

A Search for Excess Dimuon Production in the Radial Region ($1.6 < r \lesssim 10$) cm at the DØ Experiment

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On behalf of the DØ Collaboration

*(with special thanks to primary author Mark Williams
for assistance with the preparation of these slides)*

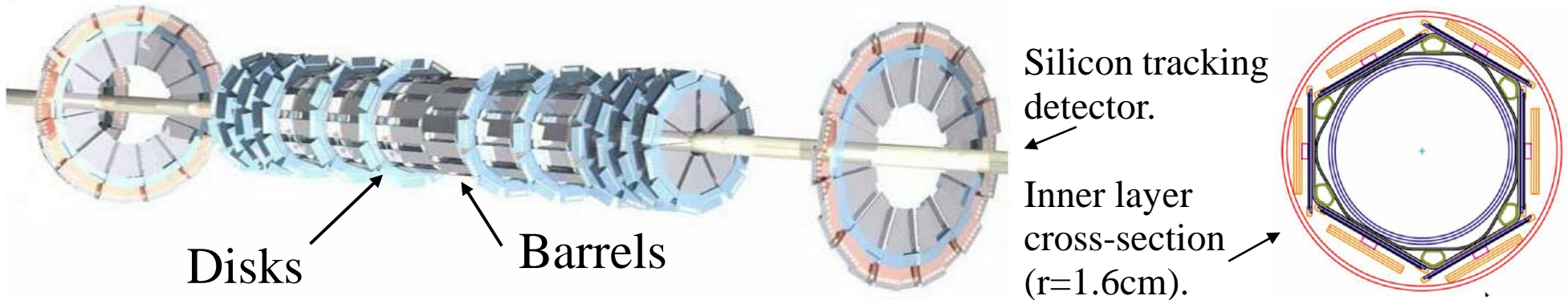
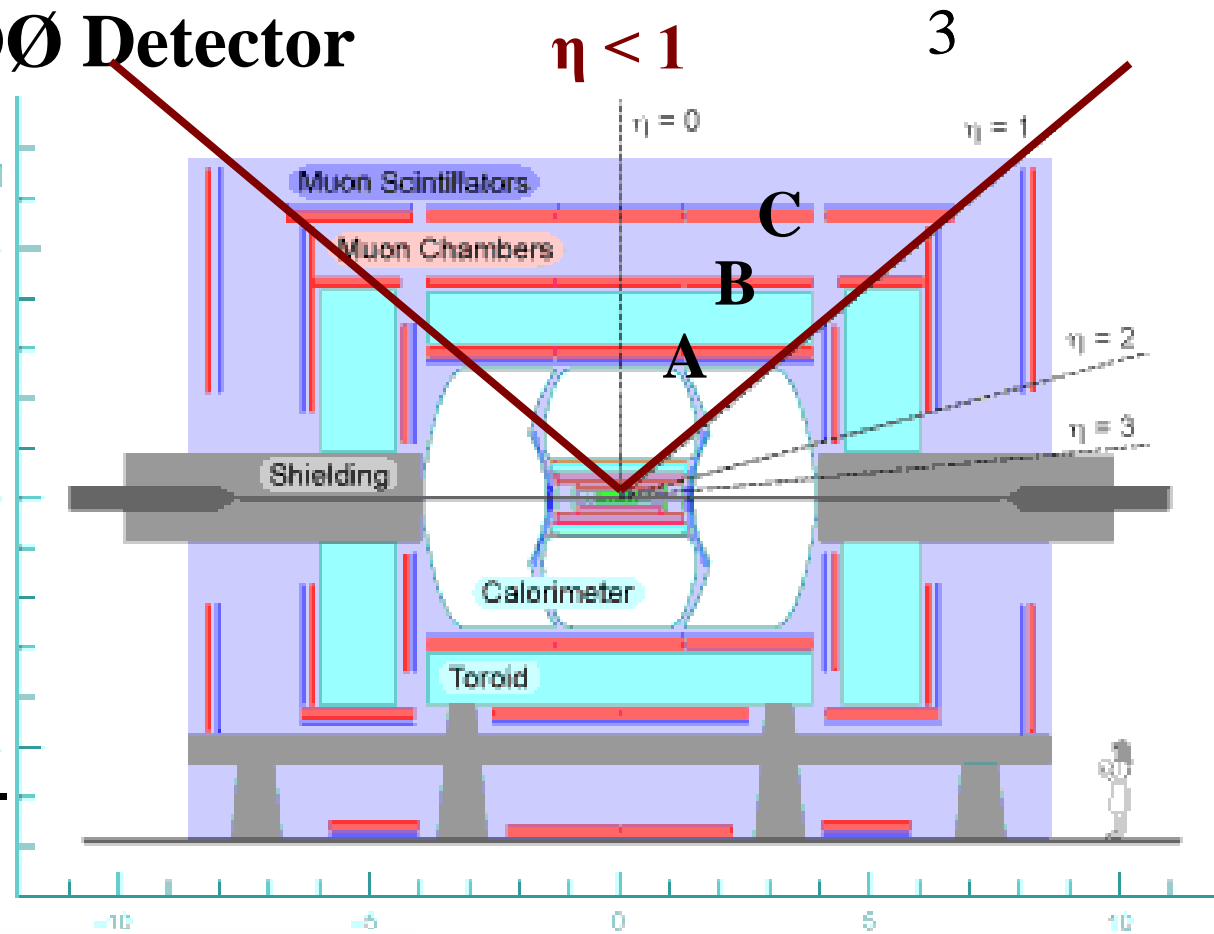


- I will report the findings of a $D\bar{D}$ analysis, motivated by the recent release of the CDF multimMuon result (arXiv:0810.5357 [hep-ex]).
- The current $D\bar{D}$ study is limited to searching for dimuon events in which one or both muons are produced at large radial distances ($1.6 \text{ cm} < r \lesssim 10 \text{ cm}$) from the primary interaction.
- Overview:
 - 1) A sample of dimuons is selected to approximately match the sample used by CDF in their analysis. These are termed '**loose**' events.
 - 2) Information from the inner-layer silicon detector is used to isolate a sub-sample of these events where both muons are produced within $r < 1.6 \text{ cm}$. These are termed '**tight**' events.
 - 3) By measuring the efficiency of the inner-layer detector, the number of expected loose events is determined, assuming that no muons are produced beyond 1.6 cm.
 - 4) The excess is measured as the difference between the observed and expected number of dimuon events.



The DØ Detector

- Inner tracking (silicon sensors + scintillation fibers) with **small decay volume** ($r < 50\text{cm}$);
- LAr/Uranium calorimeter.
- Muon tracking detector: multiple planes A-C of drift chambers on either side of 1.8T toroid magnet. Total **thickness of 14λ** (at layer C) **strongly suppresses punch-through** particles.
- Scintillation counters on either side of toroid provides **rejection of cosmic-ray muons**.



Event Selection: Primary Muons

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- A dataset corresponding to $\sim 1\text{fb}^{-1}$ of Tevatron integrated luminosity is used, with most events triggering on single or dimuon triggers.
- Dimuon events are selected provided that they satisfy the following criteria:

Requirement	CDF	D0
pT(μ)	$\geq 3 \text{ GeV}/c$	$\geq 3 \text{ GeV}/c$
η	< 0.54	< 1.0
Δz_0	$< 1.5\text{cm}$	$< 1.5\text{cm}$
Cosmic veto	$ \Delta\phi < 3.135 \text{ rad}$	$ \Delta\phi < 3.135 \text{ rad}$
Timing	N/A	$ t(A) < 10\text{ns}$ AND $ t(C) < 10\text{ns}$
M($\mu\mu$)	$5 < M(\mu\mu) < 80 \text{ GeV}/c^2$	$5 < M(\mu\mu) < 80 \text{ GeV}/c^2$

z-distance between muons at point-of-origin

Remove muons which are back-to-back in ϕ

- If more than two muons in an event satisfy these requirements, the two with largest transverse momentum (p_T) are selected.



Loose and Tight Muons

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CDF

Silicon Tracking: 5 double-sided layers
+ single-sided inner layer
1.5cm \rightarrow 10.6cm
+ additional layer (23cm)

'Loose' definition: Hits in ≥ 3 silicon layers
out of 7 available.

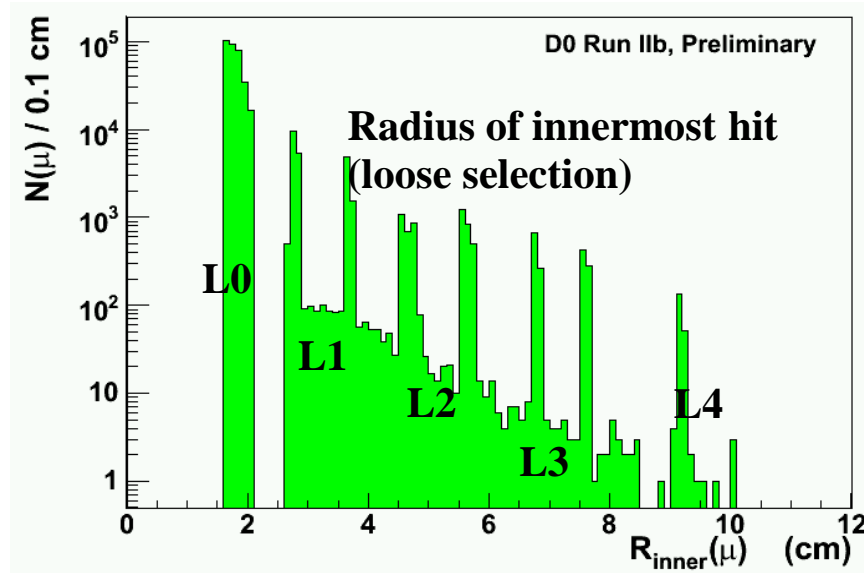
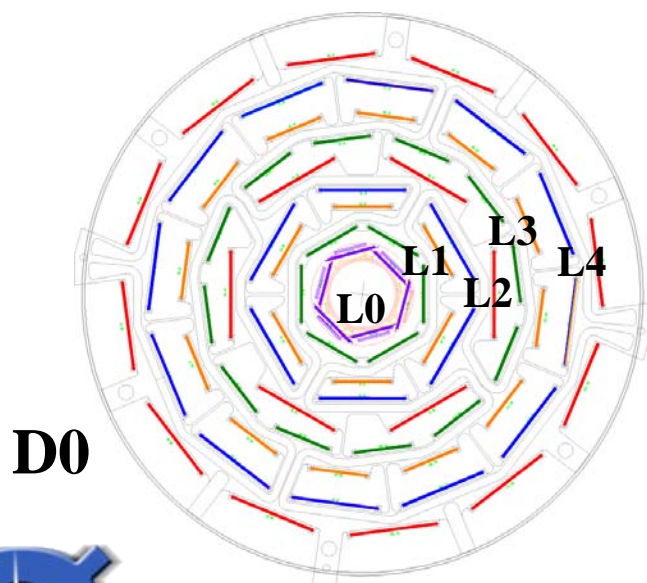
'Tight' definition: Hits in two innermost silicon layers
& ≥ 2 other silicon hits

DØ

4 double-sided layers (L1-L4)
+ single-sided inner layer (L0)
1.6cm \rightarrow 10.5cm
+ disks in transverse plane.

≥ 3 silicon hits

Hit in L0
& ≥ 2 other silicon hits



Event Counting Method

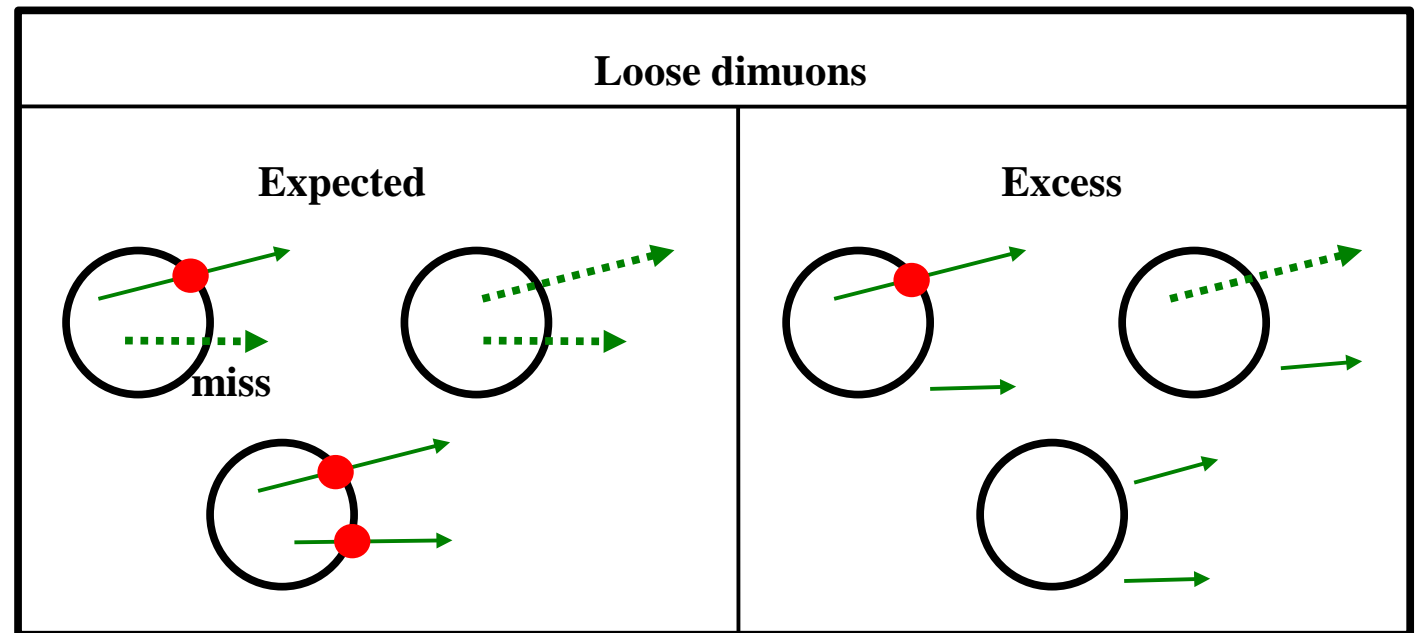
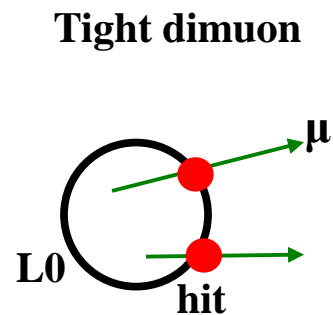
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- A loose (tight) event must contain two loose (tight) muons. An event-by-event efficiency weighted count is used:

- $N(\text{excess}) = N^{\text{obs.}}(\text{loose}) - N^{\text{exp.}}(\text{loose})$

- $N^{\text{exp.}}(\text{loose}) = \sum_i \left(\frac{1}{\epsilon_{T/L}^i(\mu_1) * \epsilon_{T/L}^i(\mu_2)} \right)$ is the number of expected loose events;

where the sum is over all tight events. $\epsilon_{T/L}^i(\mu)$ is the relative tight/loose selection efficiency for a single muon, determined as a function of the muon parameters.



Measuring Tight/Loose Efficiency: $J/\psi \rightarrow \mu\mu$ Sample 7

The single muon efficiency $\varepsilon_{T/L}(\mu)$ is determined using muons from J/ψ decays, using the same data sample used for the signal selection:

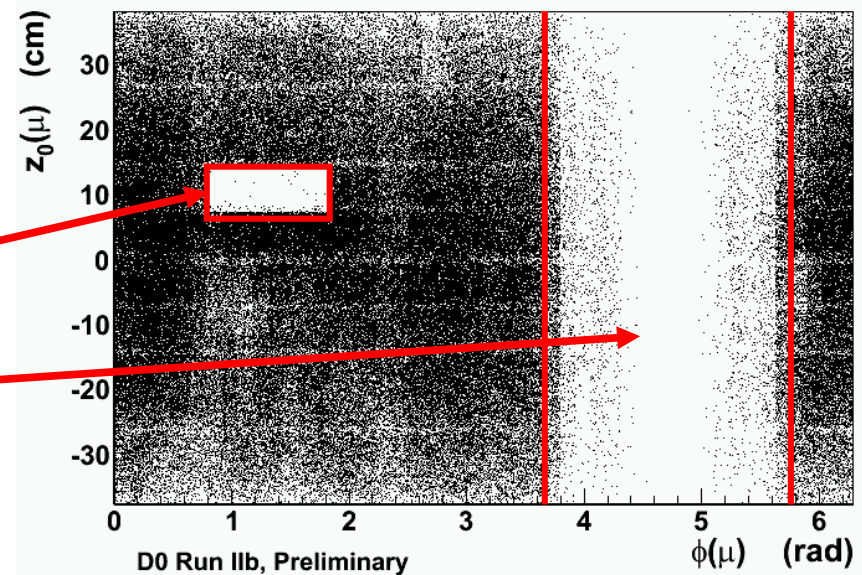
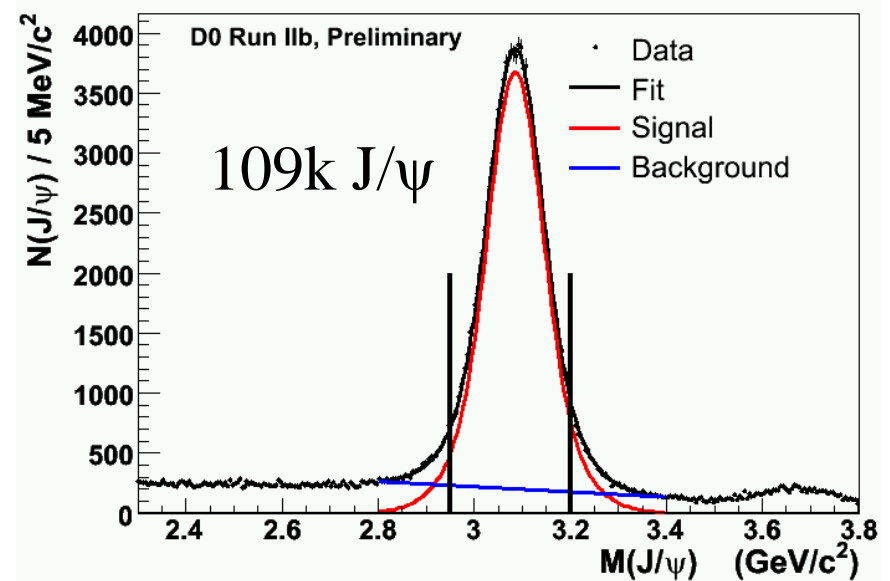
Same selection criteria as signal dimuons, except:

- $2.95 < M(\mu\mu) < 3.2 \text{ GeV}/c^2$
- Opposite charge muons;
- Muons must come from a common vertex;
- $|L_{xy}| < 1.6 \text{ cm}$ (99.9% of events)

(z, ϕ) scatter plot for tight muons in J/ψ test sample.

Events are excluded if either muon lies in the highlighted regions:

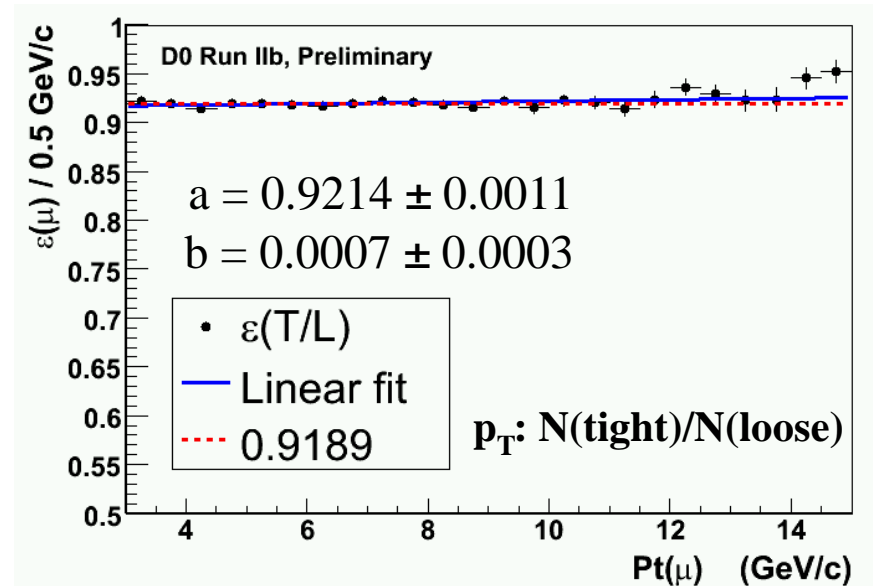
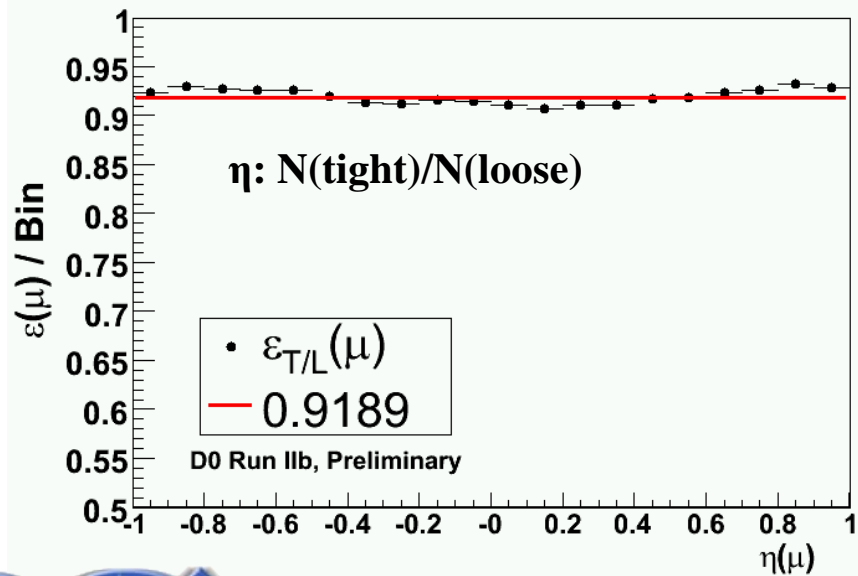
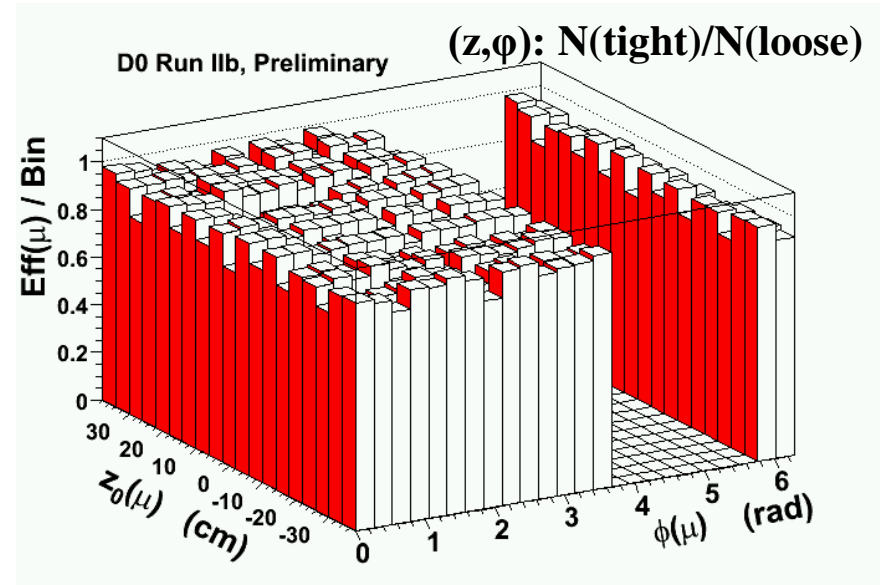
- The single inactive L0 sensor
- The bottom of the detector, where acceptance is limited by muon system coverage.



Efficiency: $\epsilon_{T/L}(\mu) = \epsilon[z(\mu), \phi(\mu)] \times F[\eta(\mu)] \times F[p_T(\mu)]$

- $\epsilon[z(\mu), \phi(\mu)]$ taken directly from 2D (z, ϕ) efficiency histogram (result of divide histograms for tight and loose muons) on a bin-by-bin basis. Here (z, ϕ) are calculated at the point of intersection with the L0 detector sensor.
- $F[\eta(\mu)]$ extracted similarly from η histogram, normalised to unity.
- p_T dependence parameterized with a linear function:

$$F[p_T(\mu)] = [a + b \cdot (p_T - 9)] / a \quad (p_T \text{ in GeV/c})$$



Using the signal dimuon sample, the event counting procedure yields the following:

$$\begin{aligned} N^{\text{obs.}}(\text{loose}) &= \mathbf{177,535} \\ N^{\text{obs.}}(\text{tight}) &= \mathbf{149,161} \end{aligned} \quad \longrightarrow \quad \mathbf{N(T)/N(L) = 0.8402 \pm 0.0009}$$

Compare $(0.9189)^2 = 0.8443 \pm 0.0011$ for the efficiency measured with the J/ψ test sample.

Using the full (z, ϕ, η, p_T) parameterization of the single muon efficiency, the expected number of loose events is:

$$N^{\text{exp.}}(\text{loose}) = \mathbf{176,823 \pm 504 \text{ (stat.)}}$$

i.e. there are 712 ± 462 (stat.) events unaccounted for in the loose sample. Repeating for OS/SS combinations separately:

N(excess)	= 712 ± 462 (stat.) ± 942 (syst)	(Total)	[0.40 ± 0.26 ± 0.53]% expressed as a fraction of $N^{\text{obs.}}(\text{loose})$
	= 2 ± 359 (stat.) ± 705 (syst)	(OS only)	
	= 710 ± 138 (stat.) ± 229 (syst)	(SS only)	

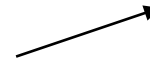
This is consistent with expectations from known sources of radially-displaced muons (punch-through, cosmic rays, decays-in-flight), which are all expected to be small, and give a total contribution of around one percent.



Statistical uncertainties are determined using ensemble tests, with the constituent efficiencies allowed to vary according to their Gaussian distributions, and the count repeated 100 times $\rightarrow \pm 0.26\%$.

Systematic uncertainties are determined by repeating the counting procedure with different binning schemes for z , ϕ , and η , and with the p_T factor completely removed from the efficiency $\rightarrow \pm 0.53\%$.

Source	$\delta[\%(\text{excess})]$
Rebin ϕ	$\pm 0.14\%$
Rebin z	$\pm 0.18\%$
Rebin η	$\pm 0.01\%$
$\mathcal{F}(p_T^\mu)$ Removed	$\pm 0.48\%$
Total	$\pm 0.53\%$



Various **cross-checks** are also made:

- The count is repeated using only those events which fire a single dedicated dimuon trigger, to check for possible trigger bias (70% of signal events, 62% of J/ψ events)
- The count is repeated with the sample divided into two time periods.
- The count is repeated for different sub-ranges of η and $M(\mu\mu)$.

In all cases the results are unchanged within statistical uncertainties.

We measure the number of J/ψ events in the signal sample, when the lower-mass window is removed, to provide a **point-of-normalisation**:

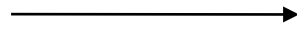
$$N(J/\psi) = 165,489 \pm 989$$

$$\text{Therefore } N(\text{excess}) / N(J/\psi) = (0.43 \pm 0.28 \pm 0.57)\%$$

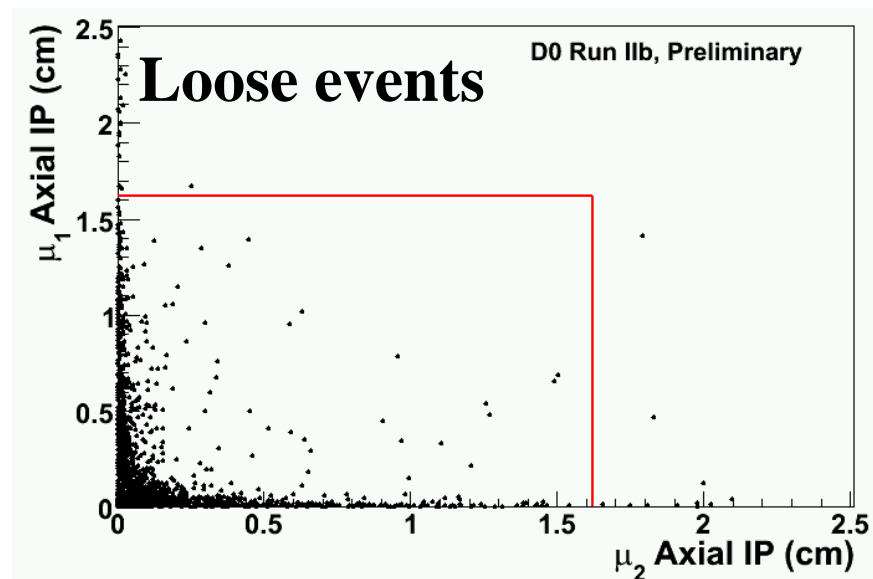
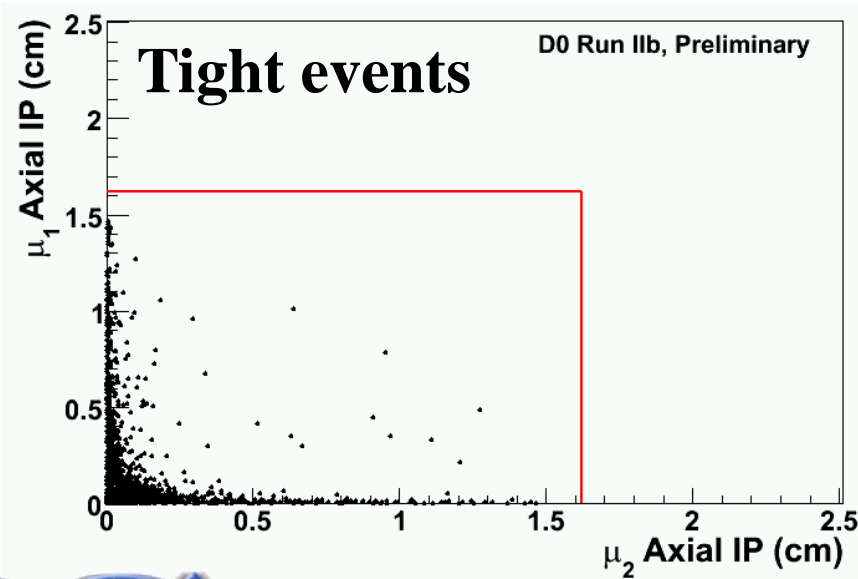
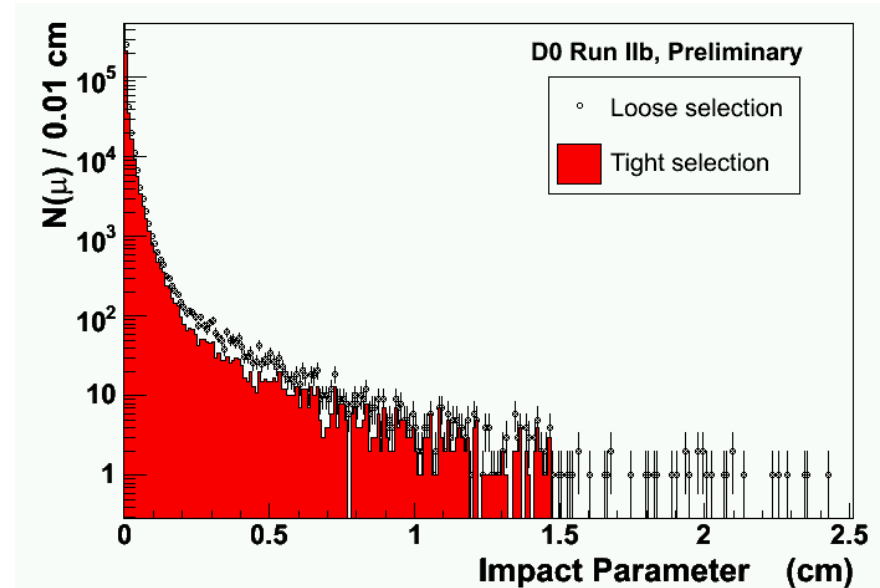
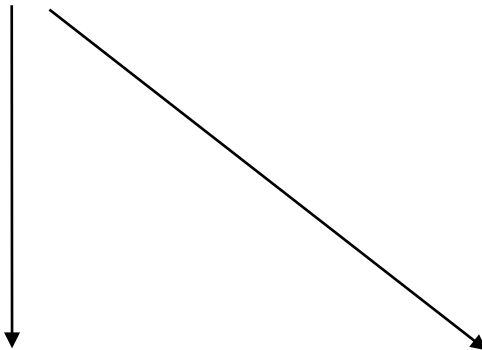


Impact Parameter Distributions

Tight/Loose distributions



Two-dimensional IP scatter plots:



2D IP Distributions



- From a sample corresponding to $\sim 1\text{fb}^{-1}$ of integrated luminosity, and an event selection scheme close to that used by CDF in their equivalent analysis, the number of dimuon events in which one or both muons are produced in the radial region $1.6 < r \lesssim 10$ cm is observed to be:

$$712 \pm 462 \text{ (stat.)} \pm 942 \text{ (syst)}$$

- This is expressed as a fraction of the total number of events in the sample:

$$N(\text{excess})/N(\text{loose}) = (0.40 \pm 0.26 \pm 0.53)\%$$

The fractional excess observed is significantly smaller than the figure reported by CDF (12%).

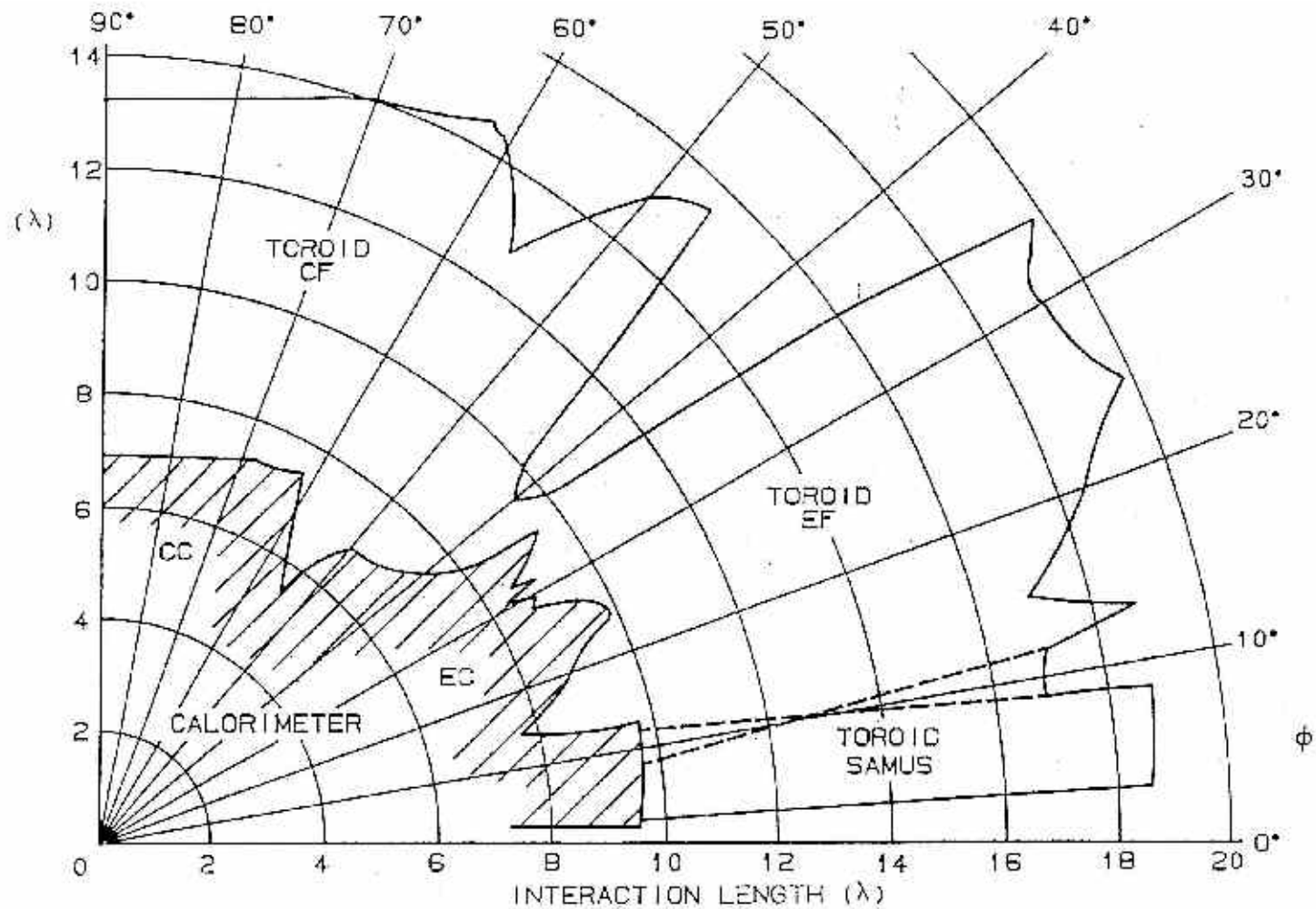
- Note that contributions from standard sources of displaced muon production (decays-in-flight, cosmic muons, hadronic punchthrough) have not been subtracted, so this represents an upper limit.



Additional Slides



Total Interaction Thickness of Muon System



TOTAL INTERACTION LENGTHS OF THE CALORIMETER AND MUON SYSTEM



Ensemble tests are used to estimate the statistical uncertainty of the Efficiency measurement, in which the constituent Efficiency factors (i.e. per-bin efficiencies for the (z,ϕ) and η factors, and the constants a and b in the p_T parameterization) are allowed to vary randomly according to the appropriate Gaussian distribution:

$N(\text{excess})$:

$$\begin{aligned} &= N(\text{Loose}) - N(\text{tight}) / \langle \epsilon_{T/L} \rangle \\ &= N(L) - N(T) + N(T)(1 - 1/\langle \epsilon_{T/L} \rangle) \\ &= N(L, \text{ not } T) - N(T)(1 - \langle \epsilon_{T/L} \rangle) / \langle \epsilon_{T/L} \rangle \end{aligned}$$

where $\langle \epsilon_{T/L} \rangle$ is an effective mean efficiency for the entire event sample, even though the calculation actually proceeds on an event-by-event basis.

The uncertainties on $N(L, \text{ not } T)$ and $N(T)$ are taken to be the square root of these numbers.

The uncertainty on $\langle \epsilon_{T/L} \rangle$ is taken from the ensemble tests.

