Analysis of a Multi-Muon Signal at Collider and Fixed-Target Experiments

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SUSY10

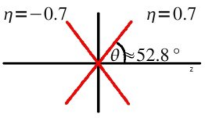
- Study of multi-muon events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$; T. Aaltonen *et al.*, arXiv:0810.5357v2 [hep-ex]
- Measurement recorded by CDFII detector
- Data set acquired with a dedicated dimuon trigger
  $\rightarrow$ Integrated luminosity up to $2100\,\mathrm{pb}^{-1}$

- Claim: Significant sample of events cannot be explained by the known QCD production (with the current understanding of the detector)

Selection criteria for the data set:

- At least two CMUP muons
- Initial muons fulfill: $p_T \geq 3\,\mathrm{GeV/c}$
  $|\eta| \leq 0.7$ $\quad 5\,\mathrm{GeV/c^2} < m_{\mu\mu} \leq 80\,\mathrm{GeV/c^2}$

- Initial muons: The two CMUP muons with the highest transverse momentum p_T
- Integrated luminosity of $742\,\mathrm{pb}^{-1}$ $\rightarrow$ 743006 events pass these cuts



Pseudorapidity:

$$\eta = -\ln\tan\frac{\theta}{2}$$

- Tight SVX selection: Initial muons are created within the beam pipe (radius of $15\,\mathrm{mm}$)

- Measured efficiency for the tight SVX: 0.1930 ± 0.0004
- If all 743006 events result from the known QCD production $\rightarrow$ Expected efficiency for the tight SVX: 0.244 ± 0.002

$$743006 - \frac{143743}{0.244} = 743006 - 589111 = 153895$$

Type	Total	Tight SVX
All	743006	143743
QCD	589111 ± 4829	143743
Ghost	153895 ± 4829	0

- 69000 ghost events result from ordinary sources, e.g. muon decays of particles with a lifetime longer than that of heavy flavors (K and π mesons) $\rightarrow$ In-flight-decays
  $\rightarrow$ Corrected ghost events: 153895–69000 = 84895

- There is a significant number of additional real muons within the ghost compared to QCD events
- Cuts on additional muons: $p_T \geq 2\,\mathrm{GeV/c} \quad |\eta| \leq 1.1$

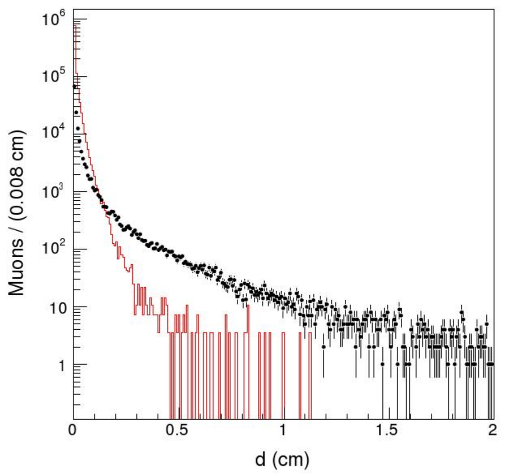
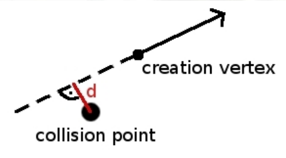


Figure 7 from arXiv:0810.5357v2 [hep-ex]

- Impact parameter distribution of initial muons (including fake ones) in ghost (black) and QCD events (red)



- Sign-coded multiplicity distribution of additional muons found in 36.8°-cones around the direction of initial muons
- An additional muon with opposite (same) sign charge increases multiplicity by 1 (10)
- Integrated luminosity of $2100\,\mathrm{pb}^{-1}$

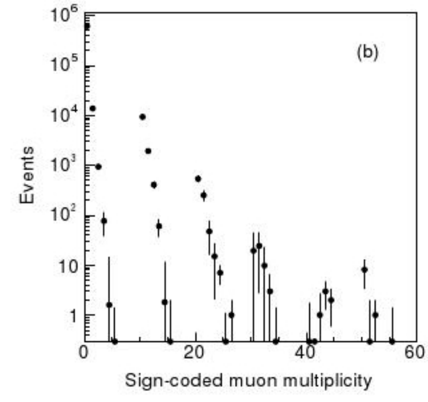


Figure 22b from arXiv:0810.5357v2 [hep-ex]

- There are 84895 ± 4829 ghost events with an integrated luminosity of $742\,\mathrm{pb}^{-1}$:

$$\sigma^{CDFII}_{p\bar{p}\to ghosts} = \frac{84895 \pm 4829}{742}\,\mathrm{pb} \approx (114.41 \pm 6.51)\,\mathrm{pb}$$

- Comparable with:

$$\sigma^{CDFII}_{p\bar{p}\to b\bar{b}\to \mu\mu} = \frac{221564 \pm 11615}{742}\,\mathrm{pb} \approx (298.60 \pm 15.65)\,\mathrm{pb}$$

$\rightarrow$ Can we find ghost events in other experiments?

- Simulation with Herwig++ 2.3.2

- Simulation of the ghost events in a simple model with the following process: $gg/q\bar{q} \to XX$
- Differential cross section:

$$\frac{d\sigma^{Simu}_{gg/q\bar{q}\to XX}}{d\cos\theta} = \frac{N_{gg/q\bar{q}}}{\hat{s}} \cdot \beta = \frac{N_{gg/q\bar{q}}}{\hat{s}} \cdot \sqrt{1 - \frac{4m_X^2}{\hat{s}}}$$

$N_{gg/q\bar{q}}$: Constant

$\sqrt{\hat{s}}$: Partonic center of mass energy

m_X: Mass of the X-particle

X-particle:

- Neutral electric charge
- Average decay length $\gamma\tau_X v \geq 15\,\mathrm{mm}$
- Decay in four elementary particles (at least one muon)
- Majorana particle (it is its own antiparticle)

Free parameters: Decay modes, branching ratios, $c\tau_X$ and m_X

- Set lifetime of the X-particle: $c\tau_X = 20\,\mathrm{mm}$
- It influences the impact parameter distribution, but no other distributions!

Decay modes of the X-particle:

- 1-muon: $X \to \mu^- \bar{\nu}_\mu u \bar{d}$ or $X \to \mu^+ \nu_\mu \bar{u} d$
- 2-muon: $X \to \mu^- \mu^+ u \bar{u}$ or $X \to \mu^- \mu^+ d \bar{d}$
- 4-muon: $X \to \mu^- \mu^+ \mu^- \mu^+$

Compare the simulation with the measurement:

- Set mass: $m_X = 1.8\,\mathrm{GeV/c^2}$
- Set branching ratios, e.g. for $q\bar{q} \to XX$: $w_1 = 0.9388$ $w_2 = 0.0502$ $w_4 = 0.0110$

- Investigation of experiments with a muon detector with sufficient coverage and a data set with high integrated luminosity
- UA1, ZEUS, H1, E605, E772, E789 and E866

- E789 has a vertex detector!
- Data set with integrated luminosity of $(17.52 \pm 1.89)\,\mathrm{pb}^{-1}$; D. M. Jansen *et al.*, PRL **74**, 3118 (1995)
- Opposite sign (OS) charged dimuons fulfill:
  $2\,\mathrm{GeV/c^2} \leq m_{\mu\mu} \leq 6\,\mathrm{GeV/c^2} \quad 3.506 \leq \eta \leq 4.605$
- Number of expected OS ghost events for the simple model with $q\bar{q} \to XX$ is appox. 647.5 ± 79.4

Change decay modes for a better reproduction of Fig. 22b:

- 1-muon: $X \to \mu^- \bar{\nu}_\mu u \bar{d}$ or $X \to \mu^+ \nu_\mu \bar{u} d$
- OS 2-muon: $X \to \mu^- \mu^+ \tau^- \tau^+$
- SS 2-muon: $X \to \mu^- \mu^- \tau^+ \tau^+$ or $X \to \mu^+ \mu^+ \tau^- \tau^-$
- 4-muon: $X \to \mu^- \mu^+ \mu^- \mu^+$

$\rightarrow$ New X-particle mass $m_X = 4.6\,\mathrm{GeV/c^2}$

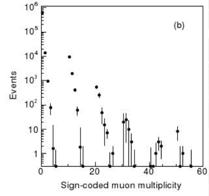
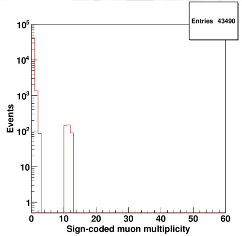
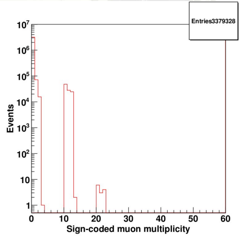


Figure 22b from arXiv:0810.5357v2

[hep-ex]



Simple Model



Breit-Wigner with Tau Decay

- Invariant mass distribution of all muons within events, in which both cones contain each at least one additional muon

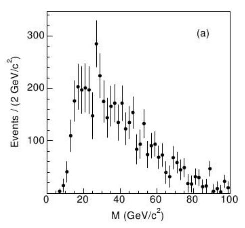
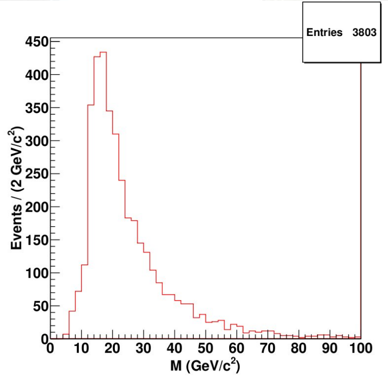


Figure 35a from arXiv:0810.5357v2 [hep-ex]

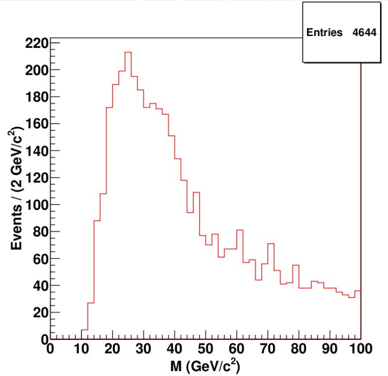
- Add a Breit-Wigner factor to the differential cross section to achieve a better reproduction:

$$\frac{d\sigma^{Simu}_{gg/q\bar{q}\to Y\to XX}}{d\cos\theta} = \frac{N^{BW}_{gg/q\bar{q}}}{\hat{s}} \cdot \frac{\hat{s}^2}{(\hat{s}-m_Y^2)^2+\Gamma_Y^2 m_Y^2} \cdot \sqrt{1-\frac{4m_X^2}{\hat{s}}}$$

m_Y: Mass of BW resonance Γ_Y: Width of BW resonance



Simple Model (Only 2-muon Decay)



Breit-Wigner with Tau Decay

- For $q\bar{q} \to Y \to XX$: $m_Y = 110\,\mathrm{GeV/c^2} \quad \Gamma_Y = 110\,\mathrm{GeV/c^2}$

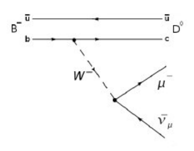
- Can reproduce the bulk of data with a simple model $\rightarrow$ Need a more complicated model to reproduce all events
- Expect measurable number of ghost events at fixed target experiments for the simple model $\rightarrow$ None for Breit-Wigner with tau decay model

- D0 did not see any ghosts; Mark Williams, for the D0 Collaboration, arXiv:0906.2969v1 [hep-ex]!
- Results of fixed target experiments can be explained by the Standard Model?!
- Can test the Breit-Wigner with tau decay model with fictitious fixed-target experiment with $\sqrt{s} = 38.8\,\mathrm{GeV}$ and an integrated luminosity of $10^5\,\mathrm{Nucl./pb}$ $\rightarrow$ For initial muons with lab energy $E_\mu \geq 5\,\mathrm{GeV}$ expect 3276.0 ± 190.4 ghosts

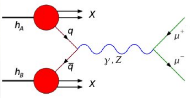
Thank you for your attention!

QCD production (dominant sources for initial muons):

- Semileptonic decays of bottom and charmed hadrons
- Prompt decays of quarkonia
- Drell-Yan production
- (Fake) muons mimicked by prompt hadrons or hadrons arising from heavy flavor decays



wikipedia.org; modified



wikipedia.org; modified

Ordinary sources for ghost events:

- Semileptonic decays of hadrons with an unexpectedly large Lorentz boost
- Muon decays of particles with a lifetime longer than that of heavy flavors (K and π mesons) $\rightarrow$ In-flight-decays
- Fake muons from decays of K_S^0 mesons and hyperons
- Secondary interactions of prompt (hadronic) tracks that occur in the detector volume

- Hyperon: Baryon containing one or more strange quark, but no charm or bottom quarks

What is the mass of the X-particle?

- Use the invariant mass distribution of all muons contained in the 27990 36.8°-cones with at least one additional muon
- Compare with simulated distributions for pure 2- and 4-muon decay for different masses for the simple model $\rightarrow m_X = 1.8\,\mathrm{GeV}/\mathrm{c}^2$

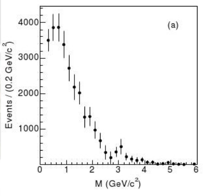
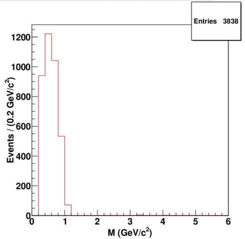
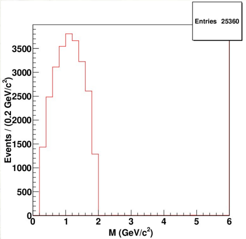


Figure 34a from arXiv:0810.5357v2 [hep-ex]



2-muon Decay



4-muon Decay

What are the branching ratios for the decay modes of the X-particle?

- Use sign-coded multiplicity distribution of additional muons found in 36.8°-cones around the direction of initial muons

- Cones with zero, one, two and three additional muons:

$$\begin{aligned} One/Zero: &\quad \frac{23192}{620307} \approx 0.0374 \\ Two/Zero: &\quad \frac{3421}{620307} \approx 0.0055 \\ Three/Zero: &\quad \frac{756}{620307} \approx 0.0012 \end{aligned}$$

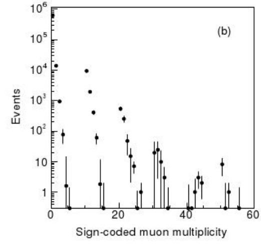


Figure 22b from arXiv:0810.5357v2 [hep-ex]

$\rightarrow$ Branching ratios for the simple model with $q\bar{q} \rightarrow XX$:
$w_1 = 0.9388 \quad w_2 = 0.0502 \quad w_4 = 0.0110$