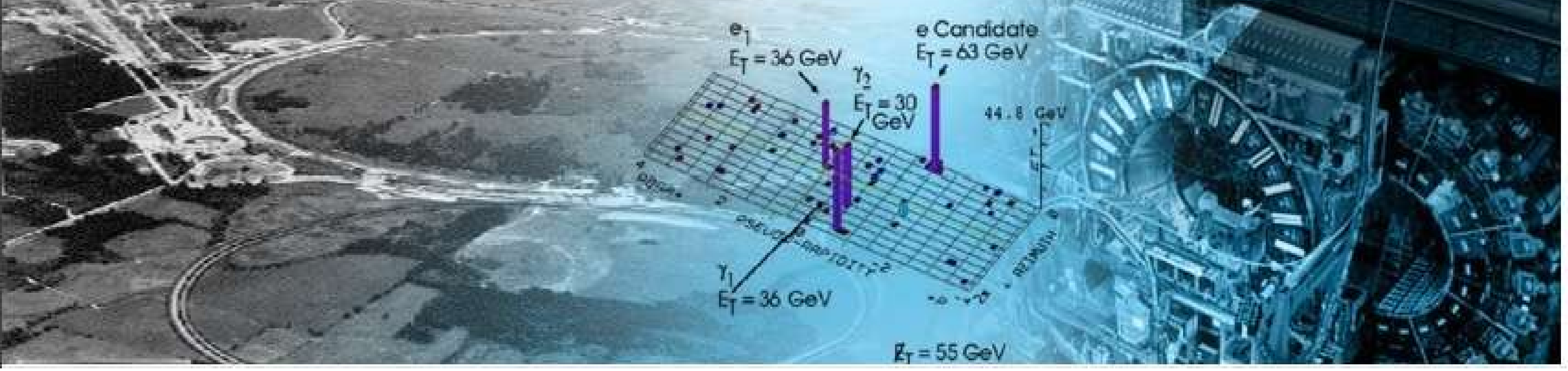


Across the Time Dimension in Search of Exotic Particles

Max Goncharov for CDF Collaboration

In This Talk ...

- **Massive Long Lived Particles**
  general things we do not understand, evidence for something out there, some theories and signatures

- ***CDF Detector***
  Time-of-Flight (TOF), Track Timing (COT), EMTiming

- **Charged Massive Particles (a.k.a. CHAMPs)**
  results from CDF with 1 fb^{-1}

- **Neutral Massive Particles (a.k.a. delayed photons)**
  results from CDF with 0.6 fb^{-1}

- **Where we would like to go**
  tools we developed, things we learned. new ideas

Why Search Beyond SM?

Standard Model is great, but some questions linger

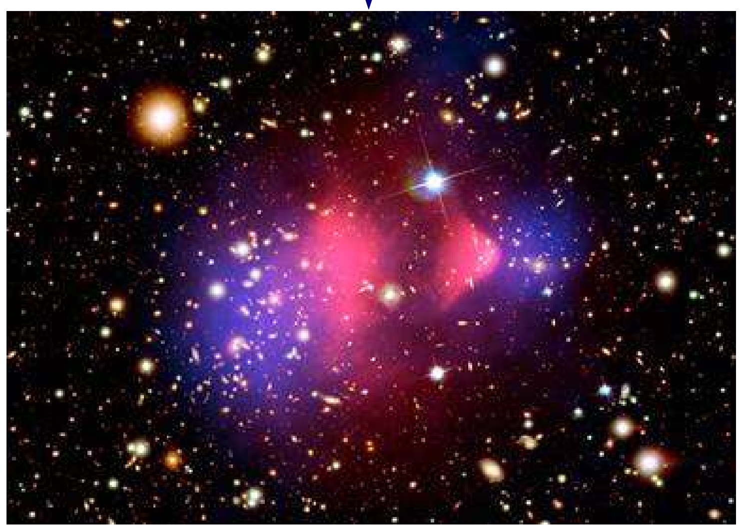
Only 3 generations?

Why so different masses?

No antimatter?

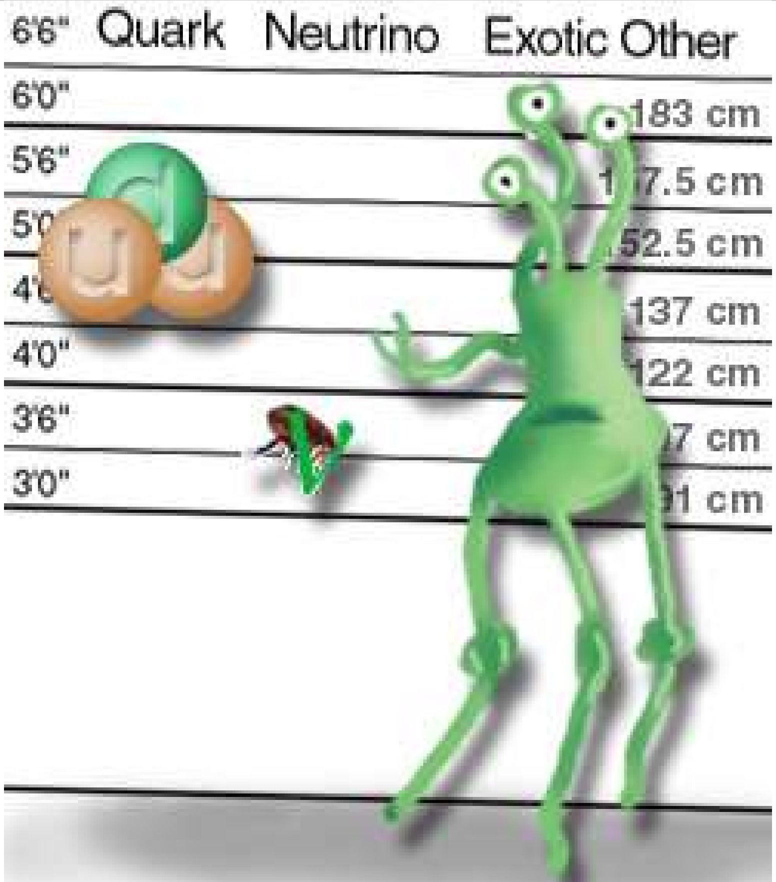
Dark Matter?!

m_t=175 GeV

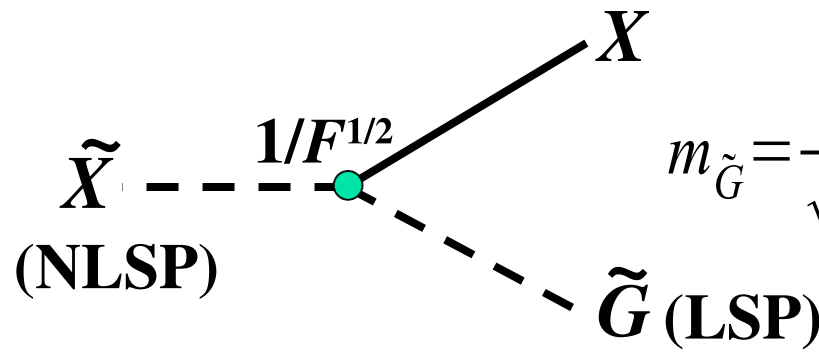


Colliding Galaxies: while normal matter (red) slows down the dark matter (blue) keeps going as if nothing happened

Massive and Long-Lived



"All right... which of you punks is responsible for dark matter?"



$$m_{\tilde{G}} = \frac{F}{\sqrt{3}\,M_{pl}}$$

Wide variety of models:

- m(G) ~ 100-200 GeV
- G is good dark matter candidate
- small $\Delta m = m(\tilde{X}) - m(\tilde{G})$=> large lifetime

SUSY (GMSB) model:

- neutralino – NLSP, m(G) ~ 10 KeV
- neutralino life-time is unconstrained

Stable Massive Particles

Standard Model extensions predict new massive particles

- ➔Most searches assume particles decay promptly
- ➔Long-lived particles would evade these searches
  - Charged Massive Particles (CHAMPs)
  - Neutral Stable Massive Particles decaying to photons
- ➔In perfect life all Standard Model backgrounds are zero
- ➔Often need to develop new tools

- ➢ all backgrounds are estimated from data
- ➢ blind analysis (learn how to estimate backgrounds, then look at the data in the signal region)
- ➢ model-independent results (but also set limits)

Stable Massive Exotic Particles

Can decay:

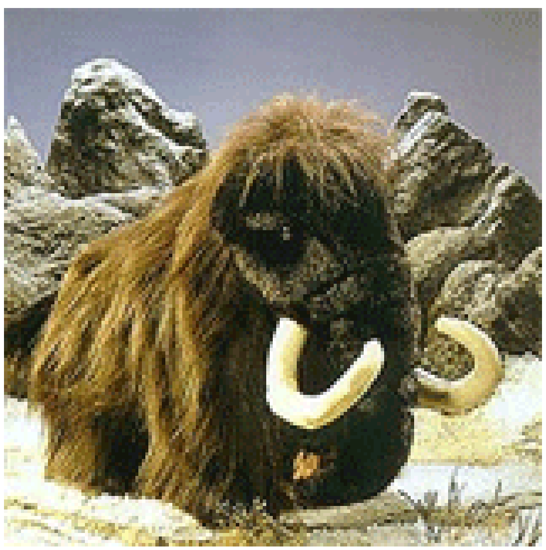
- **inside the detector**
- **outside the detector**

They can be:

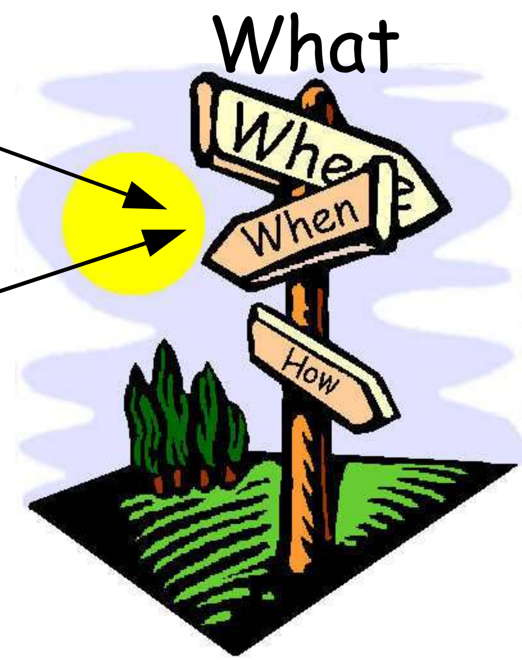
- **charged or neutral**
- **be in events with low ΣP_T**

long lifetime

large mass

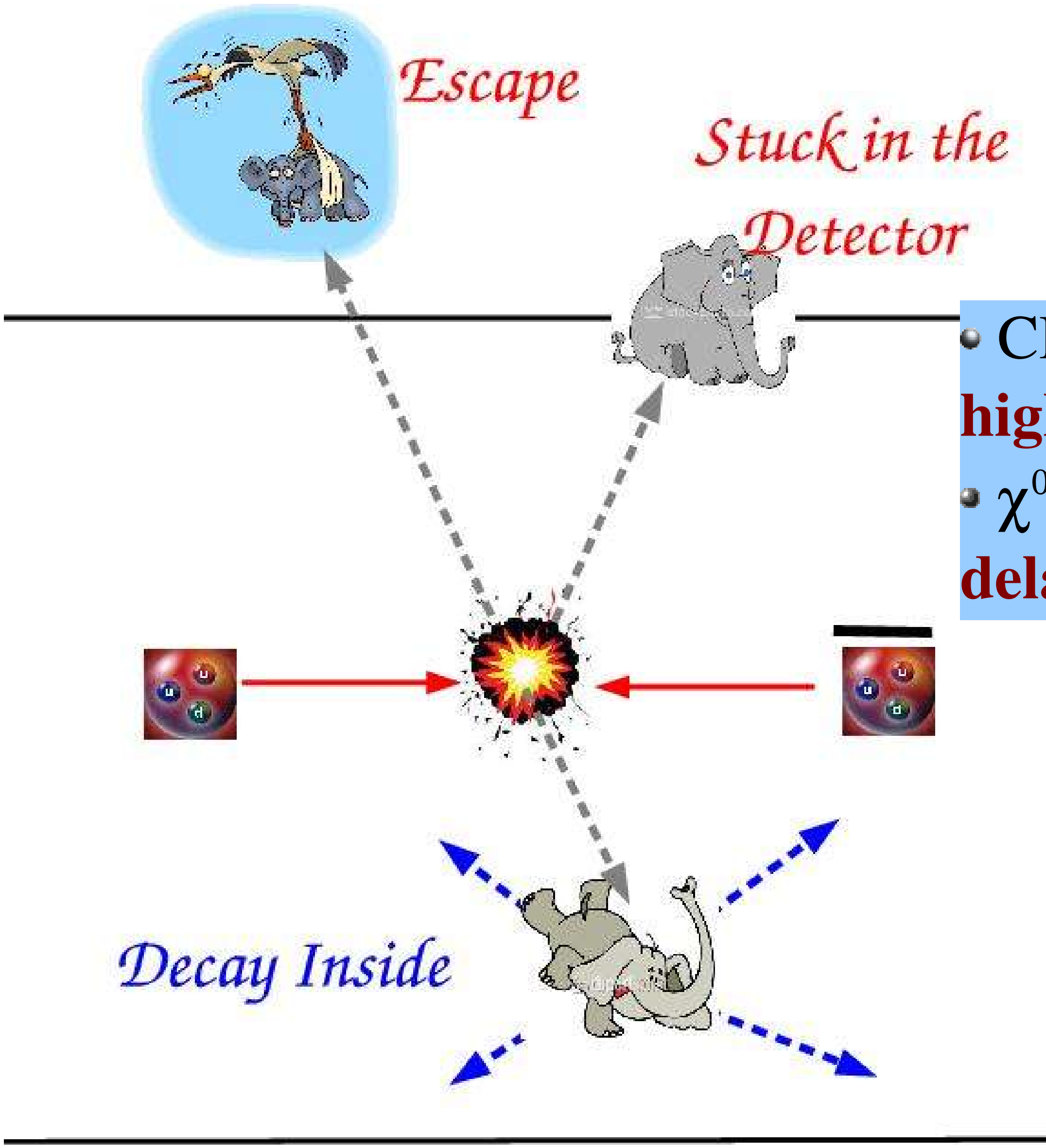


low speed



cold relic

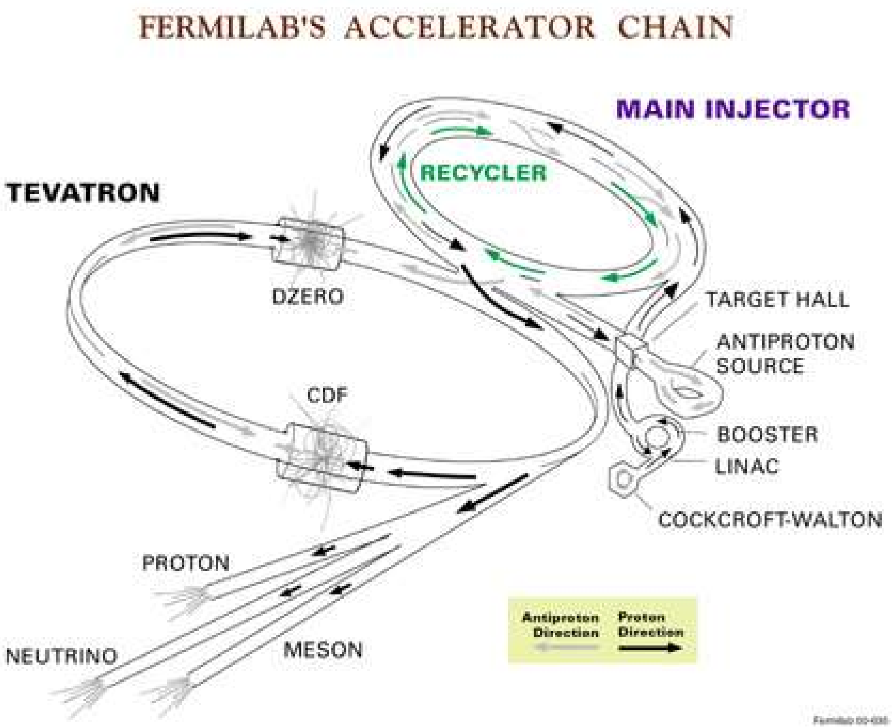
Possible Signatures

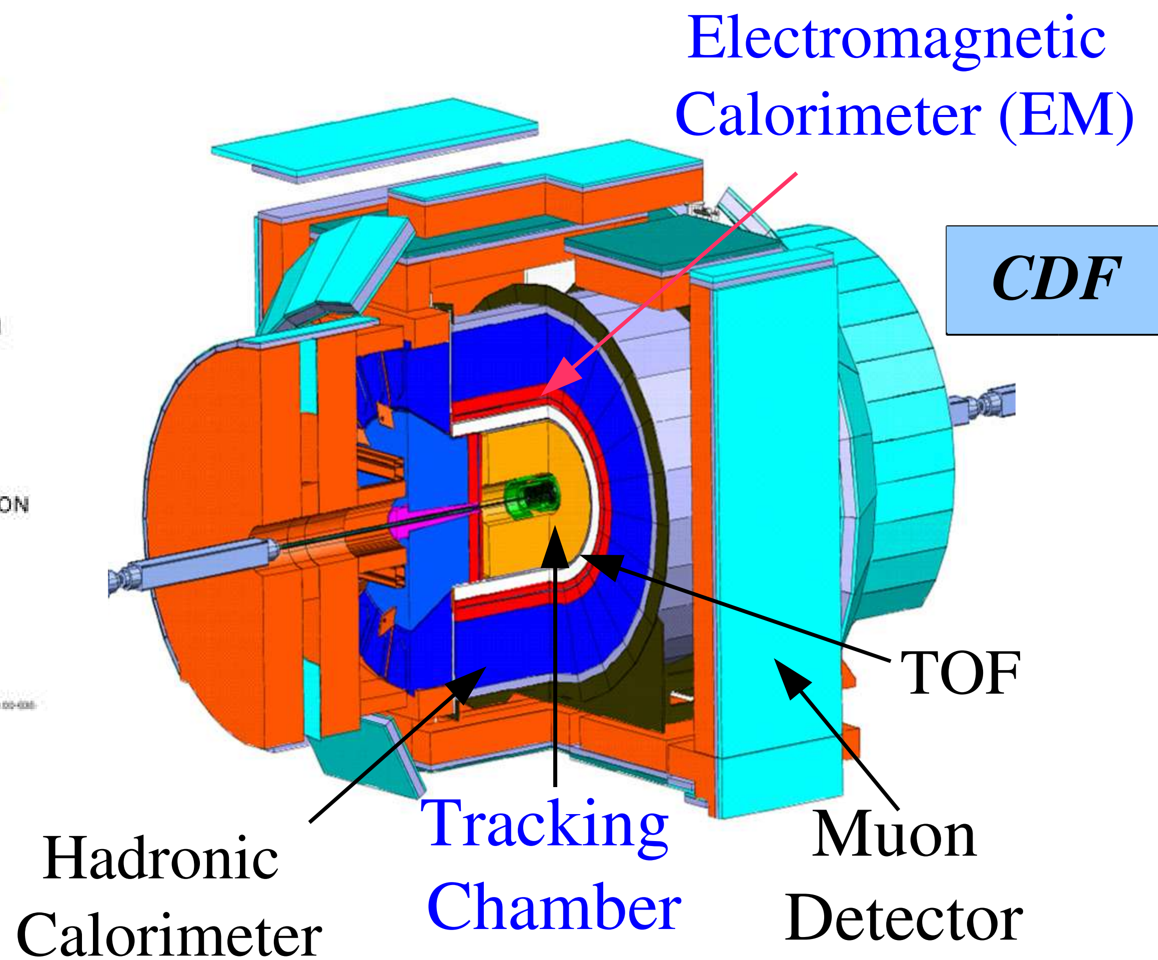


- CHAMP – charged massive particle **highly ionizing/late track**
- χ^0 decaying inside the detector: **delayed photons**

signatures should be spectacular

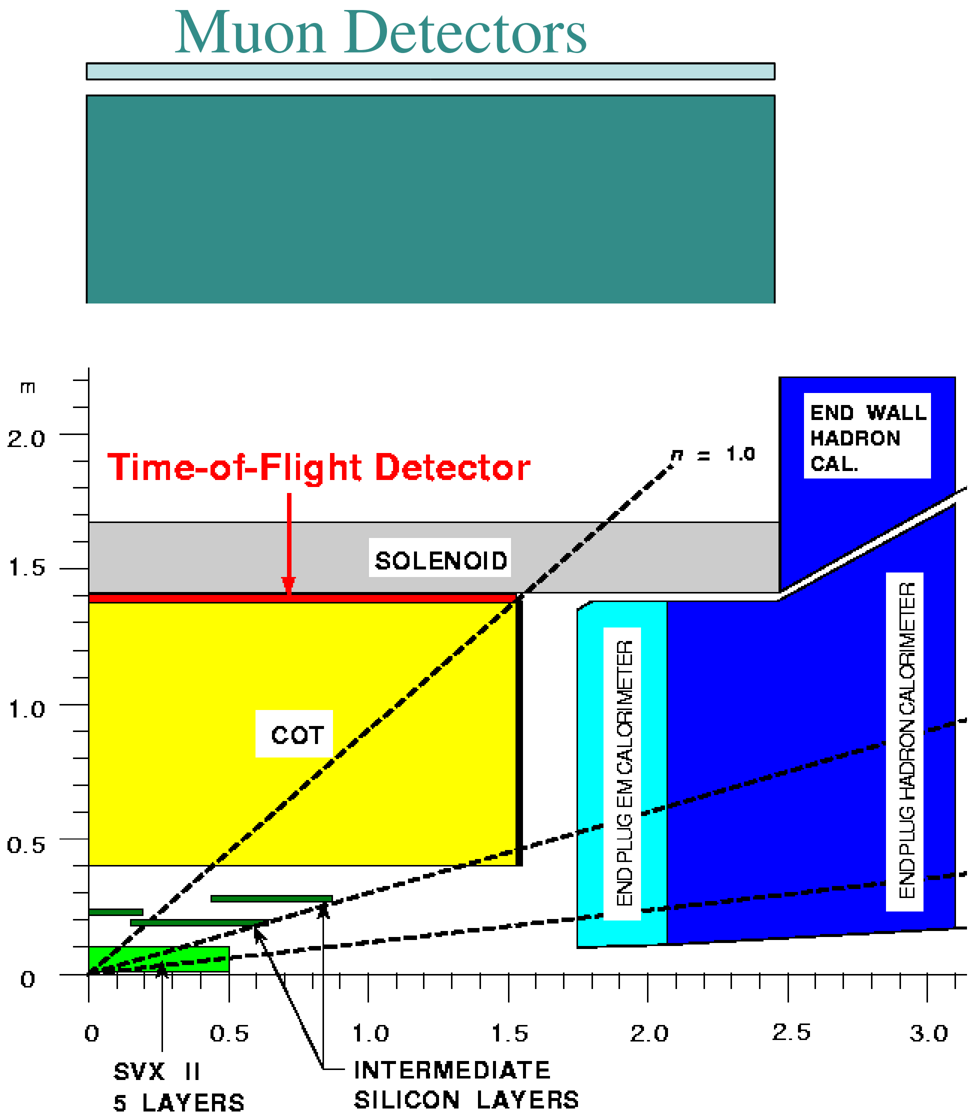
CDF Detector





CHAMPs – tracking, calorimeters, TOF, muon
Delayed Photons – tracking, EM calorimeter

Time of Flight Detector



TOF – scintillators wrapped around tracking chamber (COT) at a 1.45 m

Timing Resolution – 100 ps

Use Time-of Flight (TOF) detector to measure β for charged particles

To calculate β, need:

- candidate TOF arrival time
- independent interaction t_0
- path length

$$\beta \equiv v / c$$

Time Measurement with COT

- Drift chamber is a timing device
- Each Track produces up to 96 hits
- Each hit has timing information
- Up to 96 time measurements on a track
  - ➔Potentially lots of timing information
  - ➔Large statistics can compensate for low single-hit precision (for a track, resolution ~ 200 ps)
  - ➔Measure arrival times at wire planes and cell boundaries
    - Can measure track velocity with or without event t0
  - ➔Gaussian tails!

New Tool – EMTiming System

Adding timing to EM Calorimeter would help

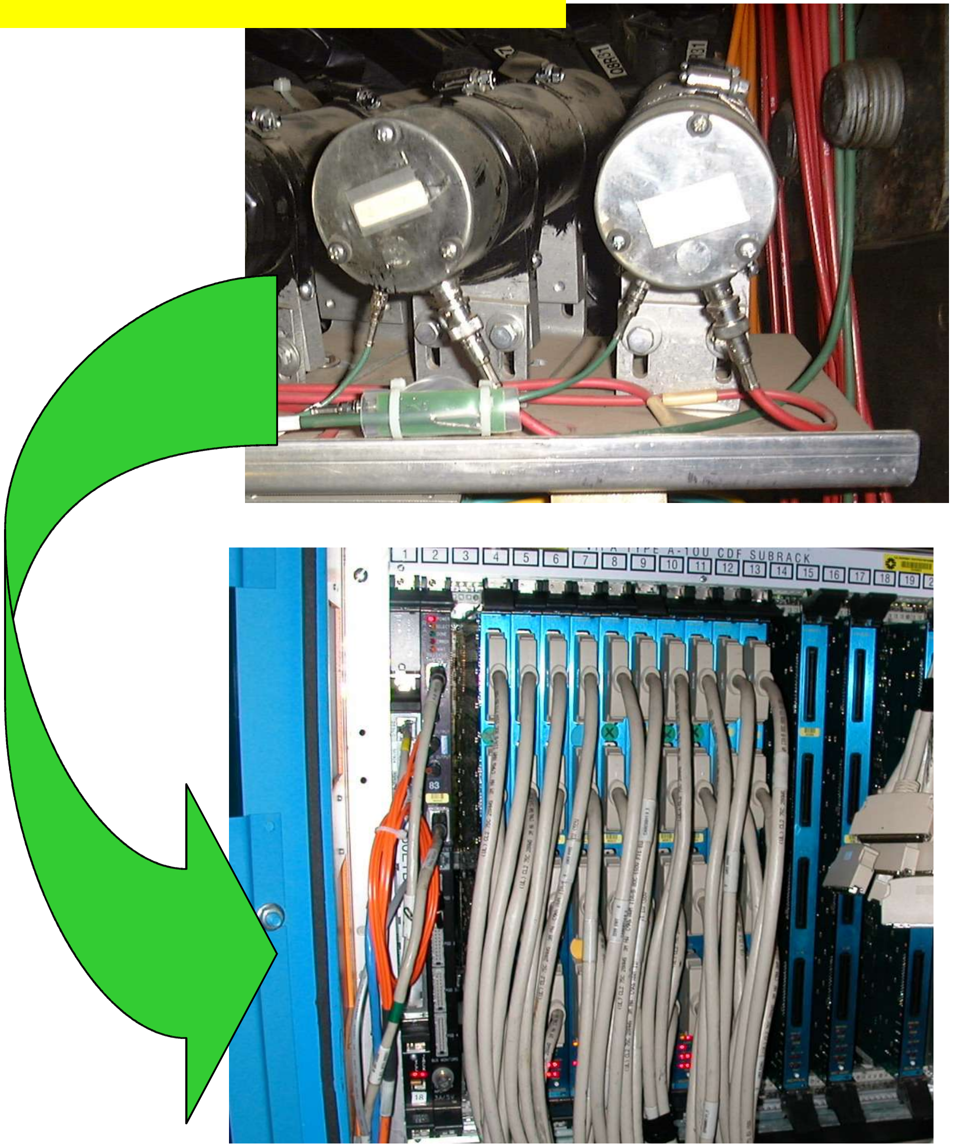
- Photon handle: provide a vitally important handle that confirms or denies that all the photons in unusual events are from the primary collision.
- Met handle: for events with large EM energy, full calorimeter coverage reduces the cosmic ray and beam halo background sources and improves the sensitivity for high-P_T physics such as SUSY, LED, Anomalous Couplings etc.
- Search for long-live particles

New Tool - EMTiming System

~2000 Phototubes

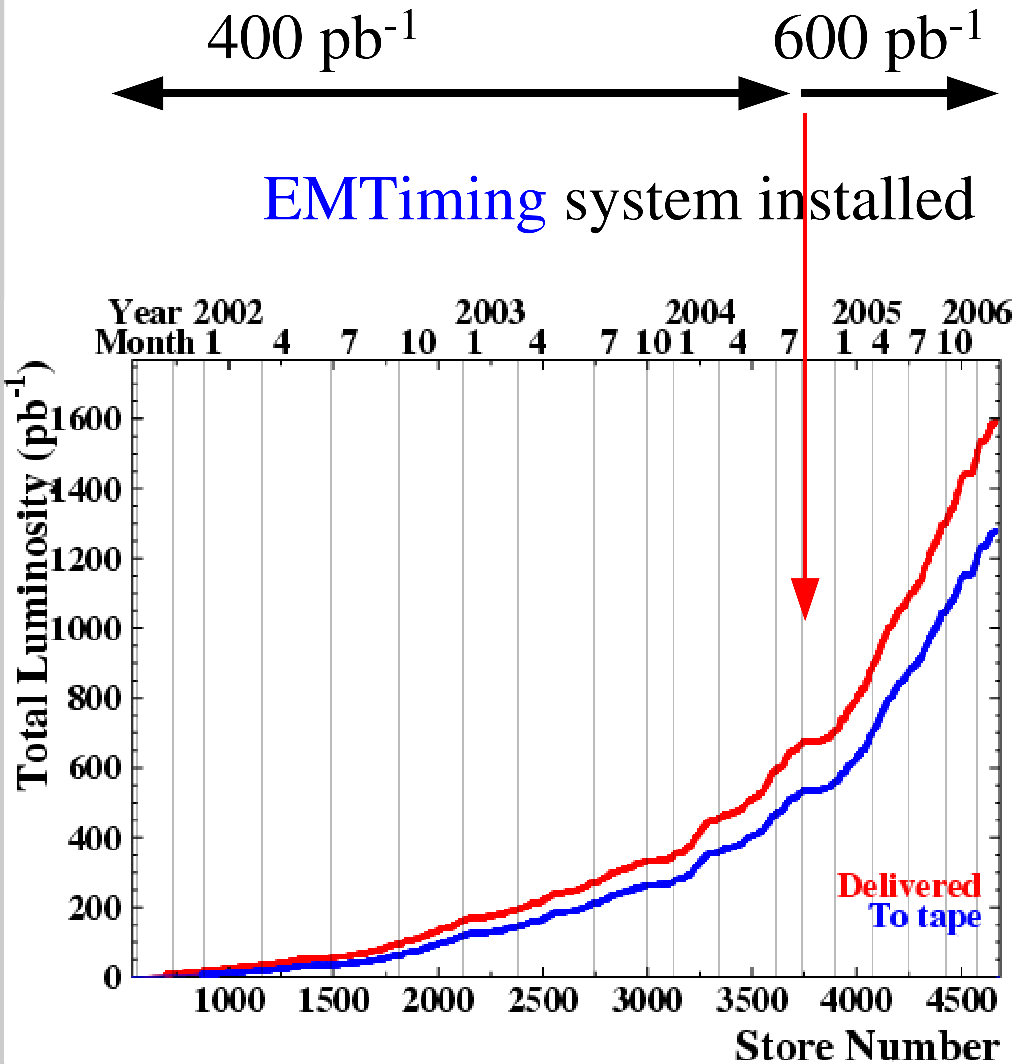
- Large system to add to existing detector (Run IIb upgrade)
- Put a TDC onto about 2000 phototubes at CDF ($|\eta| < 2$)
- TDC has 1 ns buckets
- for central detector use passive inductive pick-off to split PMT anode signal

published in NIM



http://hepr8.physics.tamu.edu/hep/emtiming/

Luminosity



- ~100% Efficient above thresholds (CEM-5, PEM-2.5 GeV)
- System resolution is ~0.6 ns
- Very uniform
- Negligible Noise
- Finished full installation October 2004. Started taking data in November (1.4 fb^{-1} and counting)
  - Commissioned in 1 week
  - All high P_T events have timing information

CHAMP Signature

Champs give a unique signature in the detector

- CHAMPs are heavy
  - Slow $\beta \equiv v/c < 1$
  - Hard to stop
- CHAMPs are slow
  - Large *dE/dx (mostly through ionization)* $dE/dX \sim 1/\beta^2$
  - ***Long time-of-flight***
- Look for high transverse momentum (P_T) penetrating objects (looks like muon) that are slow (long time-of-flight)

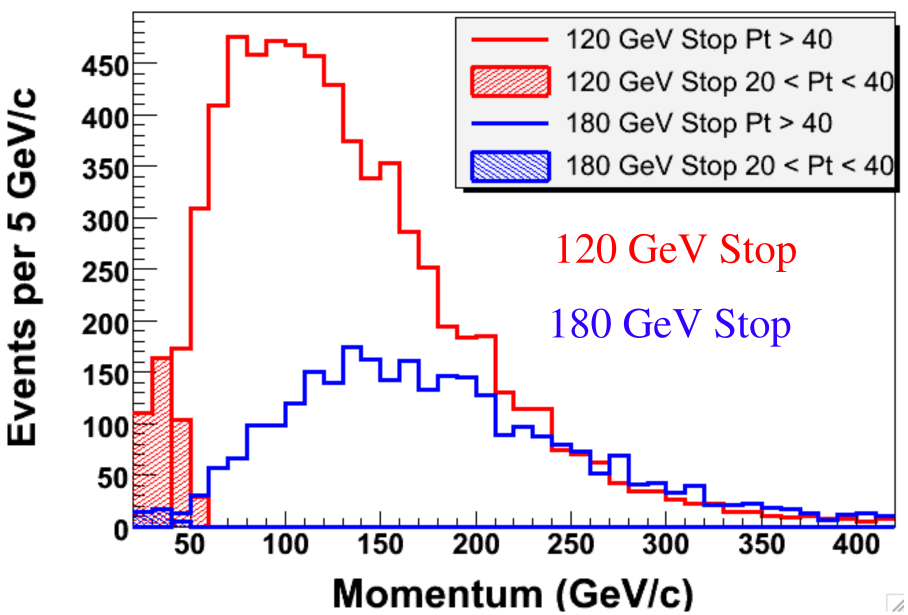
CHAMP Signal Isolation

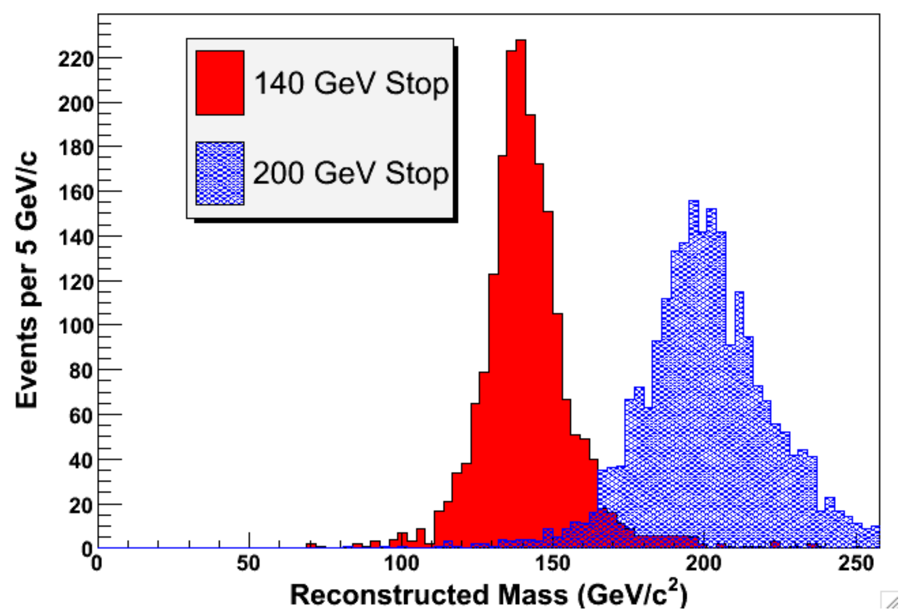
Use track momentum and velocity measurements to calculate mass

- correlated for signal, uncorrelated for background

Signal events will have large momentum

- signal region $P_T > 40$ GeV/c
- control region 20 GeV/c < P_T < 40 GeV/c
- use control region to predict background shape





Analysis Strategy

It is the mass of the muons we are after

- use beta shape in the the control region as a shape
- convolute it with the momentum

$$m = p\sqrt{1/\beta^2 - 1}$$

Show this works for electrons from Ws

- sanity check take electrons with $20 < P_T < 40$ GeV
- beta shape + momentum histogram = background prediction
- agrees with data

Show we can predict electrons with $P_T > 40$ GeV

Muons:

- split control region in 2: $20 < P_T < 30$ and $30 < P_T < 40$
- show that can predict 2 from 1
- get beta shape for $20 < P_T < 40$
- make prediction for $P_T > 40$ GeV, compare with data in the signal region

Backgrounds

- Cosmic rays
  - Time of cosmic ray tracks uncorrelated with interaction time, could appear to be CHAMPs
  - Remove by looking for backward-going track opposite candidate (identified by timing as well)
- Instrumental effects:

$$t_{Flight} = (t_{TOF} - t_{Event})$$

Mismeasured event t_0

require TOF and tracking t_0 to agree (0.5 ns)

Incorrect TOF for CHAMP candidate

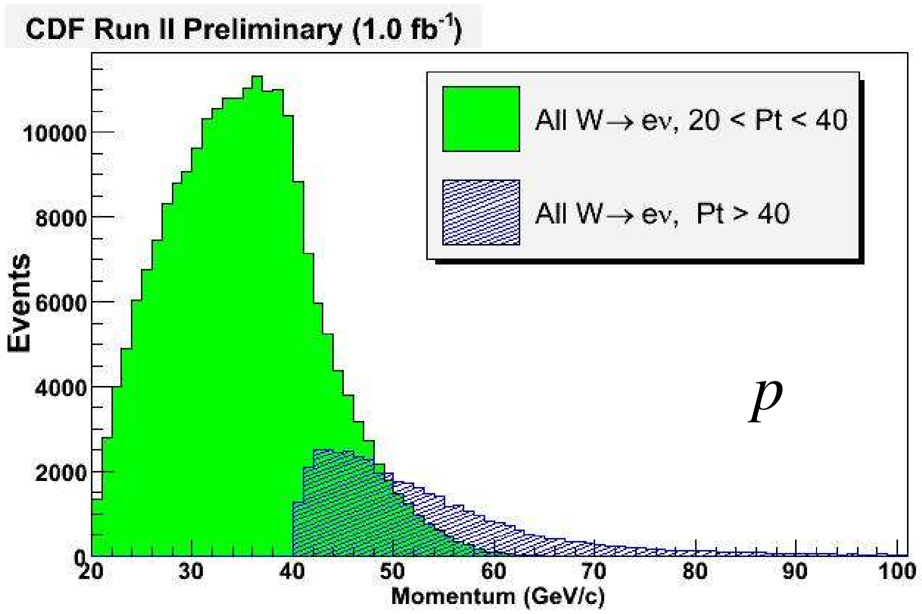
require good COT χ^2 when using TOF β

Mismeasured momentum

can get hight mass for a 6 TeV track with $\beta = 1$

require β significantly different from 1 ($\beta < 0.9$)

Electrons Sample

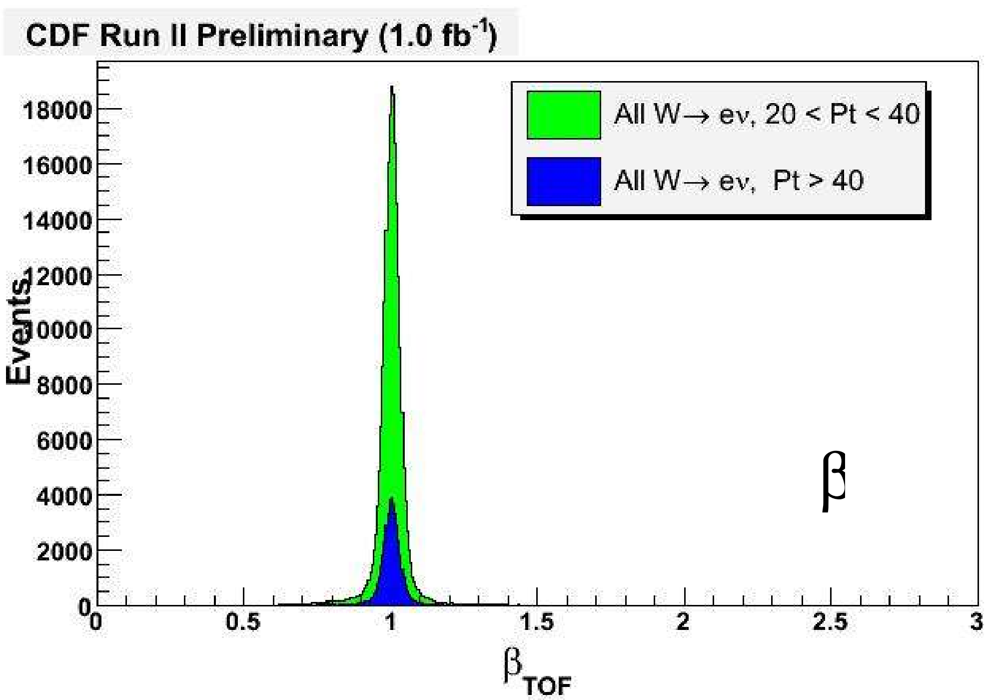


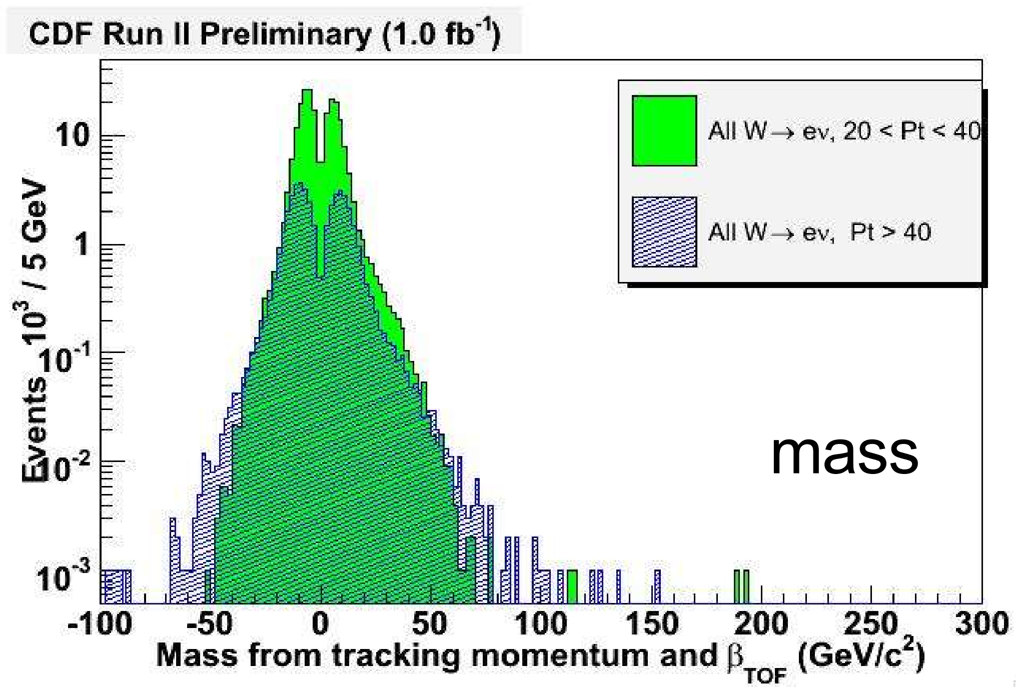
- Nice place to understand mass calculation
- Use electron momentum

β > 1 unphysical

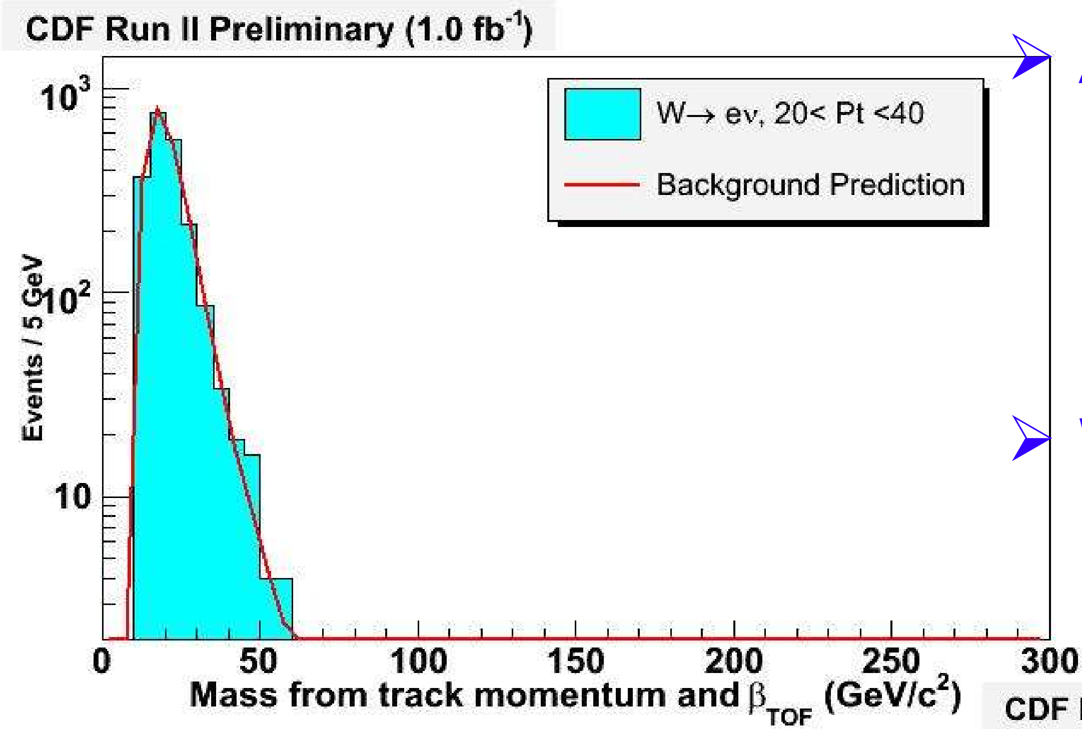
assign negative mass to "tachyons"

$$m = p\sqrt{1/\beta^2 - 1}$$





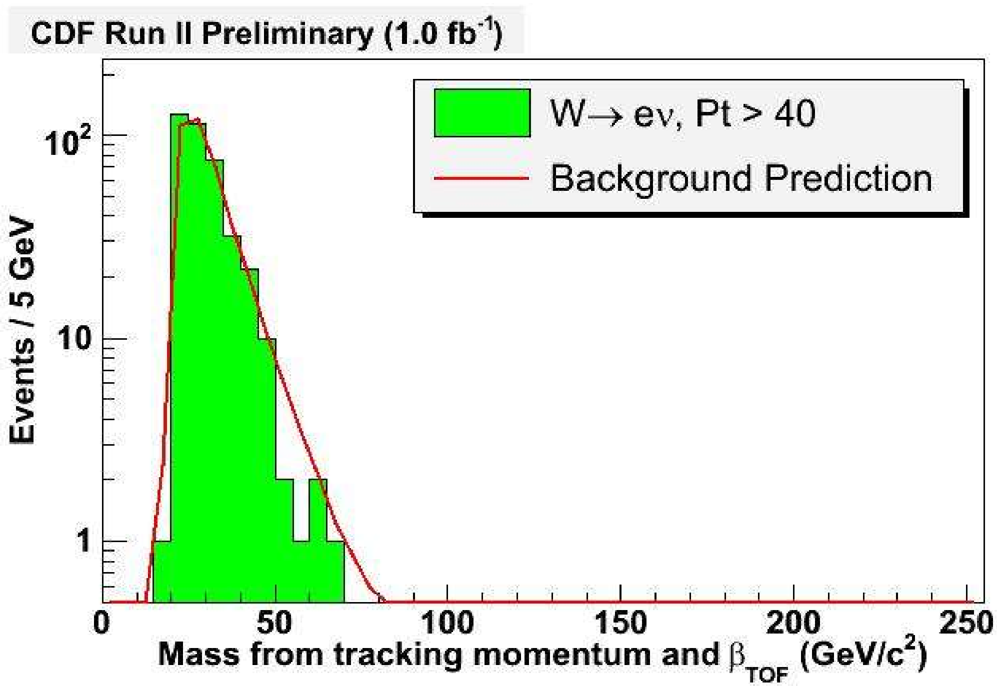
Check With Electrons



- Assume p and β are independent
  - Calculate mass bin-by-bin from p and β histograms
  - weight by bin contents
  - gives mass shape prediction
- Works!
  - p and β are largely independent in the control sample

Predictions generated from control-region β and signal-region p

Assume β matches in both regions

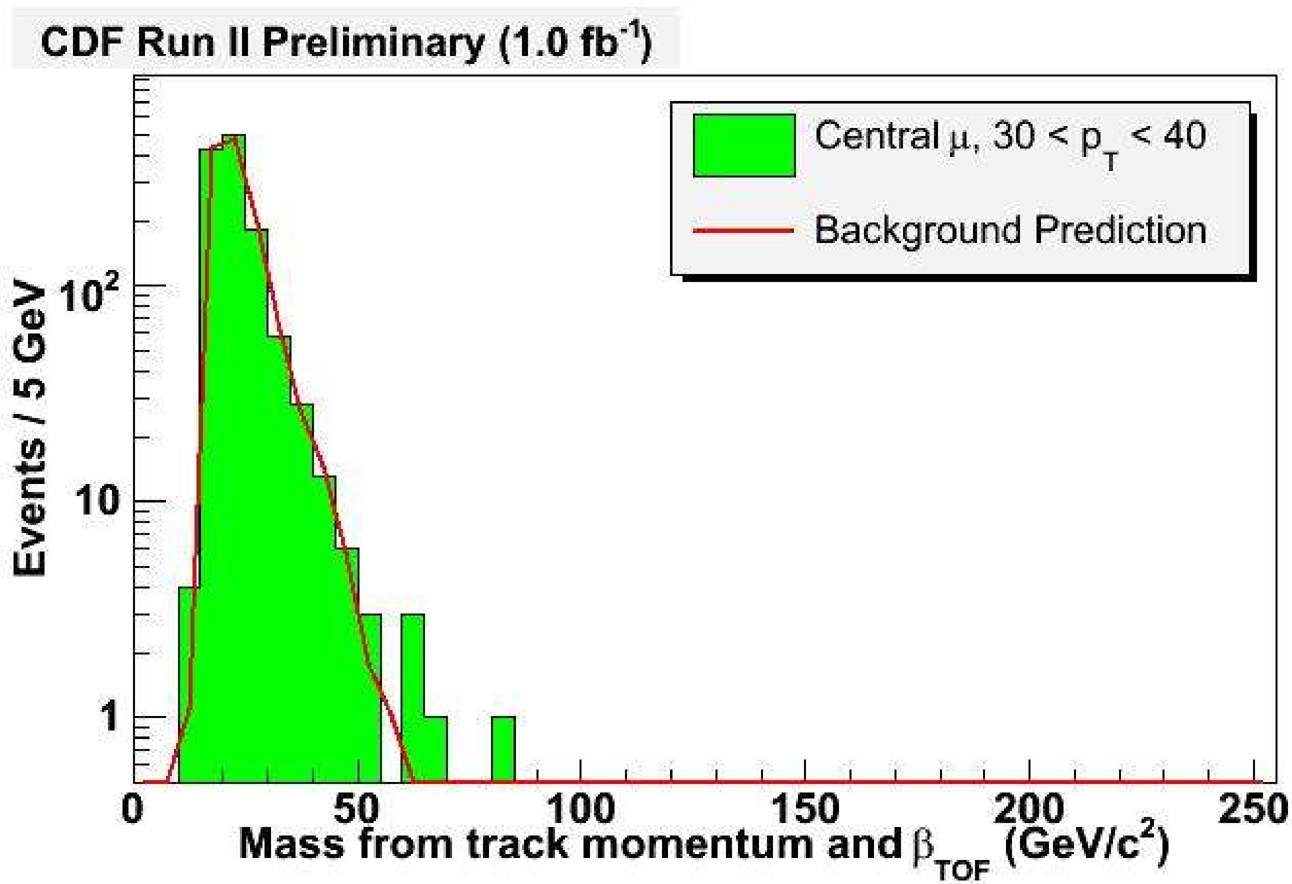


Muon Control Region

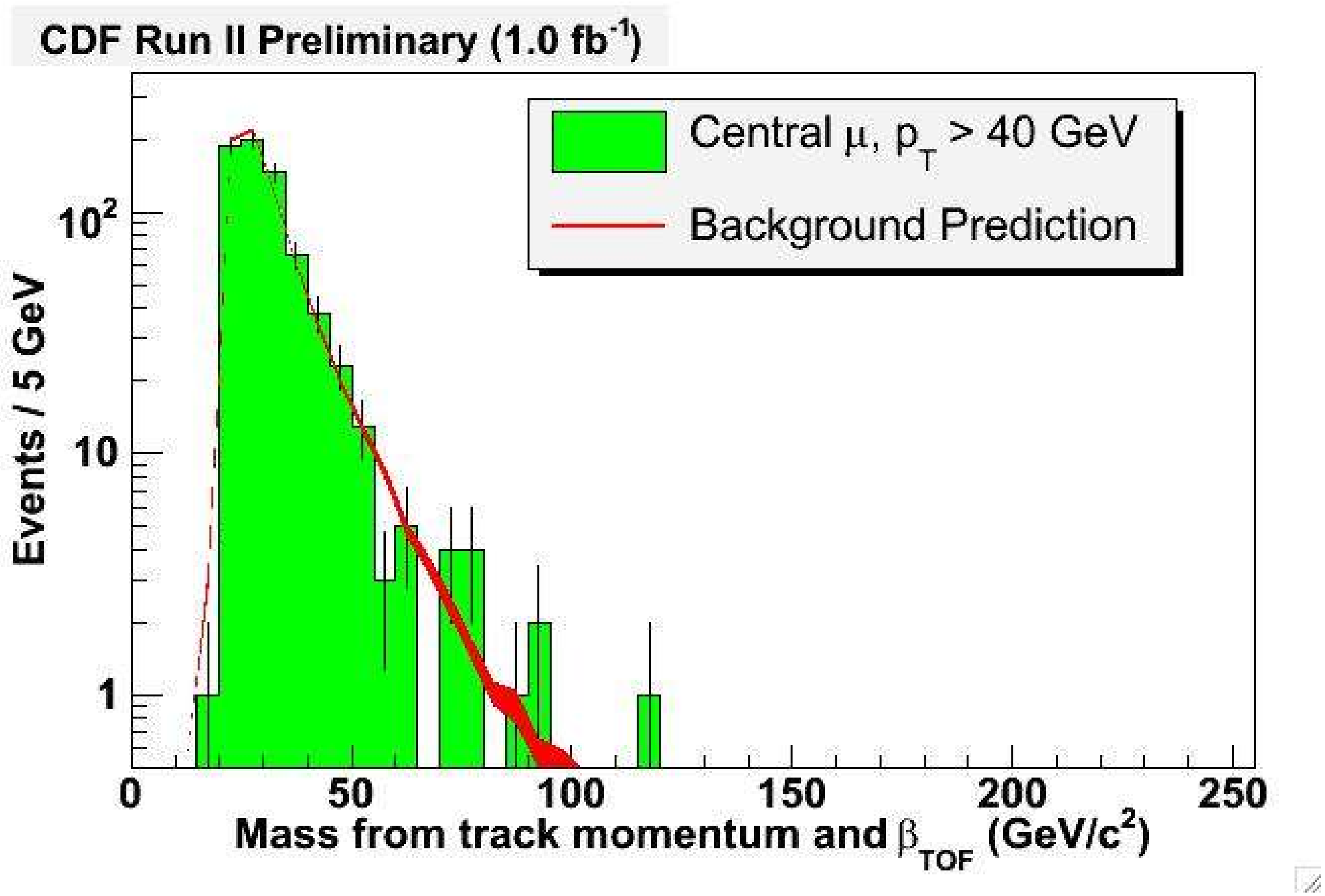
Require central muons ($|\eta| < 0.6$)

Verify background shape prediction

- use 20-30 GeV to predict 30-40 GeV region



CHAMPs – Signal Region



No CHAMP candidates above 120 GeV/c^2. Signal-region events consistent with background prediction

Model Independent Limits

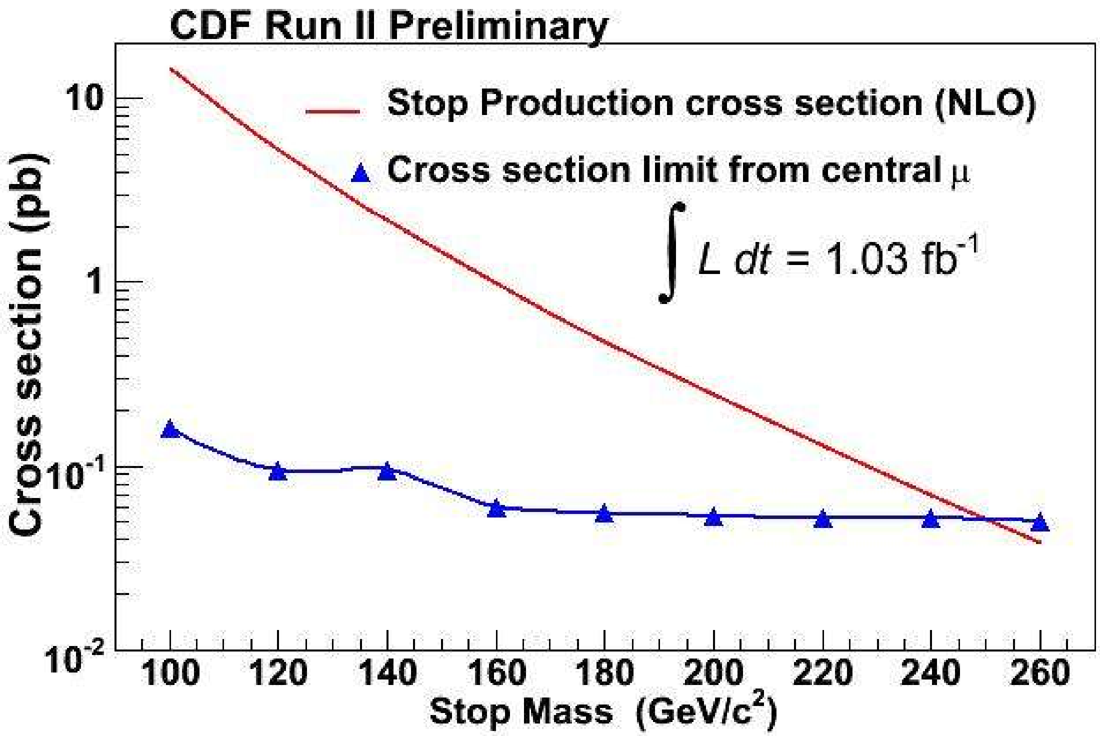
For model independence, find cross section limit for *CHAMPs fiducial to Central Muon Detectors* with $0.4 < \beta < 0.9$ and $P_t > 40$ GeV

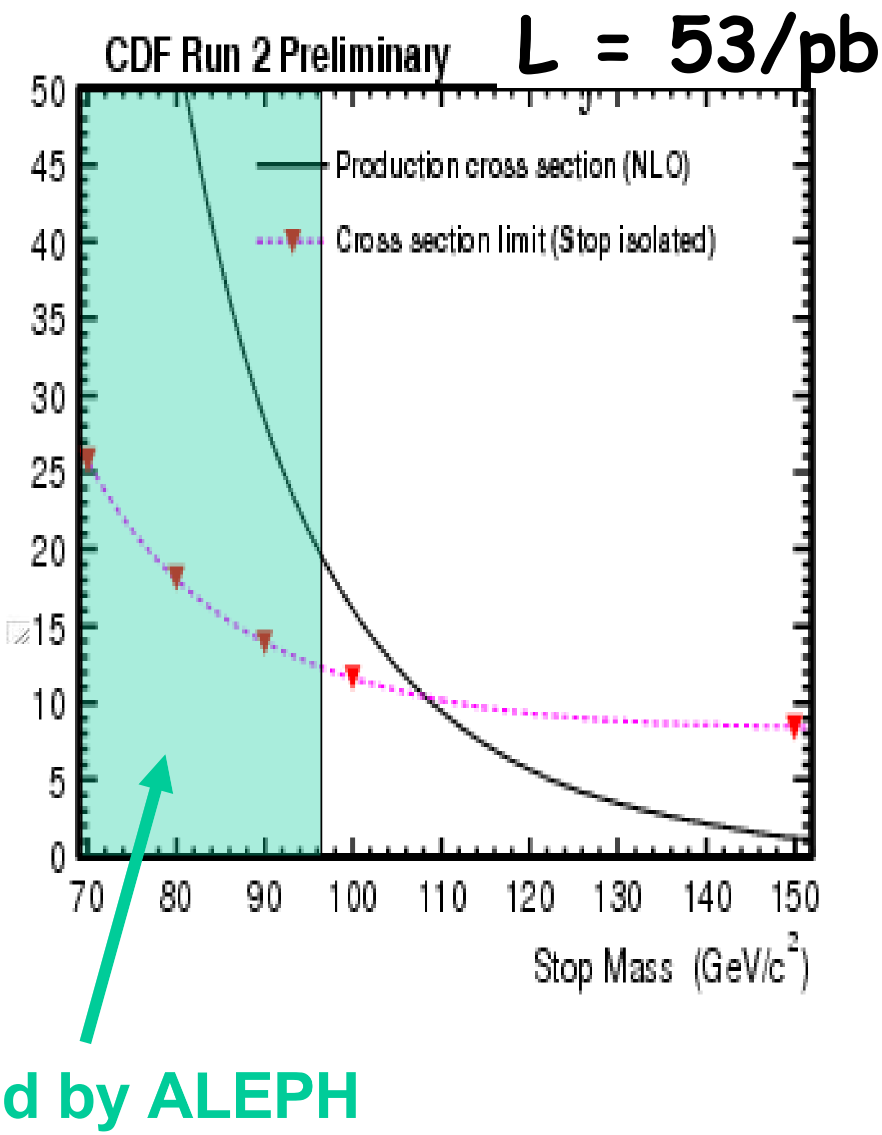
- strongly interacting (stable stop)
  - efficiency 4.6 ±0.5%
  - 95% confidence limit: $\sigma < 41$ fb
- weakly interacting (sleptons, charginos)
  - efficiency 20.0±0.6%
  - 95% confidence limit: $\sigma < 9.4$ fb

Model-dependent factors are

- β and momentum distributions
- geometric acceptance

New Stable Stop Limits





Exclude Stable Stop with mass below 250 GeV/c^2 (95% C.L.)

When We Find CHAMPs

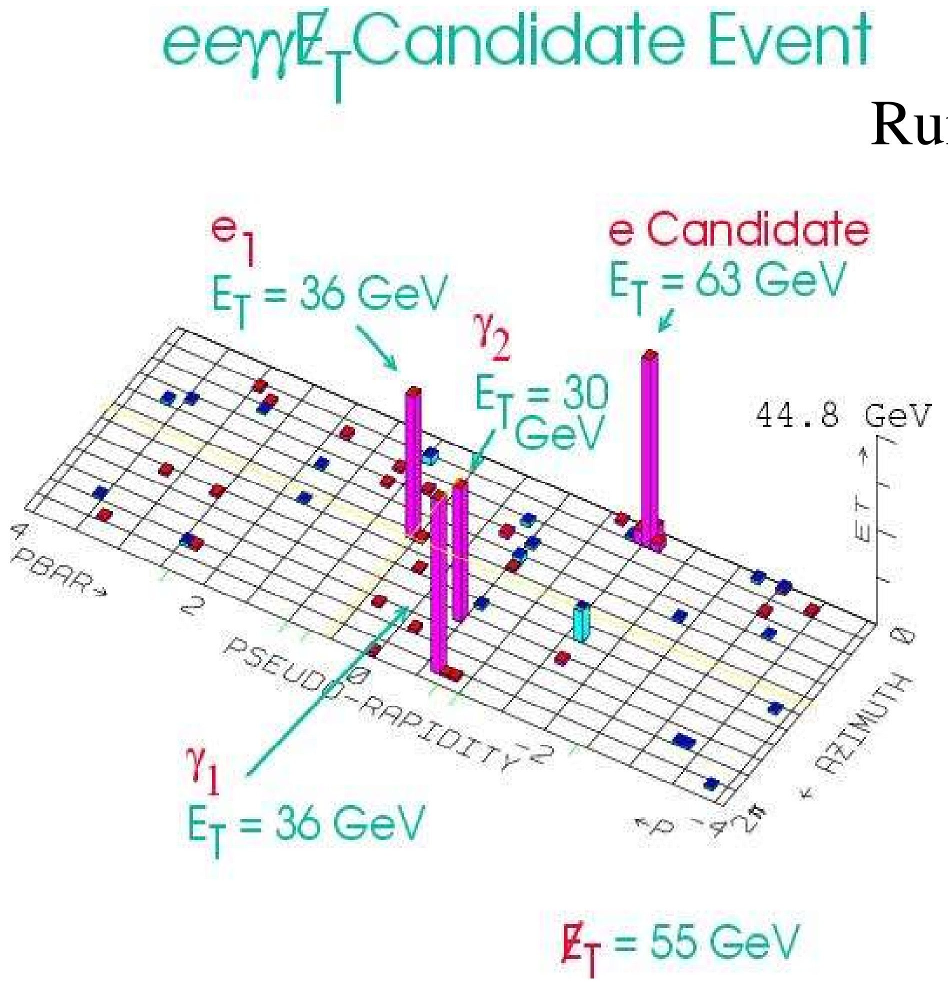
If a mass peak is observed in the CHAMP search, we have many additional handles to prove these are slow particles:

- Calorimeter timing
- Muon timing
- dE/dx

Break

Moving into neutral heavy long-lived particles

Why Photons?



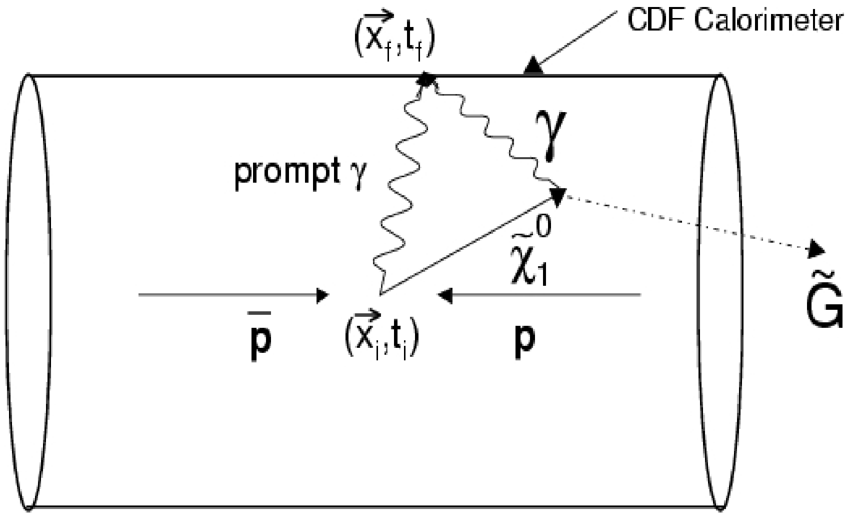
Run I

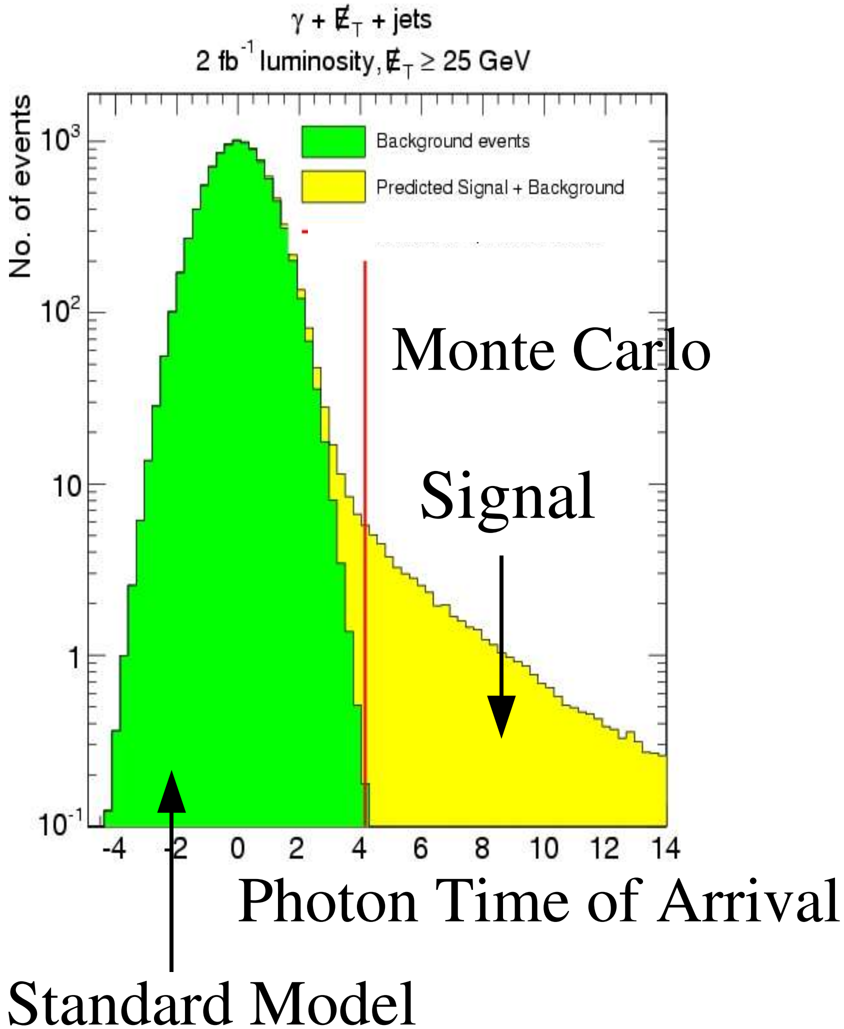
- In addition to $\gamma\gamma$+ Energy Imbalance this event has two high energy electron candidates
- Very unusual
- Total Background:

  $(1 \pm 1) \times 10^{-6}$ Events

Would be nice to have timing for the photons to prove they are from collision

Delayed Photons γ + Jet + MET





Look for non-prompt γ's that take longer to reach calorimeter.
If the χ^0 has a significant lifetime, we can separate the signal from the backgrounds.

Analysis Strategy

Sample - gamma + Jet + MET

look for photons that are late

Want to understand time shapes from various backgrounds

Non-collision backgrounds

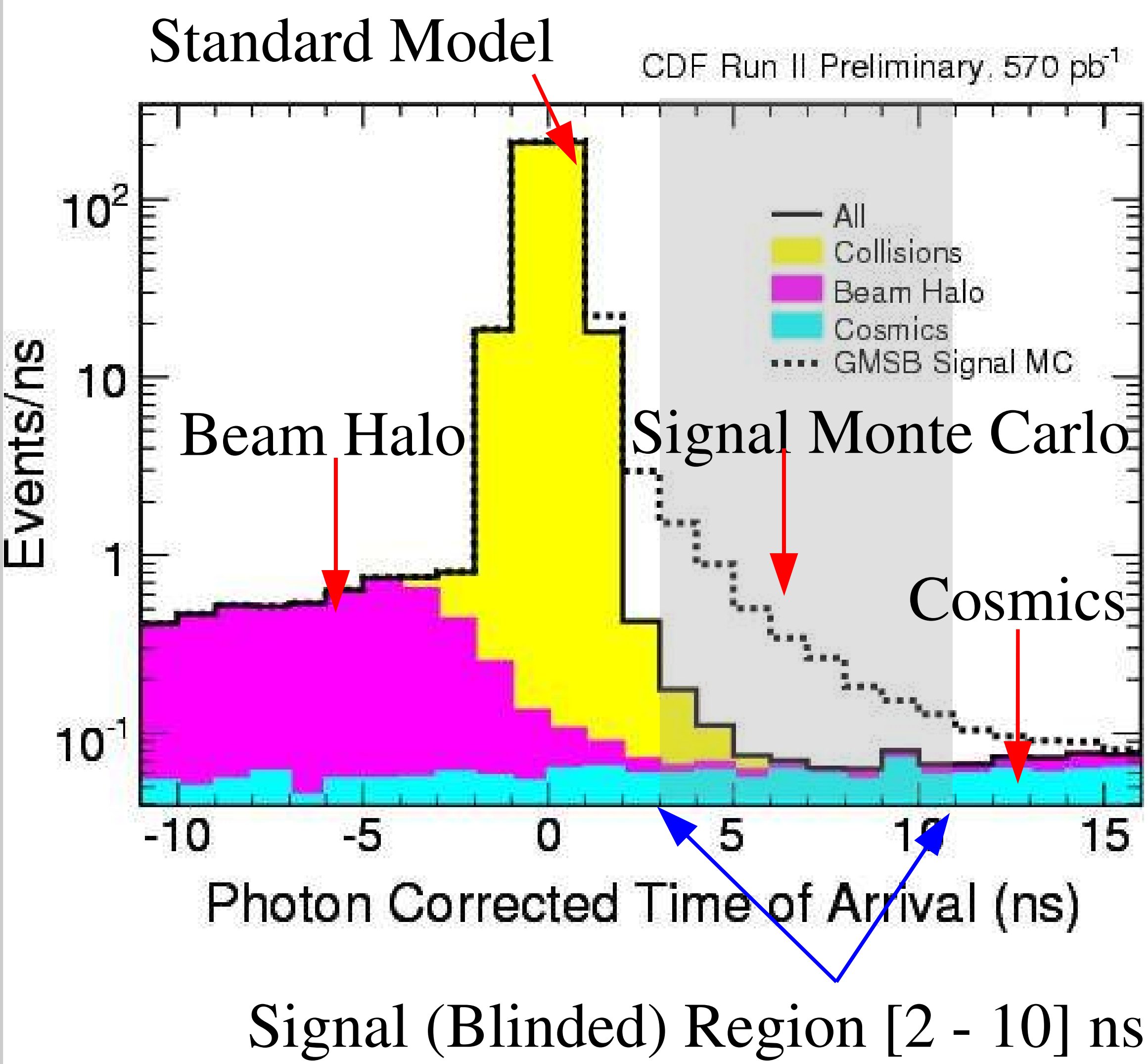
- general shape from no-track events
- separate beam halo from cosmics

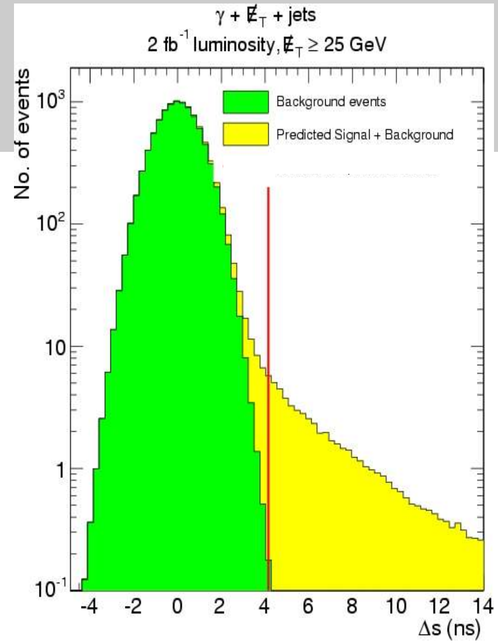
Standard Model Background

- event T0 dominates the resolution – have to subtract
- background splits in two
- guessed the primary vertex correctly
- guessed the primary vertex incorrectly

We use data in various control regions to normalize shapes and obtain background prediction in the signal region

Delayed Photons





Four Background Sources

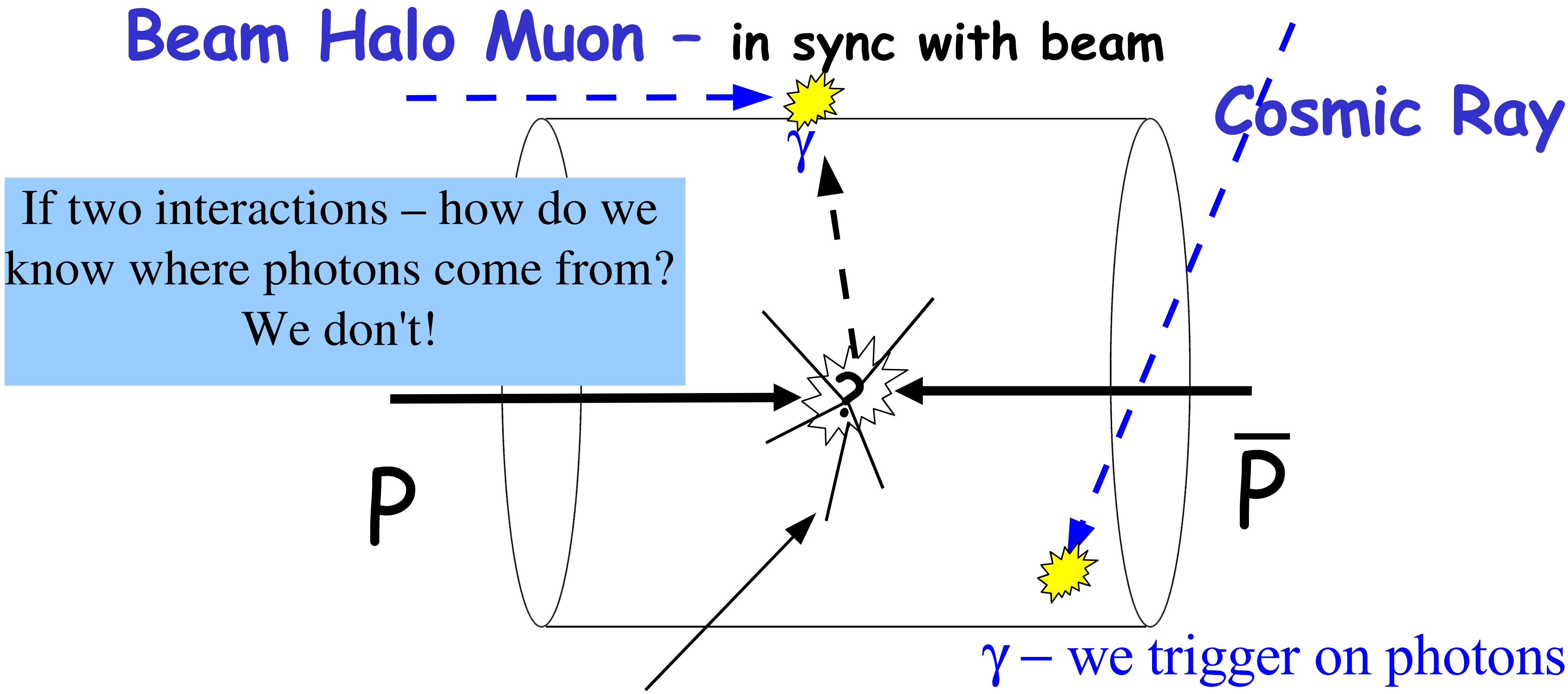
Non-collision "look-like photons"

- **Cosmics**
- **Beam Halo**

Collision photons from Standard Model

- **Right vertex**
- **Wrong vertex**

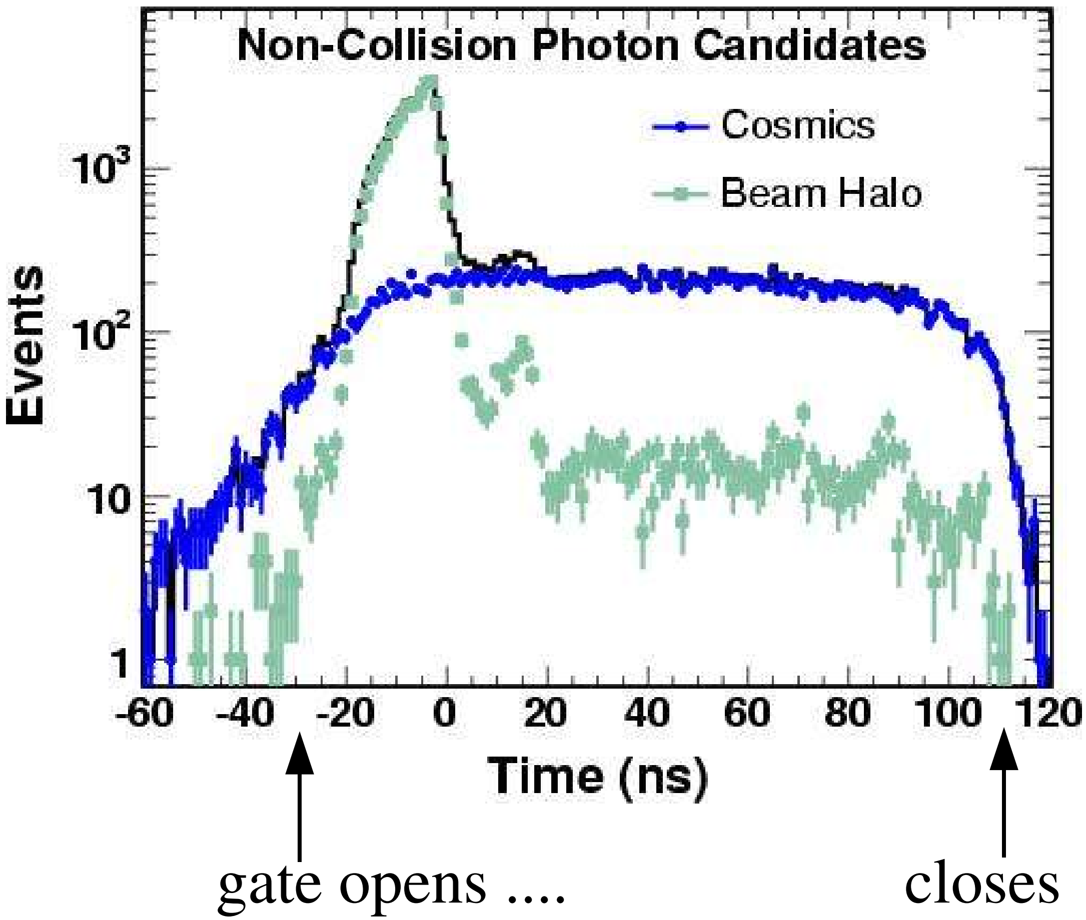
Backgrounds



Tracks – P_T and time are measured by the tracking chamber => can reconstruct event origin in time

Non-Collision Backgrounds

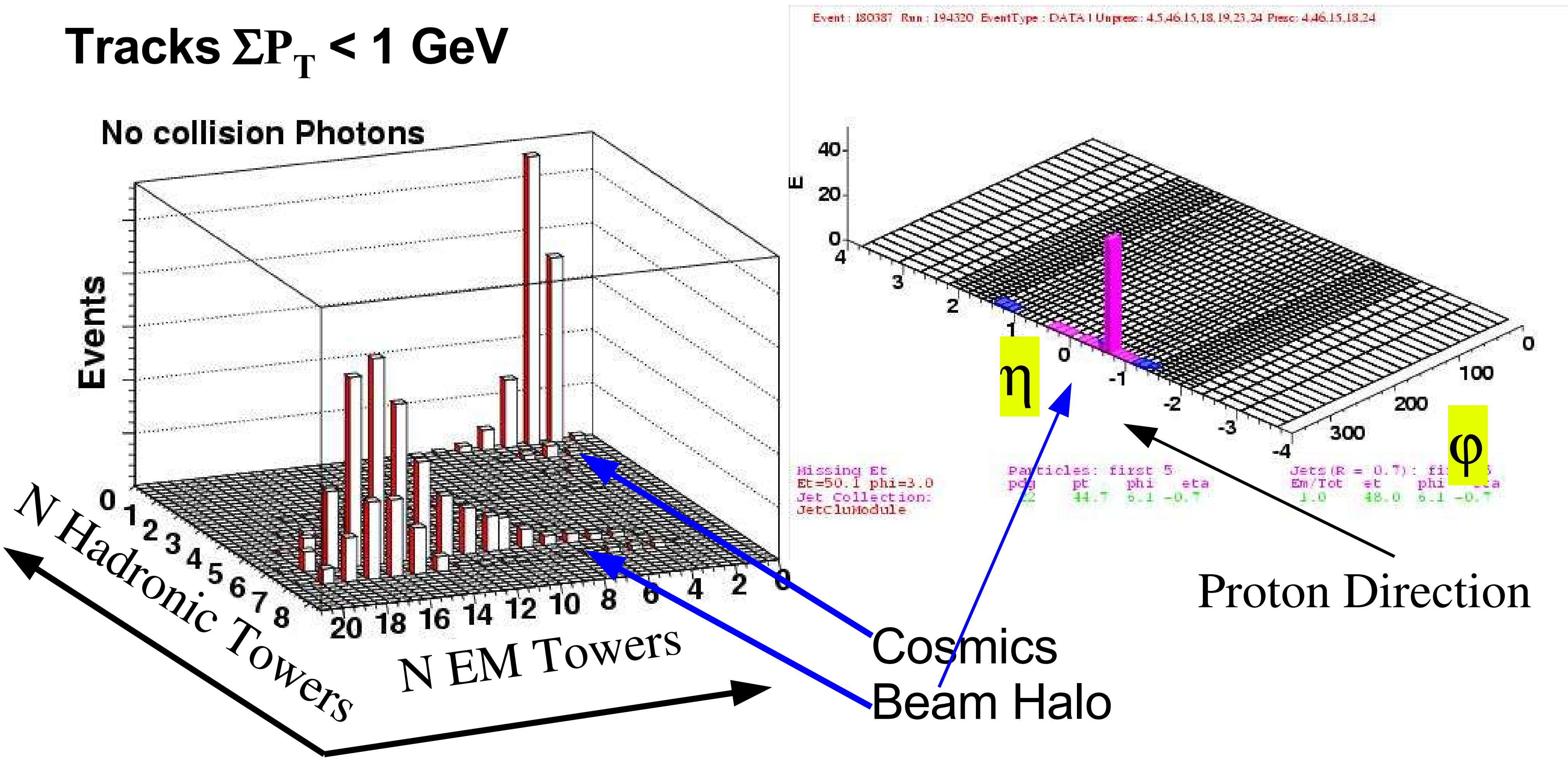
- There are lots of tracks in typical collision.
- Non-collision means there are no tracks.
- Cosmics are accidents - flat in time
- What about beam halo?



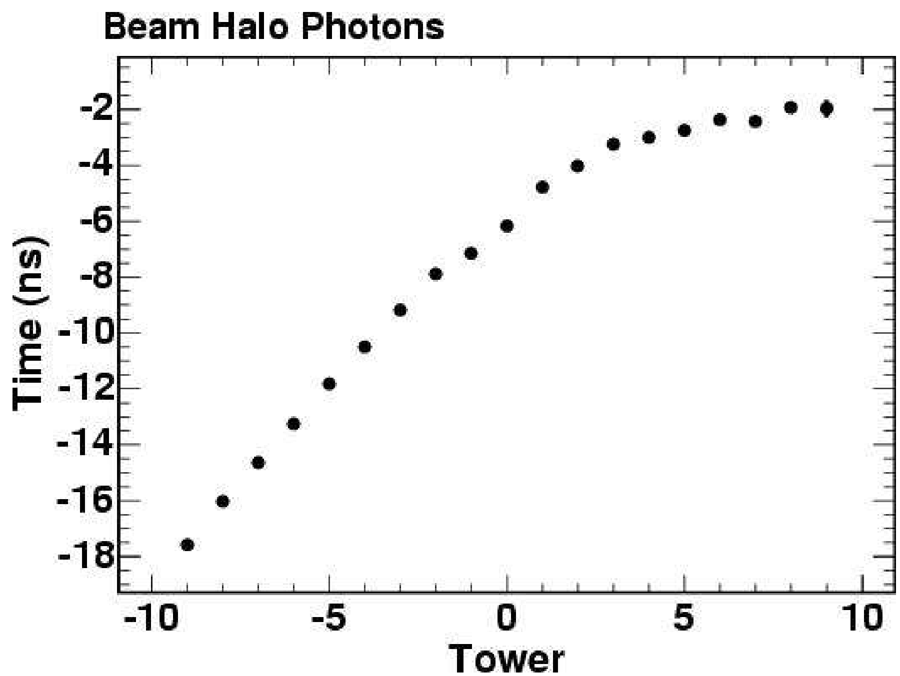
- Most would choose |T| < 6 ns
- We use shapes predictions

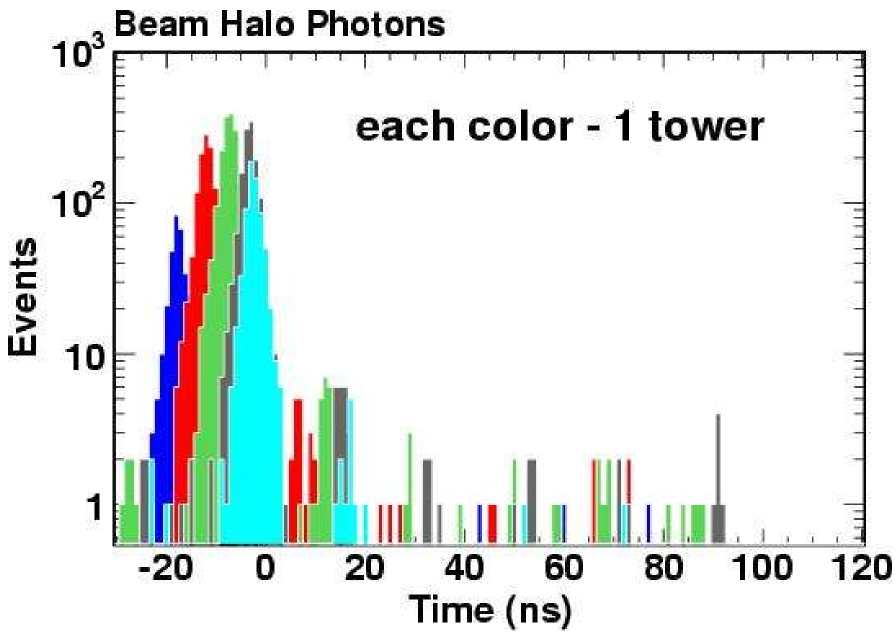
Cosmics vs Beam Halo

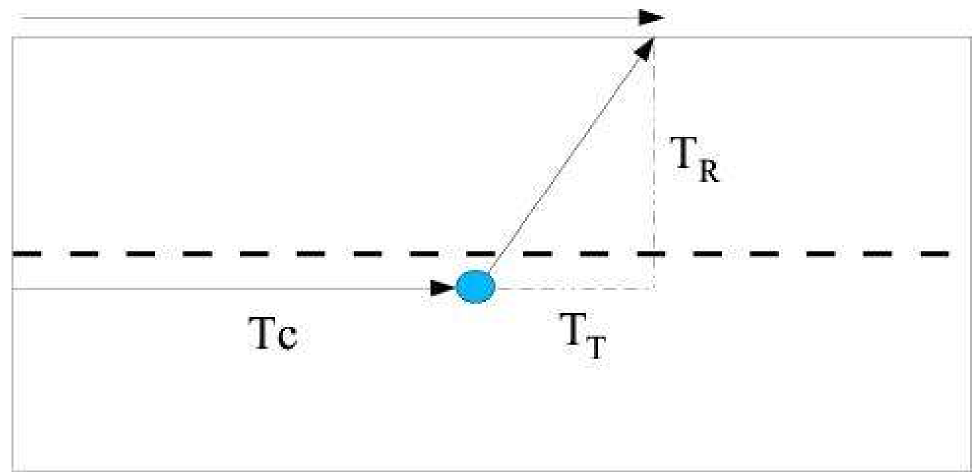
Tracks ΣP_T < 1 GeV



Beam Halo Time Shape







$$t(collision) = T_C + \sqrt{(T_T^2 + T_R^2)}$$

$$t(halo) = T_C + T_T$$

$$\delta t = T_T - \sqrt{(T_T^2 + T_R^2)}$$

$$Tower\ -9: \delta t \approx -2 T_T$$

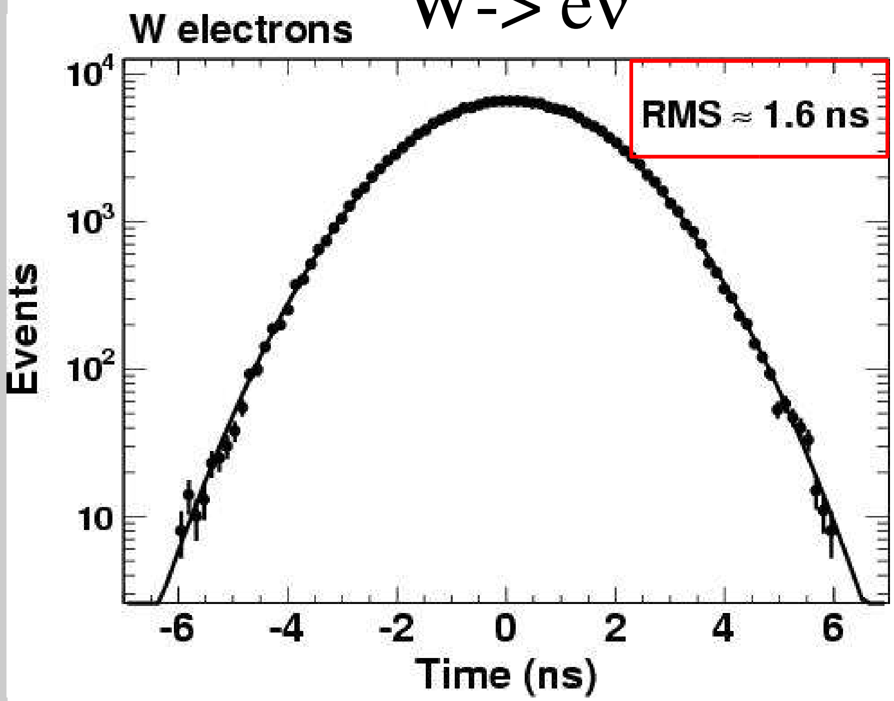
$$Center: \delta t \approx -T_R + T_T$$

$$Tower\ 9: \delta t \approx -\frac{T_R^2}{2 T_T}$$

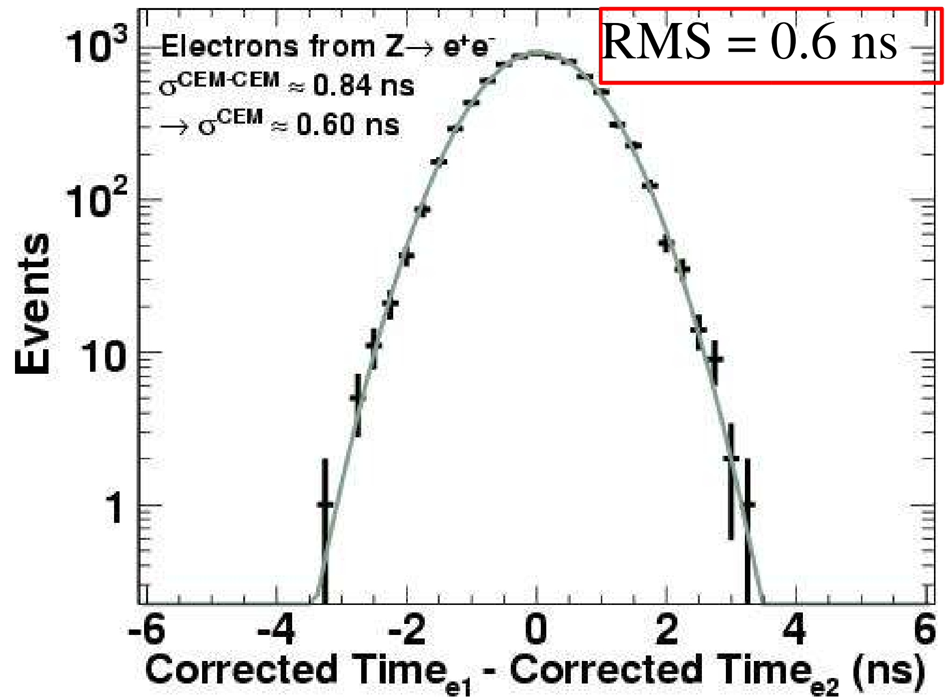
Timing Resolutions

This is how one normally measures true system resolution:

W-> eν



Z-> ee



WHEN interaction happens - RMS≈1.3 ns

It has to be subtracted from the photon arrival time

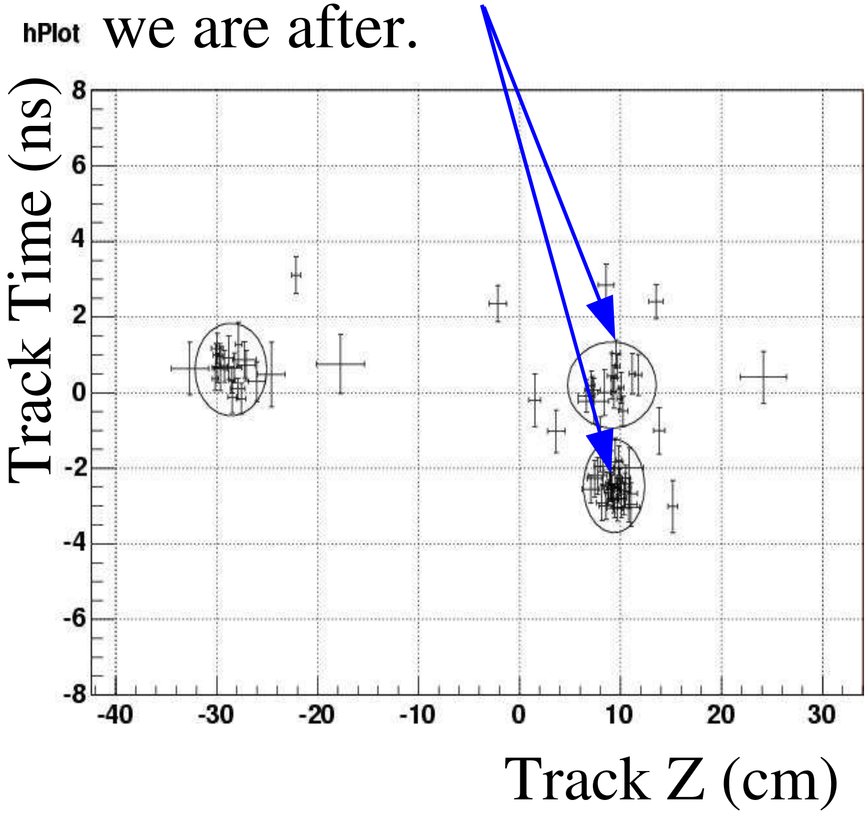
Need to reconstruct vertices in space and time

Collision Time Reconstruction

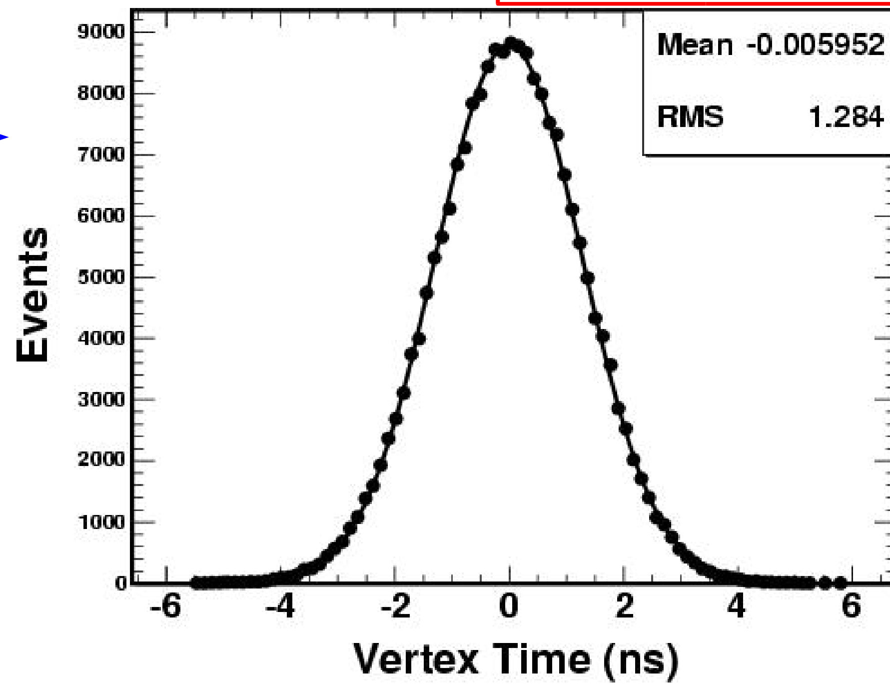
For tracks we reconstruct Z position along the beamline and time as measured by the tracking drift chamber (COT):

- plot all tracks on Z-Time plane
- do clustering

Separating those two is what we are after.



RMS = 1.28 ns



Standard Model Photons

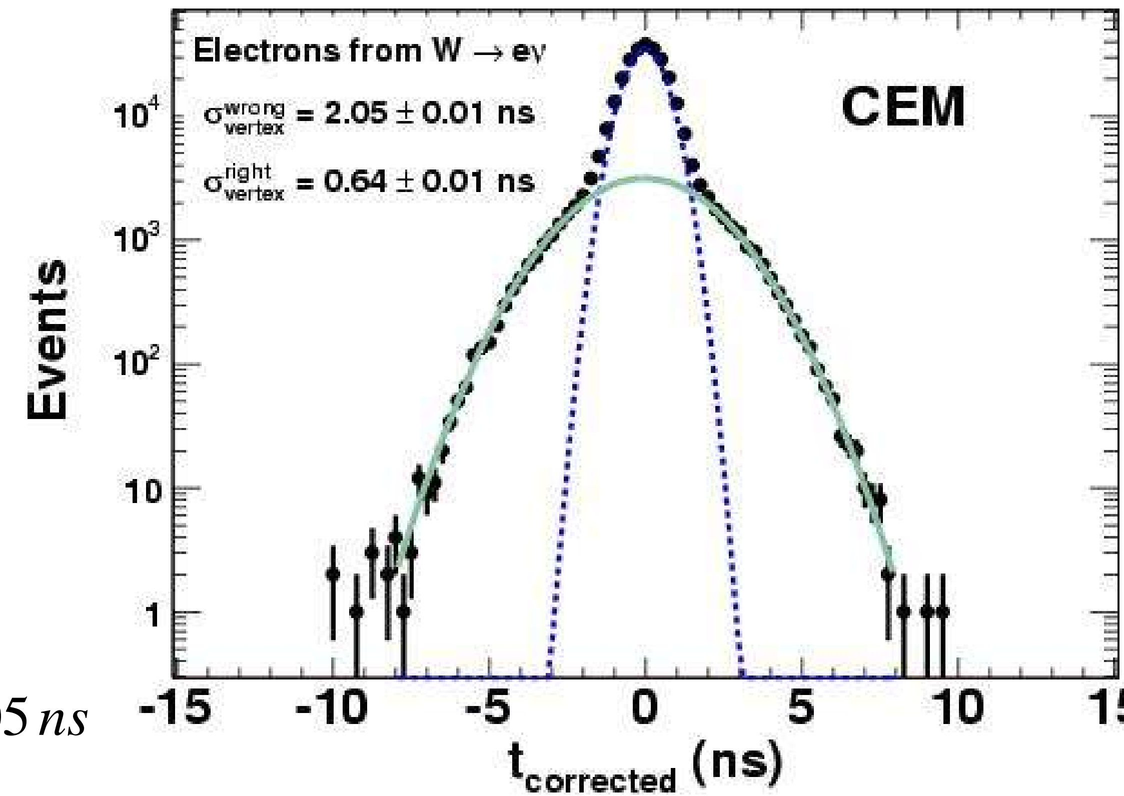
Assigning the right vertex is a tricky business as L gets high
We can measure how often mistake is made

Standard Model (SM) photon candidates
- Right vertex
- Wrong vertex

When wrong vertex picked:

$$\sigma = \sqrt{(\sigma^2(e) + \sigma^2(vertex))} = \sqrt{(1.6^2 + 1.3^2)} \simeq 2.05\, ns$$

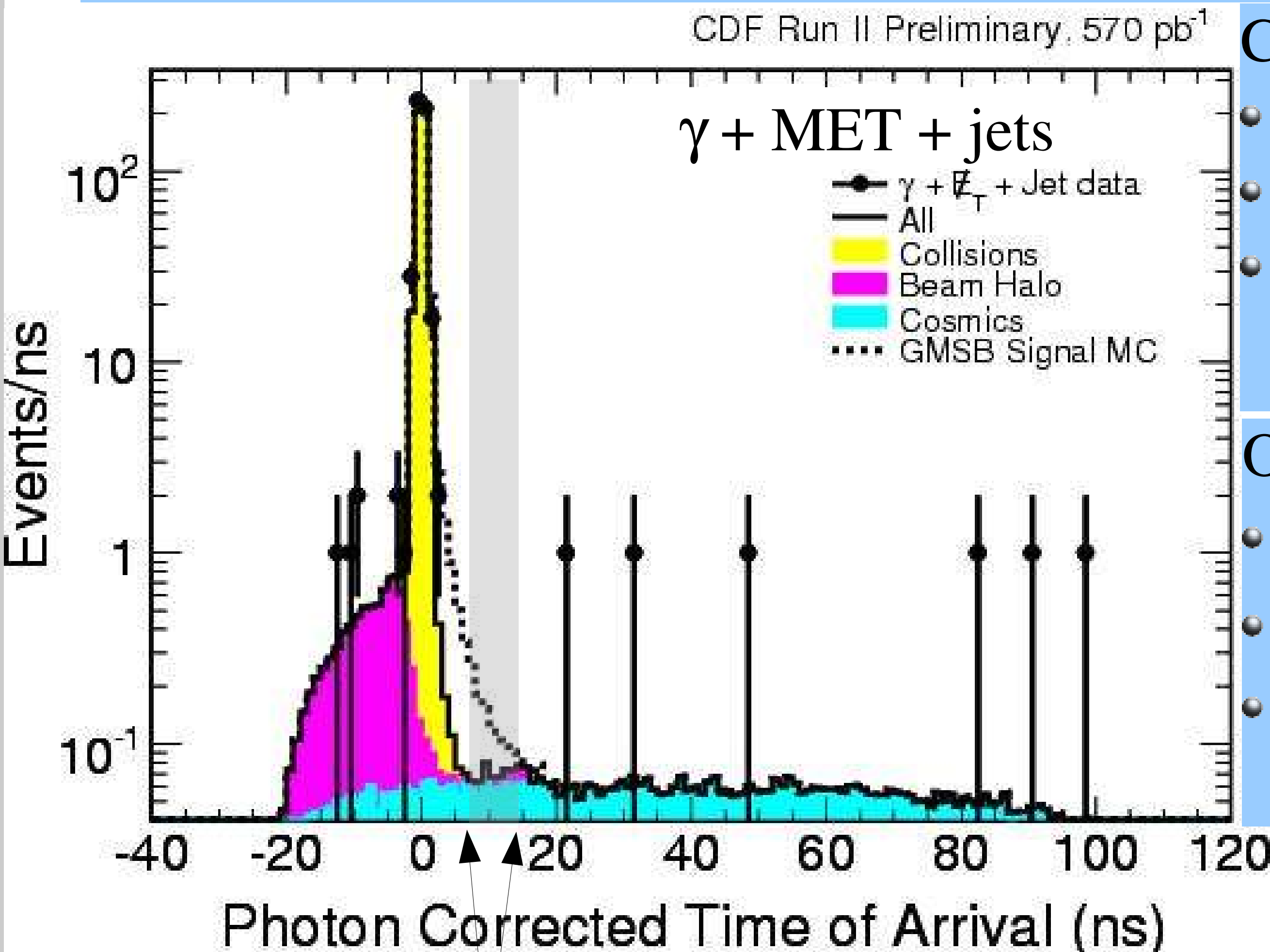
Electrons



With electrons we simulate what happens with photons by excluding electron track from vertex reconstruction

Putting It All Together

Normalize shapes to data outside the blind region



signal (blinded) region

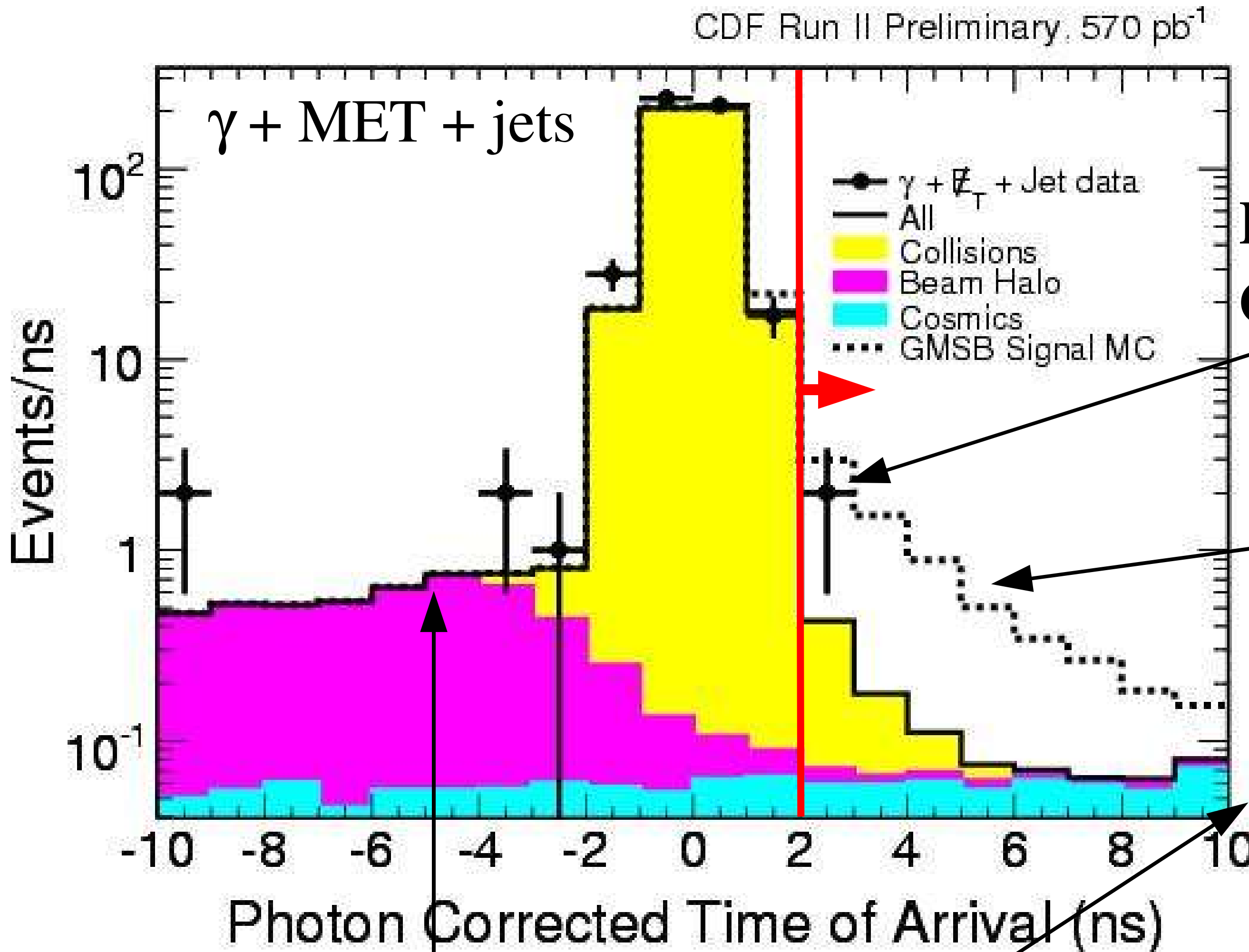
Control Regions:

- Cosmics : 30 80 ns
- Beam Halo: -20 -6 ns
- Collisions : -6 1.2 ns

Optimize for best sensitivity:

- Photon E_T>30 GeV
- Jet E_T>35 GeV
- MET>40 GeV

Delayed Photons



Predicted: 1.3 ± 0.7 events

Observed: 2 events

Would be +6 event for GMSB point:

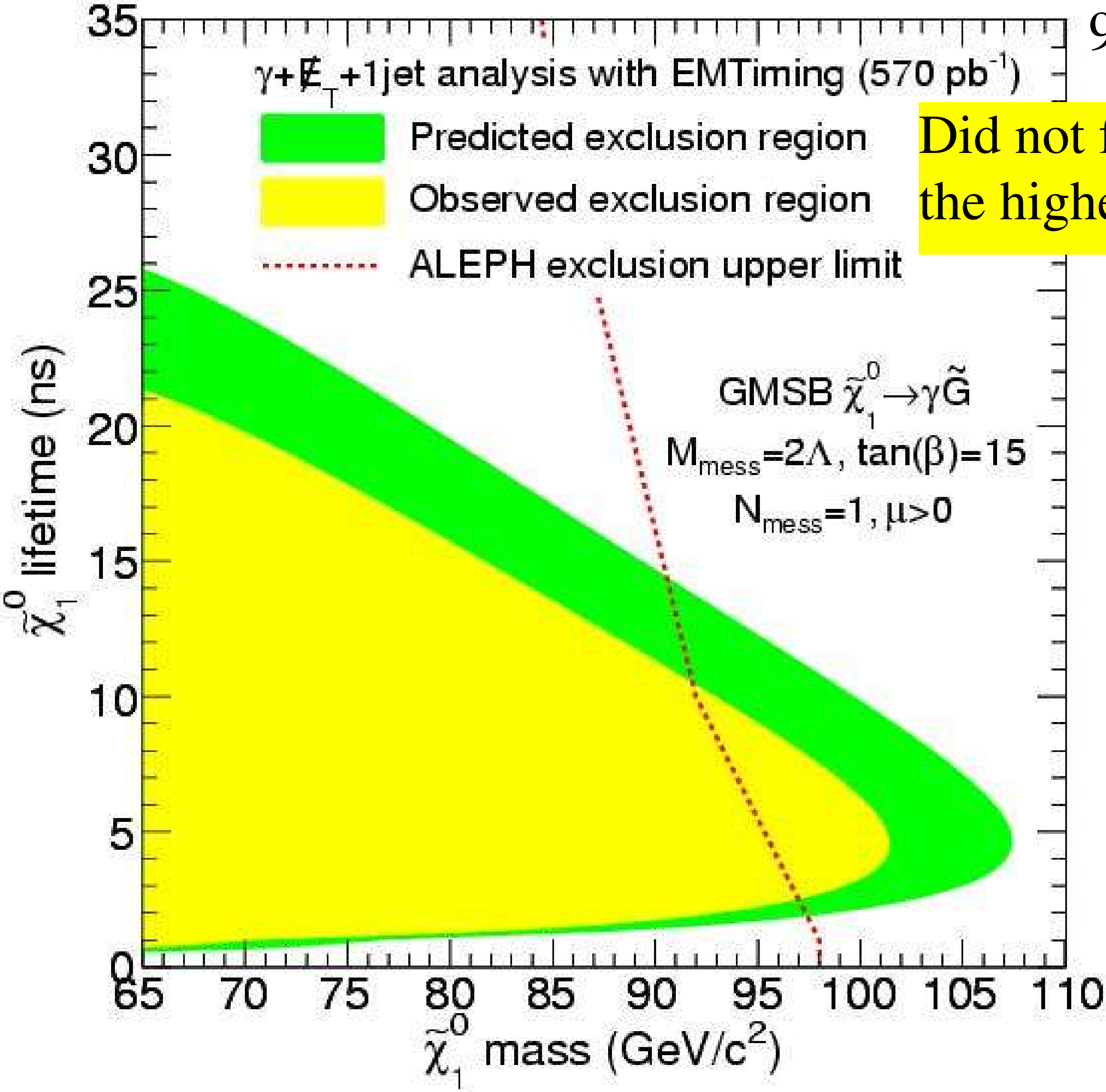
m(χ) = 100 GeV

τ(χ) = 5 ns

We know shapes

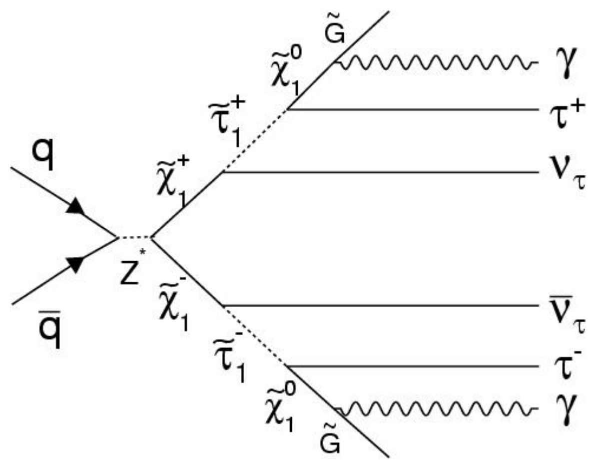
- normalize to events in control regions
- count events in signal region (2-10) ns

Delayed Photons?



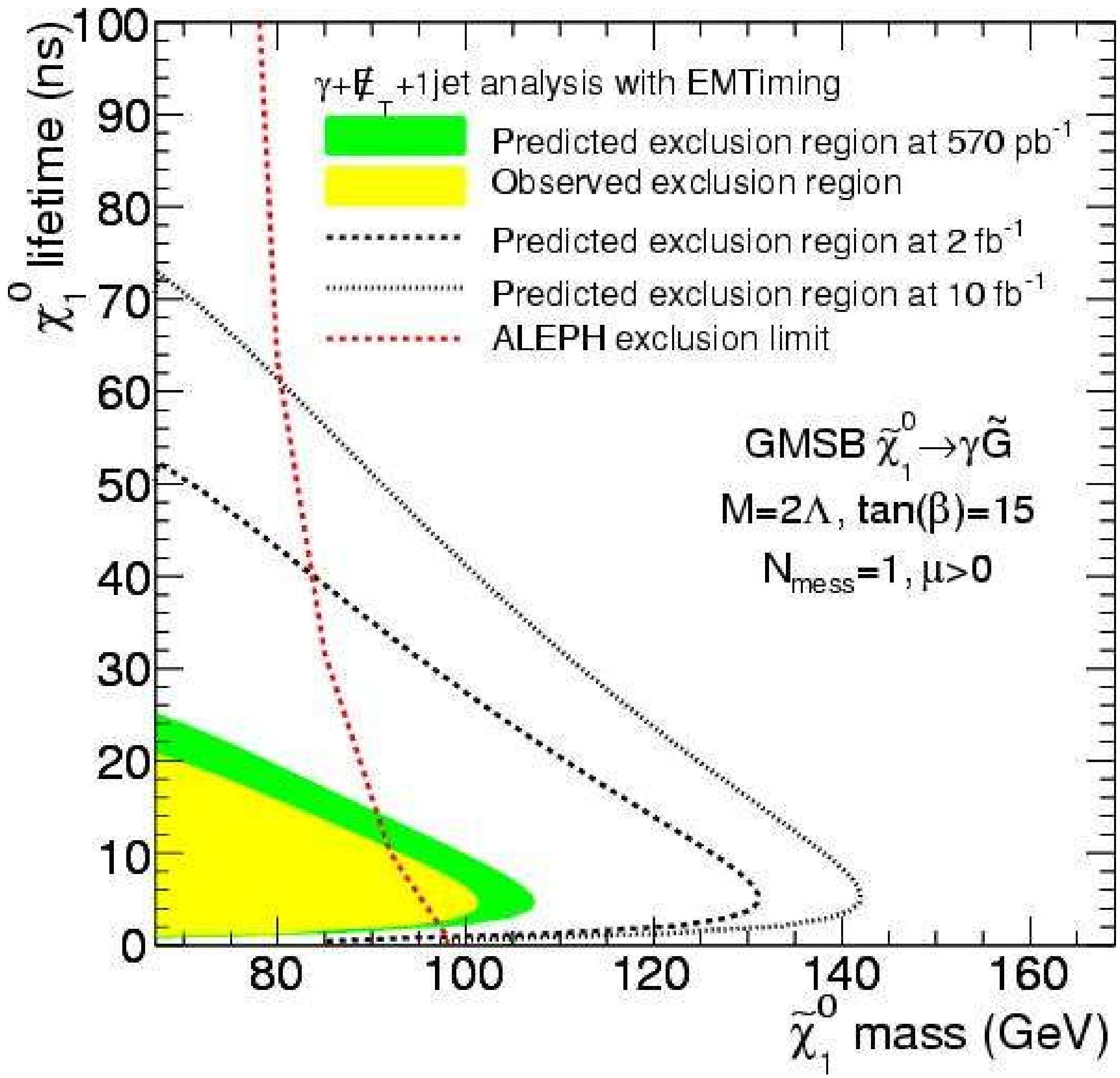
95% C.L.

Did not find anything, but have the highest sensitivity



Analysis with More Data

more data is available



What is Next?

CHAMPs $\beta>0.4$
Late Tracks

Delayed Photons

Track Timing
Calorimeter Timing
Non-Collision Rejection

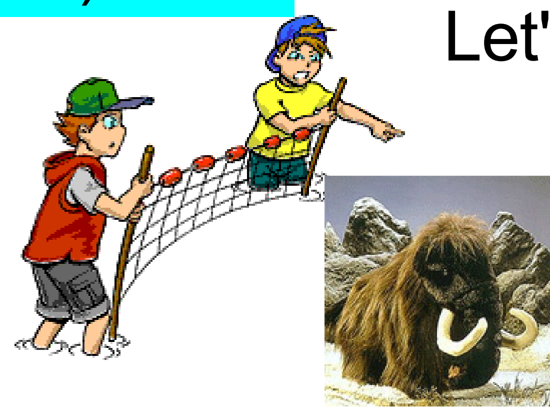
Exclusive γ+MET
(KK states ...)

Champs $\beta<0.4$
Delayed Jets

Displaced Vertex
(Hidden Valley ...)

Highly Displaced Vertex
(Hidden Valley ...)

Let's catch it !



Backup Slides

Outlook

Popular exotic signature:
2Photons + MET

Understand Collisions,
Track timing,
Cosmics and Beam Effects

CHAMPs

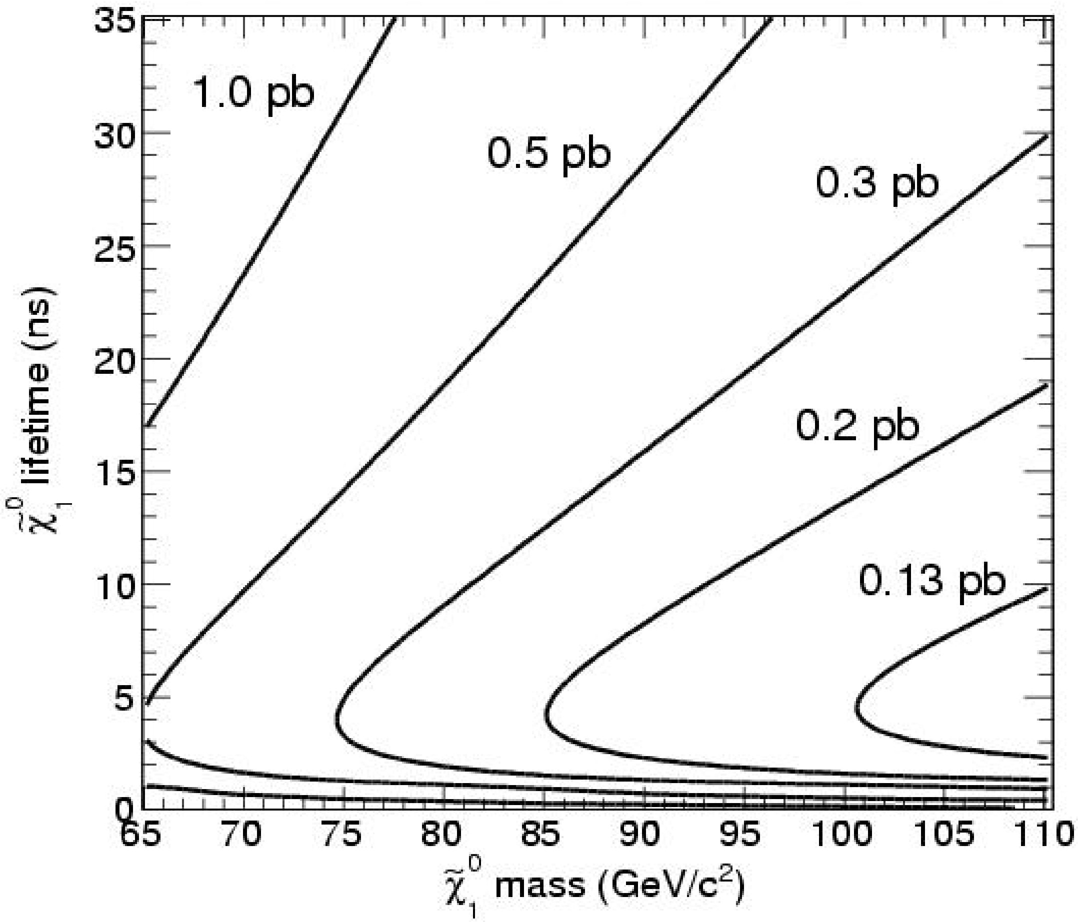
Delayed Photons

Escaping Susy

Delayed Jets

Displaced Vertices

Model Independent Limits



➢ Supersymmetry:

- stable stop squark (We use this as our reference model)
  - R. Barbieri, L.J. Hall and Y. Nomura PRD **63**, 105007 (2001)
- NLSP stau in gauge-mediated SUSY breaking
  - J.L. Feng, T. Moroi, Phys.Rev. D58 (1998) 035001
- Light strange-beauty squarks
  - K. Cheung and W-S. Hou, Phys.Rev. D70 (2004) 035009

➔ Light strange-beauty squarks
  - Matthew Strassler, HEP-ph/0607160

➢ Universal Extra Dimensions (UXDs)

- Kaluza-Klein modes of SM particles
  - T. Appelquist, H-C. Cheng, B.A. Dobrescu, PRD 64 (2001) 035002

➢ Long-lived 4th generation quarks

  - P.H. Frampton, P.Q. Hung, M. Sher, Phys. Rep. 330 (2000) 263-348.

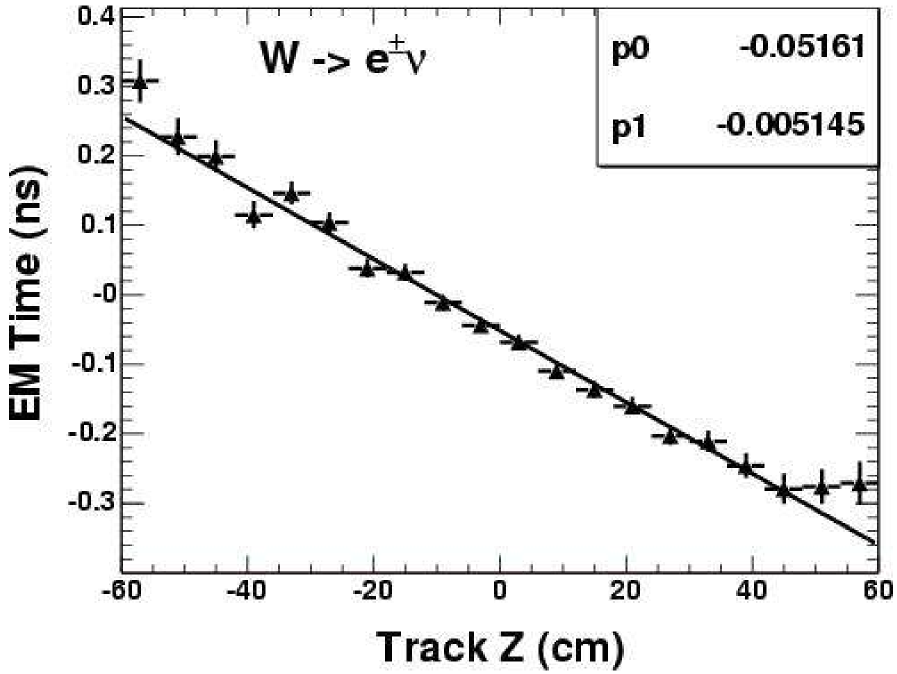
Reasons to live

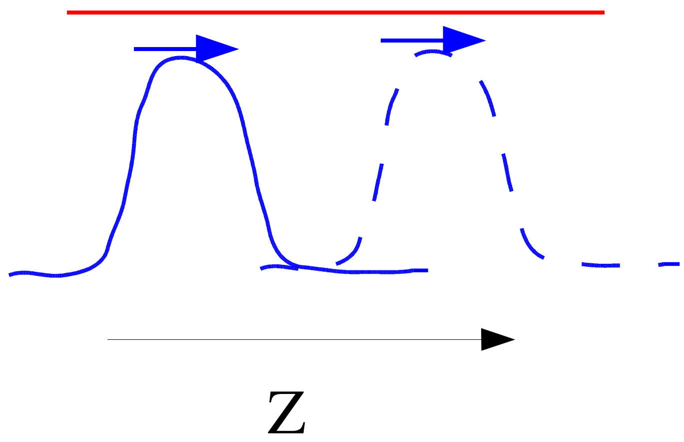
➔Particles can be long-lived if they have:

- weak coupling constants
- limited phase space
- a conserved quantity
- “hidden valley” (potential barrier)

Beam Longitudinal Width

p and p-bar bunches have different width =>
collision time is correlated with the collision location





Average z position of the interaction is given by
$Z = \exp(-(z-ct)^2/\sigma^2(p))*\exp(-(z-ct)^2/\sigma^2(pbar))$

$\sigma(p) = 55$ cm
$\sigma(pbar) = 65$ cm

Stable Stop

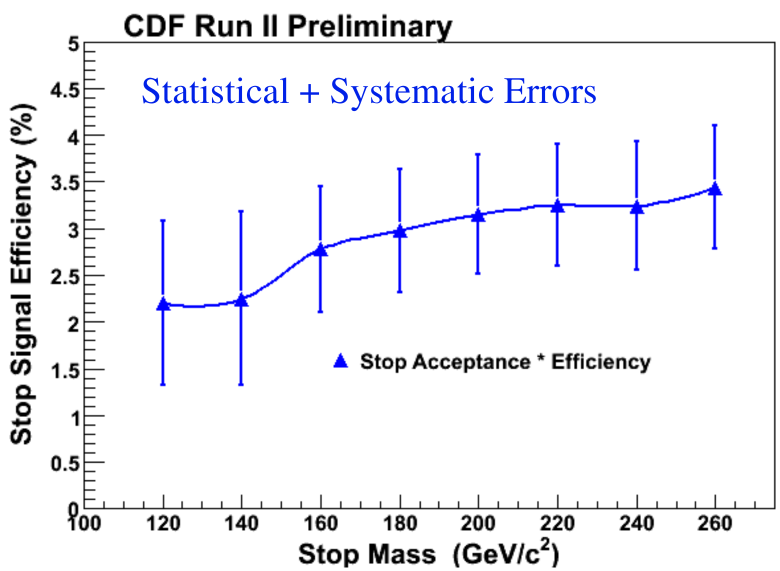
Look at Stable Stop (reference model)

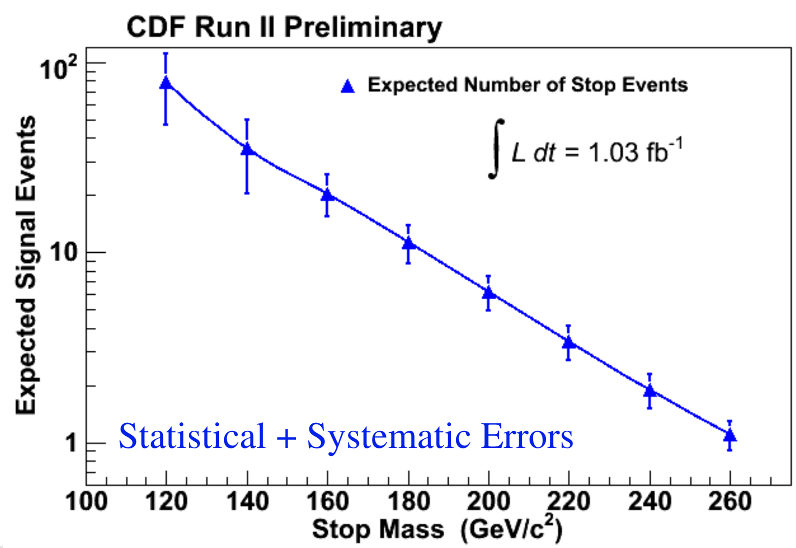
R. Barbieri, L.J. Hall and Y. Nomura PRD **63**, 105007 (2001)

➔Pair produced

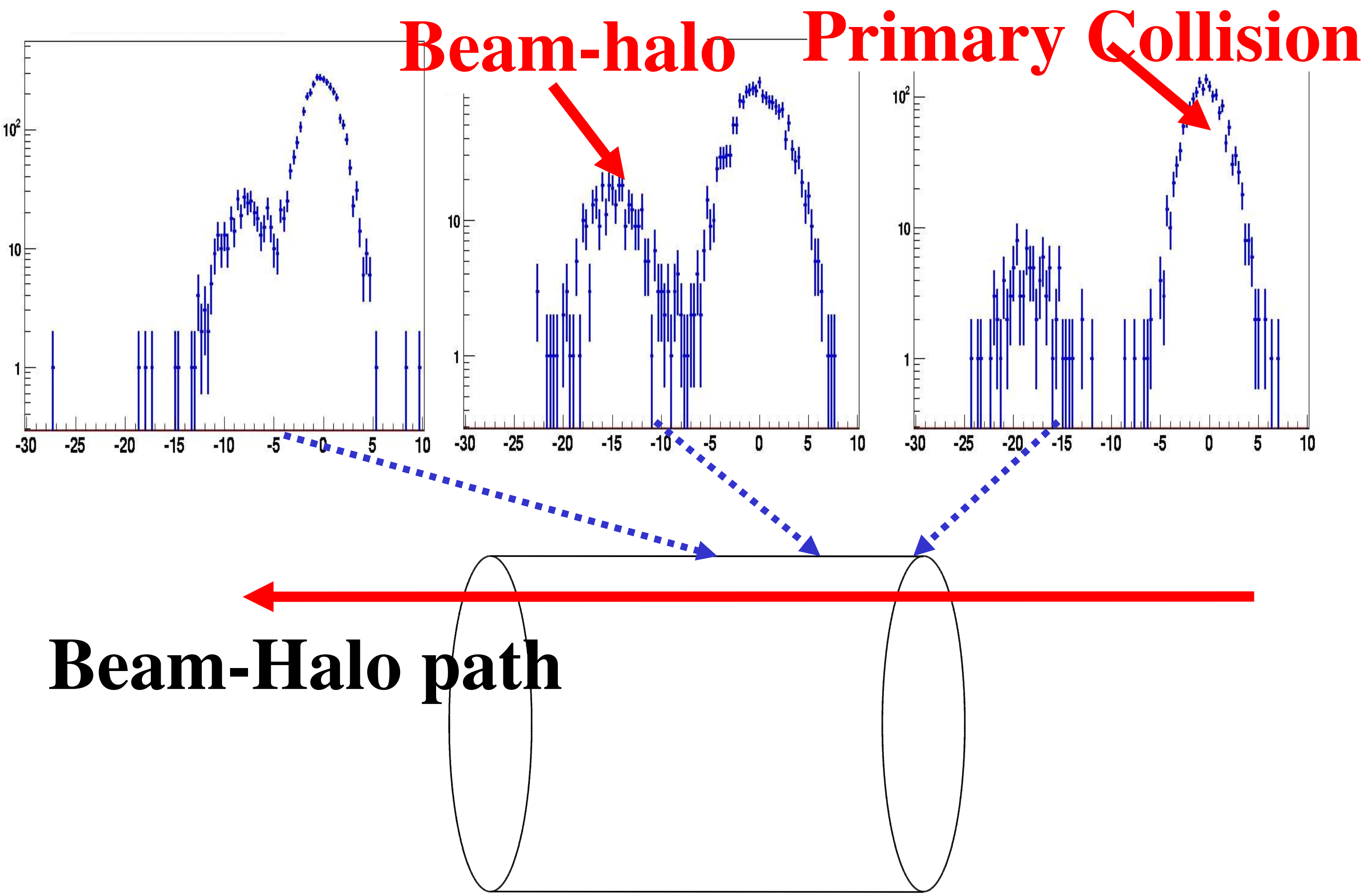
– Get kinematic and geometric acceptance
  - Pt > 40 GeV; 0.9 > β > 0.4; TOF Fiducial

– Must be charged:
  - in tracking chamber for identification
  - in muon detectors for trigger





Speed of Light with Beam Halo



Measure speed of beam-halo to be $2*10^8$ m/s

Which Model to Pick?