Hadronの物理の現状と将来
(Tevatron and LHC)

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話の内容

１. Tevatron/LHC加速器と検出器

２. 物理

   1. Electroweak, top
   2. Higgs(SM,MSSM)
   3. SUSY
   4. Strong Interaction
   5. Extra Dimension

３. まとめ

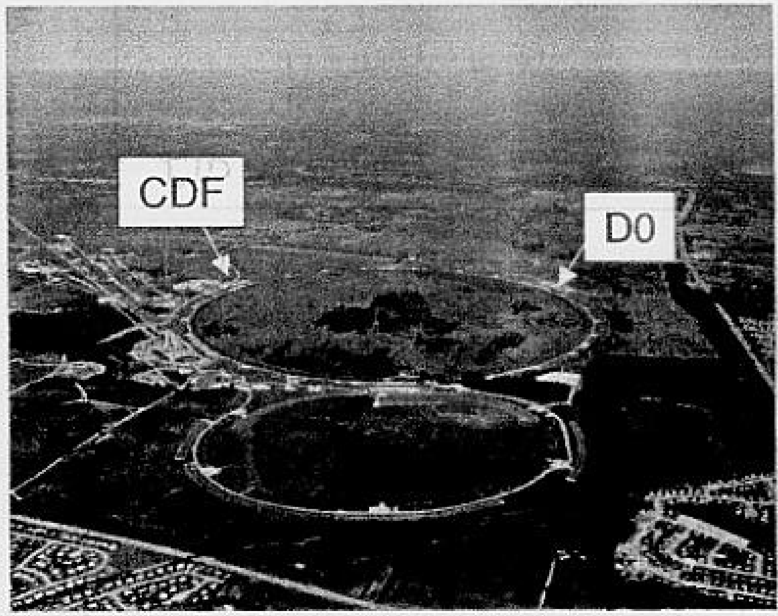
The Tevatron Run 2

Tevatron upgrade:
- Increased energy
  1.8 TeV → 1.96 TeV
- Increased luminosity
  $0.1\ fb^{-1} \rightarrow 2\ fb^{-1} \rightarrow 15\ fb^{-1}$
  (Run 1) (Run 2a) (Run 2b)

Detector upgrades:
- Higher event rates and backgrounds (electronics, DAQ, trigger)
- Considerable expansion of the physics capabilities

Physics opportunities:
- Top
- Higgs
- New Phenomena
- Electroweak
- Beauty
- QCD

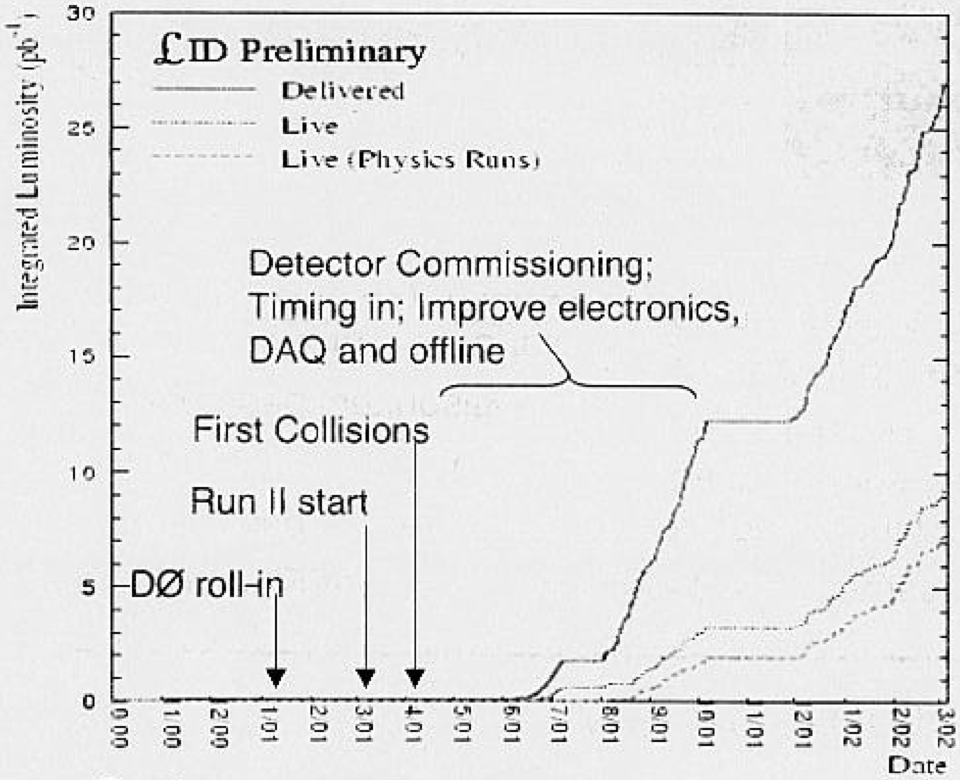
132ns → 159 bunches
p 19 abort gap 159−19 = 140
$\bar{p}$ 2×19 abort gap
Injection kicker 2 miss/injection
159−2×19−2×9 = 103
(T. Yamauchi)



	Run 1b	Run 2a	Run 2b
#bunches	6x6	36x36	140x103
√s (TeV)	1.8	1.96	1.96
typ L ($cm^{-2}s^{-1}$)	$1.6x10^{30}$	$8.6x10^{31}$	$5.2x10^{32}$
∫Ldt (pb^{-1}/week)	3.2	17.3	105
bunch xing (ns)	3500	396	132
interactions/xing	2.5	2.3	4.8

Run 2 in 2001… and 2002 plans

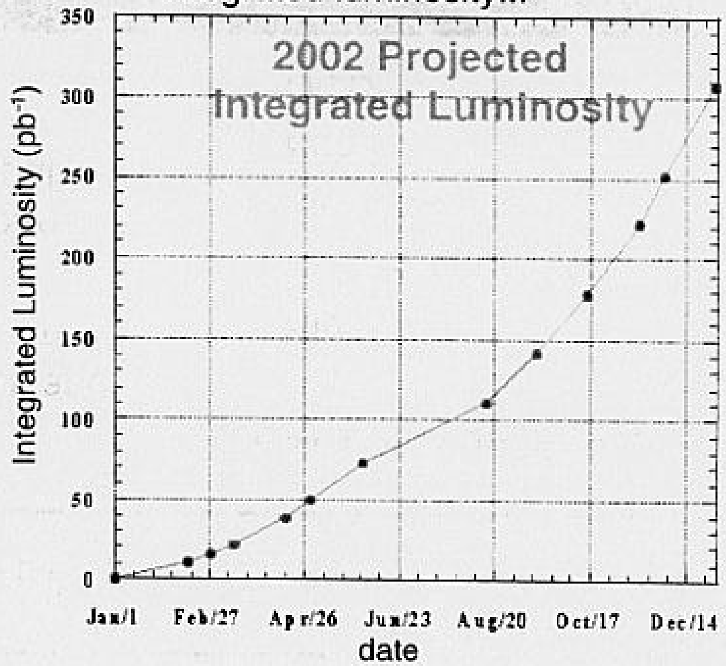
- Considerable fraction (~25%) of collected luminosity devoted to detector commissioning.
- Significant progress in identification of "physics objects": e, μ, jets, electromagnetic and jet energy scales, etc.



Roll-in CDF 2001.3
DØ 2001.1

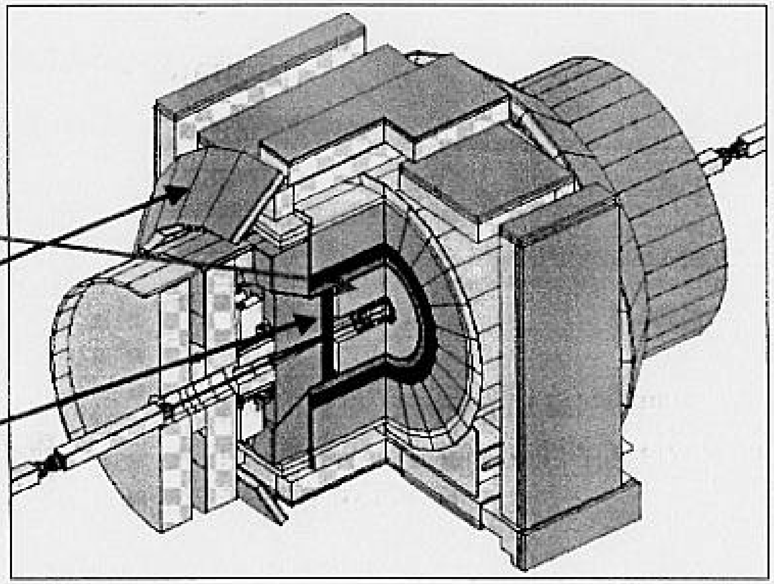
In the next few months:

- Finish detector commissioning
- Complete triggers and improve DAQ
- Debugging, calibration, alignment
- Refine reconstruction algorithms
- …
- Also looking forward to more integrated luminosity!!!



$\mathcal{L} = 300 pb^{-1}$ in 2002

CDF upgrade for RUN II



Reduced bunch spacing:

- New DAQ and Trigger
- Faster drift chamber (COT)
- Plug upgrade

Extend lepton acceptance

- Muon up to $\eta=1.5$
- Plug upgrade for electrons

Tracking and b-tagging down to $\eta=2$

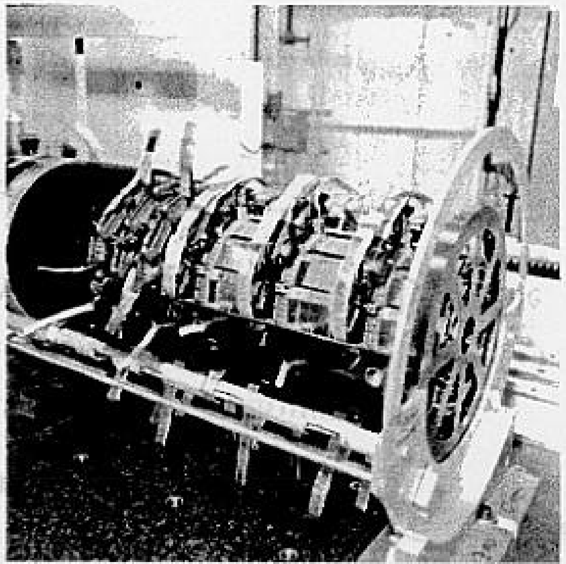
- Enhanced stereo reconstruction from COT
- 7-8 layer silicon detector (mostly double sided)
- Trigger on displaced tracks: SVT

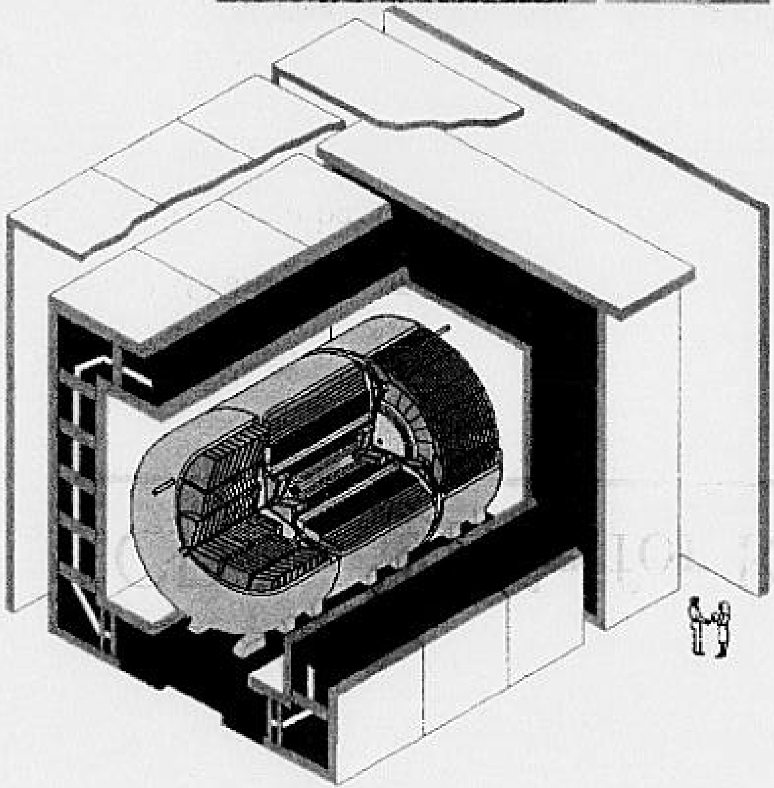
Particle id:

- TOF detector

D0

Silicon Microstrip Tracker (SMT)

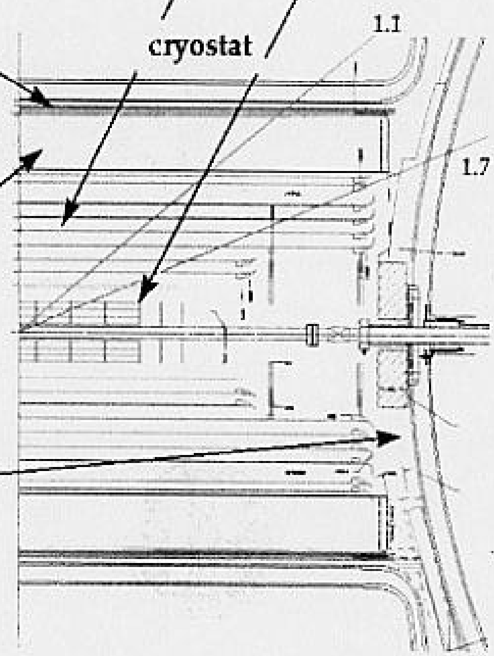




DØ Detector

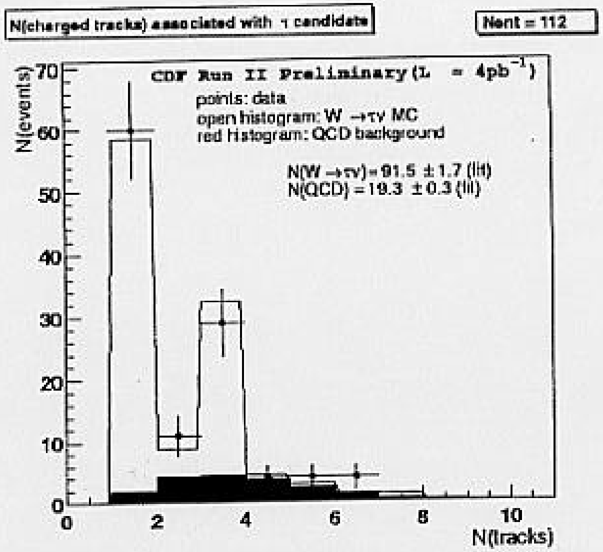
The D0 Upgrade - Tracking

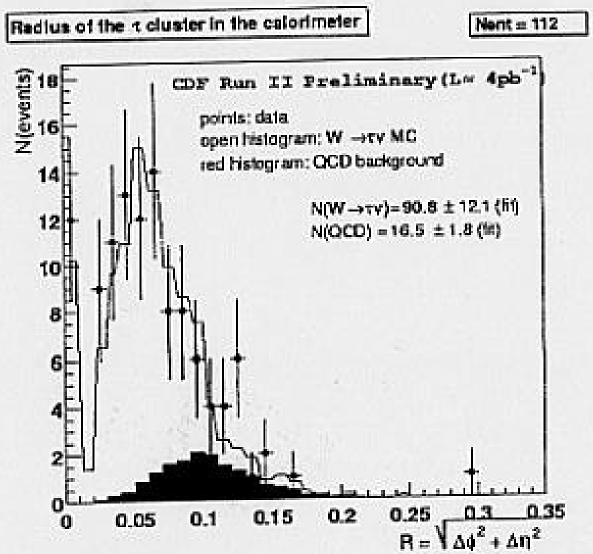
- Silicon Tracker
  - Four layer barrels (double/single sided)
  - Interspersed double sided disks
  - 840,00 channels
- Fiber Tracker
  - Eight layers sci-fi ribbon doublets (z-u-v, or z
  - 74,000 830um fibers w/ VLPC readout
- Central Preshower
  - Scintillator strips, WLS fiber readout
  - 6,000 channels
- Solenoid
  - 2T superconducting
- Forward Preshower
  - Scintillator strips, stereo, WLS readout
  - 16,000 channels

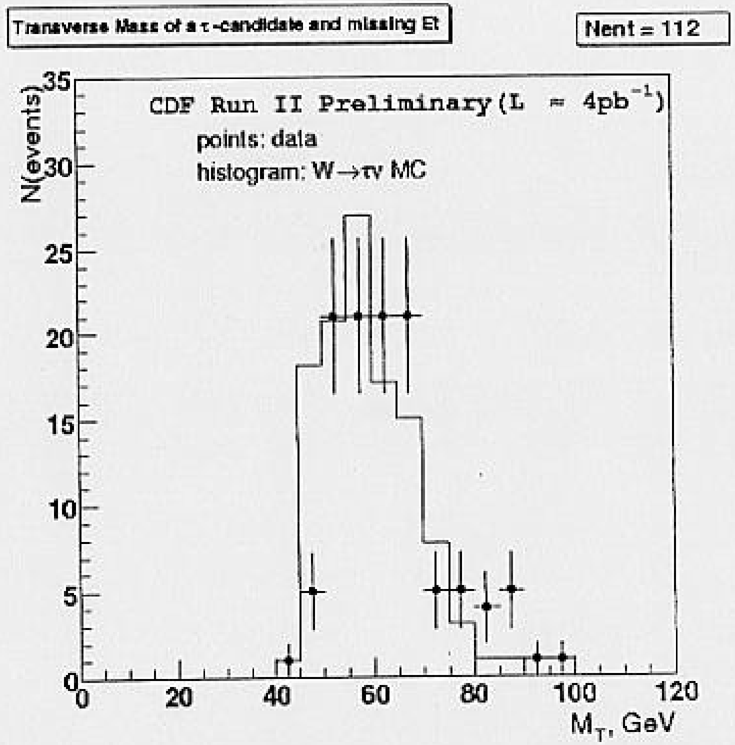


$W \rightarrow \tau\nu$

Missing $\not{E}_T$ trigger







New triggers:

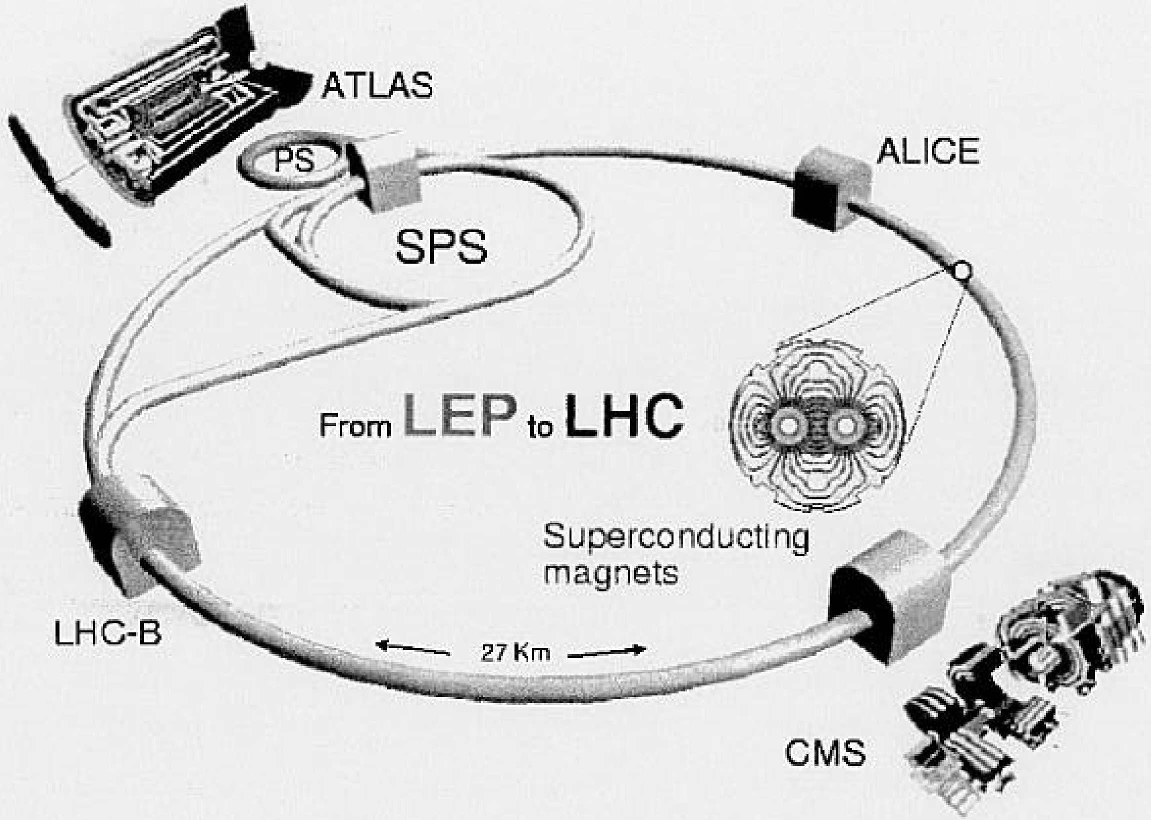
$Z \rightarrow b\bar{b}$, inclusive b-jet, b+γ

$\tau + \not{E}_T$, 2τ's (jet), ℓ+isol. t...

...

Nigel Lockyer
University of Pennsylvania and Fermilab

The Large Hadron Collider (LHC)



	Beams	Energy		Luminosity
LEP	e^+ e^-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27} ← ALICE, CMS, (ATLAS)

LHC Layout and Parameters

$$L = \frac{\gamma f k_b N_p^2}{4\pi\varepsilon_n \beta^*} F$$

- f revolution frequency
- k_b no. of bunches
- N_p no. of protons/bunch
- ε_n norm transverse emittance
- β^* betatron function
- F reduction factor xing angle

Magnetic Field

p (TeV) = 0.3 B(T) R(km)

For p= 7 TeV, R= 4.3 km

⇨ **B = 8.4 T**

Beam-beam tune shift $\xi = \frac{N r_p}{4\pi\varepsilon_n}$

Energy at collision	E	7	TeV
Dipole field at 7 TeV	B	8.33	T
Luminosity	L	10^{34}	$cm^{-2}s^{-1}$
Beam beam parameter	ξ	3.6	10^{-3}
DC beam current	I_{beam}	0.56	A
Bunch separation		24.95	ns
No. of bunches	k_b	2835	
No. particles per bunch	N_p	1.1	10^{11}
Normalized transverse emittance (r.m.s.)	ε_n	3.75	μm
Collisions			
β-value at IP	β^*	0.5	m
r.m.s. beam radius at IP	σ^*	16	μm
Total crossing angle	ϕ	300	μrad
Luminosity lifetime	τ_L	10	h
Number of evts/crossing	n_c	17	
Energy loss per turn		7	keV
Total radiated power/beam		3.8	kW
Stored energy per beam		350	MJ

$E_b = 7$ TeV to observe W_L-W_L scatt. at $\hat{s} = 1$ TeV

ATLAS (A Toroidal LHC ApparatuS)

- Liq.Ar EM calorimeter

  good e/γ id, energy, E_T^{miss}
- muon spectrometer

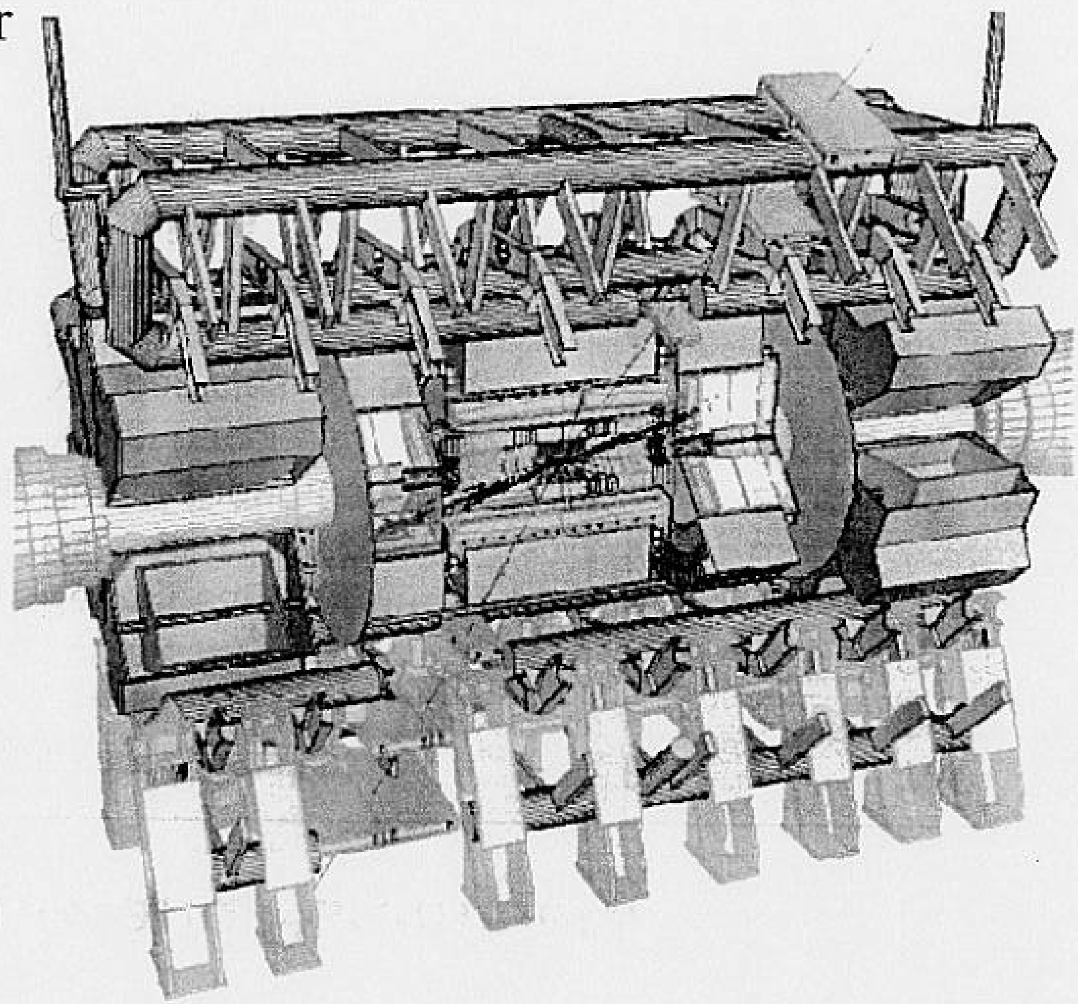
  air-core troidal magnet

  $\int Bdl$ = 2~6Tm (4~8Tm)
- inner tracking system

  pixel, silicon strip, TRT

  2T solenoid magnet

  good e/γ id, τ/b-tag

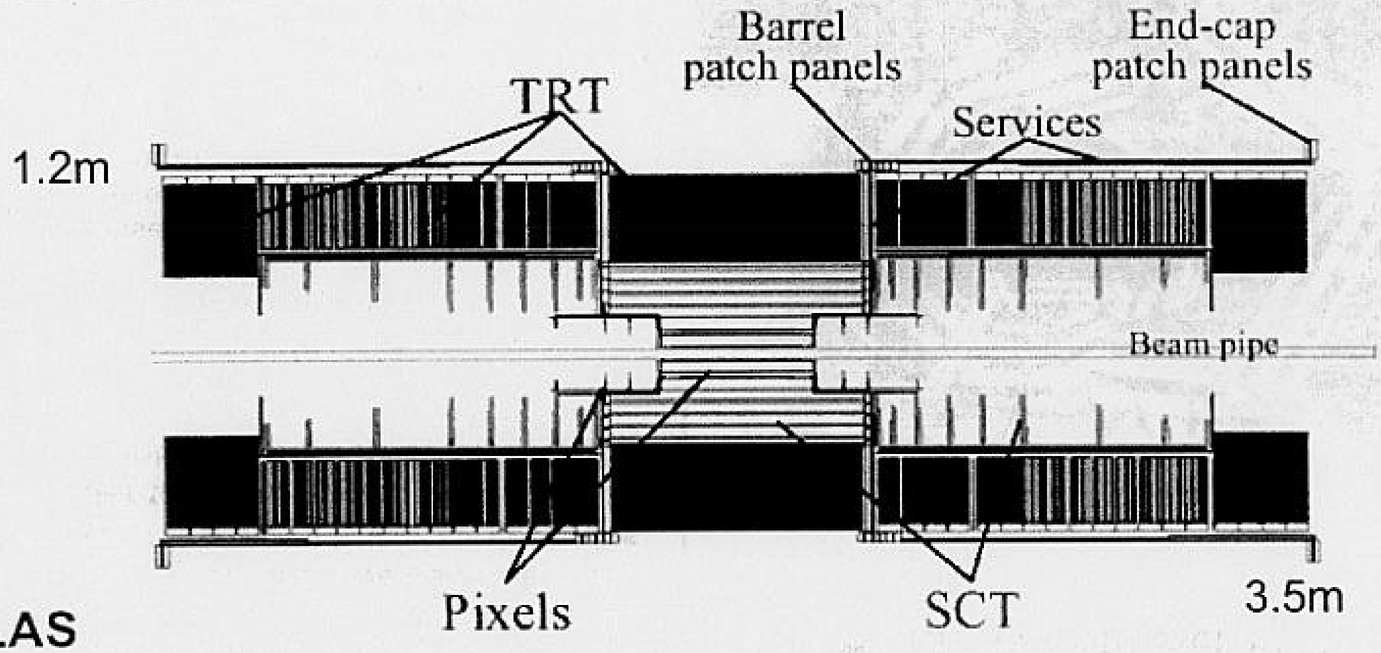


ATLAS detector

tracker $|\eta| < 2.5$

calorimeter $|\eta| < 4.9$

Trackers at LHC



ATLAS

Pixels: ~ 2.3 m^2 of silicon sensors, 140 M pixels, 50x300 μm^2, r = 4, 10, 13 cm
Si μ-strips : 60 m^2 of silicon sensors, 6 M strips, 4 pts, r = 30 - 50 cm
Straws TRT: 36 straws/track, $Xe\text{-}CO_2\text{-}CF_4$ ϕ=4mm, r = 56 - 107 cm

CMS: Si pixels surrounded by silicon strip detectors

Pixels: ~ 1 m^2 of silicon sensors, 40 M pixels, 150x150 μm^2 , r = 4, 7, 11 cm
Si μ-strips : 223 m^2 of silicon sensors, 10 M strips, 12 pts, r = 20 – 120 cm

CMS (Compact Muon Solenoid)

Basic Design Criteria of CMS

A general purpose pp detector designed to run at the highest LHC luminosity but also well adapted for studies at the initial lower luminosities in order to fully exploit the discovery potential offered by LHC

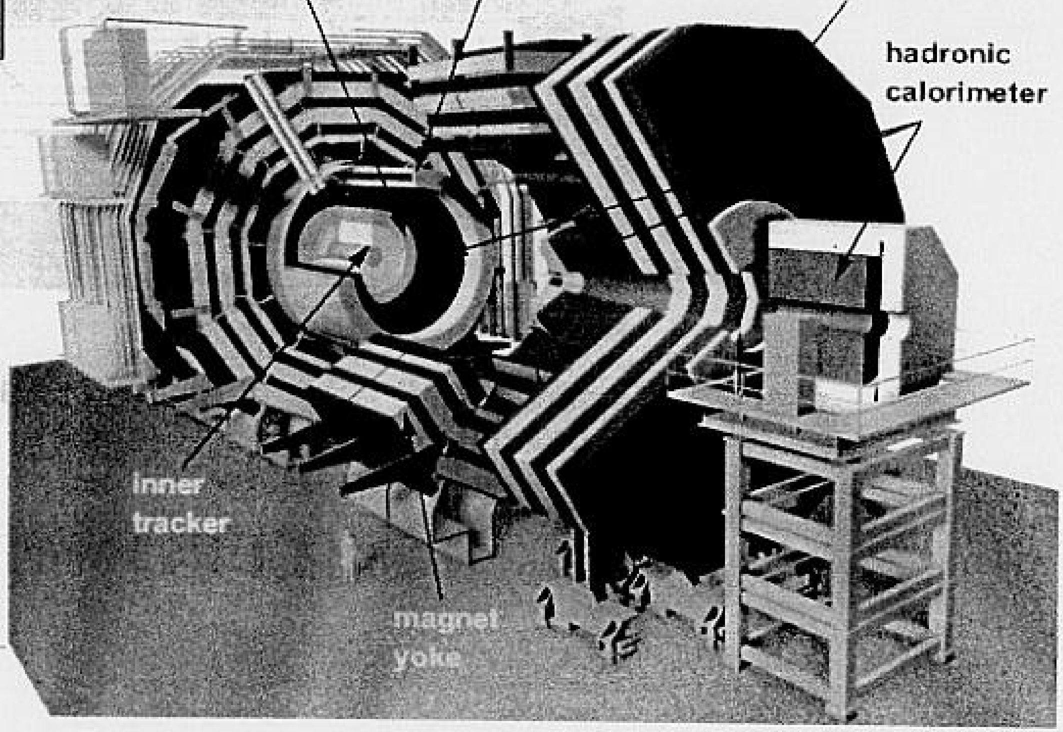
1) Very good muon ($\mu^{\pm}$) identification and momentum measurement.

2) As precise as possible a measurement of the energies of photons (γ) and electrons ($e^{\pm}$) consistent with (1).

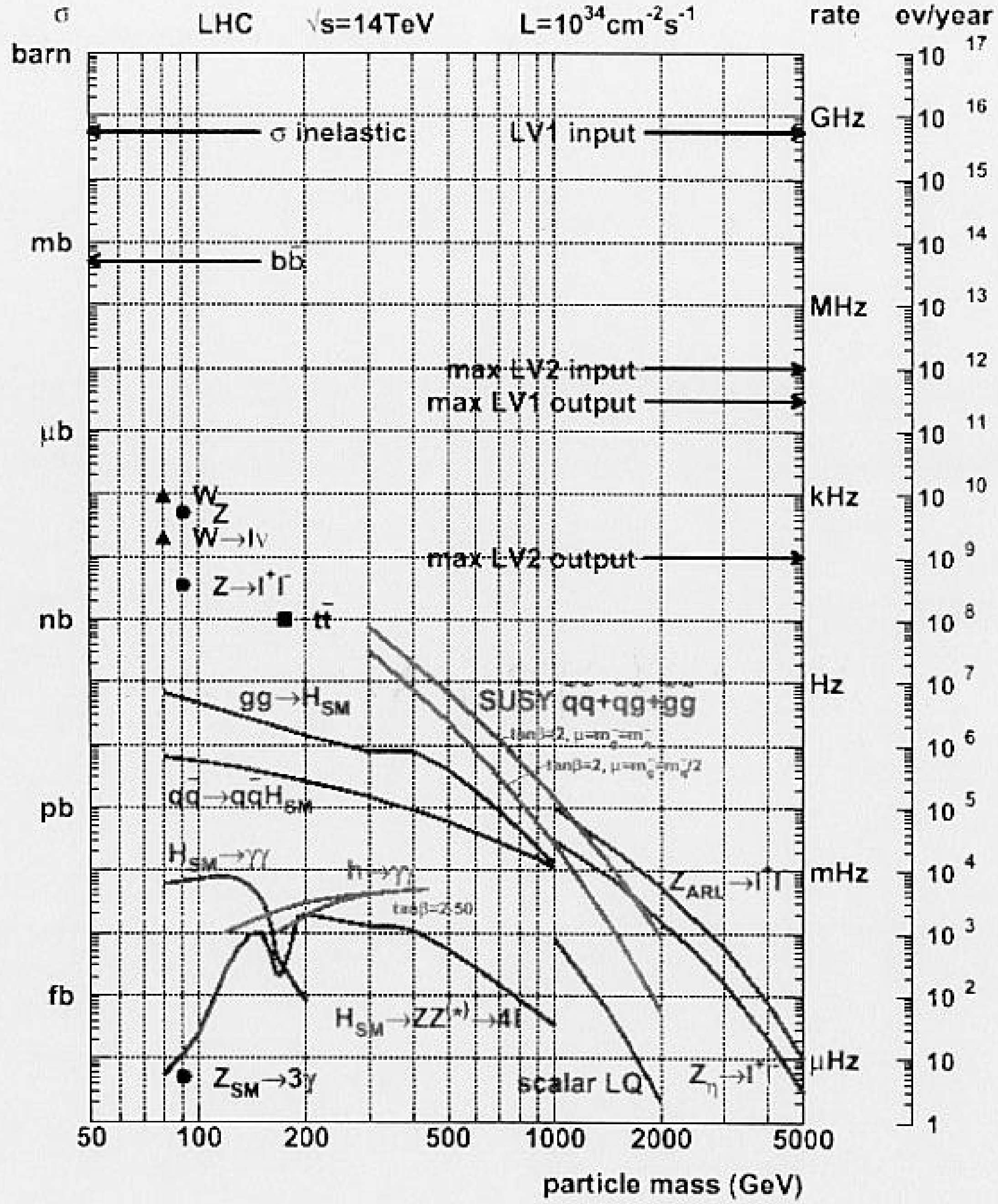
3) A central tracking detector that allows reconstruction of charged particle tracks and precise measurement of momenta to achieve (1) and (2).

4) A robust and cost effective detector.

- 4T solenoid
- Compact muon spectrometer
- EM calorimeter $PbWO_4$ for $H \rightarrow \gamma\gamma$



Electroweak physics


σ
barn
LHC
√s=14TeV
L=10^34 cm^-2 s^-1
rate
ev/year
σ inelastic
LV1 input
bb̄
max LV2 input
max LV1 output
max LV2 output
W
Z
W→lν
Z→l⁺l⁻
tt̄
gg→H_SM
SUSY q̃q̃+q̃g̃+g̃g̃
qq̄→qq̄H_SM
H_SM→γγ
h→γγ
Z_ARL→l⁺l⁻
H_SM→ZZ^(*)→4l
Z_SM→3γ
scalar LQ
Z_η→l⁺l⁻
mb
μb
nb
pb
fb
GHz
MHz
kHz
Hz
mHz
μHz
50
100
200
500
1000
2000
5000
particle mass (GeV)

M_W measurement

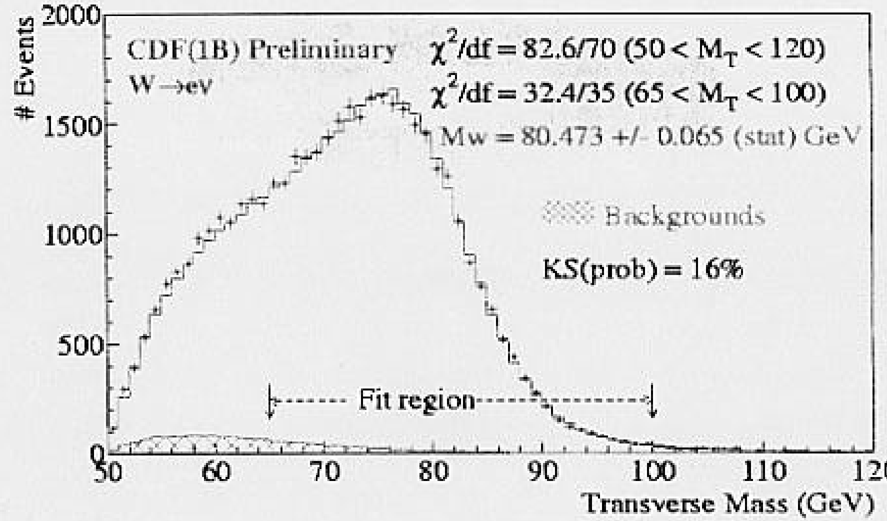
W transverse mass

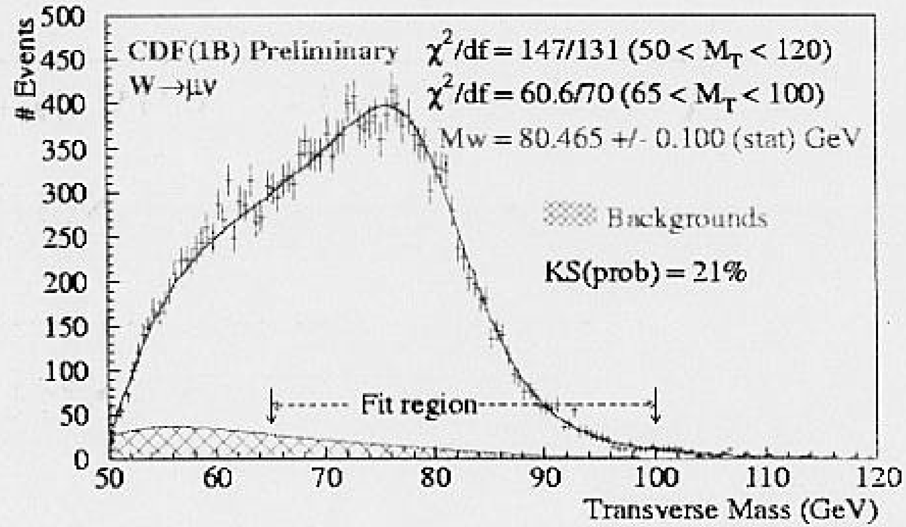
$$m_T^W = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\phi)}$$

$$p_T^\nu = -|\vec{p}_T^l + \vec{u}|$$

major uncertainty source

- E, p scale & resolution
  use $Z \to e^+e^-/\mu^+\mu^-$, Υ, J/ψ, $\psi(2s)$
- Recoil modelling
  ISR(QCD), spectator quarks, min. bias
  exploit similar production mechanism for W and Z
- p_T^W
  use of lepton pseudorapidity distributions in W and Z decays
- PDF (parton distribution)
  estimate from Z data



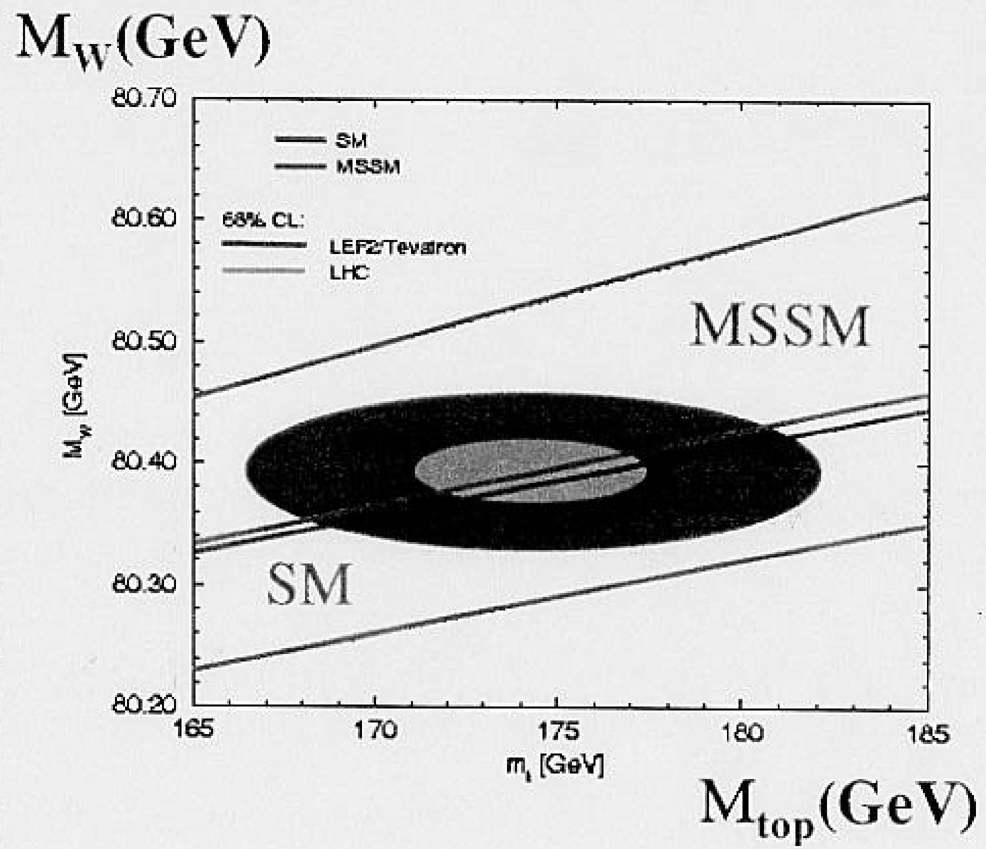


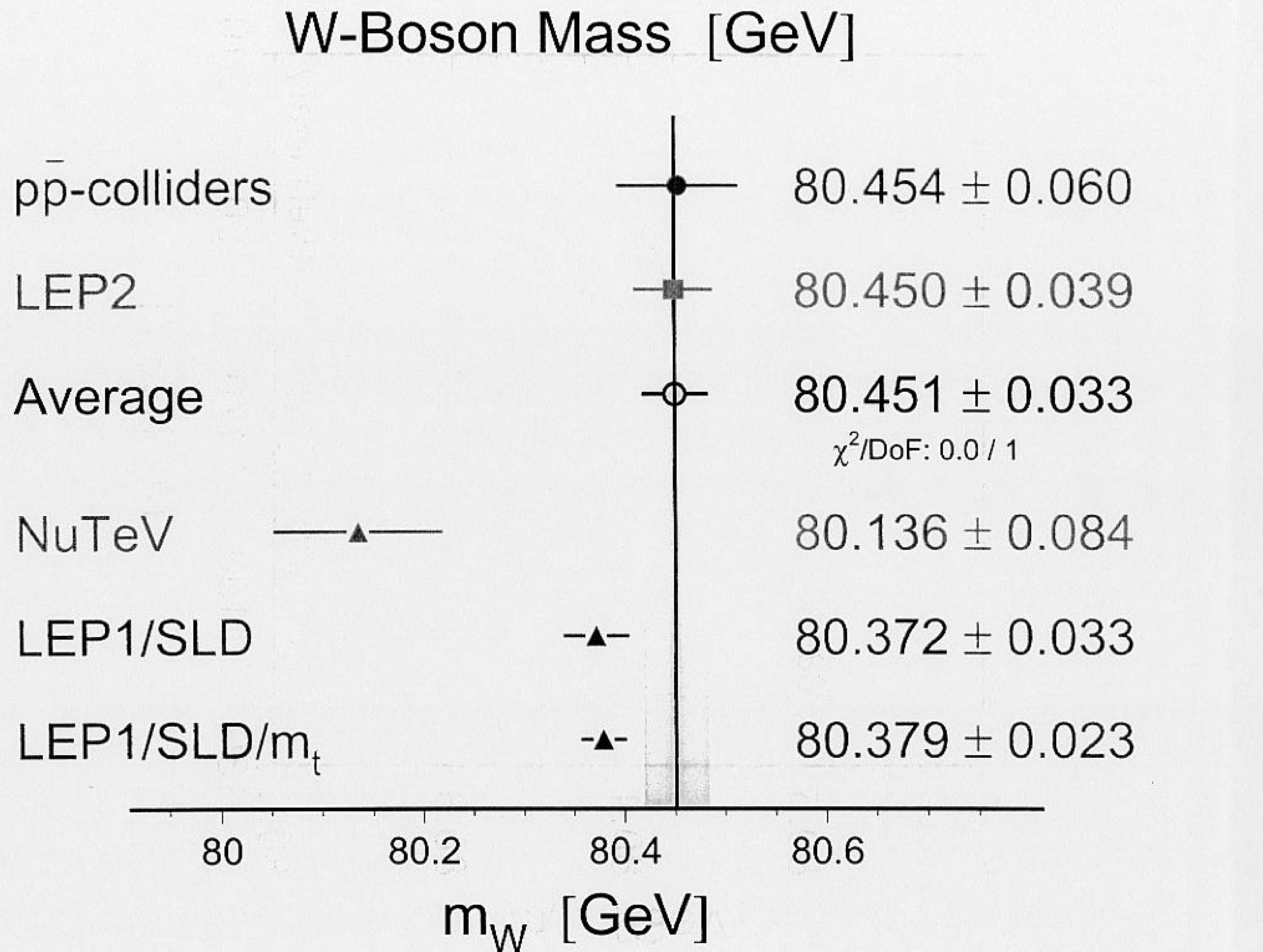
W mass

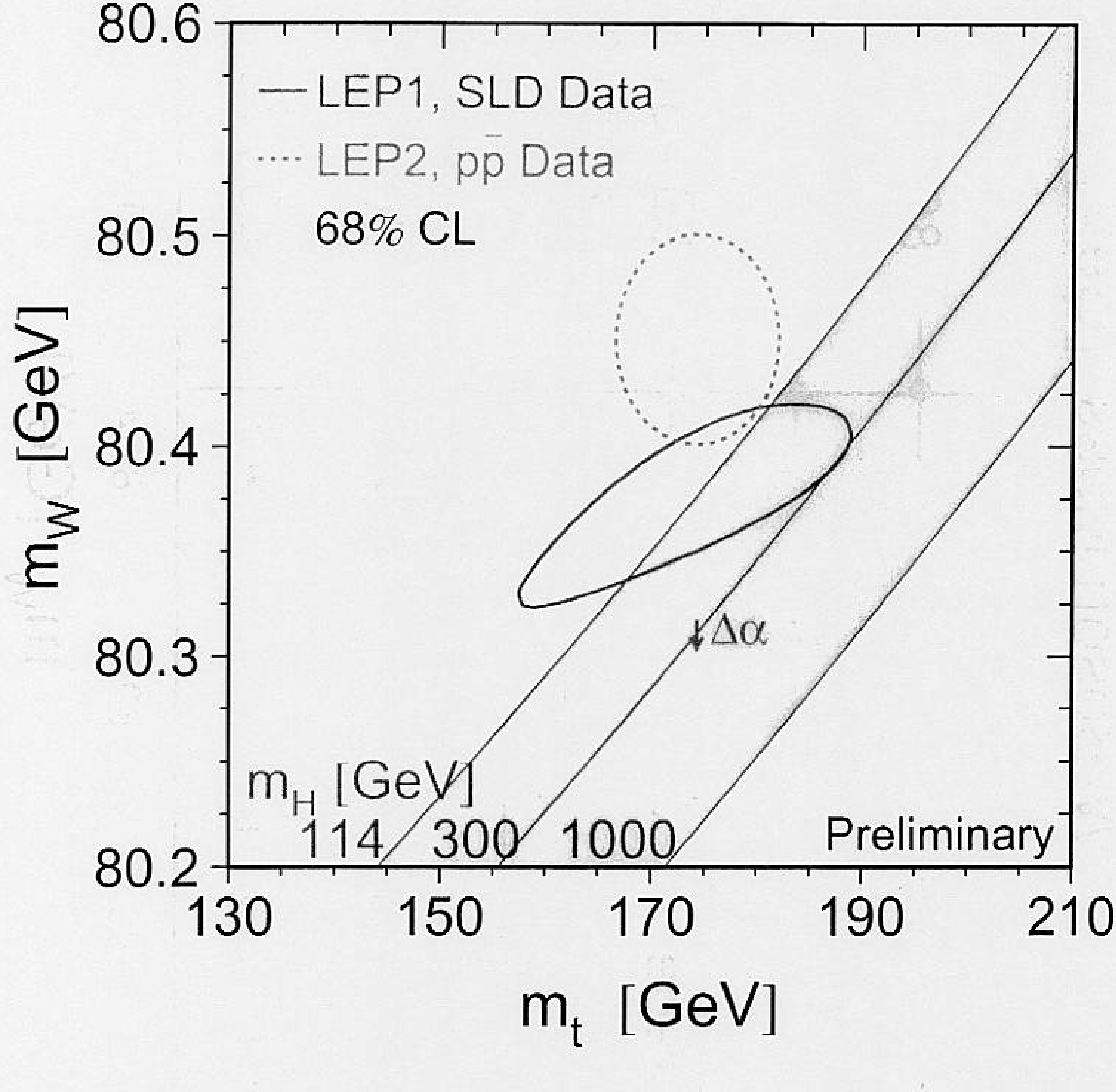
- goal

LEP2	Tevatron RUN-I	RUN-II	LHC	NLC
±35 MeV	±60 MeV	±30 MeV	±15 MeV	±10 MeV

$\Delta M_{top} = \pm 2$ GeV $\Leftrightarrow$ $\Delta M_W = \pm 12$ MeV
ultimate goal $\Delta M_W = \pm 15$ MeV

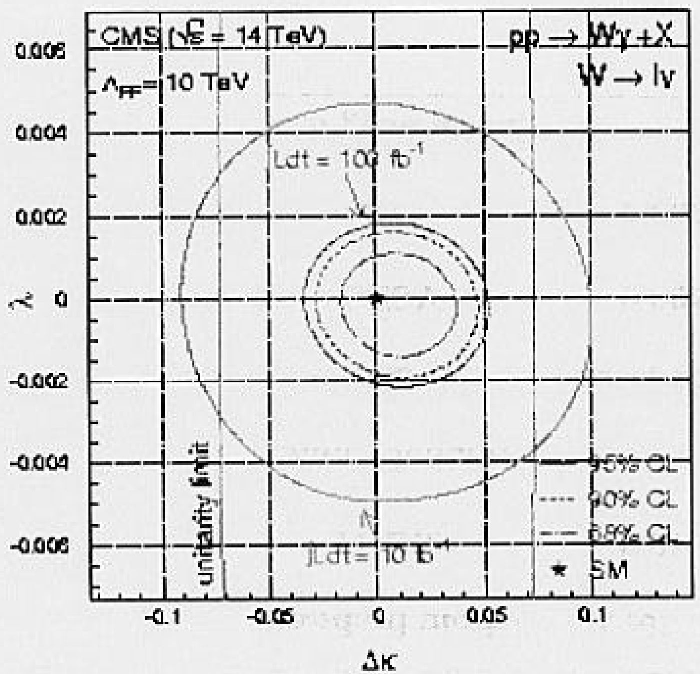



W-Boson Mass [GeV]
pp̄-colliders
80.454 ± 0.060
LEP2
80.450 ± 0.039
Average
80.451 ± 0.033
χ²/DoF: 0.0 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.372 ± 0.033
LEP1/SLD/m_t
80.379 ± 0.023
80
80.2
80.4
80.6
m_W [GeV]



80.6
80.5
80.4
80.3
80.2
LEP1, SLD Data
LEP2, pp̄ Data
68% CL
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
Preliminary
130
150
170
190
210
m_t [GeV]

TGC study at LHC



Sensitivity at 95%C.L.

Vertex	Coupling	$(m_{W\gamma}, \lvert\eta^*\rvert)$	(p_T^γ, θ^*)	p_T^γ
$WW\gamma$	$\Delta\kappa_\gamma$	0.035	0.046	0.043
$\Lambda_{FF} = 10$ TeV	λ_γ	0.0025	0.0027	0.0020
WWZ	Δg_1^Z	0.0078	0.0089	—
	$\Delta\kappa_Z$	0.069	0.100	—
$\Lambda_{FF} = 10$ TeV	λ_Z	0.0058	0.0071	—
$ZZ\gamma$	h_{30}^Z	—	—	6.4×10^{-4}
$\Lambda_{FF} = 6$ TeV	h_{40}^Z	—	—	1.8×10^{-6}

Luminosity 30(100) fb^{-1}

Form factor Λ_{FF}=10 TeV for WWγ,WWZ
6 TeV for ZZγ

increased sensitivity by pronounced high s^ at LHC !

Also we need study on
quartic gauge boson coupling (QGC)
WWWW, WWZZ, WWZγ, WWγγ
81 81 54 36 couplings

Trilinear Gauge Boson Coupling

Ellison&Wudka (hep-ph/9804322)

Model	$\lvert\Delta\kappa_\gamma\rvert$	$\lvert\lambda_\gamma\rvert$	$\lvert\tilde{\kappa}_\gamma\rvert$	
standard model	0.008 [34, 35]	0.002 [35]	10^{-22} [36, 37]	$\leftarrow d_w = 0$
2HDM	0.016 [38]	0.0014 [38]	–	up to 2 -loop
Multi-doublet	–	–	4×10^{-6} [39, 36]	
E6	2.5×10^{-5} [40]	0.003 [40]	–	
SUSY	0.005 [41]	5×10^{-5} [41]	3×10^{-4} [42]	
TC	0.002 [43]	–	7×10^{-6} [43]	
4th generation	–	–	5×10^{-3} [44]	

Table 2: Calculated values of the effective parameters in several theoretical models. The abbreviations are 2HDM (two Higgs-doublet model), SUSY (Suppersymmetry), and TC (Technicolor).

New Physics $\Delta TGC < O(10^{-2} \tilde{} 10^{-3})$!

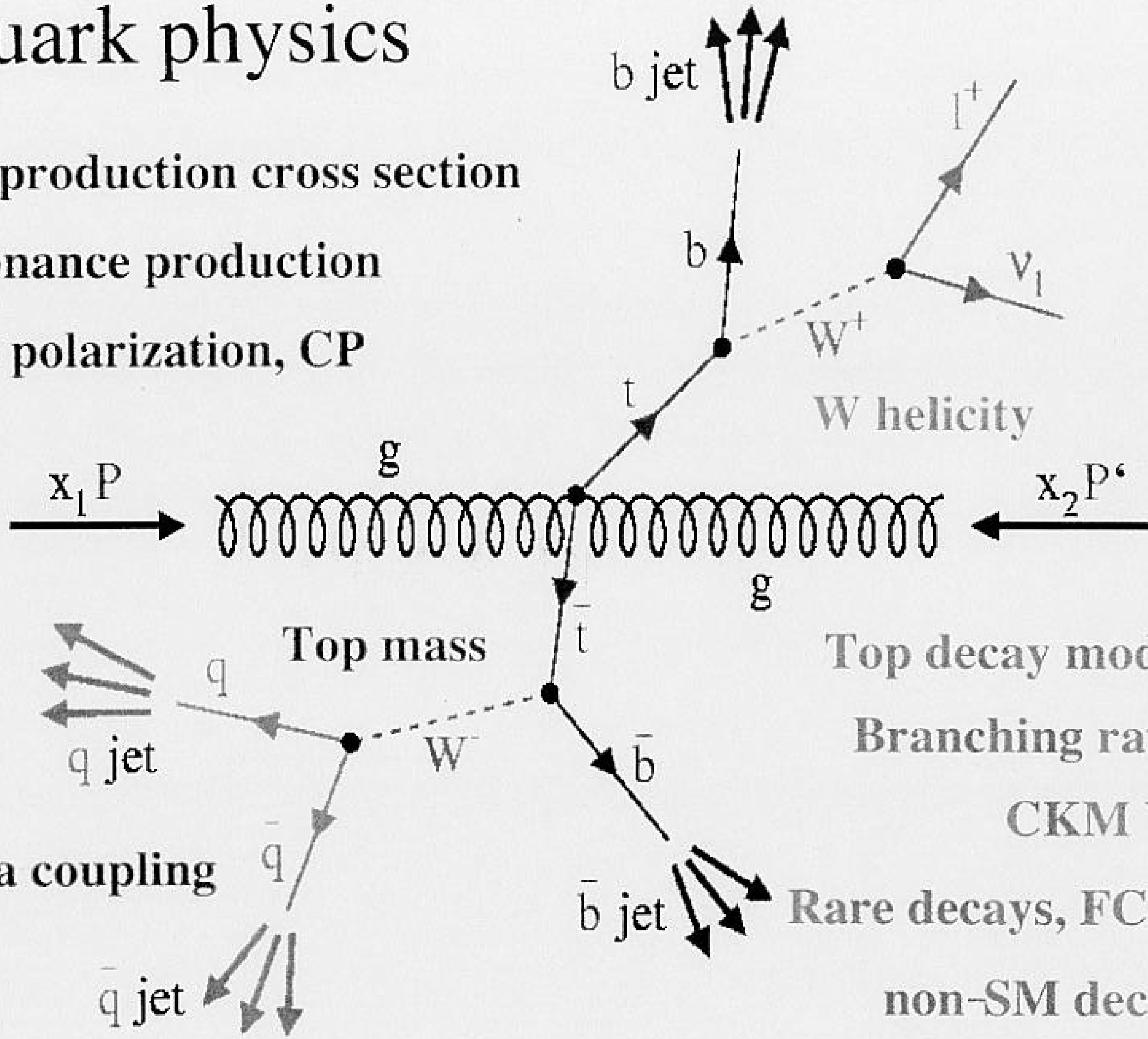
Top quark physics

top quark physics

Top production cross section

Resonance production

Spin polarization, CP



W helicity

Top mass

Top Yukawa coupling

Top decay modes

Branching ratios

CKM V_{tb}

Rare decays, FCNC

non-SM decays

Top production cross section

top factory

$\sqrt{s}$ = 2TeV $\sigma_{NLO} \cong$ 7 pb

$\sqrt{s}$ = 14TeV $\sigma_{NLO} \cong$ 800pb

- σ_{tot}=70mb for LHC

→ 10^9 interactions/sec@$10^{34}cm^2s^{-1}$

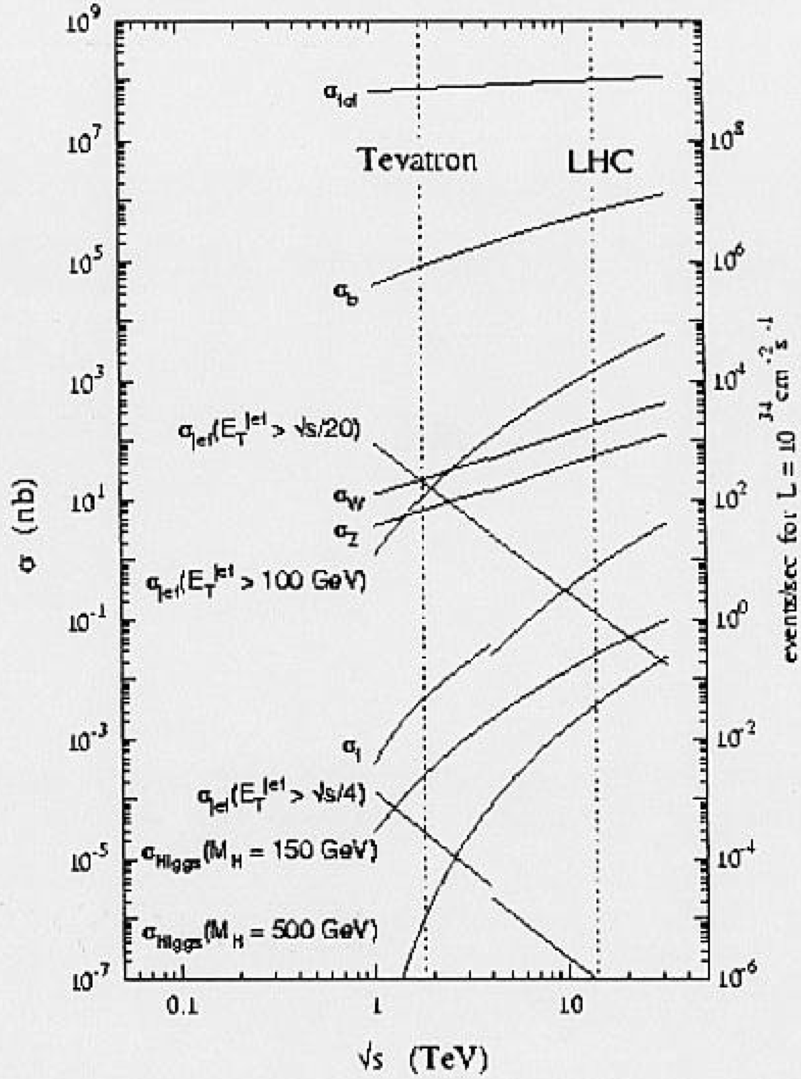
Interesting physics

W production: ~2kHz

Top production: 10Hz

Higgs production: 0.1(0.01)Hz

for M_H=100(500) GeV



Top mass measurement

high precision measurements parametric errors

	Δ_{theo}	$\delta(\Delta\alpha_{had})$ =0.00016	Δm_{top}=2GeV	Δm_{top}=1GeV
ΔM_W/MeV	6	3.0	12	6.1
$\Delta \sin^2\theta_{eff}^{lepton} x10^5$	4	5.6	6.1	3.1

- goal

Tevatron		LHC	NLC(μ μ)
RUN-I	RUN-II		
±5.1GeV	< 3 GeV	< 2(1) GeV	±0.2GeV

Higgs

自発的対称性の破れのメカニズムは何か?

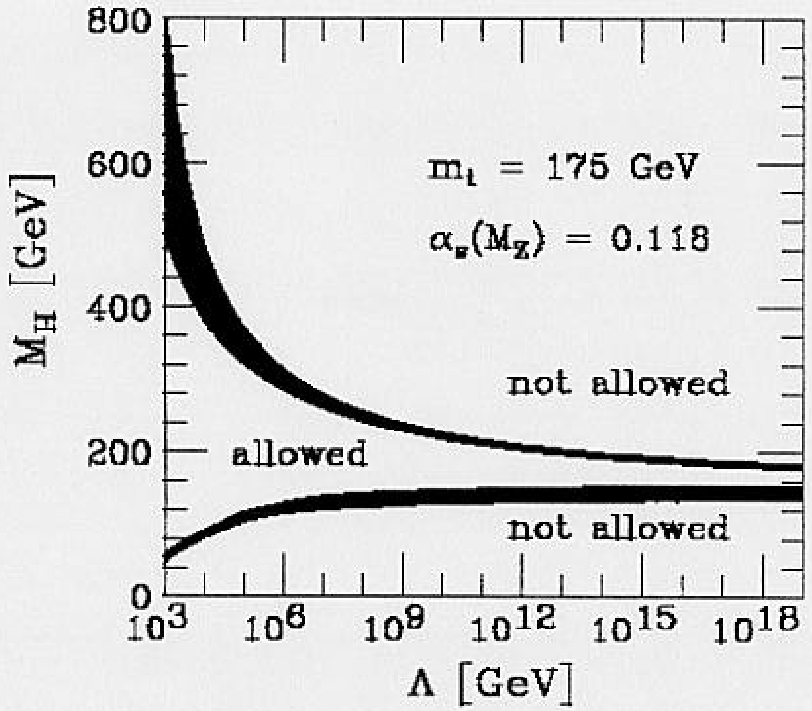
Higgs Mechanism:

- origin of particle mass
- scalar field in vacuum

SUSY

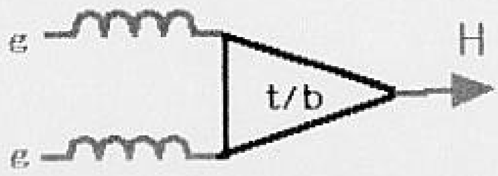
- light Higgs Mh_0<130GeV
- unification at GUT scale

If M_{Higgs}=115GeV, new physics must exist at $\Lambda<10^6$GeV.



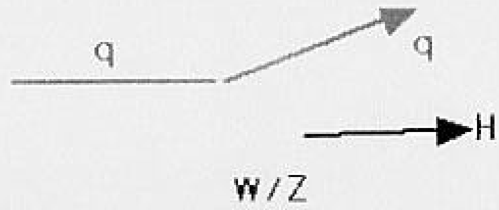
Higgs Production at Hadron Collider

gg fusion



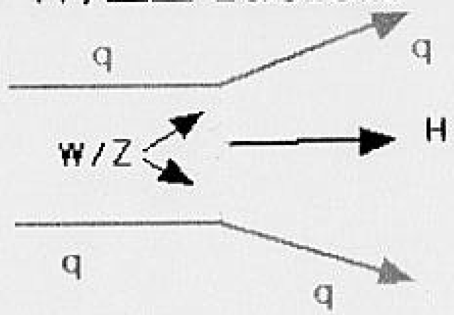
large σ, low P_t except H

Associated WH, ZH



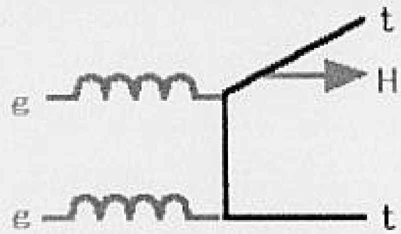
gauge boson in final state (clean)

WW/ZZ fusion



2 forward jets with $P_t \sim M_W/2$

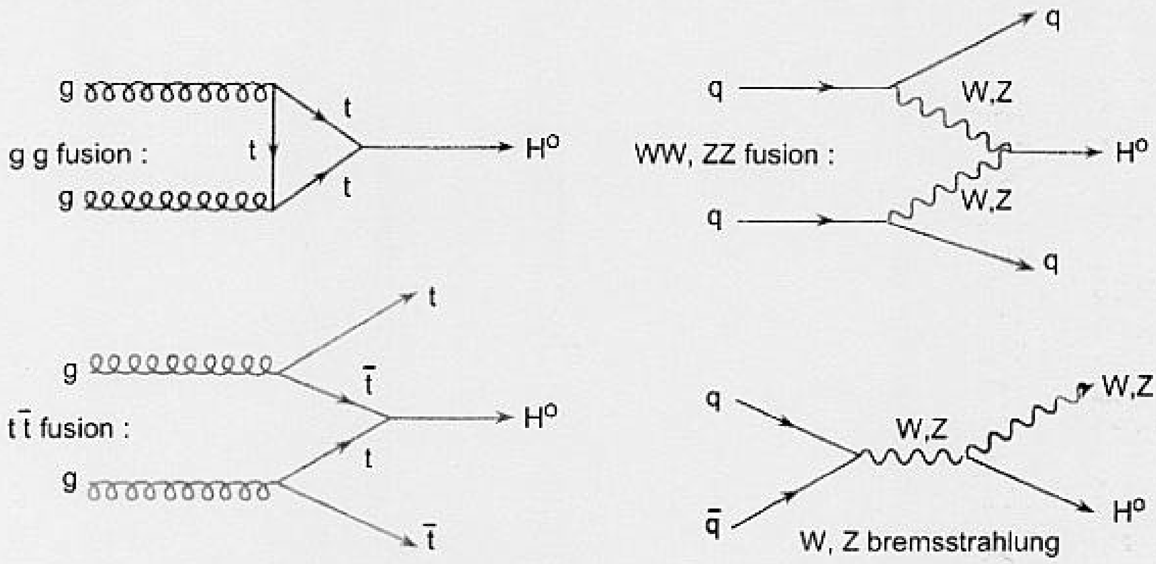
Associated ttH

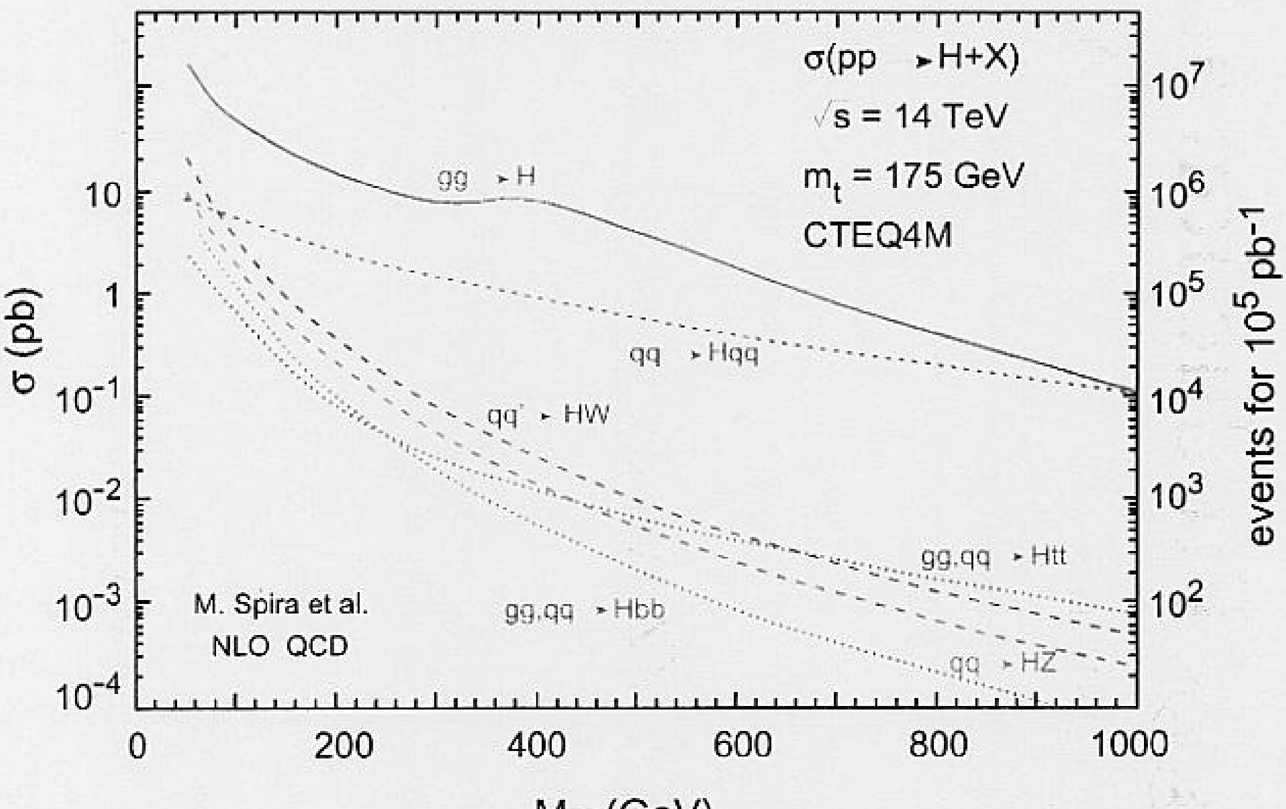


Yukawa(湯川) coupling

Higgs production&decay → Y_t, Y_b, Y_τ, g_{HWW}, g_{HZZ} information!

H^o production at hadron colliders:



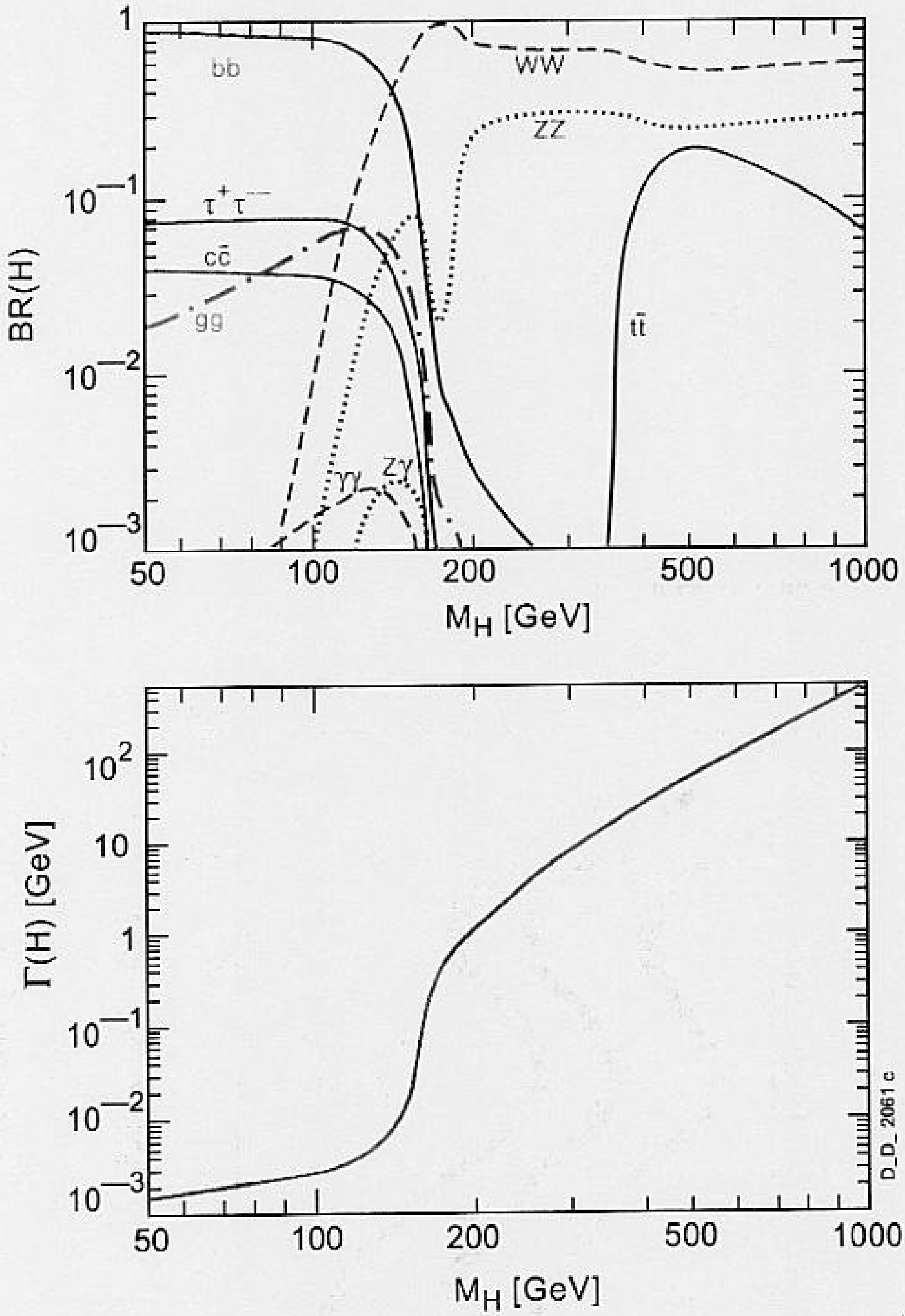


But : $BR(H \rightarrow Z_i Z_i \rightarrow 4l^-) = 1.4 ¥ 10^{-3}$

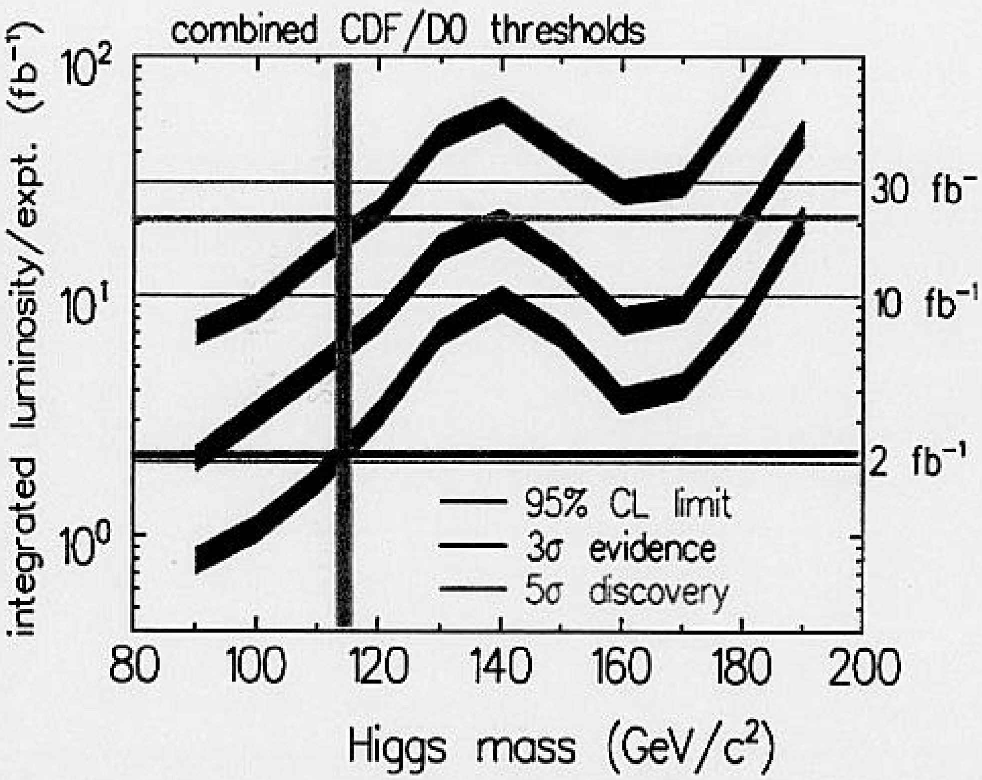
$BR(H \rightarrow Z_i Z_i \rightarrow 4\mu^-) = 3 ¥ 10^{-4}$

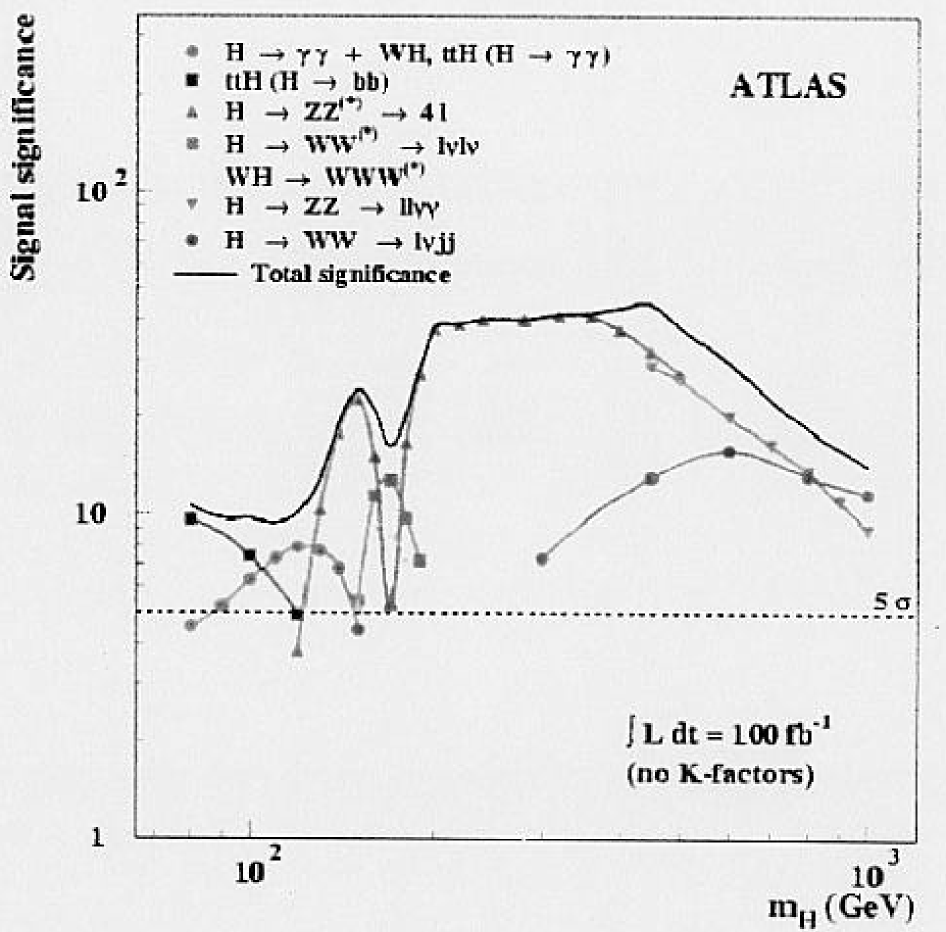
D_D_1186.c

SM Higgs
Branching ratios and total decay width



TevatronとLHCのヒッグス発見能力





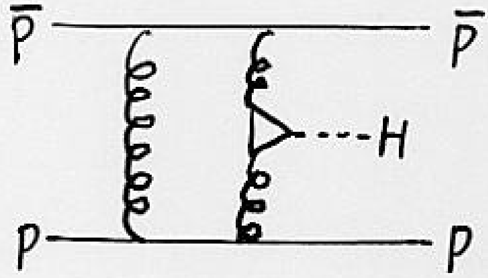
- ✓ 2 fb^{-1} needed for exclusion.
- ✓ 20 fb^{-1} needed for discovery!
  (with CDF+D0 combination)

Diffractive Higgs production CDF

(M. Albrow)

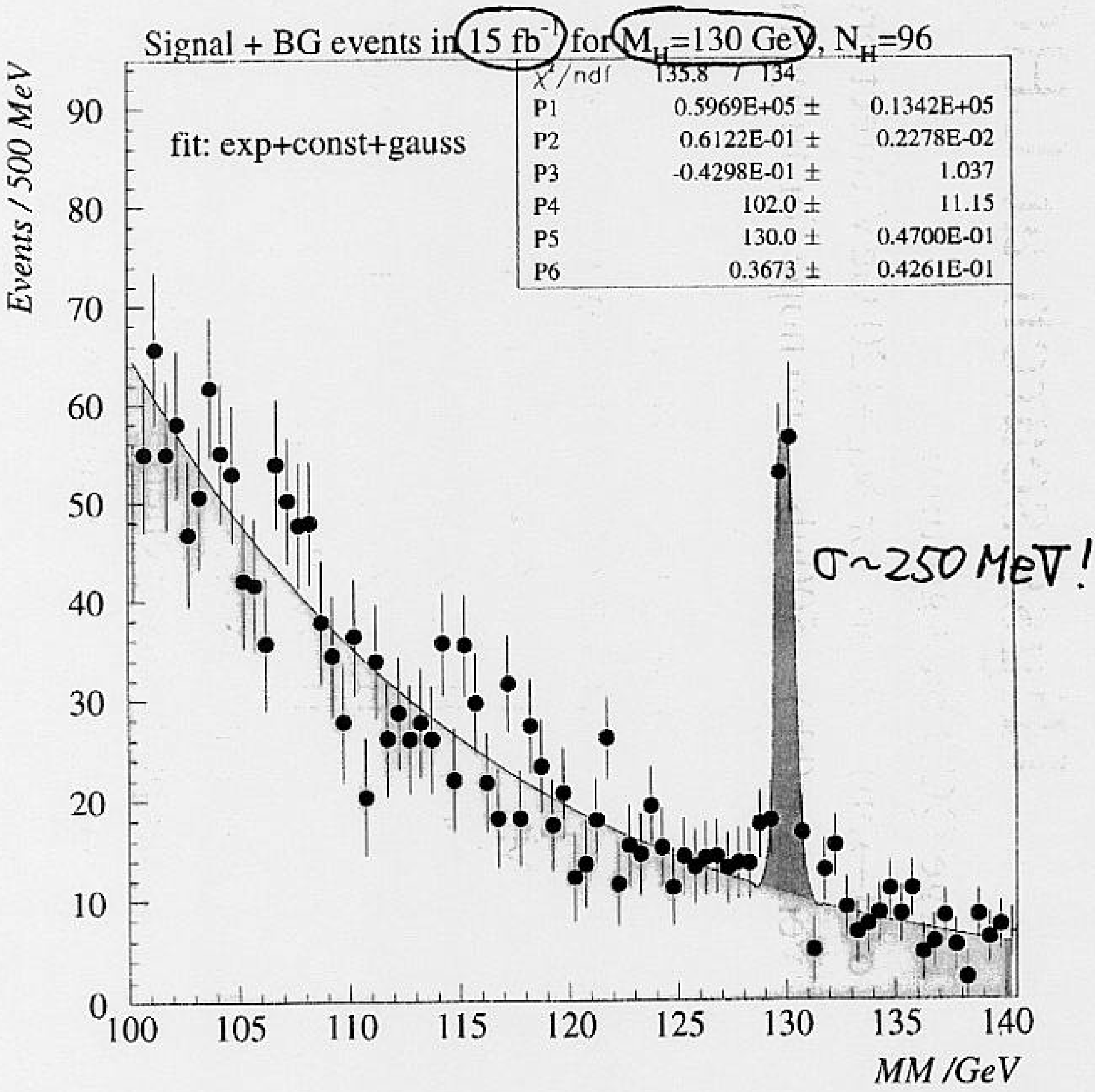
$\bar{p}p \to \bar{p}Hp$

$H \to b\bar{b}, \tau\tau, W^+W^-$



$MM^2 \simeq \xi_1 \xi_2 s$

↑ Roman POT



Higss search at LHC

- Large QCD backgrounds

  $\sigma(H \to bb) \sim$ 20pb for M_H=120 GeV direct production

  versus $\sigma(bb) \sim$ 500μb … no hope for fully hadronic final states.

$M_H < 2M_Z$: $ttH \to l bb + X$, $H \to \gamma\gamma$,

$H \to ZZ^* \to 4l$, $H \to WW^* \to l \nu l \nu$

$M_H > 2M_Z$: $H \to ZZ \to 4l$ (gold plated)

$H \to ZZ \to ll \nu\nu$

$H \to ZZ \to lljj$ (M_H>300 GeV forward jet tag)

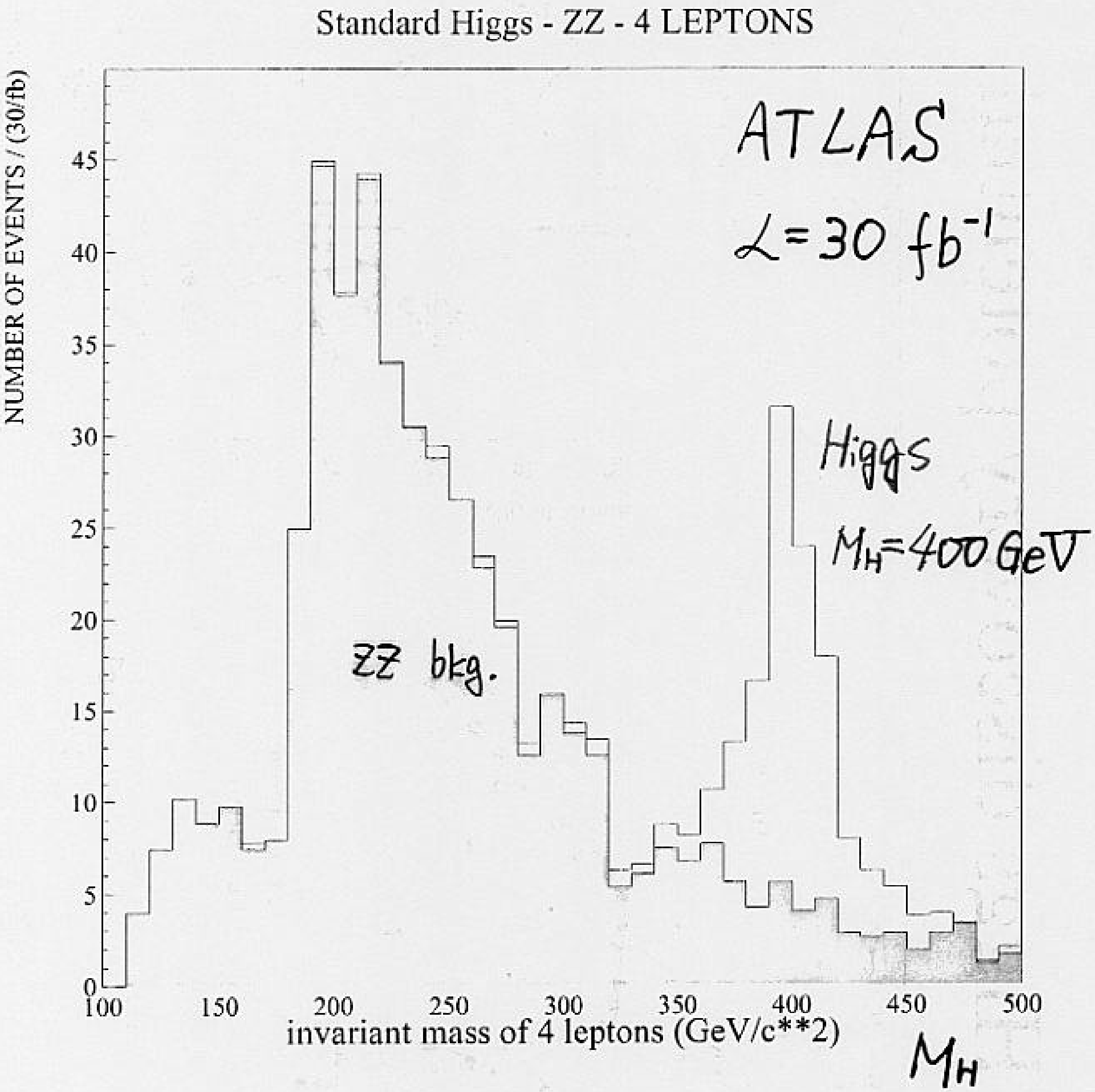
$H \to WW \to l \nu jj$

Detector requirements:

b-tag, lepton id, l/γ energy resolution,

γ/j separation, E_t^{miss} resolution, forward-jet tag etc.

$H \rightarrow ZZ \rightarrow 4$ leptons



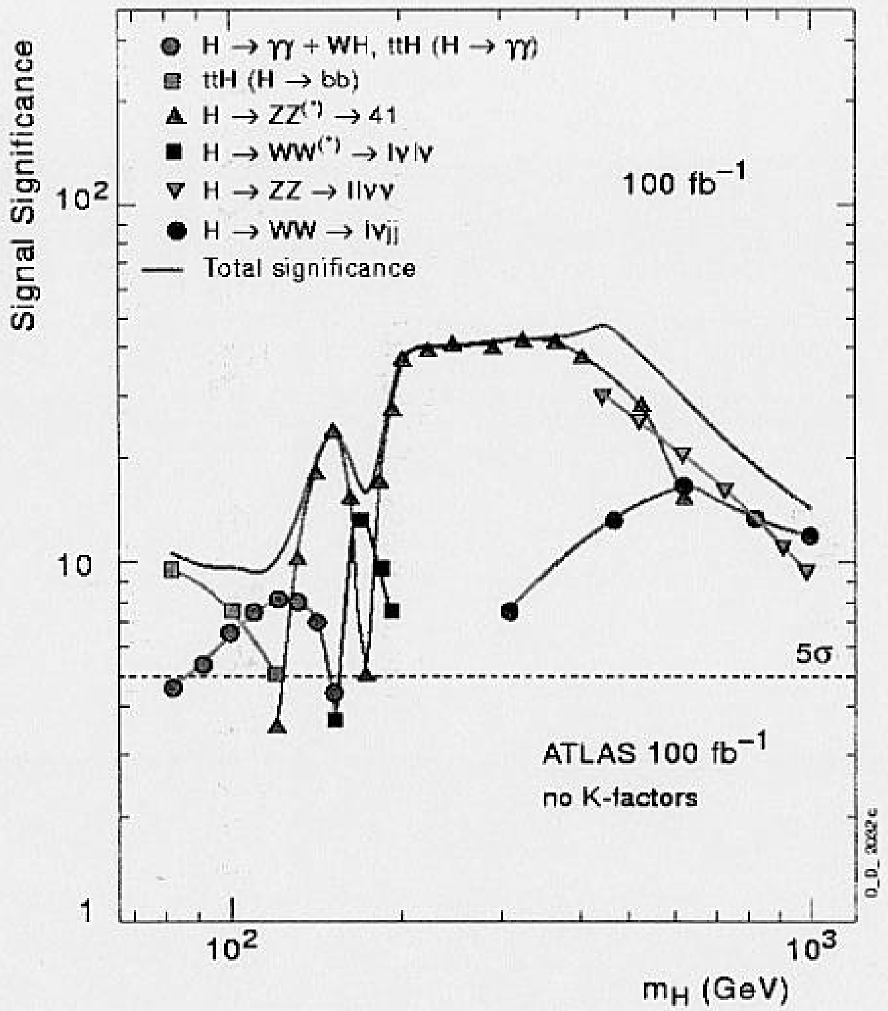
近藤敬比古先生　退官記念講演　200*年3月

Evidence of Higgs boson decaying into four leptons

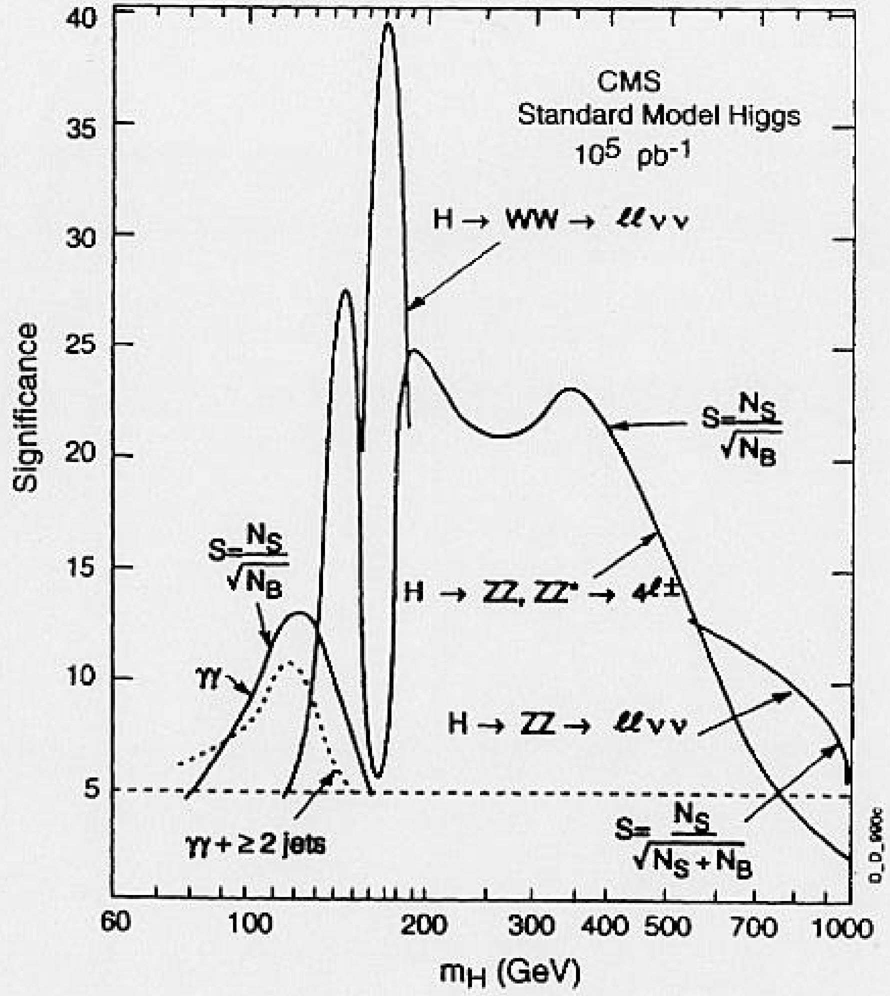
(Search for…の場合は，司会は浅井祥仁(ICEPP))

Higgs discovery potential

LHC 100 fb^{-1}

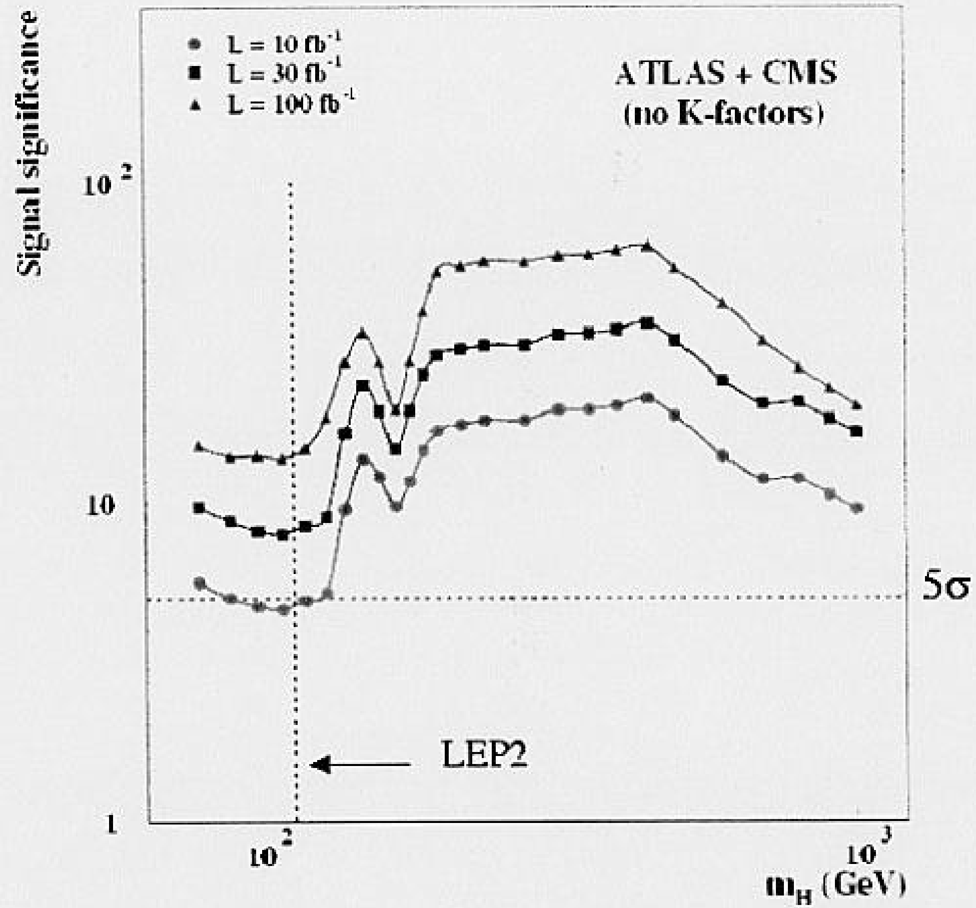


ATLAS



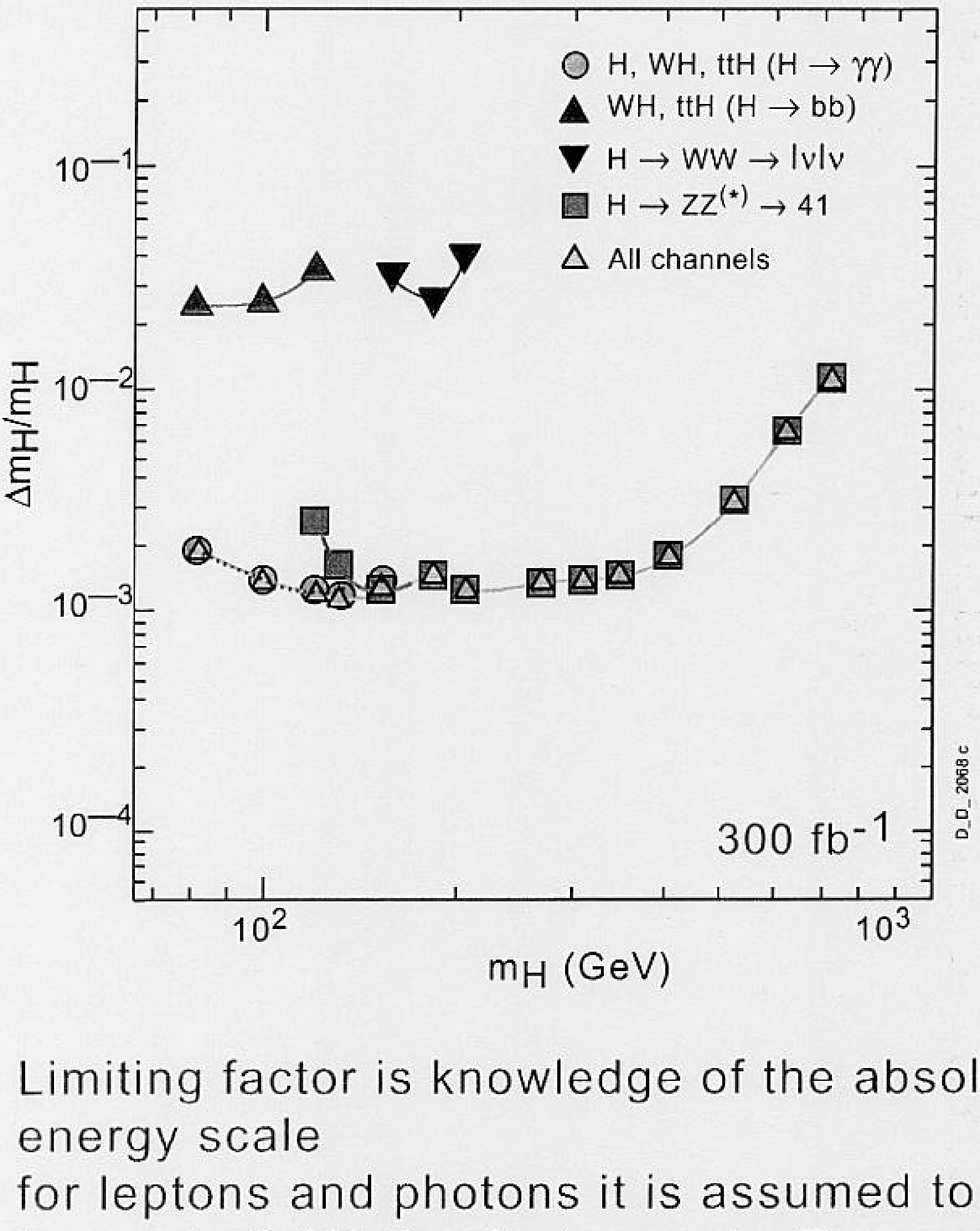
CMS

ATLAS+CMS combined performance



SM Higgs boson can be discovered at 5σ level after 1 year of LHC run (10fb^{-1}/experiment).

Precision on SM Higgs mass

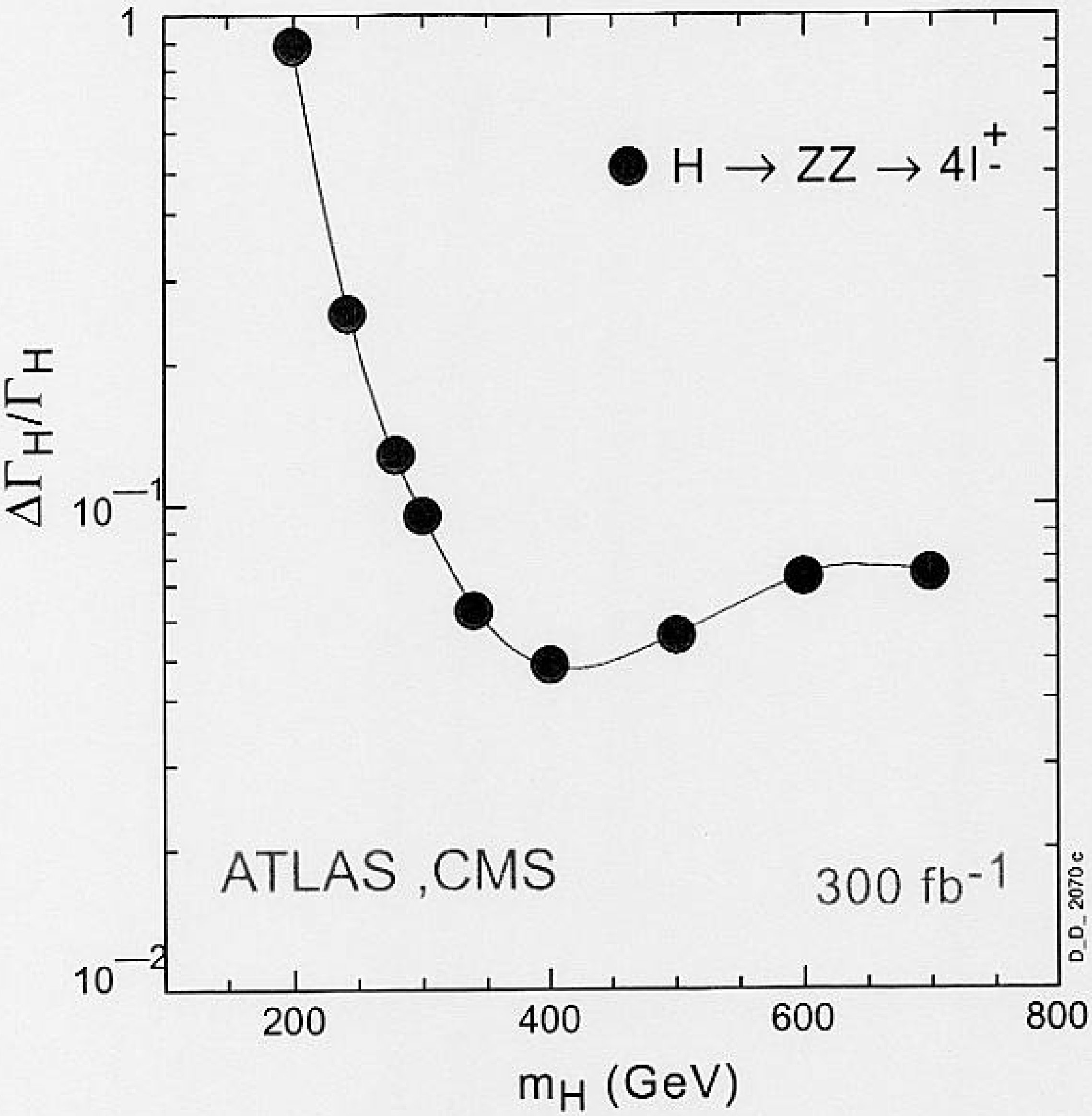


Limiting factor is knowledge of the absolute energy scale

for leptons and photons it is assumed to be known to 0.1% thanks to nearby Z

for jets it is assumed to be 1%

Precision on SM Higgs width



Limiting factor are radiative decays

systematic uncertainty assumed to be 1.5%

SUSY

MSSM HIGGS searches : h, H, A, $H^{\pm}$

Large variety of channels:

e.g.

$- h \to \gamma\gamma,\ t\bar{t}h \to t\bar{t}b\bar{b},\ H \to ZZ^{(*)} \to 4\ell$ — also in SM

$- A/H \to \mu\mu,\ \tau\tau,\ t\bar{t},\ H^{\pm} \to \tau\nu,\ cs,\ tb$
$- H \to hh,\ A \to Zh$
} typical of MSSM

$- A/H \to \chi^0_2 \chi^0_2$
$- \chi^0_2 \to h\, \chi^0_1$
} if SUSY particles accessible

Note :

-- suppression/absence of WWH, ZZH, WWA, ZZA couplings
-- strong enhancement of bbA, bbH couplings for large tanβ
} compared to SM

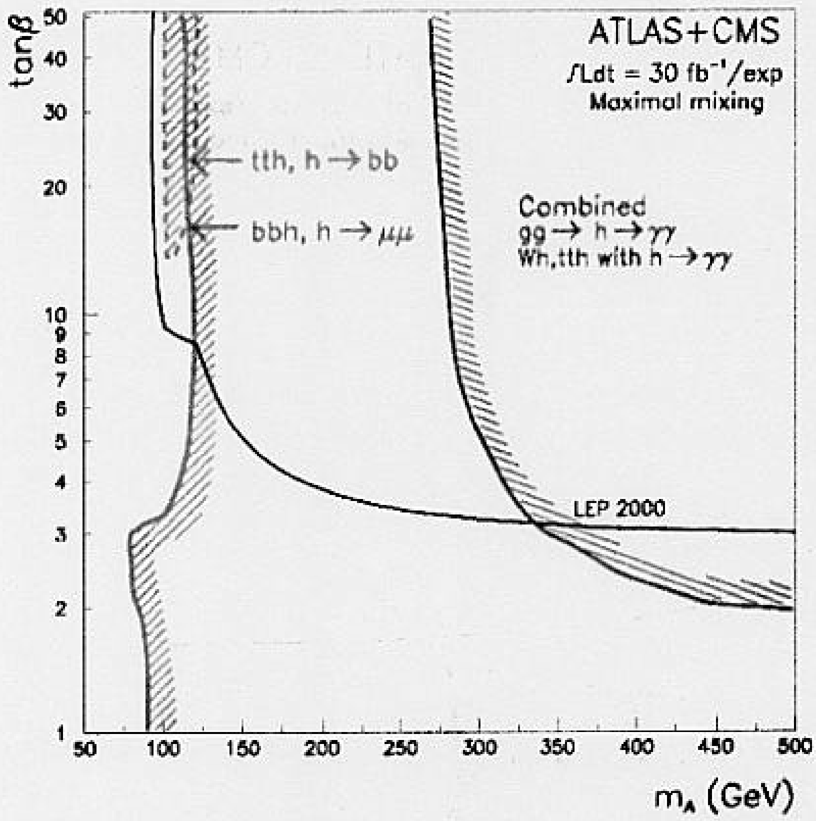
$\to A/H \to \mu\mu,\ \tau\tau$ accessible

2 steps:

❶ SUSY particles are heavy → do not contribute to Higgs production / decay

❷ SUSY particles contribute

h boson

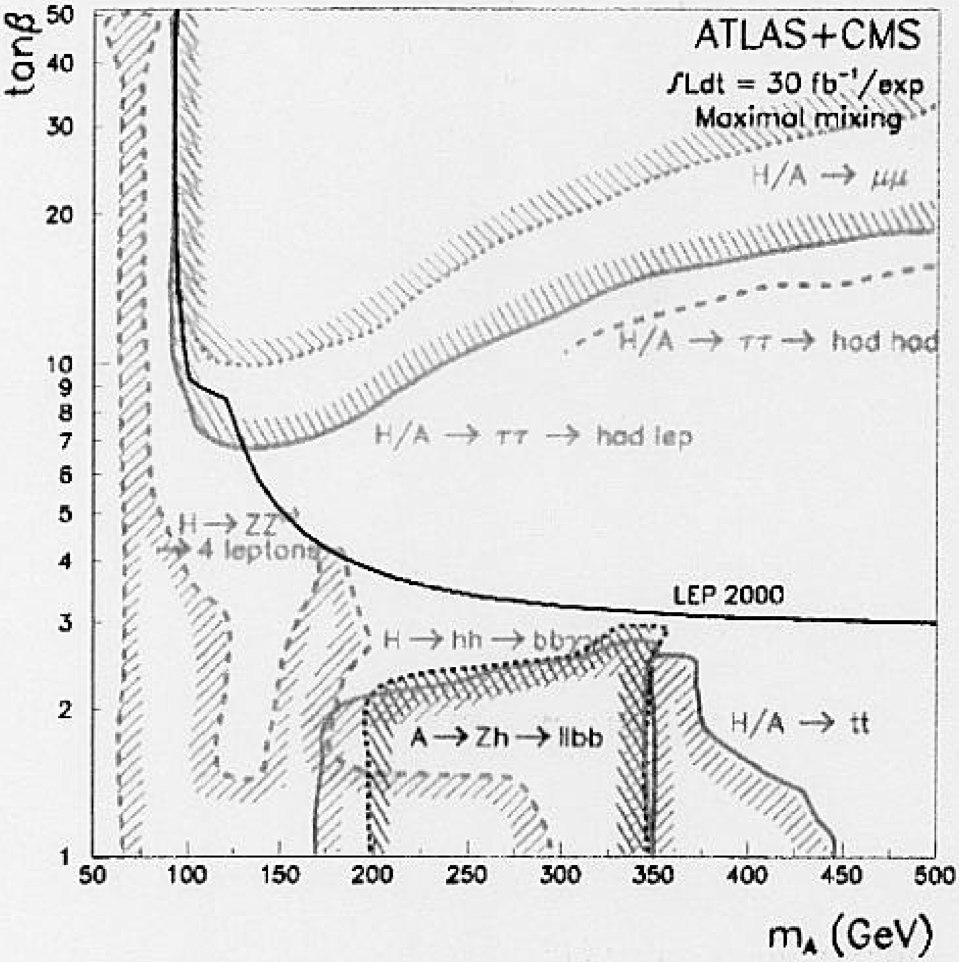


$m_A > 100$ GeV:
-- h mass close to max value (~ 130 GeV)
-- h behaves as SM Higgs → SM production and decay modes

$m_A < 100$ GeV:
-- h mass decreases
-- BR ($h \to \gamma\gamma$) and $t\bar{t}h$ production suppressed
-- large tanβ : bbh production enhanced → bb μμ channel observable

Robust coverage:
-- different production mechanisms : $gg \to h$ (loops), Wh, $t\bar{t}h$
-- different decays : $h \to \gamma\gamma$ (loops), $h \to b\bar{b}$

A and H bosons



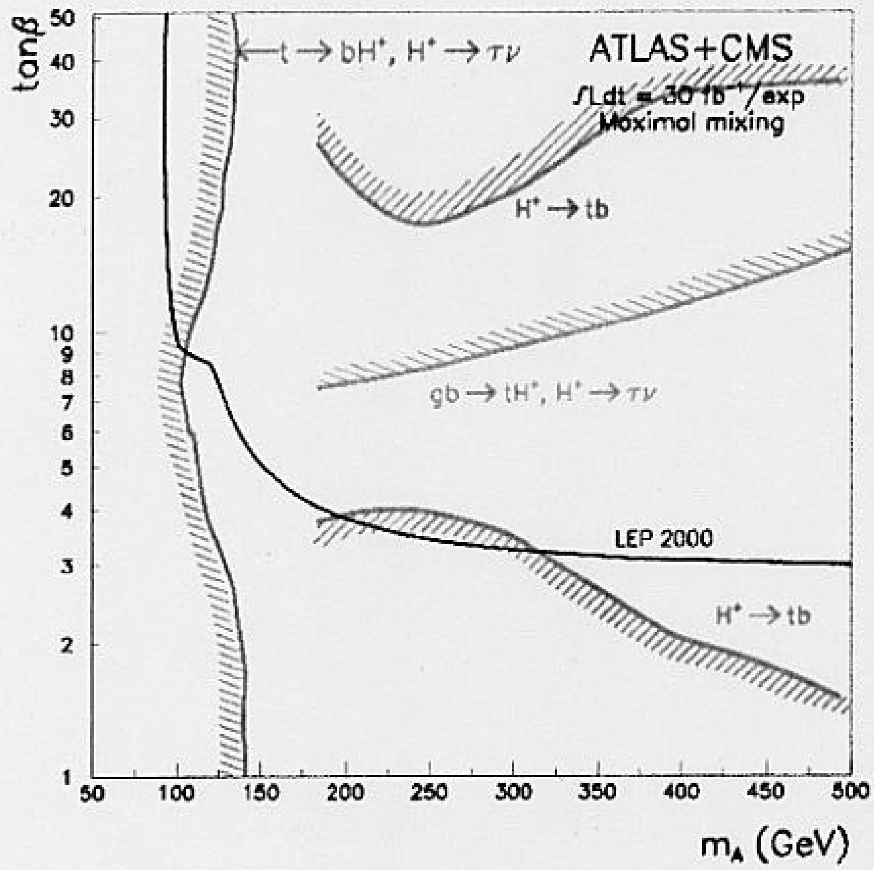
$m_A > 200$ GeV:
A and H are
~ degenerate

- Large tanβ : $b\bar{b}H, b\bar{b}A$ strongly enhanced
  e.g. σ (MSSM) / σ (SM) ≈ 5000 tanβ =30, m =300 GeV

⇒ H/A → ττ, μμ observable and cover large part of parameter space

- Small tanβ : large number of channels
  → measurement of many couplings including Hhh, AZh

$H^{\pm}$ bosons



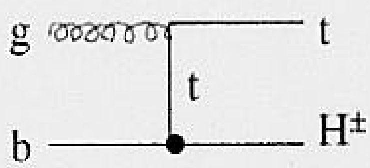
- $m_{H\pm} < m_t$: $t \to b H^+$ ($H^+ \to \tau\nu$) competes with $t \to bW$
  $\to$ count excess of τ's in $t\bar{t}$ final states

3000 $W \to \tau\nu$ 1500 $H^{\pm} \to \tau\nu$ m=130 GeV $\tan\beta=5$ 4000 fake τ from $W \to jj$	$t\bar{t}$ events, 30 fb^{-1}

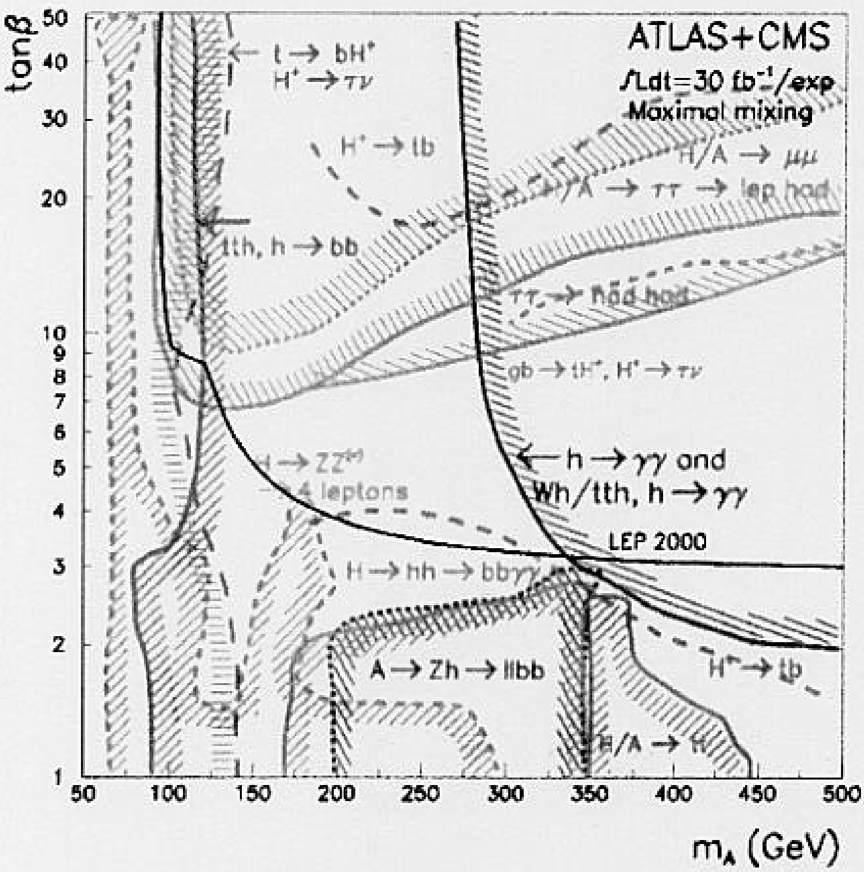
$\tan\beta \leq 1.5$: $H^{\pm} \to cs$

- $m_{H\pm} > m_t$:

  -- $gb \to H^{\pm} t \to tb\, t$
  -- $gb \to H^{\pm} t \to \tau\nu\, t$



All (almost …) channels together ….



Assuming SUSY particles are heavy

Not all channels shown

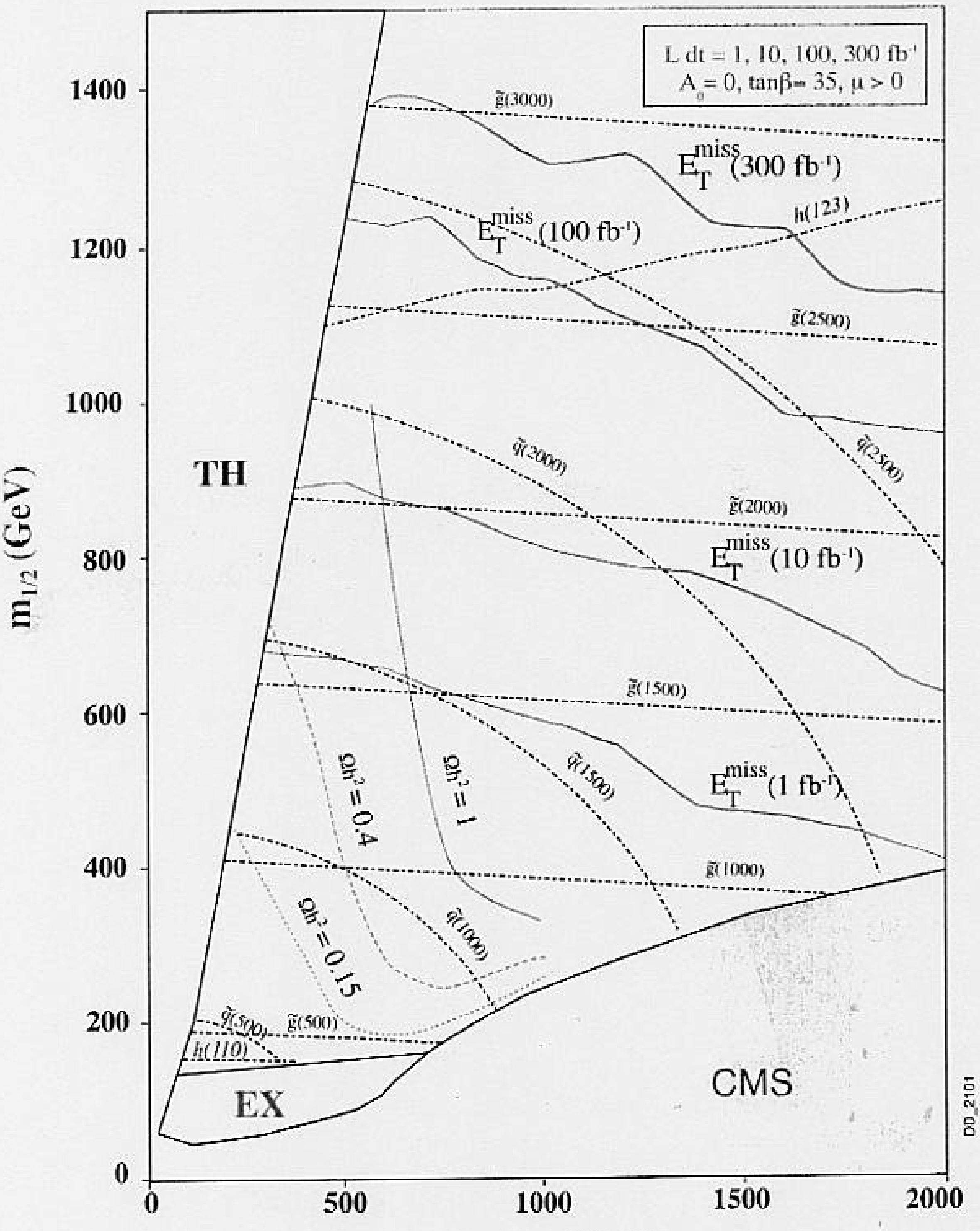
- Plane fully covered (no holes) at low L (30 fb^{-1})
- Main channels : $h \rightarrow \gamma\gamma$, $b\bar{b}$, A/H $\rightarrow \mu\mu, \tau\tau$, $H^{\pm} \rightarrow \tau\nu$

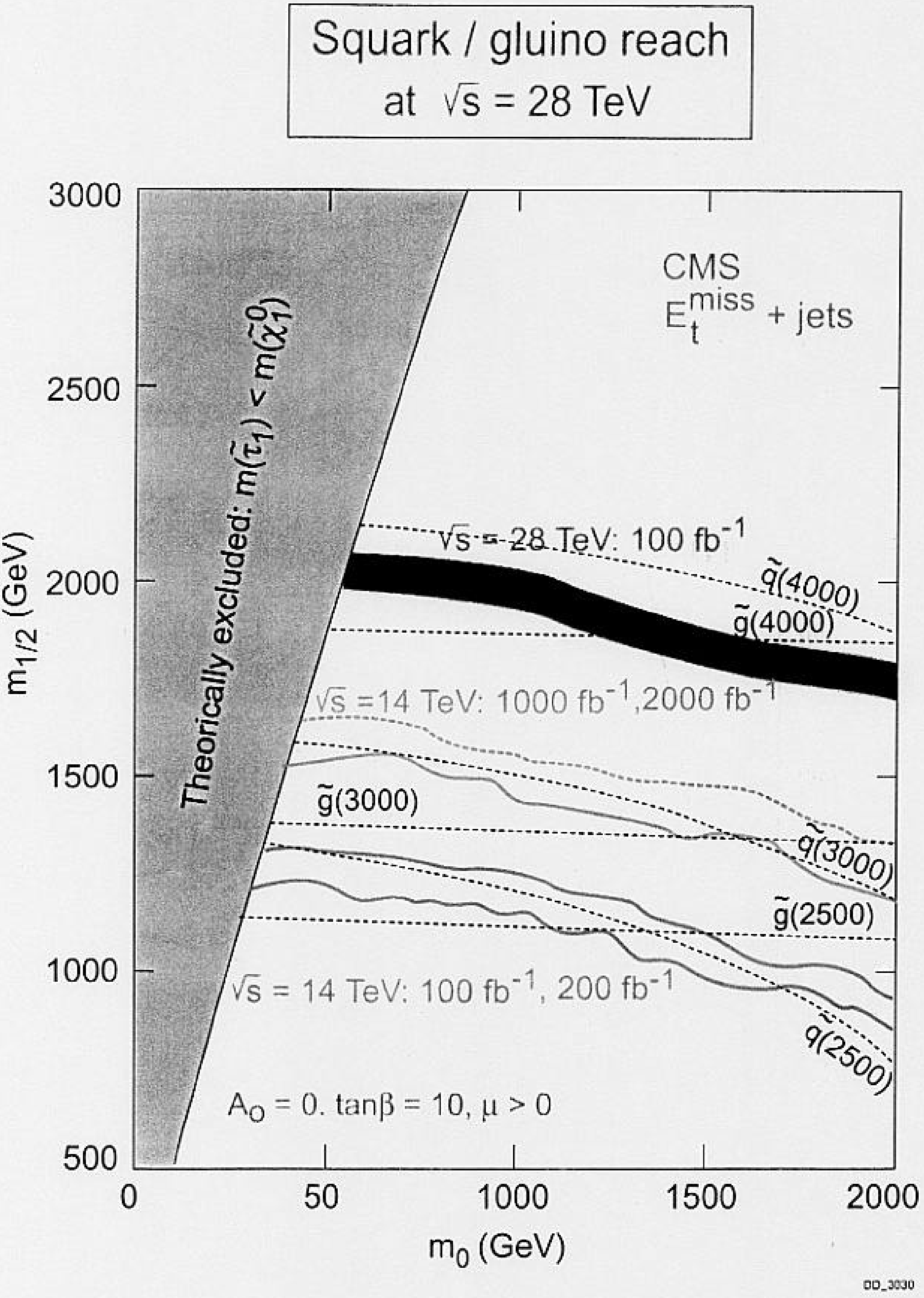
- Two or more Higgs can be observed over most of parameter space → disentangle SM / MSSM

- If LEP observes hA , LHC will observe $H^{\pm}$ and H
  if LEP observes hZ (disentangling SM / MSSM difficult)
  LHC will observe h, A, H, $H^{\pm}$ for $m_A < 400$ GeV

Uncertainties : $\Delta m_A \approx \pm 30$ GeV (e.g. from $\Delta m_h \sim 3$ GeV), $\Delta\tan\beta \approx \pm 0.7$
Impact of mixing on couplings studied for minimal mixing
but not for all possible mixing (evolving theory predictions)

The CMS $\tilde{q},\tilde{g}$ mass reach in E_T^{miss} + jets inclusive channel for various integrated luminosities





Squark / gluino reach
at √s = 28 TeV
3000
2500
2000
1500
1000
500
0
50
1000
1500
2000
$m_{1/2}$ (GeV)
m_0 (GeV)
CMS
E_t^{miss} + jets
Theorically excluded: $m(\tilde{\tau}_1) < m(\tilde{\chi}_1^0)$
√s = 28 TeV: 100 fb^{-1}
$\tilde{q}$(4000)
$\tilde{g}$(4000)
√s =14 TeV: 1000 fb^{-1},2000 fb^{-1}
$\tilde{g}$(3000)
$\tilde{q}$(3000)
$\tilde{g}$(2500)
√s = 14 TeV: 100 fb^{-1}, 200 fb^{-1}
$\tilde{q}$(2500)
A_O = 0. tanβ = 10, μ > 0
DD_3030

Strong Interaction

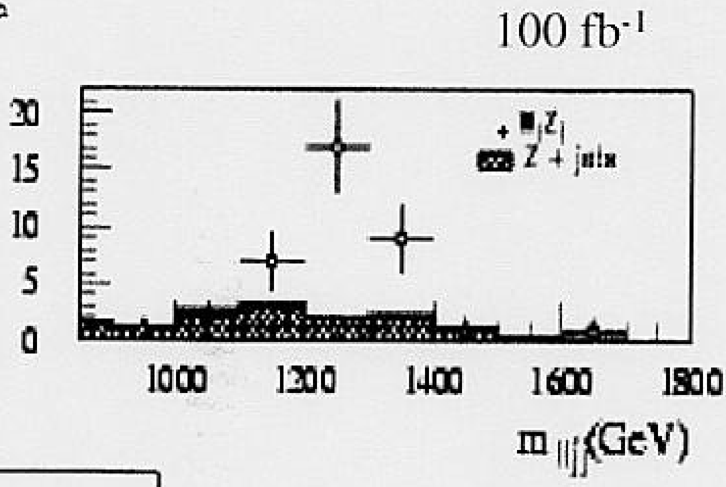
Strongly interacting Higgs

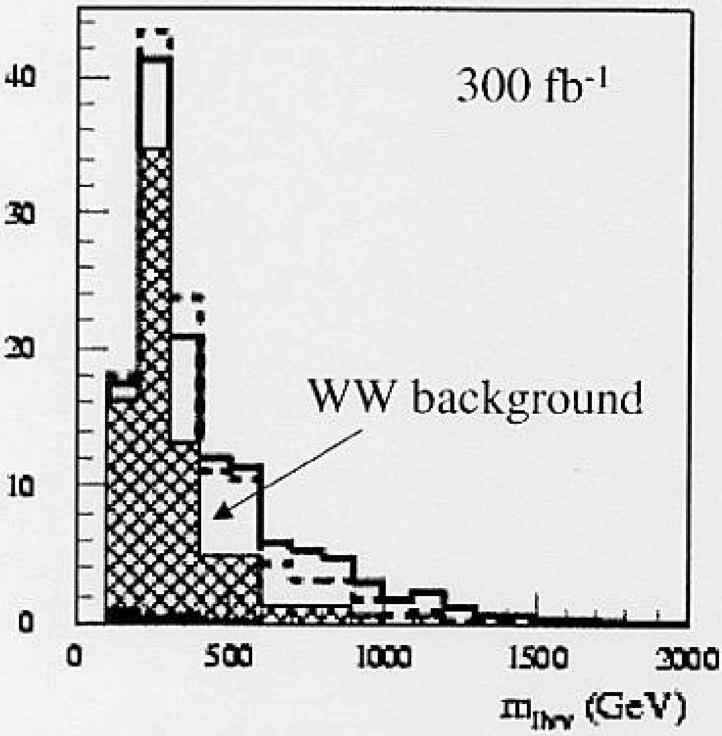
If no Higgs → EWSB probed by V_L V_L scattering
Experimental handle: forward jet tag

<u>Resonant scattering</u>

e.g.
$W_L Z_L \rightarrow W_L Z_L$

sensitivity up to
≈ 1.5 TeV





<u>Non-resonant scattering</u>

e.g.
$W_L^+ W_L^+ \rightarrow W_L^+ W_L^+$

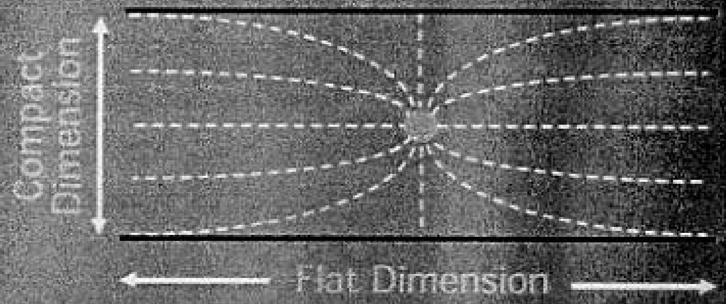
Extra-Dimension

Large Extra Dimensions

- Arkani-Hamed, Dimopoulos, Dvali (1998): there could be large extra dimensions that only gravity feels!
- What about Newton's law?

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \rightarrow \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^{n+1}}$$

- Ruled out for flat extra dimensions, but has not been ruled out for compactified extra dimensions:



$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \text{ for } r >> R$$

M_P – fundamental Planck Scale

- But: how to make gravity strong?
- $G'_N = 1/M_P^2 \sim G_F \Rightarrow M_P \sim 1$ TeV

$$M_P^{n+2} \propto M_{Pl}^2 / R^n$$

- More precisely, from Gauss's law:

$$R = \frac{1}{2\sqrt{\pi}M_S}\left(\frac{M_{Pl}}{M_S}\right)^{2/n} \propto \begin{cases} 8\times10^{12}\,m, & n=1 \\ 0.7\,mm, & n=2 \\ 3\,nm, & n=3 \\ 6\times10^{-12}\,m, & n=4 \end{cases}$$

- Amazing as it is, but no one has tested Newton's law to distances less than ~1 mm (as of 1998) or 0.15 mm (2002)
- Therefore, large spatial extra dimensions compactified at a sub-millimeter scale are, in principle, allowed!
- If this is the case, gravity can be ~10^{38} times stronger than what we think!

BH at Accelerators: Basic Idea

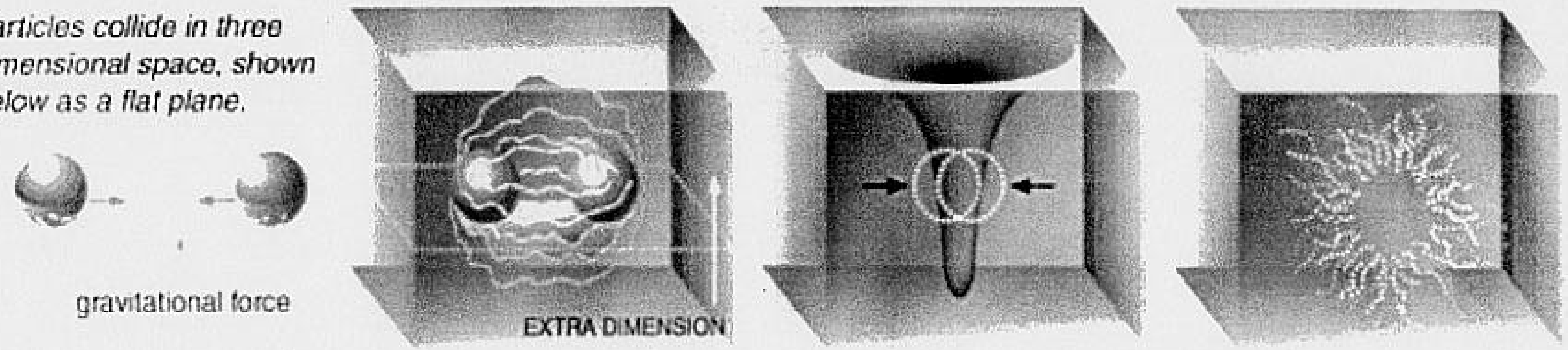
Black Holes on Demand

NYT, 9/11/01

The New York Times on the Web

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Our Assumptions

- Schwarzschild radius is given by Argyres et al., hep-th/9808138 [after Myers/Perry, Ann. Phys. **172** (1986) 304]; it leads to:

$$\sigma(\hat{s} = M_{BH}^2) = \pi R_S^2 = \frac{1}{M_P^2}\left[\frac{M_{BH}}{M_P}\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{2}{n+1}}$$

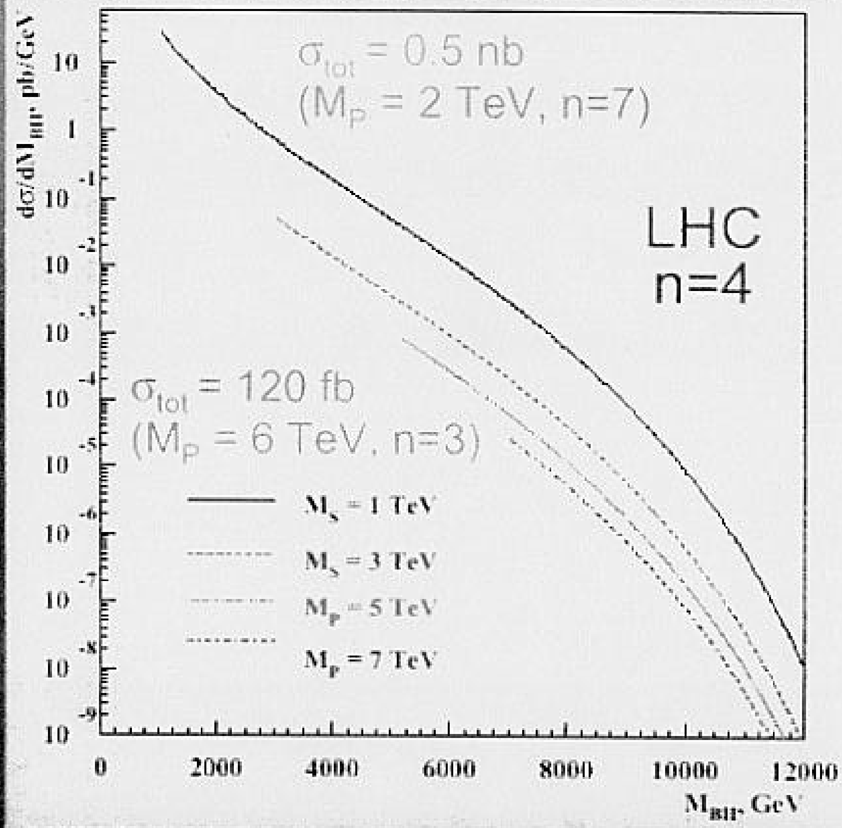
- Hadron colliders: use parton luminosity w/ MRSD-' PDF (valid up to the VLHC energies)

$$\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}}\hat{\sigma}(ab \to BH)\Big|_{\hat{s}=M_{BH}^2}$$

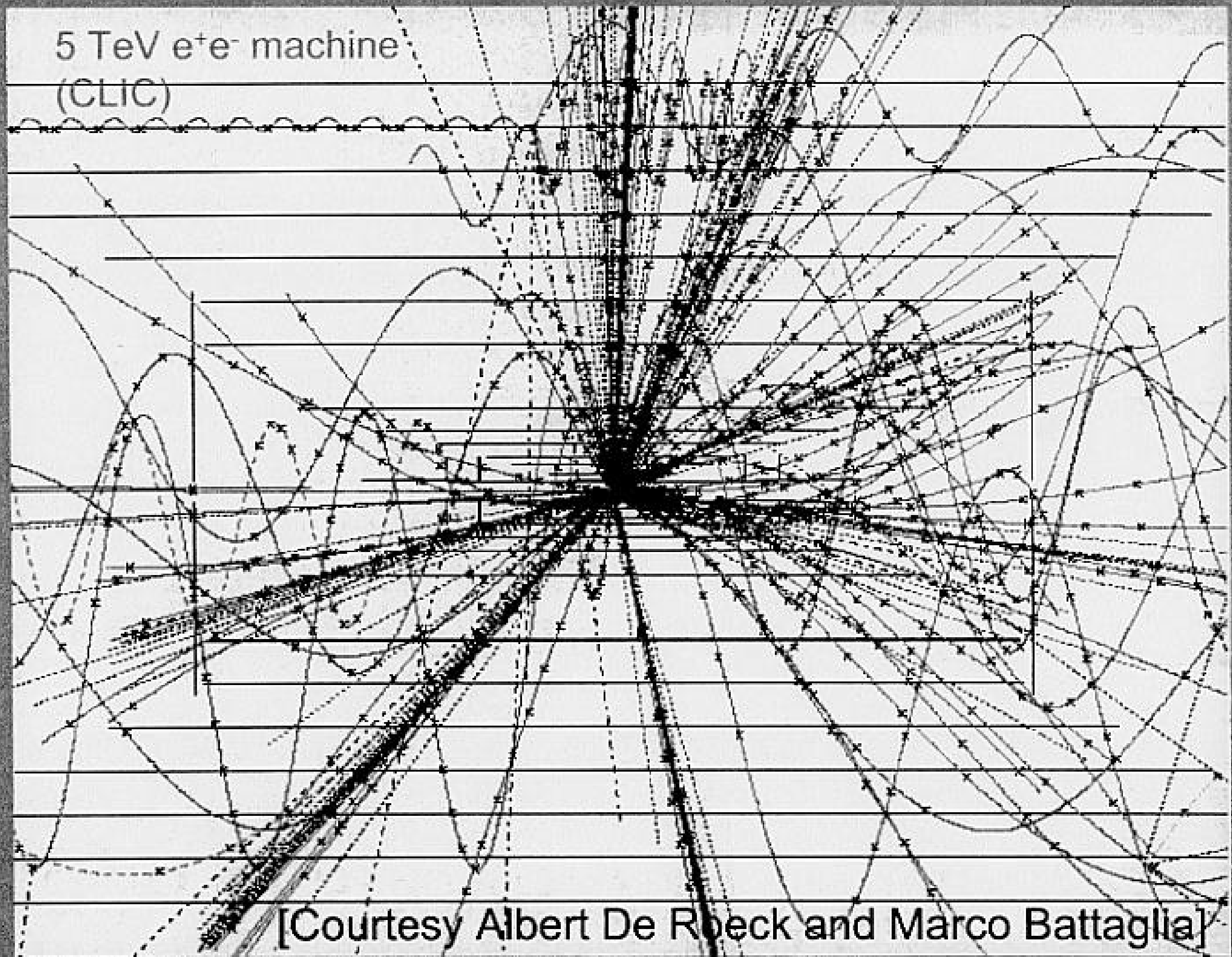
$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s}\sum_{a,b}\int_{M_{BH}^2/s}^{1}\frac{dx_a}{x_a}f_a(x_a)f_b\left(\frac{M_{BH}^2}{sx_a}\right)$$

- Note: at c.o.m. energies ~1 TeV the dominant contribution is from uu+dd interactions

[Dimopoulos, GL, PRL **87**, 161602 (2001)]



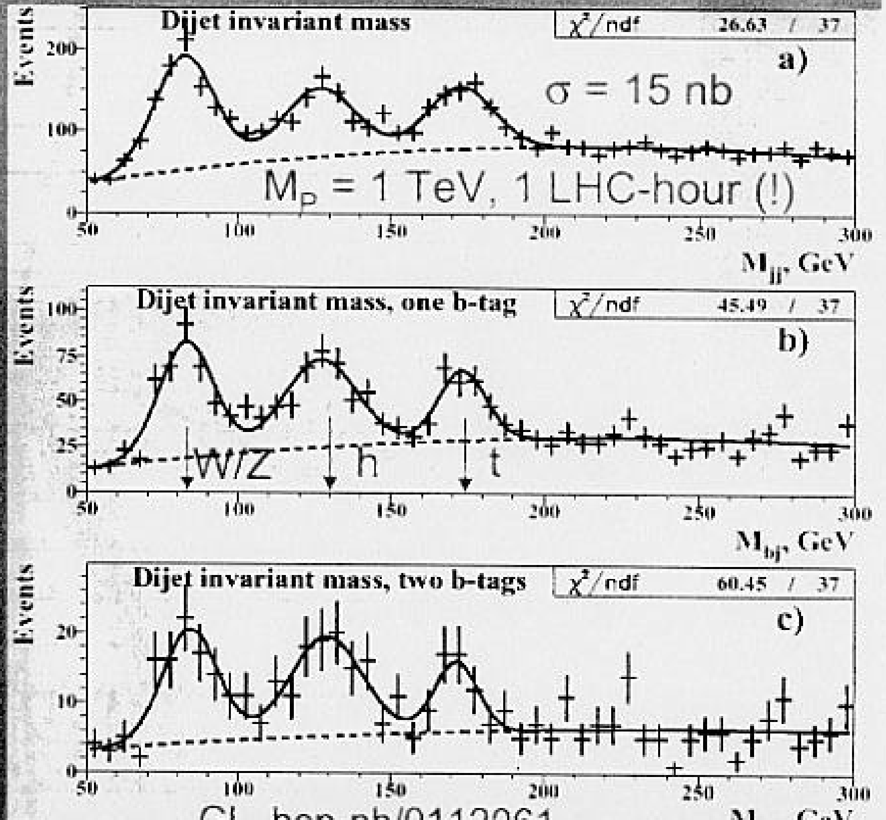
A Black Hole Event Display



[Courtesy Albert De Roeck and Marco Battaglia]

Higgs Discovery in BH Decays

- Example: 130 GeV Higgs particle, which is tough to find at either the Tevatron or the LHC
- Higgs with the mass of 130 GeV decays predominantly into a bb-pair
- Tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use a typical LHC detector response to obtain realistic results
- Time required for 5 sigma discovery:
  - M_P = 1 TeV – 1 hour
  - M_P = 2 TeV – 1 day
  - M_P = 3 TeV – 1 week
  - M_P = 4 TeV – 1 month
  - M_P = 5 TeV – 1 year
  - Standard method – 1 year w/ two calibrated detectors!



GL, hep-ph/0112061

- An exciting prospect for discovery of other new particles w/ mass ~100 GeV!

Summary

- 1990's … remarkable success of the Standard Model
  - $N_\nu=3$
  - top quark at 175GeV as predicted from LEP/SLC→Tevatron
  - non-Abelian nature of SU(2)×U(1) with W/Z vector boson

  Higgs sector remains unexplored.

- 2000's …

  Hadron Collider as Energy Frontier and Precision Machine !
  - Higgs discovery, physics beyond the Standard Model (SUSY,Extra-Dim,…)
  - We can perform precision measurements on W, top, Higgs, SUSY etc.
  - tool: W/Z boson, top, bottom, τ … and even Higgs.
  - Issues: Detector calib., QCD bkg., PDF, NLO-MC, NLL-PS.

Future: SuperLHC($L=10^{35}cm^{-2}s^{-1}$, $\sqrt{s}=28$TeV), VLHC($\sqrt{s}=O(100)$TeV) ?