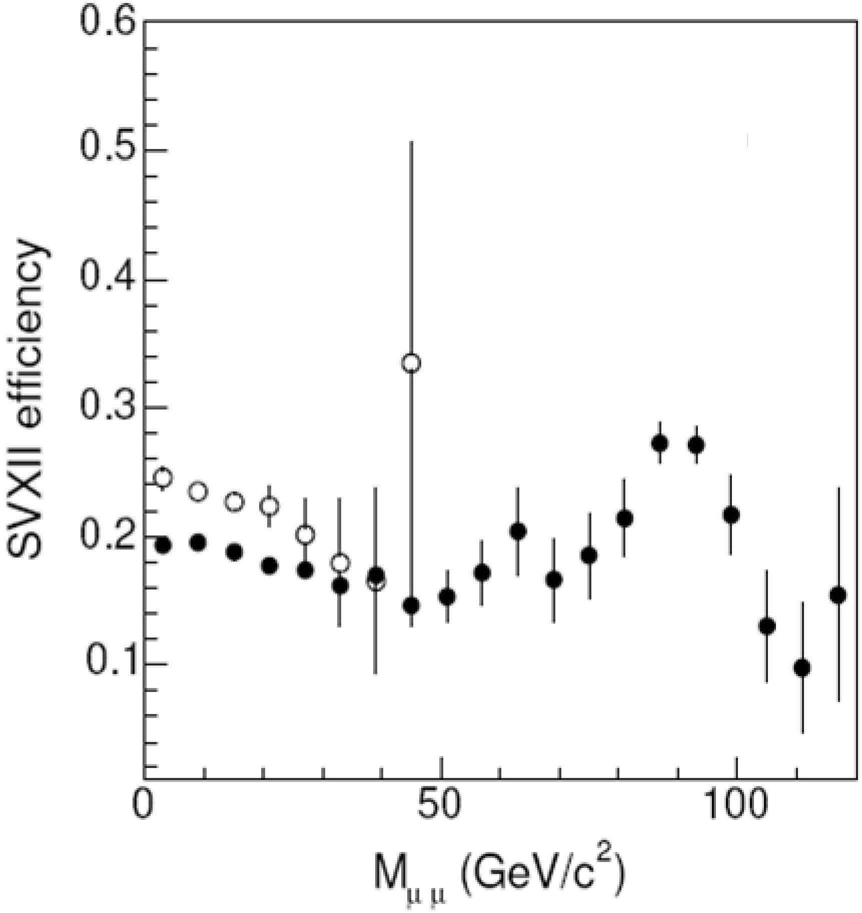
- Possible sources of ghost events:
  - 30% of the QCD contribution that pass the tight SVX selection is due to prompt hadrons that mimic a muon signal. The number of ghost events has been derived assuming that the efficiency of the tight SVX selection is the same for real and fake muons.
    This is a reasonable assumption if muons are generated by hadronic punchthrough. However, muons due to in-flight-decays of pions and kaons might correspond to mismeasured tracks that are linked to SVX II hits with an efficiency smaller than that for real muons. This contribution was considered negligible in previous experiments.
  - Long-lived particles, such as K^0_S and hyperons
  - Secondary interactions in the detectors surrounding the beam pipe
  - Heavy flavored hadrons with anomalously high Lorentz boost – however, not consistent with high IP tail



Large Lorentz boost

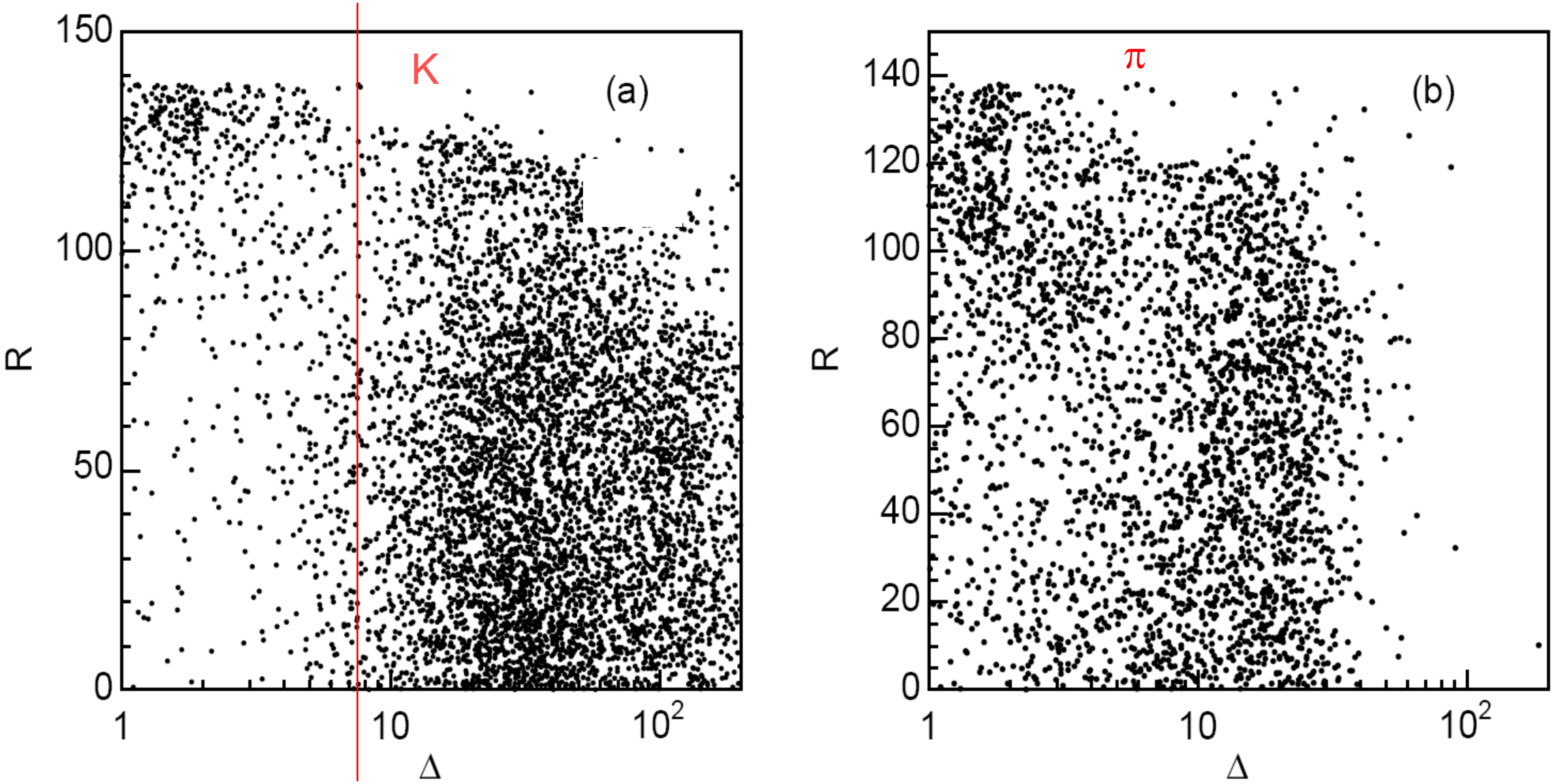




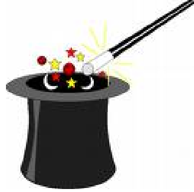


In-flight-decays

- Use a heavy flavor simulation (HERWIG) to measure the probabilty that K and π decays produce CMUP 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

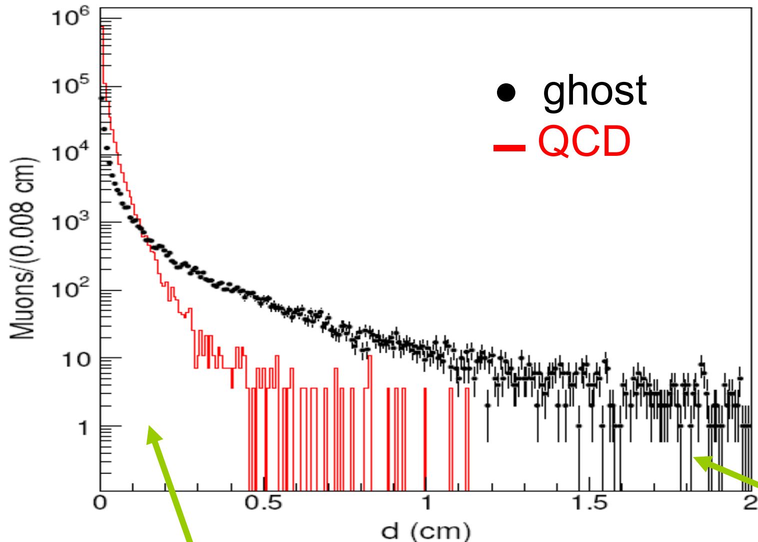


In-flight-decays

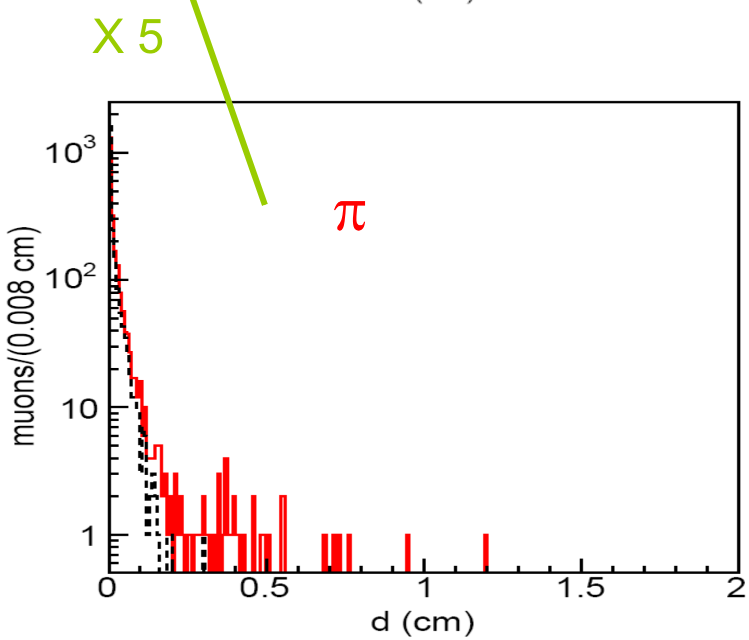
Selection		π		K
Tracks		2667199		1574610
In-flight-decays (Δ >5)		14677		40561
CMUP+L1	P=0.07%	1940	P=0.34%	5430
Loose SVX		897		3032
Tight SVX		319		1135

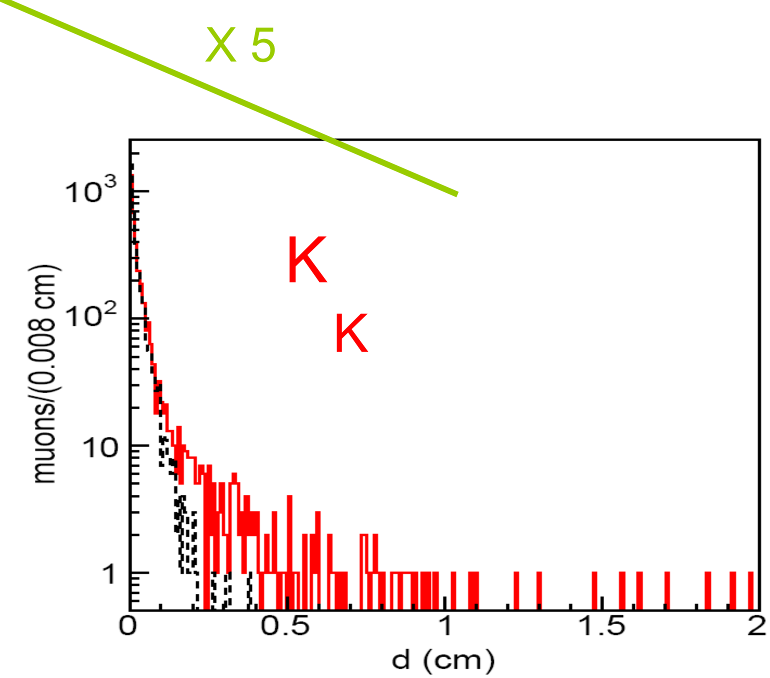
- Apply the above probabilities to tracks of a generic QCD simulation normalized to the *bb* content of the data (10^{10} track pairs) – include punchthrough probability, and ignore those cases in which both muons arise from punchthrough
- prediction: 57000 events (ghost are 154000 ±4800) – efficiency of tight and loose SVX selection 8% and 44%, respectively
- Out of the 25000 fake-dimuon events that pass the loose SVX selection, 15000 muons are due to kaon in-flight decays; 35000 are pion decays and punchthroughs

QCD, ghosts, and in-flight-decays

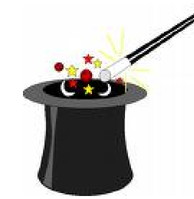


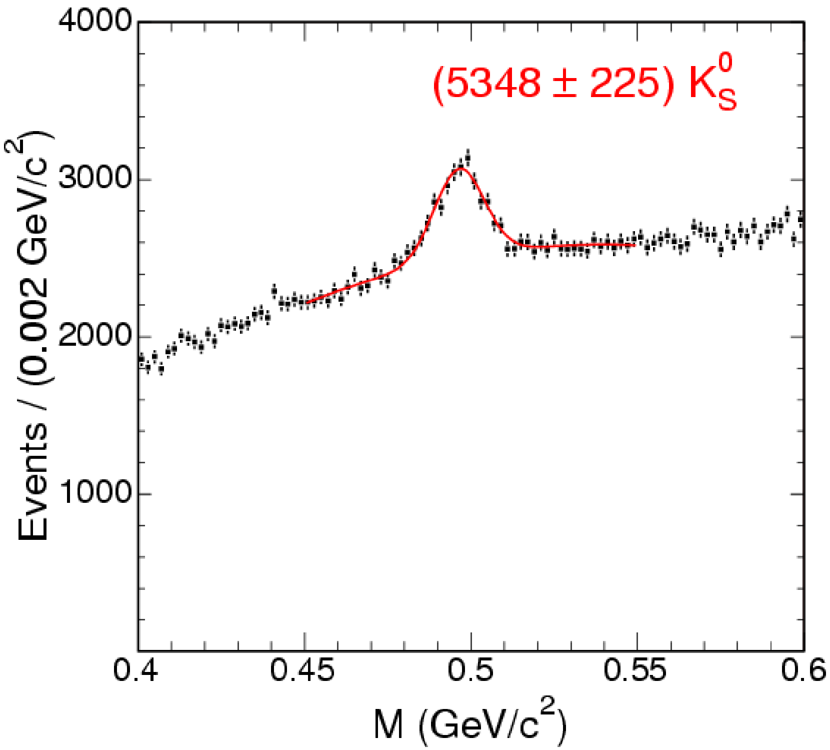
IFD prediction explains 35% of the ghost events, but only 10% of the events with d>0.5 cm

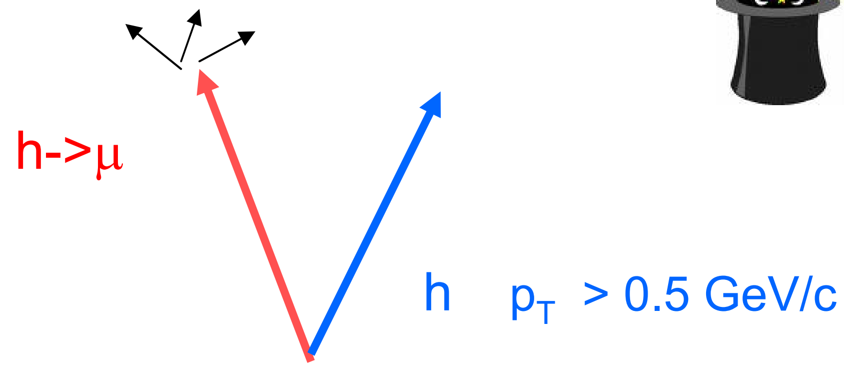


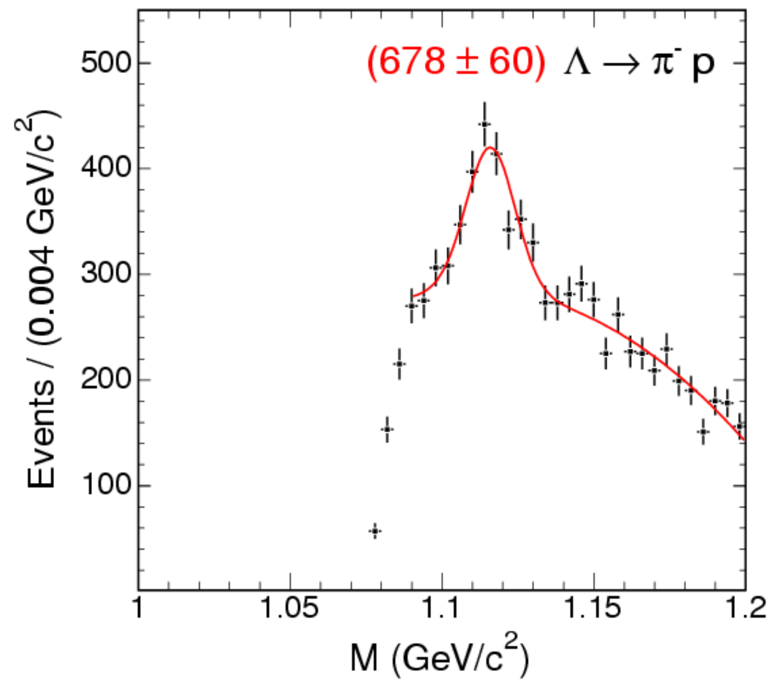


K^0_S and hyperons







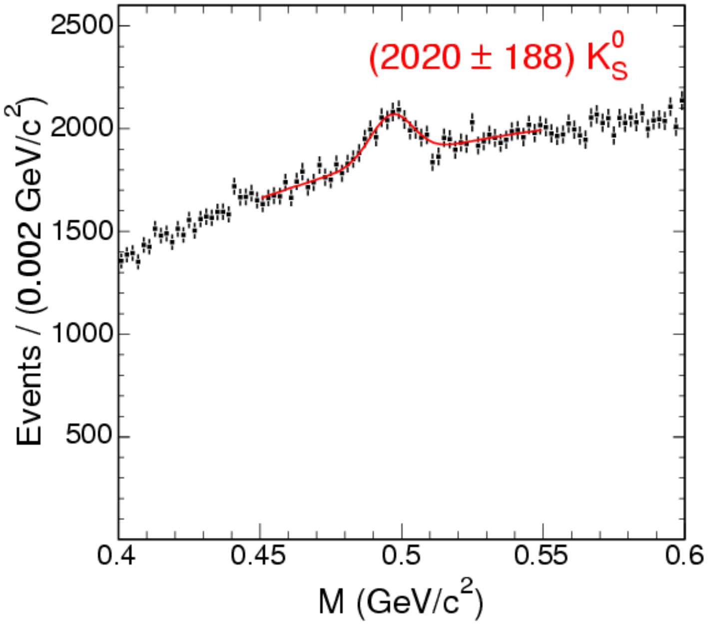


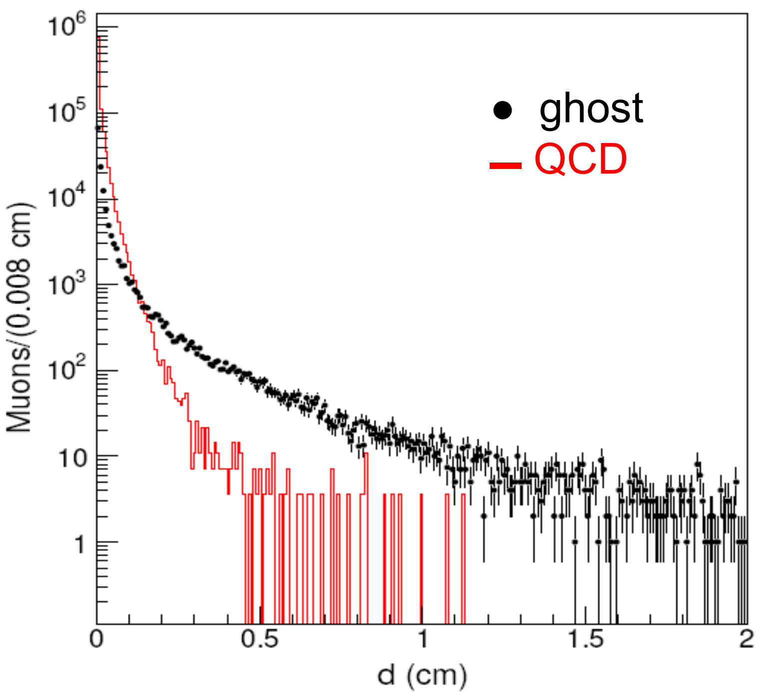
Kinematic acceptance times reconstruction efficiency ~ 50%

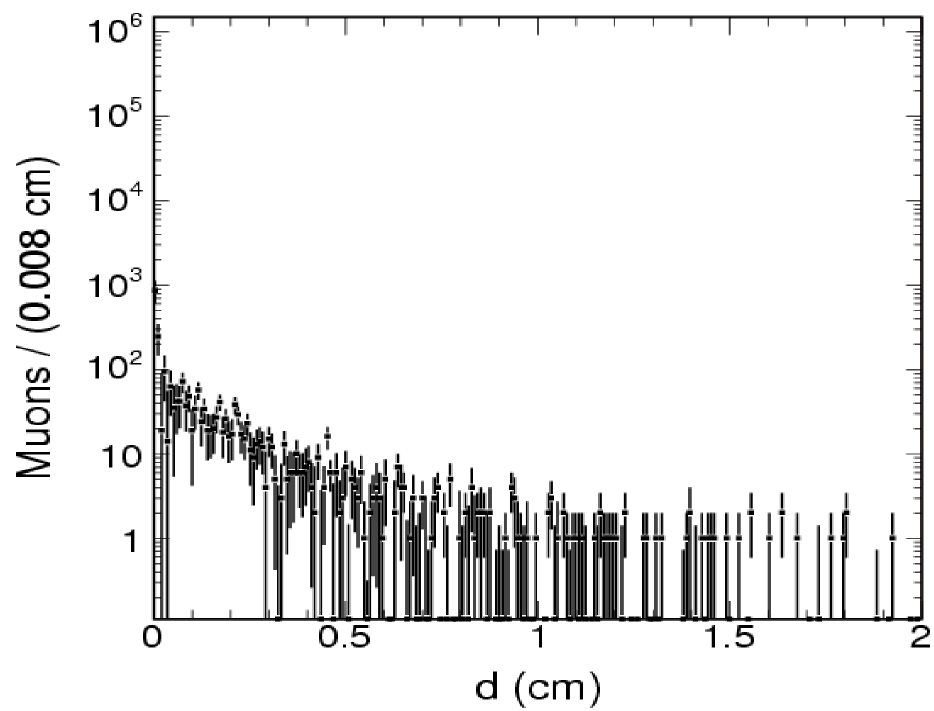
Approximately 12000 ghost events contributed by these decays

K^0_S

Loose SVX selection

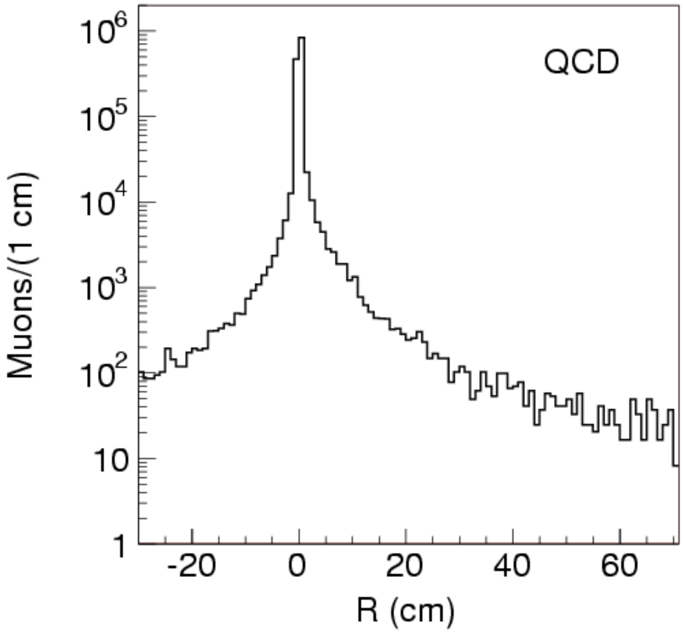


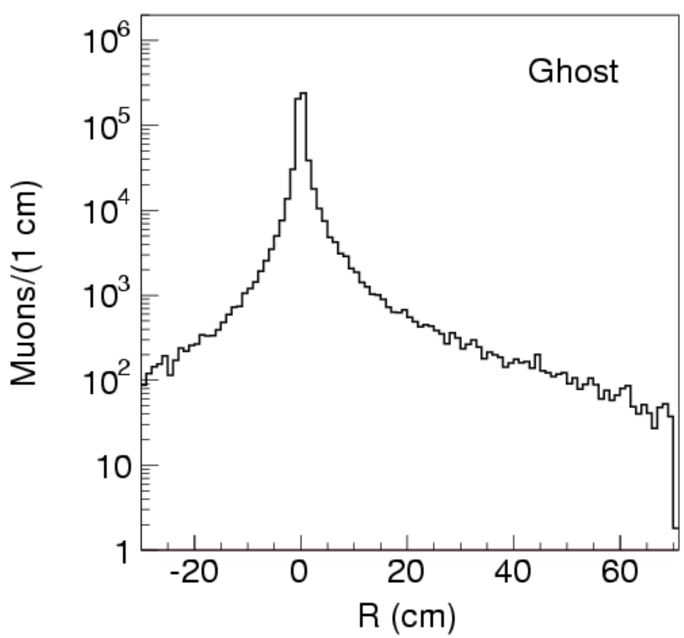


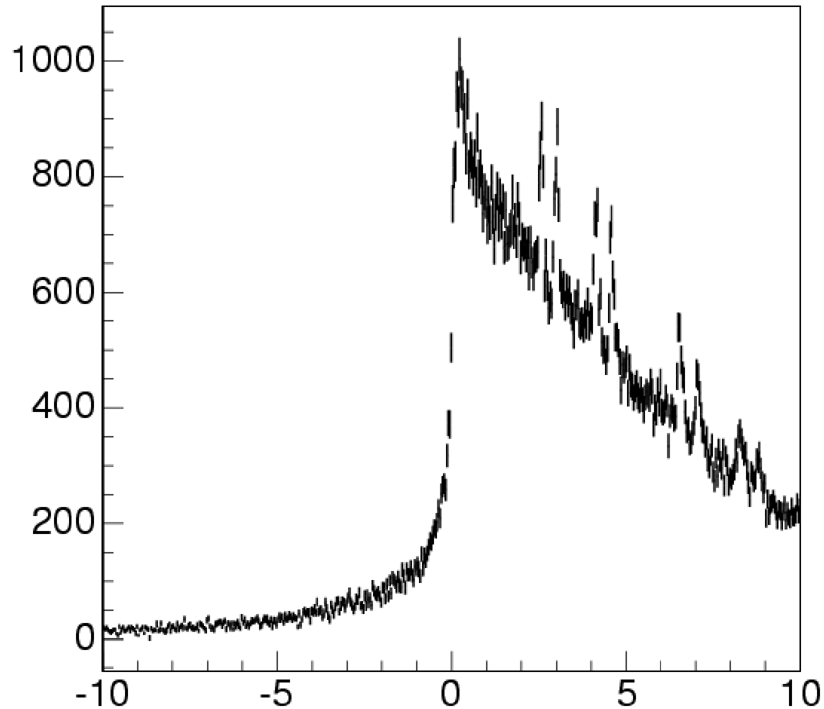


Secondary interactions

Combine initial muons with tracks with $p_T > 1$ GeV/c in a 40^0 cone

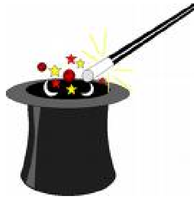






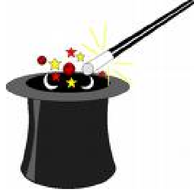
Simulation – tracks, not muons

SM sources of ghost events



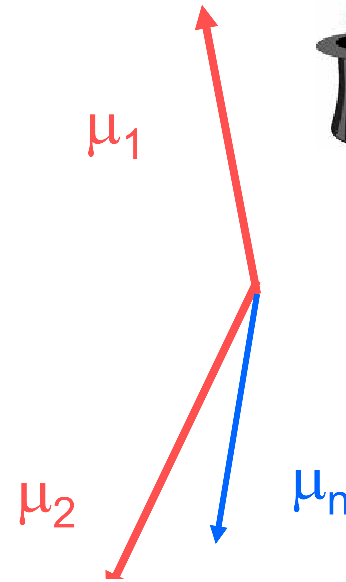
- Our prediction accounts for approximately 50% of the observed number of ghost events (70000 out 150000 events)
- The uncertainty of the rate of IFD may be large, and we cannot rule out quasi-elastic secondary nuclear interactions
- At this point of the study, we assume that ghost events can be fully accounted for by a combination of the previously studied effects
- Learned the lesson: UA1 monojets and the Altarelli cocktail
- Just loading the bases

Search for additional muons

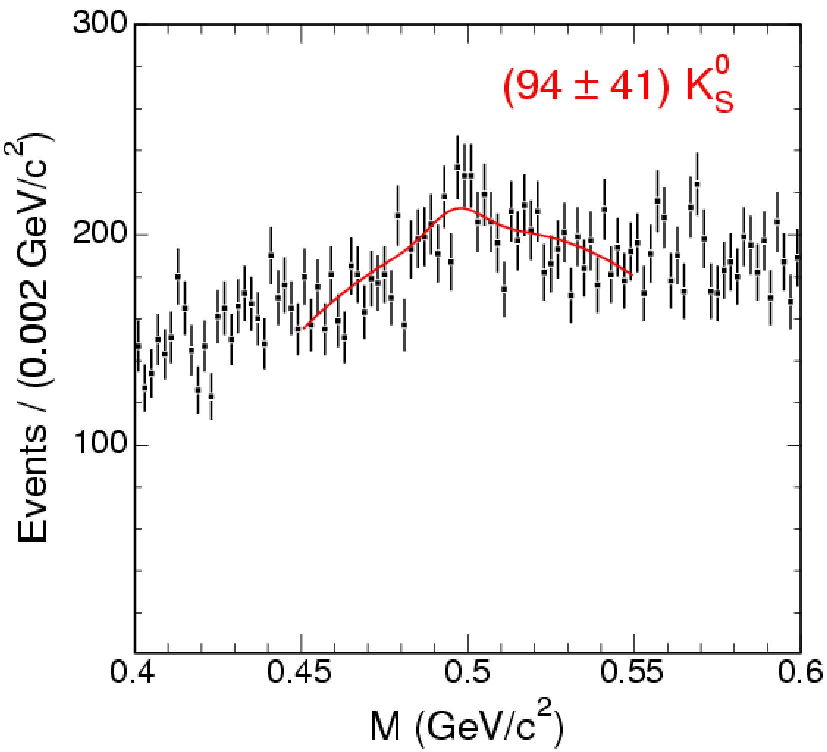


- Interesting for several reasons:
    - Ghost events may be related to the excess of low mass dileptons
    - Events due to secondary interactions or fake muons are not expected to contain a lot of additional muons
    - If ghosts events were normal QCD events with mismeasured initial muons, the rate 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
- Use CMU+CMP+CMX – ε=0.805 (sim), 0.838 (data)
- The main source of additional muons are sequential decays of single b quarks
- A sizable contribution of muons mimicked by hadrons. The hadronic punchthrough is not simulated.
- It is evaluated using a fake probability per track derived from a large sample of D^0 -> K π decays (standard practice).
- With respect to only using CMUP muons, this choice gains a factor of 5 in the acceptance at the price of an increase of the fake rate by a factor of 10

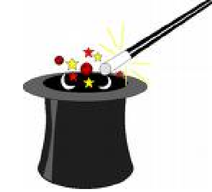
Additional muons



- The request of additional muons selects b-quark sequential decays and depresses all other 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^0_S contain an additional muon



Hit

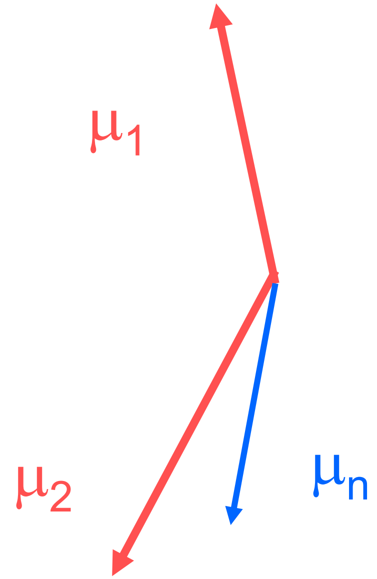


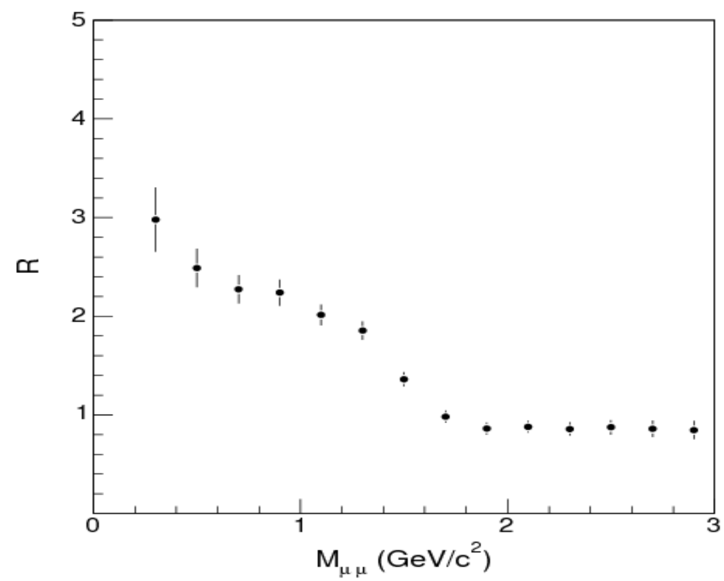
- In the data, 9.7% of the events contain at least one additional muon
- In these events, the efficiency of the tight SVX selection, only applied to the initial muons, drops from 0.193 to 0.166
- Averaged over ghost and QCD events, the efficiency of the tight SVX selection is ε=0.193, whereas it is 0.244 in QCD events.
- If ghost events were all due to IFD, K^{O}_{S} and hyperon decays, and to secondary interactions, the request of an additional muon should suppress the ghost contribution with respect to QCD events that also contains b sequential decays.
- One would expect that ε rises from 0.193 towards 0.244. In contrast, it further decreases to 0.166.

Homer

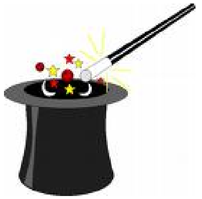
- Ghost events contain more additional muons than QCD events
- Since at least 50% of the ghost are due to sources not rich in additional muons, a fraction of the ghost events is very special.
- The remaining of this analysis is a detailed study of the ghost event characteristics in order to decode the DNA of some special events.
- The strength of the analysis is that we can verify it using QCD events in which both muons are generated inside the beam pipe
- Increase the dataset luminosity to 1426 pb^{-1}
- Use additional muons without SVX requirements
- Repeat the study of the small-mass-dilepton kinematics reported in PRD 72, 072002 (2005)

- Divide small mass muon combinations into OS and SS.
- In QCD, SS combinations only arise from fake muons and are subtracted from OS combination to remove the fake background
- Reasonable procedure for Υ , D-Y events in which additional tracks belong to the underlying event and are not charge-correlated with the initial muons
- For heavy flavors, a large number of tracks come from the fragmentation and decay of heavy quarks and are charge correlated. The relative rates of K and π tracks depends on the μ-track invariant mass
- Weight tracks in the simulation with the fake muon probability derived from the data. R is the ratio of OS-SS including fakes to real OS-SS. The average fake muon correction is 30%
- b and c quark cross sections in the simulation normalized to the data

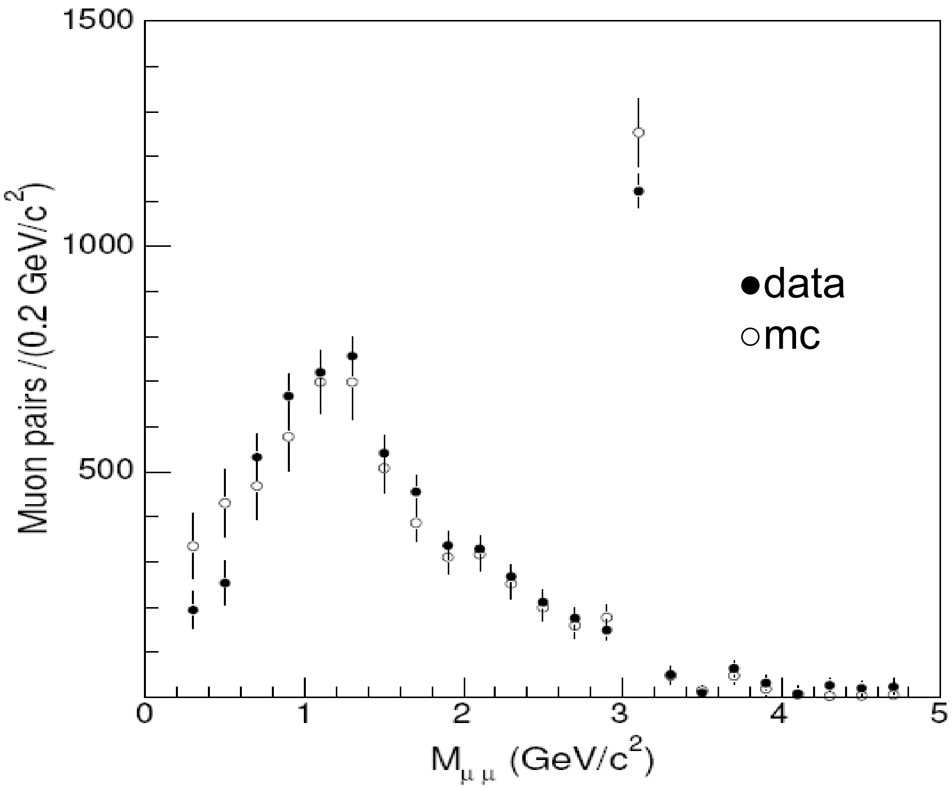




Both initial muons produced inside the beam pipe

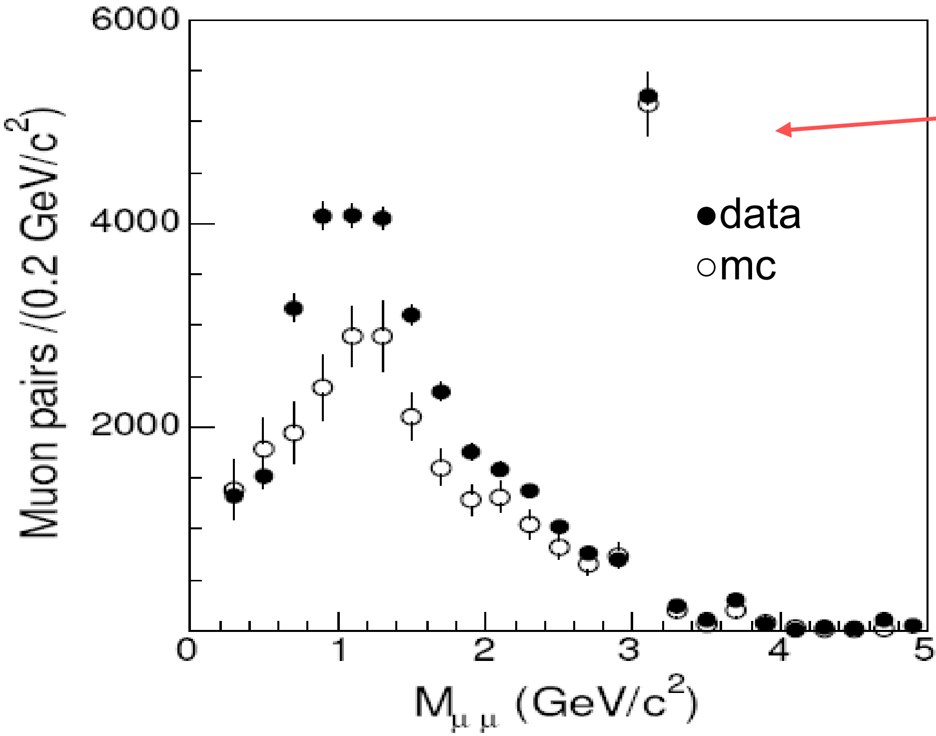


The sample has 276000 events and 140800 *bb* events

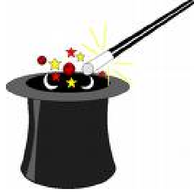


- 6935±154 in the data and 6998±293 predicted
- We understand the heavy flavor simulation and the fake muon background

No SVX requirements for the additional muons



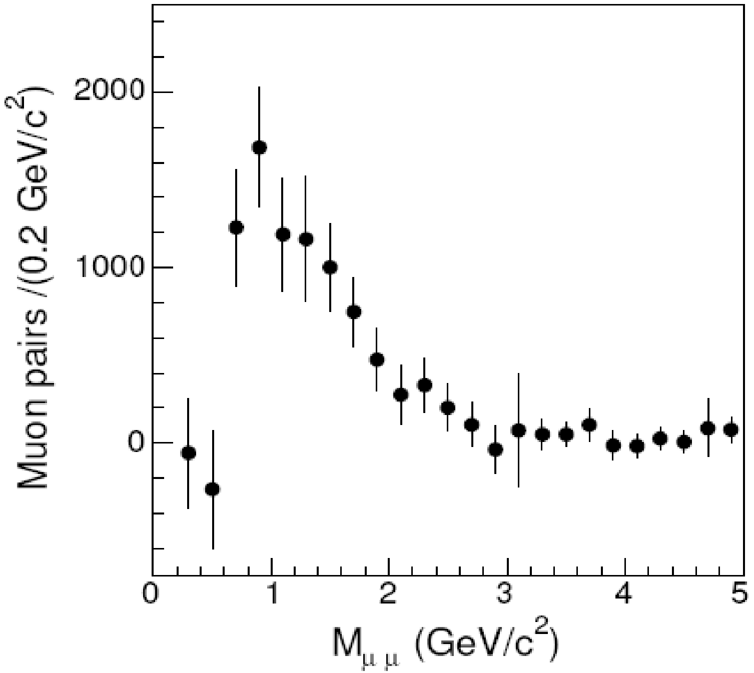
J/ψ mesons arise from $b\bar{b}$ production - Data without SVX selection agree with the prediction



	QCD	Ghost
Events	1131040	295481
OS-SS	28422±631	8451±1274
%	2.5	3.0

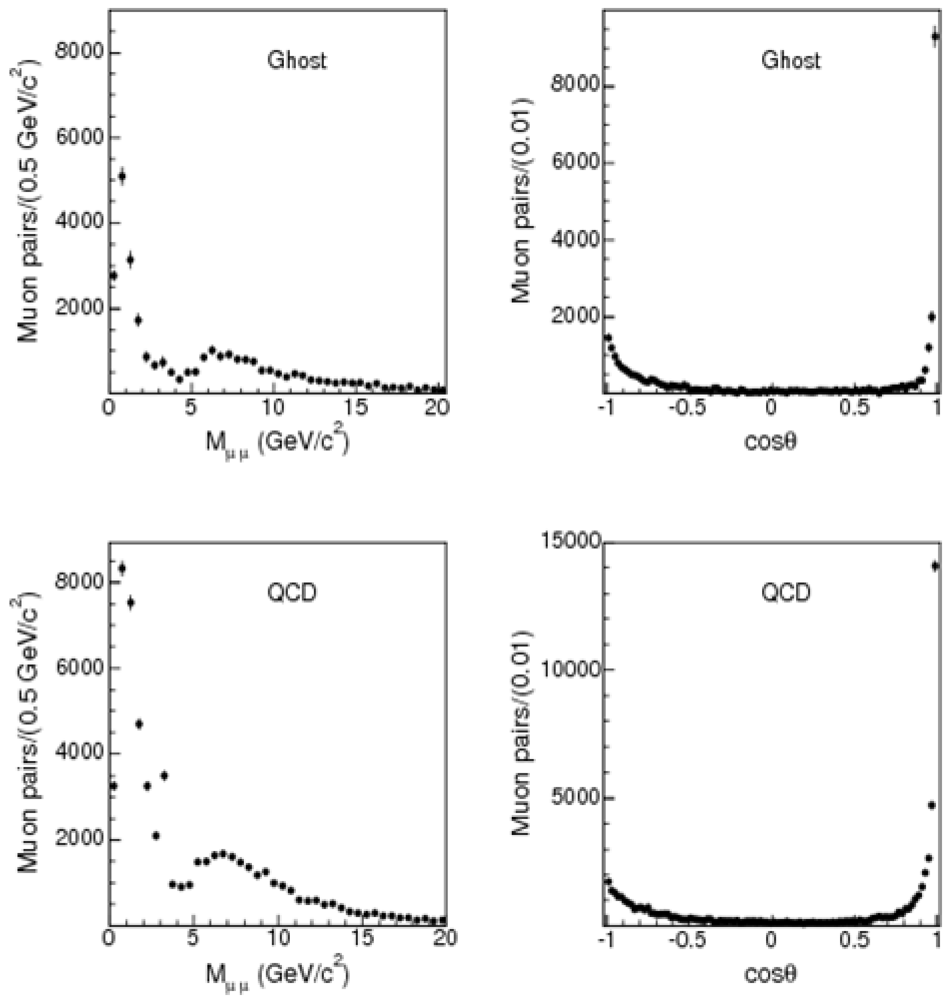
All data – initial dimuons without any SVX requirements

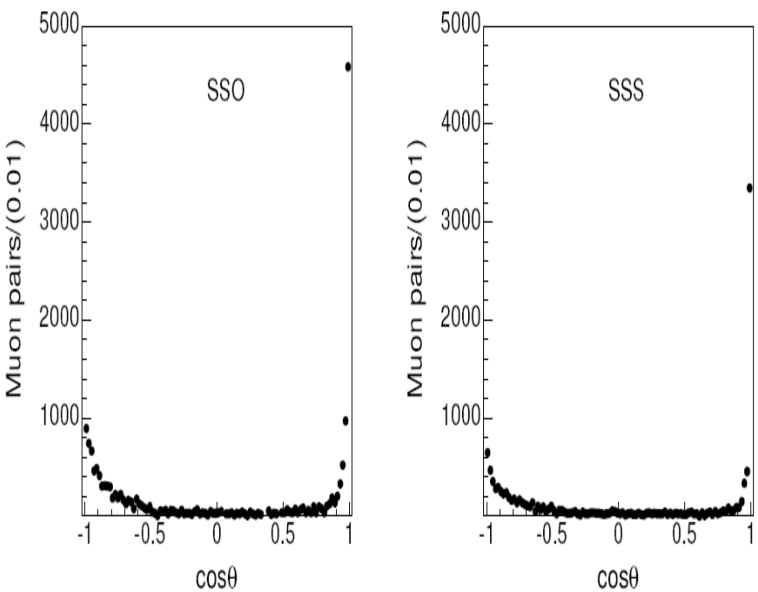
Ghost



- Search for additional muons without any invariant mass cut
- For OS initial dimuons, combine the additional muon with the one of opposite sign: OSO
- For SS initial muons, combine randomly: SSO and SSS combinations

OSO

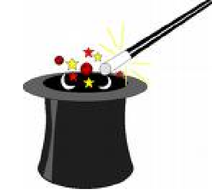




Ghost

Conclusion: continue study using $\theta < 36.8^o$

θ <36.8^{o} – additional muons , tracks, and fakes



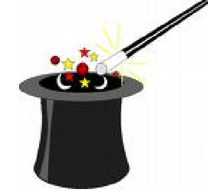
No. of tracks with p_T > 2 GeV/c and $|\eta|$< 1.1

Topology	All	SVX	QCD	Ghost
OS	1315451	207344	849770 ± 6965	465860 ± 6965
SS	893750	140238	574745 ± 4711	318004 ± 4711

The average number of tracks in ghost events is a factor of two larger than in QCD

Another surprise

θ <36.8^{o} – additional muons and fakes



ghosts

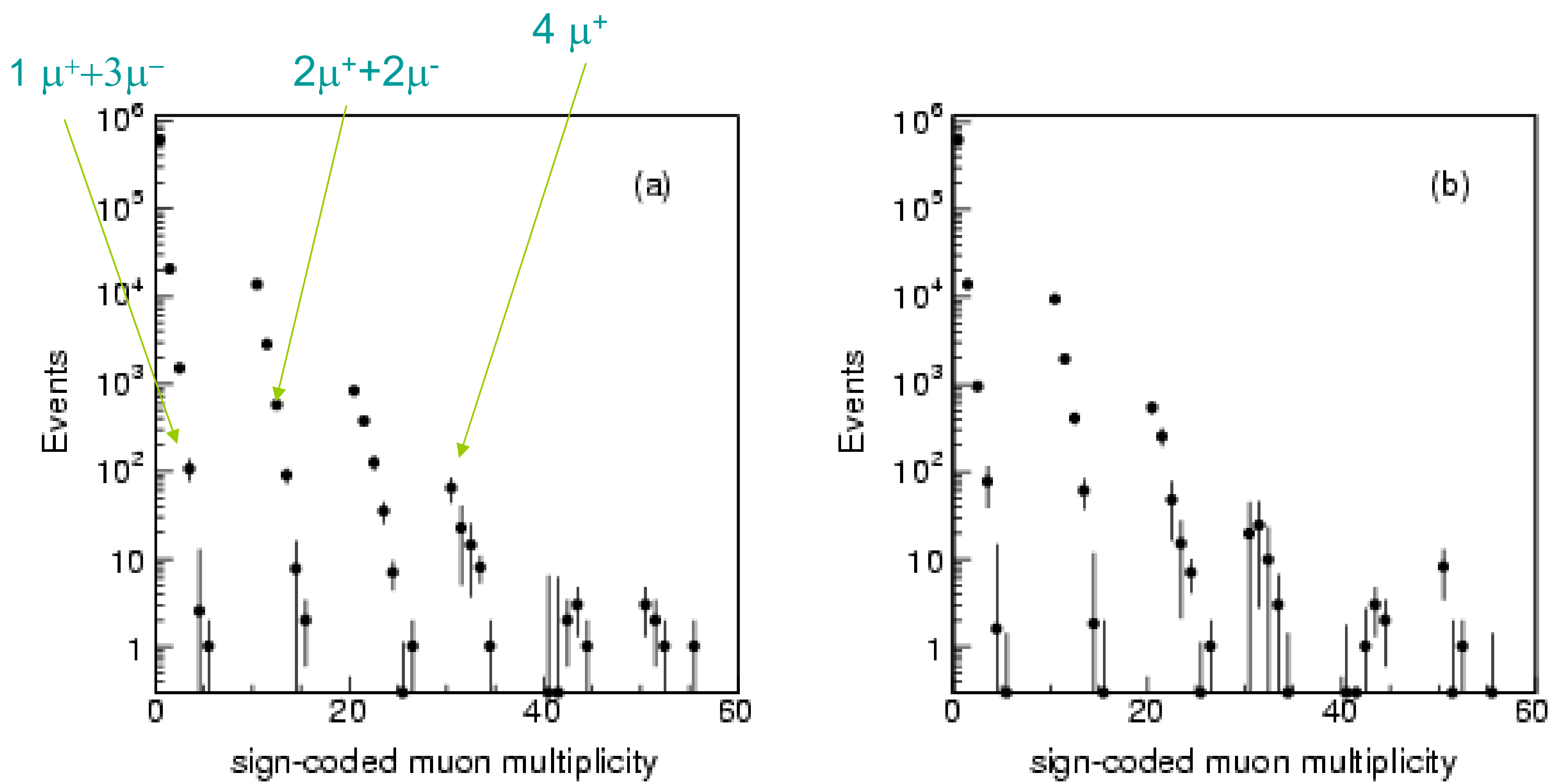
Topology	Observed	F_K	F_π
OS	28692 ± 447	15447 ± 210	9649 ± 131
SS	20180 ± 246	10282 ± 137	6427 ± 81

There are 295481 ghost events
that contain approximately 28000 real muon combinations with
SS or OS charge (9.4%) - the signal is four times larger than in the
QCD contribution

Muon multiplicity in a cone

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

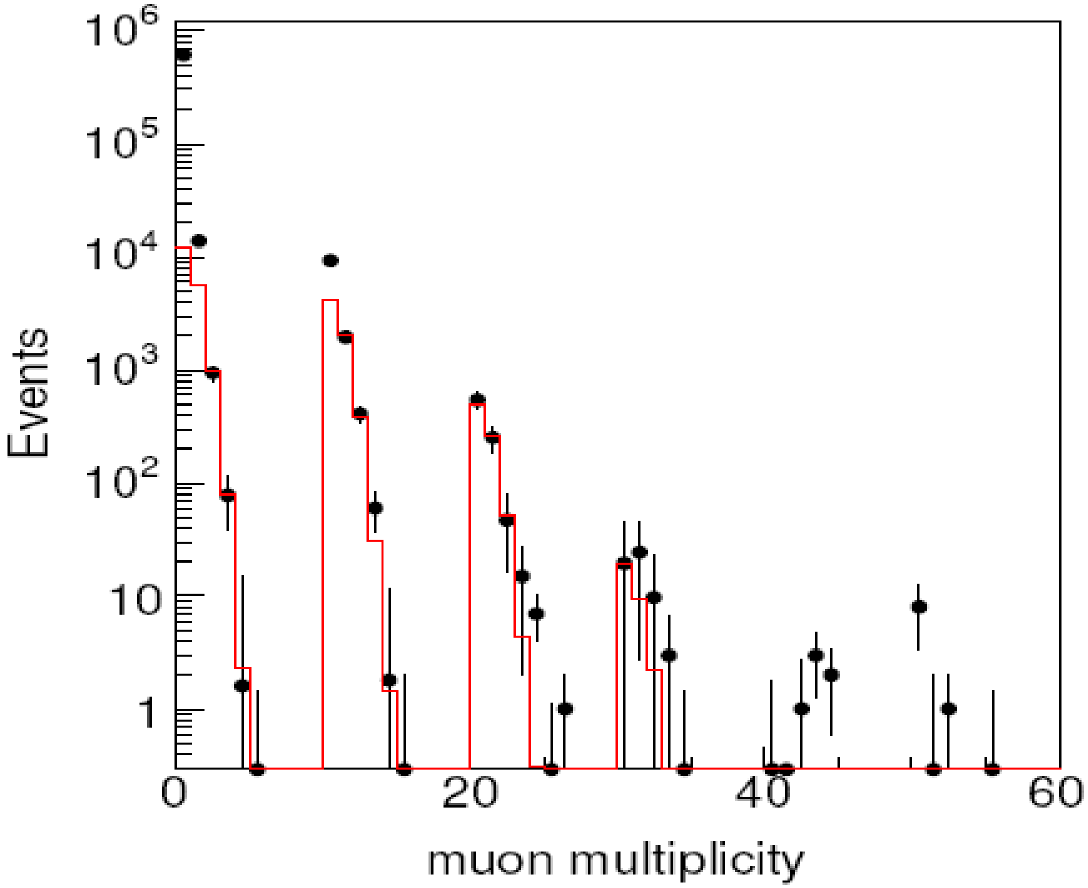
For the same number of additional muons, the bin occupancy depends on the fraction of same sign muons



Fake muon subtracted

40409 cones with at least two muons → 27530

Phenomenological conjecture
arXiv:0810.5730



Some ghost events are due to an object h_1 decaying into 8 τ leptons, and produced with transverse momentum much larger than its invariant mass

Fake muons removed assuming tracks are π

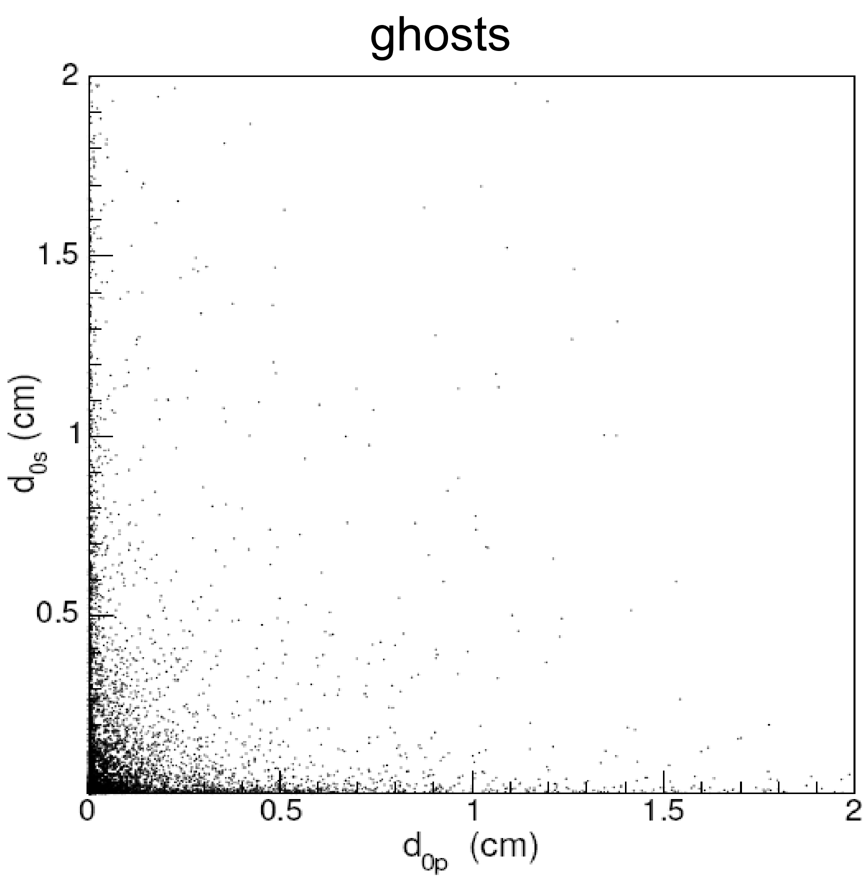
— Toy Monte Carlo: 8 $\tau \to \mu$ with BR=0.174, ε_μ = 0.5 and 0.883, ε_{kin} =1

4 τ^+ +4 τ^- – toy MC, normalized to data for bins >=11,

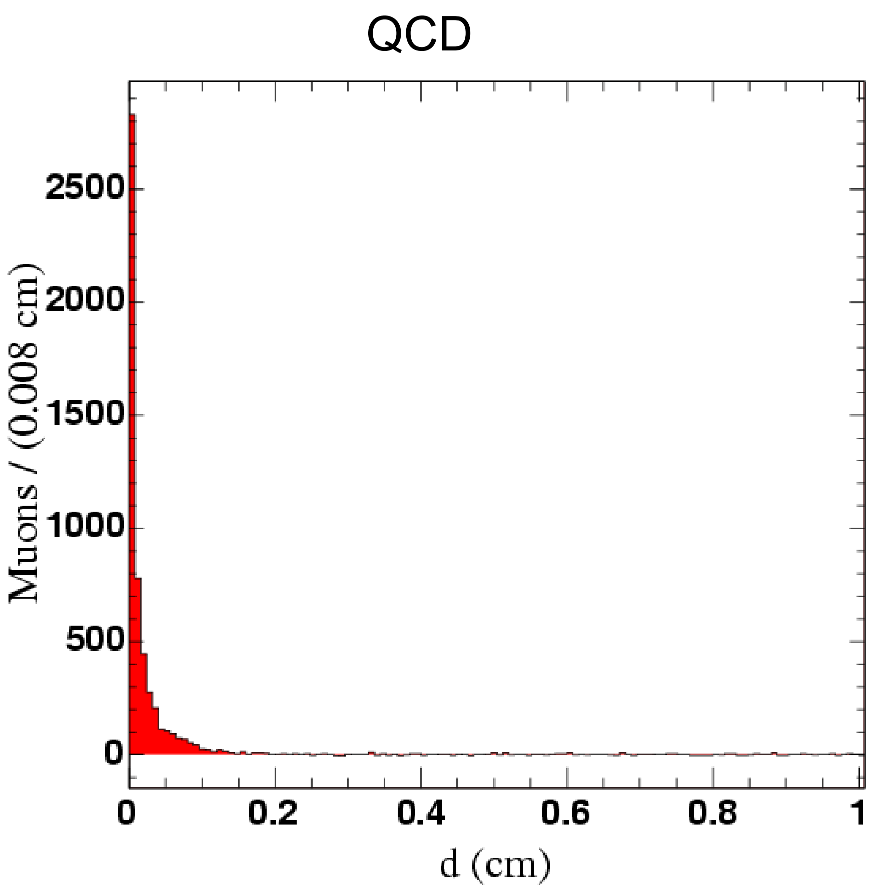
accounts for approximately 13200 (5%) of the ghost events

Impact parameter of the additional muons

Loose SVX requirements



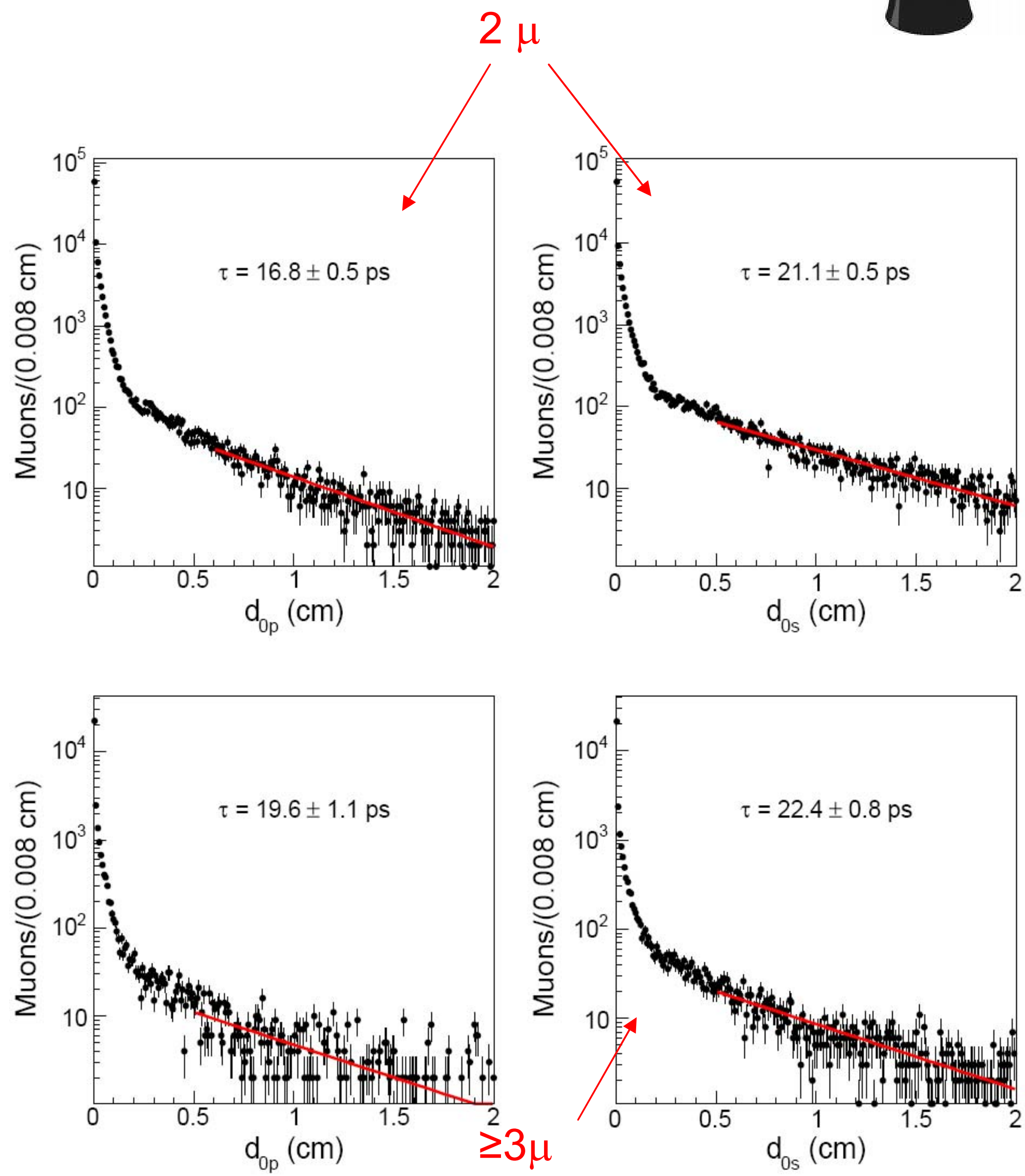
ρ = 0.03



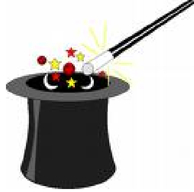
5320 OS-SS
additional muons

Lifetime estimate

- Assume that muons arise from the decay of objects with a lifetime
- No SVX requirements, no bias
- IFD or secondary interactions suppressed by the multiple muon request
- The trigger biases the IP distributrion of the initial muon
- Best estimate of the slope: τ=21.4±0.5 ps error statistical

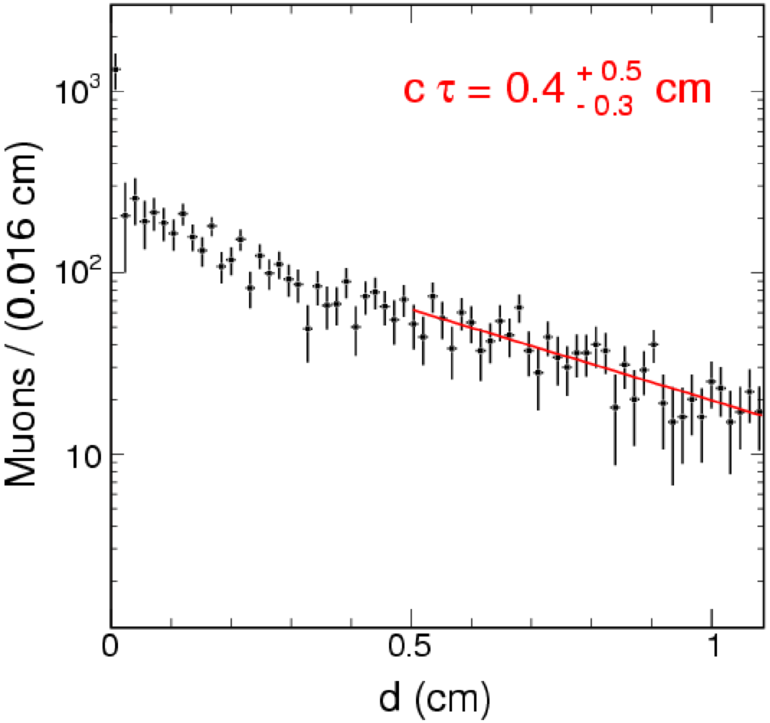


Effect of the trigger bias

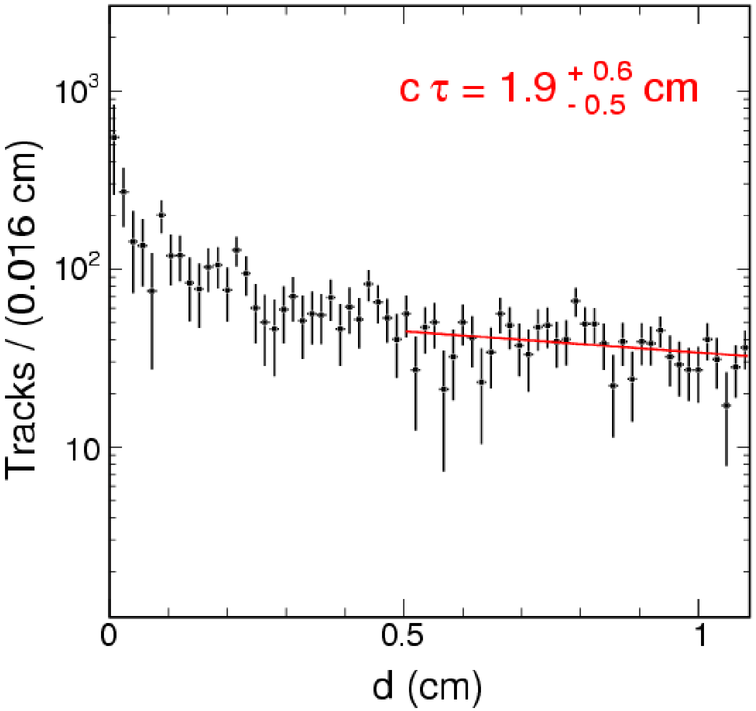


- IP distributions for K^0_S reconstructed using a CMUP muon (punchthrough) and a track with p_T>2 GeV/c in a 40^0 cone
- Distributions are sideband subtracted

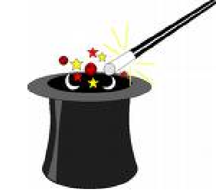
Trigger muon

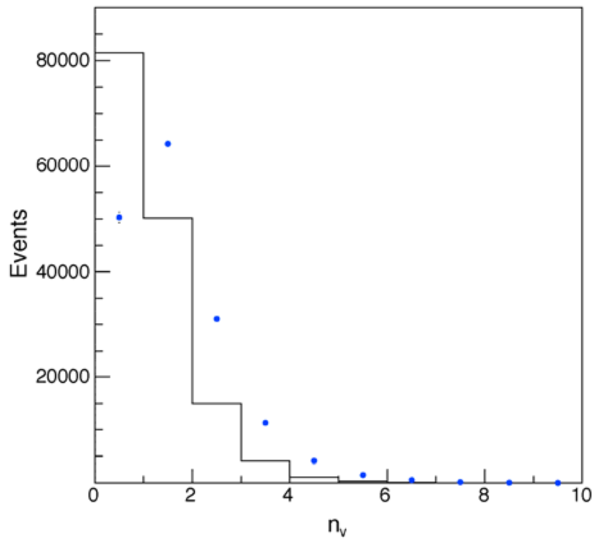


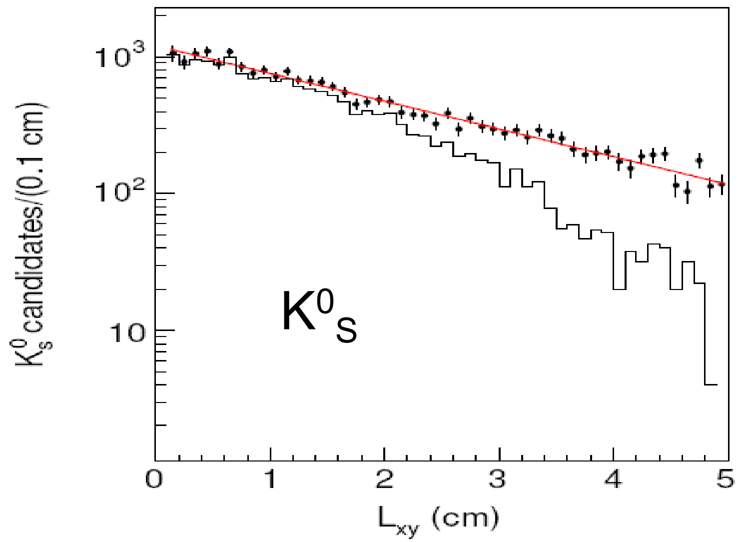
Additional track

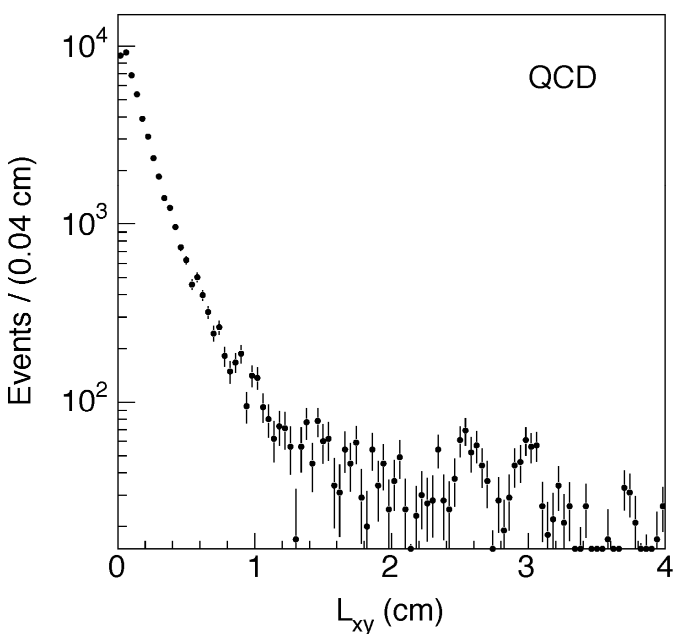


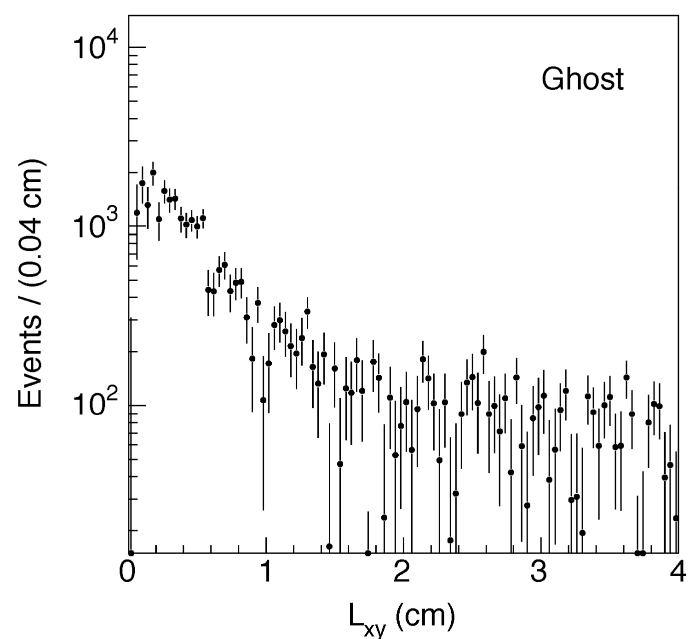
Testing the lifetime conjecture



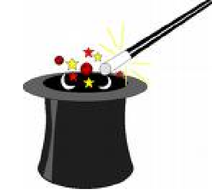








Cone correlations - test of pair production

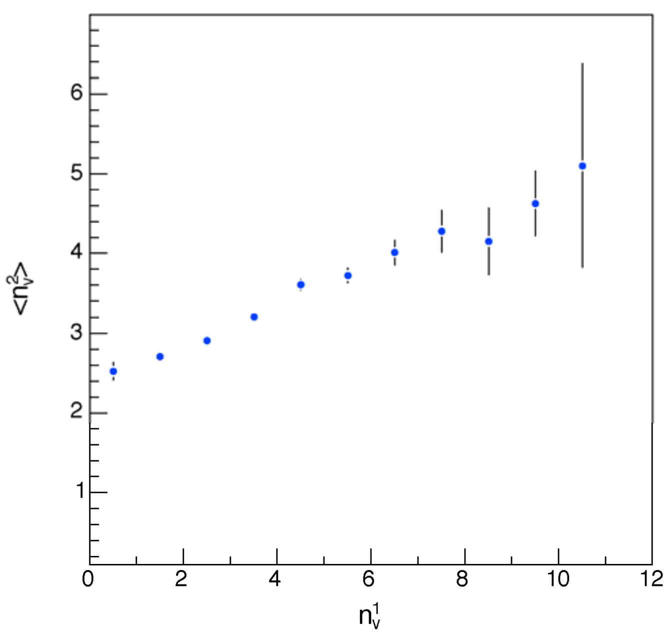


Ghost events

27790±761	cones with ≥ 2 μ	(a)
4133±263	cones with ≥ 3 μ	
3016	with ≥ 2 μ in both cones	(b)

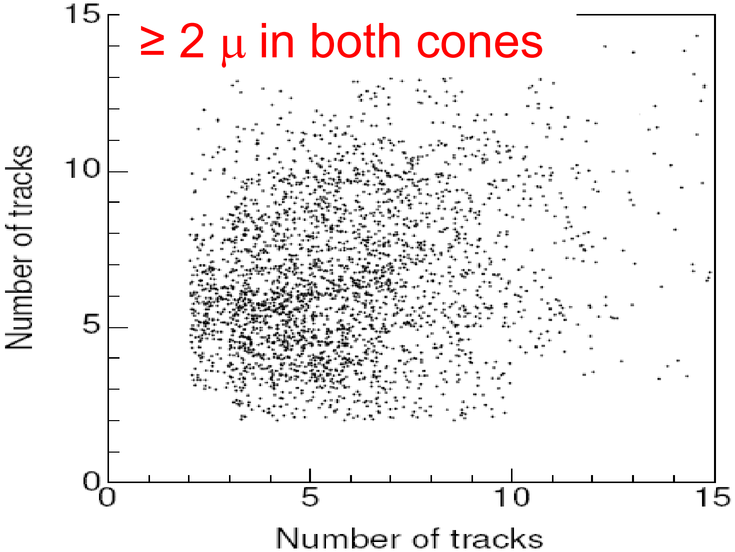
The ratio (a)/(b) = 0.11 is quite large - for comparison, in events triggered by a central jet, the fraction of events containing another central jet is 10-15% depending on the jet transverse energy

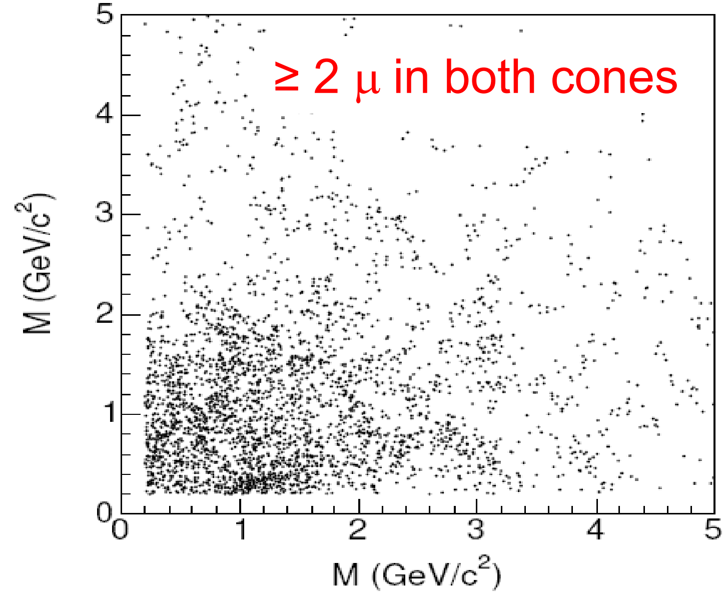
A simulation of the process ff->$h_n h_n$ yields the same ratio

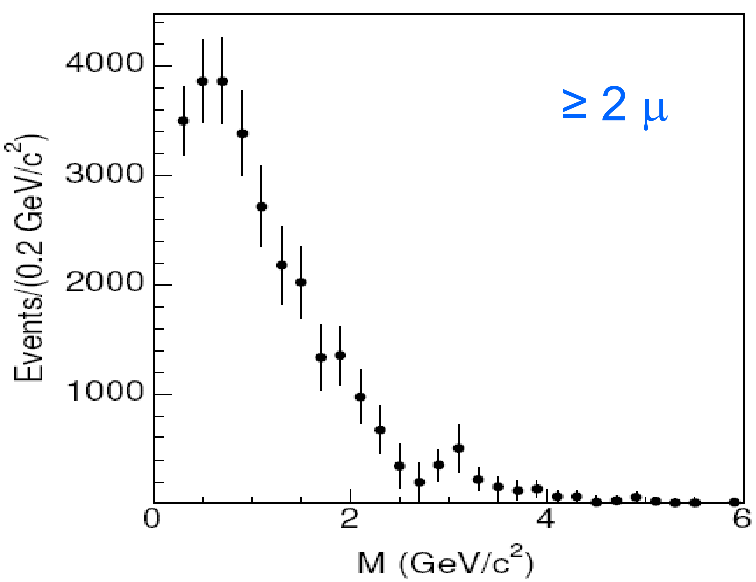


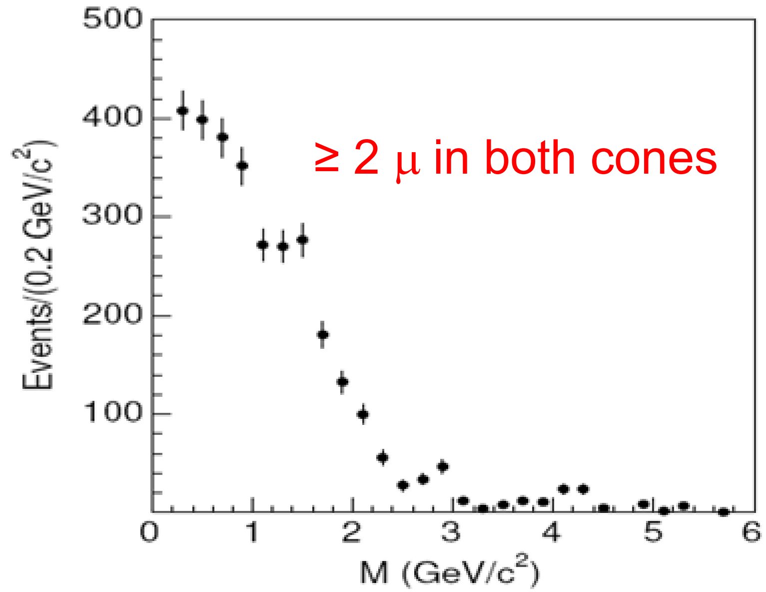
Number of secondary vertices in one cone versus the other – both cones contain at least 2 muons

Cone correlations



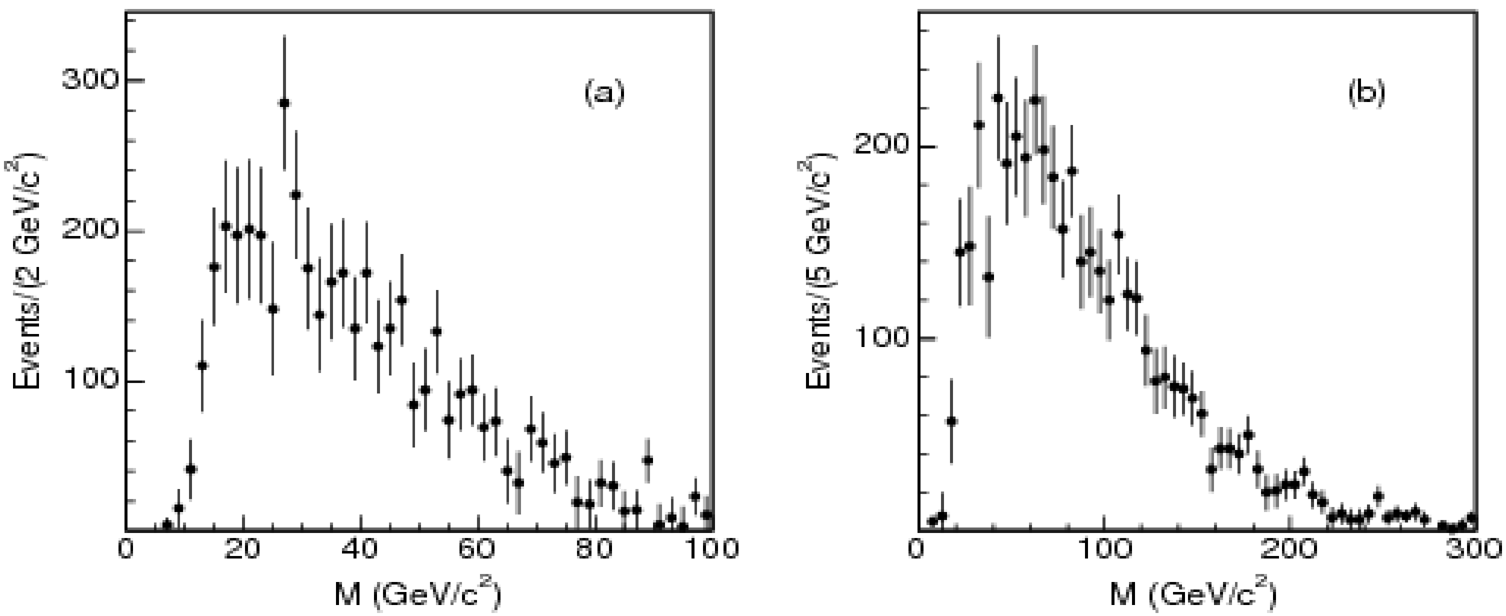




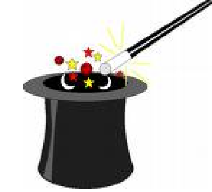


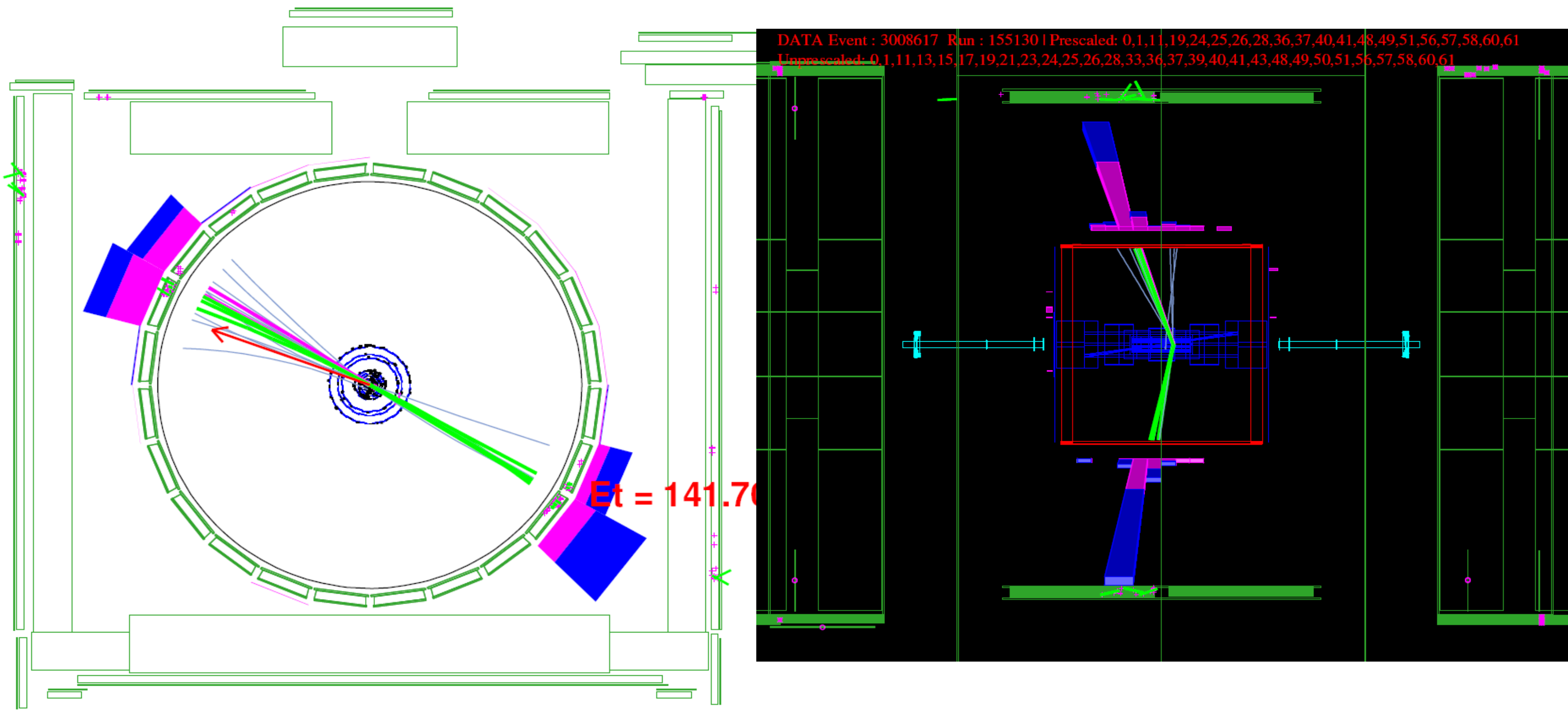
Events with two cones containing at least two muons

- Invariant mass of (a) all muons and (b) all tracks with $p_T > 2$ GeV/c. The trigger muons have $p_T > 3$ GeV/c.
- The efficiency for reconstructing additional muons is 83% and that for tracks approximately 100% - just in case you have a NP model in mind
- 2100 pb^{-1}

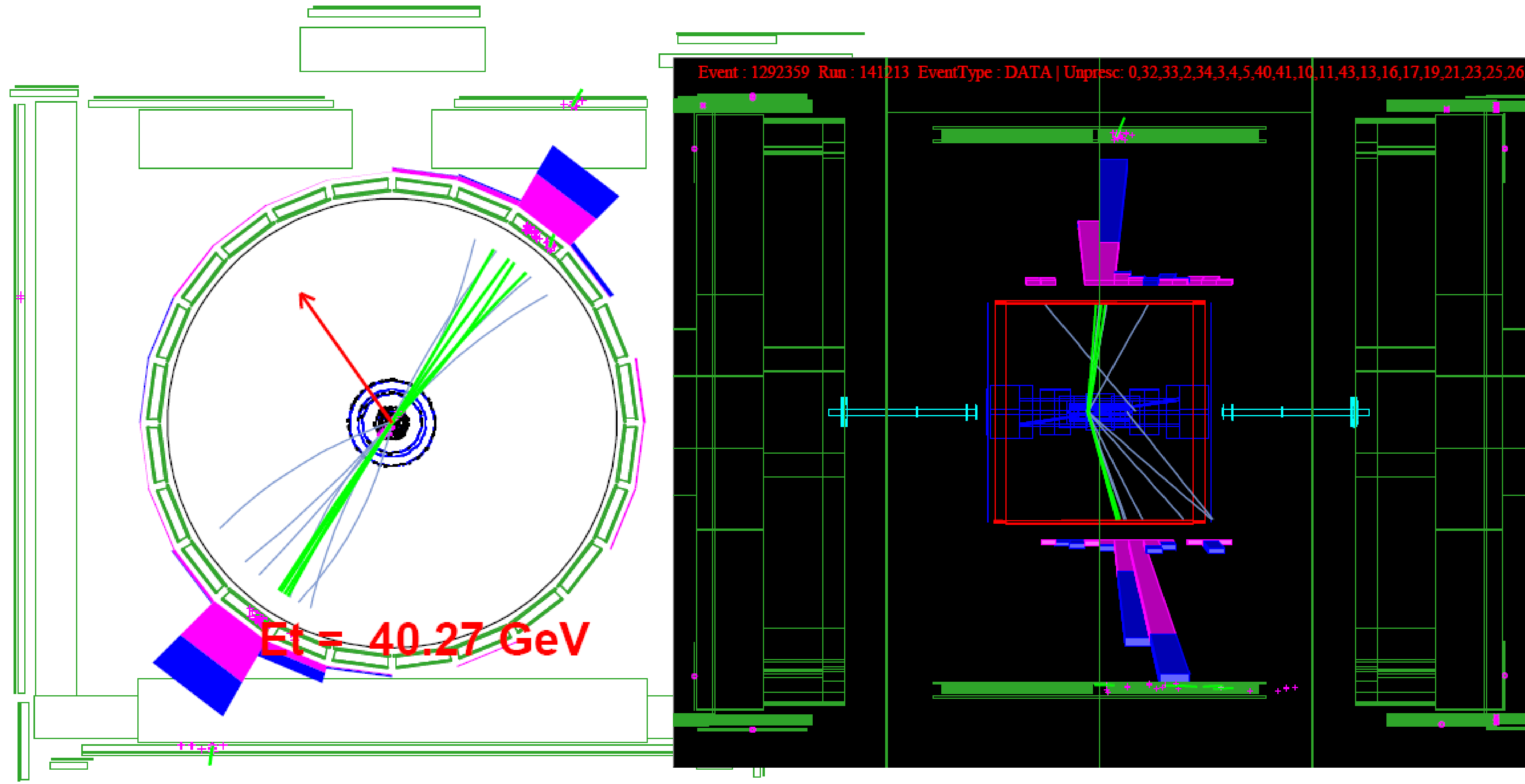


Instant gratification

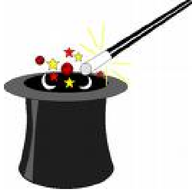




Instant gratification



A word of prudence



- In ghost events, the rate of fake muons is comparable to the signal
- We have chosen to use all muon detectors and quite loose selection criteria in order to maximize the acceptance and minimize the uncertainty of the detector efficiency
- The muon detectors have been paid with US and Italian taxpayer money. If the moneys were bigger, the detectors would have been better. However, they served us well for more than 20 years (from top to B_c discovery). We got used to them, and, as they say in Naples, every cockroach is beautiful to his mother
- Usually, we verify the fake muon prediction to a signal by using analogous data sample
- In this case, we don't have a data sample of known physics that contains as many muons and tracks in a small angular cone as ghost events
- We went through all possible cross-checks, and we see no indication of gross detector failure. However, it was a flight through choppy air and a landing in the fog.
- It could be a talk in a talk, and I leave it to the question time

Conclusions

- I have reported an interesting lack of understanding of a significant number of events acquired by CDF with a dedicated dimuon trigger
- These events offer a plausible resolution to all inconsistencies and puzzles that affected measurements of the *b*-quark production and decay at the Tevatron in the past 10 years
- A significant fraction of these events seems to be special