Search for long-lived particles at CDF

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for
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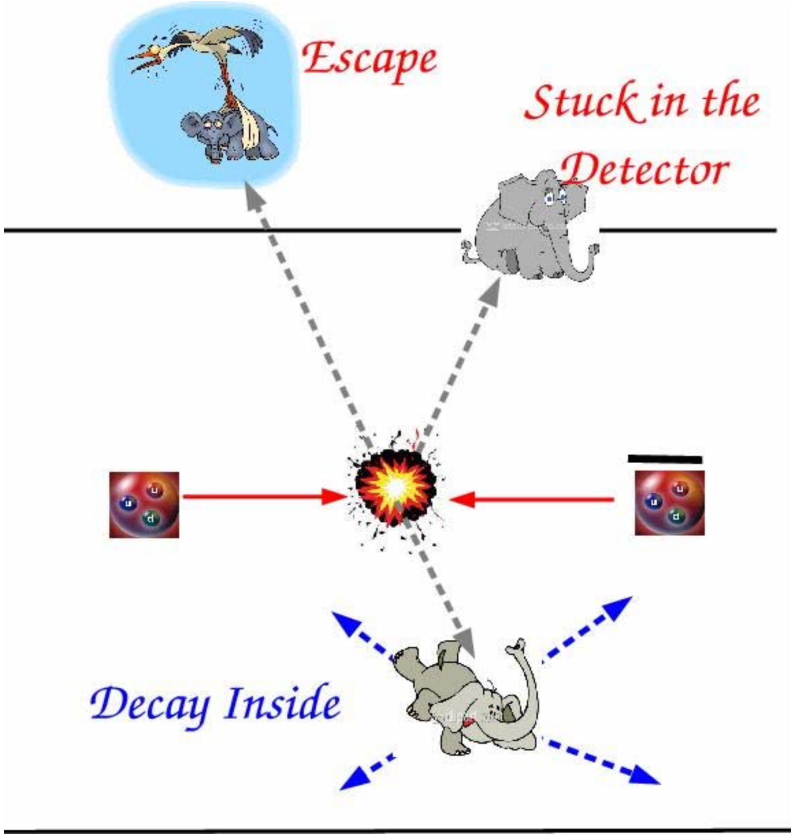
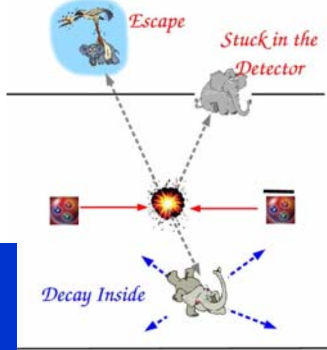
- Premises
- Search for charged massive particles (CHAMPs)
    - ➲ Analysis ➲Results
- Search delayed photons in γ+jet+MissingEnergy
    - ➲ Analysis ➲Results
- Summary ➔ Steps to the future

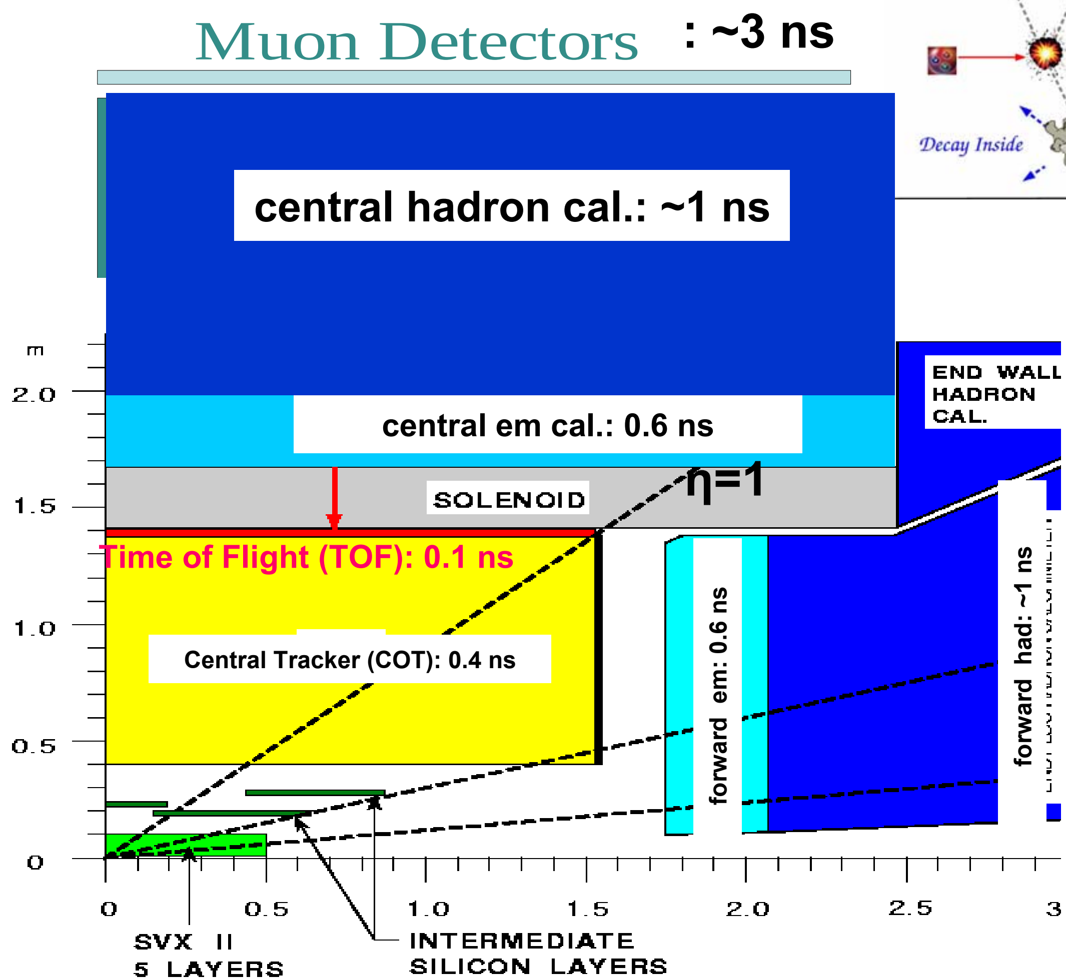
Premises

- **New heavy particles can have non-negligible lifetime**
  - [PUT YOUR FAVORITE MODEL IN HERE]
  - more examples later
- **Different signatures in collider experiments**
  - escape and noninteracting → missing energy (MET or $\not\!\!E_T$)
    - **the least information**
  - if interacts with detector or decays to products that do
    - **delayed hits**
      - **if slow or decays to visible**
    - **displaced vertex**
      - **if decays to charged**
      - **→ delayed hits too**



Detector signatures: delayed hits





- **Most subdetectors at CDF can measure time of hit arrival**

- **Long-lived particles can show up in many ways. Only two topics in this talk.**
  - CHAMPS with TOF and COT timing
  - delayed γ with central EM and COT timing

CHAMPs

- **In theory**
  - SUSY: sleptons, chargino, stop, gluino
    - **stop or gluino hadronize → charged**
  - something else?
- **If slow ($\beta < 1$) and crossing the detector**
  - delayed hit in TOF and COT
    - **with origin vertex t_0 known can reconstruct β**
  - seen in muon chambers (trigger !)
  - high ionization (dE/dX)
    - **reserved for cross-check**
- **→Reconstruct mass from β and momentum**

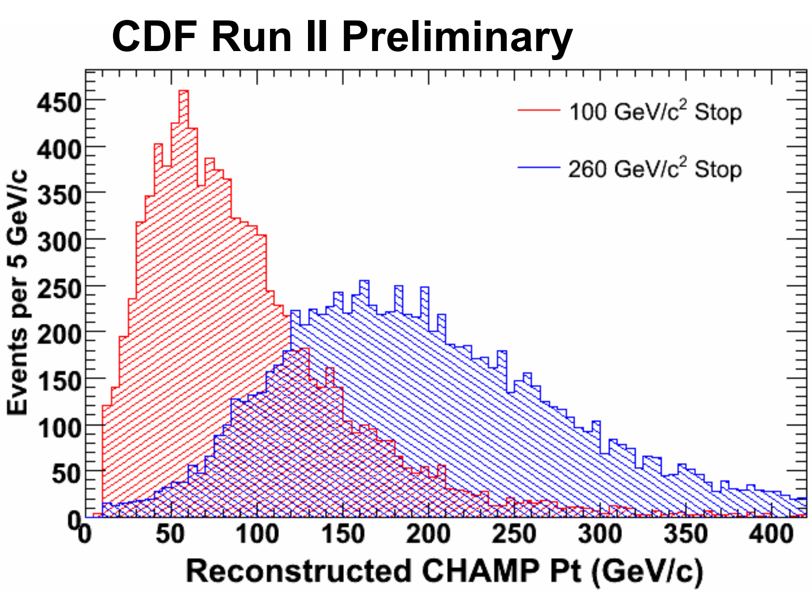
$$m_{\mathrm{TOF}} = p\sqrt{\frac{1}{\beta^2} - 1}$$

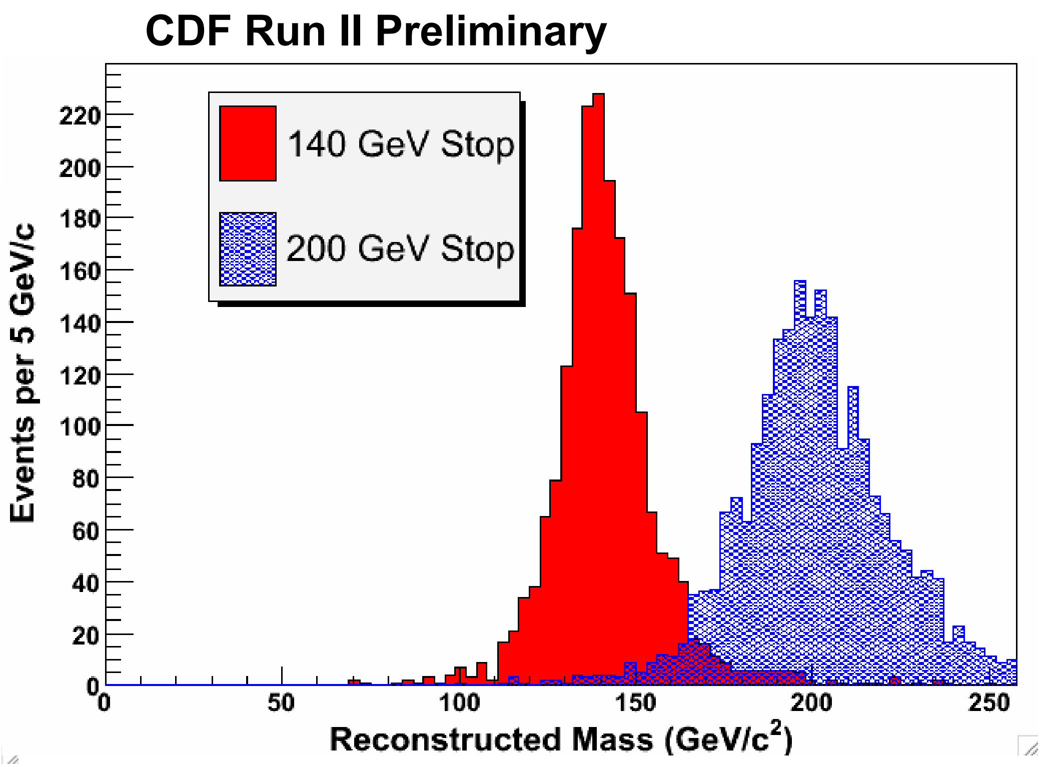
Analysis strategy

- **Simulation:**
  - check that reconstruction is possible
- **Background prediction method:**
  - β shape $\oplus$ momentum histogram = background mass prediction
  - Show this works for electrons from $W \rightarrow e\nu$
    - **use β in $20 < p_T < 40$ GeV to predict mass in $p_T > 40$ GeV**
  - Muons:
    - **check: from $20 < p_T < 30$ → predict → $30 < p_T < 40$**
    - **final: from $20 < p_T < 40$ → predict → $p_T > 40$**
- **Signal sample: muon-trigger sample**
  - $|\eta| < 0.6$, $p_T > 40$ GeV, $0.4 < \beta < 0.9$
- **Set limits (if consistent with background)**

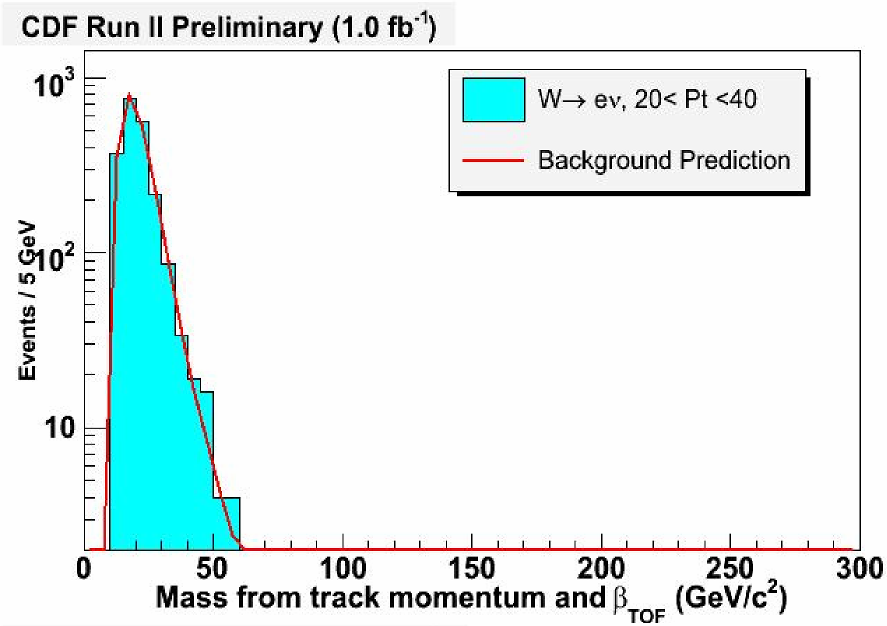
Simulation

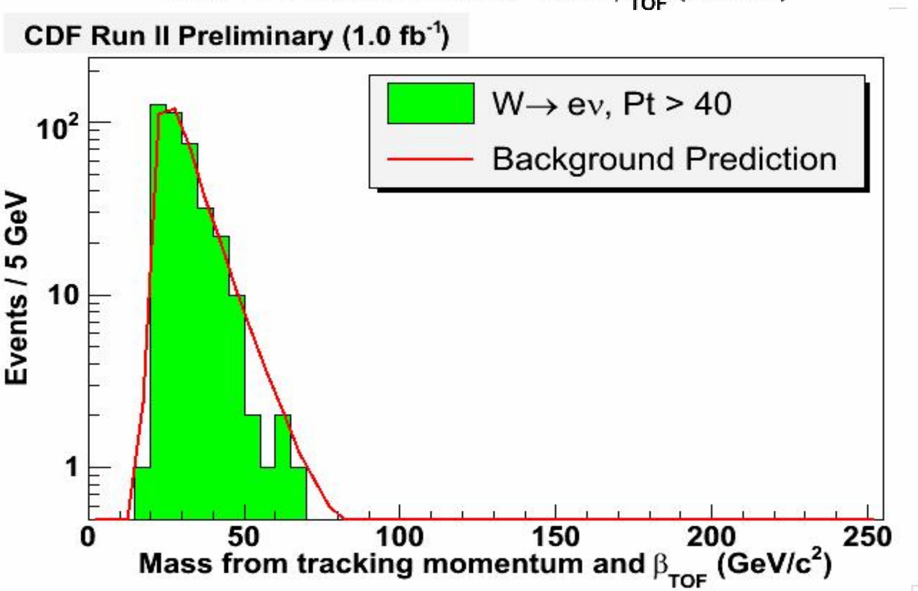
- For clean MC signal can reconstruct the input mass





Step 1: W→eν

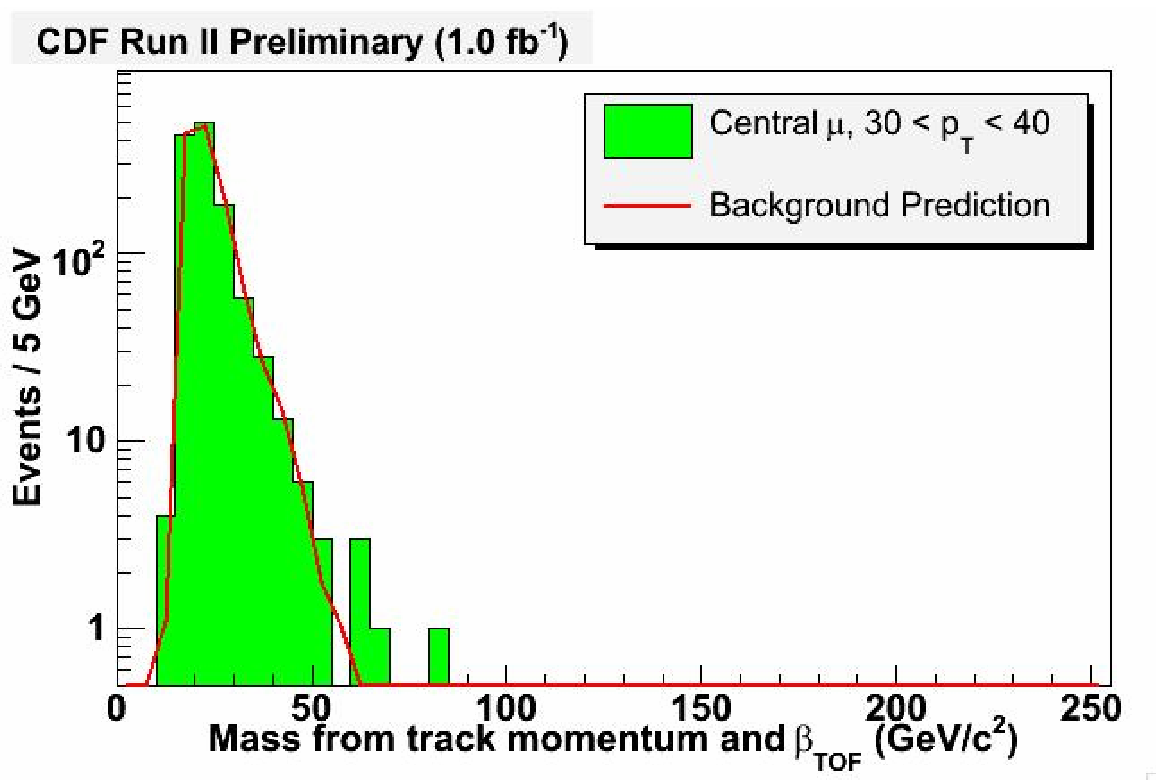




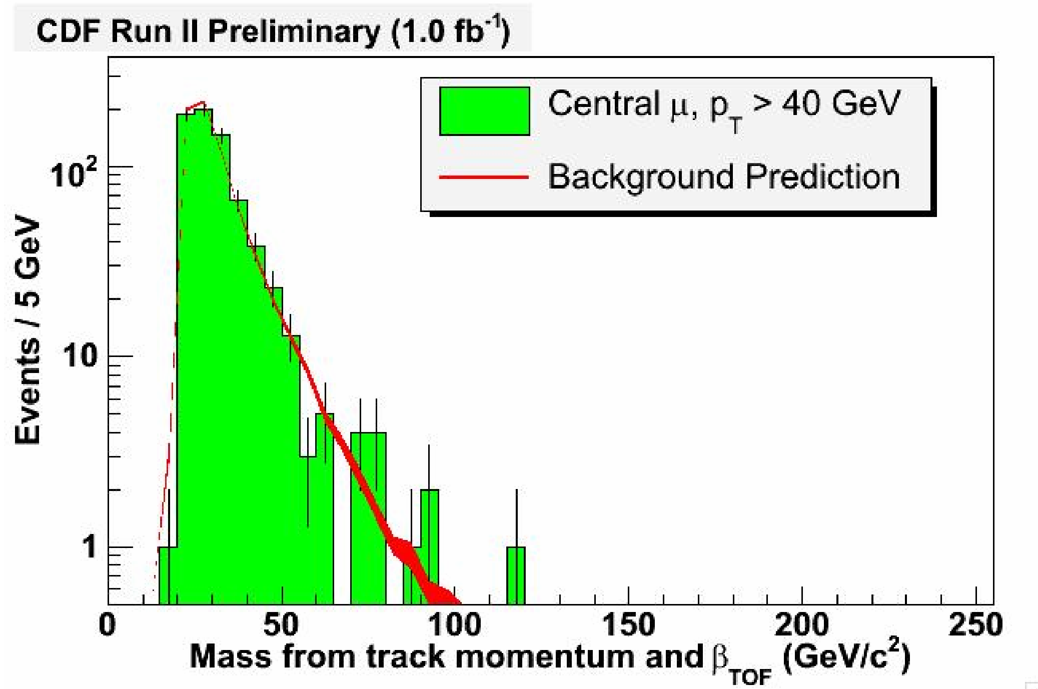
- **Assume p and β are independent**
  - Predict mass shape by convoluting p and β histograms
- **Works!**
  - p and β are largely independent in the control sample

Step 2: Muon sample (control)

- **Require central muons (|η| < 0.6)**
  - Verify background shape prediction
    - **use 20-30 GeV to predict 30-40 GeV region**



Step 3: Signal region

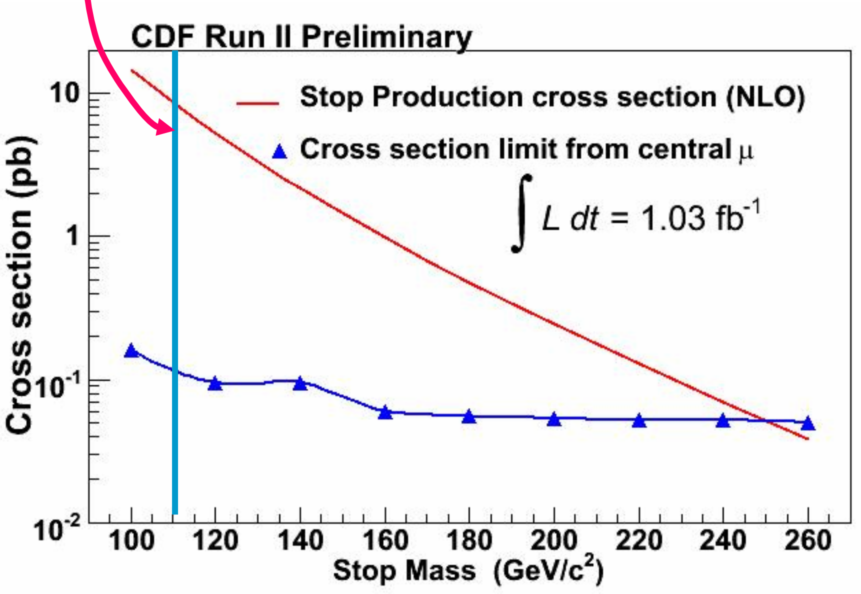


- **No CHAMP candidates above 120 GeV/c^2.**
- **Signal-region events consistent with background prediction**

CHAMPs: model limits

- **Find cross section limit for *CHAMPs with* $|\eta|<0.6$, $0.4< \beta < 0.9$ and $p_T > 40$ GeV**
  - ➔Model-dependent factors
    - β and momentum shapes
    - *geometric acceptance*
- **weakly interacting (sleptons, charginos)**
  - efficiency 20.0±0.6%
  - 95% C.L.: $\sigma < 9.4$ fb
- **strongly interacting (stable stop)**
  - efficiency 4.6 ±0.5%
  - 95% C.L.: $\sigma < 41$ fb
  - smaller due to hadronization

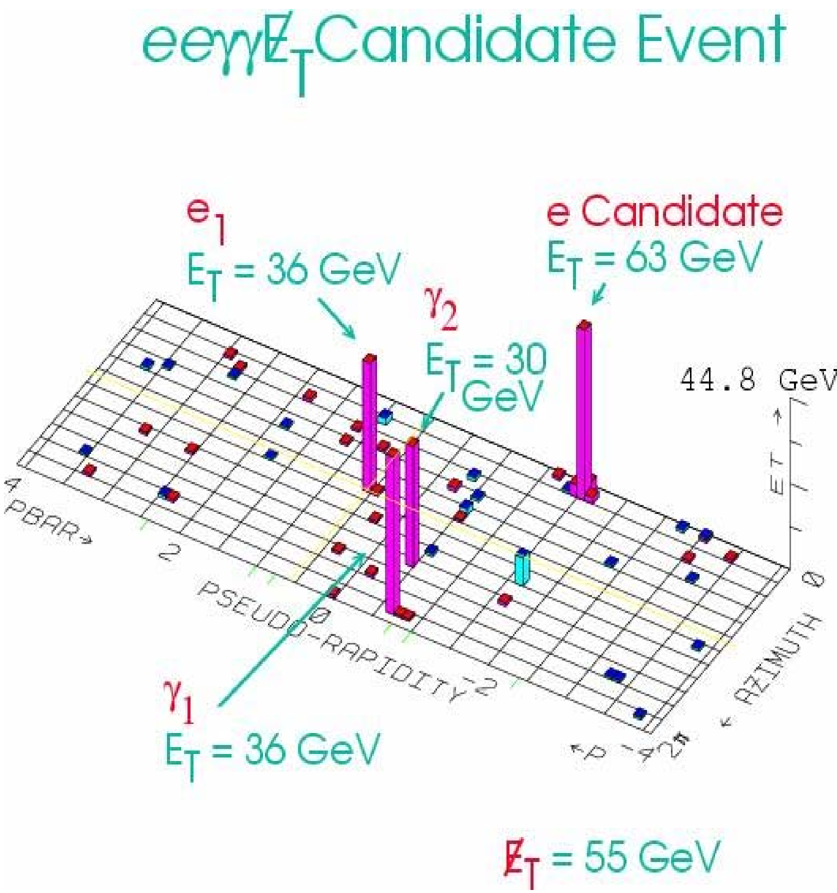
previous CDF limit with 53 pb^{-1}



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

Delayed photons

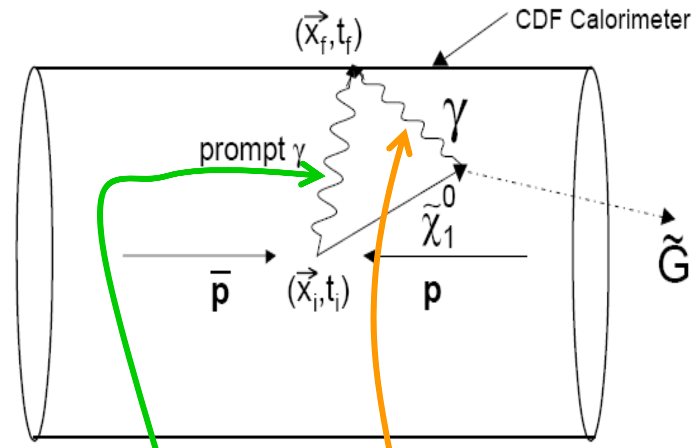
- **A rare event in RunI prompted lots of theory development at the time → GMSB**
  - Not seen in RunII ☹ (yet?)
- **GMSB -specific**
  - NLSP decays: $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
  - long life-time of $\tilde{\chi}_1^0$
    - **can be ~ns range**
      - **preferred from cosmological observations**
  - This makes delayed photons and MET
- **Signature "delayed γ" +MET is generic**
  - selectron→e+Neutral
  - stau→ τ(→ρ→γ)+X
  - something totally new
- **Here: search for γ+jets+MET**
  - GMSB as benchmark
  - 570 pb^{-1} of data
  - Based on "Prospects" study
    - **Phys. Rev. D 70, 114032 (2004)**

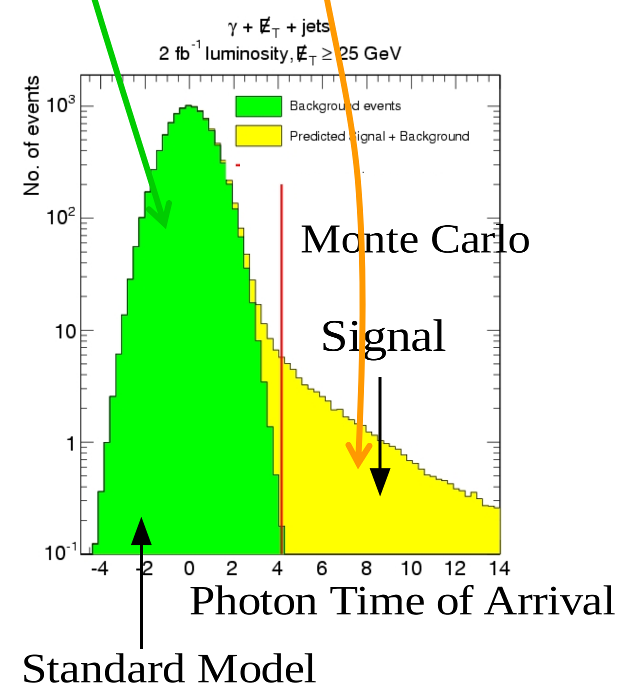


Very unexpected: ~1x10^{-6}

Delayed photon signature

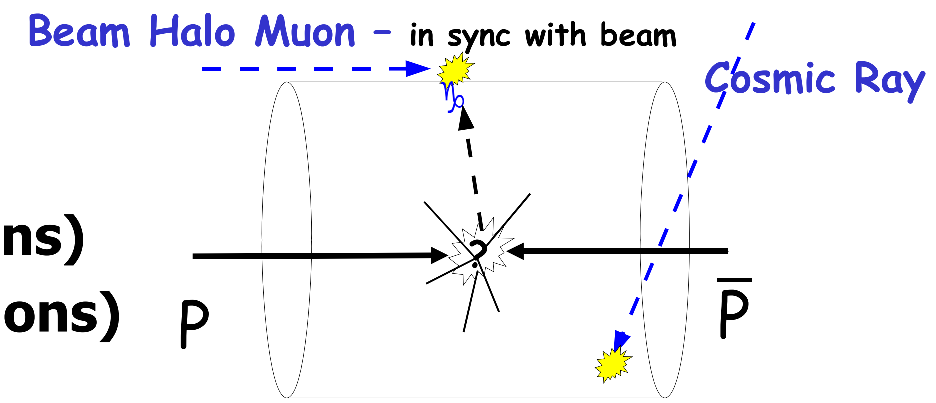
- **Path difference ↔ different times of arrival**
- **All SM signals are prompt**
- **→ Use EMTiming to discriminate**
  - Arrival @ EM-cal with 0.6 ns resolution
    - Can "see" decay vtx @ ~0.3-1.5 m
- **→Strategy**
  - Predict timing shapes for signal and background → look at data and set a limit
    - deal with SM(collision) and non-collision backgrounds

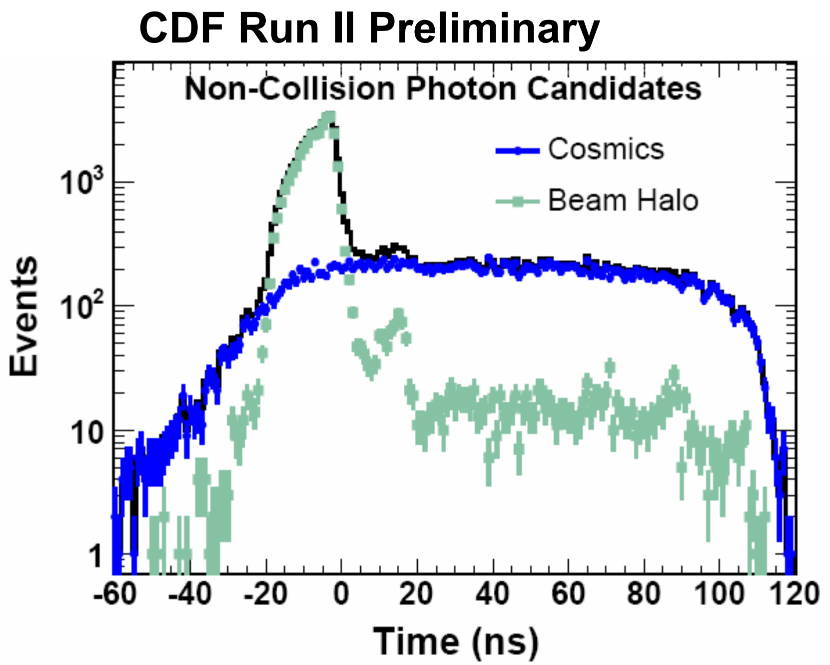




Background from data: non-collision

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



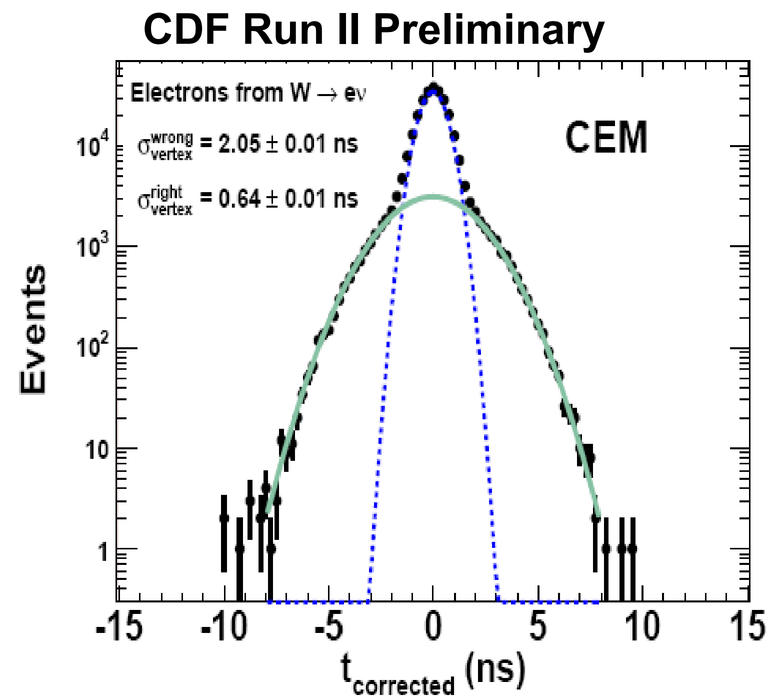


Background from data: collision (SM)

- **Multiple collisions are an issue**
  - don't know where γ is coming from
  - assume it's the vertex with the maximal Σp_T^{tracks}
    - **not always right ☹**

- **Model from W→eν sample**
  - hide e-track ➔ γ+MET sample
  - one Gaussian for right vertex
    - **σ = 0.64 ns**
  - one Gaussian for wrong vertex
    - **σ = 2.05 ns**

  - let the Gaussian-heights float in the signal shape fit



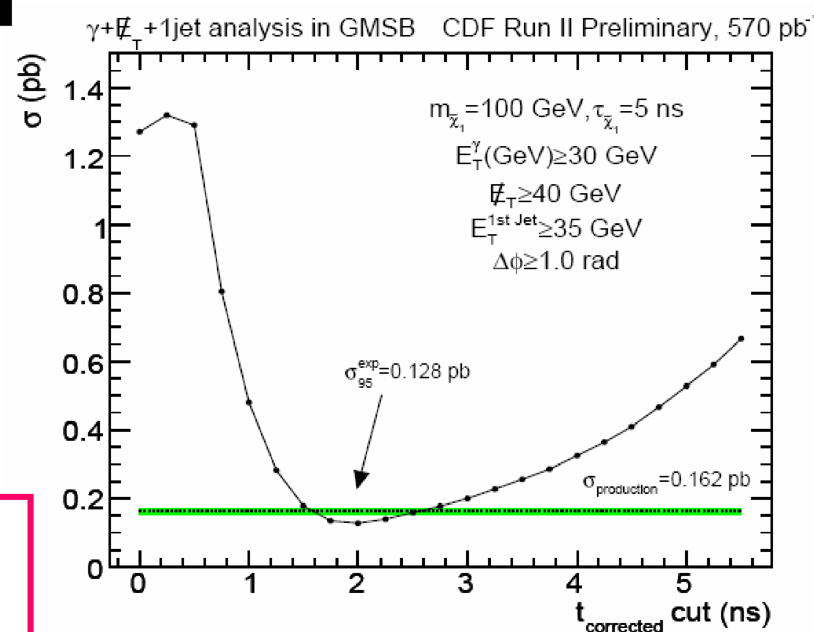
Signal MC

- **Generate with Pythia**
  - ("Snowmass" slope 8) choice of GMSB parameters
- **Simulate with standard detector simulation**
  - EMTiming response using parameterized simulation

- **Acceptance ~ 24%**
  - with pre-selections only
  - m=100 GeV, τ =5 ns
- **Acceptance** × **efficiency ~<6%**
  - with final selections

Optimization: Approach

- **Minimize expected 95% CL upper limit**
- **Optimize on**
  - t_c, MET, E_T^{γ}, E_T^{jet}, vertex Σp_T, $\Delta\phi$(MET, jet)
- **Grid search for a minimum**
  - find ~best (m, τ) reach point
  - ➔ use it's cuts for all sample



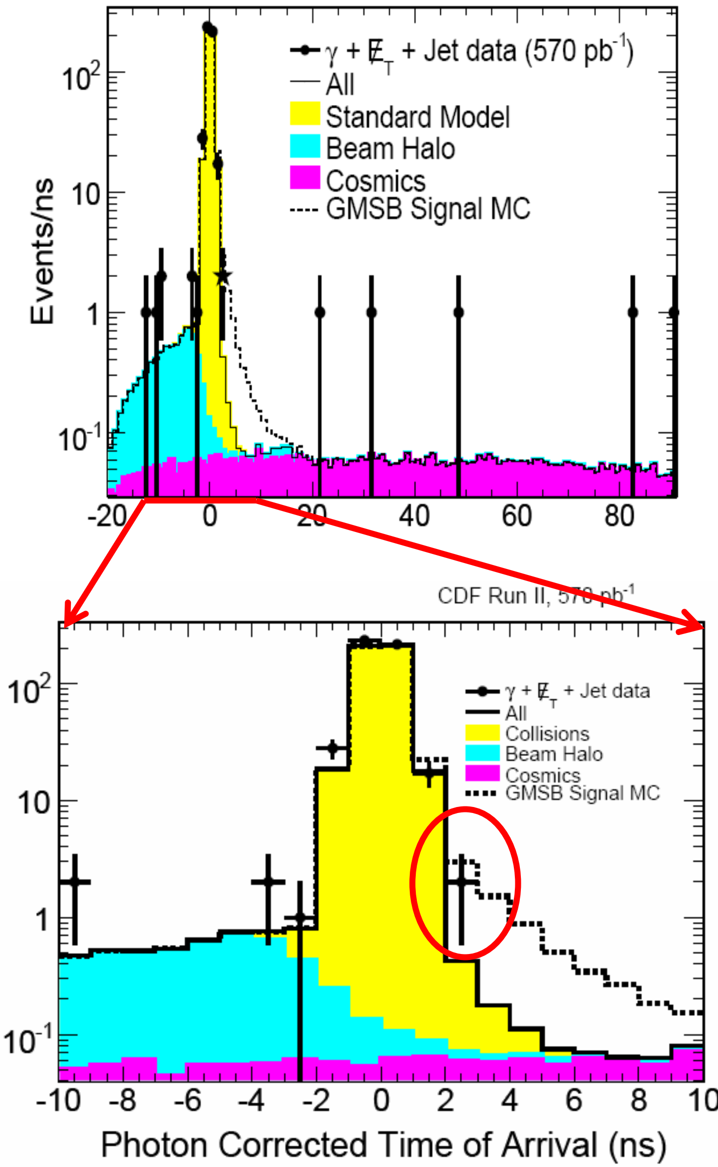
$$\not{E}_T > 40 \text{ GeV}, \; E_T^{\text{jet}} > 35 \text{ GeV}$$
$$\Delta\phi(\not{E}_T, \text{jet}) > 1 \text{ rad}$$
$$2 \text{ ns} < t_c^{\gamma} < 10 \text{ ns}$$

Optimization: Expectation → Results

- **With optimal cuts**

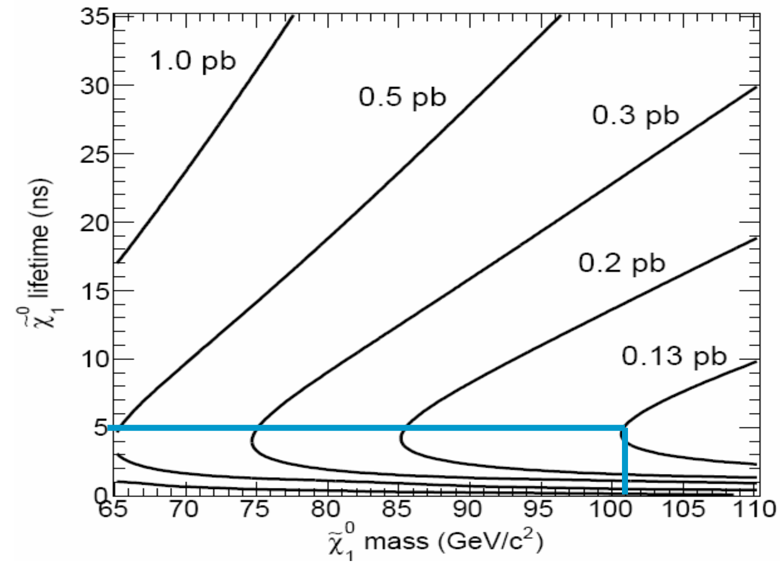
$$\not{E}_T > 40\ \text{GeV},\ E_T^{\text{jet}} > 35\ \text{GeV}$$
$$\Delta\phi(\not{E}_T, \text{jet}) > 1\ \text{rad}$$
$$2\ \text{ns} < t_c^\gamma < 10\ \text{ns}$$

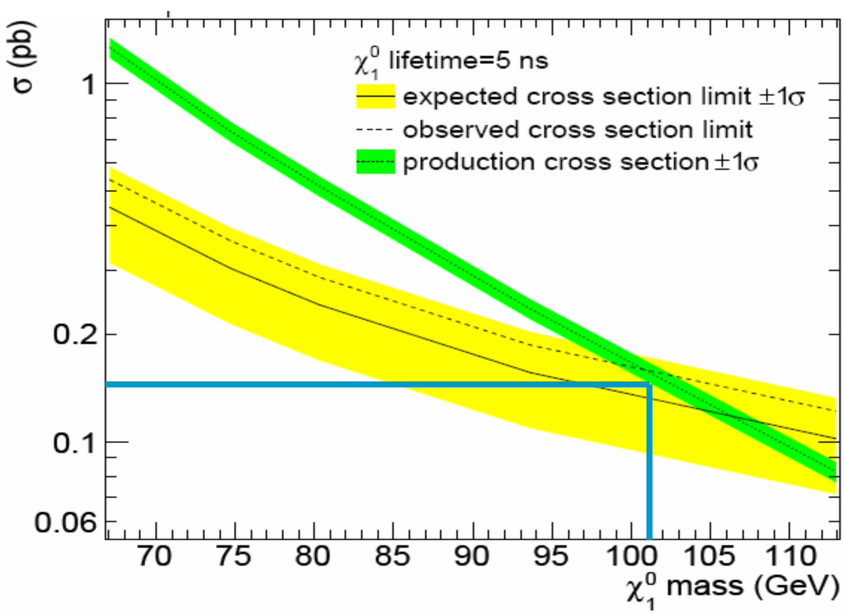
- **Expect**
  - 1.3±0.7 background events
    - **0.7±0.6 collision-SM**
    - **0.5±0.3 cosmics**
    - **0.1±0.1 beam halo**
- **Observe**
  - 2 events

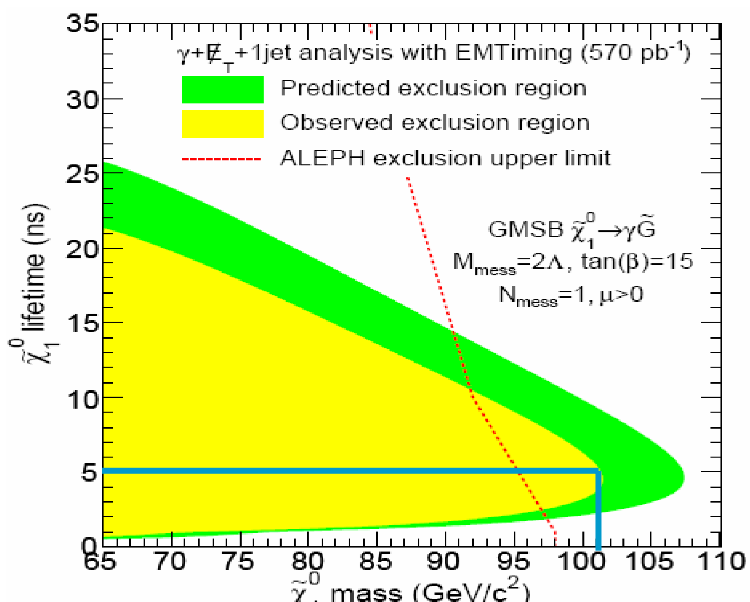


Results: Limits

- **Set cross-section limits @95% CL**
  - ~model-independent
- **Combine with expected GMSB cross-section ➔ set exclusion regions**
  - Result is better than LEP @~5 ns

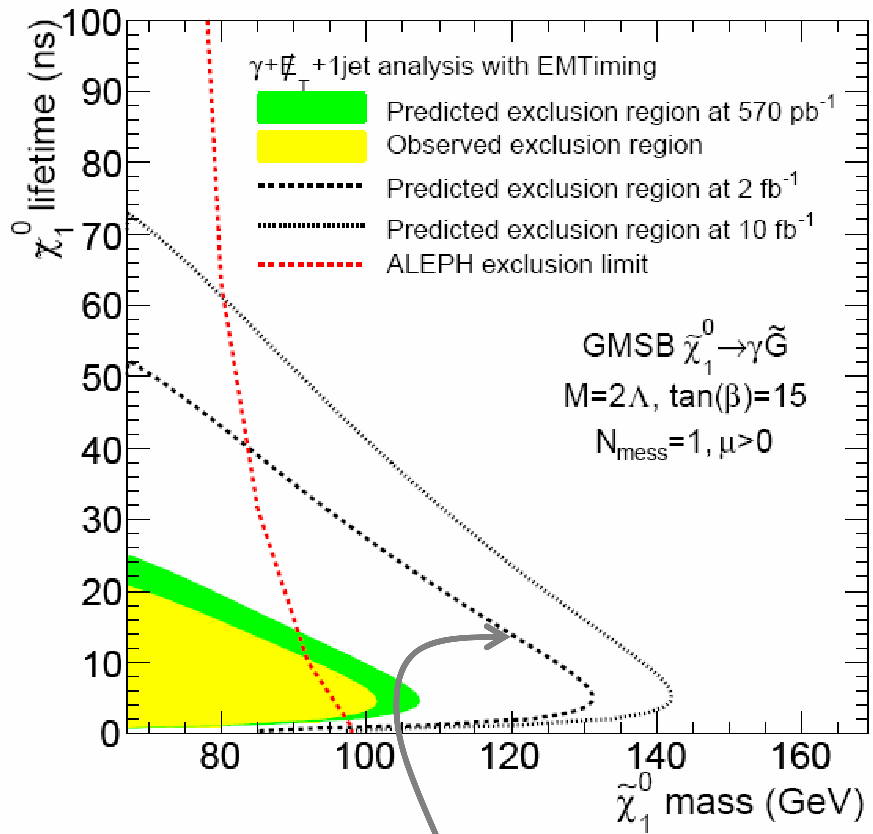






Summary/prospects for γ+jet+MET

- **First direct delayed photon search**
  - EMTiming performs well
- **Fruitful physics results**
  - PRL (accepted) [hep-ex/0704.0760]
  - PhD thesis – Peter Wagner
- **Good start for more searches with delayed photons (electrons, jets too)**
  - Update with more data to come



Can be here by the end of the year

What's next ?

Track Timing

Calorimeter Timing

Non-Collision rejection

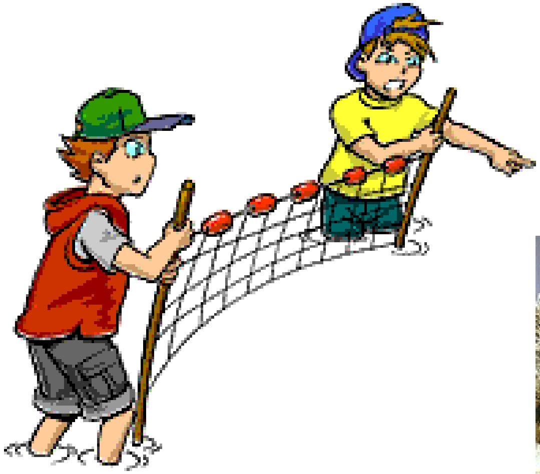
CHAMPs $\beta > 0.4$

Delayed photons

CHAMPs $\beta < 0.4$
Delayed jets

Displaced Vertices
(Hidden valley …)

Exclusive γ+MET
(KK states …)



Let's catch it !

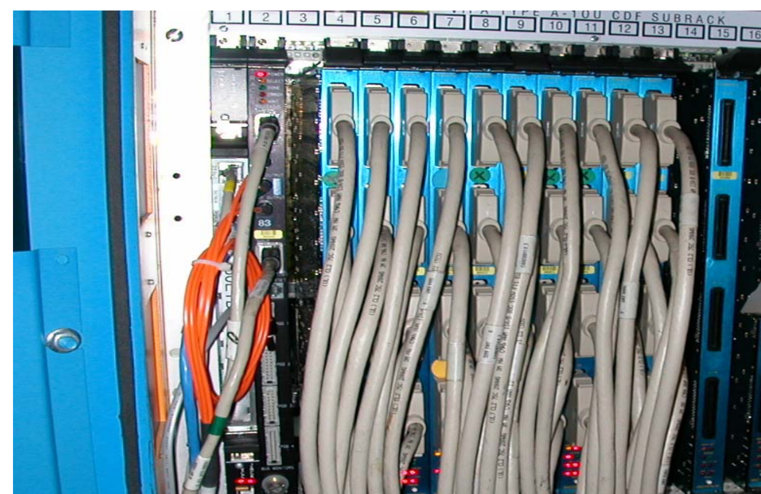
BACKUP SLIDES

Analysis strategy

- **Simulation:**
  - check that reconstruction is possible
- **Bgd prediction method:**
  - β shape $\oplus$ momentum histogram = background mass prediction
  - Show this works for electrons from $W \rightarrow e\nu$
    - **check w electrons with 20 < PT < 40 GeV**
    - **predict mass shape for electrons with PT > 40 GeV using β shape from 20<pt<40**
  - Muons:
    - **two control regions: 20 < PT < 30 and 30 < PT < 40**
    - **show that can predict 2 from 1**
    - **use β shape for 20 < PT < 40 to make prediction for PT > 40 GeV, compare with data in the signal region**
- **Signal sample: muon-trigger sample**
  - $|\eta| < 0.6$, $pt > 40$, $0.4 < \beta < 1$
- **Set limits (if consistent w bgd)**

New tools: 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**

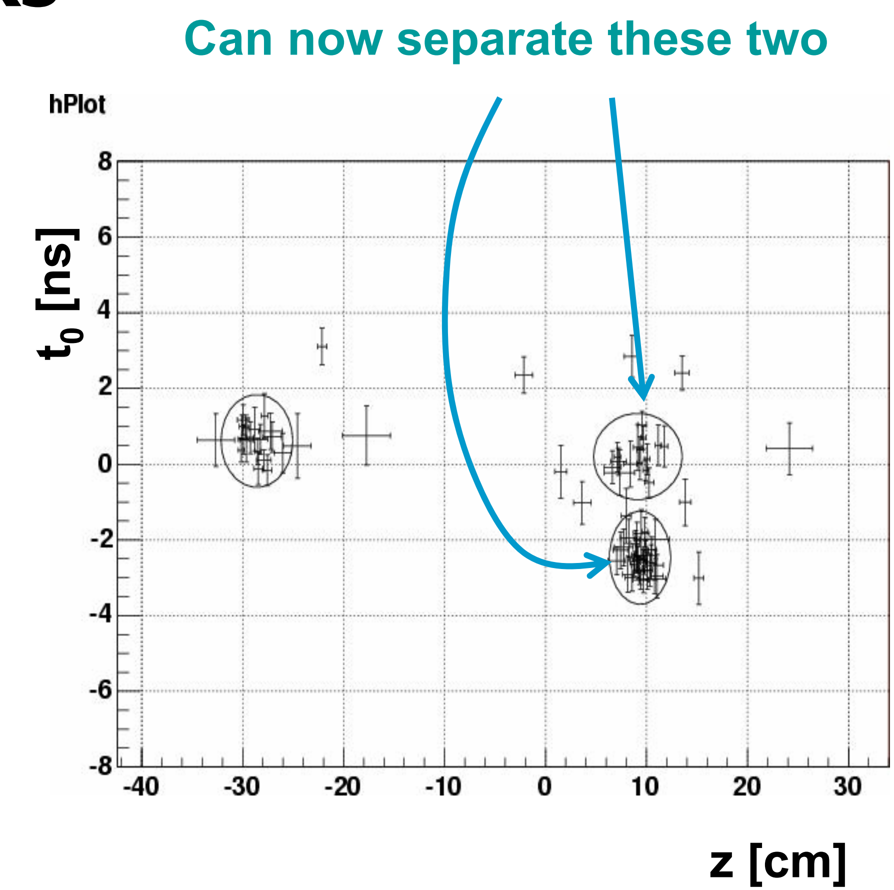
Signal MC

- **Generate w Pythia ("Snowmass" slope 8)**
- **Simulate with standard sim**
  - EMTiming response using parameterized simulation
- **Acceptance ~ 24%**
  - with pre-selections only
  - m=100 GeV, τ =5 ns

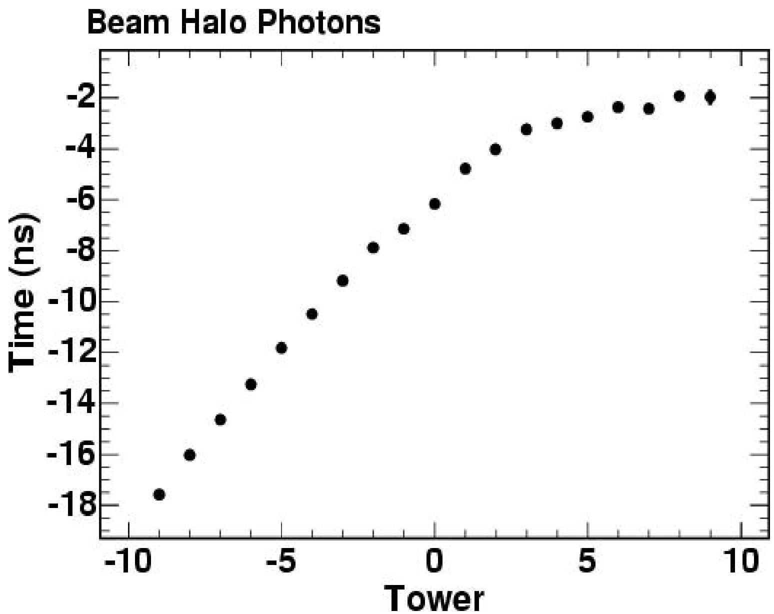
Preselection Requirements	Cumulative (individual) Efficiency (%)
$E_T^{\gamma} > 30$ GeV, $\not{E}_T > 30$ GeV	54 (54)
Photon ID and fiducial, $\|\eta\| < 1.0$	39 (74)*
Good vertex, $\sum_{\text{tracks}} p_T > 15$ GeV/c	31 (79)
$\|\eta^{\text{jet}}\| < 2.0$, $E_T^{\text{jet}} > 30$ GeV	24 (77)
Cosmic ray rejection	23 (98)*

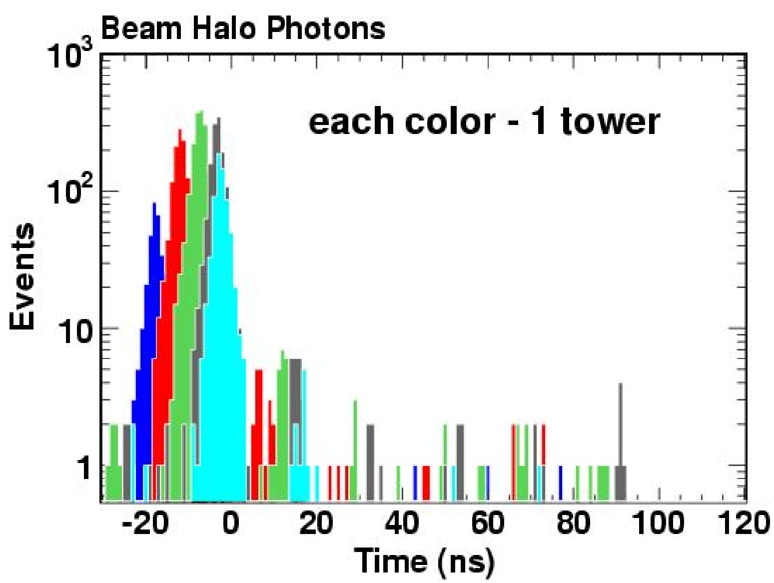
New tools: space-time vertexing

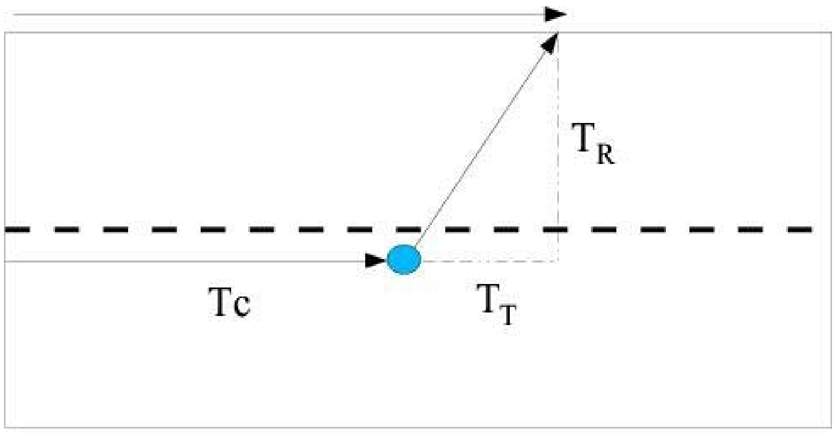
- **Use z and t_0 of COT tracks**
- **Apply expectation minimization algorithm**
  - Use resolution in z and t_0
    - σ_z~1 cm σ_t~ 0.4 ns
- **Result:**
  - high efficiency, resolution and separation of vertices overlapping in time



Beam Halo Time Shape







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

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

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

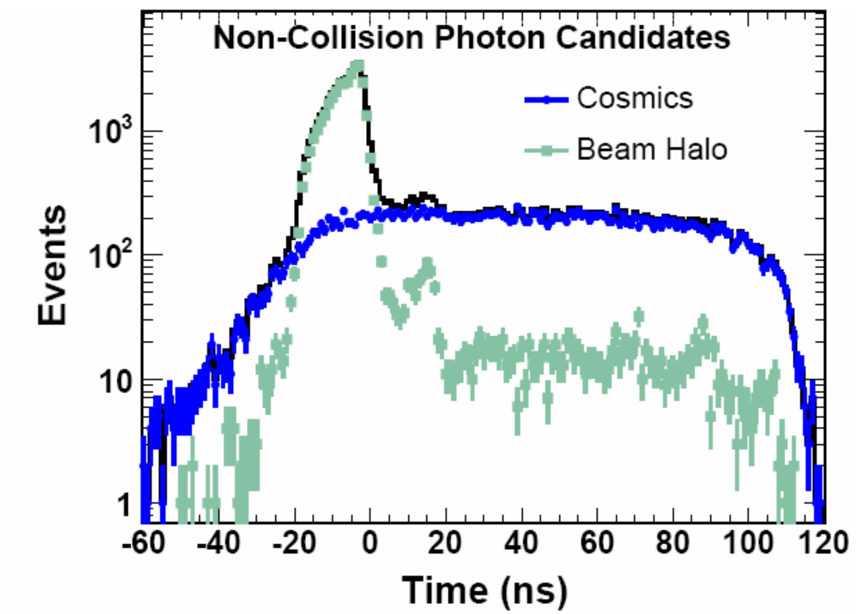
$$Tower\ -9 : \delta t \approx -2 T_T$$

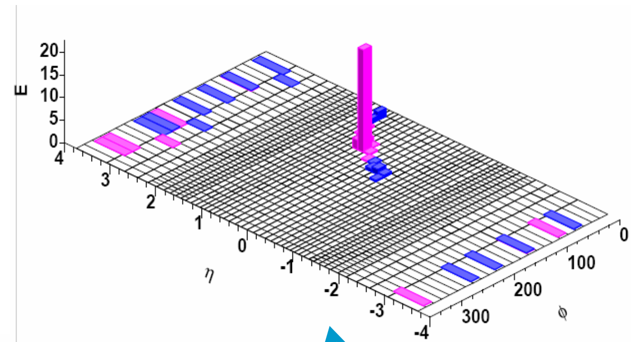
$$Center : \delta t \approx -T_R + T_T$$

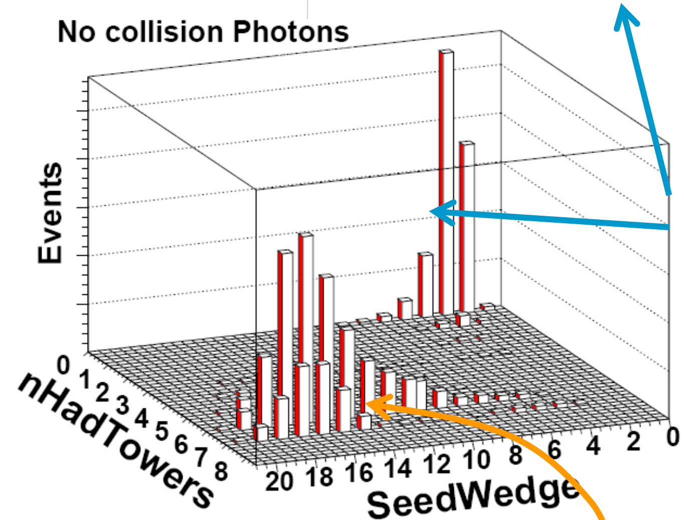
$$Tower\ 9 : \delta t \approx -\frac{T_R^2}{2 T_T}$$

Bkg from data: non-collision

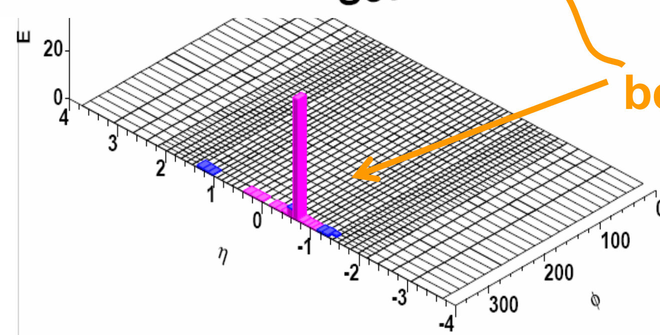
- **From outer space – cosmic (muons)**
- **From the beam – beam halo (muons)**
- **Look different in cal**
  - long traces for BH (mostly at $\phi = 0$)
  - a few towers for Cosmics
- **Separate and get the shapes**





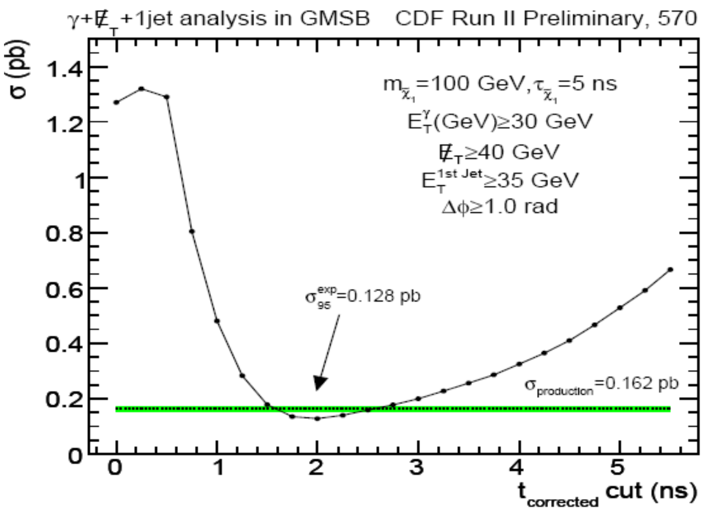


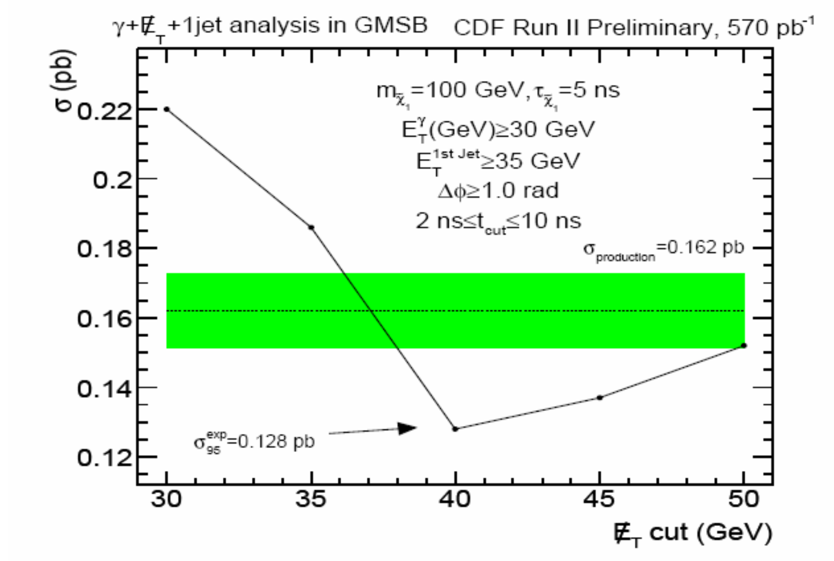
cosmics

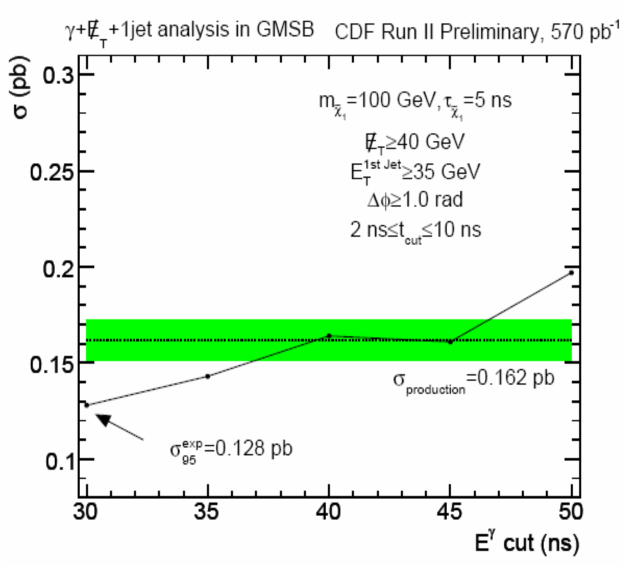


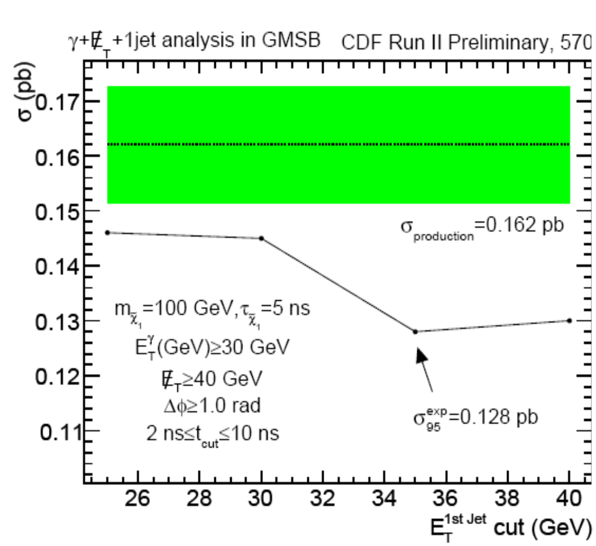
beam halo

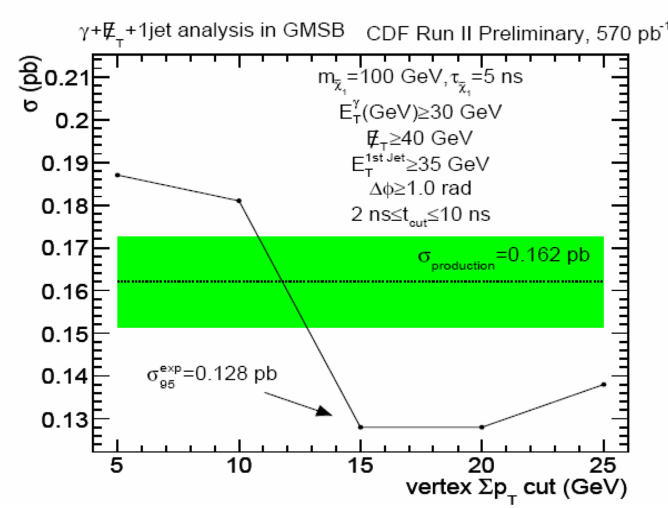
Optimization











Kinematics of 2 events