"An Interesting Lack of Understanding": CDF Multi-Muon Events

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From the ~~LHC~~ Tevatron to the Universe

Taipei, Taiwan

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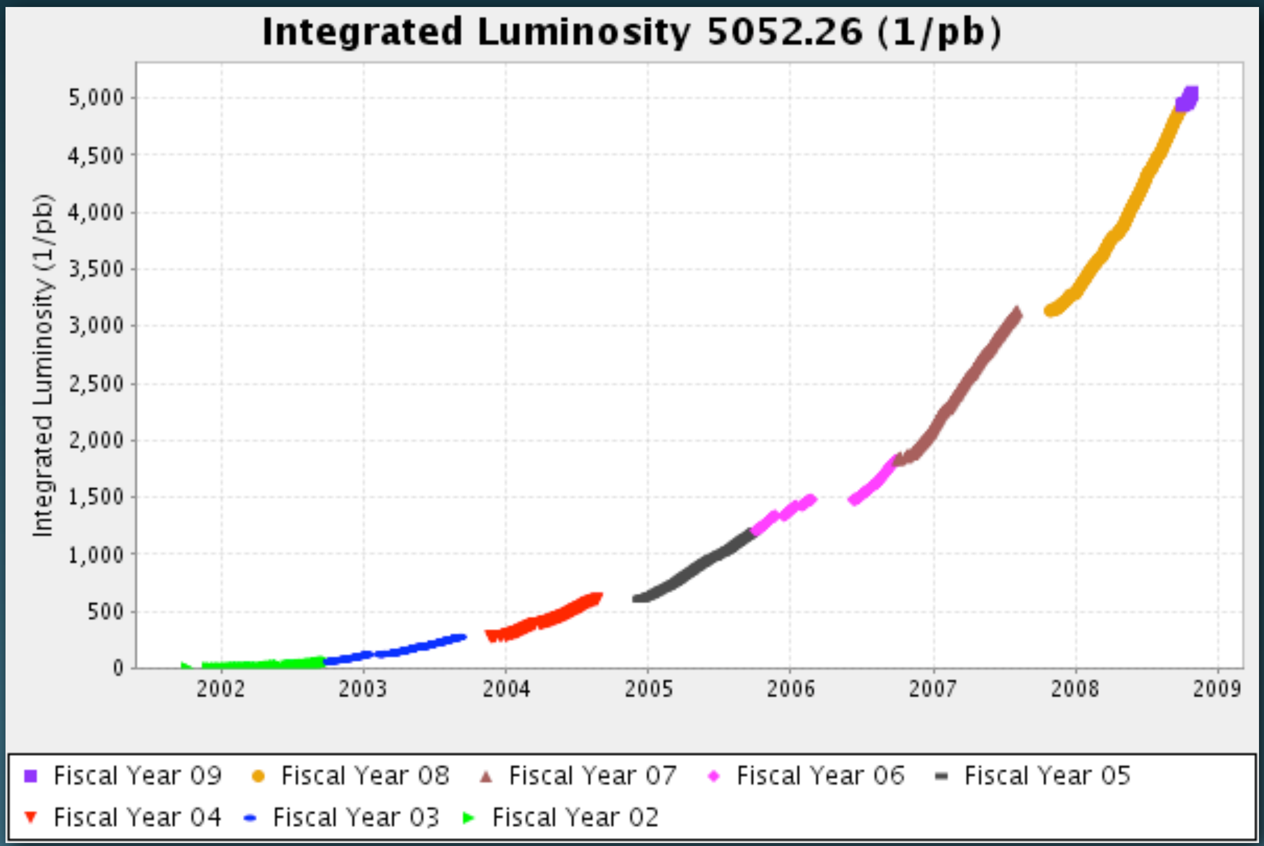
Tevatron Run 2

- the Tevatron is breaking records
- expect to analyze 5 fb^{-1} soon!



CDF's Recent Paper

FERMILAB-PUB-08-046-E

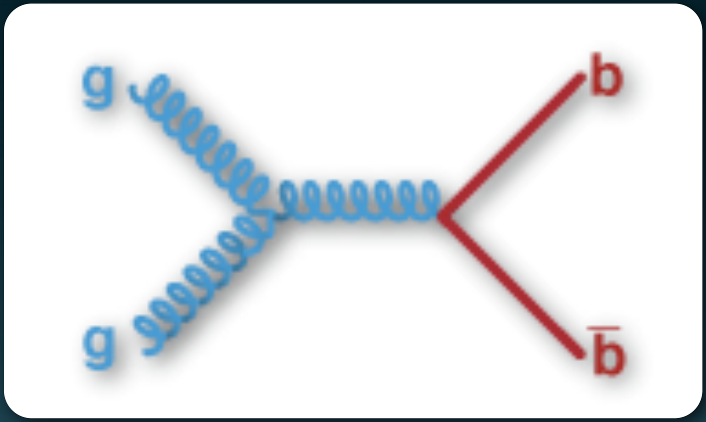
Study of multi-muon events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

Abstract

We report a study of multi-muon events produced at the Fermilab Tevatron collider and recorded by the CDF II detector. In a data set acquired with a dedicated dimuon trigger and corresponding to an integrated luminosity of 2100 pb^{-1}, we isolate a significant sample of events in which at least one of the muon candidates is produced outside of the beam pipe of radius 1.5 cm. The production cross section and kinematics of events in which both muon candidates are produced inside the beam pipe are successfully modeled by known QCD processes which include heavy flavor production. In contrast, we are presently unable to fully account for the number and properties of the remaining events, in which at least one muon candidate is produced outside of the beam pipe, in terms of the same understanding of the CDF II detector, trigger, and event reconstruction. Several topological and kinematic properties of these events are presented in this paper. These events offer a plausible resolution to long-standing inconsistencies related to $b\bar{b}$ production and decay.

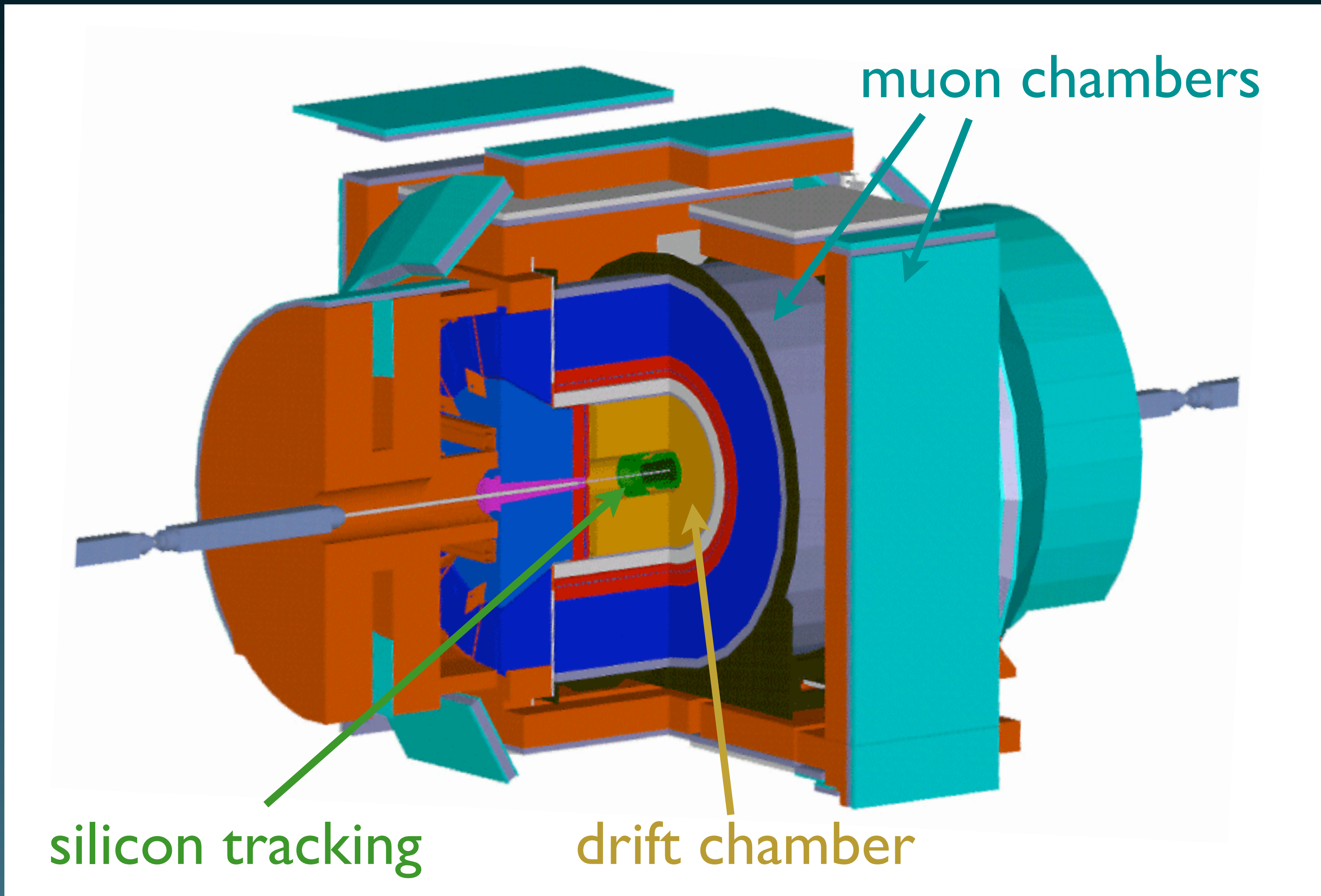
bb Production and Decay

- we produce pairs of b quarks predominantly by gluon fusion at the Tevatron: $\sigma \sim 6\ \mu b$

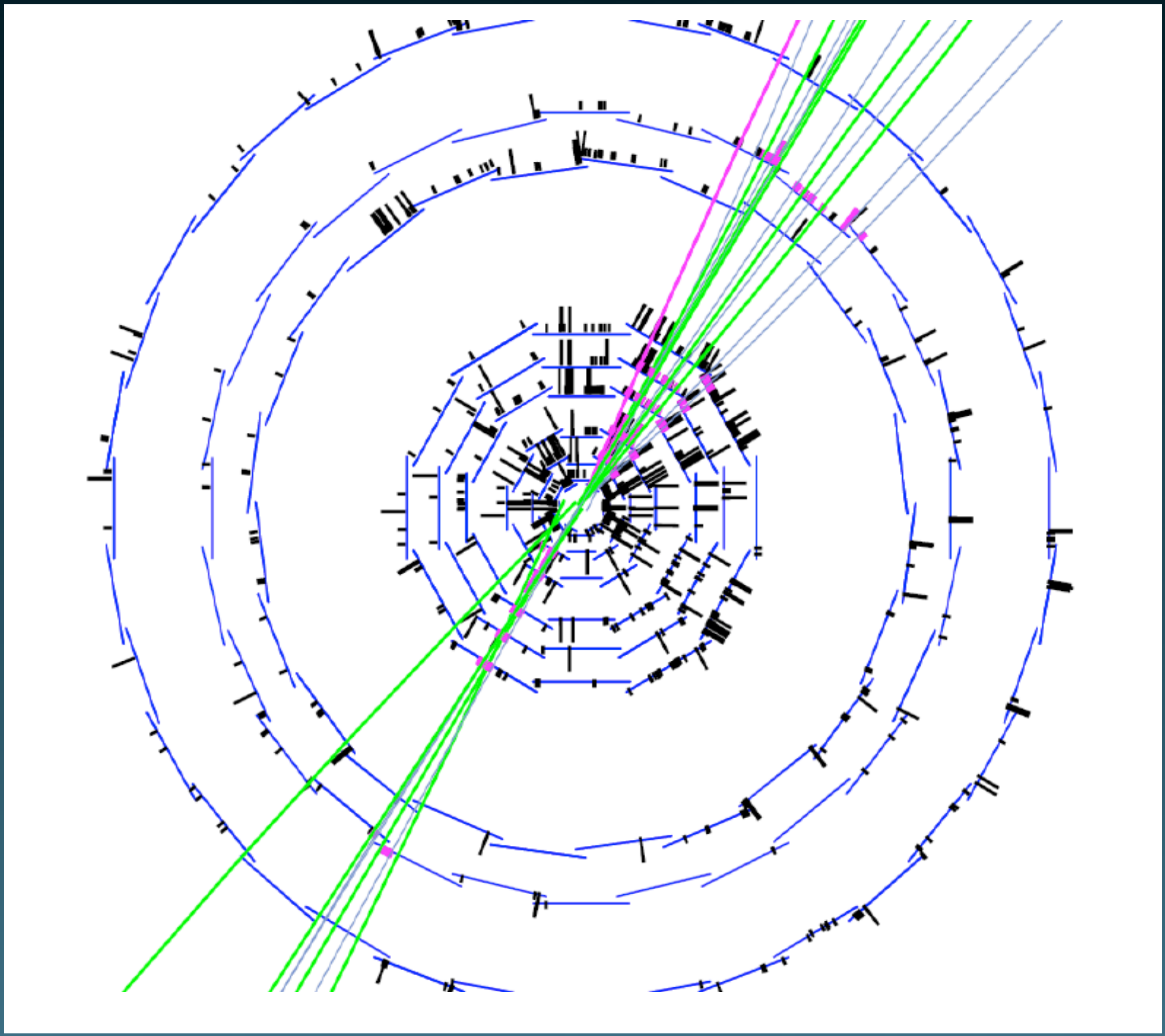


- b quarks hadronize to B mesons and baryons; lifetime is ~1.5 ps ($c\tau \sim 450\ \mu m$)
- very precise silicon detectors can readily "tag" b-quark jets by secondary vertices
- can also utilize b semileptonic decay to μ

The CDF Detector



CDF Detector

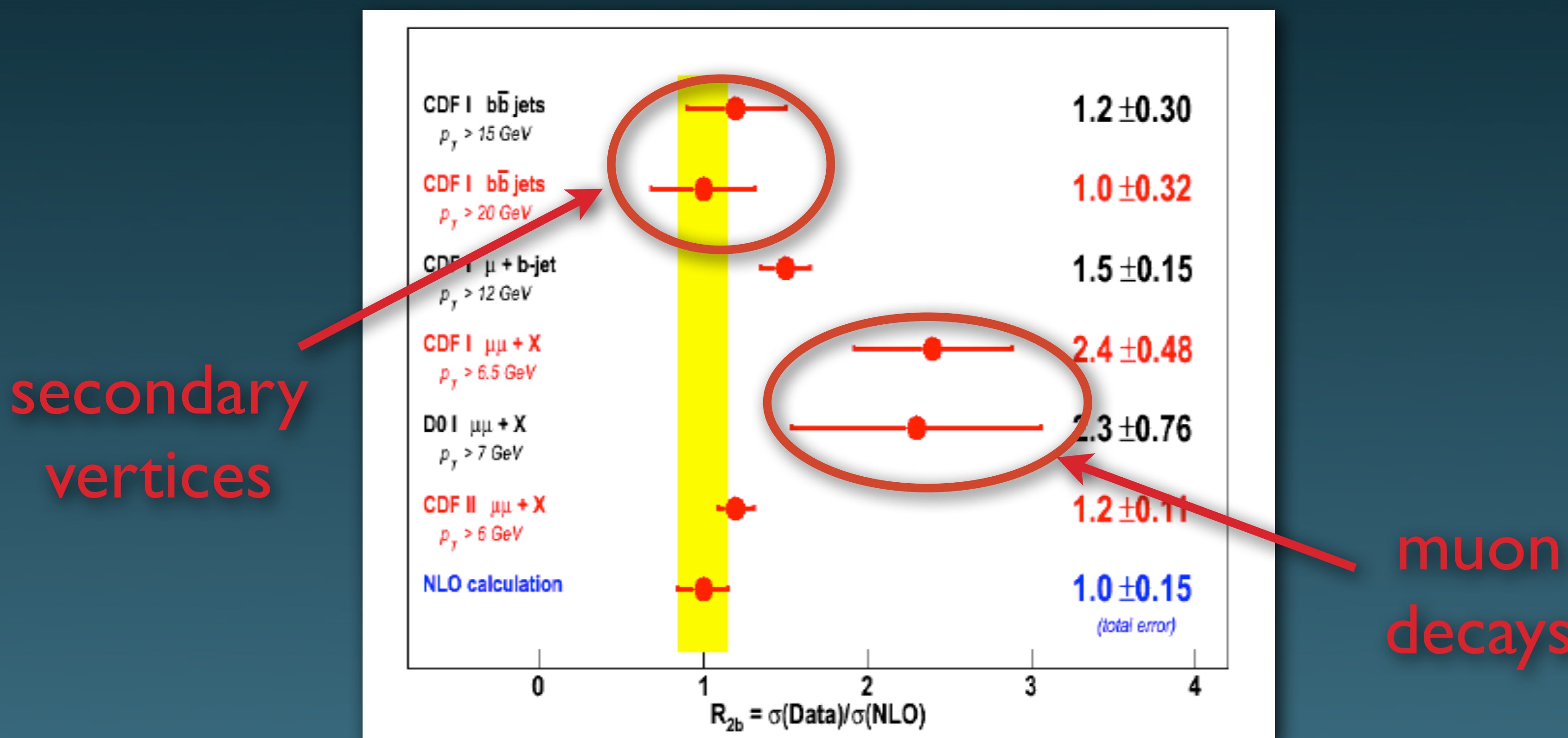


Not very typical bb event with two energetic jets, activity in the muon chambers

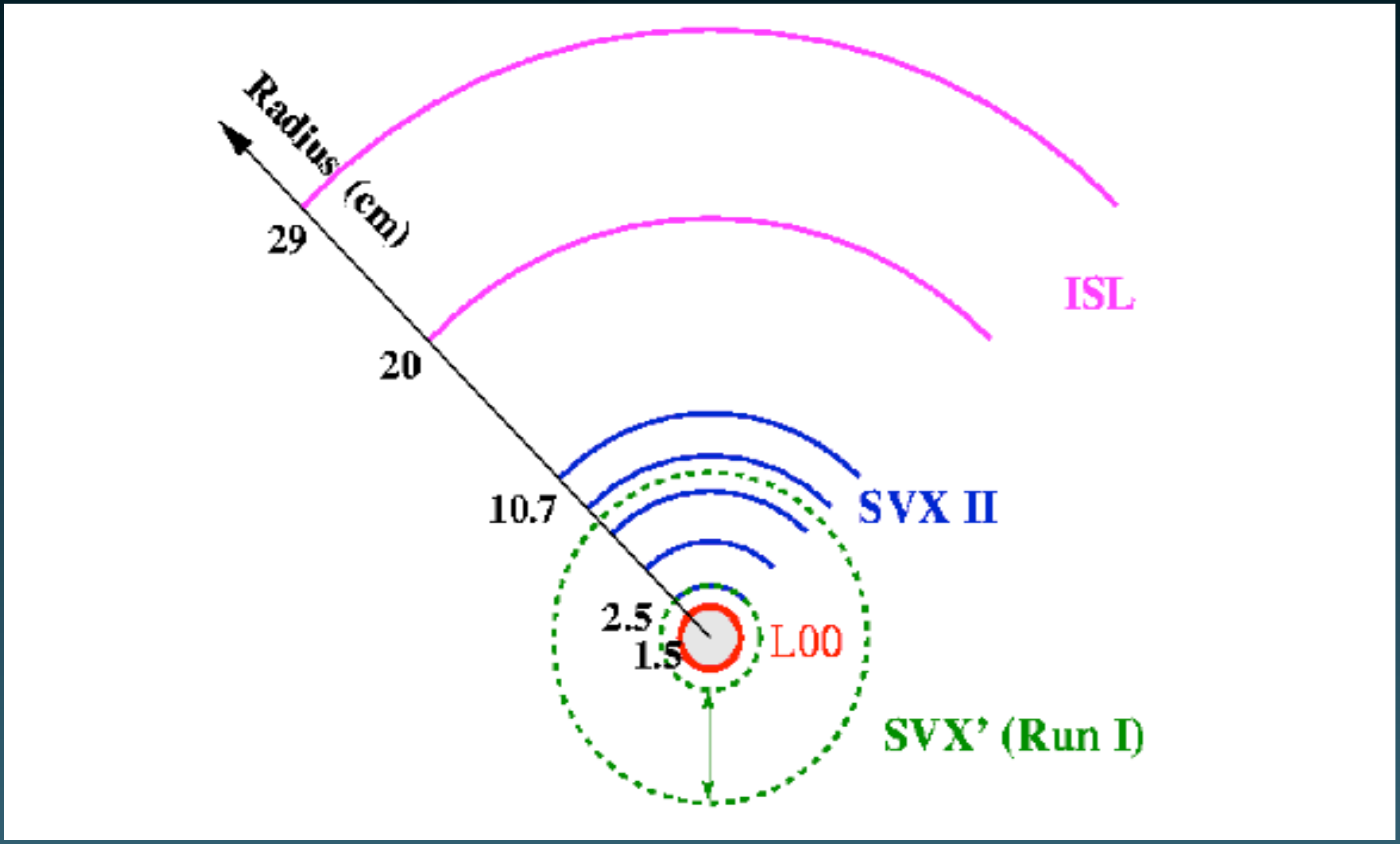
Have nine layers of double-sided silicon strip detectors

Run 1 σ(bb) Measurements

- For some years the bb cross section was too high...then at the end of Run 1 the situation solidified:



Run 1 σ(bb) Measurements



- older "loose SVX" requirement: 3 out of 8 layers have hits: tracks could originate from up to 10 cm from the IP

P. Giromini and his group asked:
why should this matter so much?

Dimuon Sample

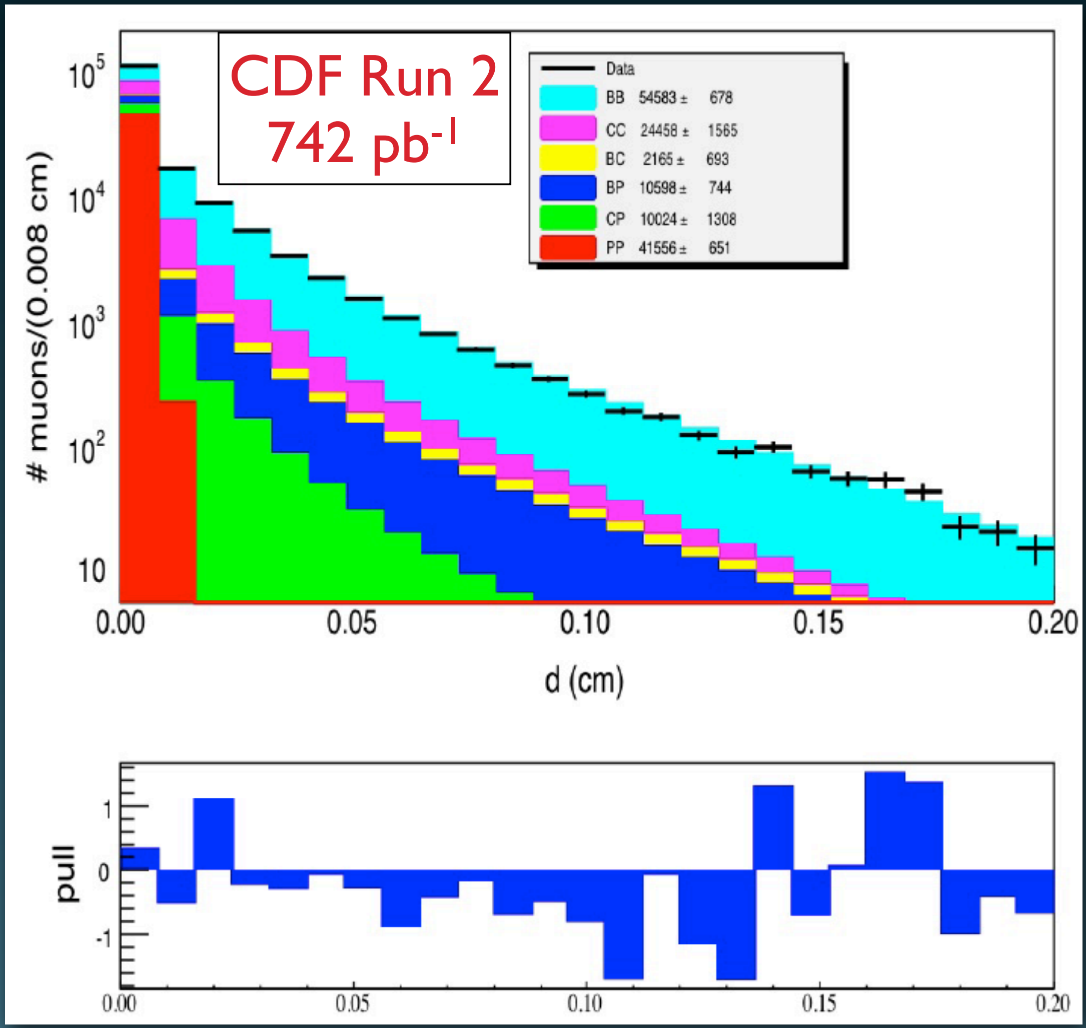
- trigger: two central muons (CMU/CMP)
- match to primary vertex
- $m_{\mu\mu} > 5$ GeV (to remove same-side μ)
- $m_{\mu\mu} < 80$ GeV (to remove Z decays)
- cosmic rays removed with $\Delta\phi < 3.135$

  - 743k dimuon events in 742 pb^{-1}
  - 144k events after tight SVX cuts

Decay Distribution

Excellent agreement between prediction of muon impact parameter and observation only if using tight SVX cuts

Call this the "QCD" contribution



SVX Selection Efficiency

- what fraction of muons from QCD pass the tight/loose SVX selections?

  tight: $\varepsilon = (24.4 \pm 0.2)\%$

  loose: $\varepsilon = (88 \pm 1)\%$

- use tagged samples of muons from Drell-Yan, Υ, J/ψ, $\mu + D^0$
- however: if we measure the tight SVX efficiency in the subsample with two identified muons we get

  tight: $\varepsilon = (19.30 \pm 0.04)\%$

SVX Selection Efficiency

This discrepancy

- explains the higher measured cross section in the di-muon sample
- went un-noticed for many years
- seems to imply a large background which is suppressed by the tight SVX cuts

We refer to this background as “ghost events”

Size of the Ghost Sample

all dimuon events

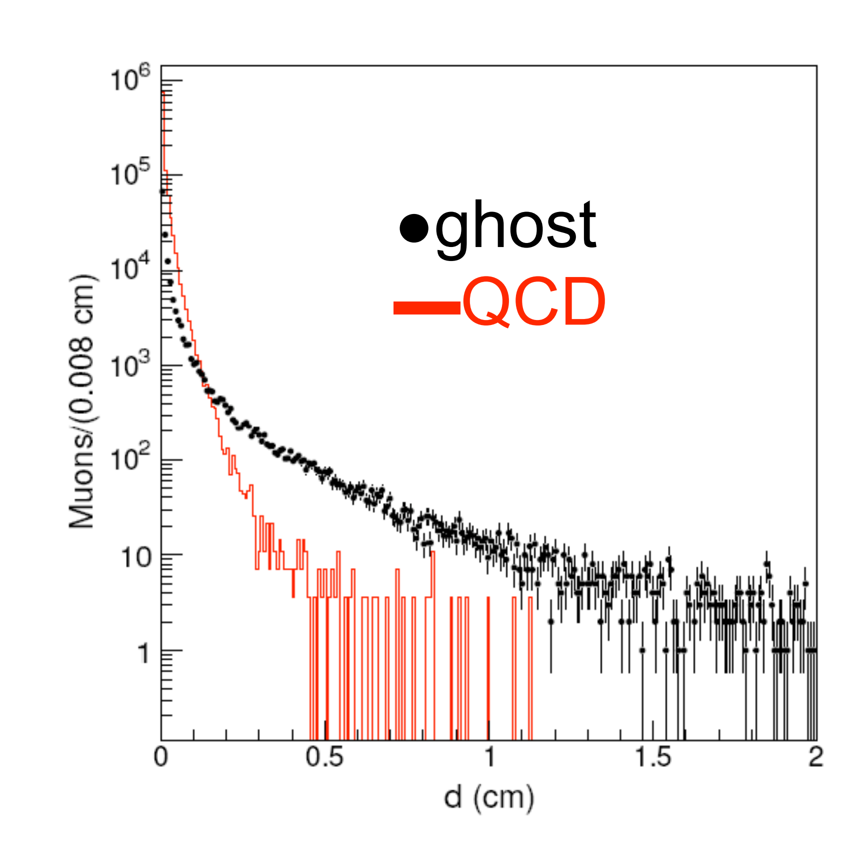
742 pb^{-1}

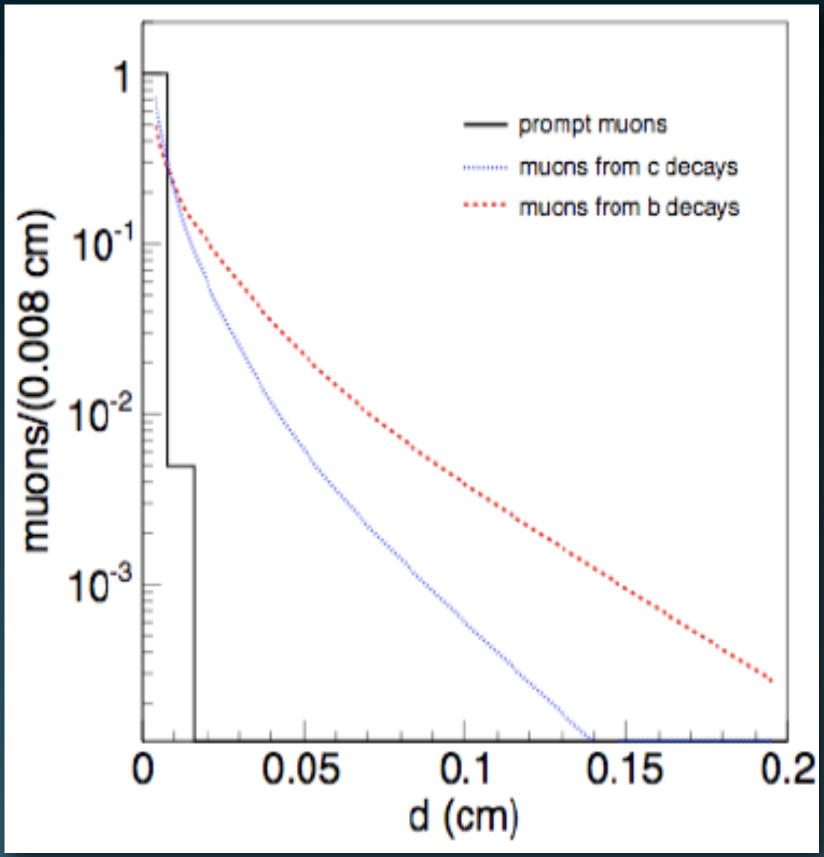
all dimuon	743006
tight SVX	143743
QCD	589000±5000
ghost	154000±5000
bb	222000±12000

QCD = [tight SVX] / 0.244

ghost sample ~ bb sample!

Ghost Impact Parameter





Ghost muons have long impact parameter tail; QCD predicts none (note horiz. scale!)

SM Sources of Ghosts

- **$K^{\pm}$, $\pi^{\pm}$ decays in flight**
- **secondary nuclear interactions**
- **K^0_s, Λ decays**

μ: from punch-through

After many months of study CDF concludes

- about half of the 153k ghost sample is explained by these sources

- only 10% of the high-impact parameter tail (>0.5 cm) is accounted for

Properties of Ghosts

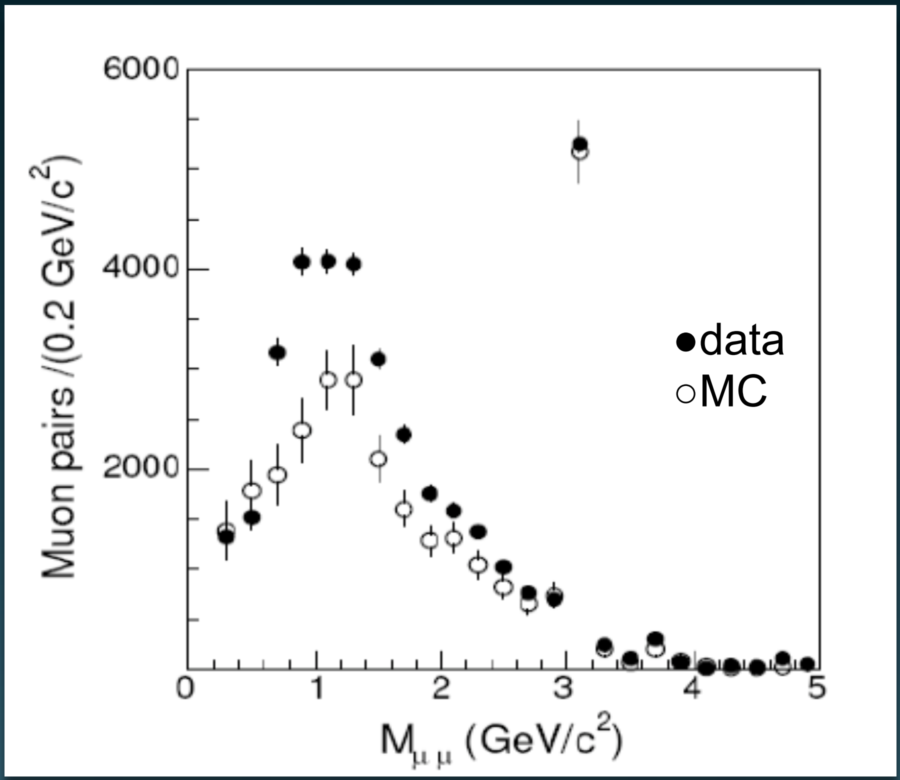
- search for additional muons accompanying the initial pair, with no SVX requirements
- in QCD mix, expect only about 1% of the events to contain additional (mainly fake) muons
- data: we observe that 9.7% of the dimuon sample events have an additional muon

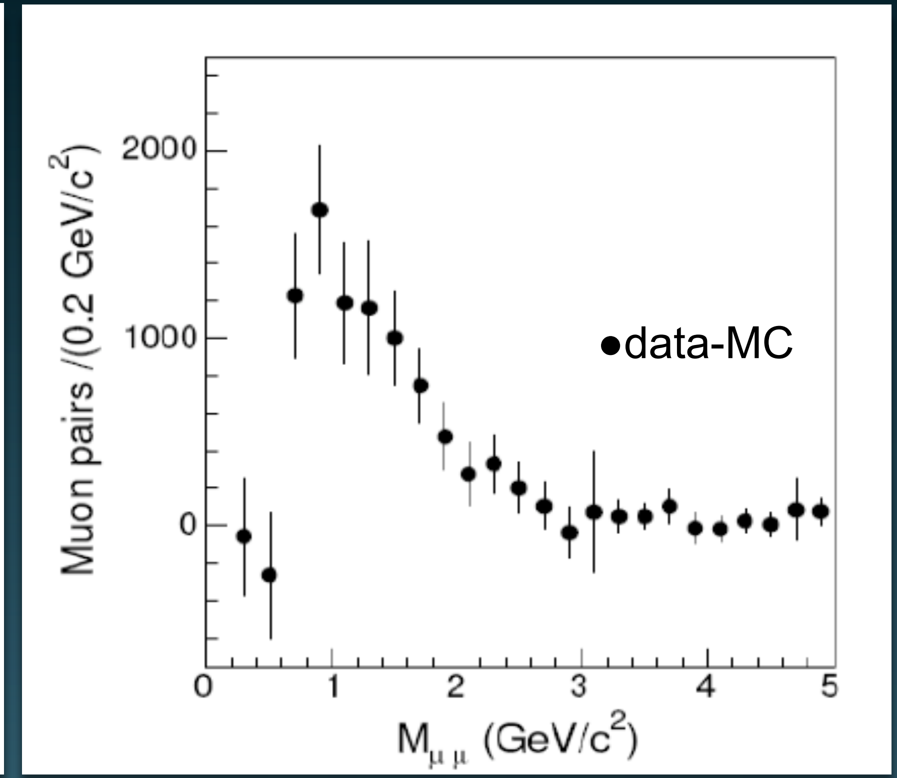
⇒ excess is 8451±1274 events

- next investigate SS/OS nature of additional muons

NB: at this point we go from 743 pb^{-1} to 1426 pb^{-1}

OS-SS in Additional Muons

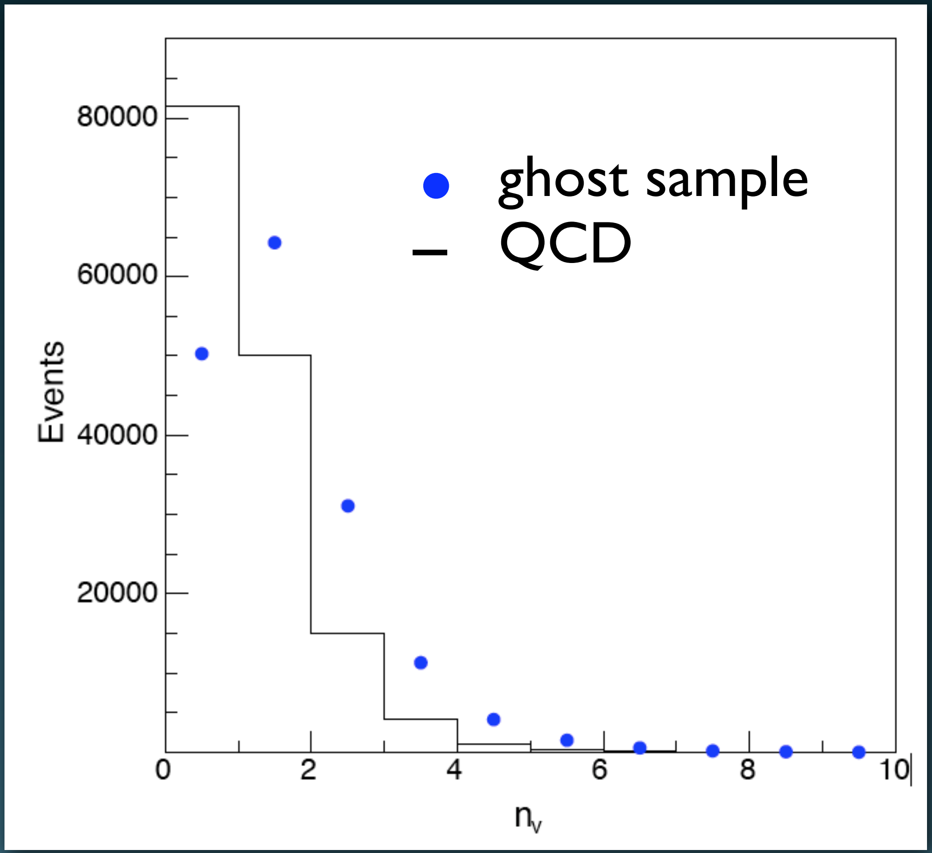




Fakes do not favor OS or SS: therefore the OS-SS excess indicates a real contribution, coming in with low invariant mass when paired with the initial muon

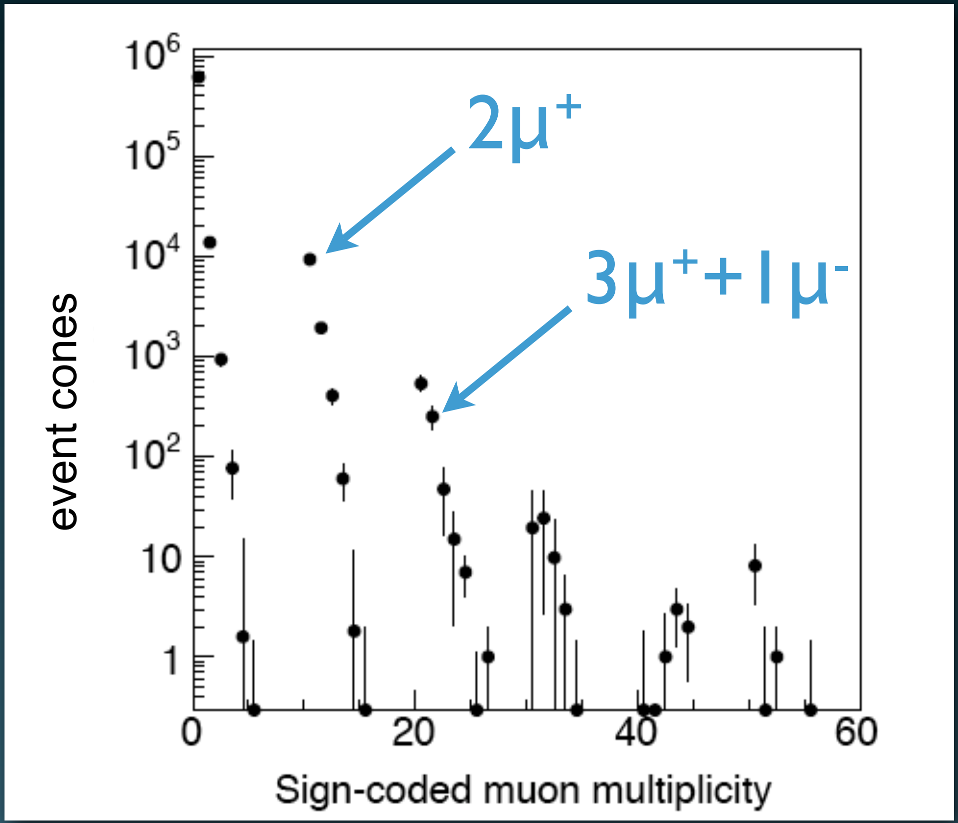
Secondary Vertices in Ghosts

- fit all opposite sign track pair vertices
    - p_T > 0.5 GeV
    - $|\eta|<1.1$
- demand $\chi^2<10$
- we find that there are many more secondary vertices in ghost events



Muons, muons, muons!

- now we look at all additional muons in a 36.8º cone around each initial muon in dimuon event
- make a strange “sign coded” multiplicity plot to keep track of SS and OS additional muons in cone



multiplicity increases by

- 10 for each SS μ
- 1 for each OS μ

Cone-cone Correlations

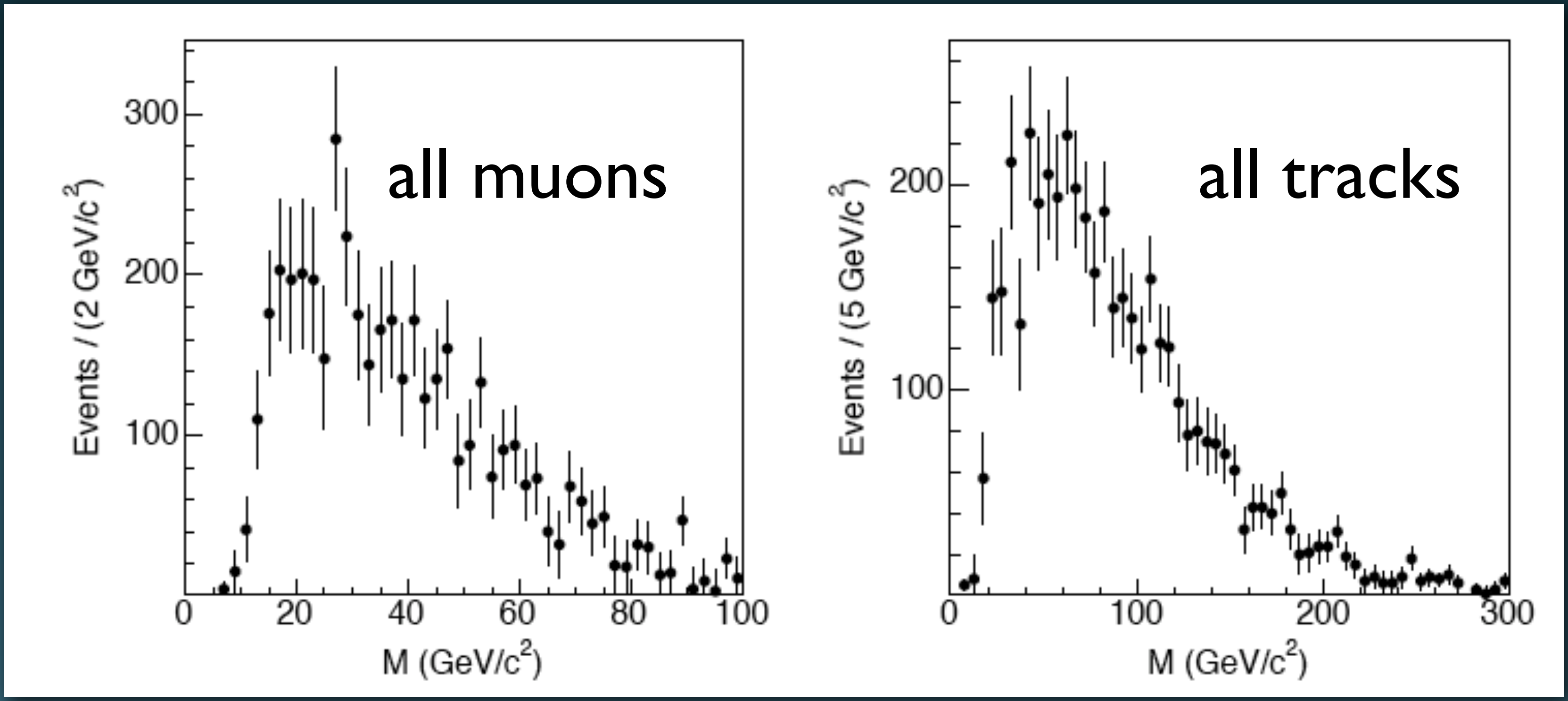
If we have multiple muons in one cone, how likely is it that there are multiple muons in the other?

cones with ≥ 2 μ	27790±761
cones with ≥ 3 μ	4133±263
events where both cones have ≥ 2 μ	3016

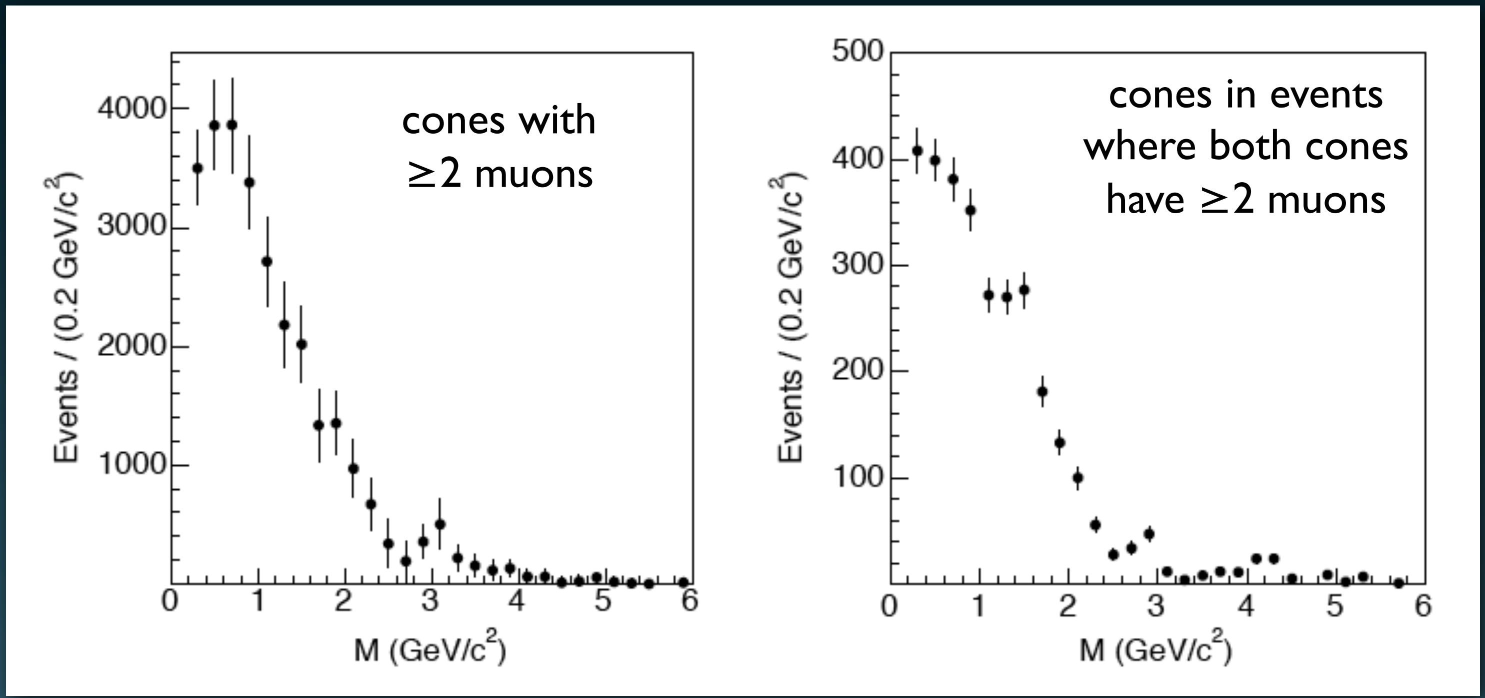
⇒ 13% of events with one multi-muon cone have another

Cone-cone Correlations

- look at invariant mass in events with two or more multi-muon cones:



Muon Mass in Multimuon Cones



- look at mass of all muons in multimuon cones
- no evidence of narrow resonance as the major source

CDF’s Conclusions So Far

- Now understand source of dimuon/ secondary vertex discrepancy in $\sigma(bb)$
- Large “ghost” background in dimuon sample:
  - large portion unexplained by K/π decay in flight, hyperons (esp. at large d_0)
  - large impact parameter tail
  - high track multiplicity - 2x n_{trk}(QCD)
  - multiple muons
  - multiple cones with multiple muons

CDF’s Conclusions So Far

- track quality of ghost muons is good
- muon cuts are loose: high efficiency, but high fake rate
- at a minimum, these results explain a number of discrepancies observed over the past decade!
- continuing to investigate!

**From this point on,
the opinions presented
are my own or others',
not necessarily CDF's**

If it's new physics, then...

- the production cross section is large, at least 10's of pb depending on the model for how you get muons
- to account for the large impact parameter distribution, need a long lived particle: $\tau \sim 20$ ps
- the "muons" just <u>might</u> be some other strange long-lived charged particle
- any interpretation will make predictions for other new phenomena or characteristics for which to look

LOTS of Questions

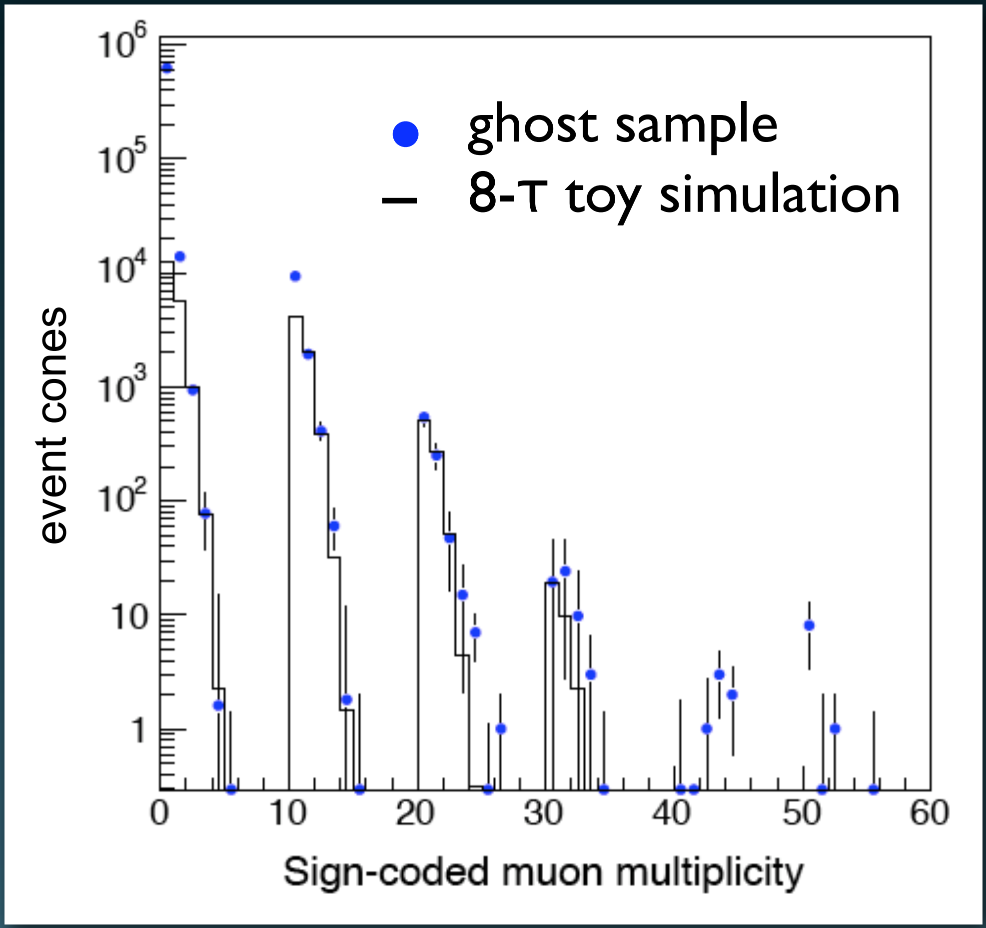
- Do ghost events show large MET?
- Does D0 (or LEP) see this effect?
- Are the ghosts from low-mass $\mu^+\mu^-$ pairs emanating from secondary vertices?
- Would be nice to see cone-cone multiplicity correlation distribution...
- Do we see an excess of electrons too?

Giromini et al. Interpretation

- arXiv:0810.5730
- conjecture: there are three states
    - h_1: ~15 GeV
    - h_2: ~ 7 GeV
    - h_3: ~ 4 GeV
- $h_1 \rightarrow 2h_2$, $h_2 \rightarrow 2h_3$, $h_3 \rightarrow \tau\tau$
- lifetime of h_3 ~ 20 ps
- one gets "jets" of 8 τ leptons!

Giromini et al. Interpretation

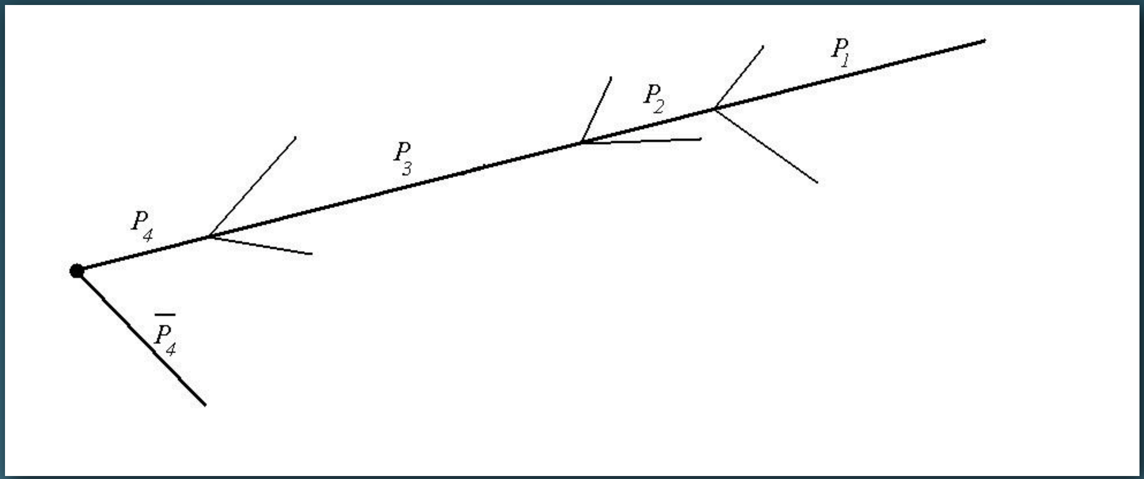
- toy simulation: $H \to h_1 h_1$, with decay chain as on previous page
- qualitatively agrees with sign coded multiplicity
- key will be to see the effect in electrons



see Domingo, Ellwanger: arXiv:0812.1167

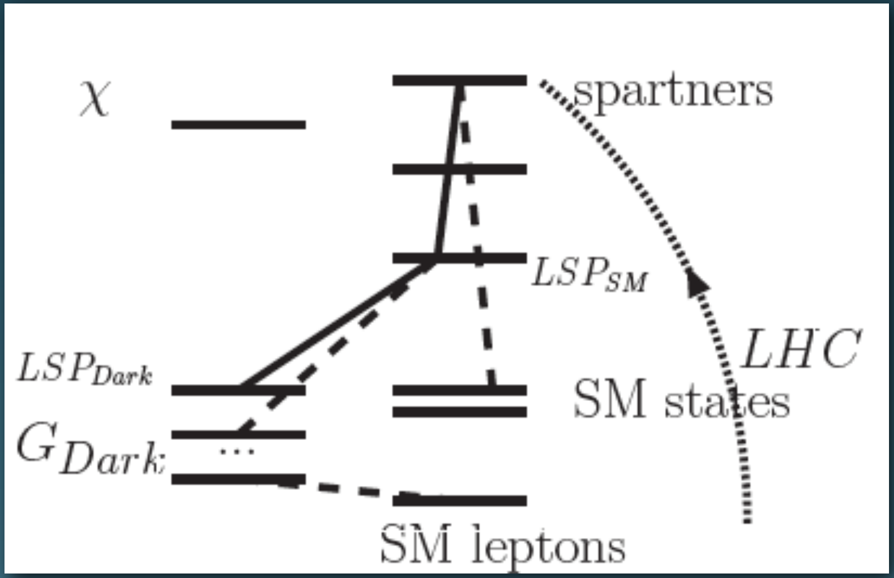
Tau Cascades?

- M. Strassler points out (arXiv:0811.1560) that absence of $\mu^+\mu^-$ resonances disfavors any Higgs-like $h \to \mu\mu$
- more plausible: "micro-cascades" of closely-spaced heavy particles P_i to leptons



Dark SUSY?

- Arkani-Hamed and Weiner (arXiv:0810.0714) postulate that WIMP dark matter is charged under a new gauge group G_{dark}, broken at the ~GeV scale
- account for INTEGRAL/DAMA/PAMELA/ATIC results
- predict collimated "lepton jets" at the LHC !



Summary

- The Tevatron may still have some suprises in store!
- Long-standing mystery regarding the bb cross section: solved!
- Large unexpected background found with
  - multiple muons,
  - produced far from the primary vertex,
  - often on both sides of the event
- In Giromini’s words, we have “an interesting lack of inderstanding”