Search for Higgs and New Phenomena at Colliders

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Higgs	SM
	MSSM
	$H^{\pm}$
SUSY	$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$
	$\tilde{g}\tilde{q}$
	$\not{R}_p$
	GMSB
$\overline{\text{SUSY}}$	$\ell + \not{E}_T$
	High Mass
indirect	LFV
	$B \rightarrow \mu\mu$

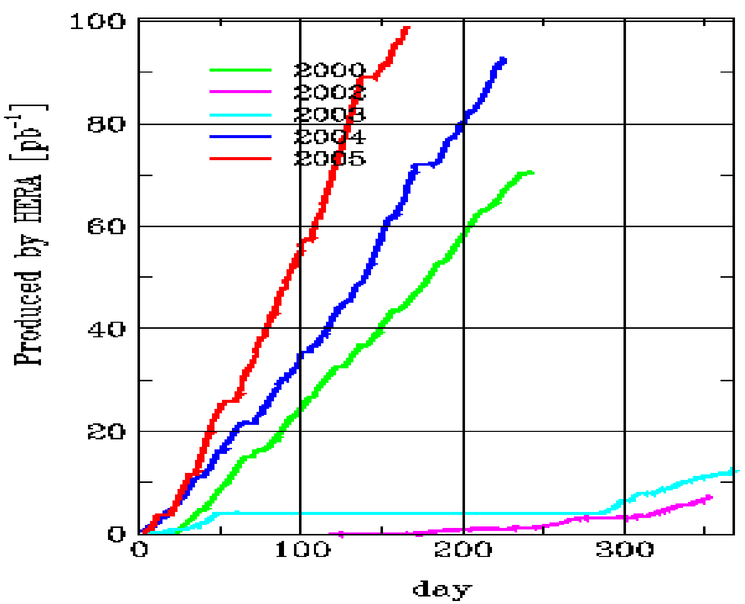
Lepton-Photon 2005

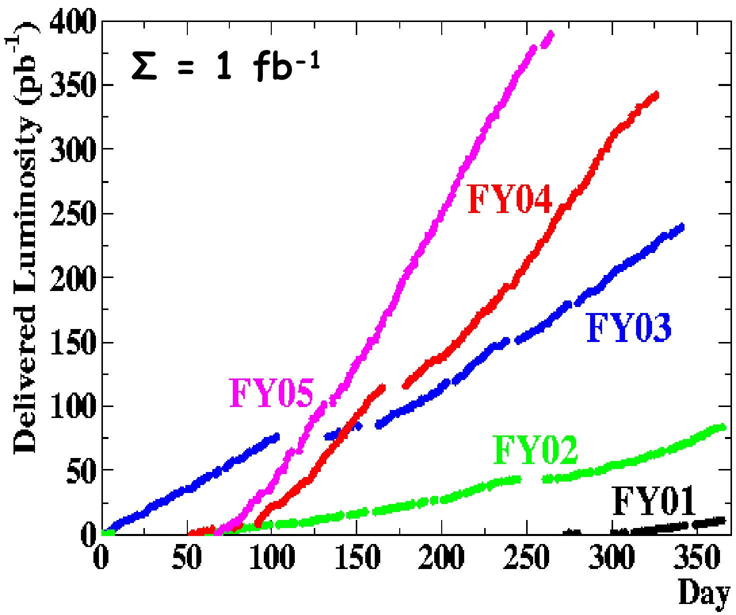
Uppsala, June 30th

LEP → HERA/Tevatron → LHC

- Large variety of excellent analyses, updates, and final results from LEP, HERA I and Tevatron Run I

- HERA/Tevatron Run II with increasing luminosities



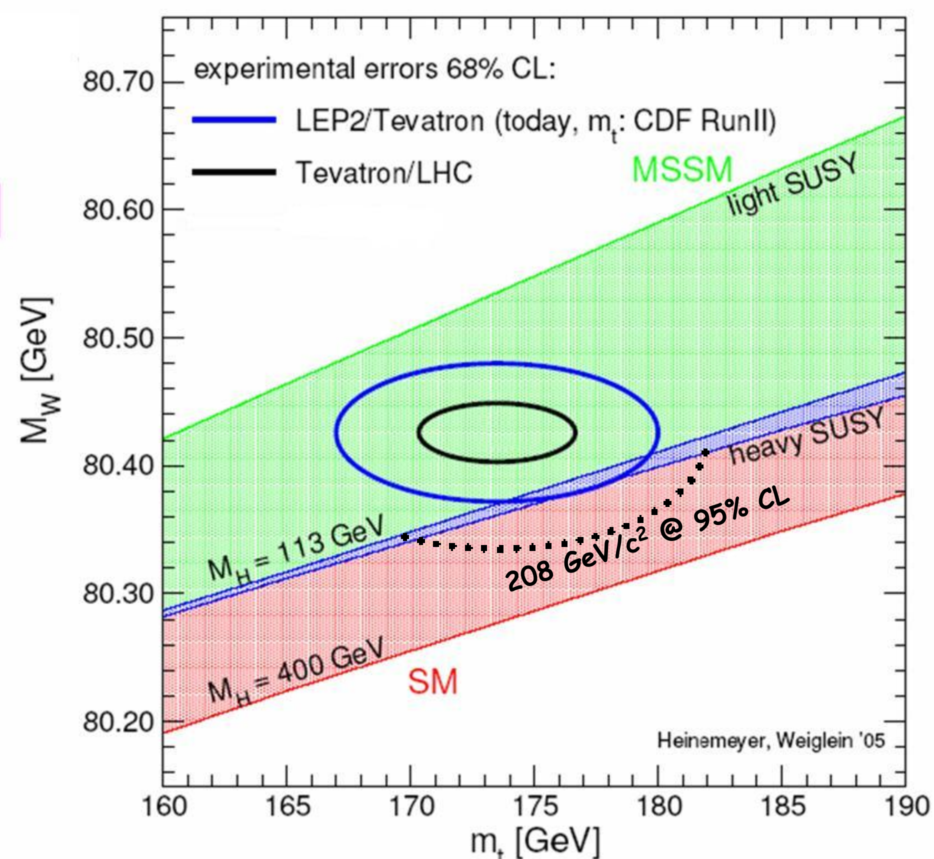


- Many LHC and ILC physics studies

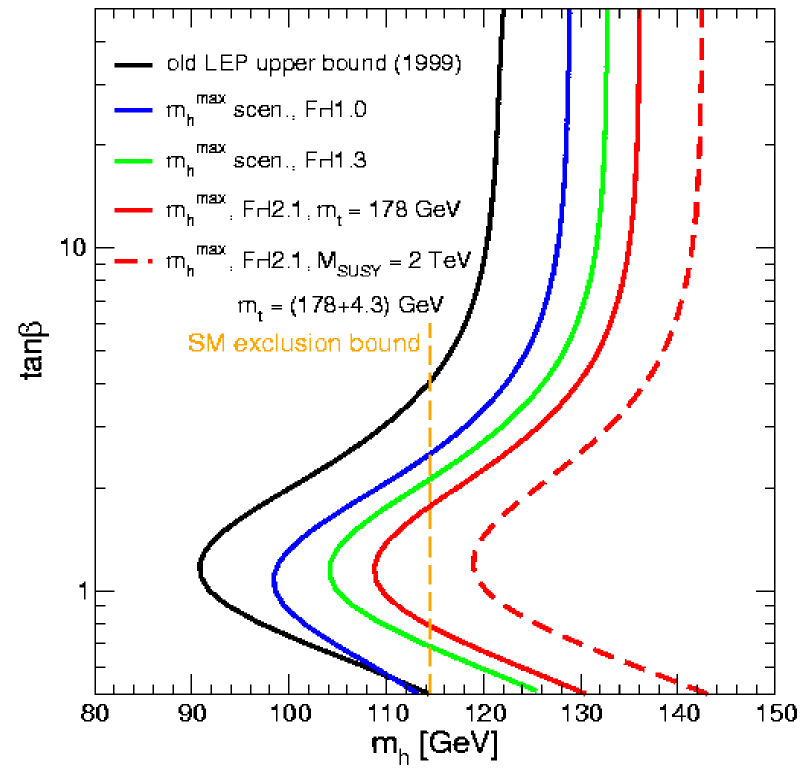
Precision EWK/Top and Higgs

CDF/D0 m_{top} went down: $174.3 \pm 3.4\, GeV/c^2$

Preliminary Tevatron average
(pending final CDF/Do review)
CDF Run II + D0 Run I results



unconstrained MSSM,
bound lower by 6/11/8 GeV/c² for mSUGRA/GMSB/AMSB

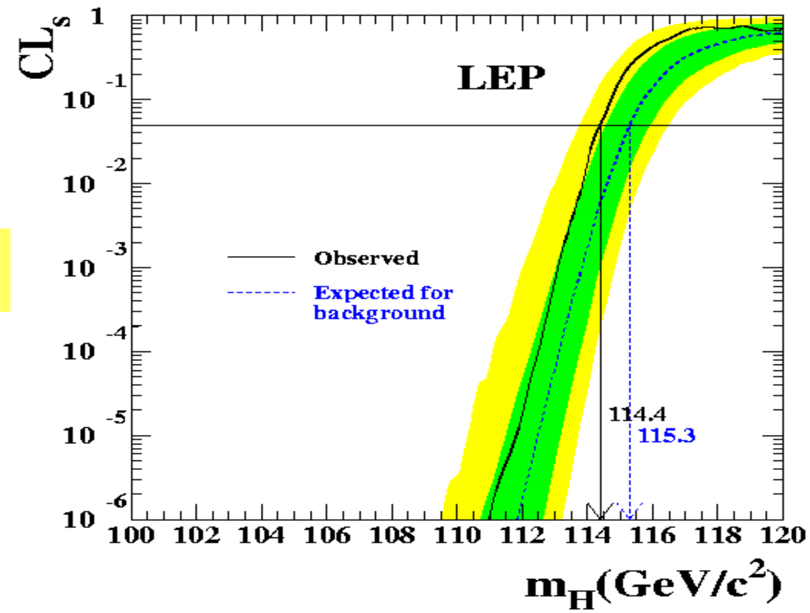


➔ m_{top} **very important**

Higgs, Standard Model

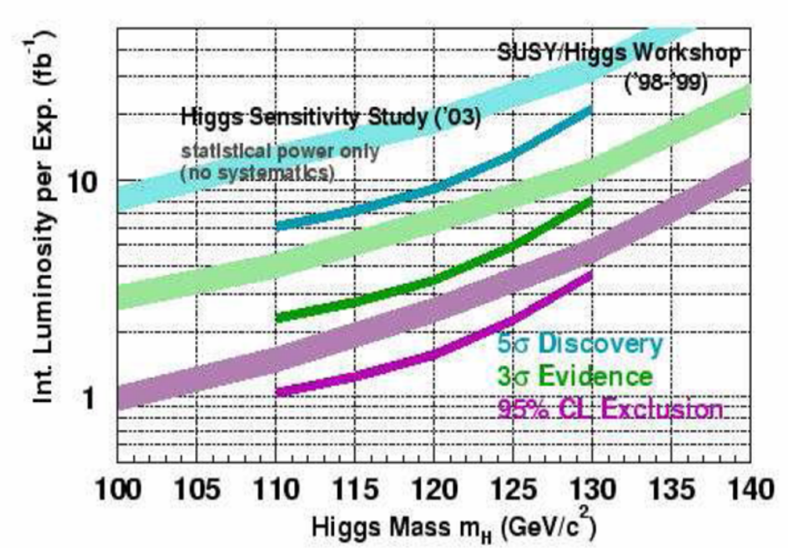
- Final LEP lower Higgs mass limit:

$m_{Higgs} \geq 114.4$ GeV/c² at 95% CL



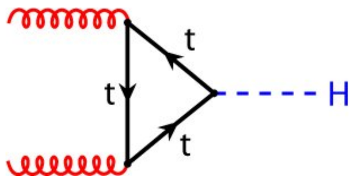
- Tevatron expected to cover up to 130 GeV/c²

di-jet mass resolution	Run I	Run II current	Run II expected
CDF	15%	17%	10%
D0		14-15%	10%

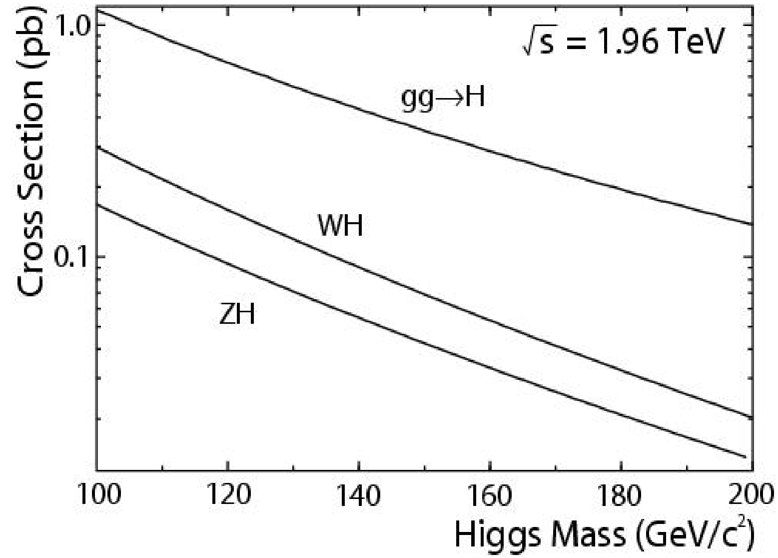


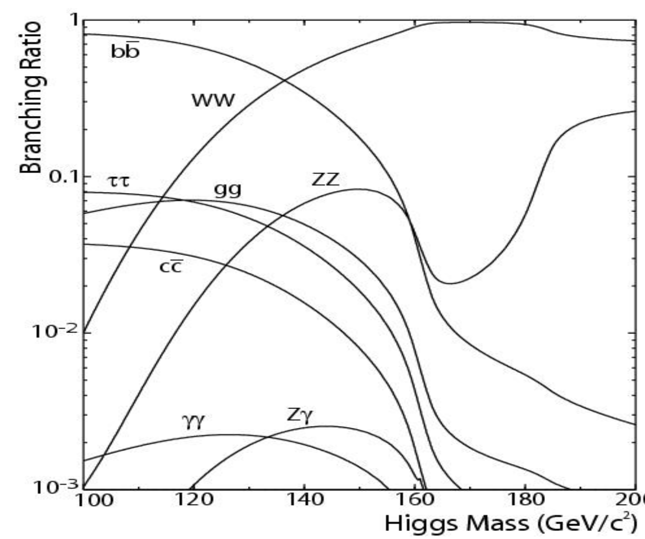
SM Higgs, Tevatron

- Main Higgs production at the Tevatron and LHC is via gluon fusion:



- The "golden" channels at the Tevatron are:
  - WH with W→ℓν, H→bb
  - ZH with Z→νν, H→bb
  - H into WW*
- Important ingredients:
  - lepton and b-tagging acceptance and efficiency
  - bb dijet mass resolution
  - understanding W/Z + jet production

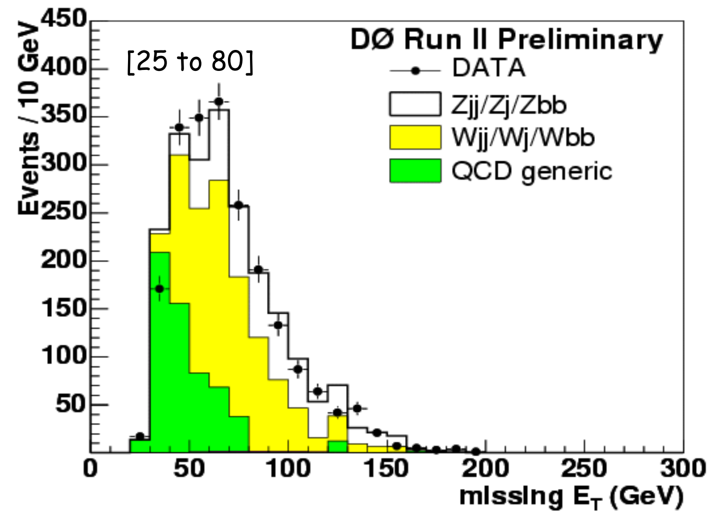


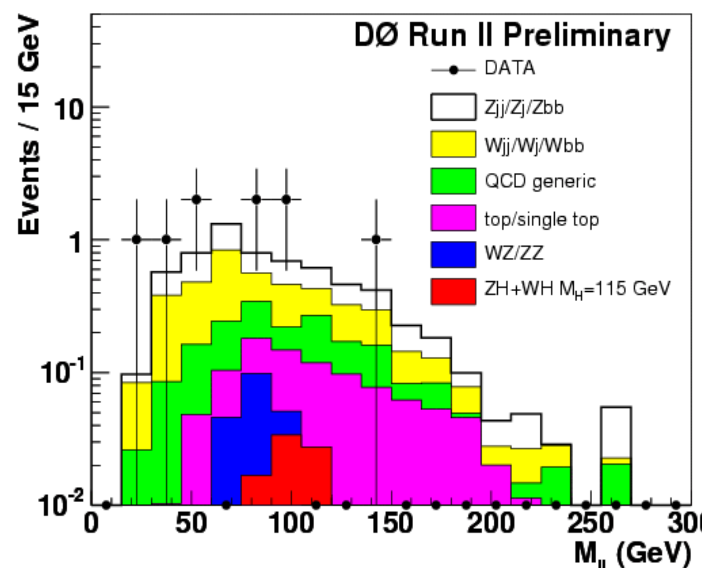


SM Higgs, ZH → ννbb

- Large Z→νν and H→bb BR make it one of the most sensitive channels
- Compare:
  - event missing E_T, $\not{E}_T$
  - jet vector sum, $\not{H}_T$
  - track vector sum, p_T

  to reduce instrumental background (jet mismeasurements)
- Main background:
  - Zbb with Z → νν
  - Wbb with W → τν,...
- ZH acceptance 0.33±0.08%

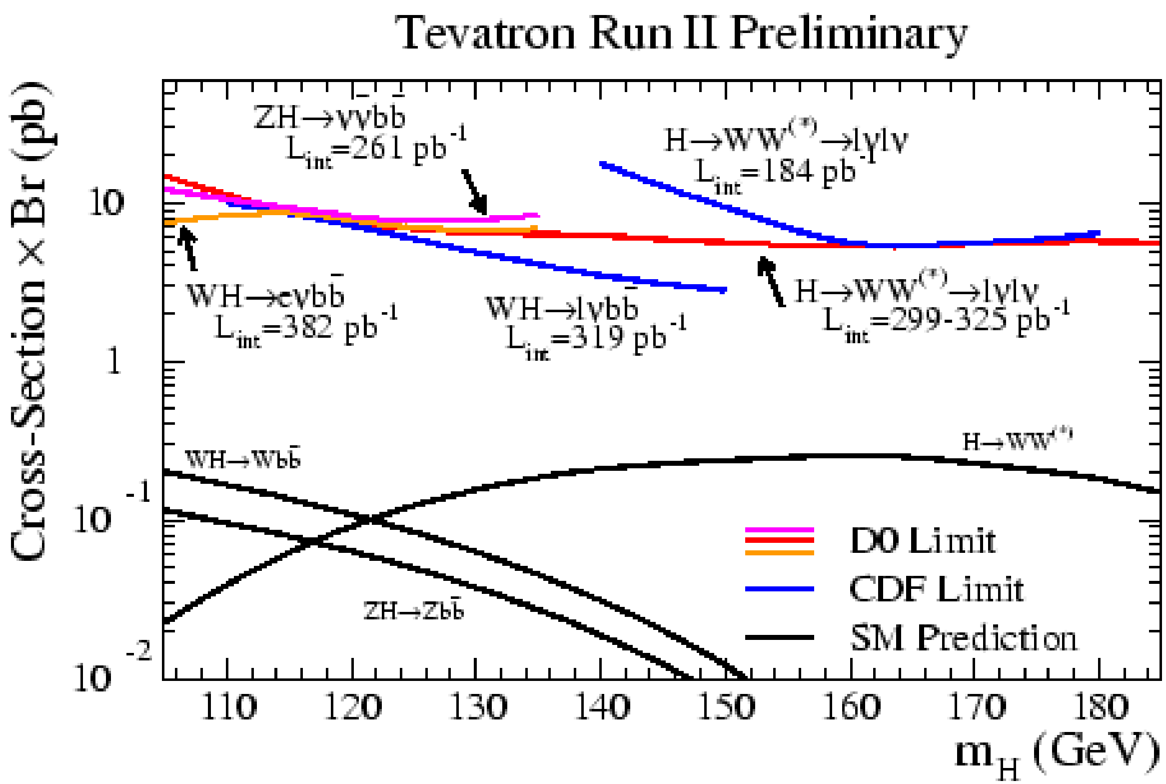




D0 Note 4774-CONF

SM Higgs, Tevatron

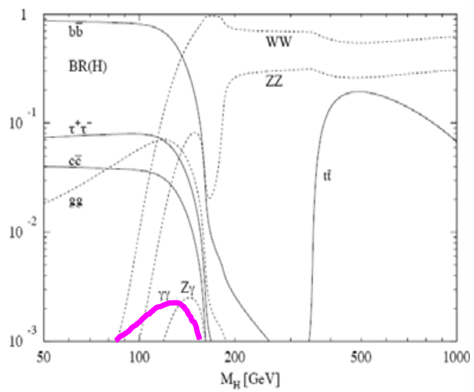
- Up to 380 pb^{-1} of Run II data analysed
- No excess over background expectations
- Sensitivity now at 3-10 pb cross-sections x BR
- Standard Model Higgs at 0.2 pb

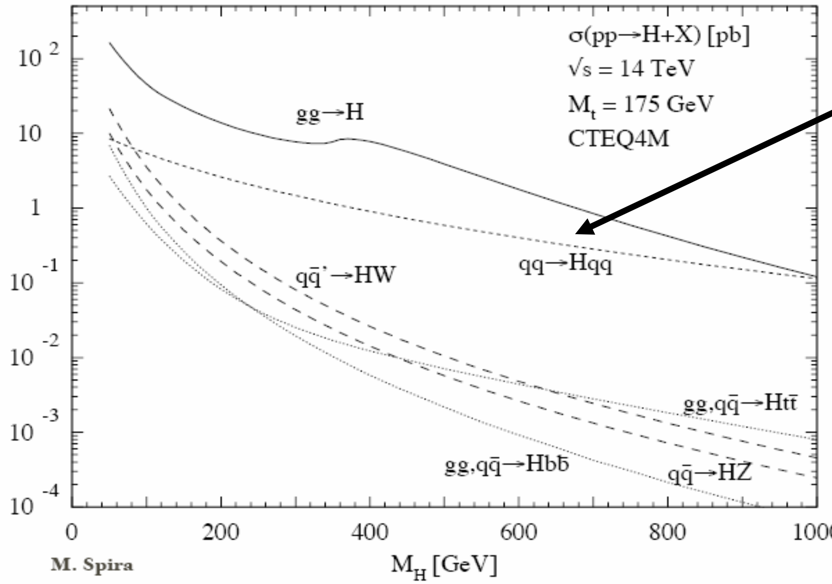


luminosity and analysis improvements

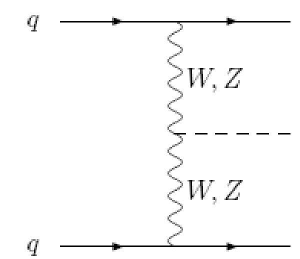
SM Higgs, LHC

- Very large Higgs production cross-section, ~1000 Higgses/day !



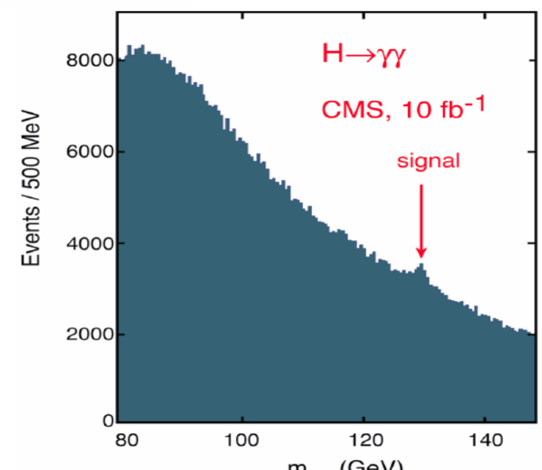


Vector Boson Fusion



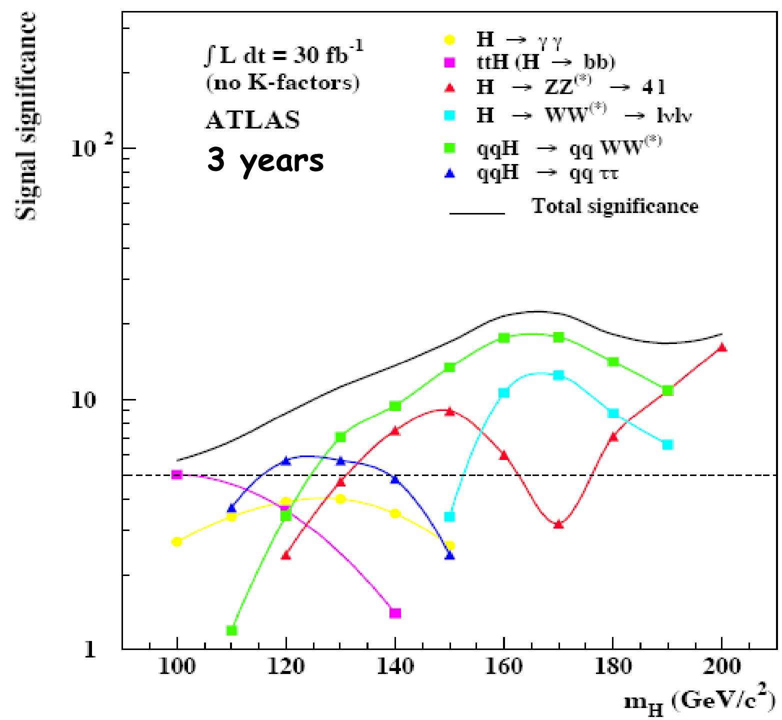
Forward tagging jets

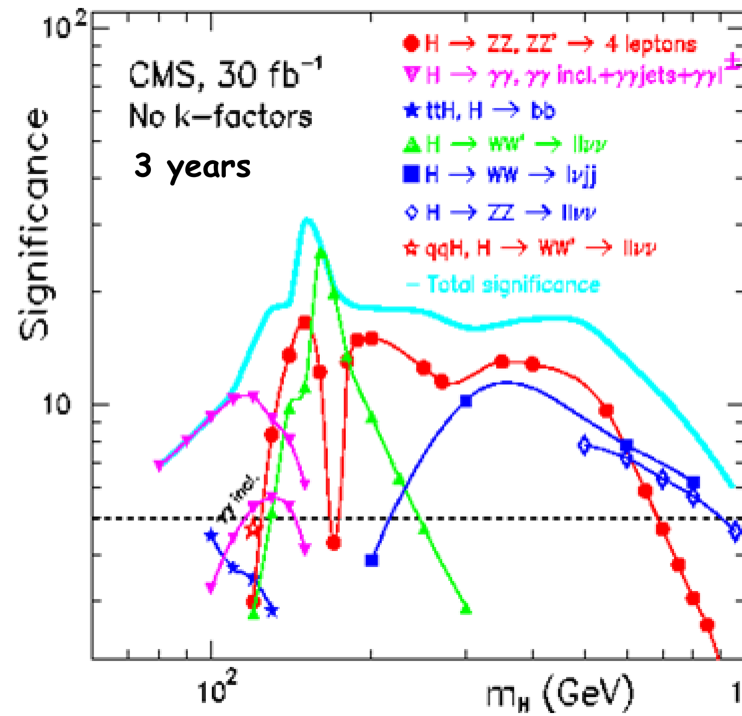
- em calorimeter with precise energy resolution, lead-tungsten crystals (CMS) and liquid argon (ATLAS), to observe γγ bump



SM Higgs, LHC

- H→ ZZ → 4 leptons clean signal for heavier Higgs
- ttH → WbWb+bb for light Higgs





- Higgs discovery up to high masses within first years, measure ratio of couplings, decay width, etc.

Supersymmetry

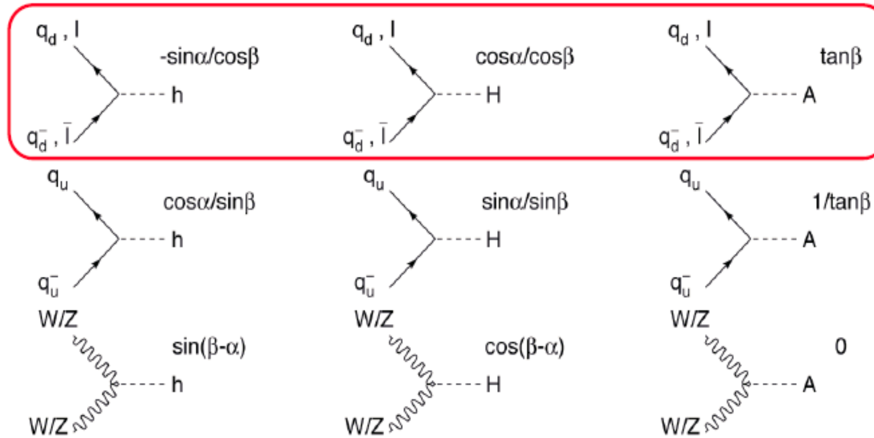
- Extend fundamental symmetry concept of particle physics to spin sector:
  - each particle has spin ½ different superpartner
- Supersymmetric extensions of the SM provide a consistent framework for gauge unification and stabilization of EWK scale
- Several SUSY breaking scenarios under consideration
  - determines SUSY structure
- MSSM, general minimal SUSY extension of the SM
  - two Higgs doublets → 5 Higgs particles (h, H, A, H^+, H^-) described by m_A and $\tan\beta$ at tree level
  - 91 real parameters, 74 phases (+complex $m_{gravitino}$)
- Constrained models and "benchmark" models

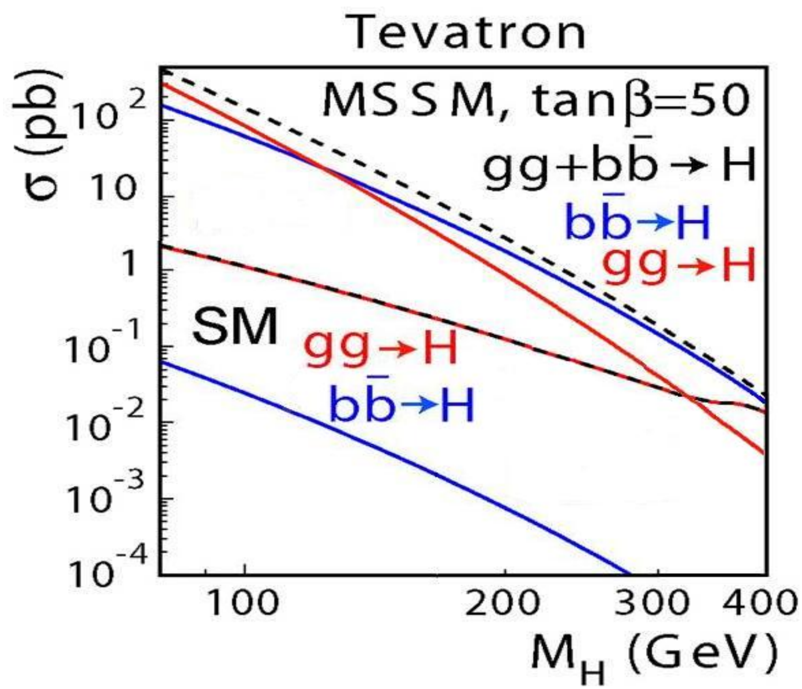
MSSM Higgs, Tevatron

- Yukawa coupling to down-type fermions enhanced by factor tanβ:
  - $\sigma(pp \to A, h/H) \approx \tan^2\beta$
- Branching ratios
  - h/H/A → bb ~90%
  - h/H/A → ττ ~10%

  independent of mass
- For large tanβ h or H and A nearly mass degenerate
- Searches:
  - bbA → bbbb
  - A → τ⁻τ⁺

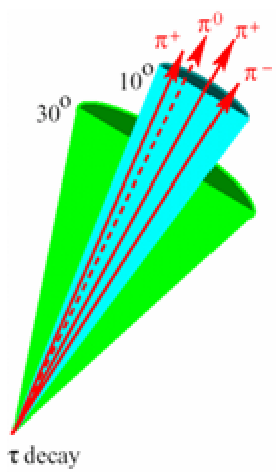
(pp→A→bb not feasible)



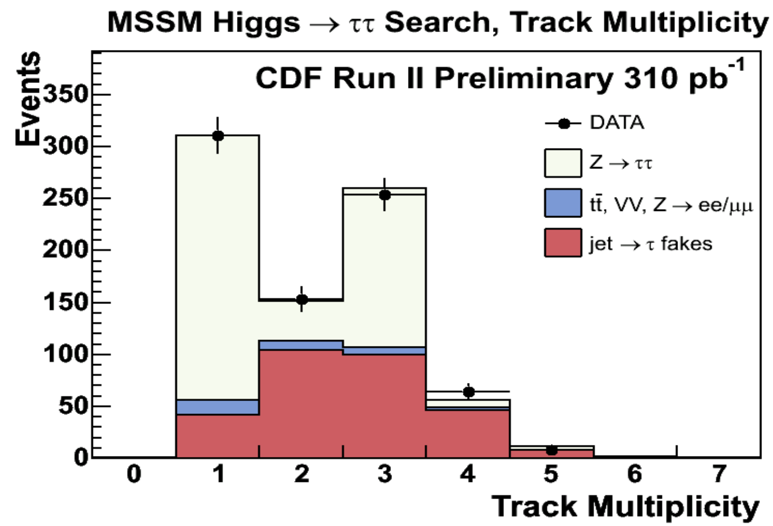


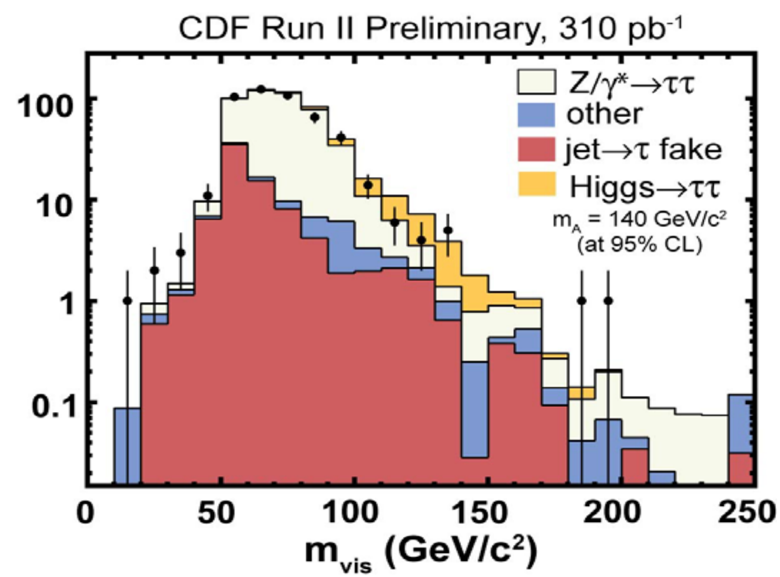
MSSM Higgs, $A \rightarrow \tau^-\tau^+$

- Use lepton + track trigger
  - one leptonic tau decay, e/μ
  - one hadronic tau decay
- Tau jets are pencil-like:

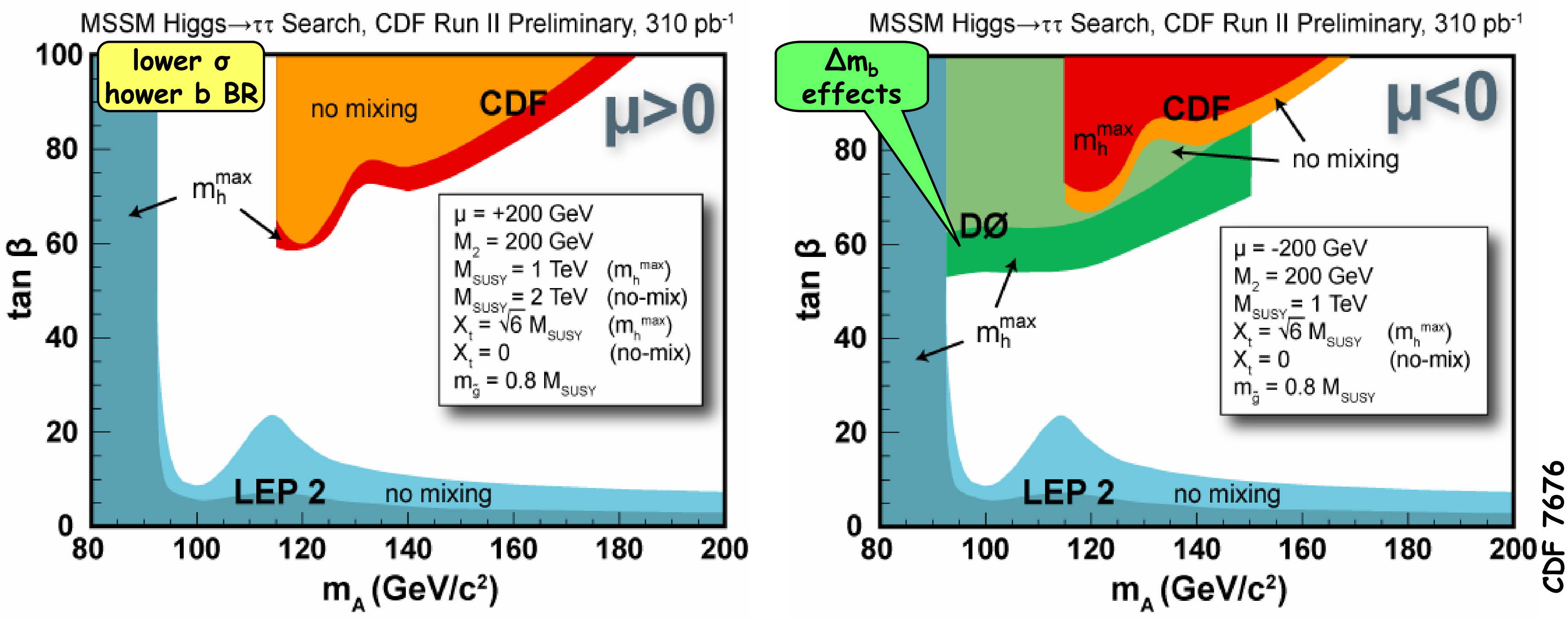


- Tau efficiency ~46%,
  - fake rate 1.5 - 0.1% /jet
- Binned likelihood fit of m_{vis} (ℓ, τ_h, $\not{E}_T$)

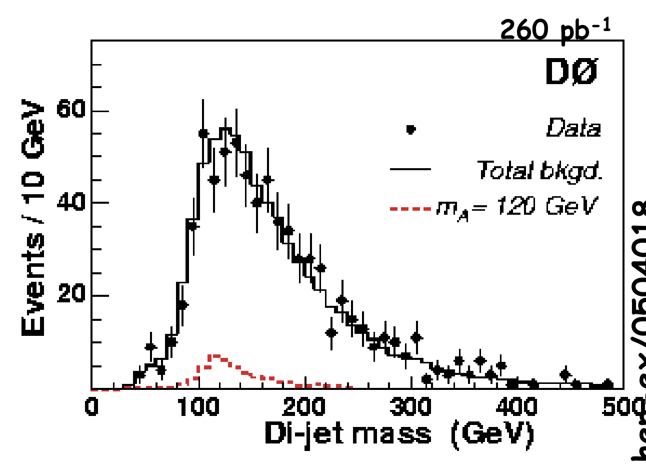




MSSM Higgs, Tevatron



- D0 bbbb analysis:
  - triple b-tag
  - mis-tag function applied to untagged jets in double b-tag sample
  - background normalization from m_{bb} fit
  - acceptance 0.4 to 1.0%

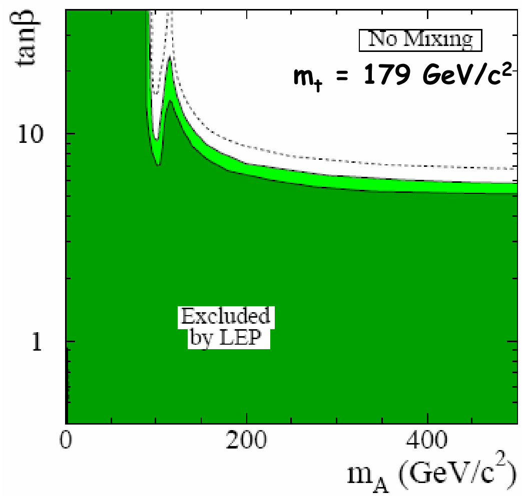


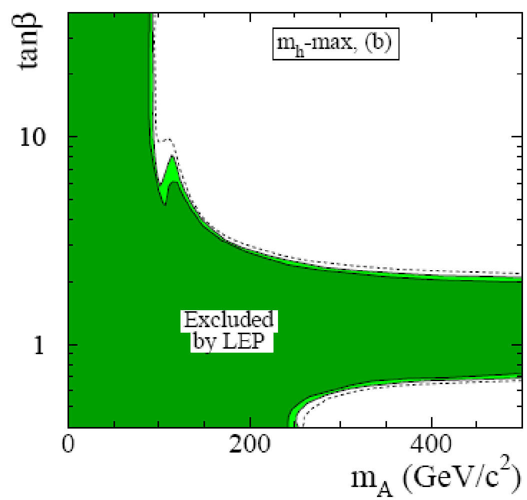
MSSM Higgs, LEP

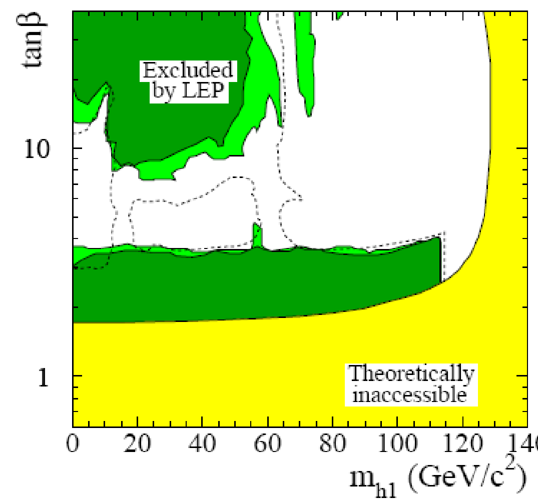
H→SM particles

- No signal of Higgsstrahlung or pair production
- Benchmark models (M_{SUSY}, M_2, μ, m_{gluino}, A)
  - no-mixing: 1000, 200, -200, 800, 0 + μ cotβ
  - m_h-max-b, flipped: 1000, 200, +200, 800, -2000+μ cotβ

stop mixing parameter







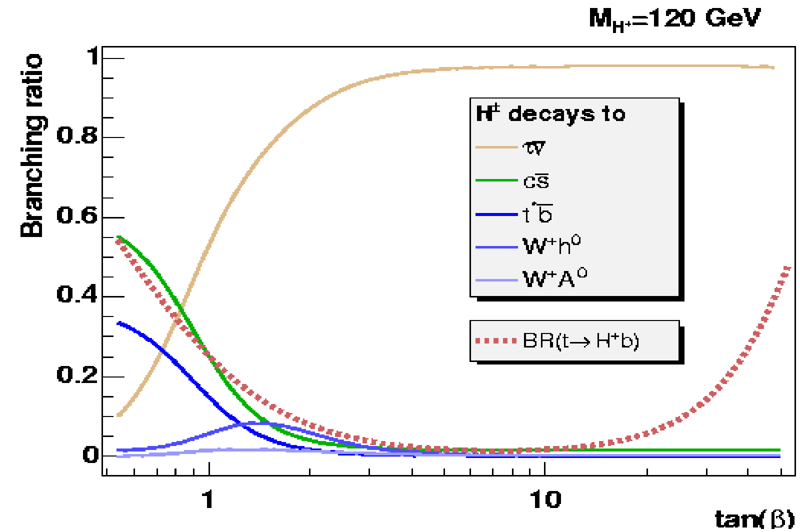
hole due to CPH/FeynHiggs BR(h_2→h_1h_1)
difference under investigation

- CP violating Higgs
  - appealing in explaining cosmic matter/anti-matter asymmetry
  - experimentally more challenging, H_1 may decouple from Z

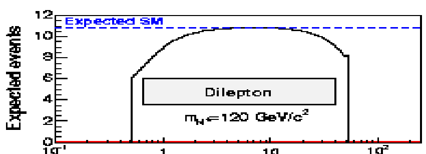
LHWG-Note 2005-01

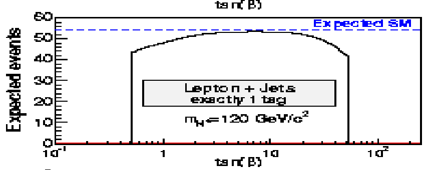
MSSM Charged Higgs

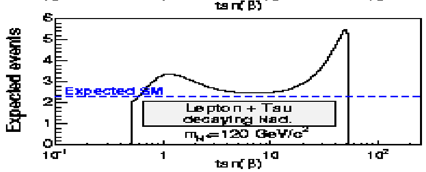
- $H^{\pm}$ can be produced in top decays: $t \rightarrow H^{+} b$
- BR competes with Wb
- cross-section measurements vary differently in analyses

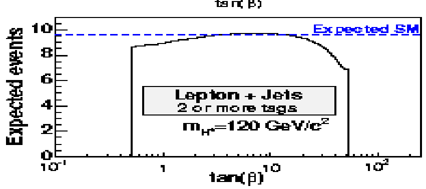


- Assume σ(tt)
- BRs from CPsuperH

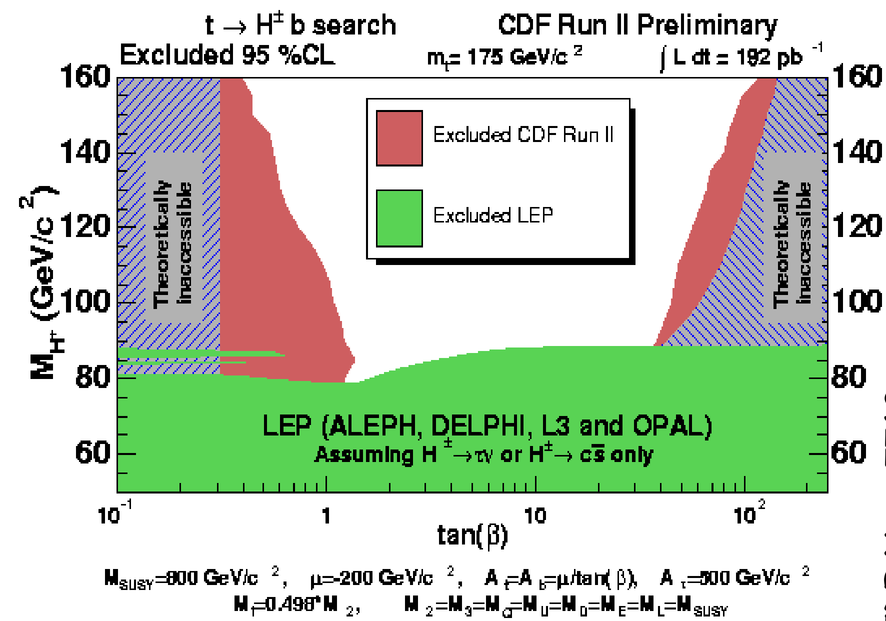








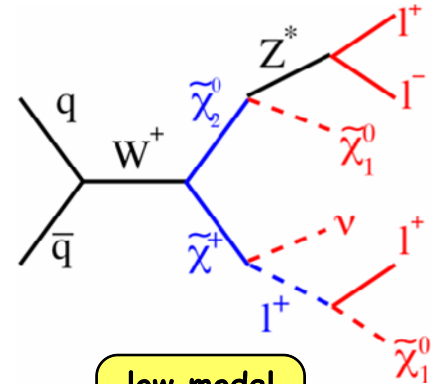
- Analyse benchmark models
- $BR(t \rightarrow H^{+}b) < 70\%$ at 95% CL



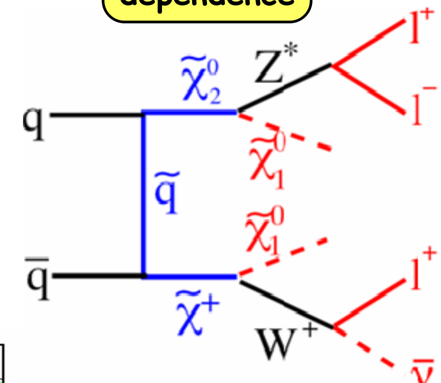
CDF Note 7712

Chargino/Neutralino, Tevatron

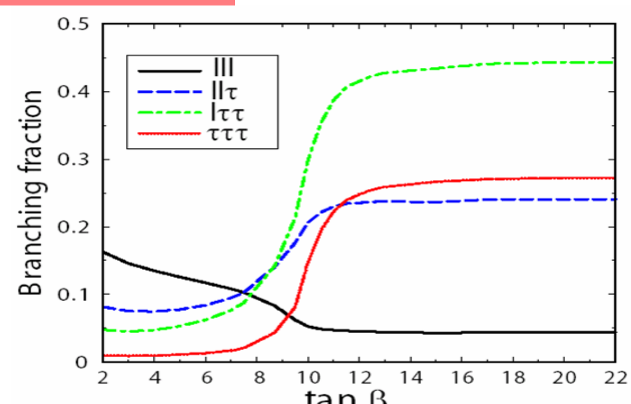
- Higgsinos and gauginos mix
  ➔ charginos/neutralinos
- LEP: $m_{\tilde{\chi}^\pm} > 103.5\ \mathrm{GeV}/c^2$



low model dependence



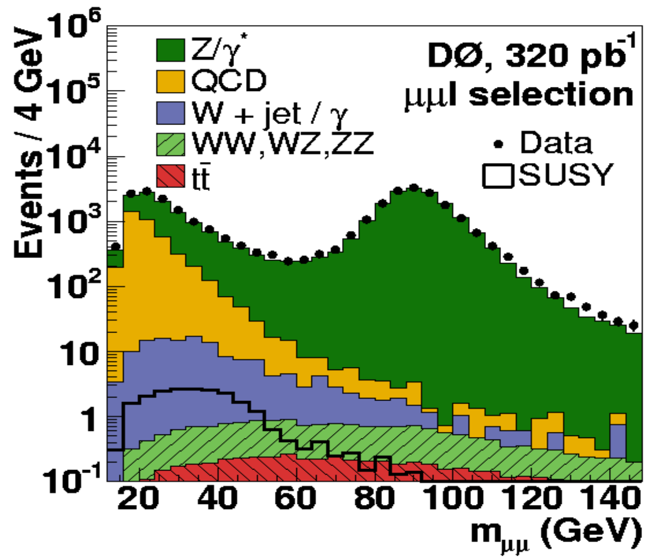
- small cross-section but
- striking signature in mSUGRA and in case of leptonic χ decays
- $\tilde{\chi}^\pm\tilde{\chi}^0 \rightarrow \ell^+\ell^-\ell^\pm\nu$ LSP LSP
- R_P → stable LSP
- 3 challenges:
  - acceptance
  - acceptance
  - acceptance



Chargino/Neutralino Search

- veto dilepton resonances
- combined $\not{E}_T$ and $p_T(t)$ cut
- main backgrounds:
  - misidentified leptons
  - di-boson production
- efficiencies measured on Z
- main uncertainty mis-id ℓ

Channel	Background expected	Observed
e e t	0.21±0.12	0
e μ t	0.31±0.13	0
μ μ t	1.75±0.57	2
$\mu^{\pm}\,\mu^{\pm}$	0.64±0.38	1
e τ_h t	0.58±0.14	0
μ τ_h t	0.36±0.13	1
Total	3.85±0.75	4



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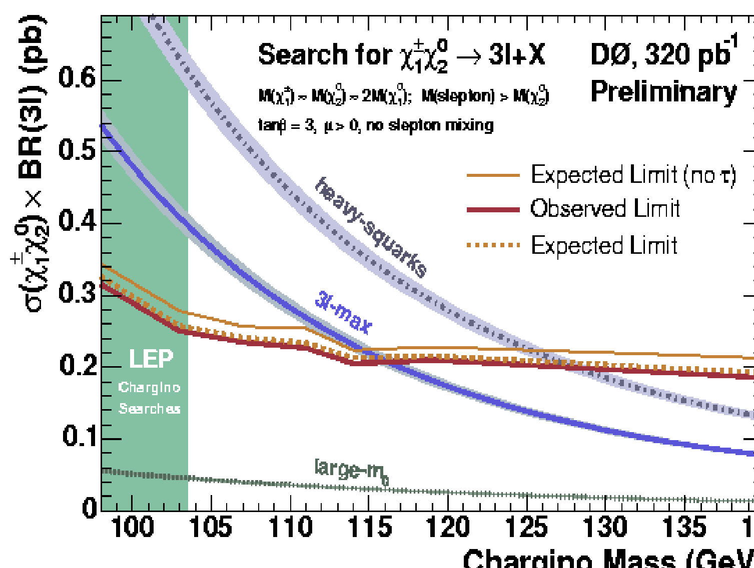


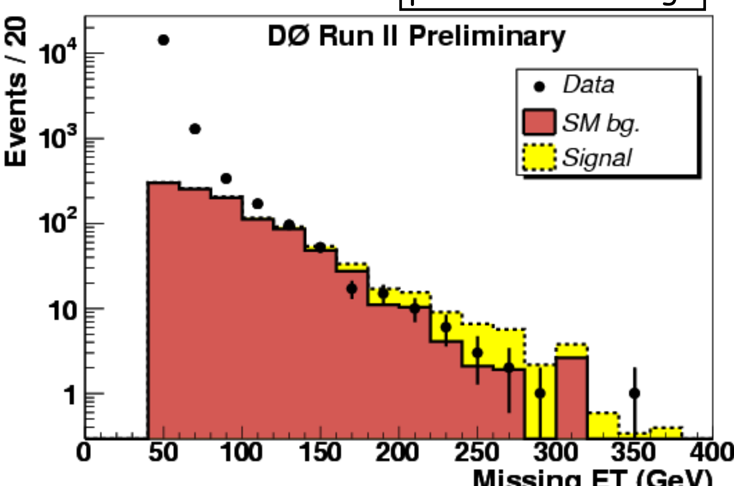
D0 Note 4740-CONF

Squark/Gluino Search

- LEP $\tilde{\chi}^{\pm}$ => $m_{\tilde{g}} \geq 320$ GeV/c^2 (mSUGRA)
- Large cross-section for coloured particles
- $\tilde{u}$, $\tilde{d}$, $\tilde{s}$, $\tilde{c}$ mass degenerate ($\tilde{b}$, $\tilde{t}$ could be lighter)
  superpartner for both helicity states
- $m_{\tilde{q}} < m_{\tilde{g}}$: $\tilde{q} \to q\tilde{\chi}^0$, $\tilde{q} \to q'\tilde{\chi}^{\pm}$ $\tilde{\chi}^{\pm} \to q\bar{q}'\tilde{\chi}^0$
  $m_{\tilde{g}} < m_{\tilde{q}}$: $\tilde{g} \to q\bar{q}\tilde{\chi}^0$, $\tilde{g} \to q\bar{q}'\tilde{\chi}^{\pm}$

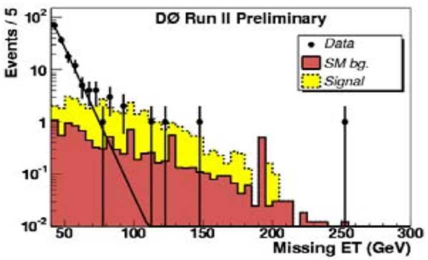
- central leading jets, not back-to-back (60/40 GeV)
- lepton veto
- $\Delta\varphi(\not{E}_T$, jet)
- backgrounds:
  - W/Z + jets (NLO from MCFM)
  - QCD multijets (from data)
- mSUGRA m_0, $m_{\frac{1}{2}}$ => $m_{\tilde{q}}$, $m_{\tilde{g}}$, $m_{\tilde{\chi}}$
- $\varepsilon(\tilde{q}\tilde{g})$ few percent (Prospino NLO)

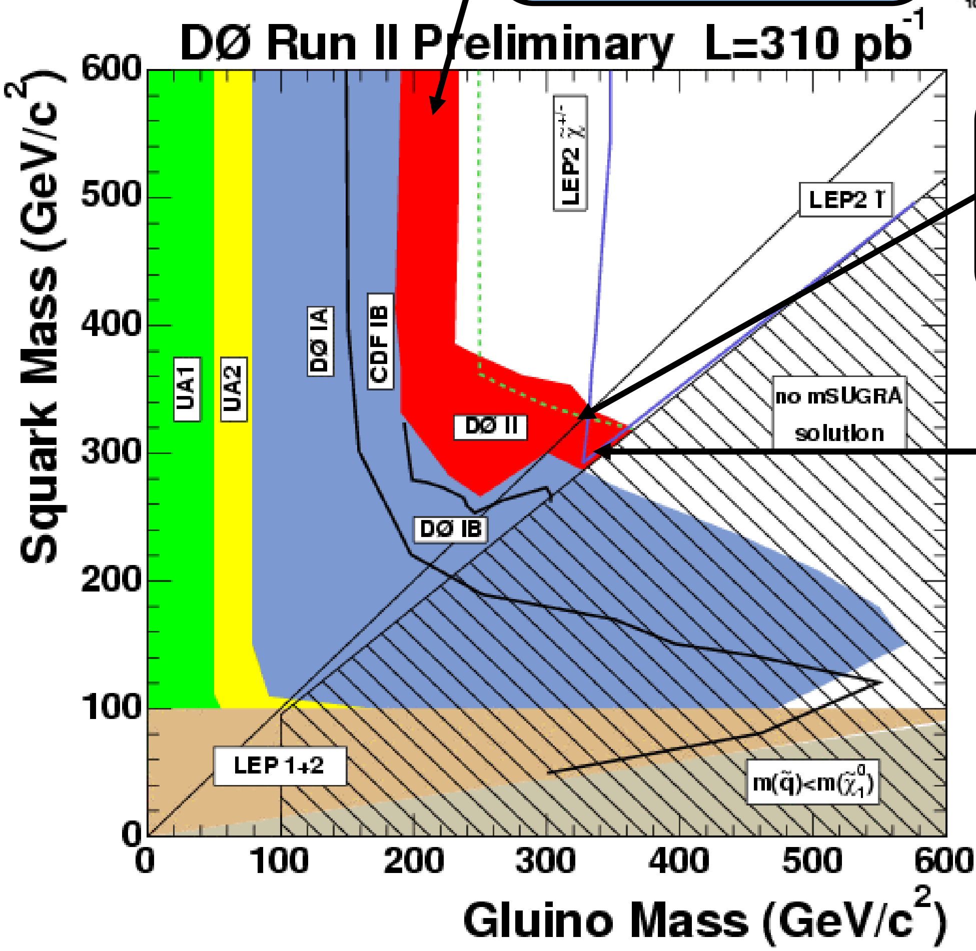
pre-selection stage



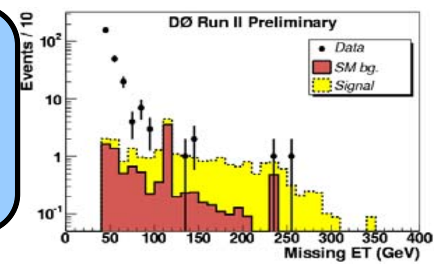
Squark/Gluino Search

4 jets
$\not{E}_T$ > 75 GeV
H_T > 250 GeV
backgrnd: 7.1±0.9
observed: 10 events

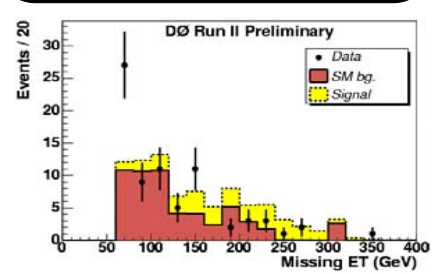




3 jets
$\not{E}_T$ > 100 GeV
H_T > 325 GeV
backgrnd: 6.1±3.1
observed: 5 events



2 jets
$\not{E}_T$ > 175 GeV
H_T > 250 GeV
backgrnd: 12.8±5.4
observed: 12 events



D0 Note 4737-CONF

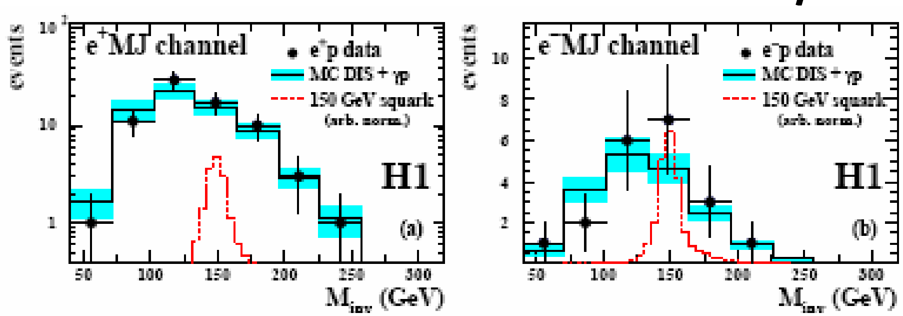
R_P Violating SUSY, HERA

- R_P ad hoc requirement

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- Third generation most interesting
- HERA ideally suited for new physics coupling to e-u/d pairs
- Resonant squark production via λ'
  - e^-p: λ'_{11k} $\tilde{d}_R$ produced
  - e^+p: λ'_{1j1} $\tilde{u}_L$ produced
- Extensive searches in various channels, including γ signatures
- "Wrong" charge: 0+0 events

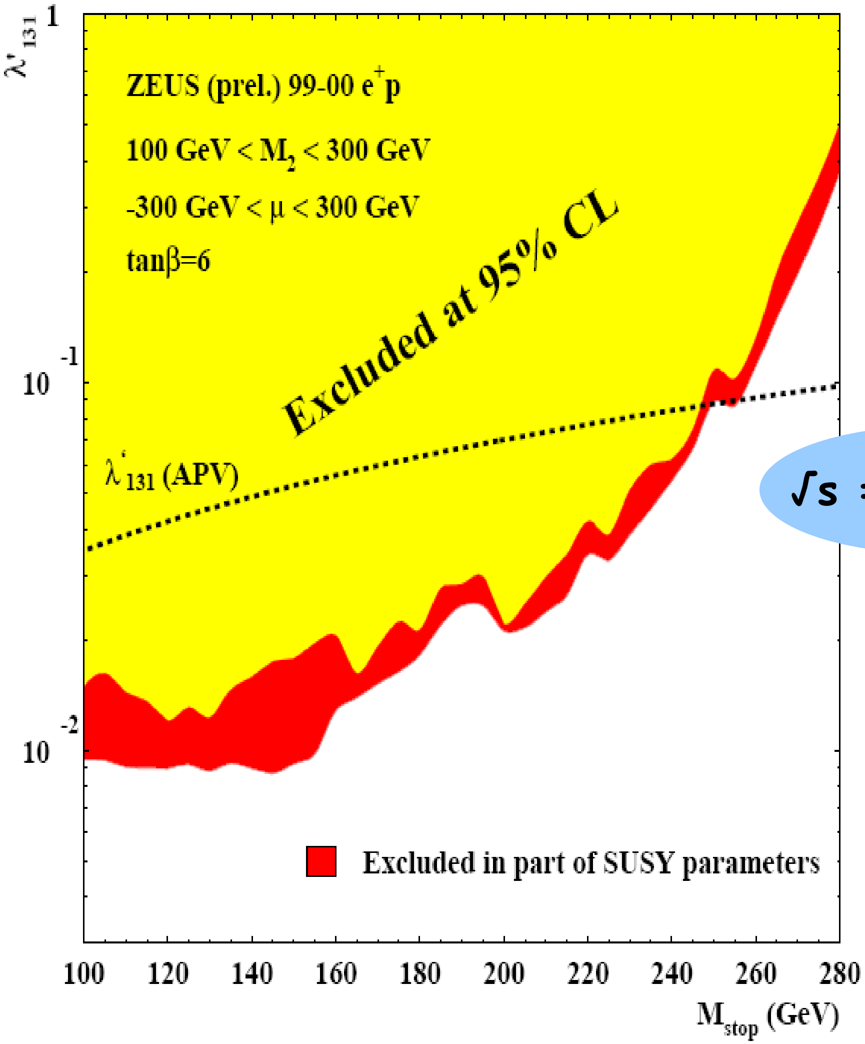
Channel	Decay process	Event topology
eq	$\tilde{q} \xrightarrow{\lambda'} e\ q$	high p_T e + 1 jet
νq	$\tilde{d}_R^k \xrightarrow{\lambda'} \nu_e\ d$	missing p_T + 1 jet
$e^{\pm}MJ$	$\tilde{q} \longrightarrow q\ X,\ X \xrightarrow{\lambda'} e^{\pm}\bar{q}q$ $\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow q\bar{q}\ Y,\ Y \xrightarrow{\lambda'} e^{\pm}\bar{q}q$	e (both charges) + multiple jets
νMJ	$\tilde{q} \longrightarrow q\ X,\ X \xrightarrow{\lambda'} \nu\bar{q}q$ $\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow q\bar{q}\ Y,\ Y \xrightarrow{\lambda'} \nu\bar{q}q$ $\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow \nu\bar{\nu}\ Y,\ Y \xrightarrow{\lambda'} \nu\bar{q}q$	missing p_T + multiple jets
$elMJ$	$\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow \ell\nu_\ell\ Y,\ Y \xrightarrow{\lambda'} e^{\pm}\bar{q}q$ $\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow \ell^+\ell^-\ Y,\ Y \xrightarrow{\lambda'} e^{\pm}\bar{q}q$ $\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow e^+e^-\ Y,\ Y \xrightarrow{\lambda'} \nu\bar{q}q$	e + ℓ (e or μ) + multiple jets
νlMJ	$\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow \ell\nu_\ell\ Y,\ Y \xrightarrow{\lambda'} \nu\bar{q}q$ $\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow \nu\bar{\nu}\ Y,\ Y \xrightarrow{\lambda'} e\bar{q}q$ $\tilde{q} \longrightarrow q\ X,\ X \hookrightarrow \mu^+\mu^-\ Y,\ Y \xrightarrow{\lambda'} \nu\bar{q}q$	ℓ (e or μ) + missing p_T + multiple jets

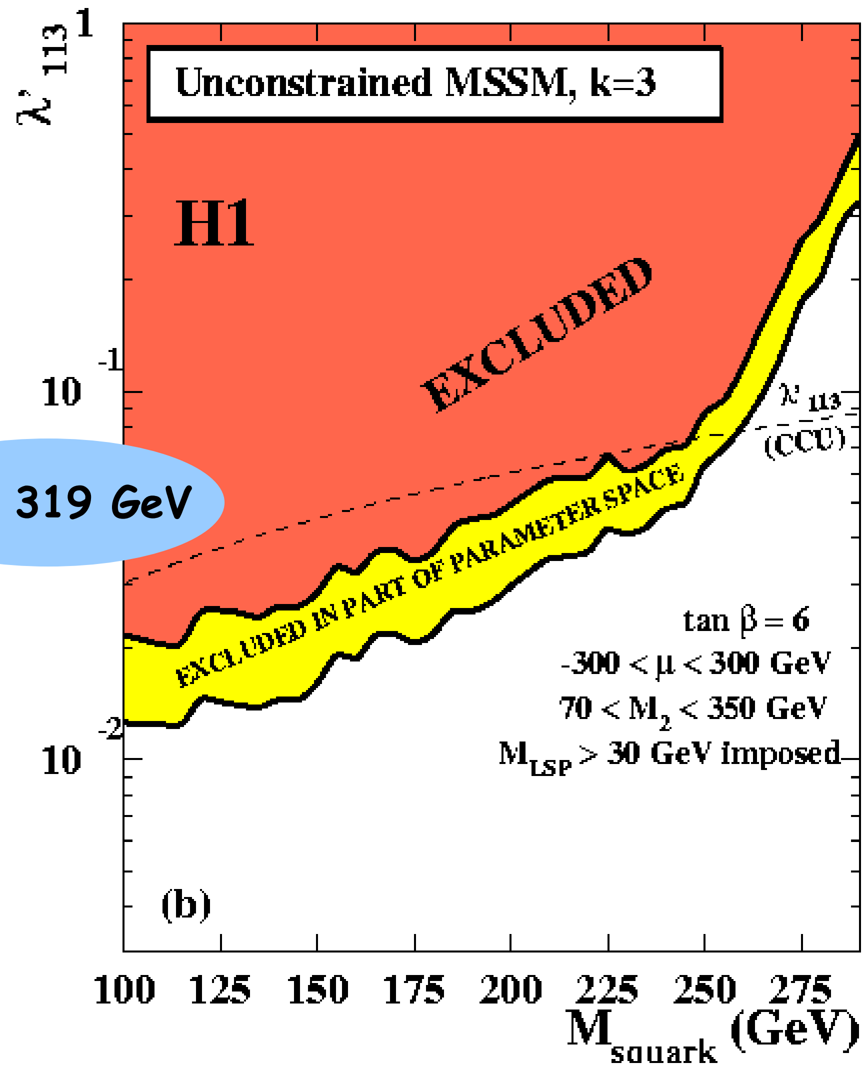


R_P Violating SUSY, HERA

top squark

bottom squark





√s = 319 GeV

Eur.Phys.J. C36 (2004) 425-440

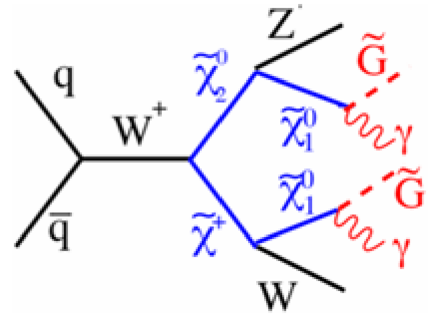
PAPER-258

GMSB SUSY $\gamma\gamma+\not{E}_T$, Tevatron

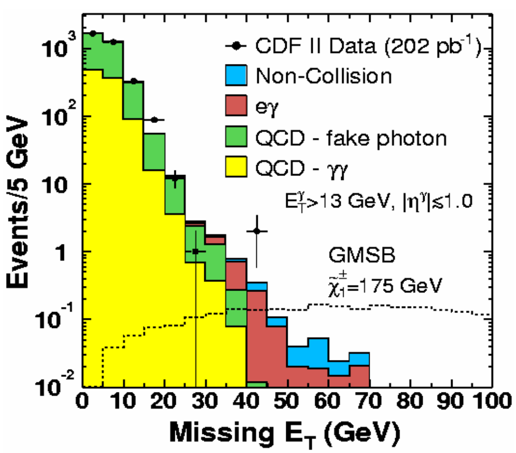
- SSB via gauge interactions
- gravitino acquires SUSY-breaking mass:

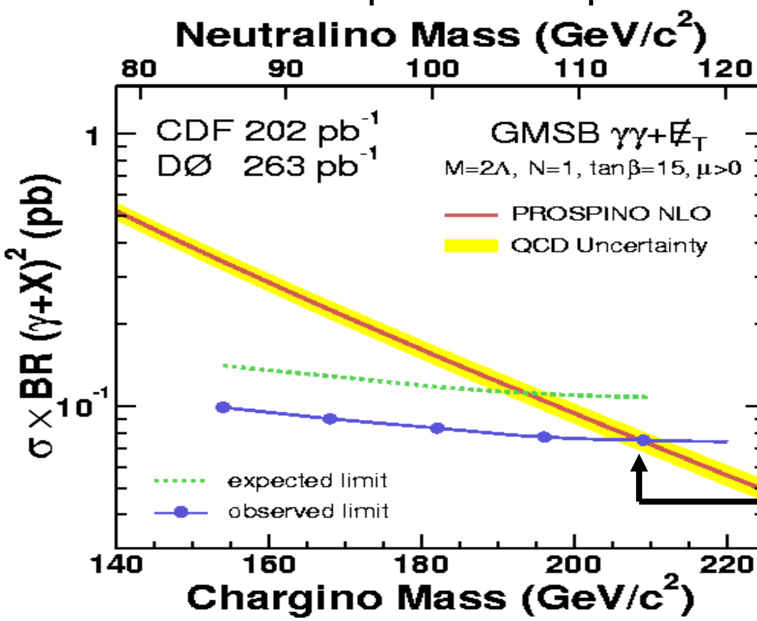
$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_{Planck}} \cong \left(\frac{\sqrt{F}}{100\,TeV}\right) eV$$

- use $\tilde{\chi}^{\pm}\tilde{\chi}^0$ production process
- D0 (CDF) selection:
  - 2 photons E_T > 20 (13) GeV
  - $\not{E}_T$ > 40 (45) GeV
- signal efficiency 6-15%



	Background Expect	Observed	Limit m_{χ^+}
D0	3.7±0.6	2	195 GeV
CDF	0.3±0.1	0	167 GeV
			209 GeV

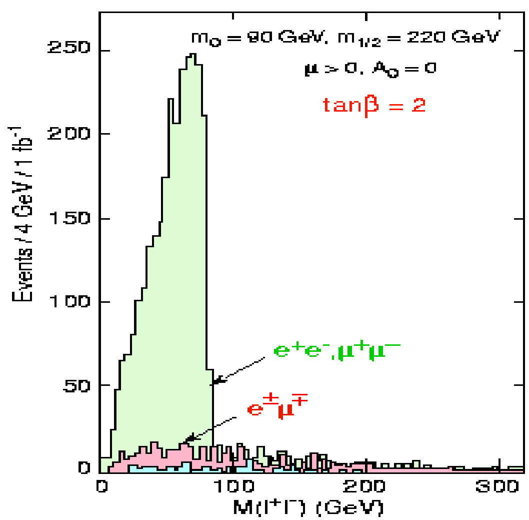


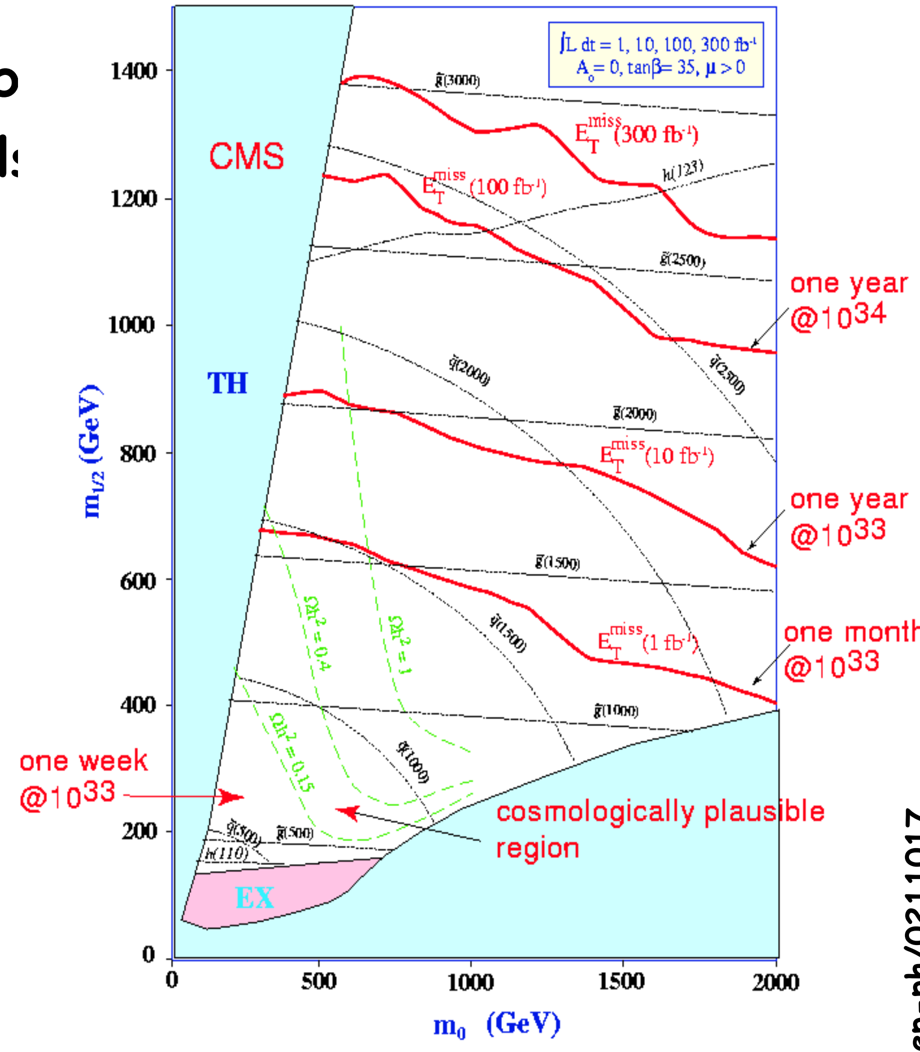


hep-ex/0504004

SUSY, LHC

- Sparticle production dominated by $\tilde{q}$, $\tilde{g}$ as at Tevatron
- 1 TeV/c^2 mSUGRA with 0.1 fb
- Similar reach in most R_P model
- Sparticle measurements:
  - $\tilde{\chi}_2^0 \rightarrow \ell\, \ell\, \tilde{\chi}_1^0$
  - $\tilde{g} \rightarrow t\, \tilde{t}_1 \rightarrow t\, b\, \tilde{\chi}_1^0$





- ILC ultimate measurments !

H1 Isolated Lepton $\not{E}_T$ Excess

- H1 observed excess of events in Run I
  - 10 GeV/c electron or muon
  - 12 GeV missing p_T and E_T
- H1 selection identical to Run I

	electron		muon		tau (new)	
	all	p_T^X>25GeV	all	p_T^X>25GeV	all	p_T^X>25GeV
H1 HERA I 118 pb^{-1}	11 11.54±1.50	5 1.76±0.30	8 2.94±0.50	6 1.68±0.30	5 5.8±1.36	0 0.53±0.10
H1 e^+p 53 pb^{-1} new	9 4.75±0.76	5 0.84±0.19	1 1.33±0.19	0 0.85±0.13		
H1 e^-p 39 pb^{-1} new	5 4.09±0.61	1 0.62±0.11	0 1.10±0.17	0 0.67±0.11		
ZEUS HERA I 130 pb^{-1}	24 $20.6^{+1.7}_{-4.6}$	2 $2.90^{+0.59}_{-0.32}$	12 $11.9^{+0.6}_{-0.7}$	5 2.75±0.21	3 $0.40^{+0.12}_{-0.13}$	2 0.20±0.05
ZEUS e^+p 40 pb^{-1} new	0 0.46±0.10	0 $0.58^{+0.08}_{-0.09}$				

Σ=26/13.38

- Observation does not fit well any new physics model

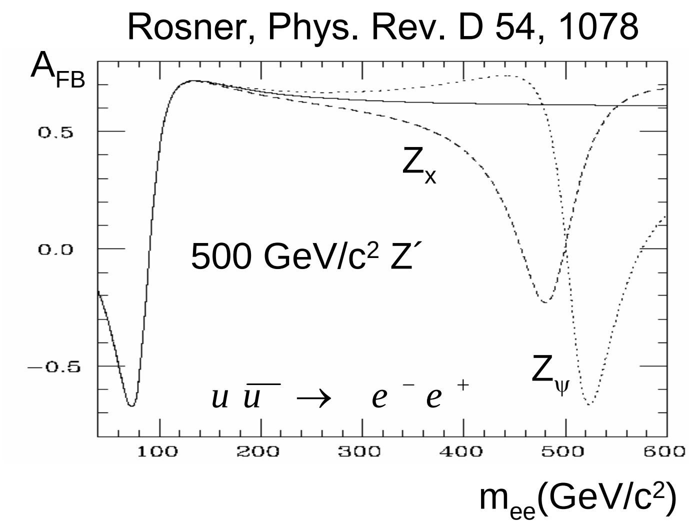
PAPER-421, 417, 257

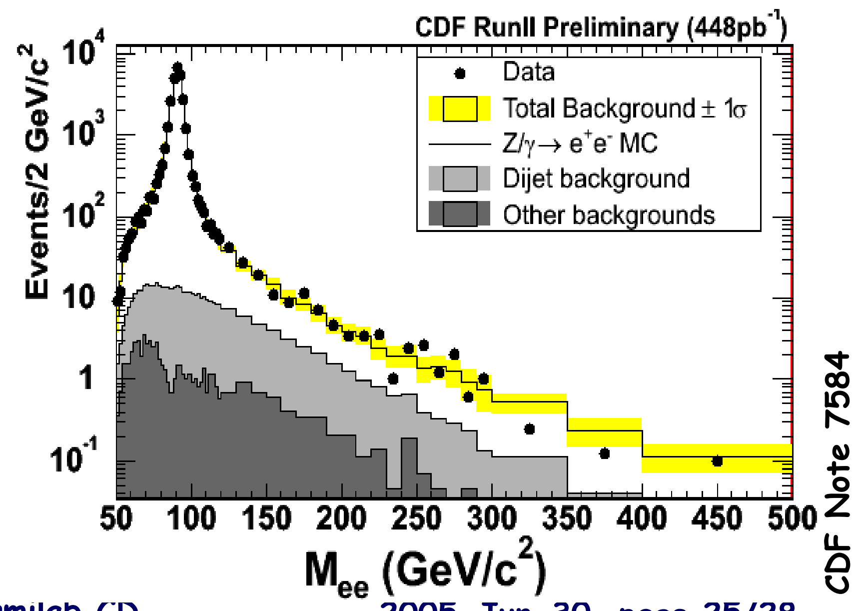
High Mass Searches

- New gauge bosons and other high mass resonances may decay into leptons, photons, jets
- Analyse two object final states
- Example: pp → e^+e^-
  - Z', LED, RS gravitons, $\not{R}_P$v, TC,…
- Refine analyses
  - generic sensitivities, spin-0,1,2
  - explore new models, d-xu, B-xL
  - include decay angle, cosΘ*
- Seq. Z' mass > 845 GeV/c^2

  within ~100 GeV of beam energy!

- Similar: μμ, ττ, eν, γγ, eγ, μγ,…
  - W', UED, ℓ*, LQ, H^{++}, …



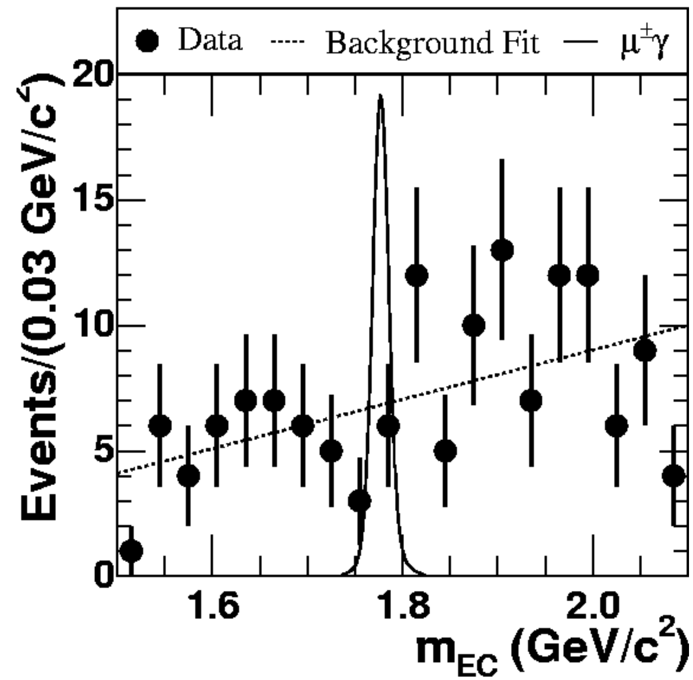


Lepton Flavour Violation

- $BR(\tau^\pm \to \mu^\pm \gamma) \approx 10^{-40}$ in SM
- LFV "unavoidable" with SUSY GUTs
- beyond MSSM with off-diagonal slepton mass matrix elements

- $2 * 10^8$ $e^+e^- \to \tau^+\tau^-$ events
- muon $p_T(\mu) > 4.5$ GeV/c
- photon $E_{cm}(\gamma) > 200$ MeV
- opposite tau as tag
- NN to discriminate background
- main background:
  - $ee \to \mu\mu$
  - $ee \to \tau\tau$ with $\tau \to \mu\nu\bar{\nu}$

  γ from initial or final state radiation
- 2σ ellipse in
  - energy constraint μγ mass
  - $\Delta E = E_{\mu\gamma} - \sqrt{s}/2$



Expect 6.2±0.5, observe 4

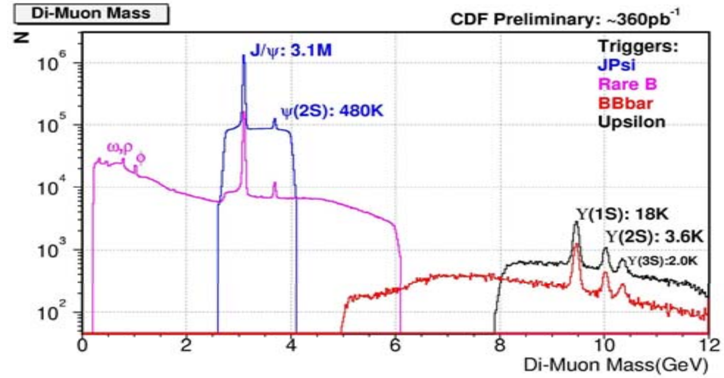
unbinned max £ fit for BR

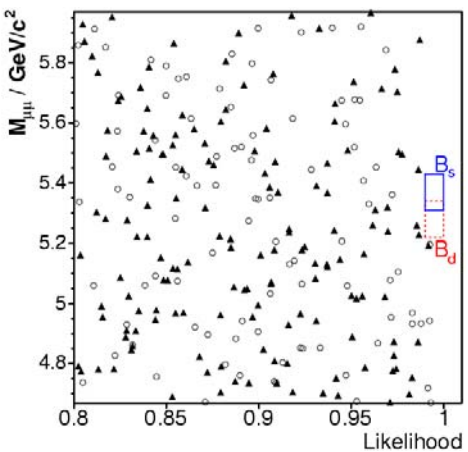
BR < $6.8 * 10^{-8}$ at 90% CL

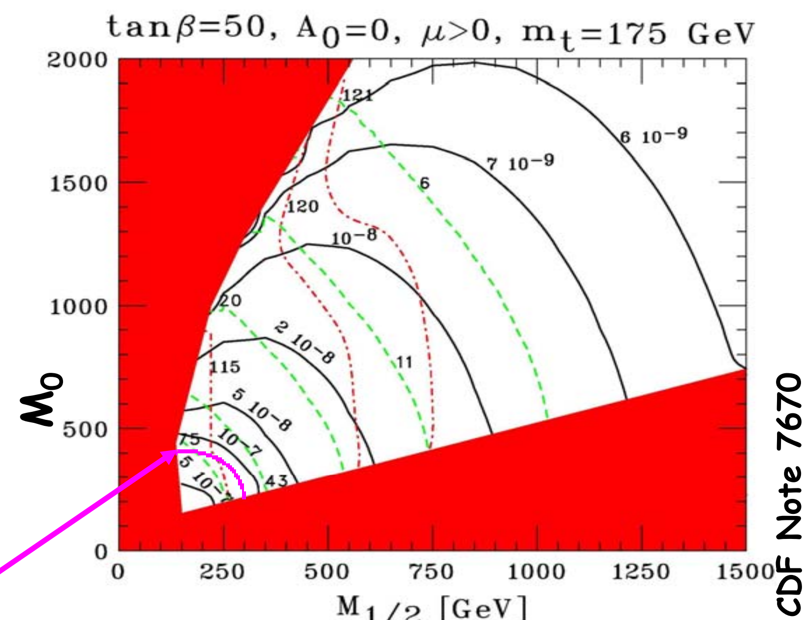
hep-ex/0502032, PAPER-141

$B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$

- FCNC heavily suppressed in SM
- New physics may enhance B_s, B_d
- MSSM BR proportional $\tan^6\beta$
- CDF $\sigma(m_{\mu\mu}) \approx 23$ MeV/c², i.e. can resolve the two decays
- normalize to $B^+ \rightarrow J/\Psi\ K^+$
- use likelihood (signal MC, background sidebands)







=> $BR(B_s) < 1.6 * 10^{-7}$ @90% CL
$BR(B_d) < 3.9 * 10^{-8}$ @90% CL

CDF+D0: $BR(B_s) < 1.2 * 10^{-7}$ @90%CL
$BR(B_d) < 3.1 * 10^{-8}$ @90%CL

Concluding Remarks

- Still no significant sign of new physics !

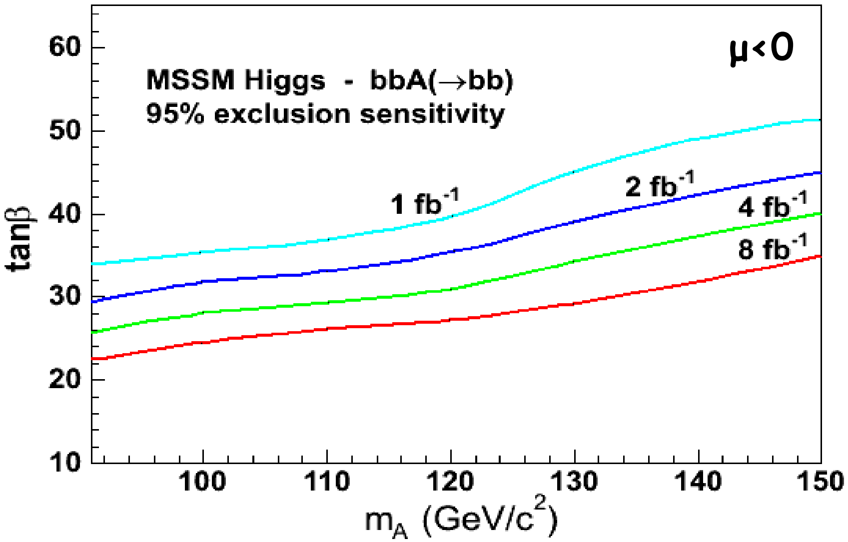
- Increasing number of signatures being investigated
- Analyses more sophisticated/refined

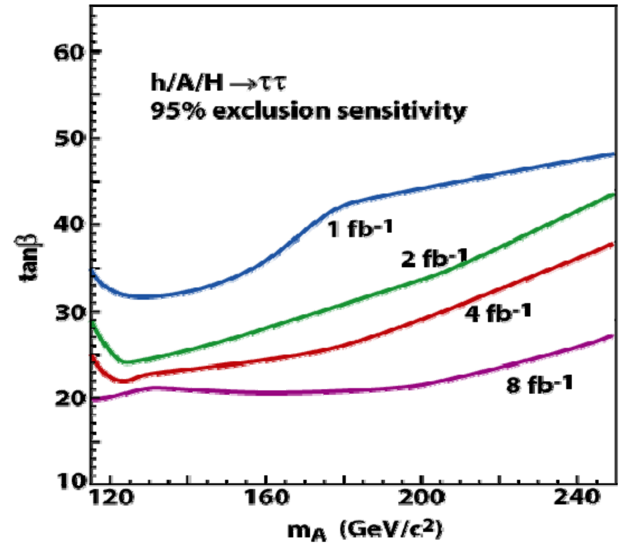
- HERA 90 pb^{-1}/>90 pb^{-1}, Tevatron > 1 fb^{-1} delivered
  ~80 pb^{-1} ~400 pb^{-1} analysed
  ≥700 pb^{-1} (mid 2007) 4.4-8.5 fb^{-1} (Oct 2009) goal

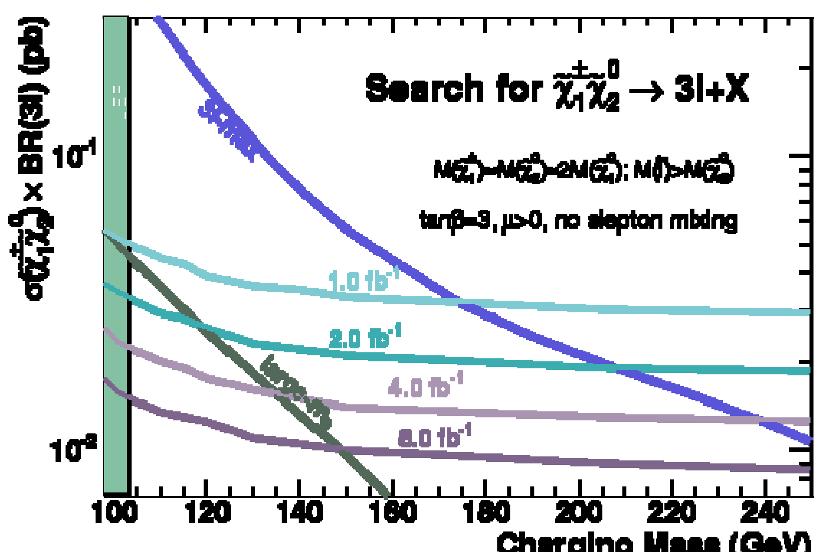
- Ongoing HERA-LHC and Tevatron-LHC workshops

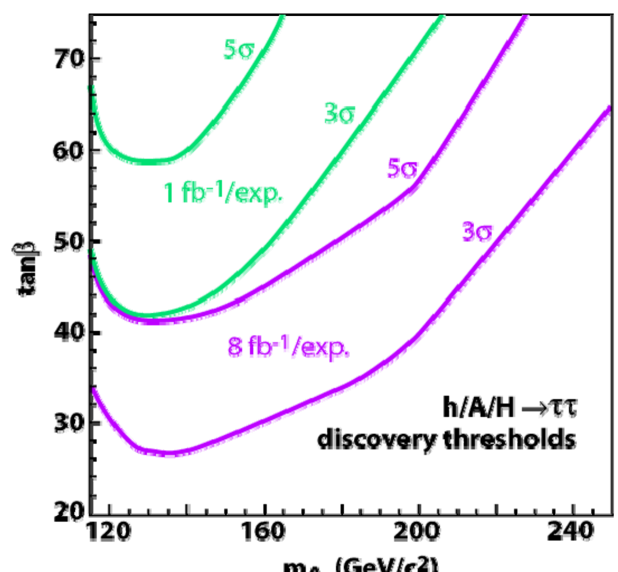
- Will HERA/Tevatron unveil new physics before LHC?

Tevatron Projections



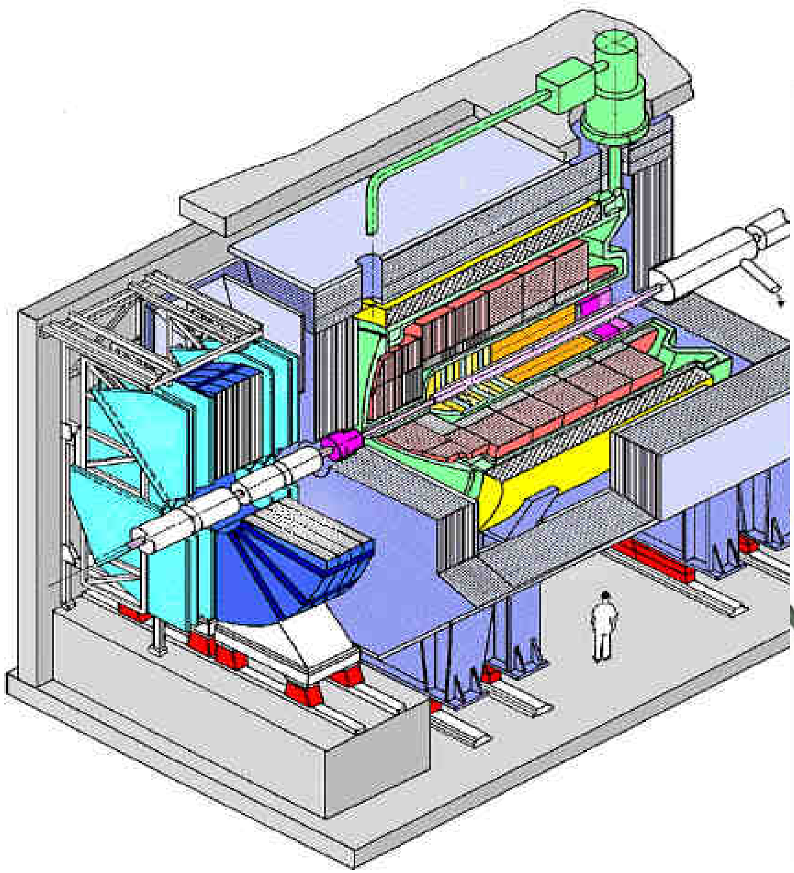


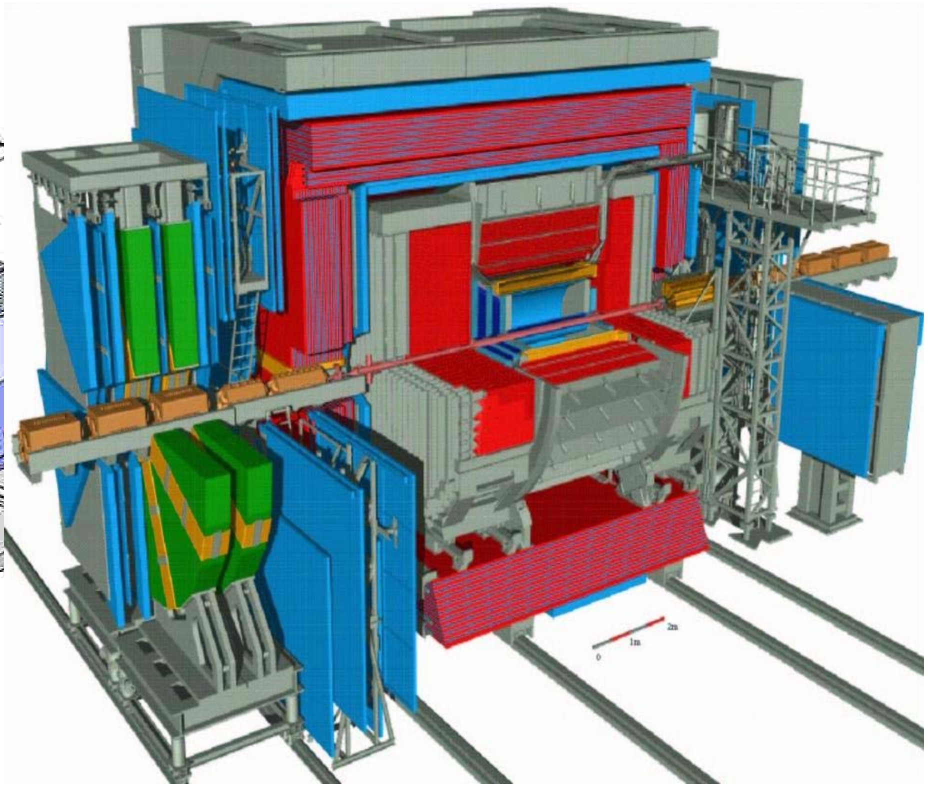




HERA H1 and ZEUS

- **Well understood, mature experiments**
  - Finely segmented compensating calorimeter
  - Good hermetic muon coverage





Fermilab Tevatron: DØ & CDF

- Well-understood, mature experiments
  - Hermetic calorimeter/muon coverage
  - Precision tracking and silicon vertex detectors