Search for Gauge-Mediated Supersymmetry in the Di-Photon Channel

presented by

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Theoretical Framework Overview

- Standard Model
  - Quantum Field Theory (Quantum Mechanics + Special Relativity)
    - Particles and Mediators described as excitations of Quantum Fields
  - Equations obtained from Action Principle and **Local Gauge Invariance**
    - Mathematical group: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
  - Incorporates Strong and Electroweak interactions (no Gravity)
    - Strong Interactions: $SU(3)_C$
    - Electroweak Interactions: $SU(2)_L \otimes U(1)_Y$
  - Classification scheme of particles (fermions) and mediators (bosons)

Theoretical Framework Overview

- Local Gauge Invariance in Electromagnetism
  - Classically: Electromagnetic field is invariant under gauge transformations
    - $A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu \lambda(x)$, $F_{\mu\nu} \rightarrow F'_{\mu\nu} = F_{\mu\nu}$
  - Classically: Field – particle interaction is invariant under gauge transformations
    - $\partial_\mu j^\mu = 0$ (Noether's Theorem)
  - Quantum Mechanically: $\mathcal{L} = \mathcal{L}_{DIRAC} + \mathcal{L}_{FIELD} + \mathcal{L}_{INT}$
    - $\mathcal{L}_{DIRAC} = i (\psi^\dagger\gamma^0) \gamma^\mu \partial_\mu\psi - m (\psi^\dagger\gamma^0) \psi$
    - $\mathcal{L}_{FIELD} = -1/4 F^{\mu\nu} F_{\mu\nu}$ (invariant under $A_\mu \rightarrow A_\mu + \partial_\mu \lambda(x)$)
    - $\mathcal{L}_{INT} = q (\psi^\dagger\gamma^0) \gamma^\mu \psi A_\mu$ (not invariant under $A_\mu \rightarrow A_\mu + \partial_\mu \lambda(x)$)

Theoretical Framework Overview

- The total Lagrangian can remain invariant as long as both a local phase and gauge transformation applied (local gauge invariance):
  - $A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu \lambda(x)$ and $\psi \rightarrow \psi' = e^{-iq\lambda(x)}\psi$
- Experiment confirms phase transformations (Bohm-Aharonov), therefore this is a defining property of the EM field.
- Local gauge invariance is required for every interaction:
  - To preserve invariance additional fields are introduced (gauge fields)
  - Particle-Field interaction is uniquely determined
  - Field equations are uniquely determined (only gauge invariant terms)
  - Mass terms for the gauge fields are not gauge invariant
    - Gauge fields have zero mass

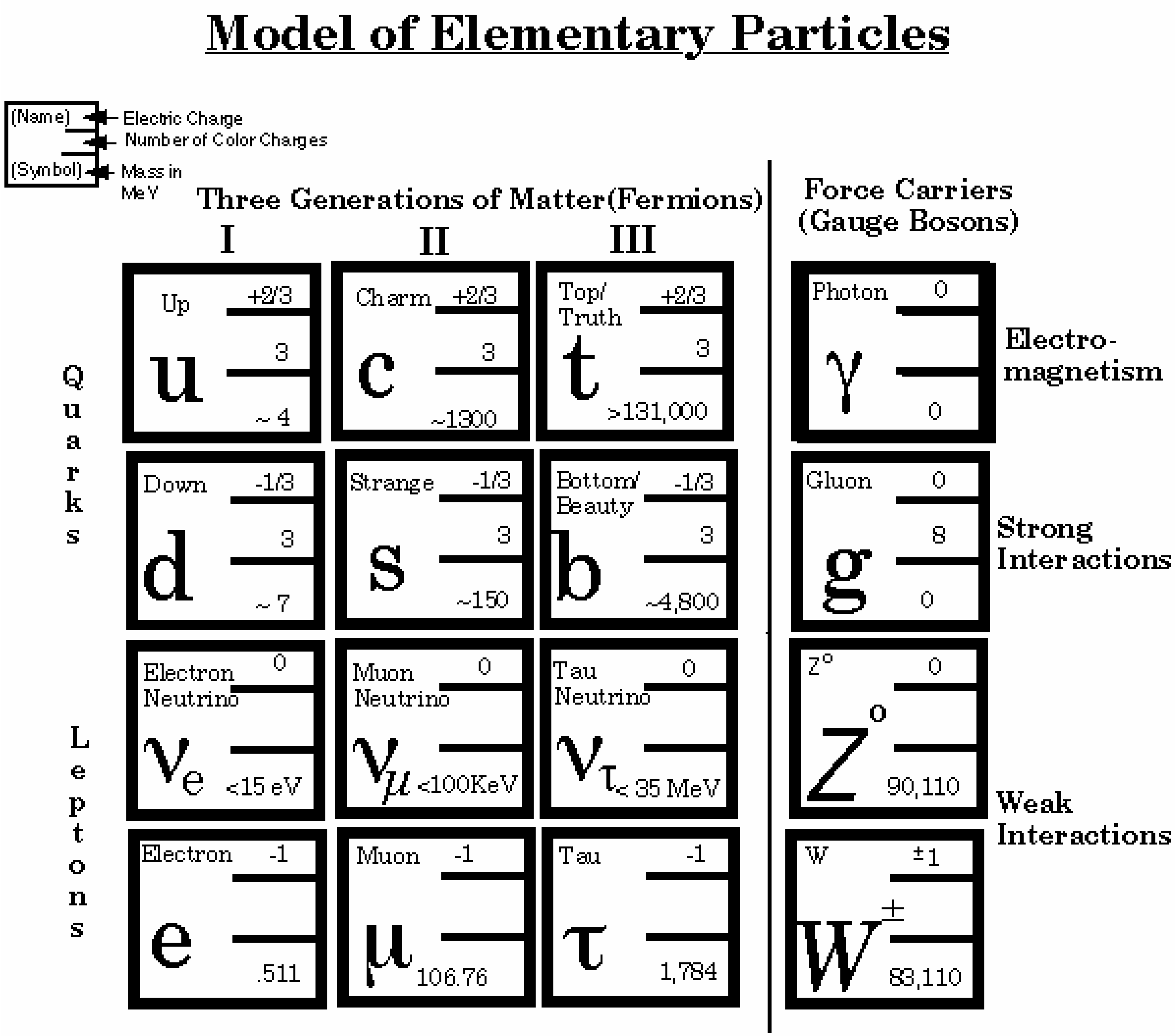
Theoretical Framework Overview

- Strong Interaction
  - Color is the conserved quantity
  - Local gauge invariance under $SU(3)_C$
  - A set of eight gauge fields (gluons) is predicted
  - Interaction's short-range is explained (confinement)

- Weak Interaction
  - For gauge invariance to exist it had to be completed
    - Electroweak Interaction
    - Local gauge invariance under $SU(2)_L \otimes U(1)_Y$
    - A set of four gauge fields W^{μ} , $\mu = 0, 1, 2, 3$ is predicted
    - Interaction is short-range (massive mediators) and not explained by the model!
    - Fermions are prohibited to have mass! (Dirac mass term)

- Higgs
  - Extra field neither fermion nor gauge field
  - Breaks the electroweak symmetry for the observable states
    - Short-range of the weak forces is explained
    - Fermions acquire mass through the Higgs field

Theoretical Framework Overview



Theoretical Framework Overview

- Standard Model problems

  - Hierarchy problem

    - Masses of particles are determined by the Higgs (~200 GeV)
    - BUT the Higgs mass is not bounded, it can be up to 10^{12} - 10^{18} GeV
    - Why is so low?

  - Higgs mass quadratically diverges in perturbation theory if the fermion and boson masses are not ‘’near’ equal’’

    - $M^2_h \sim M^2_{h0} + (g^2_F / 4\pi^2) (m^2_F - m^2_S)$

  - Gravity is not included

Theoretical Framework Overview

- Supersymmetry
  - A gauge theory that combines all particles (fermions and bosons) into “superfields”
    - All superfields now have zero mass
  - Particles and their “superpartners” have all quantum numbers the same and they differ only by one-half unit of spin
  - Number of particles in the standard model doubles
  - Among known particles there are no superpartners
    - Supersymmetry must be broken
- If Supersymmetry is broken:
  - All particles (fermions, bosons and Higgs) acquire mass determined from the energy scale where supersymmetry is broken
  - Quadratic divergences of the Higgs mass are suppressed since $m_{FERMIONS} \approx m_{SCALARS}$

Theoretical Framework Overview

- Gauge Mediation of SUSY Breaking
  - SUSY is broken in a sector of superfields not containing the known particles or their superpartners (hidden sector)
  - Gauge interactions between the hidden sector and the rest of the superfields and known particles transmit SUSY breaking
  - Experimental predictions for this class of models, do not depend from the details of the SUSY breaking, but rather from the features of the of the model after the breaking
- GMSB model features
  - Few parameters define the phenomenology
    - SUSY breaking scale in the messenger sector, $\sqrt{F}$
    - Number of messenger pairs, N_{mess}
    - Messenger mass scale, M

Theoretical Framework Overview

- GMSB model features (cont.)
  - ❖ Universal mass scale of SUSY particles, Λ
  - ❖ Ratio of Higgs vacuum expectation values, $\tan\beta$
  - ❖ sign of the Higgs sector mixing parameter, sign(μ)

➢ R-parity invariance

- ❖ $R = (-1)^{3(B-L)+2S}$ S = spin, B = baryon number, L = lepton number
- ❖ Pair-production of SUSY particles that all finally decay
- ❖ Lightest SUSY particle (LSP) must be absolutely stable
  - Cosmological constrains also require to be neutral

➢ LSP in R-parity-conserving SUSY escapes the detector

- ❖ Experimental Signature ⇒ Missing Transverse Energy

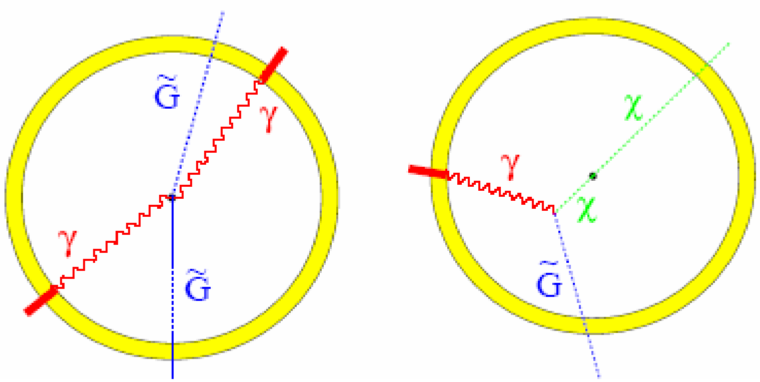
➢ Gravitino is the LSP: $m_G = 2.4 (\sqrt{F} / 100\ \text{TeV})^2$ eV

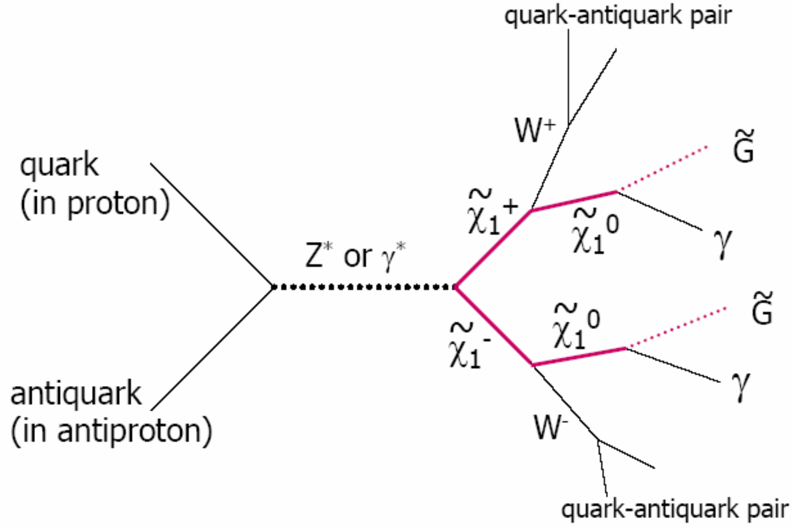
Theoretical Framework Overview

- GMSB model features (cont.)
  - Since LSP is stable, the next to LSP determines the phenomenology of GMSB models
    - NLSP is either neutralino χ^0_1 or a slepton
  - NLSP lifetime is not fixed by the model
  - Signatures depend on the NLSP type and decay length.
    - Non-pointing photons in photon plus jets final state.
    - Non-pointing Z's from the primary vertex in final state

- GMSB model features (cont.)

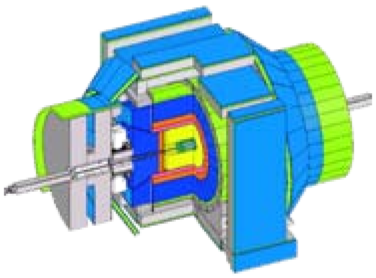
$$p\bar{p} \rightarrow gauginos \rightarrow W^{(*)}, Z^{(*)}, l + \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma + \tilde{G}\tilde{G} + X$$



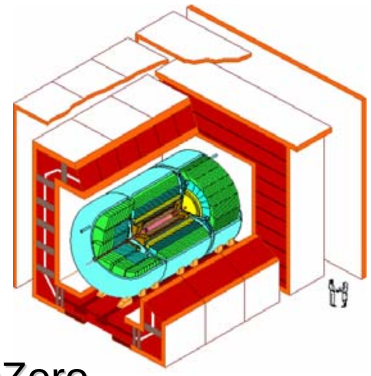


Run II - Tevatron Collider

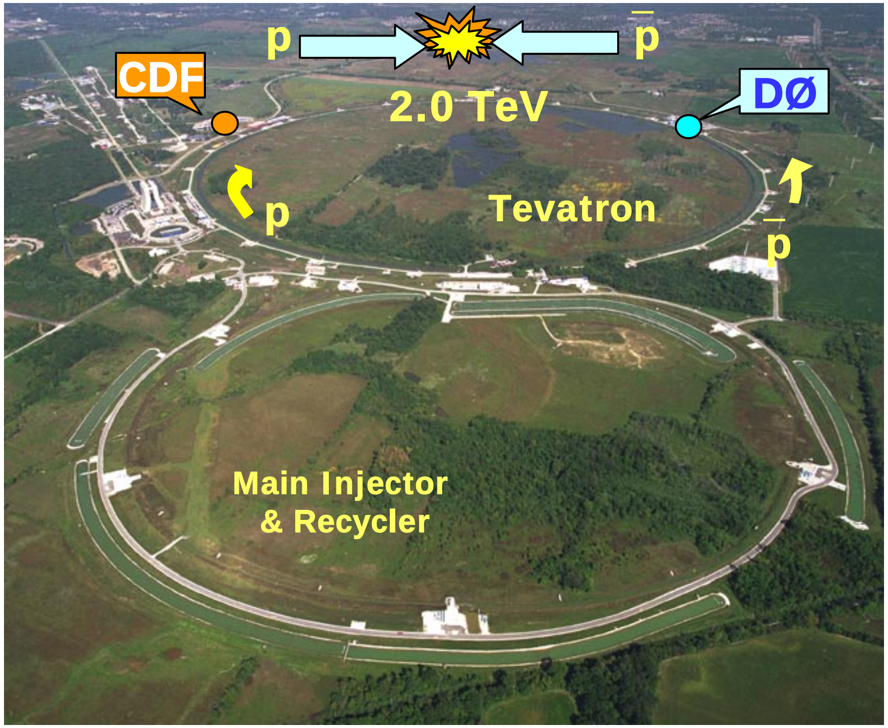
- **Run I 1992-95**
- **Run II 2001-09(?) 100 × larger dataset at increased energy**
- **Collision energy, $\sqrt{s}$ =1.96 TeV**
- **Bunch crossing, Δt = 396 ns**



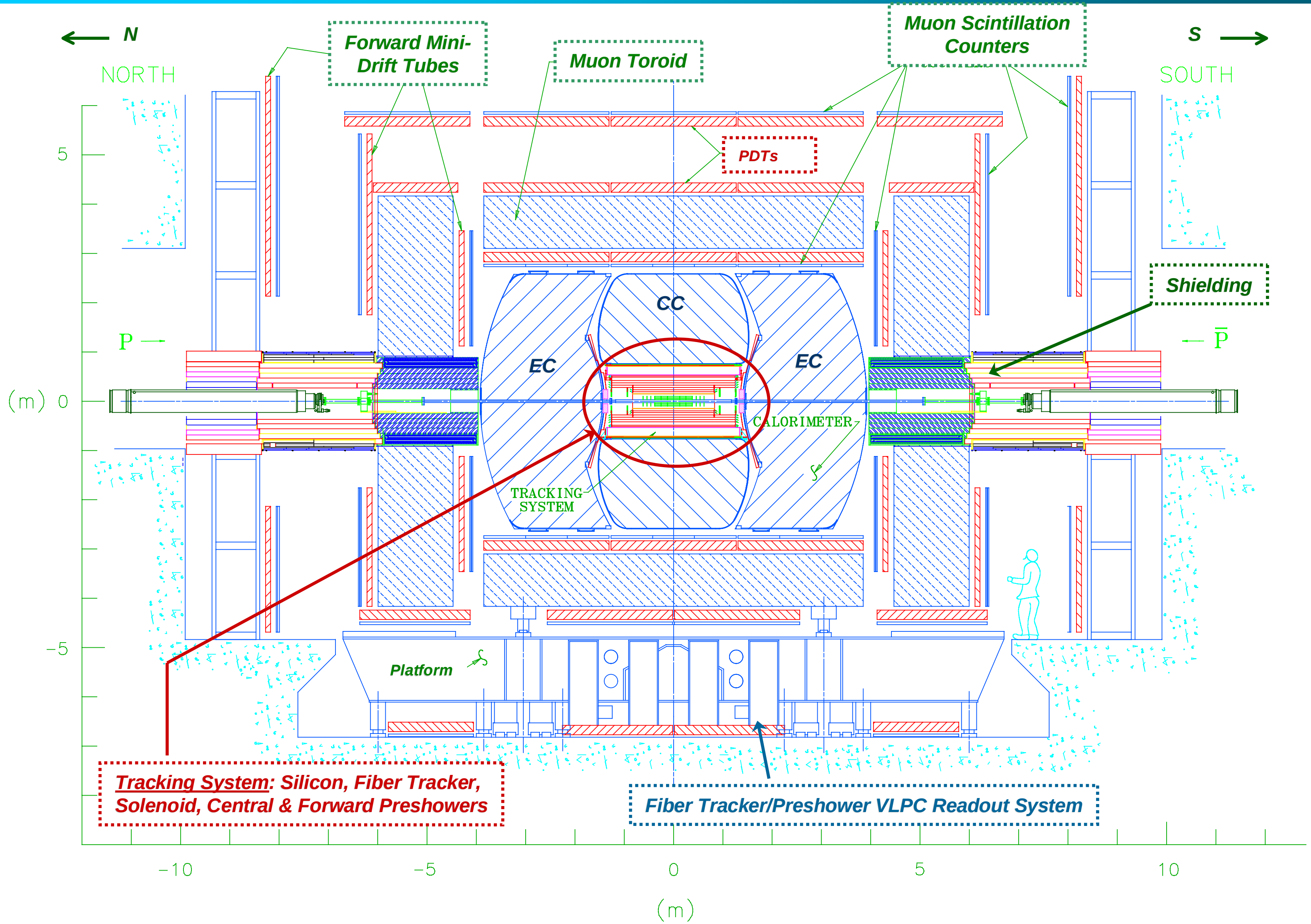
CDF



DZero

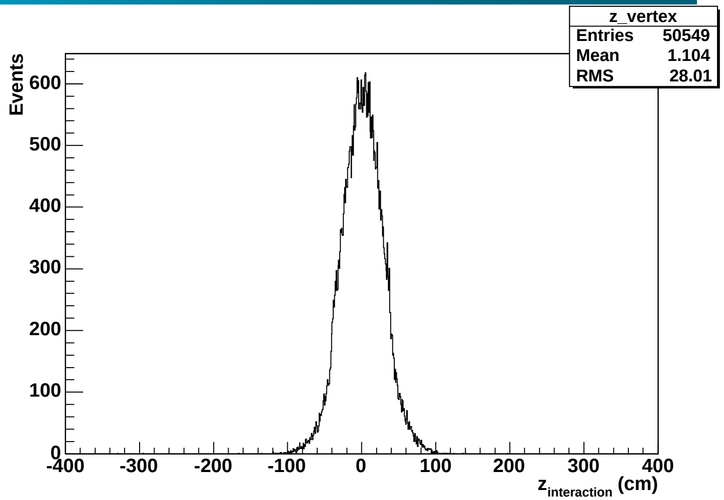


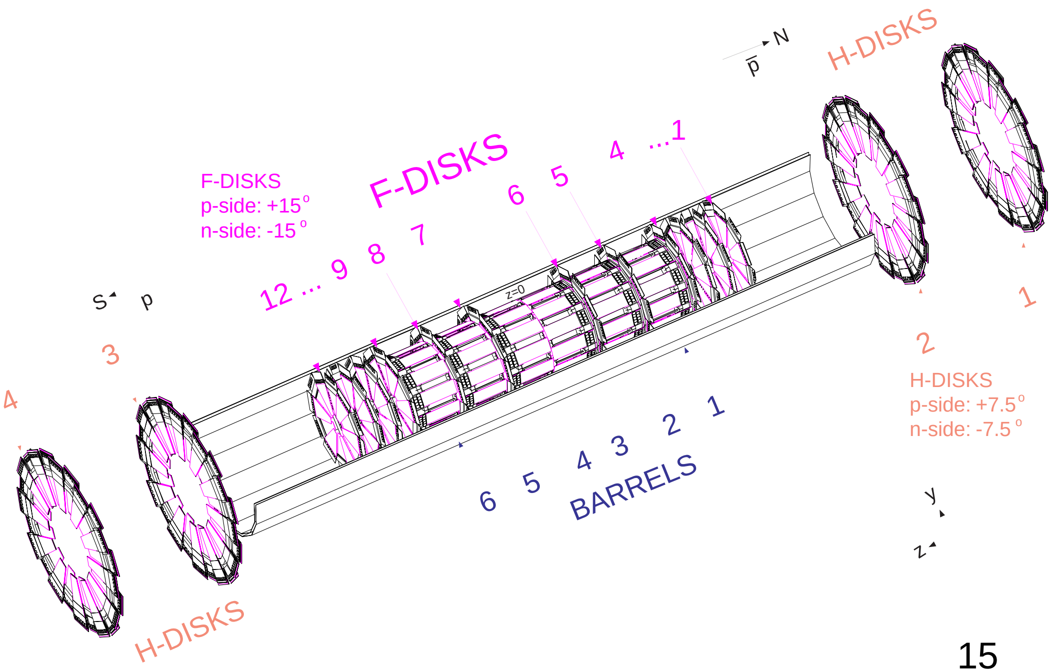
Run II - DØ Detector



Run II - DØ Detector

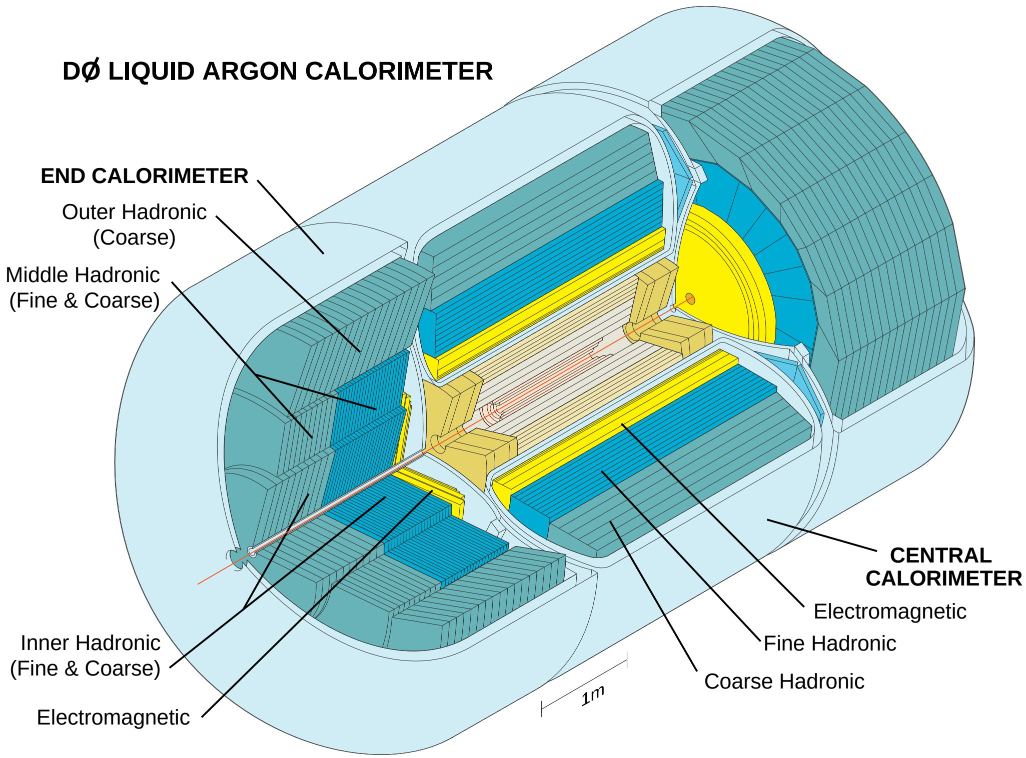
- Interaction Point
  - Protons and antiprotons collide in bunches
  - Gaussian distribution
    - z = 0 with σ = 28 cm
- Hubrid Design
  - Barrels: For r - ϕ coverage
  - Disks: For r-ϕ and r-z coverage
- Individual detectors
  - Ladders (barrels)
  - Wedges (disks)
- Measured with Optical Gauging Platform (OGP)
- Assembled under Coordinate Measuring Machine (CMM)





Run II - DØ Detector

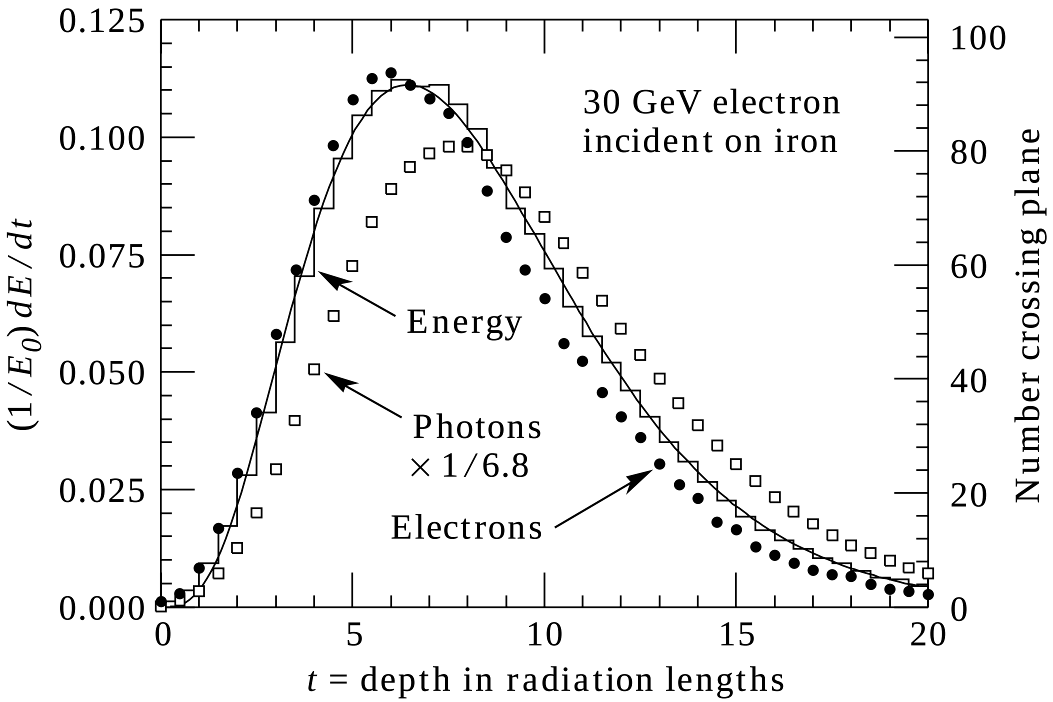
- Compensating sampling calorimeter
  - $e/h = 1 \pm 0.02$
- Liquid Argon
  - Active sampling medium
- Depleted Uranium
  - Absorber material
- Three types of modules
  - EM section
  - FH section
  - CH section
- Energy resolution
  - $(\sigma/E)^2 = c^2 + S^2/E^{1/2} + N^2/E$



Run II - DØ Detector

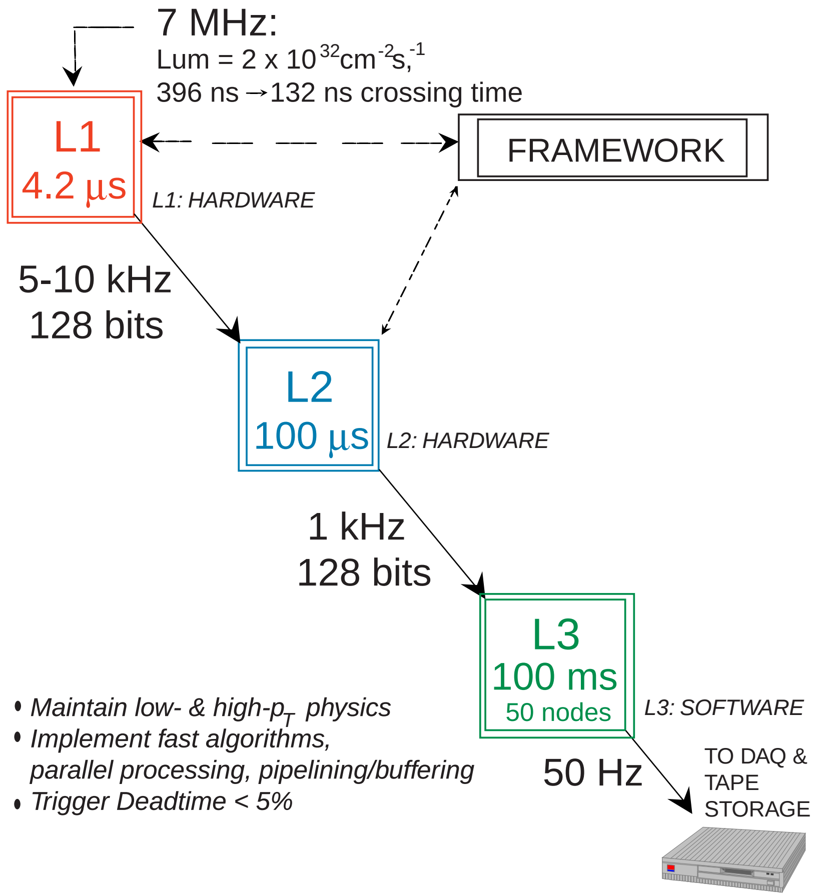
- Electromagnetic showers develops through multiplication of photons and electrons
  - Bremsstrahlung
  - Electron-positron pair production

- Electron-originated and photon-originated showers have pretty much the same profile in the calorimeter



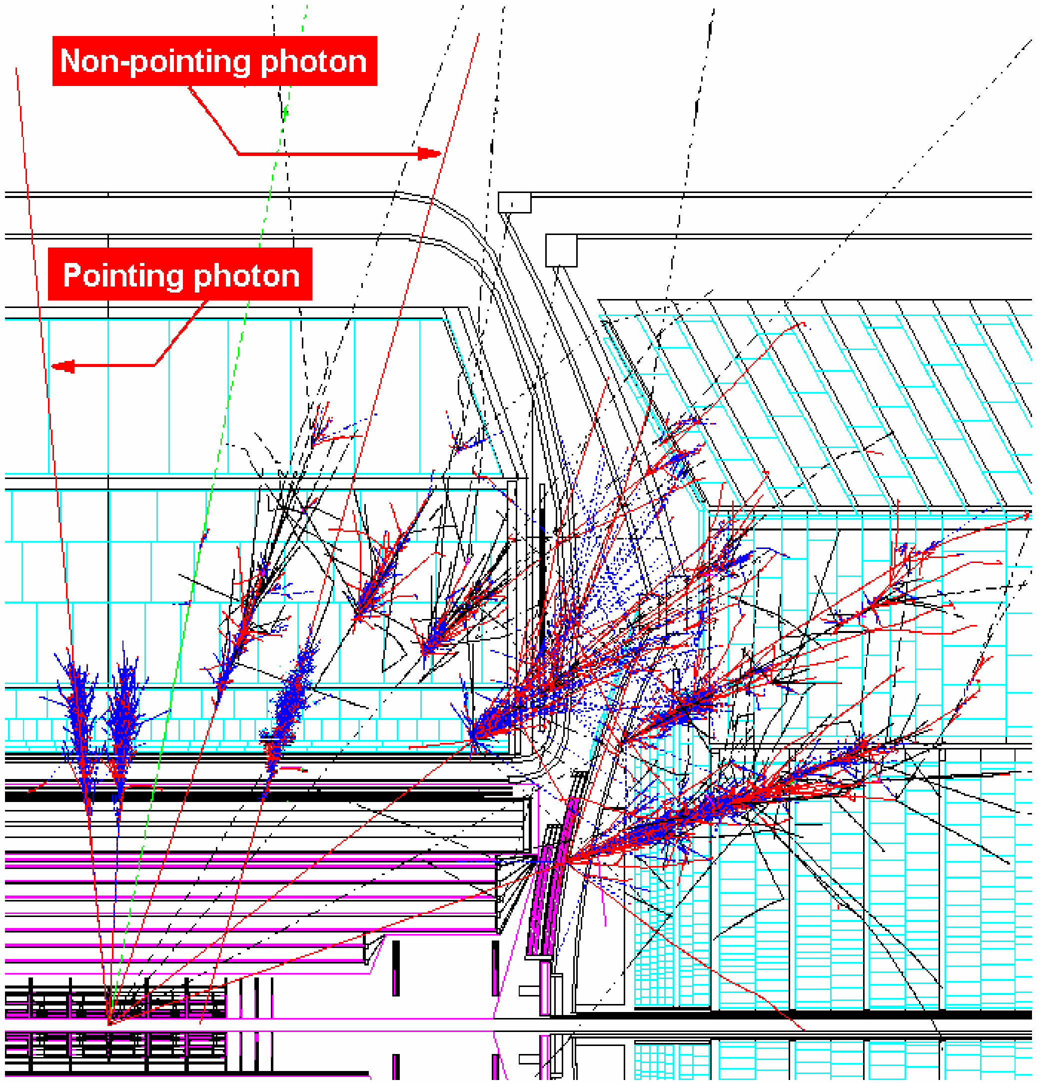
Run II - DØ Detector

- Three level trigger
  - L1: Raw detector info
    - List of candidates from each subdetector (cal E_T towers, ca;-trk match etc)
  - L2: Correlation Algorithms
    - List of trigger terms & physics objects
    - Combines correlations
  - L3: Event Filtering Algorithms
    - **Online reconstructed e,μ, j**
    - **“physics tools”**
    - **Event topologies**



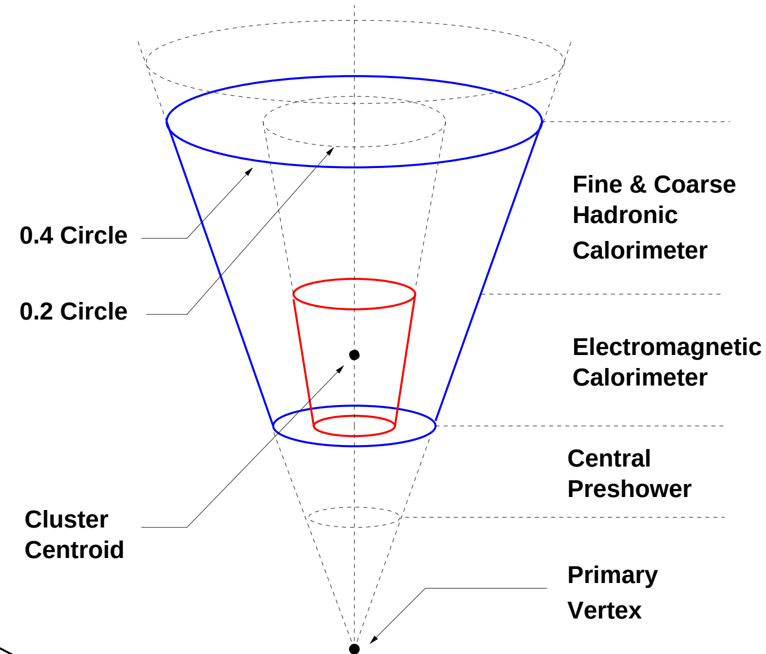
Reconstruction and Particle ID

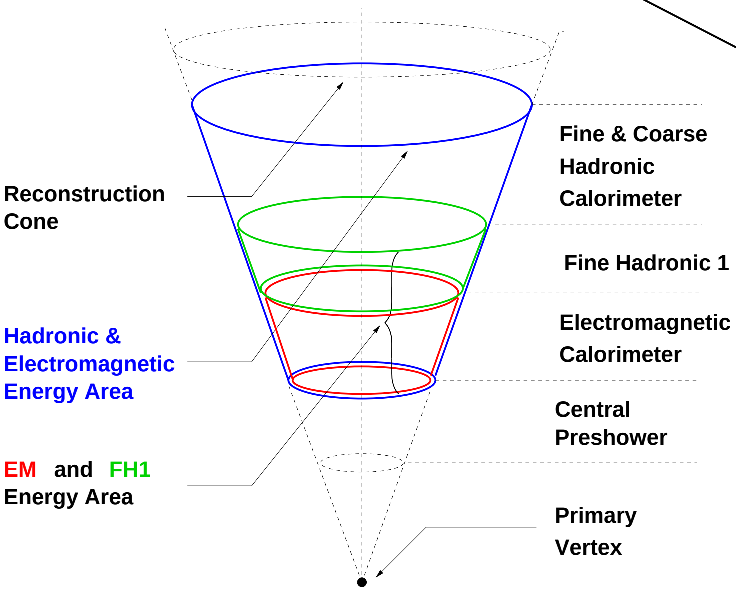
- Physics objects have to be reconstructed from detector readout
- Dedicated software for object reconstruction (DØReco)
- A set of identification variables is used in order to isolate the various candidates
- Only EM objects are used in this analysis (EMID variables)



Reconstruction and Particle ID

- Electromagnetic Isolation
  - $EM_{iso} = E_{TOT}(R<0.4)/E_{EM}(R<0.2) - 1$
  - $(\Delta R)^2 = (\Delta\phi)^2 + (\Delta\eta)^2$
  - Deep and narrow measure ⇒
    - Photons and electrons ⇒ narrow
    - Hadronic showers ⇒ wider and deeper





⇐

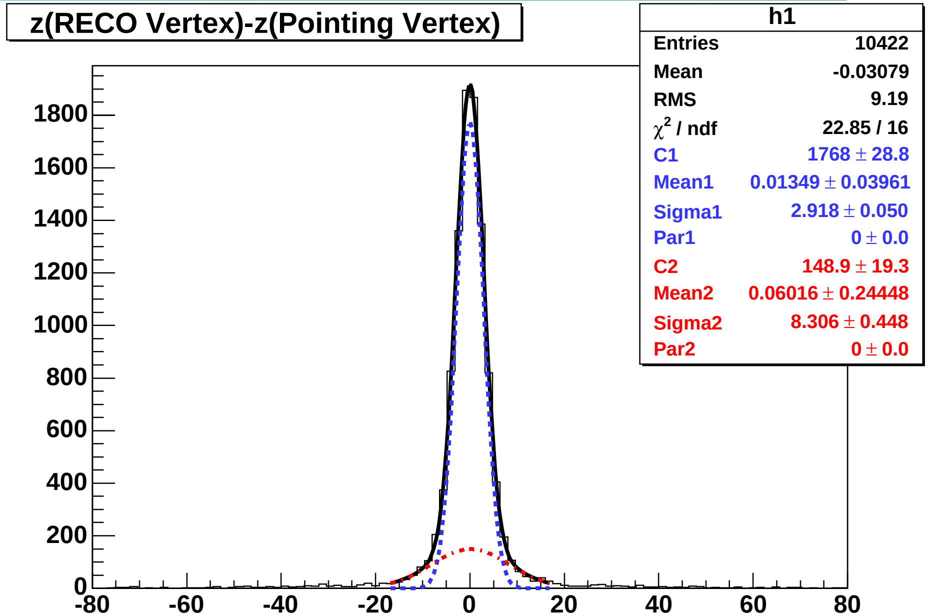
- Electromagnetic Fraction
  - $EM_{fract} = E_{EM,FH1}/E_{TOTAL}$
  - It measures the deposition of energy within the cluster

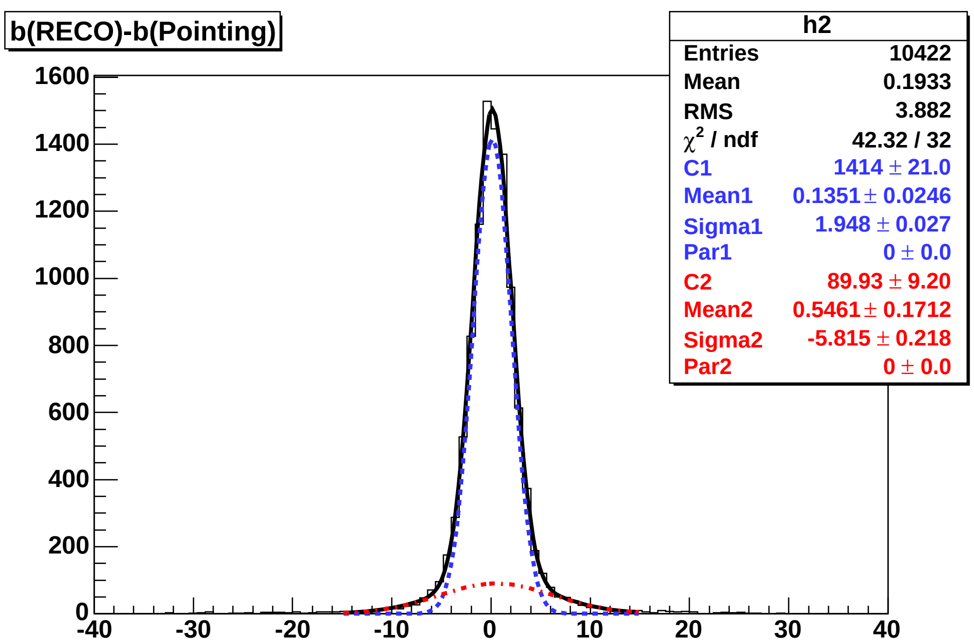
Reconstruction and Particle ID

- H-matrix variable
  - Takes into account the shape of the shower itself
    - Longitudinal shower shape
    - Transverse shower shape
    - Energy deposition within the cluster
  - It measures how similar the shower is to an electron (photon) or a hadronic shower
- Track match / veto
  - All the above variables are calorimeter based
    - Allow for QCD processes to contaminate the sample
    - Doesn't distinguishes electrons from photons
  - Tracking system (CFT and SMT) is used to reconstruct tracks
  - Tracks are matched with EM clusters spatially
    - $\chi^2_{spatial} = (\delta\phi/\sigma_\phi)^2 + (\delta z/\sigma_z)^2$

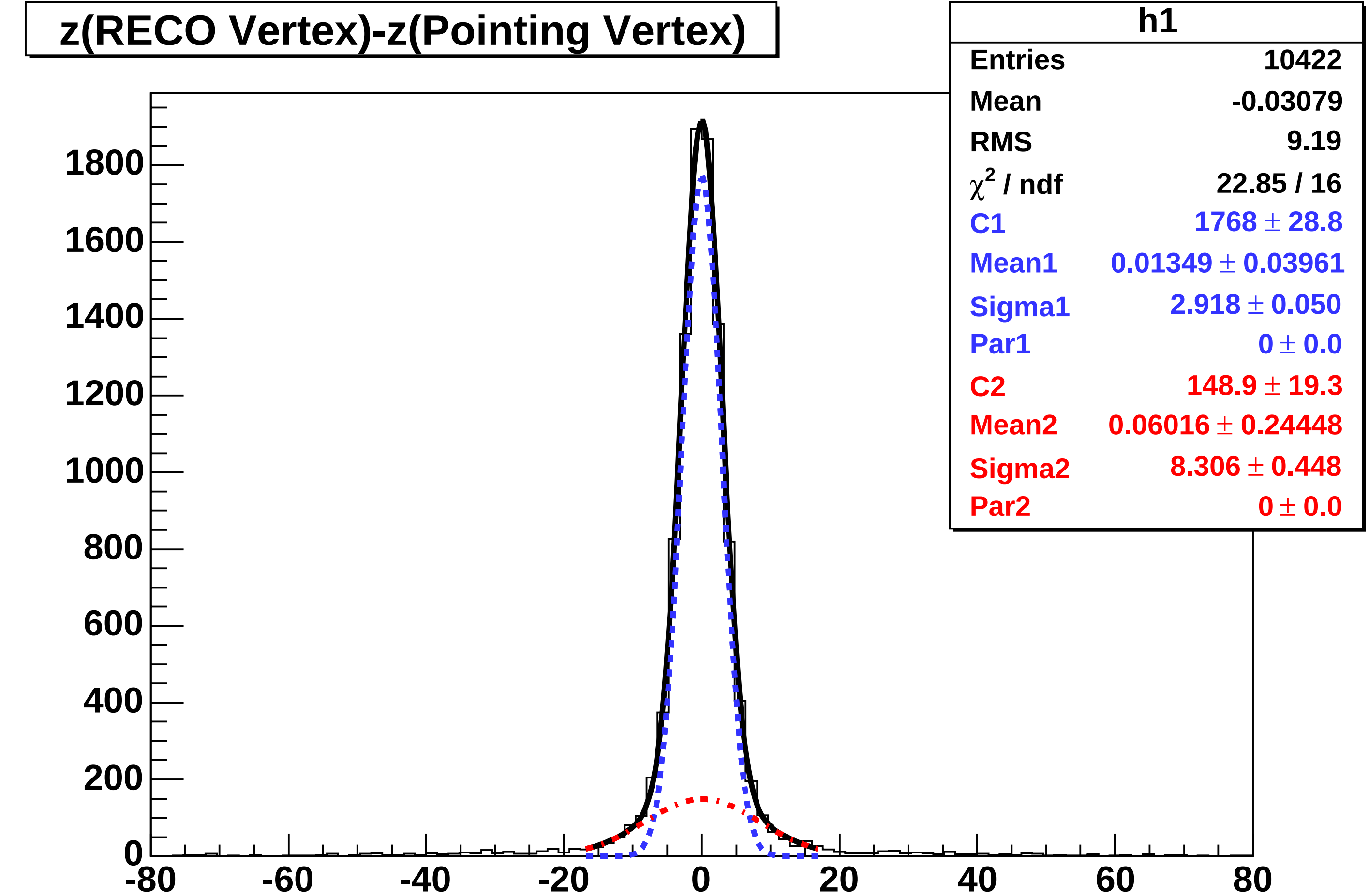
Reconstruction and Particle ID

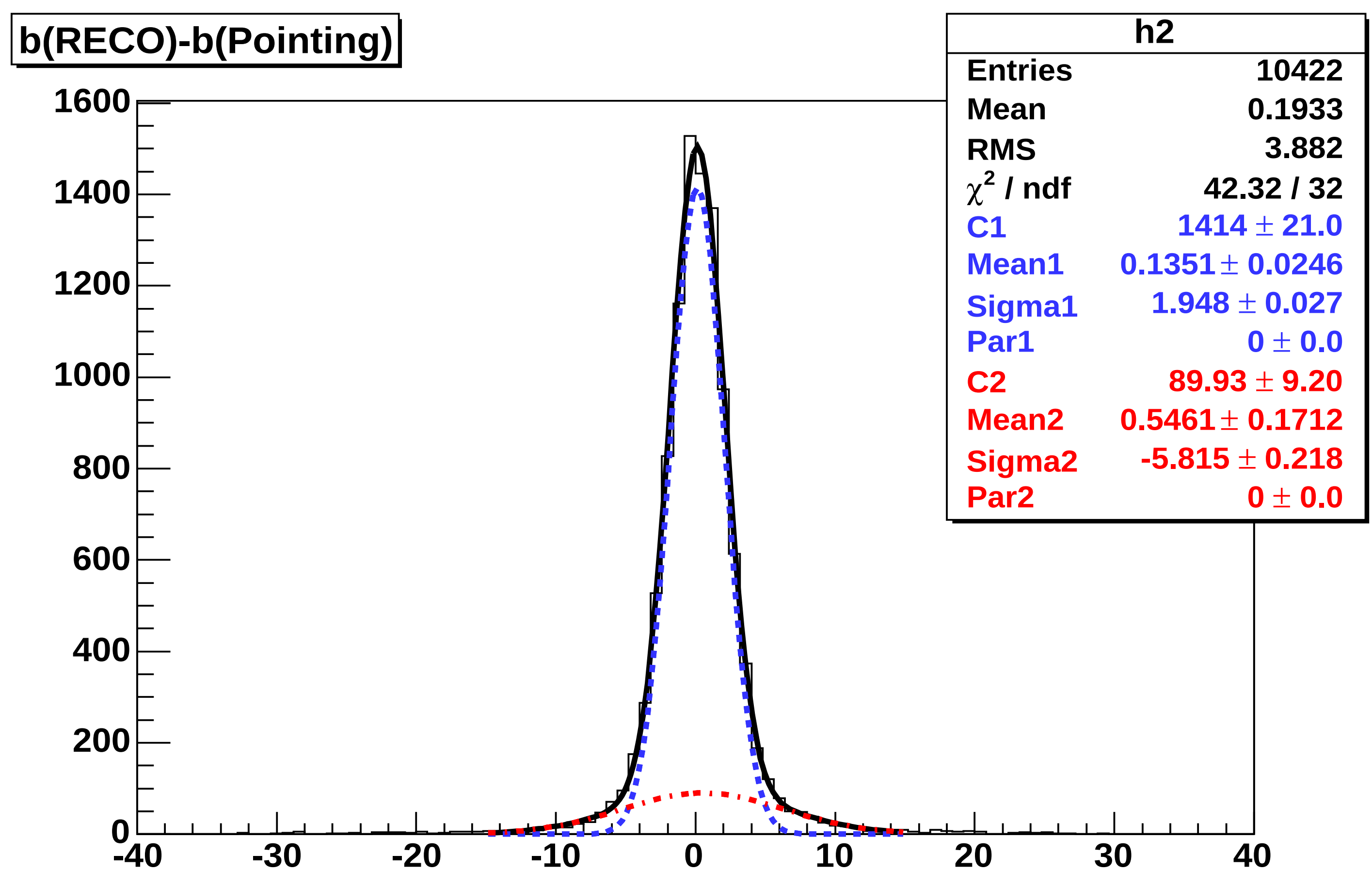
- Photon pointing
  - DØ Calorimeter has excellent segmentation
    - Transverse and Longitudinal





- Using calorimeter only information the point of origin of a photon can be found
  - Impact parameter
  - Z-position


z(RECO Vertex)-z(Pointing Vertex)
h1
Entries 10422
Mean -0.03079
RMS 9.19
χ2 / ndf 22.85 / 16
C1 1768 ± 28.8
Mean1 0.01349 ± 0.03961
Sigma1 2.918 ± 0.050
Par1 0 ± 0.0
C2 148.9 ± 19.3
Mean2 0.06016 ± 0.24448
Sigma2 8.306 ± 0.448
Par2 0 ± 0.0
1800
1600
1400
1200
1000
800
600
400
200
0
-80
-60
-40
-20
0
20
40
60
80


b(RECO)-b(Pointing)
h2
Entries 10422
Mean 0.1933
RMS 3.882
χ2 / ndf 42.32 / 32
C1 1414 ± 21.0
Mean1 0.1351 ± 0.0246
Sigma1 1.948 ± 0.027
Par1 0 ± 0.0
C2 89.93 ± 9.20
Mean2 0.5461 ± 0.1712
Sigma2 -5.815 ± 0.218
Par2 0 ± 0.0
1600
1400
1200
1000
800
600
400
200
0
-40
-30
-20
-10
0
10
20
30
40

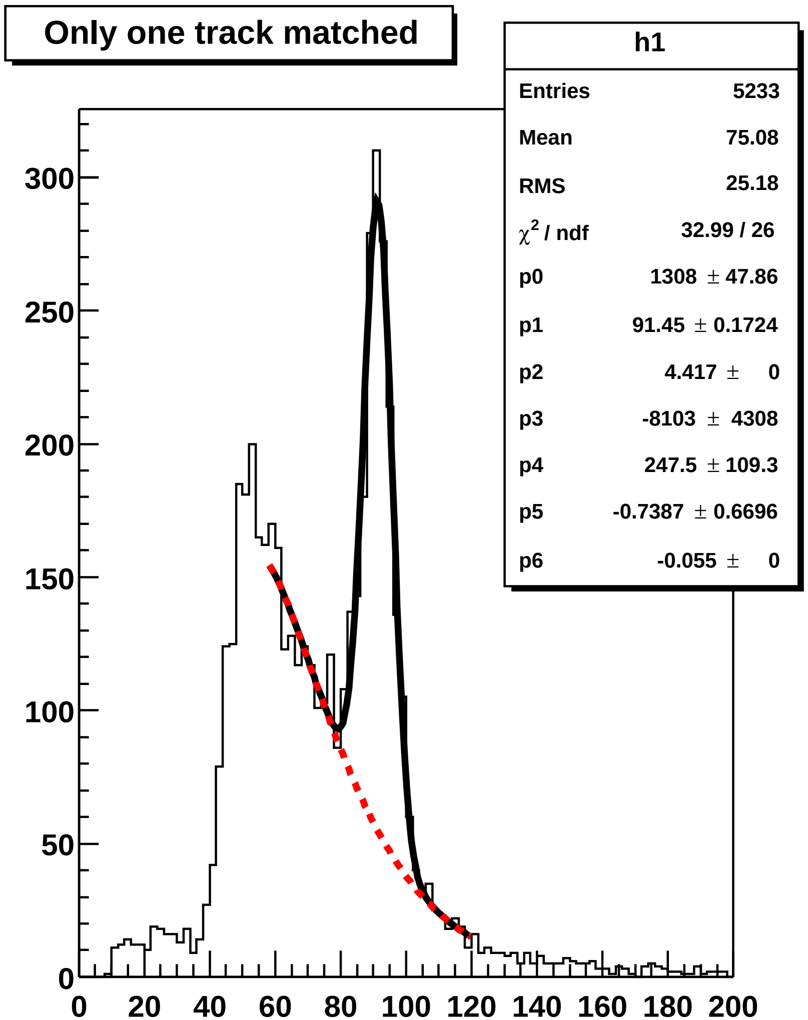
Data Sample Selection

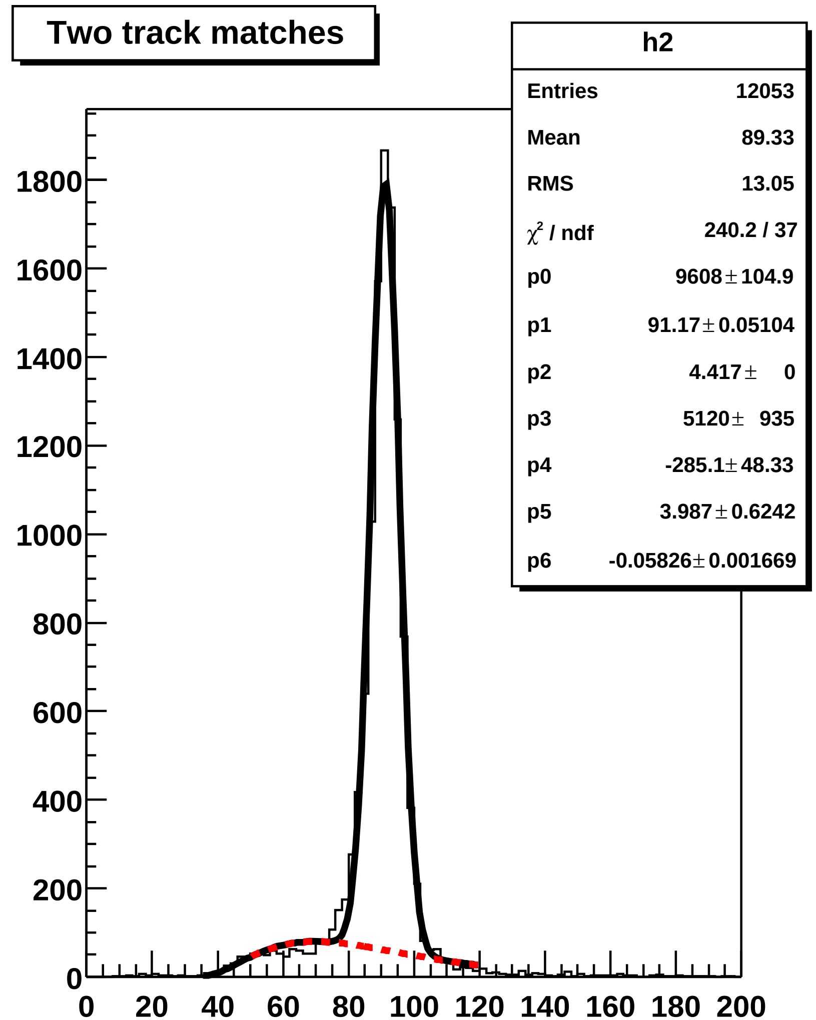
- Trigger Requirements
  - Single and di-EM triggers (threshold above 20 GeV)
    - Efficiency: $\varepsilon_{trigger}(p_T > 20\ \text{GeV}) = 0.97 \pm 0.01$
    - Luminosity: $\mathscr{L}_{RECO} = 263 \pm 17\ pb^{-1}$
- Identification - offline cuts
  - Simple cone reconstruction algorithm “scone”
  - $E_T > 20$ GeV , $|\eta_{Det}| < 1.1$, $EM_{iso} < 0.15$, $EM_{fract} > 0.90$, $\chi^2_{HMx7} < 15$
  - Track match
    - Electrons $\chi^2_{(spatial)} > 10^{-3}$, photons otherwise
    - $\varepsilon_{track} = 0.936 \pm 0.002\ (\text{stat}) \pm 0.004\ (\text{syst})$
  - Track isolation
    - $\left(\sum_{tracks} p^{(track)}_T \right)^{0.05<R<0.4}_{|z_{PV}-z_{DCA}|<2cm} < 2$ GeV
    - $\varepsilon_{trk\text{-}iso} = 0.96 \pm 0.02$

Data Sample Selection

- Identification - offline cuts (cont.)
  - Jet reconstruction
    - Reconstructed within a 0.5 cone, and for jets passing standard cuts their energy was corrected
    - Reject events for which: $\sum E_T$ (bad jets) > 30 GeV
      - $\varepsilon_{bad\ jets} = 0.97 \pm 0.02$ (sample independent)
  - Topological cuts
    - Misvertexing: $\Delta\phi$ (EM, MET) > 0.5
    - Mismeasured jets: $\Delta\phi$ (jet, MET) < 2.5

Data Sample Selection





SUSY Signal Generation

- Event generator packages
  - ➢ Branching fractions and sparticle masses with ISAJET v7.58
    - ❖ better than PYTHIA's SUSY generator
  - ➢ Event generation PYTHIA v6.202 with CTEQ5M structure functions
- Detector Simulation with DØGSTAR package
  - ➢ DØ GEANT Simulation of the Total Apparatus Response
  - ➢ Detector geometry and materials in each volume
  - ➢ Magnetic field
  - ➢ Simulates the passage of particles through the detector volume.
- Electronics Simulation with DØSim package
  - ➢ Digitization
  - ➢ Adds noise and detector inefficiencies
- Reconstruction with DØReco package
- Trigger Simulation with DØTrigSim

SUSY Signal Generation

Point	Λ TeV	$\frac{M}{\Lambda}$	$tan\beta$	N_5	$m_{\chi_1^0}$ GeV	$m_{\chi_1^+}$ GeV	σ_{TOT}^{LO} pb	K-factor	Efficiency	95% CL Limit, pb
1	55	2	5	1	69.4	122.0	0.861	1.240	0.081 ± 0.008	0.209
2	60	2	5	1	76.9	136.2	0.534	1.229	0.103 ± 0.010	0.165
3	65	2	5	1	84.5	150.5	0.338	1.219	0.118 ± 0.011	0.144
4	70	2	5	1	92.0	164.9	0.225	1.209	0.128 ± 0.012	0.133
5	75	2	5	1	99.4	179.1	0.150	1.199	0.137 ± 0.013	0.124
6	80	2	5	1	106.7	193.0	0.102	1.189	0.134 ± 0.013	0.126
7	85	2	5	1	114.1	207.2	0.070	1.179	0.126 ± 0.012	0.134
8	55	2	15	1	71.8	126.3	0.735	1.236	0.092 ± 0.009	0.184
9	60	2	15	1	79.1	140.2	0.468	1.227	0.100 ± 0.009	0.170
10	65	2	15	1	86.4	154.3	0.301	1.217	0.111 ± 0.011	0.153
11	70	2	15	1	93.7	168.2	0.204	1.207	0.124 ± 0.012	0.137
12	75	2	15	1	101.0	182.3	0.138	1.197	0.137 ± 0.013	0.124
13	80	2	15	1	108.2	196.0	0.094	1.187	0.149 ± 0.014	0.114
14	85	2	15	1	115.5	209.9	0.066	1.177	0.154 ± 0.015	0.110
15	36	10	5	2	88.4	153.1	0.311	1.217	0.119 ± 0.011	0.143
16	38	10	5	2	94.2	163.9	0.230	1.210	0.148 ± 0.014	0.115
17	40	10	5	2	100.0	174.7	0.171	1.202	0.141 ± 0.014	0.120
18	42	10	5	2	105.7	185.4	0.129	1.195	0.160 ± 0.015	0.106
19	44	10	5	2	111.4	196.0	0.099	1.187	0.143 ± 0.014	0.118
20	46	10	5	2	117.1	206.6	0.076	1.180	0.153 ± 0.015	0.111
21	48	10	5	2	122.7	217.3	0.058	1.172	0.138 ± 0.013	0.123

SUSY Signal Generation

Λ TeV	$m(\chi^0_1)$ GeV	$\sigma_{TOT}^{(LO)}$ pb	Acceptance for given mE_T cut , %					
			> 25	> 30	> 35	> 40	> 45	> 50
55	69.4	0.860	16.2	14.5	13.3	11.7	9.80	8.45
60	77.0	0.532	17.2	15.9	14.6	13.2	11.2	10.1
65	84.5	0.339	19.3	18.1	16.8	15.6	13.6	12.4
70	92.0	0.225	21.8	21.0	20.0	18.5	17.0	15.5
75	99.5	0.151	22.8	21.7	20.6	19.7	18.3	17.3
80	106.8	0.103	22.0	21.3	20.5	19.5	18.3	17.2
85	114.2	0.071	21.2	20.0	19.4	18.1	17.1	16.7

Standard Model Backgrounds

- Two sources of SM di-photon events with MET
  - Events where MET is due to mis-measurement
    - QCD: γ j , j j , γ γ (jet faking γ - dominant)
      - mE_T resolution must be similar for γ and jet faking γ
    - Drell-Yan: electrons identified as photons due to lost tracks
  - Events with true MET and lost tracks
    - W γ → e ν γ (dominant)
    - W j → e ν "γ" (jet faking γ - dominant)
    - Z → τ τ → e e + X
    - t t , W W , W Z etc.

Standard Model Backgrounds

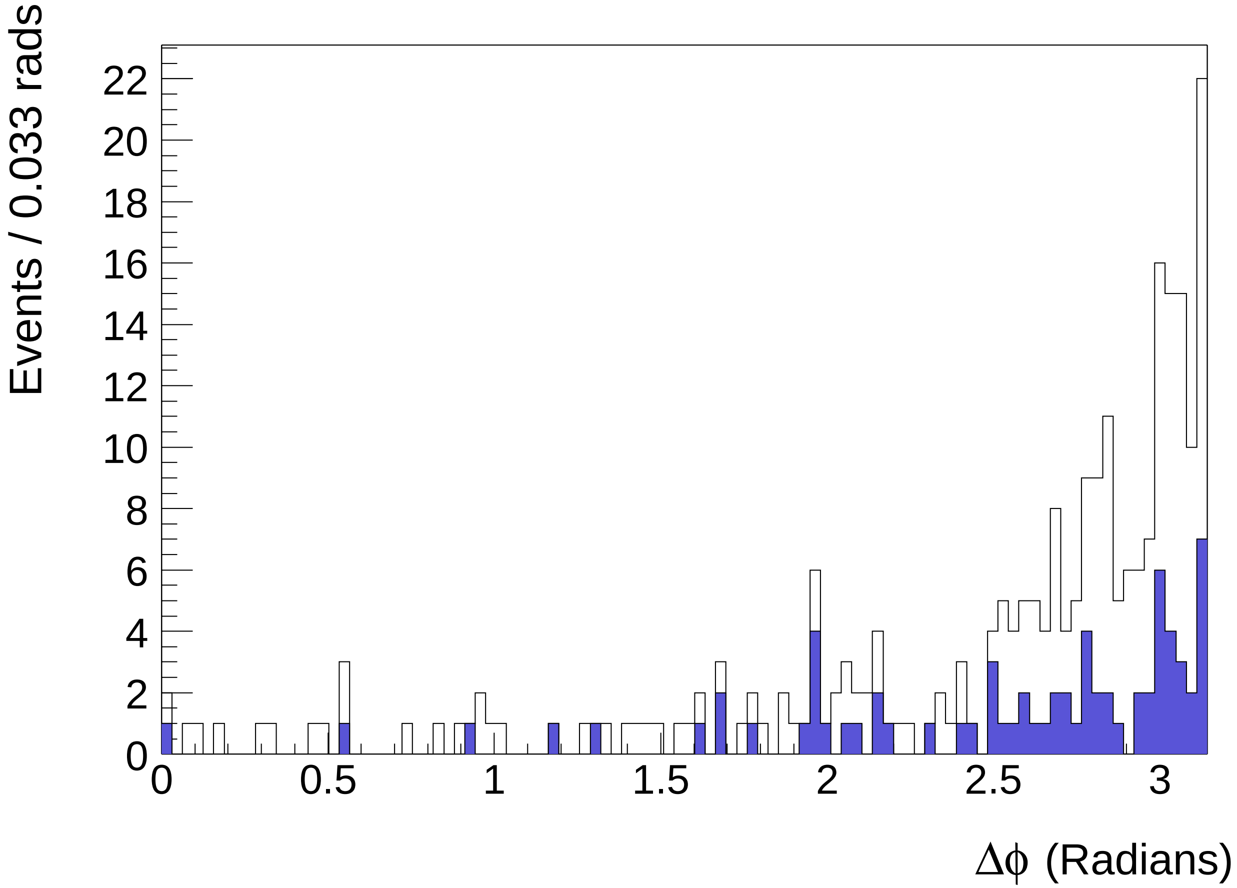
- Di-photon sample (inclusive)

  - Simple cone reconstruction algorithm "scone"

  - $E_T > 20$ GeV , $|\eta_{Det}| < 1.1$, $EM_{iso} < 0.15$, $EM_{fract} > 0.90$, $\chi^2_{HMx7} < 15$

  - Topological cuts
    - Misvertexing: $\Delta\phi$ (EM, MET) > 0.5
    - Mismeasured jets: $\Delta\phi$ (jet, MET) < 2.5

Standard Model Backgrounds



Standard Model Backgrounds

- QCD Background (and Drell-Yan)
  - Require track veto to suppress Drell-Yan
  - Idea is that MET resolution is very similar for
    - di-photon events
    - photons plus jets faking photons
  - Estimate can be done if the same cuts are used as with di-photons but with at least one EM object having reverse-photon cuts
  - Same base sample as for di-photons
  - Require HMx7 > 20 and HMx8 < 200
  - EM objects with $EM_{iso} < 0.15$ and $EM_{fract} > 0.90$

- Use low MET region (MET < 15 GeV) to normalize QCD sample to di-photon

- Predict QCD background for high-p_T

Standard Model Backgrounds

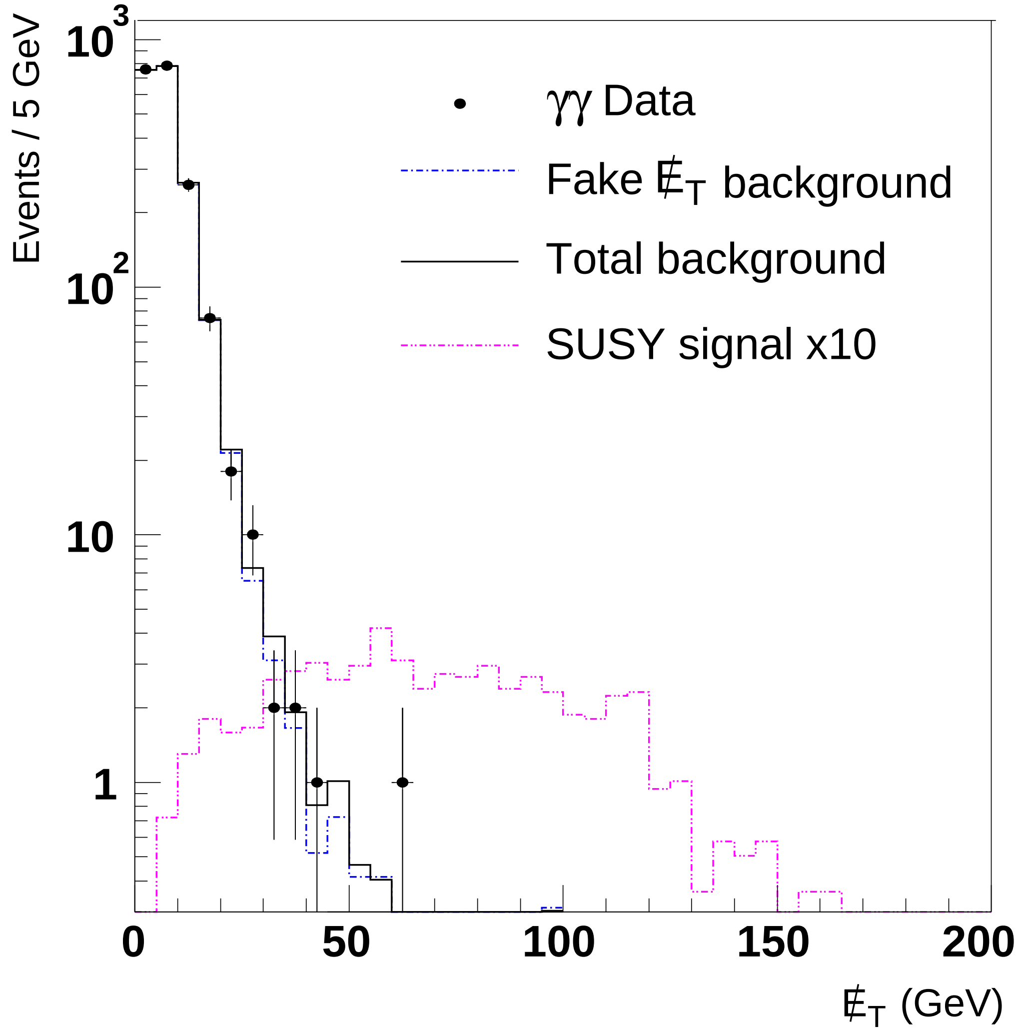
- Electroweak background
  - Electron plus photon sample used
  - Same base sample as for di-photons
  - Require track match and track isolation
    - Electrons: $\chi^2_{(spatial)} > 10^{-3}$, Photons: otherwise
    - $(\sum_{tracks} p_T^{(track)})^{0.05<R<0.4}_{|z_{PV}-z_{DCA}|<2cm} < 2$ GeV
  - Contains QCD part that is extracted as in the di-photon case

- After extraction remaining sample is multiplied by ratio $(1-\varepsilon_{trk})/ \varepsilon_{trk}$:
  - Probability an electron to be identified as photon, $(1-\varepsilon_{trk})$
  - Probability an electron to obtain background estimate to the di-photon, ε_{trk}

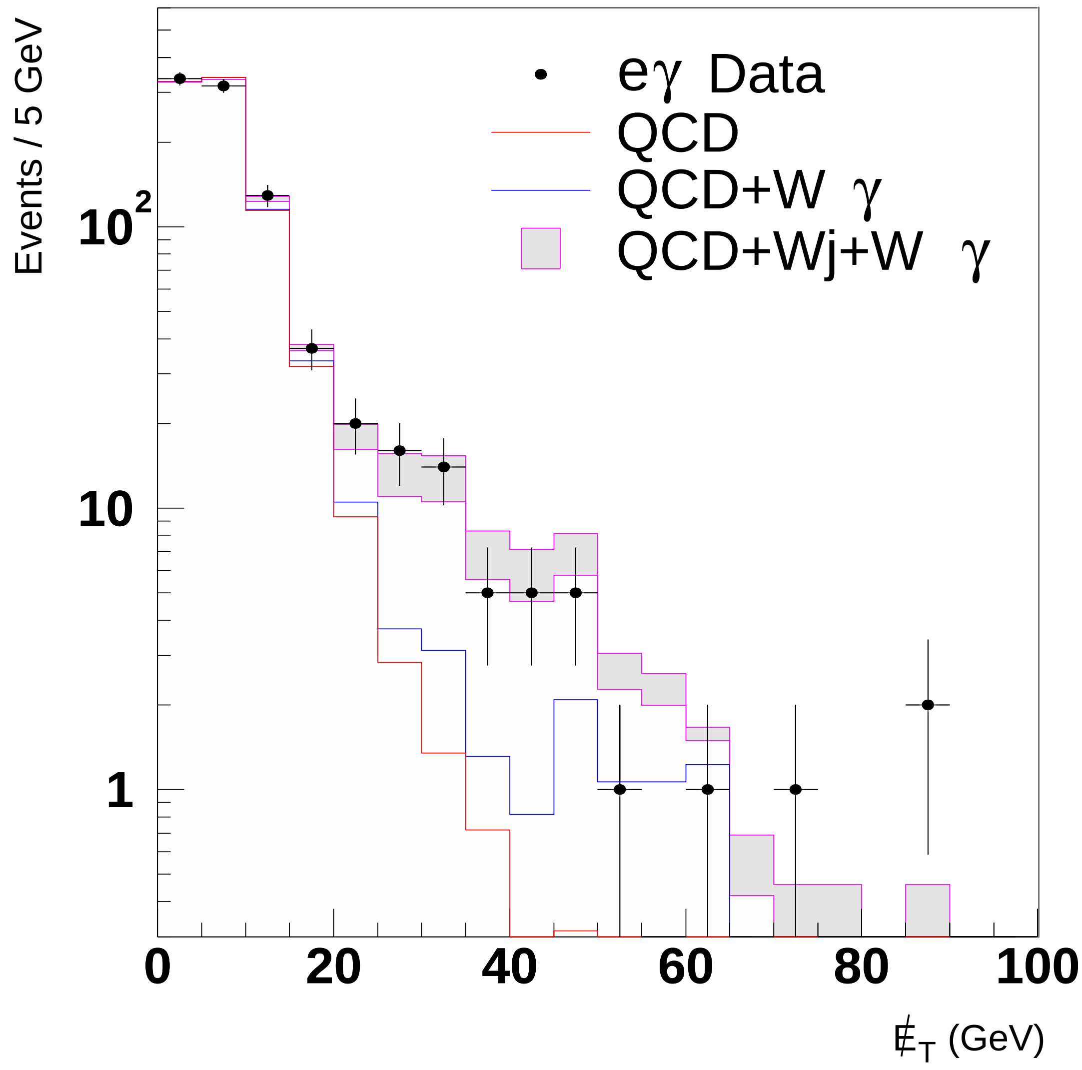
Standard Model Backgrounds

	Total events	$\not{E}_T$ < 15 GeV	> 20 GeV	> 30 GeV	> 40 GeV	> 45 GeV	> 50 GeV	> 55 GeV
$\gamma\gamma$	1909	1800	34	6	2	1	1	1
$e\gamma$	889	782	70	34	15	10	5	4
QCD	18437	17379	343	73	27	22	15	11
QCD BG to $\gamma\gamma$			35.5 ± 2.1	7.6 ± 0.9	2.8 ± 0.5	2.3 ± 0.5	1.5 ± 0.4	1.1 ± 0.3
QCD BG to $e\gamma$			15.4 ± 1.0	3.3 ± 0.4	1.2 ± 0.2	1.0 ± 0.2	0.7 ± 0.2	0.5 ± 0.2
$e\gamma$ total			54.6 ± 8.4	30.7 ± 5.8	13.8 ± 3.8	9.0 ± 3.2	4.3 ± 2.2	3.5 ± 2.0
$e\gamma$ BG to $\gamma\gamma$			3.7 ± 0.6	2.1 ± 0.4	0.9 ± 0.3	0.6 ± 0.2	0.3 ± 0.1	0.2 ± 0.1
Total BG to $\gamma\gamma$			39.2 ± 2.2	9.7 ± 1.0	3.7 ± 0.6	2.9 ± 0.5	1.9 ± 0.4	1.4 ± 0.4

Standard Model Backgrounds

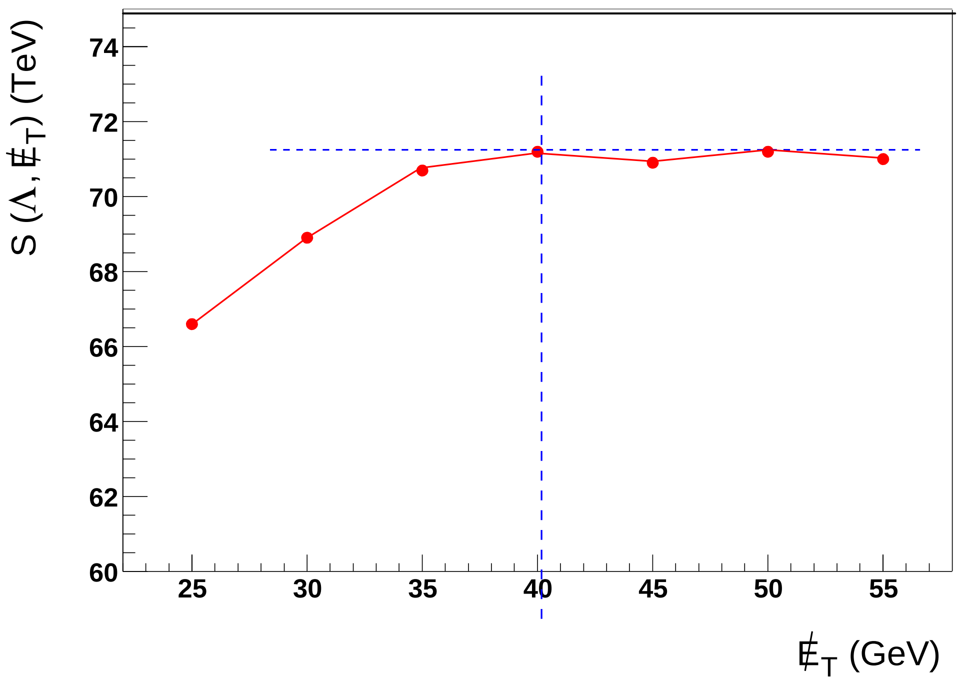


Standard Model Backgrounds

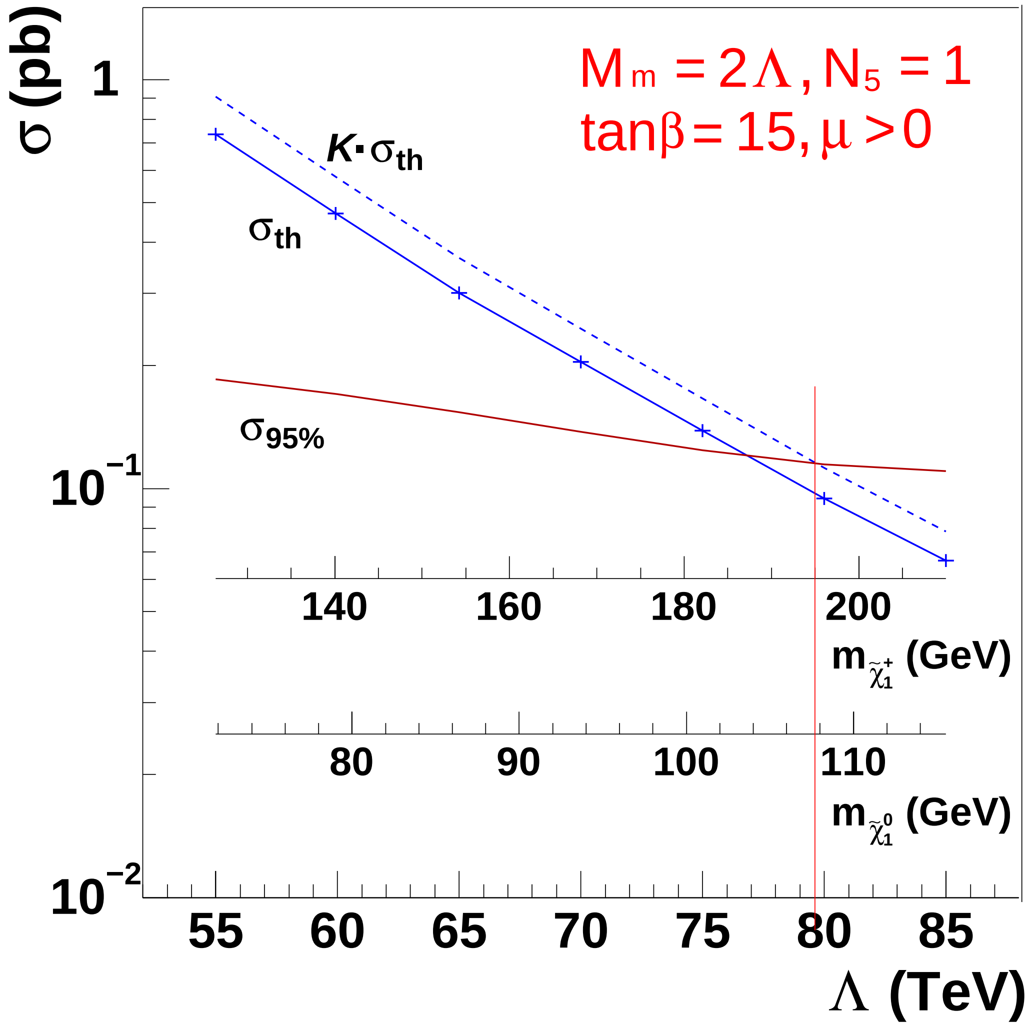


Optimization and Limits Setting

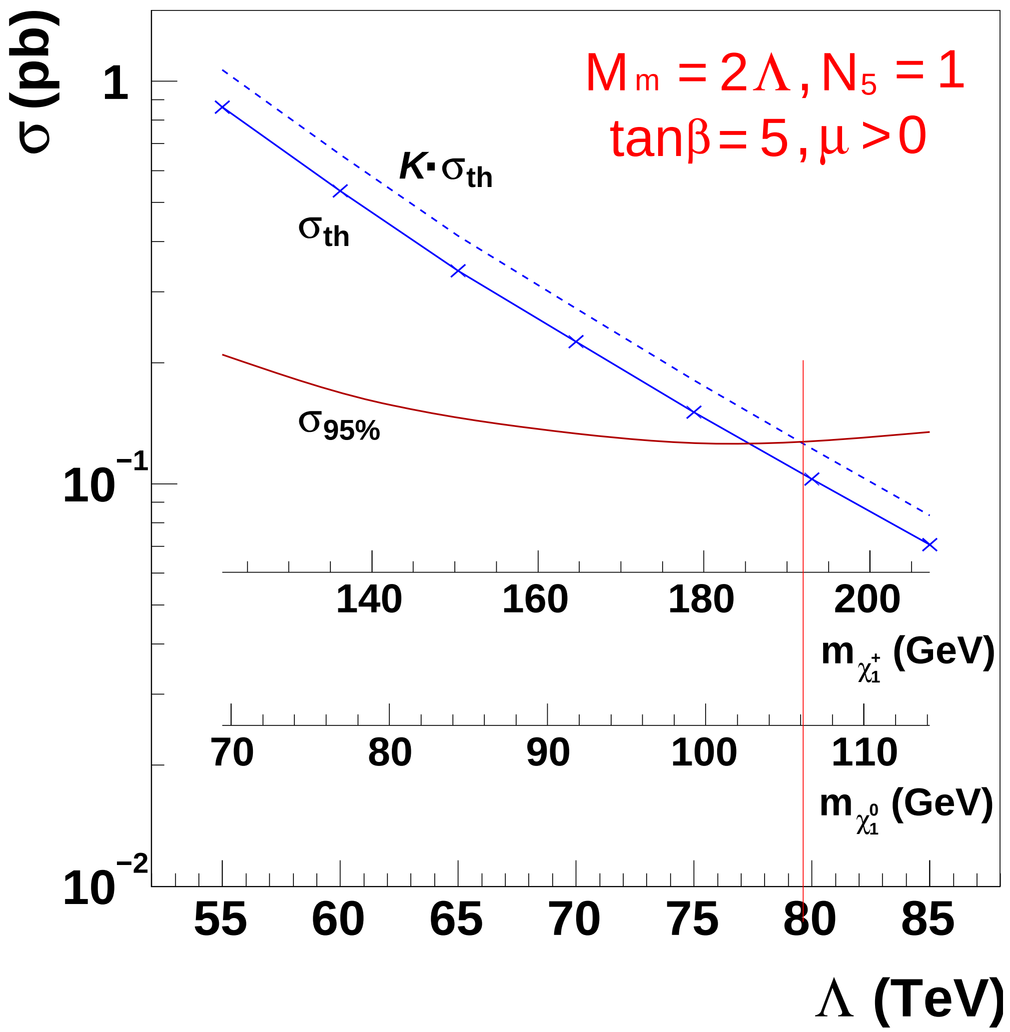
- Optimal missing E_T cut
  - ➢ Maximizing signal to background "significance"
  - ➢ Devise a measure of significance as a function of the missing E_T
  - ➢ Plot this measure for all signal points
  - ➢ Choose as optimal missing E_T the minimum
  - ➢ Optimal missing E_T cut was found to be 40 GeV
- Limit Setting
  - ➢ Standard prescription used by DØ
  - ➢ Uses Bayesian approach



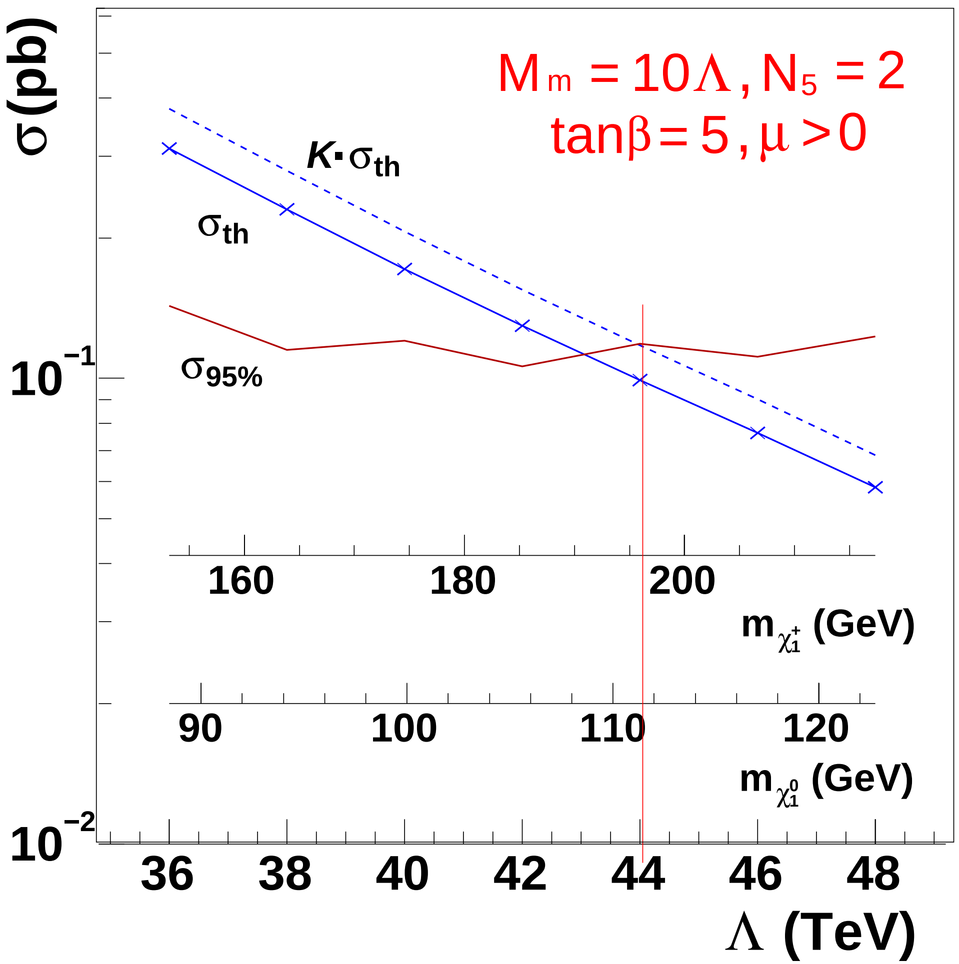
Optimization and Limits Setting



Optimization and Limits Setting



Optimization and Limits Setting



Conclusions

- No excess of events above the Standard Model background prediction is found, for all missing E_T explored.

- From the observed number of events, lower limits have been set at the 95% C.L. for masses of the lightest neutralino and chargino.
  - Lower limit of 107.7 GeV for the neutralino mass
  - Lower limit of 194.9 GeV for the chargino mass

- Results published in Phys. Rev. Lett.
  - Search for Supersymmetry with Gauge-Mediated Breaking in Diphoton Events at DØ, PRL 94, 041801 (2005).