Experimental Aspects of Higgs Particle Searches

TASI 2003

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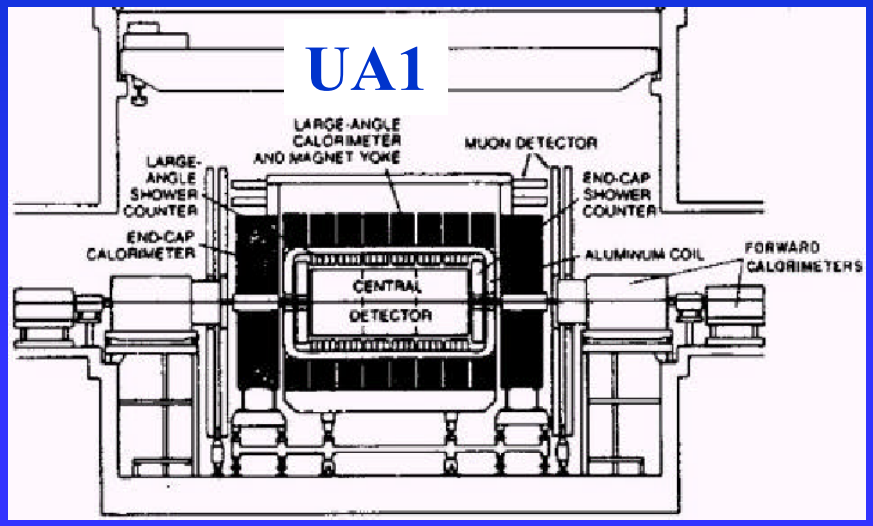
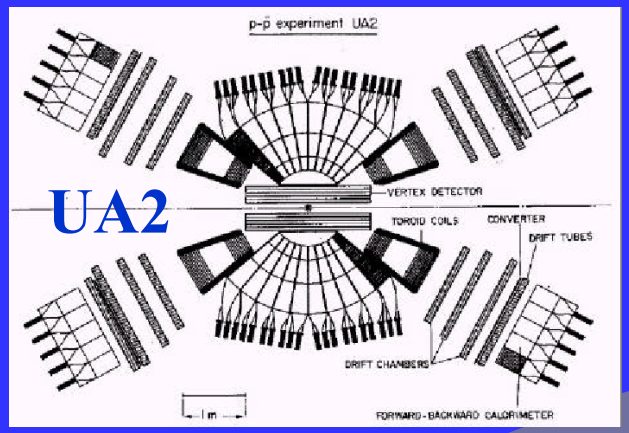
Princeton

20 Years of the W and Z Bosons





$Sp\bar{p}S \quad \sqrt{s} = 540\,\text{GeV}$

$\text{Luminosity} = 5 \times 10^{27}\ \text{cm}^{-2}/\text{s}$

Using all data from 1982-3, and combining results from UA1 and UA2:

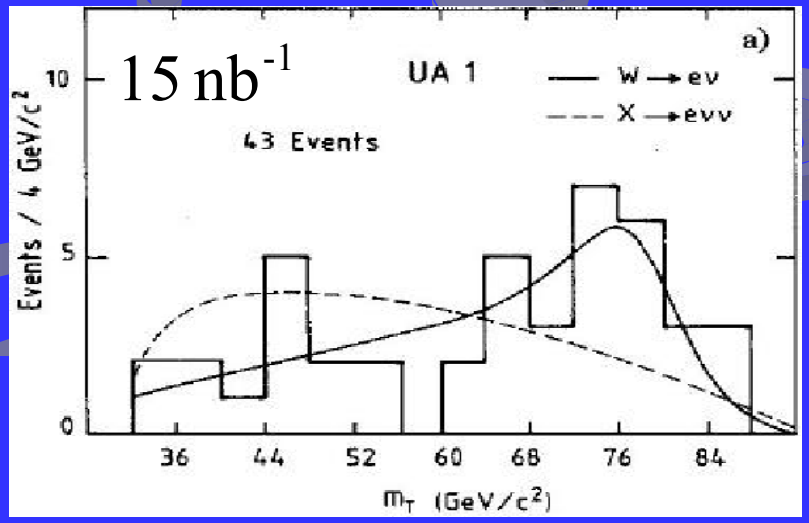
$m_{W^\pm} = 82.1 \pm 1.7$ GeV

$m_{Z^0} = 93.0 \pm 1.7$ GeV

Current values:

$m_{W^\pm} = 80.43 \pm 0.04$ GeV

$m_{Z^0} = 91.188 \pm 0.002$ GeV



Spontaneous Symmetry Breaking

Two Primordial Gauge Interactions:

$$\partial_\mu \to \partial_\mu + ig'\frac{Y}{2}B_\mu + igT_iW_\mu^i$$

Hypercharge(Y)
$U(1)_Y$ Symmetry

$$T = 0 \qquad Y = 0$$

$$B_\mu$$

Left-Handed Isospin(T)
$SU(2)_L$ Symmetry

$$T = 1 \qquad Y = 0$$

$$\begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}$$

Y

T

Higgs Field
1-complex doublet

$$T = \tfrac{1}{2} \qquad Y = 1$$

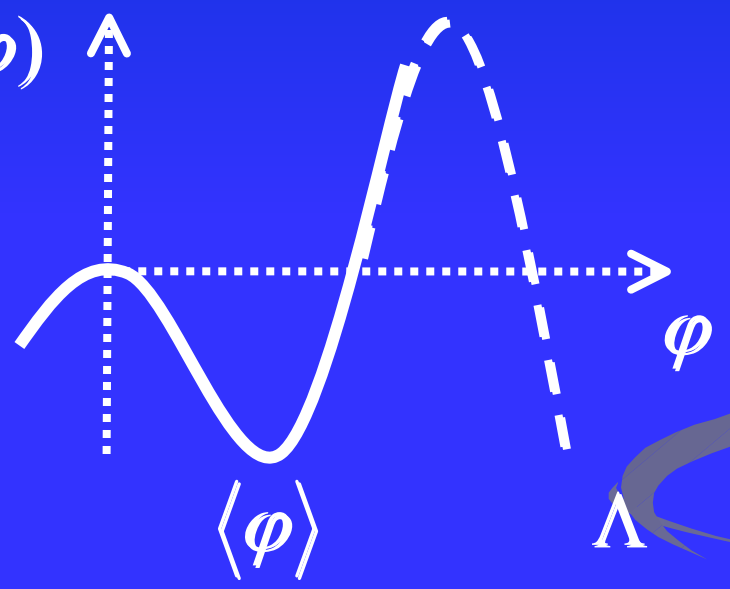
$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{C} \begin{pmatrix} \bar{\varphi}^0 \\ -\varphi^- \end{pmatrix}$$

Properties of the Physical Vacuum

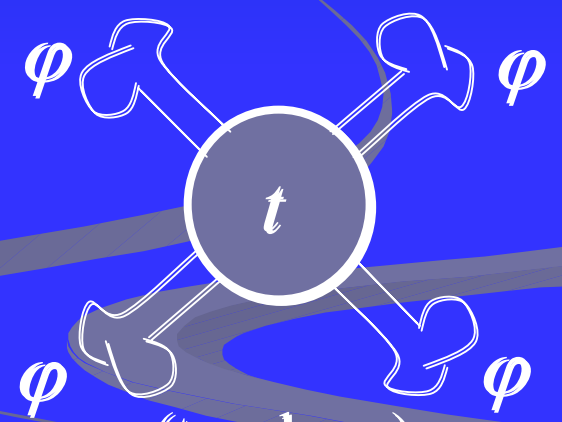
Self-Interacting Effective Potential:

$$V(\varphi) = -\mu^2\varphi^2 + \lambda\varphi^4$$

(tree-level)



$$\lambda(\Lambda) \rightarrow \text{negative}$$



(top-loop)

$$T_3\langle\varphi\rangle = -\tfrac{1}{2}$$

$$Y\langle\varphi\rangle = 1$$

$$(Q = T_3 + \frac{Y}{2})\langle\varphi\rangle = 0$$

Electric Charge(Q)
$U(1)_{EM}$ Symmetry

$$\boxed{Q = 0} \qquad A_\mu$$

$$\varphi^\pm, \mathrm{Im}\{\varphi^0\} \Rightarrow W_L^\pm, Z_L$$

$$\mathrm{Re}\{\varphi^0\} \Rightarrow \langle\varphi\rangle + H$$

missing link

Is the Z just a massive W^0?

If isospin (*T*) were an unbroken symmetry,

$$T = \tfrac{1}{2} \quad e_L^- \qquad \xrightarrow{\text{allowed}} \qquad T = 1 \quad W^0$$

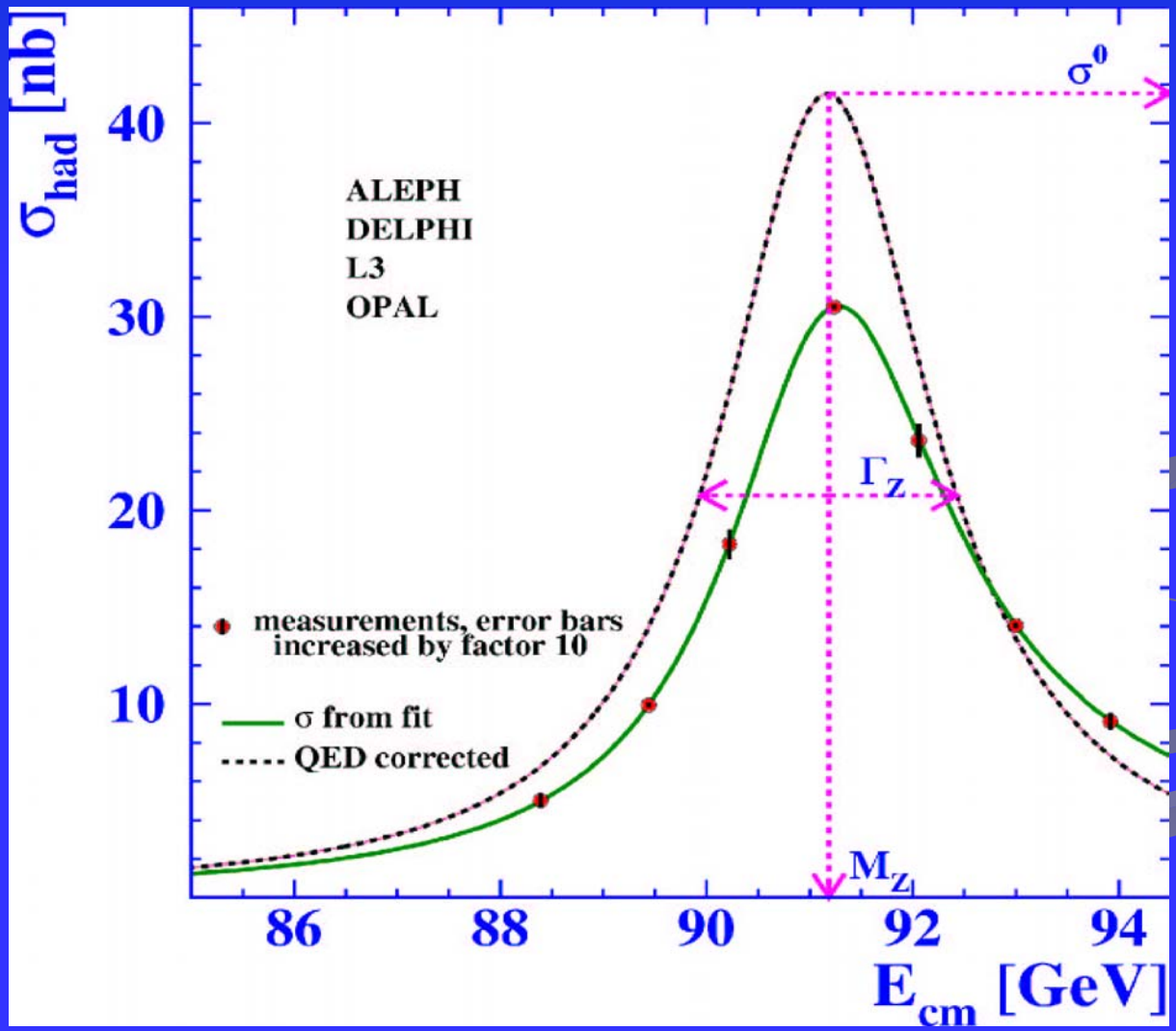
$$T = \tfrac{1}{2} \quad e_R^+$$

$$T = 0 \quad e_R^- \qquad \xrightarrow{\text{not allowed}} \qquad T = 1 \quad W^0$$

$$T = 0 \quad e_L^+$$

The measurement of $e_R^- e_L^+ \to Z$ **gives us** $\sin^2\theta_W$

Precision Measurements at the Z pole



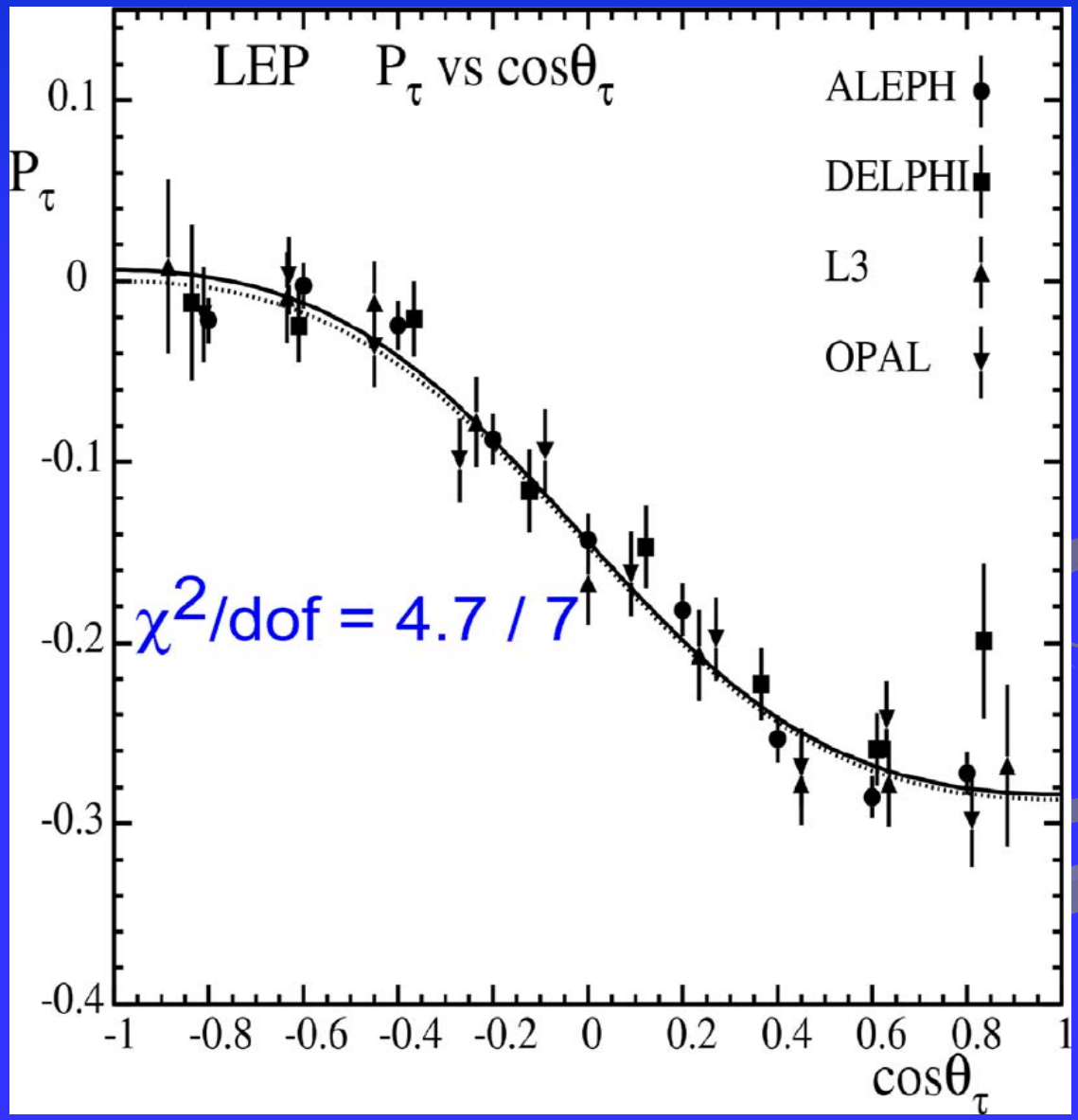
M_Z = 91.1875 (21) GeV

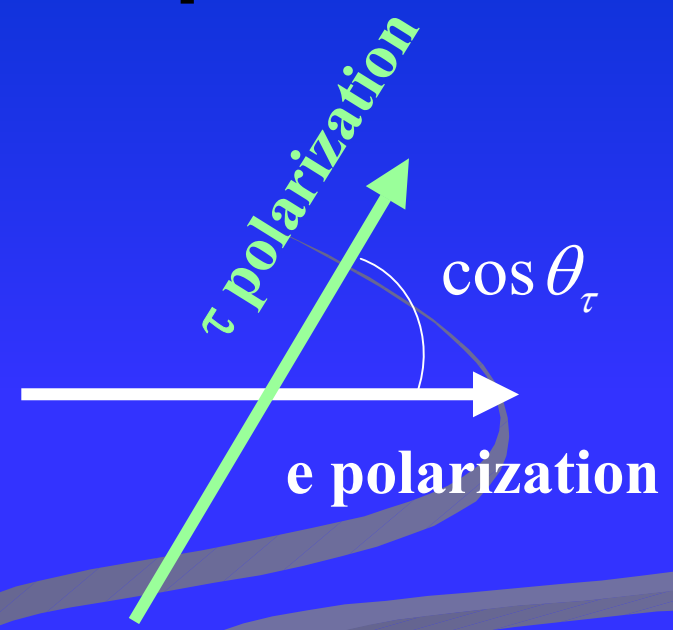
Γ_Z = 2.4952 (23) GeV

σ_0 = 41.540 (37) nb

N_ν = 2.9841 (83)

Polarization of the τ lepton





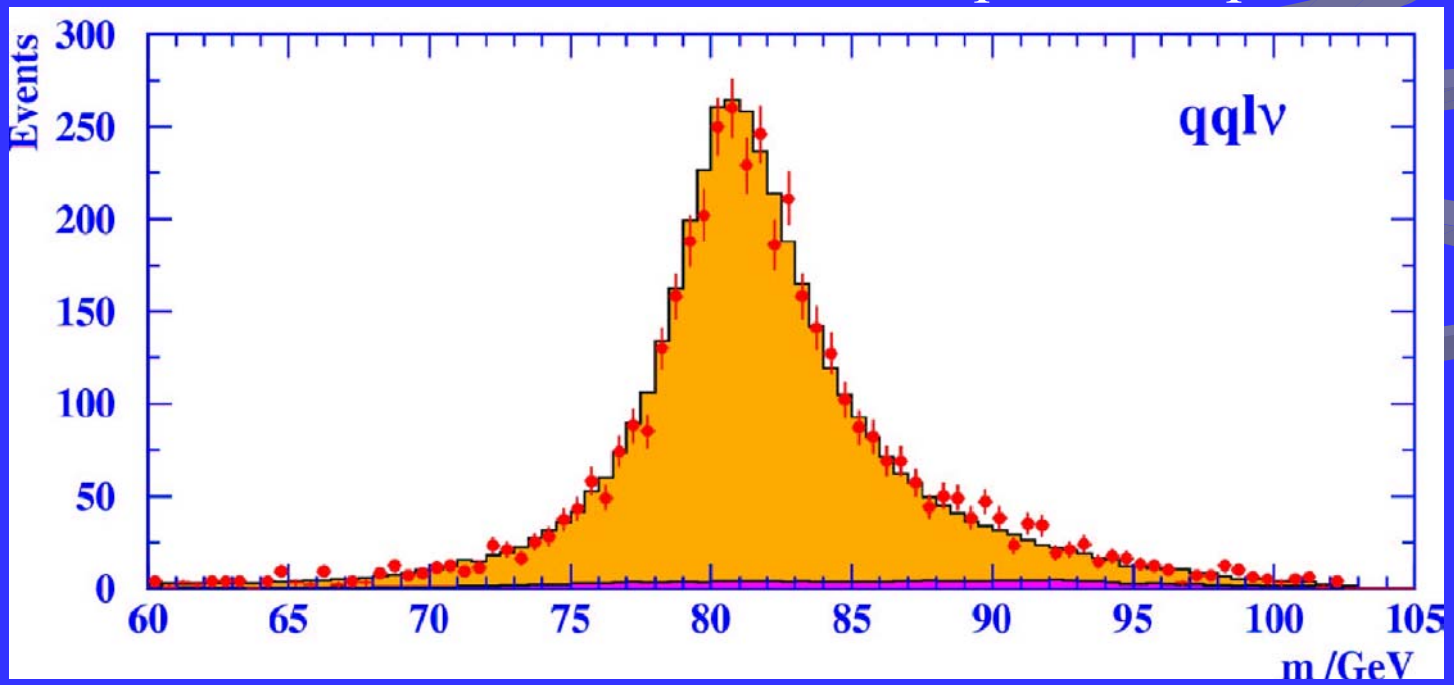
$$P_\tau(0) = -A_\tau \approx -2(1-4\sin^2\theta_{\text{eff}}^{\text{lept}}) \approx -15\%$$

Determination of W Mass from LEP2

Threshold Production Measurements

at $\sqrt{s} = 161\,\mathrm{GeV}$

were overwhelmed by above threshold
direct reconstruction methods in semi-leptonic W pair events



EW Mixing Angle

From polarization measurements, we find

$$\sin^2\theta_{eff} = 0.23148\ (17)$$

However, the tree-level relationship is

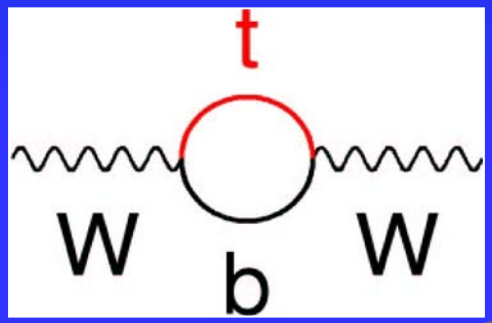
$$\sin^2\theta_W = 1 - \left(M_W / M_Z\right)^2$$
$$= 0.2277 \pm 0.0013\,(stat.) \pm 0.0009\,(\text{syst.})$$

Global Electroweak Fits

Each observable is calculated as a function of:

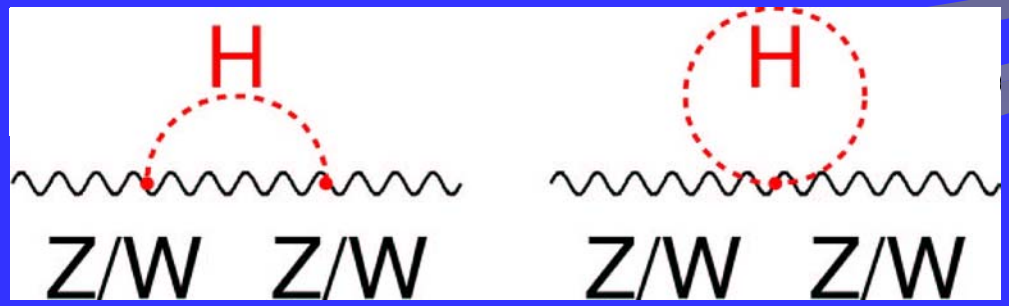
$$\Delta\alpha_{had}\ ,\ \alpha_s(M_Z)\ ,\ M_Z\ ,\ M_{top}\ ,\ M_{higgs}\ \ \text{(and } G_F\text{)}$$

Top quark loop



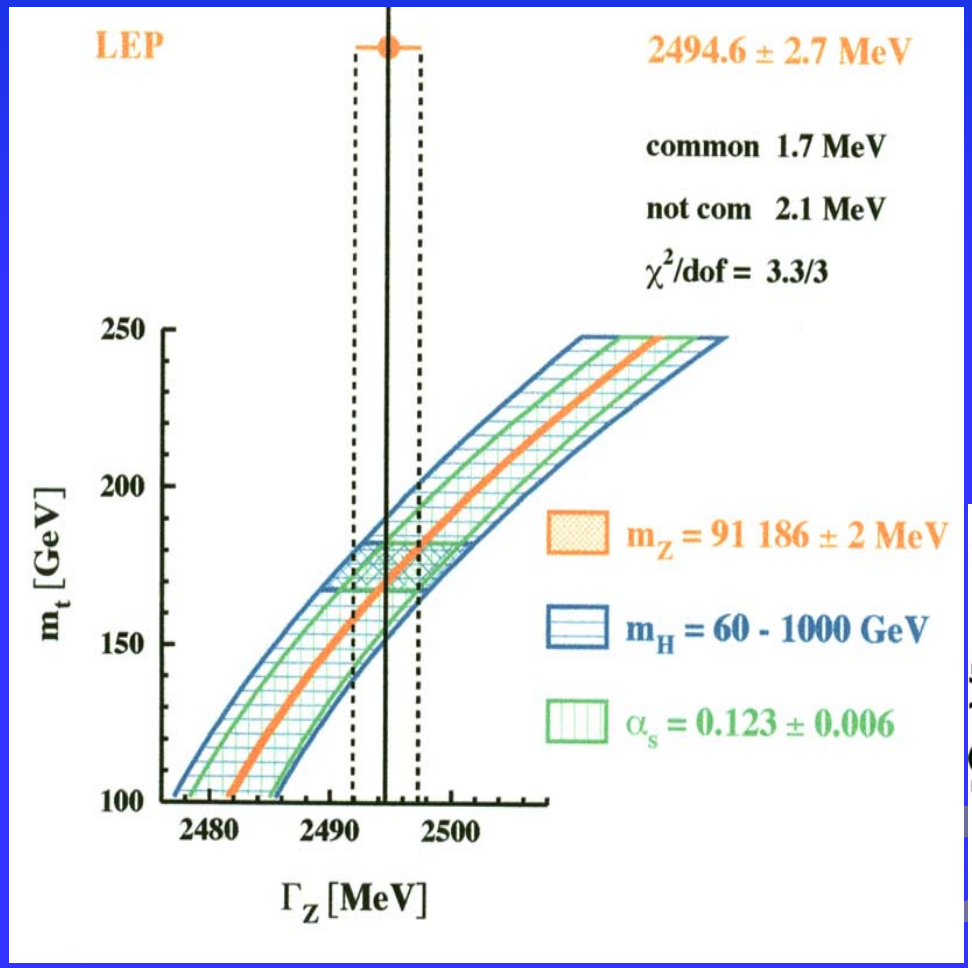
$$\Delta r^{top} \propto G_F\, M_{top}^2$$

Emission and absorption of a virtual Higgs particle



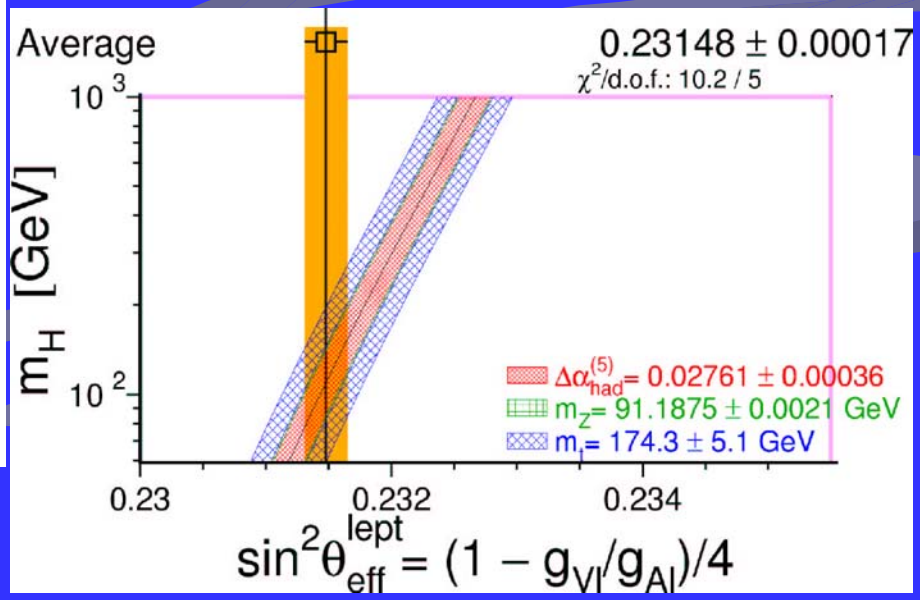
$$\Delta r^{H} \propto \log M_{higgs}$$

Mass Estimates from Radiative Corrections



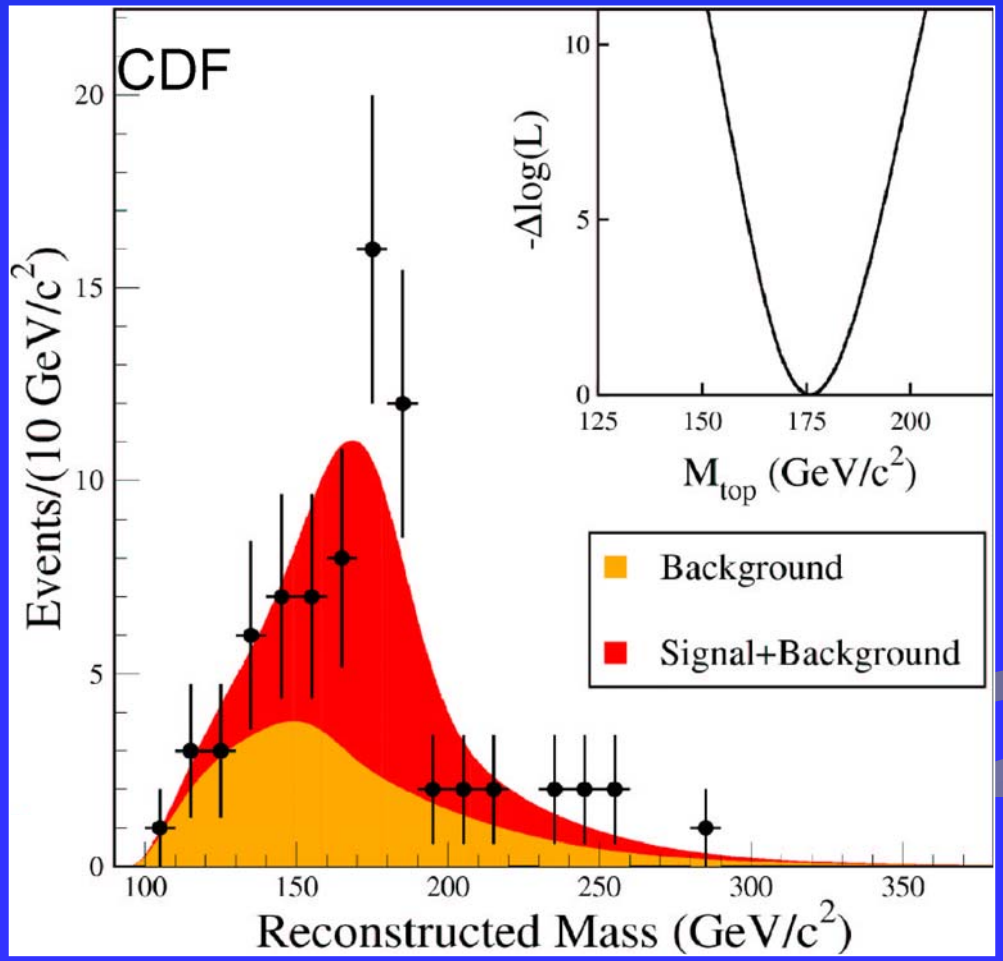
In 1994-5, the top mass was estimated from LEP data.

Now we face similar estimates for the lightest Higgs boson.



Top Mass from Tevatron Run I

Run I result: $M_{top} = 174.3 \pm 3.2$ (stat.) ± 4.0 (syst.) GeV



Recent re-evaluation of the Run I top mass from DØ:

$M_{top} = 180.1 \pm 3.6$ (stat.) ± 4.0 (syst.) GeV

(compared with ± 5.6 GeV)

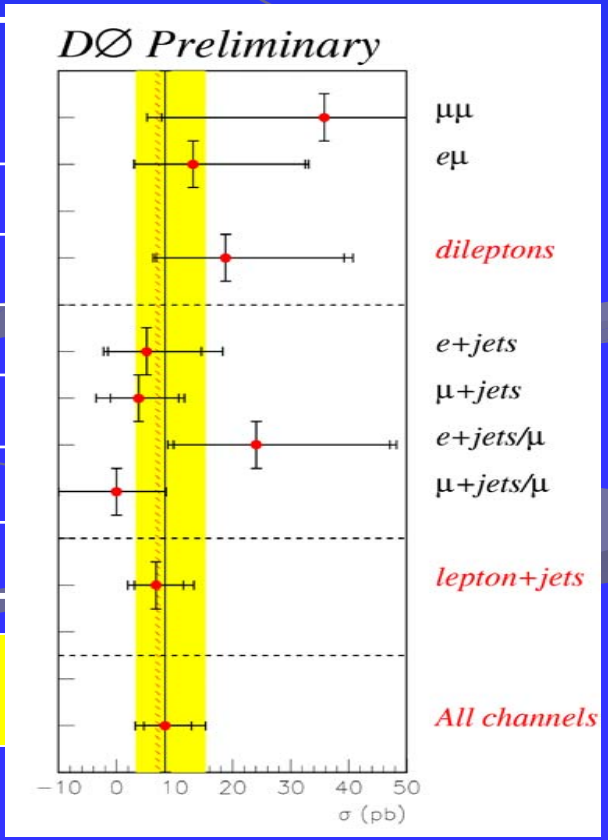
Dominant systematic from Jet Energy Scale will be reduced by scanning M_W

Run-2 Top Measurements

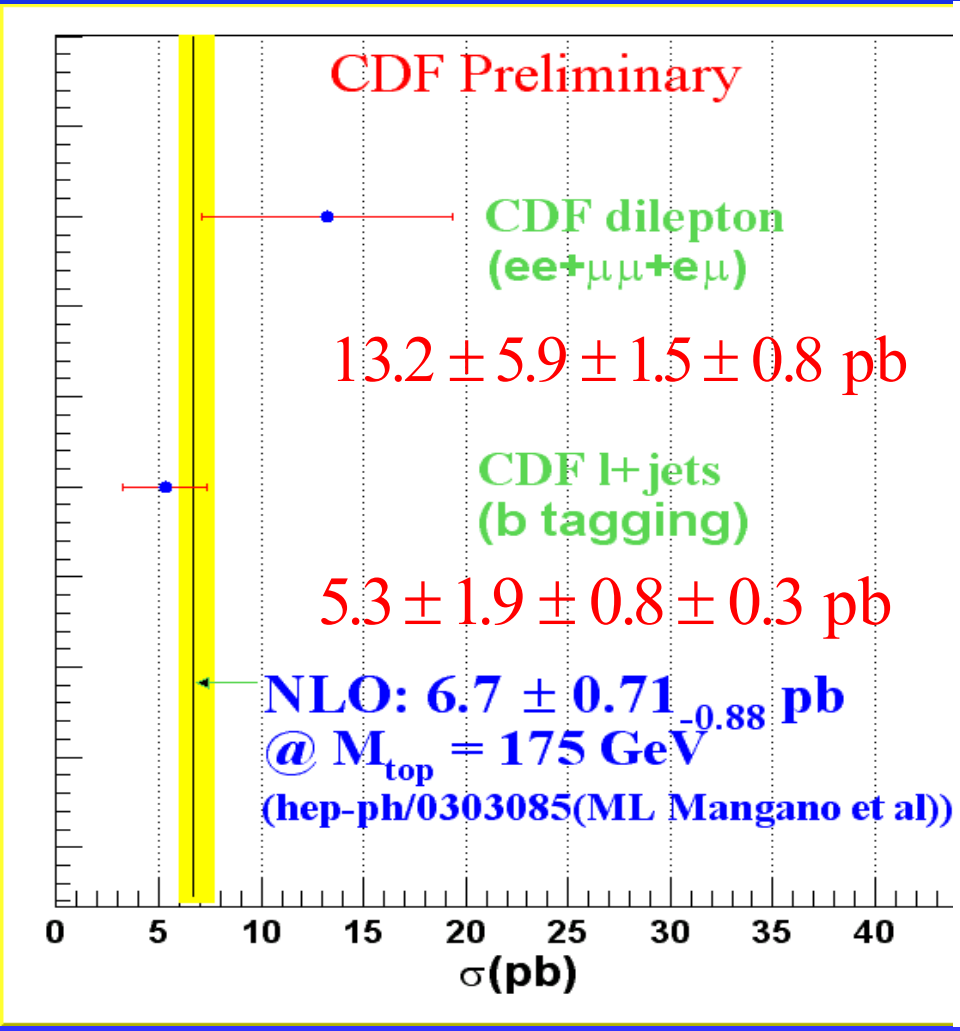
Cross-section measurements for $\sqrt{s} = 1.96\,\text{TeV}$ are being reported. Candidates seen in all channels.

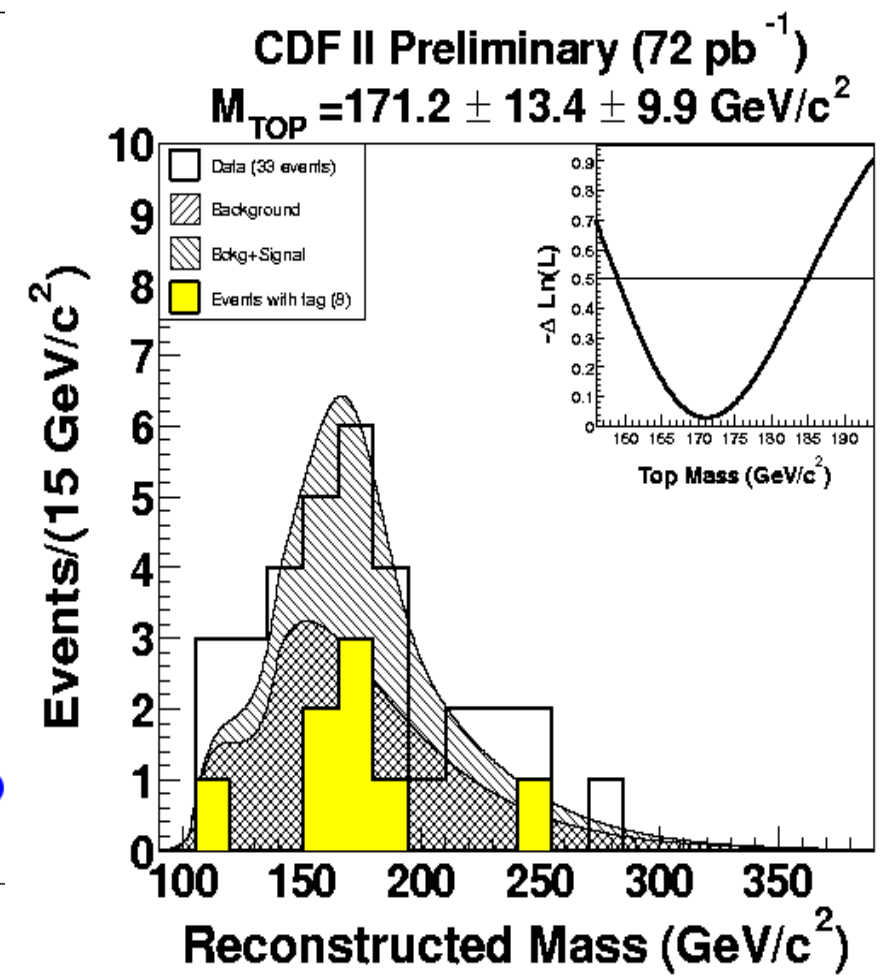
Channel	Lum(pb^{-1})	Expected Background	Expected Signal	Obs.
e+jet	50	2.7+/-0.6	1.8	4
μ+jet	40	2.7+/-1.1	2.4	4
e+jet/μ	50	0.2+/-0.1	0.5	2
μ+jet/μ	40	0.6+/-0.3	0.4	0
μμ	43	0.60+/-0.30	0.30+/0.04	2
eμ	33	0.07+/-0.01	0.50+/0.01	1

$$\sigma = 8.4\,^{+4.5}_{-3.7}\,(\text{stat})\;^{+5.3}_{-3.5}\,(\text{syst}) \pm 0.8\,(\text{lumi})\,\text{pb}$$

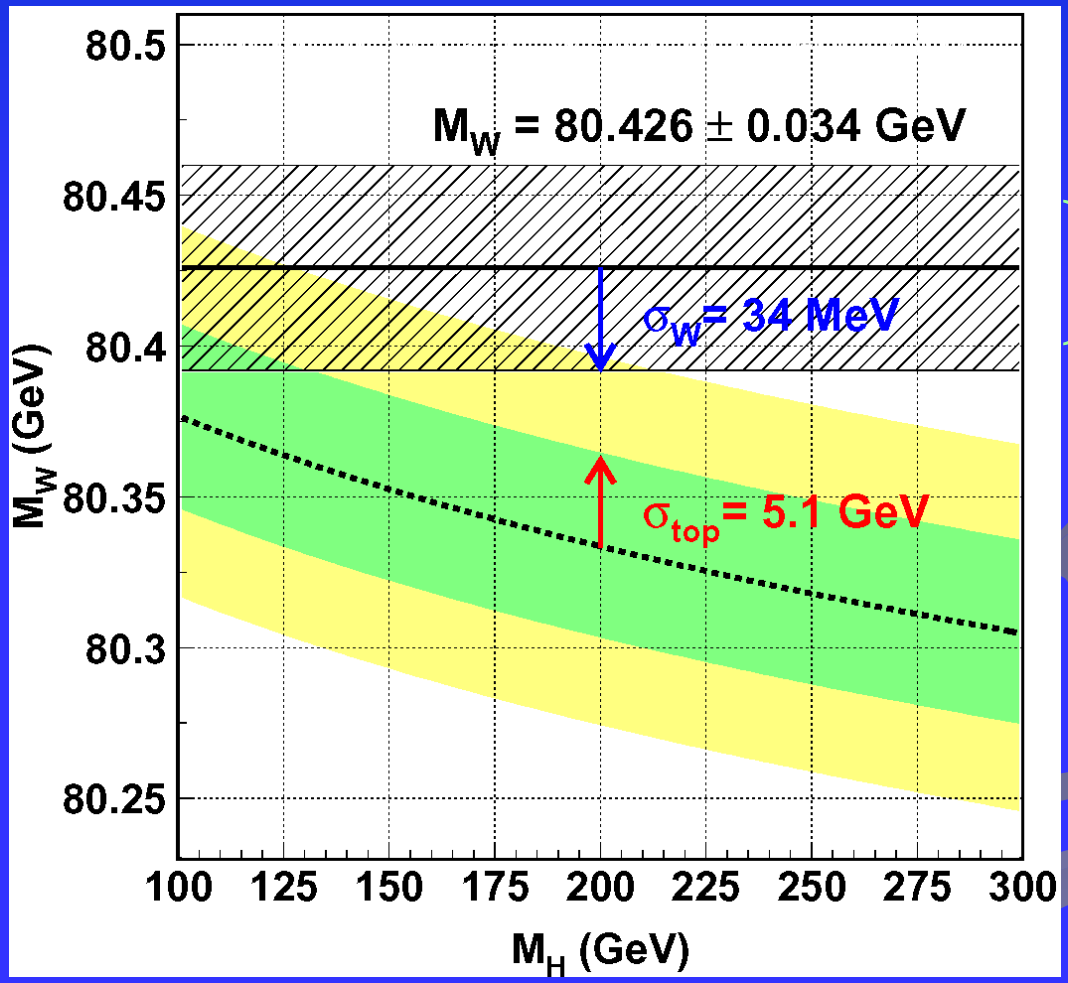


Run-2 Top Mass





Measured/Fit W Mass Constraint



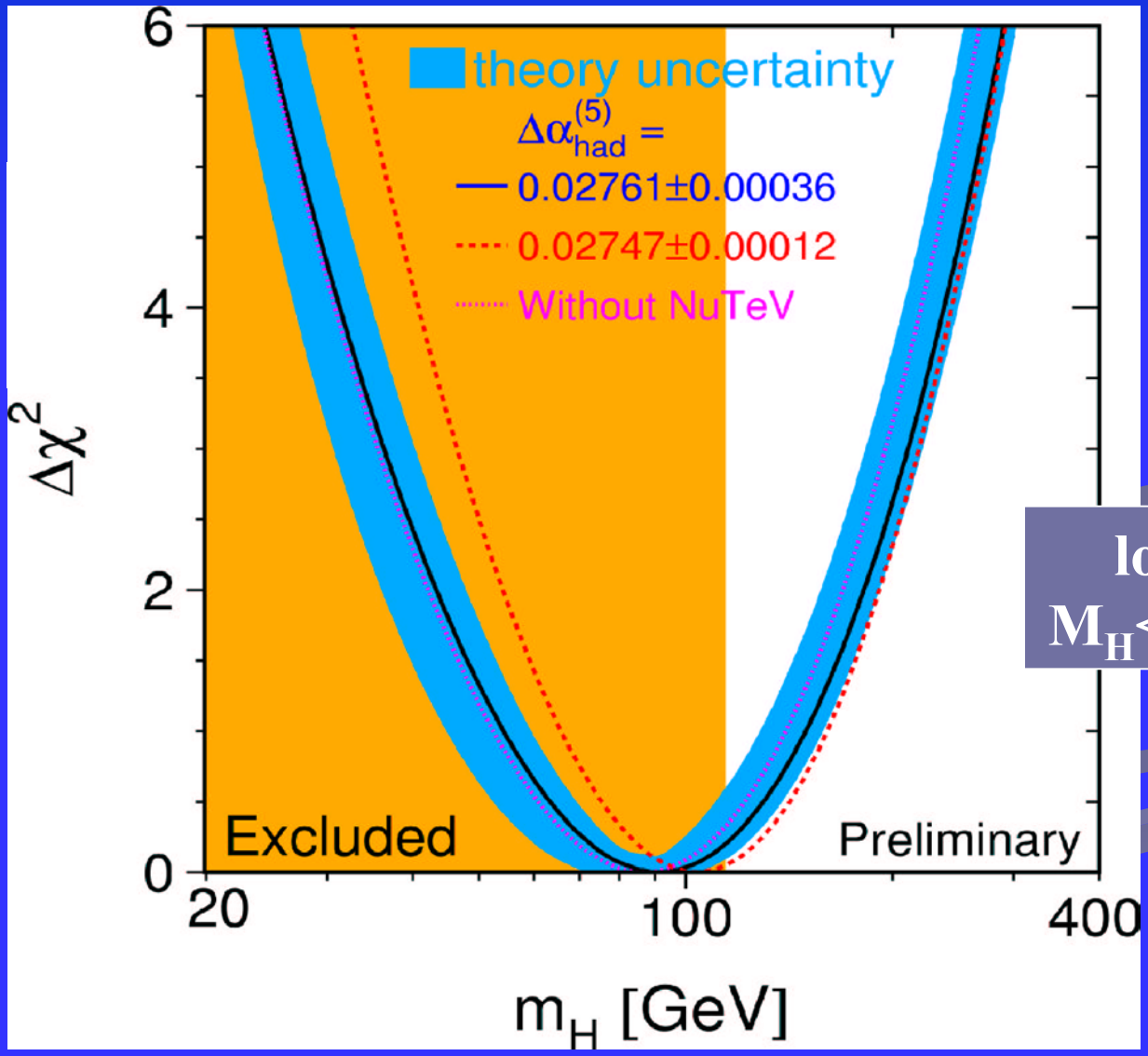
Standard Model
Precision Electroweak Data

Shrink the uncertainties on M_W and M_{top}

Low Mass Preference for the Higgs Boson

Closing-in on the Higgs Boson

TASI



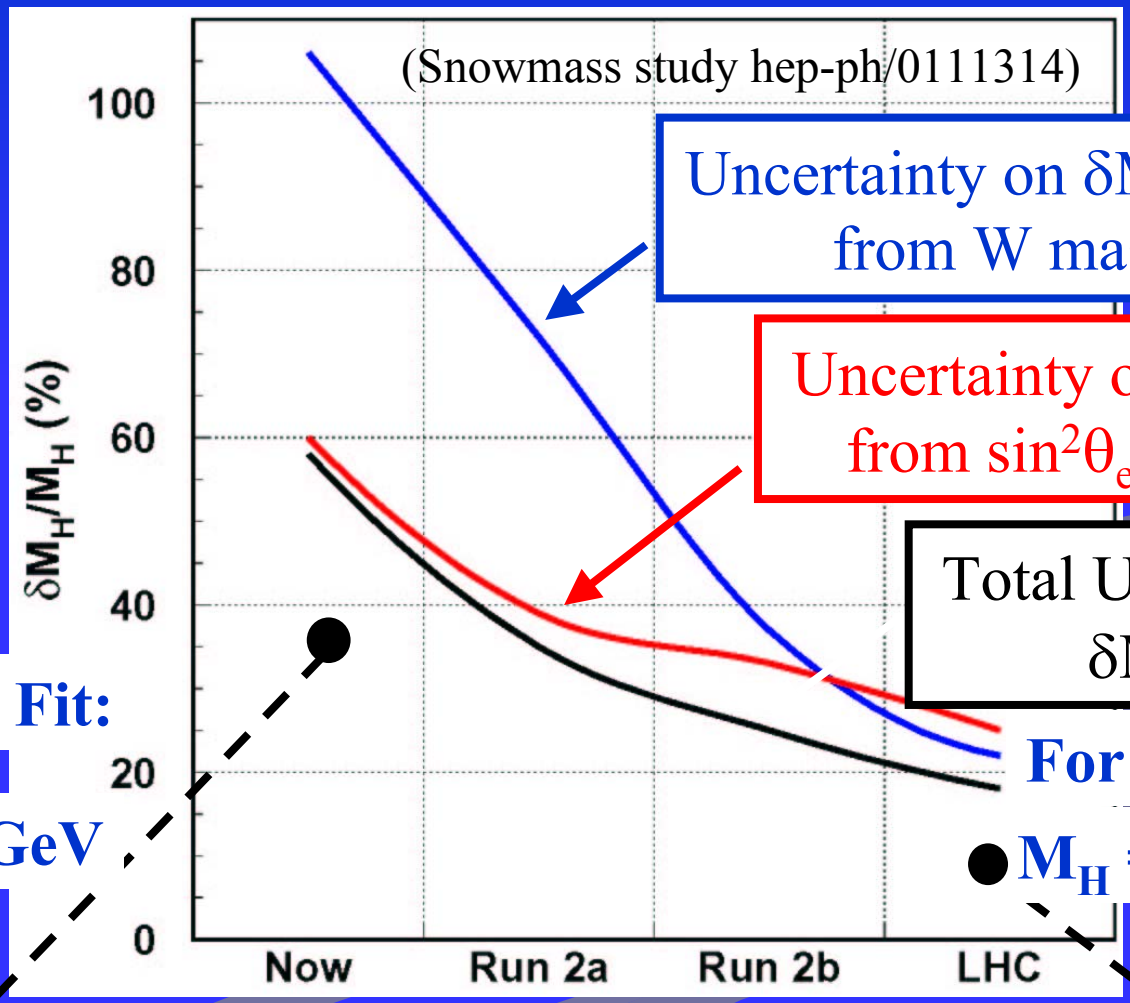
Electroweak Fit:

$$M_H = 91^{+58}_{-37}\ \text{GeV}$$

$\log M_H \approx 1.96 \pm 0.21$

$M_H < 211$ GeV @ 95% CL

Precision of Electroweak Constraints with Time



Electroweak Fit:

$M_H = 91^{+58}_{-37}$ GeV

$\log M_H \approx 1.96 \pm 0.21$

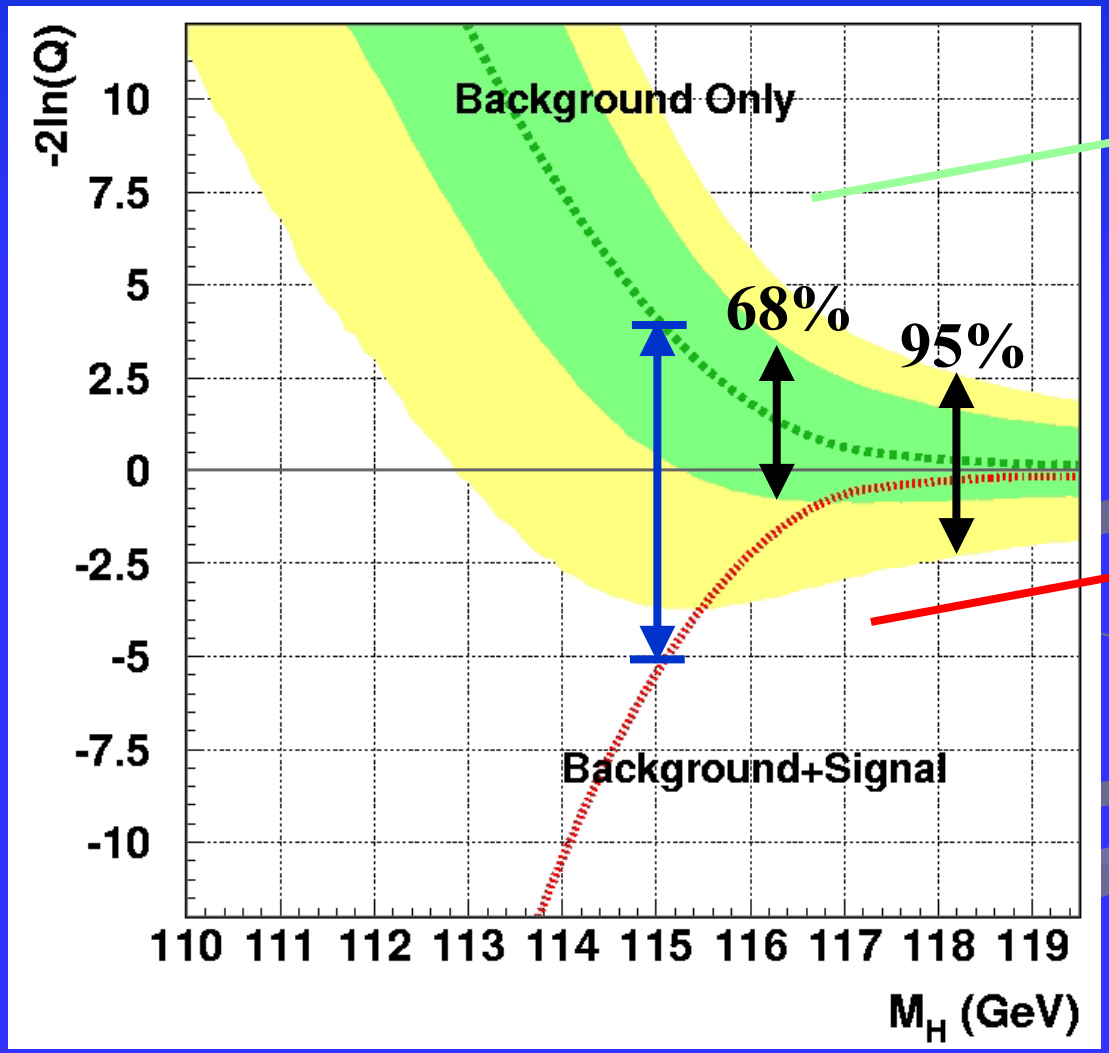
$M_H < 211$ GeV @ 95% CL

For Example:

$M_H = 115^{+19}_{-16}$ GeV

$\log M_H \approx X.XX \pm 0.06$

Scanning the Higgs Boson Mass Range

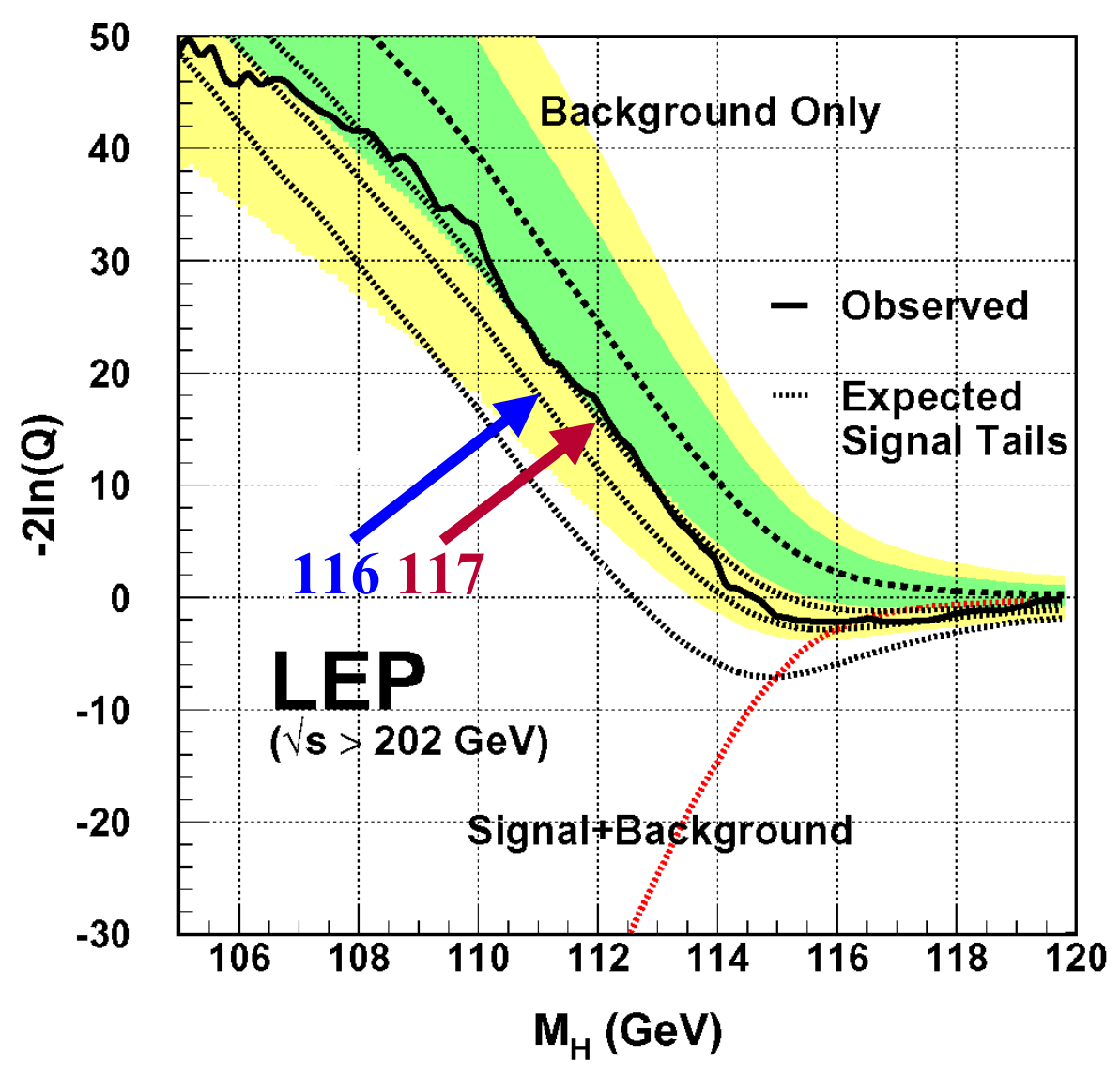


Measure median separation of hypotheses

Compare with widths of distributions

Scan versus Mass

LEP Higgs Boson Results



Very Slight Excess Compatible with Predicted Rates above:

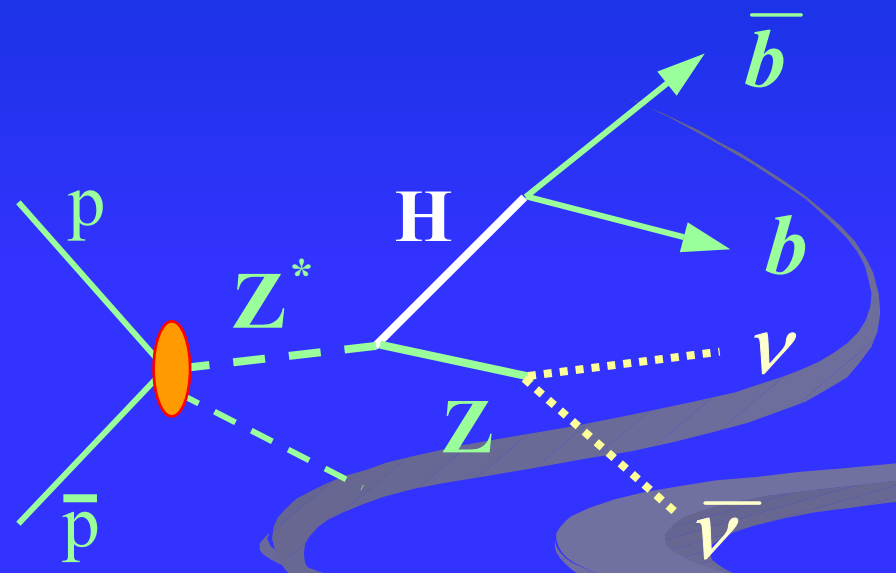
$$m_H > 116\ \text{GeV}$$

Lower Limit Set at CL=95%:

$$m_H = 114.4\ \text{GeV}$$

Higgs Boson Searches at the Tevatron

$$p\bar{p} \rightarrow Z + H$$
$$\hookrightarrow b\bar{b}$$
$$\hookrightarrow \nu\bar{\nu}$$



- 2 b-jets
- missing E_t

Double Secondary Vertex b-Tag

What are the backgrounds that produce b-jets and missing energy?

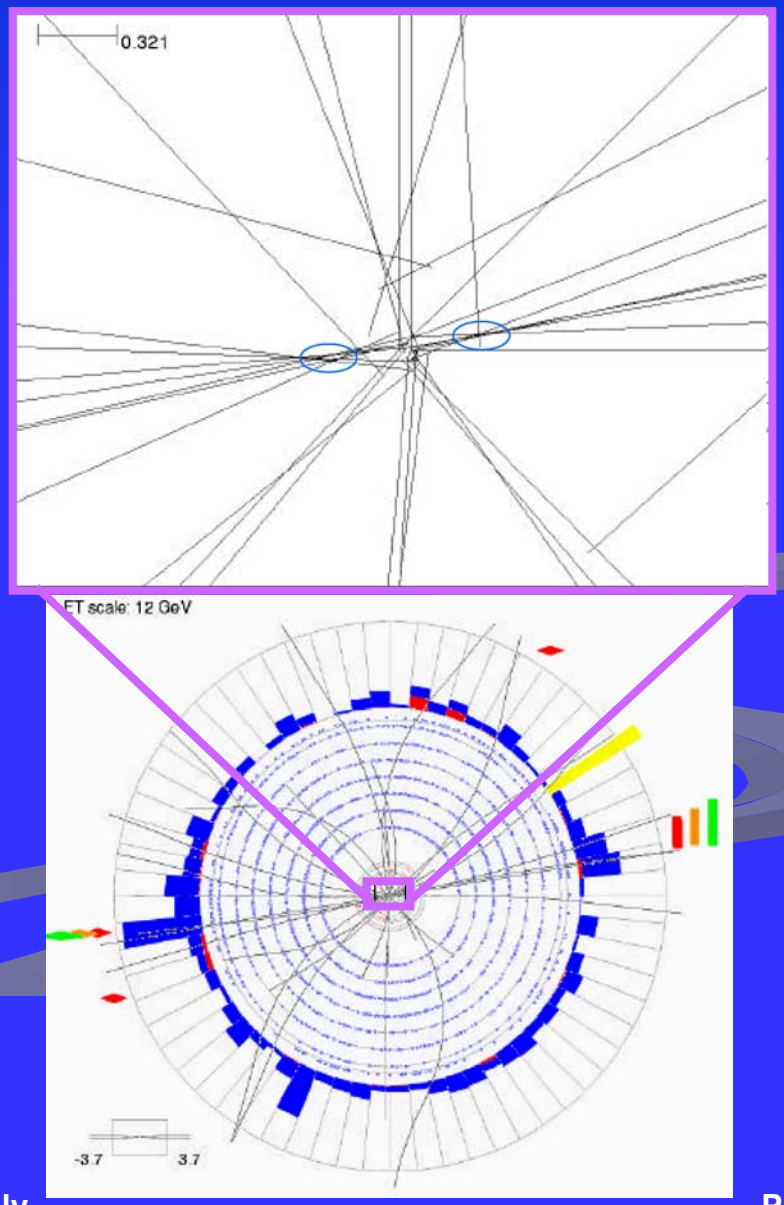
$t\bar{t}$

$t\bar{b}/qt\bar{b}$

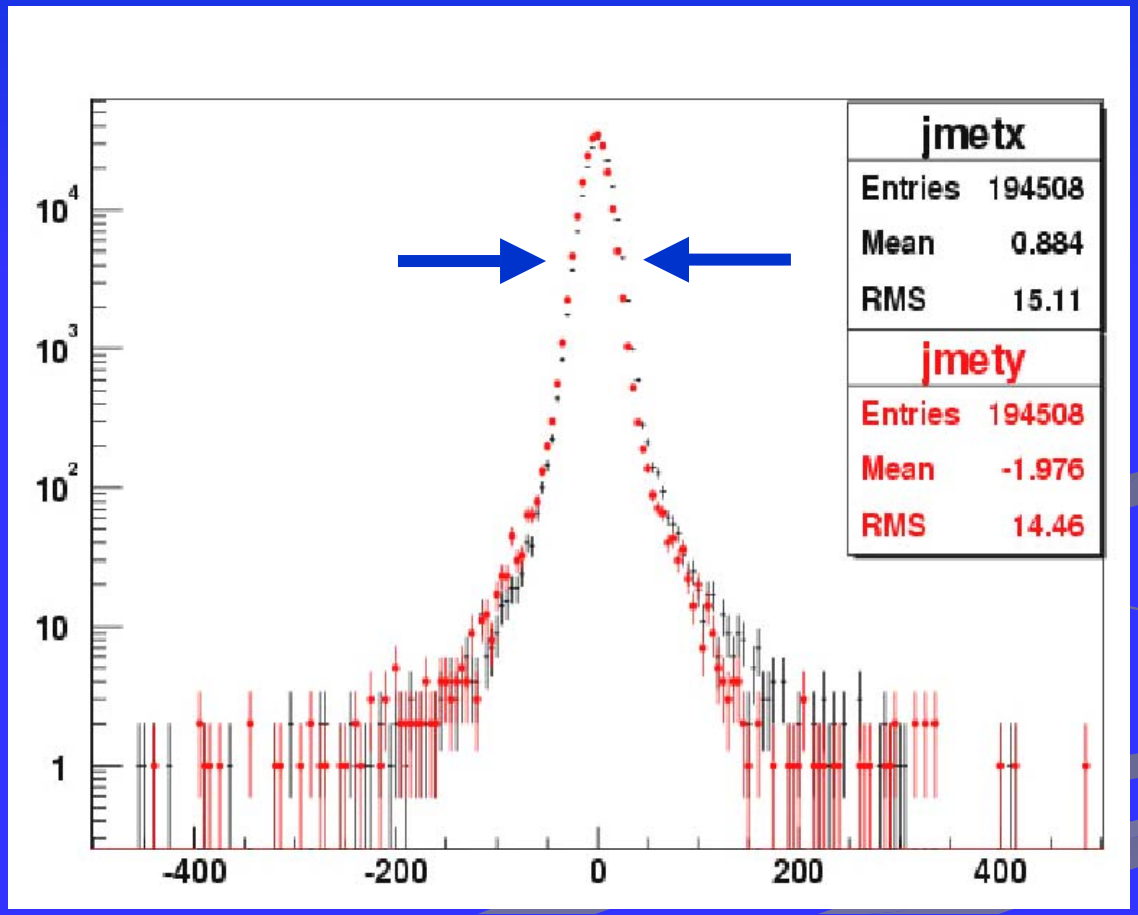
ZZ/WZ

Z+gluon/W+gluon

QCD $b\bar{b}$ + semi-leptonic decays



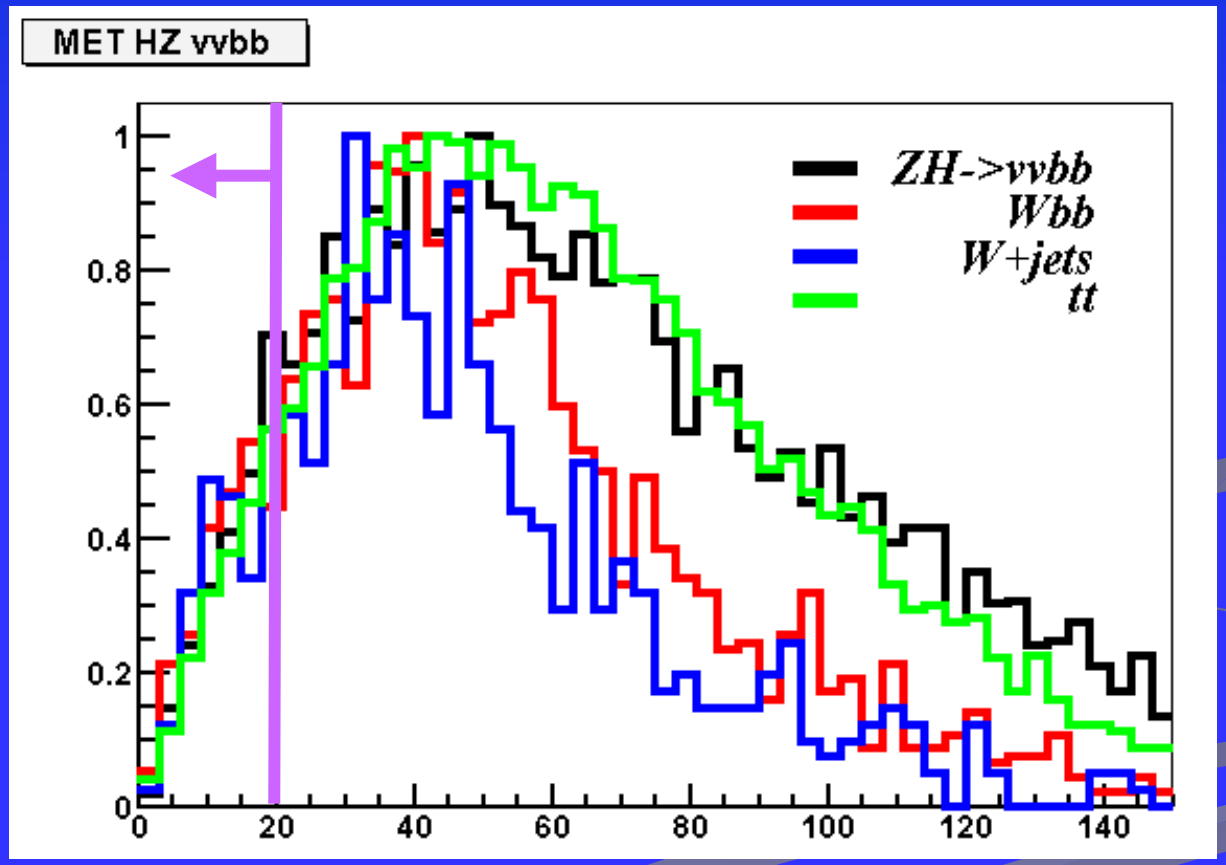
Missing Energy Resolution



Missing Energy Component (GeV)

Shrink to 10 GeV or less

Missing Energy Distribution

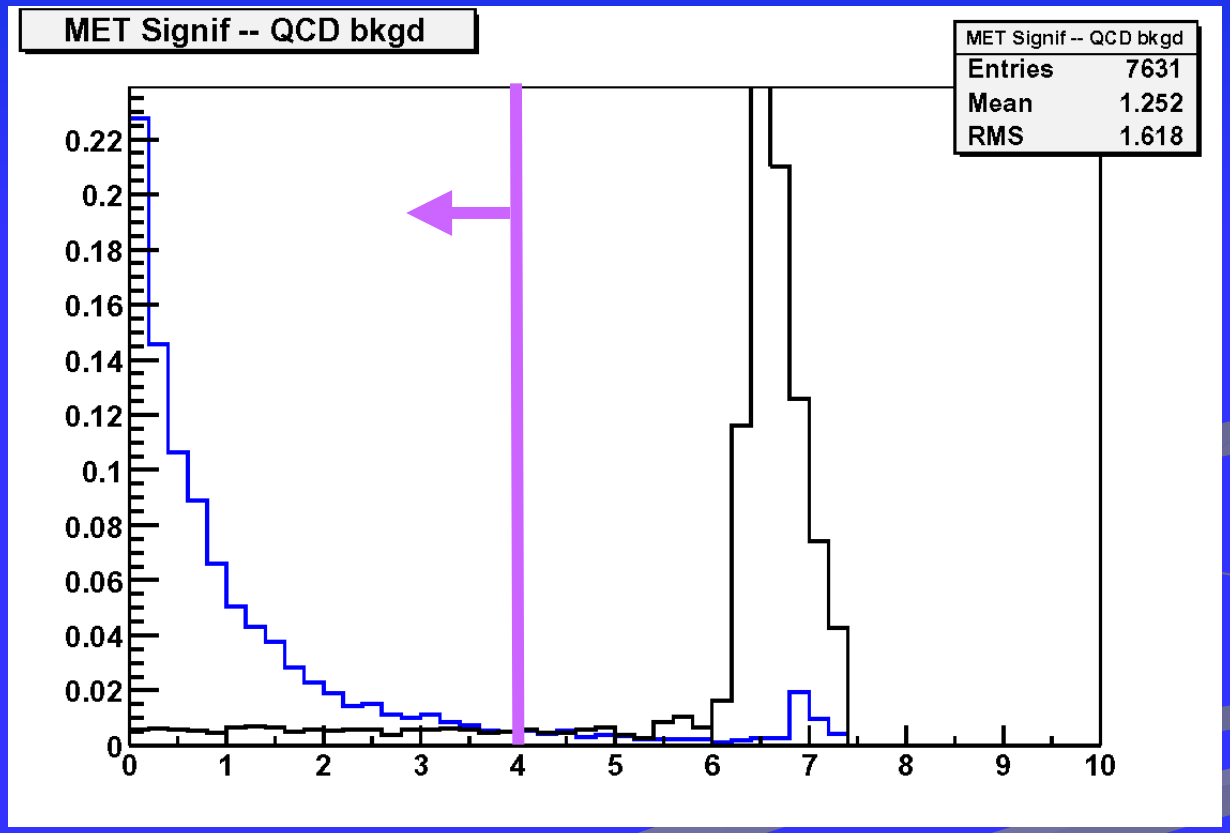


Missing Energy (GeV)

$ZH \rightarrow \nu\nu bb$

Missing Energy tends to be at least $M_Z/2$

Missing Energy Significance

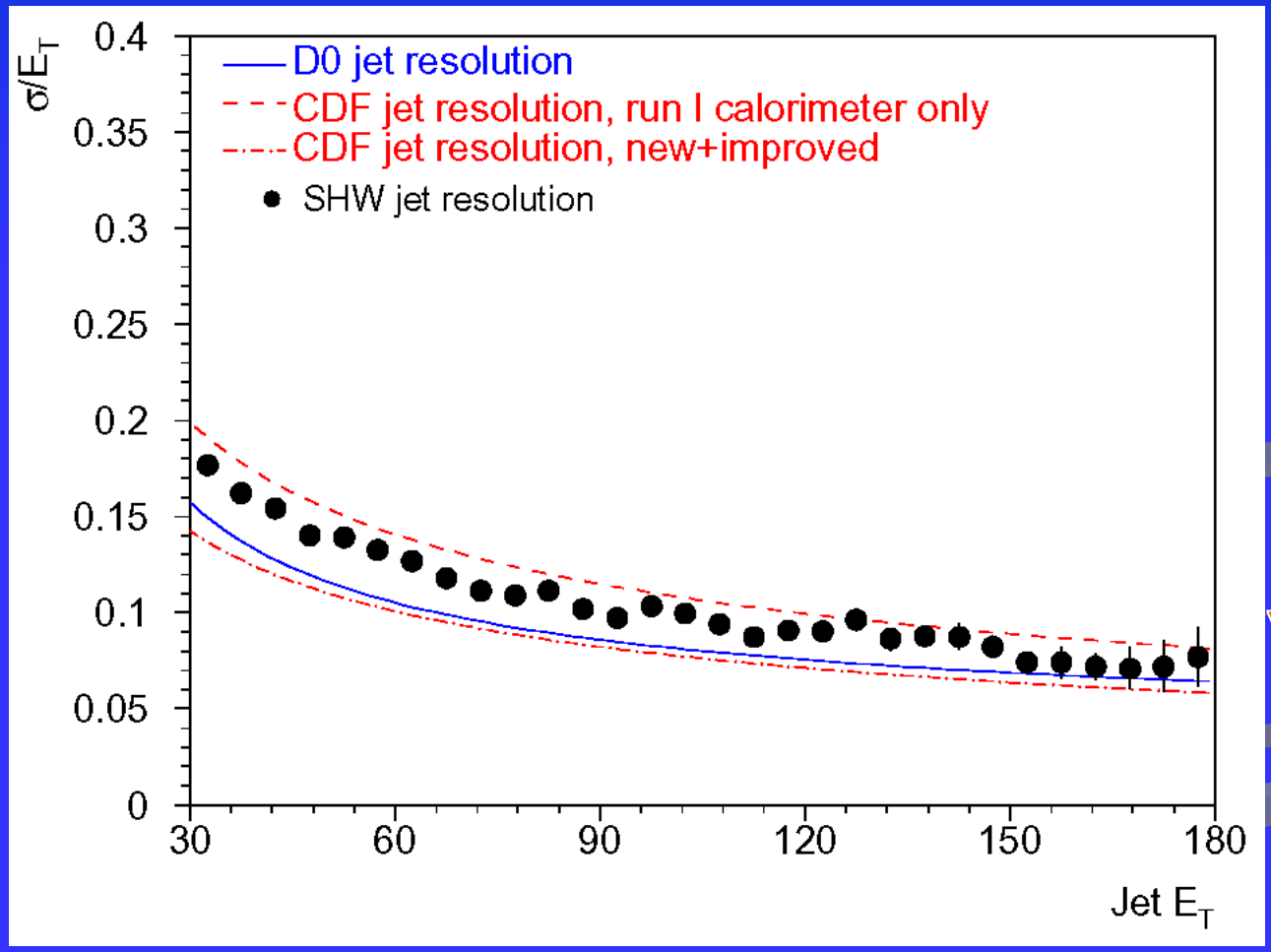


Missing Energy Significance
(MET/σ_{MET})

$ZH \rightarrow \nu\nu bb$

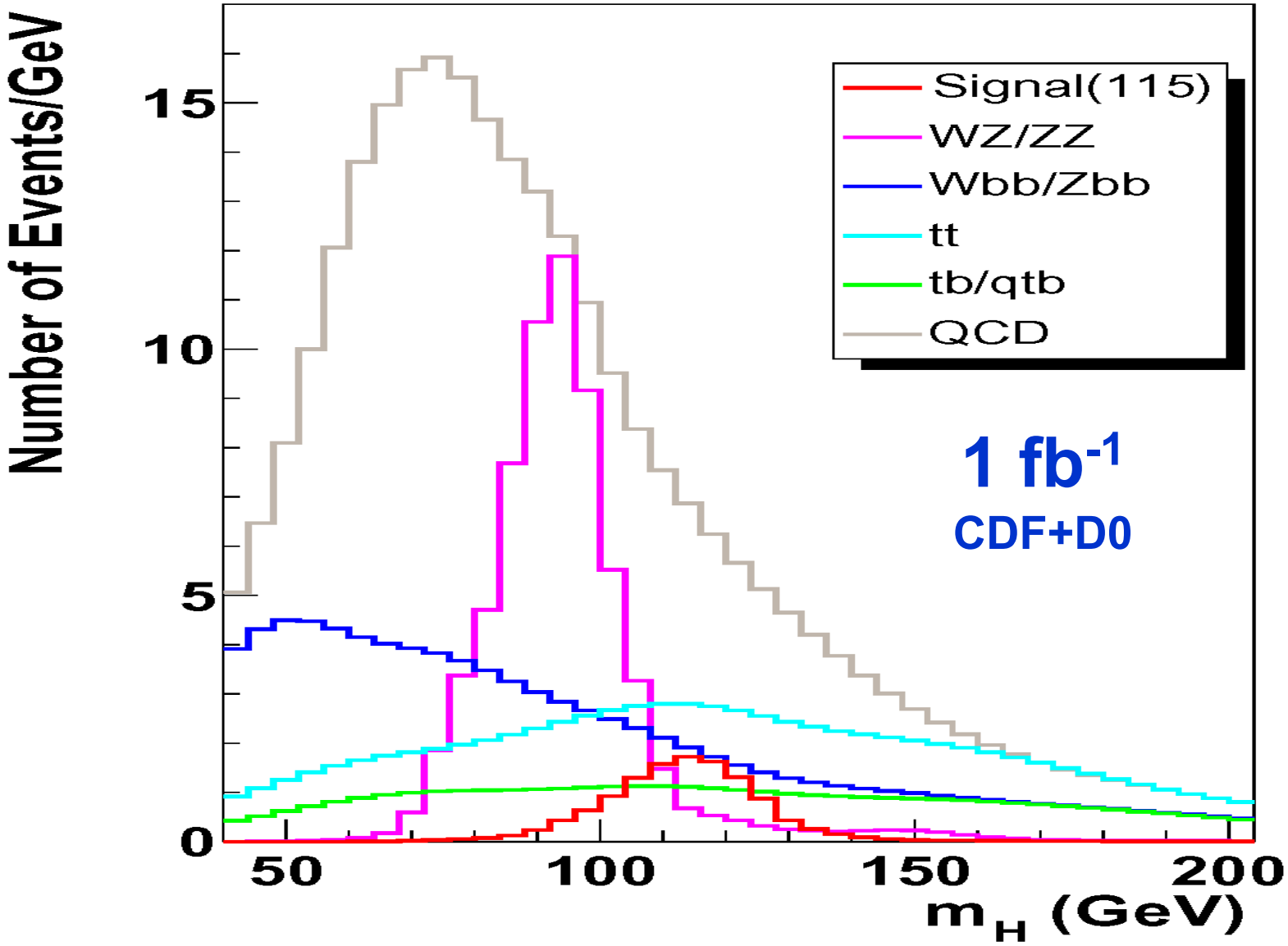
Missing Energy tends to point away from Jets

Di-Jet Mass Resolution

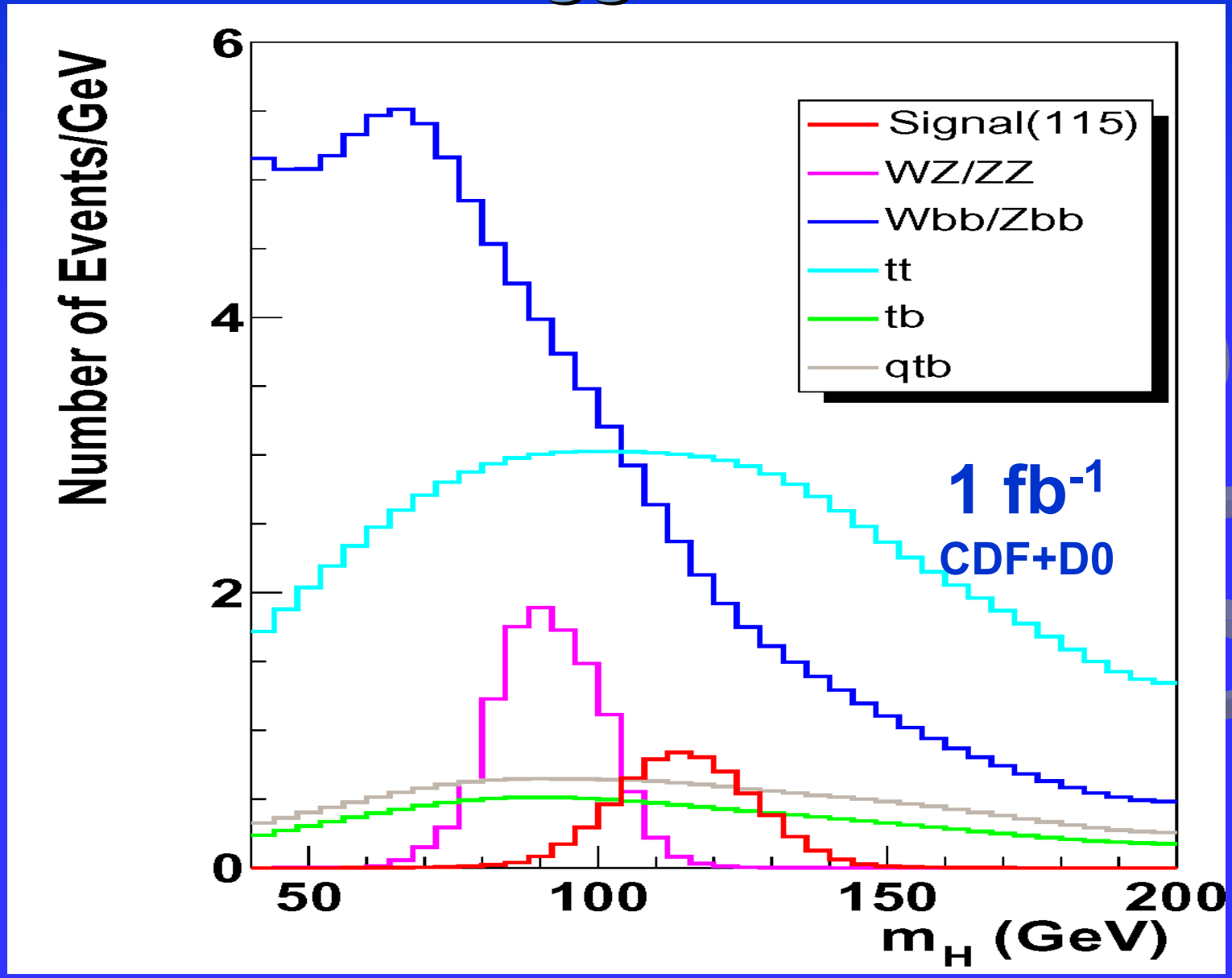


Shrink to 10% or less

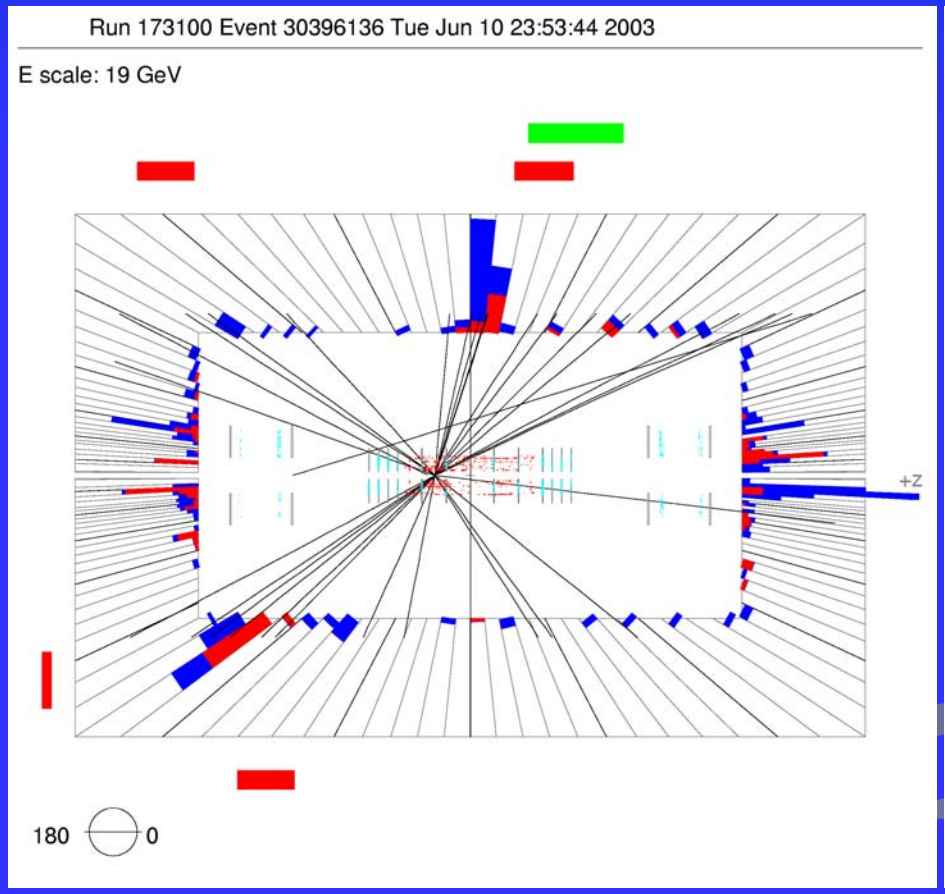
$\nu\nu b\bar{b}$ Higgs Search

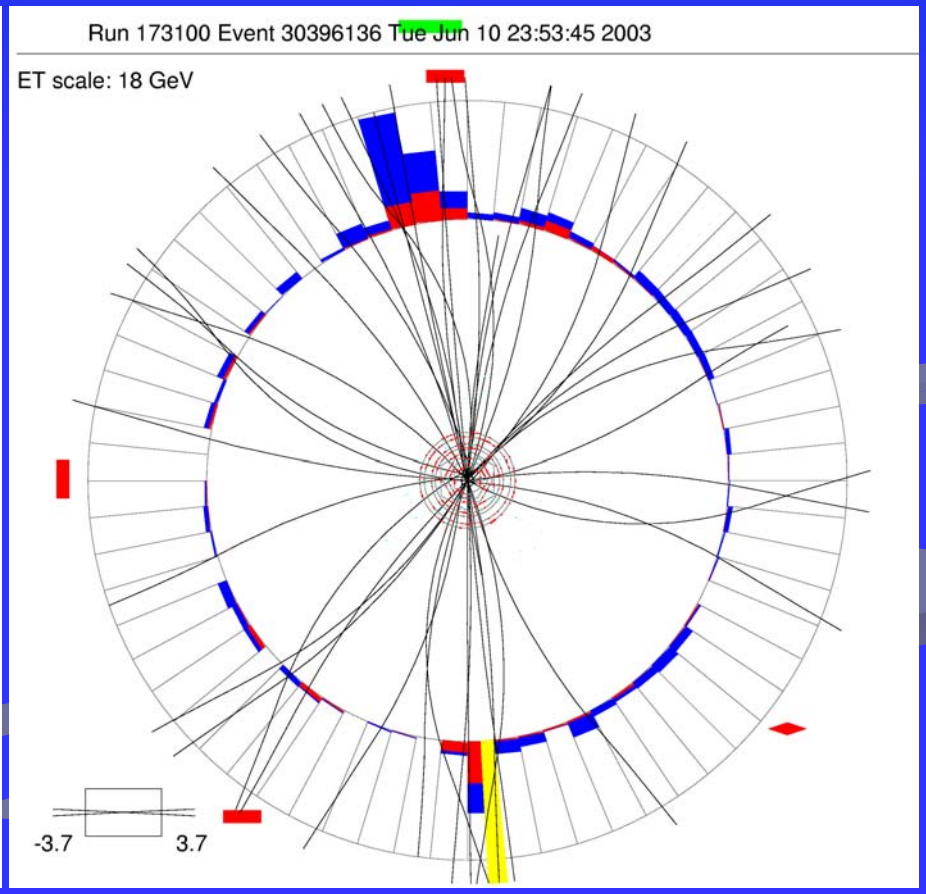


$l\nu b\bar{b}$ Higgs Search

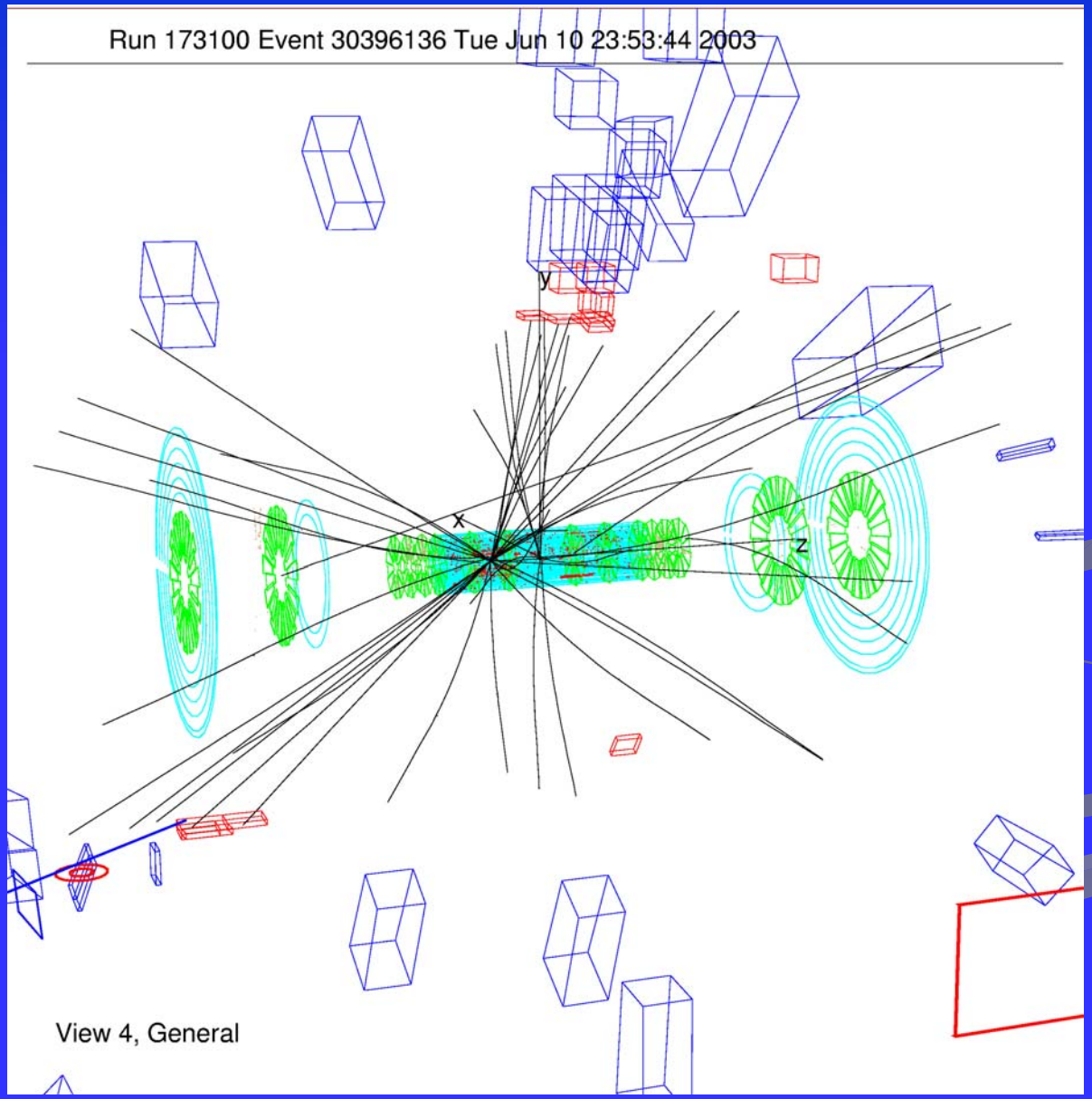


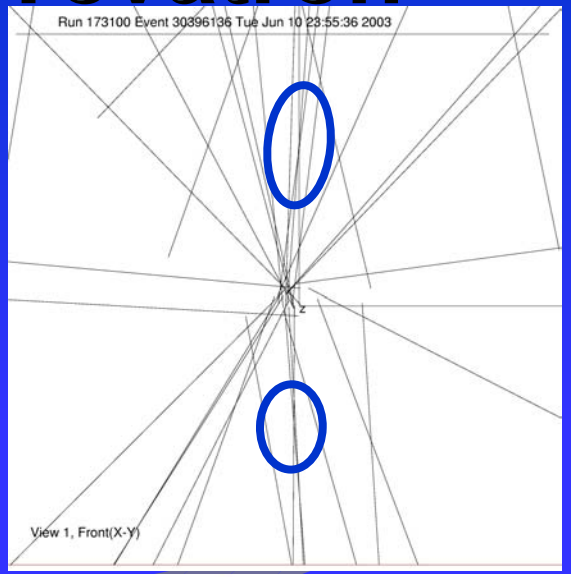
Candidate Event from Tevatron

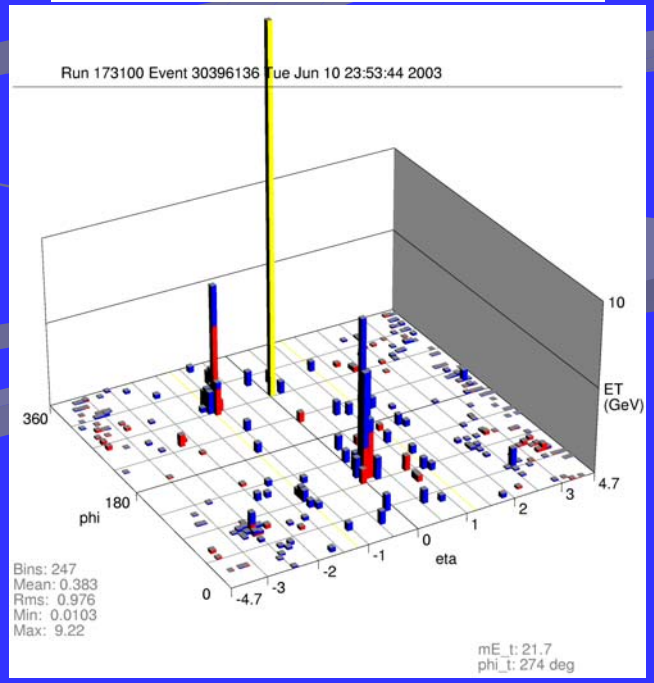




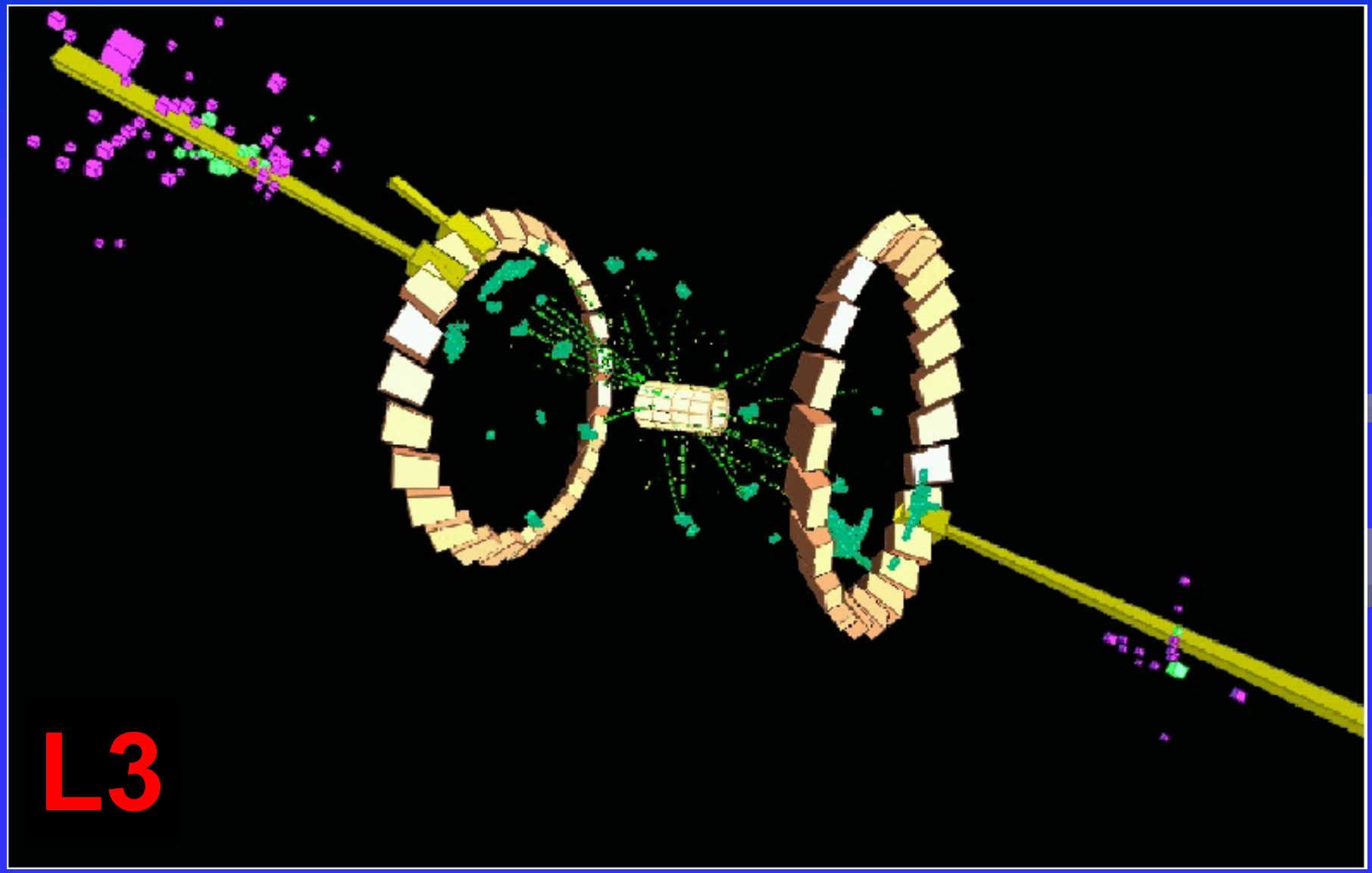
Candidate Event from Tevatron



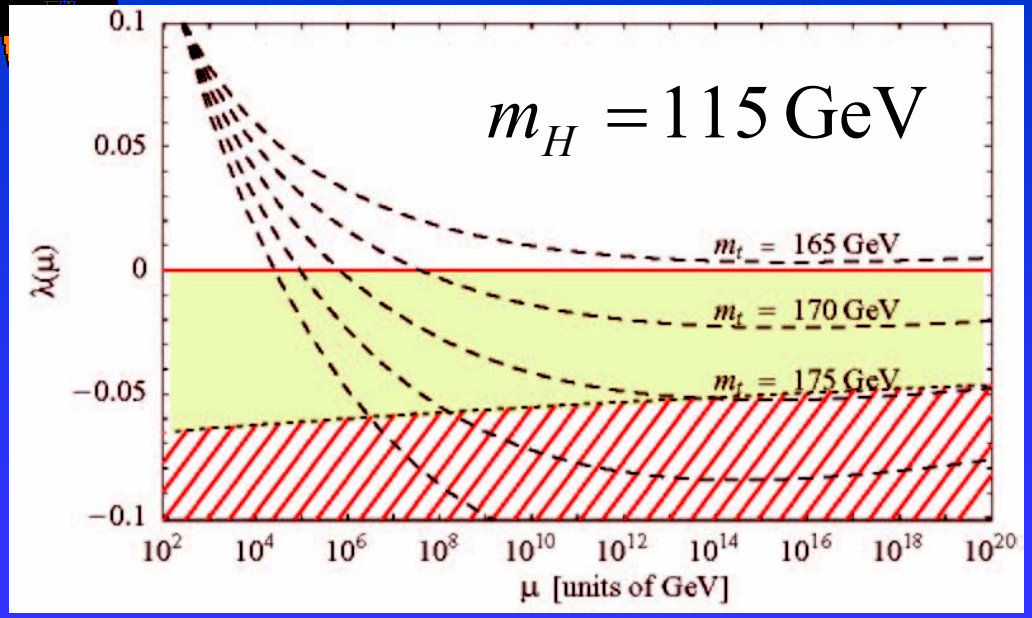




Missing Energy Event from LEP

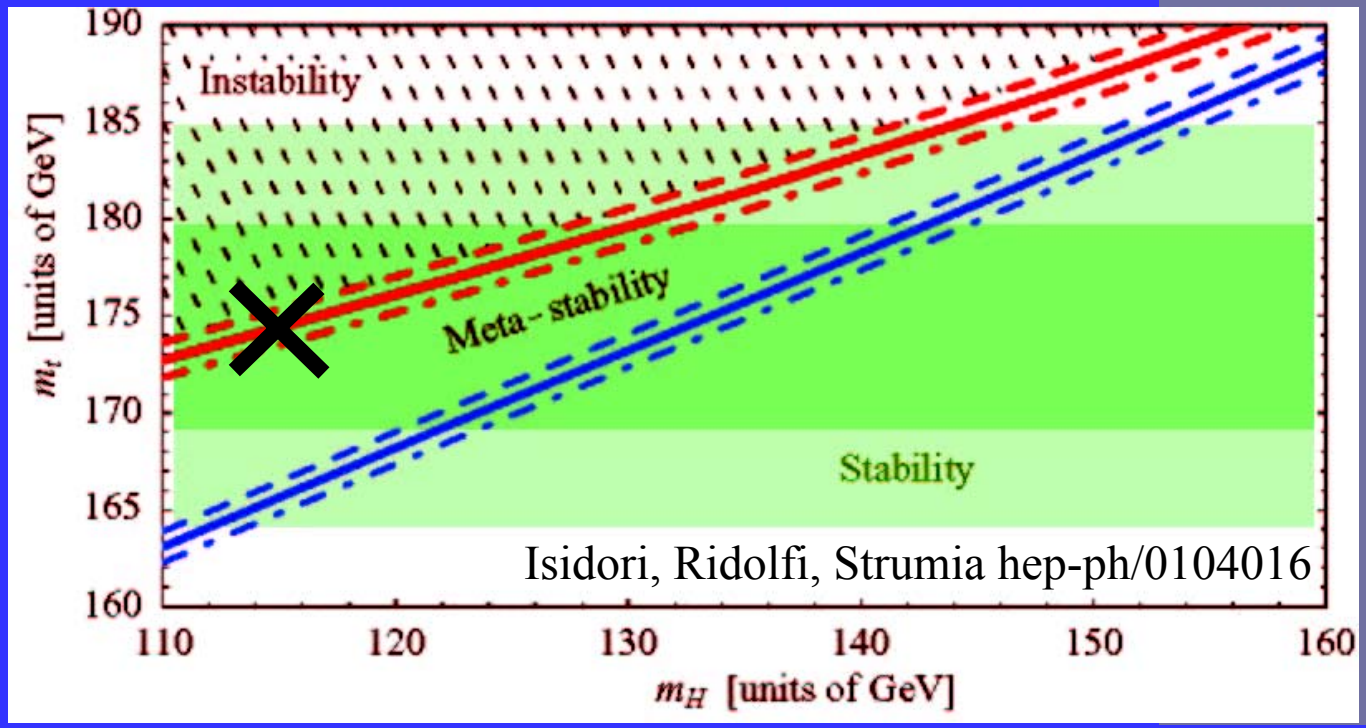


Self-Coupling λ

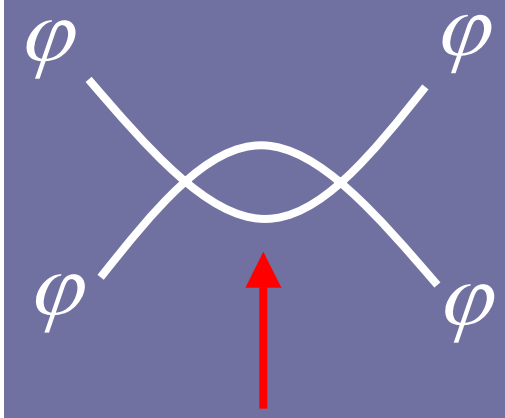


λ is negative for m_t=175 GeV at 1000 TeV

What can be done?



$\lambda(\Lambda) \rightarrow$ positive



Massive scalar or vector particles

Fermion Masses in a 1-doublet Model

1-doublet Model:

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{C} \varphi_c = \begin{pmatrix} \bar{\varphi}^0 \\ -\varphi^- \end{pmatrix}$$

Down-type mass

$$\mathcal{L}_d = -G_d \begin{pmatrix} \bar{u} & \bar{d} \end{pmatrix}_L \varphi \, d_R$$

$$\langle \varphi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$m_d = \frac{G_d v}{\sqrt{2}}$$

Up-type mass

$$\mathcal{L}_u = -G_u \begin{pmatrix} \bar{u} & \bar{d} \end{pmatrix}_L \varphi_c \, u_R$$

$$\langle \varphi_c \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$m_u = \frac{G_u v}{\sqrt{2}}$$

Same v

Fermion Masses in a 2-doublet Model

Down-type mass

$$m_d = \frac{G_d v_1}{\sqrt{2}}$$

Up-type mass

$$m_u = \frac{G_u v_2}{\sqrt{2}}$$

$$\boxed{v_1^2 + v_2^2 = v^2}$$

Electroweak Energy Scale

$$\boxed{\tan\beta = v_2 / v_1}$$

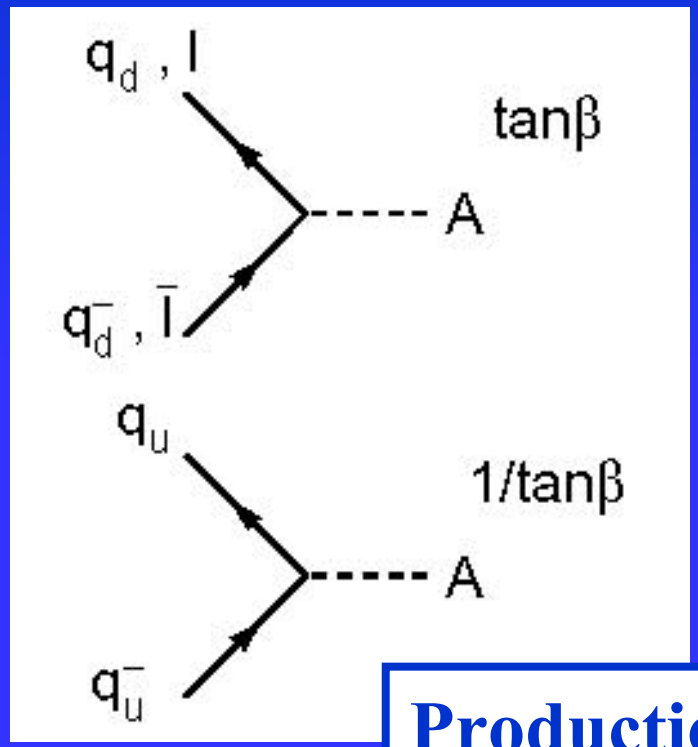
m_{top}/m_{bottom}?

8 degrees of freedom

– 3 longitudinal polarizations ($W_L^{\pm}, Z_L$)

leaves 5 Higgs bosons: $h, H, A, H^{\pm}$

Higgs-Fermion Couplings in the MSSM



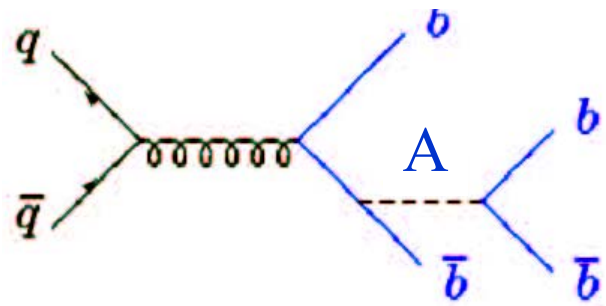
Large tanβ:

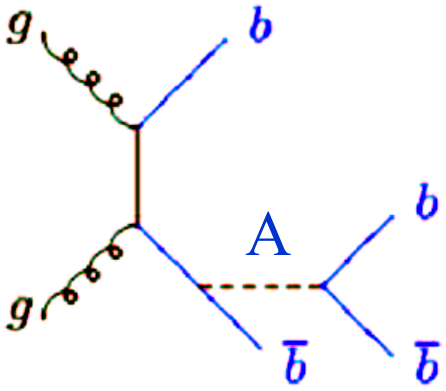
b quarks and τ leptons couple strongly to A

top quarks couple weakly to A

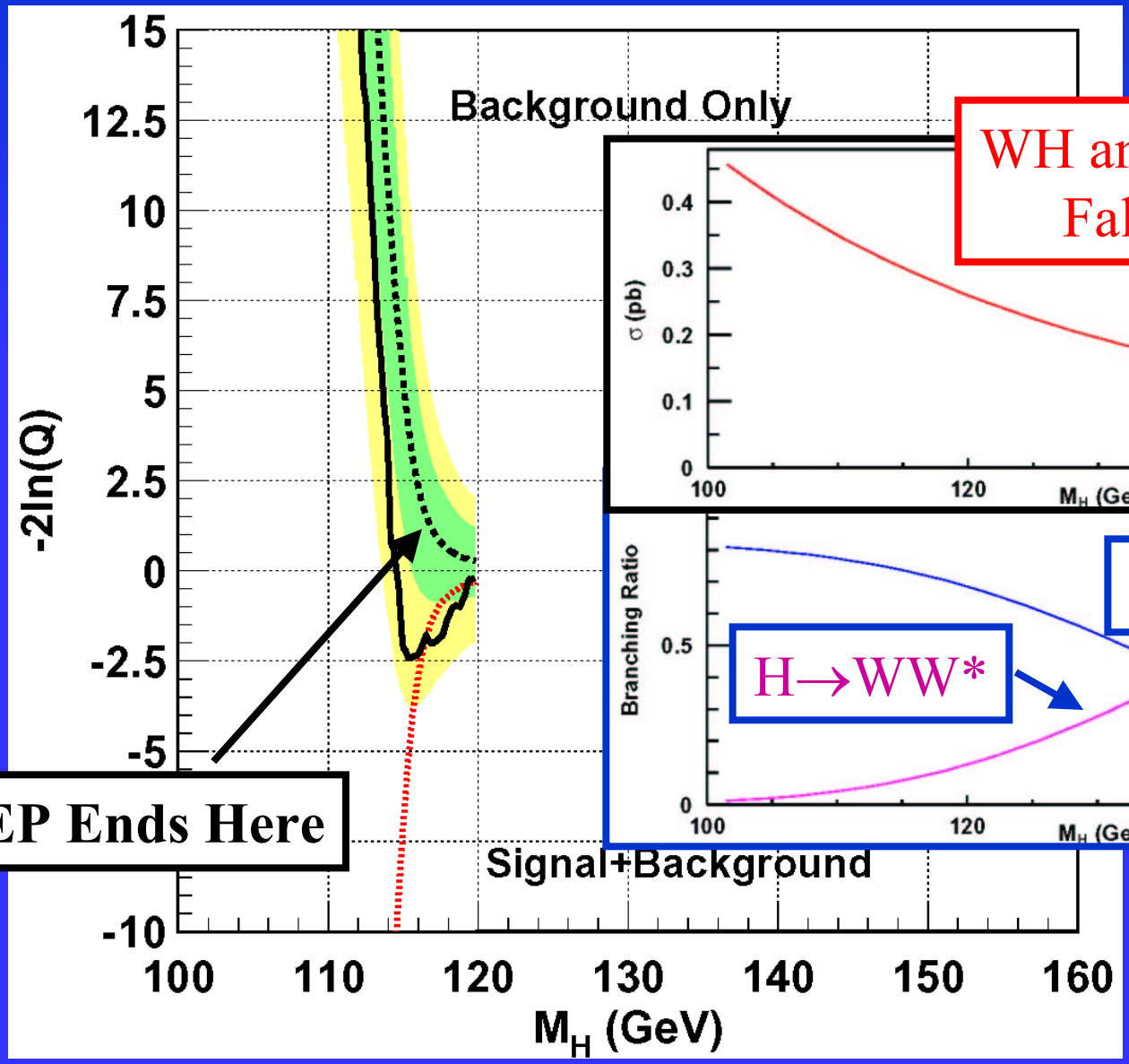
Production Mechanisms

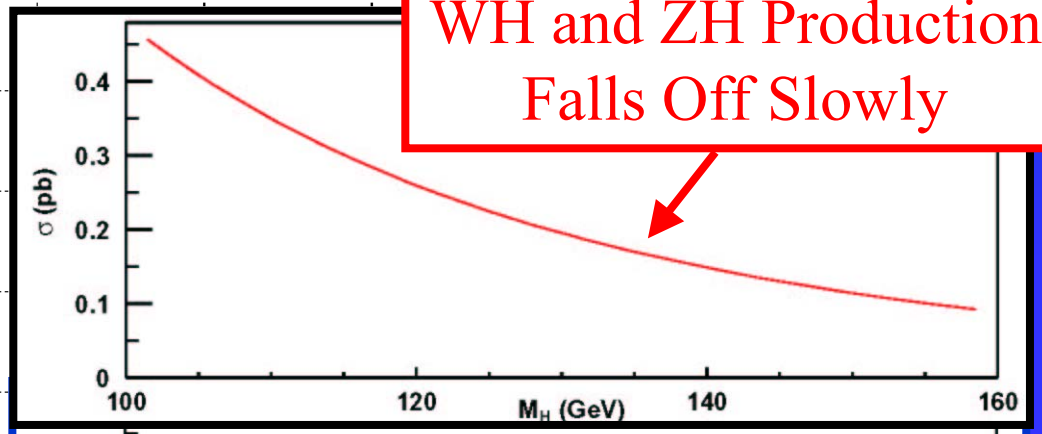
Higgsstrahlung off a b quark:



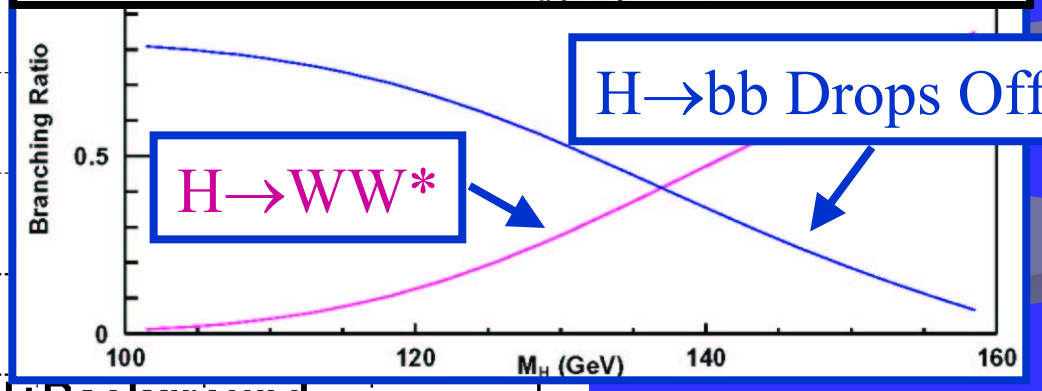


Extending the Search





WH and ZH Production Falls Off Slowly

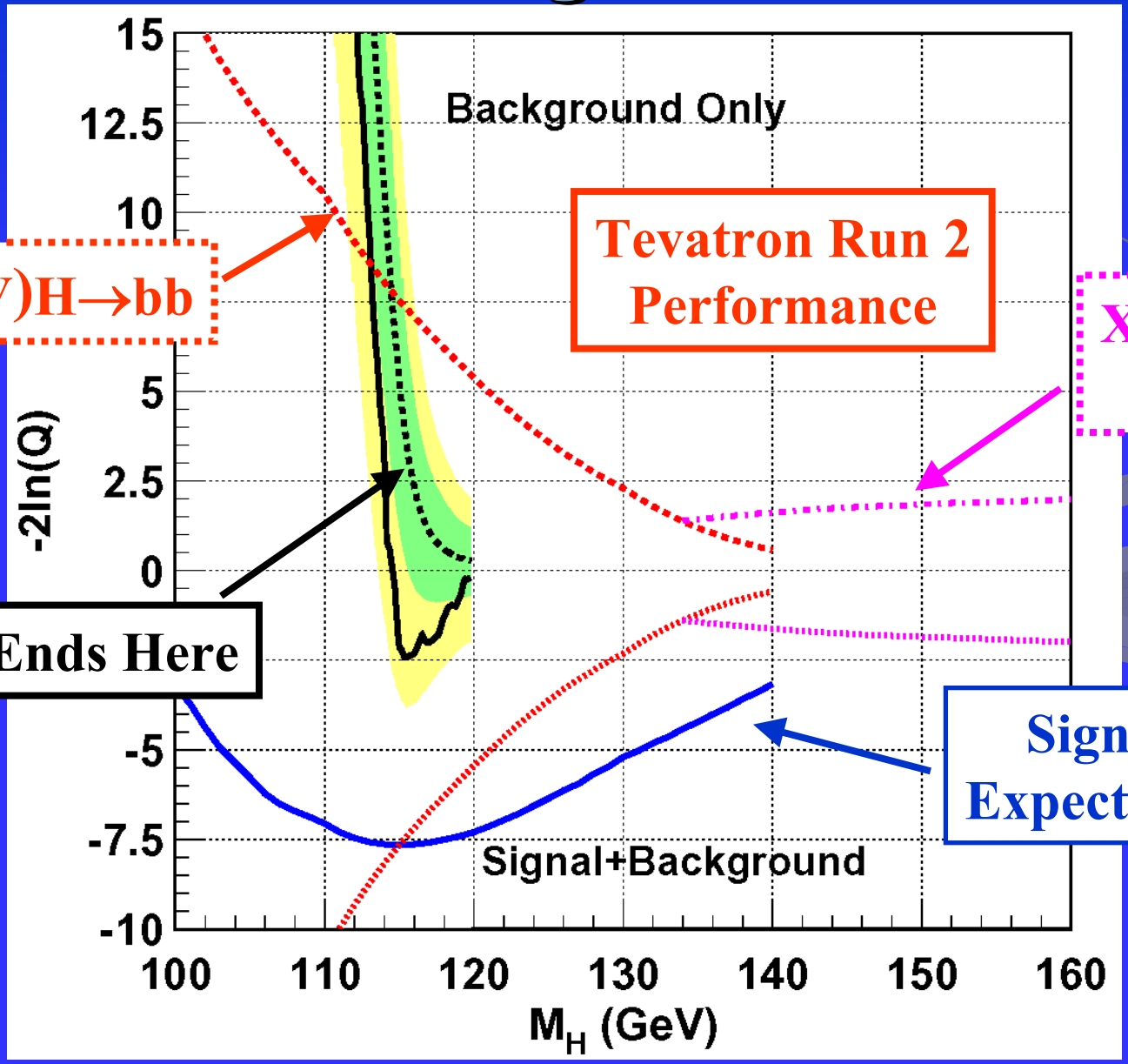


H→bb Drops Off

H→WW*

LEP Ends Here

Extending the Search



(V)H→bb

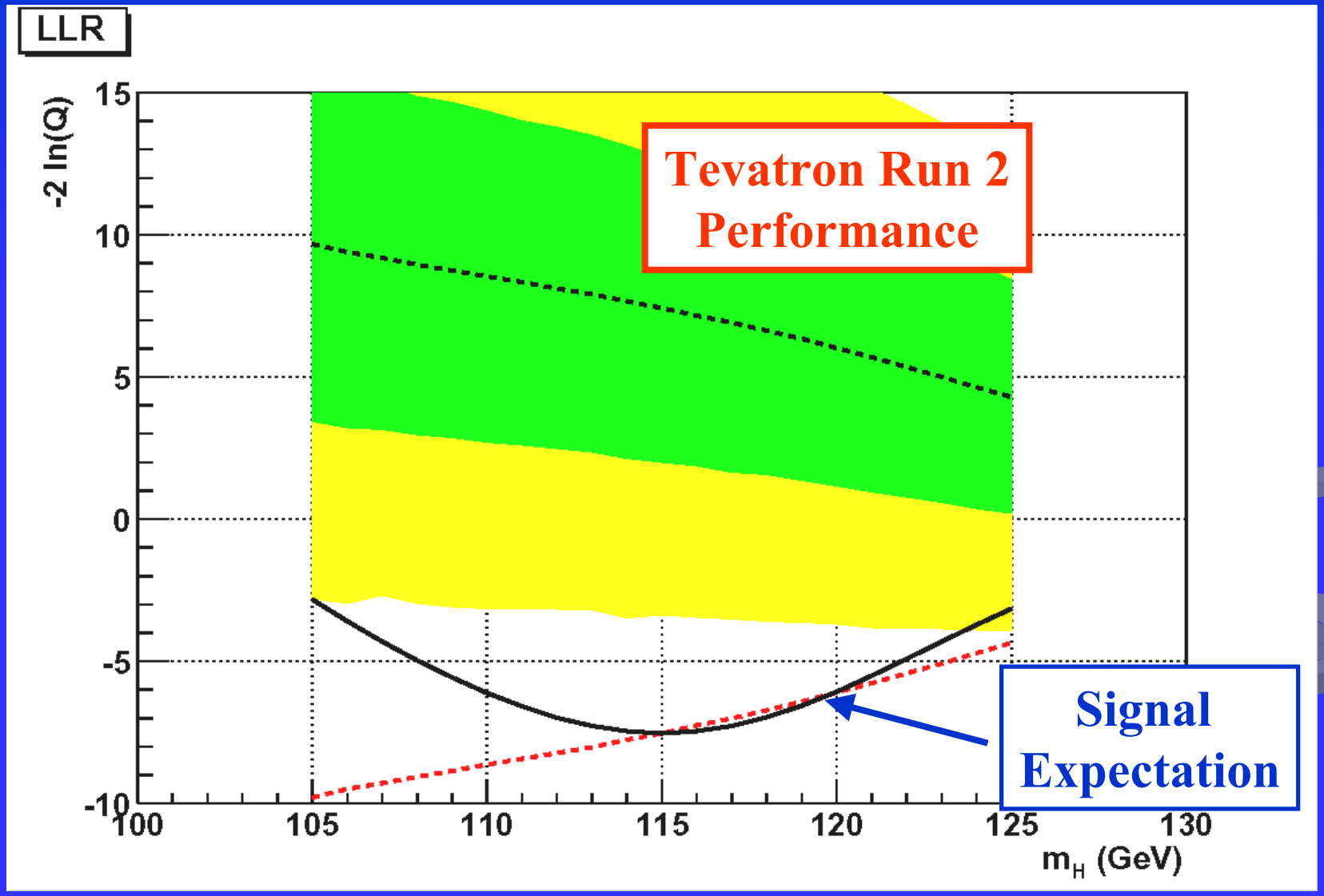
Tevatron Run 2 Performance

X+H→WW* →ℓνℓν

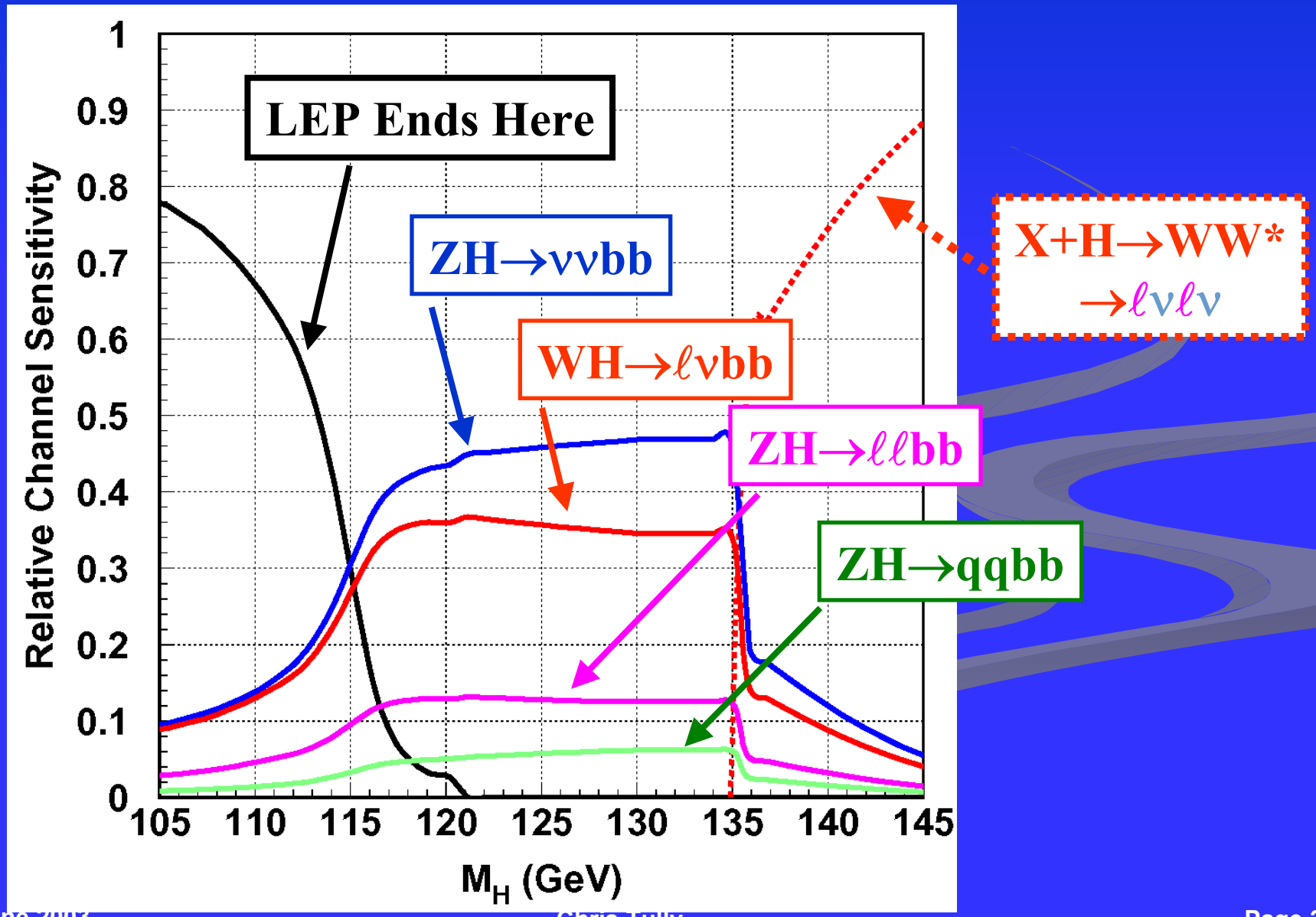
LEP Ends Here

Signal Expectation

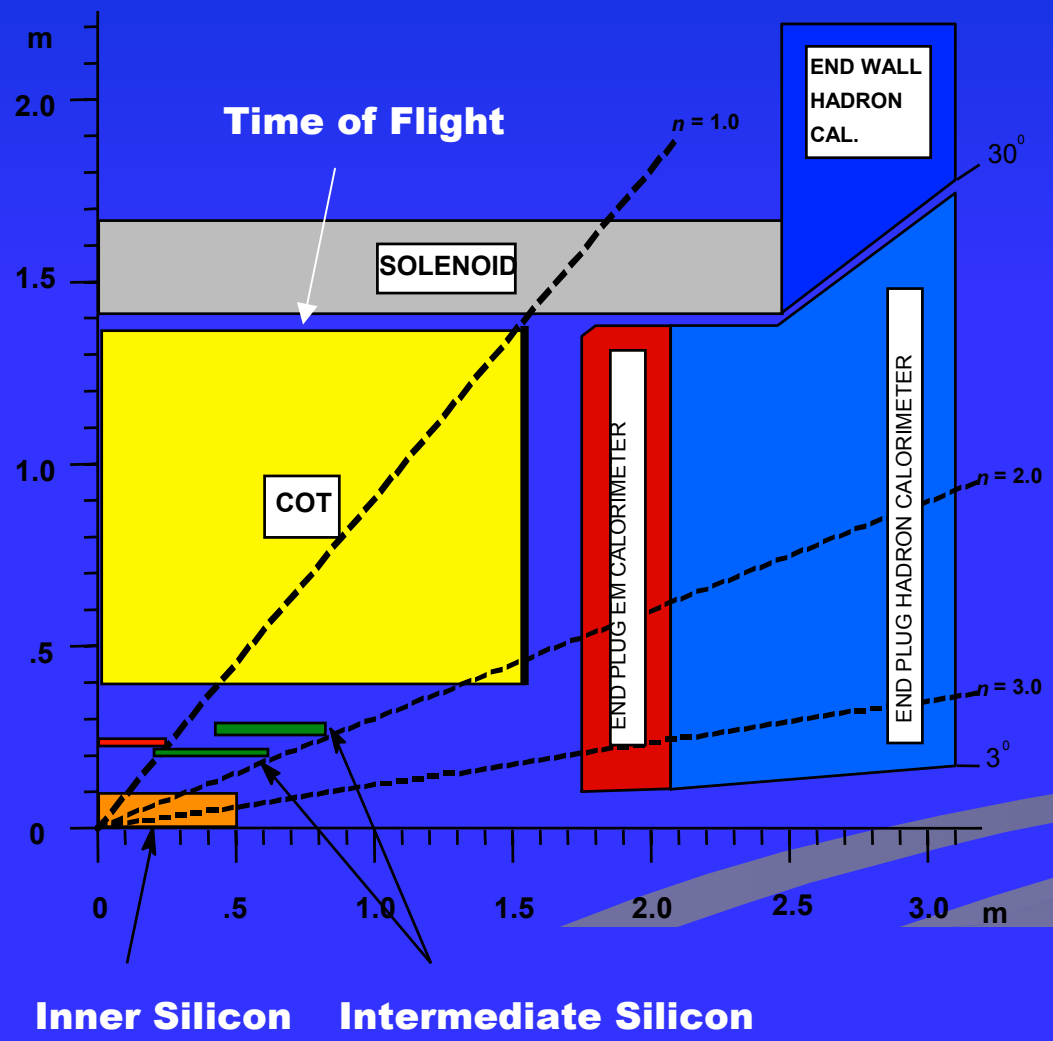
Extending the Search



Relative Channel Sensitivity



CDFII Detector



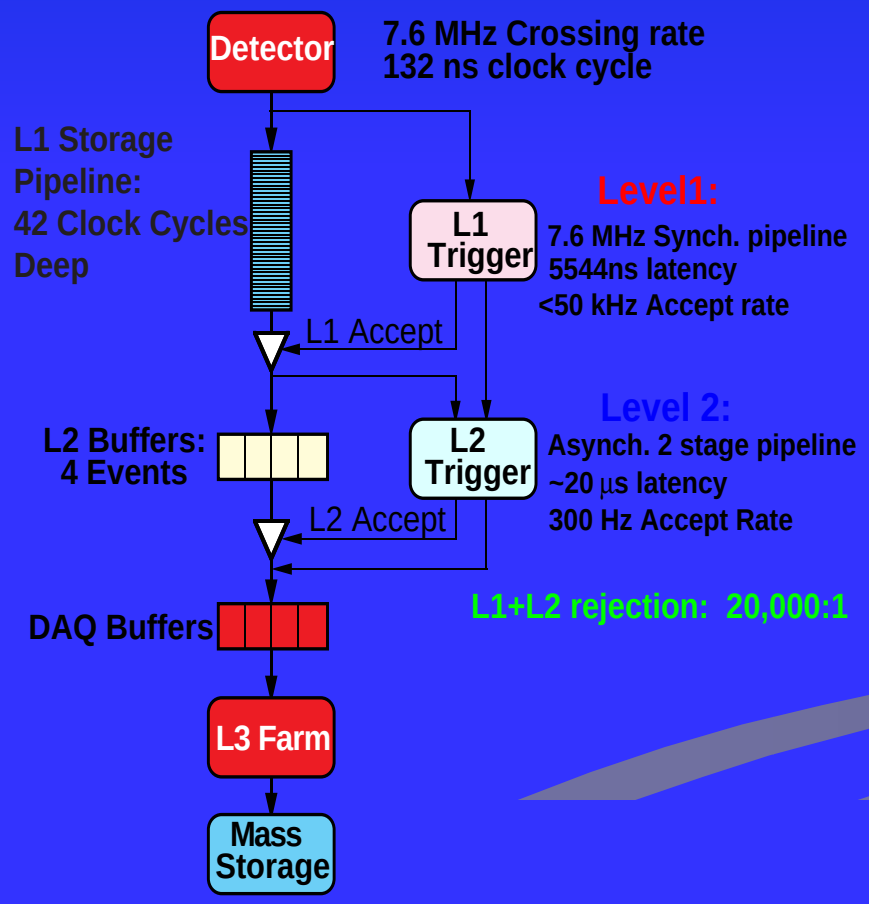
Retained from Run I

- Solenoid (1.4 Tesla)
- Central calorimeters
- Central muon detectors

New in Run II

- Tracking system
  - Silicon vertex detector (SVXII)
  - Intermediate silicon layers
  - Central outer tracker (COT)
- End plug calorimeter
- Intermediate muon detectors
- Time of flight system
- Front-end electronics
- Trigger system
- DAQ system

Trigger and DAQ



Rate at
L ~ 3E31 cm^{-2} s^{-1}

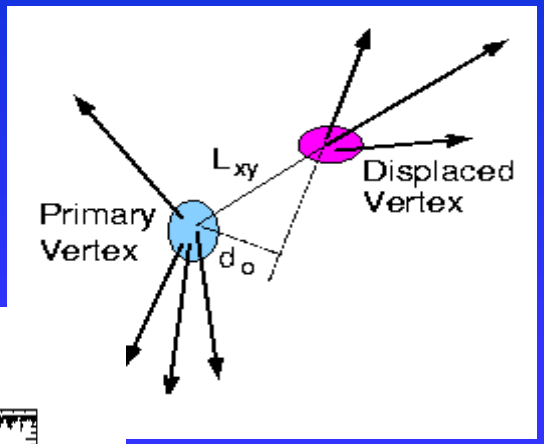
12 kHz — Calorimeter energy
Central tracker
Muon stubs

250 Hz — Cal Energy-track match
E/P, EM shower max
Silicon secondary vertex
Multi object triggers

50 Hz — Farm of PC's running fast versions of Offline Code → more sophisticated selections

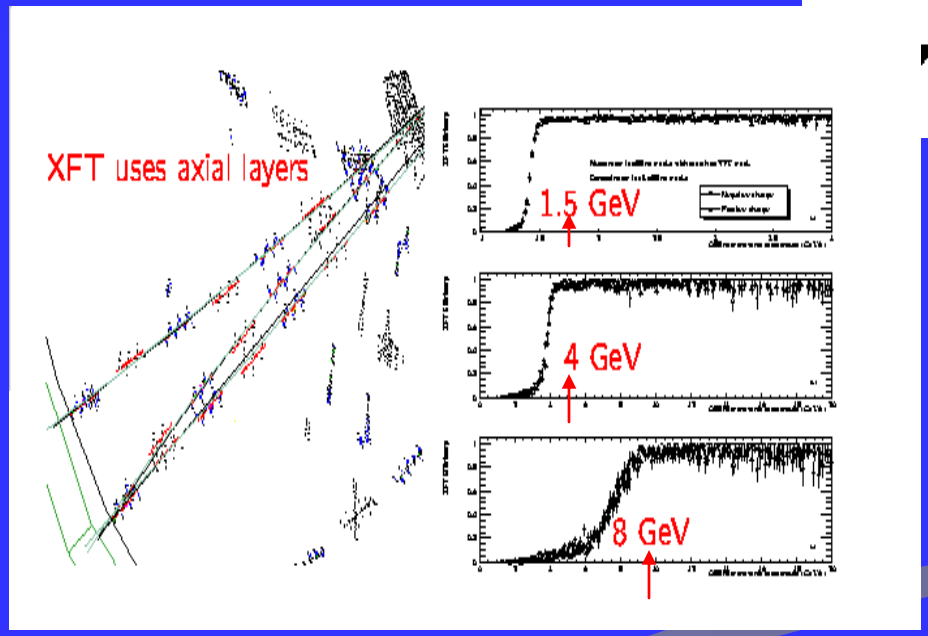
Track and Vertex Triggers

XFT:
uses COT axial to find high pT tracks at L1



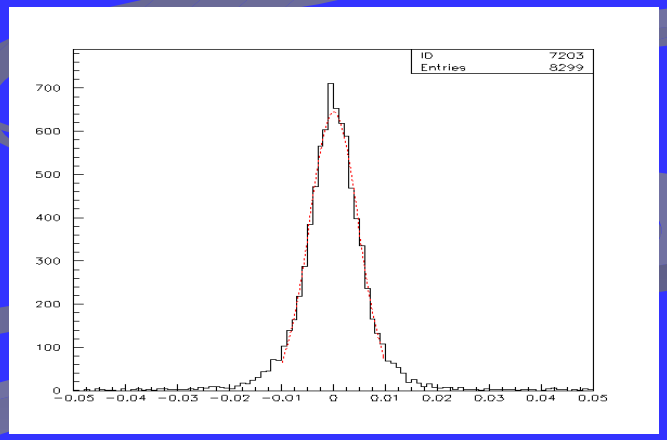
SVT:
uses L1 XFT and SVXII

Trigger b and c in hadronic decays



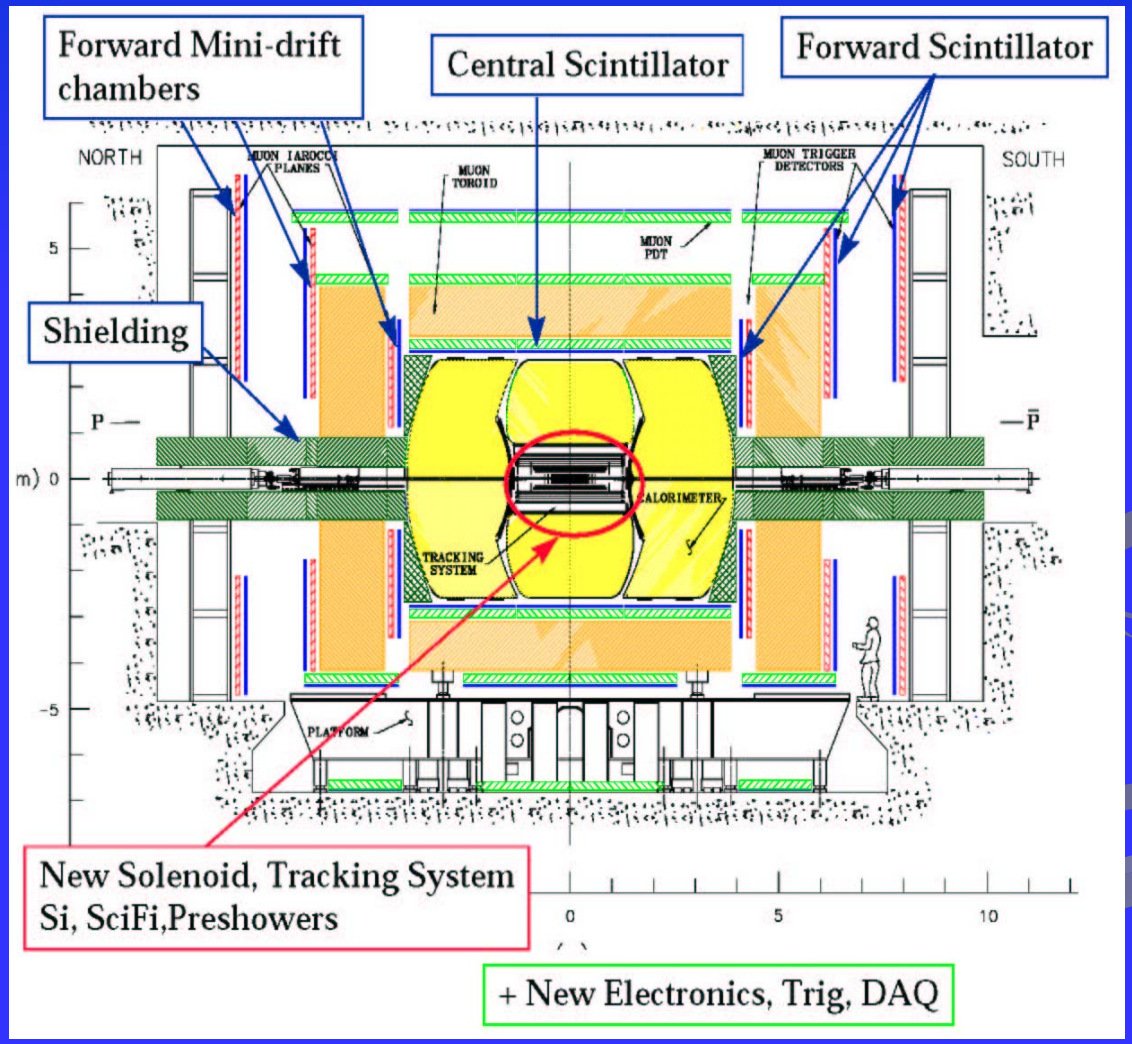
$\Delta p_T/p_T = 1.65\%\ p_T\,(\mathrm{GeV}/c)$

Impact Parameter at L2



$\sigma = 50\ \mu m$
$= 43\mu m\ (\mathrm{reso}) \oplus 25\mu m\ (\mathrm{beam})$

DØ Run II Detector



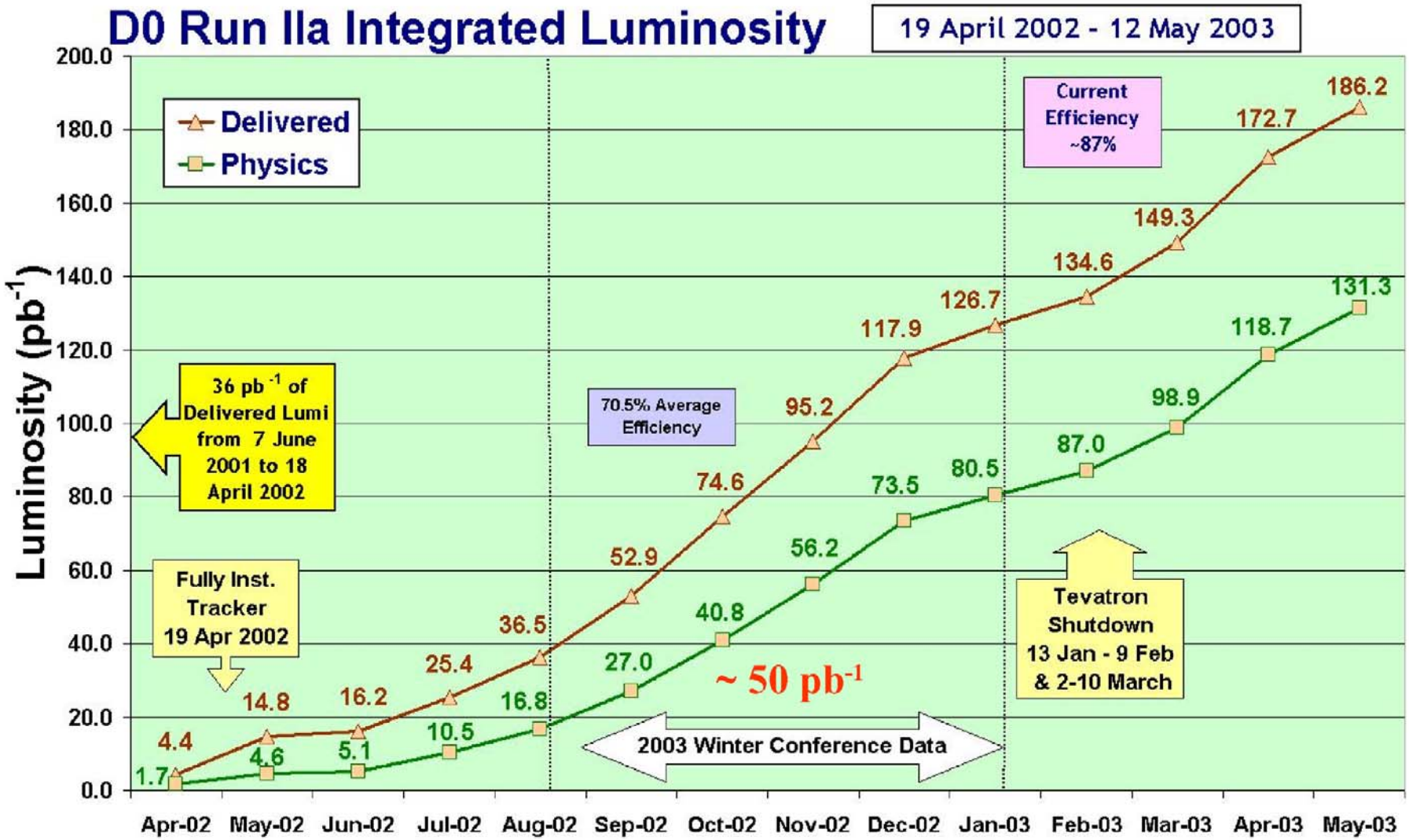
Retained from Run I

- LrAr Calorimeter
- Central muon detector
- Muon Toroid

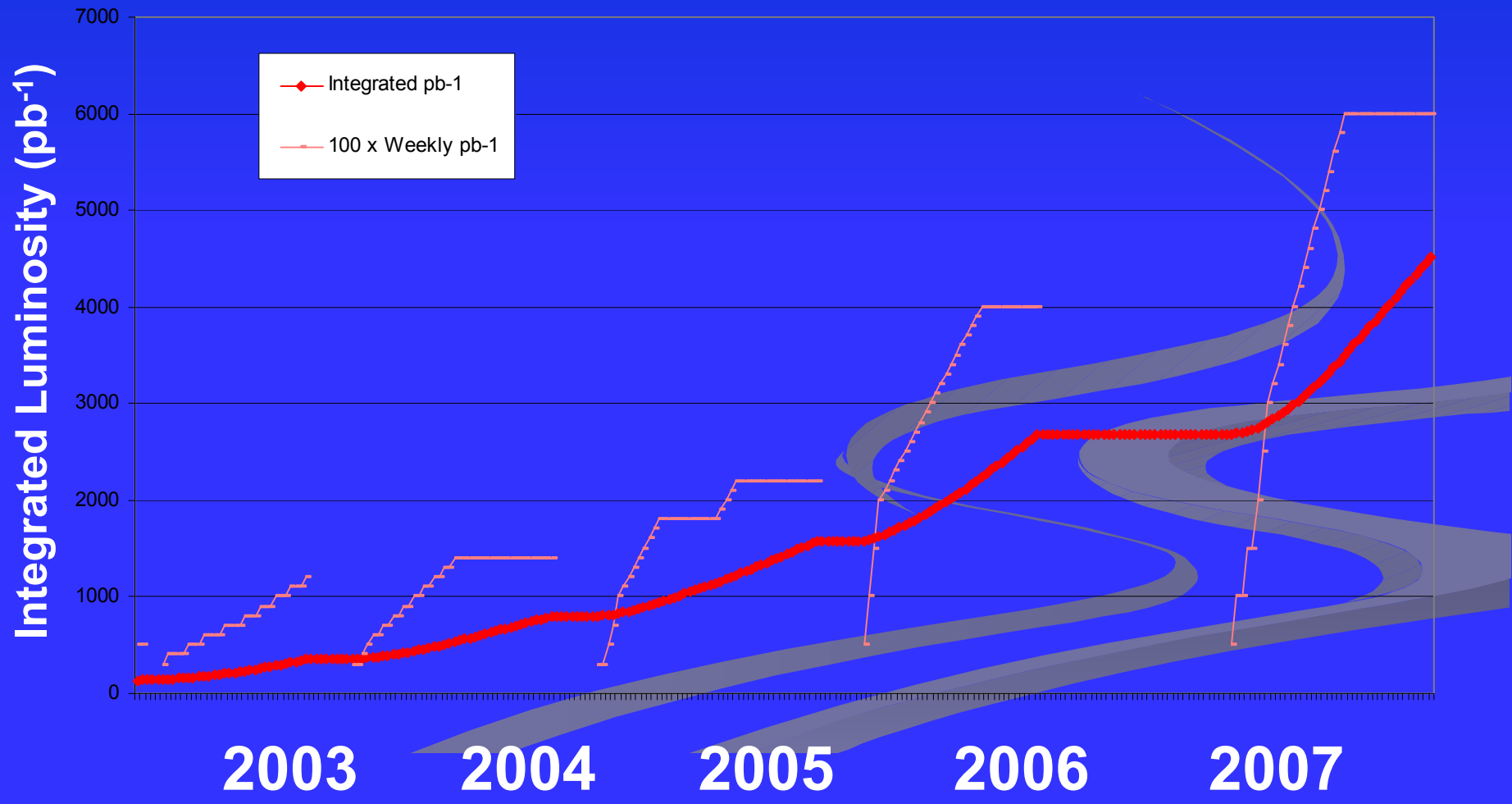
New for Run II

- Magnetic tracker
- 2 Tesla solenoid
- Silicon microvertex tracker
- Scintillating fiber tracker
- Preshower detectors
- Forward muon detector
- Forward proton detector
- Front-end electronics
- Trigger and DAQ

Tevatron Delivered Luminosity



Tevatron Projected Luminosity



Higgs' Quest

Fermilab (Chicago, USA)

LEP (Geneva, Switzerland)

LEP Dismantled
in 2000

7 years

Tevatron Run II
Picked up speed in 2002

Startup of LHC
Scheduled for 2007

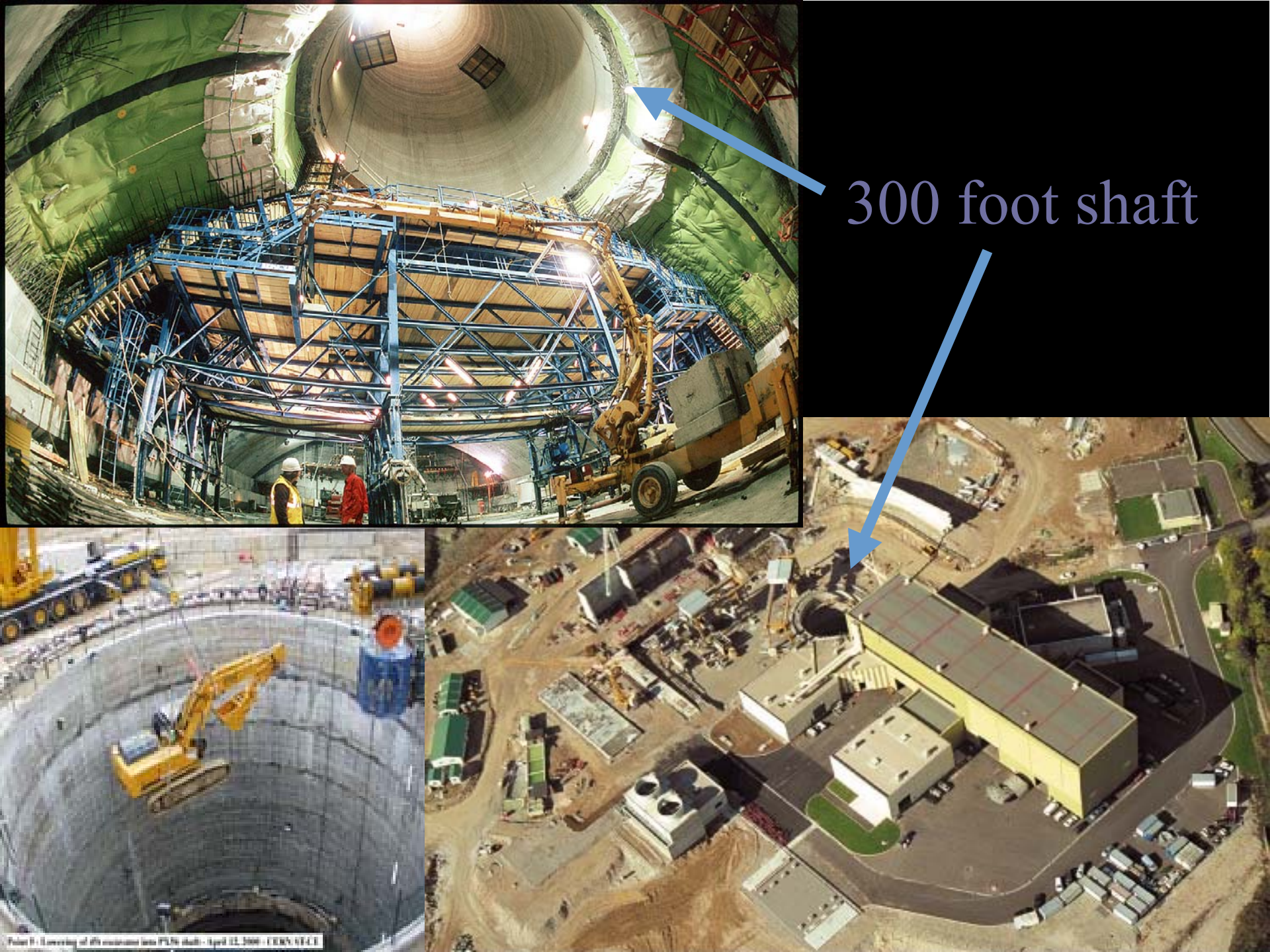
Supersymmetric Particle Searches at the LHC

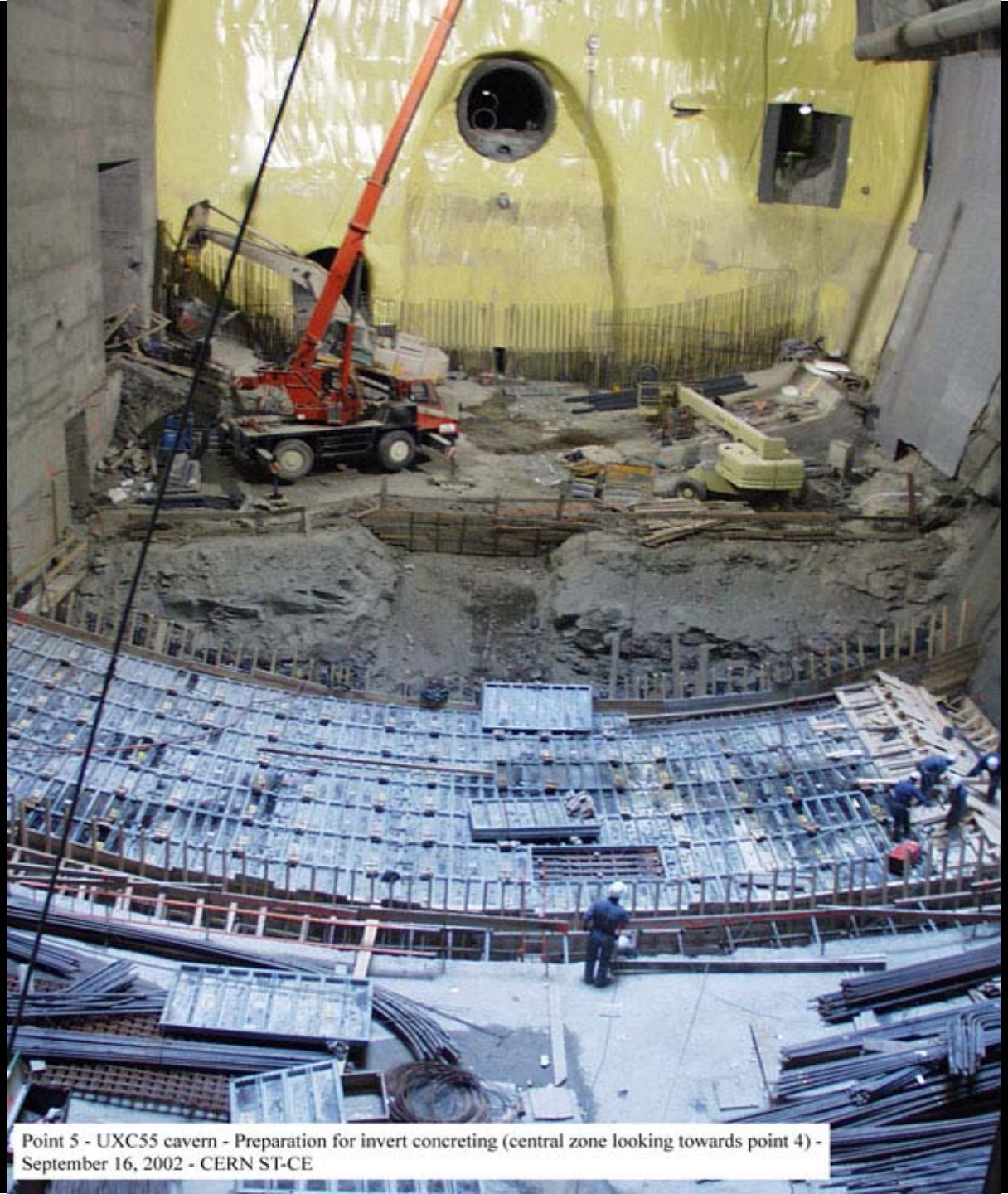
TASI 2003

Chris Tully
Princeton

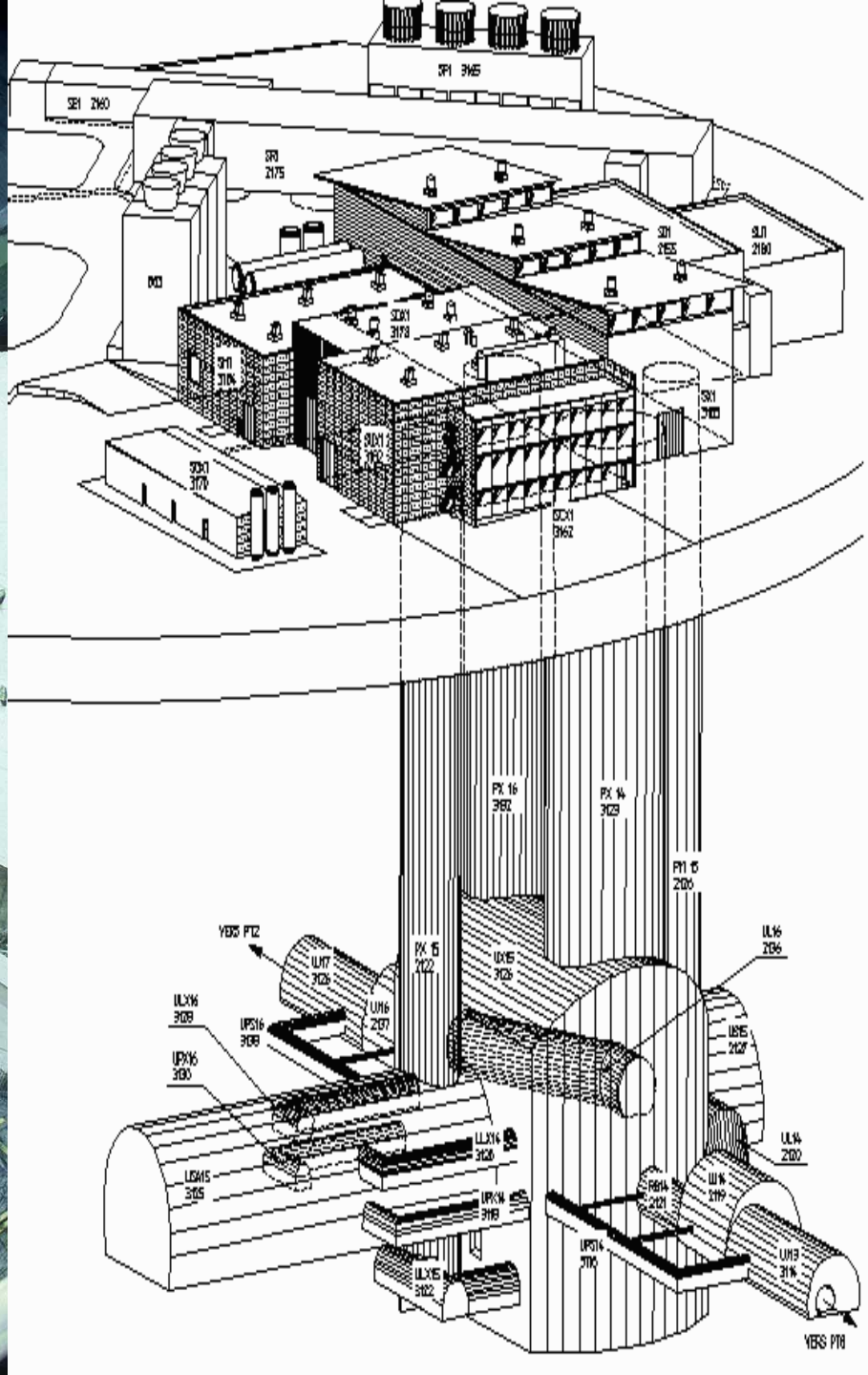
LHC Detectors Materialize

Only 3mm droop.
CMS Hadron Calorimeter
Half-Barrel and Endcap


300 foot shaft



Point 5 - UXC55 cavern - Preparation for invert concreting (central zone looking towards point 4) - September 16, 2002 - CERN ST-CE

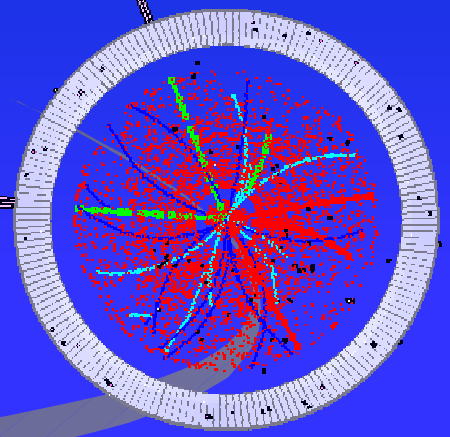

SP1 3165
SP1 2160
SP1 2175
SP1 2155
SP1 2180
SP1 3170
SP1 3160
SP1 3162
PX 16 3102
PX 14 3129
PY1 15 2206
PX 15 2122
UX15 3126
UX16 2107
UX17 3126
UL16 2206
UX16 3109
UPX16 3130
UPX16 3109
UX15 2127
UL14 2202
UL14 3128
UGX15 3125
UPX14 3118
UX14 2119
UX13 3114
UPX14 3110
UX16 3122
VERS PT2
VERS PT8

LHC Start-up

PHASE 1: LHC commissioning (T_0 to T_0 + 4 months)

- **LHC: Set-up machine. Start with one beam. Colliding beams and slowly increase # bunches and L. Collisions at L > 5 x 10^{32} at 75 ns bunch spacing.**

+ 2 pileup events i.e. 10^{33} and 25ns bunch spacing

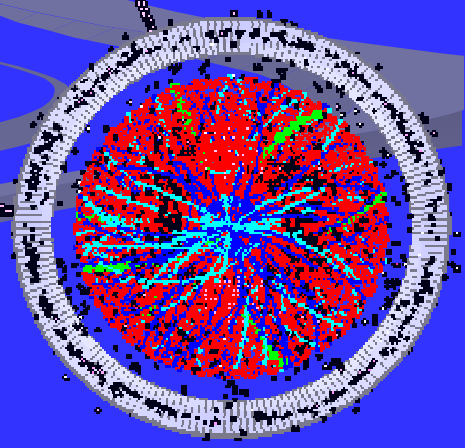


Phase2: Shutdown

PHASE 3: First physics run (T_0 + 7 mo.→ T_0 + 14 mo.)

- LHC: 75 ns and **L** ~ 10^{33} cm^{-2} s^{-1}
- Physics run, max. efficiency aiming for 5-10 fb^{-1}
- ~6 events per bunch crossing

+ 20 pileup events i.e. 10^{34} and 25ns bunch spacing



PHASE 4+n: High luminosity running

- ~20 events per bunch crossing

LHC Data Samples with 10 fb-1

Assumption: 10 fb^{-1} in 1 year @ **L** = 2 x 10^{33} cm^{-2} s^{-1}

Trigger cuts at L=2 x 10^{33} cm^{-2} s^{-1}	L1 p_T cut [GeV]	HLT p_T cut [GeV]	Exclusive rate [Hz] after HLT μ isolation
Single muon	14	19	25
Double muon	3	7	4

Channels	Pythia Cross section [nb]	Acceptance (1 μ in $\lvert\eta\rvert$<2.1)	Eff. after HLT with μ isolation	Yield for 10 fb^{-1}
W → μ ν	19.6	50 %	69 %	70 x 10^6
Z → μ μ	1.84	71 %	92 %	11 x 10^6
tt →W b W b → μ ν + X	0.126	86 %	72 %	0.8 x 10^6

Supersymmetric Particles

Superparticle	Symbol	Spin
Gluino	$\tilde{g}$	1/2
Charginos	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$	1/2
Neutralinos	$\tilde{\chi}_1^o, \tilde{\chi}_2^o, \tilde{\chi}_3^o, \tilde{\chi}_4^o$	1/2
Gravitinos	$\tilde{G}$	3/2
Sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_{eL}$	0
	$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_{\mu L}$	0
	$\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_{\tau L}$	0
Squarks	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$	0
	$\tilde{c}_L, \tilde{c}_R, \tilde{s}_L, \tilde{s}_R$	0
	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$	0

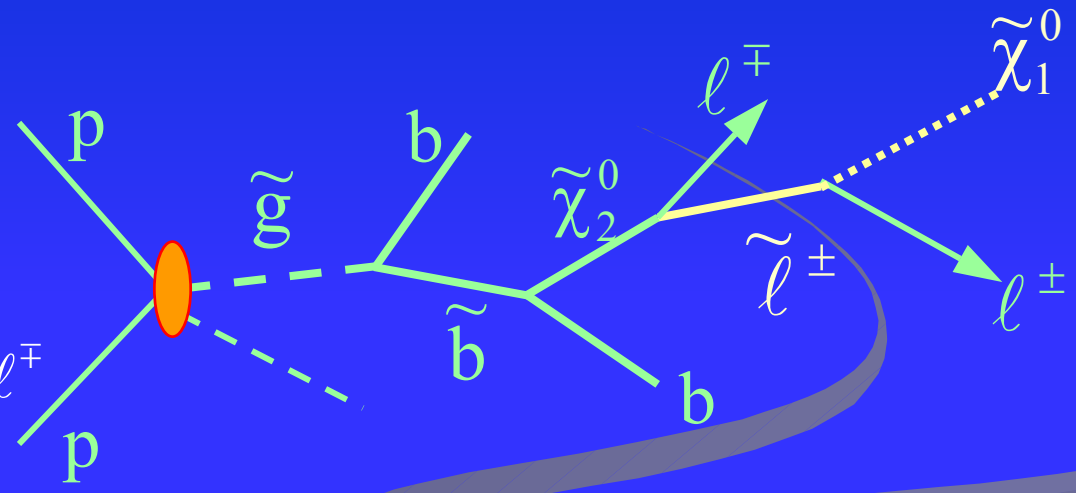
Supersymmetric Spectra

Sparticle	Mass Range (GeV)
χ_1^0	100-900
χ_2^0	180-1600
χ_3^0	250-2000
χ_4^0	320-2000
$\chi_1^\pm$	180-1600
$\chi_2^\pm$	320-2000
$\tilde{g}$	580-3800

Sparticle	Mass Range (GeV)
$e_L,\ \mu_L$	200-3500
$e_R,\ \mu_R$	140-3500
$\nu_e,\ \nu_\mu$	180-3500
τ_1	140-3500
τ_2	200-3500
ν_τ	180-3500
$u_L,\ c_L$	550-3900
$u_R,\ c_R$	530-3900
$d_L,\ s_L$	550-3900
$d_R,\ s_R$	530-3900
t_1	400-2700
t_2	570-3300
b_1	500-3300
b_2	530-3800

Decay Chains

$$pp \rightarrow \tilde{g} \rightarrow \tilde{b}b$$
$$\hookrightarrow \tilde{\chi}_2^0 b$$
$$\hookrightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^{\pm}\ell^{\mp}$$



$$pp \rightarrow \tilde{g} \rightarrow \tilde{q}q$$
$$\hookrightarrow \tilde{\chi}_2^0 q$$
$$\hookrightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^{+}\ell^{-}$$

- $\geq$ 2 high p_t isolated leptons OS (leptons = e,μ)
- $\geq$ 2 high p_t non-b jets
- missing E_t

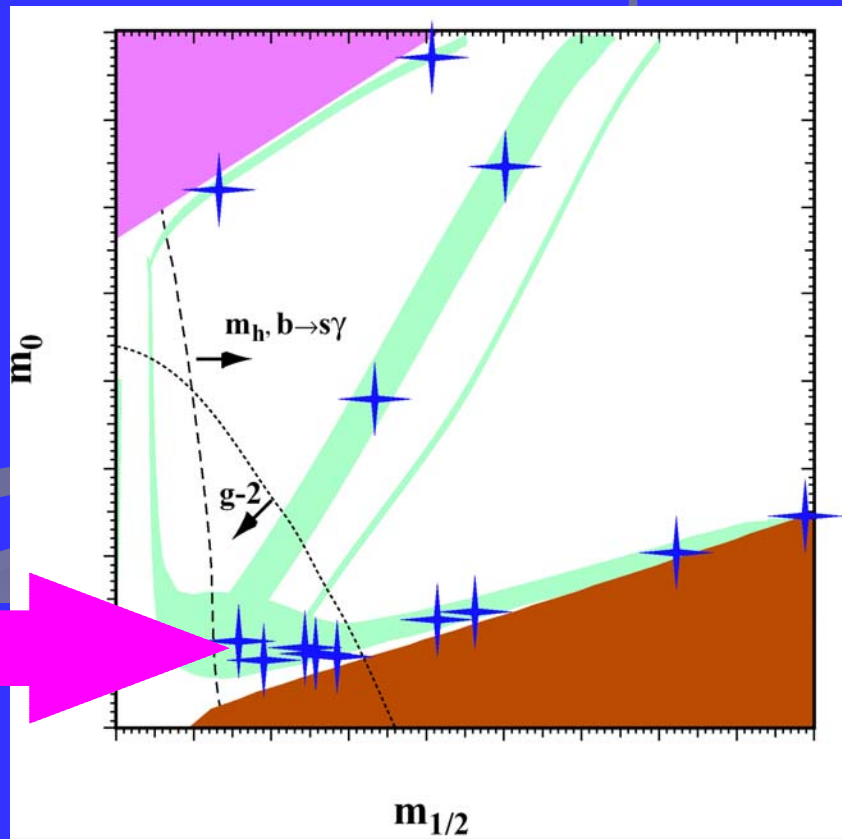
SM bkg: tt, Z+jet, W+jet, ZZ, WW, ZW, QCD jets

Benchmark Points

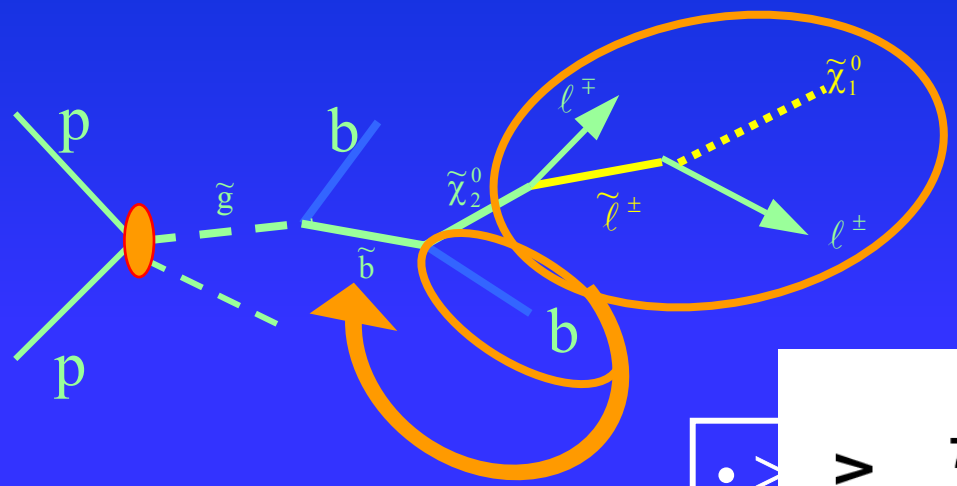
Proposed Post-LEP Benchmarks for Supersymmetry, M. Battaglia *et al.* (hep-ph/0106204)

Model	A	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	20	20	35	35	35	50	50
$\mathrm{sign}(\mu)$	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	120	121	121	123	120	122	117	122	119	117	121	116
m_t	175	175	175	171	171	175	175	175	175	175	175	175

- Rather low m_0 and $m_{1/2}$ values in order to have high SUSY cross section
- Low tan β value (tan β = 10) since BR($\chi_2^0 \rightarrow l^+l^- \chi_1^0$) depends on tan β

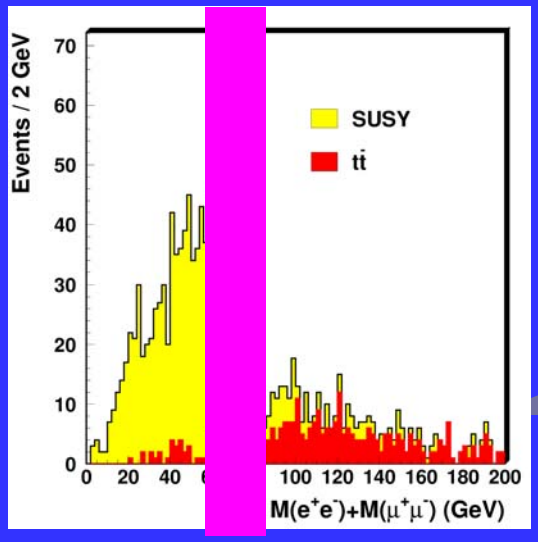


Reconstruction Method

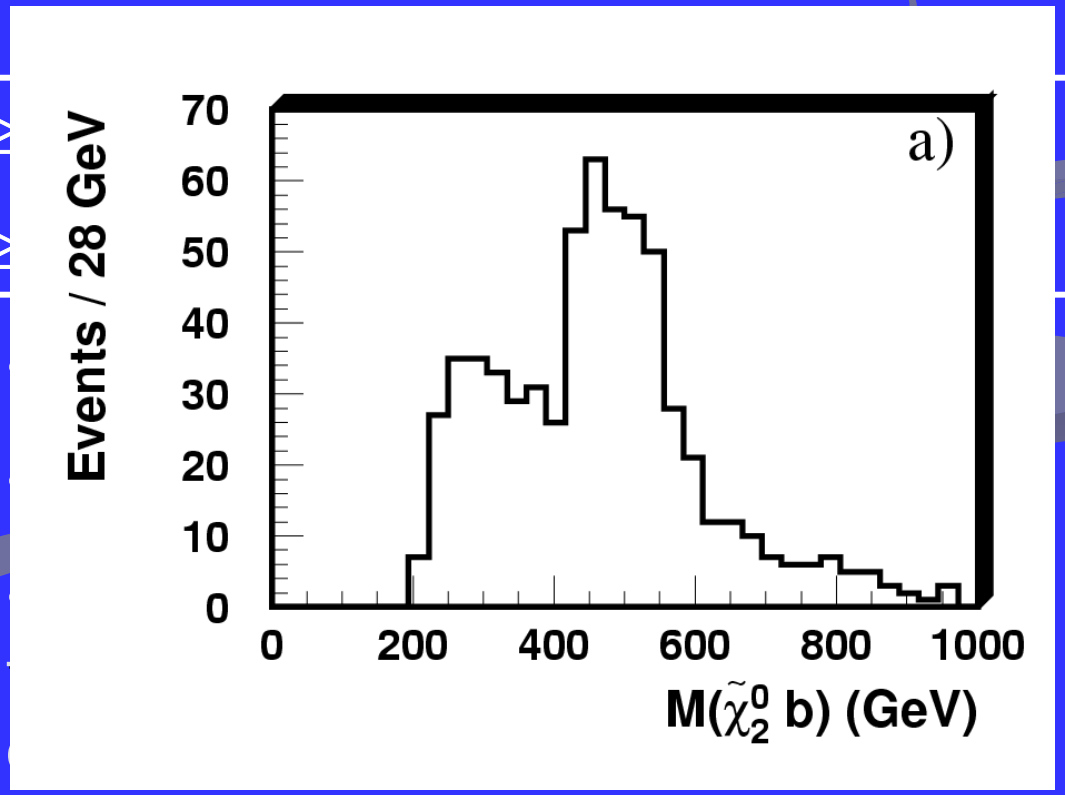


At the end-point:

$$\vec{p}_{\tilde{\chi}_2^0} = \left(1 + \frac{M_{\tilde{\chi}_1^0}}{M_{\ell^+\ell^-}}\right)\vec{p}_{\ell^+\ell^-}$$

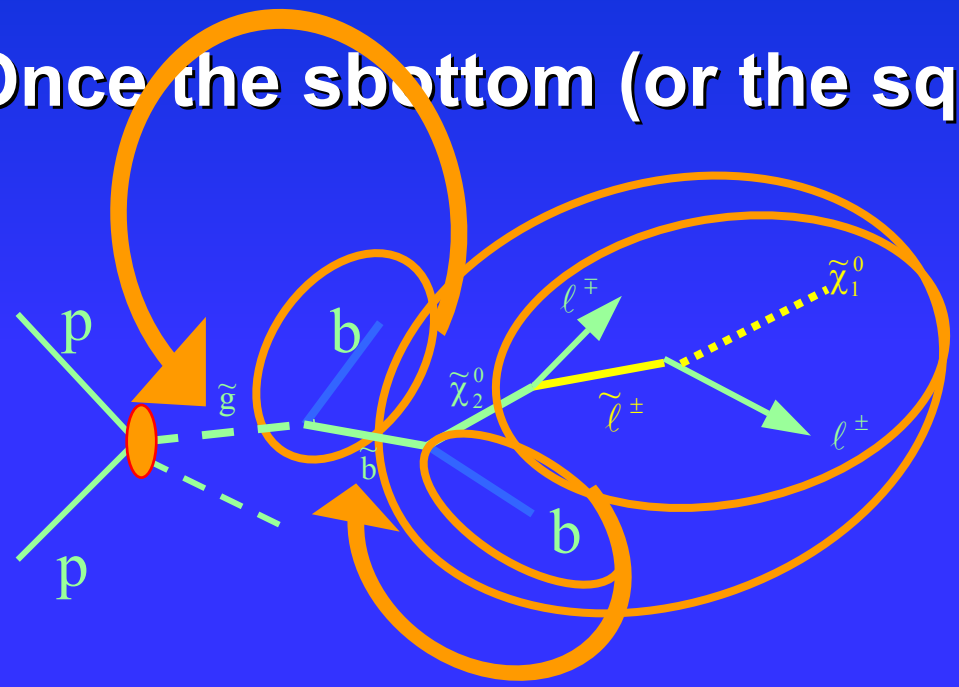


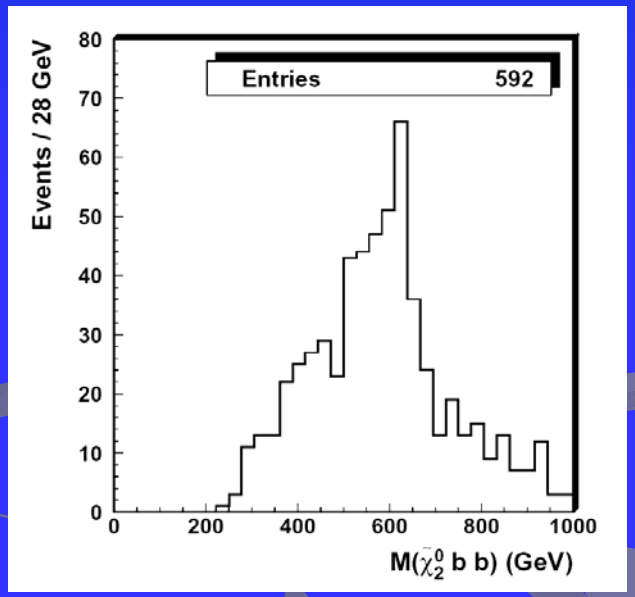
$$65\ \text{GeV} < M(\ell^+\ell^-) < 80\ \text{GeV}$$



Reconstruction Method

Once the sbottom (or the squark) is reconstructed:





- SM bkg can be reduced cutting on E_T^{miss}
- The main problem is combinatorial

Results @ Point B

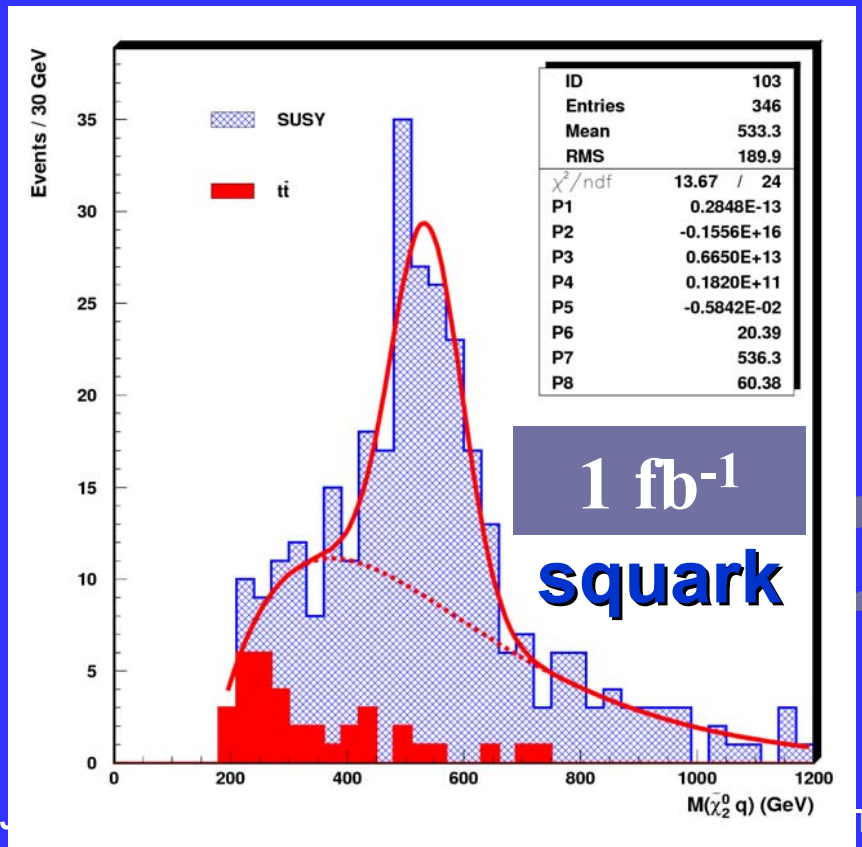
$m_{1/2} = 250$
$m_0 = 100$
$\tan\beta = 10$
$\mathrm{sign}(\mu) = +$
$A_0 = 0$

σ_{SUSY} = 57.77 pb

$BR(\tilde{\chi}_2^0 \to \tilde{\ell}\ell) = 16.44\%$ → visible dilepton edge

$\sigma \bullet BR(pp \to \tilde{q} \to \text{decay chain}) = 1.4\ \text{pb}$

$\sigma \bullet BR(pp \to \tilde{g} \to \tilde{q} \to \text{decay chain}) = 0.5\ \text{pb}$



Result of the fit:

$M(\tilde{\chi}_2^0 q) = 536 \pm 10\ \text{GeV}$

$\sigma = 60 \pm 9\ \text{GeV}$

Generated values

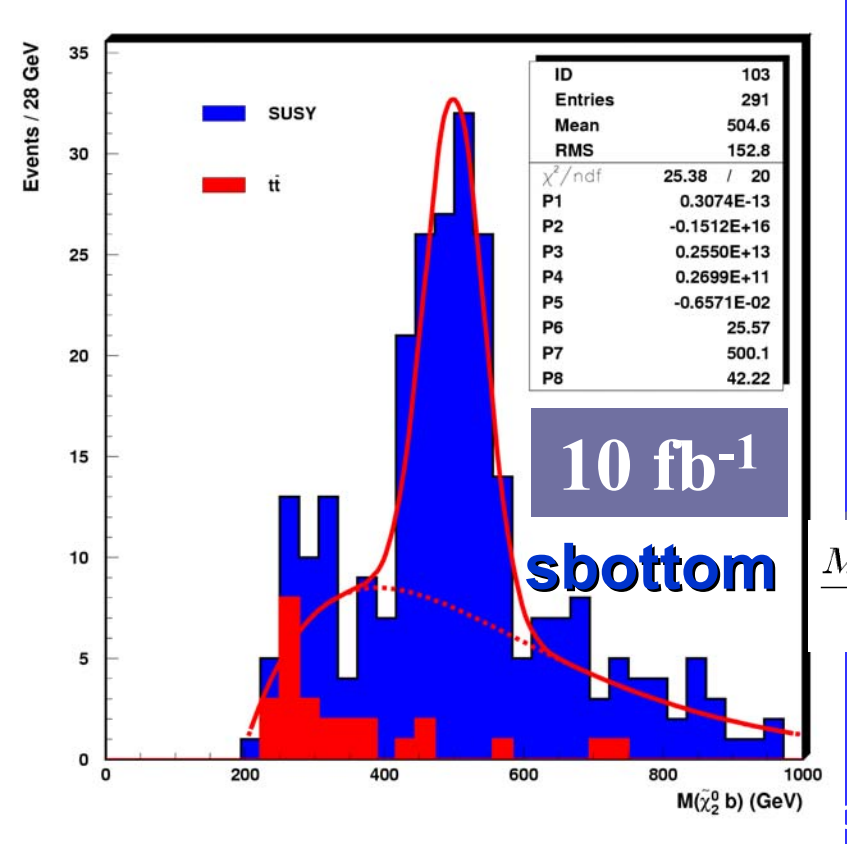
$M(\tilde{d}_L) = M(\tilde{s}_L) = 542.8\ \text{GeV}$

$M(\tilde{u}_L) = M(\tilde{c}_L) = 537.0\ \text{GeV}$

Results @ Point B

$$m_{1/2} = 250$$
$$m_0 = 100$$
$$\tan\beta = 10$$
$$\mathrm{sign}(\mu) = +$$
$$A_0 = 0$$

$$\sigma \bullet BR(pp \to \tilde{b} \to \text{decay chain}) = 0.1\ \text{pb}$$



Result of the fit:

$$M(\tilde{\chi}_2^0 b) = 500 \pm 7\ \text{GeV}$$
$$\sigma = 42 \pm 5\ \text{GeV}$$

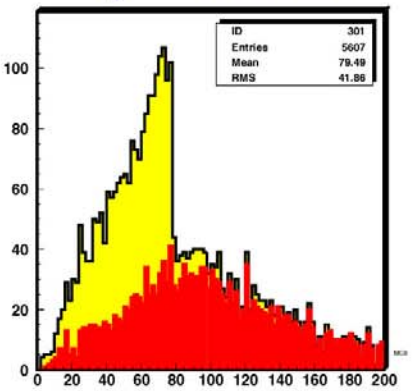
Generated value

$$\frac{M(\tilde{b}_1)\cdot\sigma\times BR(\tilde{b}_1) + M(\tilde{b}_2)\cdot\sigma\times BR(\tilde{b}_2)}{\sigma\times BR(\tilde{b}_1) + \sigma\times BR(\tilde{b}_2)} = 503.9\ \text{GeV}$$

Sparticle Reconstruction

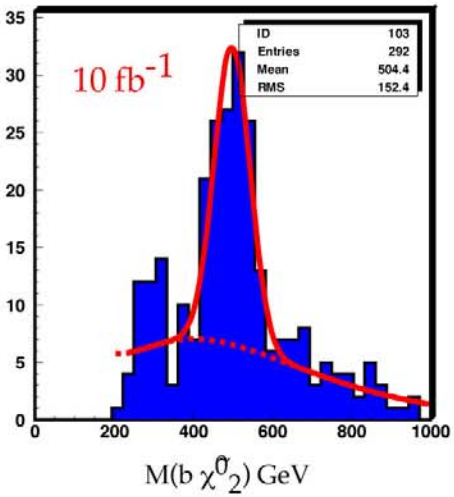
Dilepton edge

$E_t^{miss} > 100$ GeV



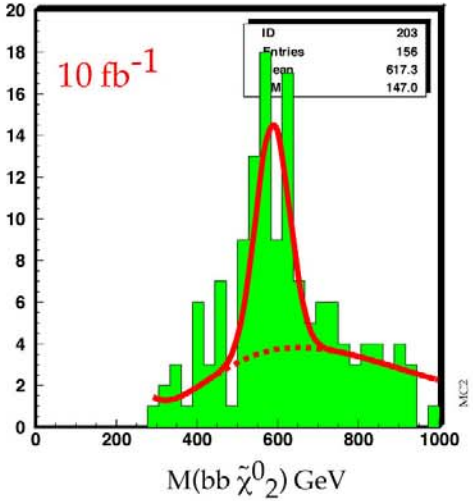
$M(e^+e^-) + M(\mu^+\mu^-)$ GeV

Sbottom reconstruction



$M(b\,\tilde{\chi}^0_2)$ GeV

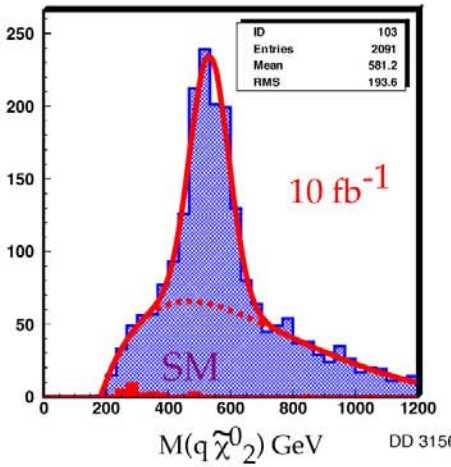
Gluino reconstruction



$M(bb\,\tilde{\chi}^0_2)$ GeV

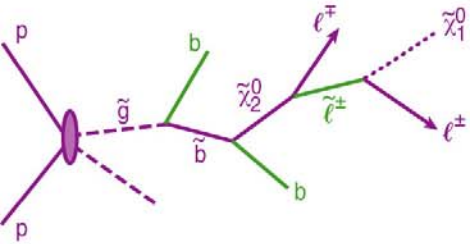
Squark reconstruction

anti-b-tag: $\sigma < 2$, b-veto



$M(q\,\tilde{\chi}^0_2)$ GeV

DD 3156



fit:

$M(b\,\tilde{\chi}^0_2)$ GeV $= 499 \pm 7$ GeV

$\sigma = 48$ GeV

generated: $M(\tilde{b}_L) = 496$ GeV

$M(\tilde{b}_R) = 524$ GeV

fit:

$M(bb\tilde{\chi}^0_2)$ GeV $= 587 \pm 11$ GeV

$\sigma = 41$ GeV

generated mass: $M(\tilde{g}) = 595$ GeV

fit:

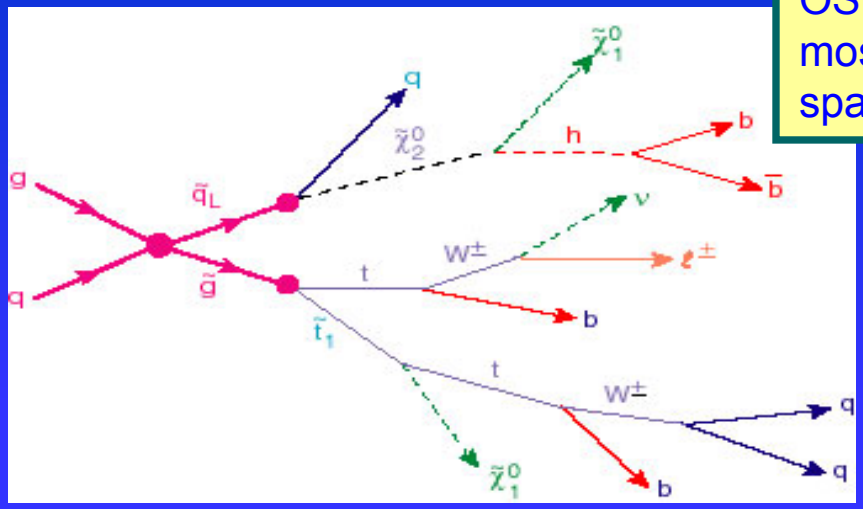
$M(q\,\tilde{\chi}^0_2) = 532 \pm 4$ GeV

$\sigma = 62$ GeV

$M(\tilde{d}_L) = M(\tilde{s}_L) = 543$ GeV

$M(\tilde{u}_L) = M(\tilde{c}_L) = 537$ GeV

SUSY



Squark, gluino production leads to lepton(s) + E_T^{miss} + jets

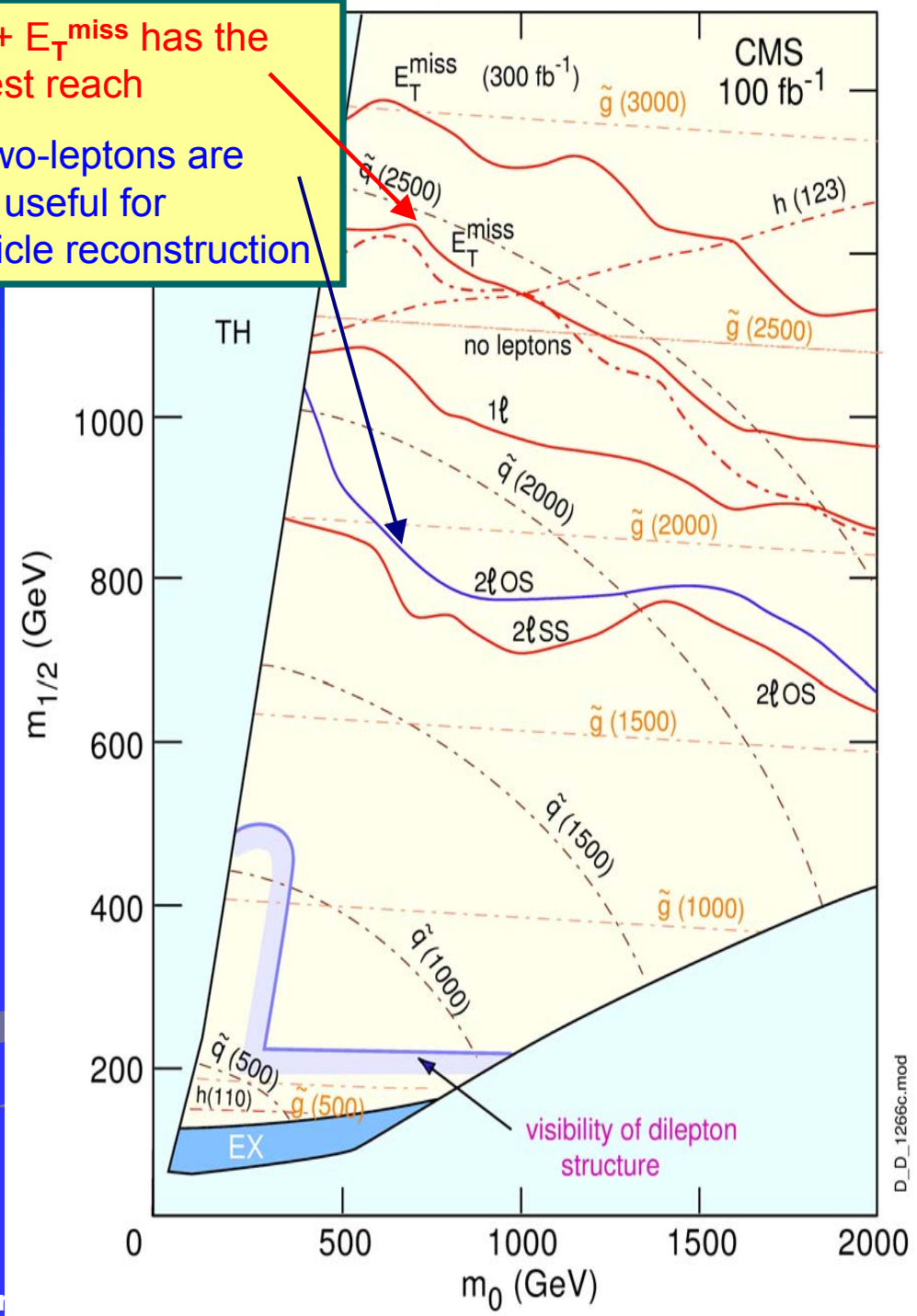
Backgrounds: W + jets, Z + jets, tt, Wtb, WW, WZ, …

$\tilde{q}$, $\tilde{g}$ pair production dominates the total cross section

Cross sections don't vary much with μ, tan β

Jets + E_T^{miss} has the highest reach

OS two-leptons are most useful for sparticle reconstruction

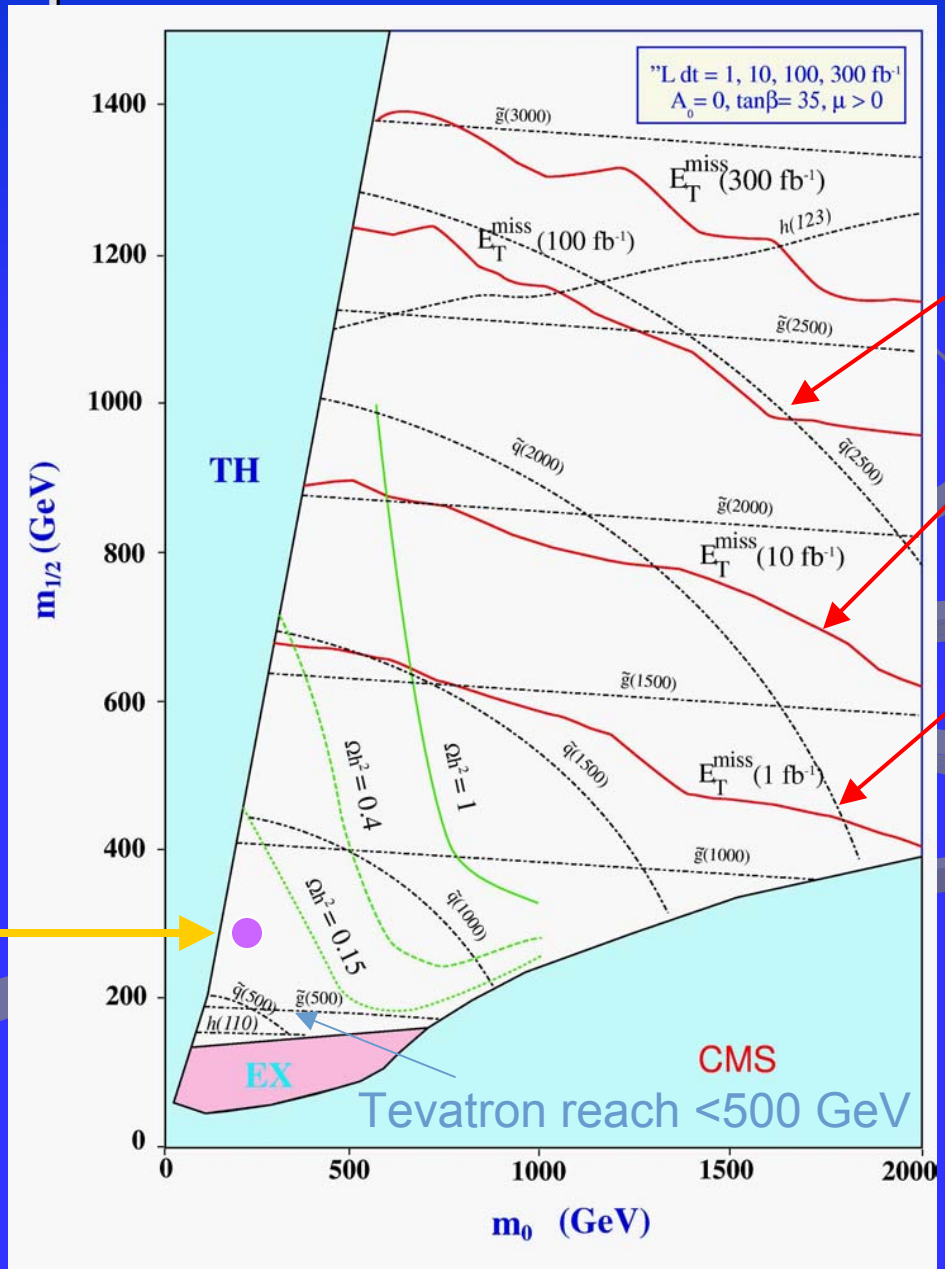


Jets + E_T^{miss} Reach vs. L

Search for SUSY can start very early!

Squarks/gluinos probed to ~1.5 TeV with 1 fb^{-1}

Up to 2.5 TeV at design luminosity and 100 fb^{-1}



~1 week @10^{33} to explore

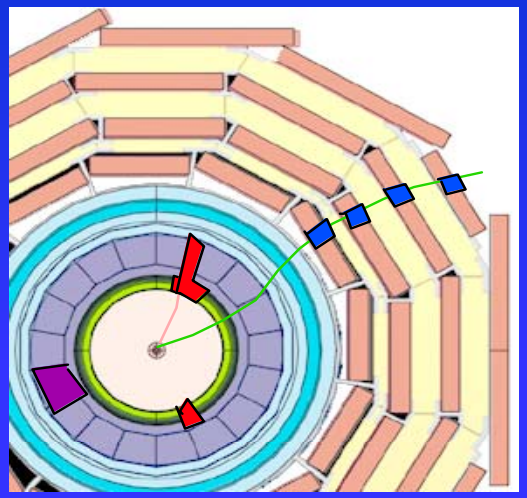
but ~1 year for sparticle reco

~1 year @ L=10^{34}

~1 year @ L=10^{33}

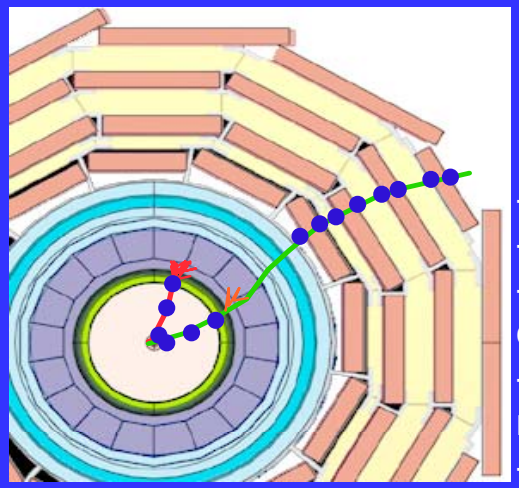
~1 month @ L=10^{33}

Event Selection



Level-1: Spec.processors
40 MHz synchronous
-Particle identification:
-high pT electron, muon, jets, missing ET
- Local pattern recognition and energy evaluation on prompt macro-granular information from calorimeter and muon detectors

99.99 % rejected 0.01 % Accepted



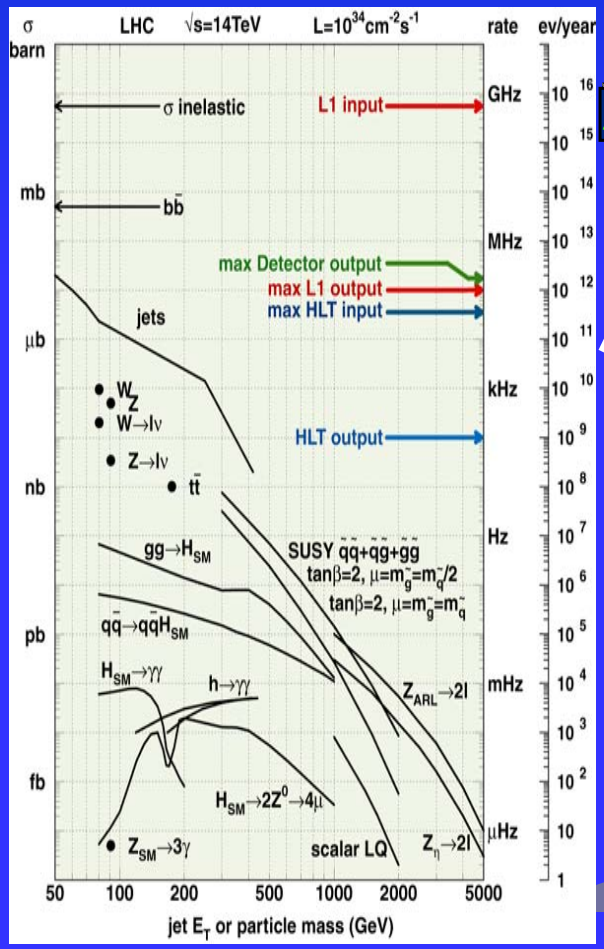
High trigger levels: CPU farms
100 kHz asynchronous farms
- Clean particle signature
- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching
- Event reconstruction and analysis

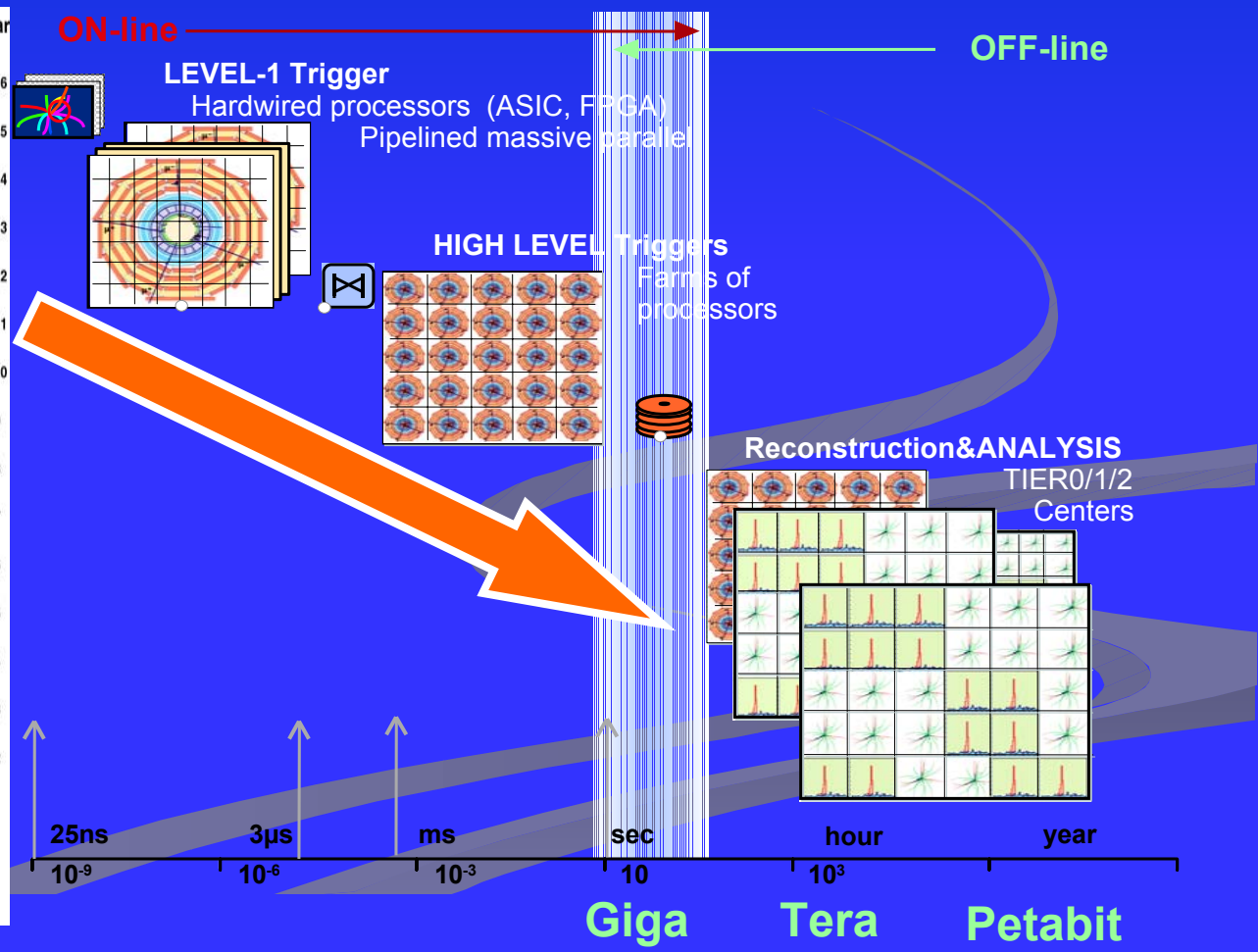
Minimum calibration for the trigger to function @ low **L**:

- **ECAL** $\Delta E/E \sim 3 - 5\%$ (final $\Delta E/E \sim 0.5\%$)
  → with minimum bias events
- **HCAL** $\Delta E/E \sim 10\%$
  → source & testbeam calibration show 5% is reachable
- **Alignment of muon system and tracker** with ~ 500 μm needed
  → hardware alignment + alignment with tracks can reach 100 microns

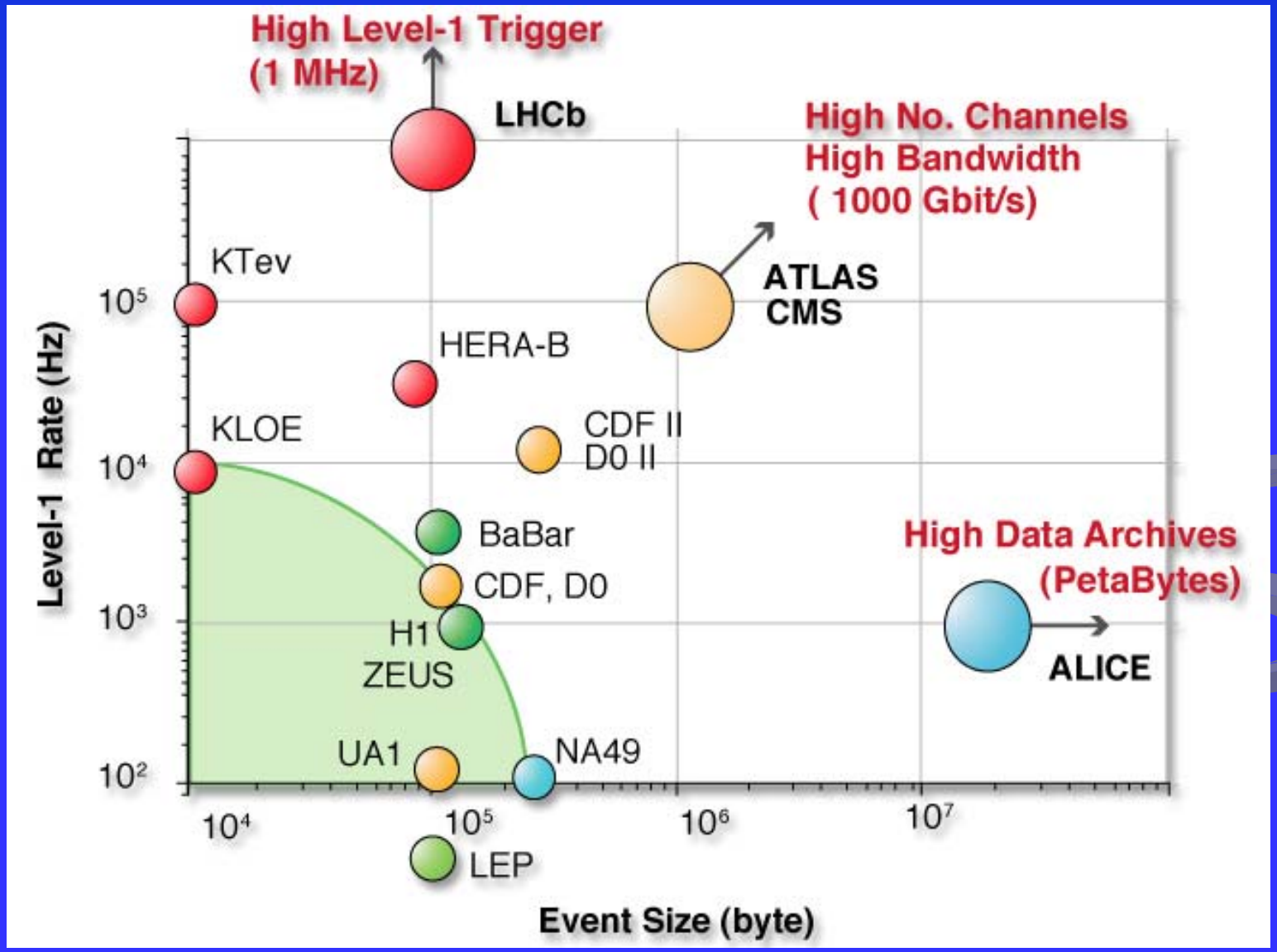
Physics Selection at LHC

TASI





Trigger/DAQ Evolution



Level-1 Trigger table ($2x10^{33}$)

Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias		0.9	16.0
TOTAL			**16.0**

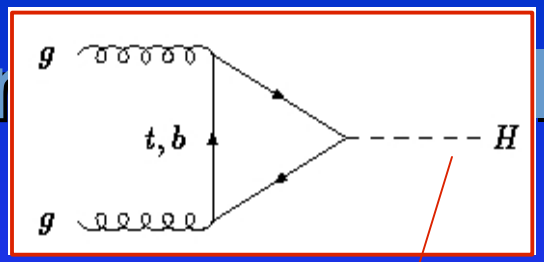
Level-1 Trigger table (10^{34})

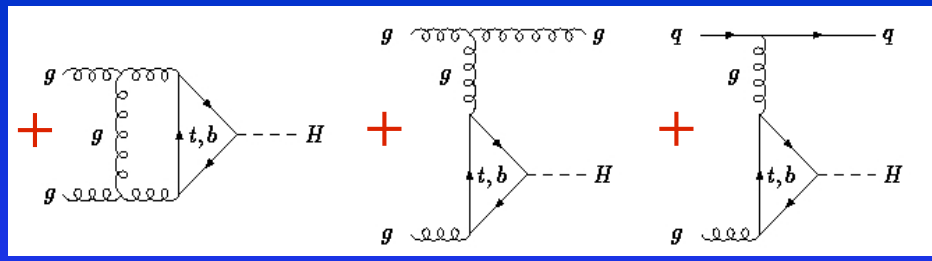
Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Isolated e/γ	34	6.5	6.5
Di-e/γ	19	3.3	9.4
Isolated muon	20	6.2	15.6
Di-muon	5	1.7	17.3
Single tau-jet	101	5.3	22.6
Di-tau-jet	67	3.6	25.0
1-jet, 3-jet, 4-jet	250, 110, 95	3.0	26.7
JetE_T^{miss}*	113*70	4.5	30.4
*Electron*jet*	25*52	1.3	31.7
*Muon*jet*	15*40	0.8	32.5
Min-bias		1.0	33.5
TOTAL			**33.5**

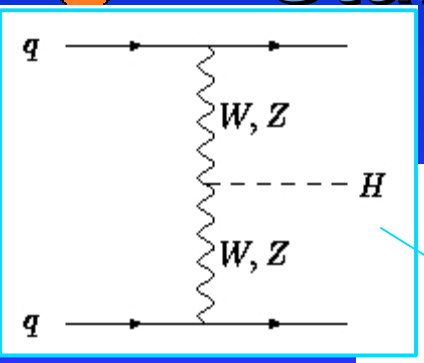
HLT Summary: $2x10^{33}$

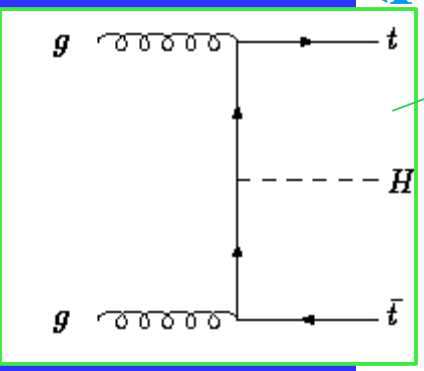
Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cuml. rate (Hz)
Inclusive electron	29	33	33
Di-electron	17	1	34
Inclusive photon	80	4	38
Di-photon	40, 25	5	43
Inclusive muon	19	25	68
Di-muon	7	4	72
Inclusive tau-jet	86	3	75
Di-tau-jet	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jet OR 4-jet	657, 247, 113	9	89
Electron * jet	19 * 45	2	90
Inclusive b-jet	237	5	95
Calibration etc		10	105
TOTAL			**105**

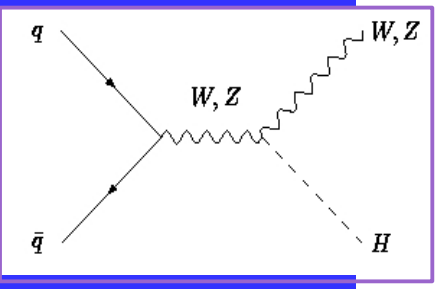
Star

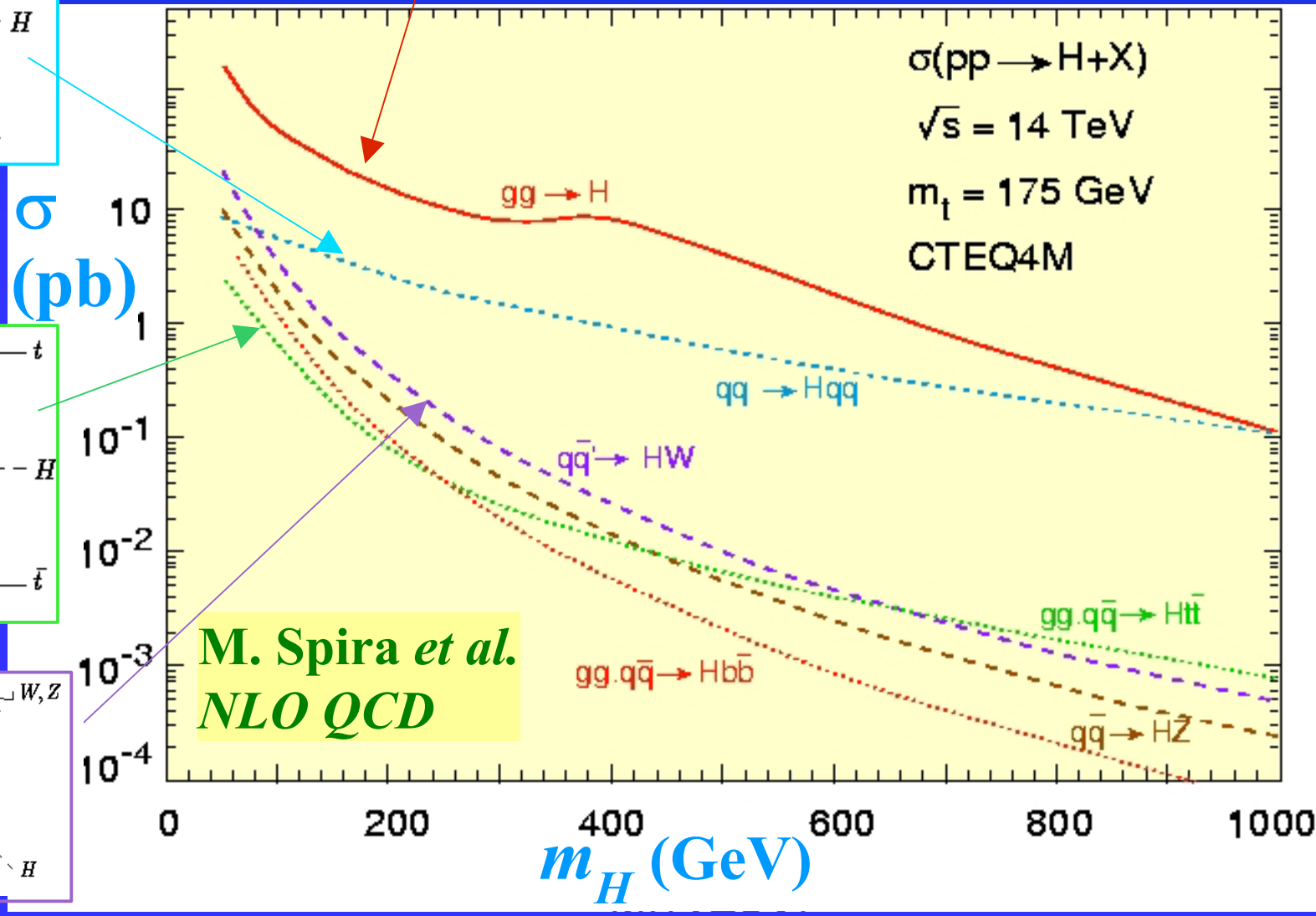












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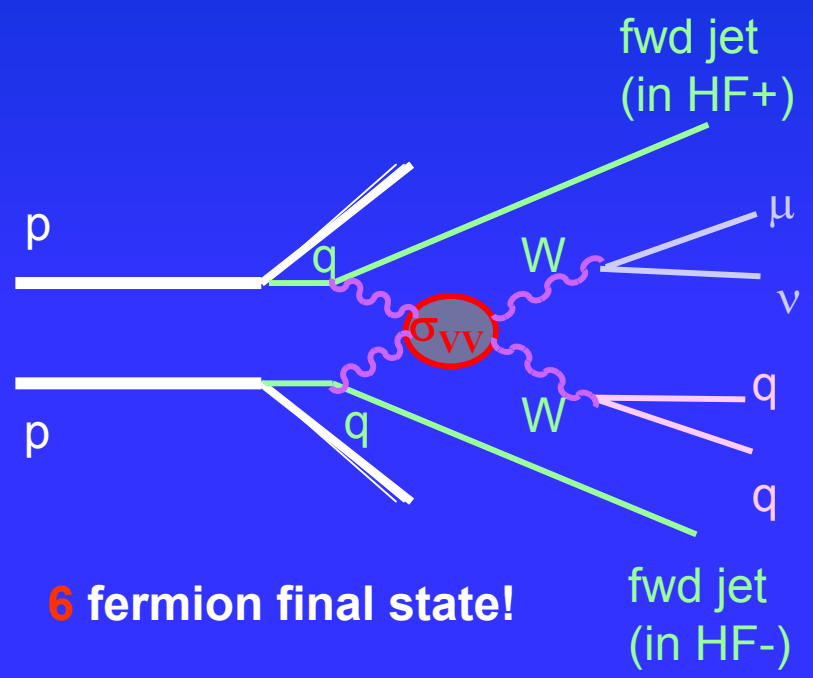
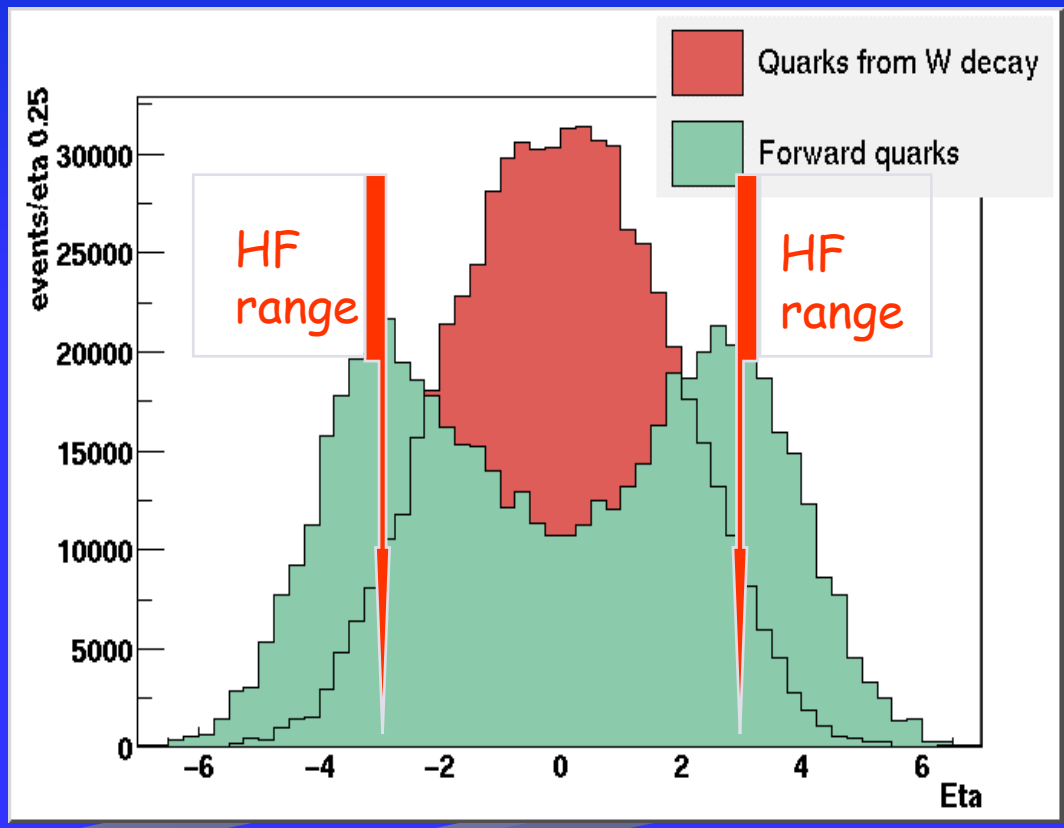
Forward Calorimeters



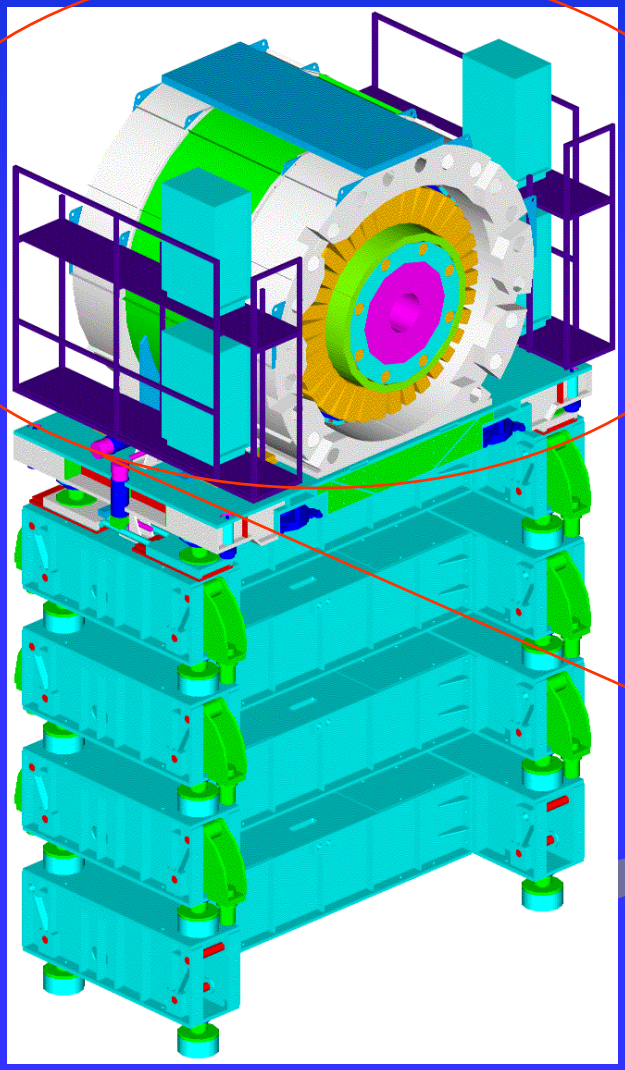
6 fermion final state!



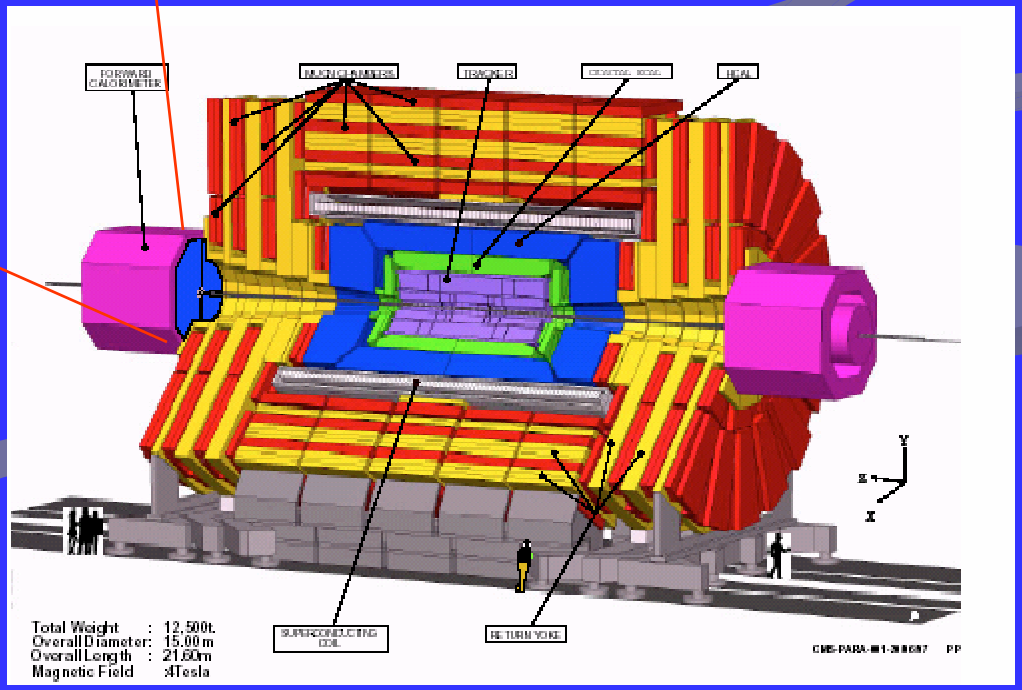
Tagging High energy forward jets: for 'physics' analysis P_t (~20 GeV/c) the jet energies concerned are ~200 GeV at the outer edge of the detector and 1 TeV at the inner edge

An energy resolution of 200%/√E is sufficient

Forward Calorimeters



CMS Detector

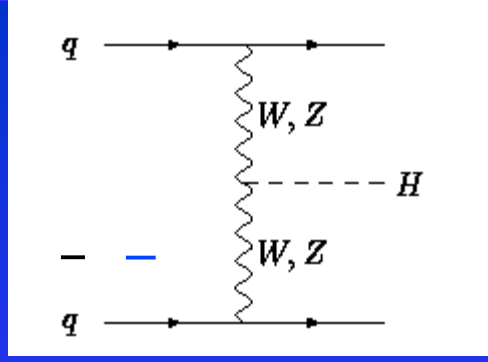


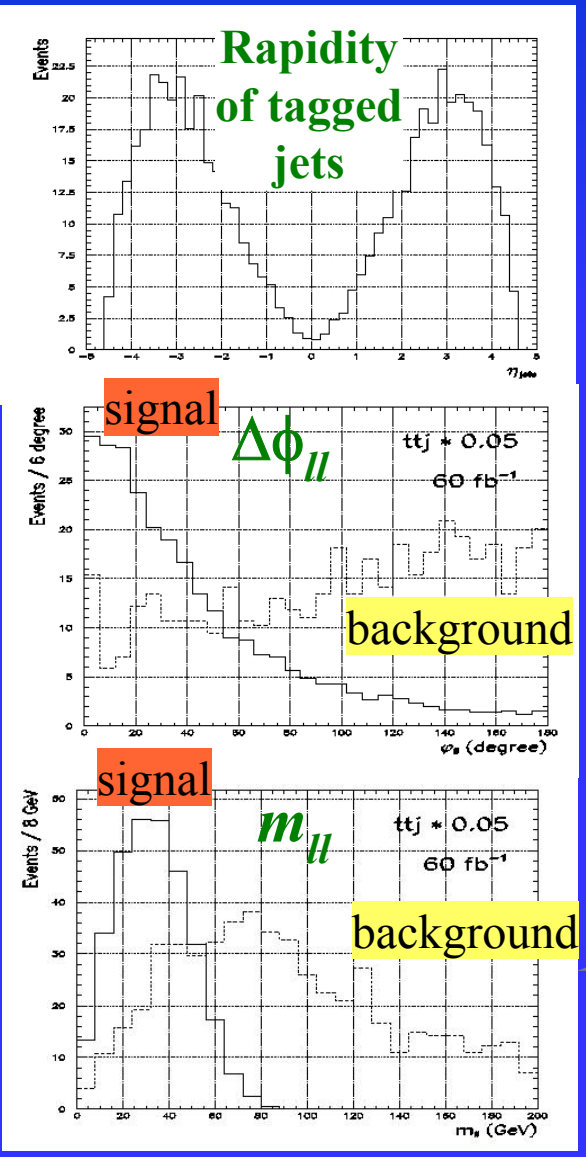
Detector Assembly

21 wedges fibered and waiting covers

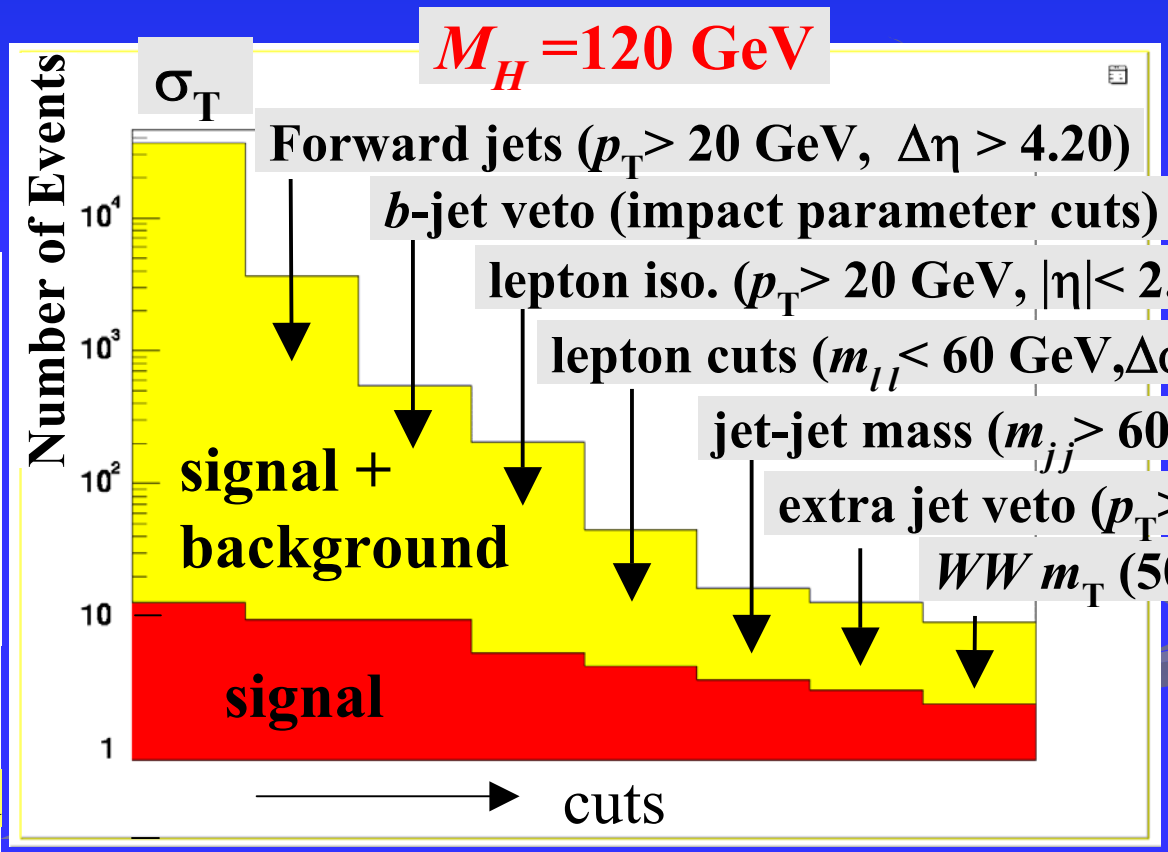
All wedges mounted on strongbacks

Vector Boson Fusion





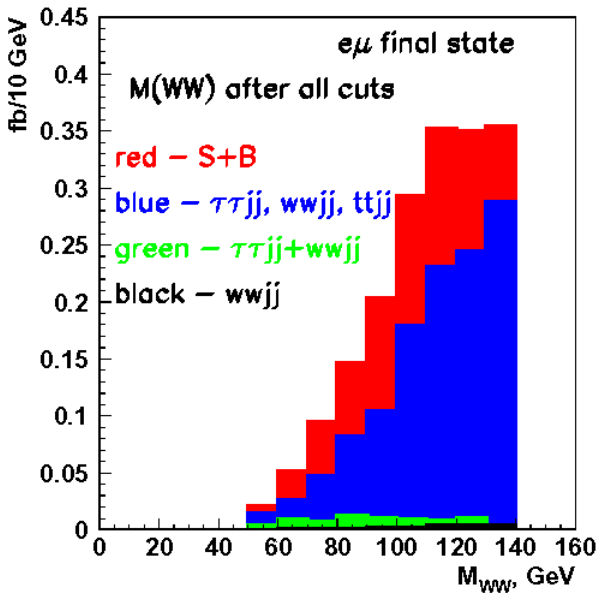
main background: $t\,t + X$



Weak Boson Fusion

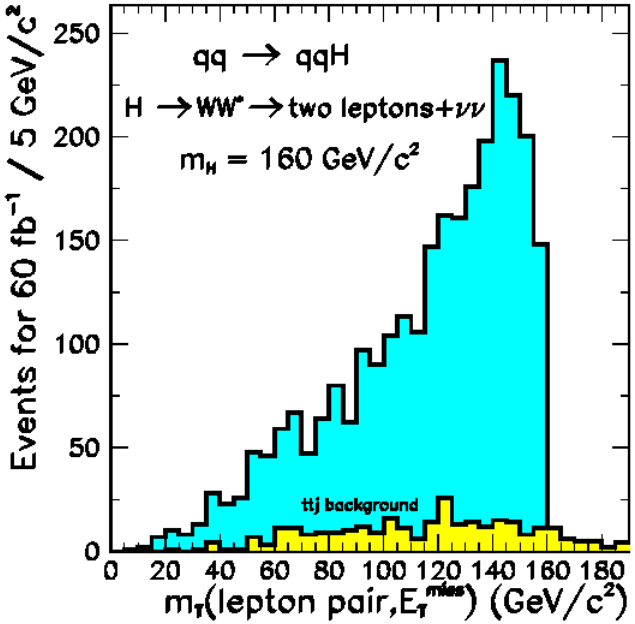
e+μ final state, M_H=120 GeV

A. Nikitenko 2001 (not published)

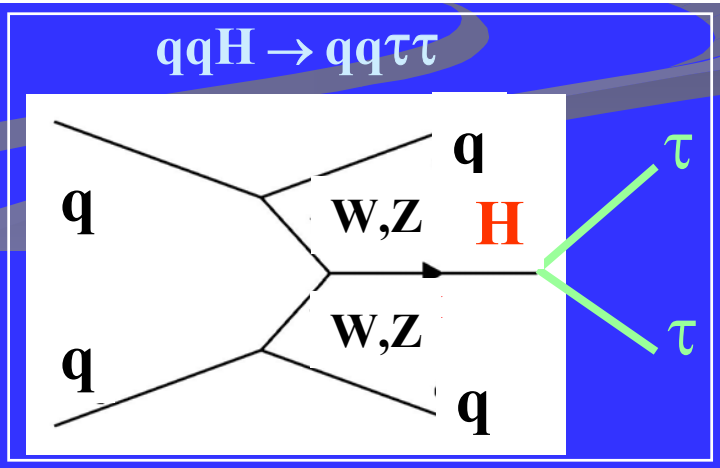


CMS Note 2002/016, M=120 GeV

CMS IN 2002/066, M=120-180 GeV



WW Mass very broad



Weak Boson Fusion

parton level study

D. Rainwater, D. Zeppenfeld 1997

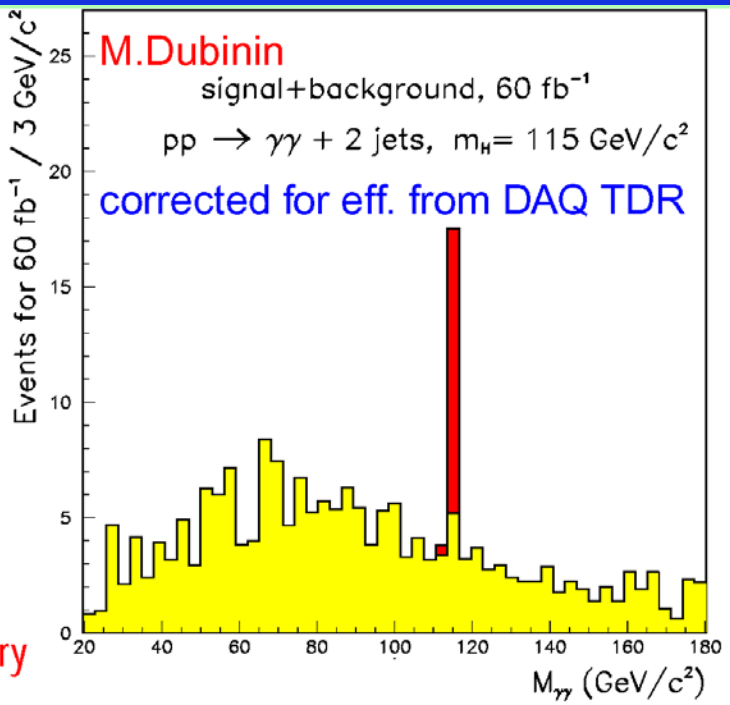
CompHEP + cmsjet study

M.Dubinin CMS Note 2001/022

reducible bkg. was not simulated in both above studies

preliminary study of S. Shevchenko et al (pythia generator + full simulation and reco) indicates dominant $\gamma + 3$ j background

T. Lee, V. Litvin. H. Newman, S. Shevchenko. 2003 preliminary



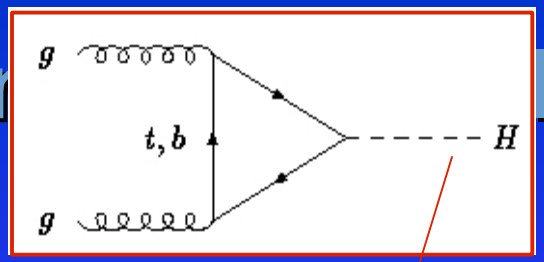
Mass window	Higgs cross section	Background cross section	Luminosity for 5 sigma
1.5 GeV	0.34 fb	0.13 fb	47 fb^{-1}
2.0 GeV	0.41 fb	0.17 fb	41 fb^{-1}
2.5 GeV	0.45 fb	0.21 fb	41 fb^{-1}
3.0 GeV	0.49 fb	0.26 fb	41 fb^{-1}
3.5 GeV	0.52 fb	0.30 fb	42 fb^{-1}
4.0 GeV	0.53fb	0.34 fb	44 fb^{-1}

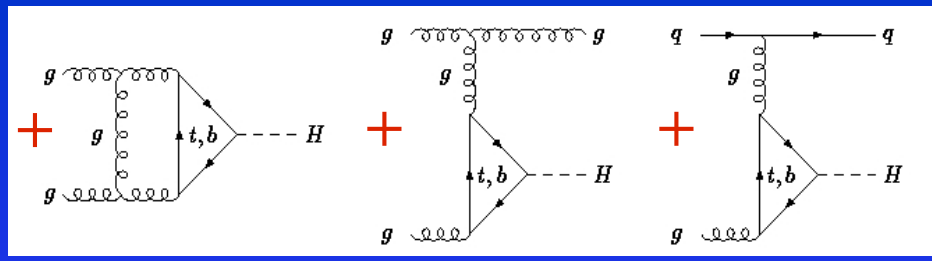
pythia may underestimates $\gamma + 3$ j bkg

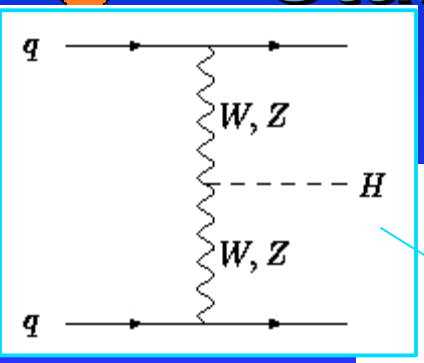
new estimates will be done with $\gamma + 3$ j CompHEP events

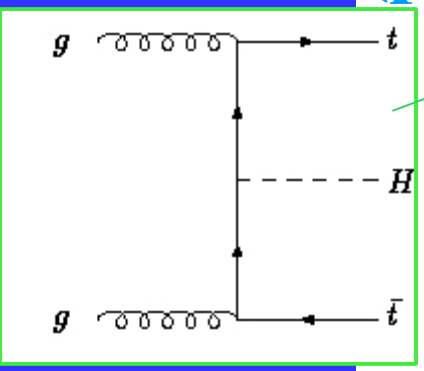
(under preparation by M. Dubinin)

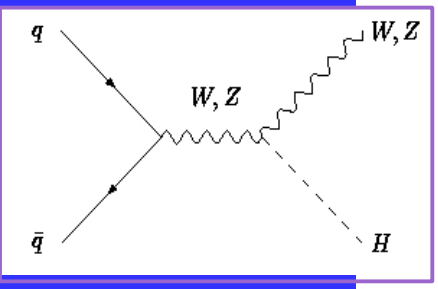
Star

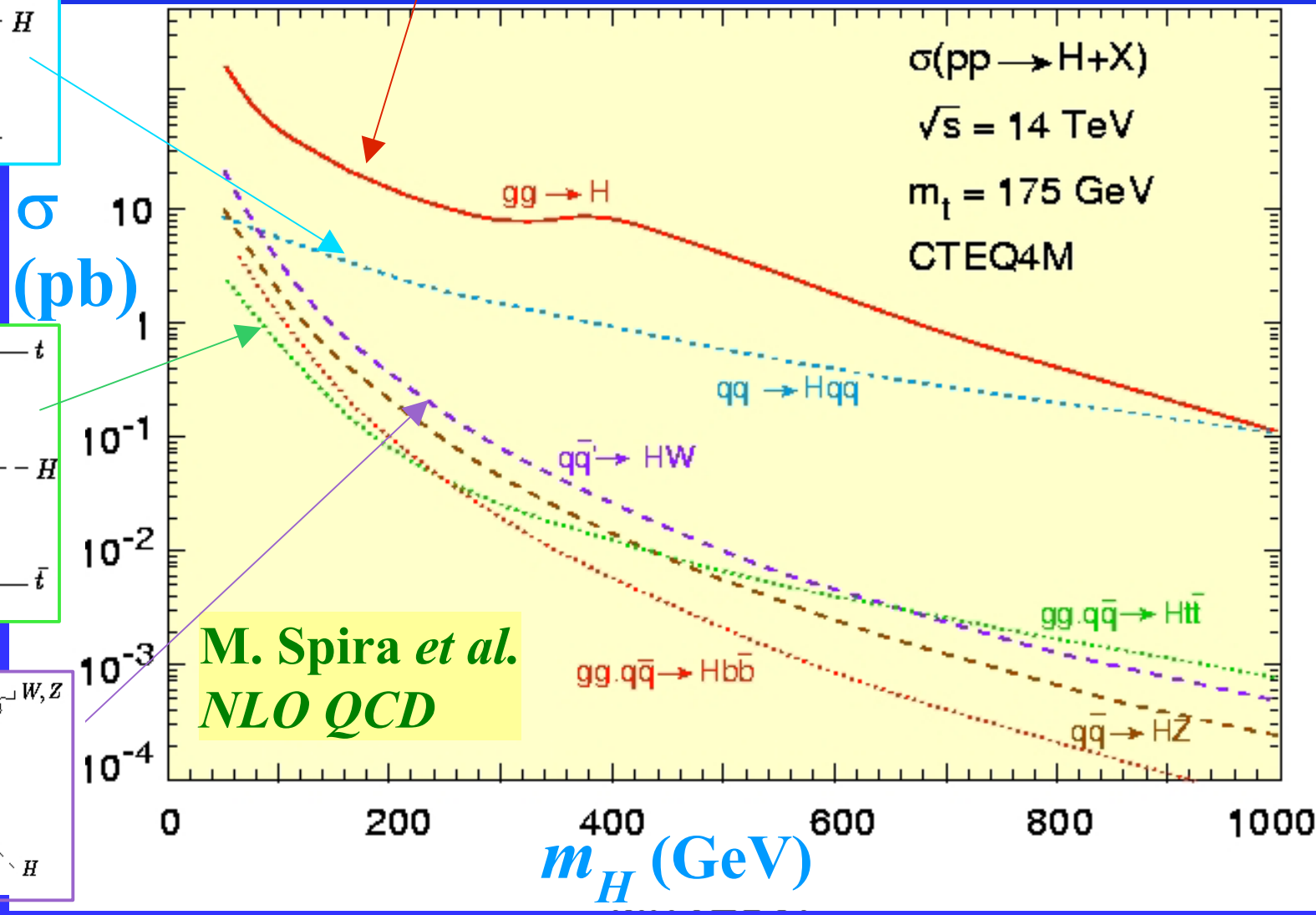












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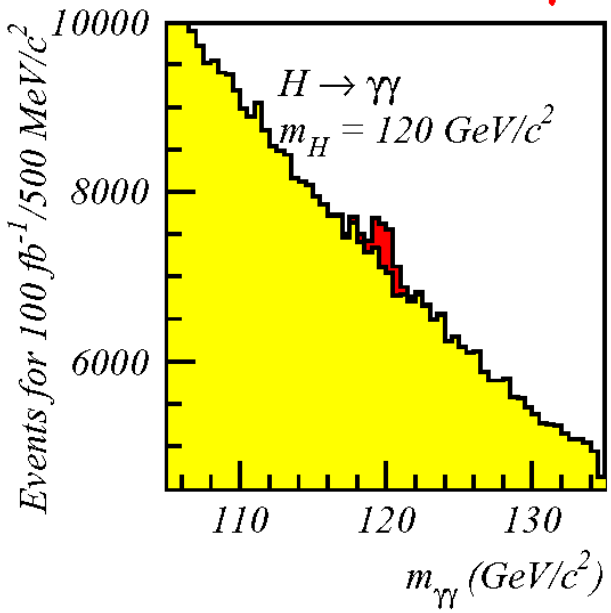
Inclusive Higgs to Photons

inclusive H->2γ



requires excellent resolution and sophisticated reconstruction

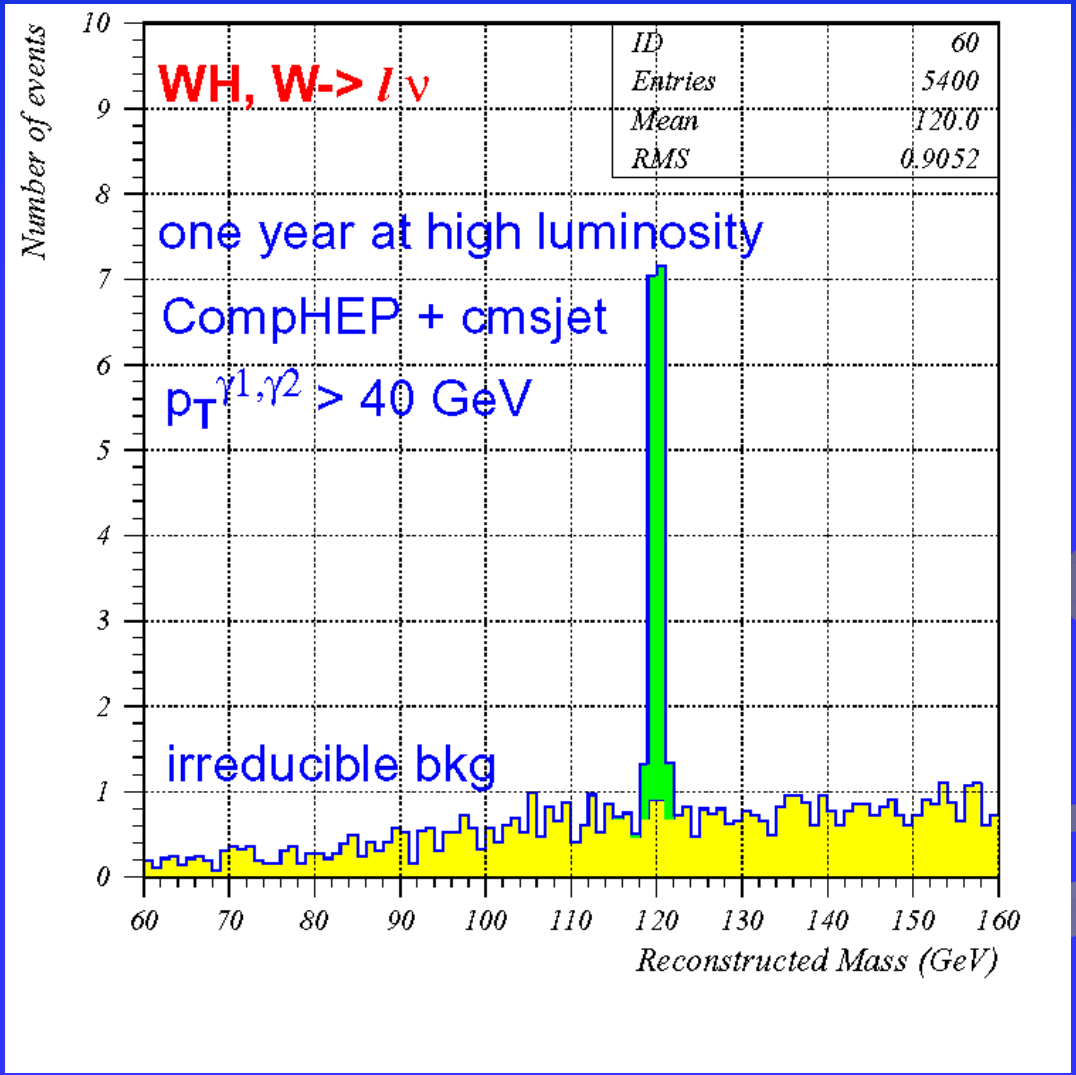
pp->H+X channels

pp->H+j, WH, ZH, ttH, (bbH?)

- less demanding to resolution
- vertex can be more easy defined
- survive even if stop is light

however, more simulation and theoretical work has to be done to prove that they are in competition with inclusive H->2γ

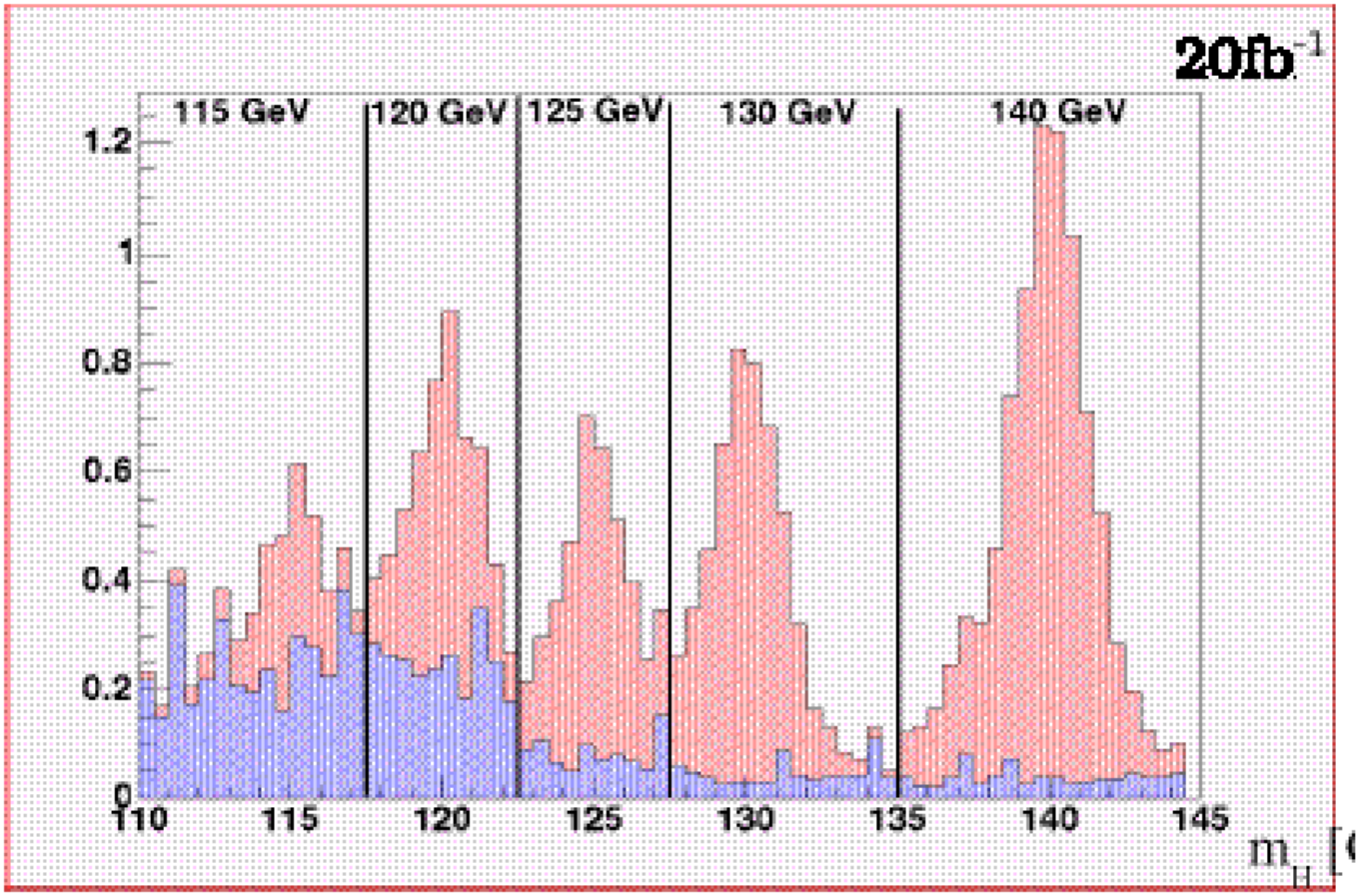
Mass Reconstruction



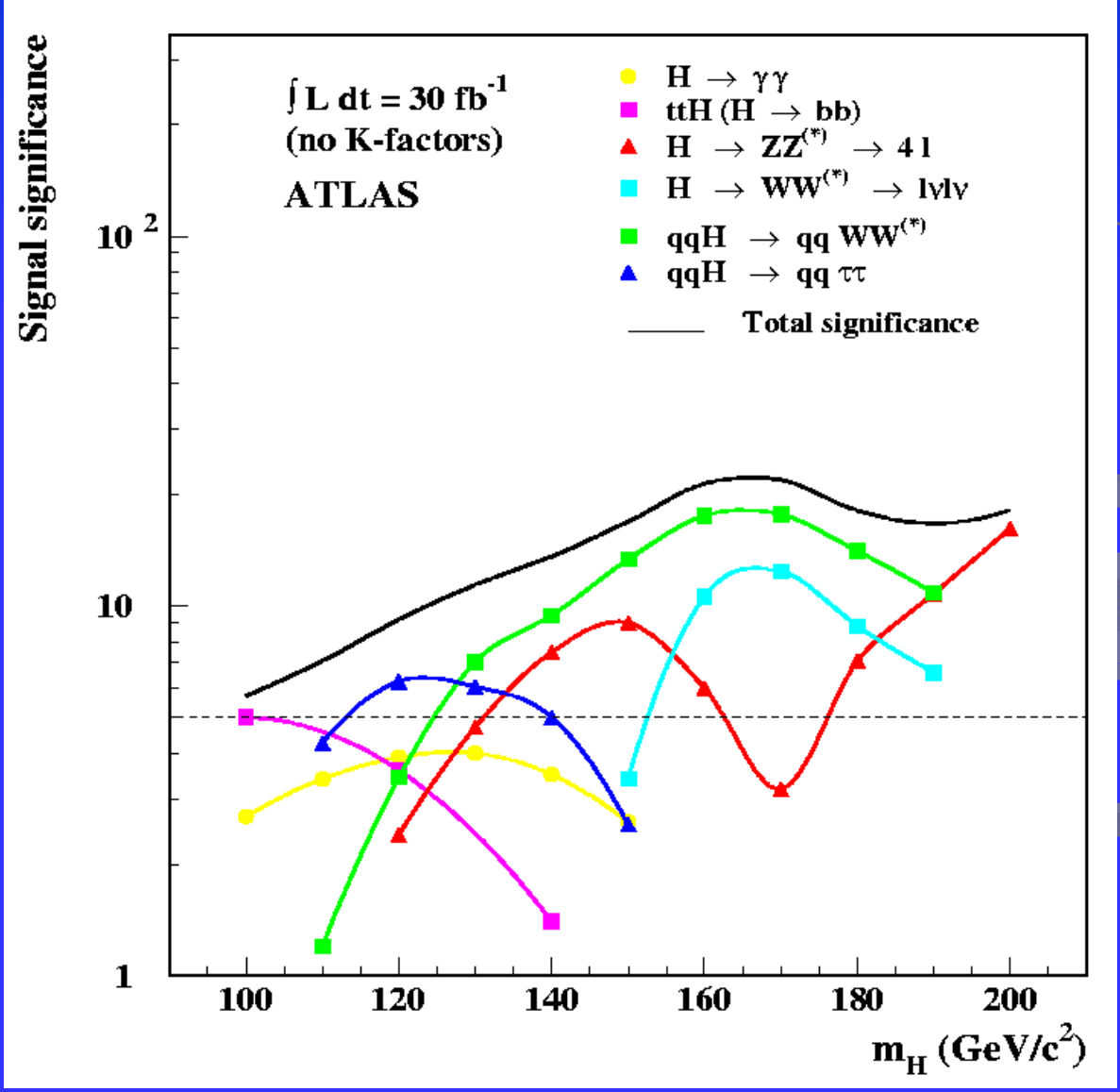
Low Background, High Resolution Mass Reconstruction is possible with enough luminosity

Higgs to ZZ* to 4μ

M_H, GeV	115	120	125	130	140
σ, GeV	1.17	1.22	1.24	1.28	1.36



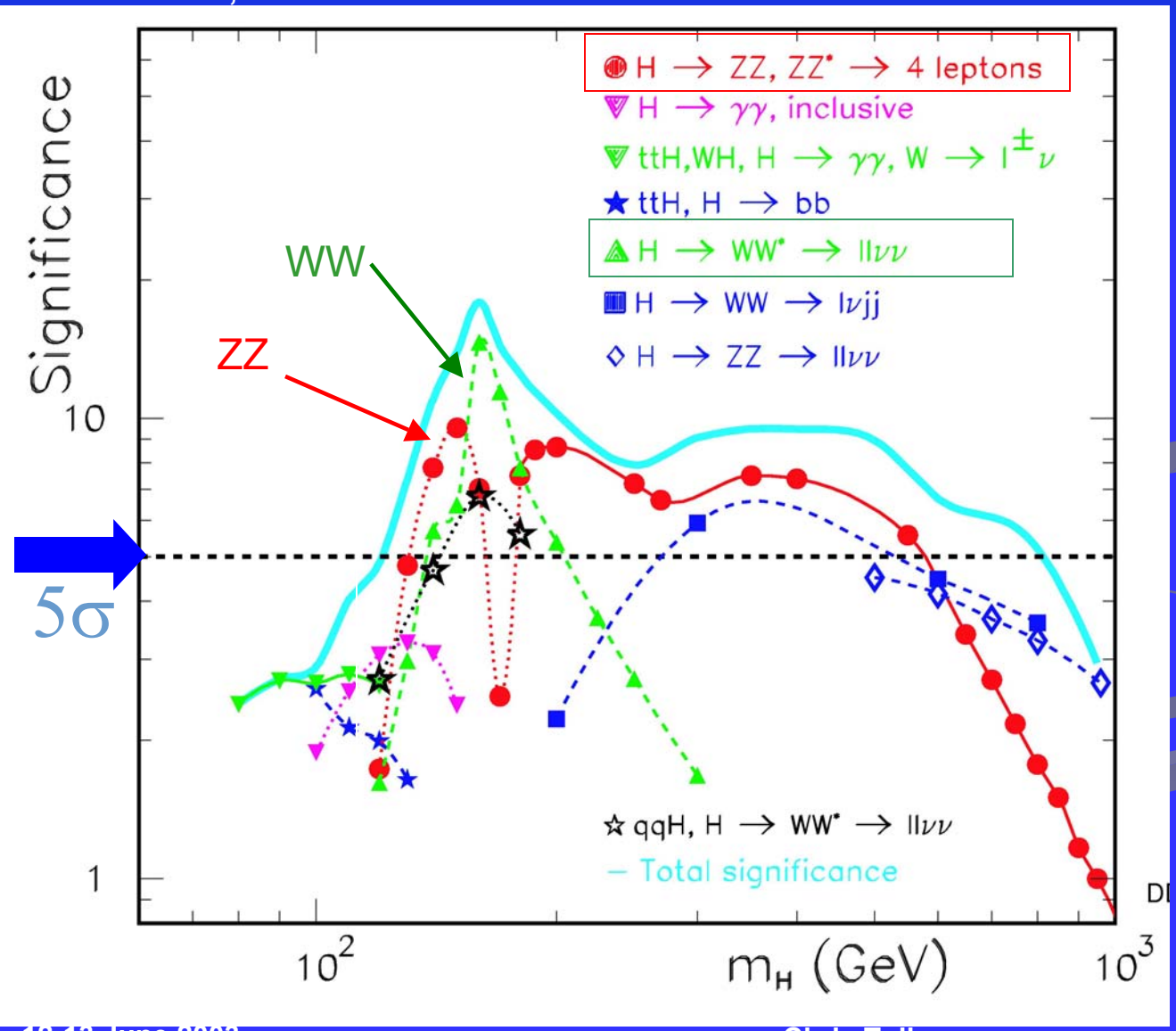
SM Higgs Discovery Potentials



SM Higgs Discovery Potential with 10 fb^{-1}

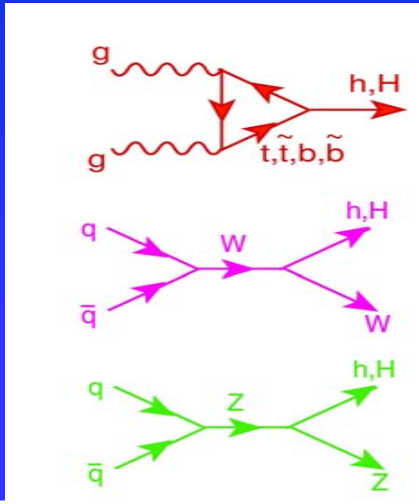
TASI

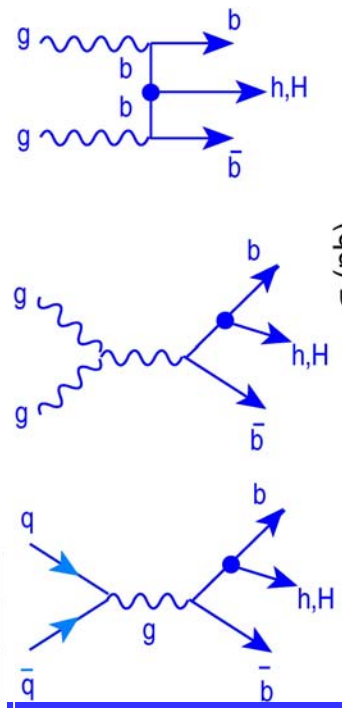
CMS, 10 fb^{-1} No k-factors

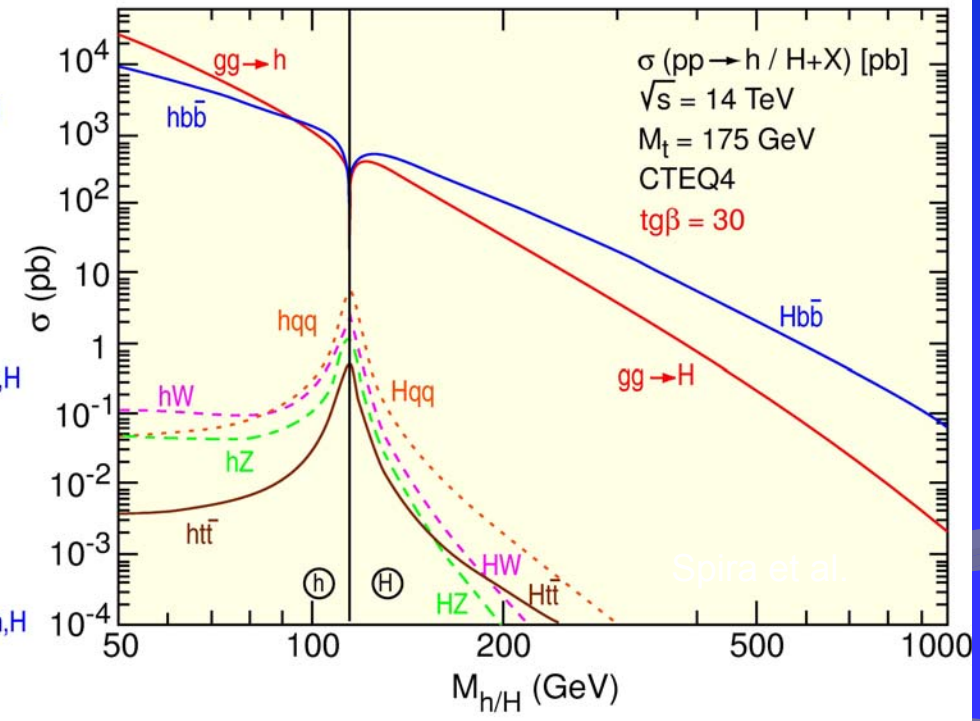


- **H → 4 leptons,**
  m_H = 120….500 GeV
- **H → WW → lνlν**
  m_H = 110….200 GeV

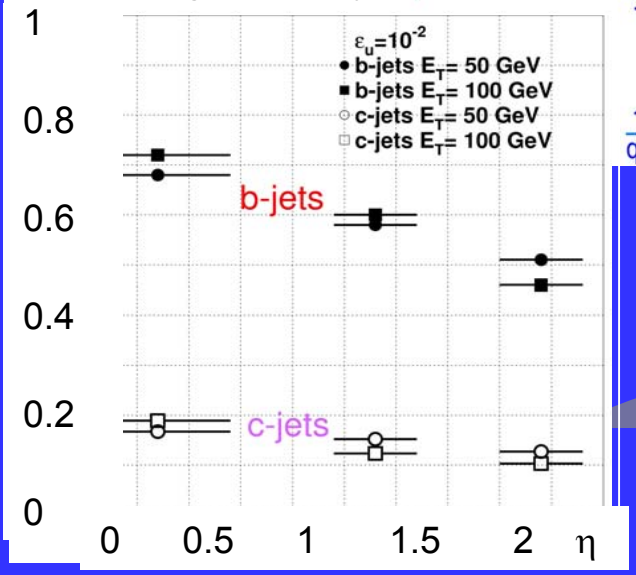
MSSM Higgs Production







b/c tagging efficiency



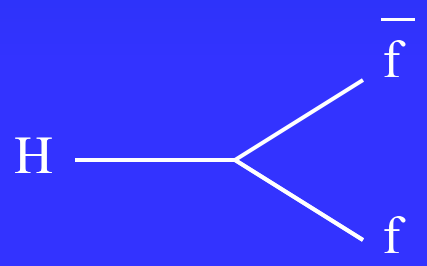
bbH final states production enhanced by $\tan^2 \beta$ in the MSSM w.r.t. SM

→ Note importance of bbH final states!

B-tagging plays a key role

MSSM Higgs Couplings to Fermions

Higgs couplings to fermions:



- $g_{h^0 t\bar{t}} \propto m_t \dfrac{\cos\alpha}{\sin\beta}$
- $g_{h^0 b\bar{b}} \propto m_b \dfrac{-\sin\alpha}{\cos\beta}$
- $g_{H^0 t\bar{t}} \propto m_t \dfrac{\sin\alpha}{\sin\beta}$
- $g_{H^0 b\bar{b}} \propto m_b \dfrac{\cos\alpha}{\cos\beta}$
- $g_{A^0 t\bar{t}} \propto m_t \cot\beta$
- $g_{A^0 b\bar{b}} \propto m_b \tan\beta$

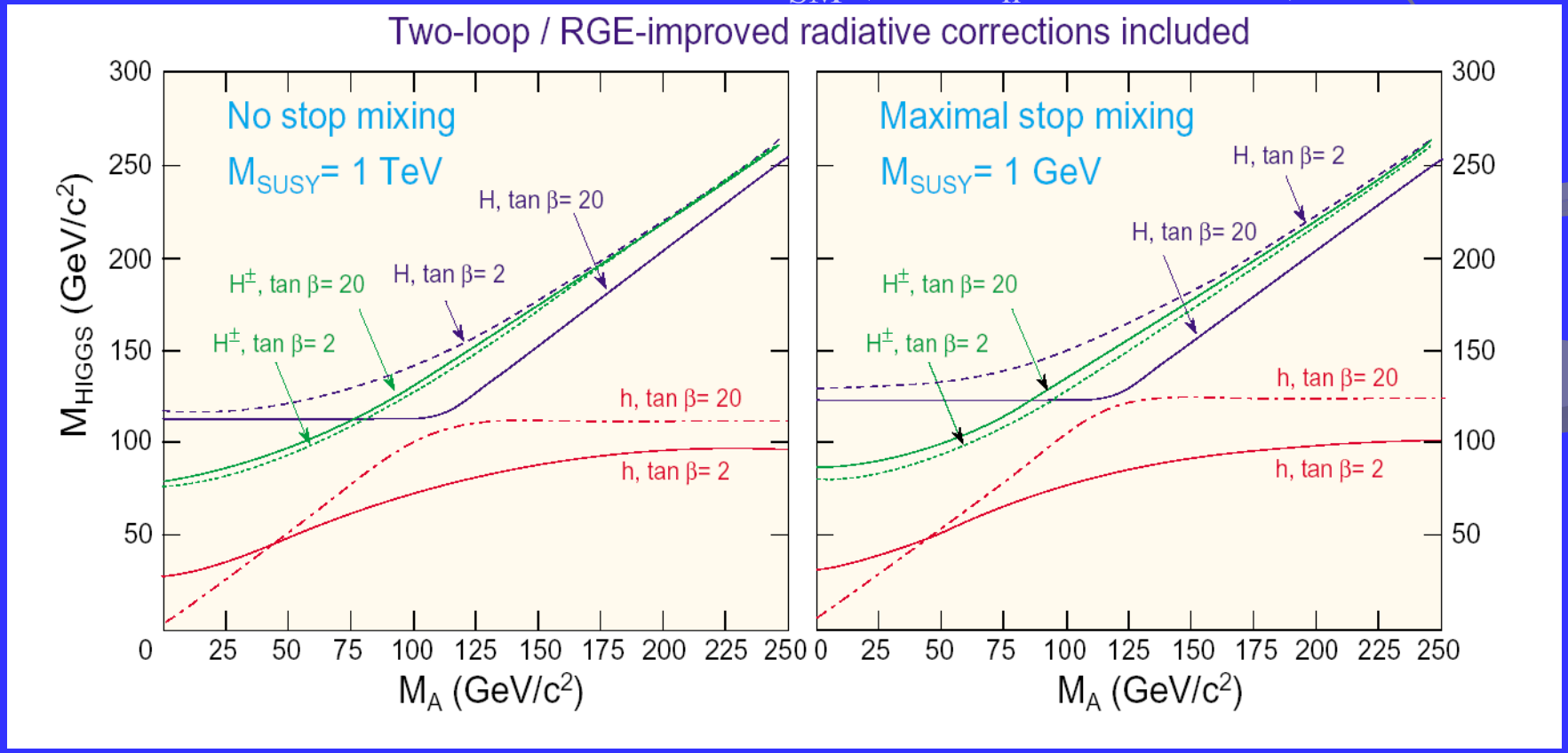
- proportional to mass → 3rd generation favoured
- tan β enhances couplings to down-type fermions

MSSM Mass Relationships

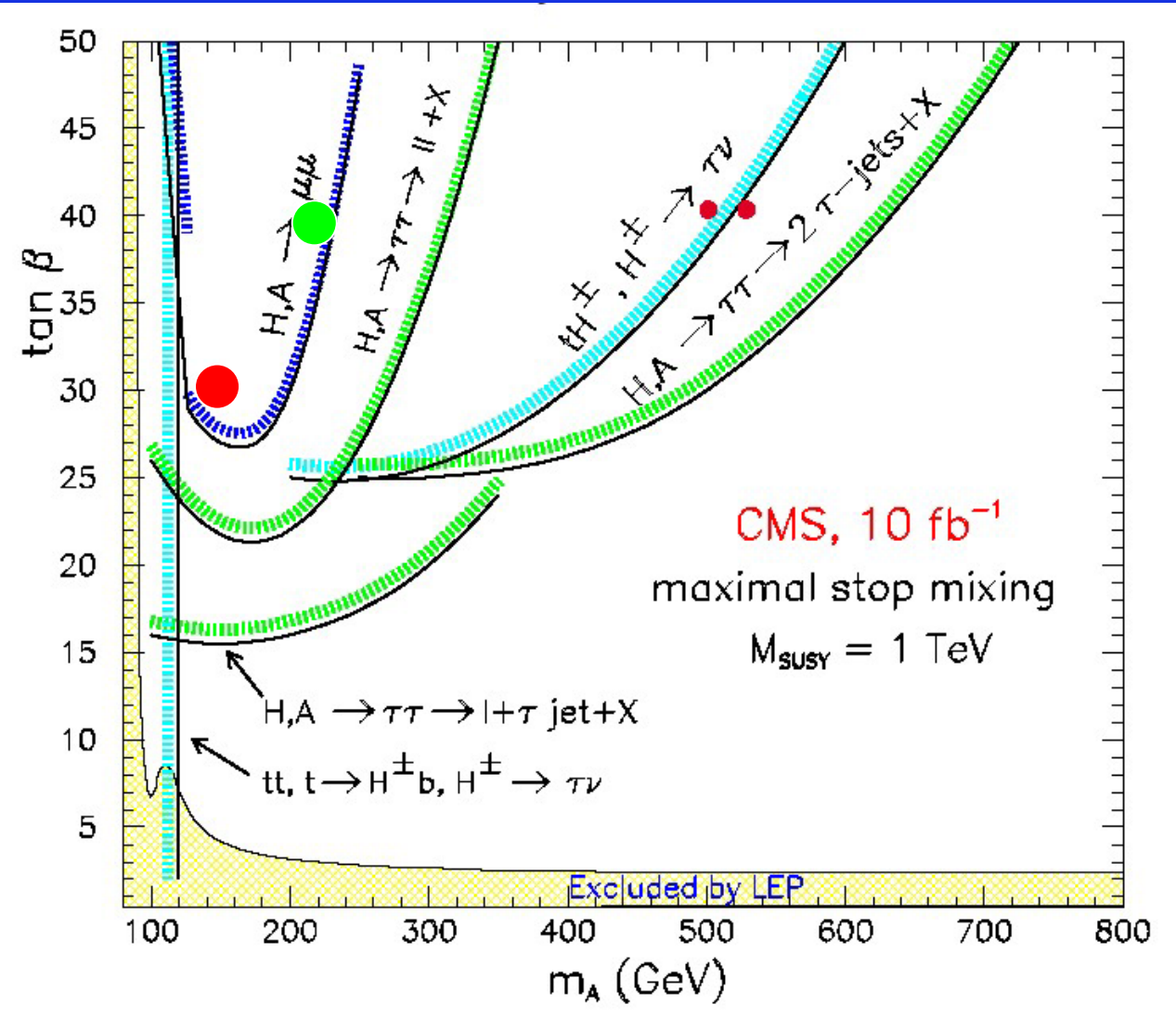
- MSSM contains 2 Higgs doublets, therefore 5 physical Higgs states: h^0, H^0, A^0, $H^\pm$

~ degenerate in mass for high m_A

looks like H_{SM} (but $m_h < 130$ GeV)



Heavy SUSY Higgs @ 10 fb-1

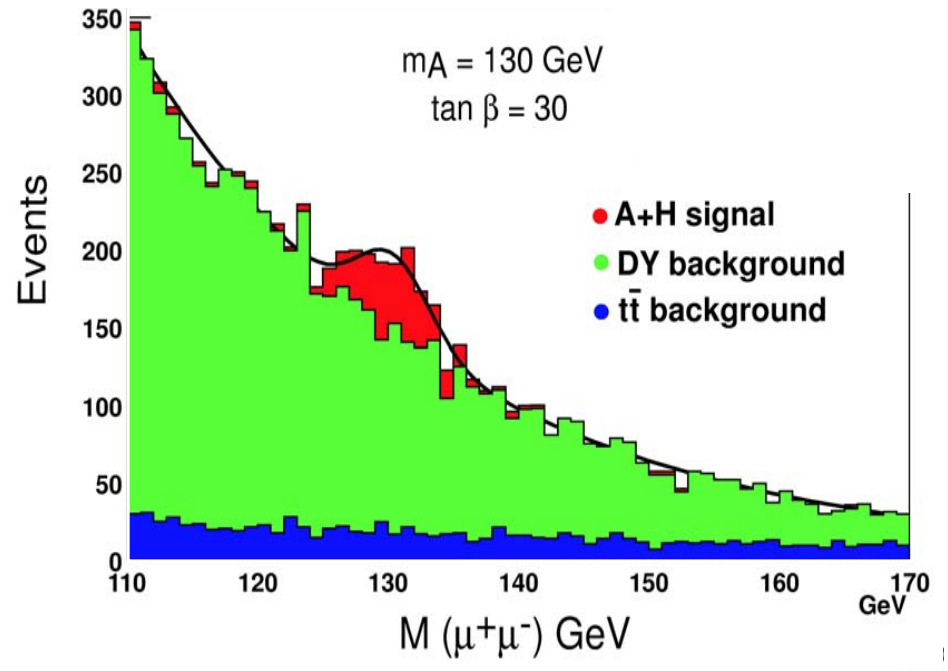


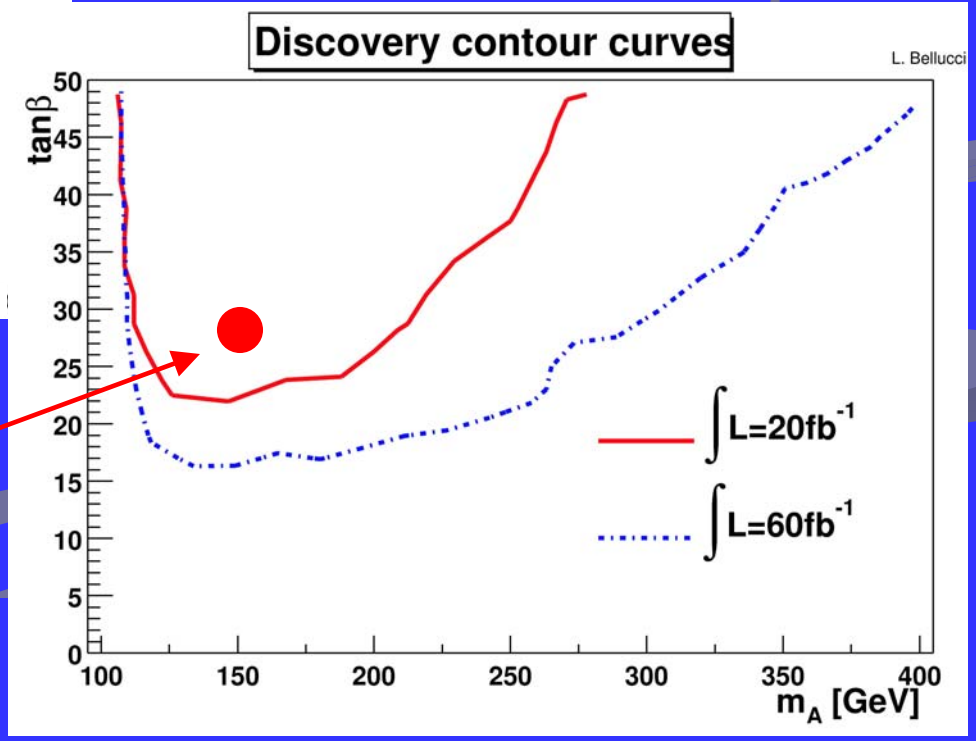
A / H → μ μ
tan β=30, m_A=130 GeV

A / H → τ τ
tan β=40, m_A=200 GeV

A / H → μ μ in bbH_{SUSY} Production

Dimuon invariant mass





Search already possible with 10 fb^{-1}

Requires b-tagging, efficient track reconstruction without ultimate track reconstruction resolution

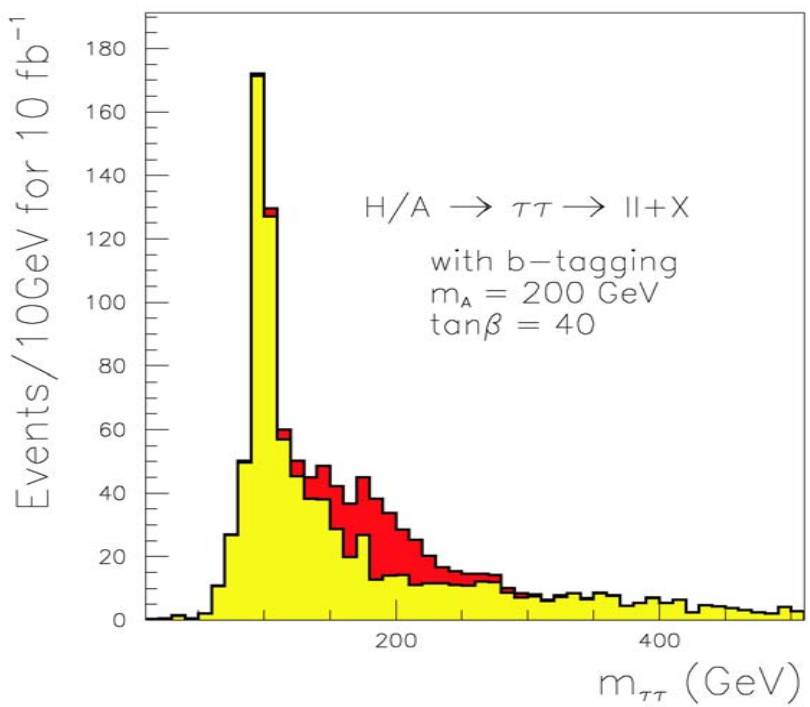
A / H → τ τ → 2 leptons

Signal: 1st and 2nd leptonic decay

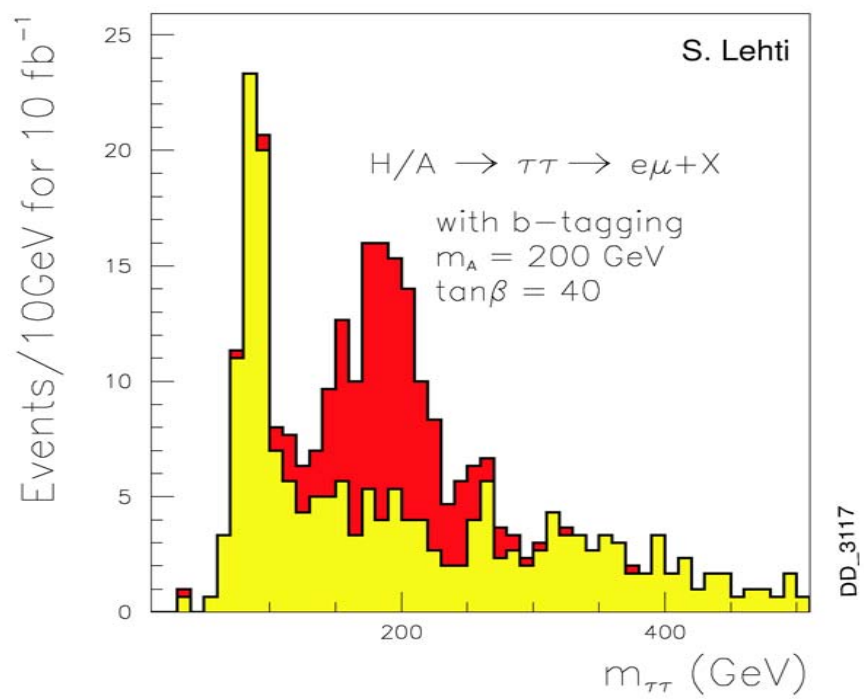
Backgrounds: Z, γ, tt, Wtb

m_A = 200 GeV, tan β = 40, 10 fb^{-1}

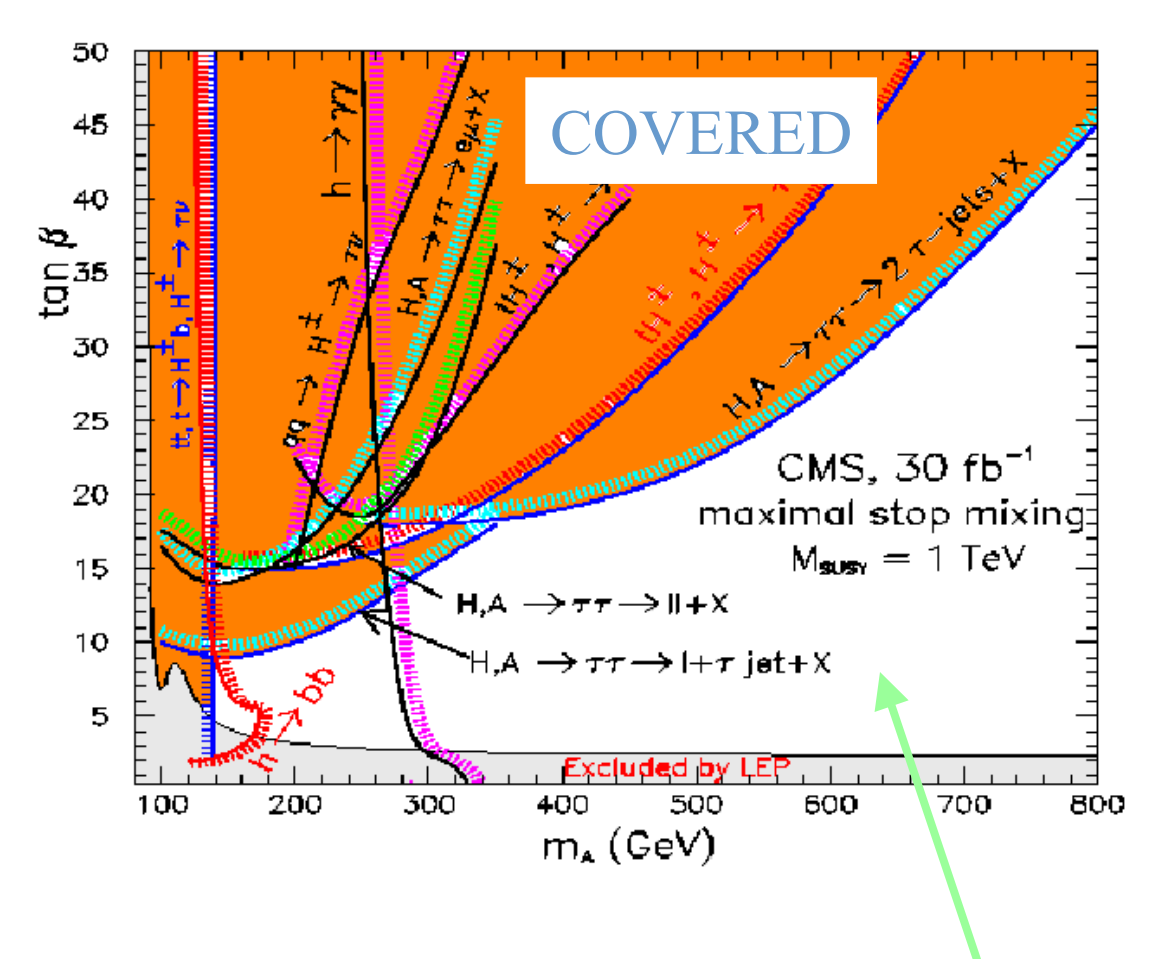
H / A → τ τ → l l + X



H / A → τ τ → e μ + X



Heavy MSSM Higgs

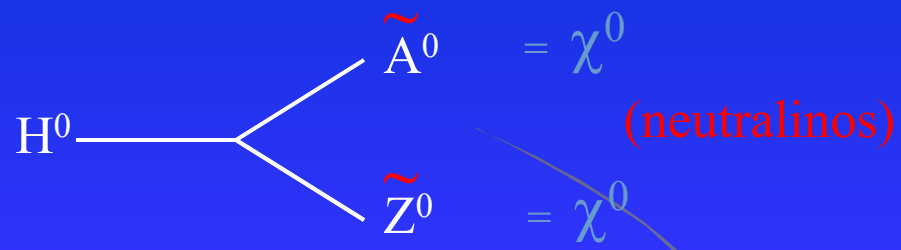


- discovery of the heavy MSSM Higgs limited to upper triangle in m_A – tan β plot
- note: the h^0 can always be found
- problem is that production mechanism (e.g. bbA^0,H^0) needs tan β enhancement

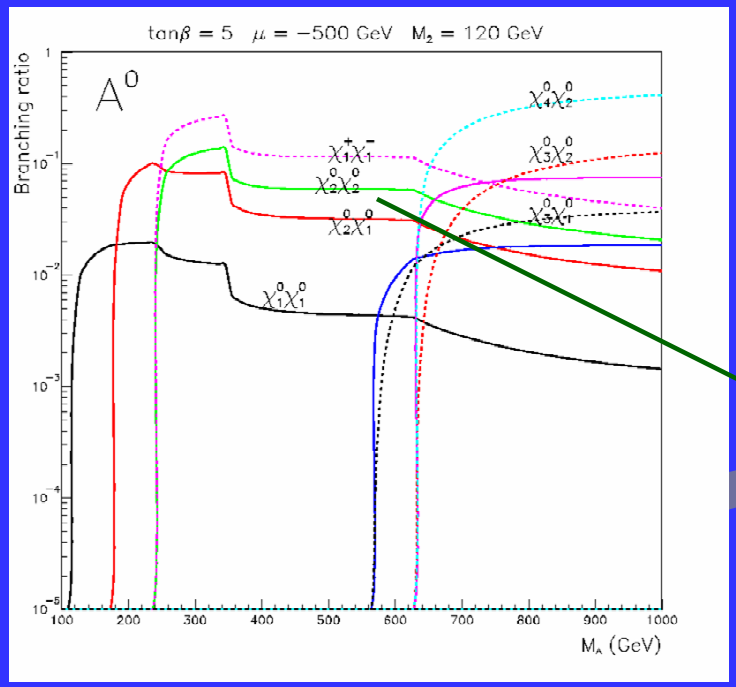
Need new ideas to cover low tanβ - high m_A region …

SUSY Decays of the Higgs

… interesting coupling:



doesn't work for SM, but remember SUSY …



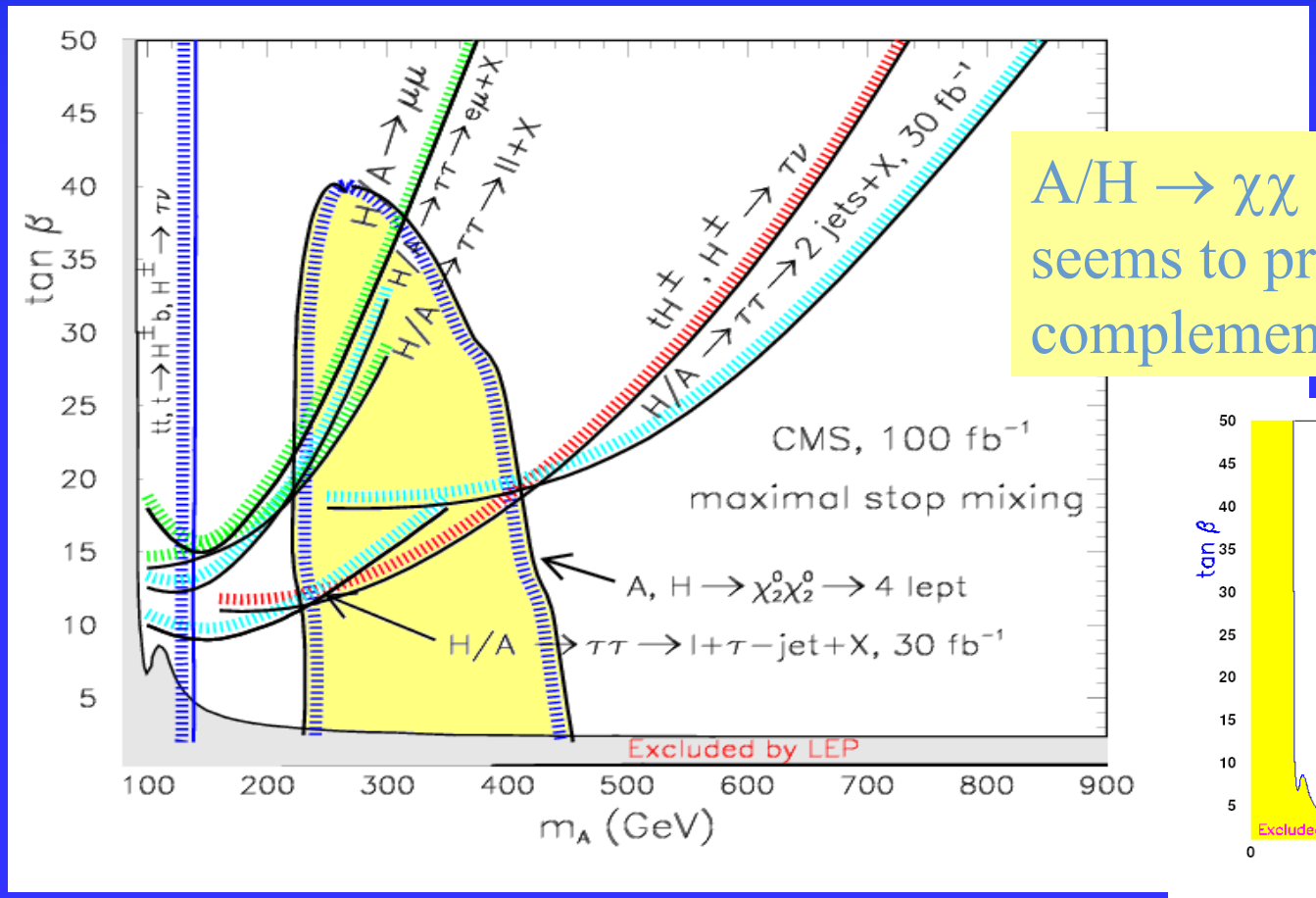
Most promising decay channel:

$$A, H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l + E_T^{miss}$$

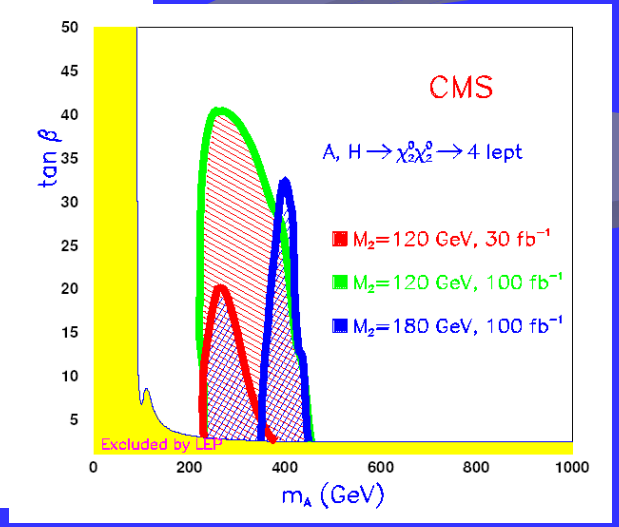
$$\hookrightarrow l^+ l^- \chi_1^0$$

SUSY Decays of the Higgs

Typical discovery reach:

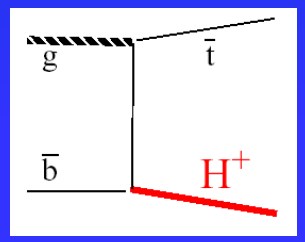


A/H → χχ → 4 leptons seems to prefer low tan β, complementary to A/H → ττ !!

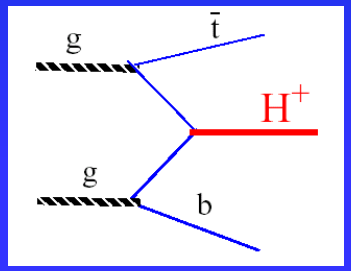


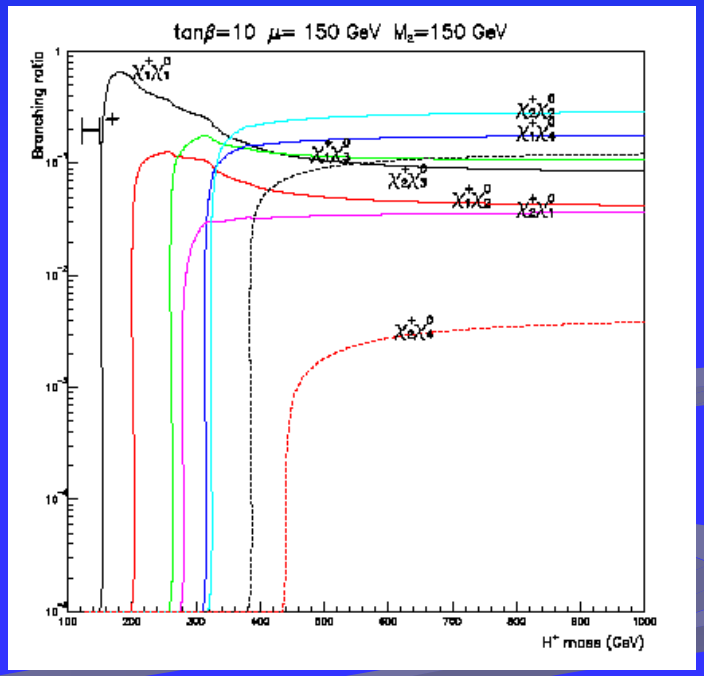
Similar Ideas for $H^{\pm}$

Analogue production mechanism for $H^{\pm}$:



+





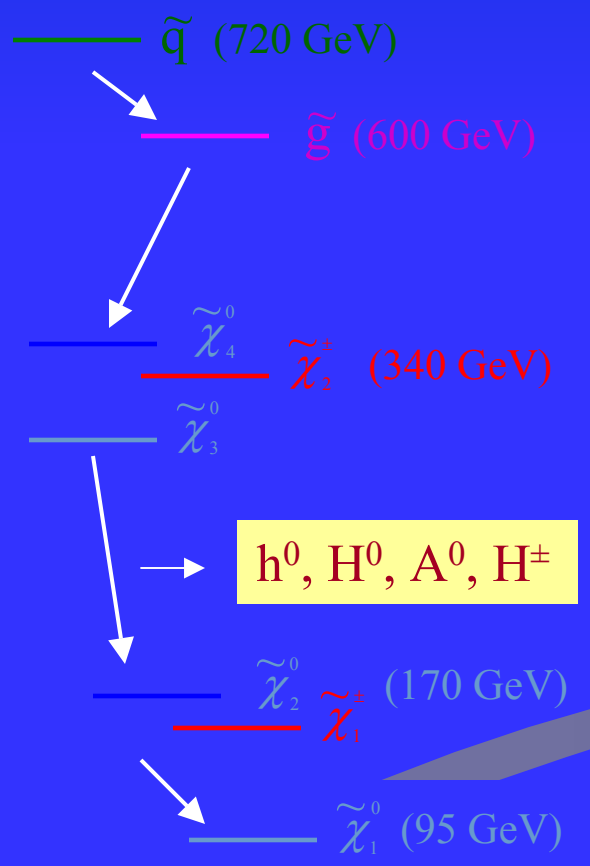
Analogue decay mode:

$$H^{\pm} \rightarrow \chi_{2,3}^{0}\, \chi_{1,2}^{\pm} \rightarrow 3l + E_T^{miss}$$

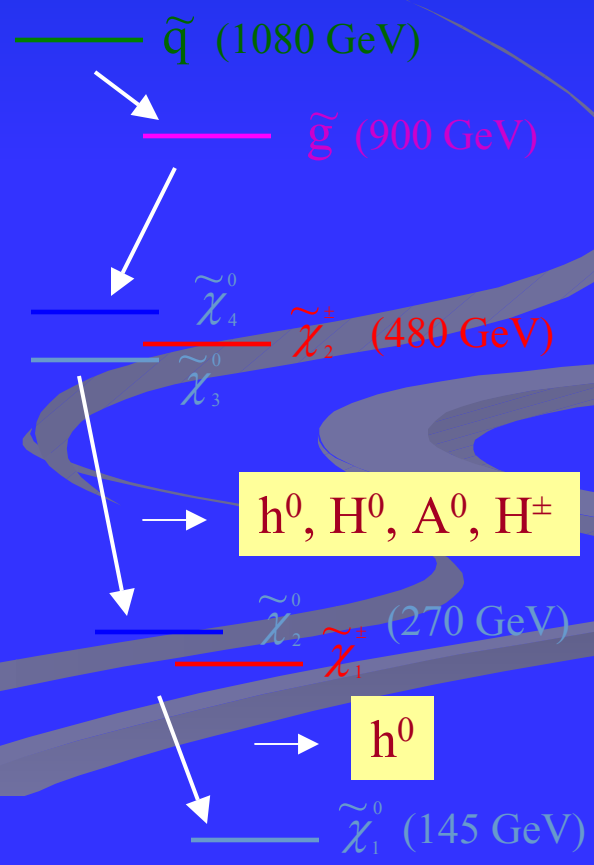
$\rightarrow$ only 3 leptons, need to reconstruct additional top ($t \rightarrow bjj$)

Higgs Production in Sparticle Cascades

Scenario 1 (big cascades)

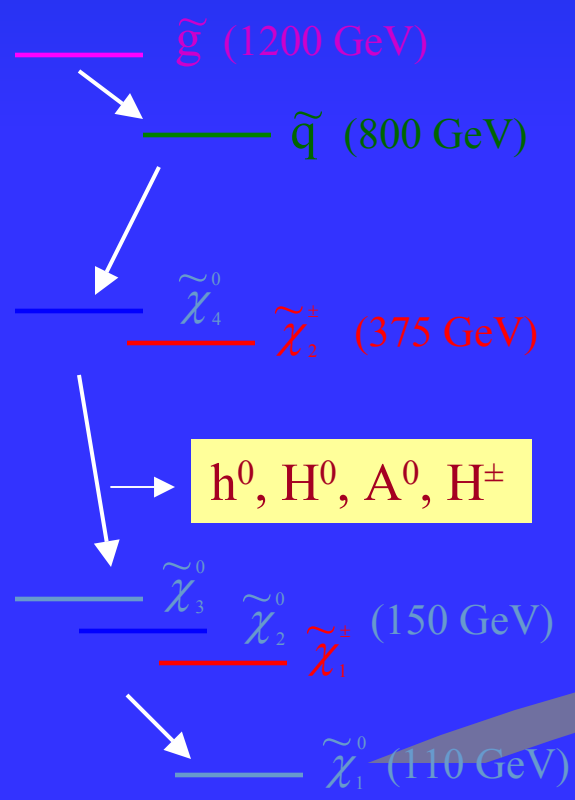


Scenario 2 (little + big cascades)

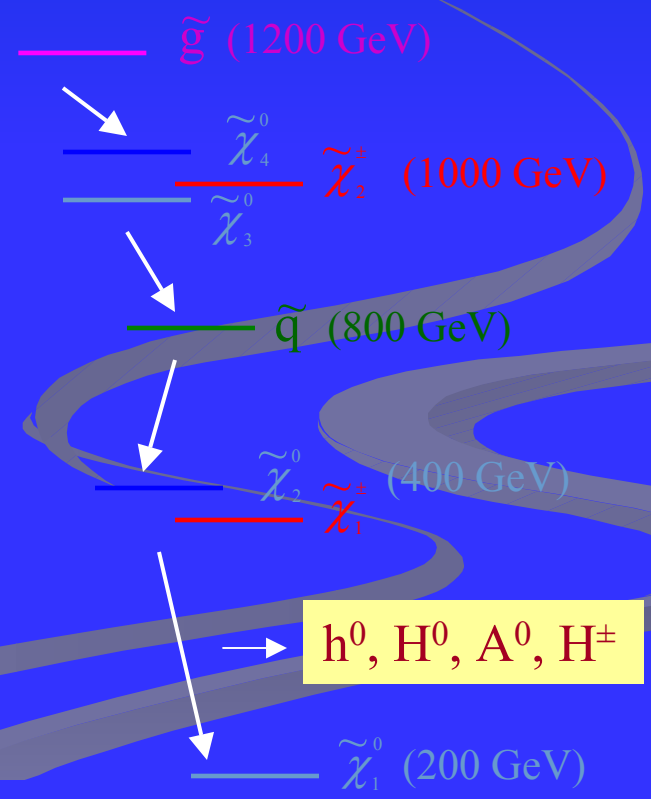


More Possibilities

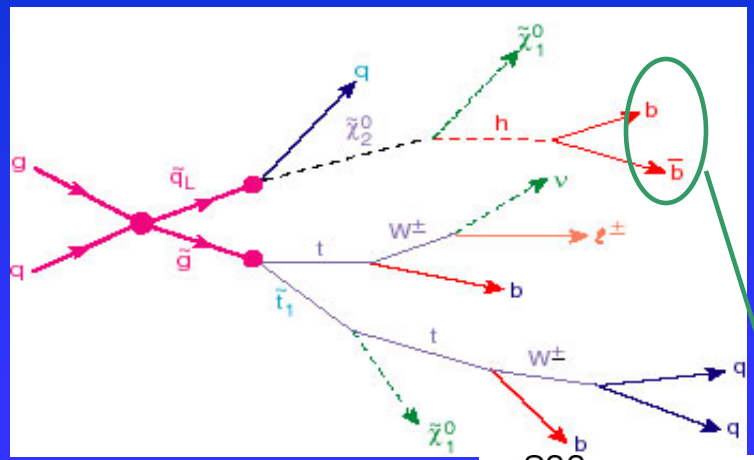
Scenario 3 (big cascades)



Scenario 4 (little cascades)



h → bb production in squark/gluino cascades

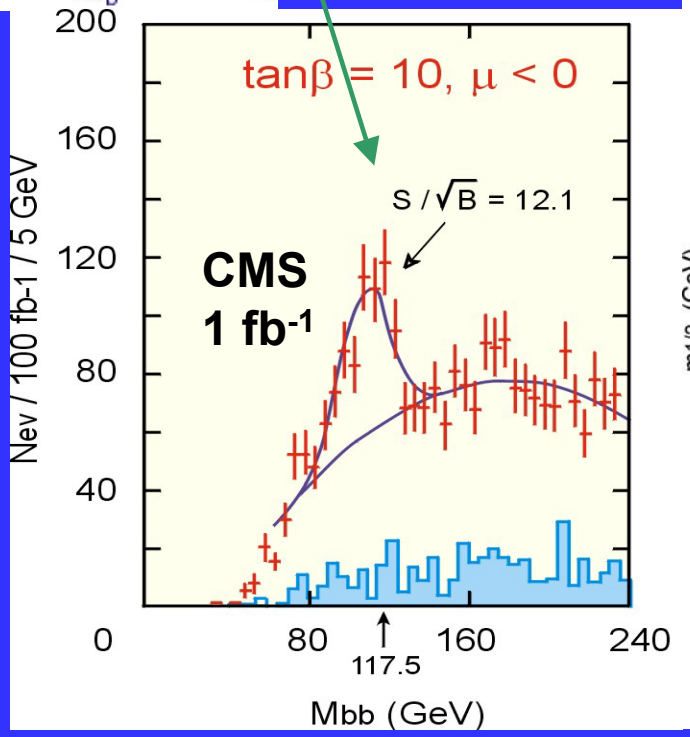


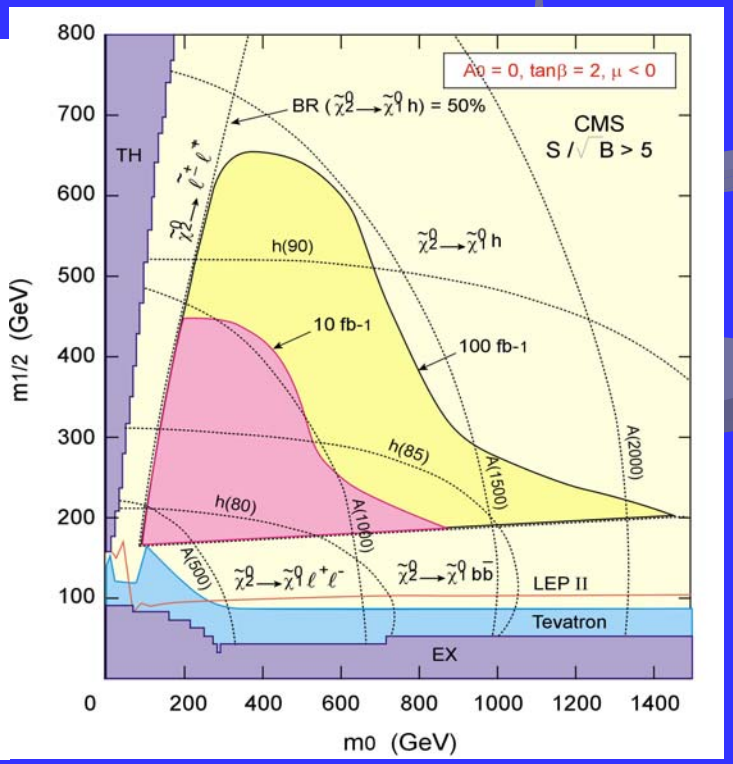
Signature: B-jets + lepton + E_T^{miss}

→ Requires b-tagging + jet counting + full calo coverage for E_T^{miss}

Low tan β regime

Search can start at a few fb^{-1}





Thoughts To Take Away

- What is the current theoretical guidance behind the SUSY and Higgs searches?
- How does one judge the discrimination power of different search topologies?
- When can theorists “raise the bar”?