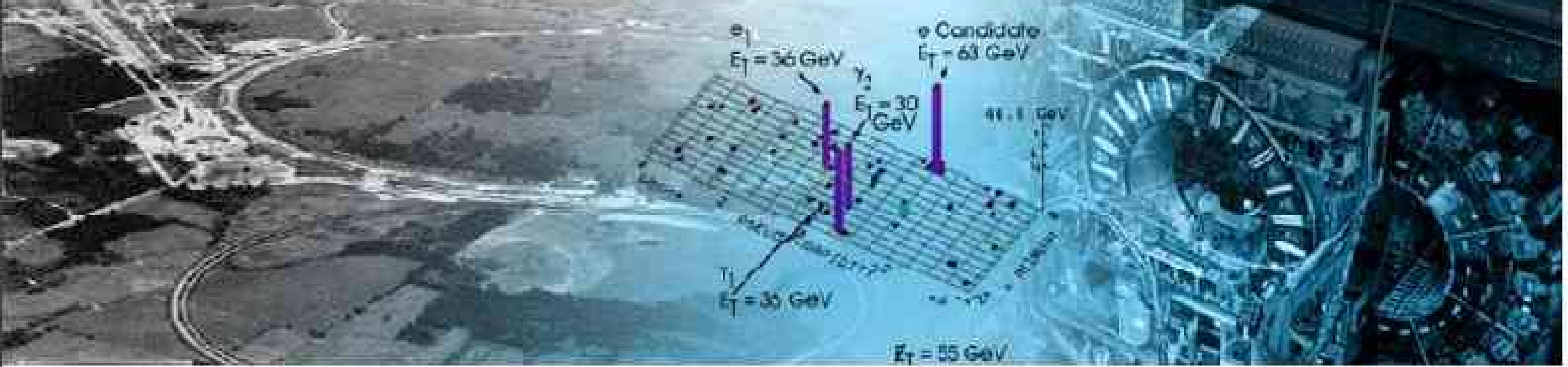


Searches for Heavy Long Lived Particles at Tevatron

Max Goncharov, Texas A&M University

In This Talk ...

- **Massive Long Lived Particles**

some theories and signatures

- **Timing Detectors**

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

- **Charged Massive Particles (a.k.a. CHAMPs)**

result from CDF with 1 fb^{-1}

- **Neutral Massive Particles (a.k.a. delayed photons)**

result from CDF with 600 pb^{-1}

- ***Search for Stopped Gluinos***

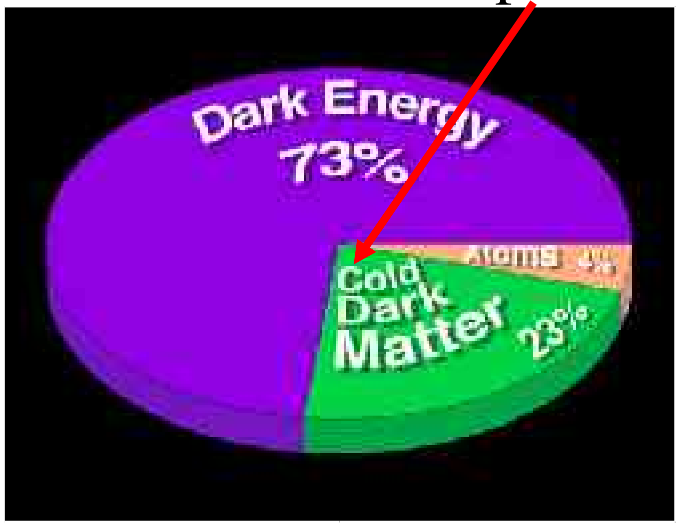
result from D0 with 410 pb^{-1}

- **Where we would like to go**

future searches

Dark Matter

Want to find those particle



Many different theories.

Which direction to go?

Should look everywhere: the answer might be in an unexpected place

➢signature based searches

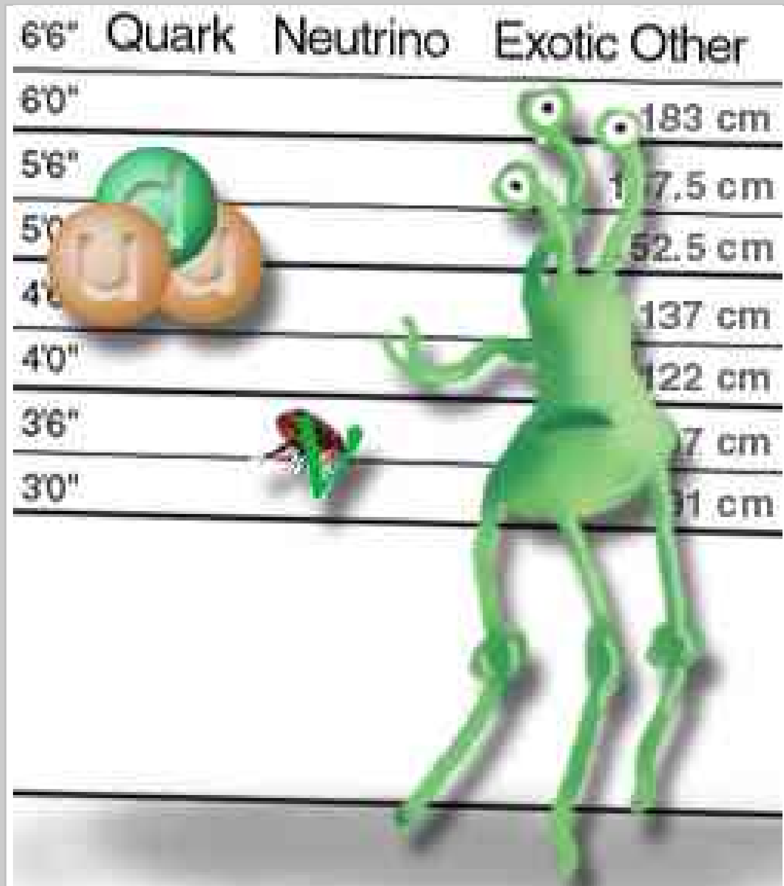
Stable Massive Particles

Standard Model extensions predict new massive particles.

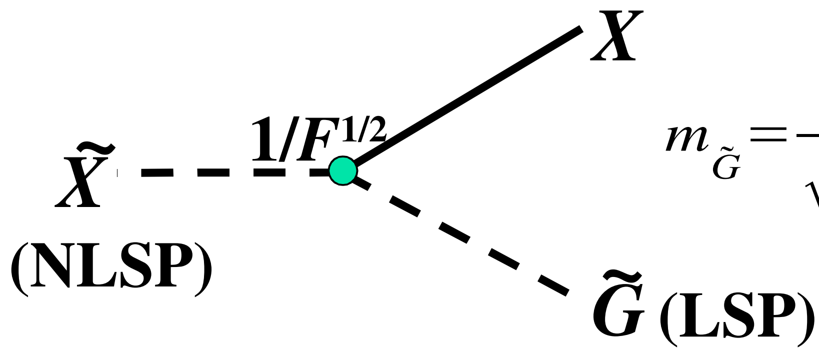
Long Lifetime arises from various cosmological observations.

- Most searches assume particles decay promptly
- Long-lived particles would evade these searches
  - 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)

Massive and Long-Lived



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



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

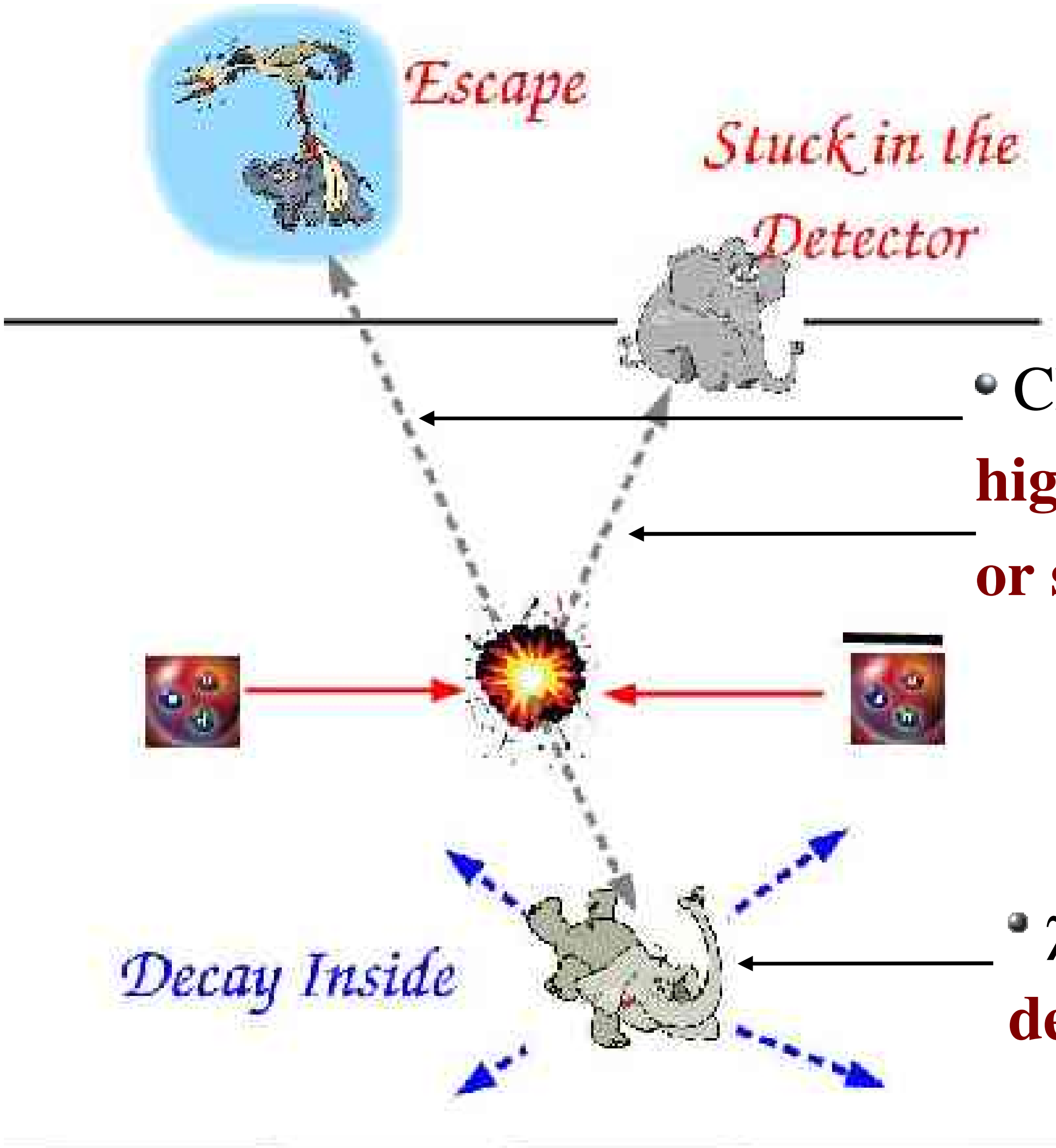
Wide variety of models:

- 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

Possible Signatures



- CHAMP – charged massive particle

highly ionizing/late track

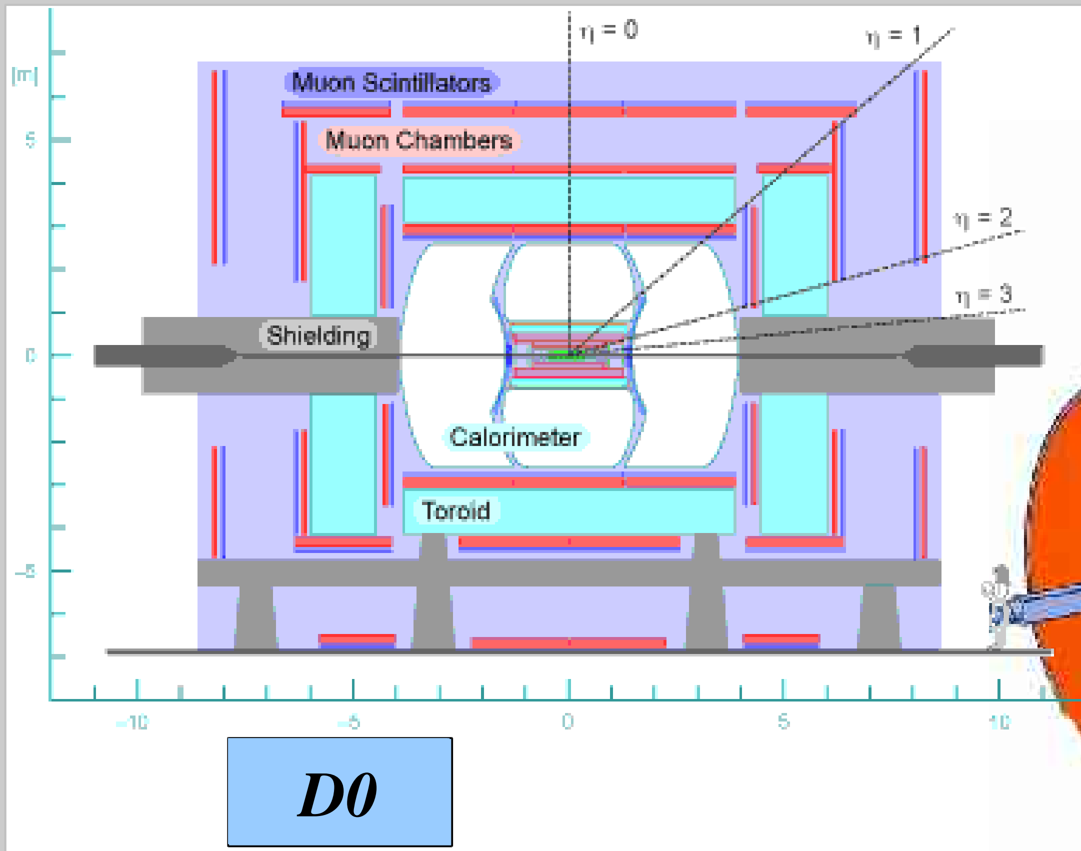
or something stuck in the detector

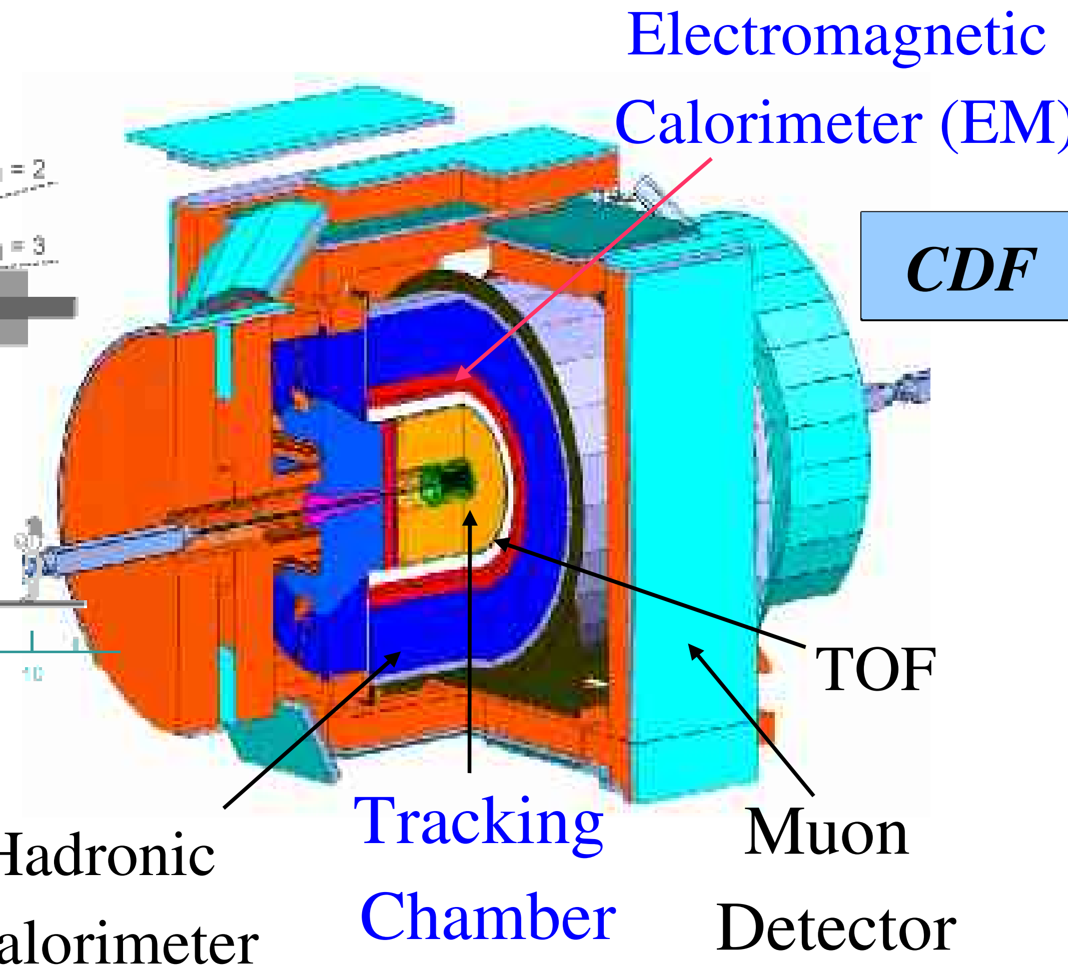
- χ^0 decaying inside the detector:

delayed photons

signatures should be spectacular

CDF Detector





CHAMPs – tracking, calorimeters, TOF, muon

Delayed Photons – tracking, EM calorimeter

Stopped Gluino – calorimeter, muon system

Timing Detectors

Time Of Flight (TOF at CDF) – scintillators wrapped around tracking chamber (COT at CDF) at a 1.45 m. Resolution ~ 100 ps.

CHAMP – track with $\beta < 1$ $\beta \equiv v/c$

- candidate TOF arrival time
- independent event T_0
- path length

Drift chamber (COT at CDF) is also a timing device

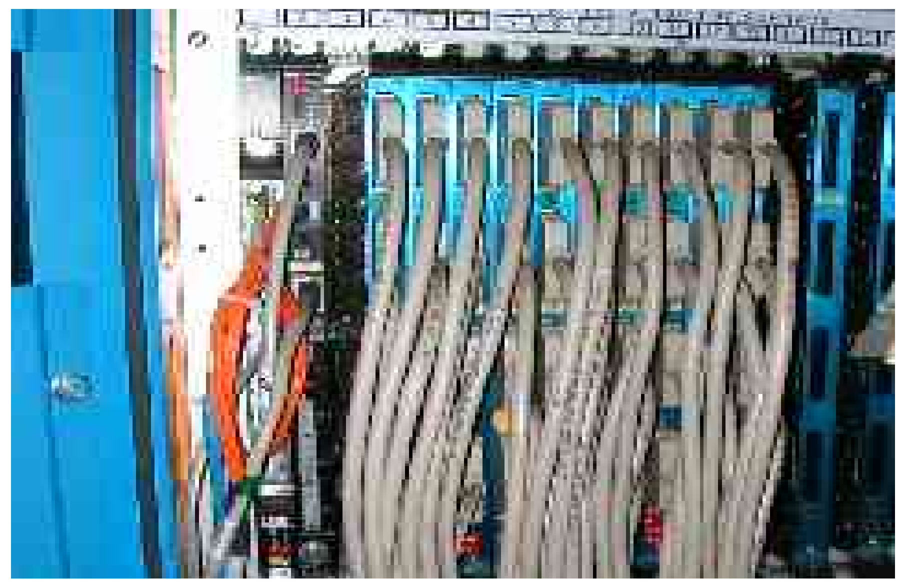
Each track produces up to 96 hits

Each hit has timing information

- resolution ~ 200 ps
- measure track without event T_0
- measure event T_0
- Gaussian tails

New Tool - EMTiming

- Part of Run IIb upgrade
- Analog pulse 2000 phototubes➔TBoard➔ discriminator ➔TDC in 1ns bins
  - Cover most EM cal ($|\eta| < 2$)
  - for CEM use passive inductive pick-off (a.k.a. splitter) to get PMT pulse
- ~100% Efficient above thresholds
  - CEM-5 GeV, PEM-2.5 GeV
- System resolution ~0.6 ns
- Very uniform, Negligible Noise
- Finished installation October 2004.
  - Begin data-taking in Nov. 04
  - Commissioned in 1 week
- By now have ~ 2 fb^{-1} w EMTiming



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

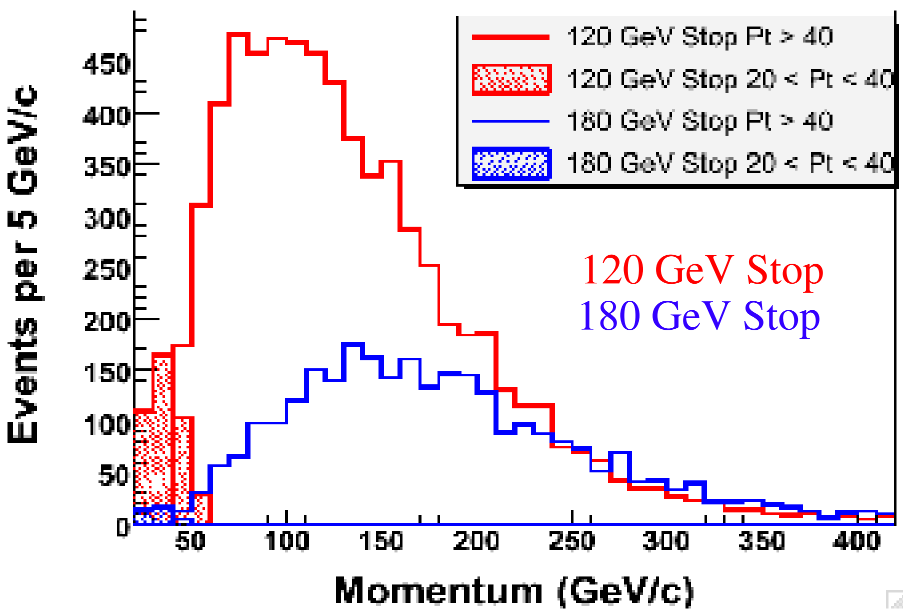
Use track momentum and velocity measurements to calculate mass

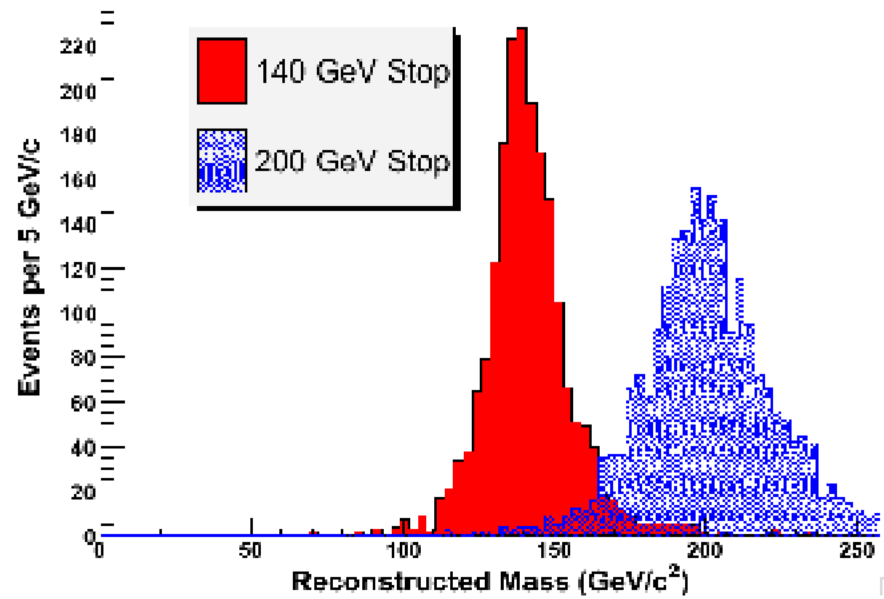
$$m = p\sqrt{1/\beta^2 - 1}$$

- 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

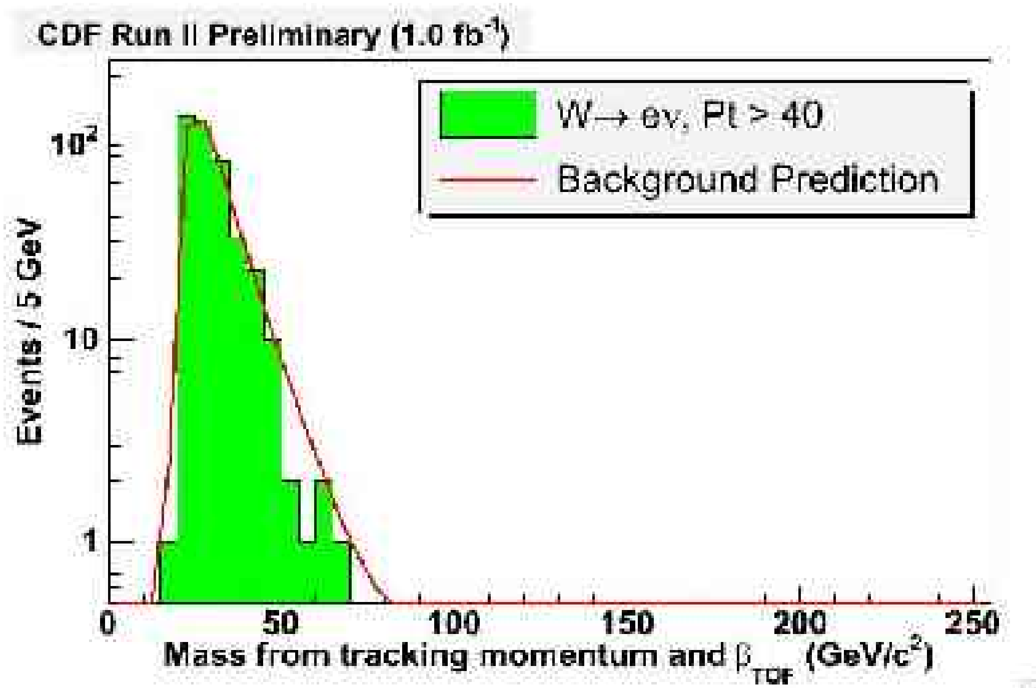
It is the mass of the muons we are after

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

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

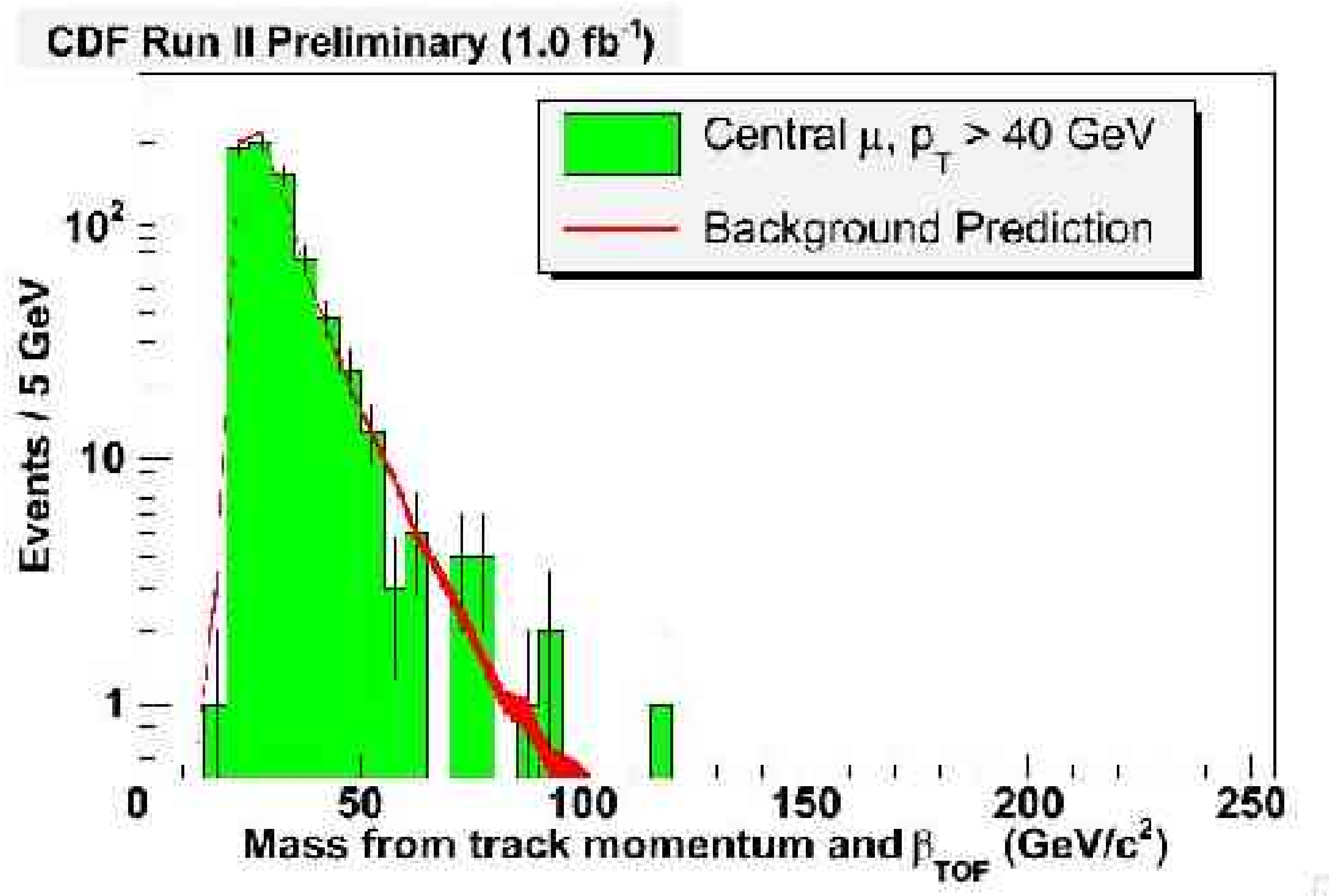
Show this works for electrons from Ws

- sanity check take electrons with 20 < P_T < 40 GeV
- beta shape + momentum histogram = background prediction
- Show we can predict electrons with P_T > 40 GeV



Repeat for muons →

CHAMPs – Signal Region



No CHAMP candidates above 120 GeV/c². Signal-region events consistent with background prediction

Model Independent Limits

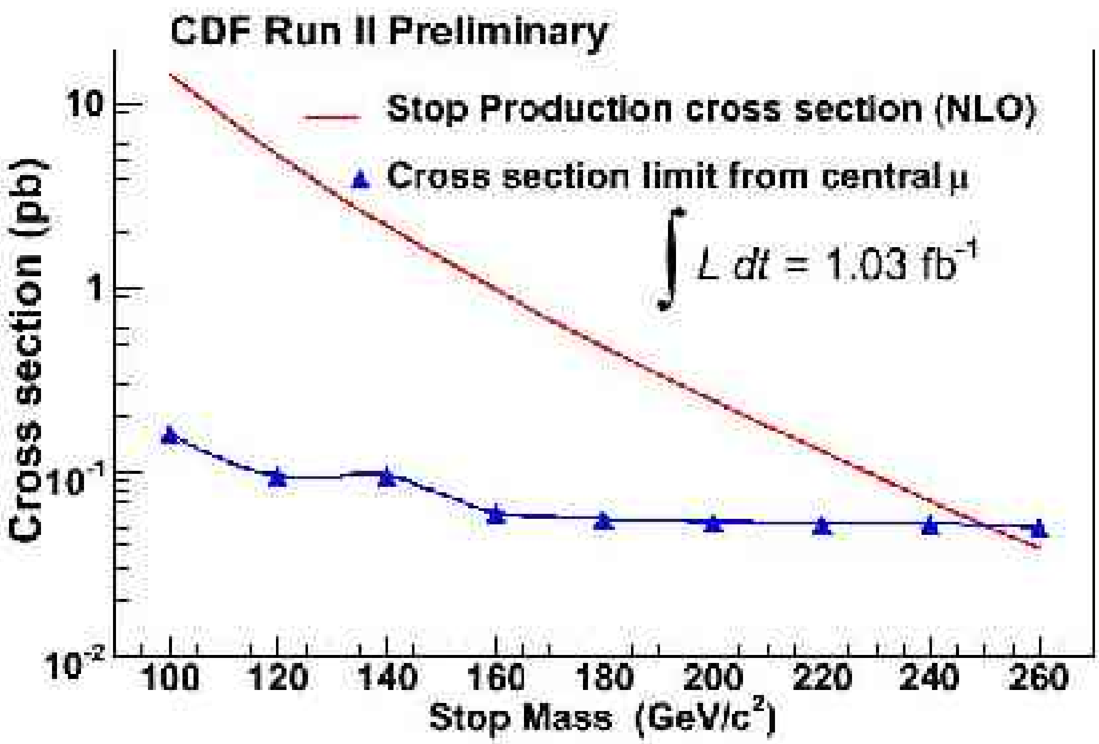
For model independence, find cross section limit for *CHAMPs fiducial to Central Muon Detectors* with $0.4 < \beta < 0.9$ and $Pt > 40$ GeV

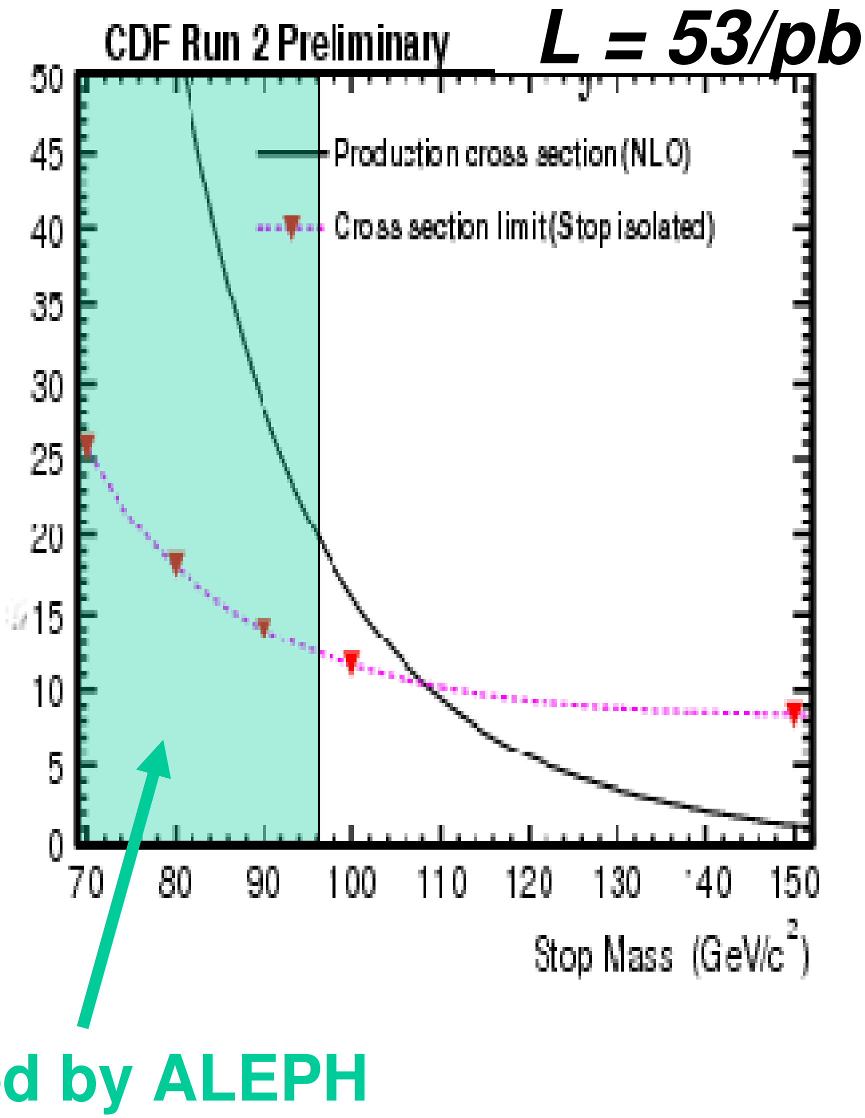
- strongly interacting (stable stop)
  - efficiency 4.6 ±0.5%
  - 95% confidence limit: $\sigma < 41$ fb
- weakly interacting (sleptons, charginos)
  - efficiency 20.0±0.6%
  - 95% confidence limit: $\sigma < 9.4$ fb

Model-dependent factors are

- β and momentum distributions
- geometric acceptance

New Stable Stop Limits





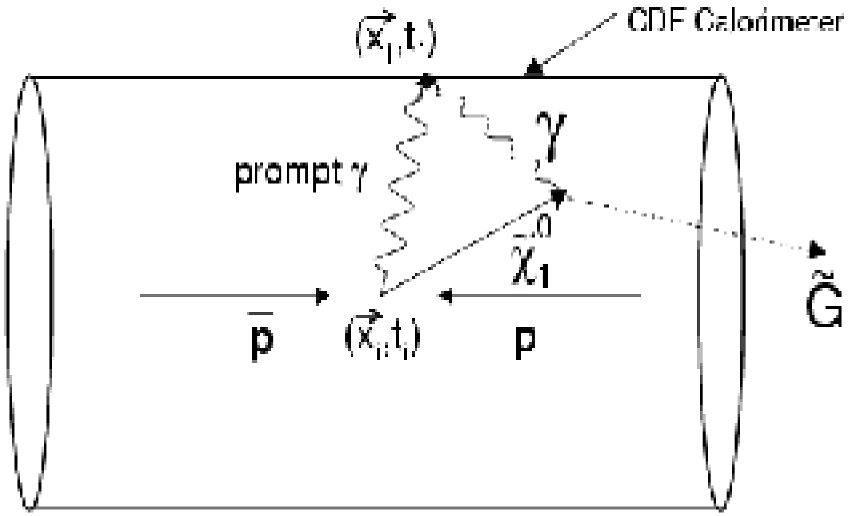
Exclude Stable Stop with mass below 250 GeV/c² (95% C.L.)

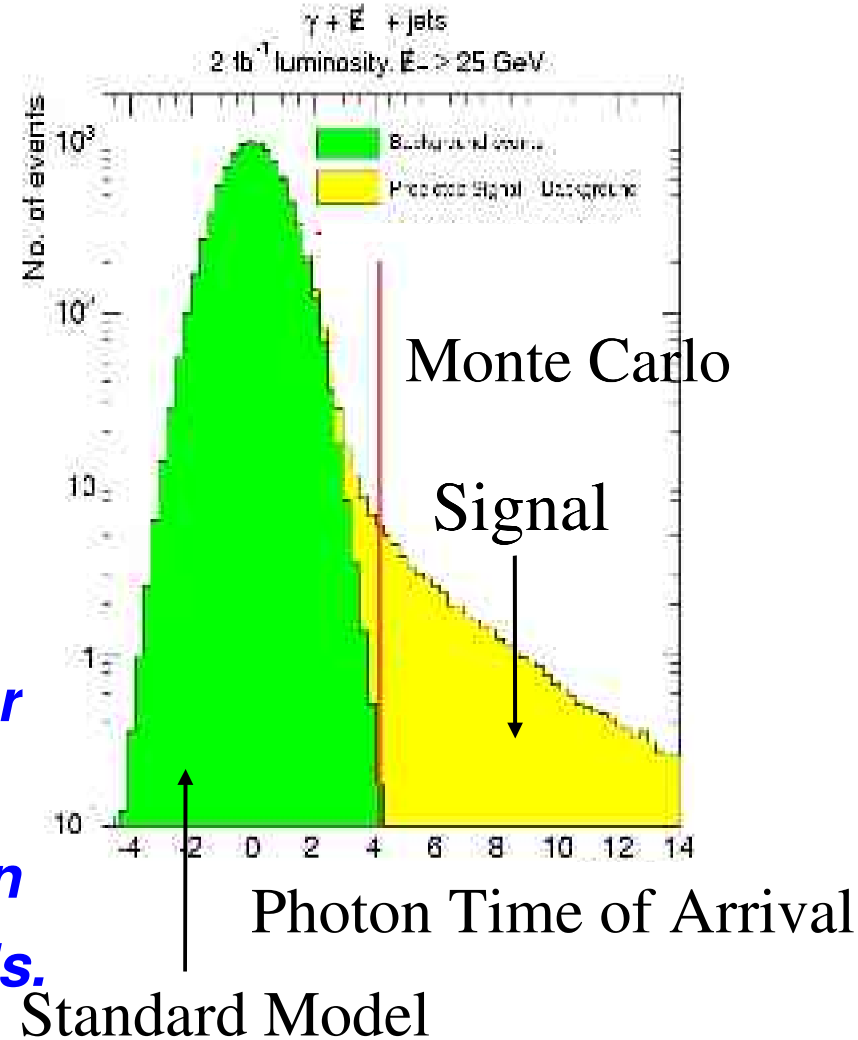
When We Find CHAMPs

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

Delayed Photons   γ + Jet + MET



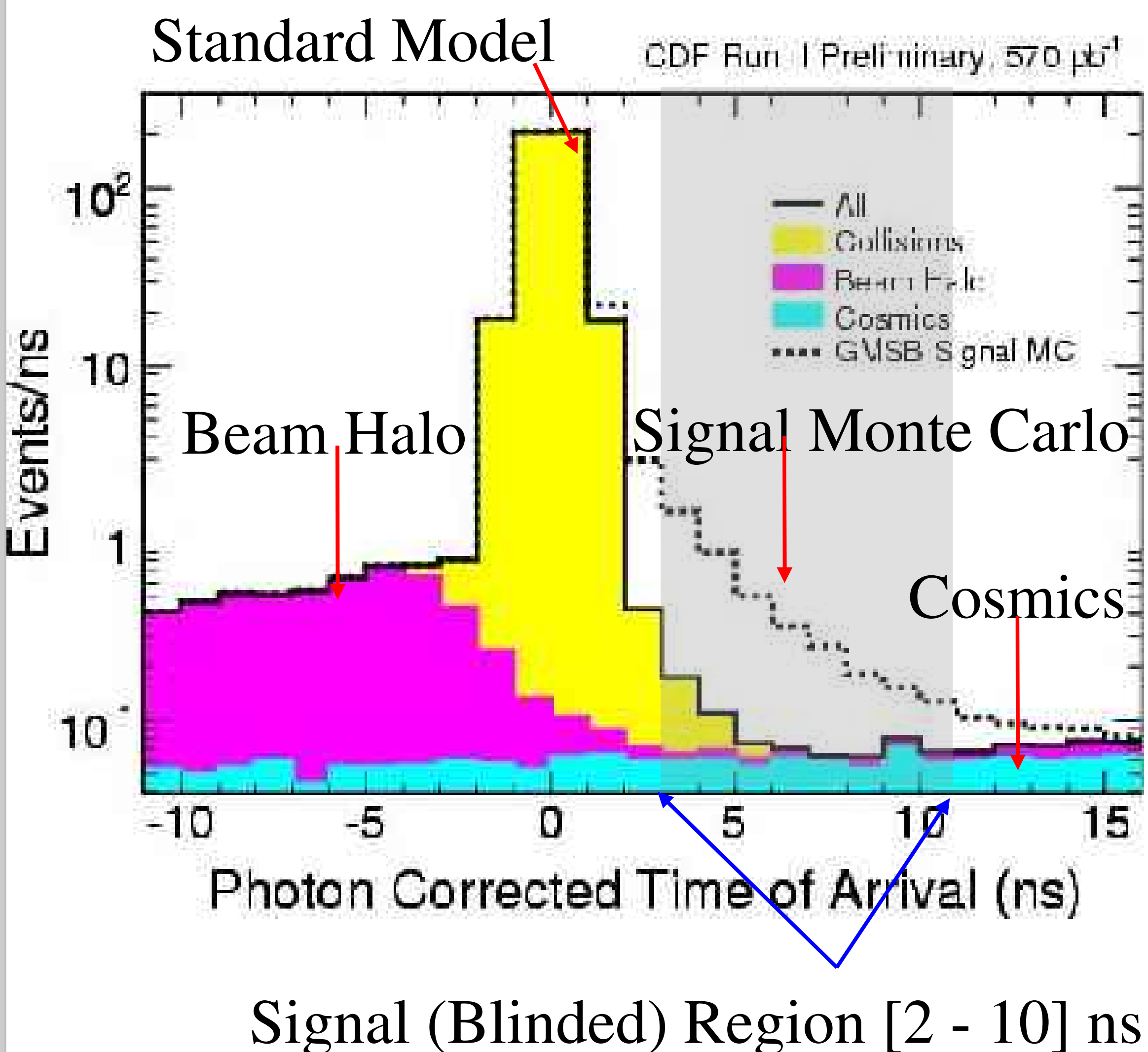


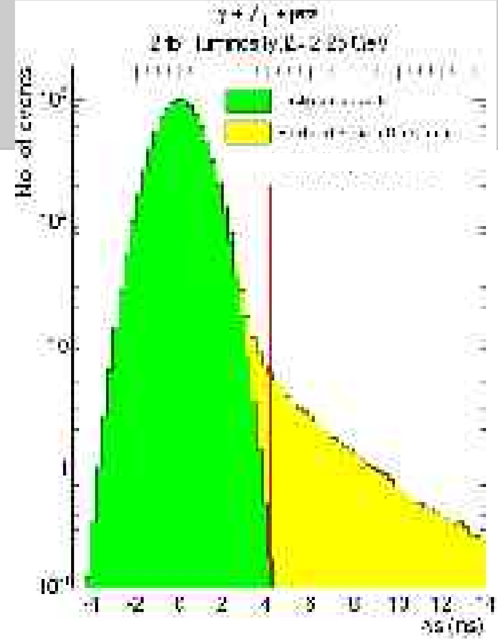
Look for non-prompt γ's that take longer to reach calorimeter.

If the χ^0 has a significant lifetime, we can separate the signal from the backgrounds.

- Not just for photons
  - delayed electron would look the same (track too displaced)

Delayed Photons





Four Background Sources

Non-collision "look-like photons"

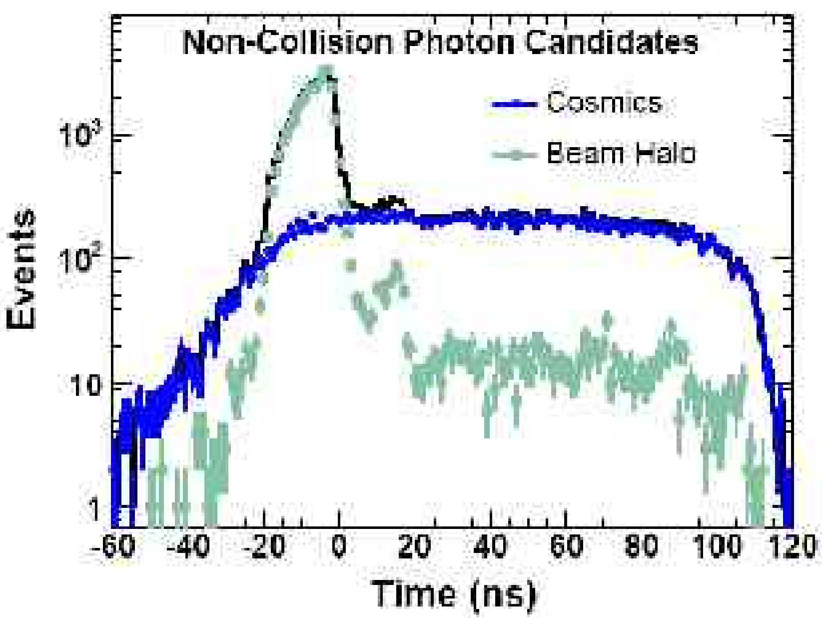
- **Cosmics**
- **Beam Halo**

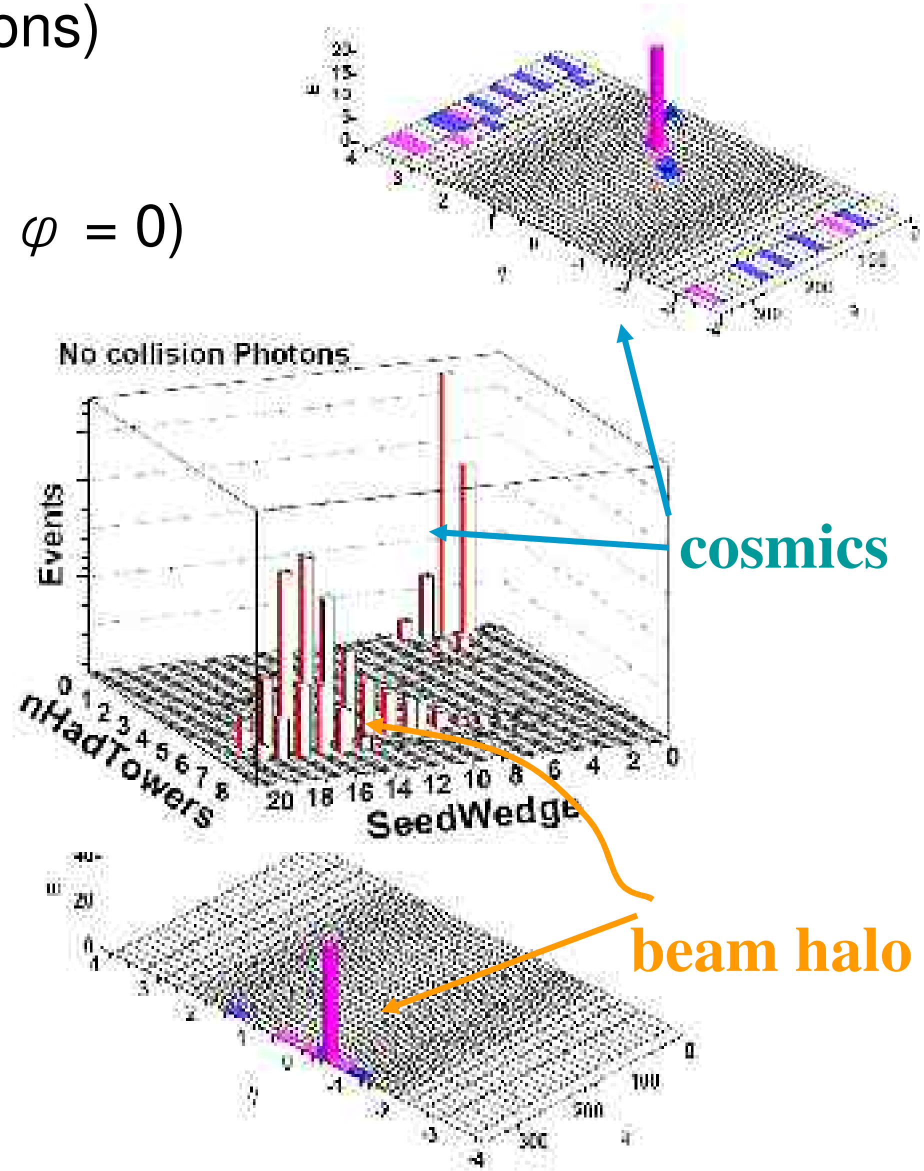
Collision photons from Standard Model

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

Non-Collision Background

- From the beam – beam halo (muons)
- From outer space – cosmic (muons)
- Look different in cal
  - long traces for BH (mostly at $\varphi = 0$)
  - a few towers for Cosmics
- Separate and get the shapes



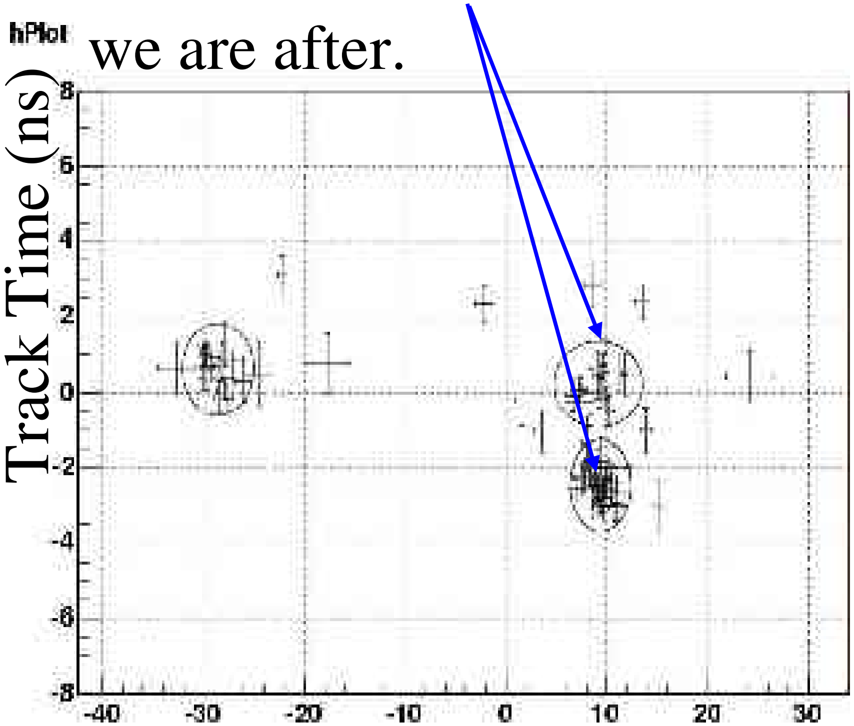


Multiple Interactions

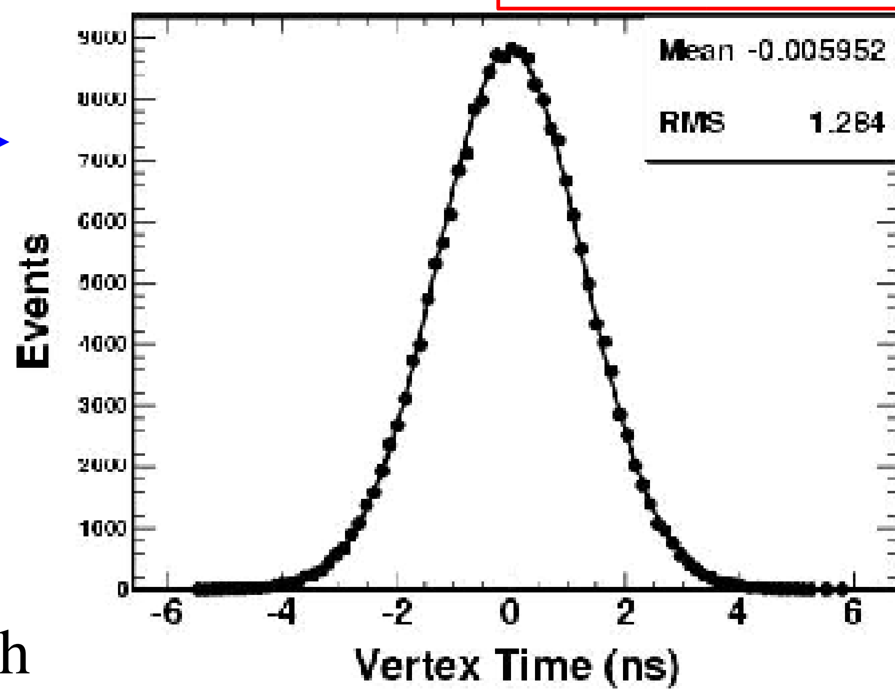
For tracks we reconstruct Z position along the beamline and time as measured by the tracking drift chamber (COT):

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

Separating those two is what we are after.



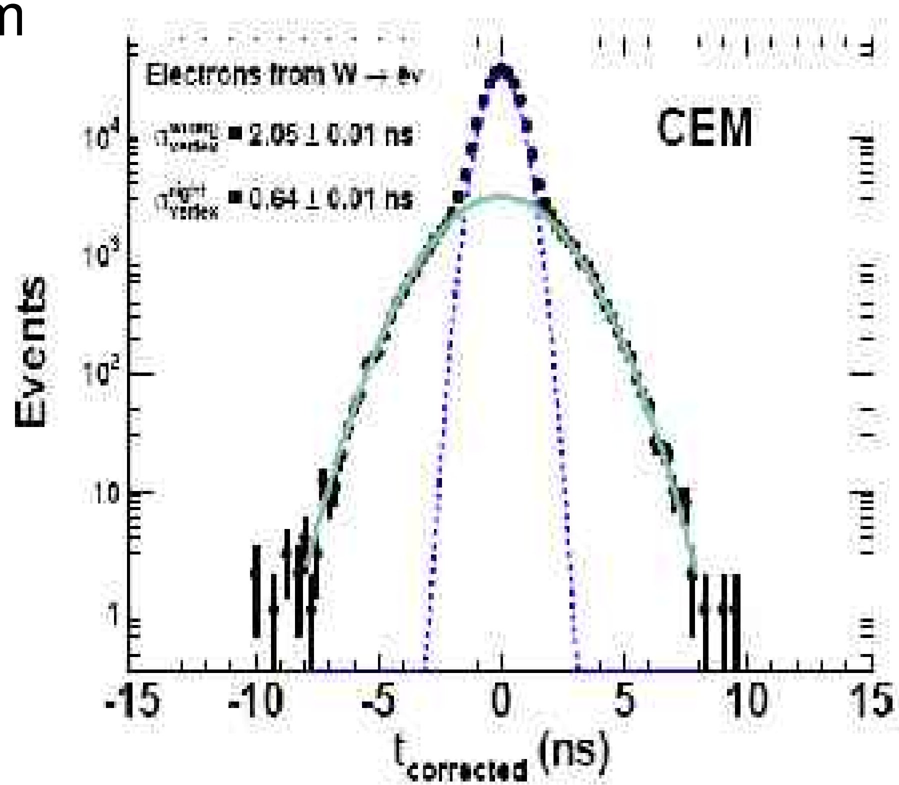
RMS = 1.28 ns



Employ Expectation Maximization with Gaussian Mixtures

Prompt Background

- Multiple collisions are and issue
  - don't know where γ is coming from
  - assume it's the max sumPt vertex
    - not always right ☹
- Use W→eν sample
  - hide e-track ➔ γ +MET sample
  - one Gaussian for right vtx
    - σ = 0.64 ns
  - one Gaussian for wrong vtx
    - σ = 2.05 ns



e track removed to mimic photon

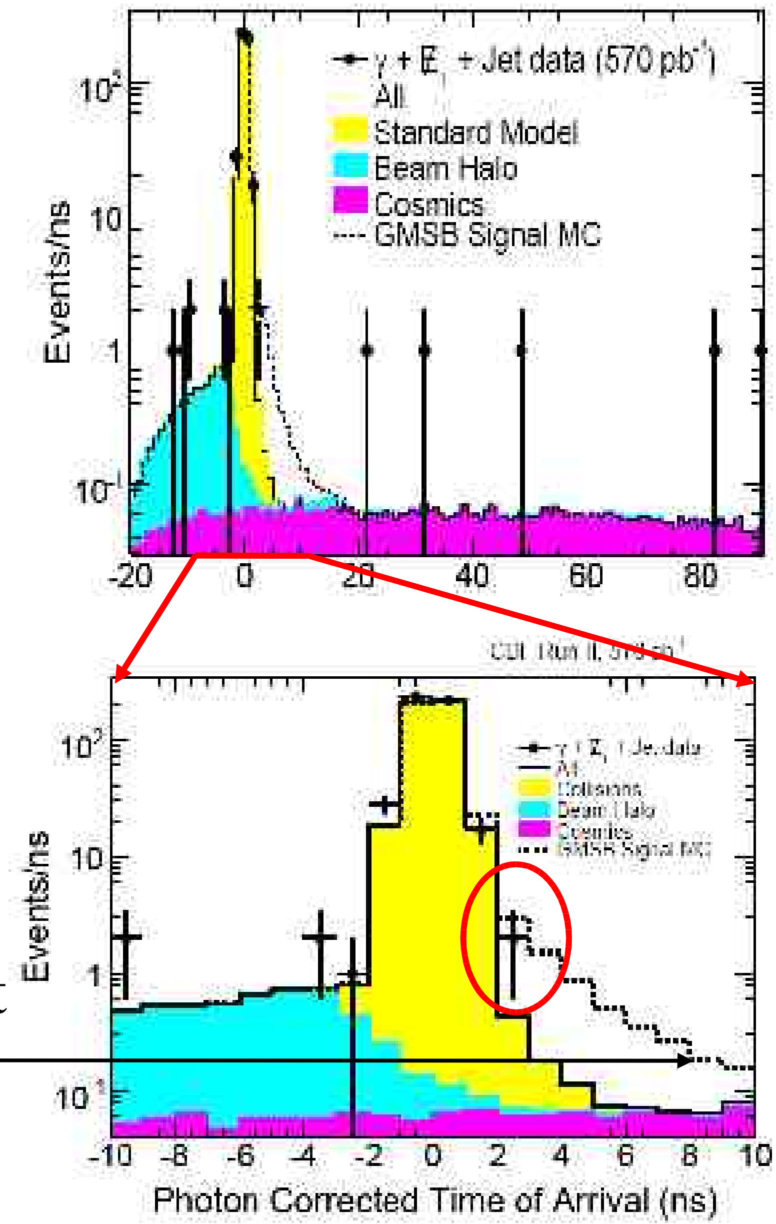
– let them float in the signal shape fit

Putting It All Together

- With optimal cuts

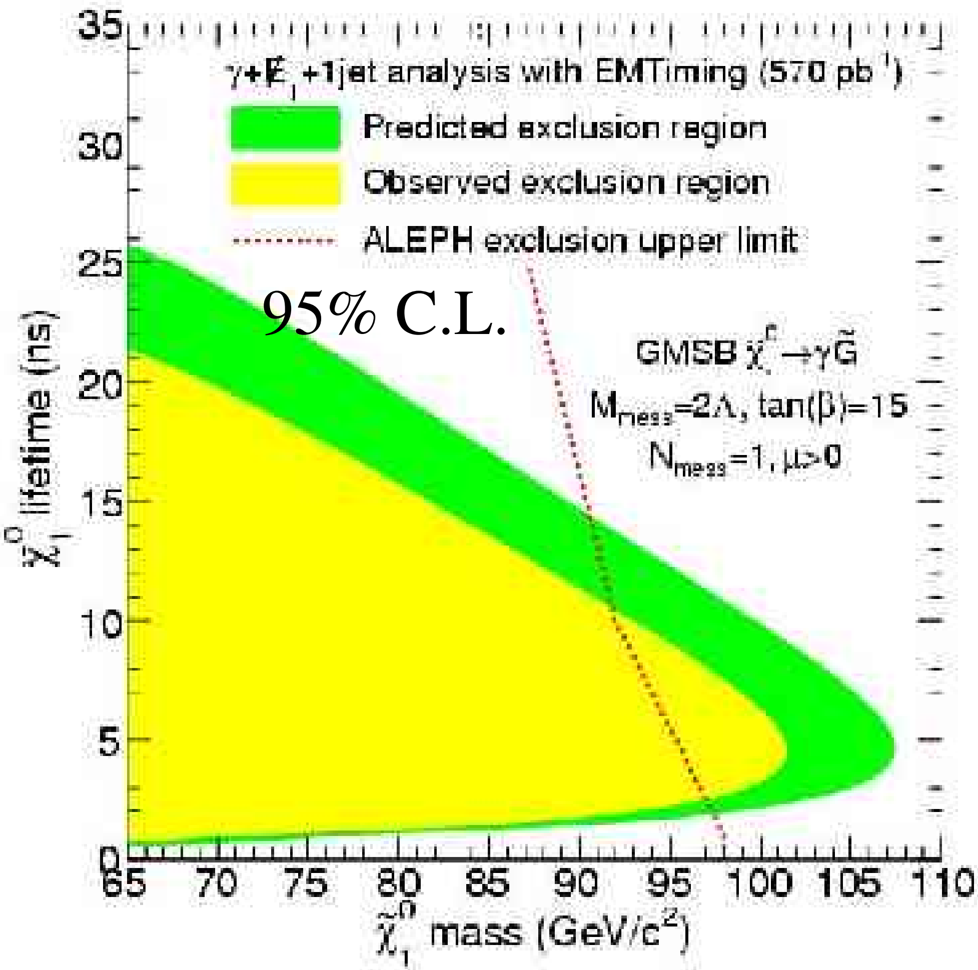
$$\not{E}_T > 40\ \mathrm{GeV},\ E_T^{\mathrm{jet}} > 35\ \mathrm{GeV}$$
$$\Delta\phi(\not{E}_T, \mathrm{jet}) > 1\ \mathrm{rad}$$
$$2\ \mathrm{ns} < t_c^{\gamma} < 10\ \mathrm{ns}$$

- Expect
  - 1.3±0.7 bgd events
    - 0.7±0.6 collision-SM
    - 0.5±0.3 cosmics
    - 0.1±0.1 beam halo
- Observe
  - 2 events

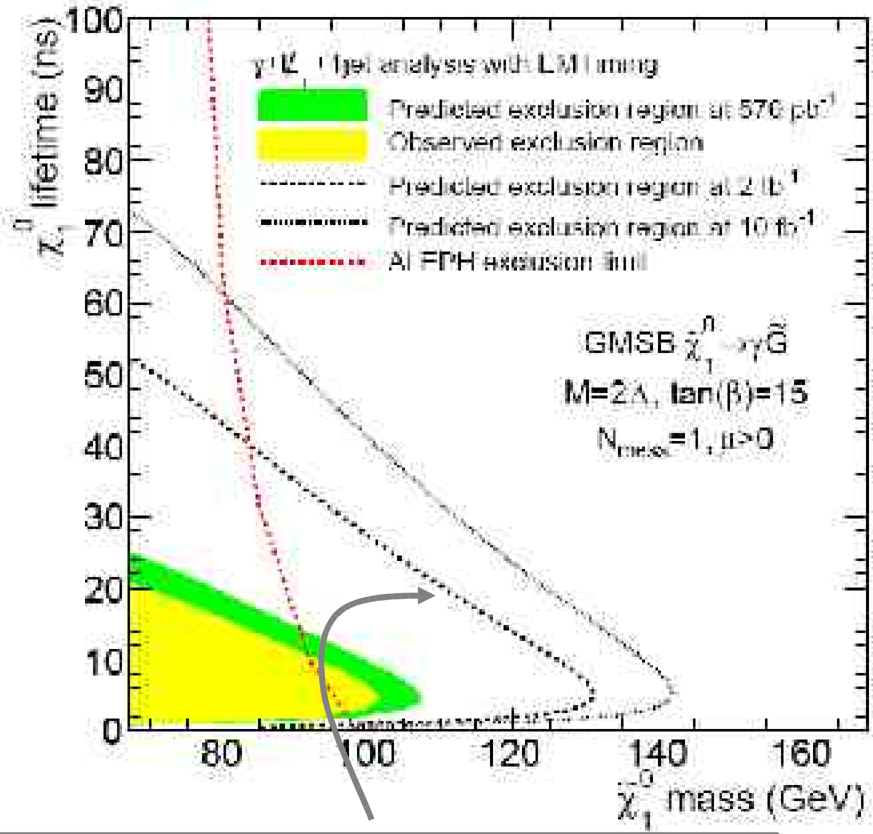


Would be +6 event for GMSB point:
m(χ) = 100 GeV
τ(χ) = 5 ns

Delayed Photons?



Did not find anything, but have the highest sensitivity at ~5 ns



Can be here by the end of the year

Split-Susy

- Another type of SUSY model is known as split-SUSY
- In split-SUSY, all scalar supersymmetric particles are heavy (> 1 TeV)

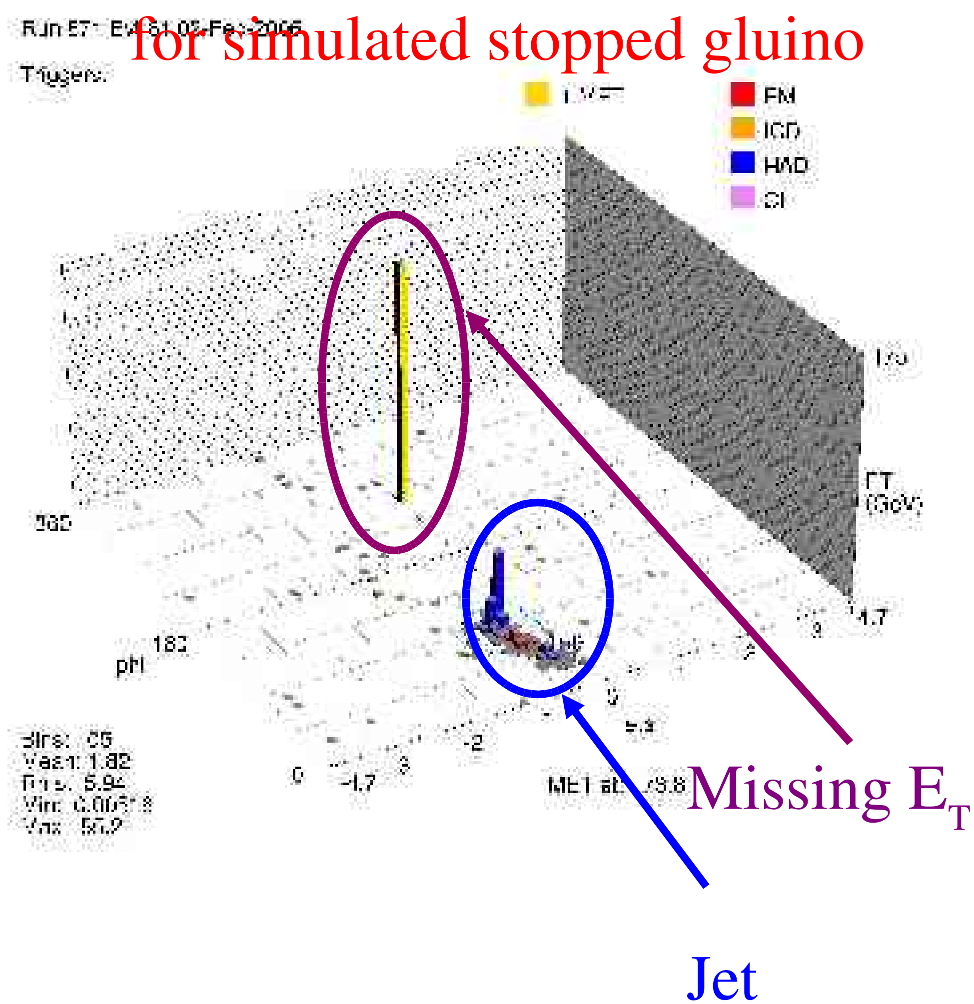
The gluino is the only weak-scale colored supersymmetric particle.

Its decays to a gluon and a neutralino are suppressed, resulting in a long gluino lifetime (from nanoseconds to hours)

Stopped Gluino

- A gluino is produced and hadronizes, coming to rest in the calorimeter
- Some time later (in another bunch crossing), it decays to a gluon jet (and a neutralino)

Calorimeter Energy Lego Plot for simulated stopped gluino



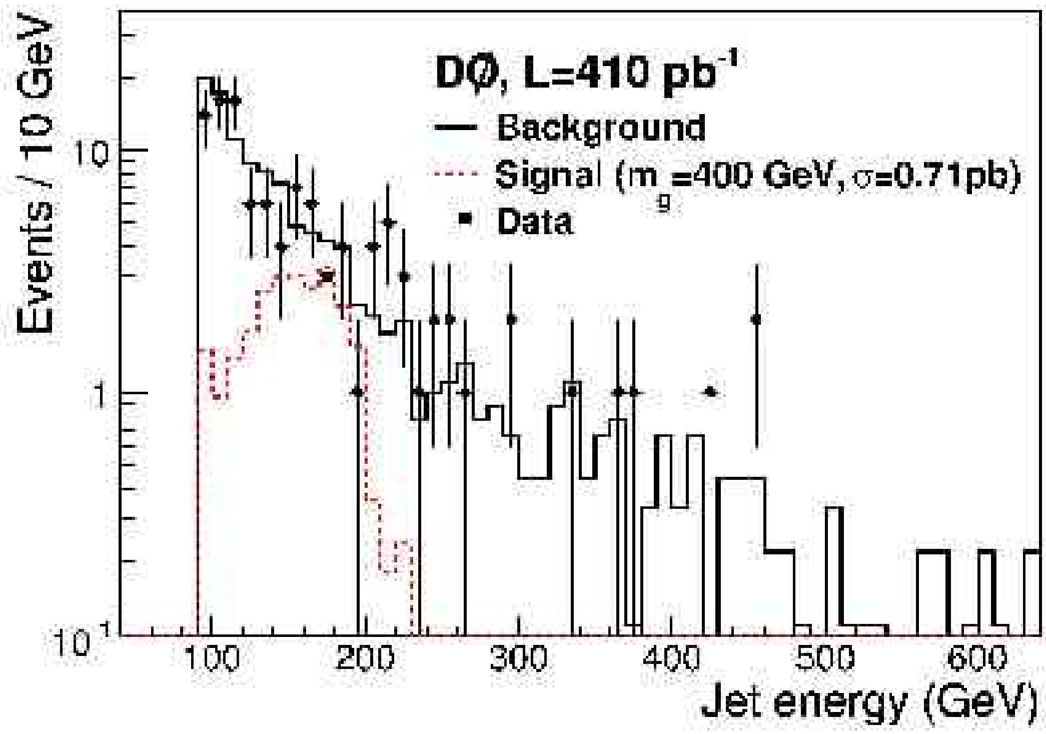
Look for wide jet, missing energy, and veto interaction

Stopped Gluinos: Data

Background – cosmic rays

wide jets (with muon stub) x muon efficiency

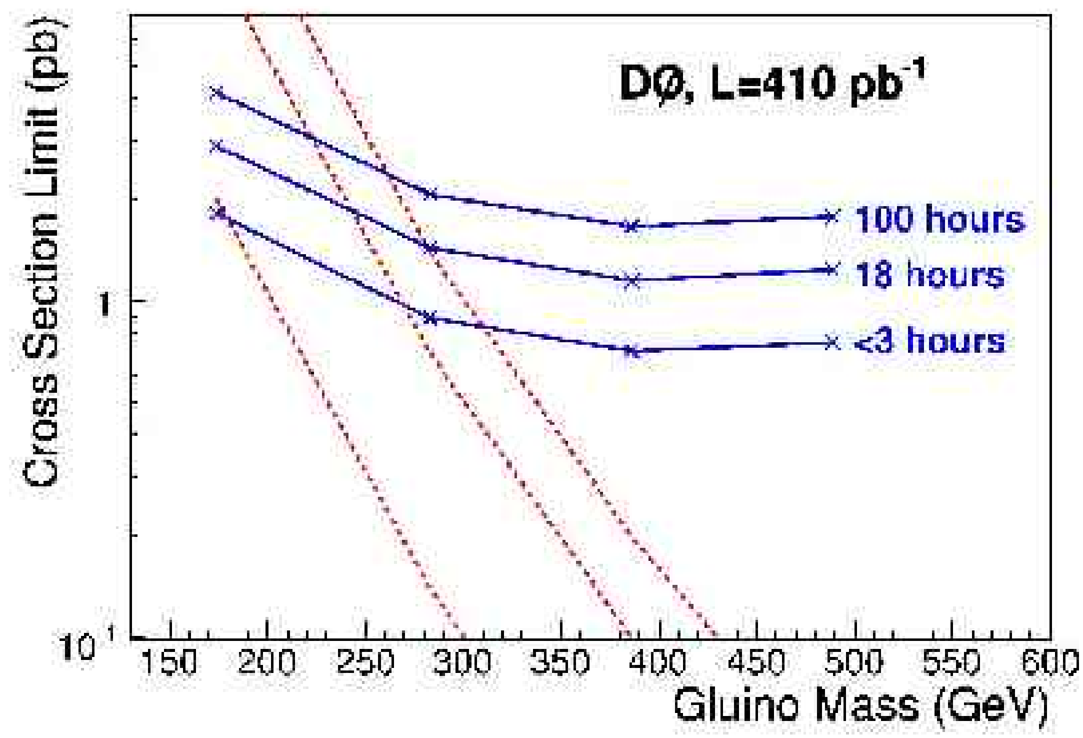
Muon efficiency : use narrow jets



Limits

- No excess of events is observed
- Limits are set on the gluino production cross section

Jet E Range (GeV)	Data	Bgnd.	Signal Efficiency
94.6-111.6	46	48.18	0.05
126.8-171.8	32	37.84	0.10
169.3-233.8	27	21.56	0.11
214.2-286.6	14	9.57	0.10



What is Next?

CHAMPs β>0.4

Late Tracks

Delayed Photons

Track Timing

Calorimeter Timing

Non-Collision Rejection

Exclusive γ+MET

(KK states ...)

Champs β<0.4

Delayed Jets

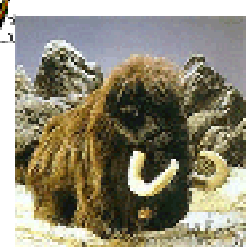
Displaced Vertex

(Hidden Valley ...)

Highly Displaced Vertex

(Hidden Valley ...)

Let's catch it !



Backup Slides

Reasons to live

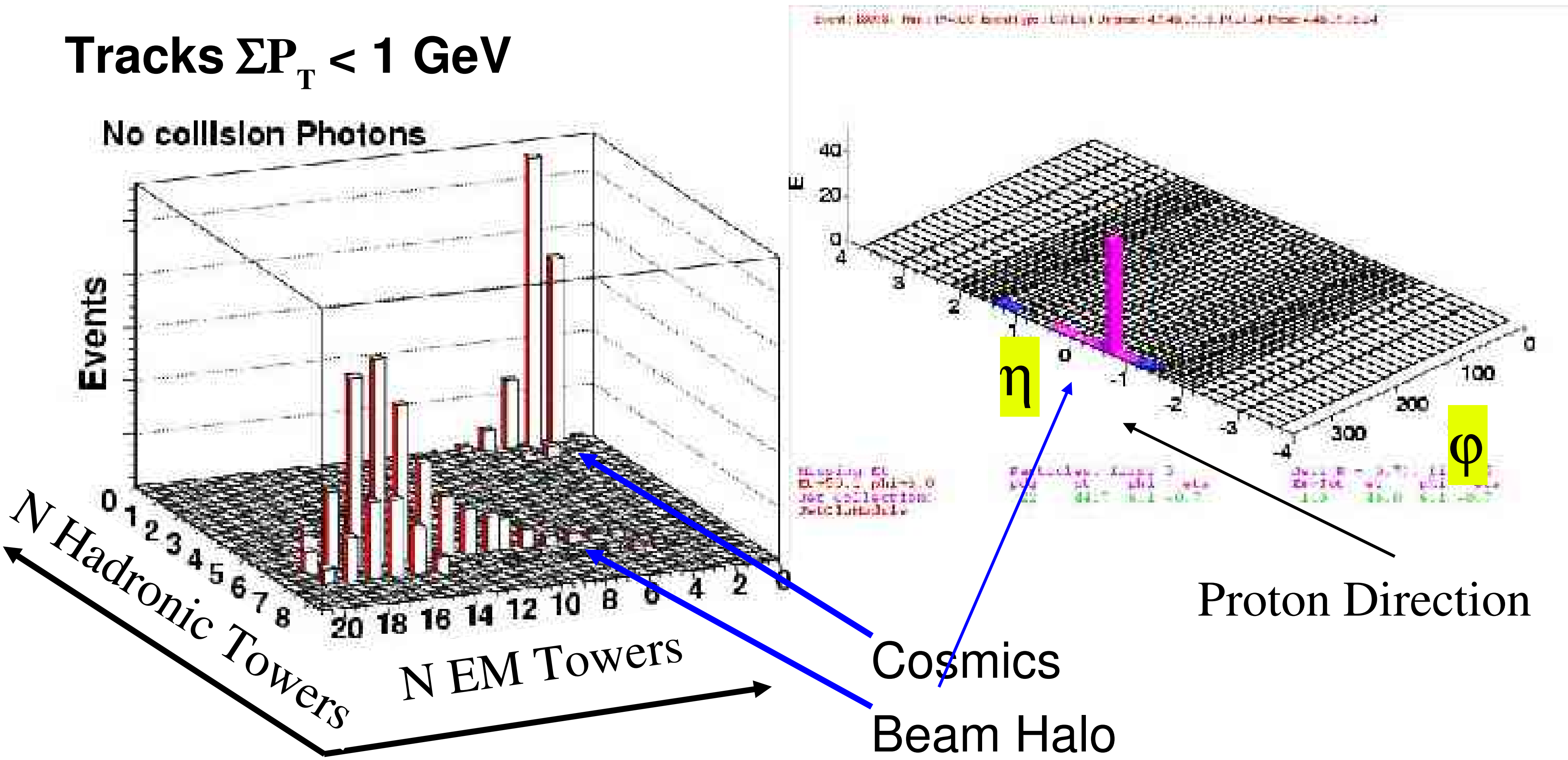
- Particles can be long-lived if they have:
  - weak coupling constants
  - limited phase space
  - a conserved quantity
  - “hidden valley” (potential barrier)

Papers

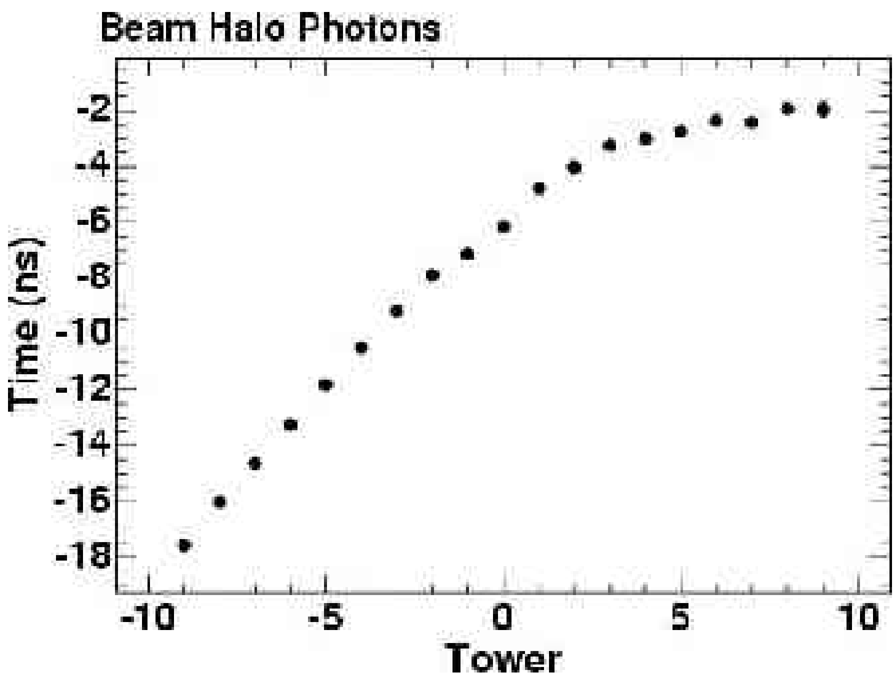
- Supersymmetry:
  - stable stop squark (We use this as our reference model)
    - R. Barbieri, L.J. Hall and Y. Nomura PRD **63**, 105007 (2001)
  - NLSP stau in gauge-mediated SUSY breaking
    - J.L. Feng, T. Moroi, Phys.Rev. D58 (1998) 035001
  - Light strange-beauty squarks
    - K. Cheung and W-S.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

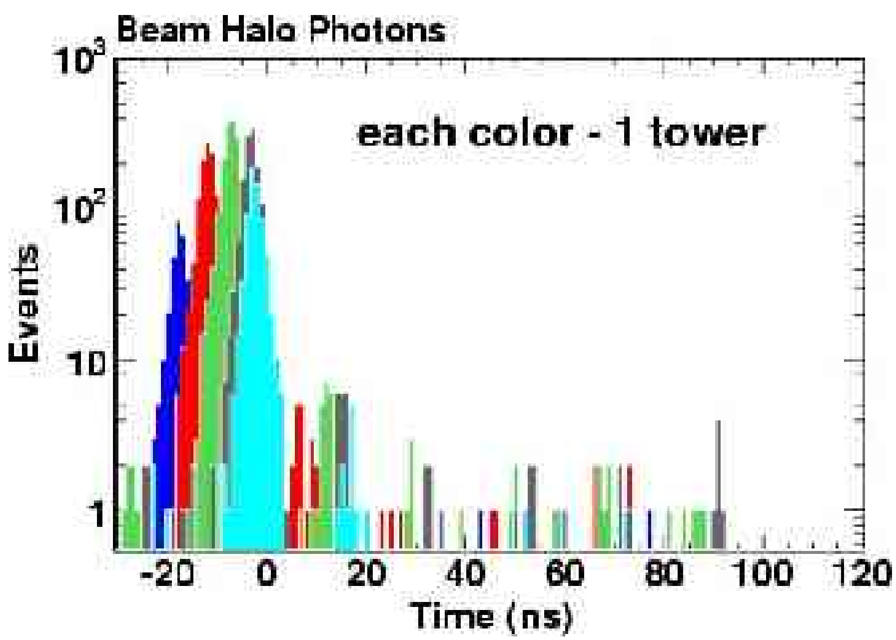
Cosmics vs Beam Halo

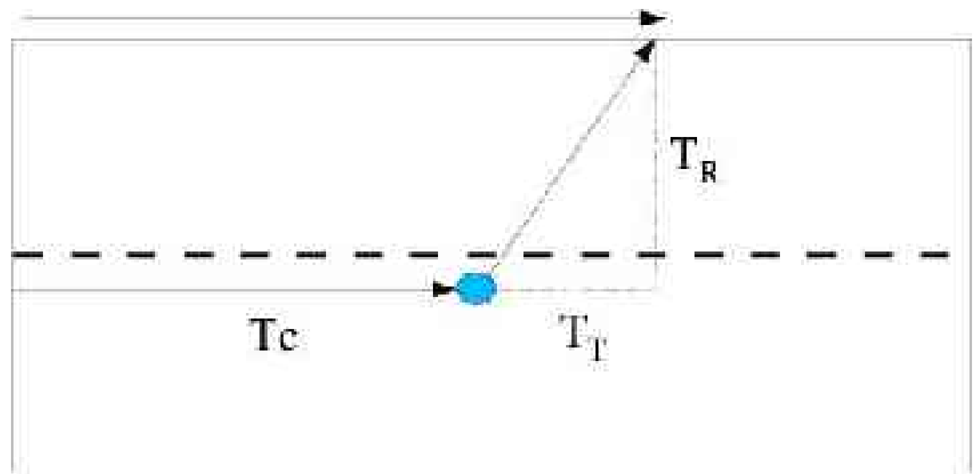
Tracks $\Sigma P_T < 1$ GeV



Beam Halo Time Shape







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

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

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

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

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

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

Break

Moving into neutral heavy long-lived particles