IV International Symposium on LHC Physics,
Fermilab, May 1-3, 2003

CMS Physics Reach at High and Super-High Luminosities

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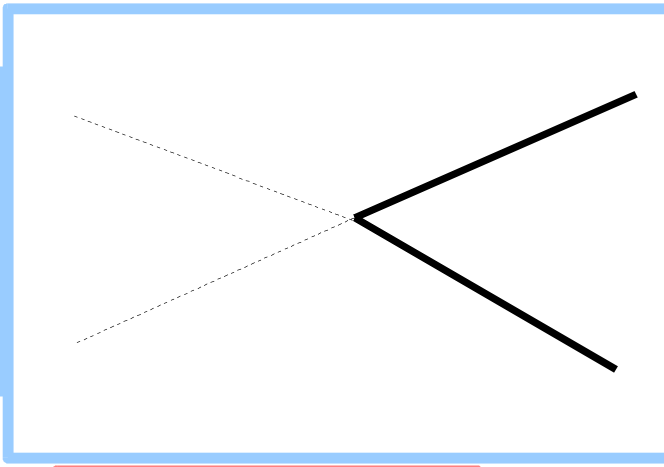
Boston University

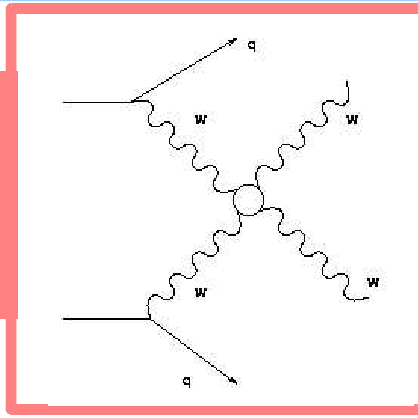
Reaching for what?

Big Picture:



FIRST look at the TeV mass scale to find a clue to the hierarchy problem...
(*What lies between the weak scale and the Planck mass?*)

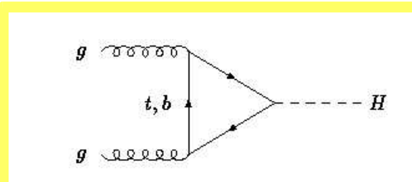
Medium Picture:



EXPLORE the mechanism for electroweak symmetry breaking...
(*How do W/Z interact at high energies?*)

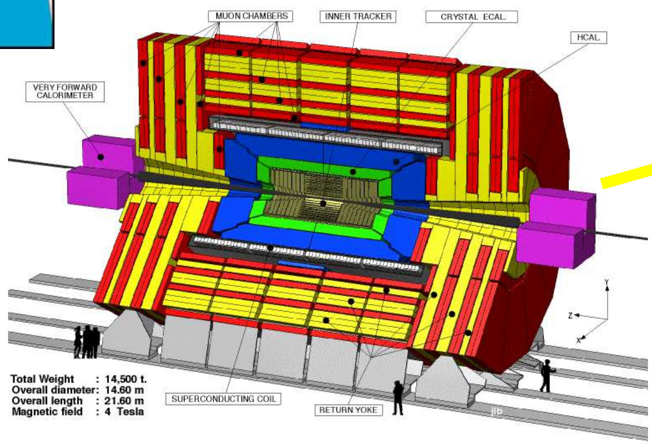
Small Picture:

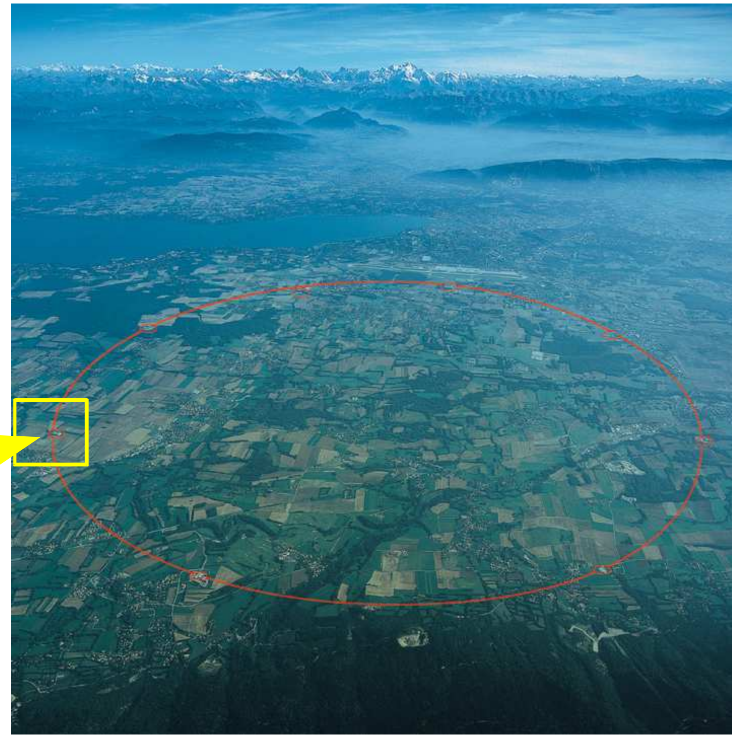
NAIL down the elusive Higgs...

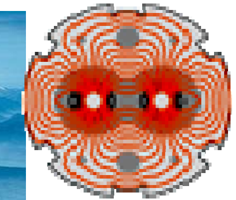


pp collisions
$\sqrt{s}$ = 14 TeV

Compact Muon Solenoid





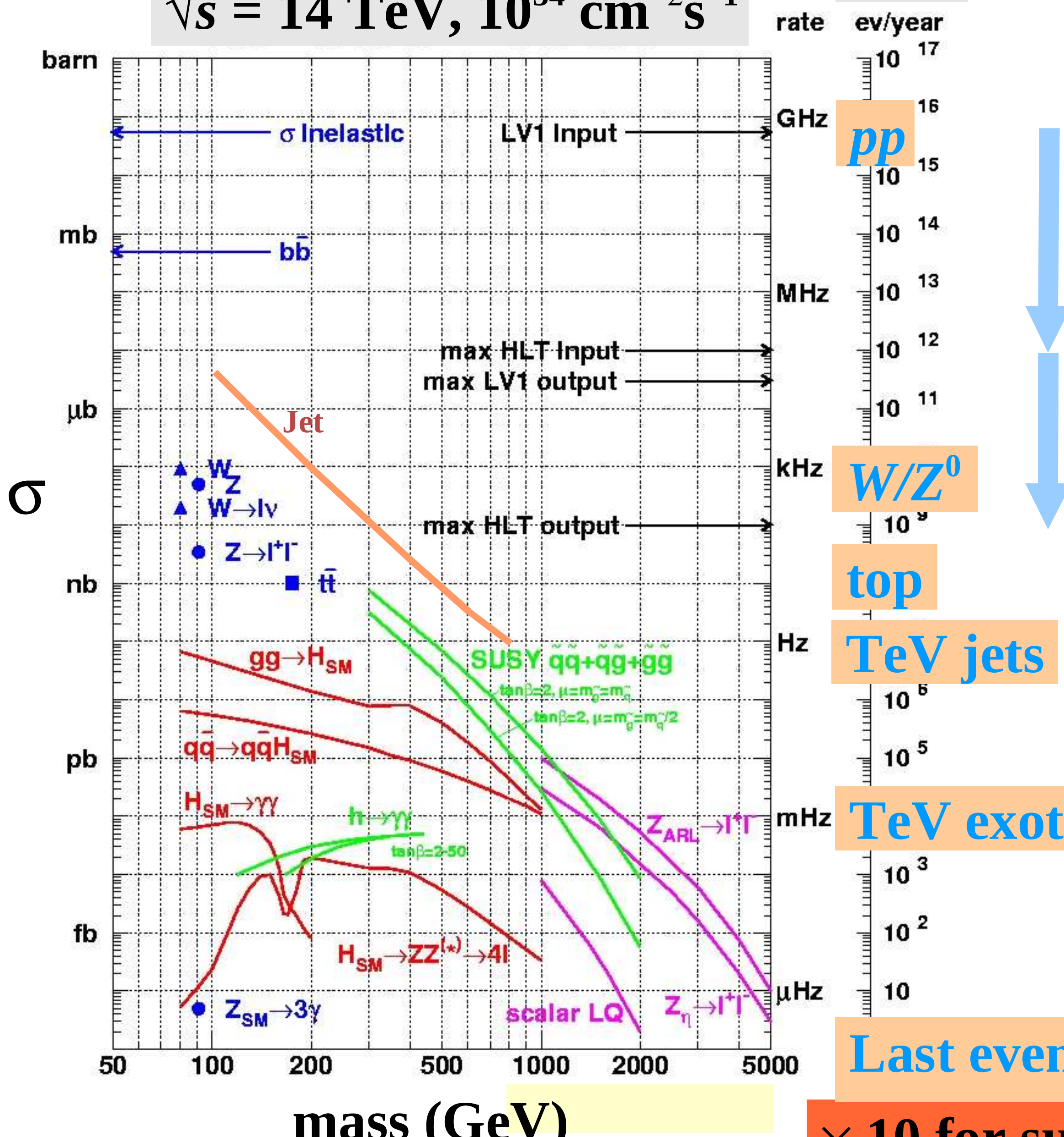


	instantaneous ($cm^{-2}s^{-1}$)	*integral 1 month*	*integral 4 months (LHC y)*
low luminosity (initial)	2×10^{33}	5 fb^{-1}	20 fb^{-1}
high luminosity (design)	10^{34}	25 fb^{-1}	100 fb^{-1}
super-high luminosity	10^{35}	250 fb^{-1}	1000 fb^{-1}

Needs hardware upgrades!

LHC Rates

$\sqrt{s}$ = 14 TeV, 10^{34} cm^{-2}s^{-1}



Last event: x_F = ½

× 10 for super-high lum.

L1 trigger (high lum.)

Trigger	(GeV) *Thresh.*	(kHz) *Rate*
iso. e/γ	34	6.5
2 e/γ	19	3.3
iso. μ	29	6.2
2μ	5	1.7
τ	101	5.3
2τ	67	3.6
jet	250	1.0
3jet	110	1.0
4jet	95	1.0
jet•E_T^{miss}	113/70	4.5
e•jet	25/57	1.3
μ•jet	15/40	0.8
min. bias		1.0
total (10% overlap)		33.5

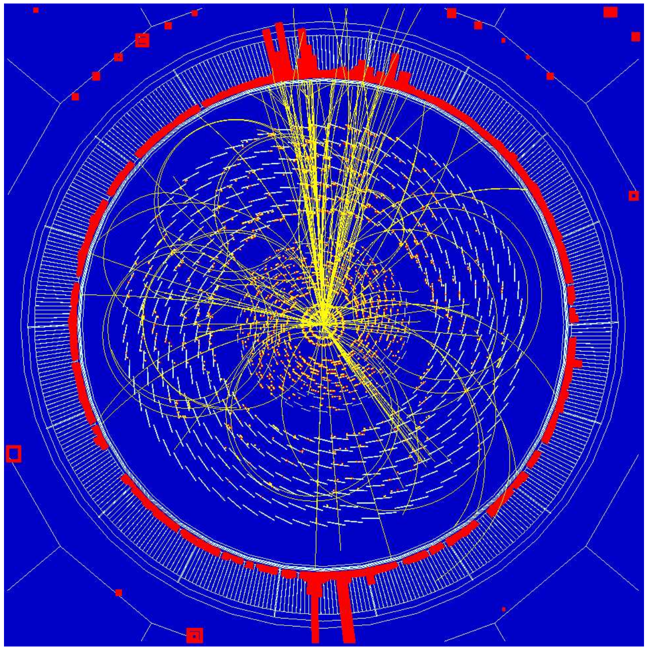
(designed for 100 kHz with ×3 safety)

Calculating Reach

Calculating physics reach at the next collider has become a cottage industry in the last 20 years.

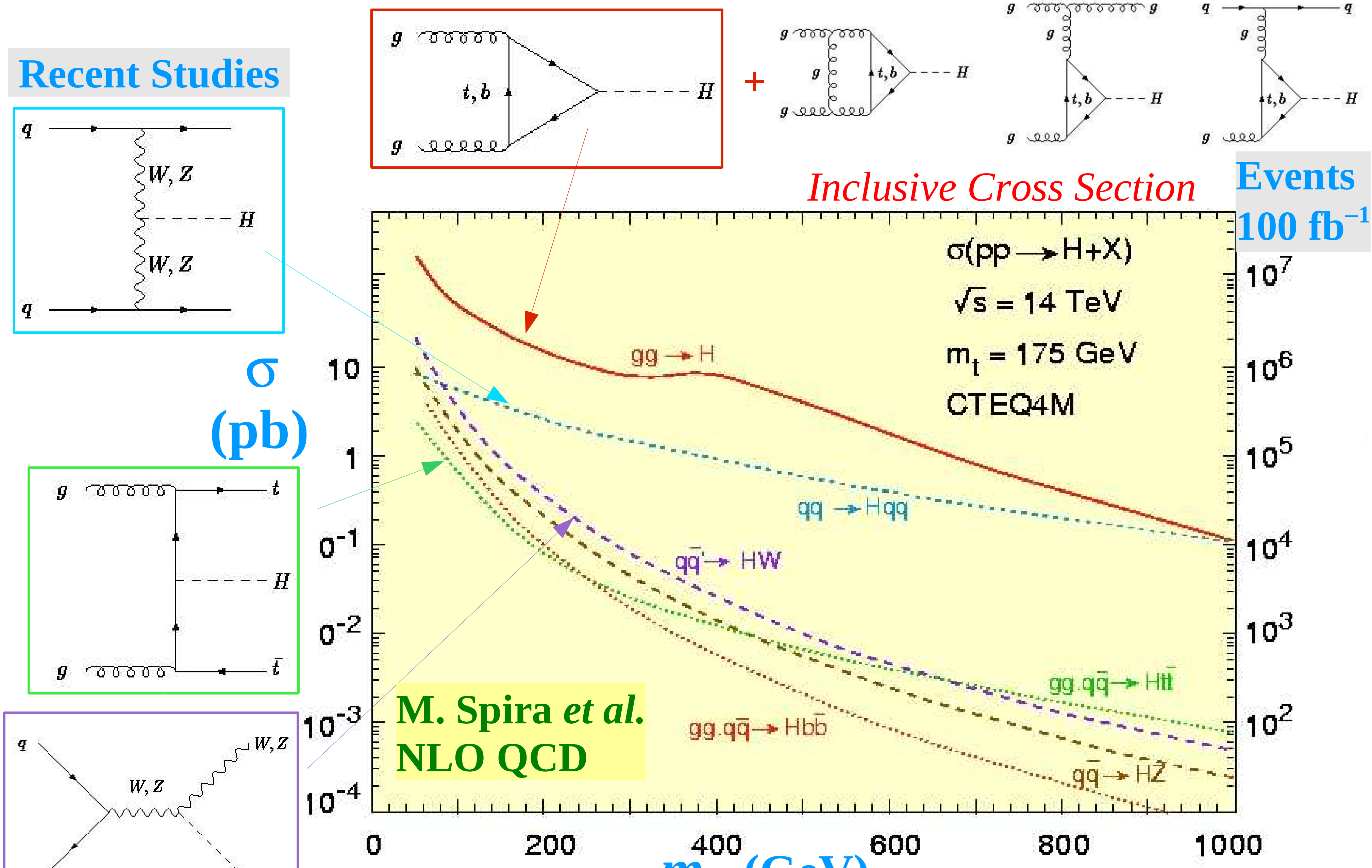
True reach involves many subtleties:
Trigger, detector resolution and efficiency, event pileup, and the ubiquitous QCD backgrounds (which always seem to be underestimated!).

For processes near the limit of detection (usually the most interesting) we need a full simulation and event reconstruction (ORCA = *Object-oriented Reconstruction for CMS Analysis*)



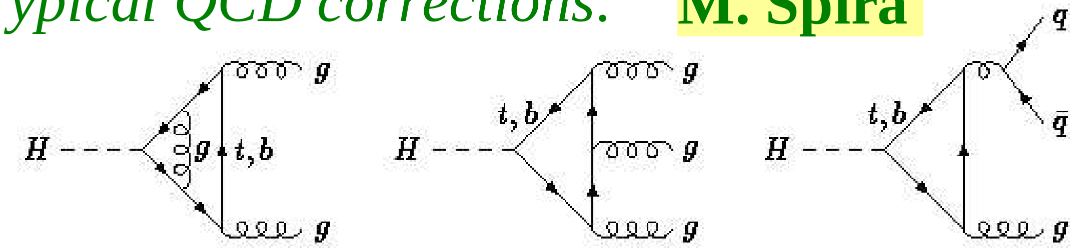
CPU time needed on a GHz P-3 is 500 s to simulate a TeV-scale event!

Standard-Model Higgs

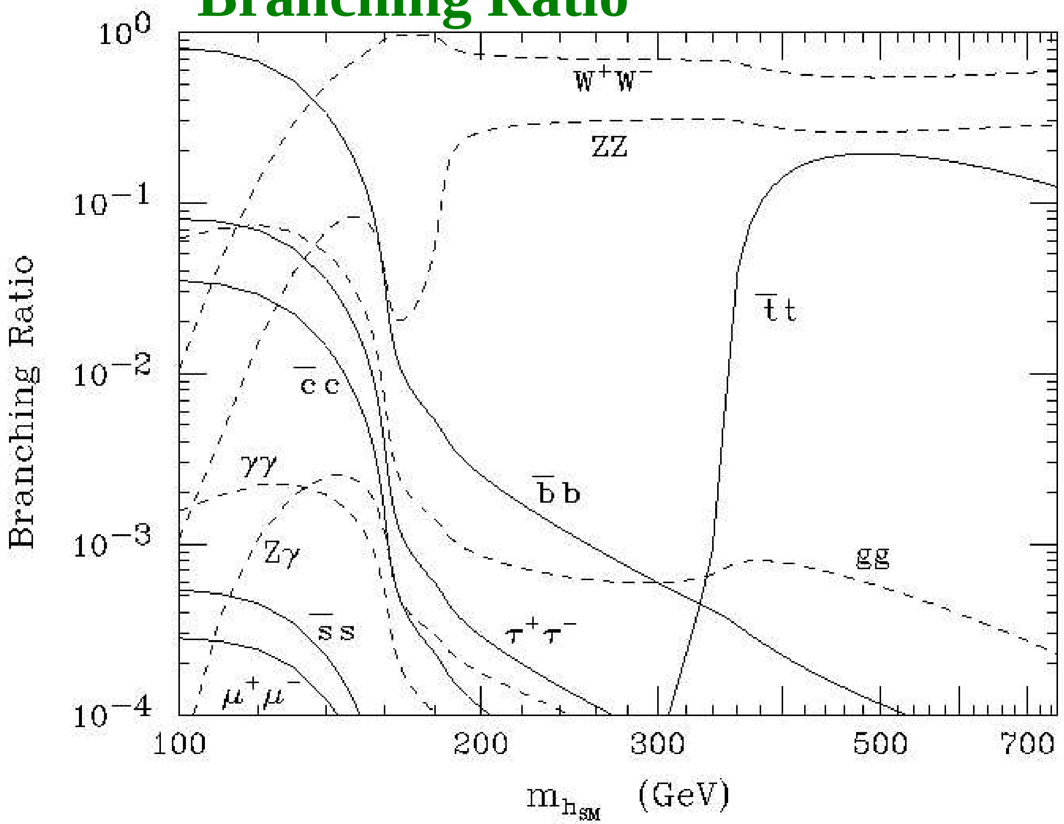


SM: H^0 Branching Ratio and Width

Typical QCD corrections: **M. Spira**

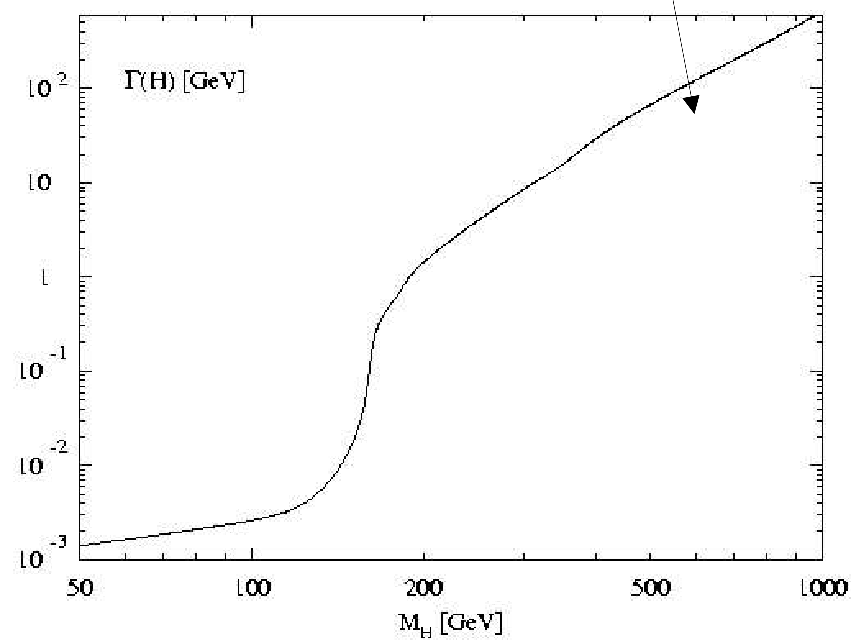


Branching Ratio



Total Width

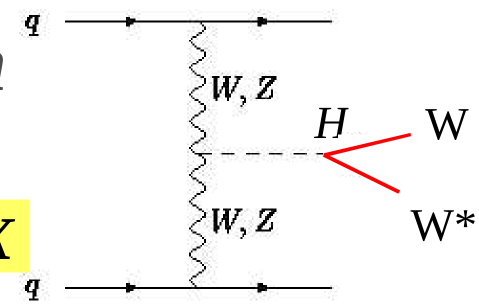
"toilet bowl"



SM: qqH⁰ — *Vector Boson Fusion*

(depends only on *WWH* coupling, not top)

$H^0 \to WW^* \to l^+\nu\, l^-\nu$ **main background:** $\bar{t}\,t + X$



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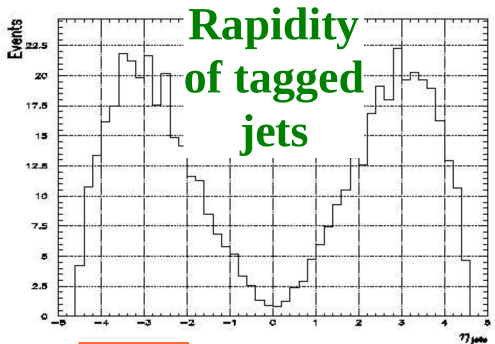
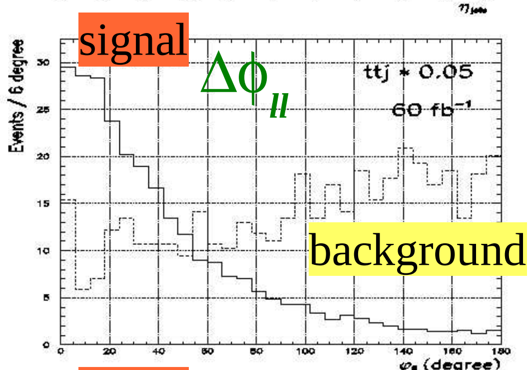
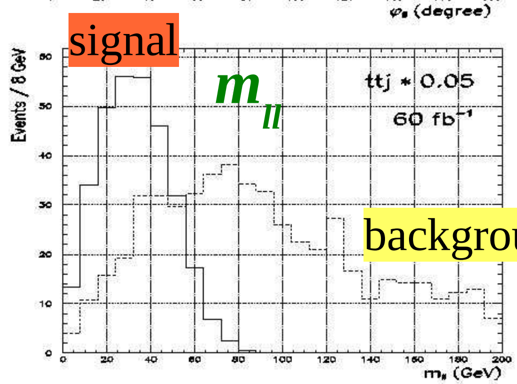
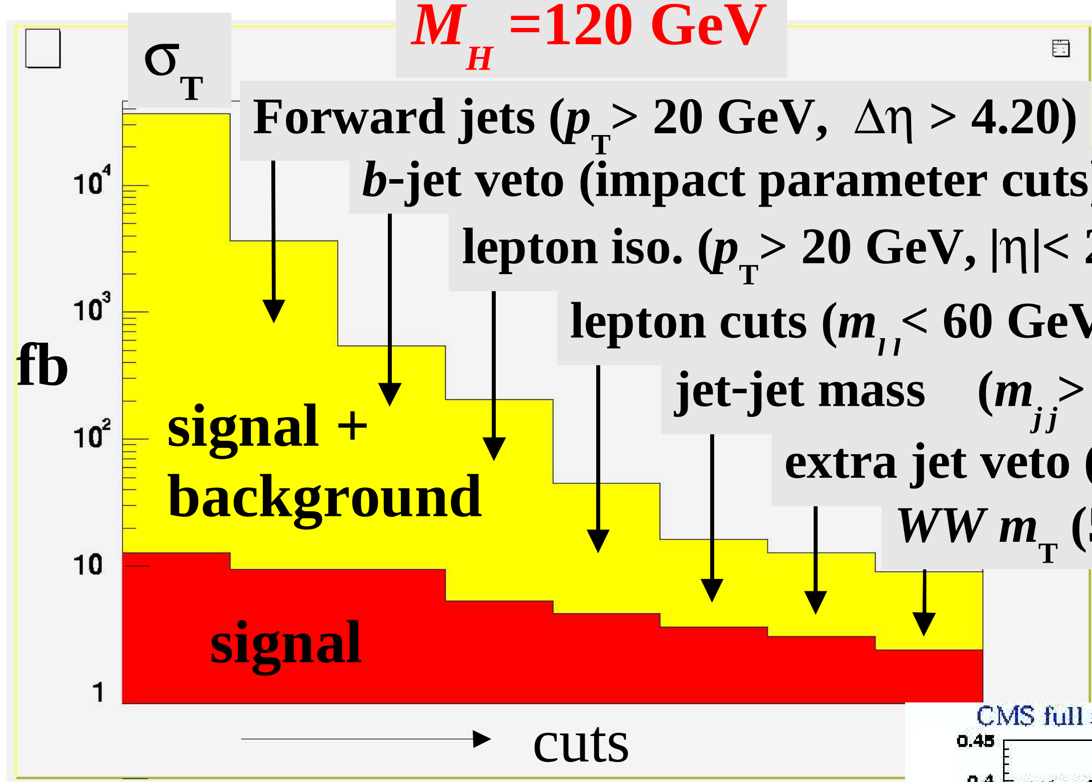


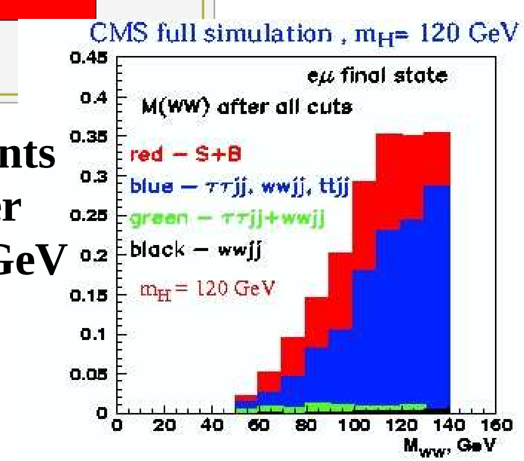






100 fb⁻¹: 220 events, 680 background

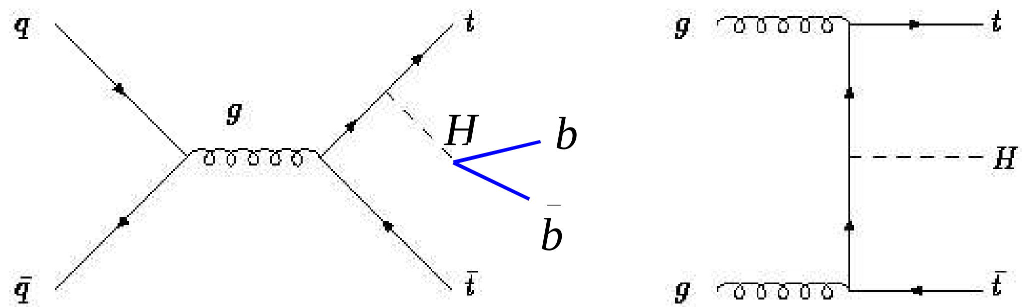
events per 10 GeV



SM: $t\bar{t}H^0$

final state:

$q\bar{q}b\ l\nu\bar{b}\ b\bar{b}$



main backgrounds:

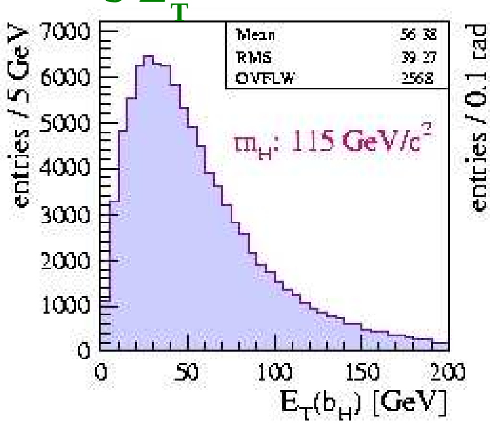
$t\bar{t}b\bar{b}$, $t\bar{t}Z$

event selection:

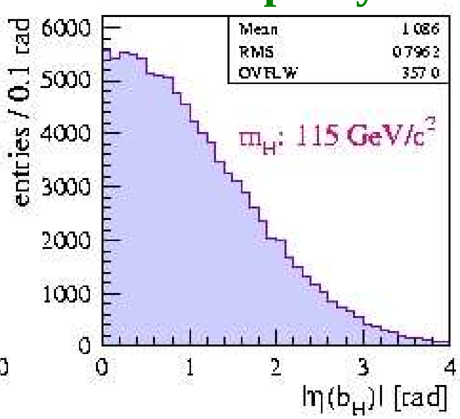
lepton, 4 *b*-tag jets, 2 non-*b* jets, *W* mass, *t* mass (2)

V. Drollinger *et al.*

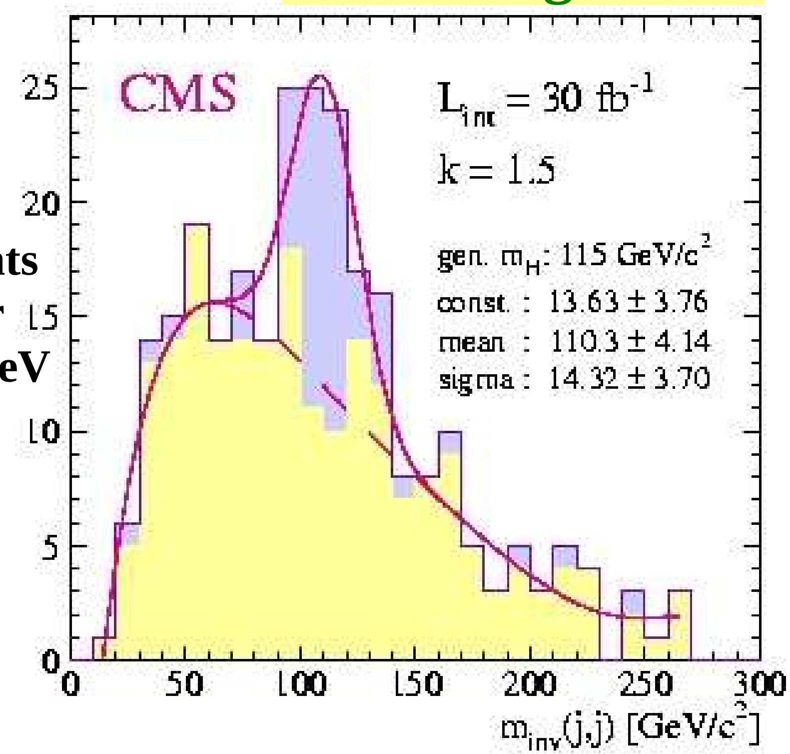
b E_T



b **Rapidity**



events per 10 GeV

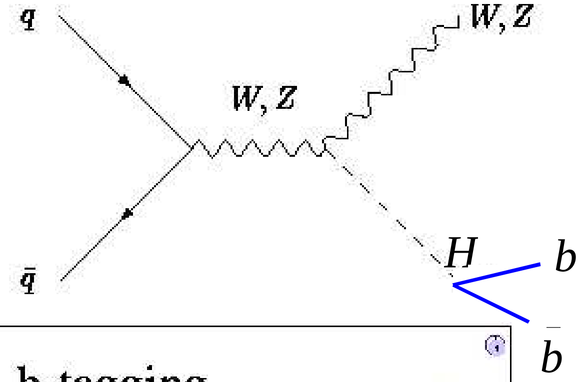


efficiency:

$t\bar{t}H$ (115 GeV)	1.3%
$t\bar{t}b\bar{b}$	0.4%
$t\bar{t}Z$	0.2%

SM: $WH^0 \rightarrow Wb\bar{b}$

final state: $l^{\pm}\nu\,\bar{b}b$



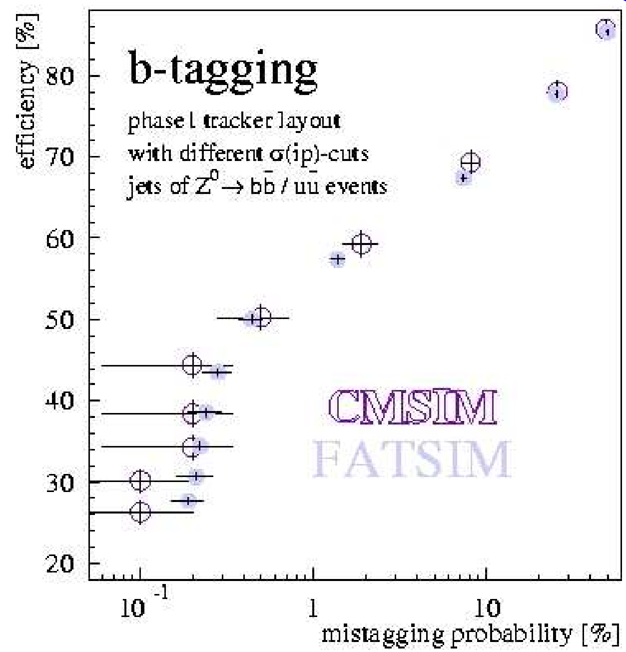
σ = 2.5 pb at M_H=100 GeV,

huge backgrounds from:

***$t\bar{t}$* (570 pb), *$t\bar{b}$* (320 pb),**

***Wjj* (30 pb),*WZ* (27 pb)**

***b*-tag is important**



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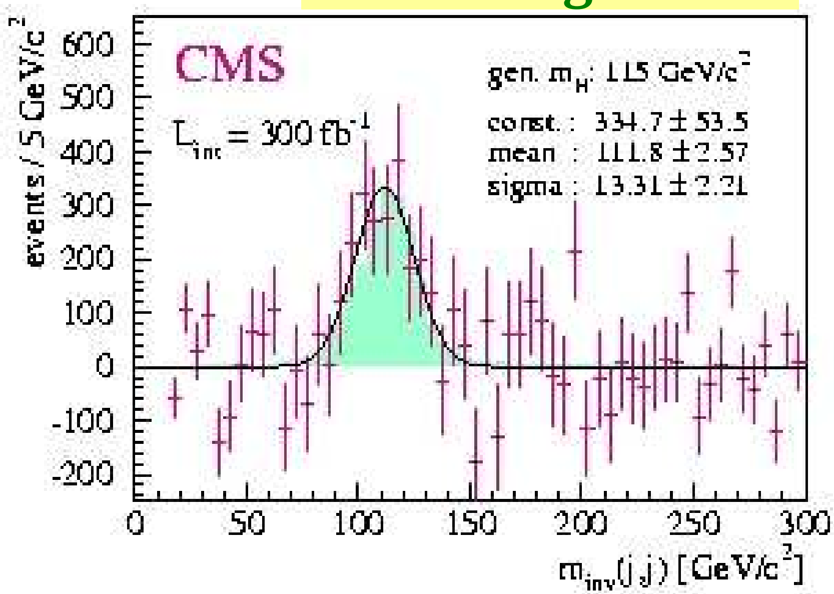
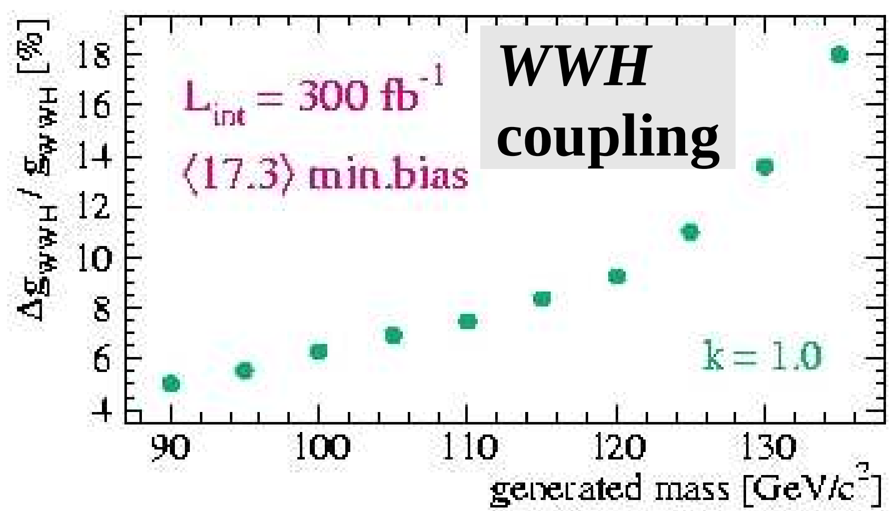
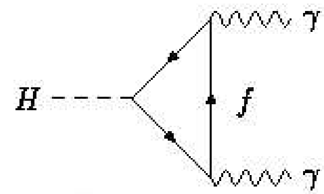


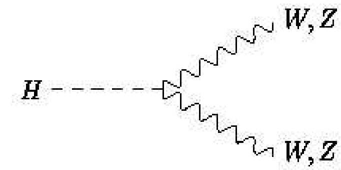


SM: γγ, WW, Z Z

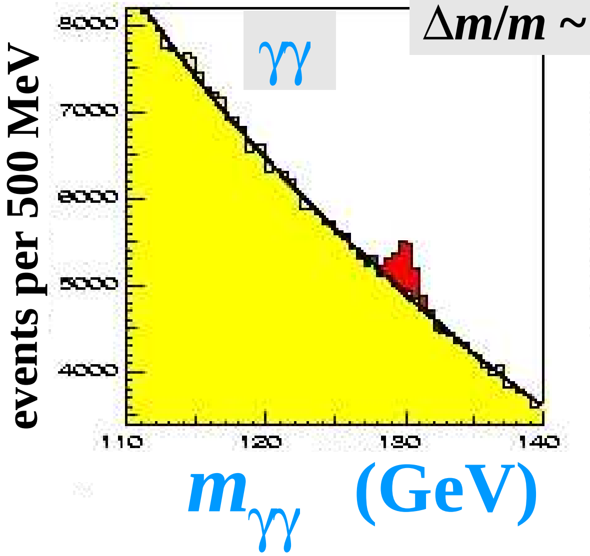
CMS Warhorses

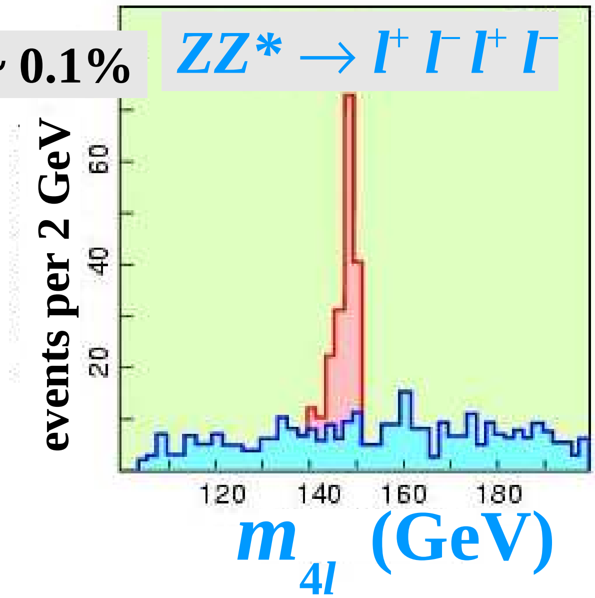
100 fb^{-1}

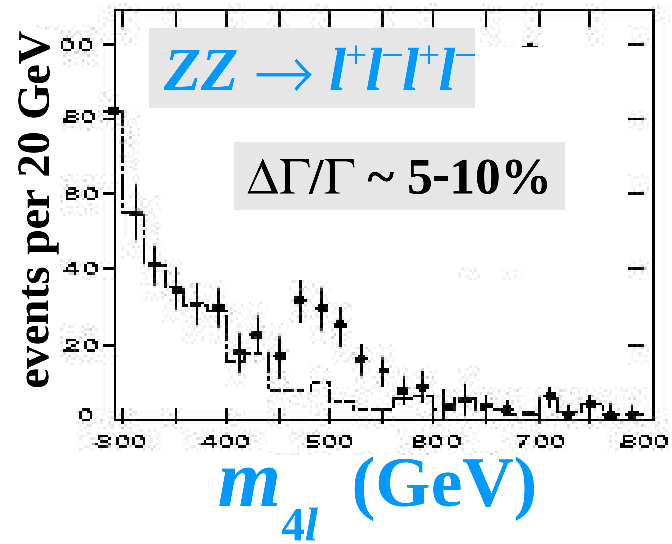




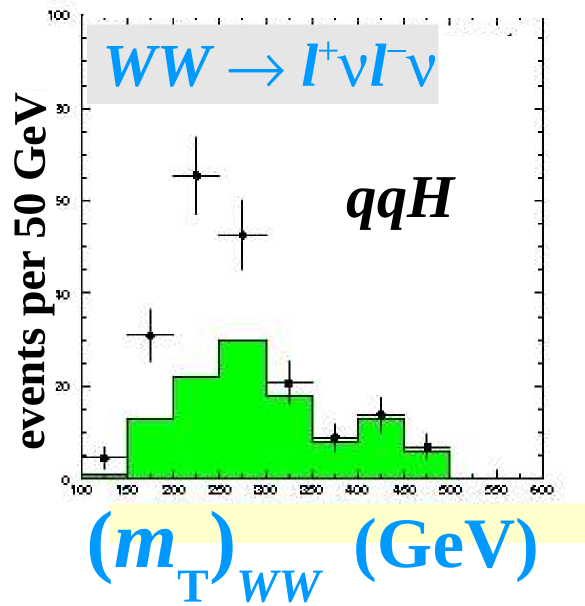
$\Delta m/m \sim 0.1\%$

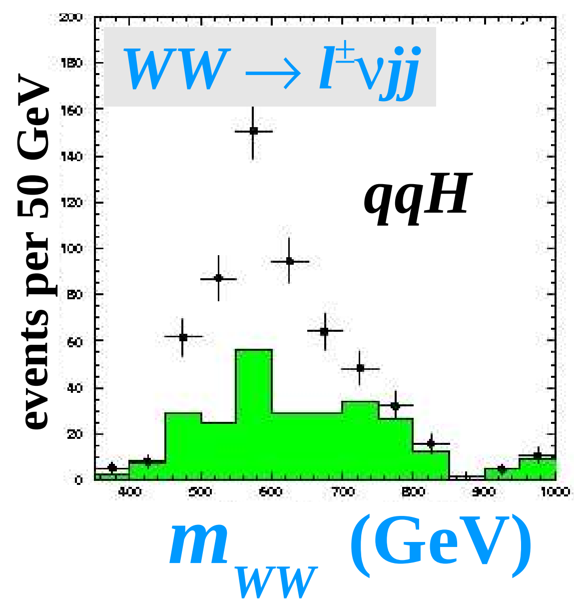


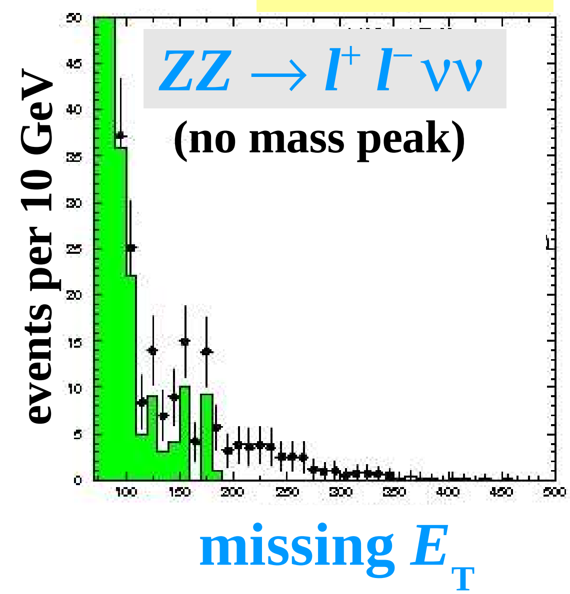




M. Dittmar



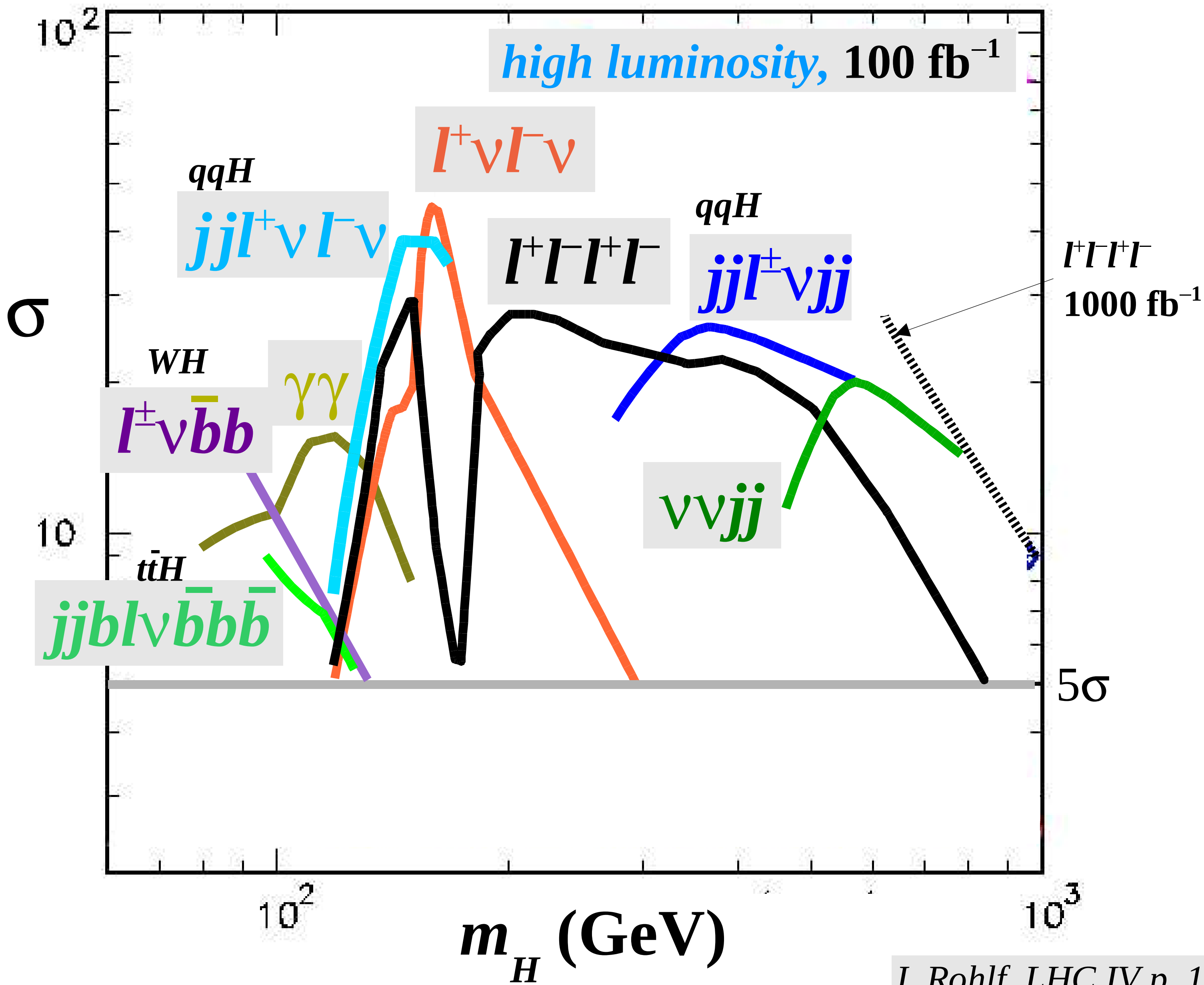




SM Higgs: Summary

Observable in multiple modes over entire mass range.

signal significance



MSSM Higgs

Minimal Supersymmetric Standard Model

... a 3-ring circus of Higgs bosons

- **Two parameters:**

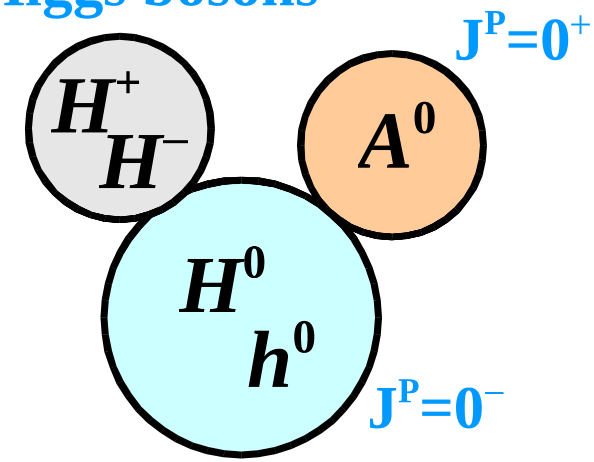
$\tan\beta = \frac{v_u}{v_d}$ (where $v_u = \sqrt{2}\langle\Phi_u^0\rangle, v_d = \sqrt{2}\langle\Phi_d^0\rangle$) and m_{A^0}

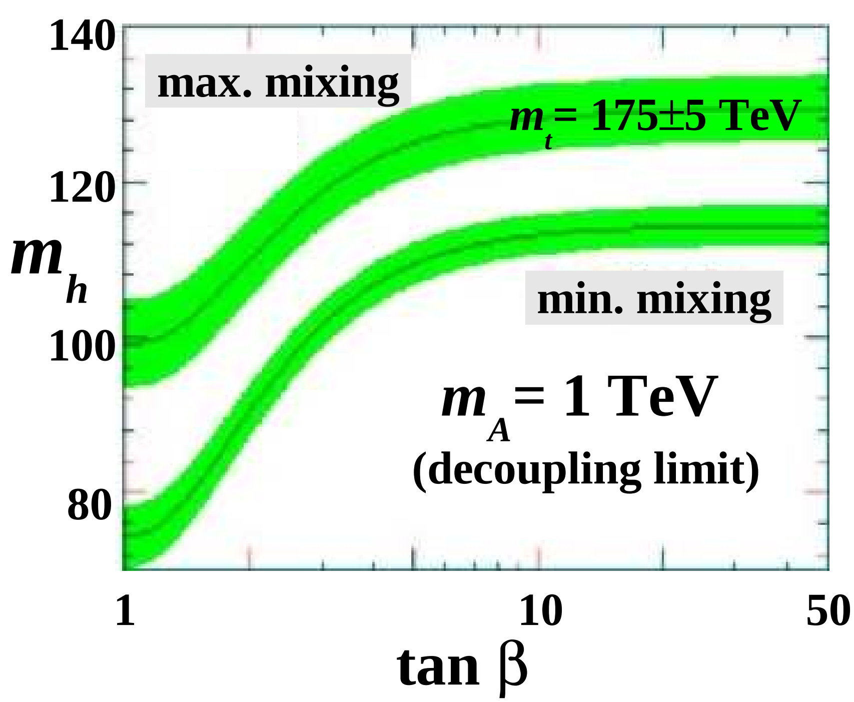
- **LEP limits are substantial!**

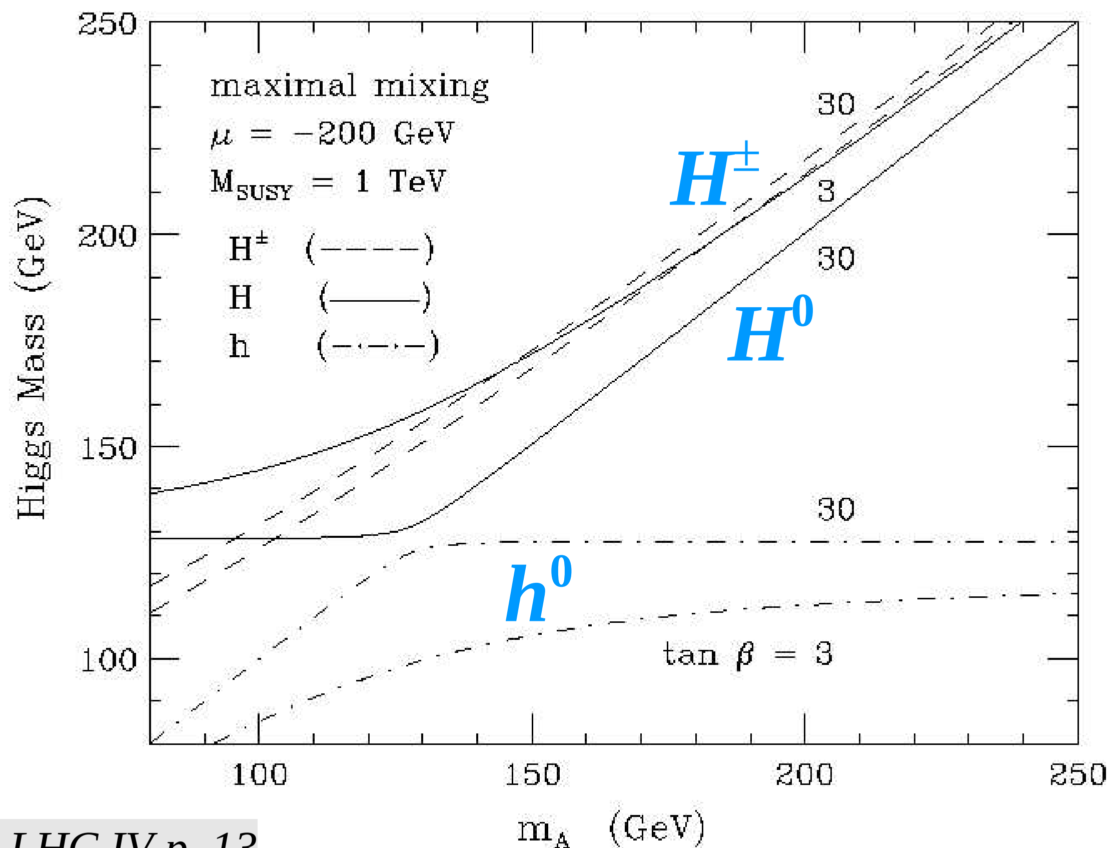
⇒ stay alive with maximal top-squark mixing

- ***h^0* behaves like *SM*-Higgs and is light**

⇒ low-mass *SM* channels are important





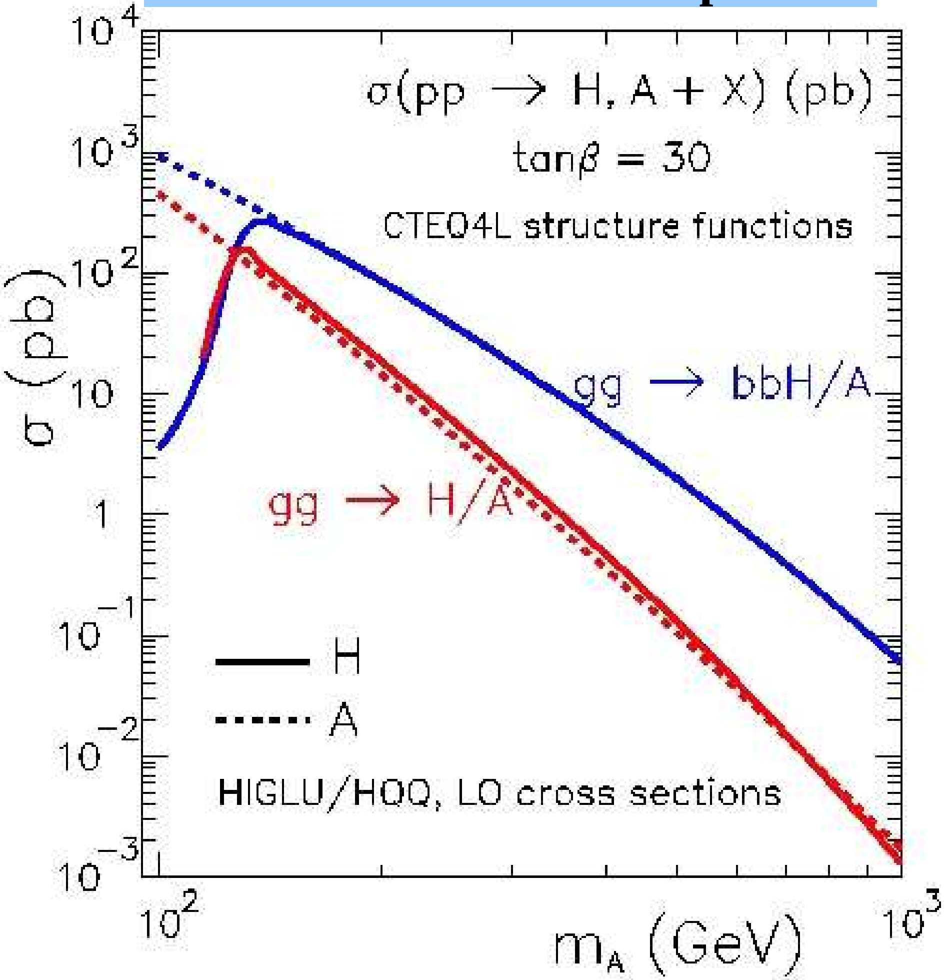


Review of Higgs Physics:
J. Gunion PASCOS 03.

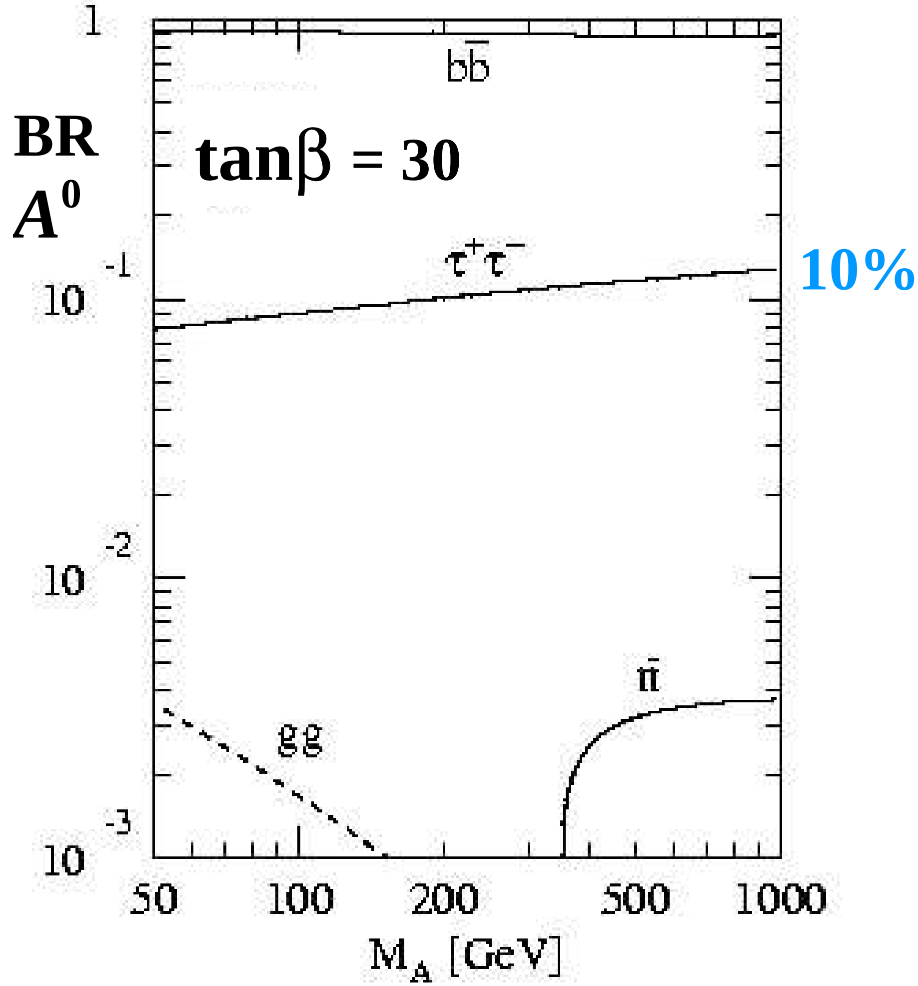
MSSM Higgs

couplings:
$b\bar{b}H^0, b\bar{b}A^0 \sim \tan\beta$
$\tau^+\tau^- H^0, \tau^+\tau^- A^0 \sim \tan\beta$

Radiation from *b's* is important

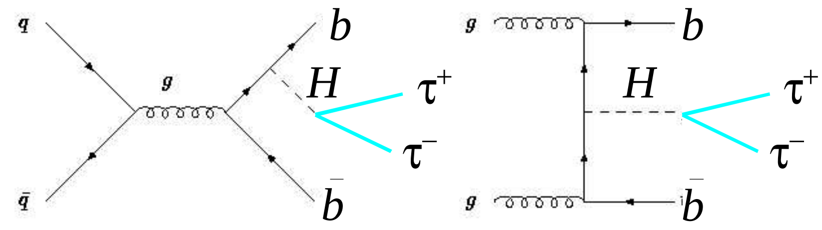


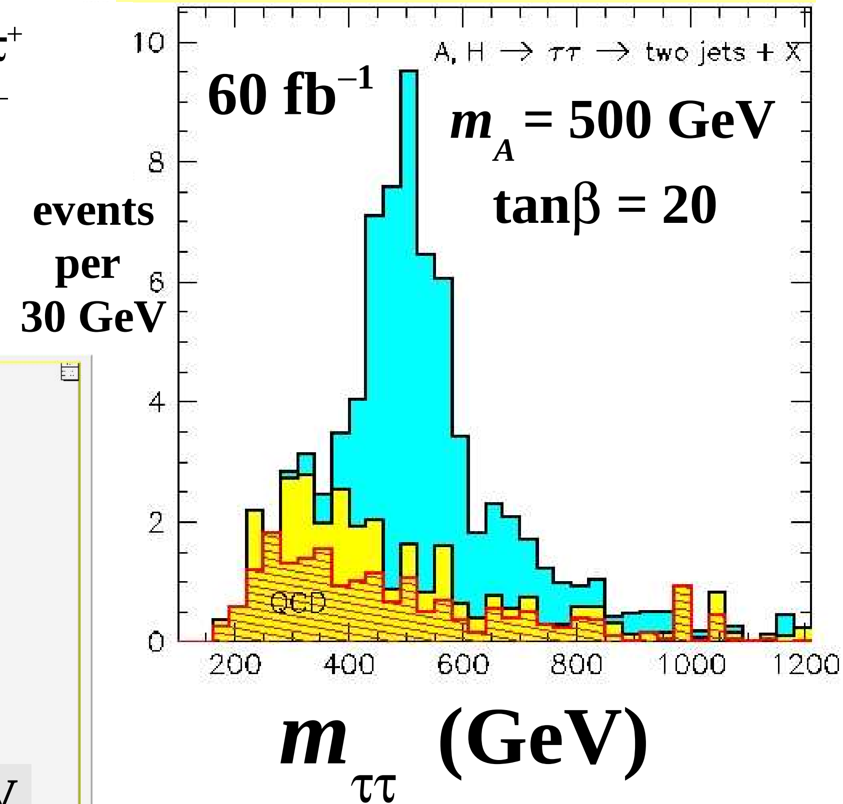
$\tau^+\tau^-$ also an important decay



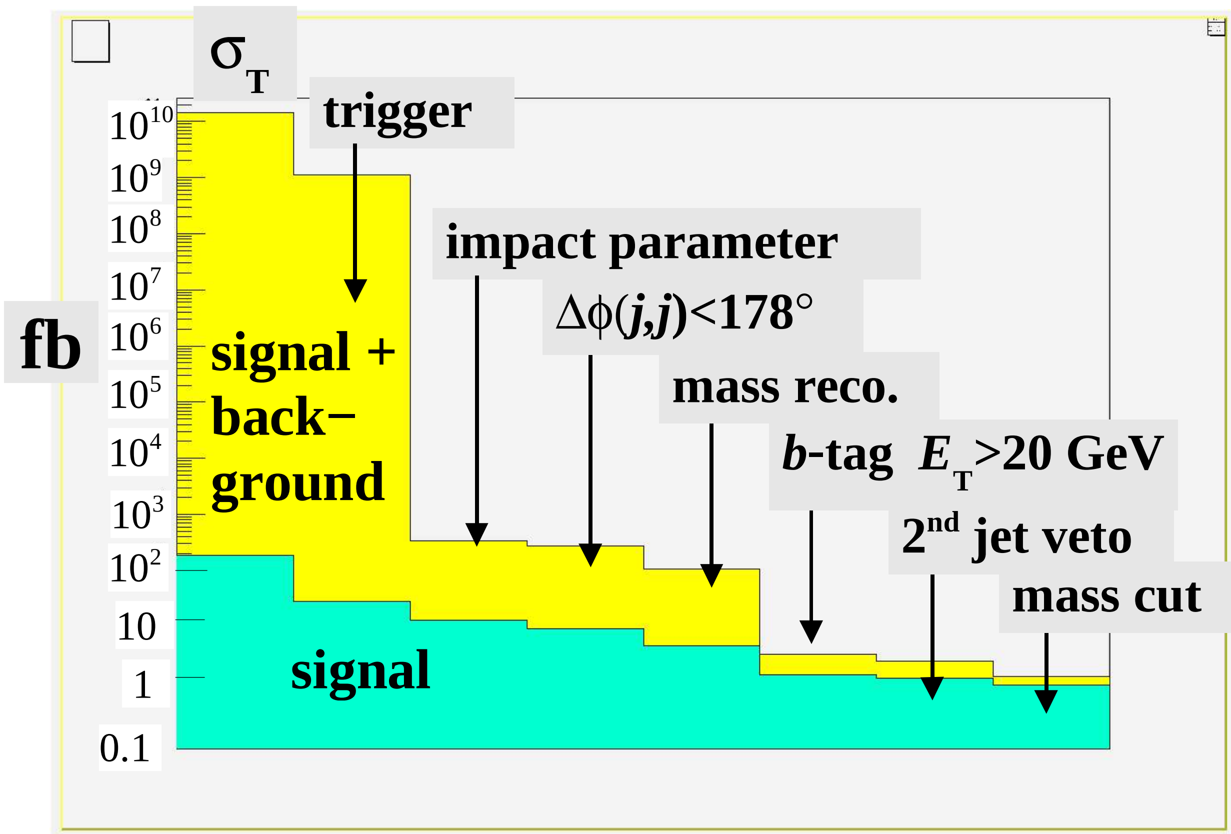
MSSM: $b\bar{b}H^0/A \rightarrow b\bar{b}\tau^+\tau^- \rightarrow b\bar{b}jj$

R. Kinnunen, A. Nikitenko



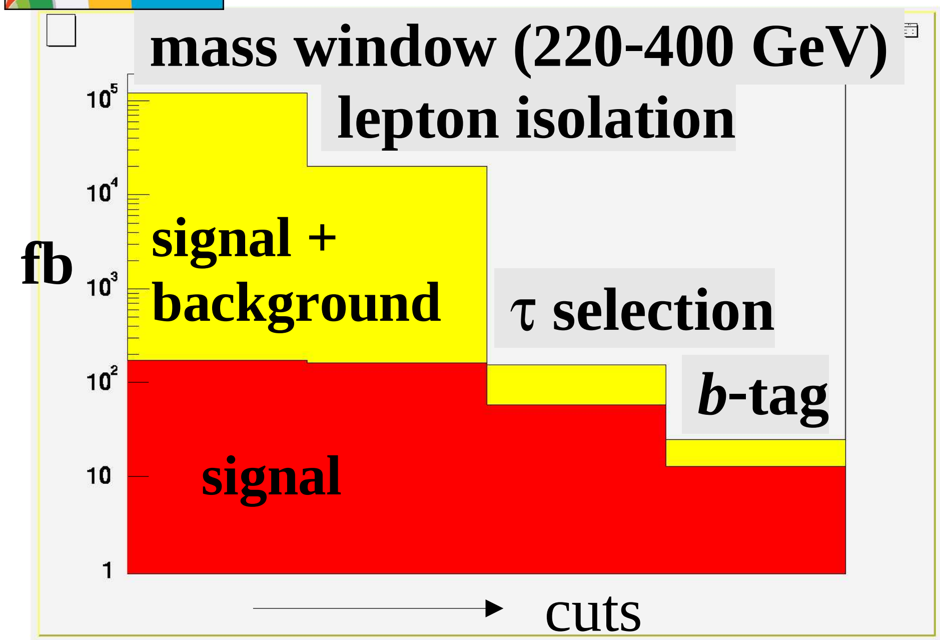


Background dominated by QCD



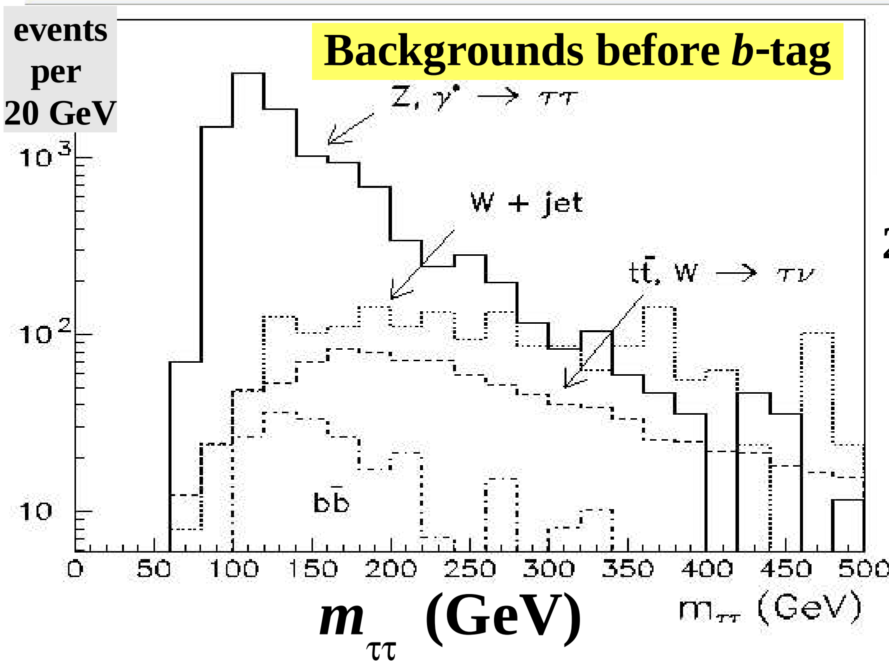
20% background from
***W*, *Z*, top after cuts**

MSSM: $b\bar{b}H^0/A \rightarrow b\bar{b}\tau^+\tau^- \rightarrow b\bar{b}l^\pm j$

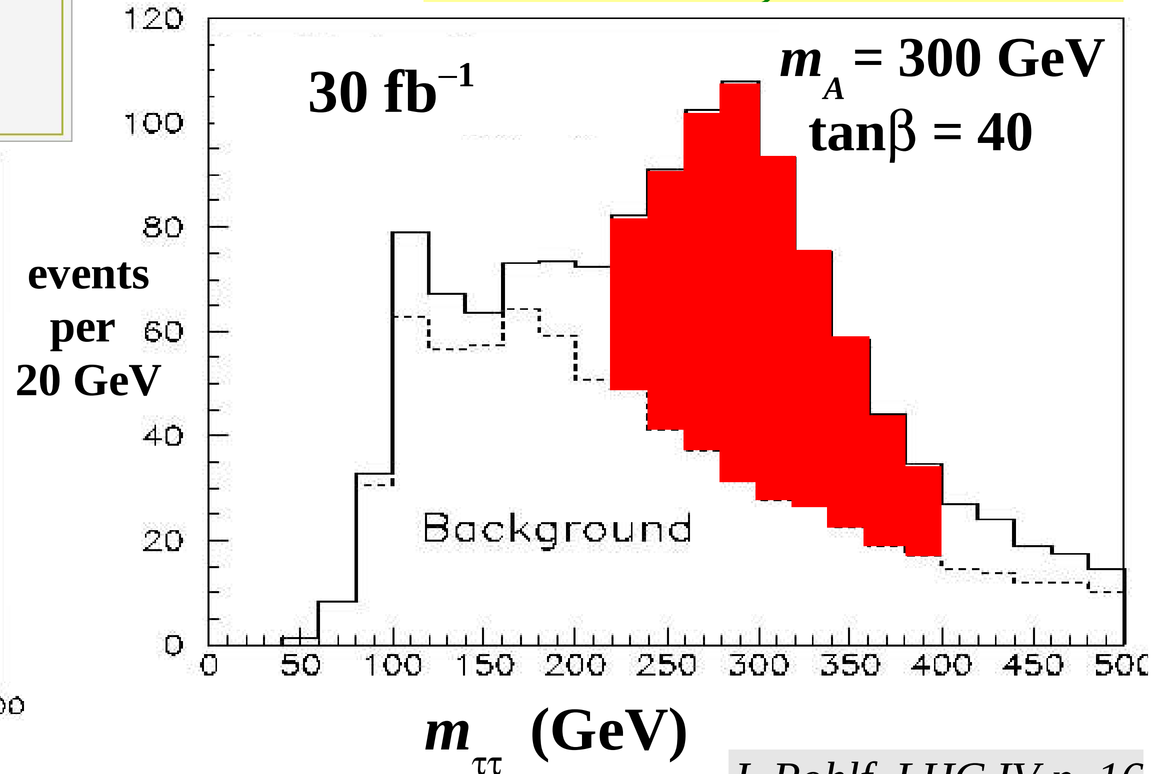


τ-selection reduces *b* background
***b*-tag reduces *W/Z* background**

After cuts, $W\rightarrow\tau$ from top dominates background



R. Kinnunen, A. Nikitenko

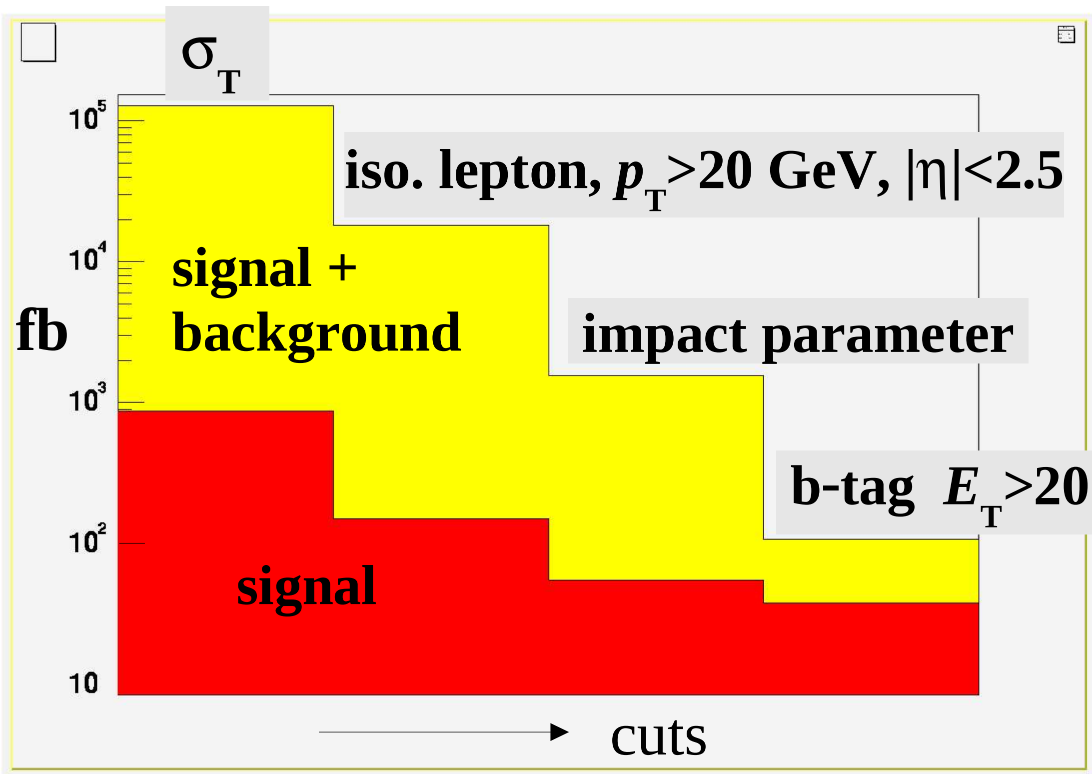


MSSM: $b\bar{b}H^0/A^0 \rightarrow b\bar{b}\tau^+\tau^- \rightarrow \bar{b}be\mu$

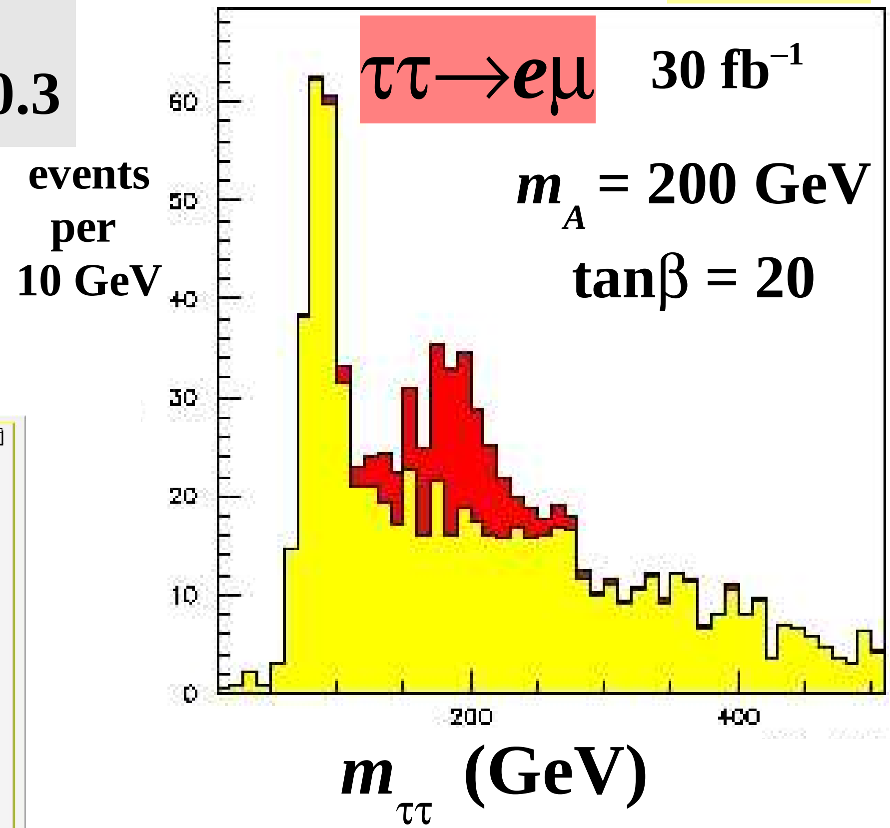
2 isolated high-p_T leptons:

no track p_T>2 GeV with ΔR < 0.3

main background from top, *Z*
***b*-tag suppresses the *WW* background**



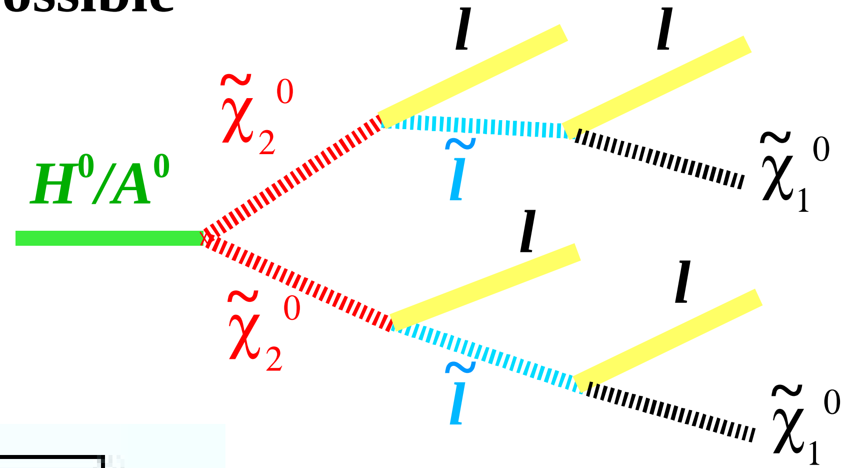
S. Lehti



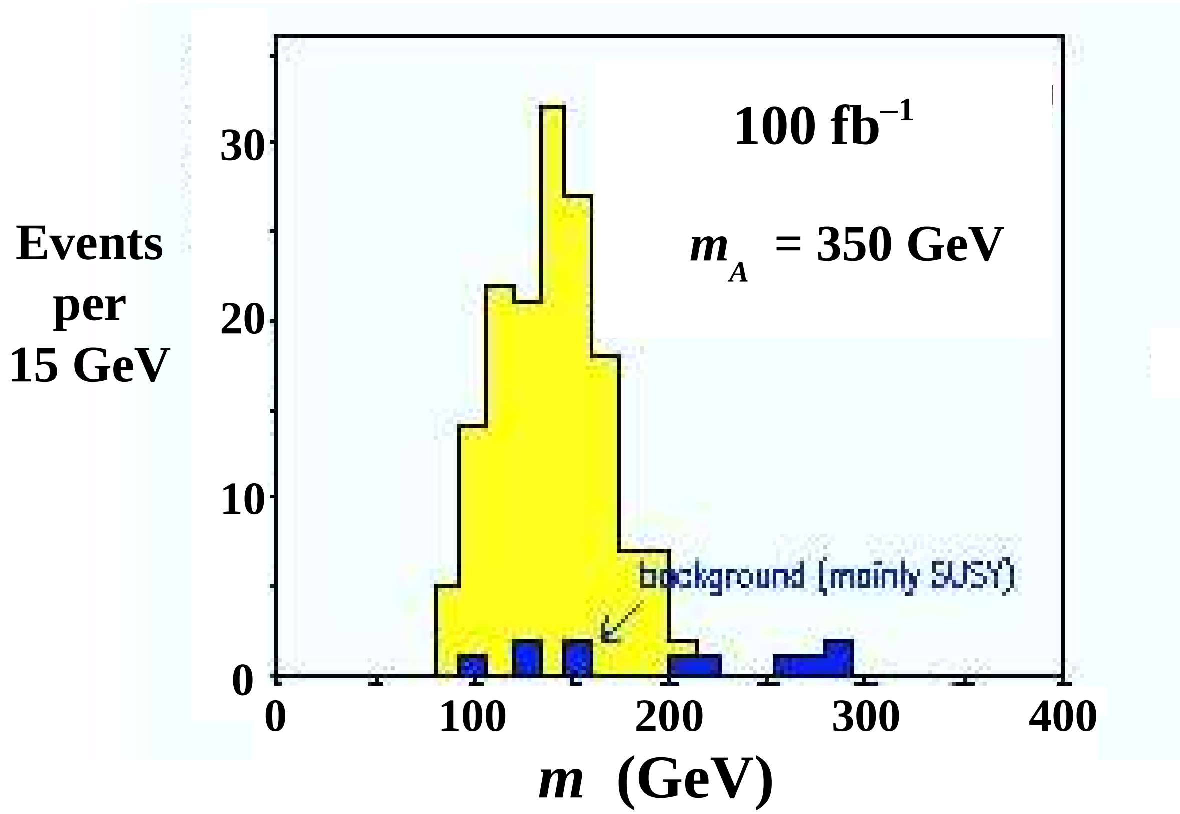
(e^+e^- and $\mu^+\mu^-$ suffer from high DY background)

MSSM: $H^0/A^0 \rightarrow \chi^0\chi^0 \rightarrow 4l$

Easy target if kinematically possible

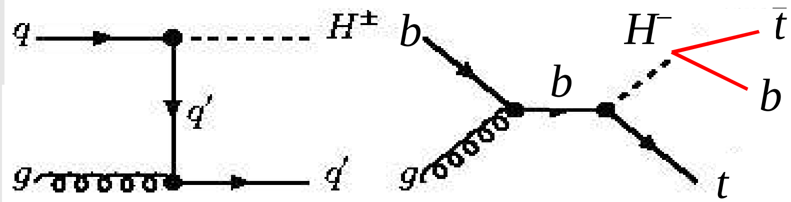


Backgrounds from SM ($t\bar{t}$, ZZ, $Zb\bar{b}$, $Zc\bar{c}$, $Wt\bar{b}$) and SUSY are suppressed with jet and Z veto

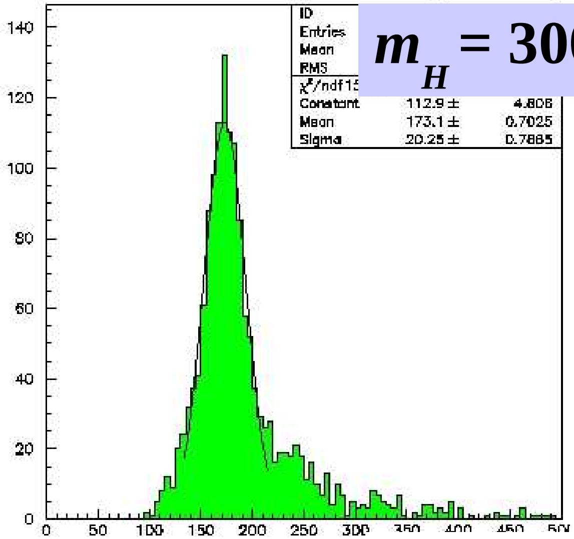


MSSM: $tH^- \rightarrow t\bar{t}b$
$\bar{t}H^+ \rightarrow \bar{t}t\bar{b}$

Radiation from a *b*-quark



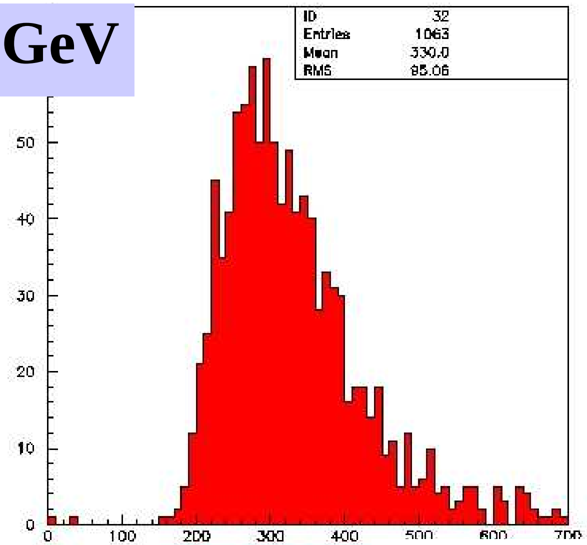
semileptonic *t*



m_t (GeV)

Higgs mass (*t* + *b*)

m_H = 300 GeV

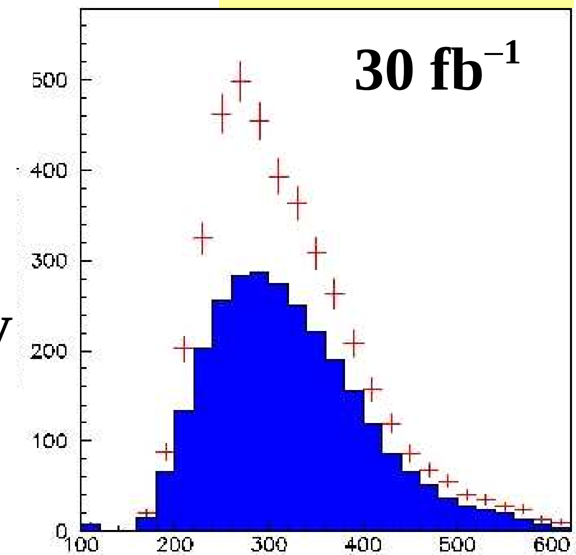


m_{tb} (GeV)

Event selection:
lepton from *W*, p_T>15 GeV
5 jets p_T > 20 GeV, |η|< 2.4
3 *b*-tags

P. Salmi *et al.*

events per 20 GeV



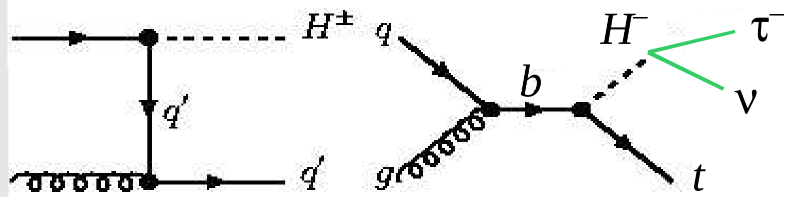
m_H (GeV)

Backgrounds:
$t\bar{t}$ + jet (two *b*'s and one mistag)
$t\bar{t}\,b\bar{b}$

MSSM: $tH^- \to t\tau^-\nu$

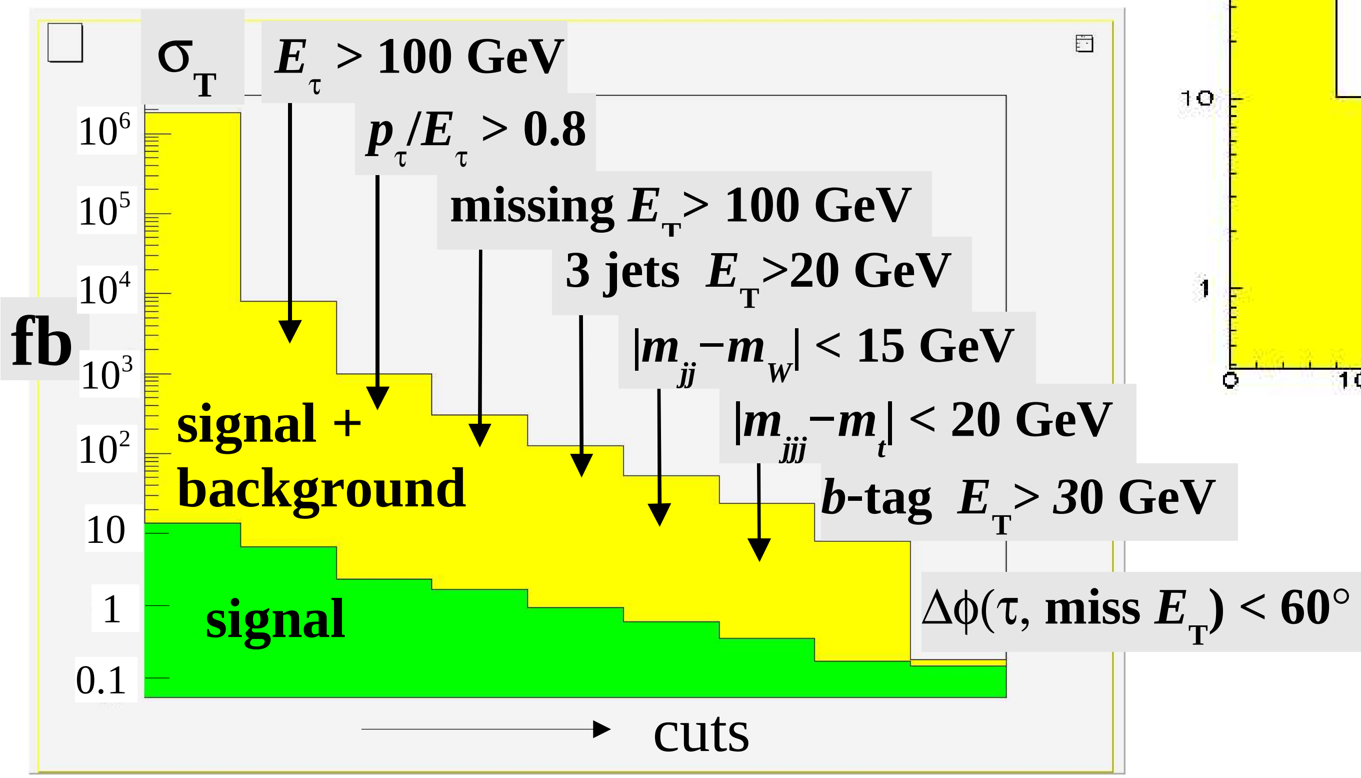
$\bar{t}H^+ \to \bar{t}\tau^+\nu$

Radiation from a b-quark

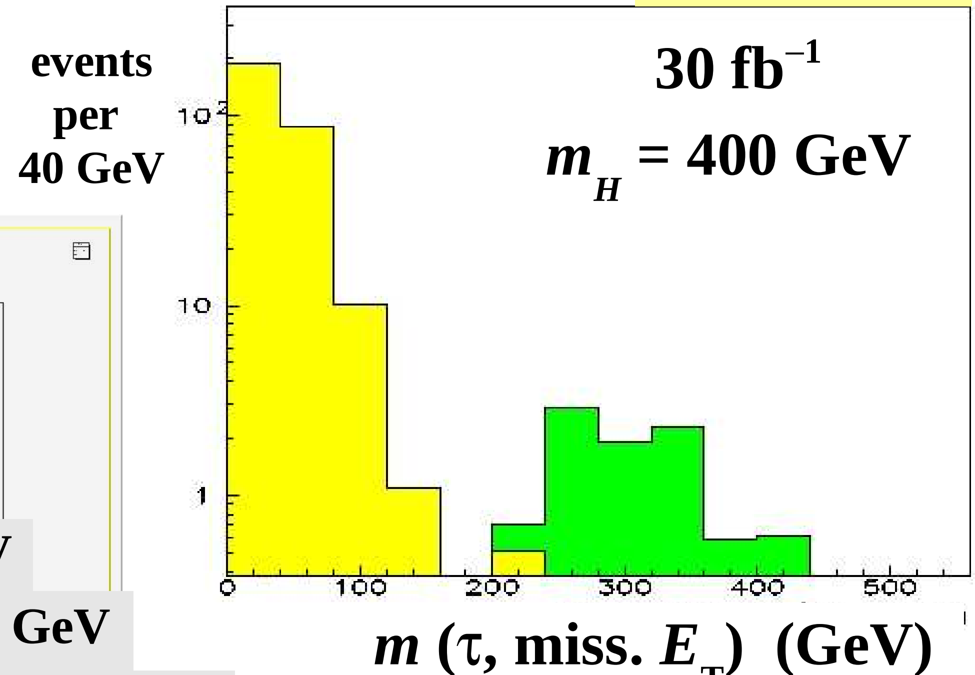


hadronic tau decay

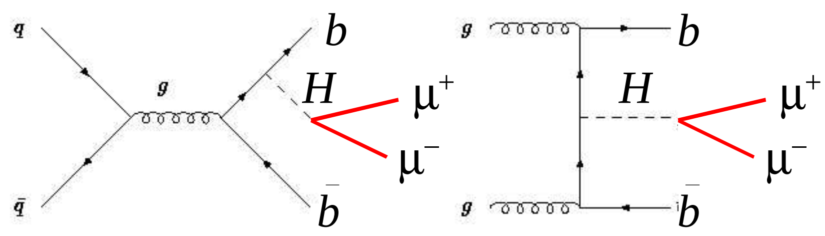
Main backgrounds:
$t\bar{t}$, $W + X$



R. Kinnunen



MSSM: $b\bar{b}H^0/A^0 \rightarrow b\bar{b}\mu^+\mu^-$



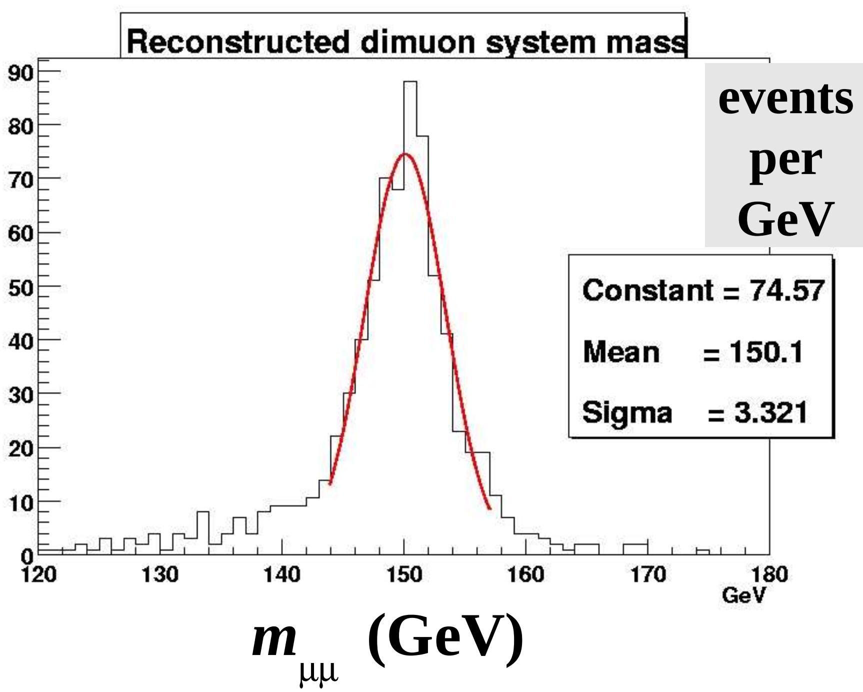
small BR:

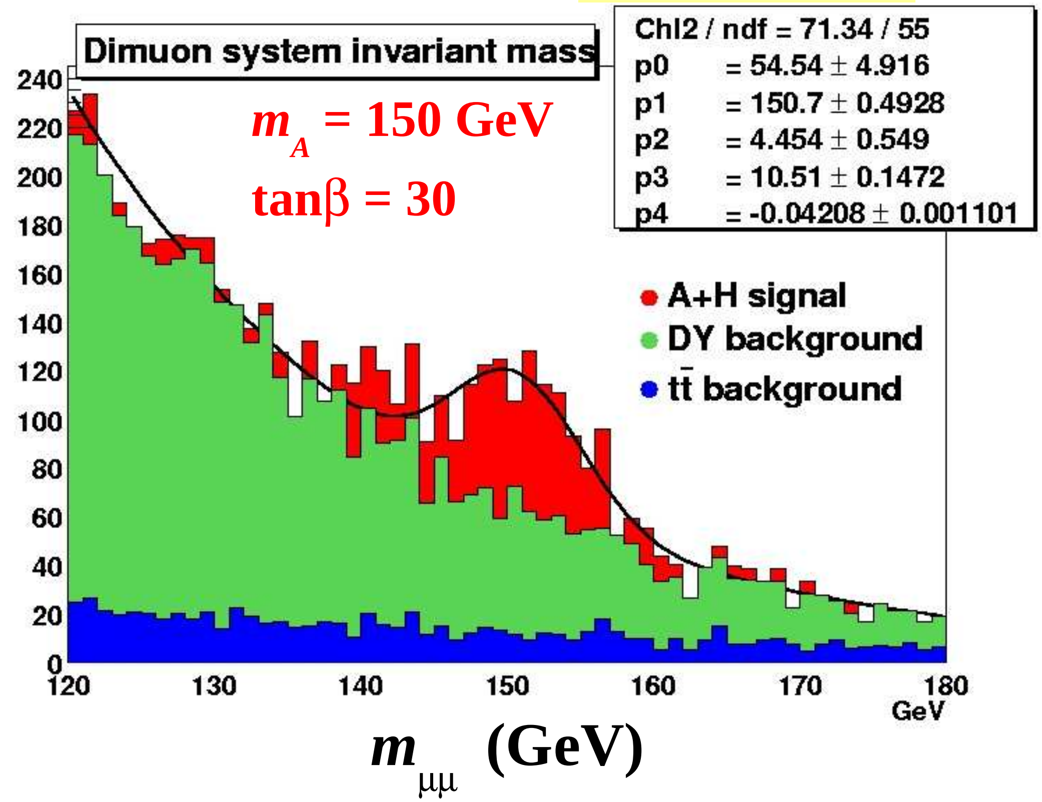
$(m_\mu/m_\tau)^2 = 4 \times 10^{-3}$

clean signature

20 fb^{-1}

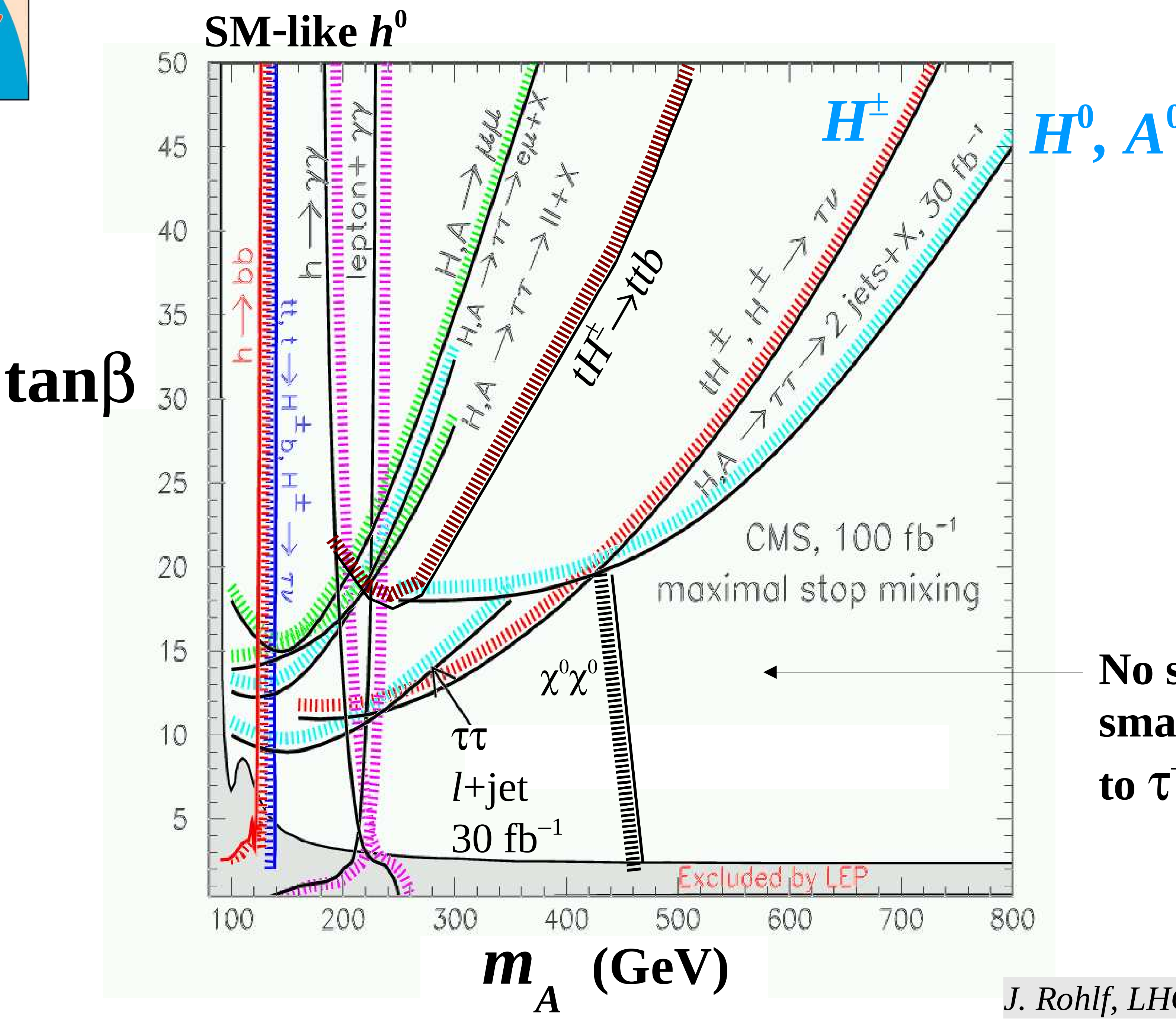
R. Kinnunen





$t\bar{t}$ background reduced with central jet veto

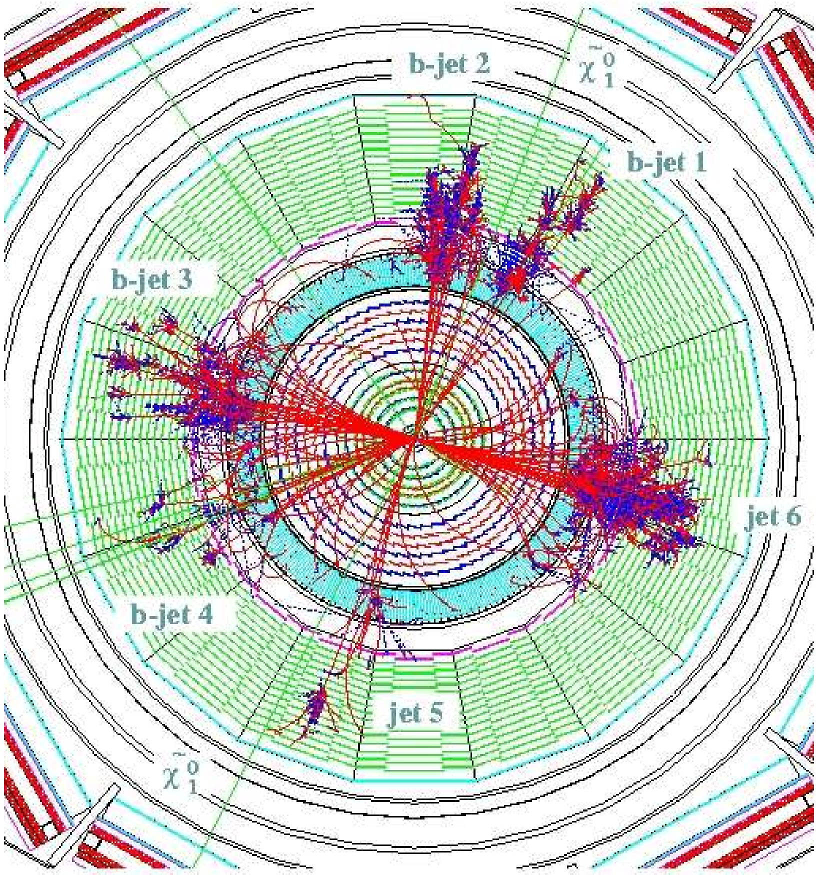
MSSM Higgs: Summary

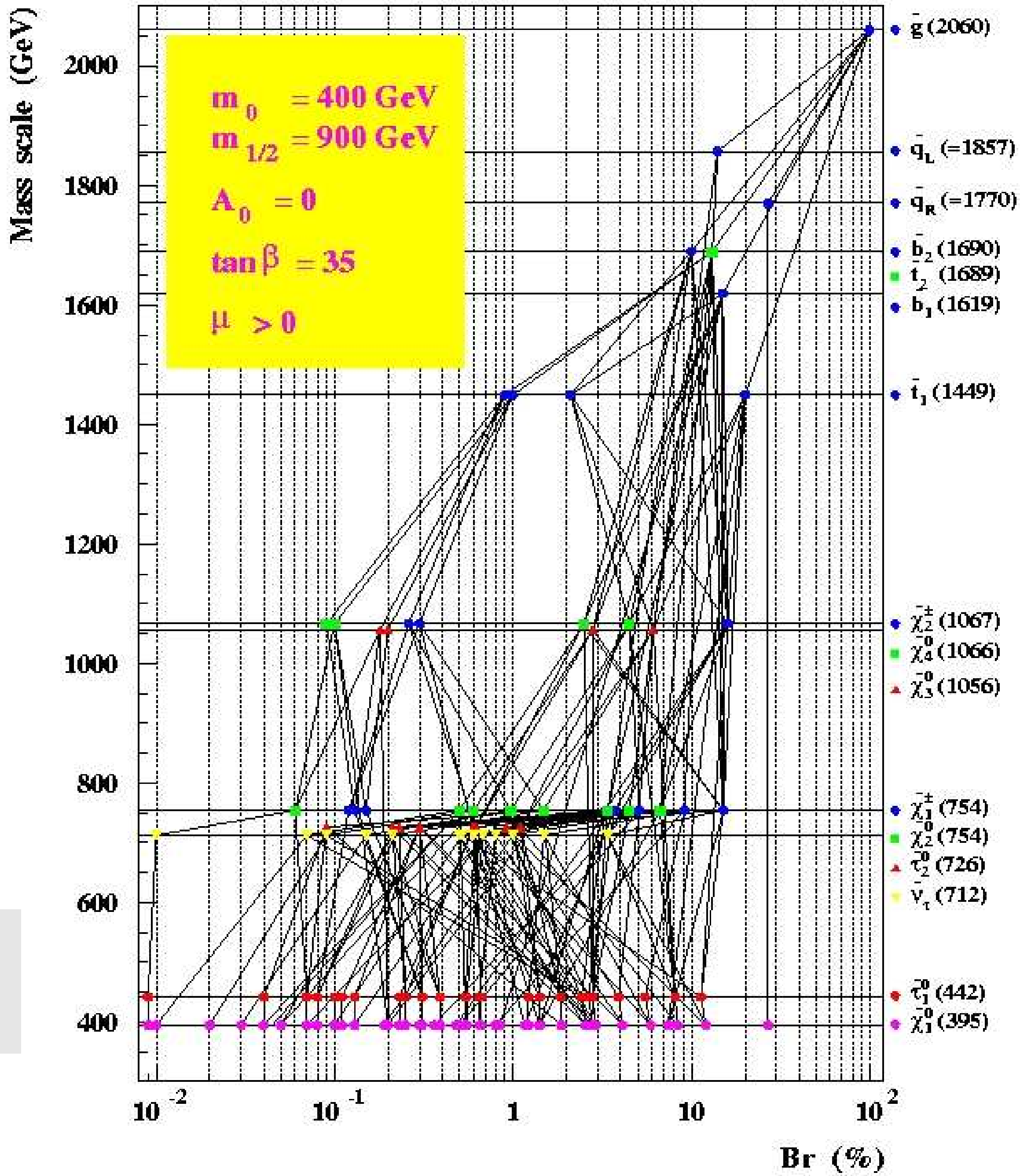


No signal: small BR to $\tau^+\tau^-$

SUSY: Sparticle Search

Supersymmetry

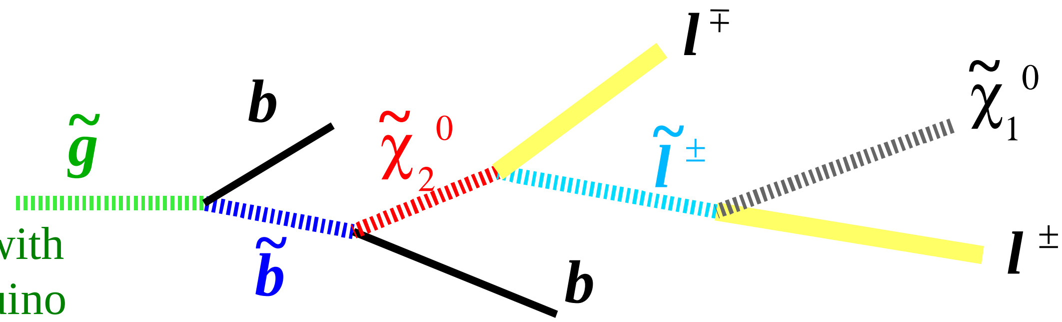




Distinctive signature of leptons, jets, missing E_T for some events

J. Rohlf, LHC IV p. 23

Sparticle Reconstruction



pair−produced with squark or 2nd gluino (1 or 2 jets + missing E_T)

Event signature:

2 leptons, p_T>15 GeV, $|\eta|$< 2.4

2 b-jets, p_T>20 GeV, $|\eta|$< 2.0

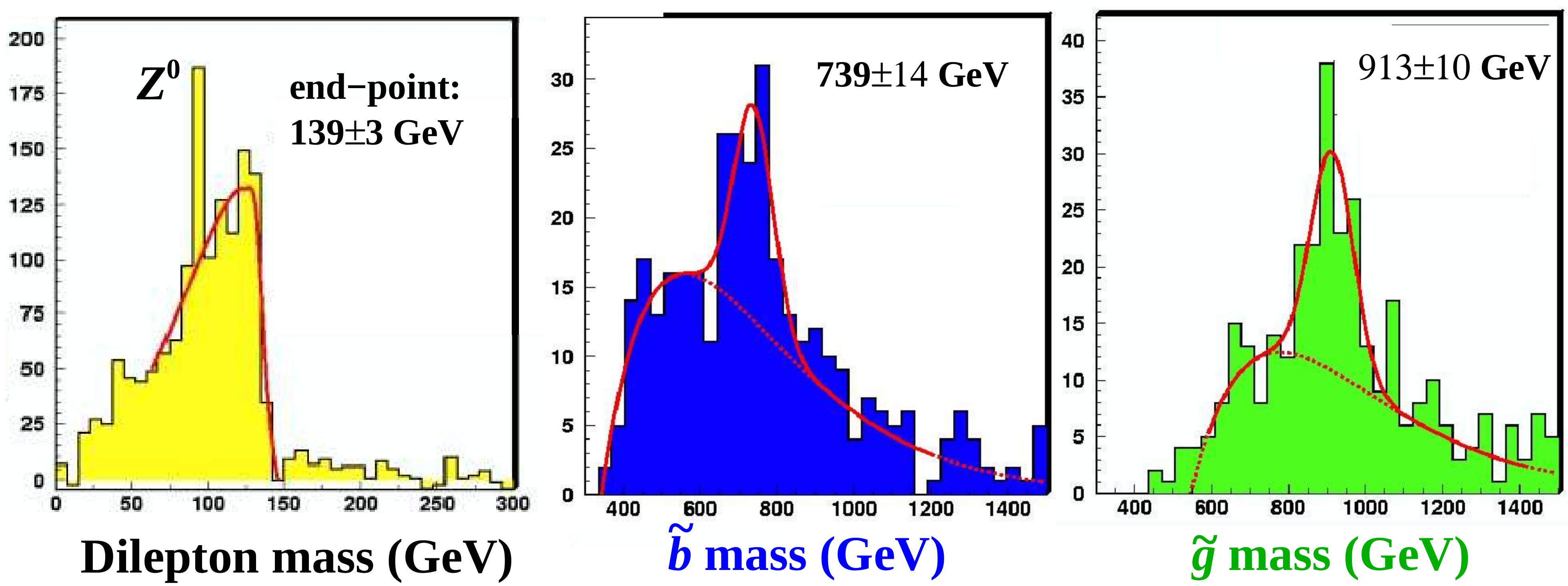
Large Missing E_T

SM backgrounds:

$t\bar{t}$, Z+jet, W+jet, ZZ, WW, ZW

Example: $m_{1/2}$ = 375 GeV, m_0 = 120 GeV, tanβ = 20

500 fb^{-1} **missing E_T > 250 GeV** **A. Tricomi *et al.***

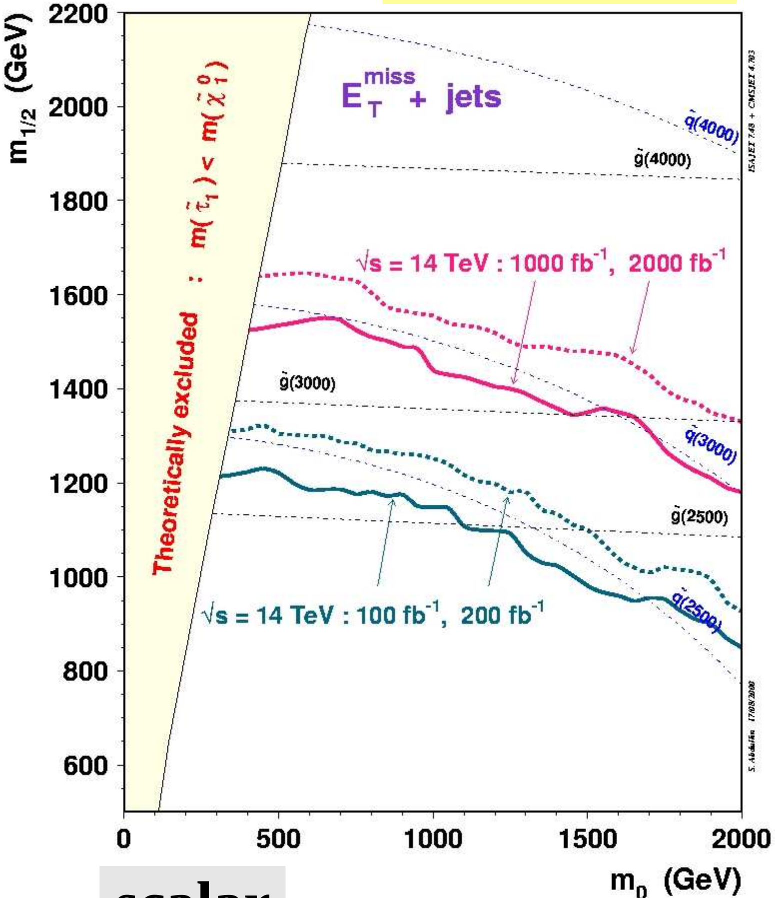


mSUGRA

Minimal Supergravity

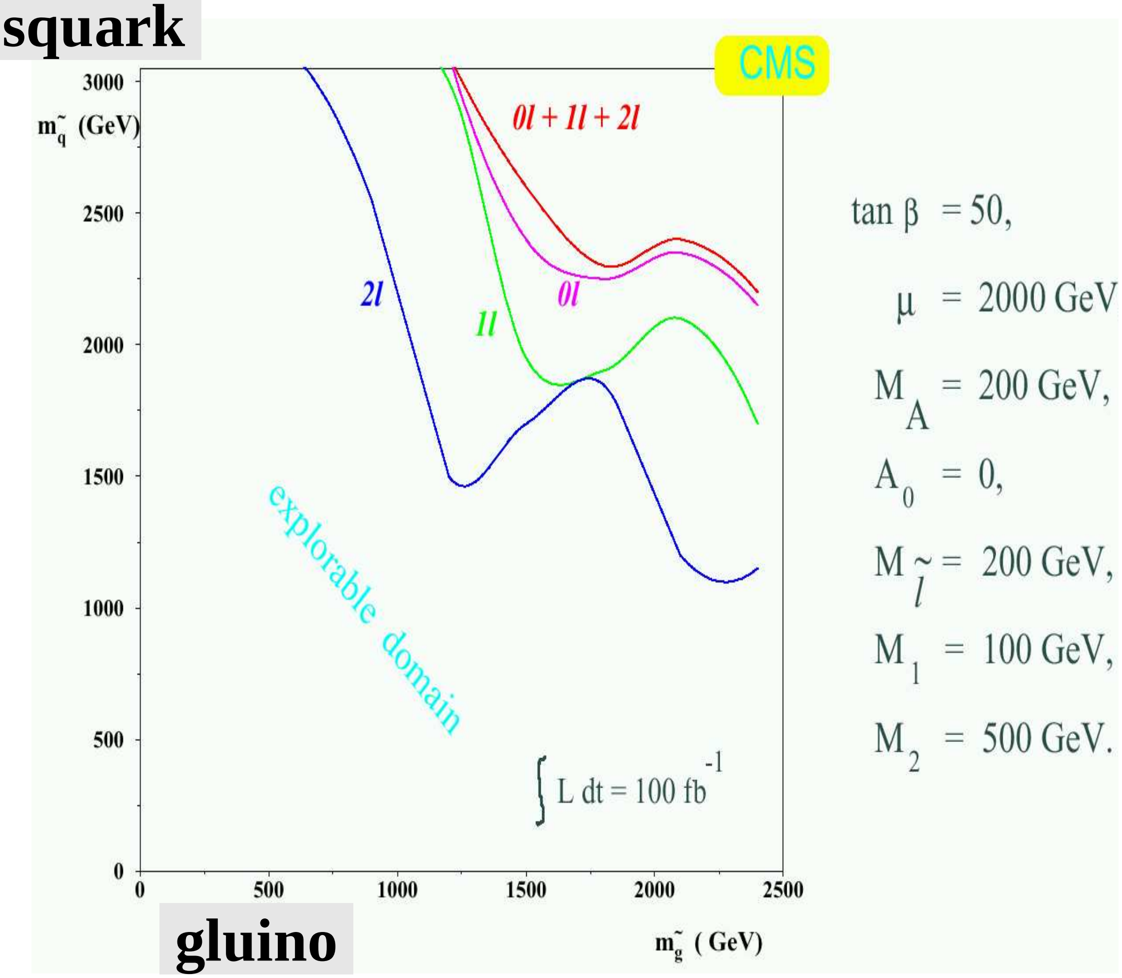
gaugino

S. Abdoulline



scalar

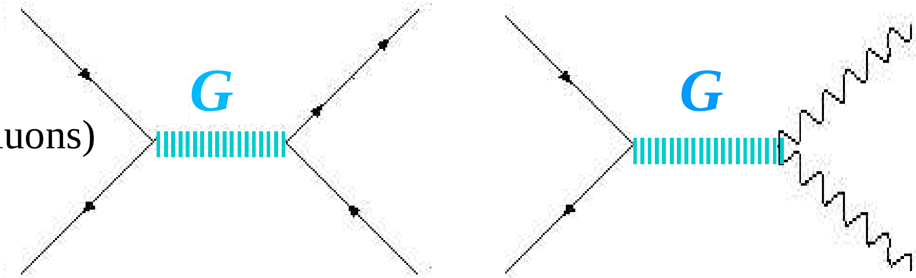
squark



gluino

Kaluza-Klein Graviton

(or gluons)

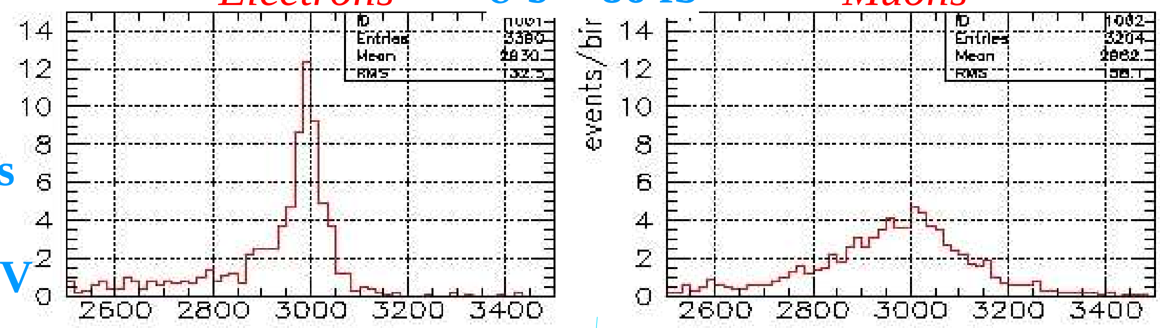


Randall-Sundrum Model

Exploiting the geometry of spacetime to solve the hierarchy problem.

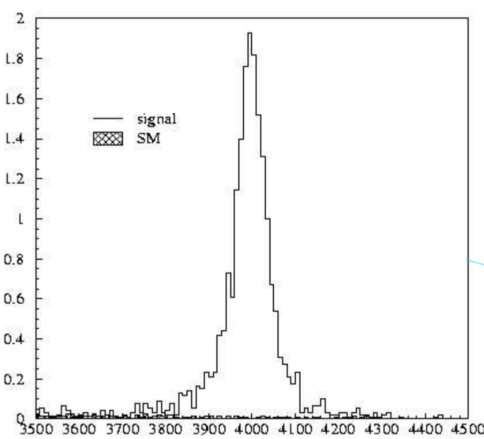
Electrons $\sigma \bullet b$ = 86 fb *Muons*

events per 20 GeV

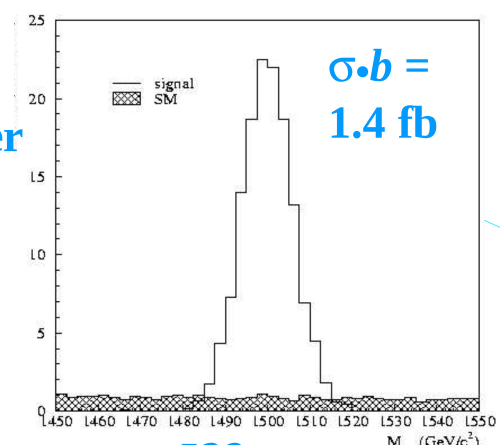


$m_{e^+e^-}$ $m_{\mu^+\mu^-}$

events per 10 GeV



events per 2.5 GeV

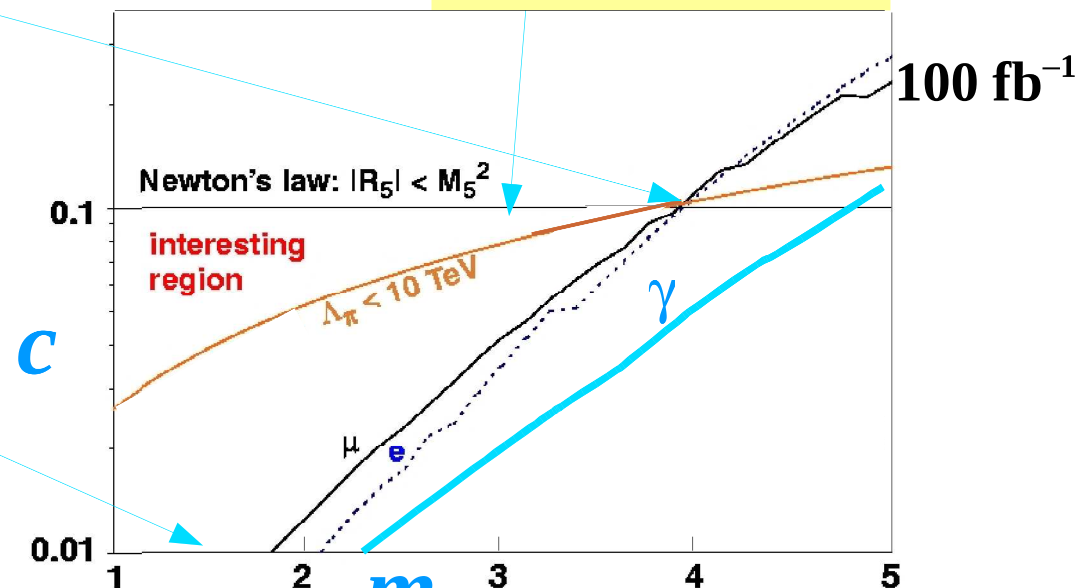


$\sigma \bullet b$ = 1.4 fb

$m_{\gamma\gamma}$

G. Wrochna *et al.*

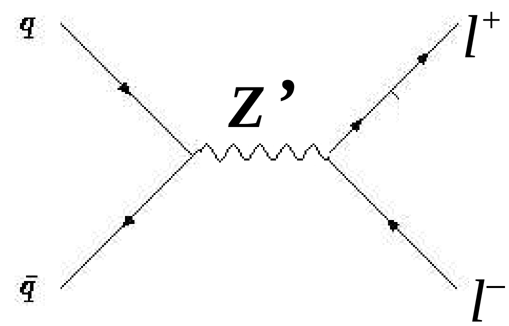
c

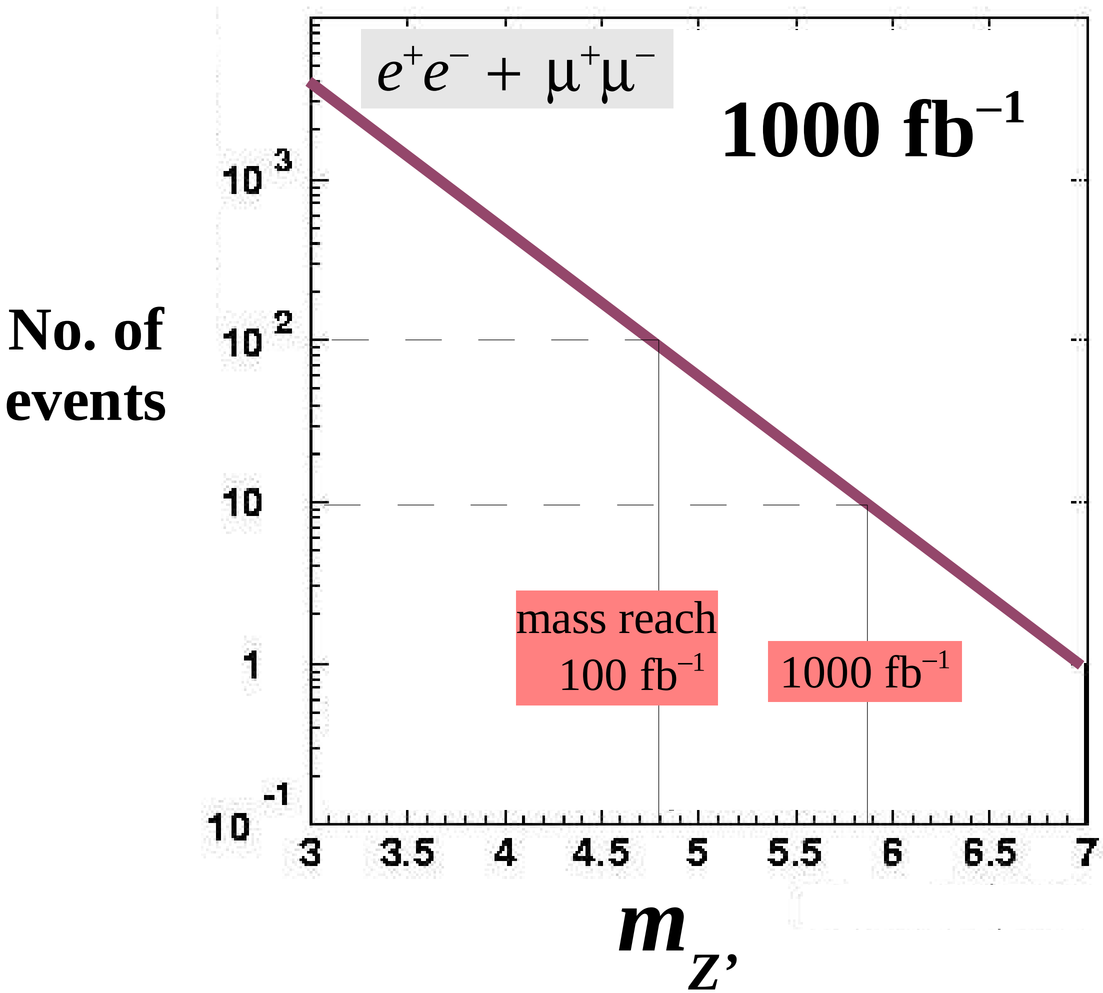


m_G

J. Rohlf, LHC IV p. 26

Z’



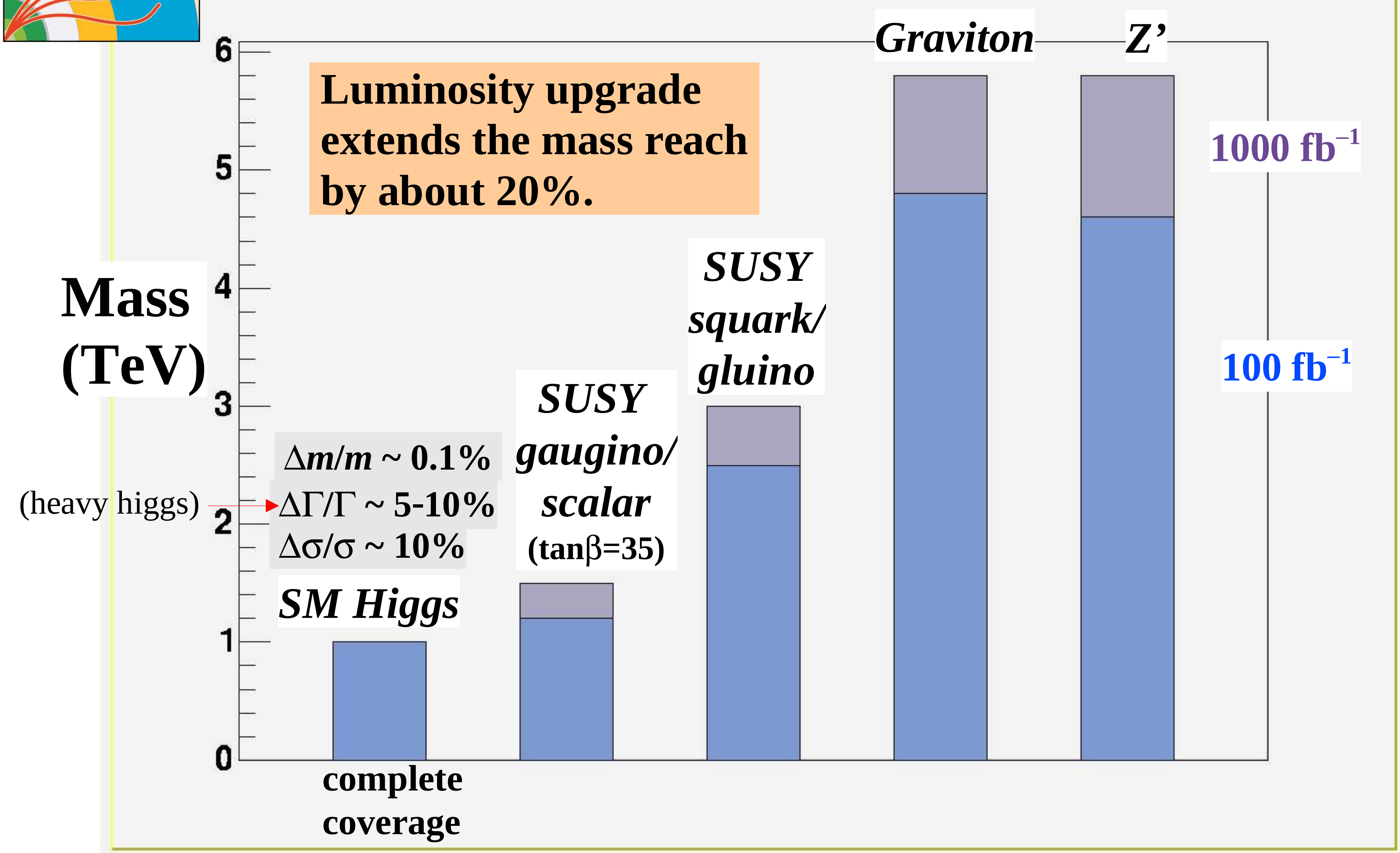


Corrected for:

- **acceptance**
- **reconstruction efficiency**
- **resolution**
- **crystal saturation**
- **pileup at 10^{35} cm^{-2}s^{-1}**

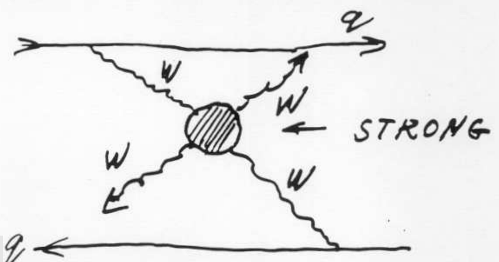
Backgrounds:
Drell-Yan 2%
$t\bar{t} < 1\%$

CMS Mass Reach: Summary



Longitudinal W/Z^0 Scattering

UNITARITY LIMIT : $\sqrt{s} = 1.7$ TeV
$G_F s = 8\sqrt{2}\,\pi$, NOT $G_F s = 1$.
SEARCH FOR $W_L W_L$ SCATTERING



L. Okun
ITEP
Moscow
09.10.89

HISTORIC ANALOGY

1. CLASSICAL RADIUS OF ELECTRON
$r_0 = e^2/mc^2 \simeq 10^{-13}$ cm
AT $r < r_0$ CED FAILED.

BUT THERE IS NOTHING SPECIAL
at $r \sim 10^{-13}$ cm OR $p \sim 400$ MeV/c
r_0 – "A PAPER TIGER"

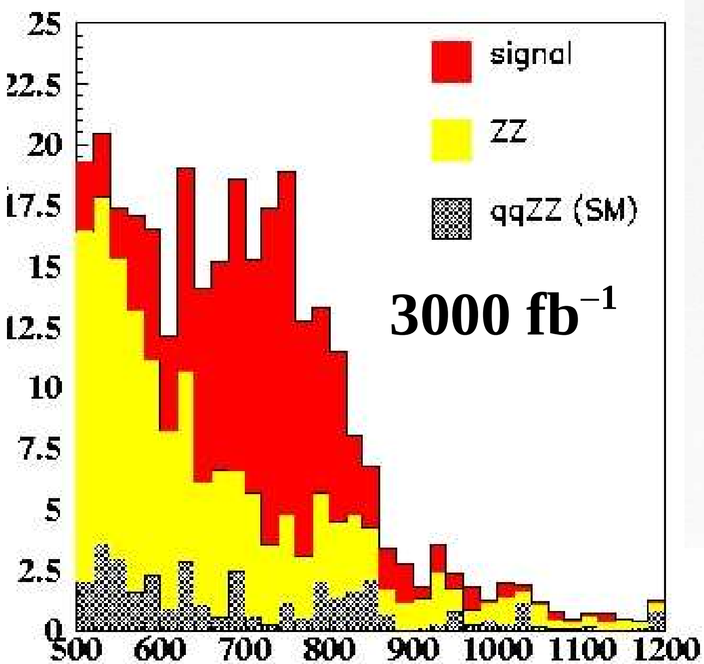
2. HOWEVER AT $r_B = r_0/\alpha^2 = \hbar^2/me^2$
NEW FUNDAMENTAL PRINCIPLE
QUANTUM MECHANICS

3. AND AT $\lambda_c = r_0/\alpha = \hbar/mc$
RELATIVISTIC QUANTUM FIELD
THEORY

r_B and λ_c WERE REAL "TIGERS" 5

Possible scenario:

$Z^0Z^0 \rightarrow$ 4 leptons



events per 20 GeV

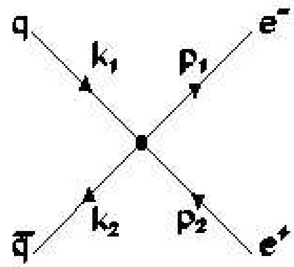
m_{ZZ}

J. Rohlf, LHC IV p. 29

Super-high luminosity is essential!
(more energy would be better)

Compositeness

Contact interaction
modifies Drell-Yan

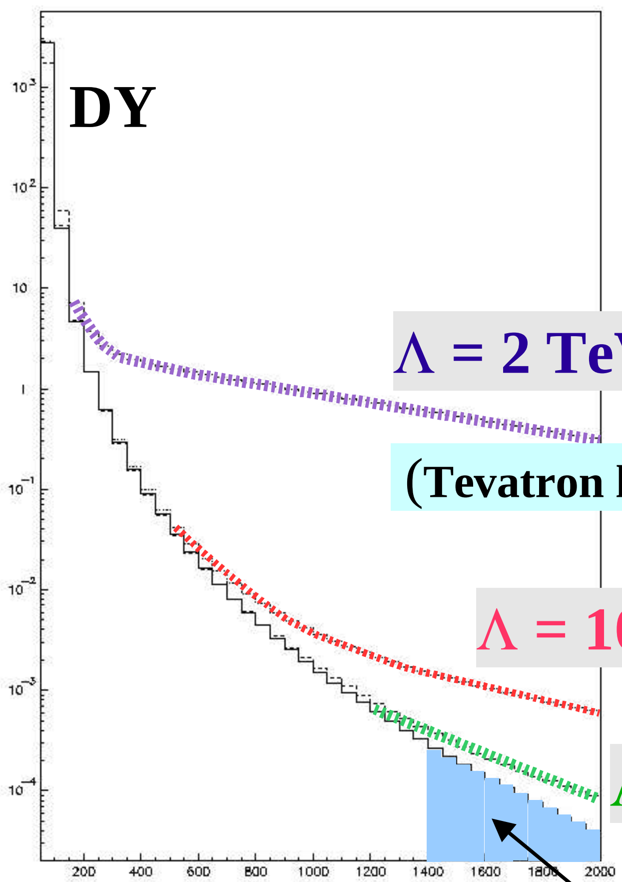


Cross section gets a term $s/(\alpha\Lambda^2)$, where $s = m^2_{e^+e^-}$

Dominates when $s >> \alpha\Lambda^2$

A. Gupta *et al.*

σ (pb)



Λ = 2 TeV

(Tevatron limit)

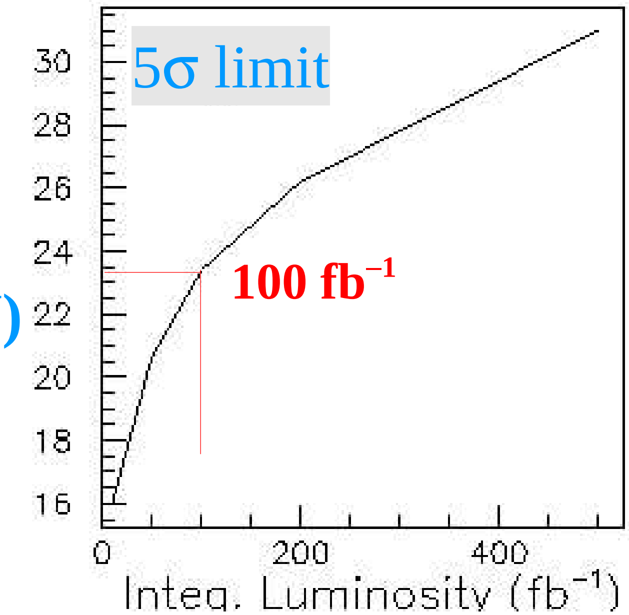
Λ = 10 TeV

Λ = 20 TeV

$m_{e^+e^-}$

132 ev,
100 fb^{-1}

Λ (TeV)



1000 fb^{-1} ⇒ reach to Λ = 50 TeV

Complimentary search:
jet angular distribution

discovery

energy of probe

LHC
5 TeV

50 years
× 5000

today's limit
400 GeV

Tevatron
UA1

quark
1 GeV

50 years
× 100

p, n
100 MeV

nucleus
10 MeV

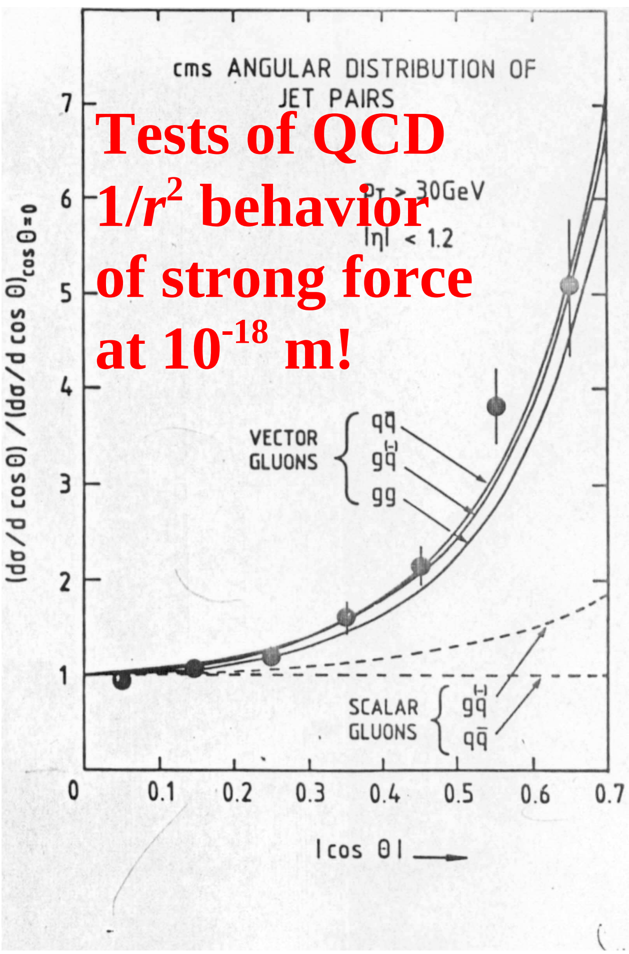
J. Rohlf, LHC IV p. 30

My last invited talk at Fermilab was 20 years ago...

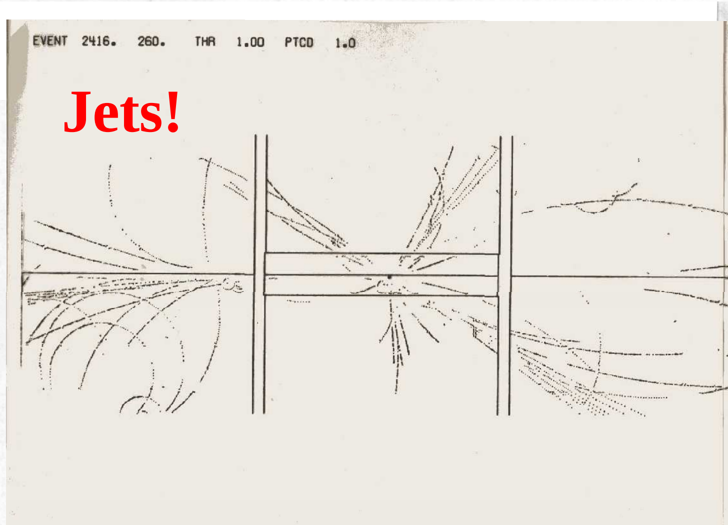
Proceedings Of The 12th International Conference On High-Energy Accelerators

Held At Fermilab August 11-16, 1983

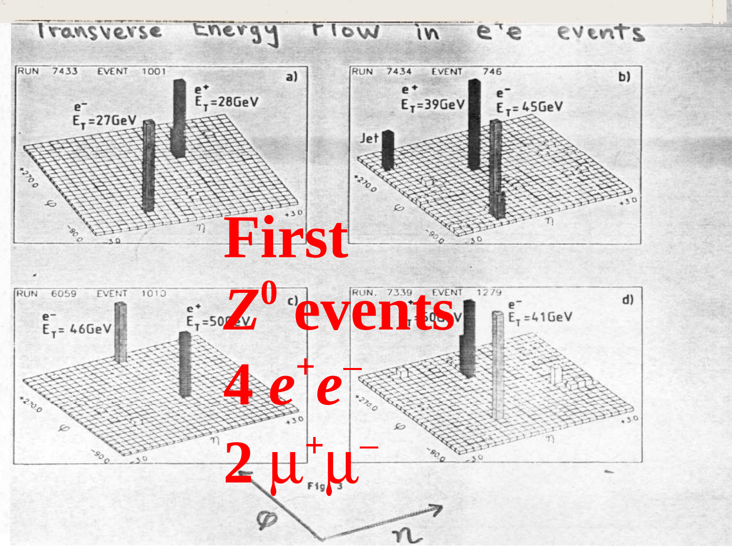
Tests of QCD
$1/r^2$ behavior of strong force at 10^{-18} m!



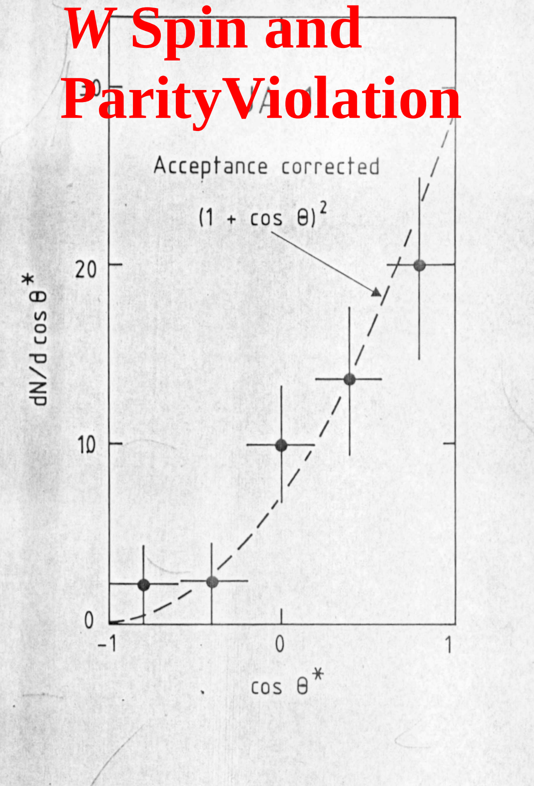
Jets!



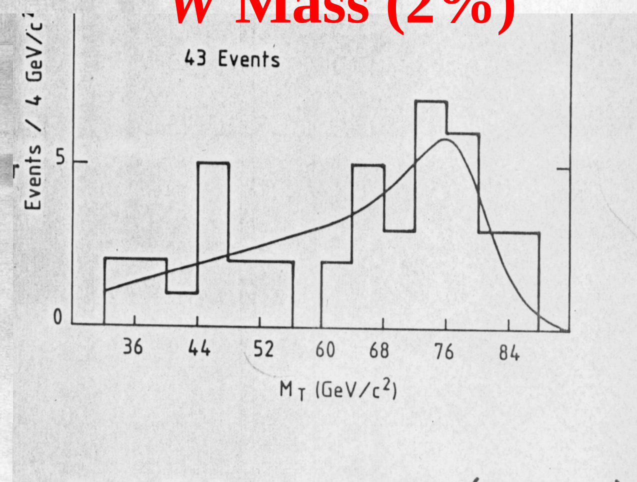
First Z^0 events
4 e^+e^-
2 $\mu^+\mu^-$



***W* Spin and Parity Violation**



***W* Mass (2%)**



$m_W = 80.9 \pm 1.5$ GeV (UA1 units)

$\Gamma_{W\to all} < 7$ GeV

Where we stood then...

Proceedings Of The 12th International Conference
On High-Energy Accelerators

Held At Fermilab August 11-16, 1983

M. Veltman (SLAC Accelerator Summer School, 1982) quoted by Leon Lederman:

"The outstanding problems in today's theory of particles are such that none of the projections beyond the standard model can be considered with any confidence. What we need is experimental guidance: exposure to the no-mans land of lepton-lepton or quark-quark collisions up to the mass range of 1 TeV and beyond."

Where we stand now...

From: "M.J.G. Veltman"
To: James Rohlf
Date: Fri, 7 Mar 2003 13:20:25 +0100
Dear Jim;
Well, you know as well as I do that essentially nothing has changed. Supersymmetry and strings have not come closer to reality. The Higgs is more elusive than ever. I am happy to see that I saw that correctly in 1982.
Best wishes,
Tini

Summary and Outlook

In the two years since Sardinia, we have come at least one year closer to the realization of TeV physics!

When I get invited back to Fermilab in 2023, I hope to be able to report on some exciting new physics from CMS... ...that was NOT anticipated at this conference!