LHC Physics and the CMS Detector

On behalf of the CMS Collaboration

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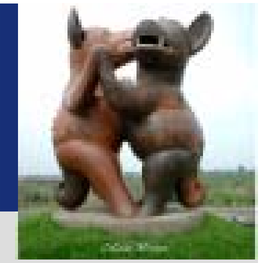
The IX Mexican Workshop on Particles and Fields - Nov. 18, 2003 - Colima, Mexico

Evolution of Gauge Concept: 20th Century Triumph



- EM: field potentials ⇒ gauge freedom

  $\partial_\mu F^{\mu\nu} = j^\nu = (\rho, \mathbf{j})$ ($F^{\mu\nu} \equiv \partial^\nu A^\mu - \partial^\mu A^\nu$)

  $\partial^\mu \partial_\mu A^\nu - \partial^\nu(\partial_\mu A^\mu) = j^\nu$

  → *Maxwell eqns. invariant for*

  $A^\mu \to A'^\mu = A^\mu + \partial^\mu \chi$

- QM: phase invariance ↔ gauge invariance

  $\partial_\mu \to D_\mu = \partial_\mu + iq\, A_\mu$ ≡ *covariant derivative*

- QFT: Fields become operators
  - QED Free massless photon:

  $L_{em} = -1/4\, F^{\mu\nu} F_{\mu\nu}$

  $L_{em} = -1/4\, F^{\mu\nu} F_{\mu\nu} + (m^2/2) A^\mu A_\mu$

  ***not** gauge invariant!*

Covariant derivative
→ particle interactions

e.g Free Dirac spinors:

$L_D = \underline{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi$

Now require gauge/phase invariance

$\partial_\mu \to D_\mu = \partial_\mu + ie\, A_\mu$

$L_D \to L_D' = L_D + j^\mu A_\mu$

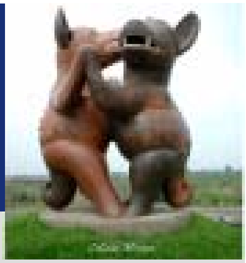
where $j^\mu = e\, \underline{\Psi}\, \gamma^\mu \Psi$

$L = -1/4\, F^{\mu\nu} F_{\mu\nu} + \underline{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi + j^\mu A_\mu$

Euler-Lagrange→

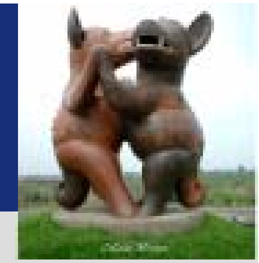
$\partial^\mu \partial_\mu A^\mu - \partial^\mu(\partial_\nu A^\nu) = j^\mu$

The Standard Model (SM)



- Gauge theories:
  - Classical EM Gauge Invariance
  - Quantum Mechanics Phase Invariance
    - presence of $A\mu$
  - Quantum Field Theory
    - QED - U(1)
      - gauge invariance ↔ massless photon
    - QCD - $SU(3)_c$
      - Gauge invariance implies massless gauge quanta (8 gluons)
      - Quark confinement ↔ jet production
- What about the weak force ? And Gravity ?

Weak Force



- Weak Nuclear Force
  - Hints of SU(2) gauge symmetry
    - Doublets
    - Universal Coupling G_F
  - But short-ranged $\Rightarrow$ massive gauge quanta
    - Interactions only observed over short distances (effectively contact interactions)
    - Coupling $G_F \sim 1/M^2$
  - **How to reconcile ?**

- An example from Nature: Superconductivity

$$j^\mu = (-q^2/m)\,|\psi|^2 A^\mu \quad \text{(London)}$$

$$\partial^\mu \partial_\mu A^\nu - \partial^\nu(\partial_\mu A^\mu) = (-q^2/m)\,|\psi|^2 A^\nu \equiv -M^2 A^\nu$$

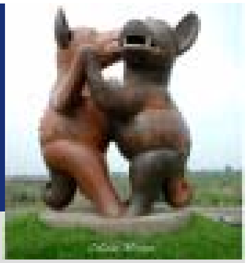
Cooper pair (boson) wave function ψ with non-zero constant ground state

$\rightarrow$ massive photon!

Supercurrents screen the EM field making it effectively short-range

$\therefore$ Massive gauge quanta are possible when gauge symmetry is broken!

EWK Symmetry Breaking



- Glashow Weinberg Salam $SU(2) \otimes U(1)$

  $L = -\frac{1}{4} \mathbf{W}^{\mu\nu} \cdot \mathbf{W}_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}$

  $W^{\mu\nu}{}_i = \partial^\nu W^\mu{}_i - \partial^\mu W^\nu{}_i + g\epsilon^{ij\kappa} W^\mu{}_j W^\nu{}_k$ *and* $B^{\mu\nu} = \partial^\nu B^\mu - \partial^\mu B^\nu$

- Add a scalar doublet field

  $\phi^\dagger = 2^{-1/2} (\phi_1 - i\phi_2, H - i\phi_o)$ with potential $V(\phi) = \mu^2 \phi\phi^\dagger + \lambda |\phi\phi^\dagger|^2$ $(\lambda > 0)$

  - The most general SU(2) invariant & renormalizable potential
  - $\mu^2 > 0$ symmetry retained $(T > T_c)$
  - $\mu^2 < 0 \Rightarrow \langle\phi\rangle_o \neq 0.0$ $(T < T_c)$

  $L_\phi = (D_\mu \phi)^\dagger (D_\mu \phi) - V(\phi)$

  - where $D_\mu = \partial_\mu + ig(\tau/2) \cdot \mathbf{W}_\mu + ig'/2 \; B_\mu$
  - choose a gauge with $\phi^\dagger = 2^{-1/2} (0, v+H)$, $\langle H \rangle_o = 0$
  - **This choice breaks the symmetry!**

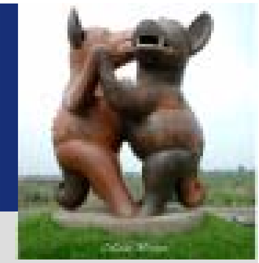
- **Lagrangian now has 3 Massive Vector Gauge Bosons and massless photon:**

  $W_\mu^\pm = 2^{-1/2} (W_\mu^1 \pm W_\mu^2)$ $M_W^2 = \frac{1}{4} g^2 v^2$

  $Z_\mu^o = (g^2 + g'^2)^{-1/2} (-g' B_\mu + g W_\mu^3)$ $M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2$

  $A_\mu = (g^2 + g'^2)^{-1/2} (g B_\mu + g' W_\mu^3)$ $M_A^2 = 0$

The Higgs & its couplings



- Electroweak Couplings satisfy

  $g\sin\theta_W = e = g'\cos\theta_W \quad (M_Z = M_W/\cos\theta_W)$

  From μ decay $G_F/2^{1/2} = g^2 / 8M_W^2 = 1 / 2v^2$

  Predict:

  $\Rightarrow M_W \sim 80$ GeV

  $M_Z \sim 91$ GeV

  also generate masses for fermions:

  $L = \lambda_d \, \underline{Q}_L \, \phi \, d_R$

  $\lambda_d = 2^{1/2} m_d/v \sim m_d/M_W$

  - *Coupling proportional to fermion mass*

  Is the top quark special ?

  $\lambda_t = 2^{1/2} m_t/v = 2^{1/2}(174.1)/(246) = 1$

$\Gamma(H \to f\underline{f}) = (N_c g^2/32\pi)\,(m_f^2 / M_W^2)(1-4m_f^2/M_H^2)M_H$

$\Gamma(H \to W^+W^-) = (g^2/128\pi)\,(M_H^2/ M_W^2)f(x)M_H$

where $f(x) = (1-x)^{1/2}\,(1-x+3x^2/4)$

and $x = 4\, M_W^2 / M_H^2$

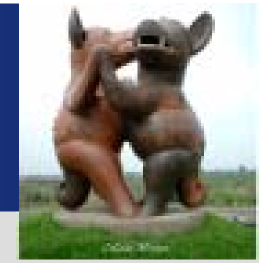
$\Gamma(H \to W^+W^-) / \Gamma(H \to ff) \sim M_H^2 / m_f^2$

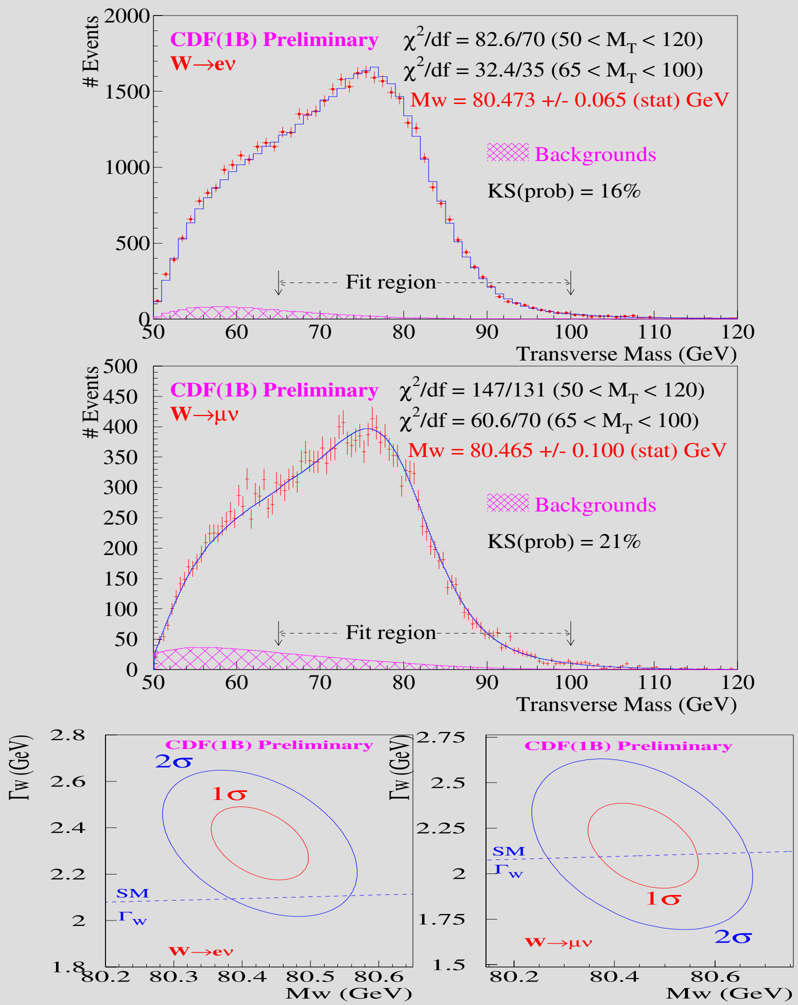
And the Higgs term itself:

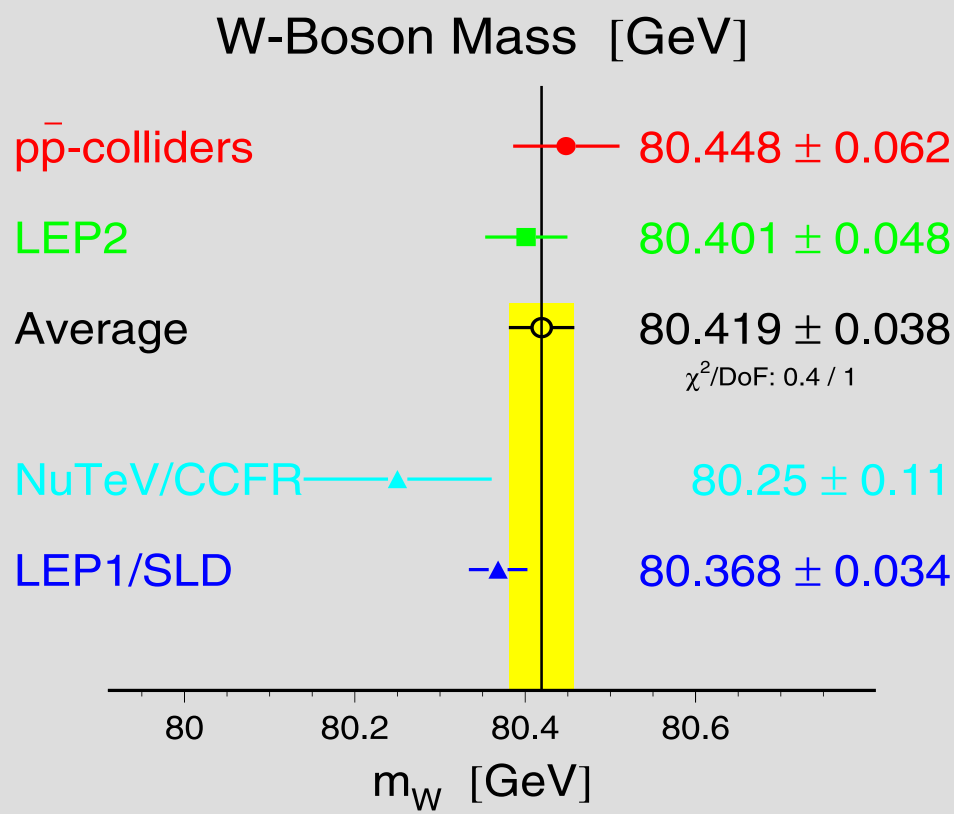
$2v^2\lambda\, H^2 \quad \Rightarrow \quad M_H = (2\lambda)^{1/2}\, v$

- We know everything about the Standard Model Higgs except
  - its mass
  - whether or not it exists

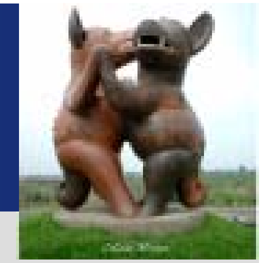
W was right where it was expected…

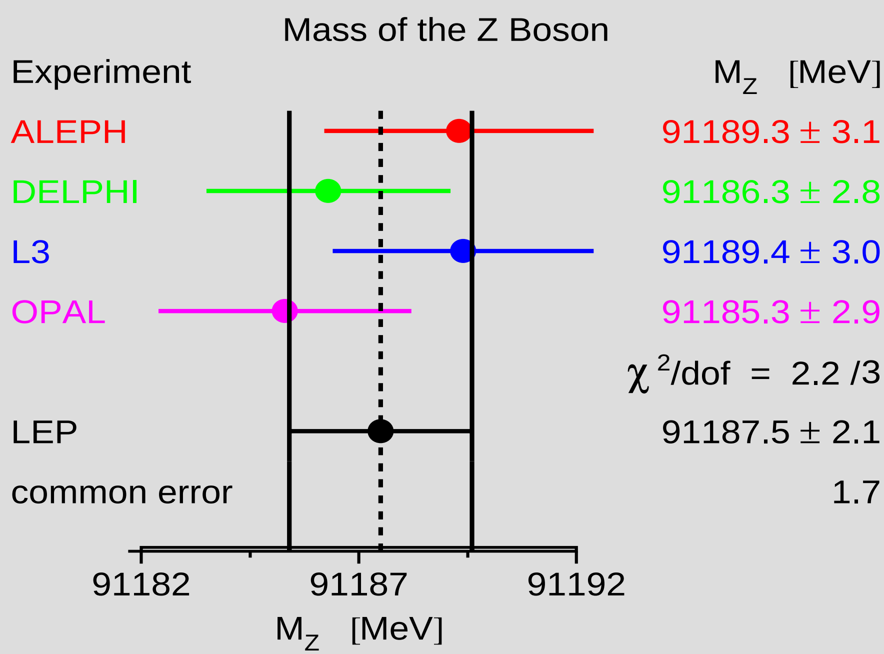


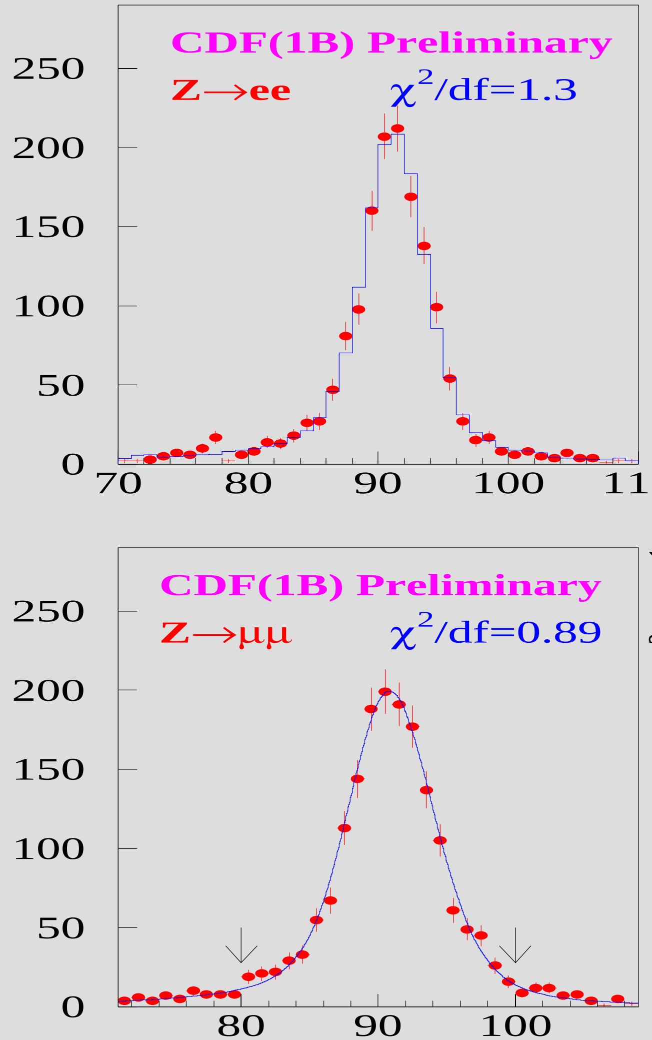




And the Z as well

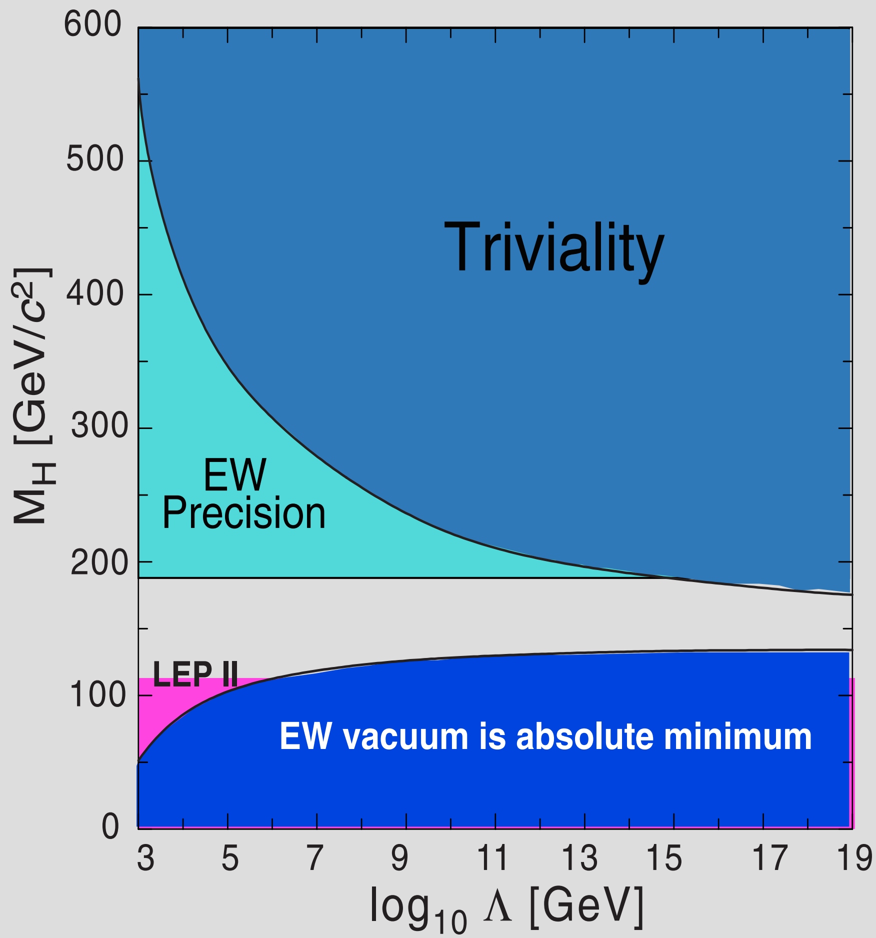






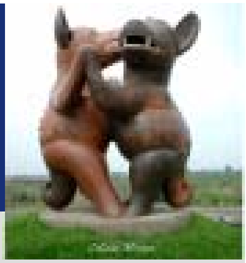
The W and Z were discovered by UA2 and UA1 at CERN

SM Higgs Mass Bounds



- Triviality:
  - To avoid having the higgs self-coupling vanish (which would trivialize the whole concept), you need a cut-off Λ at which new physics would be required.
- Vacuum stability:
  - Require $V(\phi_o) < V(0)$ - i.e. so that the choice of ground state breaks symmetry as required. For some masses this requires new physics above a scale Λ.
- EWK Precision Measurements:
  - $M_H < 188$ GeV at 95% CL
  - But this should not be taken for granted!
- LEP II direct searches:
  - $M_H \geq 114$ GeV at 95% CL

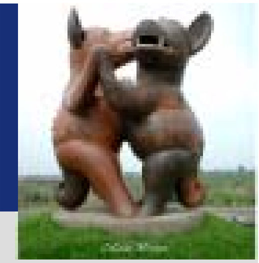
Beyond Standard Model



- Problems with the SM
  - Hierarchy Problem: the fundamental scale is the Planck scale ($M_p \sim 10^{19}$ GeV) ?
    - What is the underlying reason for EWK symmetry breaking and why at such low energy ?
  - Fermion and Higgs Masses ?
    - What determines them?
  - Gravity ?
    - How to reconcile with Quantum Mechanics?
- Fundamental Scalar Theories are Fundamentally pathological
    - Quadratic divergences

- Candidates For Replacing the SM:
  - Supersymmetry (SUSY)
    - Symmetry: bosons $\leftrightarrow$ fermions
    - A SUSY partner $\forall$ SM particle
    - Requires $\geq$ 2 Higgs doublets
  - SUSY Is quite appealing
    - Superpartners cancel divergent terms in M_H.
    - As a local symmetry $\Rightarrow$ spin-2 graviton appears
    - Appears in string theories
    - Yiedls gauge coupling unification at $\sim 10^{16}$ GeV if there are exactly 2 higgs doublets (+ singlets)
  - But there are other possibilities…

Large Extra Dimensions (LED)

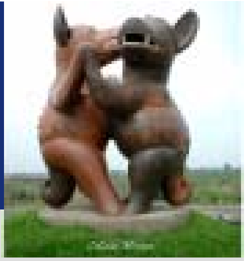


- δ extra compact dimensions with large radius R

  e.g. model of Arkani-Hamed, Dimopolous, Dvali: (ADD)*
  - SM propagates on 3+1 subspace
  - Graviton (G_{KK}) sees all 4+δ dimensions
    - G_{KK} appears to be massive to observers in 3+1 dimensions
  - ➢ Weakness of gravity could be due to large R
- ➢ Alternative solution to hierarchy problem
  - R related to G_N and δ via a fundamental mass scale M_D:
  - $G_N^{-1} = 8\pi R^{\delta} M_D^{2+\delta}$
  - – G_{KK} coupling to SM is weak but large R $\Rightarrow$ large phase space
  - States basically form a continuum
  - At colliders, couplings ~ $(E/M_D)^{2+\delta}$ ~ unity (E ~ process energy and one assumes M_D ~ TeV)
  - M_D ~ 1 TeV $\Rightarrow$ deviations from Newton's law at distances $R < 10^{(32/\delta - 19)}$
  - Non-accelerator Experiments at ~ 150 μm see no deviations $\Rightarrow$ $\delta > 2$

*Many other models exist which are quite different in their details but similar in basic concept.

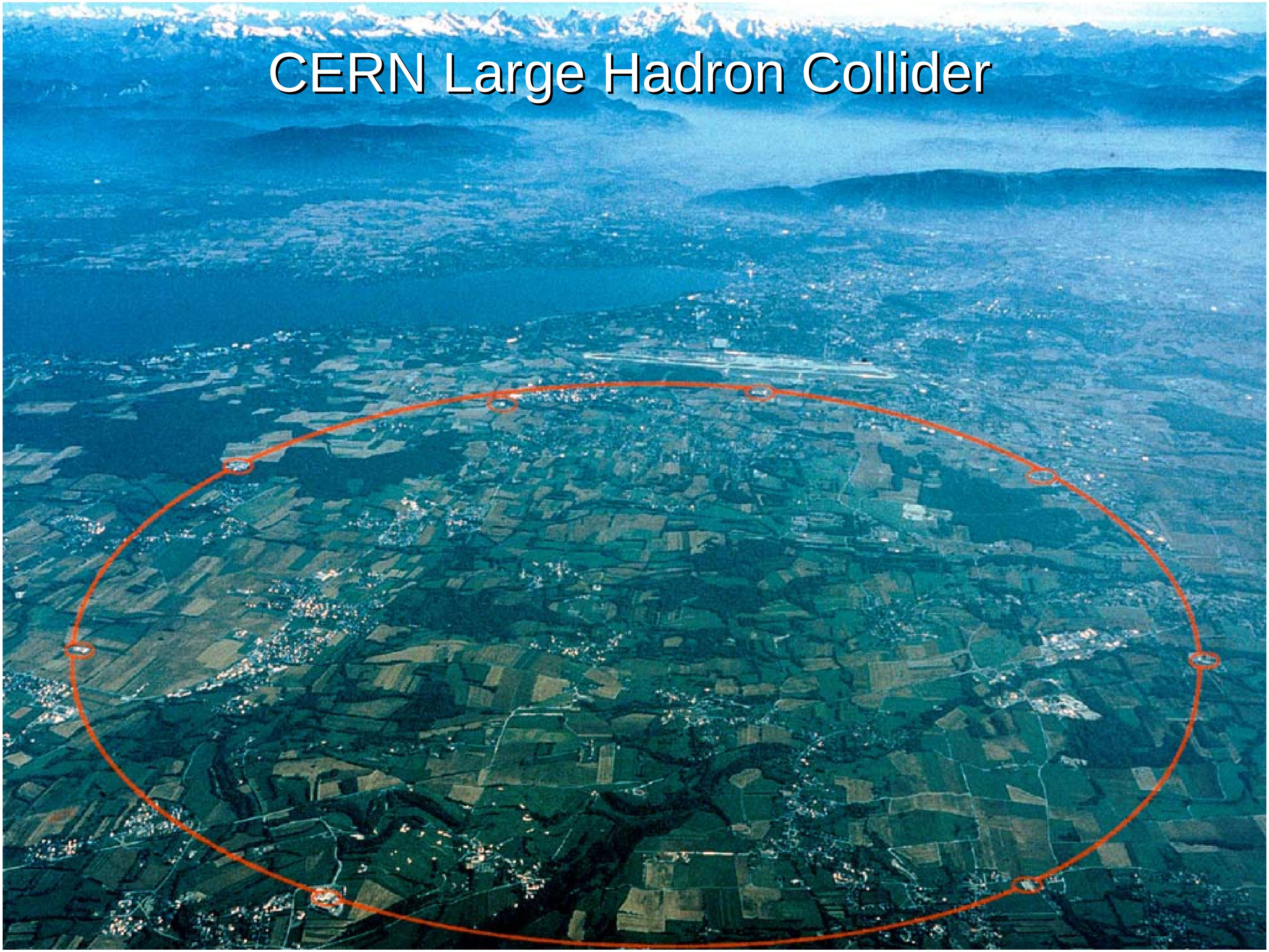
Experimental focus today



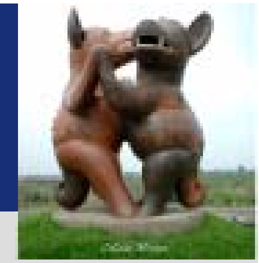
- Questions at the leading edge …
  - Why is the universe predominantly matter?
    - What is and what causes CP violation (see *talk by H. Quinn*)?
  - How do particles acquire mass ?
    - What is the origin spontaneous symmetry breaking ?
  - Why are energy scales so broadly distributed ?

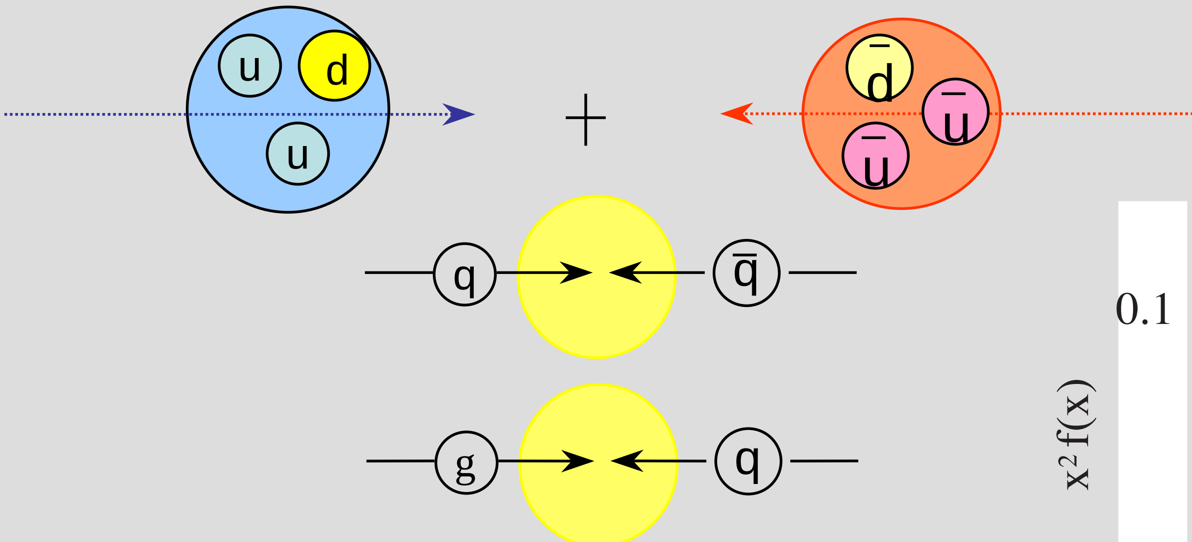
Λ_{QCD} ~ 0.2 GeV << EW vev ~ 246 GeV << M_{GUT} ~ 10^{16} GeV << M_{PL} ~ 10^{19} GeV

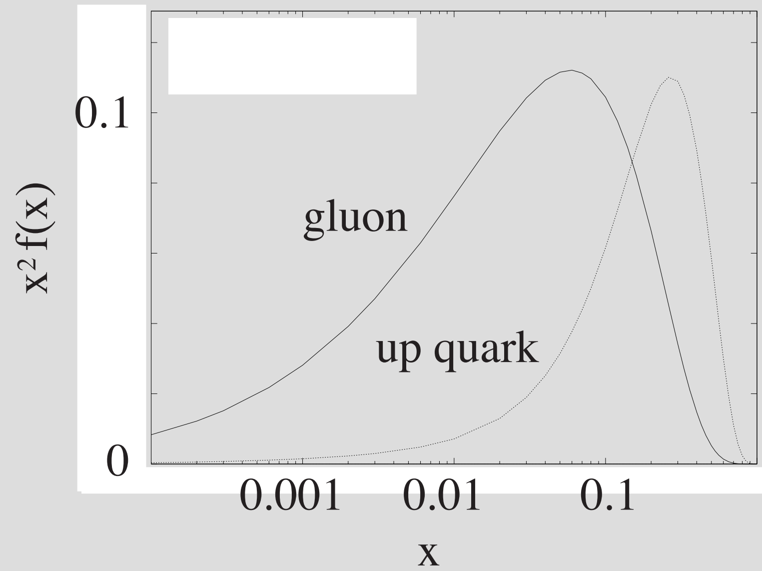
  - So what in the heck is there beyond the standard model ?
    - Is the universe supersymmetric ?
    - Are there large extra dimensions ?
  - What is the composition of galactic dark matter ?
    - Weak scale supersymmetry ?


CERN Large Hadron Collider

Colliding Partons



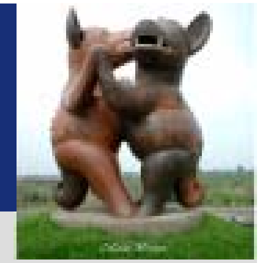




⇒Broadband: Production of particle states
with cm energies ranging from a few to 100's of GeV

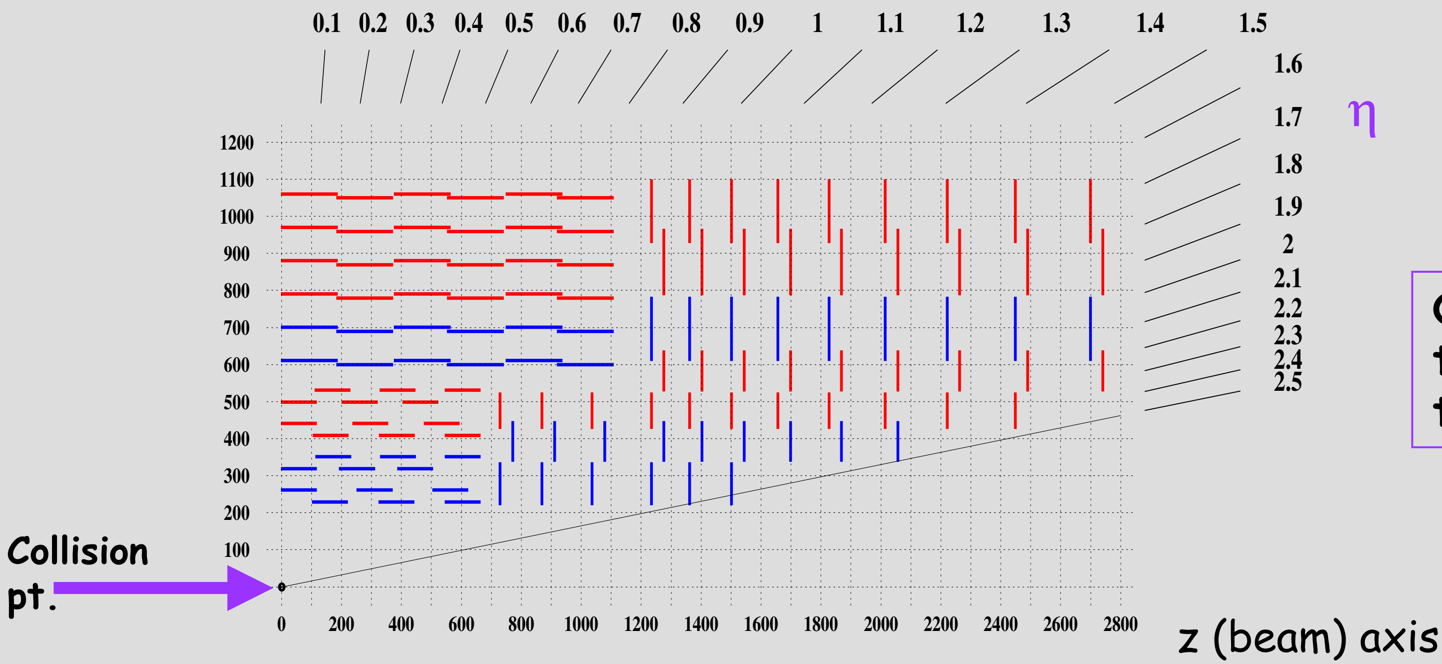
But you do not know the longitudinal momentum

Hadron Collider Jargon:PDF’s, P_T, and η



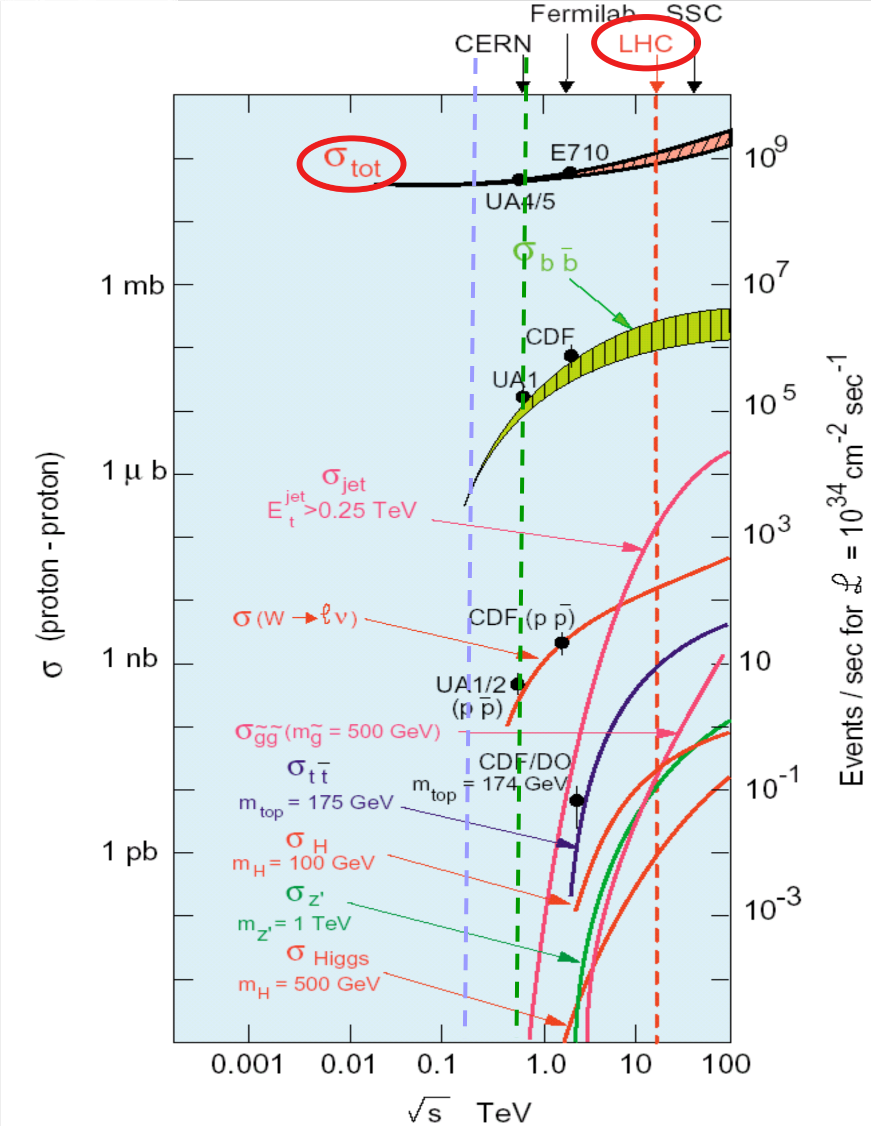
- Really colliding ‘partons’:qg, qq, gg
  - q can be a valence (u,d) or a sea (virtual) quark (..,s,c,b…).
- Momenta given by Parton Distribution Functions (PDF’s)

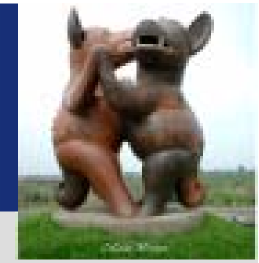
  $\Rightarrow$ Can’t balance all components
  - $P_T \equiv$ Transverse Momentum must balance.
  - $Pz \equiv$ Longitudinal Momentum (along the beam) unknown.
  - Coordinates (r,η,ϕ) with $\eta = -\ln(\tan(\theta/2))$
  - Distributions $(dN/d\eta)$ invariant under boosts in z



Quadrant of the CMS silicon tracker

Challenge and Reward



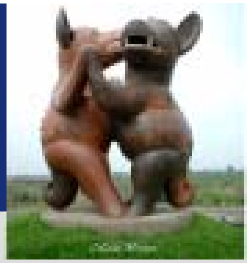


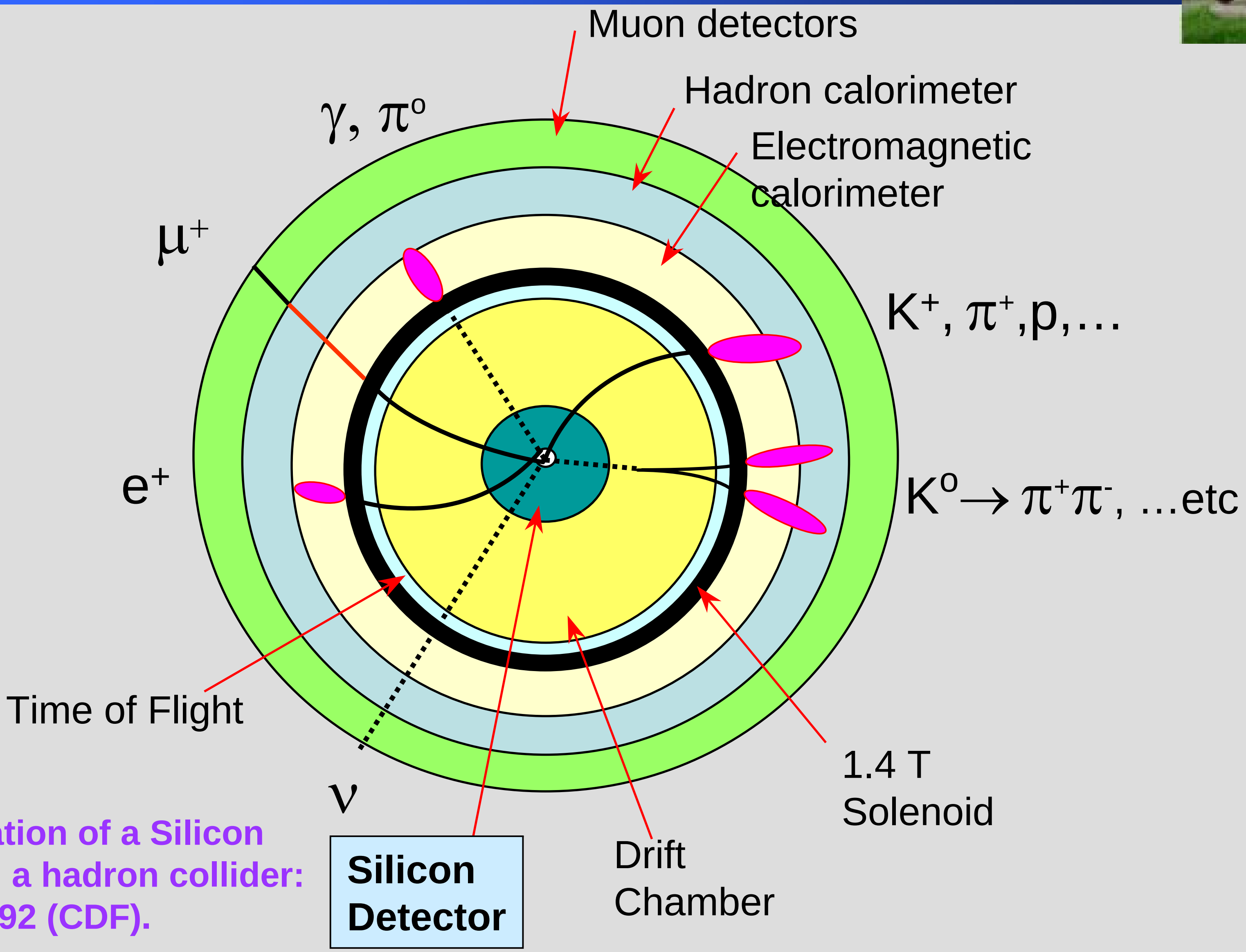
- Higher Energy
- Broadband production

⇒ **Discovery machines**

- Physics cross-section is high!!!
- What's interesting is rare
- The ability to find rare events is a consequence of evolved detector design and technological innovations
  - Multi-level trigger systems and high speed pipe-lined electronics
  - Precision, high rate, calorimetry
  - High rate wire tracking detectors
  - Highly radiation-tolerant Silicon microstrip and Pixel detectors

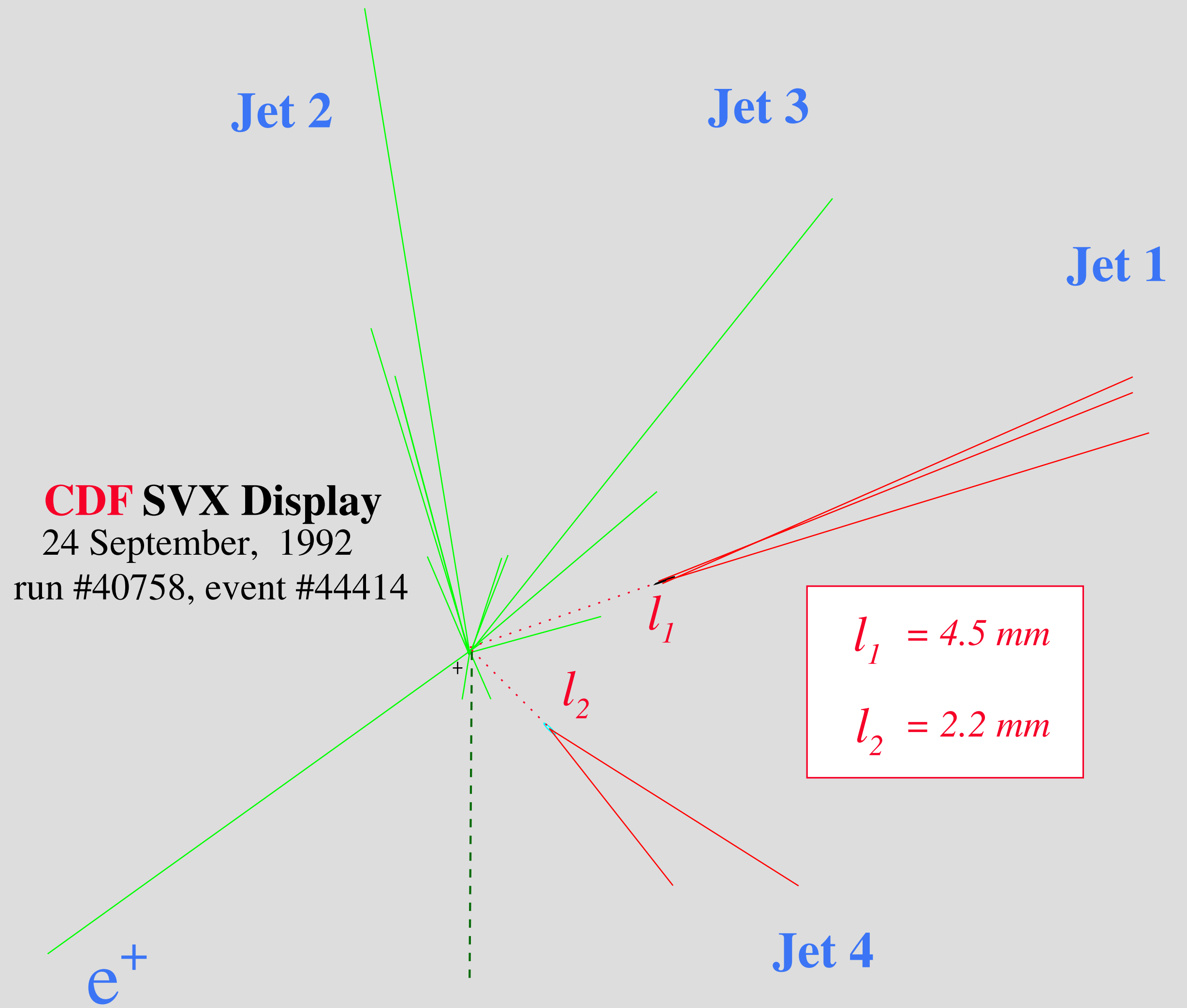
Hadron Collider Detectors





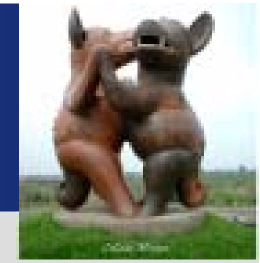
First operation of a Silicon detector in a hadron collider: May 12, 1992 (CDF).

First candidate $t\bar{t}$ event

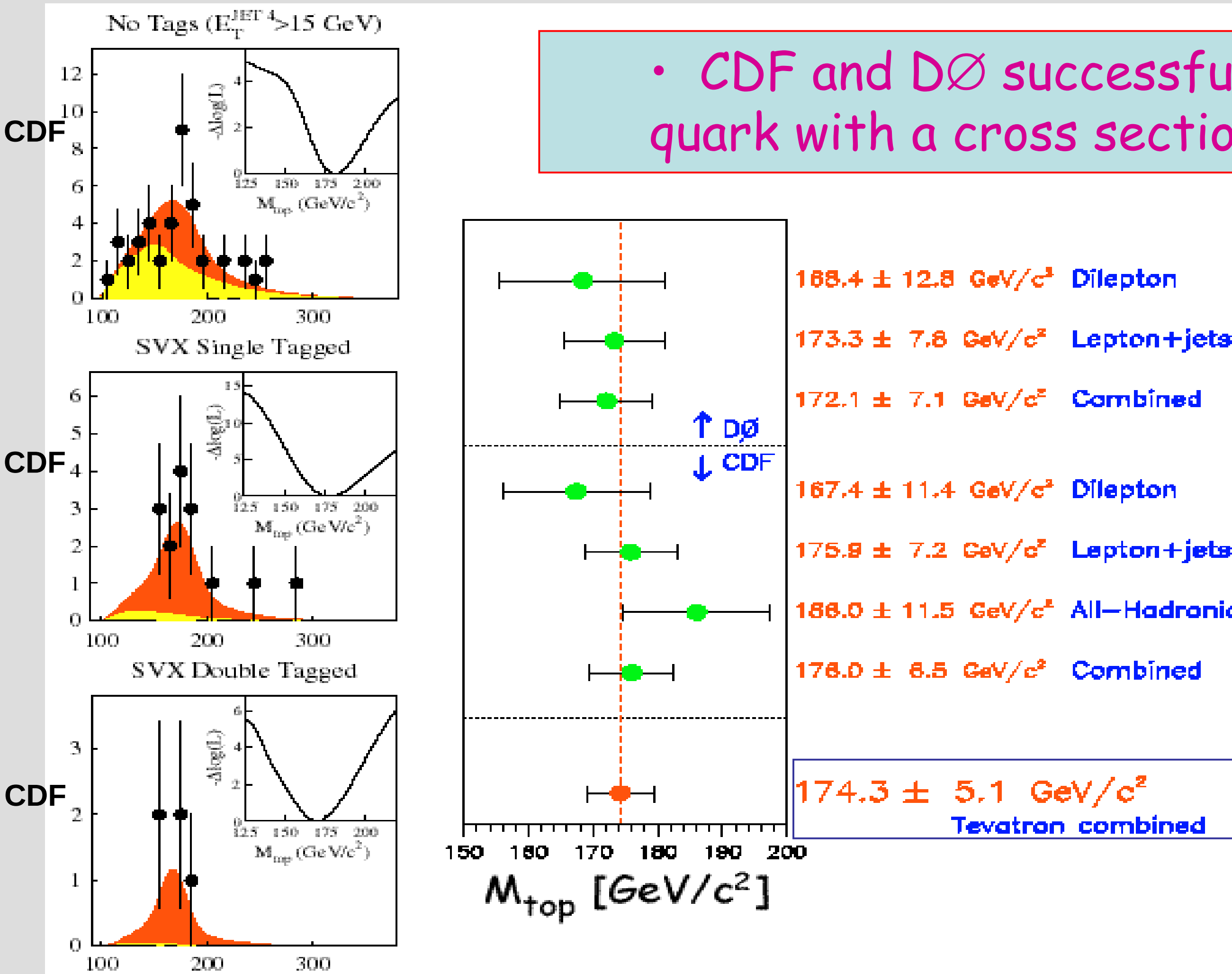


$$M_{top}^{Fit} = 170 \pm 10 \text{ GeV/c}^2$$

Tevatron: Top Discovery

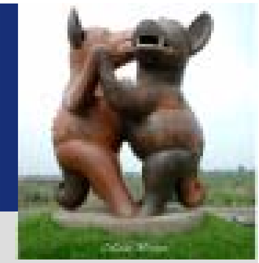


Displaced Vertex b tagging



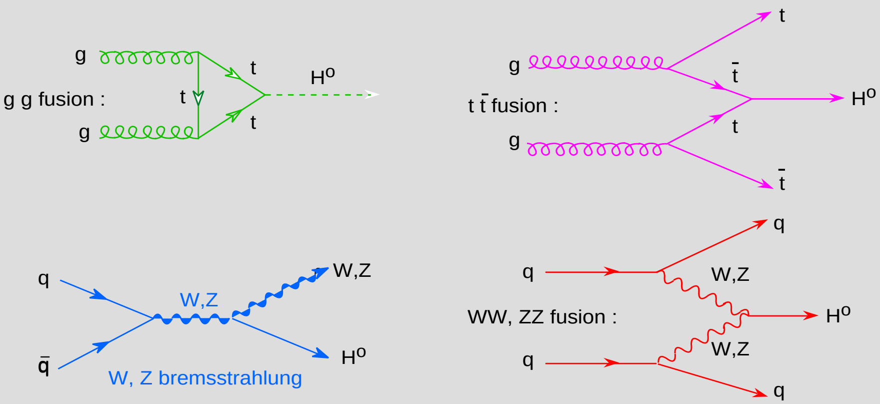
- CDF and D∅ successfully found the top quark with a cross section of ~ $10^{-10}\ \sigma_{tot}$

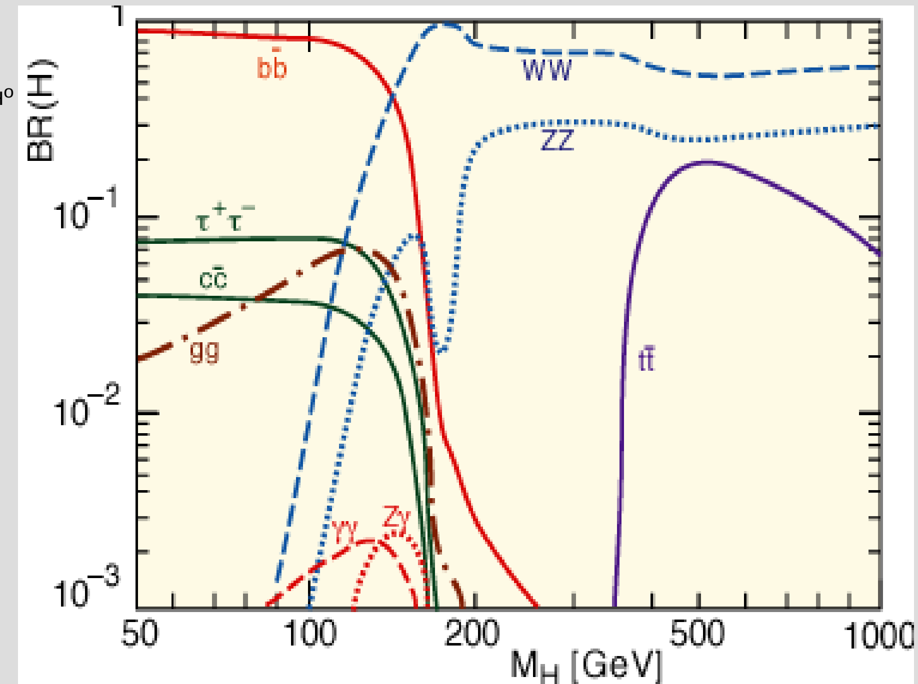
SM Higgs at the LHC



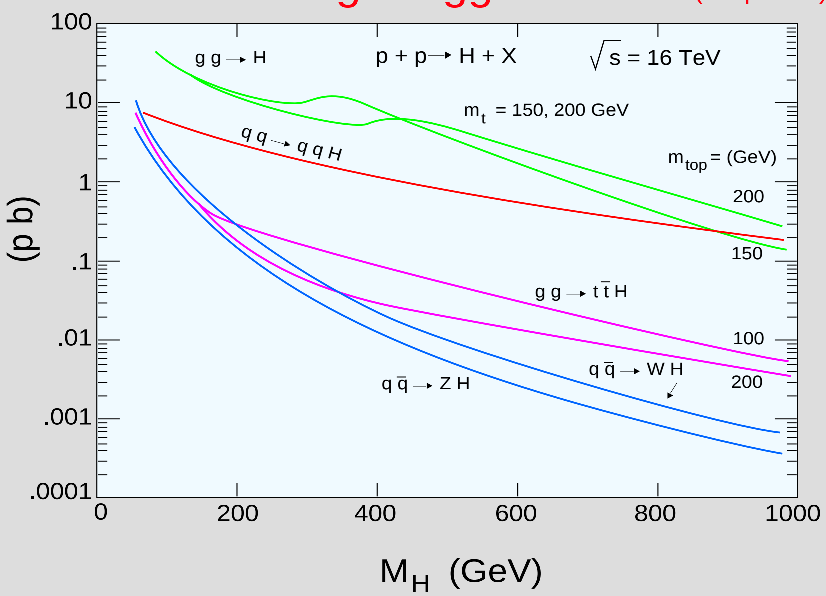
LHC SM Higgs Production

Production and Decay



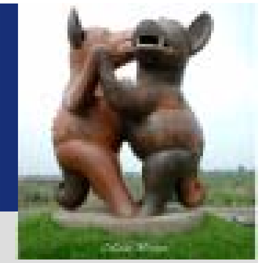


LHC: the Large Higgs Creator (P.Sphicas)



To a large extent, the quest for the Higgs drives the design of the LHC detectors. Nevertheless, essentially all other physics of interest require these same capabilities are excellent

Strategies for Finding SM Higgs

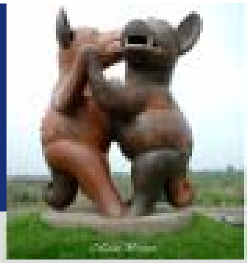


At LHC the SM Higgs is accessible in the entire mass range from the present LEP limit of 114.1 GeV up to 1 TeV.

Depending on mass different decay channels must be used based upon production and decay, and SM backgrounds:

90 GeV < m_H < 120 GeV	**$H \rightarrow$ bb in WH, ttH**
100 GeV < m_H < 150 GeV	**$H \rightarrow \gamma\gamma$ in incl. prod.,WH, ttH**
130 GeV < m_H < 200 GeV	**$H \rightarrow ZZ^* \rightarrow$ 4l (leptons)**
140 GeV < m_H < 180 GeV	**$H \rightarrow WW \rightarrow l\ \nu\ l\nu$**
200 GeV < m_H < 750 GeV	**$H \rightarrow ZZ \rightarrow 4l$**
500 GeV < m_H < 1000 GeV	**$H \rightarrow ZZ \rightarrow 2l + 2\nu$**
$m_H \sim$ 1 TeV	**$H \rightarrow WW \rightarrow l\nu$ + 2 Jets**
$m_H \sim$ 1 TeV	**$H \rightarrow ZZ \rightarrow 2l$ + 2 Jets**

Light SM Higgs Decays



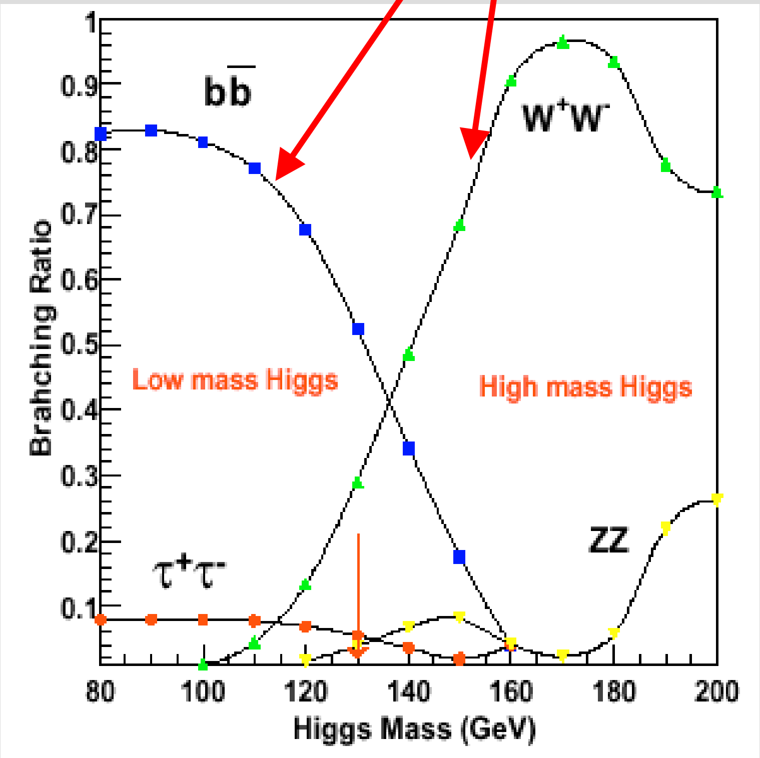
- $m_H < 130$: $H \to b\bar{b}$ dominant:
  - $\Rightarrow$ $W(l\nu, qq')b\bar{b}$, $Z(\nu\nu, ll, q\bar{q})b\bar{b}$
  - $\Rightarrow$ $t\bar{t}H$
    - $\Rightarrow$ **Need excellent jet and missing energy resolution, tracking for b tagging, excellent electron and muon identification**

Also $H \to \gamma\gamma$

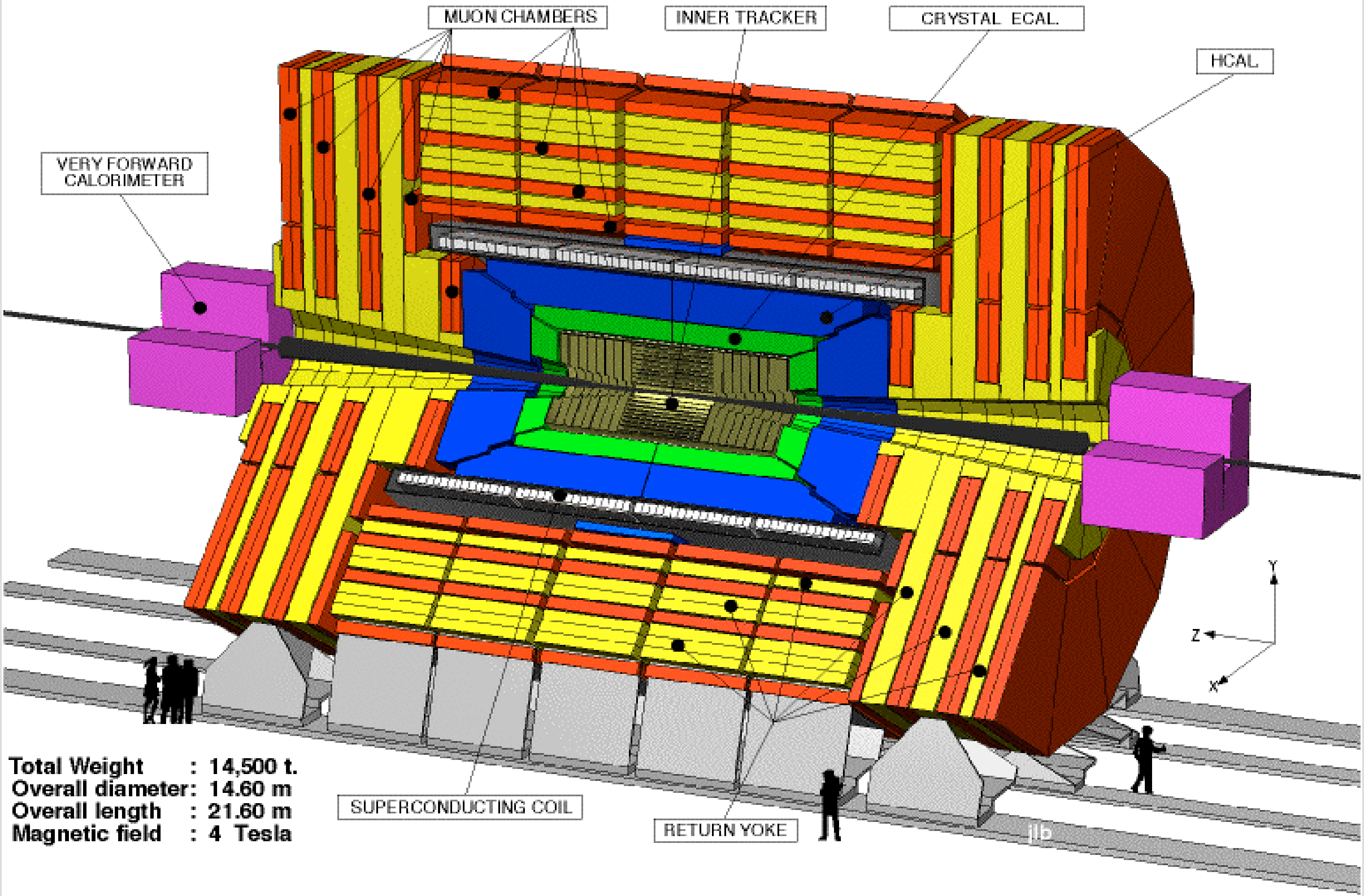
- $\Rightarrow$ **Need extraordinary electromagnetic calorimeter resolution !**

- $130 < m_H < 200$: $H \to WW$ dominant:
  - $\Rightarrow$ $W^+W^-, W^+W^-W^{\pm}, W^+W^- Z$:
  - $l^+l^-\nu\nu$, $l^+l'^+\nu\nu jj$, $l^+l^-l'^{\pm}$ final states
- *MSSM Higgs*:
  - many of the same channels as SM and enhanced association to $b\bar{b}$ at large $\tan\beta$

Lepton id, b tagging and $\not{E}_T$ are crucial

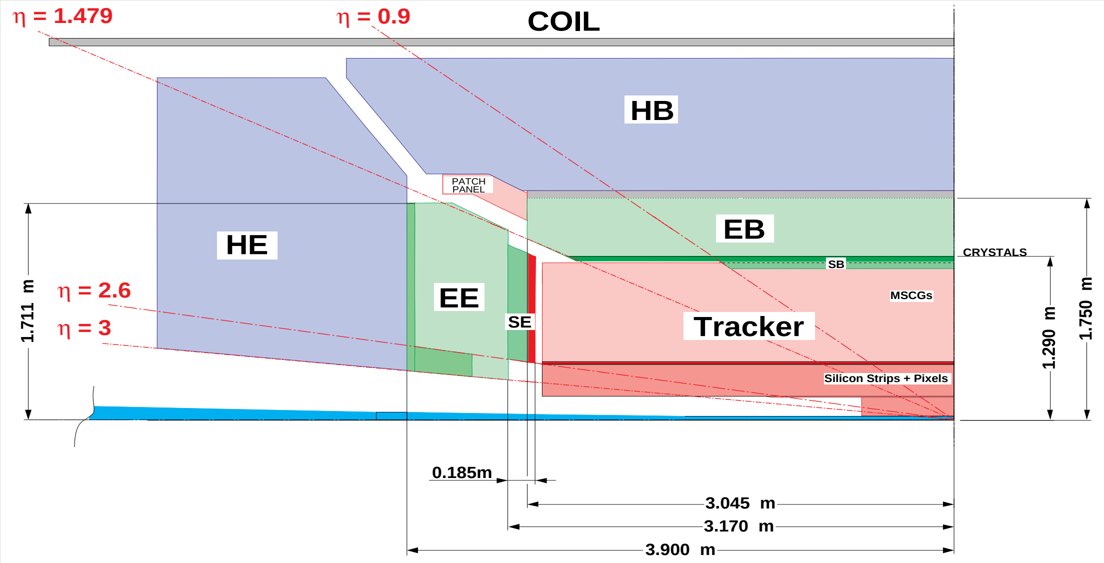


CMS Experiment at CERN



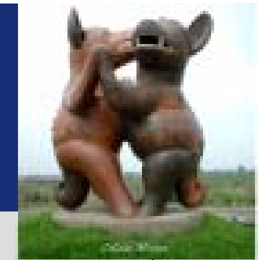
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

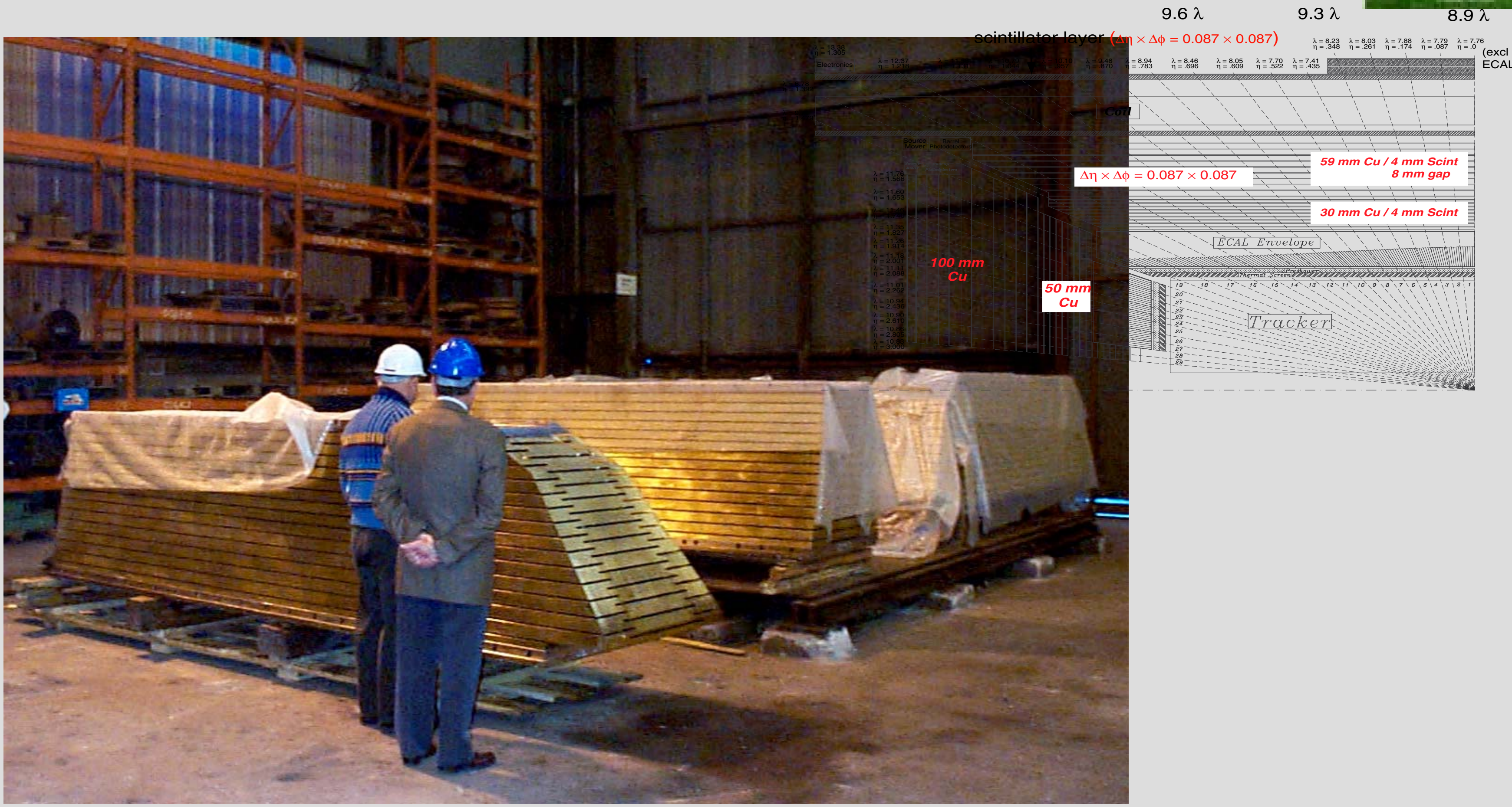
CMS Inner Detector



- Inside of the 4 Tesla Solenoid Field
  - Pixels: at least 2 Layers everywhere
  - Inner Si Strips: 4 Layers
  - Outer Si Strips: 6 Layers
  - Forward Silicon strips: 9 large, and 3 small disks per end
  - EM Calorimeter: $PbWO_4$ crystals w/Si APD's
  - Had Calorimeter: Cu+Scintillator Tiles

CMS Hadron Calorimeter

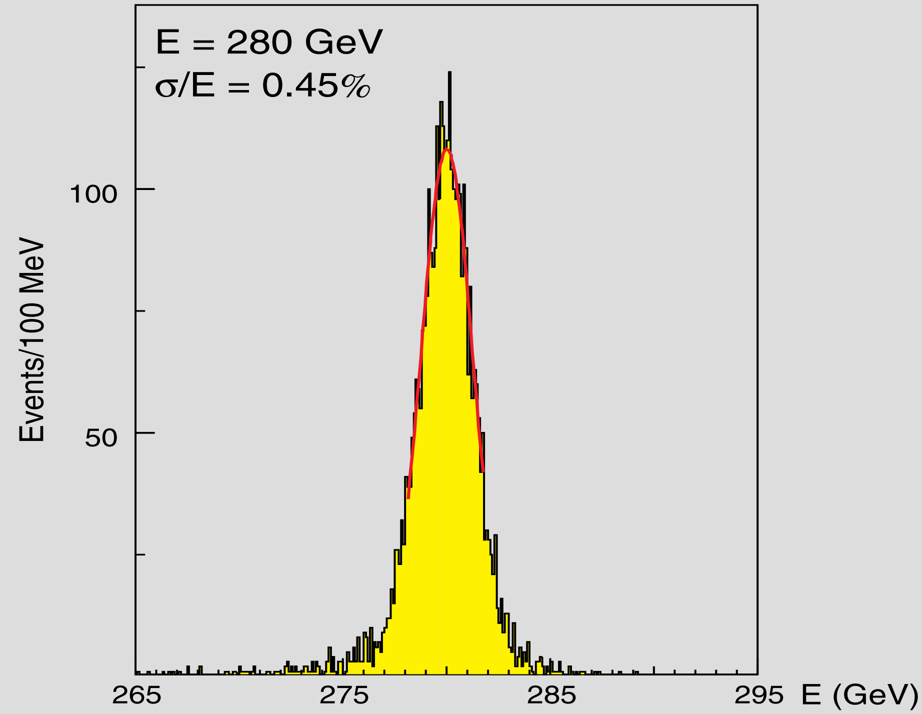




- Inside of the 4 Tesla Solenoid Field

  Hadronic Calorimeter: Cu+Scintillator Tiles

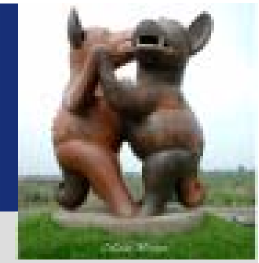
CMS EM Calorimeter



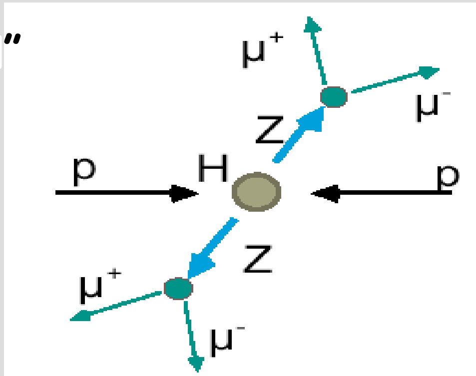
Energy reconstructed in 3× 3 crystals with 280 GeV electrons.

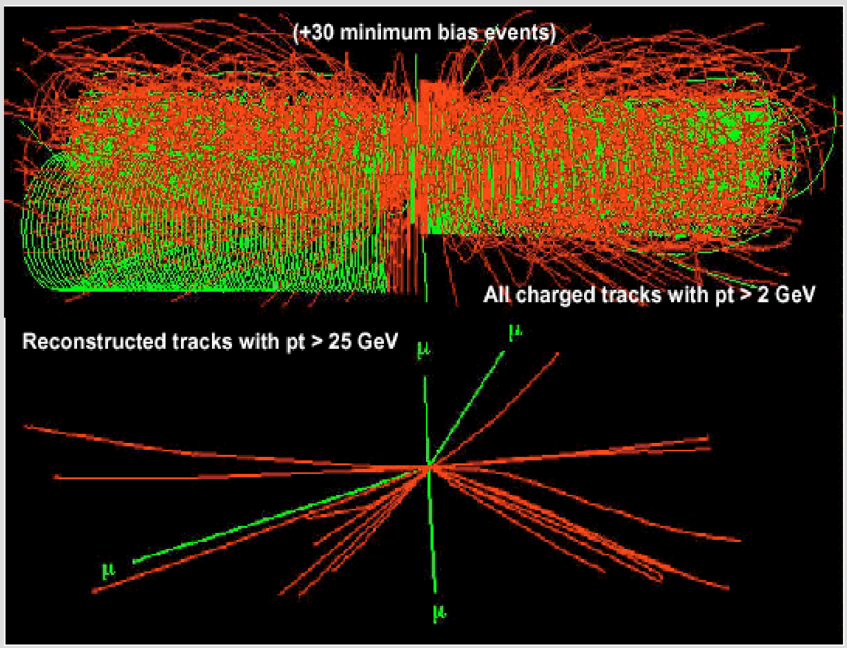
CMS EM calorimeter	Barrel	End cap
Stochastic Term	2.7% $E^{-1/2}$	5.7% $E^{-1/2}$
Constant Term	0.55%	0.55%
Noise	155-210 MeV	205-245 MeV
No. $PbWO_4$ Crystals	17,000	5,382

Tracking Challenges



"Golden Channel"





Efficient & robust Tracking

⇒**Fine granularity to resolve nearby tracks**
⇒**Fast response to resolve bunch crossings**
⇒**Radiation resistant devices**

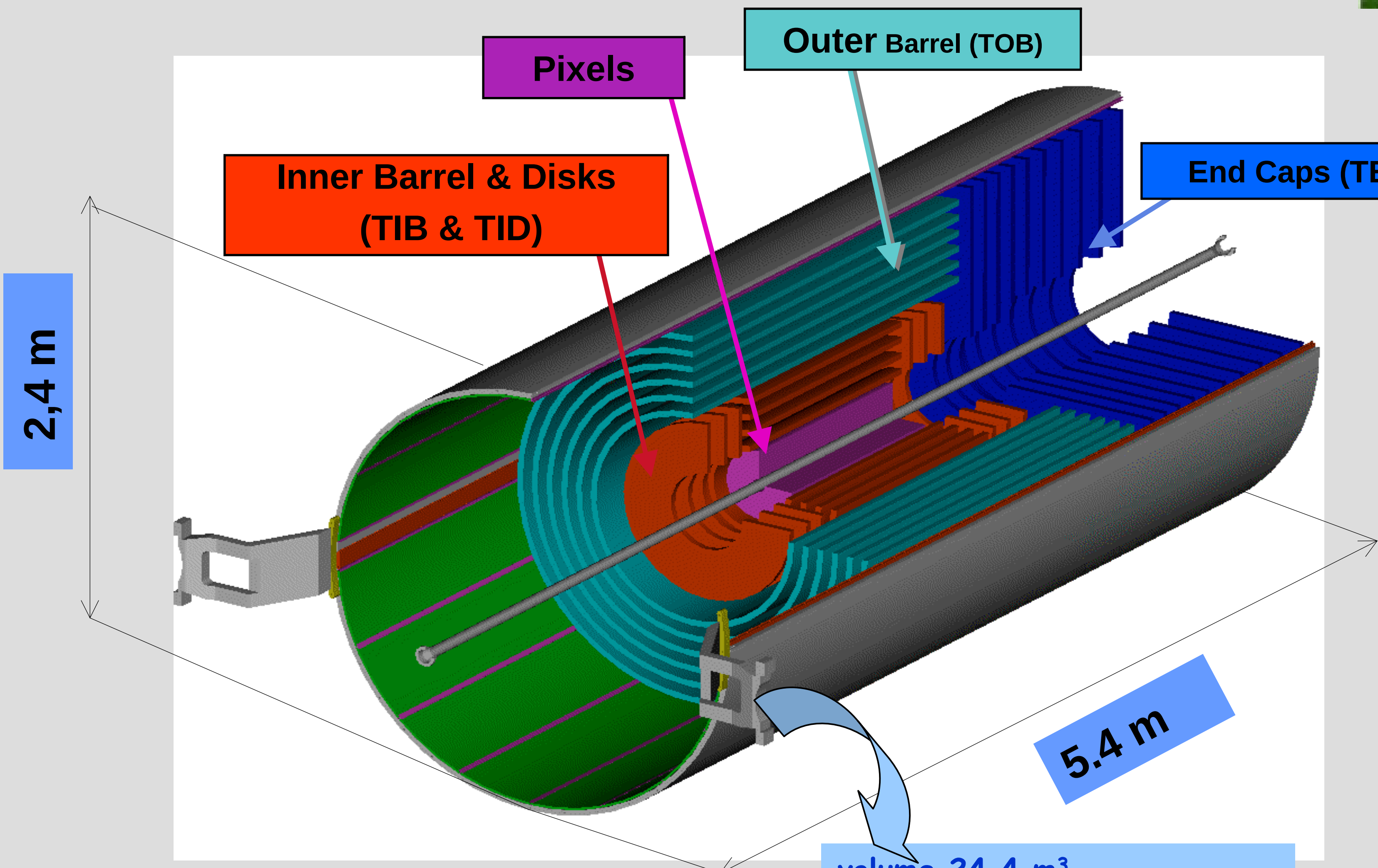
Reconstruct high pt tracks and jets

⇒ **~1-2% P_T resolution at ~ 100GeV (μ's)**

Tag b/τ through secondary vertex

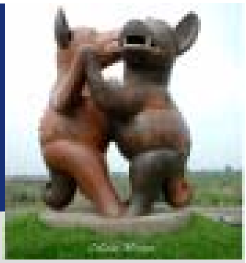
⇒ **Asymptotic impact parameter σ_d ~ 20μm**

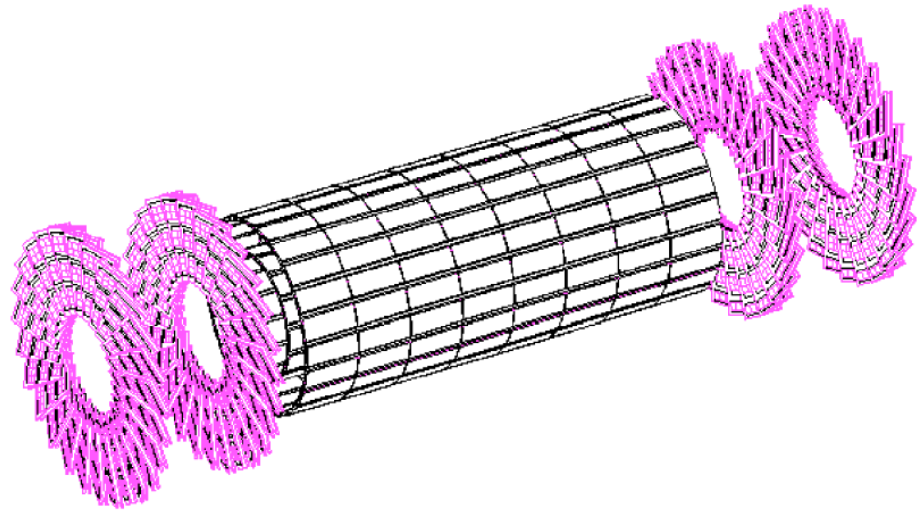
CMS Tracker



volume 24.4 m^3
running temperature – 10 ^{0}C

Pixels





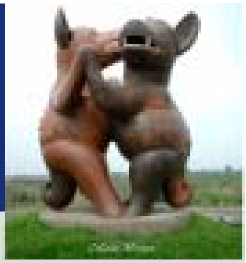
Why Pixels ?

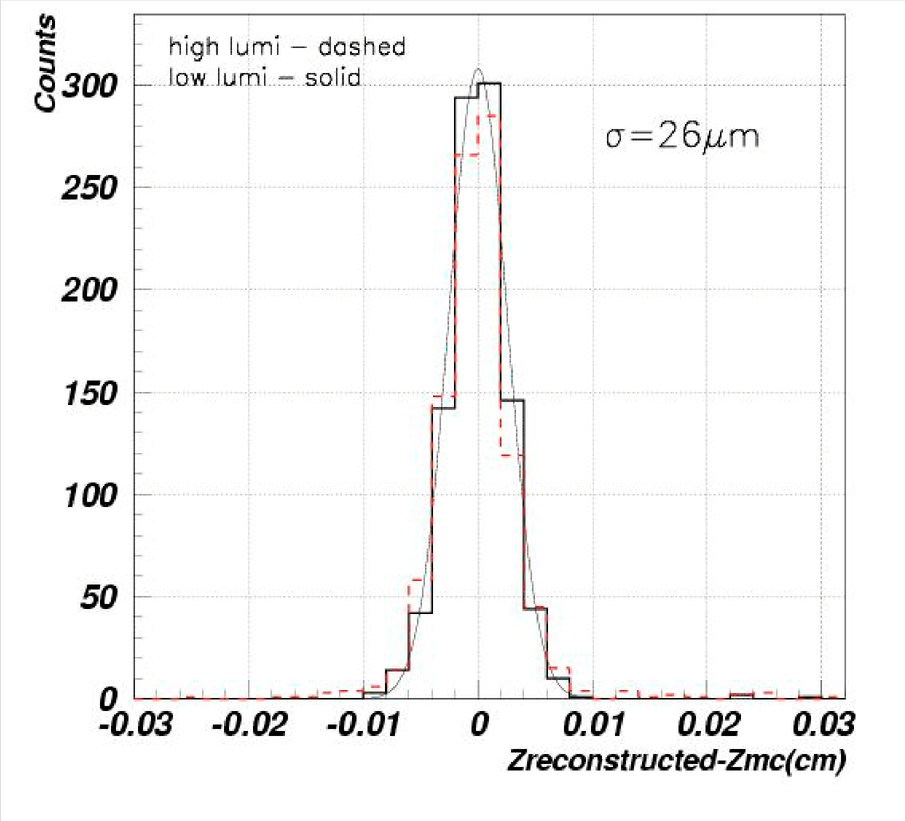
- Displaced track detection
  - Key to b jets for SUSY and Higgs
- Fast primary vertex
  - 3D space points
- Granularity
  - Peak occupancy ~ 0.01 %
    - Starting point for pattern recognition
  - Radiation tolerance

CMS Pixels

- 45 million channels
  - 100 μm x 150 μm pixel size
- 3 barrel radii: 4, 7 and 11 cm
- 2 disks per end (upgradeable to 3)
- Pseudorapidity coverage
  - Full coverage to 2
  - Partial coverage to 2.5

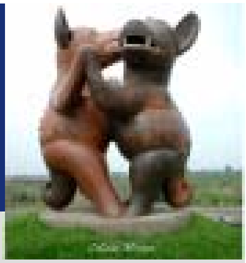
Pixel standalone vertex finding





- Only pixel hits are used to find primary vertices:
  - Very good position resolution and high efficiency.
  - Applied in High Level Triggers

CMS Microstrip Tracker



From the CMS tracker technical design report:

"The design goal of the central tracking system is to reconstruct isolated high p_t tracks with an efficiency of better than 95% and high pt tracks within jets with an efficiency better than 90%.."

"The momentum resolution required for isolated charged leptons in the central rapidity region is

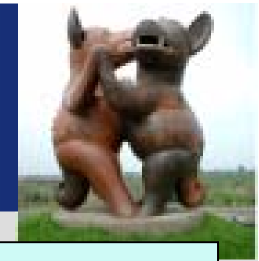
$$\Delta p_T/p_T = 0.1\, p_T\, (\text{TeV})..\text{"}$$

$\Rightarrow$ $Z \rightarrow \mu+\mu-$ with $\Delta m_z < 2$ GeV up to $P_z \sim 500$ GeV

12 layers have momentum resolution:

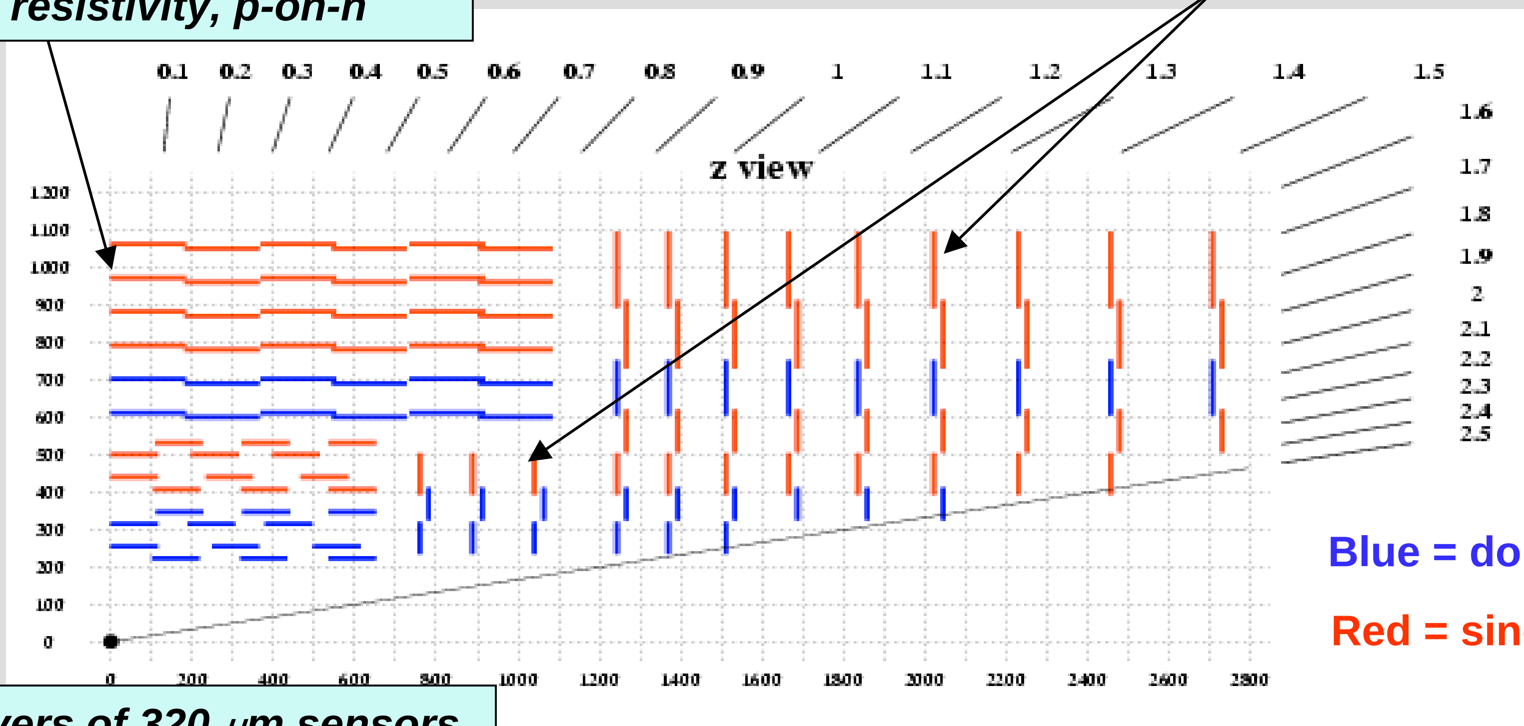
$$\frac{\Delta p}{p} \approx 0.12\left(\frac{pitch}{100\,\mu m}\right)^1\left(\frac{1.1m}{L}\right)^2\left(\frac{4T}{B}\right)^1\left(\frac{p}{1Tev}\right)$$

Silicon Strips



6 layers of 500 μm sensors high resistivity, p-on-n

9+3 disks per end



Blue = double sided

Red = single sided

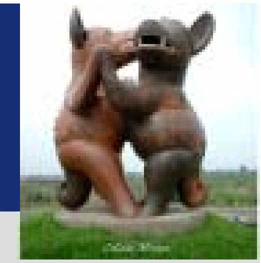
4 layers of 320 μm sensors low resistivity, p-on-n

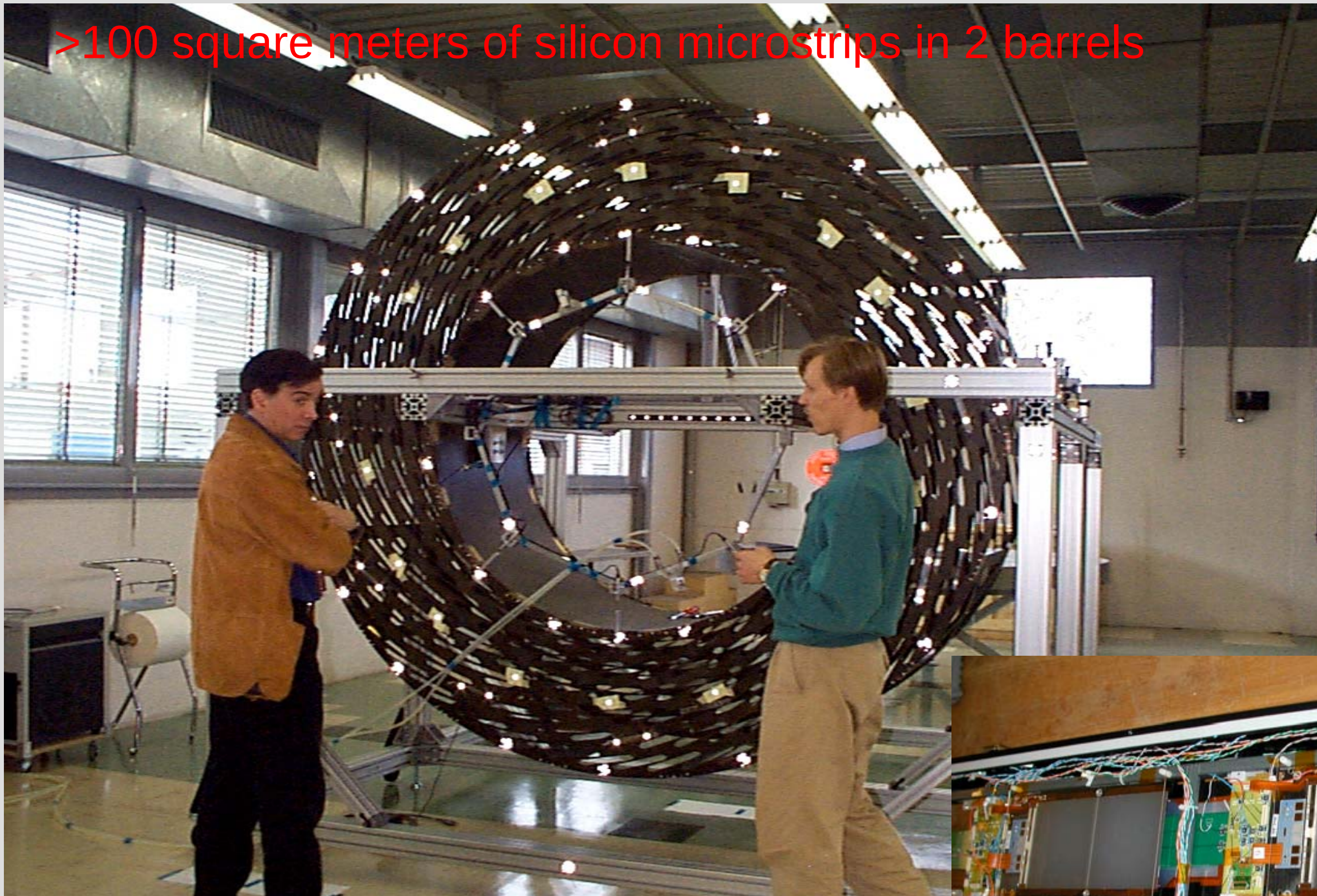
$\sigma/p_T \sim (15 \bullet p_T \oplus 0.5)$ % $|\eta| \leq 1.6$

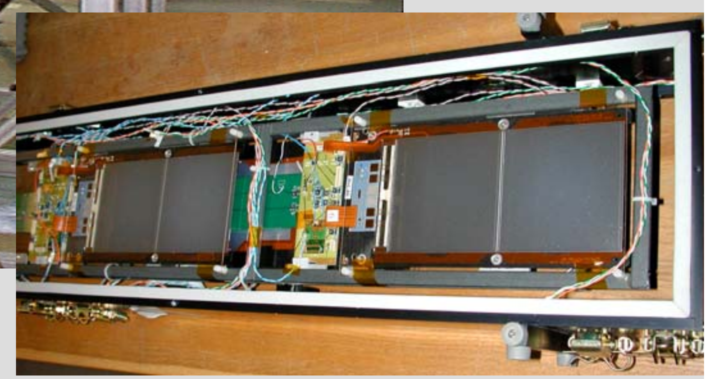
$\rightarrow 4.5 \bullet \sqrt{p}$ % when combined w/μ detectors

$\sigma/p_T \sim (60 \bullet p_T \oplus 0.5)$ % $|\eta| \sim 2.5$ p_T in [TeV/c]

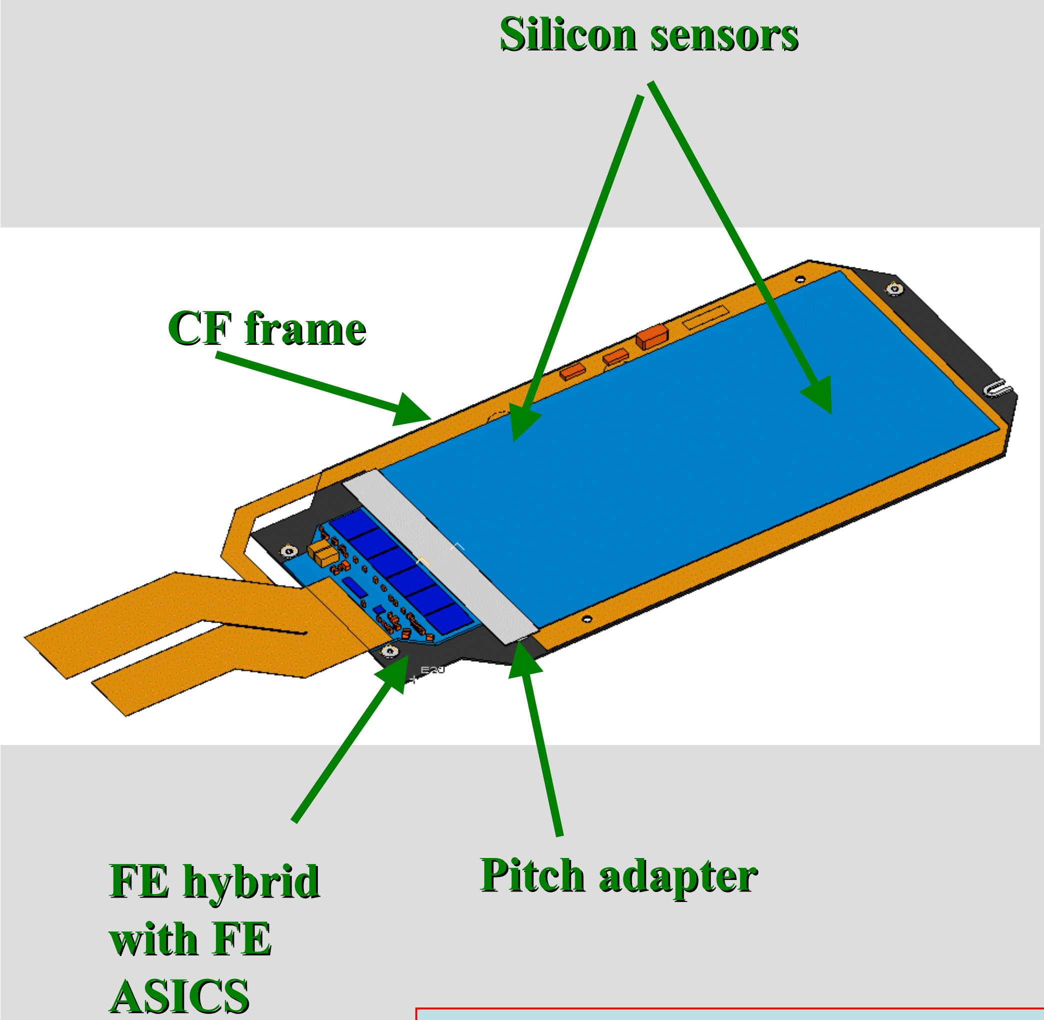
Tracker Outer Barrel







Some Tracker Numbers



- 6,136 Thin wafers 300 µm
- 19,632 Thick wafers 500 µm

- 6,136 Thin detectors (1 sensor)
- 9,816 Thick detectors (2 sensors)

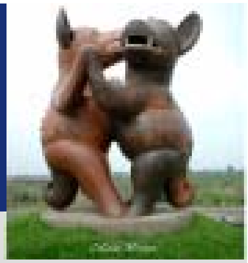
- 3112 + 1512 Thin modules (ss +ds)
- 4776 + 2520 Thick modules (ss +ds)

- 10,016,768 individual strips and readout electronics channels

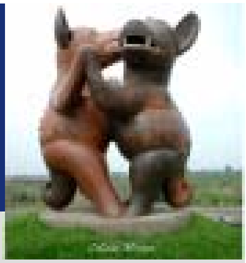
- 78,256 APV chips
- ~26,000,000 Bond wires

- 470 m^2 of silicon wafers
- 223 m^2 of silicon sensors ($175\ m^2 + 48\ m^2$)

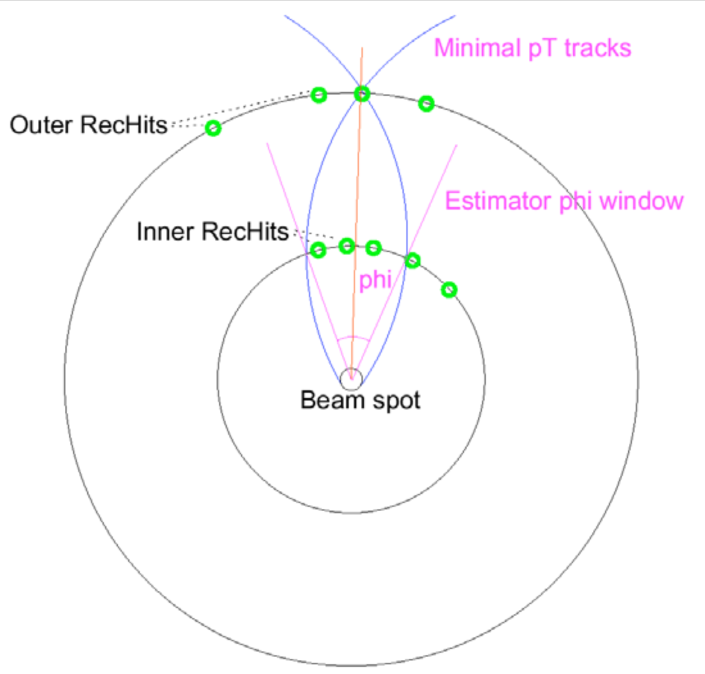
Requires automation for assembly



Pattern Recognition

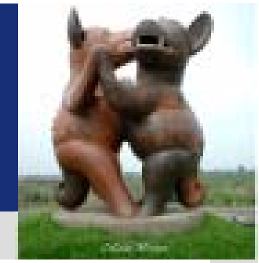


- Inside out tracking.
- Start with Pixel hits (lowest occupancy 0.01 %)

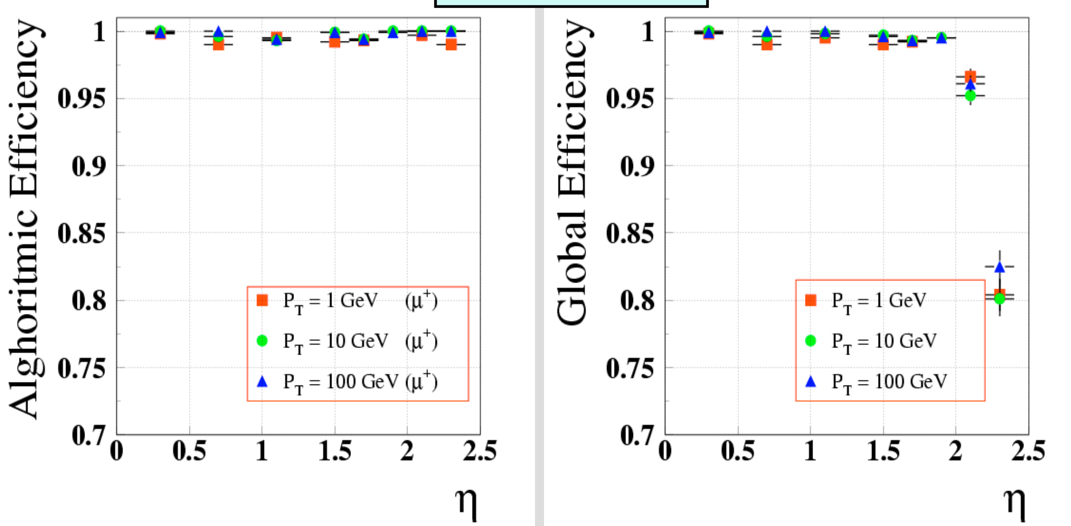


- Track segment propagation from layer to layer:
  - Kalman-combinatorial Filter, Deterministic Annealing Filter, MultiTrackFilter

Track Reconstruction Efficiency

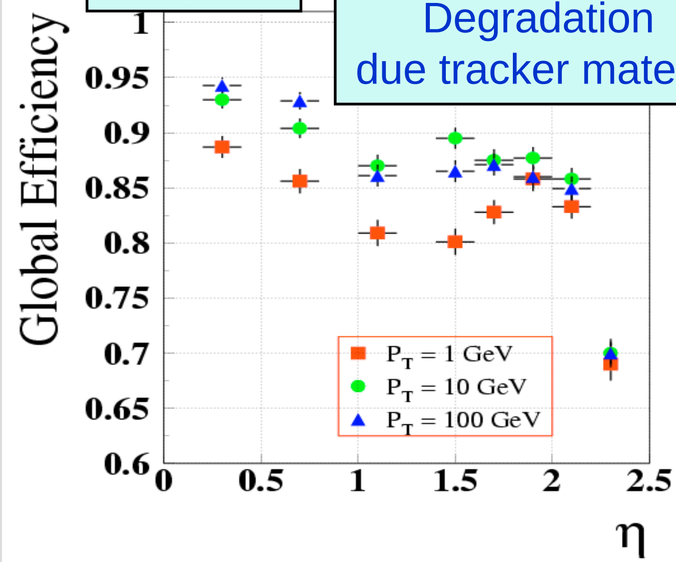


Single μ

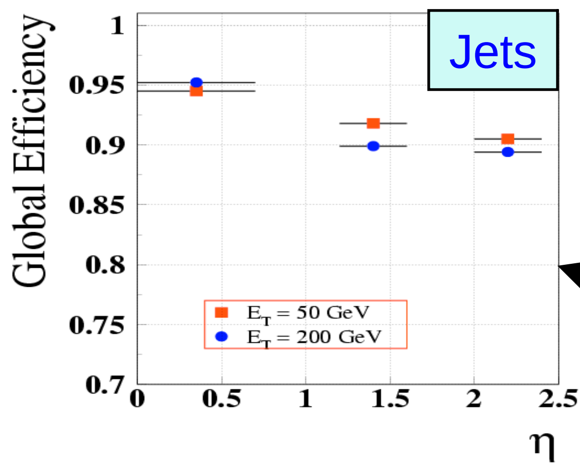


Single π

Degradation due tracker material



Jets



Global efficiency: selected RecTracks/all SimTracks

Algorithmic efficiency: selected RecTracks/selected SimTracks

SimTrack selection: at least 8 hits, at least 2 in pixel

Global efficiency limited by pixel geometrical acceptance

Efficiency for particles in a ηϕ cone of radius 0.4 around jet axis

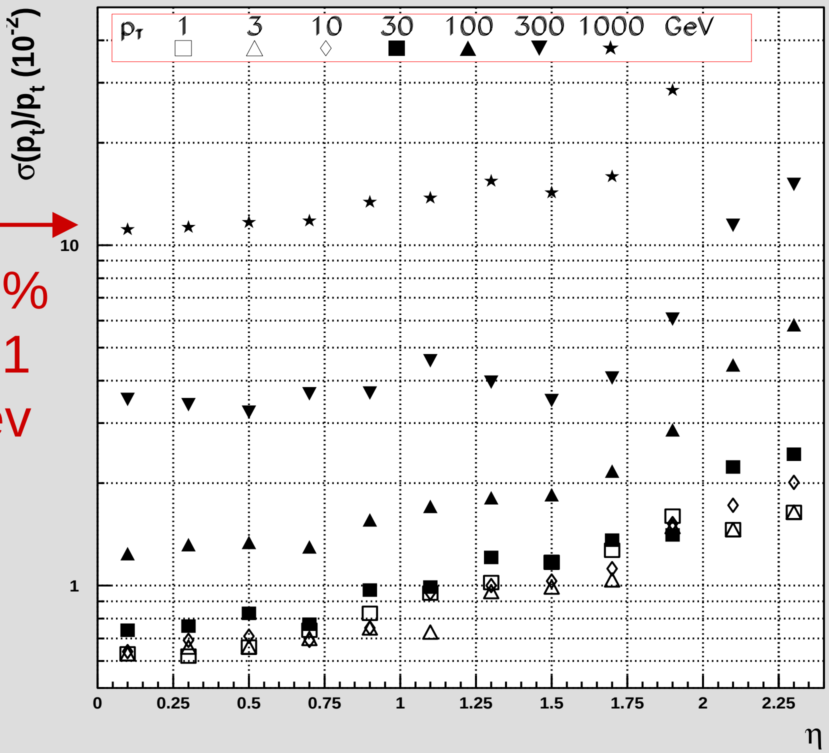
No significant degradation compared to single pions

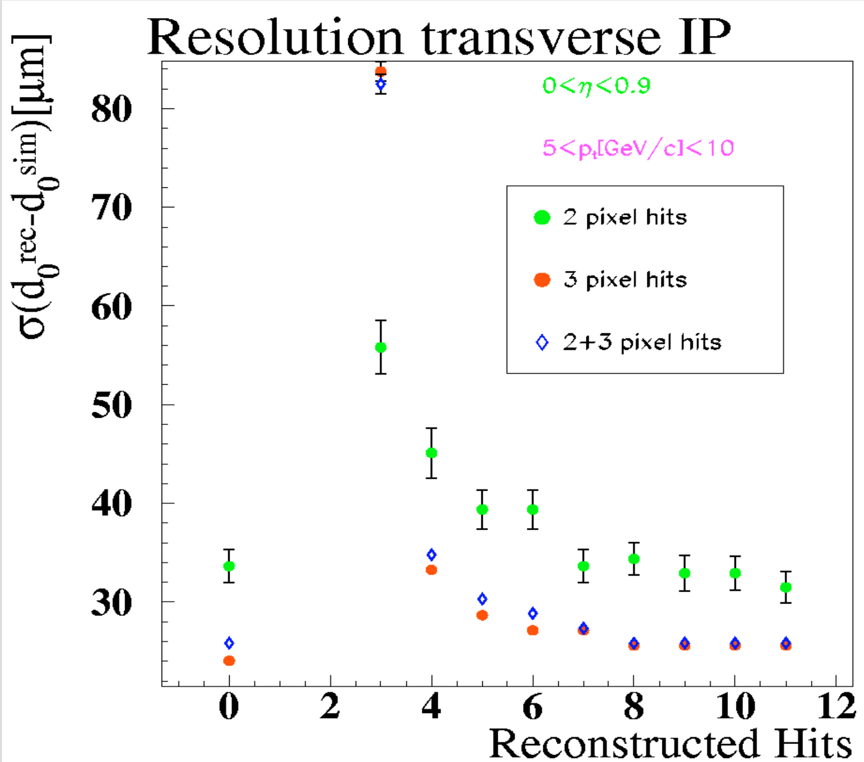
Jets E_T = 50-200 GeV

Fake Rate < 1 %

P_t and Impact Parameter Resolution

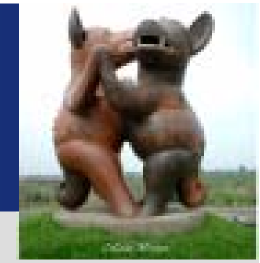
10%
at 1
Tev

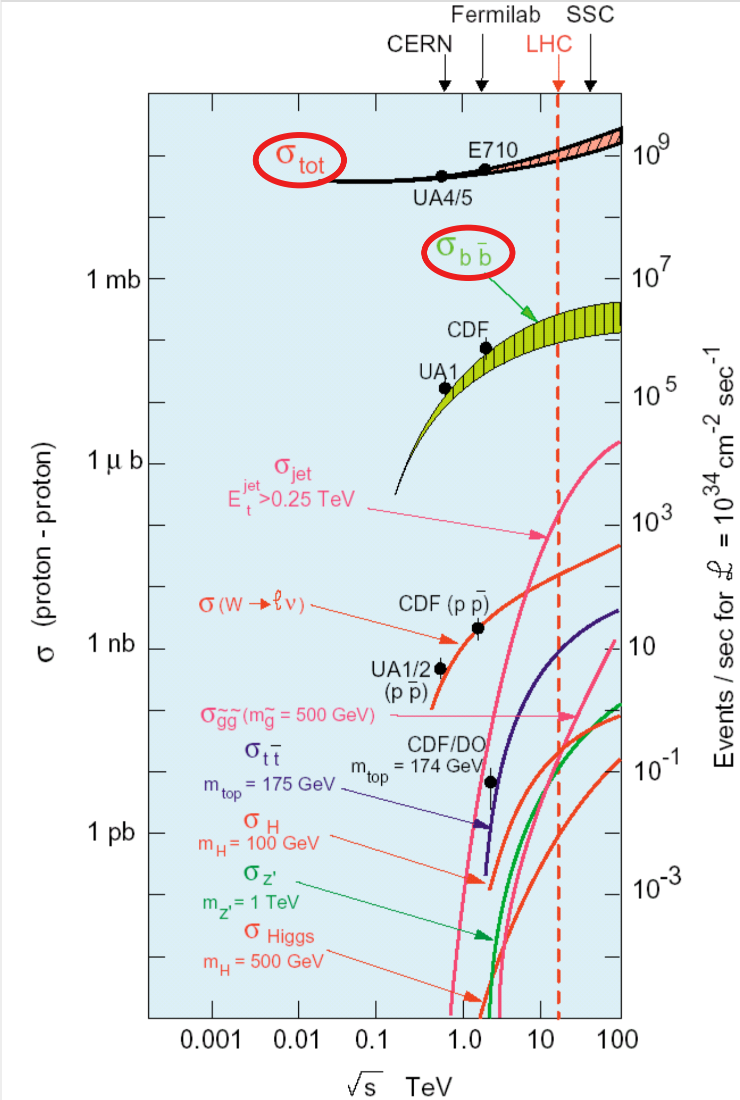




Sagitta at 1 TeV ≈ 180 μm

Trigger Challenge





Lot of b's and τ's from interesting Physics

- Supersymmetry
- Higgs decays
- Top, B physics

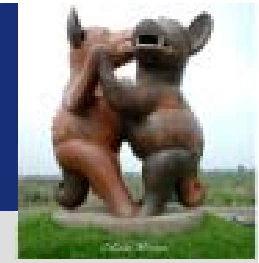
Large QCD backgrounds

The Challenge

L1: 40 MHz input

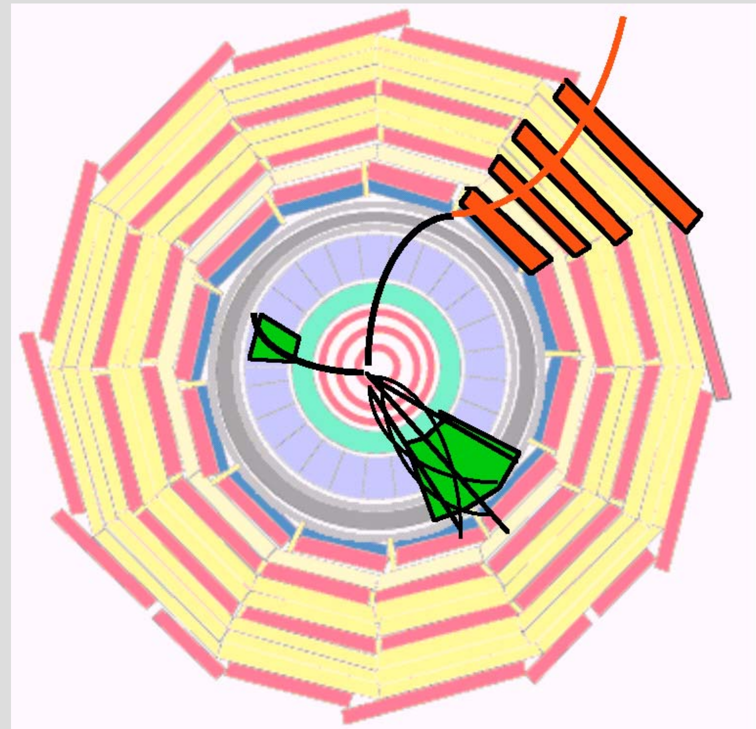
L1:100 KHz output

Write to offline:100 Hz



Tracker in High Level Triggers

- Do something only when needed.
  - reconstruction on demand: never do anything until it is requested
- Generally not interested in reconstructing the full event at trigger
  - regional tracking

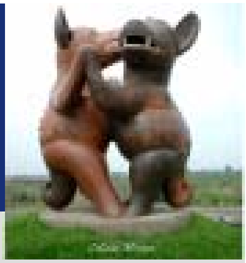


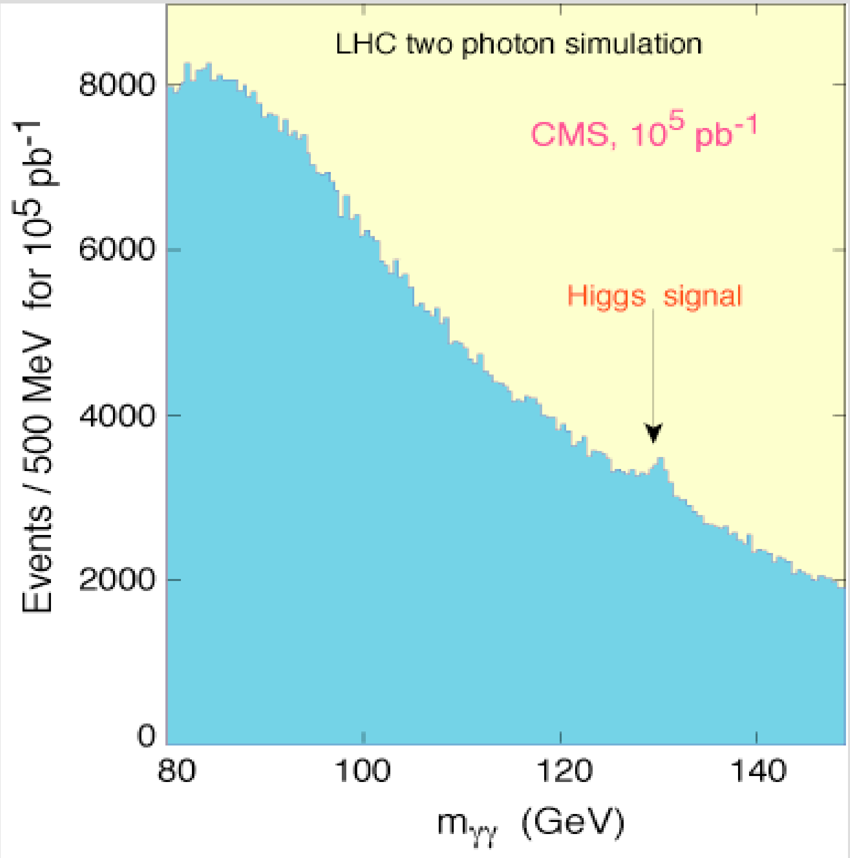
region around a L1 calo jet

Construction is well underway

How might it all perform?

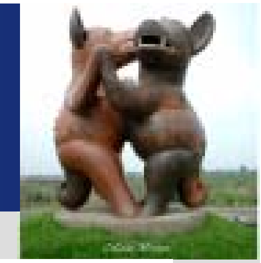
$H \rightarrow \gamma\gamma$

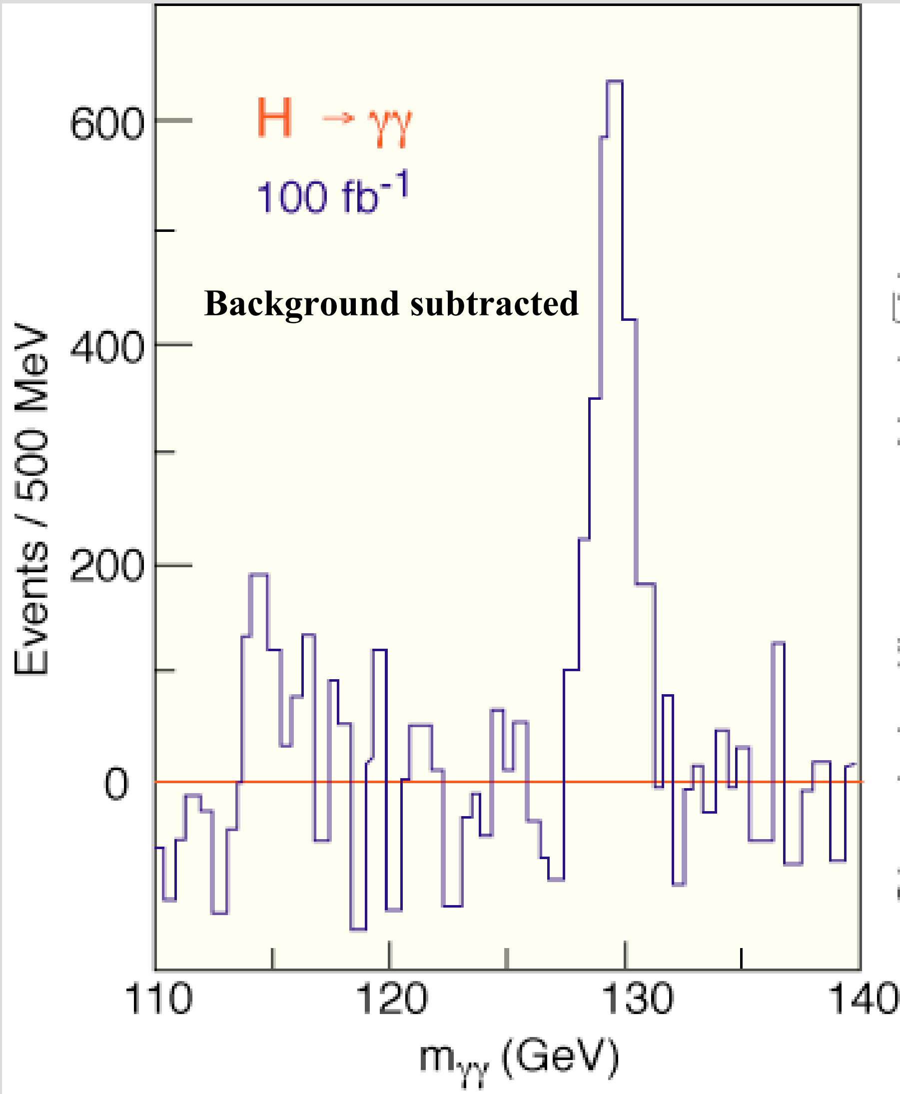


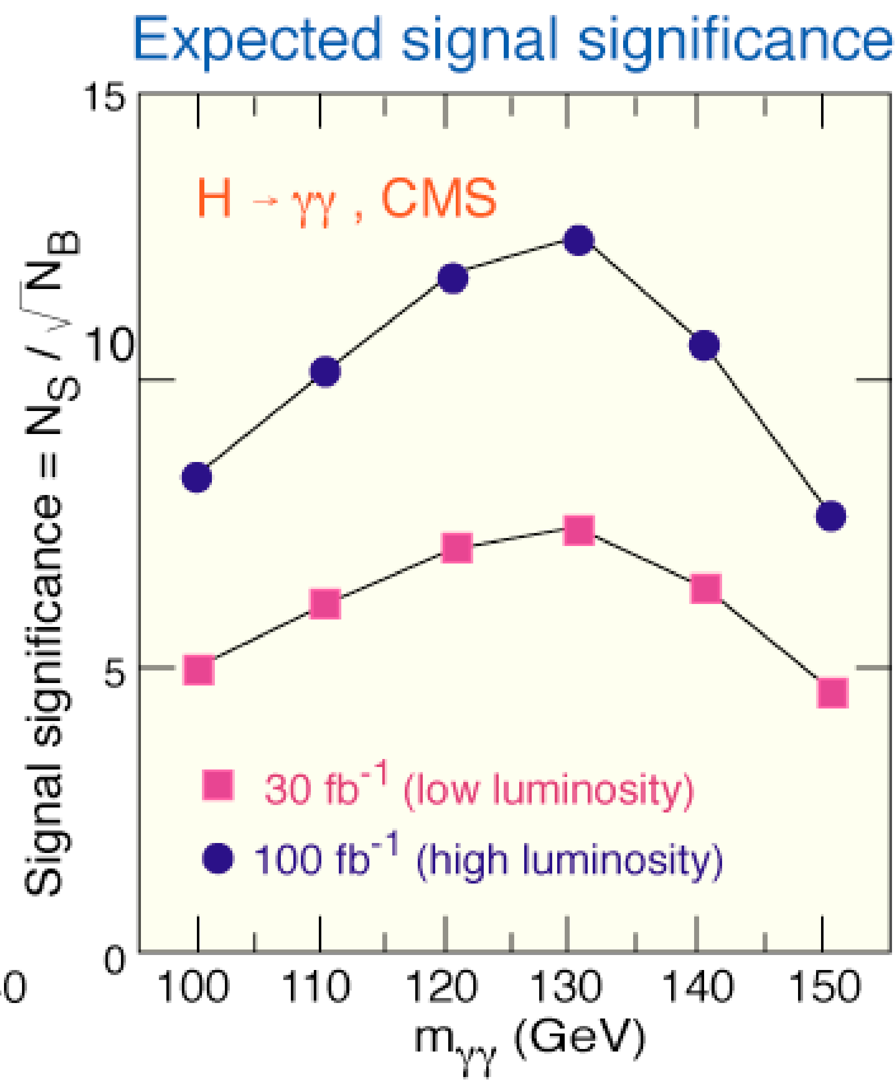


- The crystal electromagnetic calorimeter has been optimized for this channel.
- $\Delta m_H/m_H$ < 1% needed.
- Irreducible bkgds at $m_{\gamma\gamma}$ = 100 GeV:
  - $qq \rightarrow \gamma\gamma$
  - $gg \rightarrow \gamma\gamma$
  - Isolated bremsstrahlung
- Main reducible background:
  γ + jet with "jet" = $\pi^0 \rightarrow \gamma\gamma$
  – less than 15% of irreducible background

$H \to \gamma\gamma$





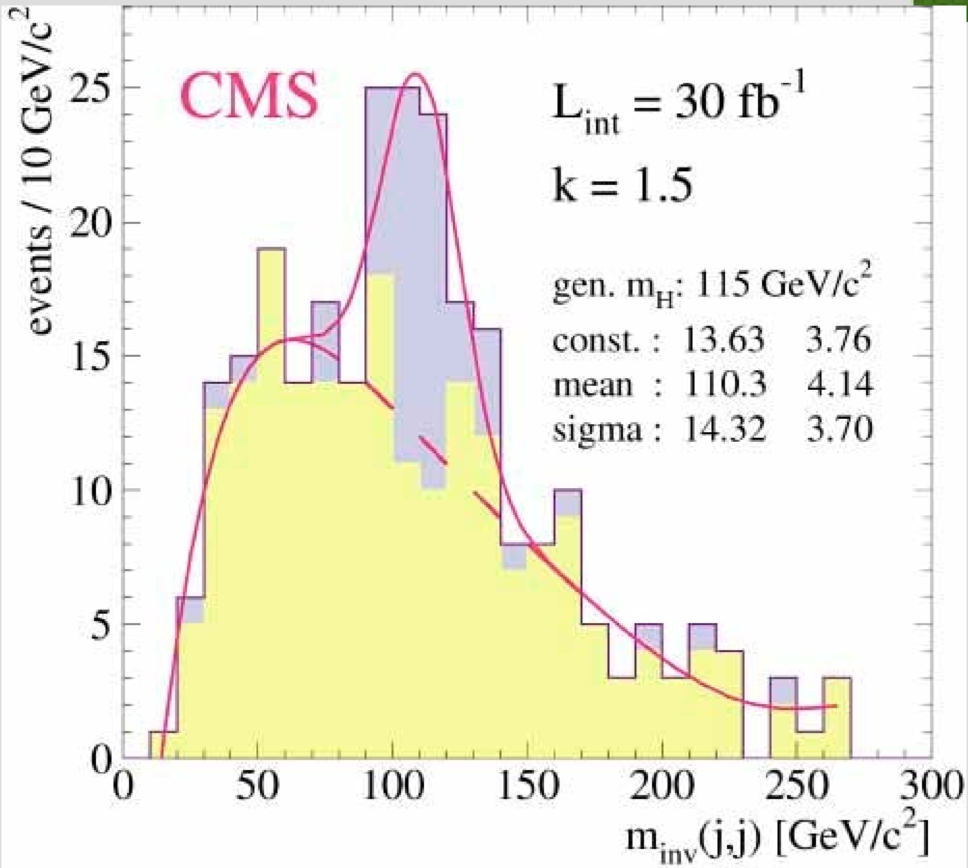


$ttH \to l^{\pm}\nu q\bar{q}bbbb$

For $H \to bb$ only associated production is feasible!

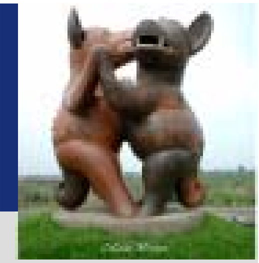
Event selection:
1 isolated e or μ, 6 jets of which 4 must have a b-tag. Reconstruction of both t's by kinematic fit necessary to suppress combinatorial $b\bar{b}$ background.
Backgrounds: ttZ, ttbb, ttjj

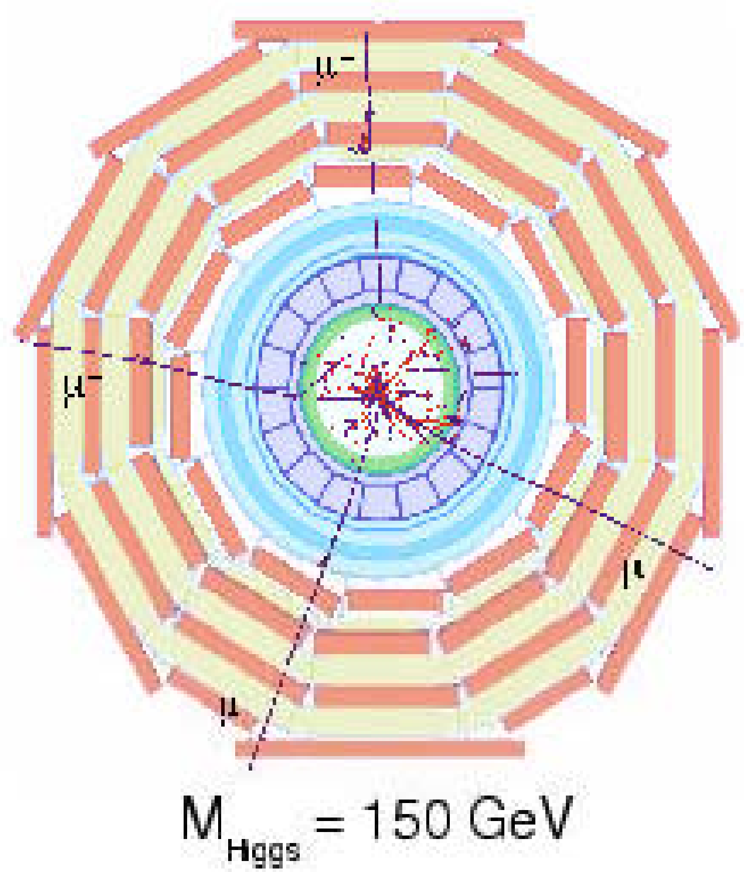
Results for m_H = 115 GeV:
$S/\sqrt{B}$ = 5.3, $\Delta m/m_H$ = 3.8%

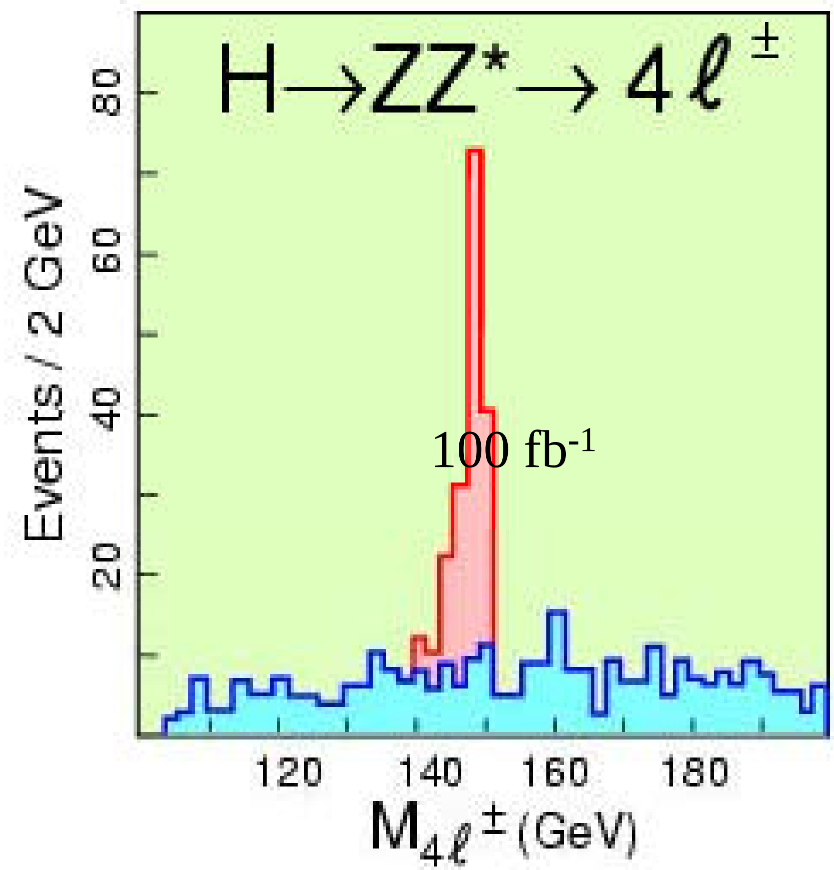


ttH and and $H \to \gamma\gamma$ are only way to explore the 115 GeV mass region!

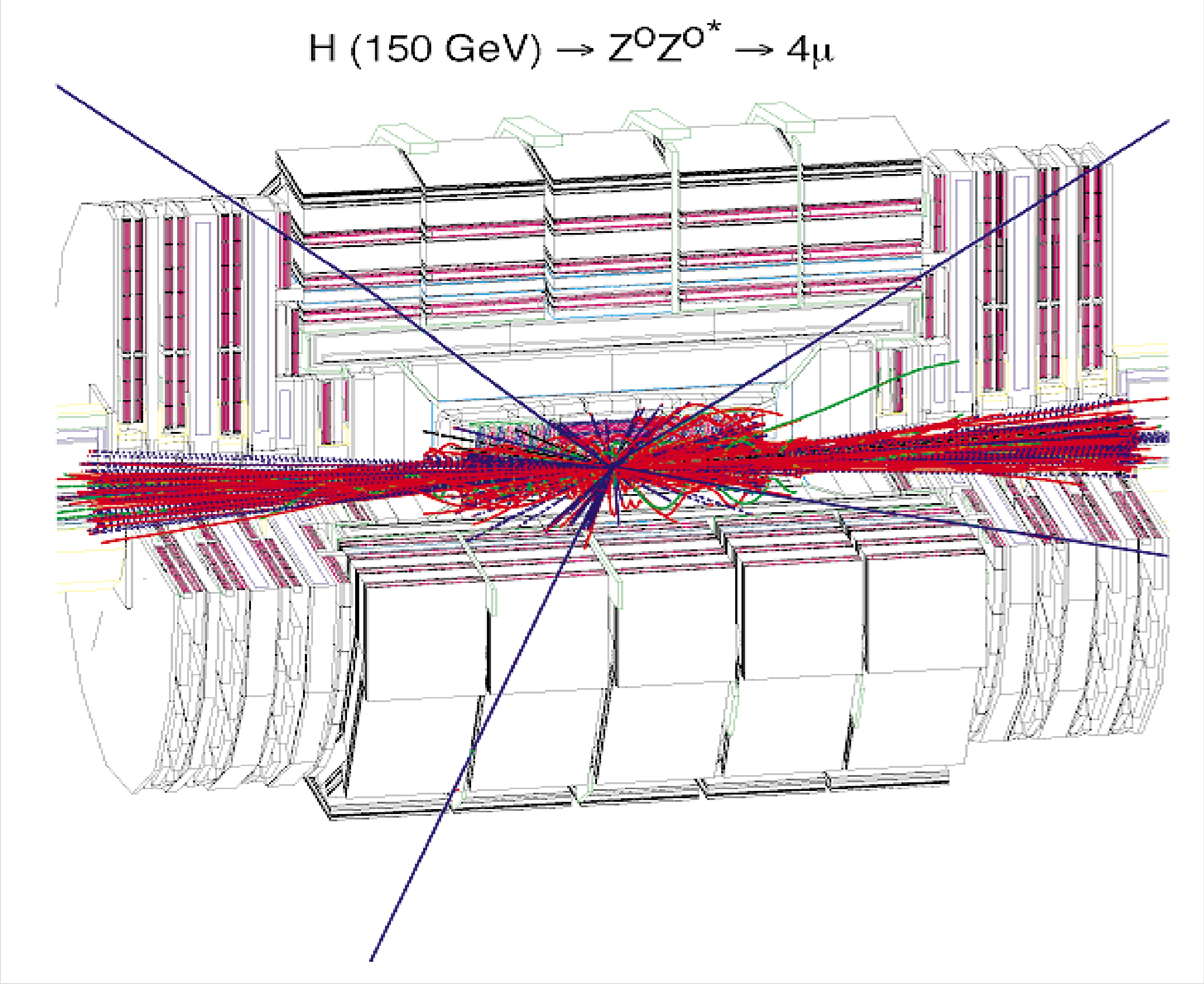
$H \rightarrow ZZ^* \rightarrow 4l$



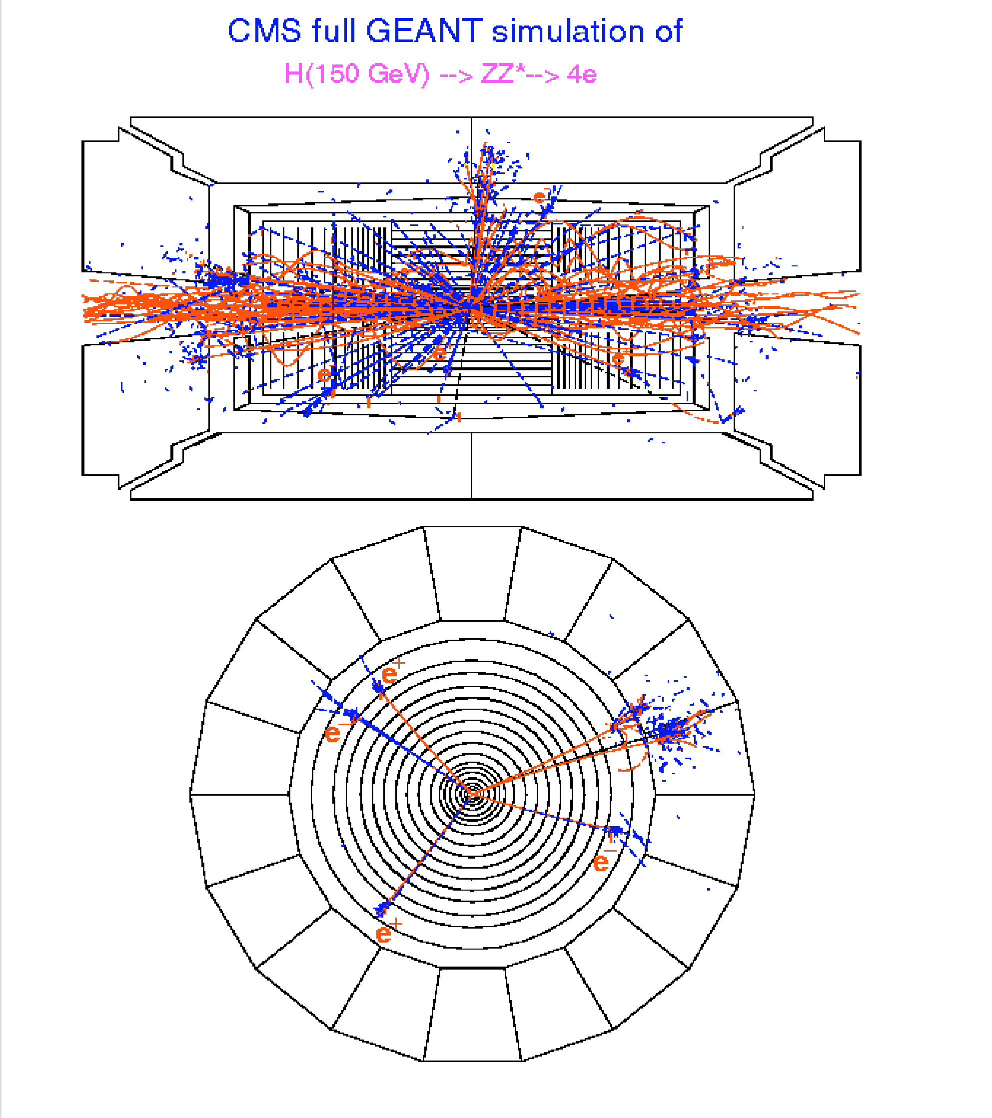




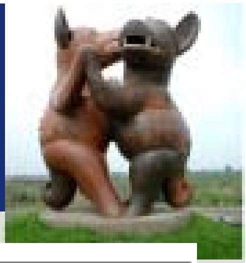
4μ Event



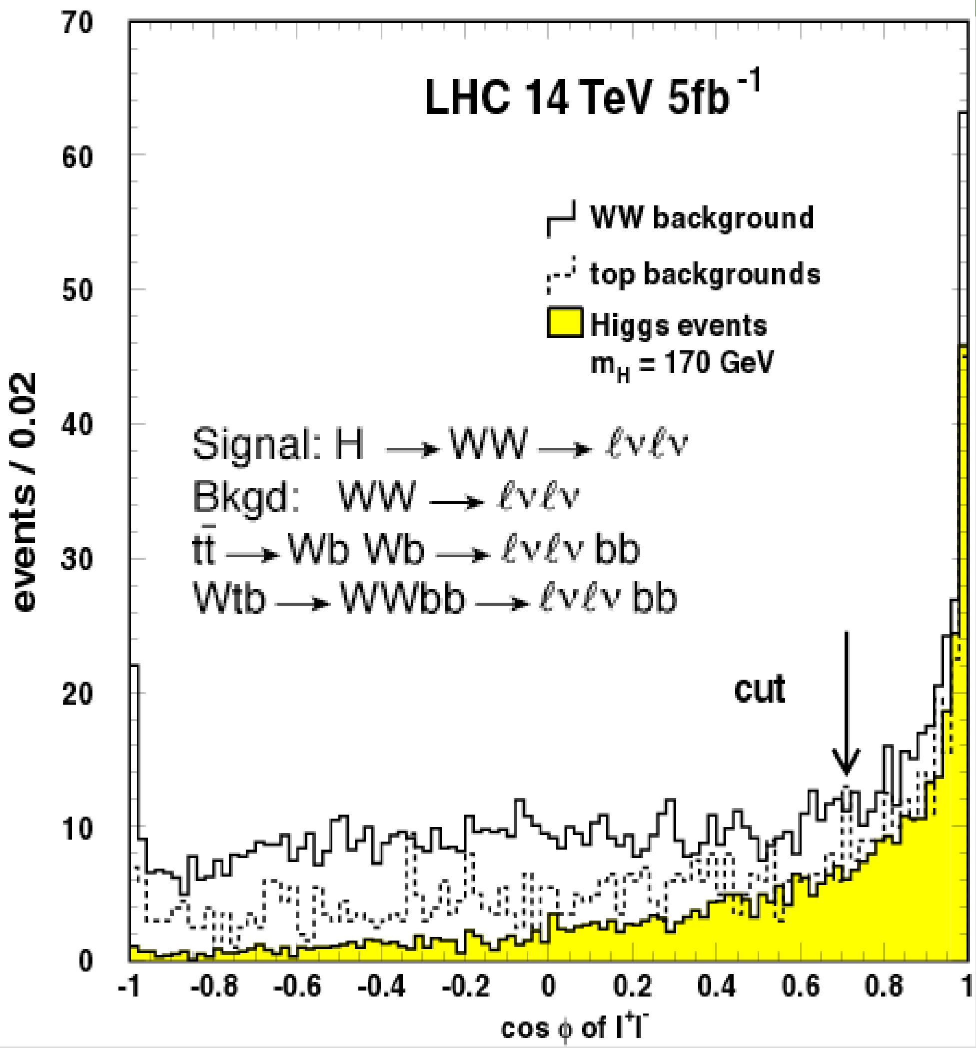
$H \rightarrow ZZ^* \rightarrow 4e$



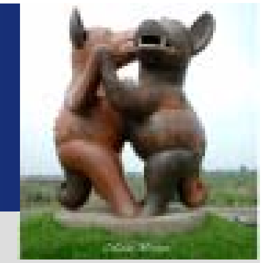
$H \rightarrow WW \rightarrow l\nu + l\nu$ for $m_H \sim 2m_W$

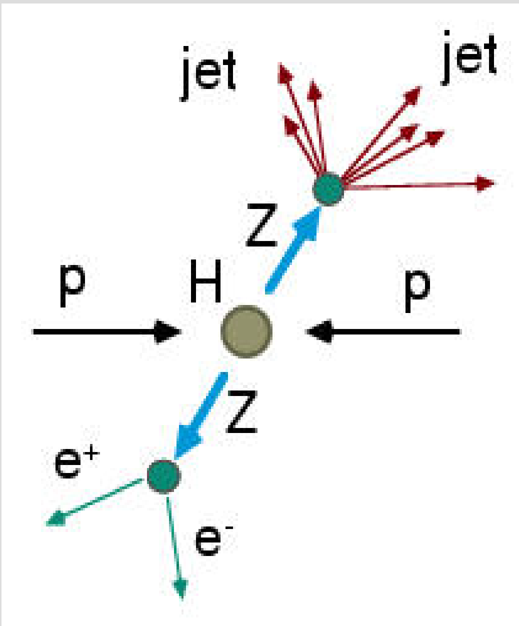


- For m_H = 170 GeV the BR is about 100 times larger than in $H \rightarrow ZZ^* \rightarrow 4l$.
- Can make use of W^+W^- spin correlations to suppress "irreducible" background:
  - Look for l^+l^- pair with small opening angle.
  - The mass can only be determined indirectly from rates and shapes.
- **5σ discovery can be made with 30 fb^{-1} in the mass range 130 to 190 GeV.**

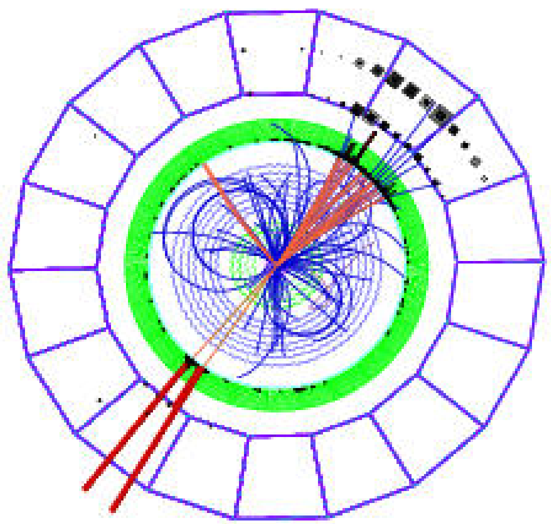


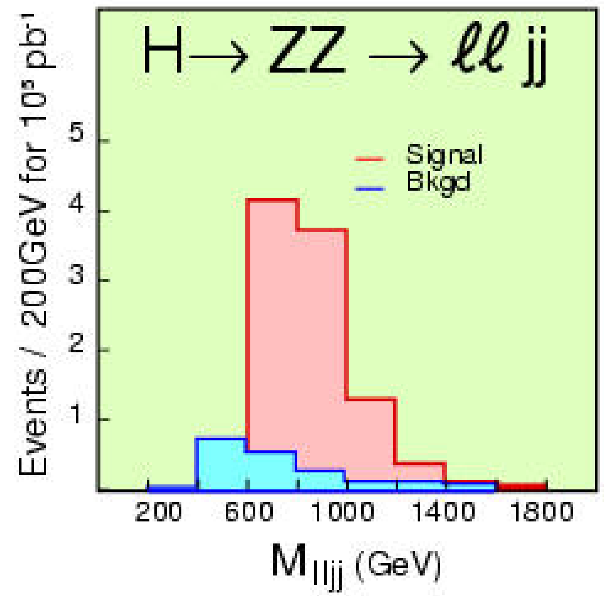
$H \to ll\nu\nu$, $lljj$, $l\nu jj$



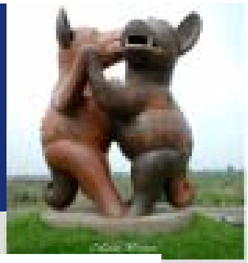


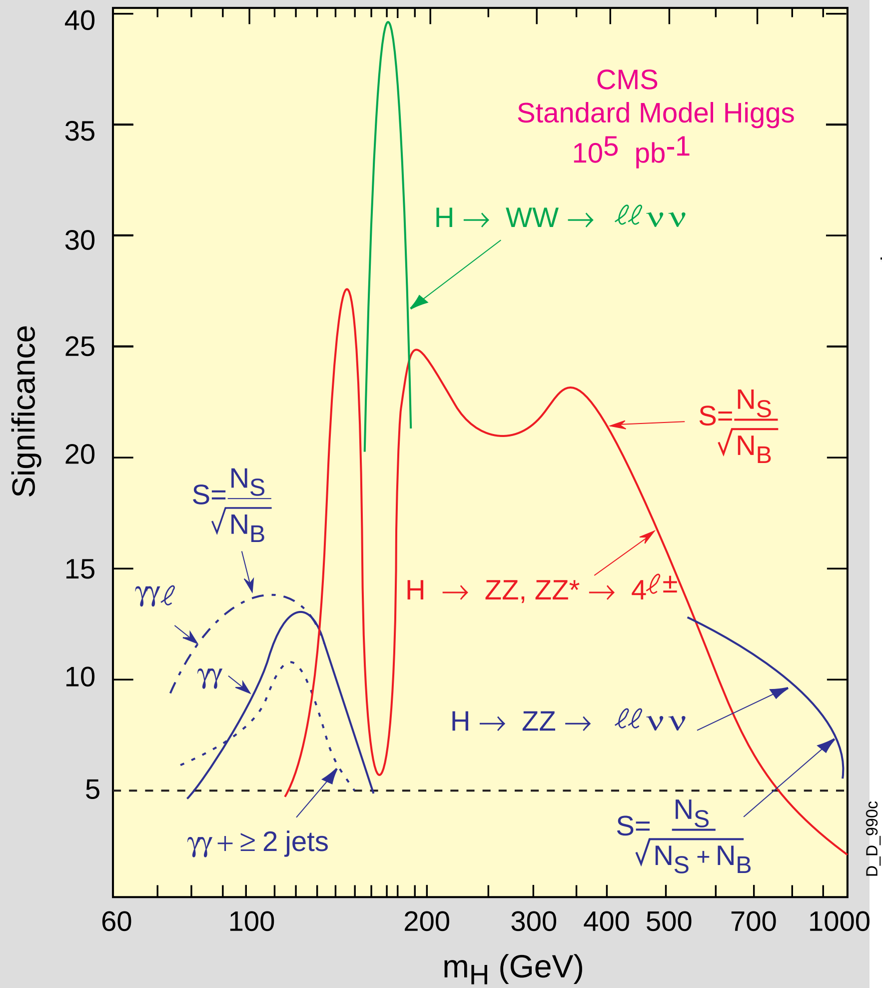
As Higgs width increases and production rates fall with higher masses one must use channels with larger branching ratios.
Need to select leptons, jets and missing energy.



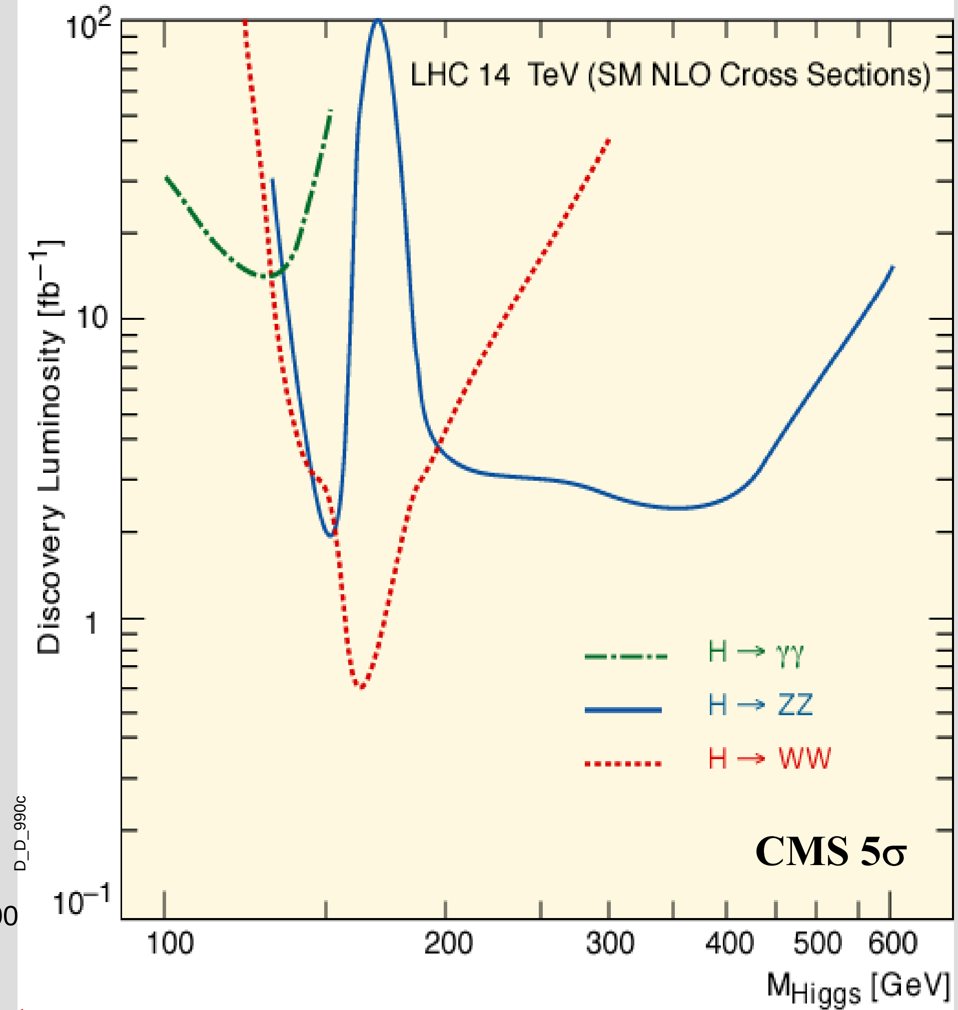


Standard Model Higgs in CMS



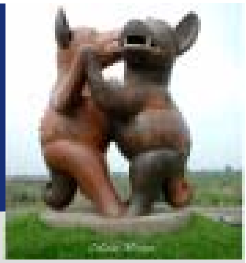


Significance for 100 fb^{-1}



5 σ - Contours

The Higgs Sector in the MSSM



The MSSM has 5 Higgs bosons: h^0, H^0, A^0 and $H^\pm$.
Two parameters are needed: m_A, $\tan\beta$.
In the limit of large m_A the couplings of h^0 are similar to SM. Couplings of A and H to quarks of 1/3 charge and leptons enhanced at large $\tan\beta$. A does not couple to WW, ZZ. Couplings of H to WW and ZZ for large m_A and $\tan\beta$ are suppressed.

The following decay channels can be used as for the SM Higgs:

h, A $\rightarrow \gamma\gamma$ (for $m_A < 2\, m_t$ due to branching ratio)

h, H $\rightarrow$ ZZ* (no H -> ZZ at large mass since BR too low)

$t\bar{t}h \rightarrow t\bar{t}\, b\bar{b}$

The following decay channels open up:

H, A $\rightarrow \tau\tau, \mu\mu$ (τ-channels enhanced over SM for large $\tan\beta$)

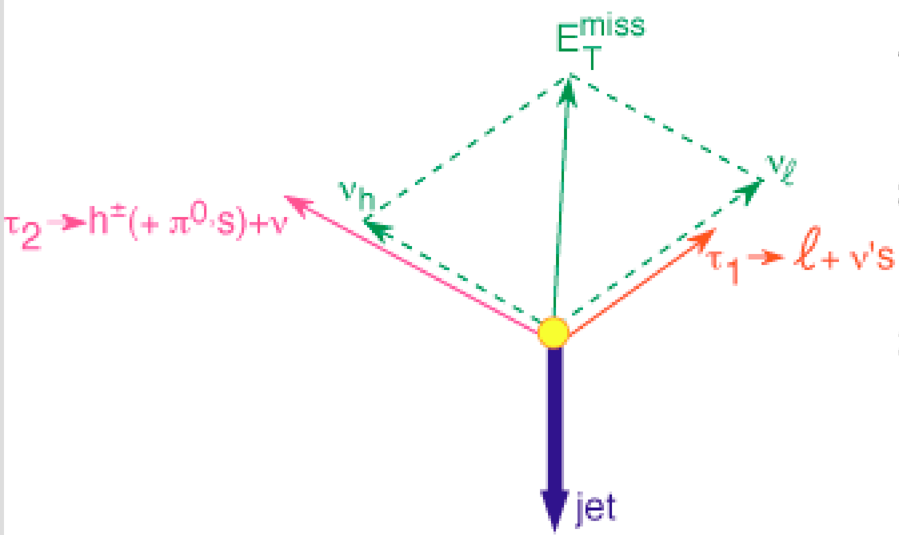
H, A $\rightarrow$ hh; A $\rightarrow$ Zh; A $\rightarrow t\bar{t}$

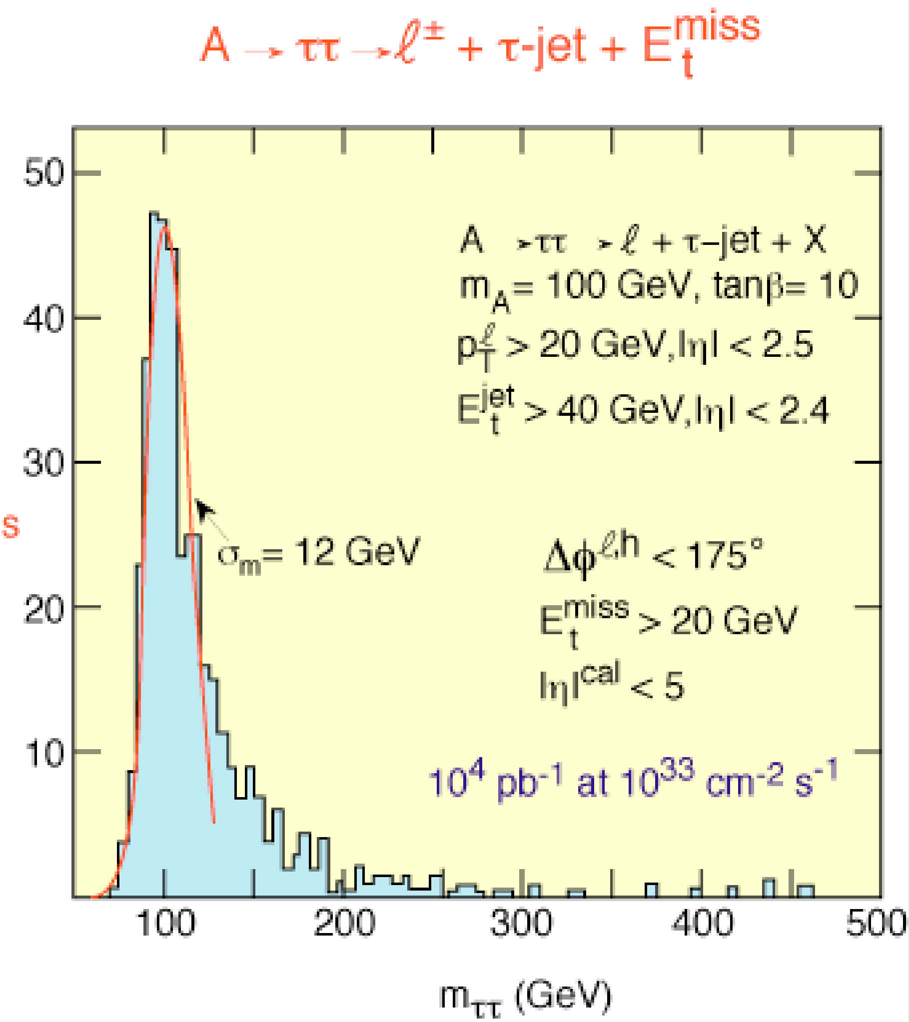
A, H $\rightarrow$ sparticles

$H^\pm \rightarrow \tau\nu$, tb

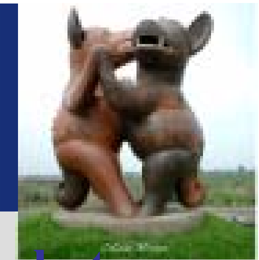
Mass Determination for H/A → ττ

Mass reconstructed assuming ν directions parallel to lepton and τ-jet.

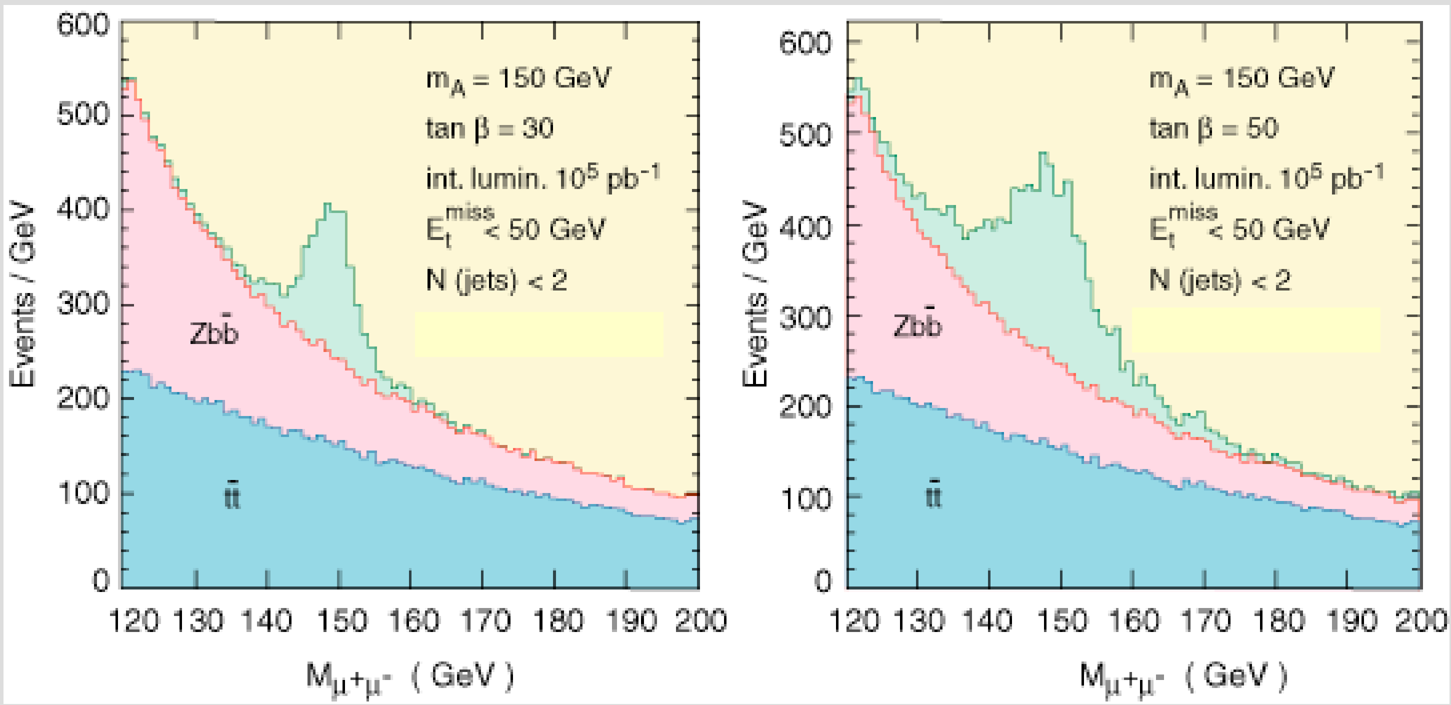




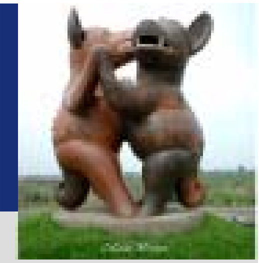
H/A → μμ



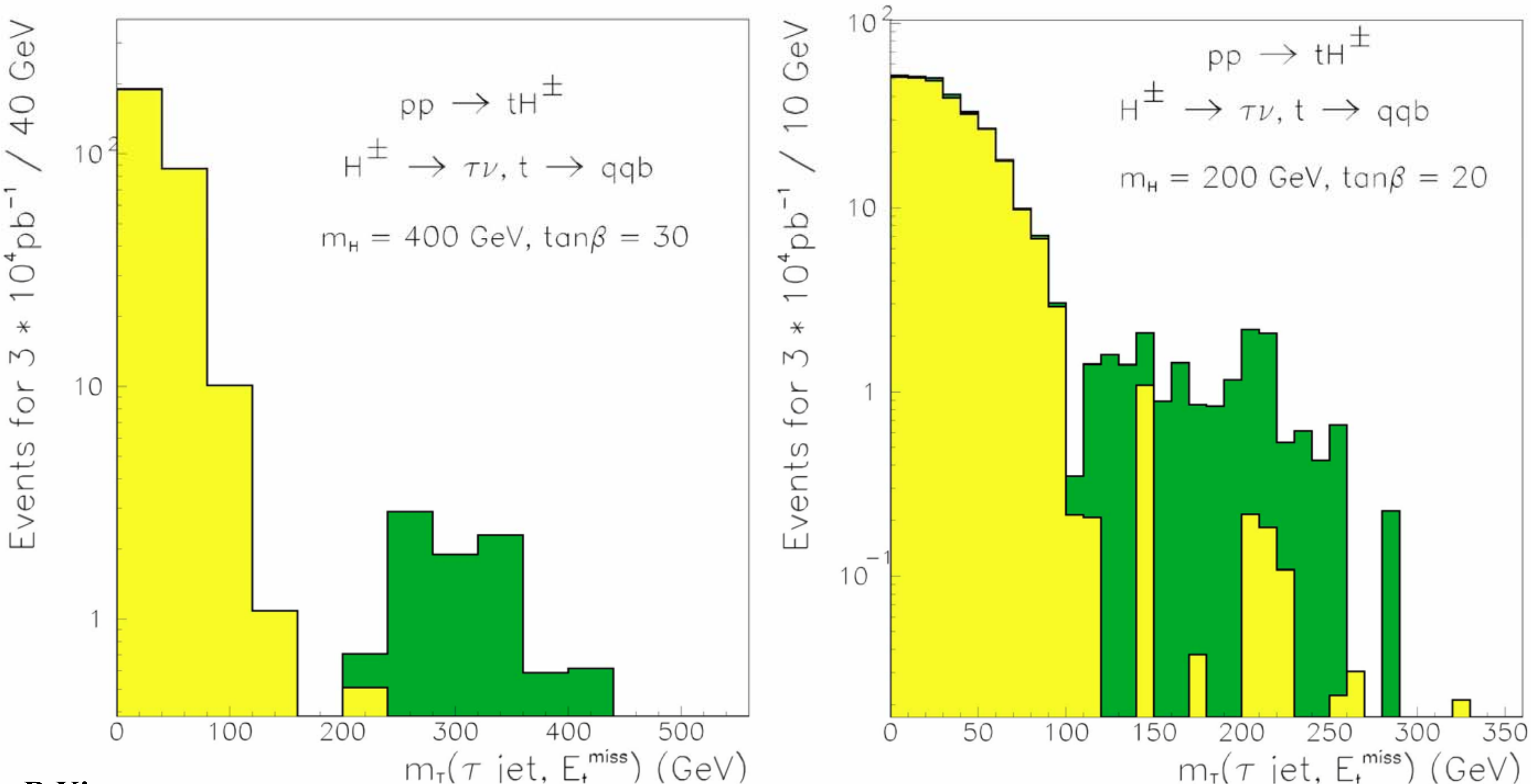
BR smaller than that for ττ-channel by $(m_\mu/m_\tau)^2$. Somewhat compensated by better resolution for μ's. Useful for large tanβ.



Charged Higgs



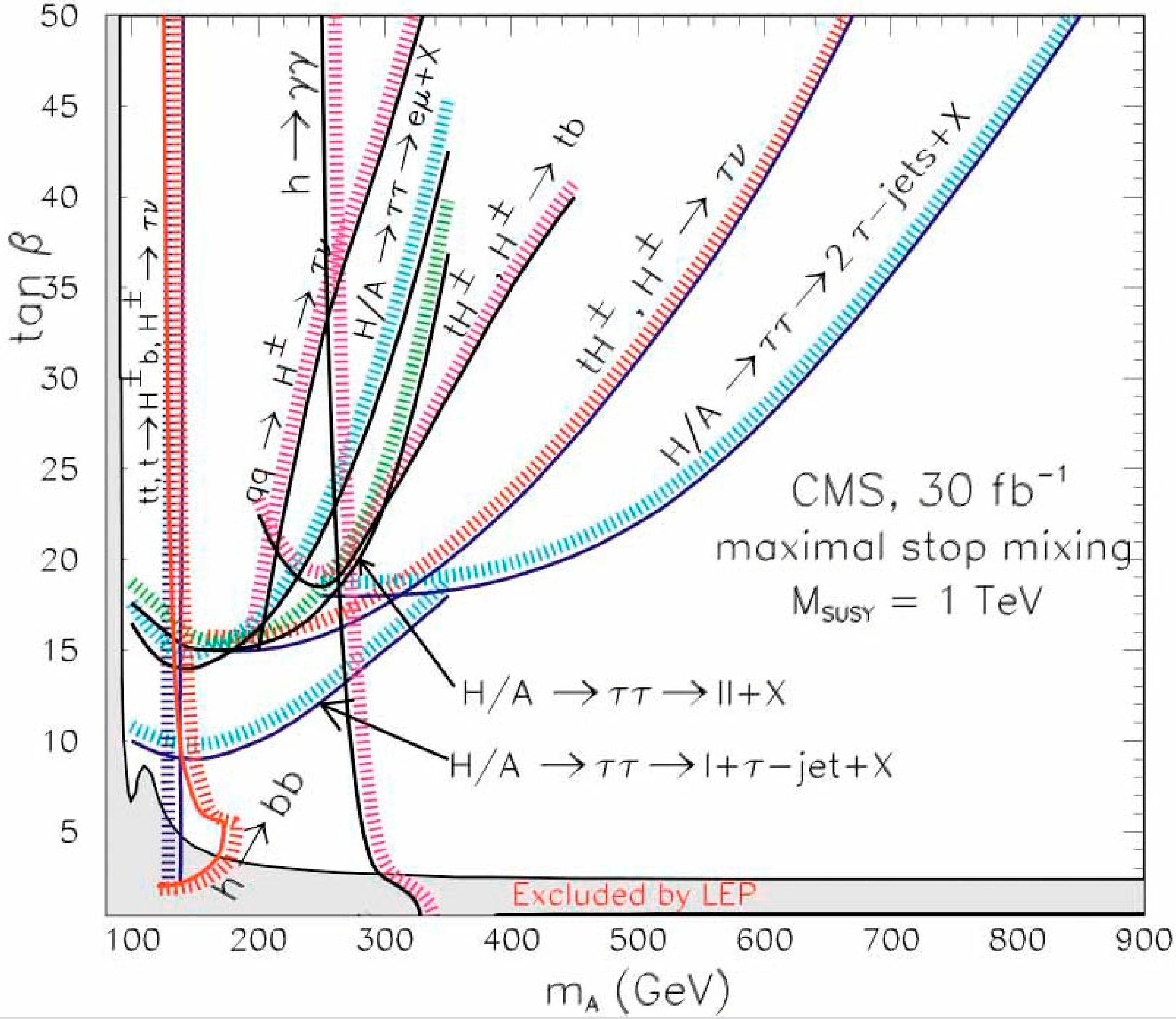
$gb \rightarrow tH^{\pm}$, $H^{\pm} \rightarrow \tau\nu$, $t \rightarrow qqb$



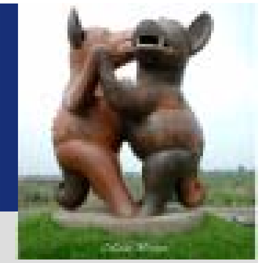
R.Kinnunen

Transverse mass reconstructed from τ-jet and E_T^{miss} for $pp \rightarrow tH^{\pm}$

5σ reach for MSSM Higgs in 30 fb^{-1}



MSSM SUSY Particle Spectrum



MSSM particle content :

- squarks (spin-0) : $\tilde{d}_L, \tilde{u}_L, \tilde{s}_L, \tilde{c}_L, \tilde{b}_1, \tilde{t}_1, \tilde{d}_R, \tilde{u}_R, \tilde{s}_R, \tilde{c}_R, \tilde{b}_2, \tilde{t}_2$
- sleptons (spin-0) : $\tilde{e}_L, \tilde{\nu}_{eL}, \tilde{\mu}_L, \tilde{\nu}_{\mu L}, \tilde{\tau}_1, \tilde{\nu}_{\tau L}, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_2$
- charginos (spin-$\frac{1}{2}$) : $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$
- neutralinos (spin-$\frac{1}{2}$) : $\tilde{\chi}_1^0, \tilde{\chi}_2^0 ; \tilde{\chi}_3^0, \tilde{\chi}_4^0$
- gluino (spin-$\frac{1}{2}$) : $\tilde{g}$
- higgs bosons : (spin-0) : h, H, A, $H^{\pm}$

MSSM parameters :

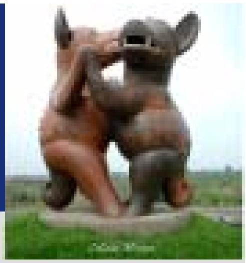
$m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{\ell}}, A_t, A_b, \mu, m_A, \tan\beta$

Minimal SUGRA parameter set :

$m_0, m_{1/2}, \tan\beta, A_0$ and sign(μ)

SUSY Particle Production

- qq, gg → h, H A, $H^{\pm} H^{\mp}$,
- qq, gg, qg → $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$, (strong production)
- qq, qg → $\tilde{g}\tilde{\chi}_i^0, \tilde{g}\tilde{\chi}_i^{\pm}, \tilde{q}\tilde{\chi}_i^0, \tilde{q}\tilde{\chi}_i^{\pm}$ (associated production)
- qq → $\tilde{\chi}_i^{\pm}\tilde{\chi}_j^{\mp}, \tilde{\chi}_i^{\pm}\tilde{\chi}_j^0, \tilde{\chi}_i^0\tilde{\chi}_j^0$ ($\tilde{\chi}$ pair production)
- qq → $\tilde{\ell}\tilde{\nu}, \tilde{\ell}\tilde{\ell}, \tilde{\nu}\tilde{\nu}$ (slepton pair production)



SUSY Particles

Supersymmetric particles may have striking signatures due to cascade decays to final states with leptons, jets and missing energy.

Shown here is a $\tilde{q}\tilde{q}$ event:

$\tilde{q} \to \tilde{\chi}_2^0\, q$

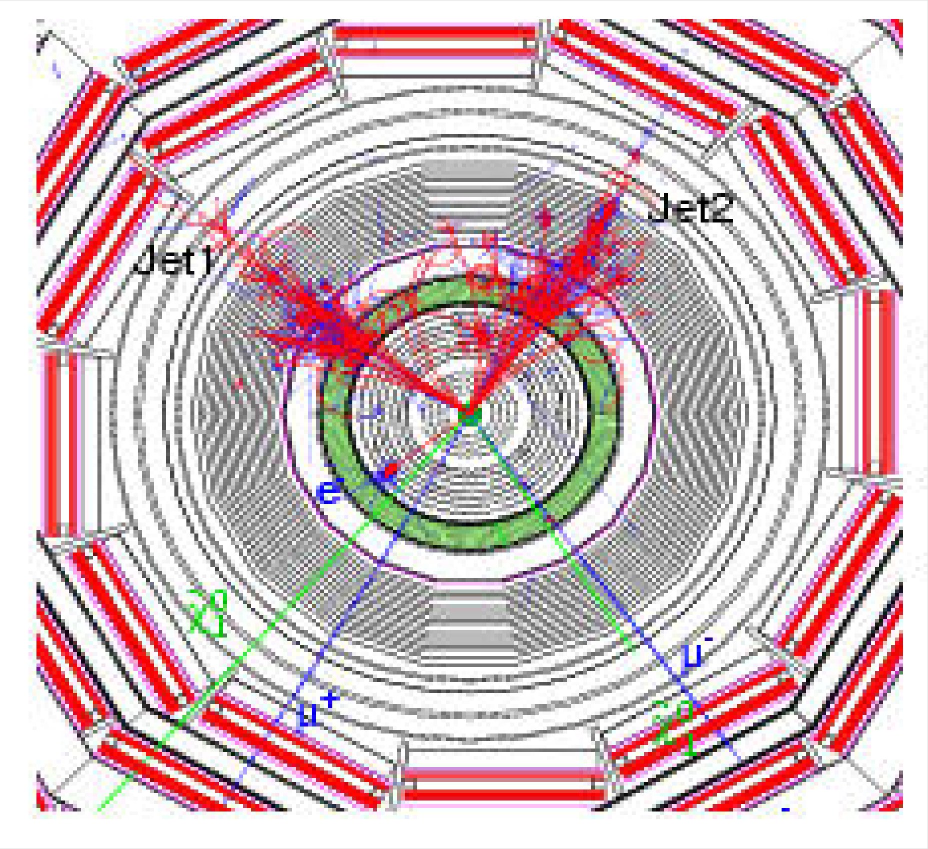
$\quad\hookrightarrow \tilde{\mu}\, \mu$

$\qquad\hookrightarrow \tilde{\chi}_1^0\, \mu$

$\tilde{q} \to \tilde{\chi}_1^{\pm}\, q$

$\quad\hookrightarrow \tilde{e}\, \nu$

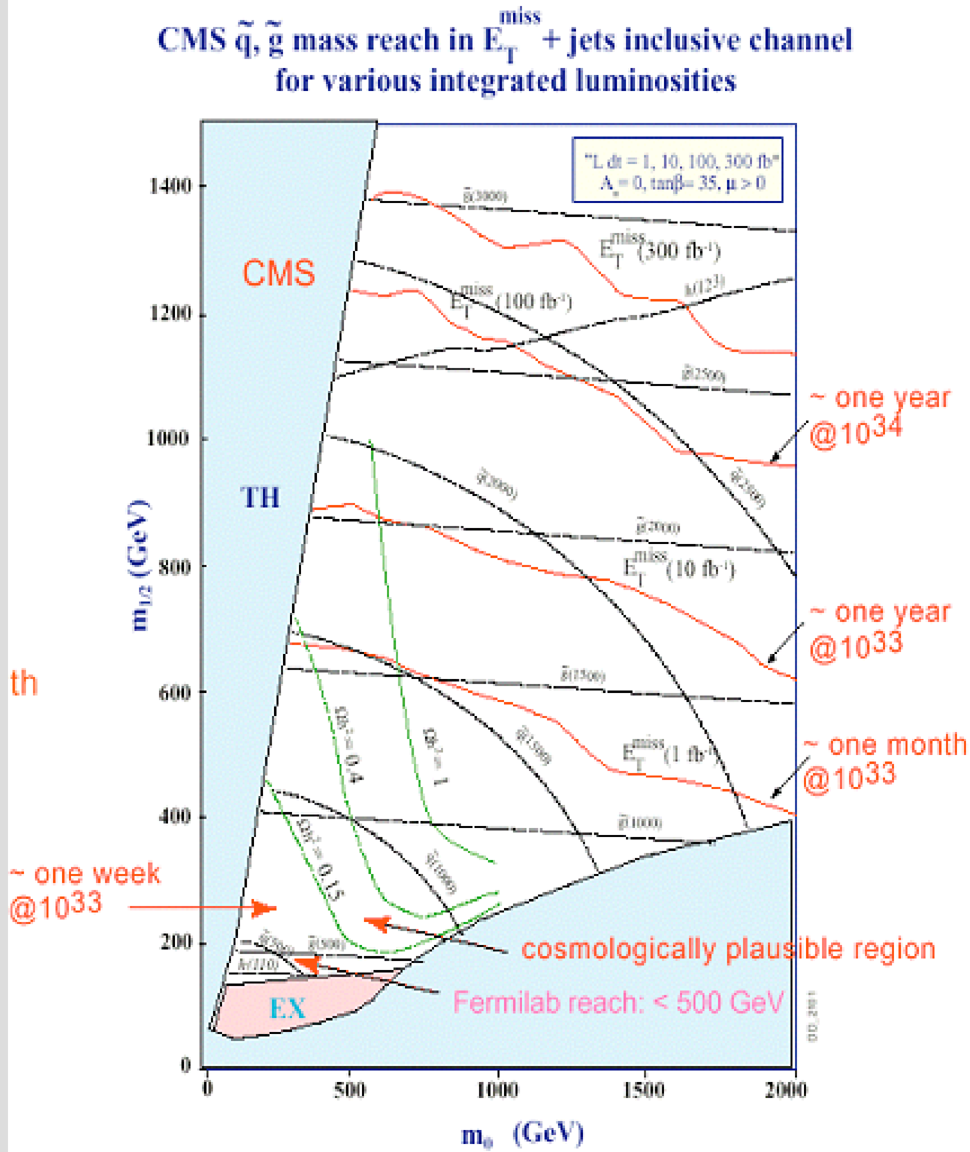
$\qquad\hookrightarrow \tilde{\chi}_1^0\, e$



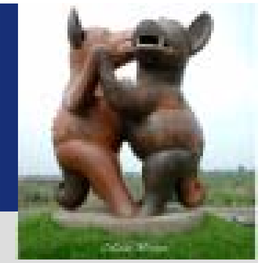
Squarks and Gluinos

The figure shows the $\tilde{q}$, $\tilde{g}$ mass reach for various luminosities in the inclusive E_T^{miss} + jets channel.

- SUSY could be discovered in one good month of operation …



Gluino reconstruction



$pp \rightarrow \tilde{g} \rightarrow b\tilde{b}$ (26 %)

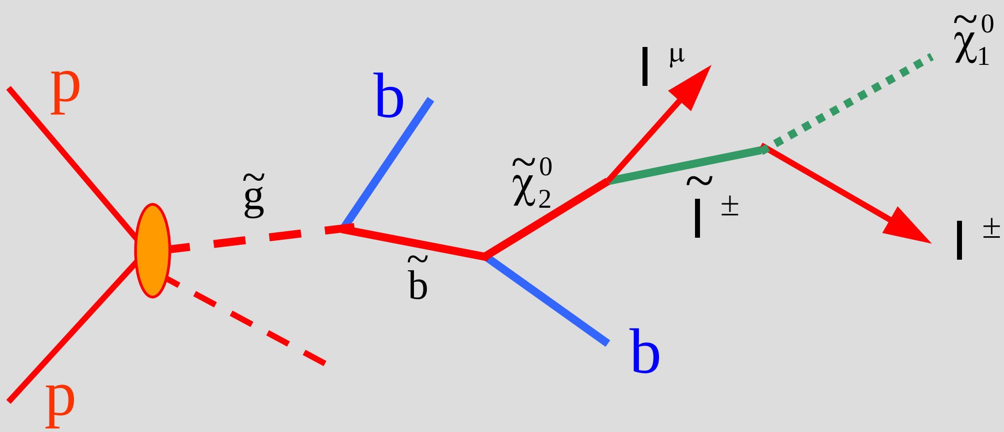
$\rightarrow \tilde{\chi}_2^0 b$ (35 %)

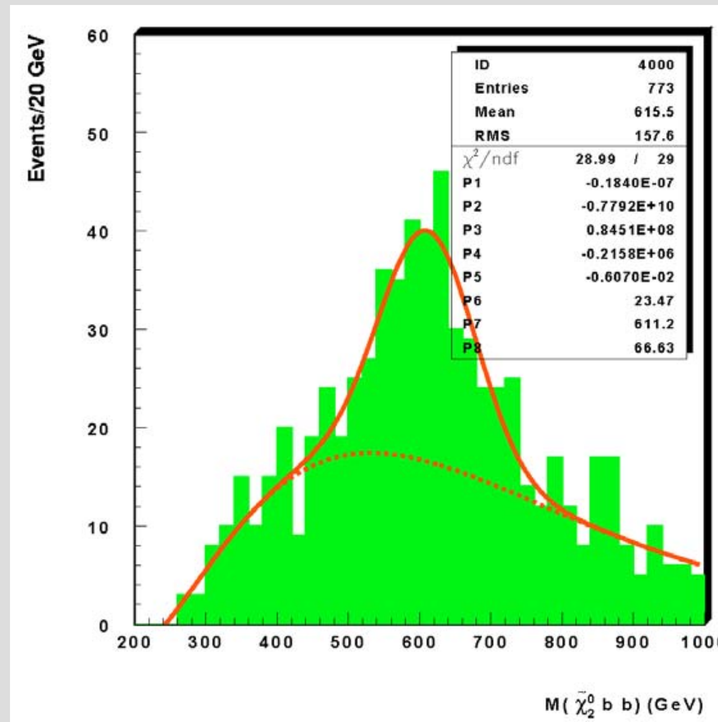
$\rightarrow \tilde{\chi}_1^0 l^+ l^-$ (0.2 %)

$\rightarrow \tilde{l}^{\pm} l^{\mu} \rightarrow \tilde{\chi}_1^0 l^+ l^-$ (60 %)

Event final state:

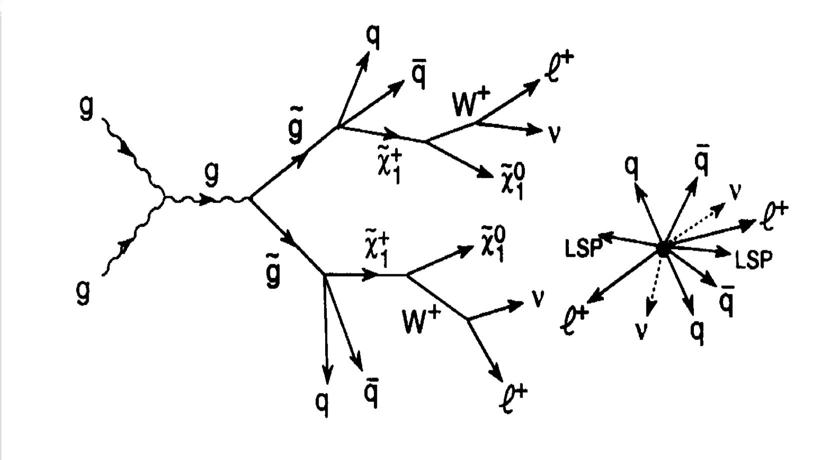
- **≥ 2 high p_t isolated leptons OS**
- **≥ 2 high p_t b jets**
- **missing E_t**

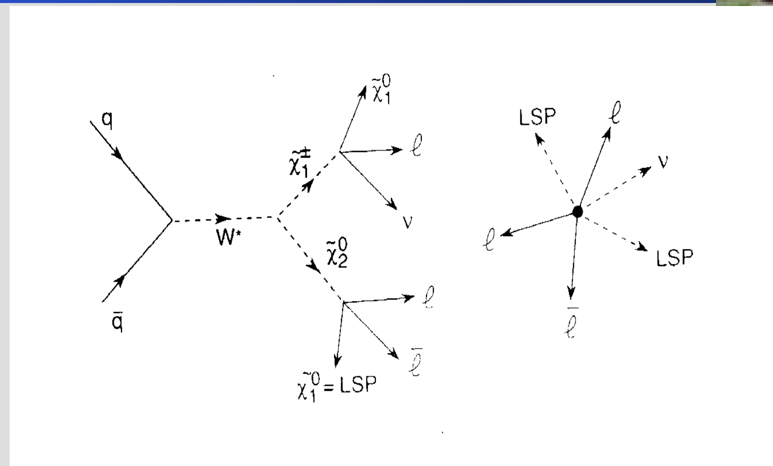




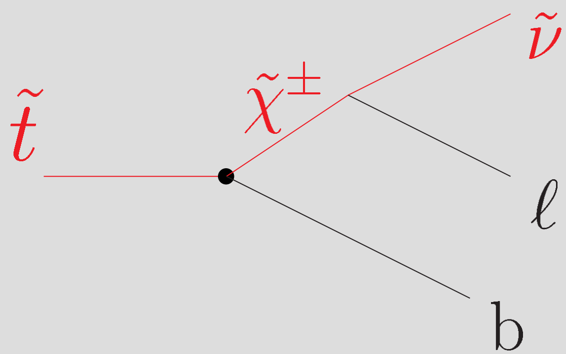
M. Chiorboli

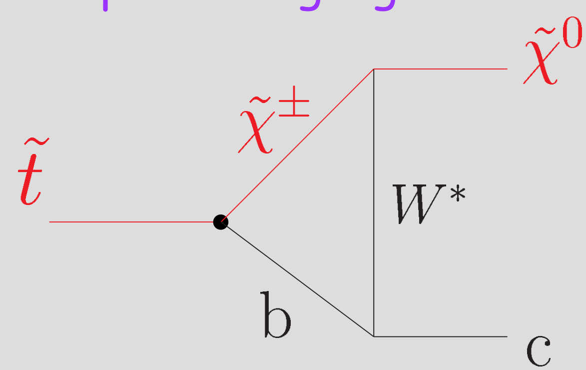
Charginos, Neutralinos, Sleptons





gluino pair production w/ cascade to like sign di-leptons or gauginos to tri-leptons

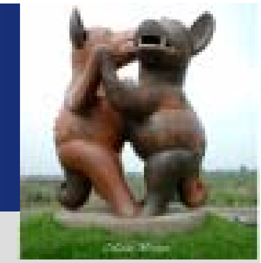




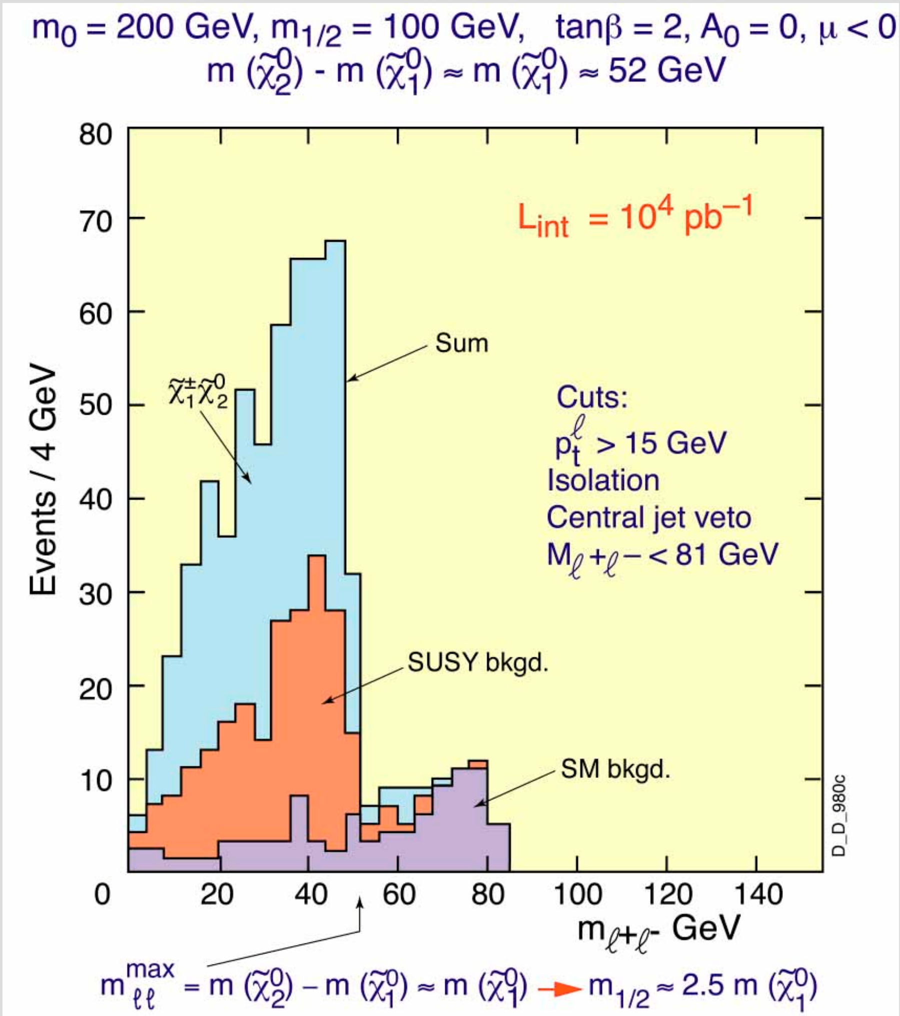
$\Rightarrow c\bar{c}\not{E}_T$

stop pair production to top-like decays with bottom or cascades to charm

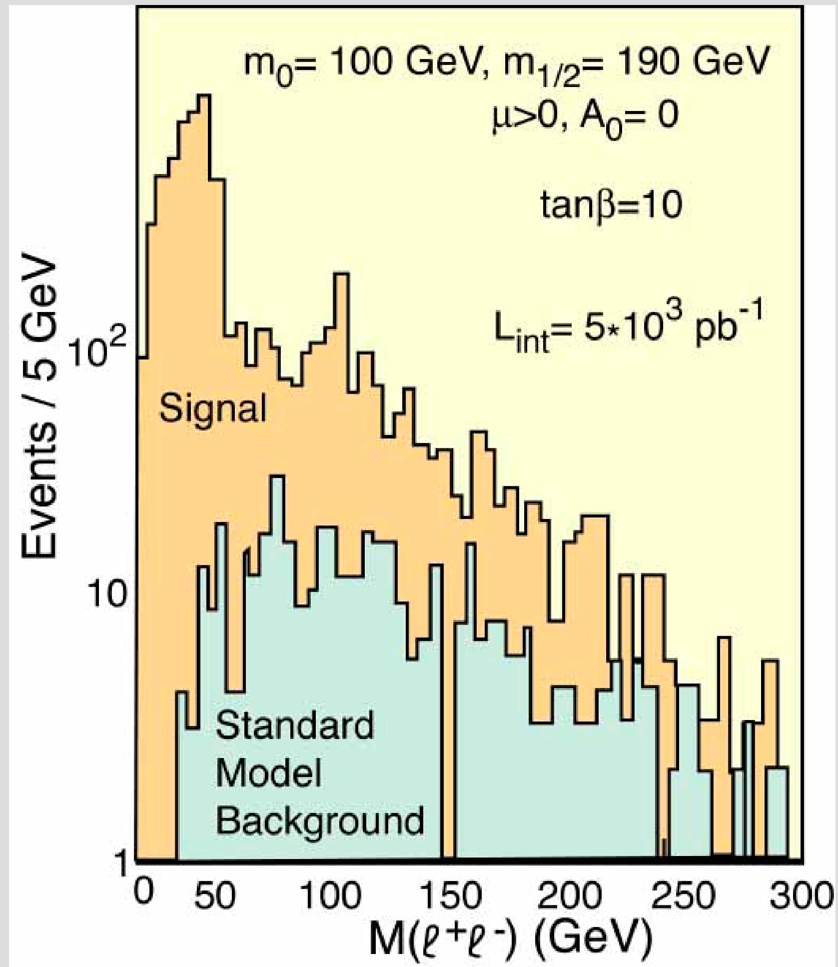
Neutralino and Slepton Mass Determination



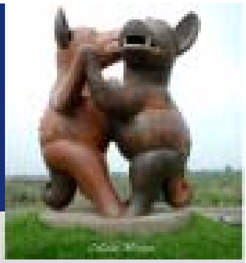
Final state with: 3l, no jets, E_T^{miss}



L. Rurua



Gauge Mediated SUSY Breaking



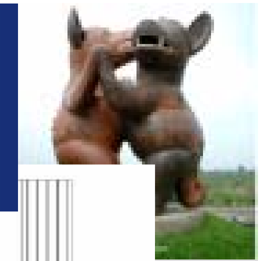
LSP = Gravitino ($\tilde{G}$) **NLSP = neutralino ($\tilde{N}_1$) or stau ($\tilde{\tau}$)**

- **Long-lived $\tilde{\tau}$ looks like heavy (nonrelativistic) muon**
- **Neutralinos decaying far from interaction point give non-pointing γ's**

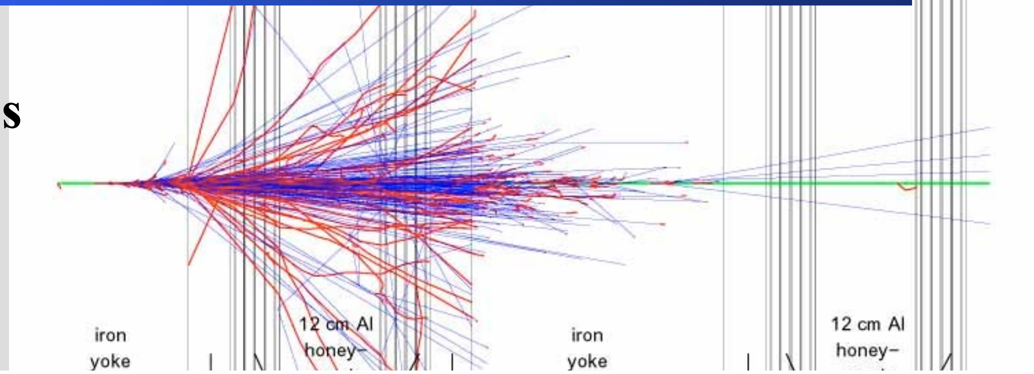
Experimental possibilities

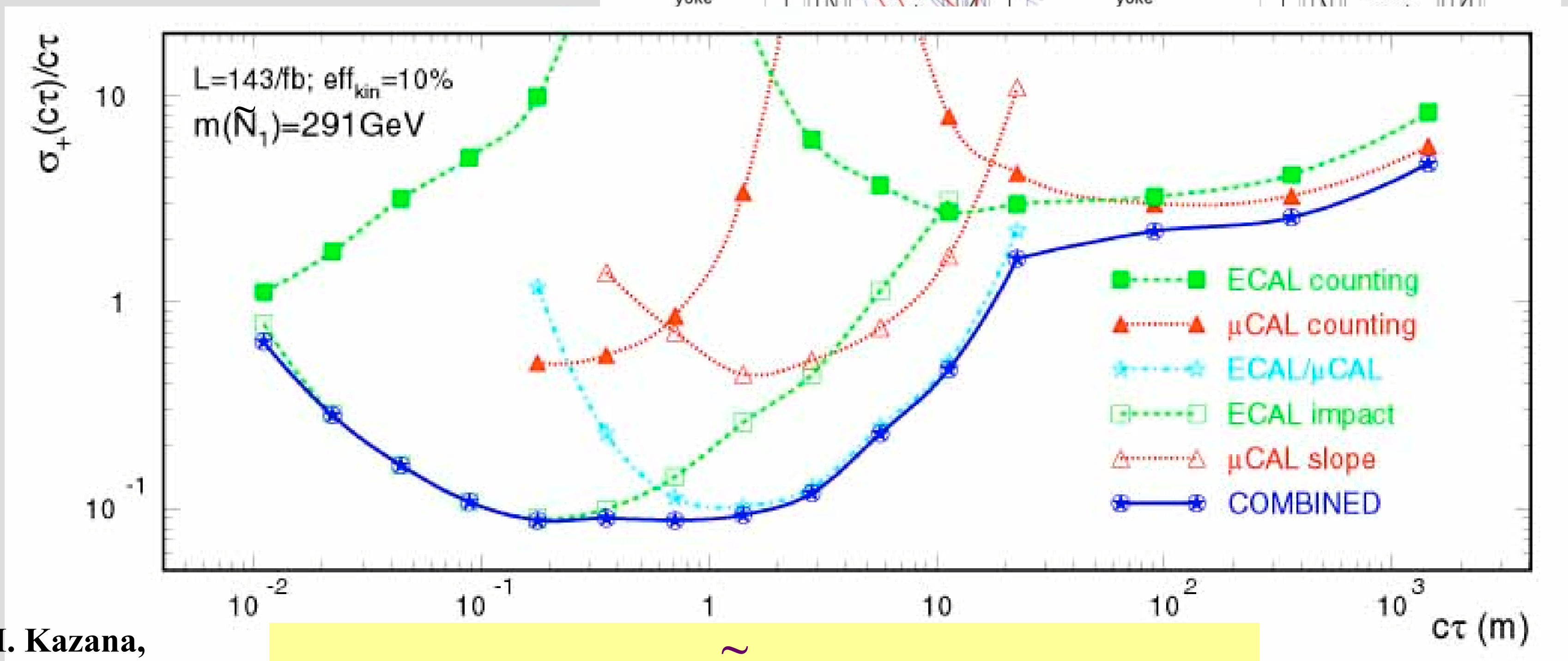
NLSP	short lived	decaying	long lived
$\tilde{N}_1 \rightarrow \tilde{G}\gamma$	like MSSM +2γ	cτ measurement by • ECAL counting • μCAL counting • ECAL/μCAL ratio • ECAL impact par. • μCAL slope	like MSSM
$\tilde{\tau}_1 \rightarrow \tilde{G}\tau$	like MSSM +2τ	both cτ and mass measurement	mass measurement by TOF method

Neutralino life time measurement



If the $\tilde{N}_1 \to \tilde{G}\gamma$ decay happens inside the muon system, the photon will develop an electromagnetic shower.

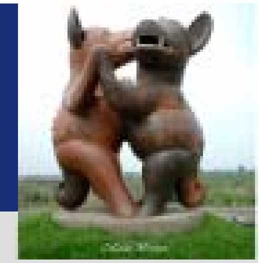




M. Kazana,
G. Wrochna,
P. Zalewski

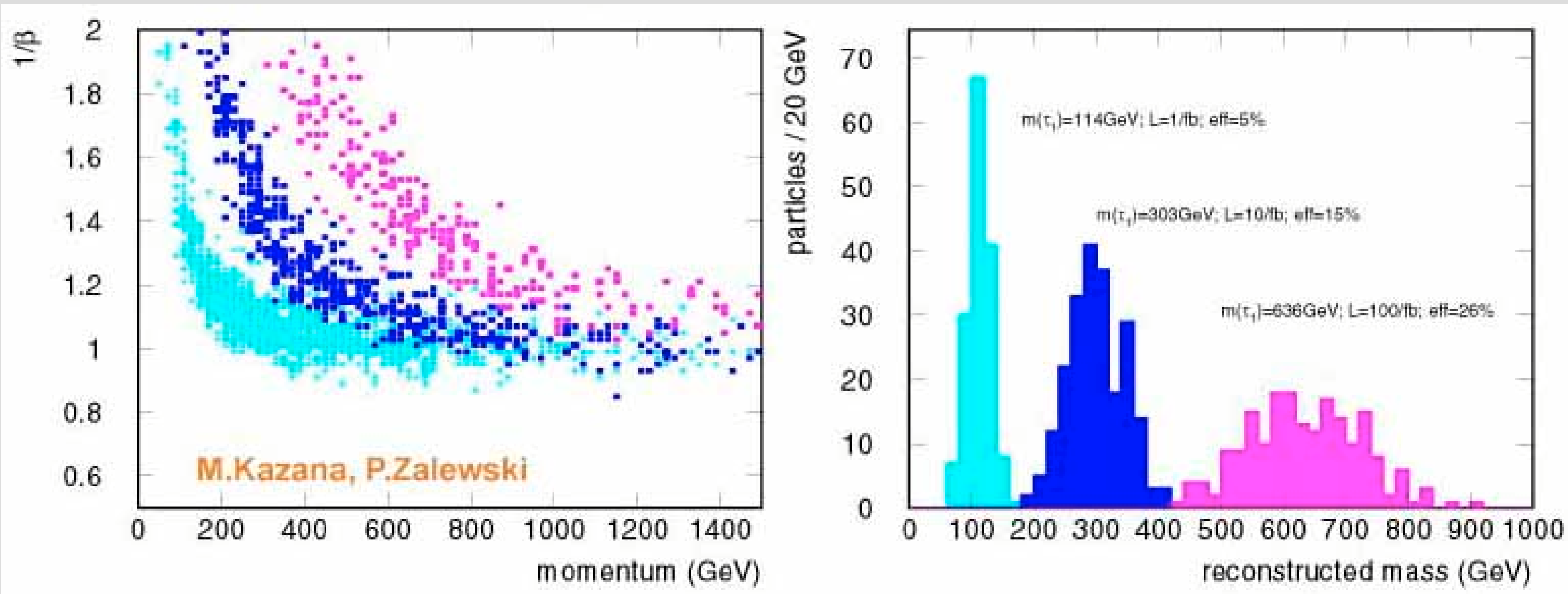
CMS can measure $\tilde{N}_1$ $c\tau$ from 1 cm to 1 km for scenarios with σ_{SUSY} > 100 fb

Mass measurement of long-lived staus



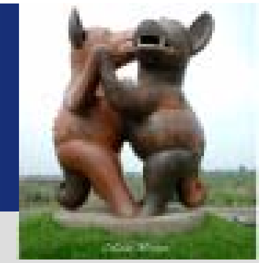
Method: TOF in Muon Barrel Drift Tubes -> $1/\beta$ -> mass

GMSB scenarios: **n=3 (gaugino masses are related to sfermion masses via $\sqrt{n}$), $M/\Lambda = 200$ (Λ…effective scale of MSSM SUSY breaking, M…messenger mass), $\tan\beta = 45$, σ_{SUSY} = 1fb … 1pb, $\tilde{q},\tilde{g}$ masses (1..4) TeV, $\tilde{\tau}$ mass (90…700) GeV**



CMS can measure $\tilde{\tau}$ mass from 90 to 700 GeV with $L = 100\ fb^{-1}$.
Upper limit corresponds to σ_{SUSY} = 1 fb and $\tilde{q},\tilde{g}$ masses of ~ 4 TeV.

Summary



- The Standard Model Higgs can be discovered over the entire expected mass range up to about 1 TeV with 100 fb^{-1}.
  - Below 200 GeV mass can be explored with several channels.
  - Below 130 will be the most challenging.

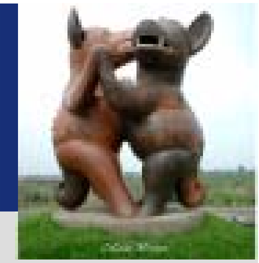
- Most of the MSSM Higgs boson parameter space can be explored with 100 fb^{-1}, all of it can be covered with 300 fb^{-1}.

- The mass reach for squarks and gluinos is in excess of 2 to 2.5 TeV

- (m_0 < 2 to 3 TeV, $m_{1/2}$ < 1 TeV) for all tanβ within mSUGRA. Sleptons can be detected up to 400 GeV mass in direct searches. $\tilde{\chi}_1^0$ can be found up to 600 GeV mass.

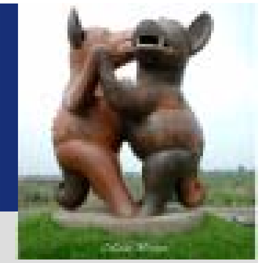
- GMSB scenarios have been studied. Neutralino lifetime and long-lived susy tau mass measurements can be performed.

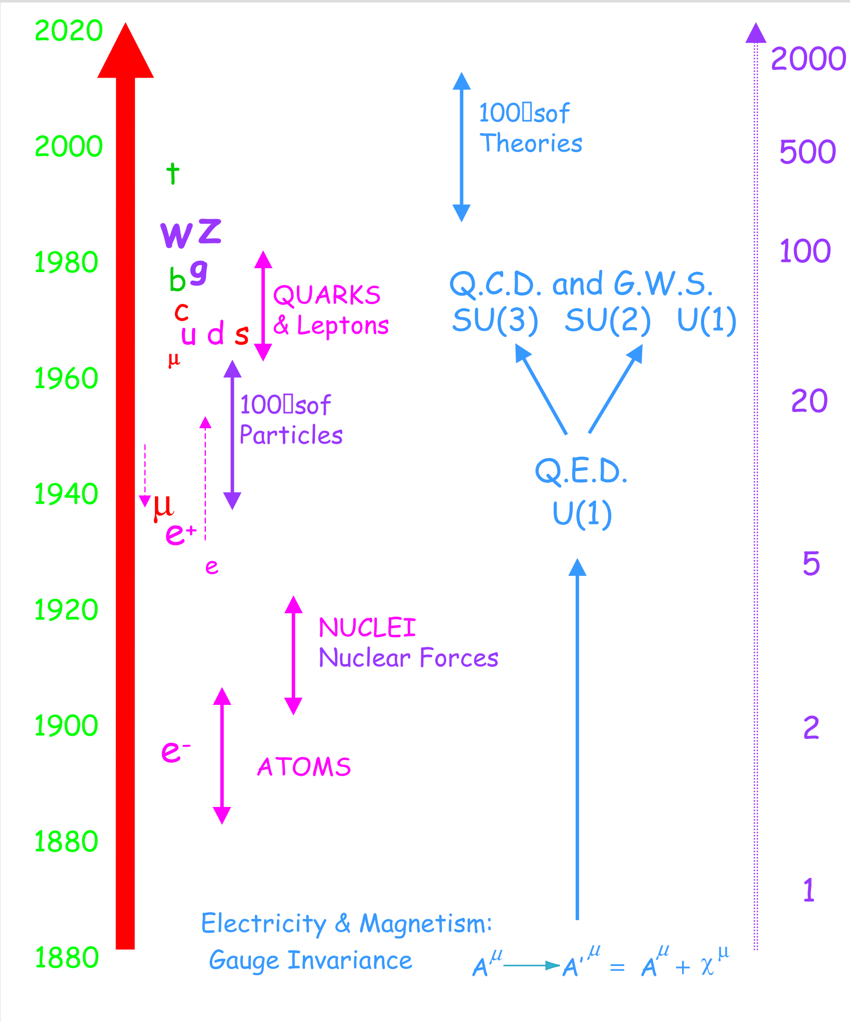
Summary



- If Electroweak symmetry breaking proceeds via new strong interactions many resonances and new exotic particles will certainly be seen
- New gauge bosons with masses less than a few TeV can be discovered
- Signals for extra dimensions could be revealed if the relevant scale is in the TeV range
  - If the true planck scale is ~ 1 TeV, we may create black holes and observe them evaporate by Hawking radiation

History of particle physics

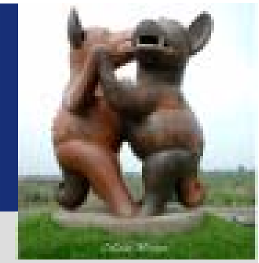




- Parallel experimental and theoretical developments
  - Discovery of several layers of fundamental particles
  - Realization of the importance of Gauge symmetries
  - And some accidental symmetries…

- Where are we now ?

Supersymmetric Higgs



- Minimal Case of 2 doublets:
  - $\tan\beta = v_2/v_1$ and $v_1^2 + v_2^2 = v^2$
  - After W,Z masses, 5 remaining d.o.f.
    - **5 physical higgs bosons h_o, H_o, A_o, $H^{\pm}$**
    - Scalar potential has one free parameter
      - masses are expressed in terms of

        m_A and $\tan\beta$
  - Large radiative corrections (at one-loop)

    $M_h^2 < M_Z^2 + (3G_F/(2^{1/2}\pi^2))\ M_t^4 \ln(1+m^2/M_t^2)$

    $M_h < 130$ GeV

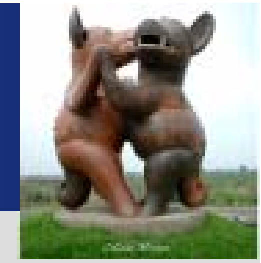
    < 150 GeV

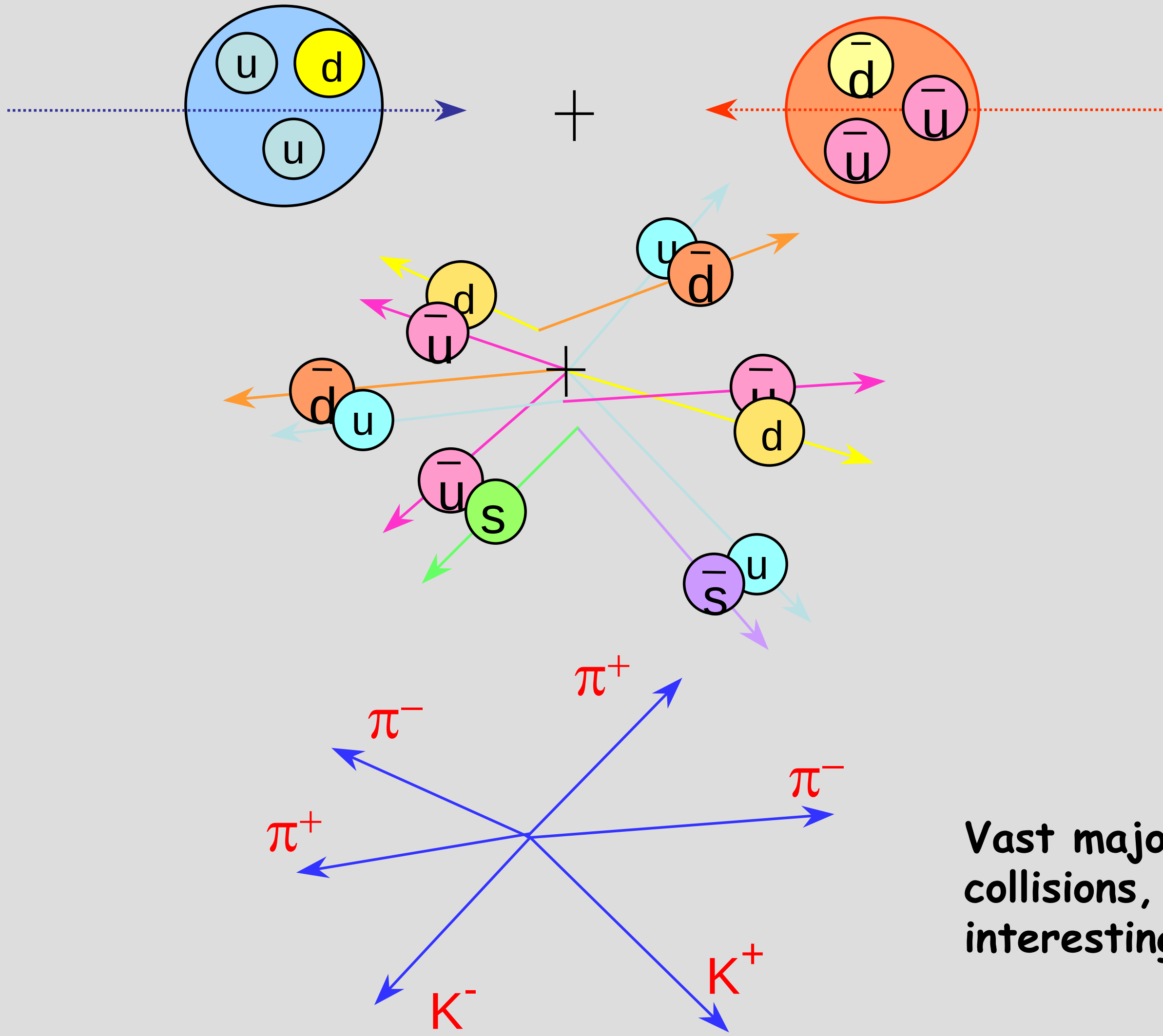
    » **(if there are Higgs singlet(s) in addition to the two doublets)**
  - Some Important features
    - Couplings to W,Z now shared

      $g_{h_oVV}^2 + g_{H_oVV}^2 = g_{HVV}^2$ (SM)

•Fermion couplings also (S.Dawson hep-ph/9411325)

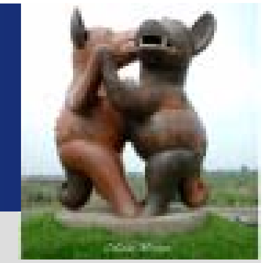
“Minimum Bias” Events

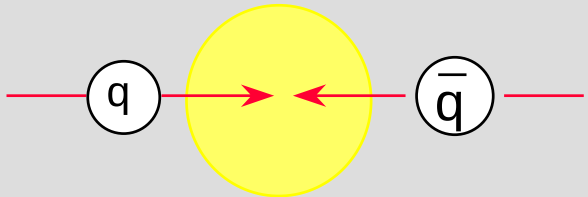




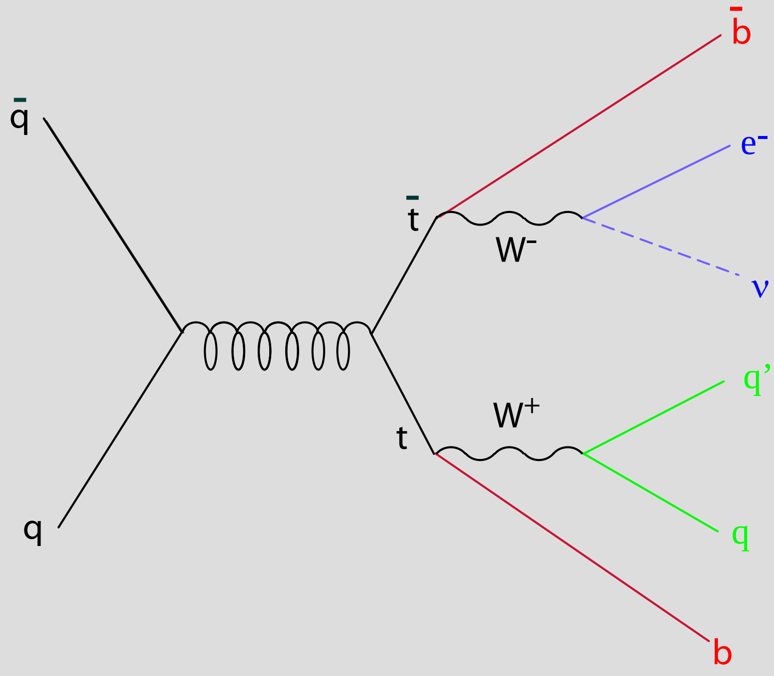
Vast majority of collisions, but not interesting…

Rare Collisions

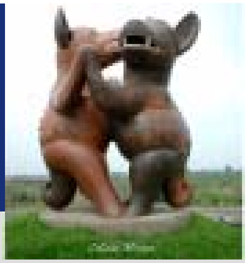




Quark-Antiquark Annihilation



Example: top quark pair production

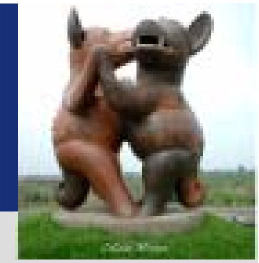


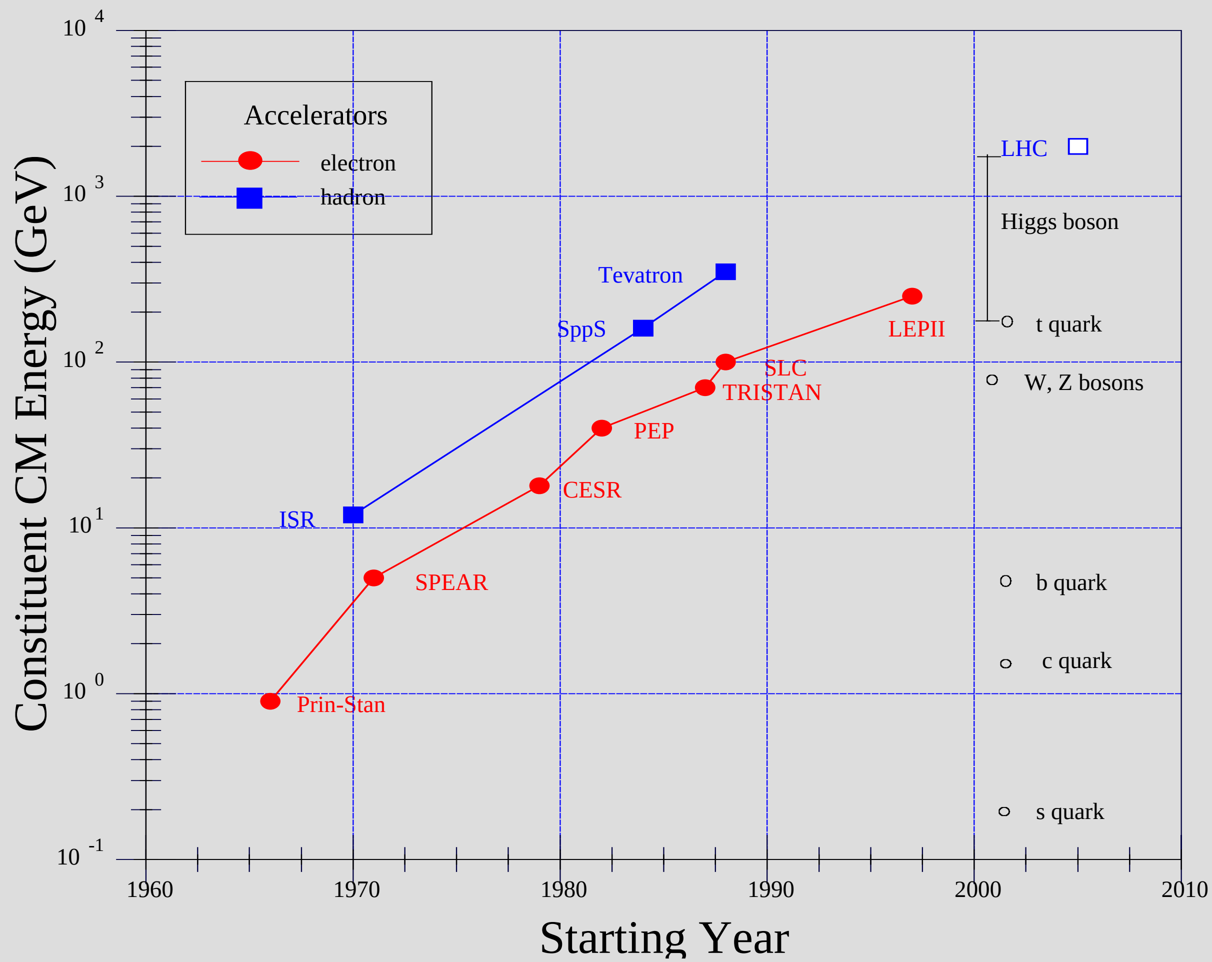
What's Next ?

- Hadron Colliders have 2 main discovery goals.
  - Find the Higgs
  - Find direct evidence of something beyond the standard Model
    - e.g. SUSY partners, Large extra dimensions, Mini-black holes
    - More likely something not yet thought up
    - Possibly even nothing!

- And there's much to be learned about the Standard Model !
  - Precision electroweak measurements
    - Mw, Mtop , $\alpha_s(Q^2)$
  - B Physics
    - CKM and CP Violation
    - Bs mixing

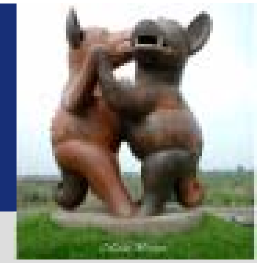
Why Collide Hadrons ?

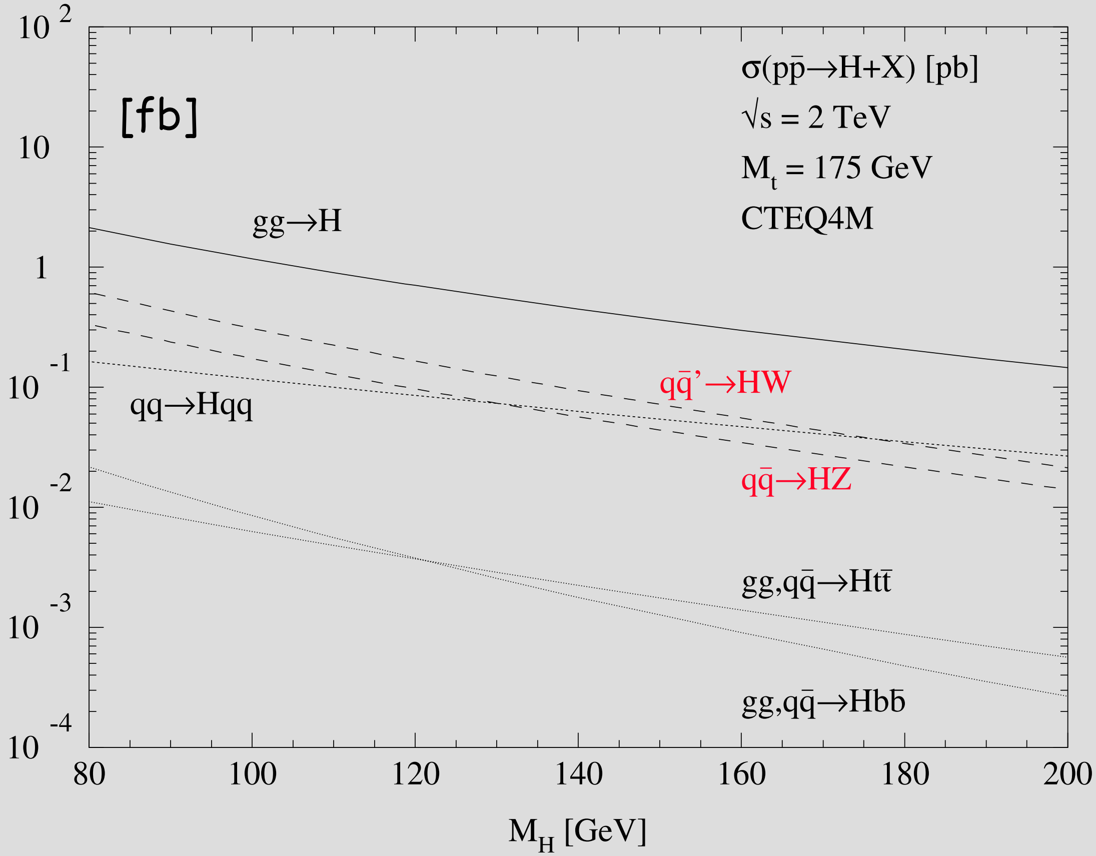




Hadron colliders are great discovery machines

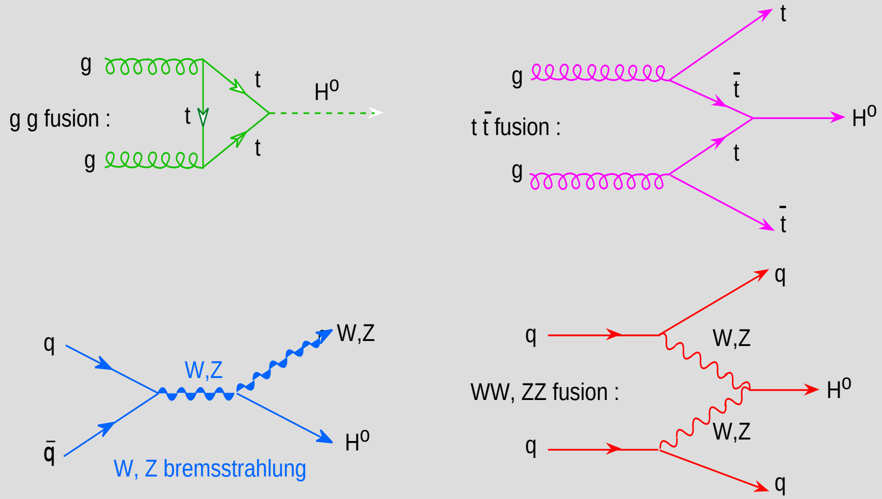
Tevatron: SM Higgs Production

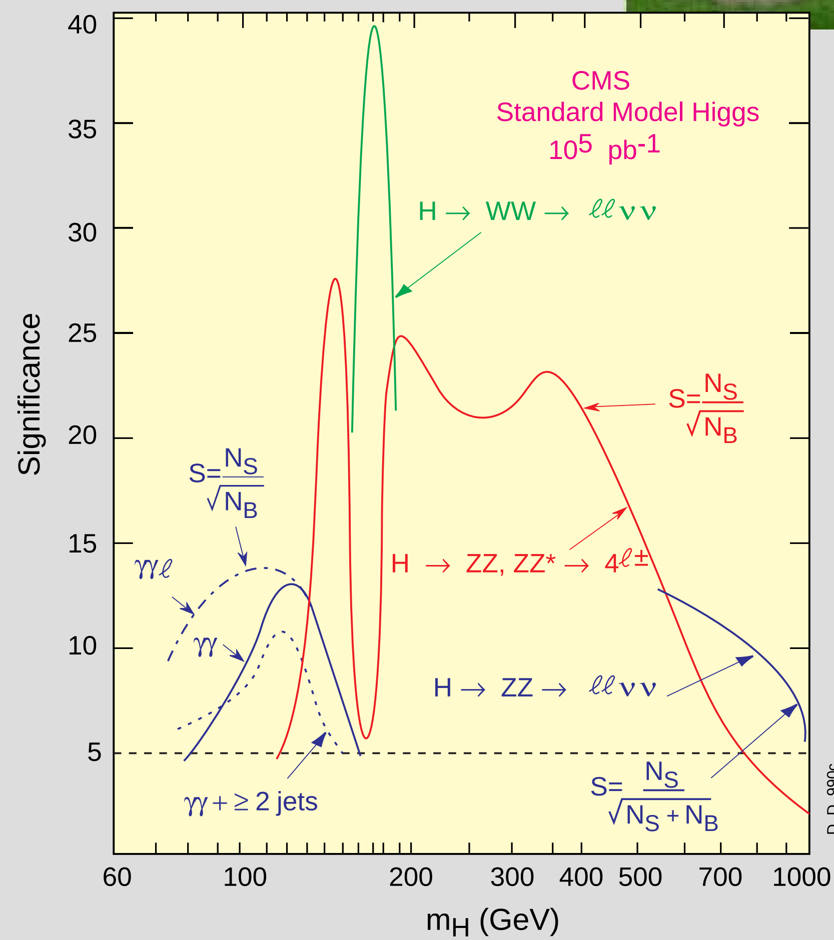




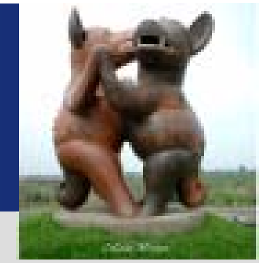
- gg→ H dominates but swamped by dijets
- qq′ → HV factor 5-10 lower but backgrounds are more rare (tt,Wbb,Zbb,WZ)

Higgs @ CERN's Large Hadron Collider (LHC)

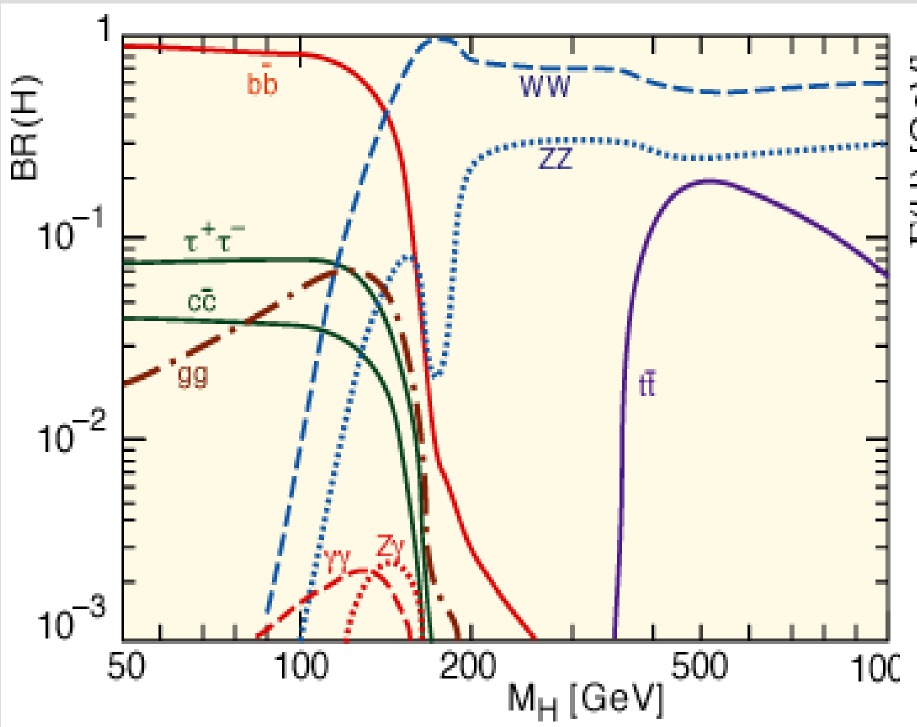


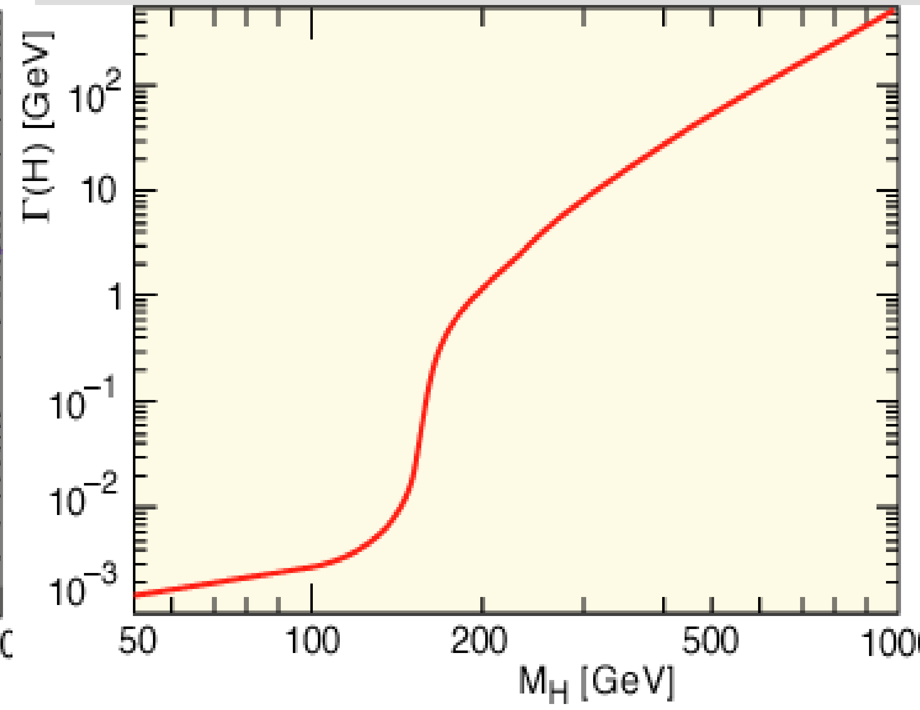


- SM Higgs Search strategies
  - $H \to b\bar{b}$ $90 \leq m_H \leq 120$ GeV/c^2
  - $H \to \gamma\gamma$ $100 \leq m_H \leq 140$ GeV/c^2
  - $H \to ZZ^* \to 4l^\pm$ $130 \leq m_H \leq 200$ GeV/c^2
  - $H \to WW \to l\nu l\nu$ $140 \leq m_H \leq 200$ GeV/c^2
  - $H \to ZZ \to 4l^\pm$ $200 \leq m_H \leq 750$ GeV/c^2



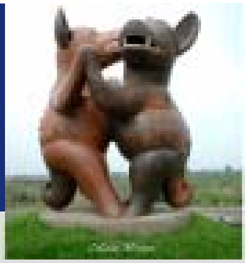
Standard Model Higgs

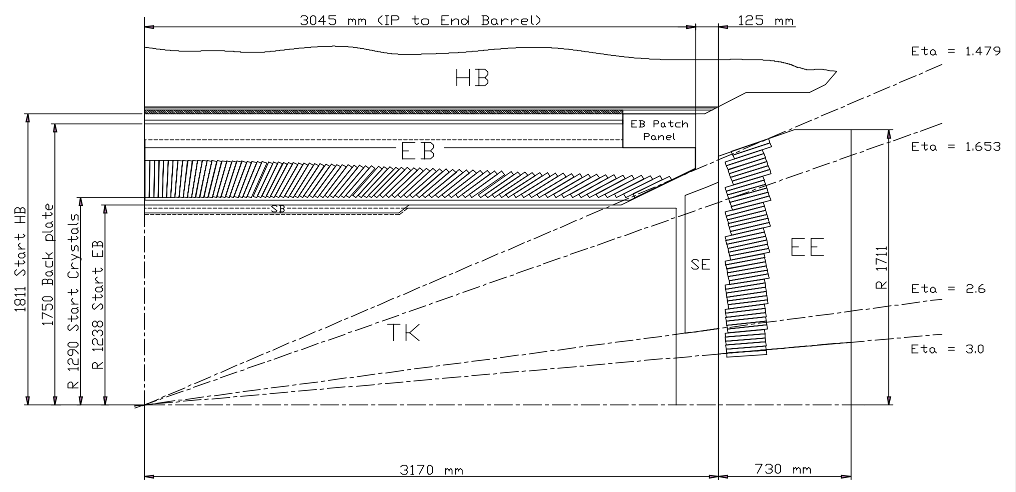




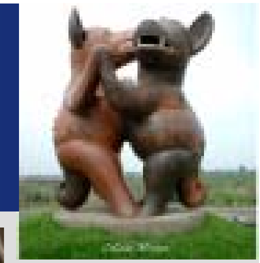
Branching ratios **Total decay width**

CMS EM Calorimeter





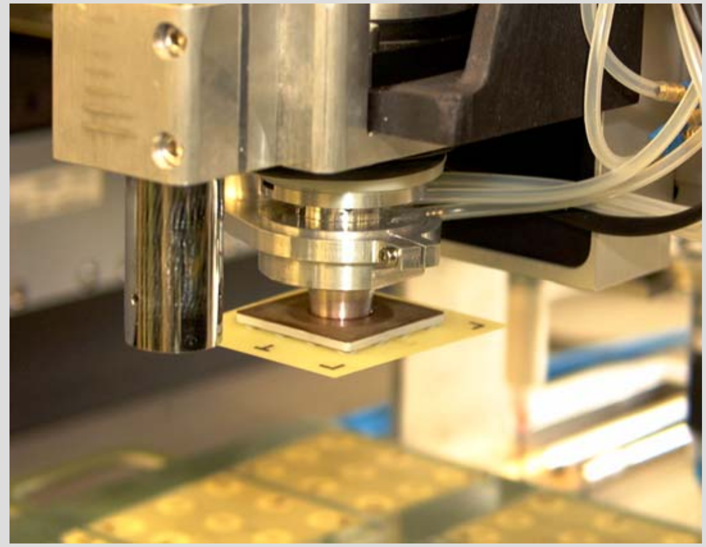
Parameter	Barrel	Endcaps
Pseudorapidity coverage ECAL envelope: r_{inner}, r_{outer} [mm] ECAL envelope: z_{inner} z_{outer} [mm]	$\|\eta\| < 1.48$ 1238, 1750 0, ±3045	$1.48 < \|\eta\| < 3.0$ 316, 1711 ±3170, ±3900
Granularity: $\Delta\eta \times \Delta\phi$ Crystal dimension [mm^3] Depth in X_0	0.0175×0.0175 typical: $21.8 \times 21.8 \times 230$ 25.8	0.0175×0.0175 to 0.05×0.05 $24.7 \times 24.7 \times 220$ 24.7
No. of crystals Total crystal volume [m^3] Total crystal weight [t]	61 200 8.14 67.4	21 528 3.04 25.2
Modularity 1 supermodule/Dee 1 supercrystal unit	36 supermodules 1700 crystals (20 in ϕ, 85 in η) –	4 Dees 5382 crystals 36 crystals

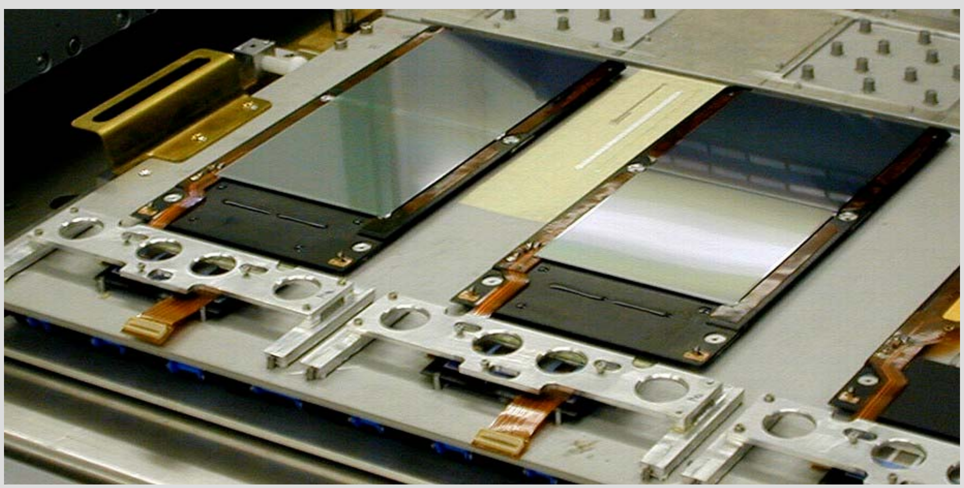


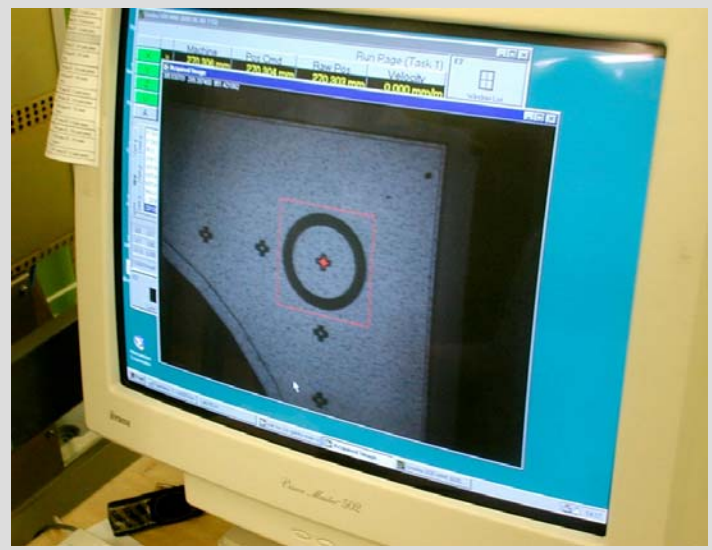
Automation

Special robot - GANTRY - was developed for assembling CMS Silicon tracker components.

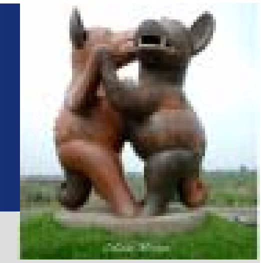
Positioning accuracy ±1.6 μm
Production time 10 min/module

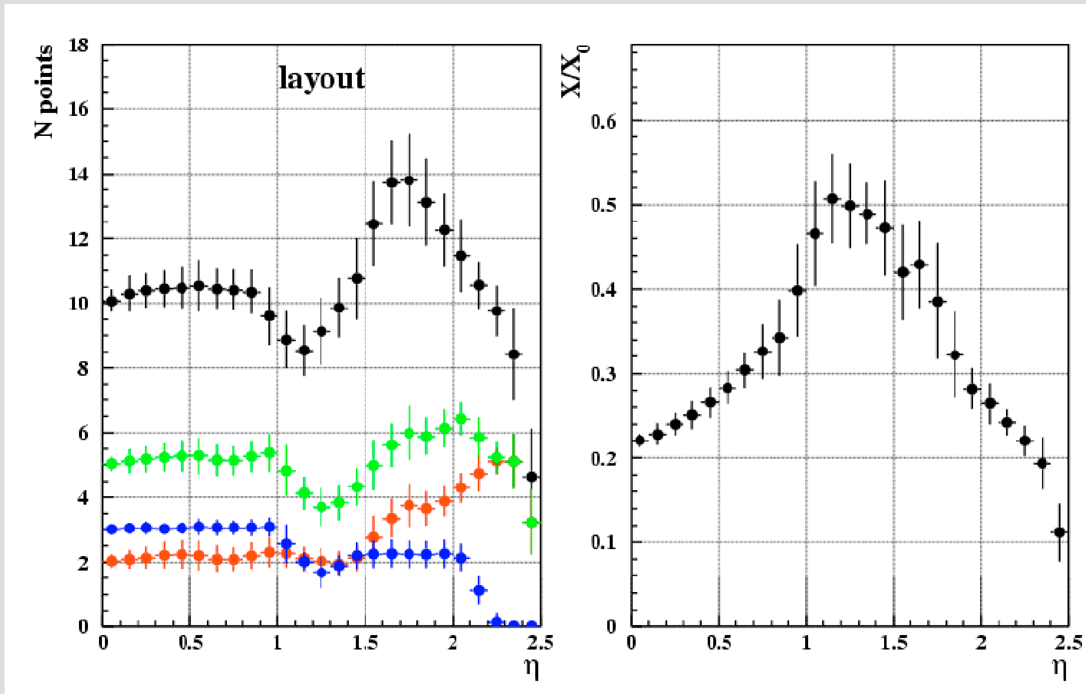






Tracker Coverage & Material

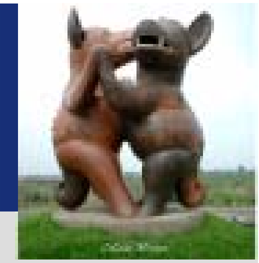


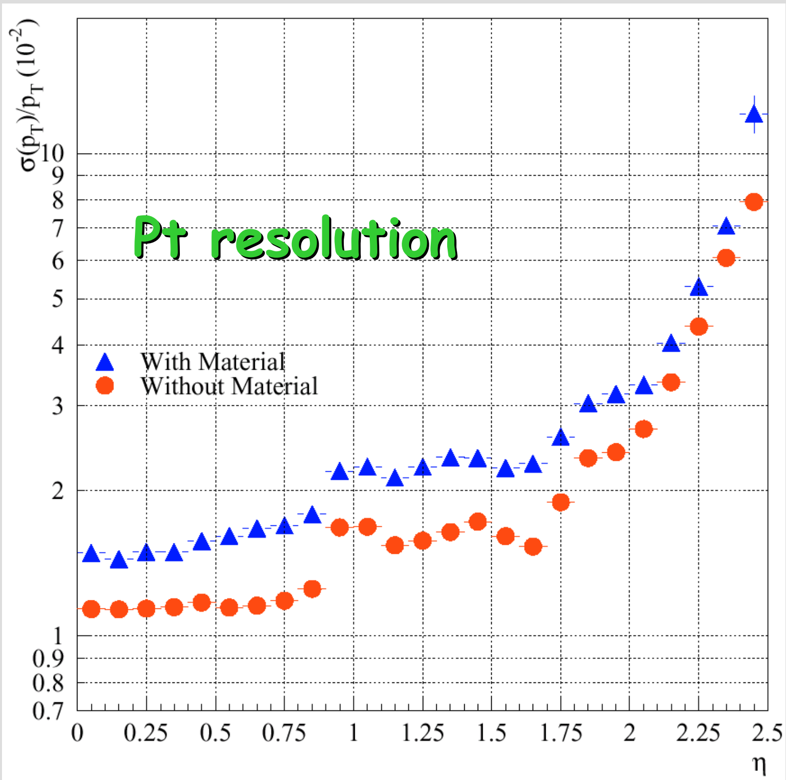


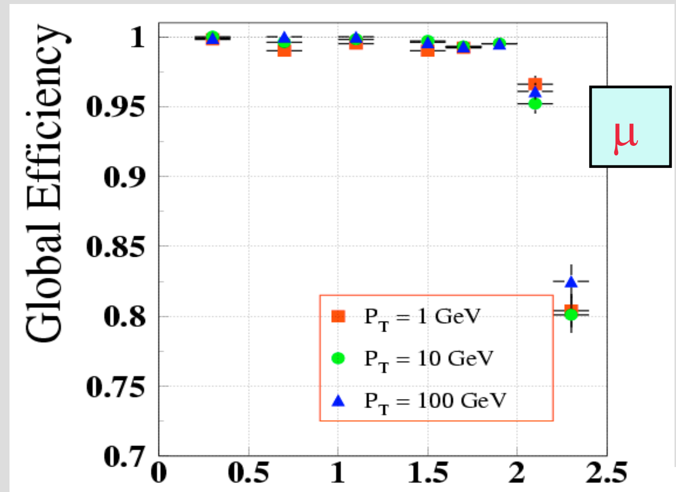
Tracking layers vs. pseudorapidity:

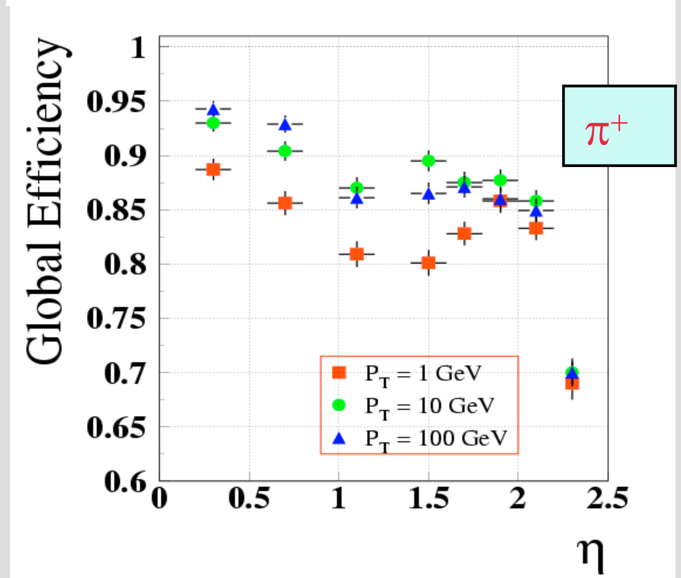
Total, double(axial+stereo), double inner, double outer.

Material Effects



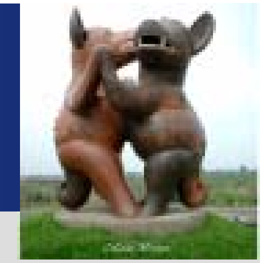




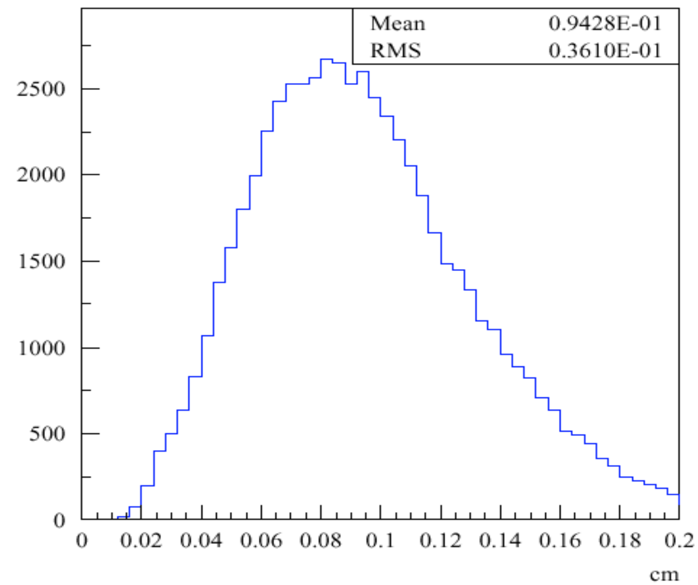


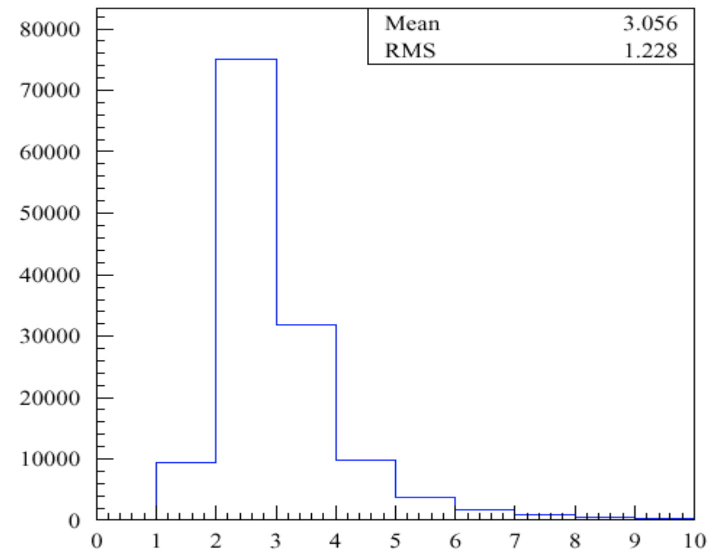
π^+ efficiency lower than μ due to secondary interactions with detector material

Pixels to Strips: worst case



100 GeV b jet without PU

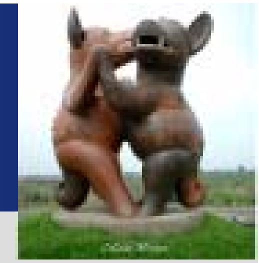




Uncertainty in $r-\varphi$

➽ Long propagation distance!

Number of candidates on BarrelSilicon 1

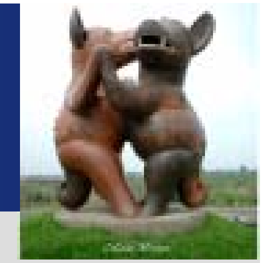


Material

- The LHC Pixel Vertex and Silicon Strip Trackers suffer from significantly more material in their fiducial acceptance than previous detector Trackers due to
  - high power dissipation and associated cooling
  - rigid mechanical supports distributed within the tracking volume

- The material limits efficiency and track parameter resolution
    - This is most evident for electrons, for which a specialized track reconstruction strategy is currently under development
- ECAL resolution for electrons, and converted γ's is also affected

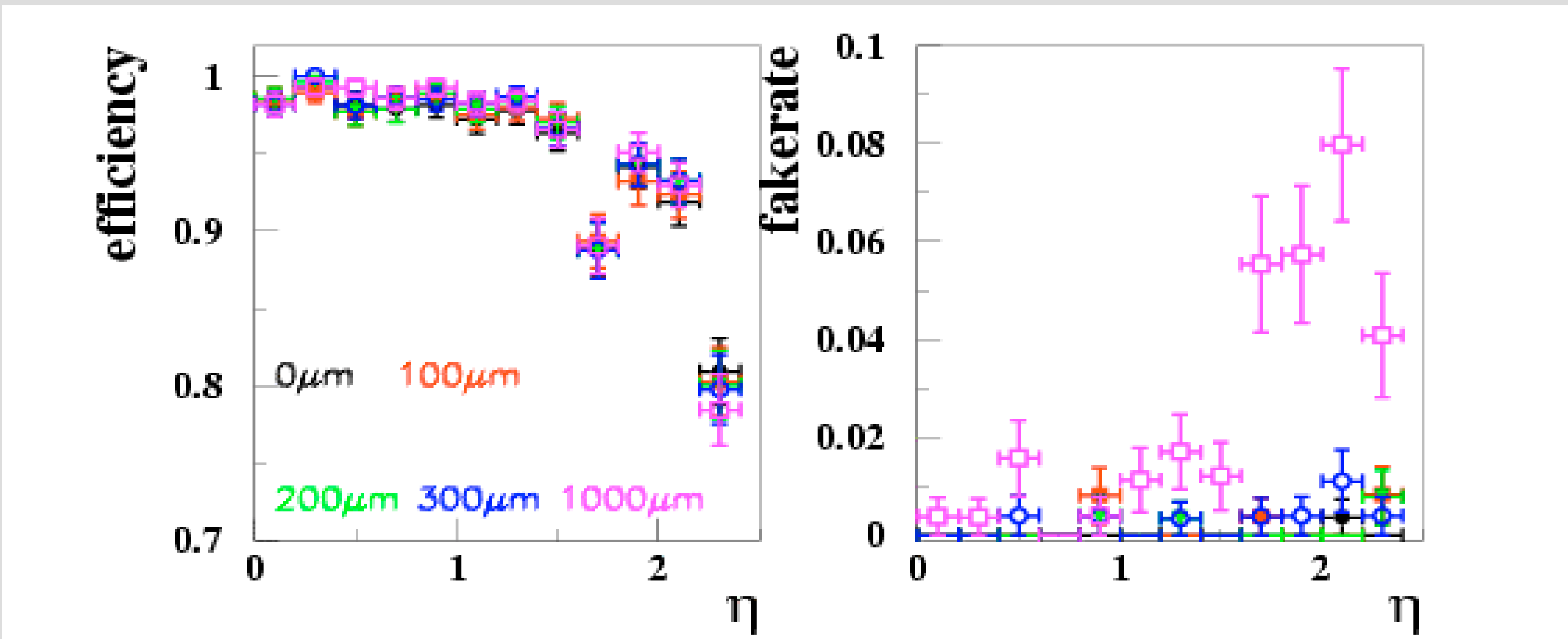
  - Driven by these considerations, a great deal of engineering effort has gone into achieving the current level of material within the tracking volume



Misalignment Effects

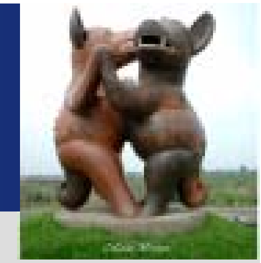
W→μν events with pile-up at 2x10^33

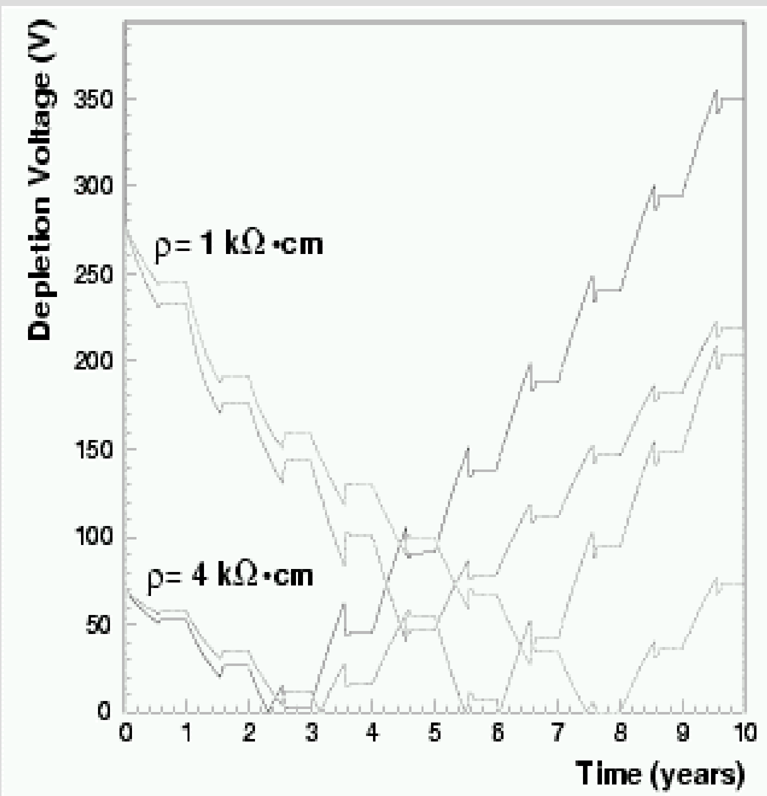
- random movements of rods / wedges: reconstruct tracks with $P_T >$ 20GeV



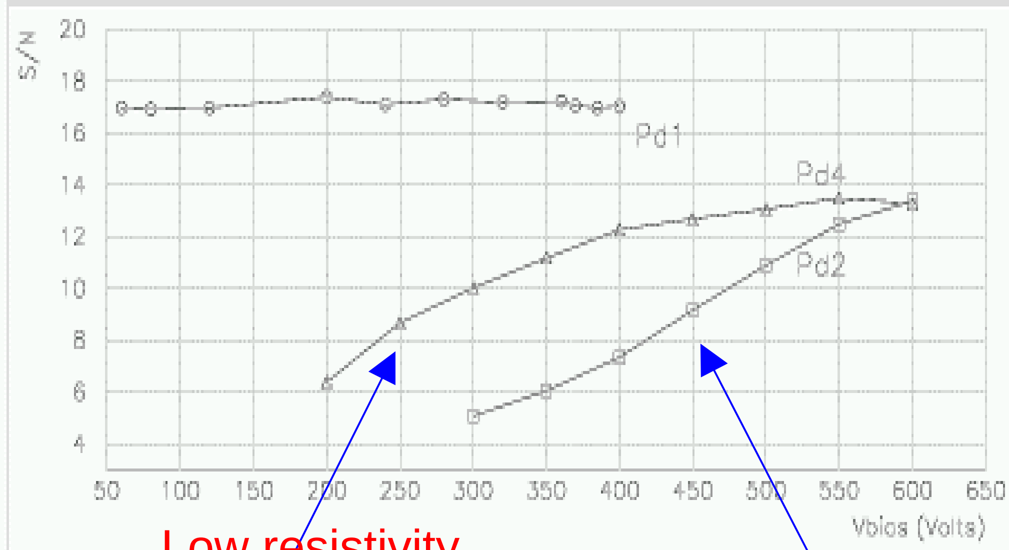
Pattern recognition works even with fairly large misalignments at 2x10^33
(survey/laser alignment accuracy significantly better than 1 mm)

Radiation Hardness





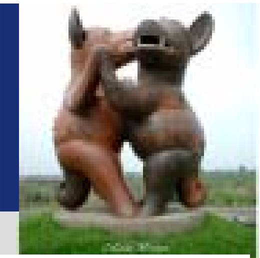
Test beam with detectors irradiated at 2.1×10^{14} n/cm^2



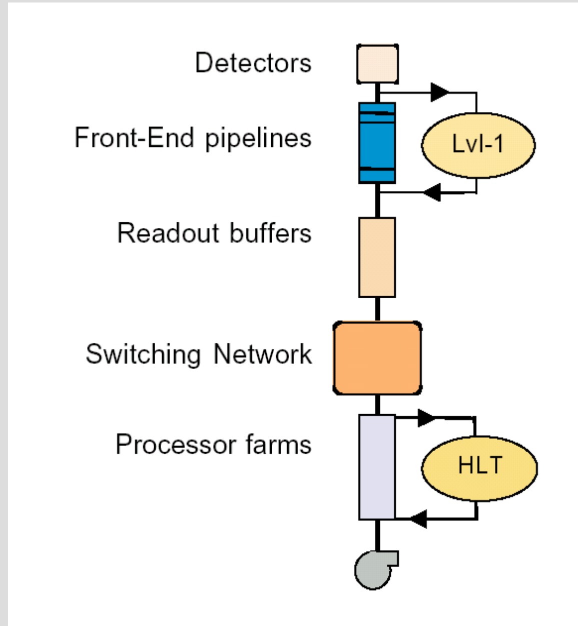
Low resistivity
1.4 kΩ cm

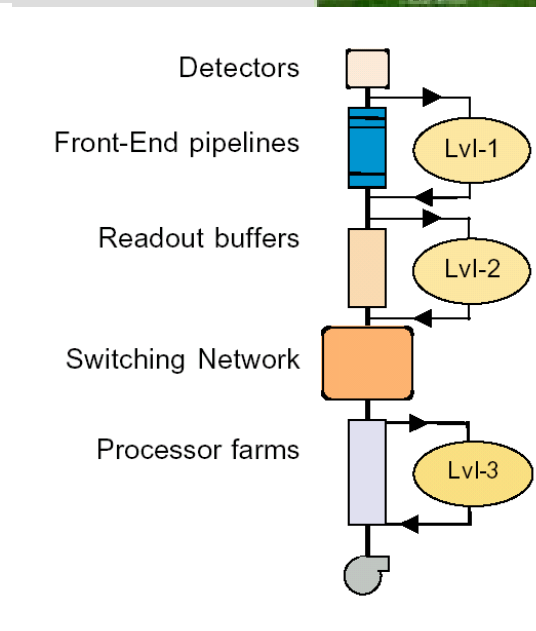
High resistivity
6 kΩ cm

Triggering



- General idea:
  - Benefit from full offline analysis to select events.
- All data available after L1
  - Only need ∞ CPU power
  - What can be done with a reasonable number of commercial CPUs?
    - 100kHz from L1 can be handled by ~5000 CPUs if events can be processed in ~50 ms.
    - Assuming Moore's Law to 2007, this means algorithms must run in ~500 ms *now* on 1 GHz machines



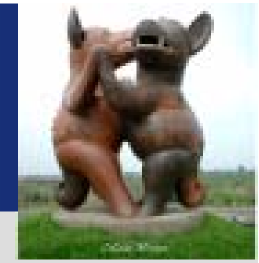


CMS

HLT functionality depends on data rate and CPU resources available

Traditional

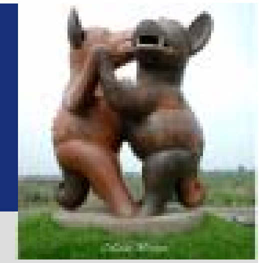
Tracker in High Level Triggers



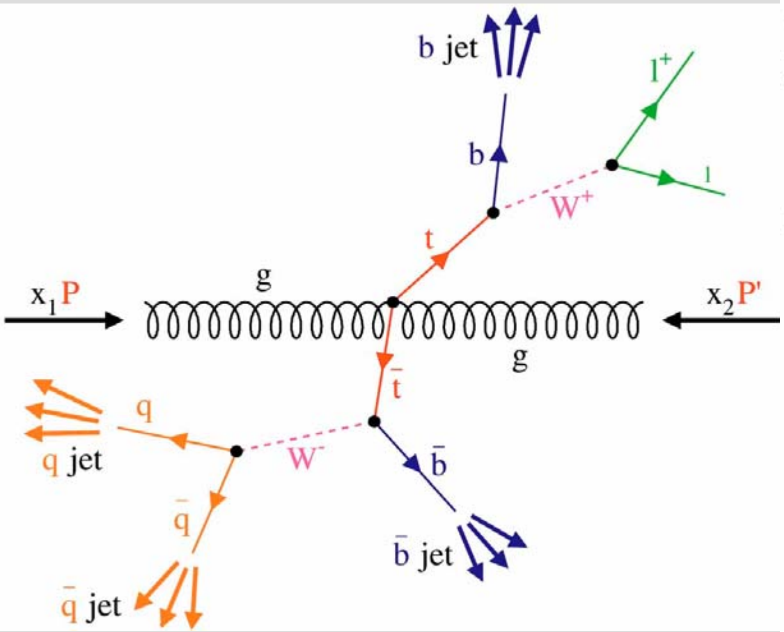
- The Tracker is well suited for
  - Track reconstruction
  - (P,S)Vertex reconstruction
  - Impact parameters etc....
- and hence
  - b-tagging
  - τ-tagging
  - precision measurements (refinements) of jets and momenta

- The Tracker is the most precise subsystem, but is (thought to be) slow
  - not used at all for L1
- Extensive studies have been performed to answer the question:
  - what can we do in ~500 ms?

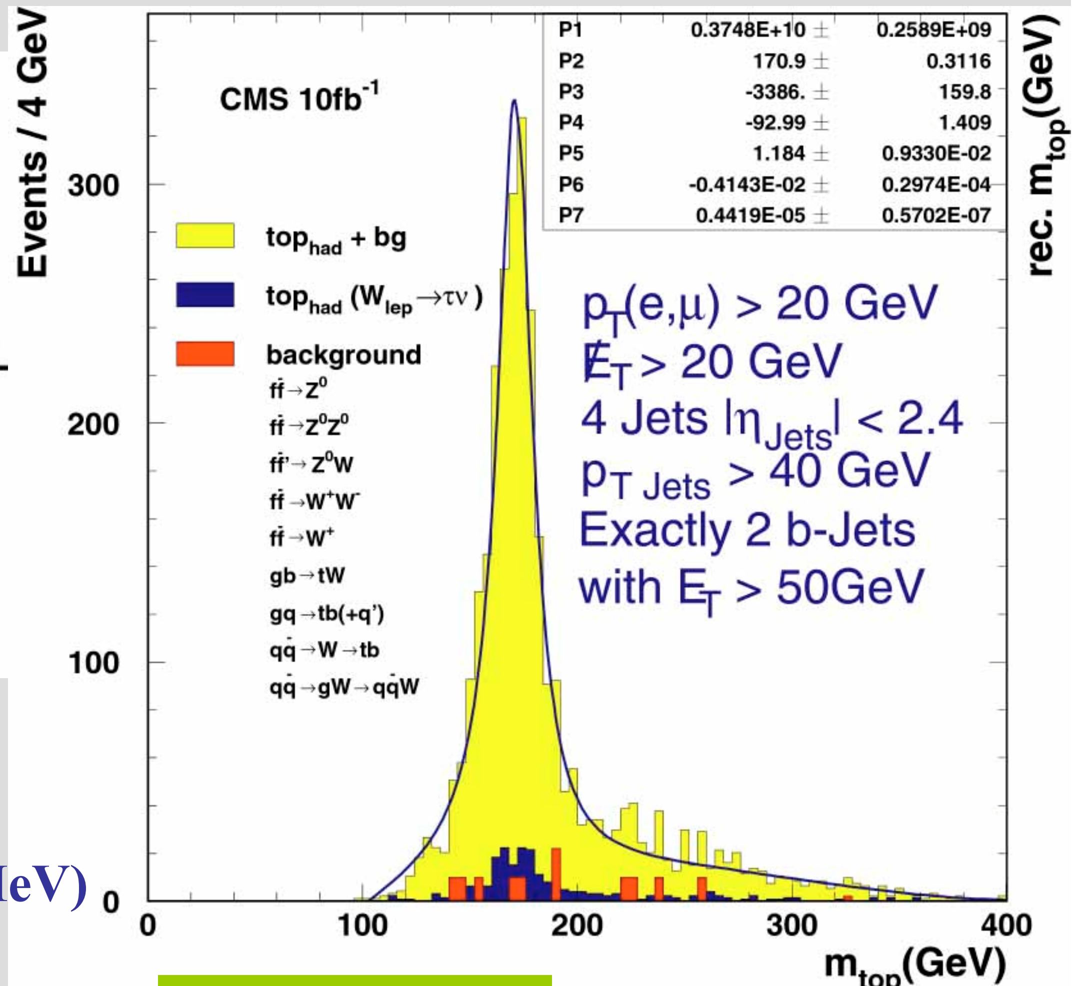
Top quark mass determination



$pp \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to$
$\to$ 2 b-Jets + 2 light quark jets + $l\ \nu_l$



Reconstructed top-mass from bqq̄'

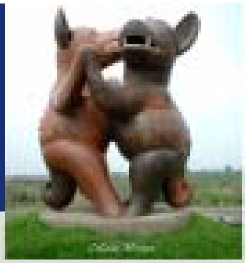


- **No dangerous background**
- **Systematic uncertainty of top p_T-spectrum dominates ($\lesssim$ 400 MeV)**

Expected total error for 10 fb^{-1}: **$\Delta m_t \lesssim$ 900 MeV**

L. Sonnenschein, E. Boos, S. Slabospitsky et al.

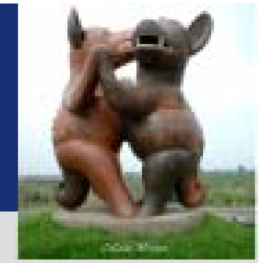
H -> hh



Dominant decay to $b\bar{b}b\bar{b}$. Problem is triggering: need soft muons in jets. Sensitivity for tanβ < 3 and 250 GeV < m_A < 2 m_t.

Easier to trigger is the channel H -> hh -> $b\bar{b}\,\tau^+\tau^-$. In MSSM most of the accessible region is excluded by LEP, but in more general models this channel might be relevant.

H -> hh -> $\gamma\gamma\, b\bar{b}$ can be triggered on, but rates are low. Background is small, however, and there is a convincing sharp peak in the $\gamma\gamma$ mass distribution.

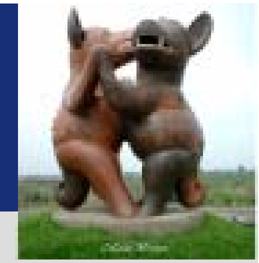


A -> Zh

Can use the leptonic decay of the Z in the trigger. In the analysis 2 electrons (muons) with E_T > 20 GeV (p_T > 5 GeV) of invariant mass within ± 6 GeV of the Z peak and 2 jets with E_T > 40 GeV are required. One or two b-tags are also required. Background comes mainly from $t\bar{t}$ and $Zb\bar{b}$ events (for smaller m_A).

Signal to background ratio is quite good for moderate m_A and small $\tan\beta$, but this region is already excluded in MSSM by LEP.

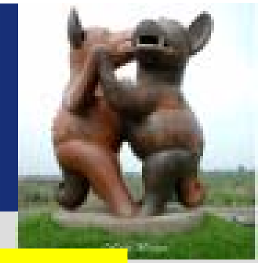
A, H -> $t\bar{t}$



This is the dominant decay channel for large masses. Background comes from QCD $t\bar{t}$ production. It is large, but significant signal can be extracted if background can be correctly estimated. The search is based on the $WWb\bar{b}$ final state, with one W decaying leptonically. The trigger requires an isolated lepton. In the analysis 2 b-jets are required in addition.

Determination of mass will be difficult as there is no observable mass peak. The mode is likely to be used as a confirmation of a signal seen in other channels.

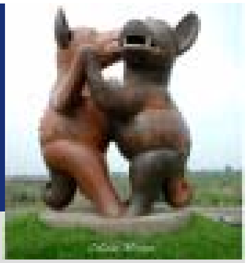
Charged Higgs



In the MSSM the decay $t \rightarrow bH^{\pm}$ may compete with the Standard Model $t \rightarrow bW^{\pm}$ if kinematically allowed. $H^{\pm}$ decays to $\tau\nu$ or cs depending on tanβ. Over most of the range $1 < \tan\beta < 50$ the mode $H^{\pm} \rightarrow \tau\nu$ dominates. The signal for $H^{\pm}$ production is therefore an excess of τ's in tt events. The τ polarization leads to harder pions from $\tau \rightarrow \pi\nu$ than from W decays. For 30 fb^{-1} the discovery range is almost independent of tanβ for $m_A \lesssim 160$ GeV.

If mass of $H^{\pm}$ is larger than m_t it cannot be produced in t-decays. It can be produced by $gb \rightarrow tH^{\pm}$, $gg \rightarrow t\bar{b}H^{\pm}$, $qq' \rightarrow H^{\pm}$. Again the search focusses on the decay $H^{\pm} \rightarrow \tau\nu$. One can use the decay $t \rightarrow bqq$ so that E_T^{miss} gets contribution only from $H^{\pm}$ decay resulting in a Jacobian peak.

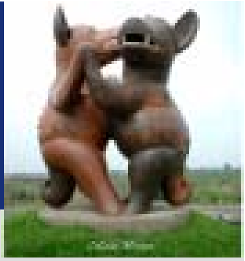
Charged Higgs



$q\bar{q}' \rightarrow H^{\pm}$ with $H^{\pm} \rightarrow \tau\nu$ is difficult because of large background from $q\bar{q}' \rightarrow W \rightarrow \tau\nu$. The τ-polarizaton method must be used. The Higgs mass and tanβ can be extracted using fits to the transverse mass distributions.

Selection of $gb \rightarrow tH^{\pm}$ with $H^{\pm} \rightarrow tb$ requires an isolated lepton from one of the t's. The Higgs signal is extracted by tagging of 3 b-jets, reconstruction of the leptonic and hadronic t-decays and reconstructing the mass from a t and one b-jet.
Identification of Higgs peak is difficult as background is concentrated in the signal area.

SUSY Higgs to Sparticles



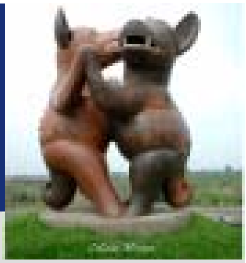
If neutralinos/charginos are light the branching ratios of H and A into these sparticles is sizeable. Most promising with respect to background are channels with leptonic decays of the sparticles:
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \lambda^+ \lambda^-$ **and** $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \lambda^+ \nu$.

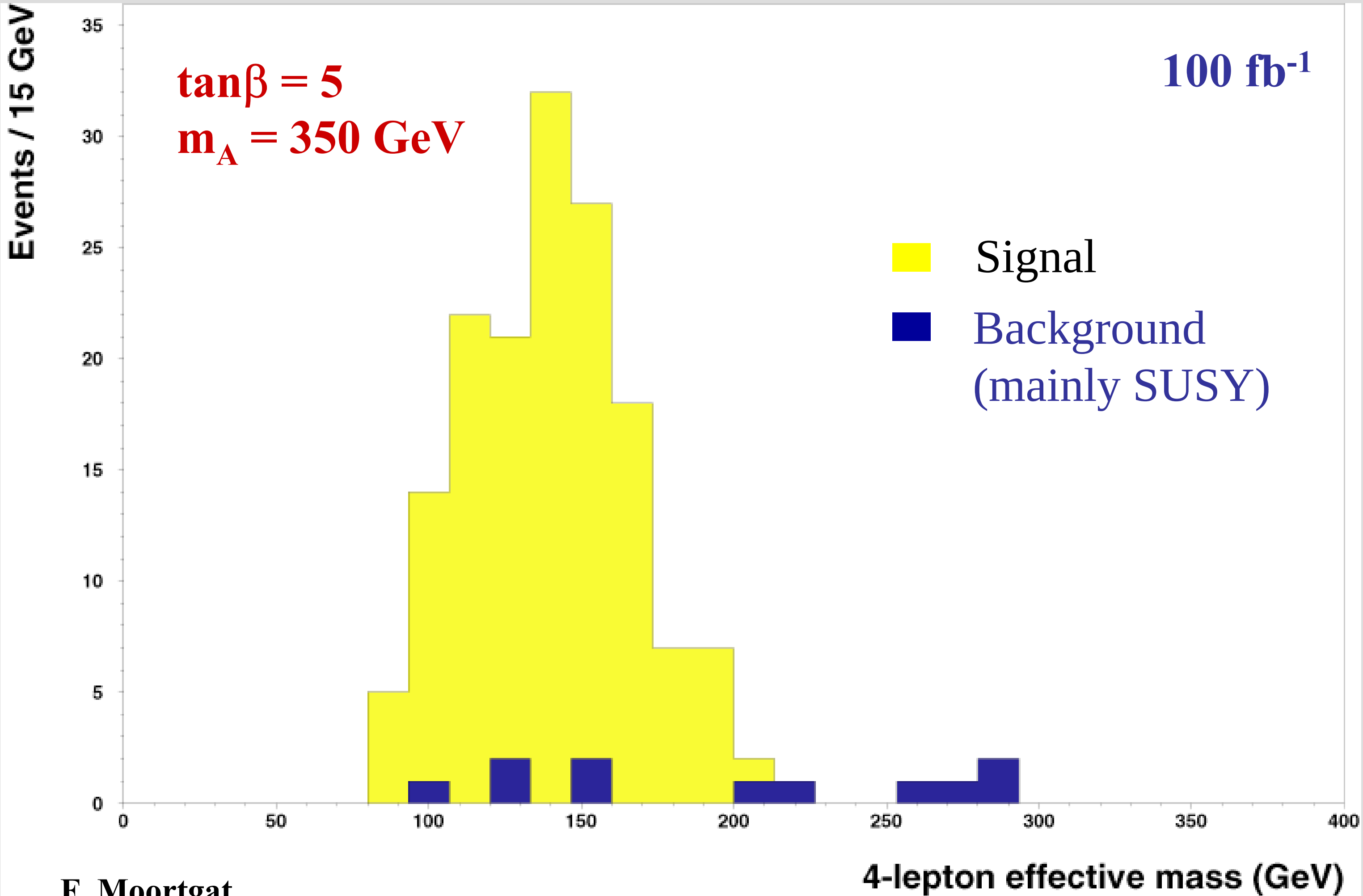
Signal:
A, H -> $\tilde{\chi}_2^0 \tilde{\chi}_2^0 \to 4\lambda + X$

Backgrounds:
SM: **ZZ, Zb$\bar{b}$, Zc$\bar{c}$, t$\bar{t}$, Wt$\bar{b}$**
SUSY: $\tilde{q}/\tilde{g}$, $\tilde{\lambda}\tilde{\lambda}$, $\tilde{\nu}\tilde{\nu}$, $\tilde{q}\tilde{\chi}$, $\tilde{\chi}\tilde{\chi}$

In the following only the case m($\tilde{\lambda}$) > m($\tilde{\chi}_2^0$) will be considered.

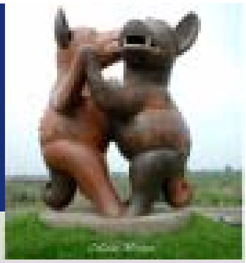
SUSY Higgs to Sparticles





F. Moortgat

Sparticles



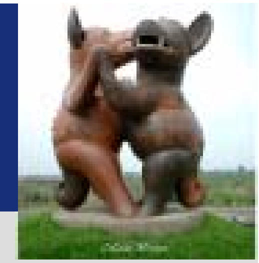
If SUSY is relevant to electroweak symmetry breaking then gluino and squark masses should be of order 1 TeV.

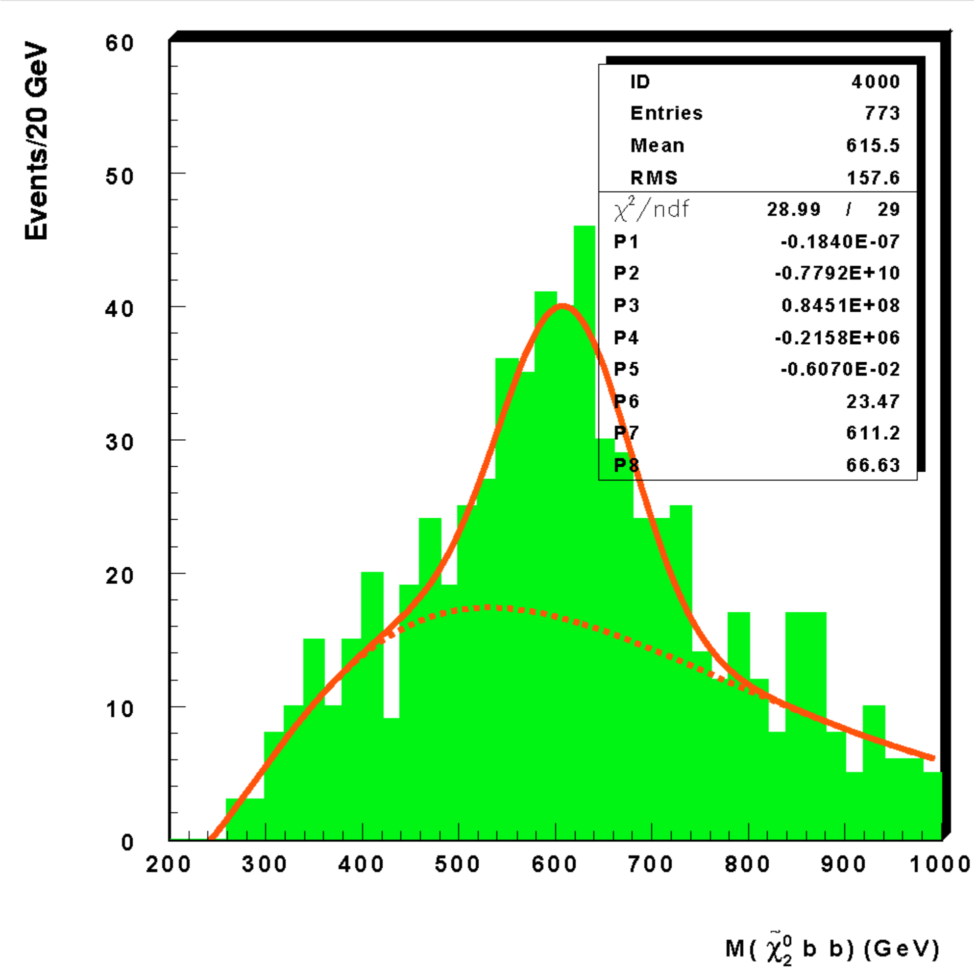
As in general many SUSY particles are produced simultaneously, a model with a consistent set of masses and branching ratios must be used in the simulations.

Traditionally CMS uses the Supergravity (SUGRA) model, which assumes that gravity is responsible for the mediation of SUSY breaking.

Another possible model is the Gauge Mediated SUSY Breaking Model (GMSB) which assumes that Standard Model gauge interactions are responsible for the breaking.

Gluino Reconstruction





Result of fit:

$M(\tilde{\chi}_2^0 bb) = 611.2 \pm 9.2$ GeV

$\sigma = 66.6$

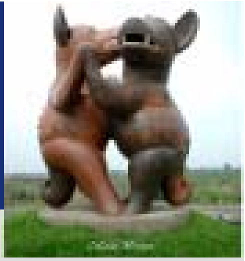
Generated mass:

$M(\tilde{g}) = 643.3$ GeV

m_0	100 GeV
$m_{1/2}$	250 GeV
tan β	10
A_0	0
sign μ	+

M. Chiorboli

Charginos, Neutralinos, Sleptons



Example for Drell-Yan production of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$:

$qq \to W^* \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \lambda \nu + \tilde{\chi}_1^0 \lambda^+\lambda^-$

Search in 3λ and no jets channels, possibly also with E_T^{miss}. Backgrounds: $t\bar{t}$, WZ, ZZ, $Zb\bar{b}$, $b\bar{b}$, other SUSY channels

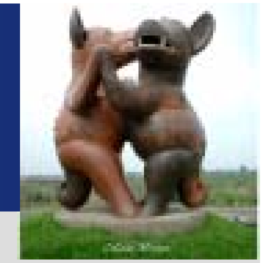
In SUGRA the decay products of SUSY particles always contain $\tilde{\chi}_1^0$'s. Kinematic endpoints for combinations of visible particles can be used to identify particular decay chains.

Examples:

$\lambda^+\lambda^-$ mass distribution from $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\, \lambda^+\lambda^-$ has sharp edge at the endpoint which measures $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$;

$\tilde{\chi}_2^0 \to \tilde{\lambda}^{\pm}\lambda^{\mu} \to \tilde{\chi}_1^0\, \lambda^+\lambda^-$ has different shape with an edge at the endpoint which measures the square root of:

$$\frac{[m^2(\tilde{\chi}_2^0) - m^2(\tilde{\lambda})]\,[m^2(\tilde{\lambda}) - m^2(\tilde{\chi}_1^0)]}{m^2(\tilde{\lambda})}$$



SUSY Higgs in CMS

5σ significance contours