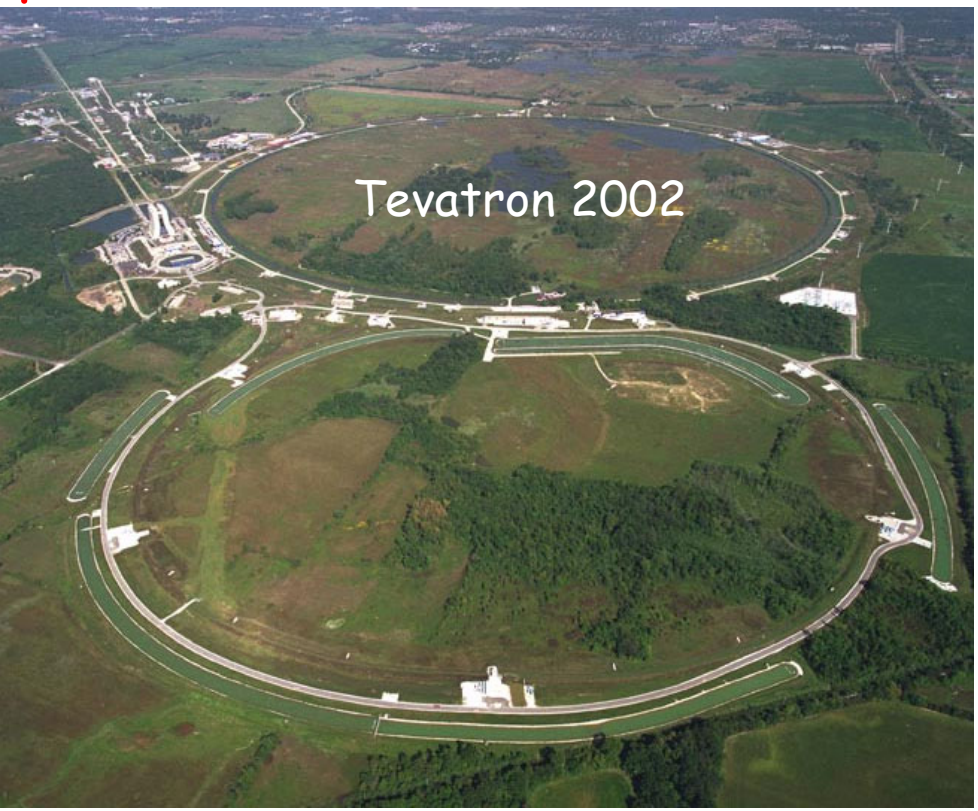
Thomas Hebbeker, RWTH Aachen

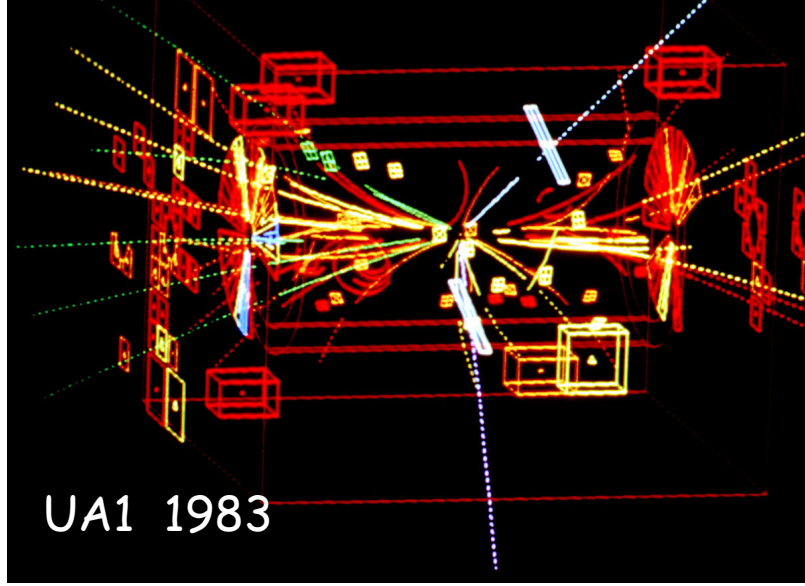
Belgian-Dutch-German school

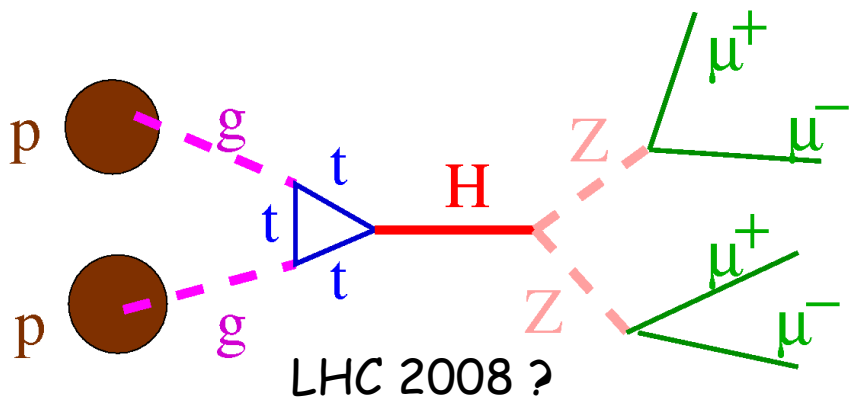
September 2003

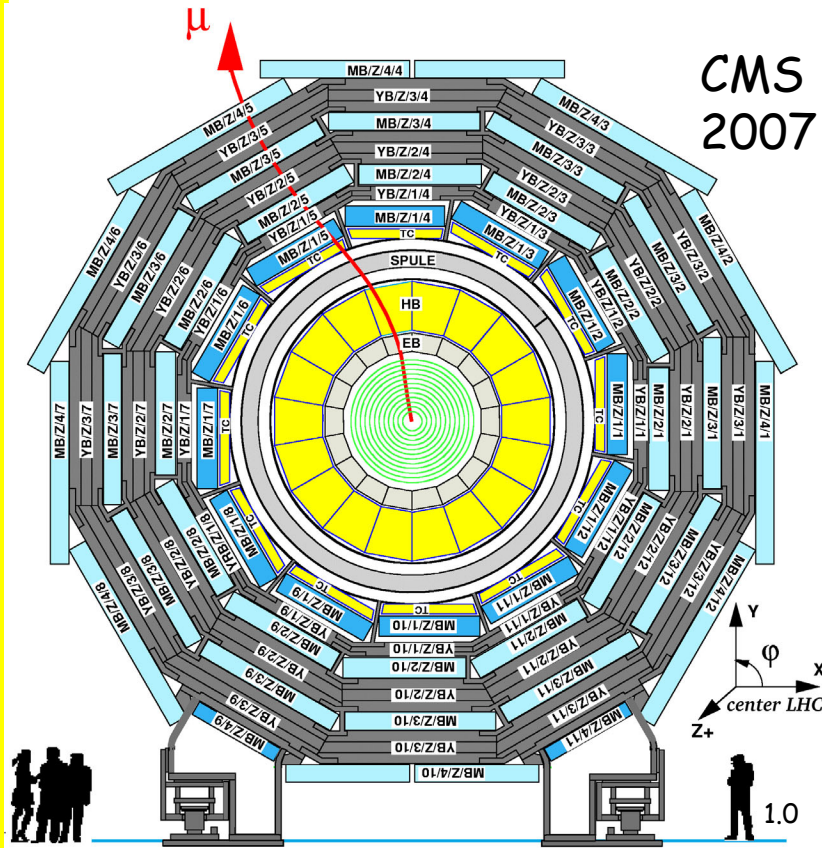
part IV

p p physics









pp physics

Part I Introduction

Part II Standard Model Physics

Part III Higgs

Part IV New Phenomena

- SUSY
  - motivation
  - searches:
    - R-Parity conserved
    - R-Parity violated
- Extra dimensions
- Black holes

References

SUperSymmetry

Particle	Spin	Susy-Partner	Spin
ν_e	1/2	$\tilde{\nu}_e^L$	0
e^-	1/2	$\tilde{e}_L^-, \tilde{e}_R^-$	0
u	1/2	$\tilde{u}_L, \tilde{u}_R$	0
d	1/2	$\tilde{d}_L, \tilde{d}_R$	0
γ, Z, h, H, A	1, 0	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	1/2
$W^\pm, H^\pm$	1,0	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	1/2
g	1	$\tilde{g}$	1/2

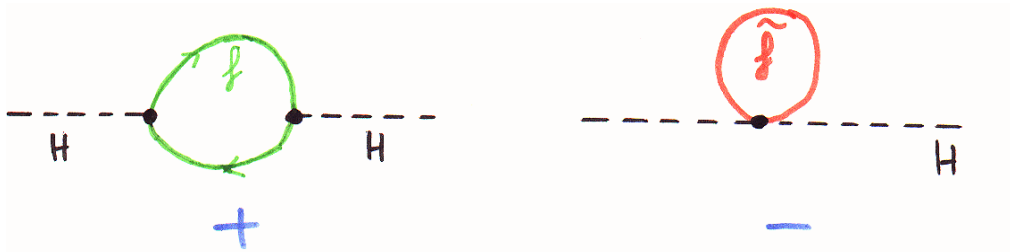
if R-parity (-1 for sparticles) is conserved:
⇨ LSP = Lightest SUSY particle = $\tilde{\chi}_1$ = stable

SUSY

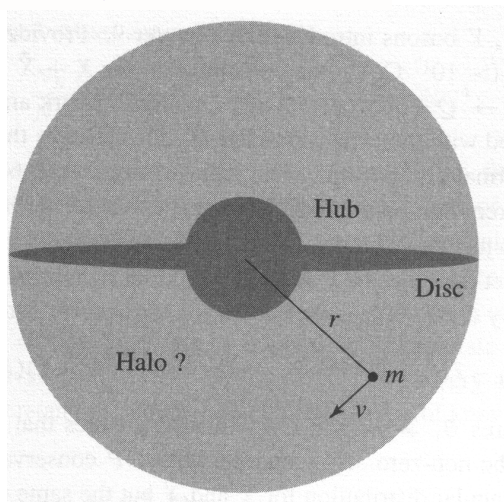
Nice features:

- symmetry relating bosons (forces) $\Leftrightarrow$ fermions (matter)
- higgs mass m_H

  under control



- grand unification (incl. gravity!) possible
- neutralino = dark matter candidate

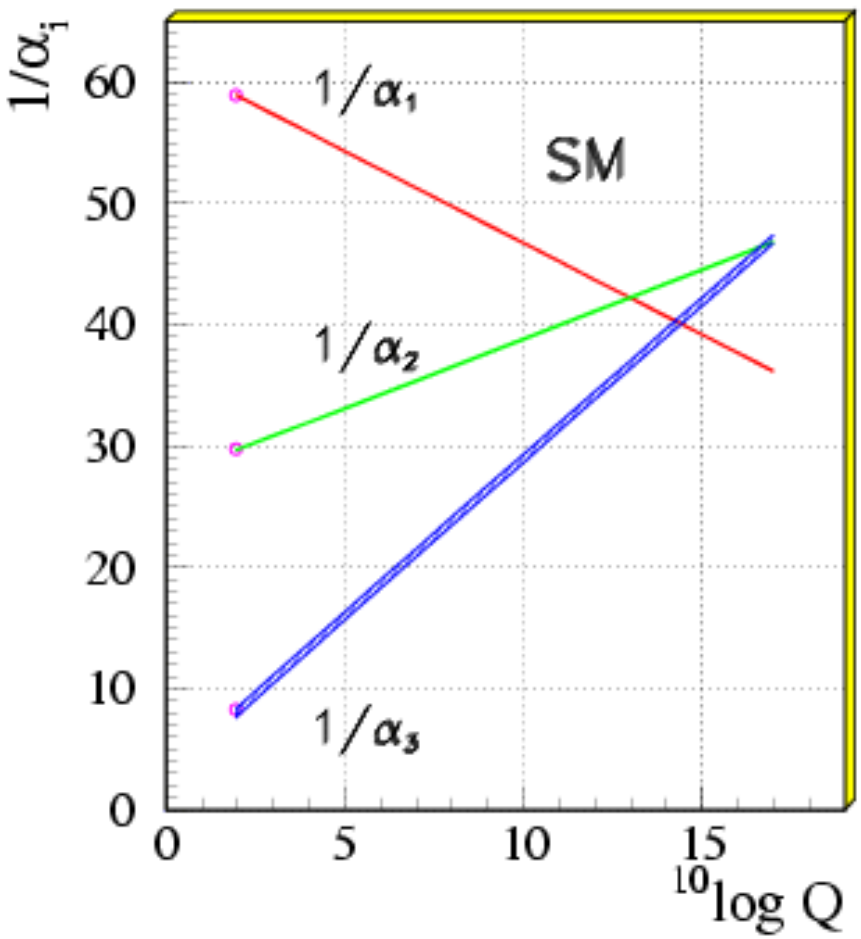


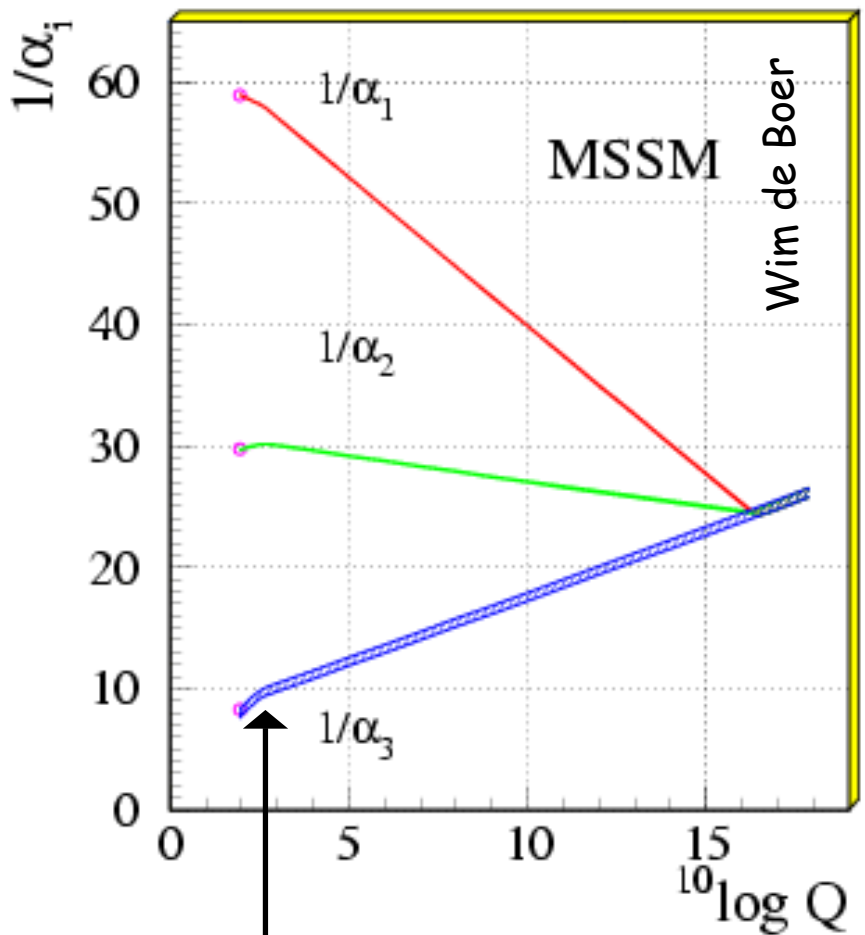
Other properties:

- SUSY broken: no sparticle seen yet
- > 100 new parameters $\Rightarrow$ Minimal Model (MSSM, MSUGRA)

Grand Unification ?

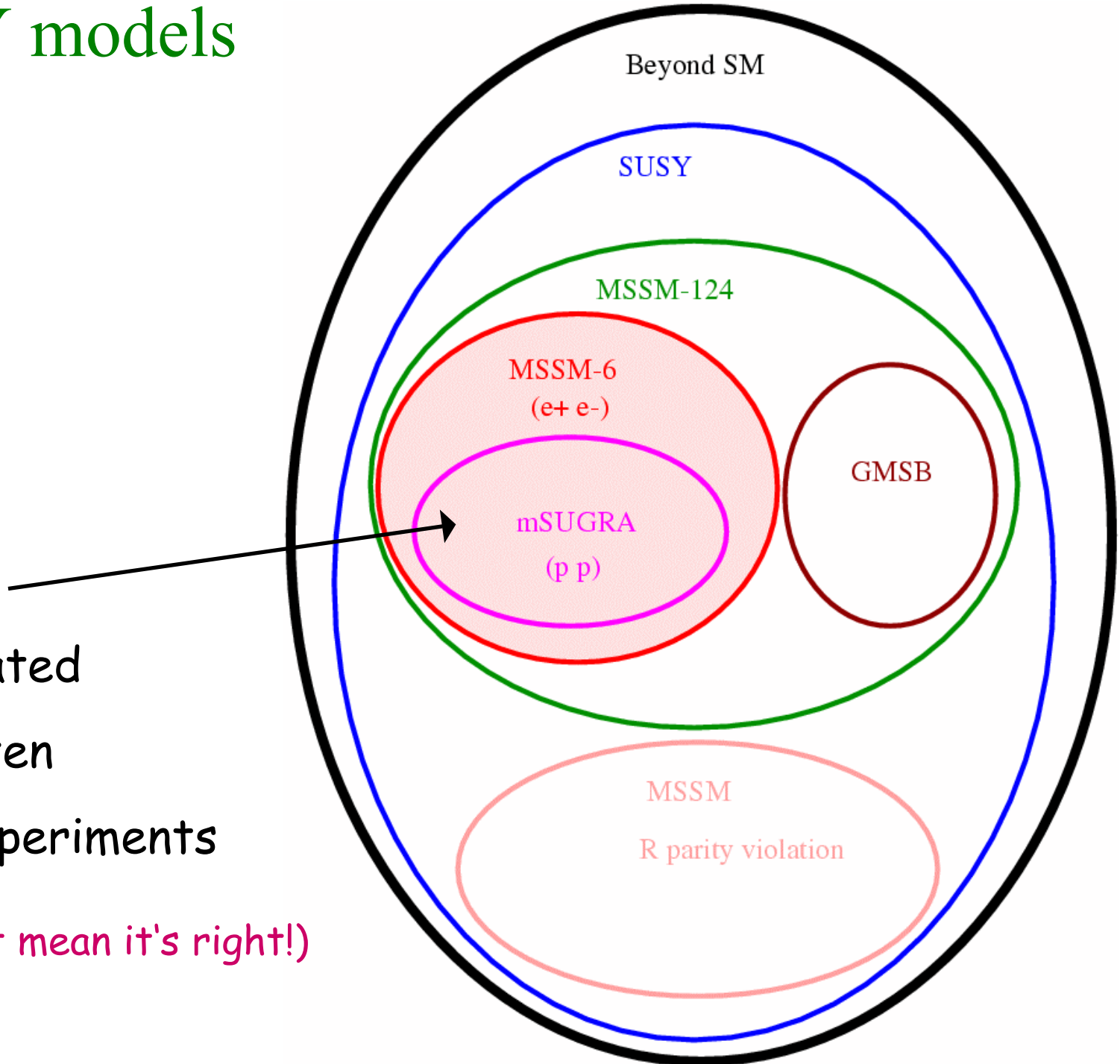
Unification of the Coupling Constants in the SM and the minimal MSSM





SUSY mass scale ~ TeV

SUSY models



investigated

most often

by pp experiments

(does not mean it's right!)

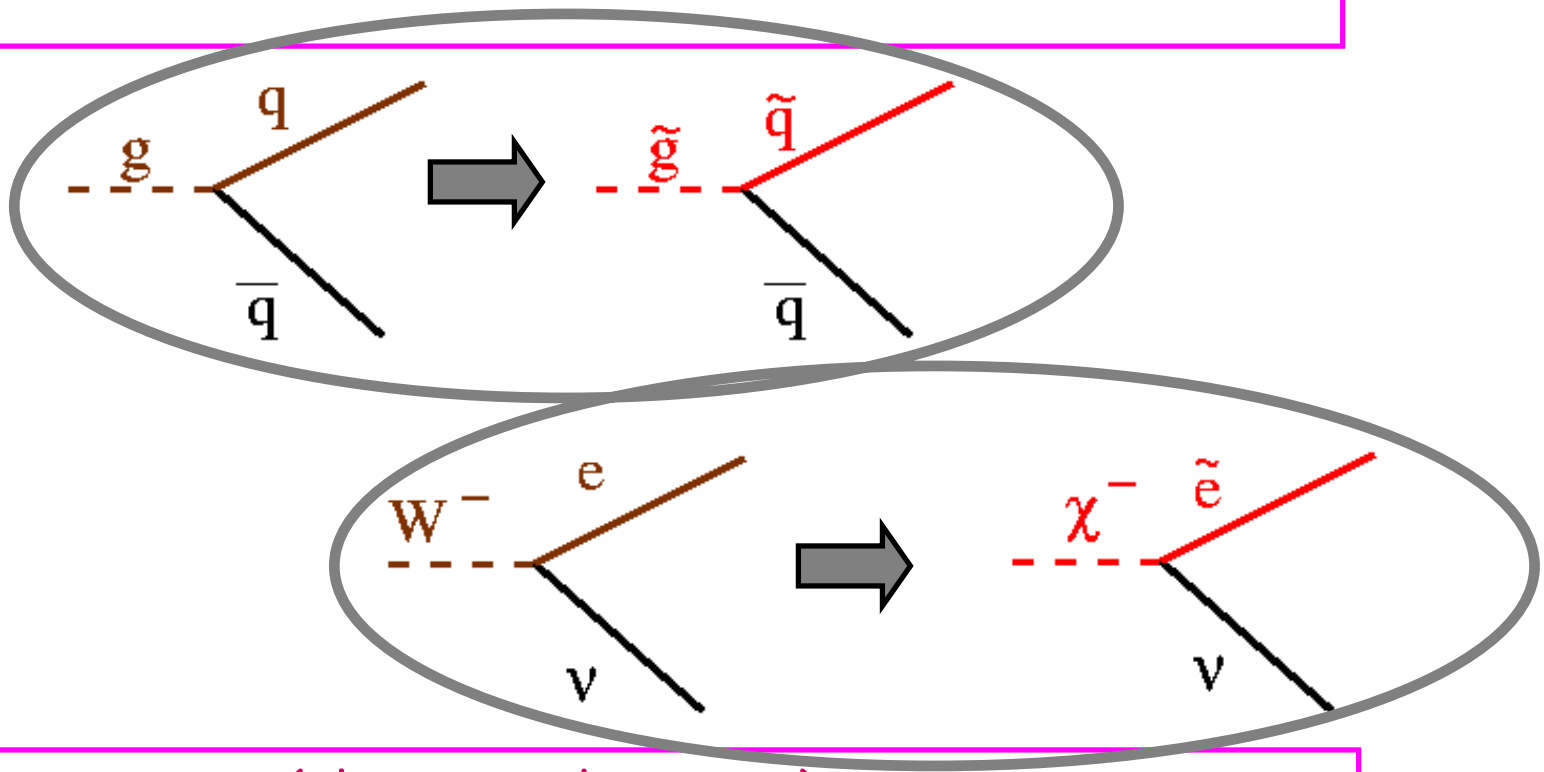
SUSY interactions (R conserved)

Feynman graphs:

take any SM vertex with 3 or 4 particles

replace two legs by the corresponding sparticles (~)

Examples



Coupling constants (electroweak, strong):

same as in SM !

MSUGRA parameters

MSUGRA = Minimal SUperGRAvity model

m_0 = universal scalar mass at GUT scale (s..., higgs)

$m_{1/2}$ = universal gaugino mass at GUT scale (...inos)

$\tan\beta$ = v_2/v_1 = ratio of higgs vacuum expectation values

A_0 = universal sfermion mass mixing parameter [GUT]

$\mathrm{sgn}\,\mu$ = sign of higgsino mass parameter

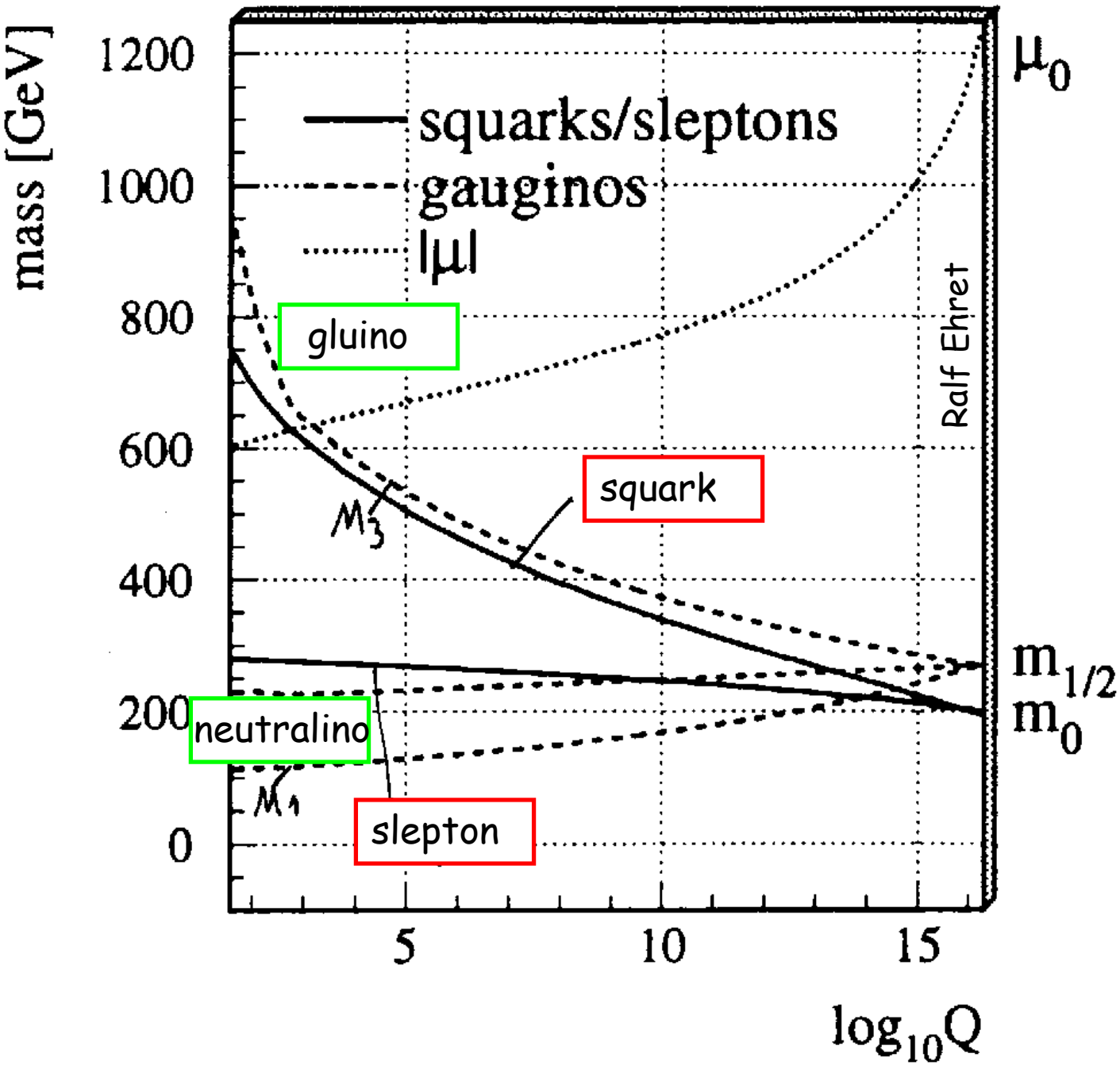
Required:

M(SUSY) < 1 TeV

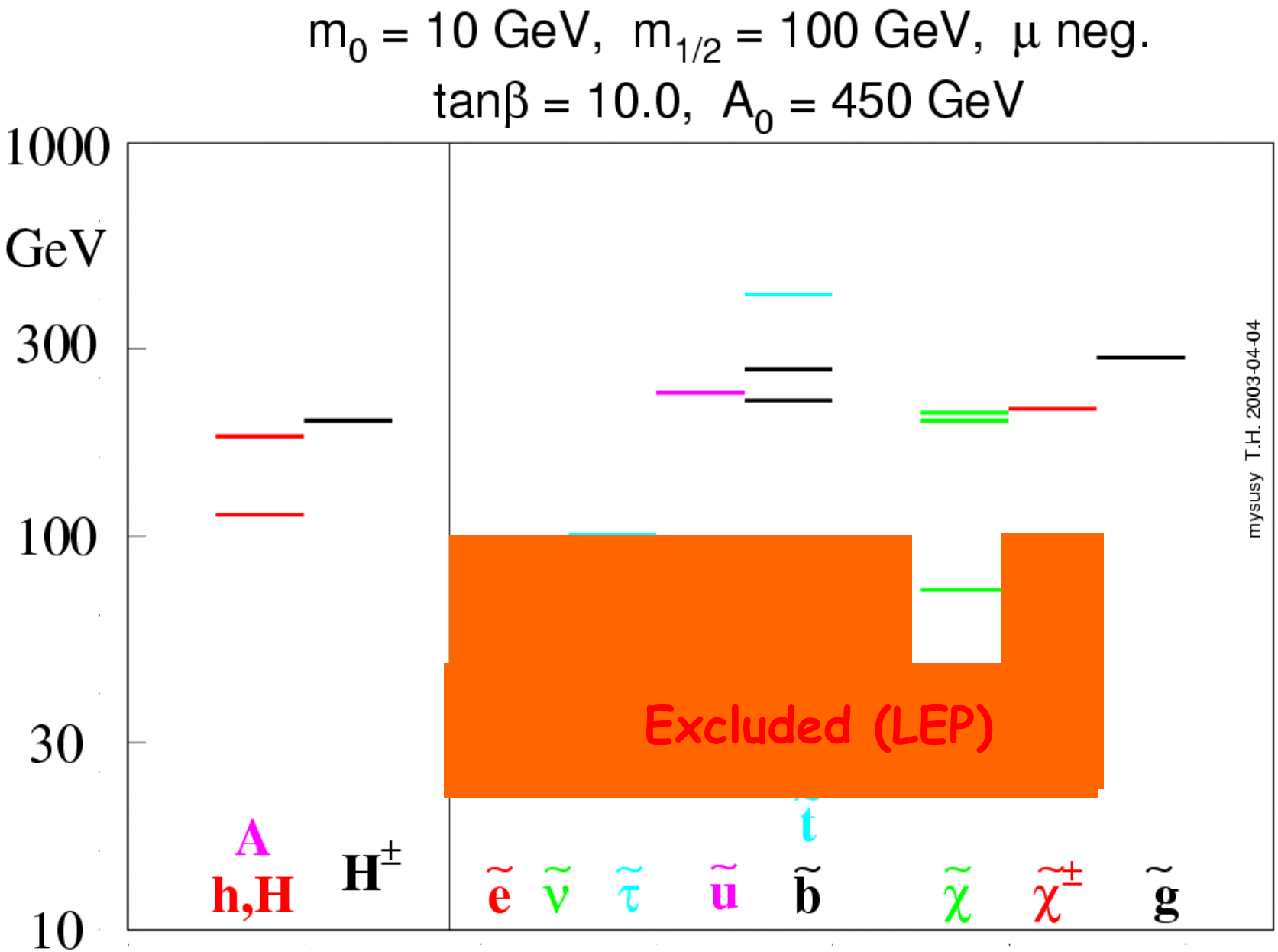
LSP without electromagnetic and strong coupling

Note: m_h given by m_0 ... **LEP higgs limit = severe constraint**

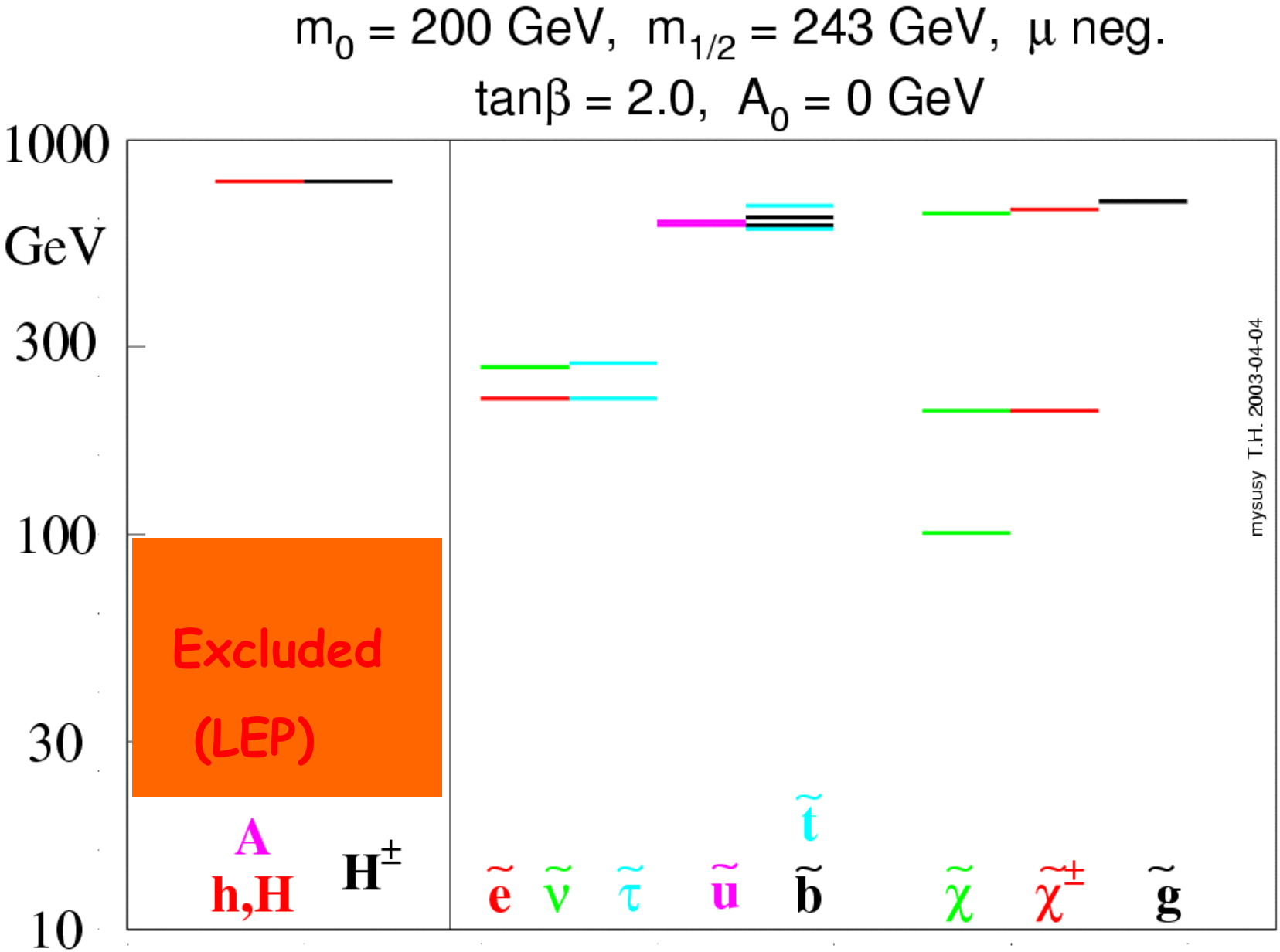
MSUGRA masses

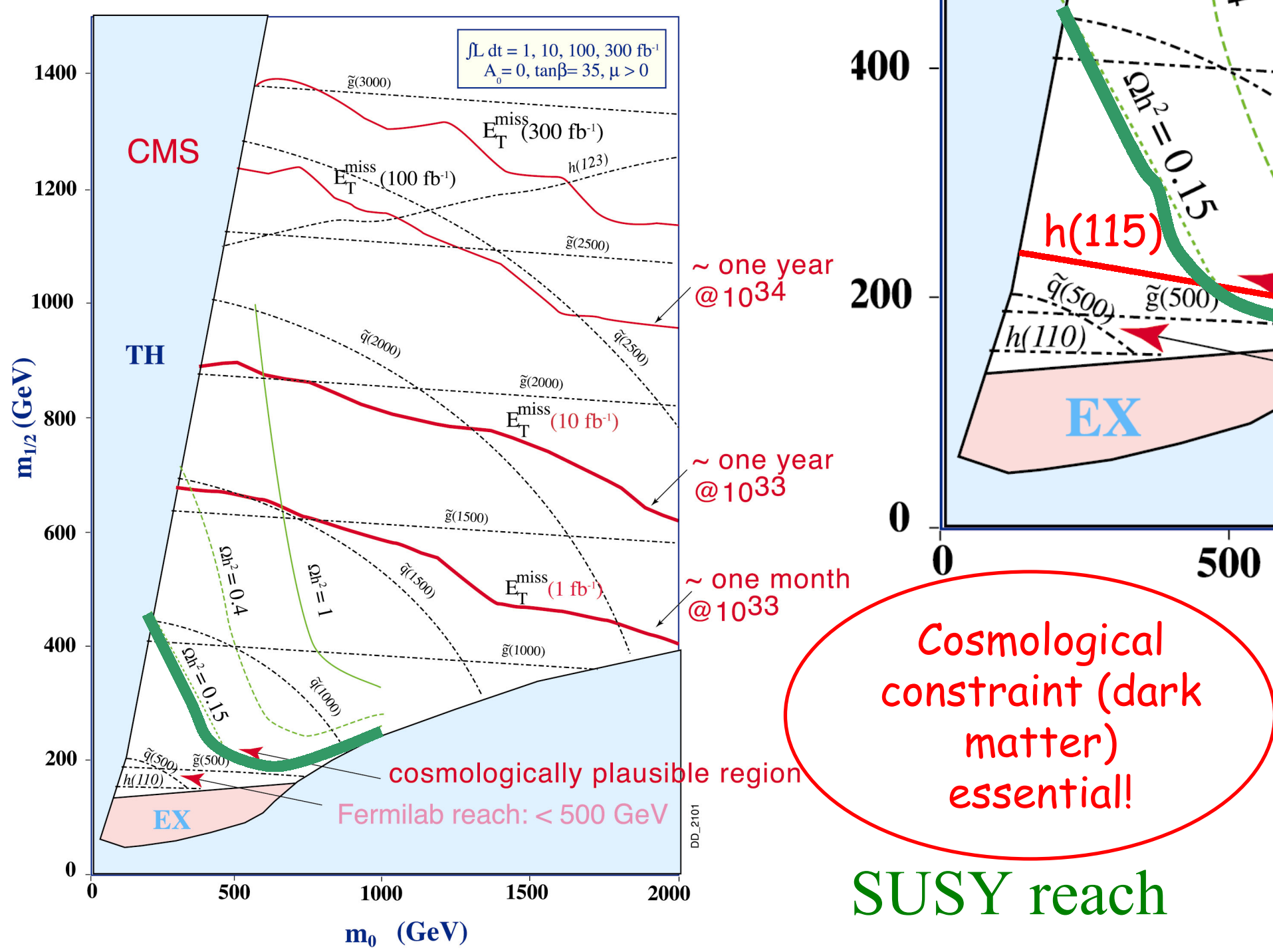


MSUGRA scenario 1



MSUGRA scenario 2





Cosmological constraint (dark matter) essential!

SUSY reach

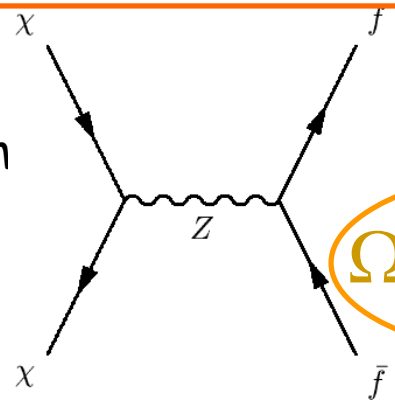
Cosmological Constraints I

Assume: neutralino = $\tilde{\chi}_0$ =dark matter = WIMP

Early universe:

theory

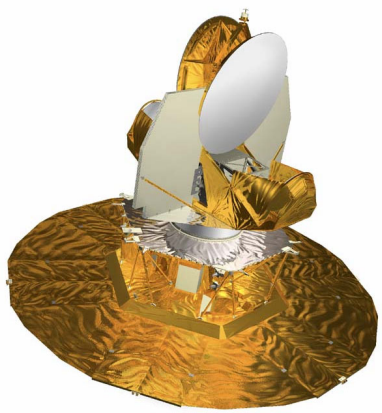
1) Very high temperature and pressure:
   creation and annihilation: equilibrium
2) High temperature and pressure:
   annihilation dominates: $N(\tilde{\chi}_0)\downarrow$
3) Low temperature and pressure:
   freeze out: $N(\tilde{\chi}_0) = const$



$$\Omega_{DM} = f(m_\chi, \ldots)$$

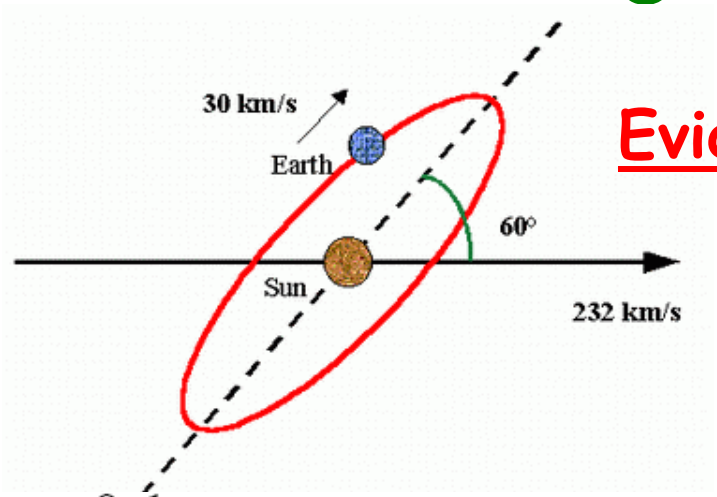
observation

WMAP measurement of cosmic microwave background

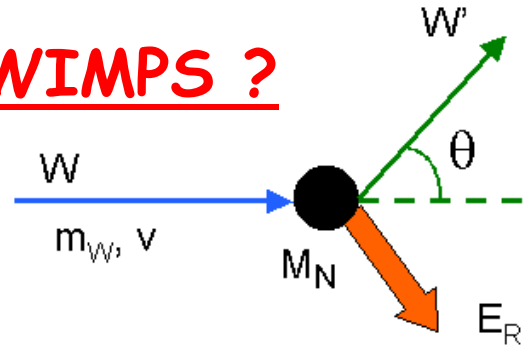


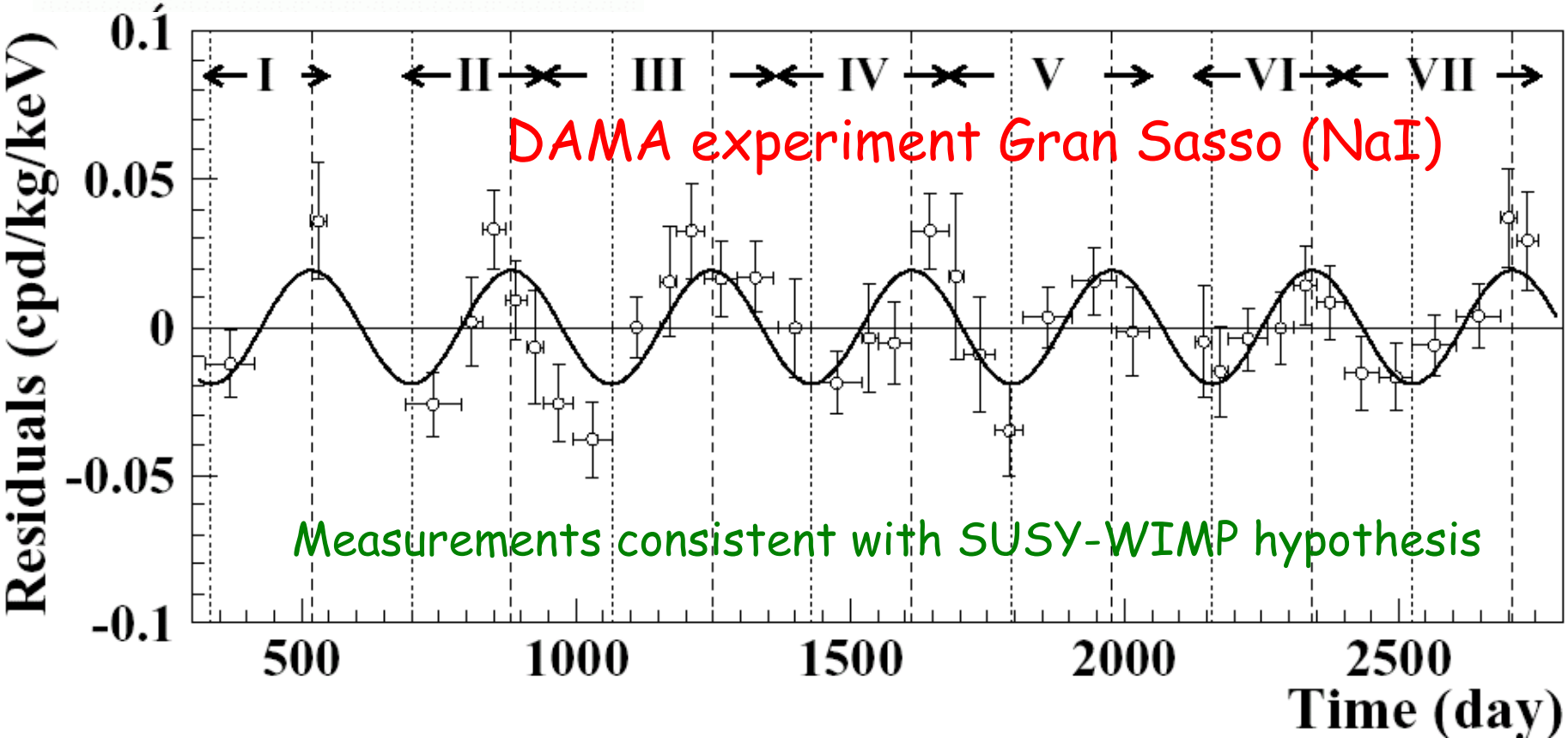
$$\Omega_{DM} = 0.23$$

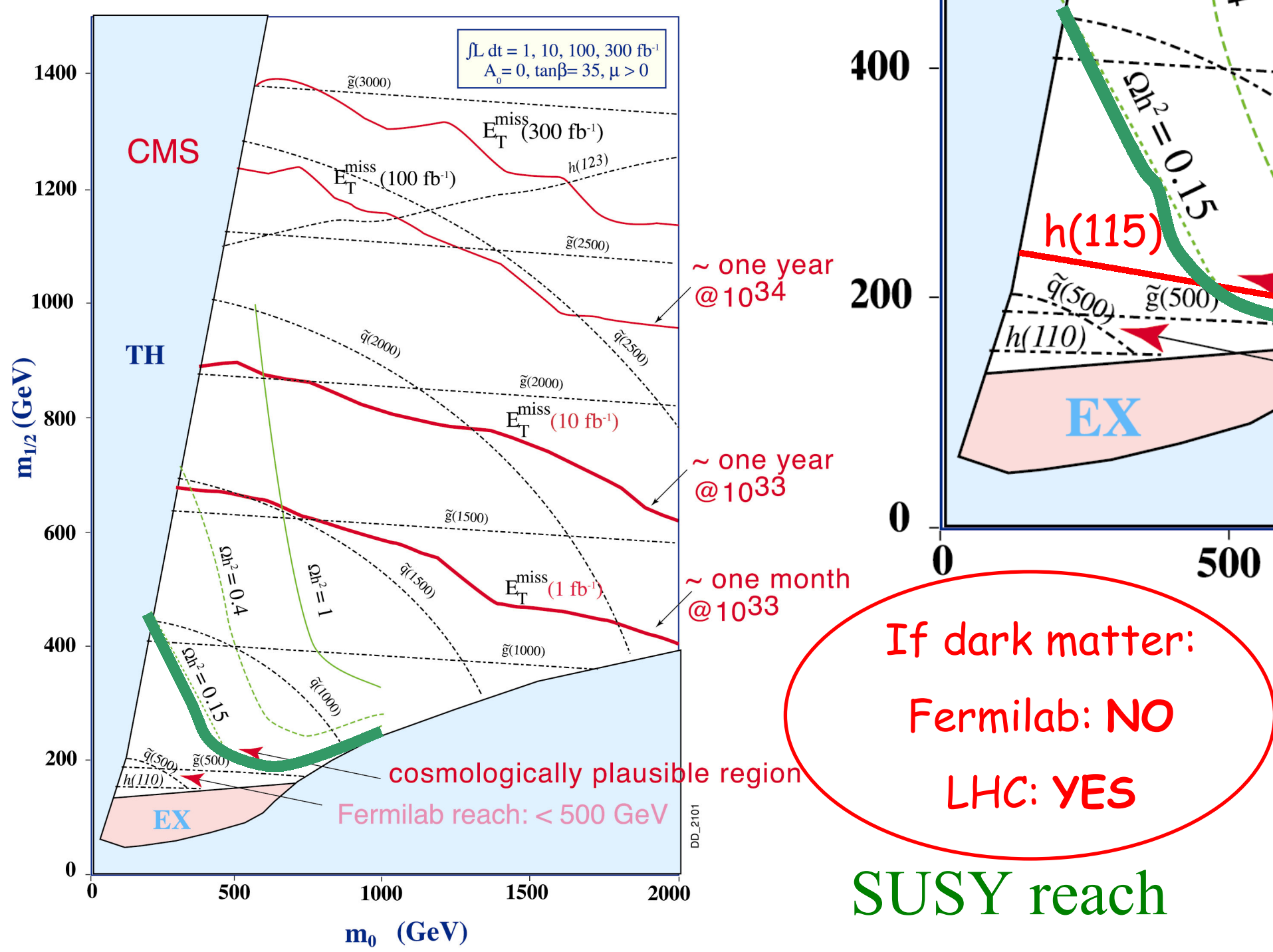
Cosmological Constraints II



Evidence for relic WIMPS ?







If dark matter:

Fermilab: **NO**

LHC: **YES**

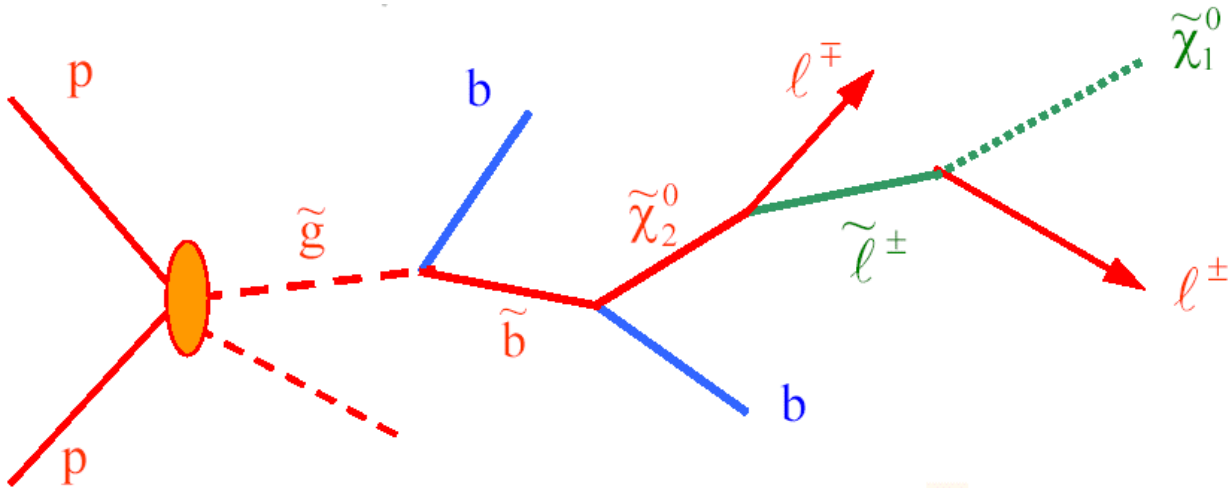
SUSY reach

SUSY search in pp

strategy:

high SM QCD background: jets

need something beyond: **leptons and/or missing energy**

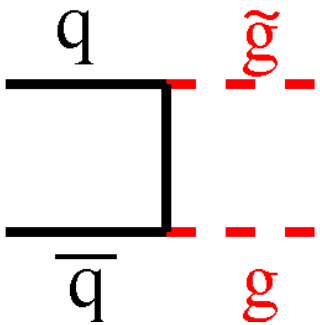


Examples:

- squarks and gluinos (missing energy) — strong
- neutralinos and charginos (leptons and missing energy) — electroweak

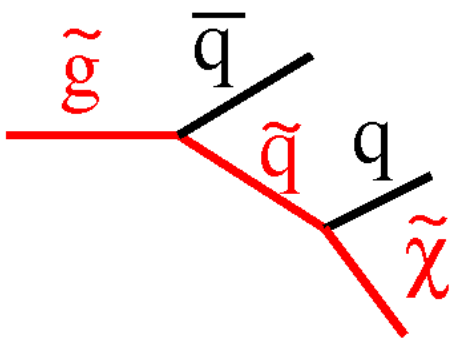
Jets + Missing Energy: Squark and Gluino Search

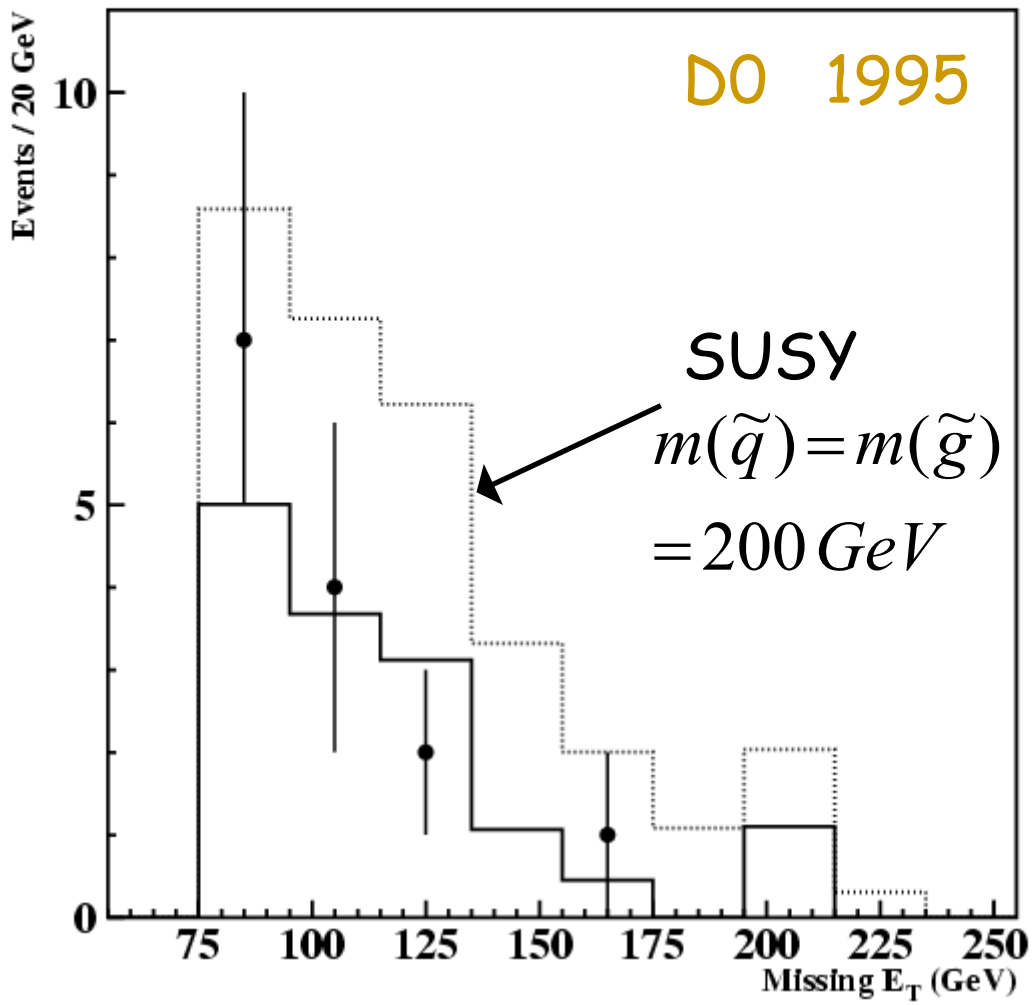
Production (ex.):



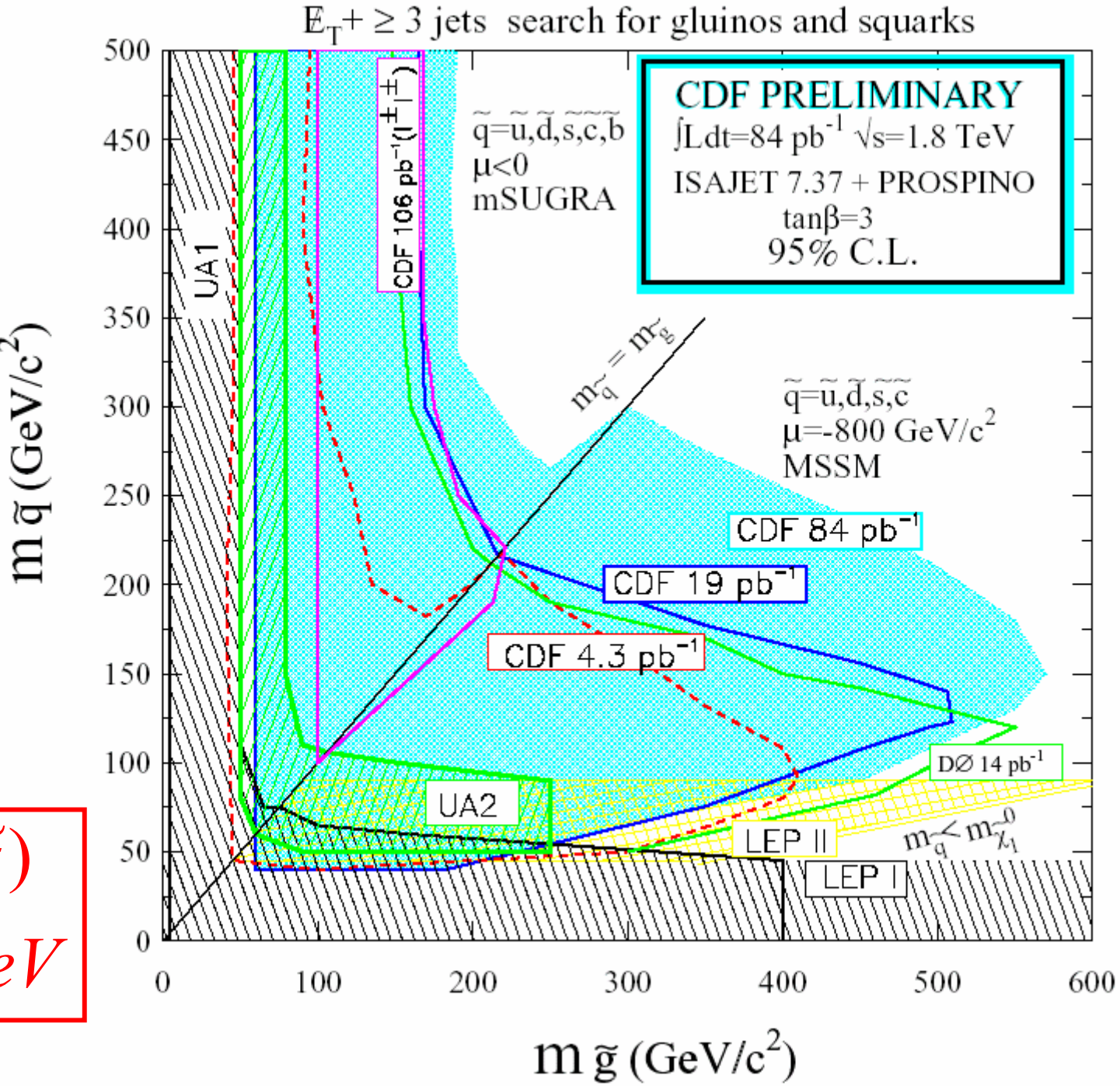
cross section large !

Decay (ex.):





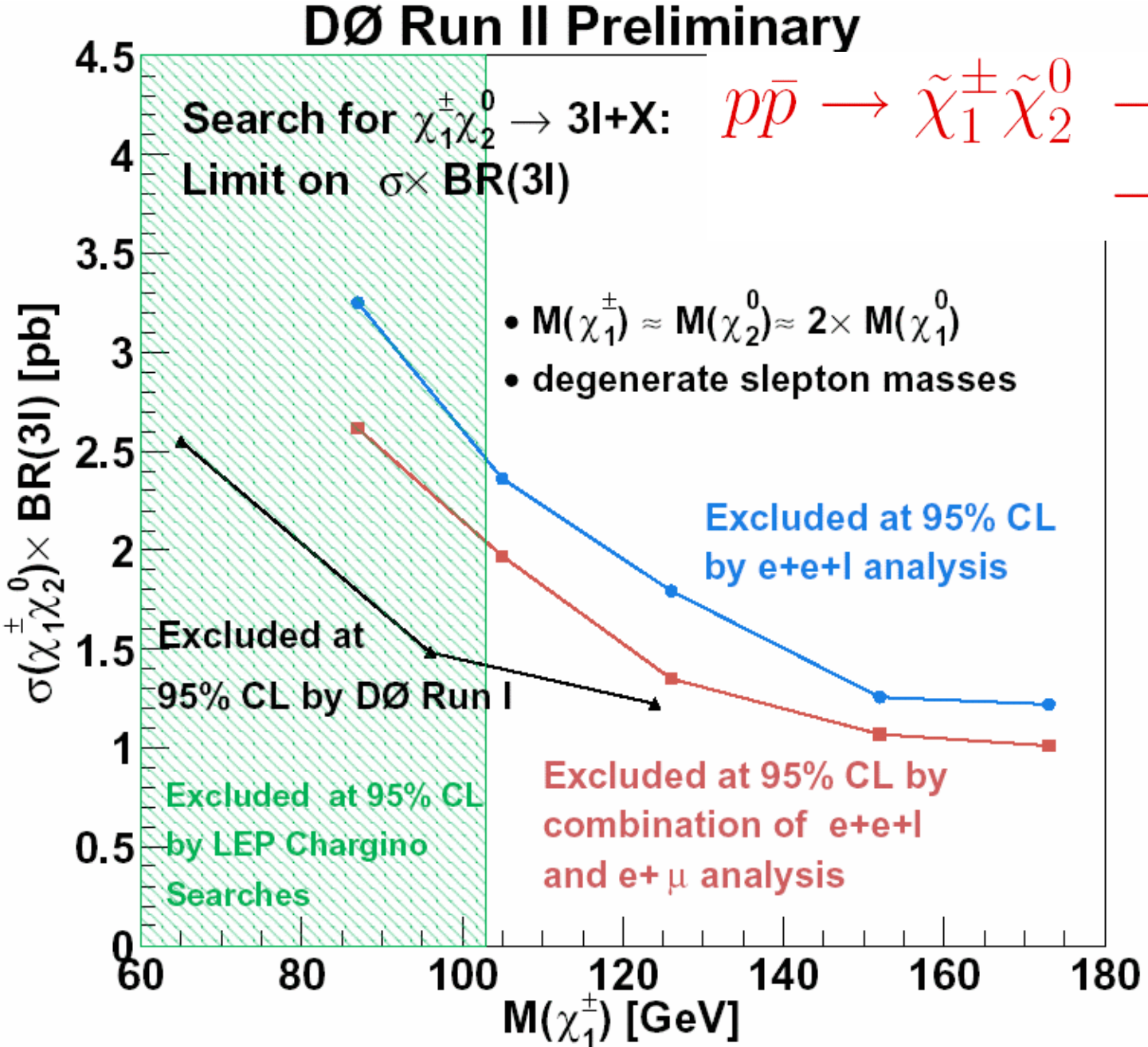
Results



$$m(\tilde{q}), m(\tilde{g}) > \sim 200\, GeV$$

Leptons: Hunting Charginos and Neutralinos

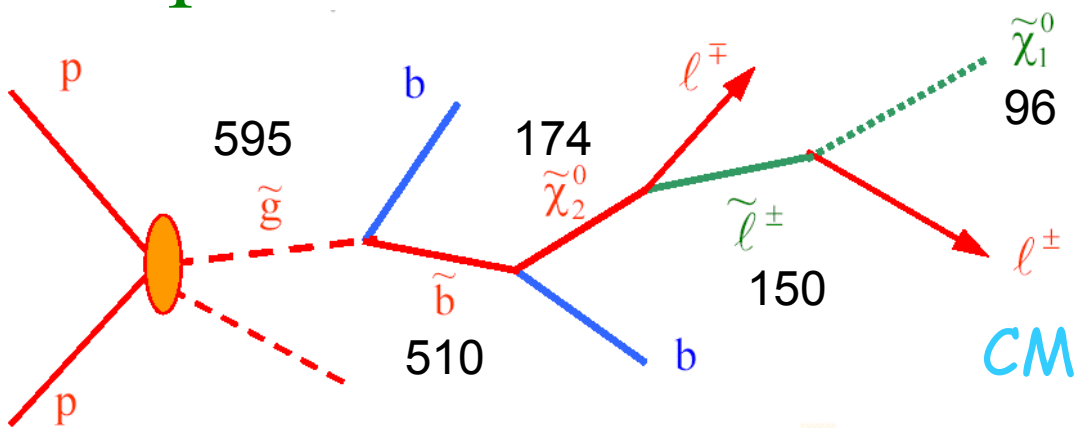
T.Hebbeker



Expected SUSY xsection factor ~10 lower

No (improved) SUSY limit yet

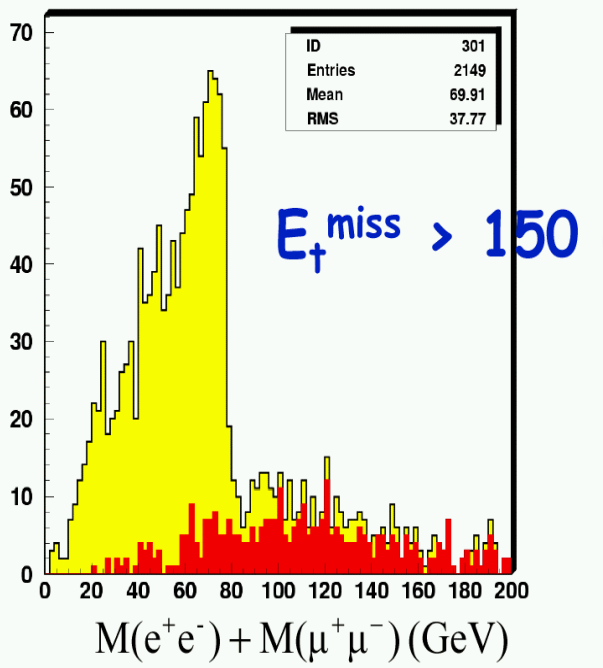
SUSY particle reconstruction



(assume neutralino mass)

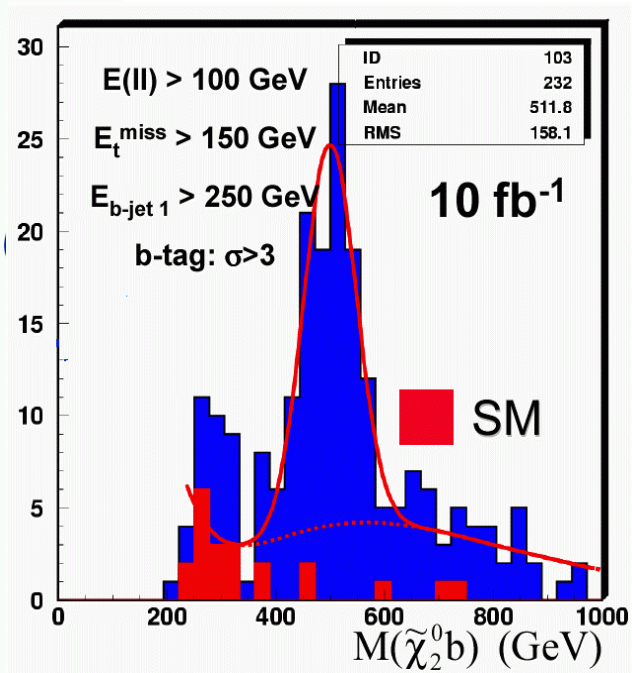
CMS MC study

(neutralino 2)



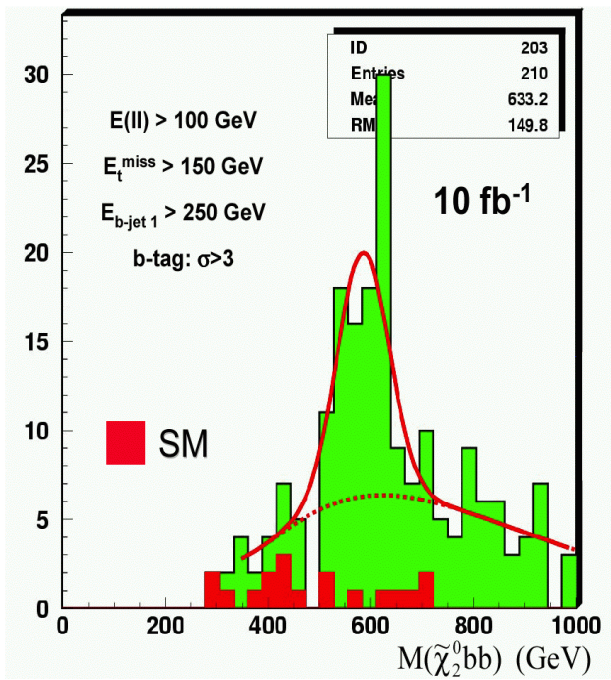
edge 78.9 +/- 2.1 GeV

sbottom



499.4 +/- 6.6 GeV

gluino



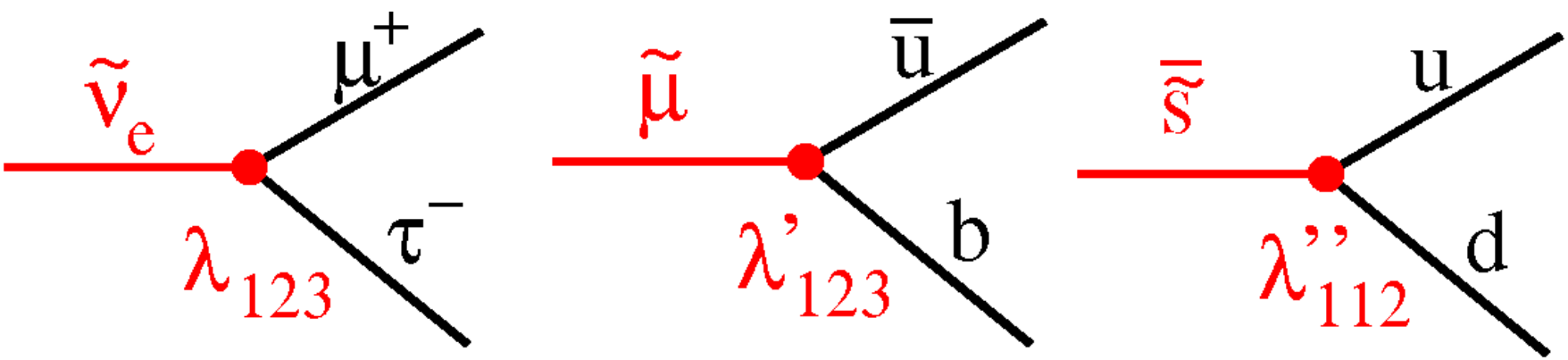
585.1 +/- 11.1 GeV

Chiorboli/Tricomi

SUSY with R parity violation

- neutralino unstable, no dark matter candidate !
- lepton and/or baryon number violated

Example diagrams:



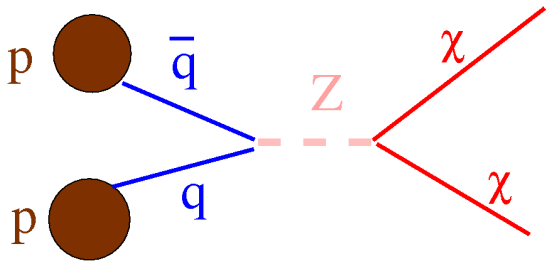
violates L

violates L

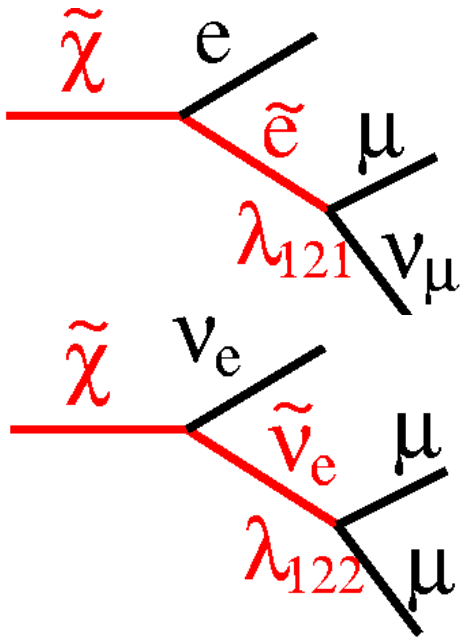
violates B

Example: Neutralino Decays via $\lambda_{121}, \lambda_{122}, \ldots$

production:

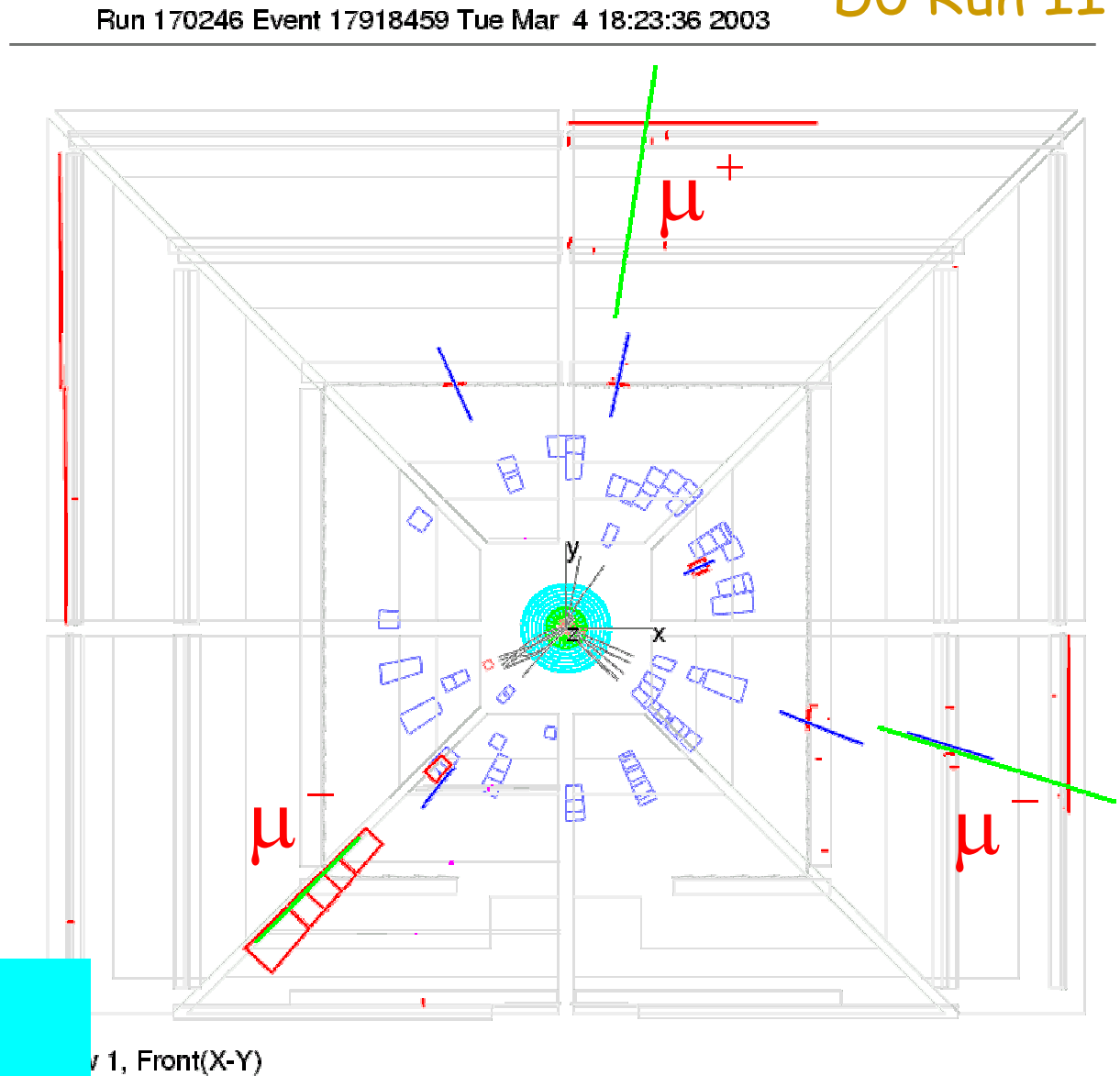


decay (examples):



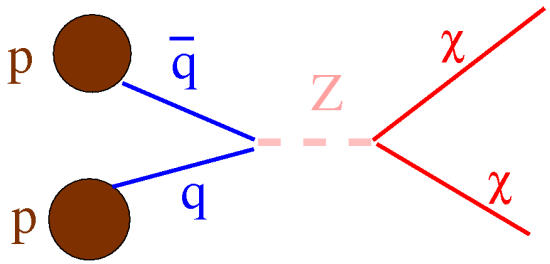
signature:

at least 3 charged leptons!

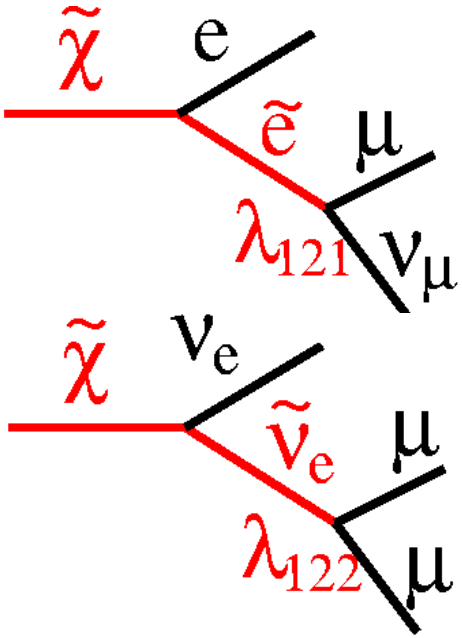


Example: Neutralino Decays via $\lambda_{121}, \lambda_{122}, \ldots$

production:

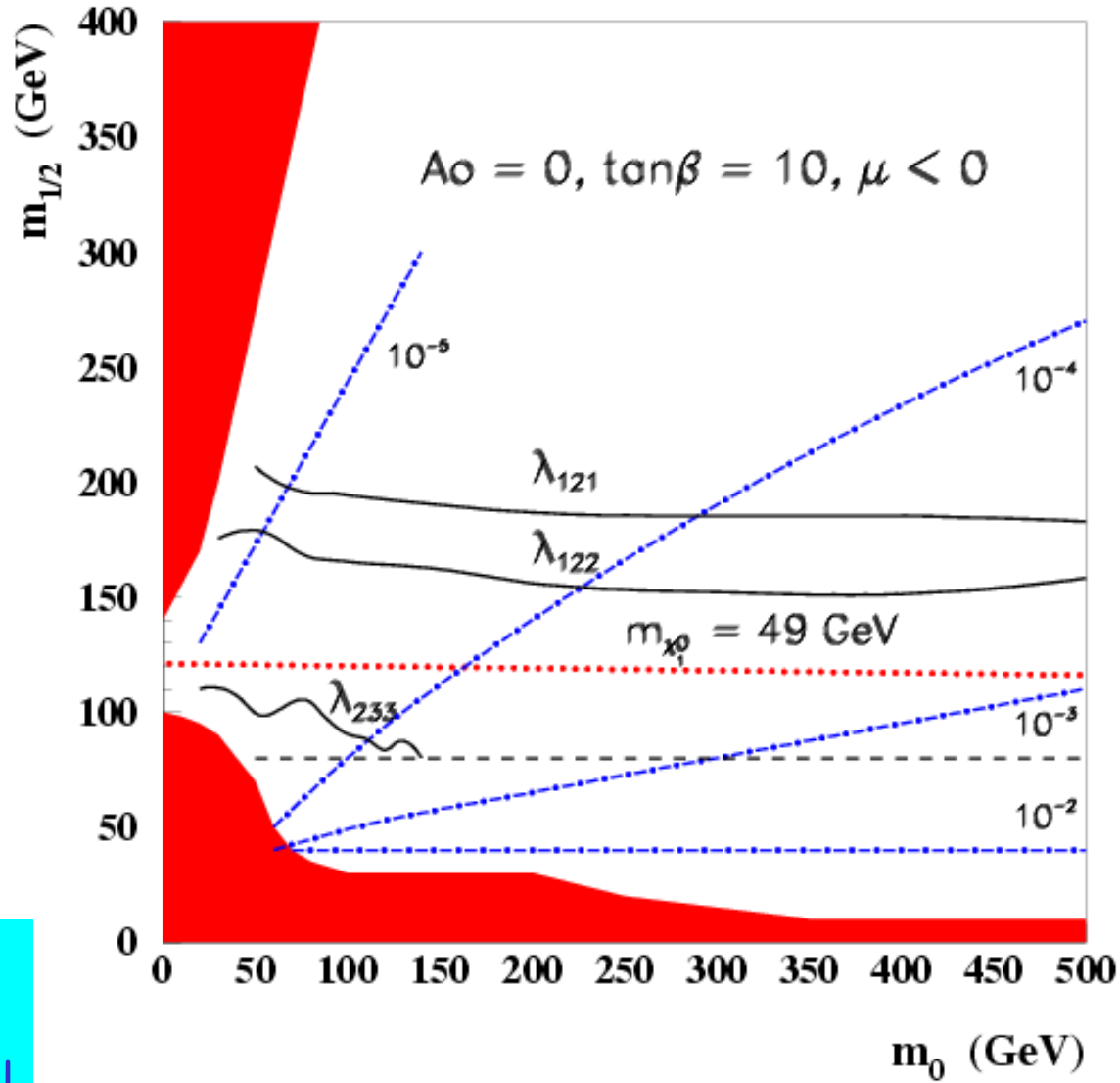


decay (examples):



upper limits:

DØ Run



experimental signature:

at least 3 charged leptons!

(Large) Extra Dimensions

Why is gravity so different from the other interactions ?

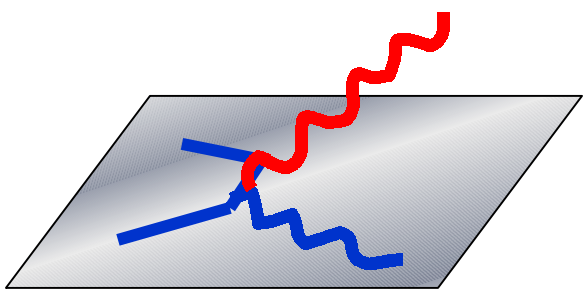
mass and length scales:

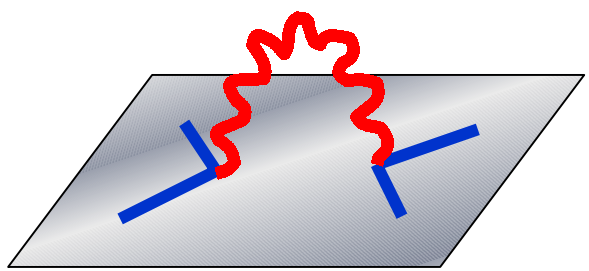
$$M_{ew} \sim 10^2\, GeV \qquad l_{ew} \sim 10^{-18}\, m$$

$$M_{Pl} \sim \frac{1}{\sqrt{G_N}} \sim 10^{19}\, GeV \qquad l_g \sim 10^{-35}\, m$$

Idea: only one fundamental scale M_S ~ 100 – 1000 GeV

gravity appears weak since gravitons propagate in 4 + n dimensions („dilution")

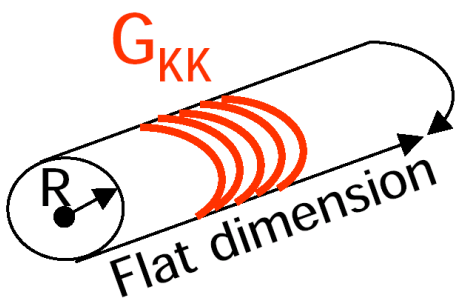




Arkani-Hamed, Dimopoulos, Dvali

Extra Dimensions: phenomenolgy

n extra dimensions of space with size R:



Compactified dimension

$$V \sim \frac{1}{M_{Pl}^2} \frac{m_1 m_2}{r} \Rightarrow V \sim \frac{1}{M_S^{2+n}} \frac{1}{R^n} \frac{m_1 m_2}{r}$$

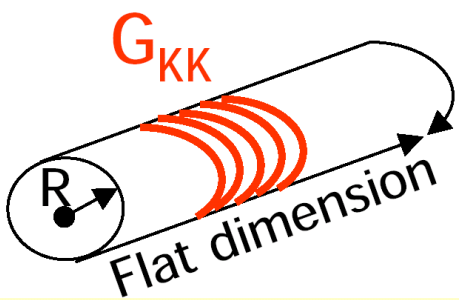
- deviations from Newton/Einstein laws for r < R

  therefore n=1 and n=2 ruled out!

- gravitons G show up in high energy physics experiments as real or virtual particles } **pp colliders!**

Extra Dimensions: phenomenolgy

n extra dimensions of space with size R:



Compactified dimension

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

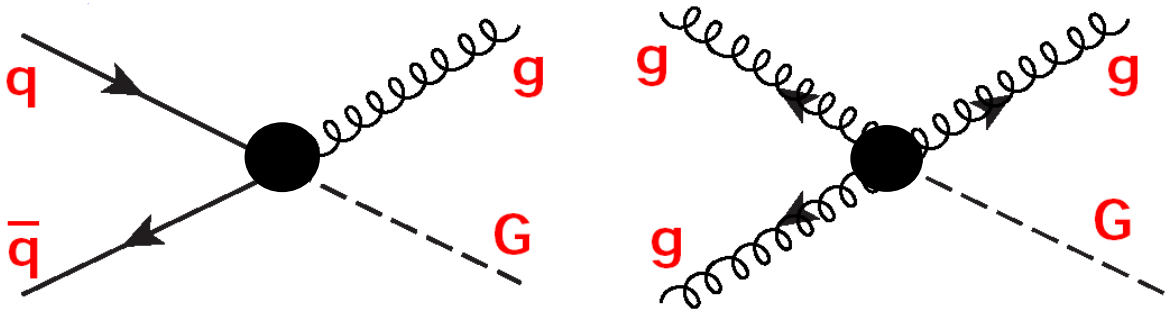
- deviations from Newton/Einstein laws for r < R

  therefore n=1 and n=2 ruled out!

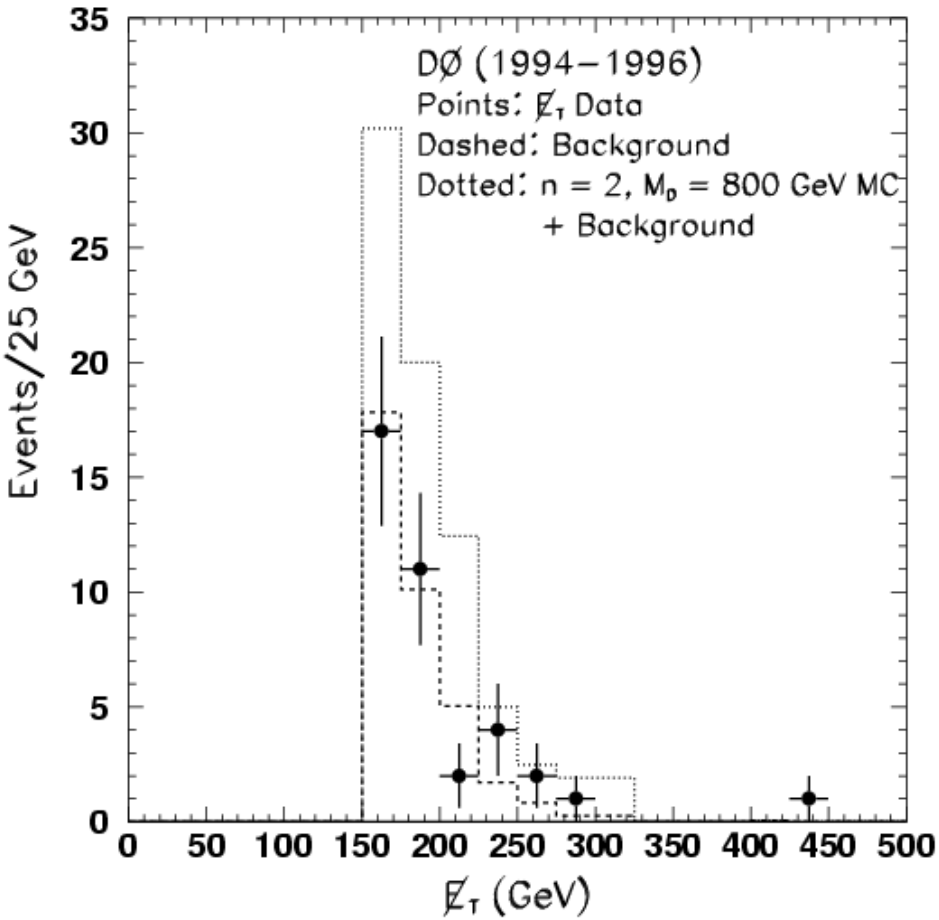
- gravitons G show up in high energy physics experiments as real or virtual particles

pp colliders!

Real Graviton Emission in p p



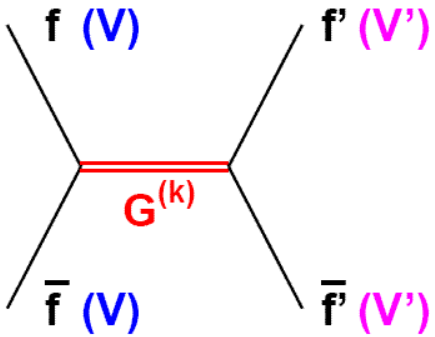
Monojet signatures!

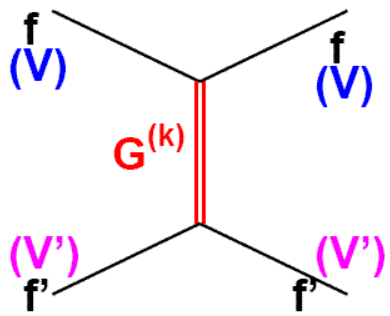


resulting lower limits on M_S/GeV:

n=2	n=3	n=4	n=5	n=7
890	730	680	640	620

Virtual Graviton effects in p p





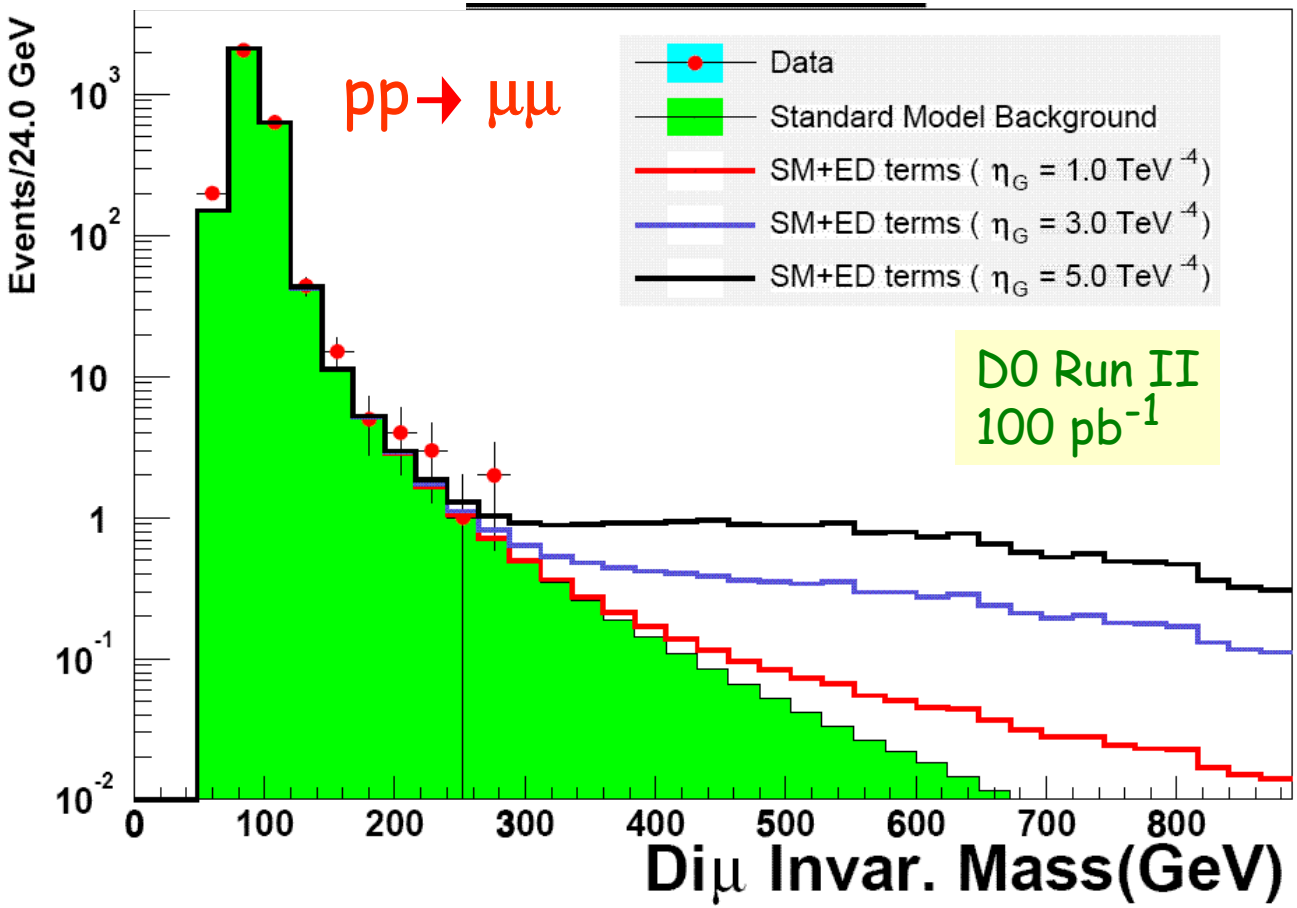
SM cross sections modified!

All D0 analyses

$(ee, \mu\mu, \gamma\gamma)$

combined:

$$M_S(n=2) > 1.38\,TeV$$



Black holes ?

predicted in large extra dimension models

production: mass 1 – 10 TeV, xsection large (~ nb)

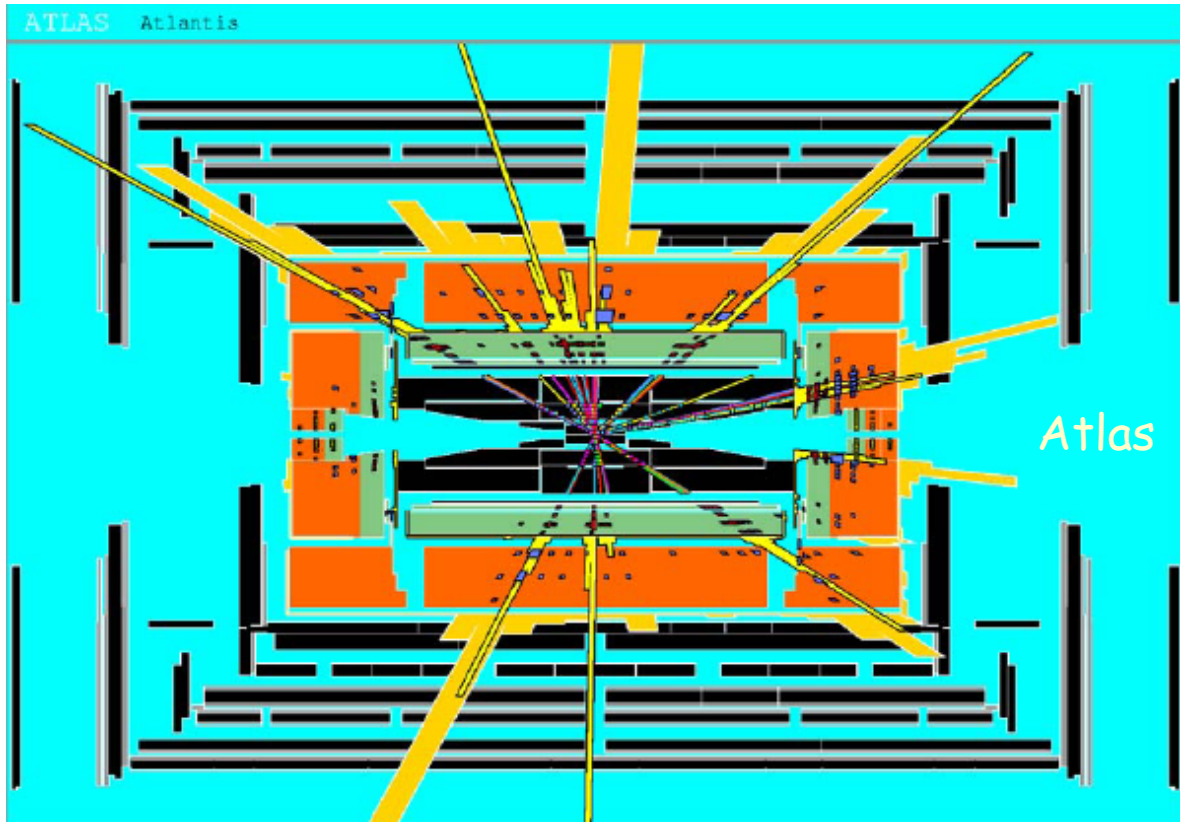
decay:

Hawking radiation

All SM d.o.f. equally likely

Multiplicity up to 30

Decay also into higgs!



pp physics

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  - motivation
  - searches:
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References

References

- lectures:

  F. Gianotti, LHC physics

  www.wlap.org/cern/lectures/summer/2000/gianotti

  J. Womersley, Physics at Hadron Colliders

  d0server1.fnal.gov/users/womersley/brazil1.pdf...brazil4.pdf

- experimental homepages:

  www-cdf.fnal.gov

  www-d0.fnal.gov

  atlas.web.cern.ch

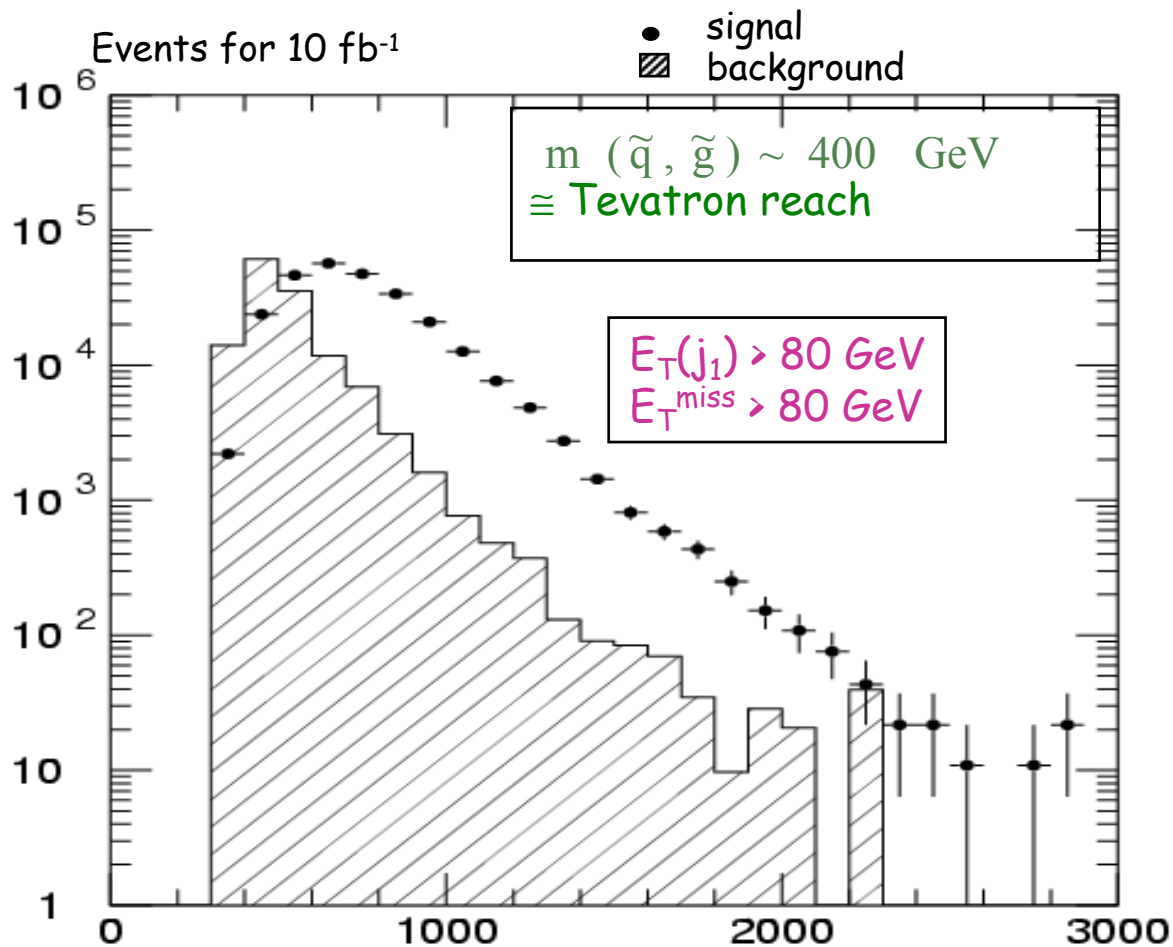
  cmsinfo.cern.ch

- theory:

  Physics at Run II workshop

  fnth37.fnal.gov/run2.html

Appendices



$$M_{eff} = E_T^{miss} + \sum_{i=1}^{4} p_T\,(\text{jet}_i) \quad (\text{GeV})$$

Inclusive $\ell^+\ell^-$ + E_t^{miss} final states

m_0 = 200 GeV, $m_{1/2}$ = 160 GeV,
tgβ = 2, A_0 = 0, μ<0