Particle Physics @ Future Colliders

↓

1 - Standard Model

tested @ SLC/LEP: $E_{cm} \sim 200$ GeV, $\mathcal{L} \sim 10^{32}\ cm^{-2}s^{-1}$

Higgs boson? Tevatron, LHC

2 - Beyond the Standard Model

in particular supersymmetry

3 - Benchmark supersymmetric scenarios

prospects for future colliders?

4 - e^+e^- linear collider physics

great for Higgs: supersymmetry?

5 - High-energy frontier

CLIC : VLHC? muon colliders?

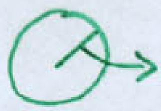
(J.E. + De Roeck + Gianotti: hep-ex/0112004)

High-Energy Cross Sections

$$\sigma_{\text{interesting}} \sim 1/E^2_{\text{Energy}}$$

$\wr$

determined by Compton wavelength:

 size $R \sim 1/E$

similarly for production of new, heavy particles:

$$\sigma_{\text{new}} \sim \frac{1}{m^2_{\text{heavy}}}$$

possible standard of comparison:

LEP: $\mathcal{L} = 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ @ $E_{cm} = 200\,\text{GeV}$

scale desirable luminosity $\mathcal{L} \sim E^2$

e.g., LHC: $\mathcal{L} = 10^{34}\,\text{cm}^{-2}\text{s}^{-1} \Rightarrow m_{\text{new}} \sim 1\,\text{TeV}$

CLIC @ $E_{cm} = 5\,\text{TeV}$

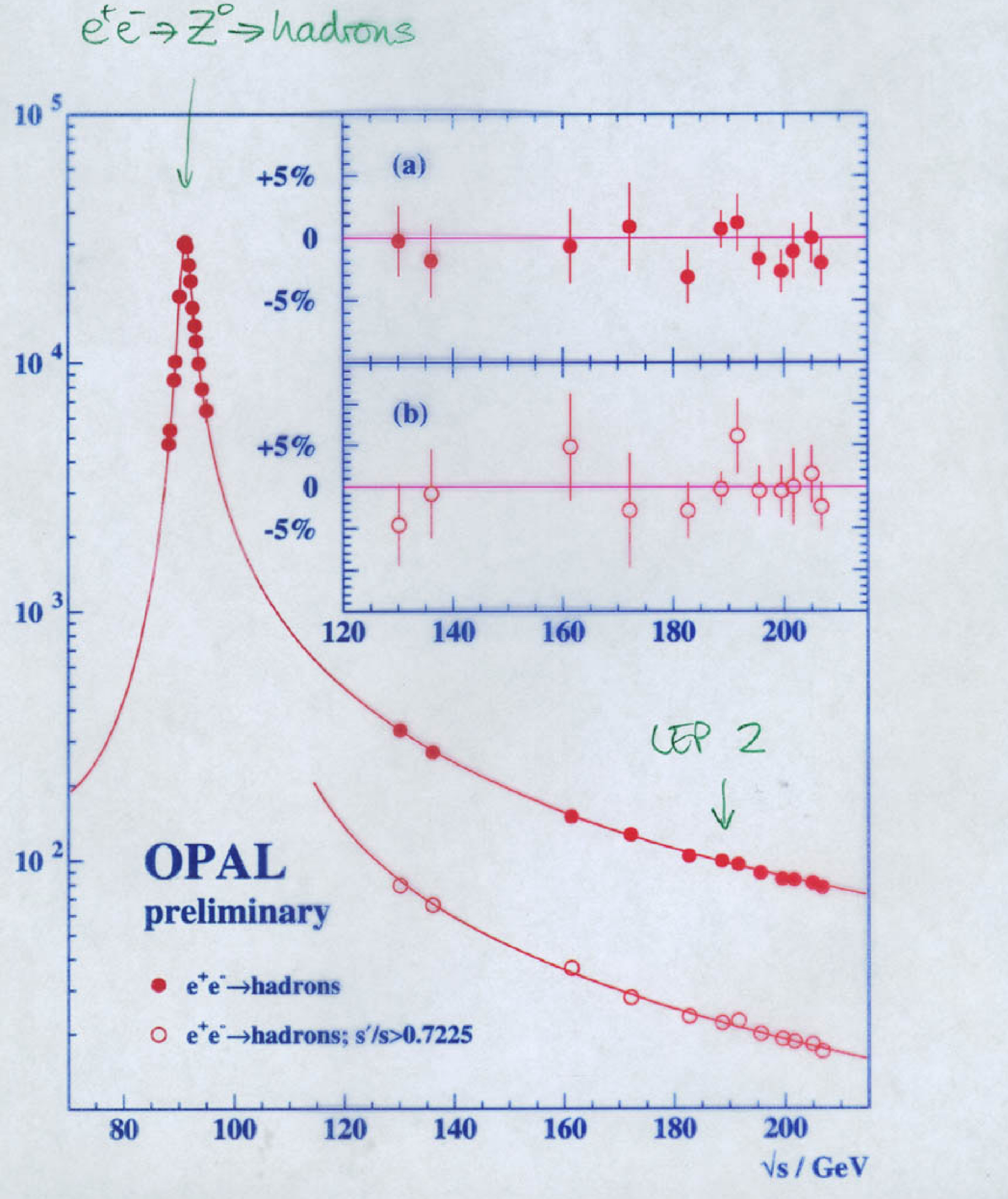
needs $\mathcal{L} \sim 10^{32} \times \left(\frac{5.0}{0.2}\right)^2 \simeq 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$

n'th generation factories: $\mathcal{L} \times 10^n$

The Standard Model of Particle Physics

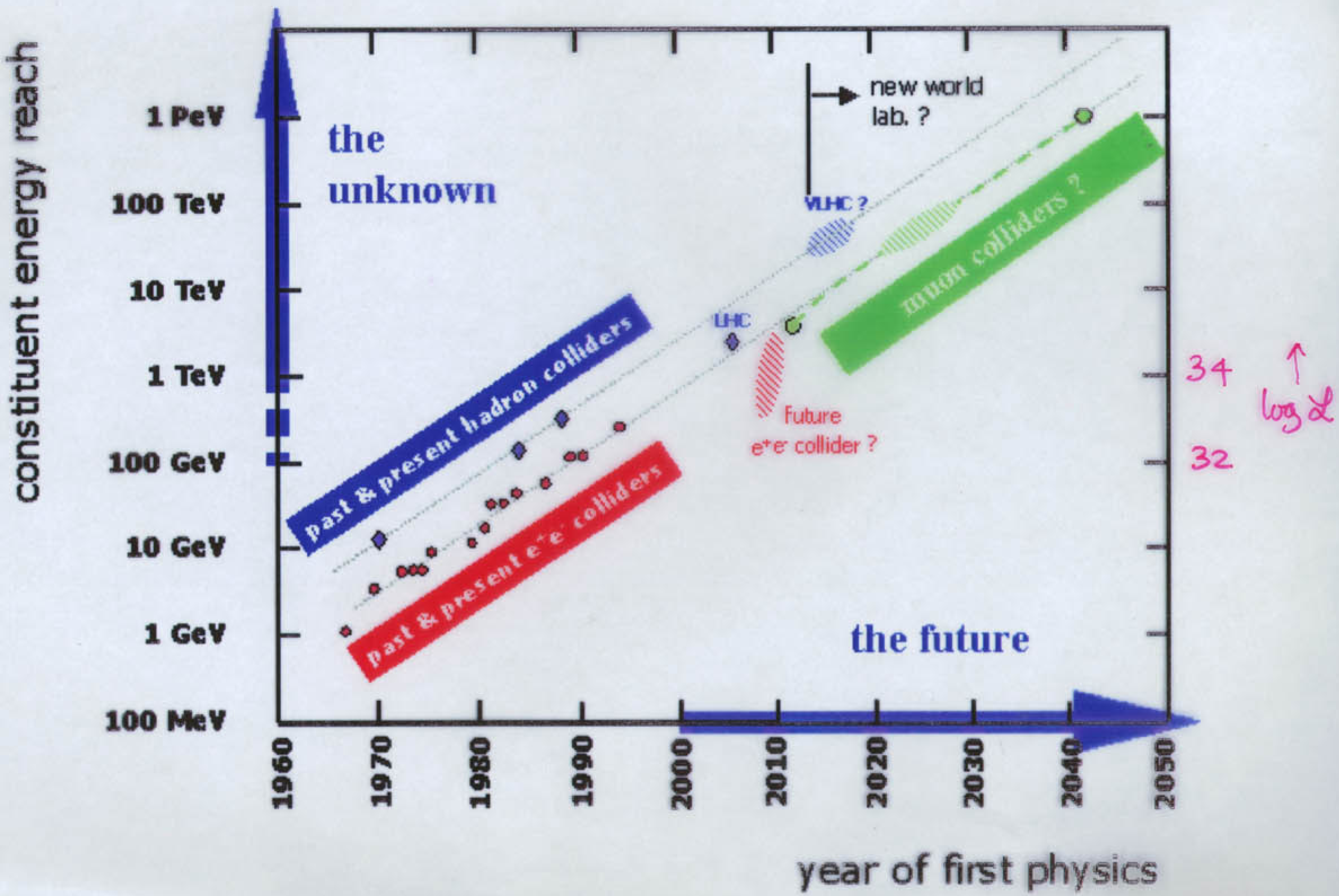
- Three generations of fermions make up matter
  6 quarks, electron + two heavier siblings, 3 neutrinos
- Four fundamental forces between them
  electromagnetic, strong, weak, gravity
- All carried by messenger particles
  photon, gluons, W & Z, graviton (?)
- Massless: photon, gluon, graviton
- Massive: quarks, electrons, W & Z Why ? How ?

Verification du Modèle Standard



Sounds great, but …

- Where do the masses come from?
- Are the fundamental forces unified?
- Why so many different types of particles?
- How to explain all the parameters?
  6 quark masses, 3 lepton masses, 2 boson masses, 4 weak mixing angles and phases, 3 gauge couplings, 1 strong CP phase
- 19 + neutrino masses, mixing angles, …



constituent energy reach
1 PeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
the unknown
new world lab. ?
VLHC ?
LHC
muon colliders ?
past & present hadron colliders
past & present e⁺e⁻ colliders
future e⁺e⁻ collider ?
the future
34
32
log $\mathcal{L}$
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
year of first physics

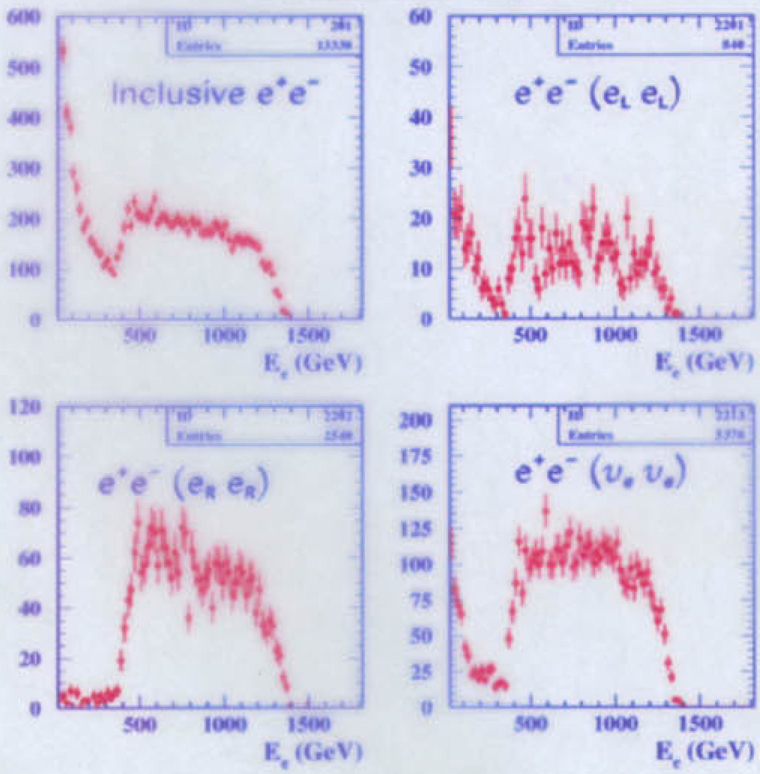
SUSY

Case Study: sneutrino pair production

sneutrino mass determination

E.G. $m_{1/2} = 300$ GeV, $m_0 = 1450$ GeV, $\tan\beta = 10$, $A = 0$ GeV, $sign(\mu) > 0$ (mSUGRA) (KM1)

CLIC beamstrahlung (10^{35})



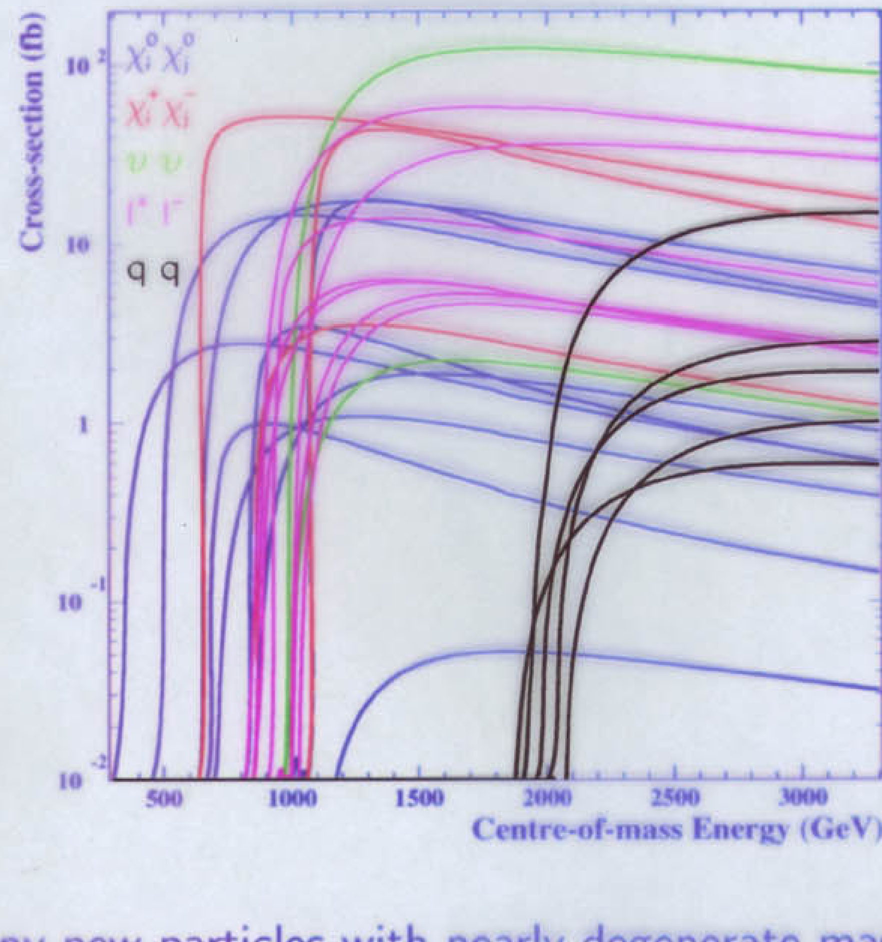
Signal $\tilde{\nu}_e\tilde{\nu}_e \to e^+\tilde{\chi}_1^- e^-\chi_1^+(180)$

Typical 'box' shape of the signal preserved in CLIC environement

SUSY

Particle pair thresholds

$m_{1/2} = 400$ GeV, $m_0 = 400$ GeV, $\tan\beta = 35$,
$A = -400$ GeV, $sign(\mu) < 0$ (mSUGRA)

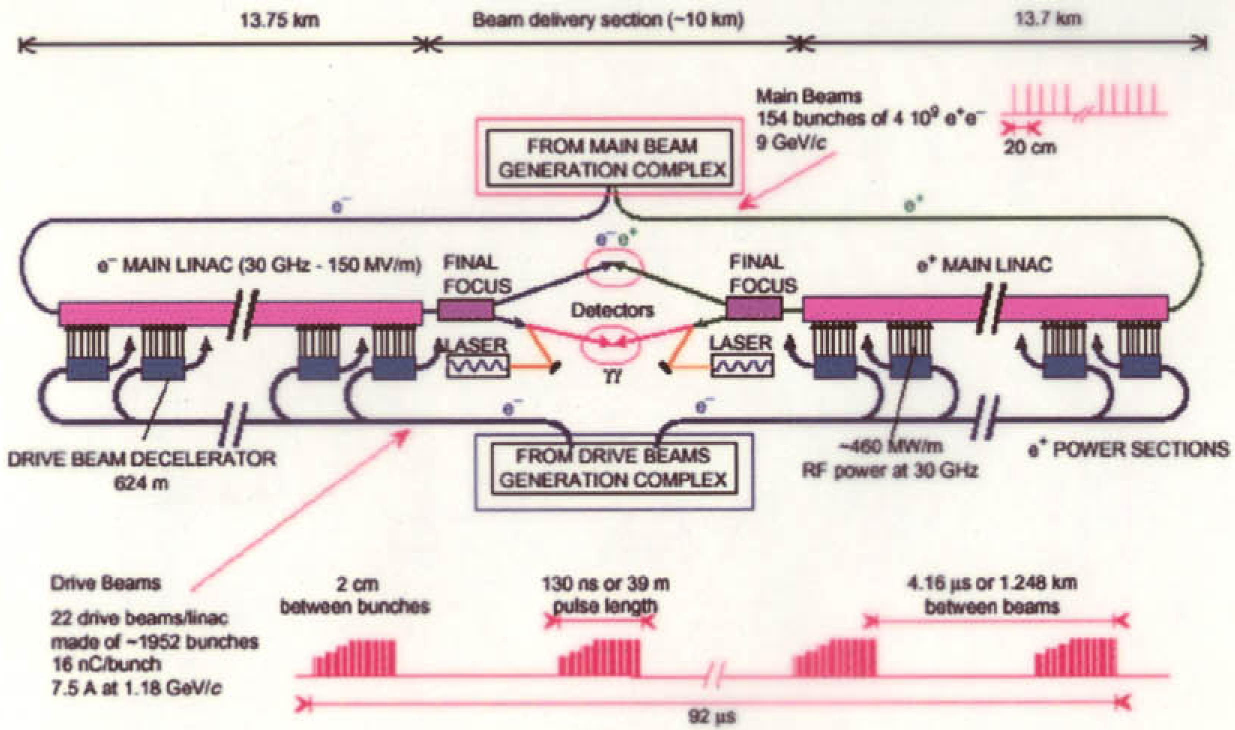


Many new particles with nearly degenerate masses

CLIC Parameters

Beam param. at I.P. E_{CM} =	0.5 TeV	1 TeV	3 TeV	5 TeV
Luminosity ($10^{34}cm^{-1}s^{-1}$)	0.5	1.1	10.6	14.9
Mean energy loss (%)	3.6	9.2	32	40
Photons /electrons	0.8	1.1	2.2	2.6
Rep. Rate (Hz)	200	150	75	50
10^9 $e^{\pm}$ / bunch	4	4	4	4
Bunches / pulse	150	150	150	150
Bunch spacing (cm)	20	20	20	20
H/V ε_n (10^{-8} rad.m)	188/10	148/7	60/1	58/1
Beam size (H/V) (nm)	196/4.5	123/2.7	40/0.6	27/0.45
Bunch length (μm)	50	50	30	25
Accel.gradient (MV/m)	100	100	150	200
Two linac length (km)	7	14	27.5	35
Power / section (MW)	116	116	231	386
RF to beam effic. (%)	35.5	35.5	26.6	19.4
AC to beam effic. (%)	14.2	14.2	10.6	7.8
AC power (MW)	68	102	206	310

CLIC Layout



13.75 km
Beam delivery section (~10 km)
13.7 km
Main Beams
154 bunches of 4 10⁹ e⁺e⁻
9 GeV/c
20 cm
FROM MAIN BEAM GENERATION COMPLEX
e⁻
e⁺
e⁻ e⁺
e⁻ MAIN LINAC (30 GHz - 150 MV/m)
FINAL FOCUS
FINAL FOCUS
e⁺ MAIN LINAC
Detectors
LASER
LASER
γγ
e⁻
e⁻
DRIVE BEAM DECELERATOR
624 m
FROM DRIVE BEAMS GENERATION COMPLEX
~460 MW/m
RF power at 30 GHz
e⁺ POWER SECTIONS
Drive Beams
22 drive beams/linac
made of ~1952 bunches
16 nC/bunch
7.5 A at 1.18 GeV/c
2 cm
between bunches
130 ns or 39 m
pulse length
4.16 µs or 1.248 km
between beams
92 µs

- We will need a LC
- Complementary to LHC

  exploration ⊕ precision
- Need widest possible energy range

  initial ⊕ extensions ⊕ back to Z/WW
- Should converge on single project

presume a LC in the ~ TeV E_{cm} range will be built

Linear Collider coverage of Supersymmetric dark matter region

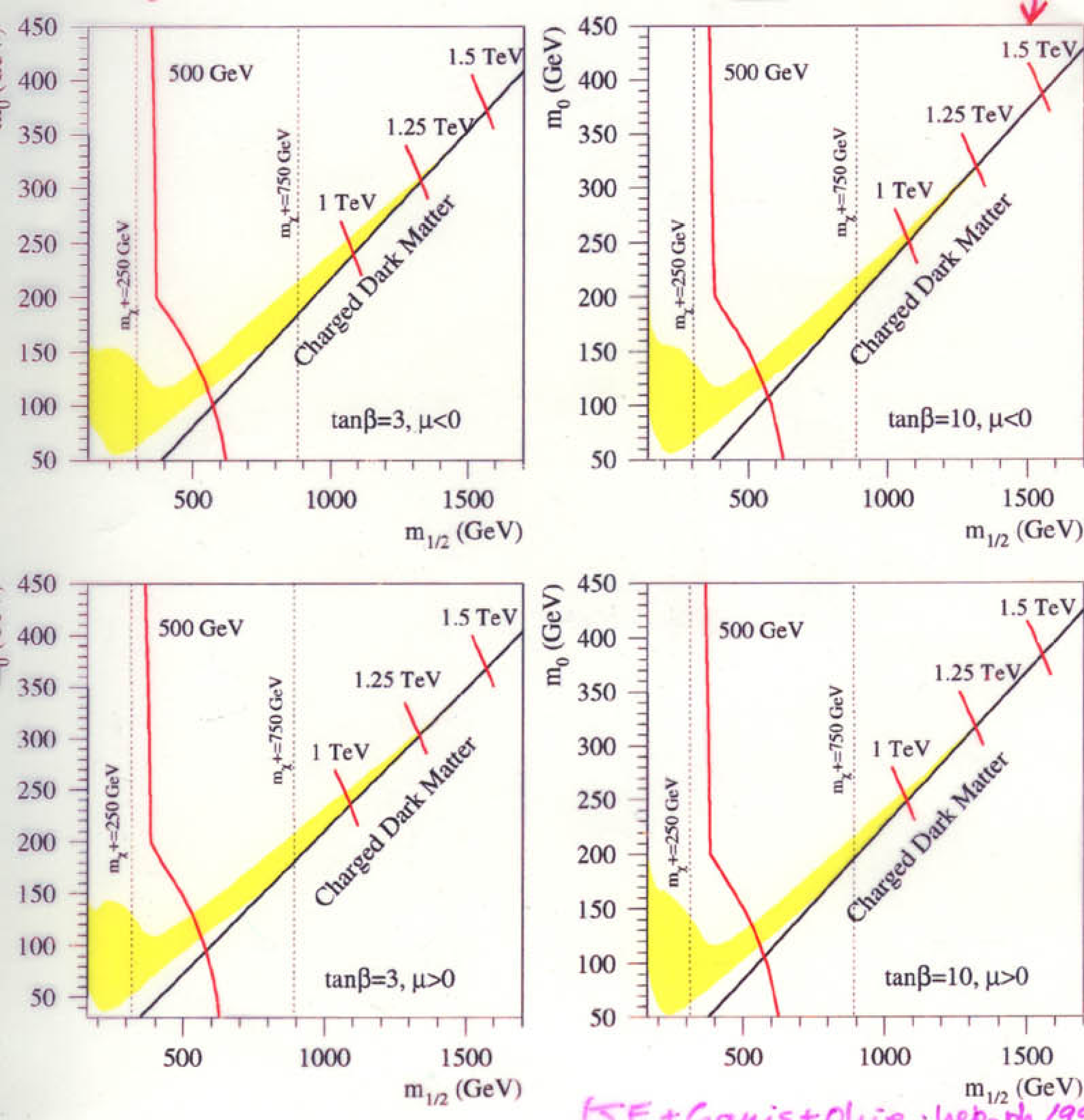
what E_{cm} is needed?

$\Omega h^2 \leq 0.3$

reach with $e^+e^- \to \chi\chi'$

reach with $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$

Cross section limit σ_{lim} = 1 fb



(J.E. + Ganis + Olive: hep-ph/9912324)

Expected Precision @ LC

$\tilde{\mu}_R \to \mu\chi$ $\tilde{\mu}_L \to \mu\chi_2$

$\tilde{\nu}_e \to e^{\mp}\chi^{\pm}$ $\chi^{\pm} \to q\bar{q}\chi$

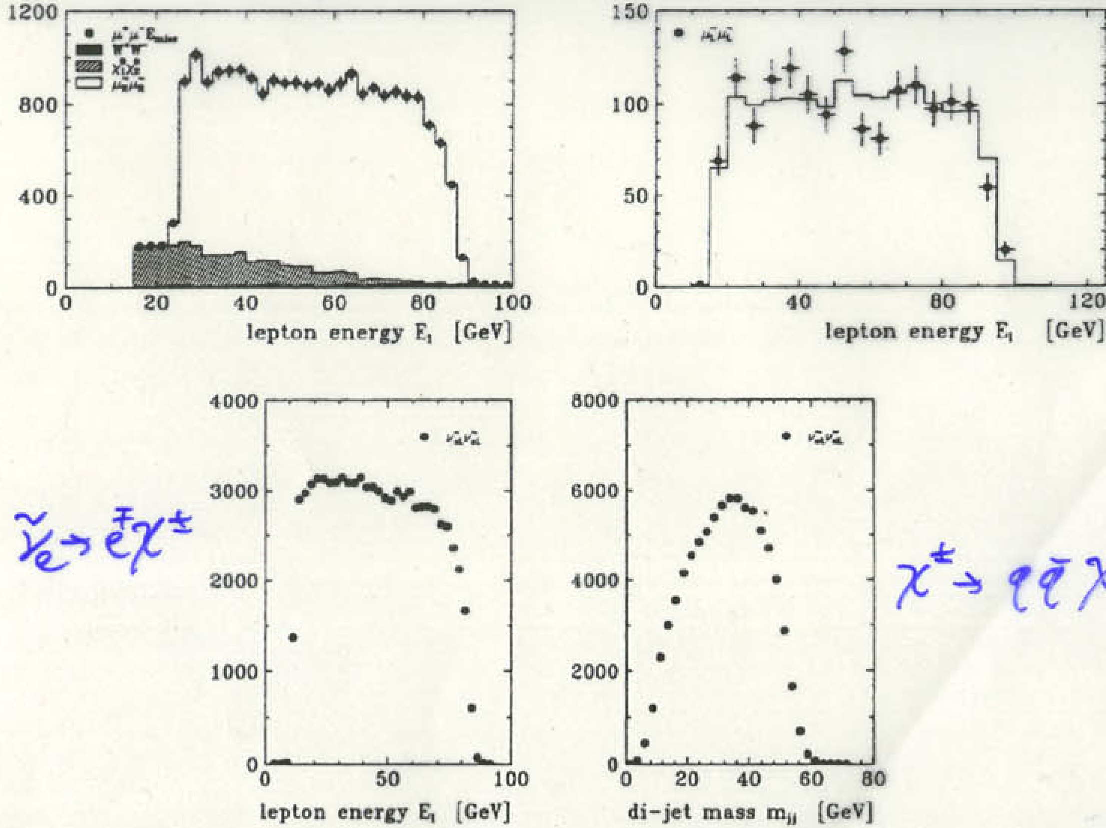
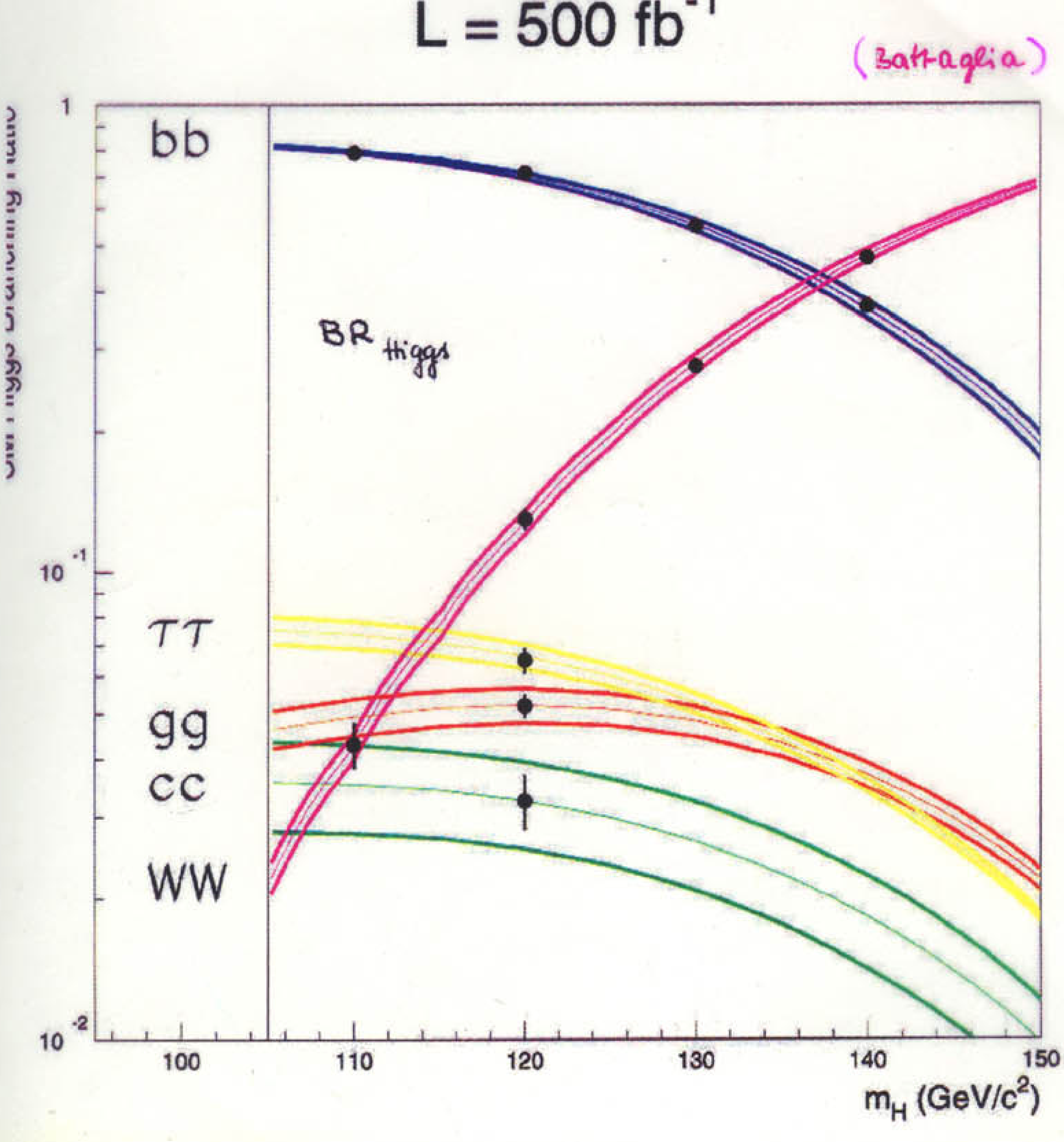


Figure 2: Examples of slepton production. Lepton energy spectra of $\tilde{\mu}_R \to \mu\chi_1^0$ at 320 GeV (upper left), $\tilde{\mu}_L \to \mu\chi_2^0$ at 500 GeV (upper right) and $\tilde{\nu}_e \to e^{\mp}\chi_1^{\pm}$ at 500 GeV (lower left). Di-jet mass spectrum of $\chi_1^{\pm} \to q\bar{q}'\chi_1^0$ (lower right).

(Blair + Martyn

Accurate Measurements of Higgs Decays

@ an e^+e^- linear collider



4- e^+e^- Linear Collider Physics

- very clean experimental environment
- egalitarian production of new weakly-interacting particles
- polarization
- $e\gamma$, $\gamma\gamma$, e^-e^- colliders "for free"
- complementary to LHC

what energy scale?

$2m_t$? $m_Z + m_H$? $2\tilde{m}$?

(m_H ↑ estimated) ($\tilde{m}$ ↑ unknown)

how/when to fix energy scale?

- flexibility essential

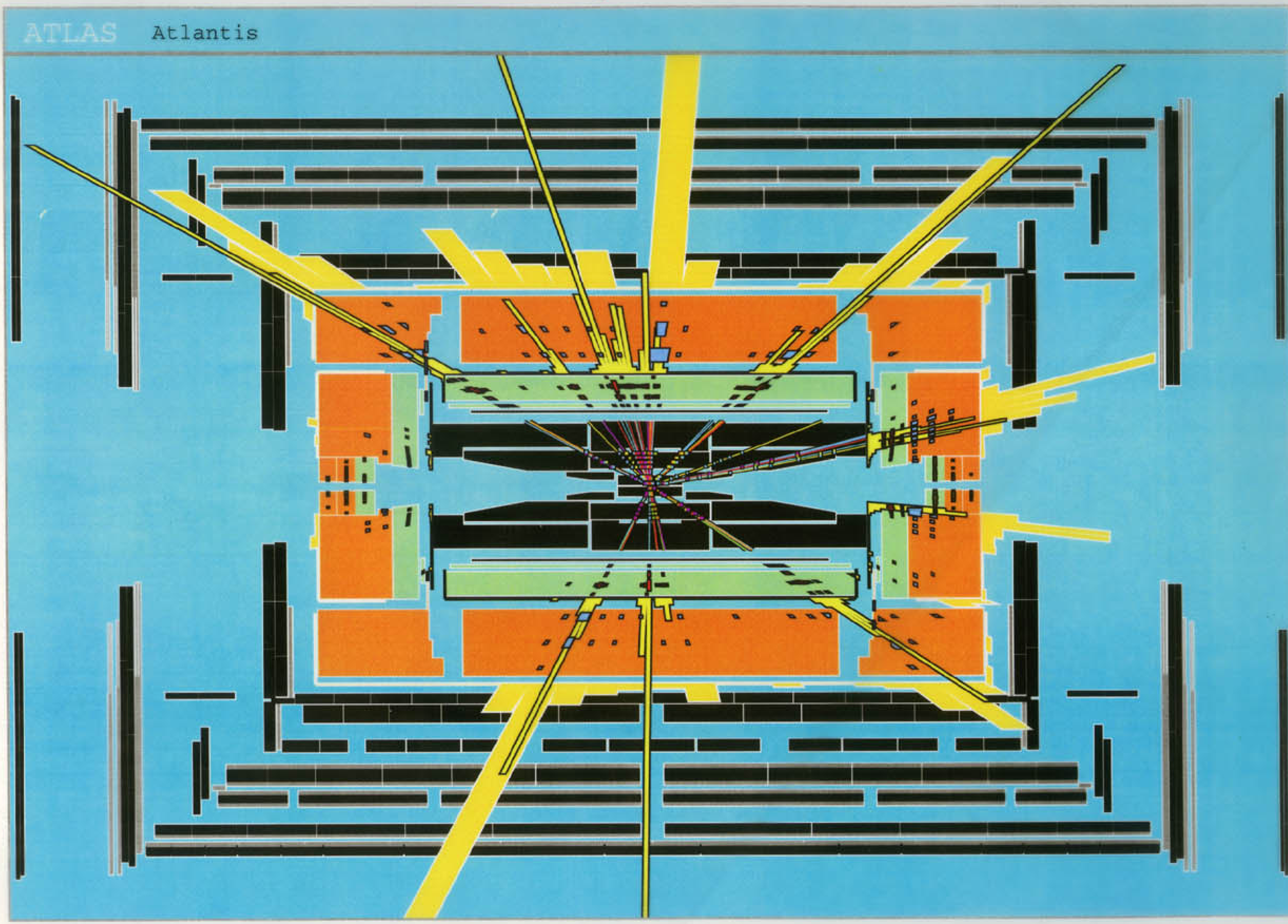
$m_Z, 2m_W \longleftarrow ?$ $\longrightarrow$ 2 TeV

m_Z ↑ 10^9 polarized Z?

$2m_W$ ↑ δm_W

2 TeV ↑ for reach comparable to LHC

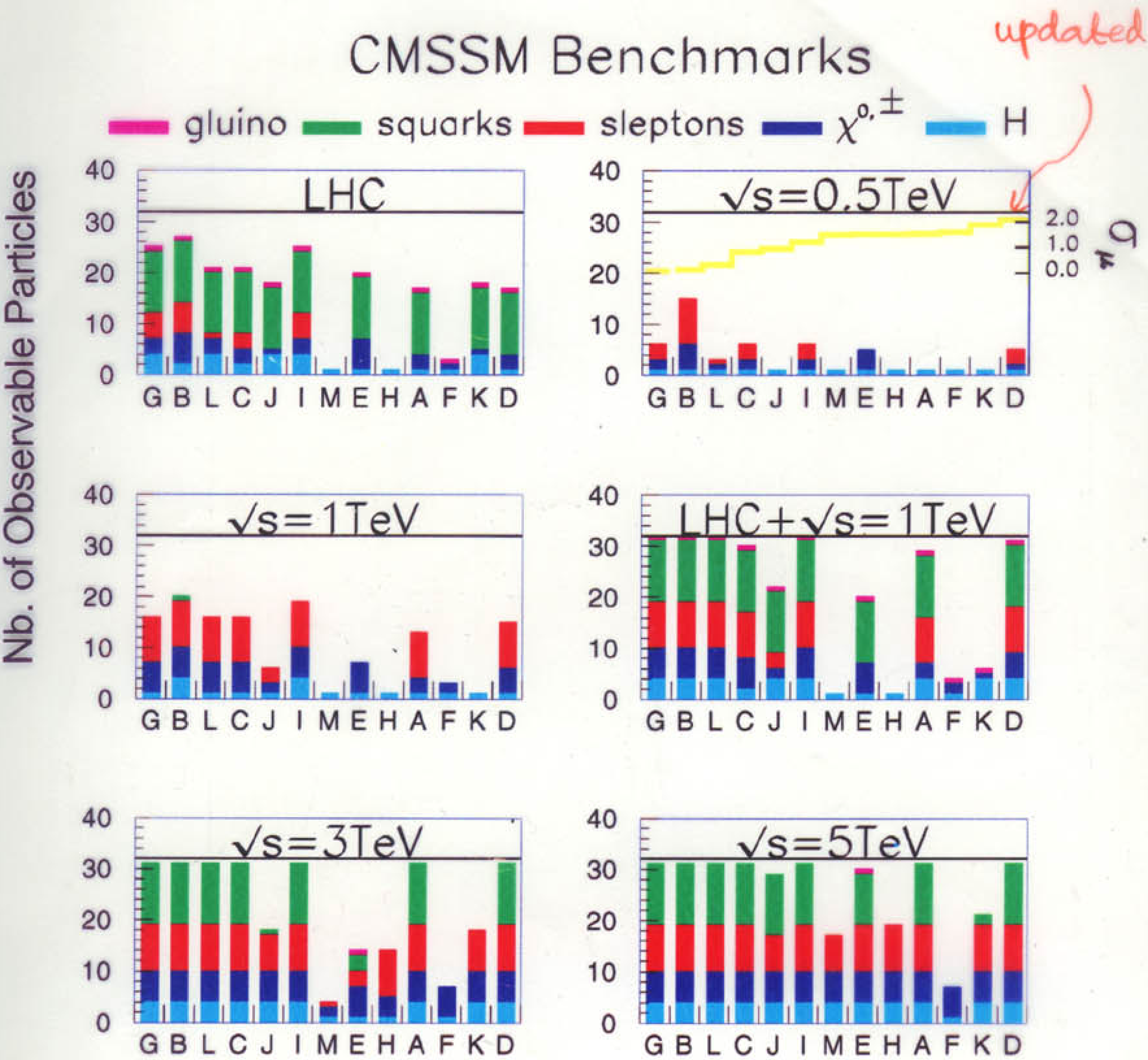
Black hole production at LHC?



Observability of Supersymmetry

(Battaglia et al. : hep-ph/0106204

with future accelerators



Superrsymmetry @ LHC

GEANT figure

mSUGRA : $m_0 = 1000$ GeV, $m_{1/2} = 500$ GeV, $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$

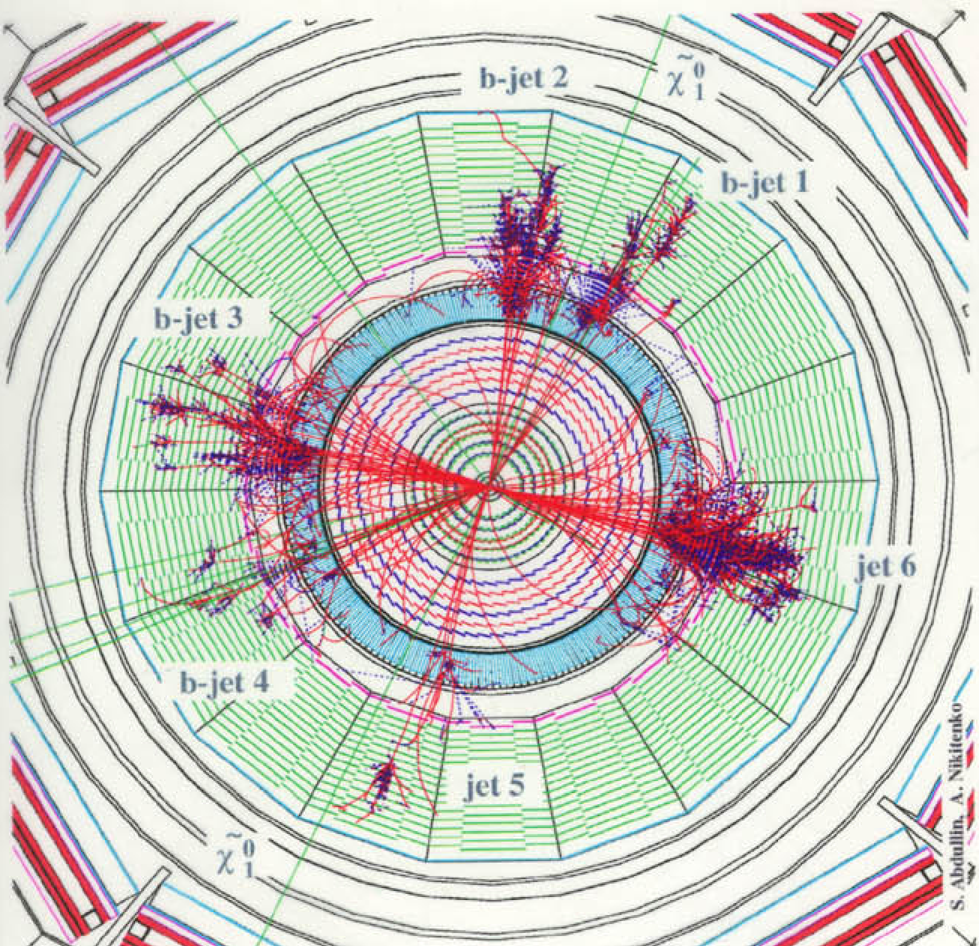
$\tilde{g} \rightarrow \tilde{t}_1 \bar{t}$

- $\bar{t} \rightarrow W^- + \bar{b}$ (jet4, E_T = 113 GeV)
  - $W^- \rightarrow s$ (jet5, E_T = 79 GeV) + $\bar{c}$
- $\tilde{t}_1 \rightarrow \tilde{\chi}_2^+ + b$ (jet3, E_T = 536 GeV)
  - $\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^+ + Z \rightarrow \nu \bar{\nu}$
    - $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + W^+ \rightarrow \tau^+ \nu$
      - $\tau^+ \rightarrow e^+ \nu$

$\tilde{u}_L \rightarrow \tilde{\chi}_2^0 + u$ (jet6, E_T = 1196 GeV)

- $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h$
  - $h \rightarrow b$ (jet1, E_T = 206 GeV)
  - $h \rightarrow \bar{b}$ (jet2, E_T = 320 GeV)

$E_T^{miss} = 380$ GeV



$m_{\tilde{g}}$ = 1266 GeV

$m_{\tilde{u}_L}$ = 1450 GeV

$m_{\tilde{t}_1}$ = 1026 GeV

$m_{\tilde{\chi}_2^0}$ = 410 GeV

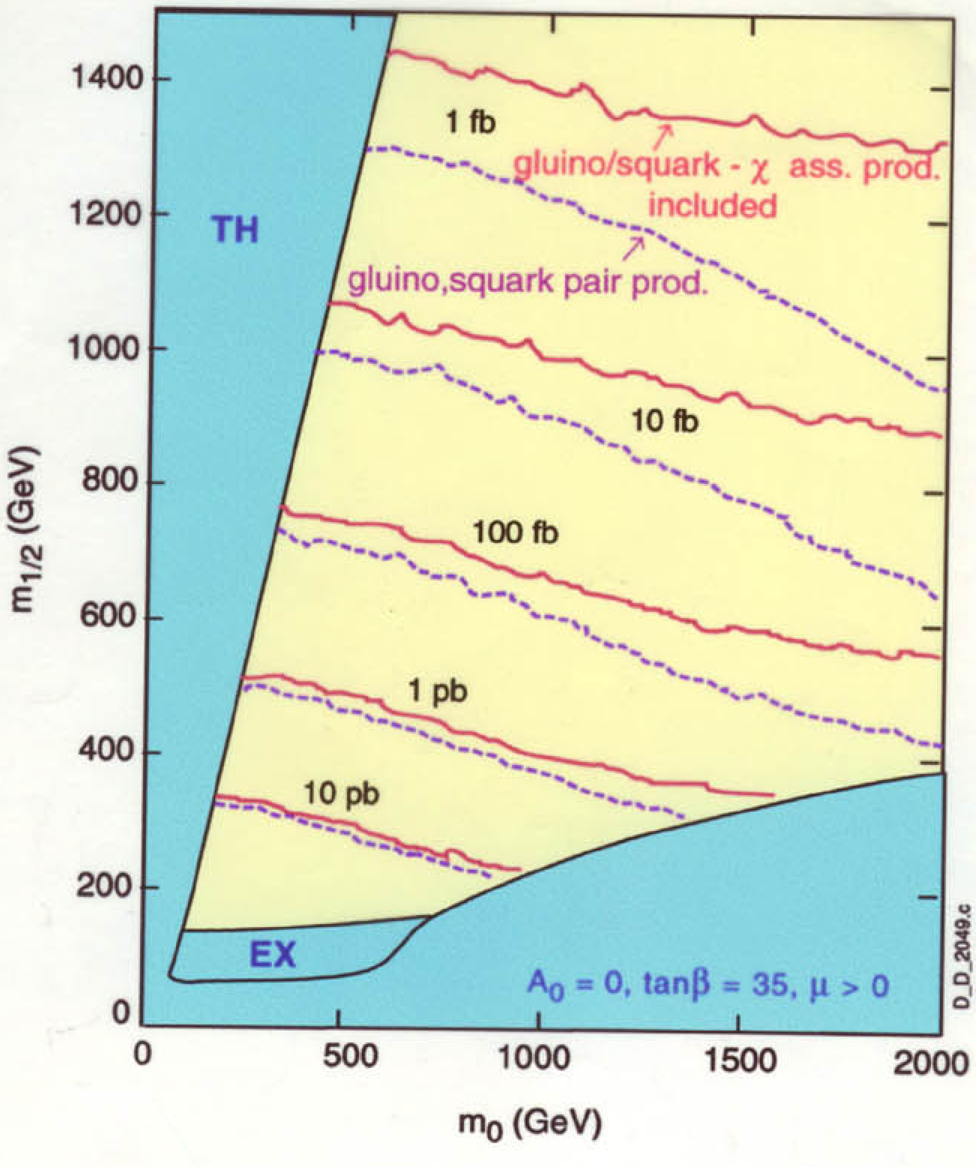
$m_{\tilde{\chi}_1^0}$ = 214 GeV

m_h = 119 GeV

S. Abdullin

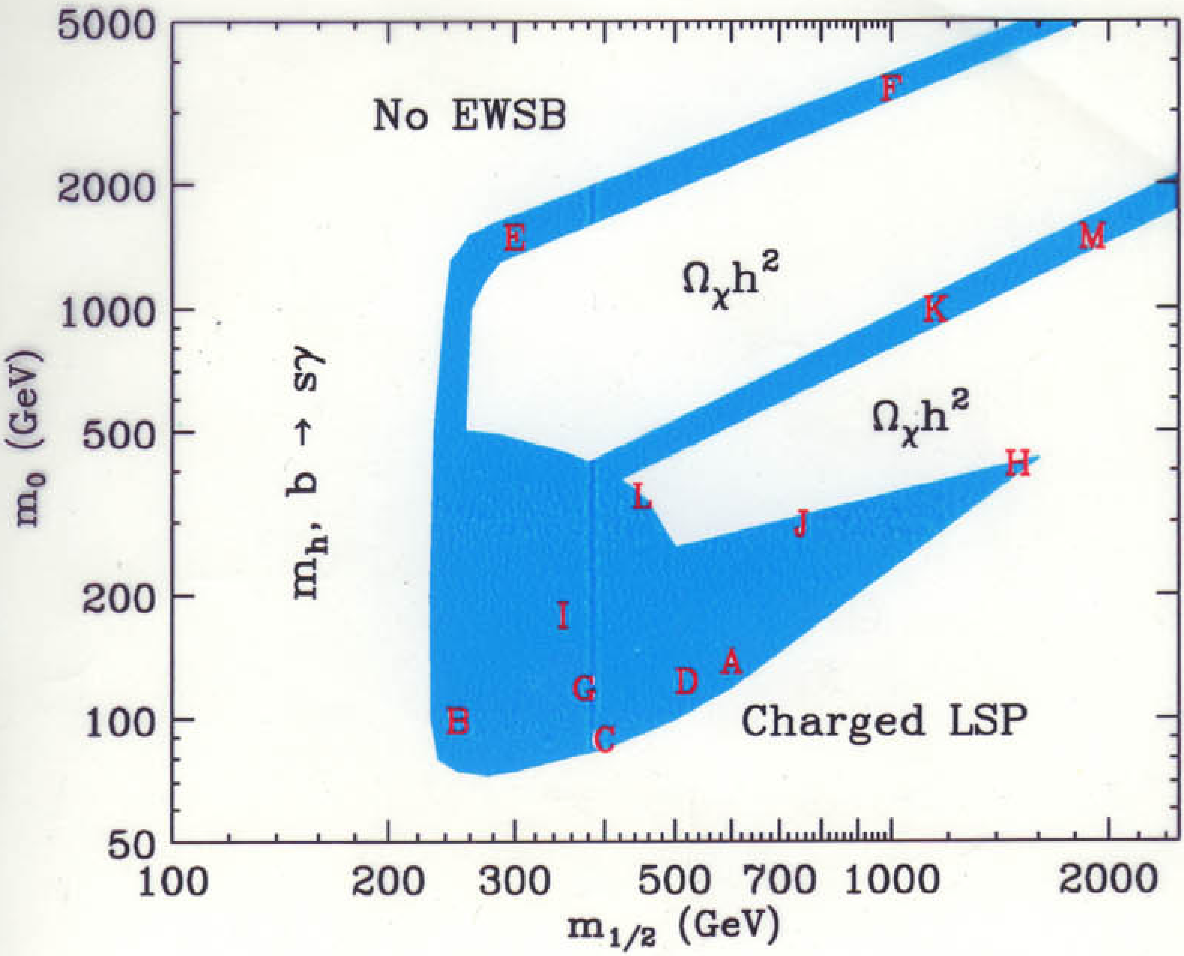
Oct.2000

SUSY total cross sections (mSUGRA)



3- Benchmark Supersymmetric Scenarios

illustrated range of allowed possibilities



(Battaglia + De Roeck + J.E. + Gianotti + Matchev + Olive + Pape + Wilson

Benchmark Supersymmetric Scenarios

- Compatible with all accelerator constraints:

LEP searches, Higgs, b to s gamma, …

- Allowed cosmological relic density

→ Baseline for comparing future accelerators:

LHC and Linear Collider (TESLA, NLC, JLC)

Supersymmetric Parameter Space

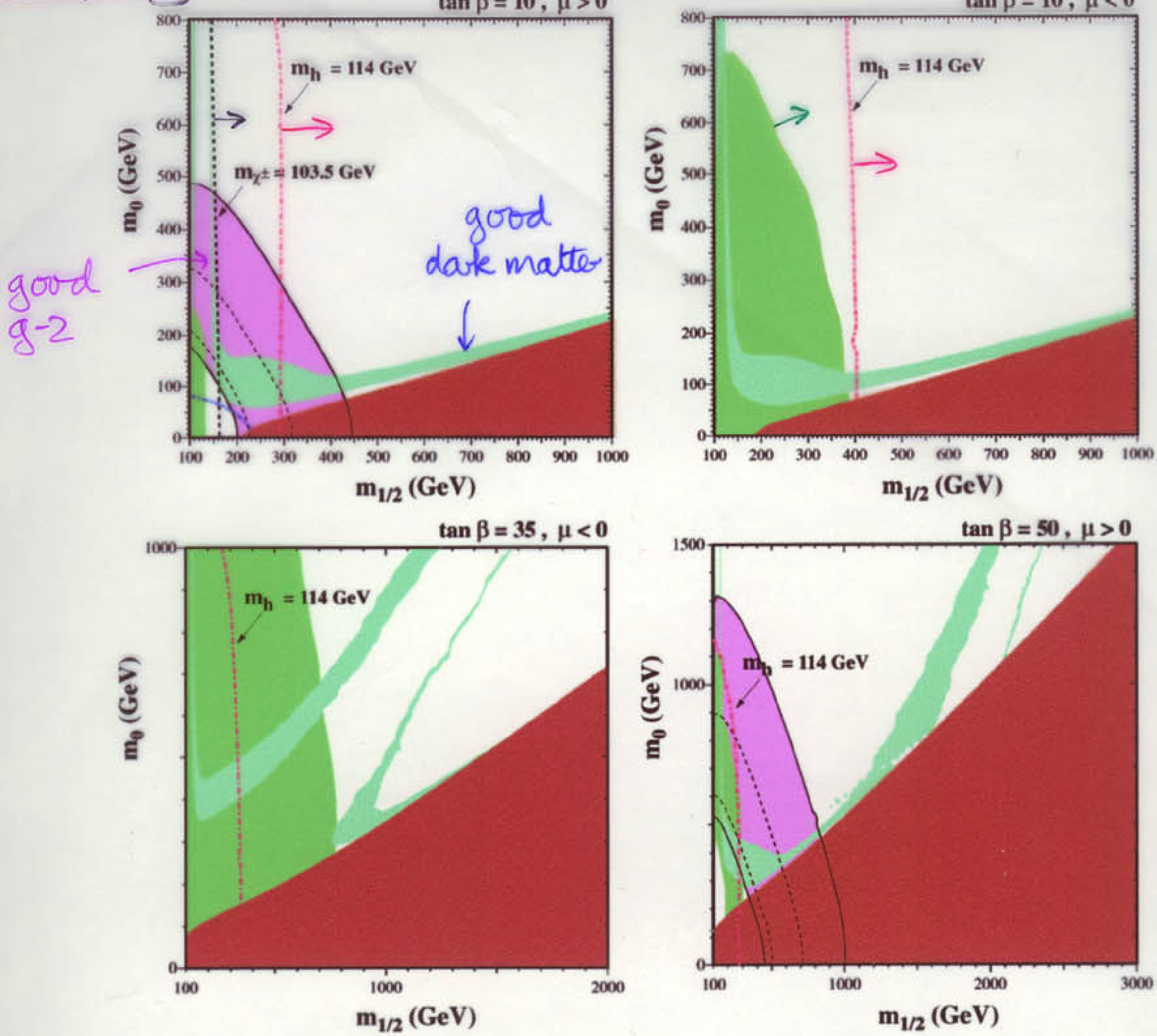
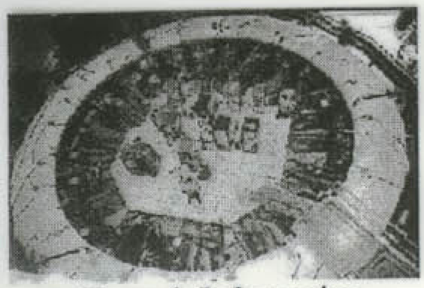


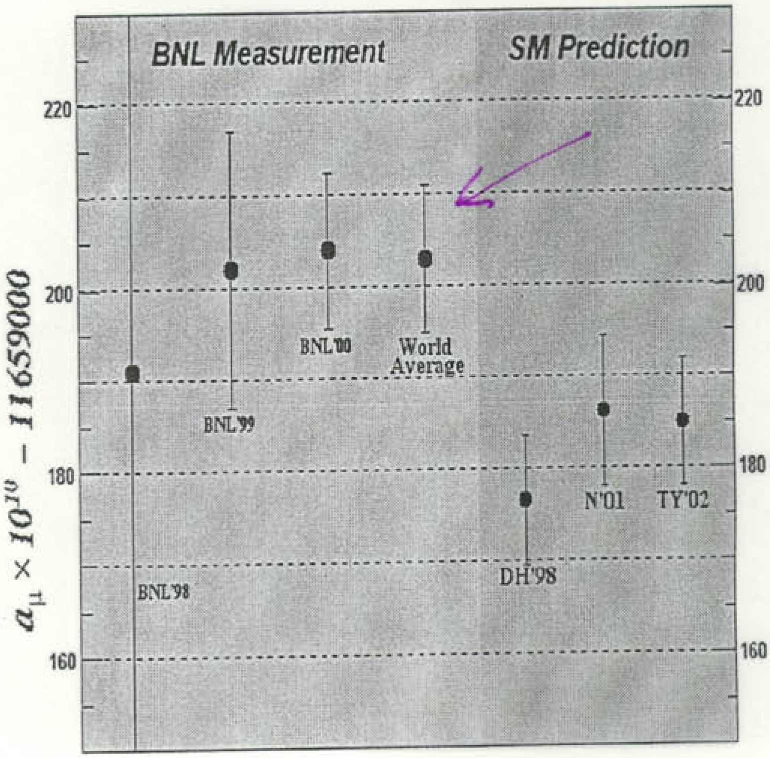
Figure 1: *The* $(m_{1/2}, m_0)$ *planes for (a)* $\tan\beta = 10$ *and* $\mu > 0$, *(b)* $\tan\beta = 10$ *and* $\mu < 0$, *(c)* $\tan\beta = 35$ *and* $\mu < 0$ *and (d)* $\tan\beta = 50$ *and* $\mu > 0$, *assuming* $A = 0, m_t = 175$ *GeV and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV. The near-vertical (red) dot-dashed lines are the contours* $m_h = 114.4$ *GeV as calculated using* `FeynHiggs` *[?], and the near-vertical (black) dashed line in panel (a) is the contour* $m_{\chi^\pm} = 103.5$ *GeV. The medium (dark green) shaded regions are excluded by* $b \to s\gamma$, *and the light (turquoise) shaded areas are the cosmologically preferred regions with* $0.1 \leq \Omega_{\tilde{\chi}} h^2 \leq 0.3$. *In the dark (brick red) shaded regions, the LSP is the charged* $\tilde{\tau}_1$, *so this region is excluded. The regions allowed by the E821 measurement of* a_μ *at the 2-*σ *level, as discussed in the text, are shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-*σ *ranges.*



The E821 Muon (g-2) Home

The new muon (g-2) value was announce[d] 2002!

$a_{\mu^+}(BNL'00) = 11\,659\,204\,(7)\,(4) \times 10^{-10}$ (0.7 ppm)



References:

- BNL'98 PRL 86 2227
- BNL'99 PR 62D 091101
- BNL'00 to be publ.
- DH'98 PL 435B 427 (LOL corr.)
- N'01 PL 513B 53
- TY'02 PR 65D 093001

Experimental constraints

no sparticles seen: $m_{\chi^\pm} \gtrsim 104\,\text{GeV}$

spartner of $W^\pm/H^\pm$ →

$m_{\tilde{e}} \gtrsim 100\,\text{GeV}$

also squarks, gluinos, ...

no Higgs seen: $m_H > 114.4\,\text{GeV}$

sensitive to sparticle masses:

$$\delta m_H^2 \propto \frac{m_t^4}{m_W^2} \ln\left(\tilde{m}^2/m_t^2\right)$$

$b \to s\gamma$ decay:

agreement with Standard Model limits sparticle loop contributions

$(g-2)_\mu$:

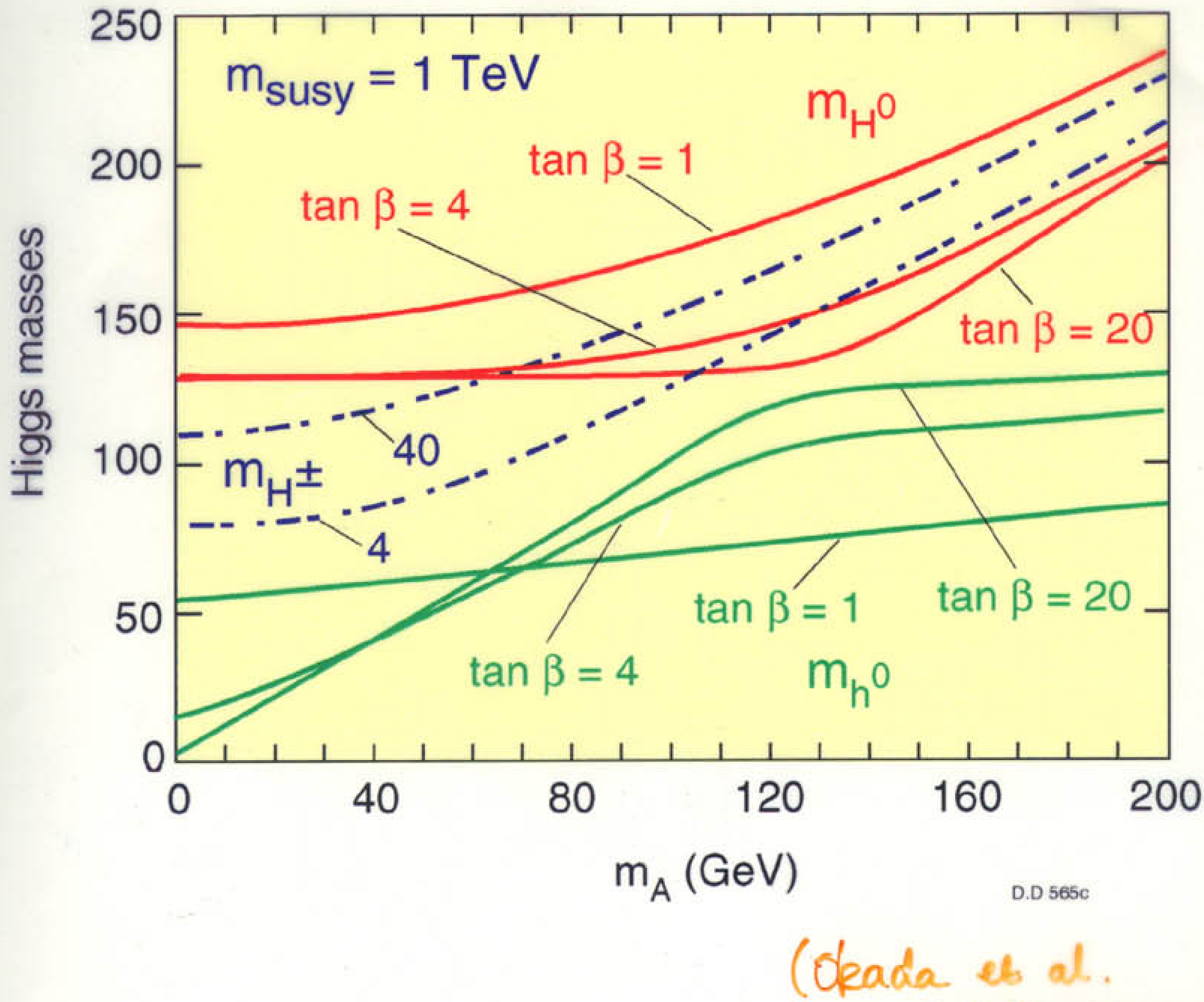
consistent with MSSM:

is discrepancy significant?

cosmological relic density

Higgs Masses in Supersymmetry

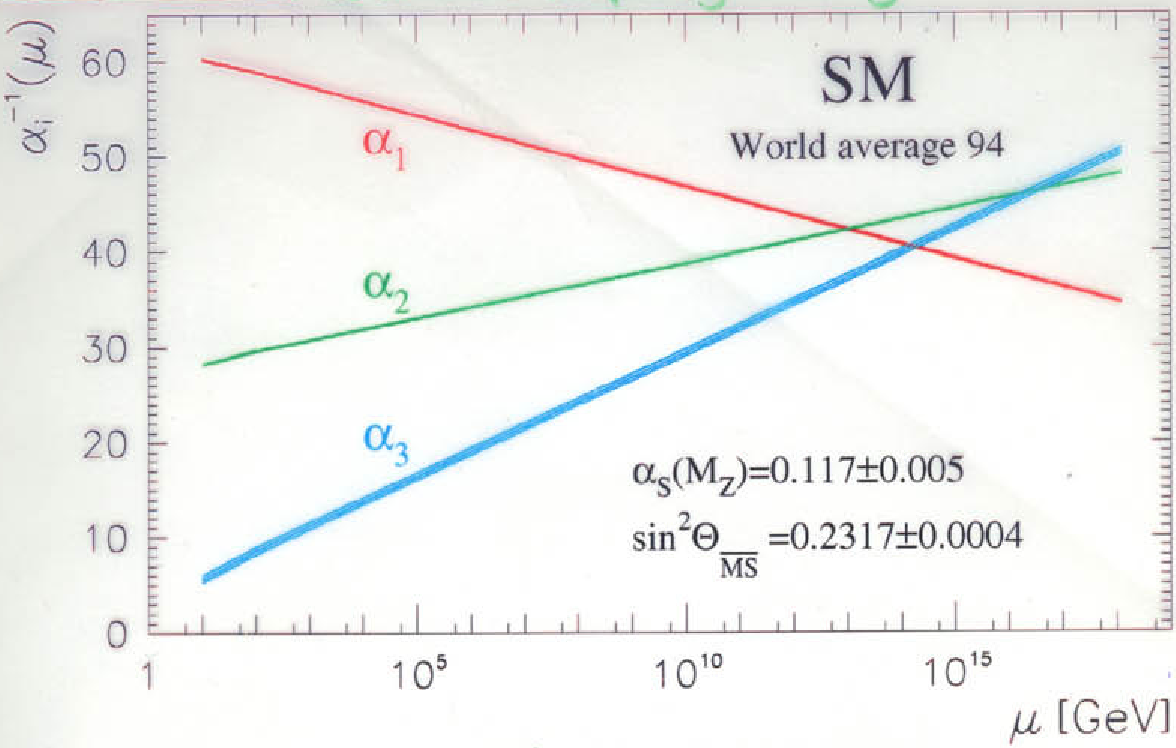
$m_{h,\ H,\ H^\pm}$ versus m_A, for various tg β
and M_{top} = 174 GeV



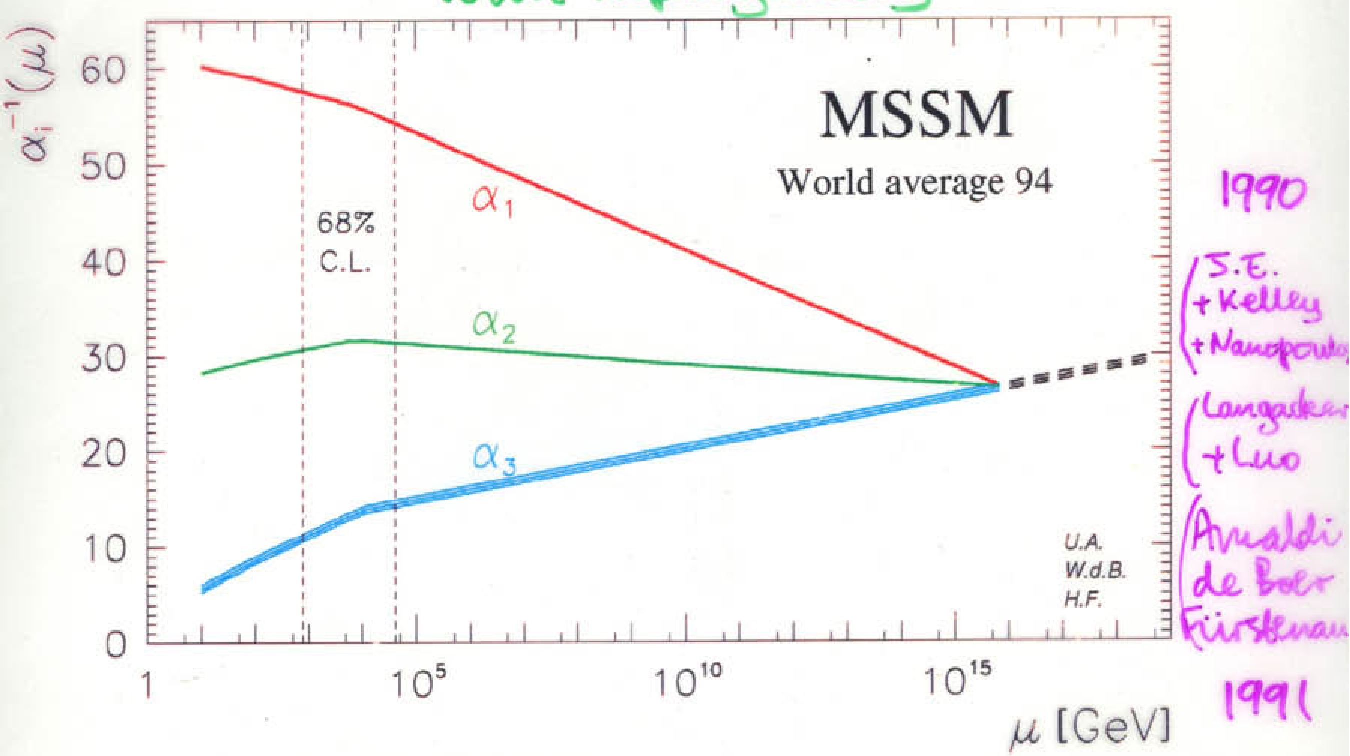
D.D 565c

(Okada et al.
(J.E. + Ridolfi + Zwirner
(Haber + Hempfling

Unification? without supersymmetry



with supersymmetry



Glasgow HEP Conference 1994 :

$M_S=10^{3.7\pm0.8\pm0.4}$ GeV $\quad M_U=10^{15.9\pm0.2\pm0.1}$ GeV

return to this later!

Why Supersymmetry?

Hierarchy Problem:

why is $m_W \ll m_P$? ← energy : gravity ~ other forces : $m_P \sim 10^{19}$ GeV

alternatively

why is $G_F \gg G_N$? $\frac{1}{m_W^2} \sim 10^{34} \times \frac{1}{m_P^2}$

or

why is $V_{Coulomb} \gg V_{Newton}$? $e^2 \gg G_N m^2 \sim m^2/m_P^2$

Set by hand?

what about quantum corrections?

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right) \Lambda^2 \gg m_W^2$$

↑ cut off $\Lambda \sim m_P$?

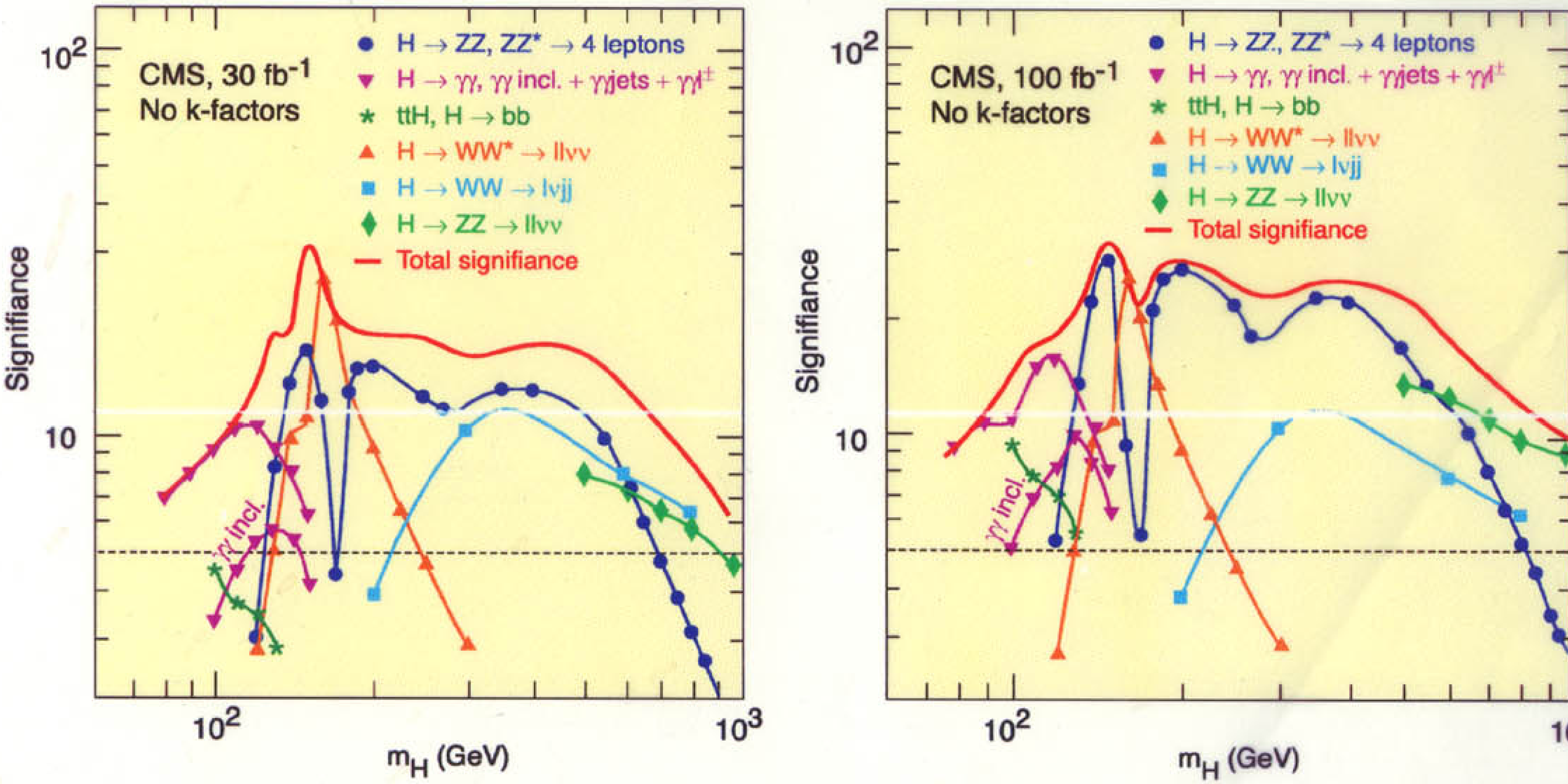
made **naturally** small by supersymmetry:

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)(m_B^2 - m_F^2)$$

$$\lesssim m^2_{H,W} \quad \text{if} \quad |m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2$$

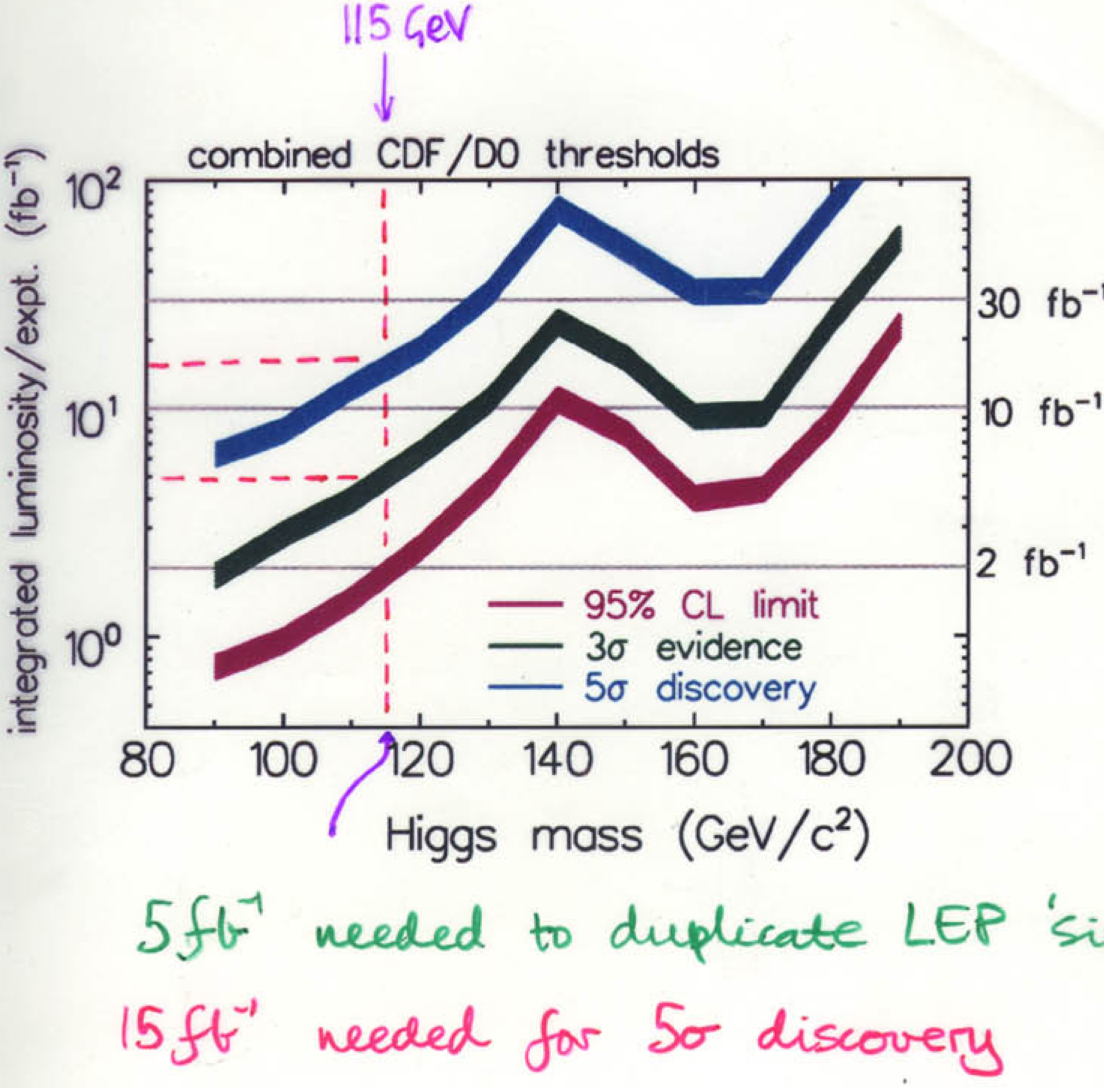
↑ low-energy supersymmetry

CMS discovery potential for SM Higgs



LMC Higgs event

Prospects for the Tevatron Collider



5 fb^{-1} needed to duplicate LEP 'signal'

15 fb^{-1} needed for 5σ discovery

(Tevatron Higgs Working Group

Where do we go from here?

Prospects for Higgs Discovery

Tevatron — will have chance if $m_H = 115\,GeV$

if heavier?

not before 2007?

LHC — will discover it @ any mass

will observe 2 or 3 decay modes

measure mass to ~ 1%

cover MSSM parameter space

↘ several times?

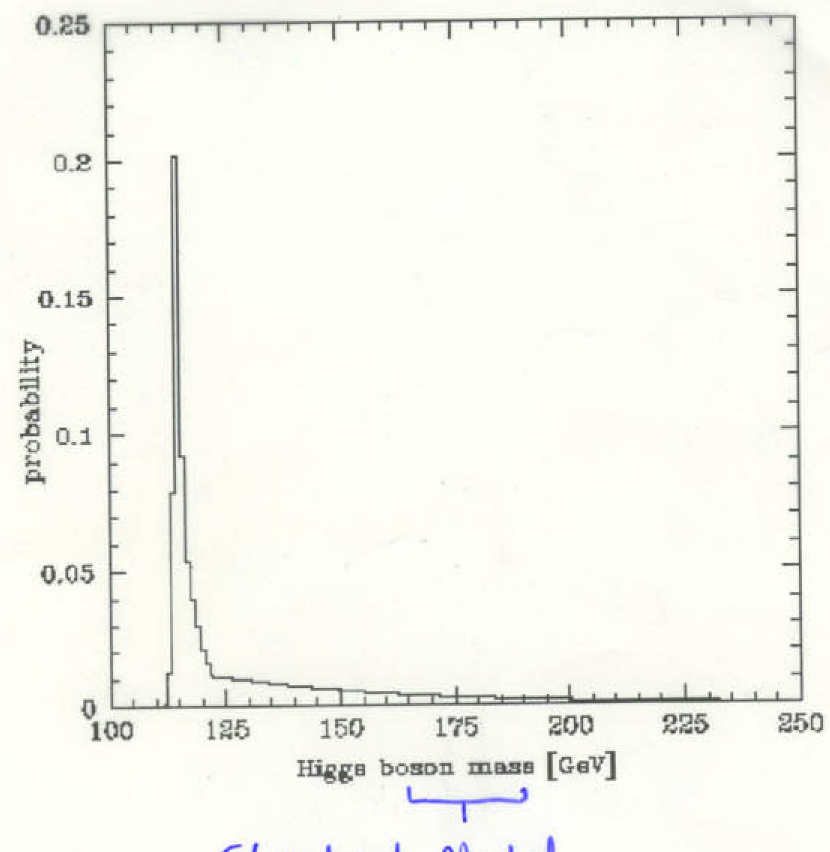
new analysis including LEP, universality, cosmology

measure MSSM parameters?

Probability Distribution for Higgs Mass

combining precision measurements

⊕ direct limits



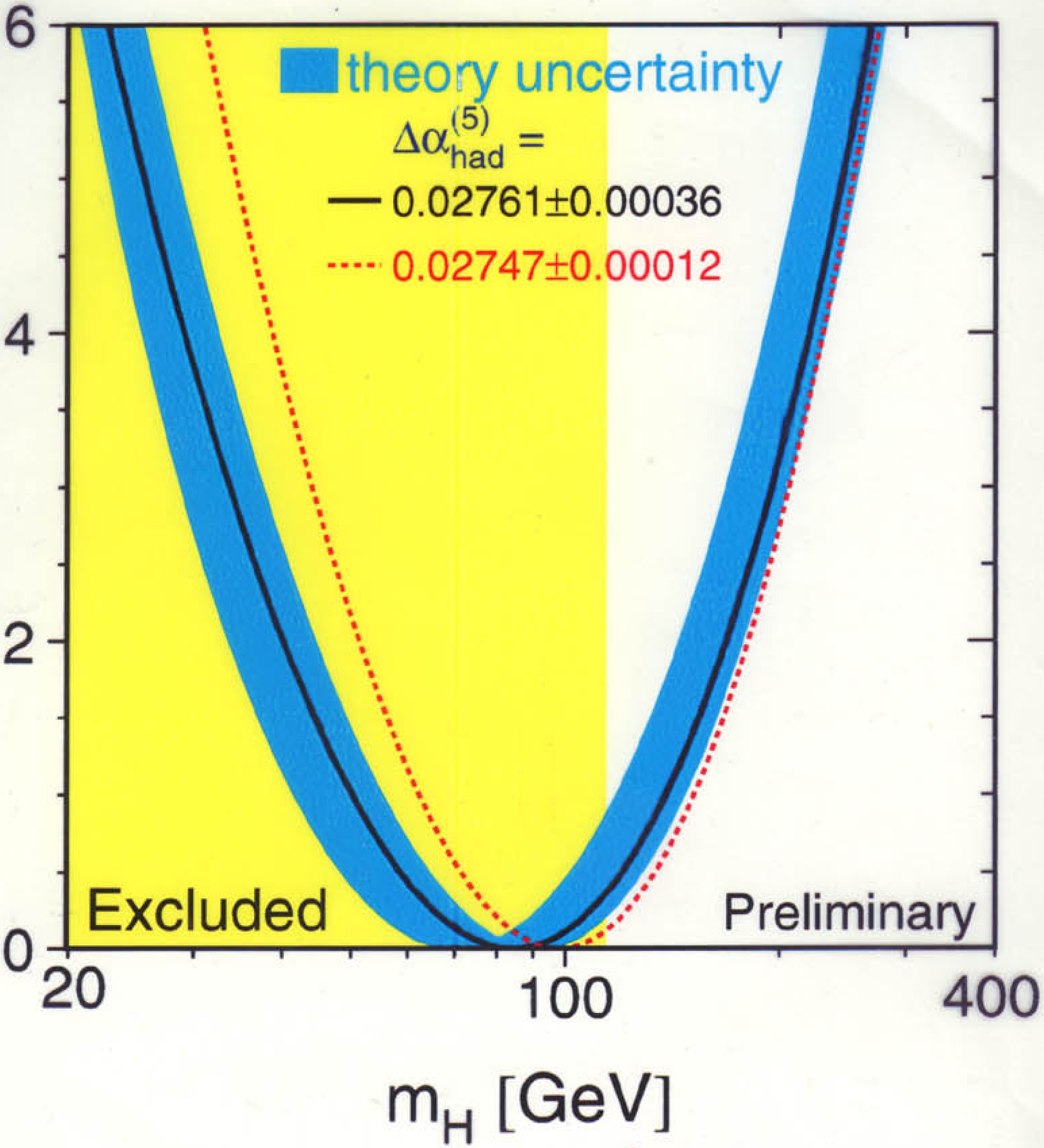
(Erler: hep-ph/0010153

Precision Electroweak Data

favour a light Higgs boson

$m_H < 199$ GeV @ 99% c.l.

~ 115 GeV 'most likely'



(LEP EWWG

The Higgs Boson

massless vector particles have

e.g., the photon — 2 polarization states

$\lambda = -1, +1$

massive vector particles have

e.g., the $W^{\pm}, Z^0$ — 3 polarization states

$\lambda = -1, 0, +1$

in order to acquire mass, $W^{\pm}, Z^0$ must combine with spin-0 field states

(Higgs, Brout + Englert

minimal Higgs model

complex Higgs doublet $\Rightarrow$ 4 states

3 eaten by the $W^{\pm}, Z^0$

1 physical state: Higgs boson

known couplings: $g_{Hff} \propto m_f$

unknown mass: $m_H > 114.4$ GeV (LEP