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

Mark Williams

Fermilab International Fellow

Lancaster University

On behalf of the DØ Collaboration

Introduction

• I will report the findings of a DØ analysis, motivated by the release of the CDF multimuon result (arXiv:0810.5357 [hep-ex]).

• The current DØ study is limited to searching for dimuon events in which **one or both muons** are produced at large radial distances (1.6 cm < r $\lesssim$10 cm) from the primary interaction.

• These muons are not required to originate at a common vertex – they are allowed to come from separate points, to include the possibility of a multi-muon cascade.

• There are clearly differences between the two detectors, making a direct comparison of absolute numbers difficult.

• However, I will show that D0 is expected to be sensitive to sources of radially-displaced muons, in terms of triggering, reconstruction and event selection.

Analysis Strategy

Overview:

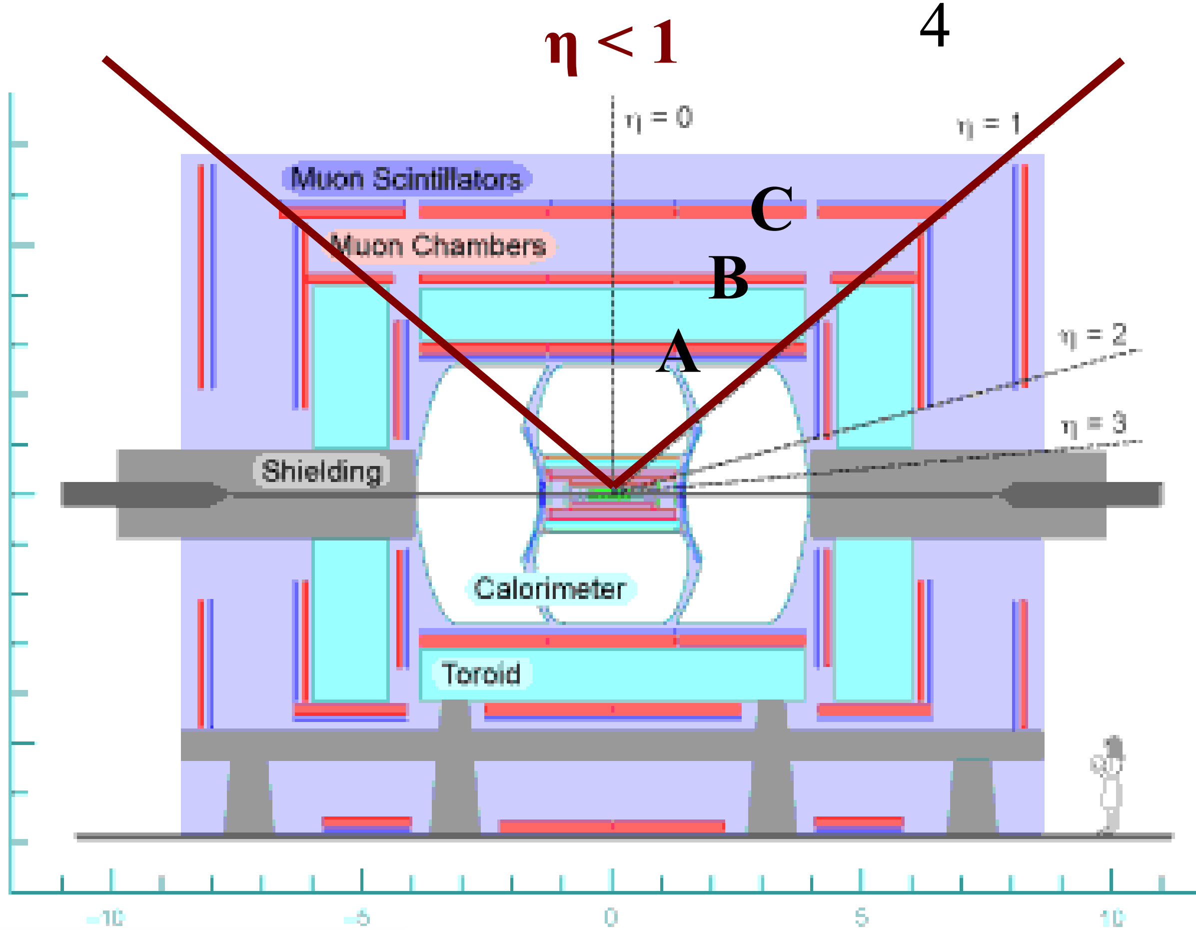
1) A sample of dimuons is selected to approximately match the sample used by CDF in their analysis. These are termed **'loose'** events.
2) Information from the inner-layer silicon detector is used to isolate a sub-sample of these events where both muons are produced within $r < 1.6$cm. These are termed **'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 loose dimuon events.

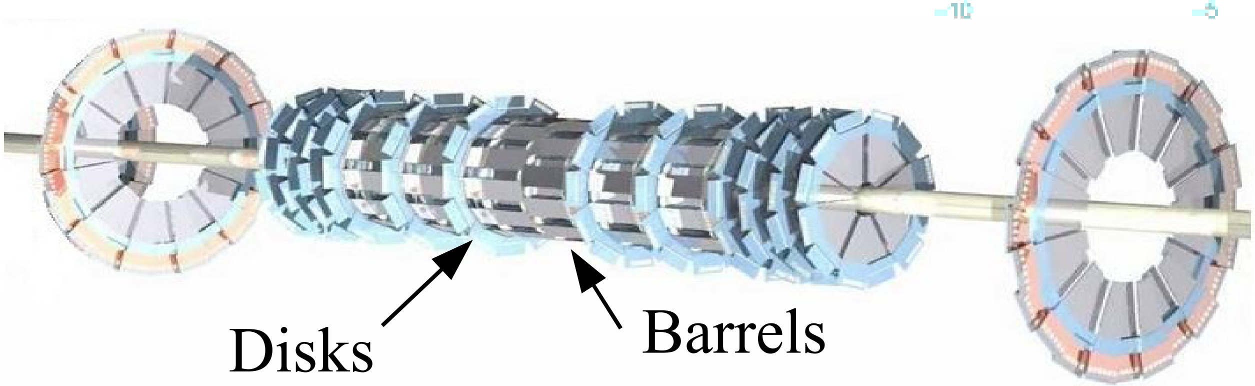
In the absence of a detailed breakdown of muon sources (from prompt or heavy-flavor production, decays-in-flight of pions/kaons, fakes), the strategy is to **use strict muon hit requirements** to suppress known sources of excess muons as much as possible.

This will therefore give an upper-limit on N(excess).

The DØ Detector

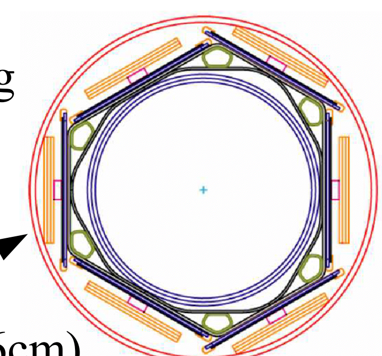
- Inner tracking (silicon sensors + scintillation fibers) with **small decay volume** (r<50cm);
- Muon tracking detector: multiple planes A-C of drift chambers on either side of 1.8T toroid magnet. Total **thickness of 14λ** (at layer C) **strongly suppresses punch-through** particles. Minimum pT to penetrate to layer C is ~**3→3.5 GeV/c**, depending on location.
- Scintillation counters on either side of toroid provides **rejection of cosmic-ray muons and out-of-time beam noise**.





Silicon tracking detector.

Inner layer cross-section (r =1.6cm, 1.76cm).



LANCASTER UNIVERSITY

Event Selection: Primary Muons

• A dataset corresponding to ~0.9fb^{-1} of Tevatron integrated luminosity is used, from recent Run IIb running (August – December 2008).

• 70% of selected events satisfy a dedicated dimuon trigger, which imposes no track-matching requirements, and applies less strict muon criteria than the offline cuts. Remaining events mostly trigger on other single or dimuon triggers.

• The two highest pT muons in each event are selected, provided that they satisfy the following criteria:

Requirement	D0
pT(μ)	≥ 3 GeV/c
|η|	< 1.0
Δz_0	< 1.5cm
Cosmic veto	$\|\Delta\varphi\| < 3.135$ rad
Timing	$\|t(A)\|<10$ns AND $\|t(C)\| < 10$ns
M(μμ)	$5 < M(\mu\mu) < 80$ GeV/c^2

z-distance between muons at point-of-origin

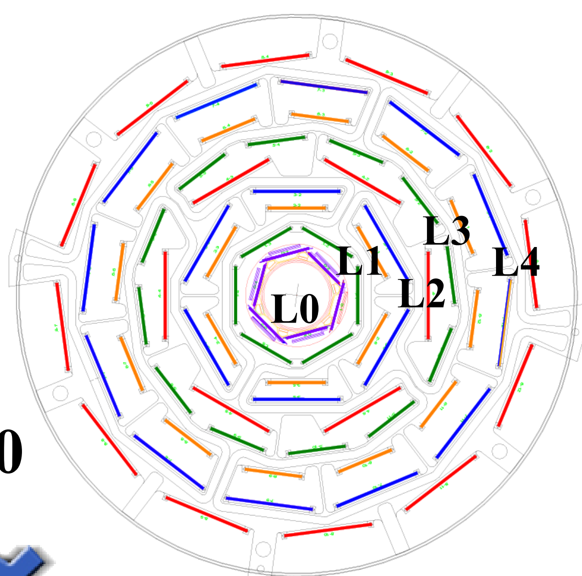
Remove muons which are back-to-back in φ

Muons must be associated with 'in time' hits inside and outside the toroid magnet

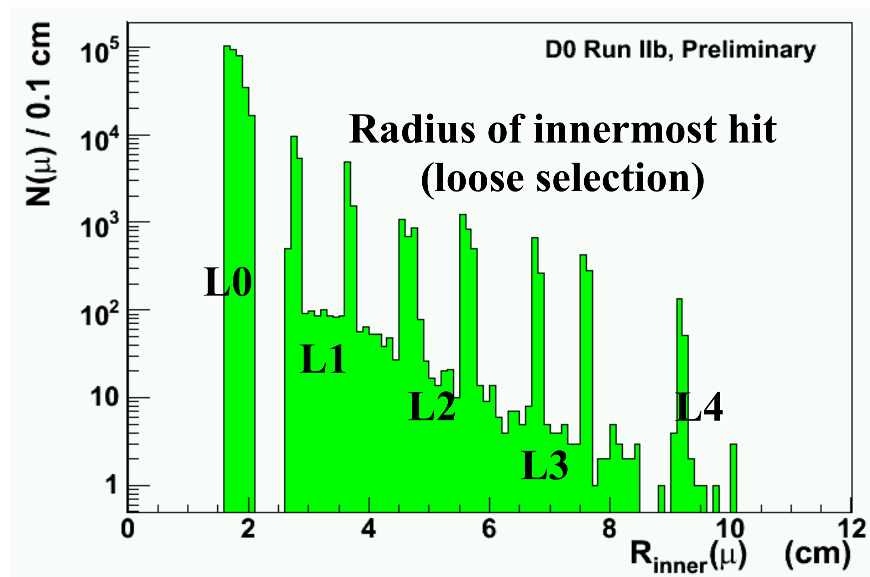
• Both muons must be associated with matched multi-hit muon tracks in drift-chamber layers on either side of toroid – strict quality cuts help to reject fakes.

Loose and Tight Muons

	CDF	DØ
Silicon Tracking:	5 double-sided layers + single-sided inner layer 1.5cm → 10.6cm + additional layer (23cm)	4 double-sided layers (L1-L4) + single-sided inner layer (L0) 1.6cm → 10.5cm + disks in transverse plane.
'**Loose**' definition:	**Hits in ≥ 3 silicon layers** out of 7 available.	**≥ 3 silicon hits**
'**Tight**' definition:	**Hits in two innermost silicon layers** **& ≥ 2 other silicon hits**	**Hit in L0** **& ≥ 2 other silicon hits**



D0



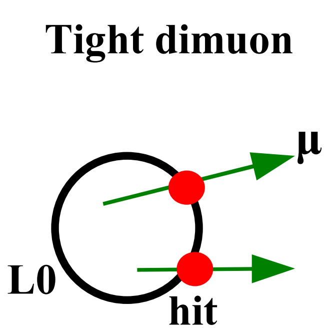
Event Counting Method

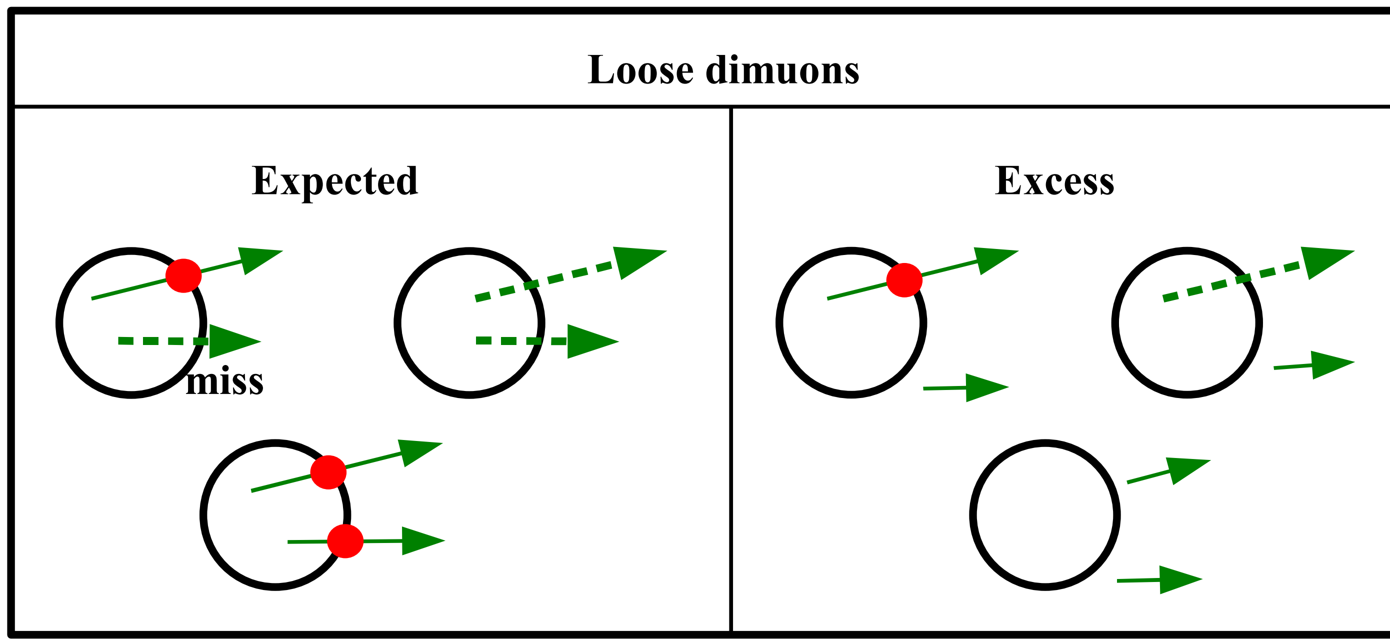
- A loose (tight) event must contain two loose (tight) muons. An event-by-event efficiency weighted count is used:

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

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

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



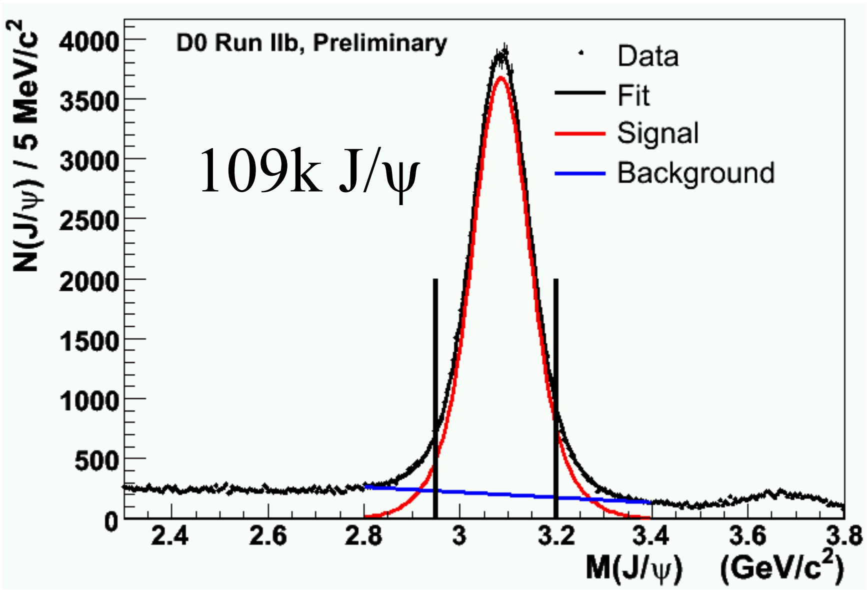


Measuring Tight/Loose Efficiency: J/ψ→μμ Sample

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:

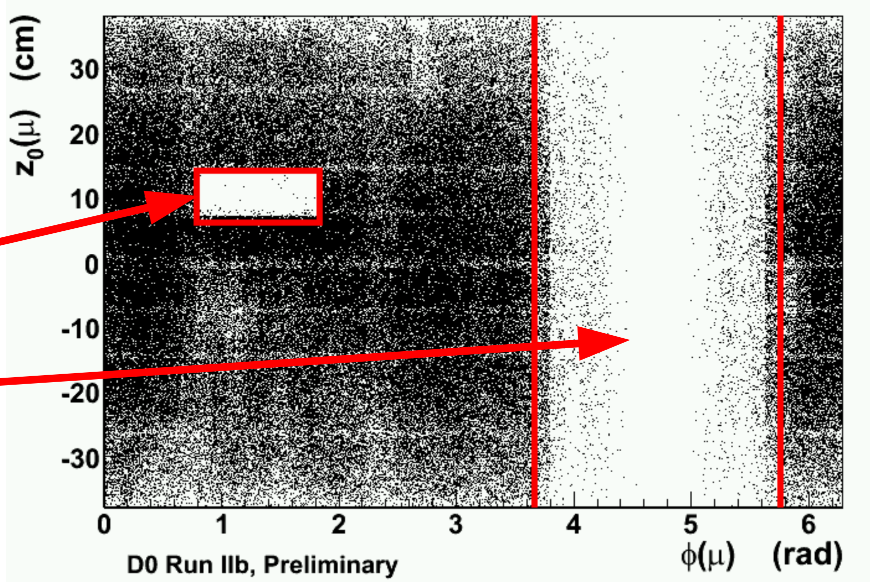
Same selection criteria as signal dimuons, except:

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



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

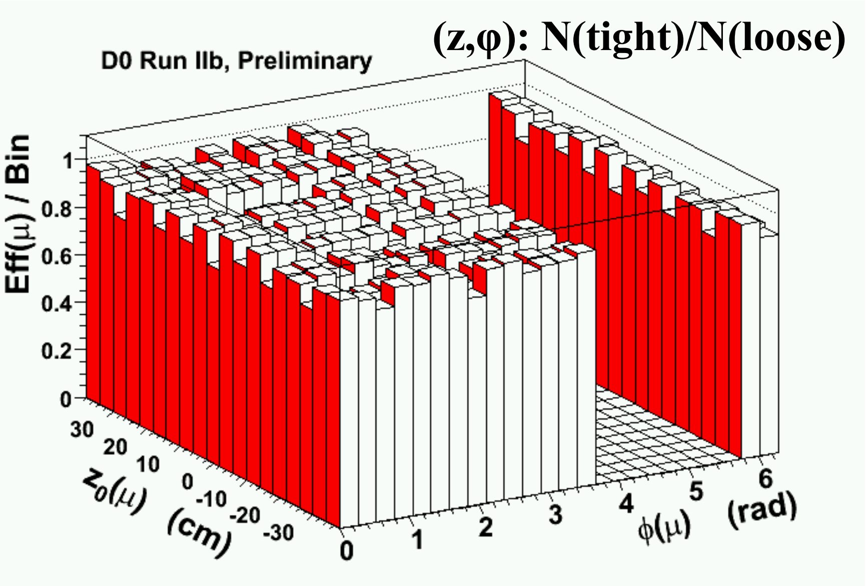
Events are excluded if either muon lies in the highlighted regions:
- The single inactive L0 sensor
- The bottom of the detector, where acceptance is limited by muon system coverage.

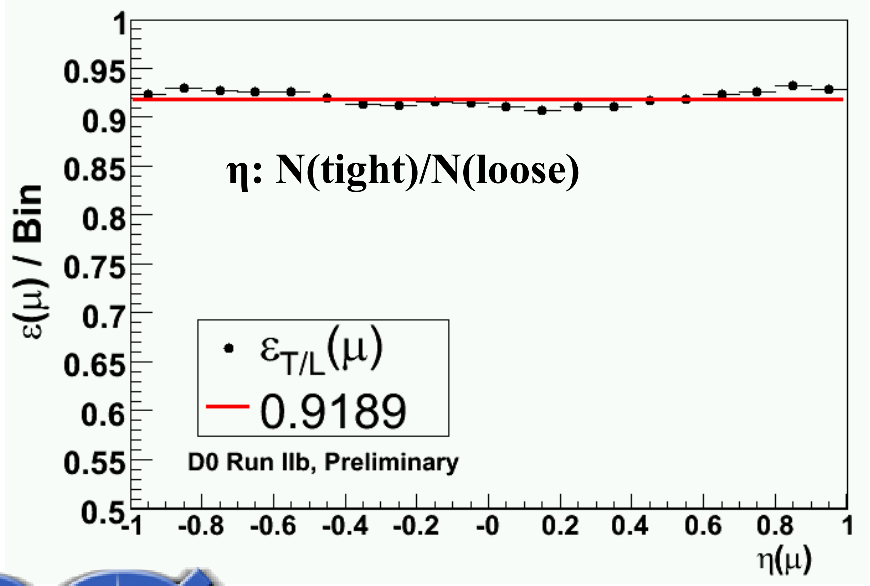


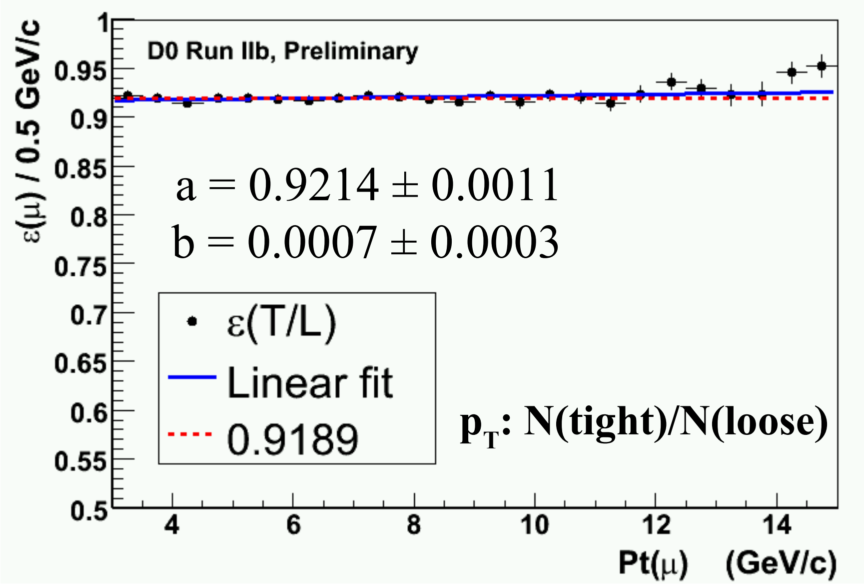
Efficiency: $\varepsilon_{T/L}(\mu) = \varepsilon[z(\mu),\varphi(\mu)] \times F[\eta(\mu)] \times F[p_T(\mu)]$

- **ε[z(μ),φ(μ)]** 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[η(μ)]** extracted similarly from η histogram, normalised to unity.
- p_T dependence parameterized with a linear function:

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







Results

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

$N^{obs.}$(loose) = **177,535**
$N^{obs.}$(tight) = **149,161** ⟶ **N(T)/N(L) = 0.8402 ± 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:

$N^{exp.}$(loose) = **176,823 ± 504 (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)**
	= **2 ± 359** (stat.) ± **705** (syst)	**(OS only)**
	= **710 ± 138** (stat.) ± **229** (syst)	**(SS only)**

[0.40 ± 0.26 ± 0.53]%
expressed as a fraction of $N^{obs.}$(loose)

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.

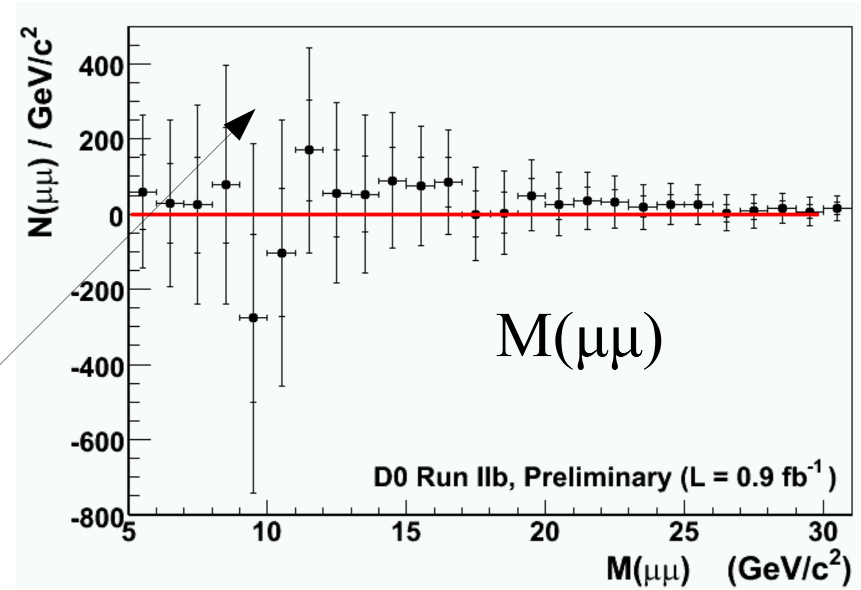
N(excess) in Different Kinematic Regions

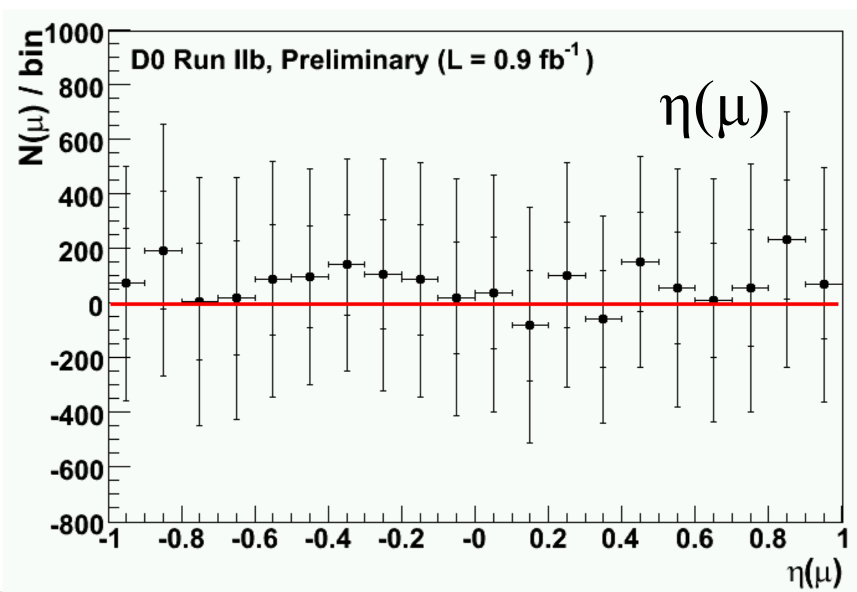
Calculation of N(excess) is repeated separately in bins of different kinematic and geometrical variables:

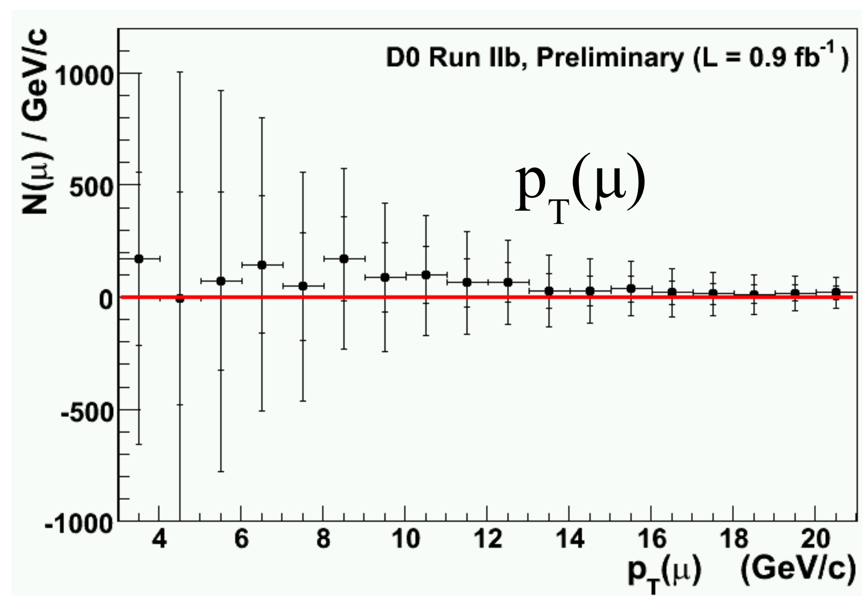
• No significant excess is observed in any bins in M(μμ), η, p_T or φ.

• In particular, the absence of an Υ peak indicates that the expectation-subtraction method is correctly accounting for prompt-prompt dimuons.

• Uncertainties are correlated from bin-to-bin.







Uncertainties and Checks

Statistical uncertainties are determined using ensemble tests, with the constituent efficiencies allowed to vary according to their Gaussian distributions, and the count repeated 1000 times → ± 0.26%.

Systematic uncertainties are determined by repeating the counting procedure with different binning schemes for z, φ, and η., and with the pT factor completely removed from the efficiency → ± 0.53%.

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

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

- The count is repeated using only those events which fire the 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.

In all cases the results are unchanged within statistical uncertainties.

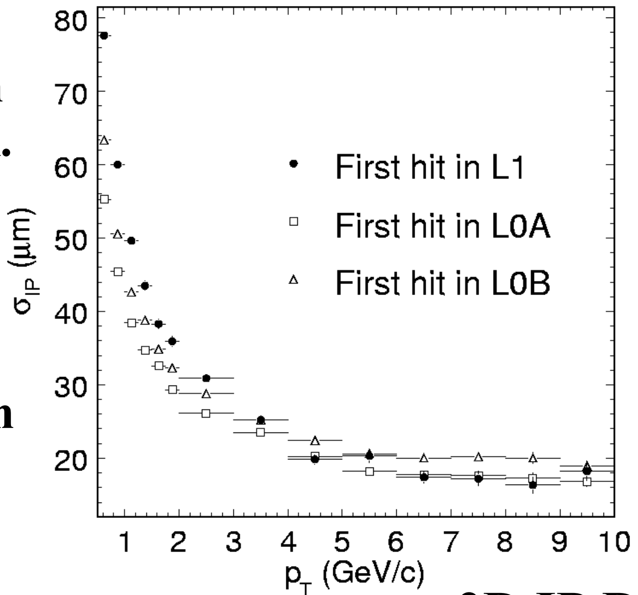
We measure the number of J/ψ events in the signal sample, when the lower-mass window is removed, to provide a **point-of-normalisation**:

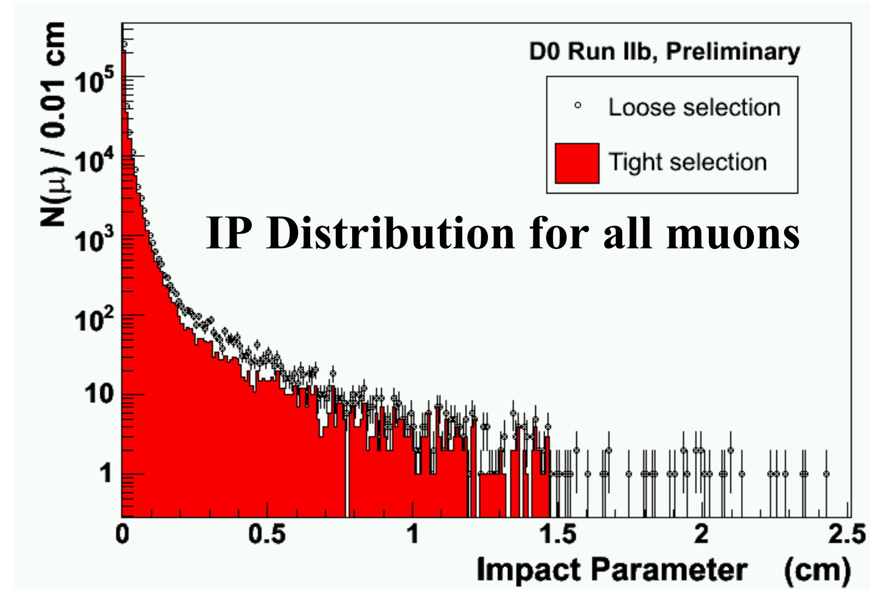
N(J/ψ) = 165,489 ± 989
Therefore N(excess) / N(J/ψ) = **(0.43 ± 0.28 ± 0.57)%**

Impact Parameter Distributions

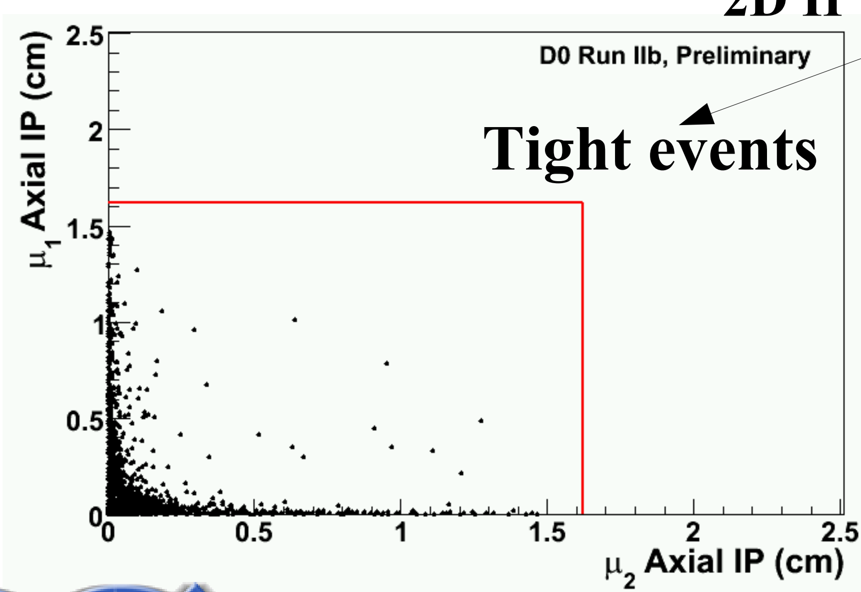
IP Resolution vs. pT: around 17μm for 5 GeV/c track.

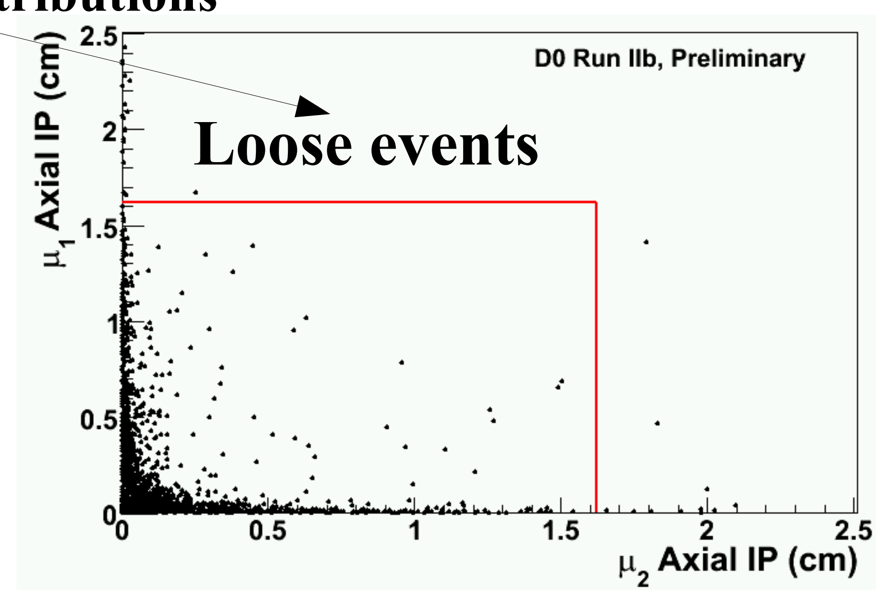
'Tight' SMT tracks have around 10-20% better IP res. than 'loose' SMT tracks.





2D IP Distributions





Contribution from $\Upsilon \rightarrow \mu\mu$ Decays

- Distribution of M(μμ), for tight events, is fitted by χ^2 minimization in the range 6→15 GeV/c^2.
- Signal: 3 Gaussians with same width;
- Background: Gaussian + 4^{th}-order polynomial;
- Results:

  N(Υ) = 18,515 ± 646

  N(Υ) / N(tight) = (12.4 ± 0.4) %

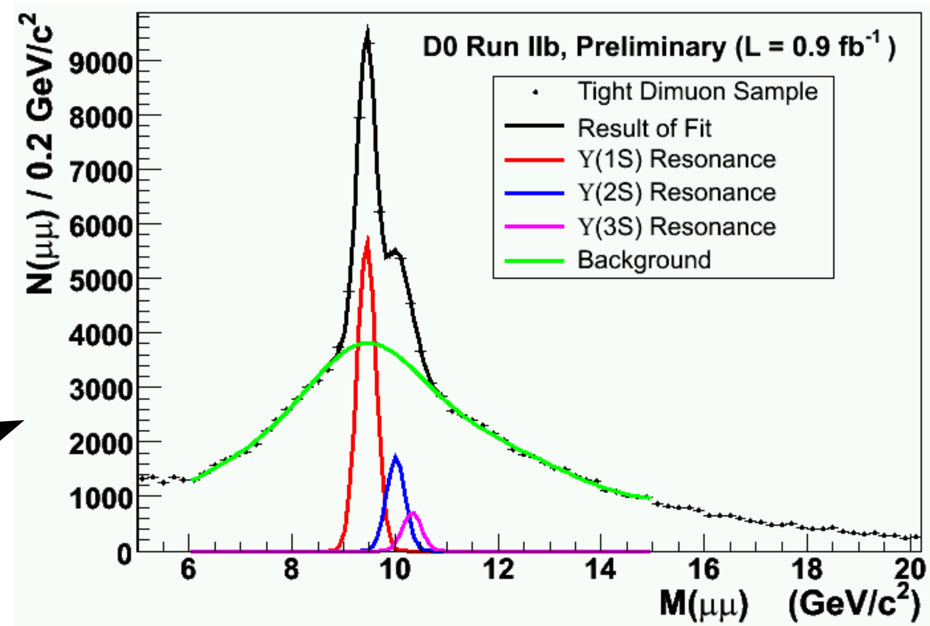
  σ(Υ) = 182.5 ± 4.1 MeV/c^2

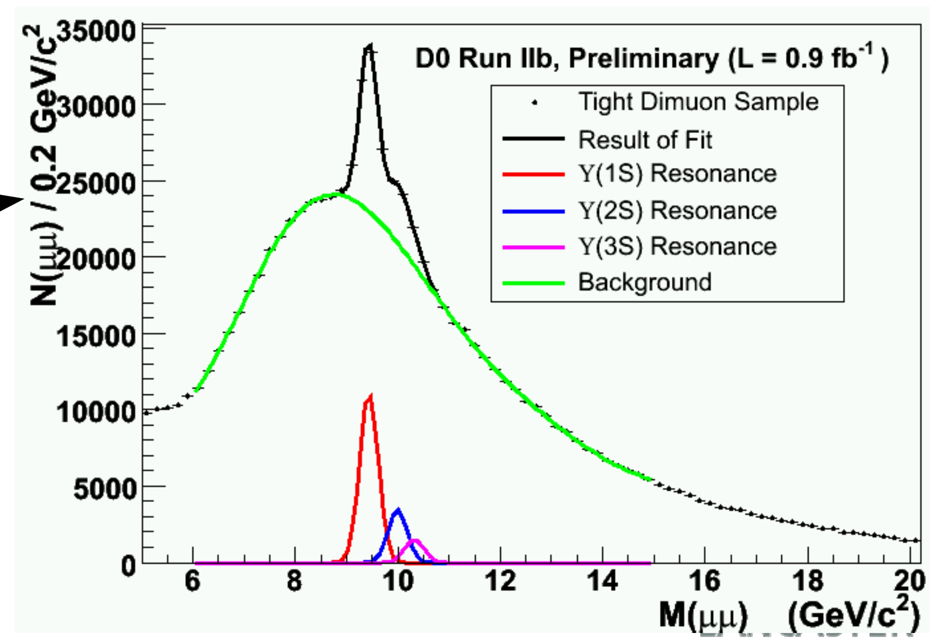
  χ^2 = 30 / 34 degrees-of-freedom

Υ(1S-3S) masses are consistent with PDG values.

- Non-resonant background peaks directly under Υ(1S) peak – due to the toroid thickness.
- Loosening muon hit criteria to accept those contained by the toroid gives broader, lower-mass non-resonant shape, distinct from the Υ structure.
- Fit parameters are consistent within ±1σ for the two samples, **N(Υ) = 37,055 ± 997**

  N(Υ) / N(tight) = (4.2 ± 0.1) %





Conclusions

• From a sample corresponding to ~0.9 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 ± **462** (stat.) ± **942** (syst)

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

N(excess)/N(loose) = (0.40 ± 0.26 ± 0.53)%

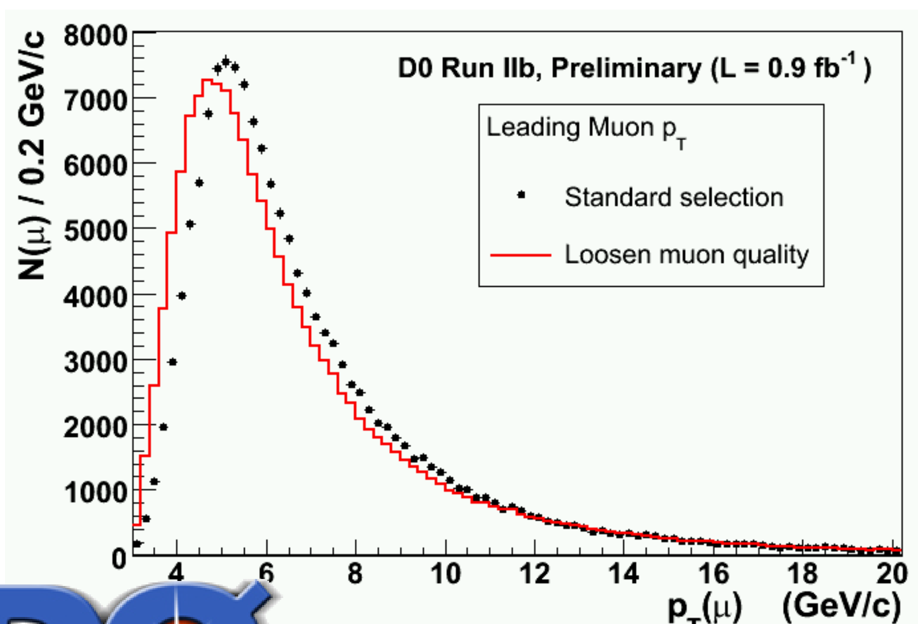
The fractional excess observed is significantly smaller than the figure reported by CDF (12%).

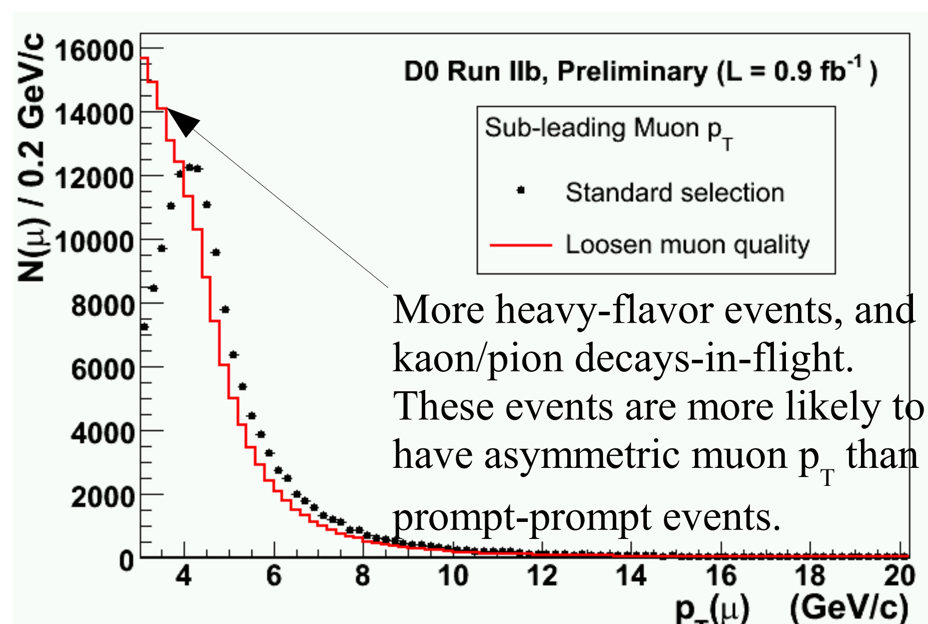
• Note that contributions from standard sources of displaced muon production (decays-in-flight, cosmic muons, hadronic punchthrough) have not been subtracted, so this represents an upper limit.

Additional Slides

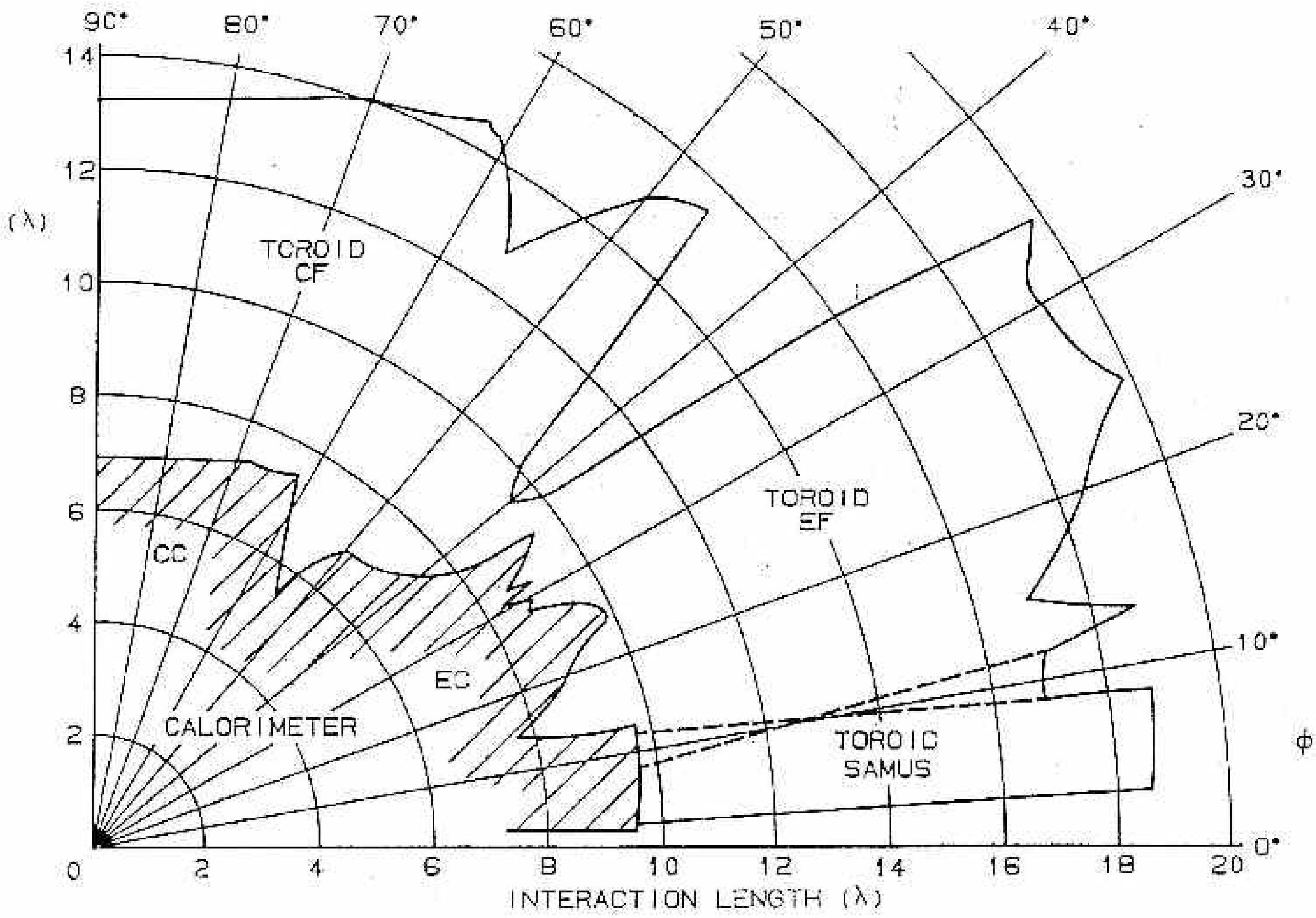
Loosening Muon Hit Requirements

- The default selection requires very tight hit criteria on the muons. The 'alternative' selection used to demonstrate the M(μμ) shape uses much looser selection requirements, accepting muons with a single hit on one side of the toroid, and no timing cuts.
- The sample fraction from Υ decays changes from 12.4% → 4.2% under the alternative cuts. Clearly, non-Υ sources are more significant.
- The fraction from poorly reconstructed muons, beam noise, cosmic rays and hadronic punchthrough is expected to increase. So is the fraction of events from heavy-flavor decays, and decay-in-flight of pions and kaons (due to reduced p_T threshold).
- The effect of this changed p_T threshold can be observed in the leading and sub-leading muon p_T from each choice of cuts.





Total Interaction Thickness of Muon System



TOTAL INTERACTION LENGTHS OF THE CALORIMETER AND MUON SYSTEM

Statistical Uncertainties

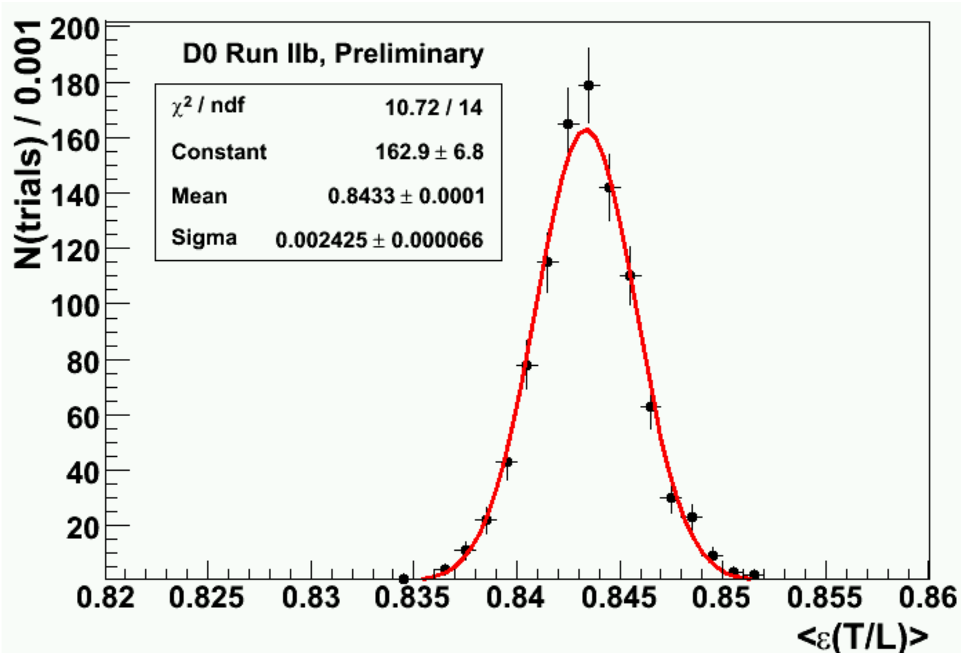
Ensemble tests are used to estimate the statistical uncertainty of the Efficiency measurement, in which the constituent Efficiency factors (i.e. per-bin efficiencies for the (z,φ) and η factors, and the constants *a* and *b* in the pT parameterization) are allowed to vary randomly according to the appropriate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

N(excess):

$= N(\text{Loose}) - N(\text{tight})/\langle \varepsilon_{T/L} \rangle$

$= N(L) - N(T) + N(T)(1 - 1/\langle \varepsilon_{T/L} \rangle)$

$= N(L, \text{not } T) - N(T)(1-\langle \varepsilon_{T/L} \rangle)/\langle \varepsilon_{T/L} \rangle$



where $\langle \varepsilon_{T/L} \rangle$ 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, not T) and N(T) are taken to be the square root of these numbers.

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