MIKE ALBROW
FEB. '99
LAKE GENEVA, WI

PHYSICS AT VLHC

INTRODUCTION : HISTORY OF STUDIES
$p\overset{(-)}{p}$ COLLIDERS

BIG ISSUES : MASS, FLAVOR, UNIFICATION

PARTON PROCESSES ($q, \bar{q}, g \rightarrow$)

SUSY THINGS

WW THINGS ... EXOTIC THINGS

DETECTORS

OTHER MACHINES IN TUNNEL

SUMMARY & PERSONAL CONCLUSIONS

VLHC

VERY LARGE HADRON COLLIDER.

IS LHC = Last Hadron Collider ?

AFTER SSC TERMINATION, THOUGHTS ABOUT LONG-TERM FUTURE.

1994 : INDIANA ACCELERATOR WORKSHOP

1996 : SNOWMASS

PHYSICS ... MACHINE ... DETECTORS

THINK OF $\times 10$ IN ENERGY
" " $\times \frac{1}{10}$ " COST/TeV } cf LHC

ACTUALLY 50 TeV + 50 TeV pp (x 7)
$\mathcal{L} = 10^{34}\ cm^{-2} s^{-1}$ (=LHC)

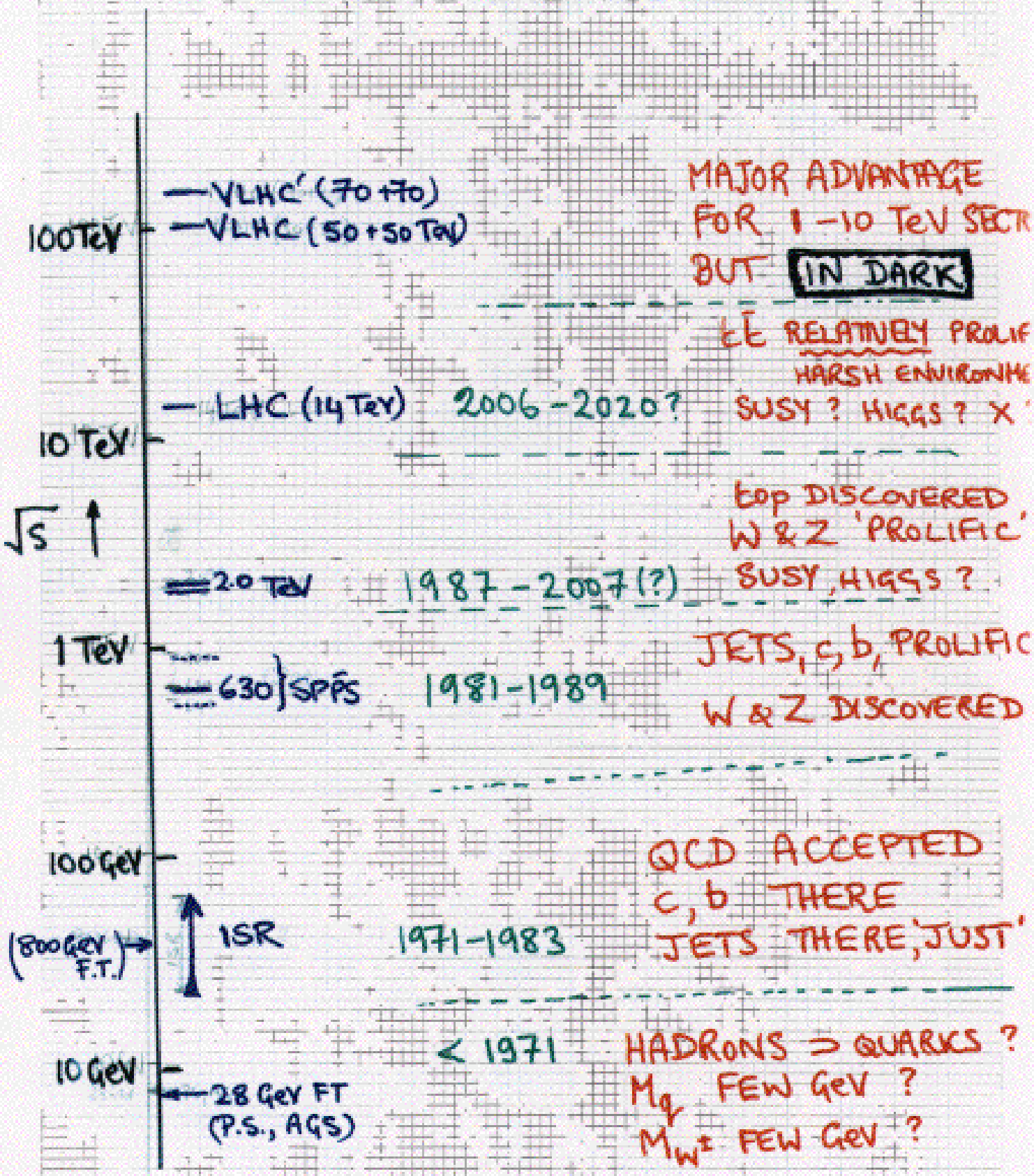
→ MUST FIND BIG ECONOMIES /TeV

→ INTERNATIONAL (WORLDWIDE) COLLABN.

→ 2 POSSIBLE SITES, CERN OR FERMILAB

"MOST OBVIOUS"

A BRIEF HISTORY OF HADRON COLLIDERS



PHYSICS @ VLHC (50 TeV + 50 TeV)

(A) ALL THE STUDIES DONE FOR SSC

esp. EHLQ "BIBLE", $\supset \sqrt{s} = 100$ TeV

(B) ALL THE STUDIES DONE FOR LHC (14 TeV)

(C) SNOWMASS 96' VLHC "PINK BOOK"

E. MALAMUD

(D) VERY LARGE HADRON COLLIDER
PHYSICS AND DETECTOR WORKSHOP

MAR 13-15 1997 150 PARTICIPANTS

D. DENISOV & S. KELLER (ORGANIZERS)

"YELLOW BOOK"

& SUMMARY BOOK

VLHC STUDY GROUP : COORD. E. MALAMUD

ACCELERATOR PHYSICS	MISHRA
ACCELERATOR SYSTEMS	FOSTER
CONSTRUCTION INSTLN.	LACH
PHYSICS + DETECTORS	DENISOV + KELLER

VLHC Phy + Det.
3.97

WORKING GROUPS & CONVENERS

PHYSICS

New Strong Dynamics
L. Simmons, J. Womersley

Supersymmetry
G. Anderson, M. Paterno

Exotics
U. Baur, S. Eno, H. Frisch

Full Rapidity Physics
C. Taylor, A. Brandt

Precision Measurements of Heavy Objects
S. Parke, G. P. Yeh

DETECTORS

Issues related to Multiiple Interactions
G. Snow, F. Paige

Particle Identification
F. D. Snider, S. Chivukula

Tracking
R. Lipton, Tao Han

Calorimetry
G. Apollinari, J. Lykken

Muon Detection
T. LeCompte, M. Berger

(WRITTEN SUMMARIES INTO YELLOW BOOKS)

ELLIS, STIRLING, WEBB

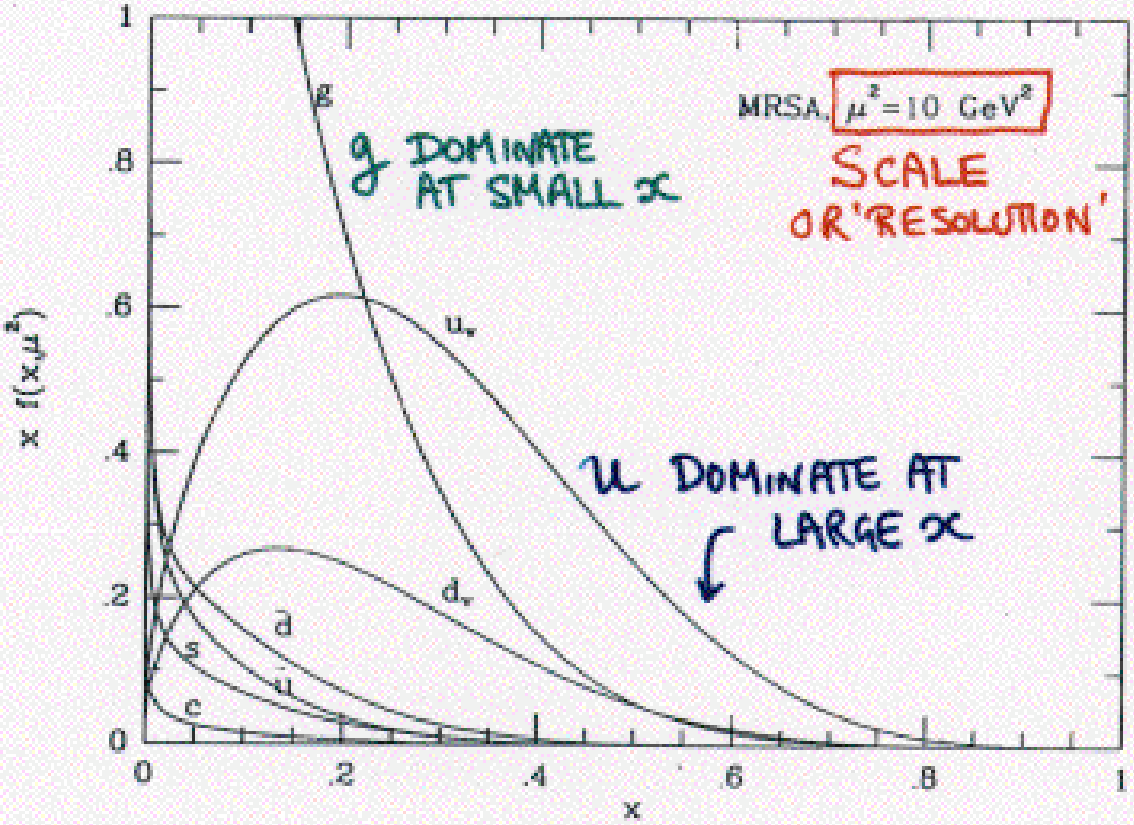


Fig. 4.3. Quark and gluon distribution functions at $\mu^2 = 10$ GeV^2, from ref. [7].

$x = p_{PARTON}/p_{PROTON}$

BROAD BAND BEAMS OF $q, \bar{q}, g$

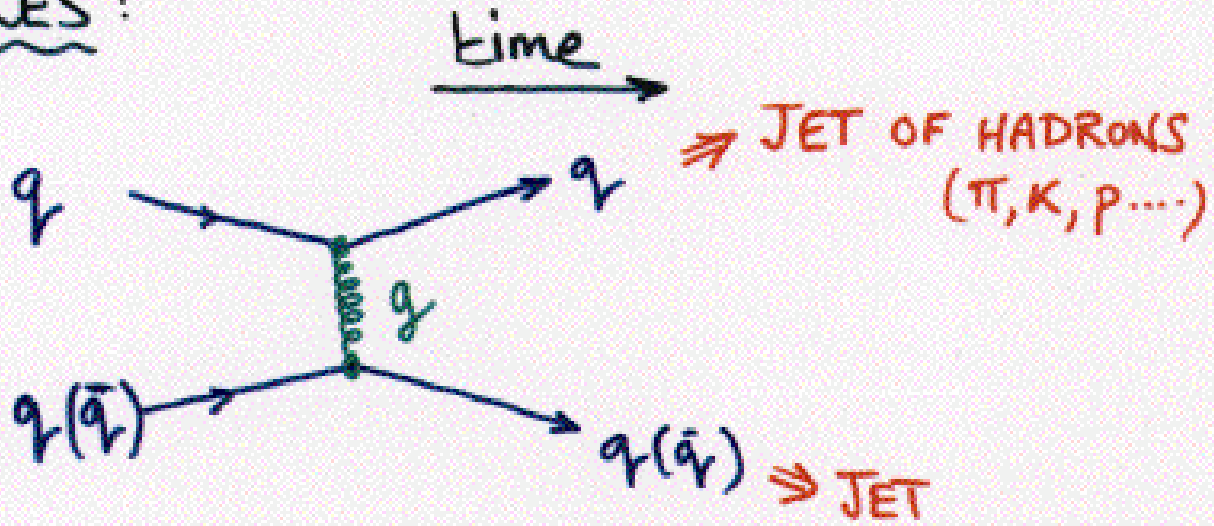
NO SPECIAL THRESHOLD.

FOR HIGH MASS REACH:

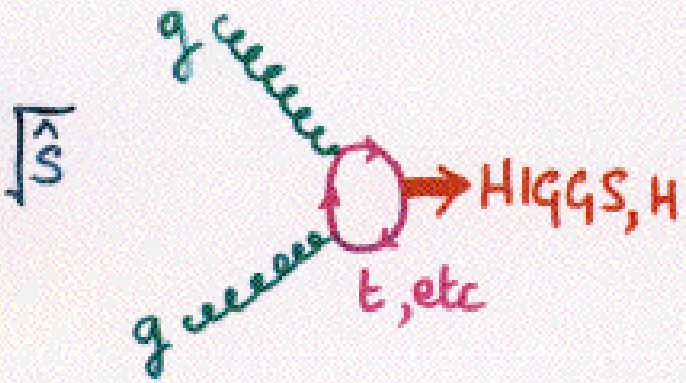
GET $\sqrt{s}$ AS HIGH AS POSSIBLE
THEN PUSH LUMINOSITY!

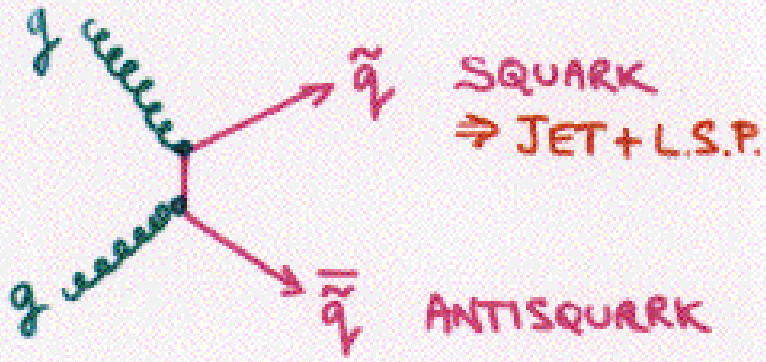
PARTON PROCESSES

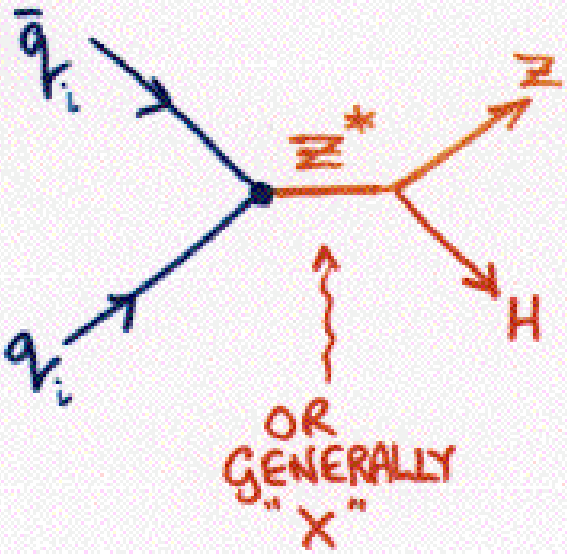
EXAMPLES :

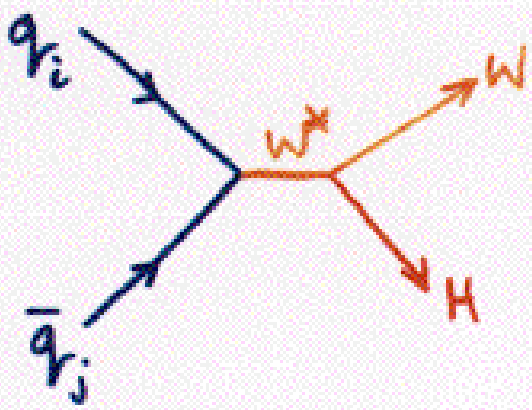


(LARGEST E_T PROBES SMALLEST DISTANCES)









etc....

EHLQ
(1/250)

DIFFERENTIAL gg LUMINOSITY

$\frac{\tau}{\hat{s}}\frac{d\mathcal{L}}{d\tau}$ (nb) ↑

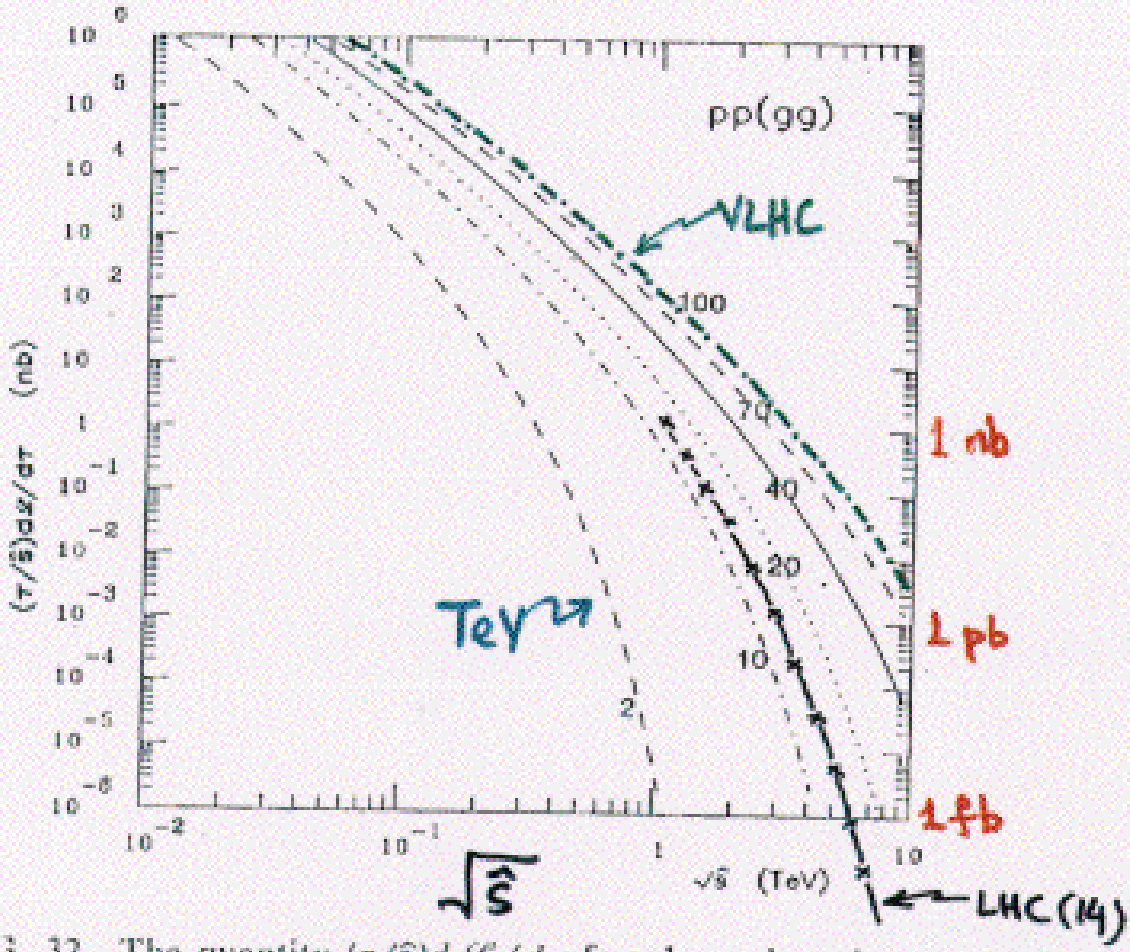


FIG. 32. The quantity $(\tau/\hat{s})d\mathcal{L}/d\tau$ for gluon-gluon interactions in proton-proton collisions. Collider energies $\sqrt{s}$ are given in TeV.

$$\tau = \frac{\hat{s}}{s} = \frac{M^2}{s} \; ; \; \frac{\tau}{\hat{s}} = \frac{1}{s}$$

eg. TAKE $\boxed{\hat{s} = 6 \pm 1 \text{ TeV}}$

$$\frac{\tau}{\hat{s}}\frac{d\mathcal{L}}{d\tau} \equiv \frac{1}{s}\frac{d\mathcal{L}}{d\tau}\Big|_{VLHC} \sim 100 \text{ pb}, \quad \frac{1}{s}\frac{d\mathcal{L}}{d\tau}\Big|_{LHC} \sim 1 \text{ fb} \quad \Big\} 10^5$$

× FACTORS LIKE $\left(\frac{\alpha_s}{\pi}\right)^2$ → REAL CROSS SECTIONS

× LUMINOSITY → RATES $\quad R \sim L \times \int \frac{\tau}{\hat{s}}\frac{d\mathcal{L}}{d\tau} d\tau \times \left(\frac{\alpha_s}{\pi}\right)^2$

~ 50 /yr @ 6TeV (±5%) gg VLHC

SUSY – BEAUTIFUL!

BUT SYMMETRY BADLY BROKEN

$m(\tilde{e}) \gg m(e)$ etc.

EXPECT $100 \leq M(\text{SUSY}) \leq 1000$ GeV
(expt.) (theory)

INTERESTING FOR TeV & LHC ! ('naturalness')

SUSY MAY BE DISCOVERABLE AT TeV ...
HOPE SO, BUT LHC WOULD HAVE FIELD DAY STUDYING IT. (cf b @ ISR, TeV)

IF LHC $\not\Rightarrow$ SUSY, SUSY DEAD ← (?

IF LHC DISCOVERS SUSY, VLHC MAY HAVE FIELD DAY STUDYING IT, RATES $\gg$ LHC [fn(M)]

→ SOME SUSY (1st gen?) V. MASSIVE (>TeV) ?

12 $\tilde{q}$

9–12 $\tilde{\ell}$

$\tilde{W}, \tilde{Z}, \tilde{\gamma}, \tilde{g}$

MASSES

DECAY TRANSITIONS

PRODUCTION

etc.

SUSY - IF RELEVANT
- IS BROKEN !

NEED A FRAMEWORK - MODEL - OF SUSY

- "MEDIATOR" BETWEEN SM SECTOR & SUSY SECTOR

GRAVITY ?

GAUGE INTERACTIONS ?

NEW FIELDS

- LOGICALLY POSS.
- FCNC SMALL
- COSMOLOGY ? $m(\tilde{\zeta}) \sim eV$

(POSTPONING THE "DESERT")

GAUGINO MASSES INVOLVE MESSENGER FIELDS

$M_M \sim 10 - 100$ TeV

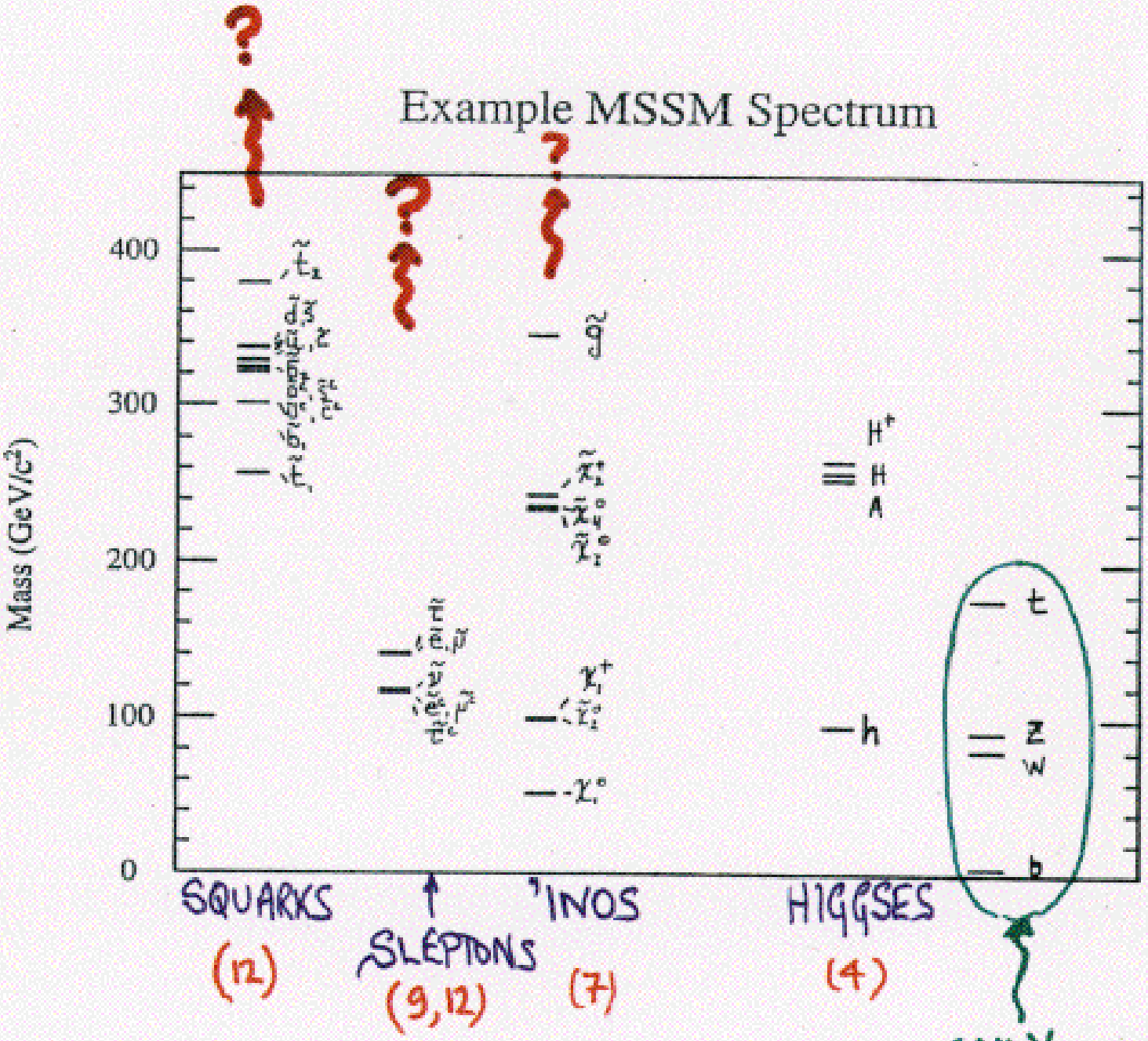
NEW PHYSICS BEYOND SUSY S.M.

CANNOT SAY IF IN VLHC REACH.

(FIRST OBSERVATIONS OF SUSY PARTICLES MAY CHANGE THIS NEGATIVE STATEMENT.)

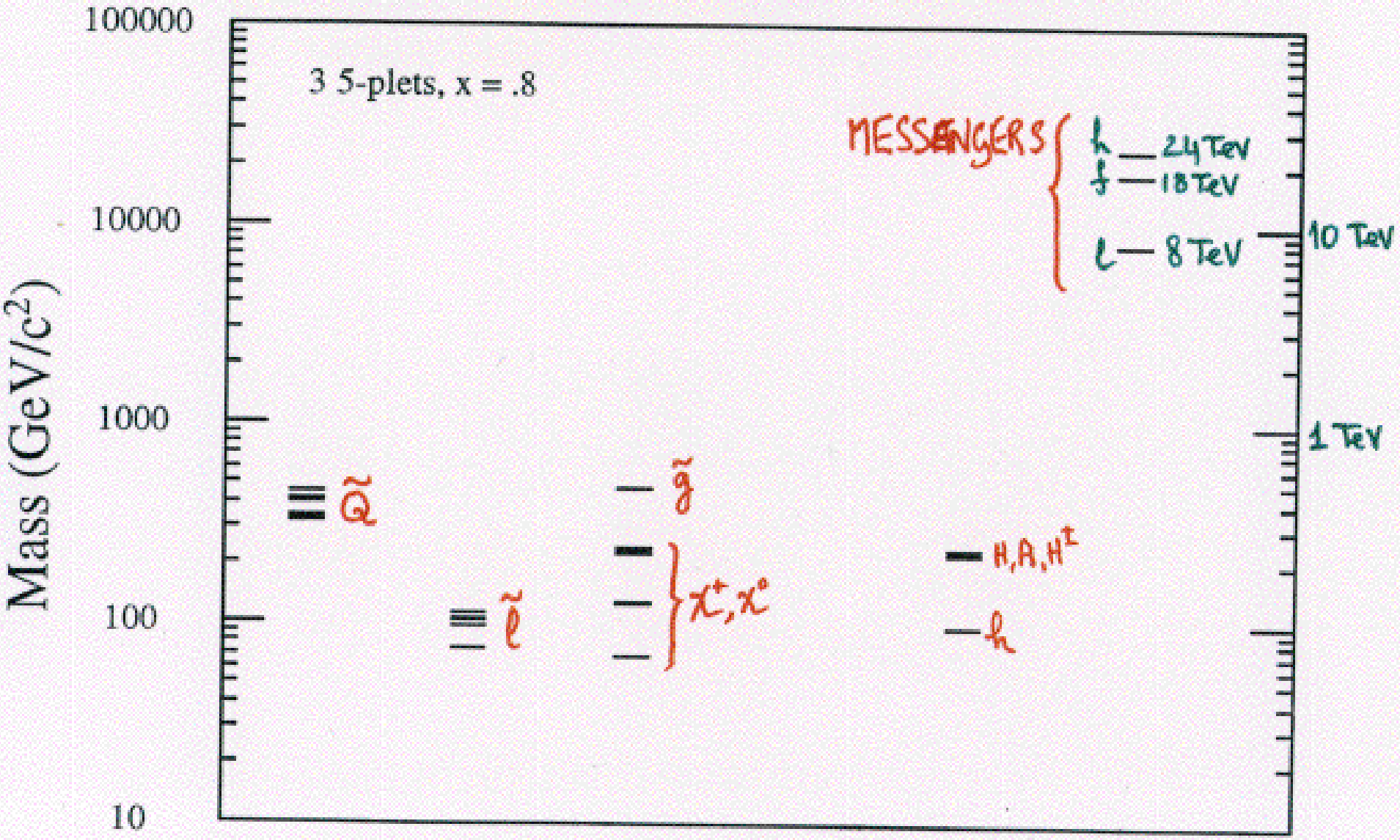
1st generation especially?

SUSY MESSENGERS !



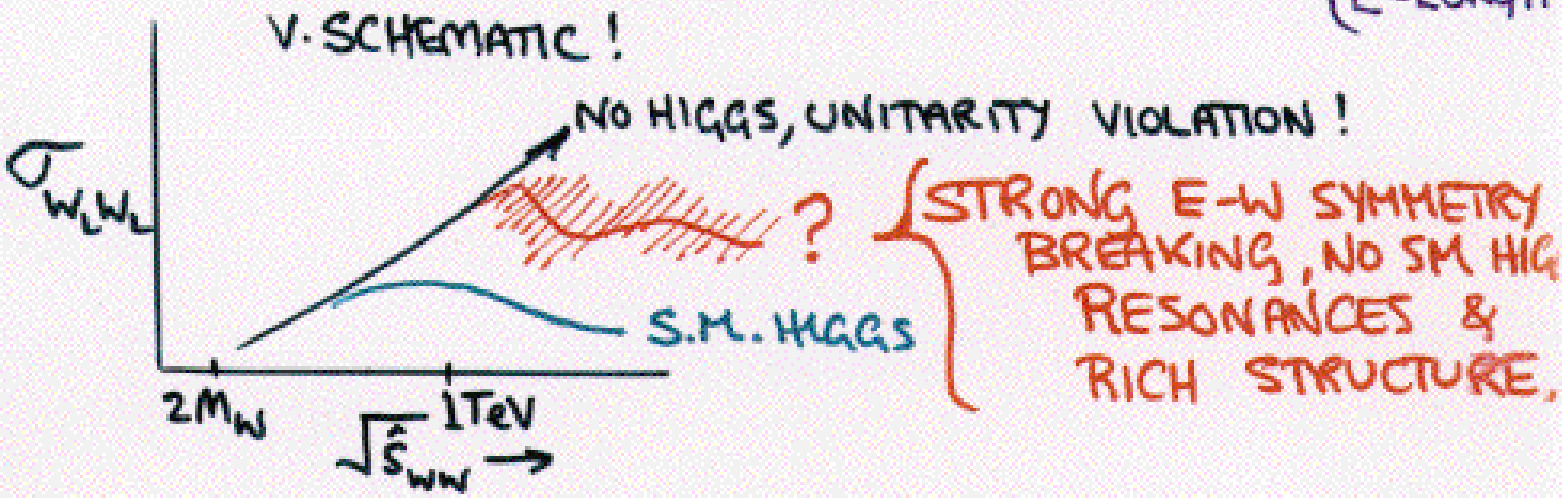
VERY RICH FIELD

Example Light Messenger Spectrum



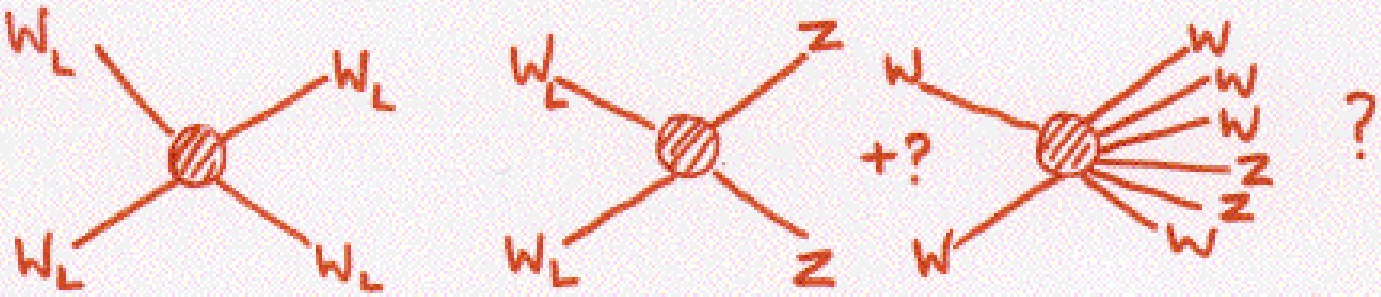
$W_L W_L$ SCATTERING

(L = LONGIT



LHC WILL AT BEST GLIMPSE THIS DOMAIN.

BURNING QUESTIONS OF E-W SYMMETRY BREAKIN

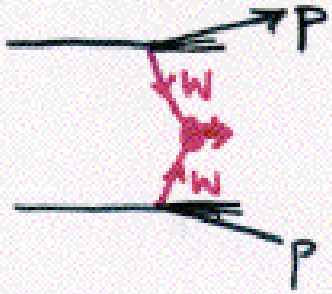


"$\pi\pi \rightarrow \pi\pi$" "$\pi\pi \rightarrow 6\pi$"

PHASE SPACE, σ FOR MULTI-W PRODN. :

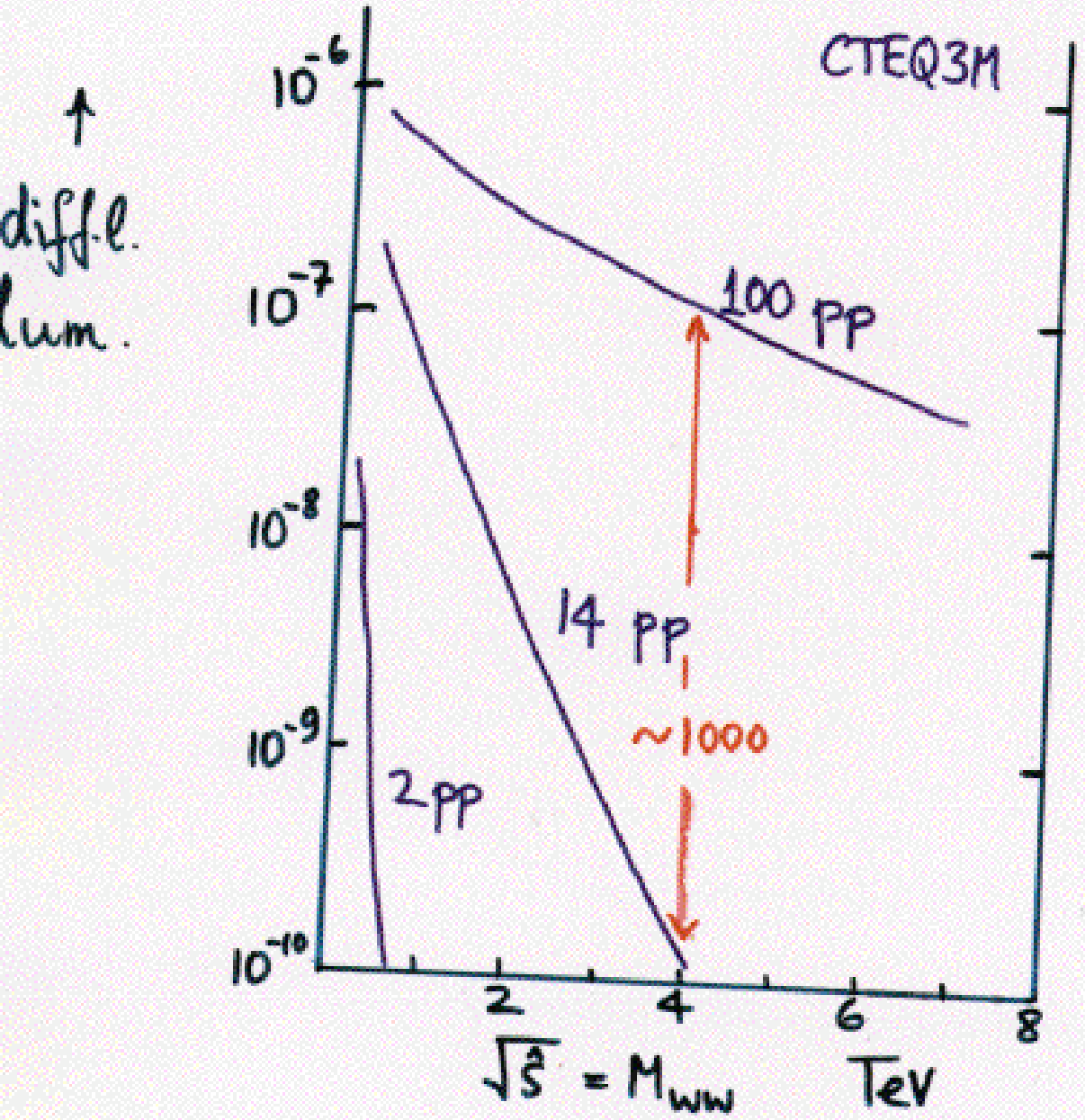
VLHC $\gg$ LHC

$\mu^+\mu^-$ COLLIDER ALSO IF $\sqrt{s}$ > "MANY TeV"



W. KILGORE

$W_L^+ W_L^-$ Luminosity vs M_{WW}



$\times \mathcal{L}_{machine}$ → RATES

$W^+W^+ + W^-W^-$ ~ SAME

$W^+Z + W^-Z$ ~ SAME

~100/yr @ 4 TeV

cf 0.1/yr @ LHC

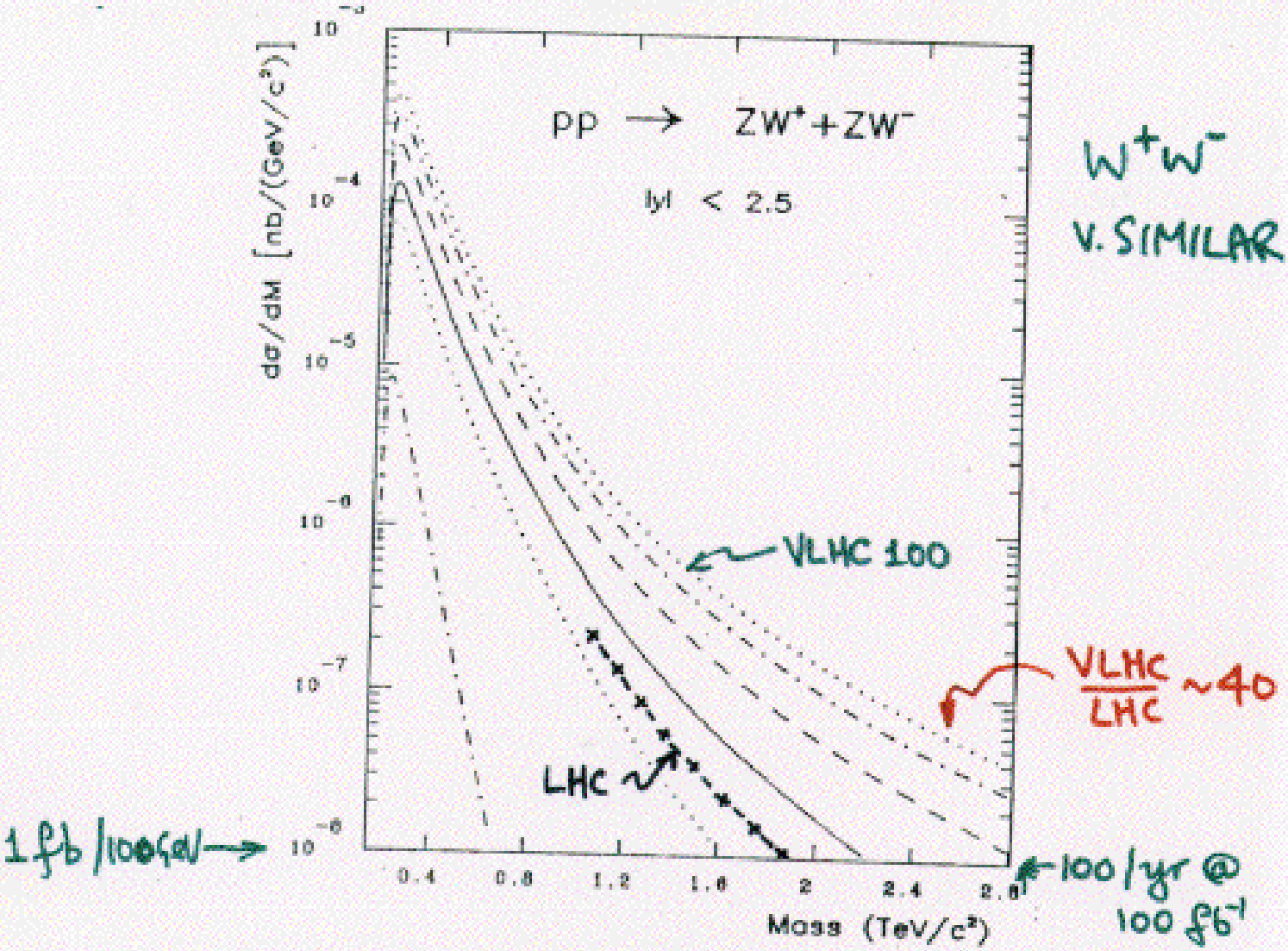


FIG. 128. Mass spectrum of $W^{\pm}Z^{0}$ pairs produced in pp collisions, according to the parton distributions of Set 2. Both W and Z^{0} must satisfy $|y| < 2.5$.

LHC : 100/yr @ 1.9 TeV

VLHC ~2000/yr " 1.9 TeV

100/yr @ 3.7 TeV

(QCD or E-Wk) INSTANTONS

PART OF STANDARD MODEL

(POLYAKOV, t'HOOFT and others ...)

TUNNELING OF VACUUM BETWEEN STATES

$\Rightarrow \quad q + q \to 7\bar{q} + 3\bar{\ell}$ e.g.

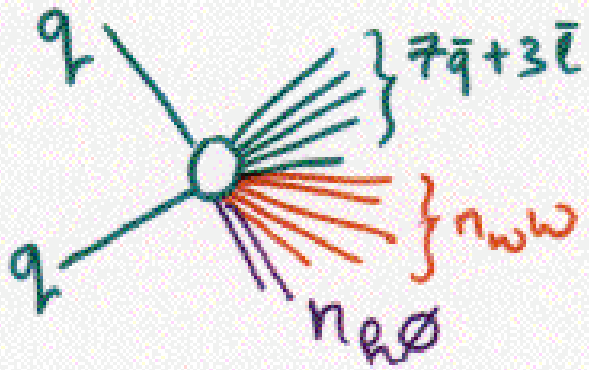
HIGH ENERGY (10's of TeV ?) PHENOMENON

BUT EXPONENTIALLY SUPPRESSED $\sim e^{-4\pi/\alpha}$

AT LEAST AT LOW ENERGY.

THIS SUPPRESSION MAY (RINGWALD, ESPINOSA, BALITSKY ...)

BE OVERCOME BY MULTI-GAUGE BOSON EMISSION



$\sim n! e^{-4\pi/\alpha}$

$n! = n_W + n_h$

→ NON-PERTURBATIVE

MULTIPLE HIGGS & W's .... ENVIRONMENT ?

The conclusion from the Strong Interaction Working Group:

The VLHC should be designed to probe the TeV scale in detail, since the physics associated with electroweak symmetry breaking will be there. If the LHC has discovered this physics, the VLHC will be able to explore it in depth. If this physics lies just beyond the reach of the LHC, we will nonetheless know it must exist, and the VLHC will catch it. ... While a compelling case for studying the TeV scale exists, far less is known about what might lie at higher scales. A challenge for theorists is to identify the possibilities for 10 TeV-scale physics.

EXOTICS

BEYOND SM, WE DO NOT KNOW WHAT WE WILL SEE! VAST POSSIBILITIES.

SCALAR LEPTOQUARKS (& gens 1, 2, 3)

TeV II → 250 GeV, LHC → 1.5 TeV
VLHC → ~7 TeV

W', Z'

CDF, DØ NOW ~700 GeV

VLHC ~25 TeV

q^*

VLHC 30 TeV

COMPOSITENESS SCALE:

LHC COULD SEE EFFECTS @ Λ_c ~10-15 TeV
HIGH E_T JET XS, ANG. DISTBNS.

VLHC COULD PROBE TO ~100 TeV!

↳ $\cong 10^{-19}$ cm
μfm

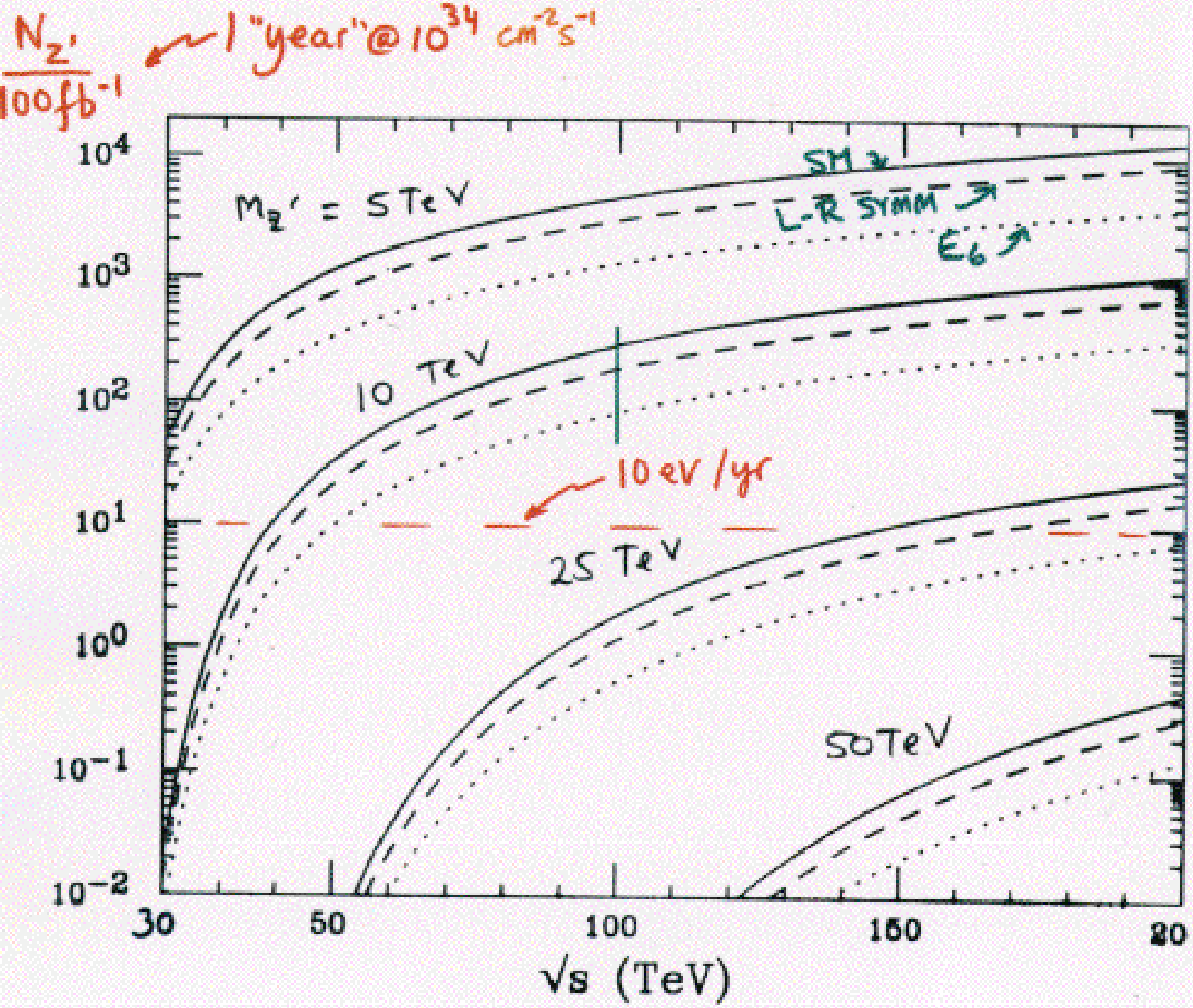
TOPCOLOR

TECHNICOLOR

⋮

Z′ PRODN. IN PP

MANY MODELS



REACH IS ~20-25 TeV DEP. ON B/G.

@ $M_{Z'}$ = 10 TeV ~100/year cf 0 at LHC.

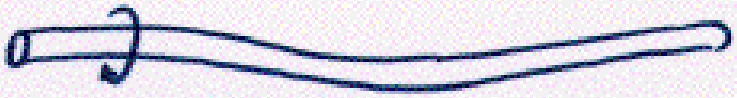
Conclusions from the exotics working group:

In this brief report, we have discussed the search for contact interactions and new heavy particles, which appear in popular non-supersymmeti extensions of the SM, at the VLHC. The search potential of the VLHC for these new states is truly enormous; for a collider with a center of mass energy of 100 TeV or more, the limits are in general in the multi-ten TeV region.

NEW !! LAST YEAR ....MUCH THEORETICAL ACTIVITY

"LARGE" (cf $L_{Planck} = 1.6 \times 10^{-33}$ cm !) INTERNAL DIMENSIONS

SUPERSTRING THEORIES $\rightarrow 3_{SPACE} + 1_{TIME} + 6$ OR 7 CURLED UP 'SPACE'



ADDITIONAL DIMENSION MANIFEST ONLY WITH HIGH 'RESOLUTION' (SMALL R_i)

NATURAL SCALE FOR $R_i \sim L_{Planck}$ OR $L_{GUT} \sim 10\text{-}100\ L_{Pl.}$

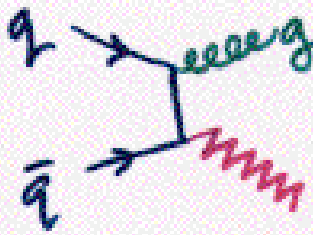
REALIZATIONS

- SCALES R DO NOT ALL HAVE TO BE SAME, AND CAN BE $\gg L_{Pl.}$
- WHILE GRAVITY OPERATES IN ALL 10- OR 11-dim, (THE "BULK"), GAUGE THEORIES (ELECTROWEAK & STRON CAN OPERATE ON FEWER ("WALLS" OR 'SURFACE')
- UPPER LIMITS FOR R_i ARE EXPERIMENTAL

POSSIBLE CONSEQUENCES (some v. speculative).

- COULD BE (e.g.) 2 CURLED UP DIMENSIONS OF 'GRAVITY ONLY' TYPE WITH $R \lesssim$ mm !

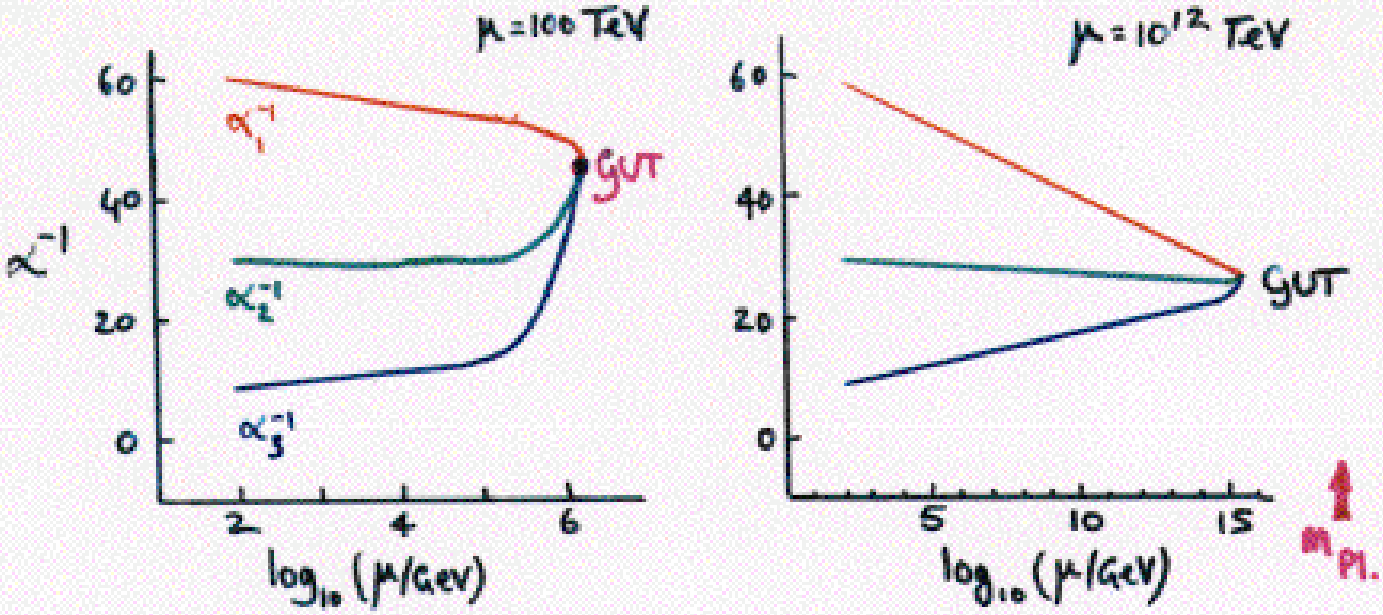
→ $\frac{\hbar c}{R} \gtrsim 2.10^{-4}$ eV ← LEVEL SPACING FOR SPECTRUM OF 'GRAVITON' STATES (KALUZA-KLEIN)



K.K. GRAVITONS ⇒ MISSING ENERGY

- STRING SCALE FOR OTHER CURLY DIMENSIONS (WALL) NOT KNOWN. COULD BE AS LOW AS 10 TeV.

→ AFFECTS q-q SCATTERING, JET E_T SPECTRA $t\bar{t}$ PRODUCTION ....



- GUT-SCALE COULD BE MUCH LOWER (THAN THOU
- NEW PARTICLES • INFLATION • UHE COSMIC RAYS ...

DETECTORS @ VLHC

* REALIZATION : VLHC @ 10^{34} $cm^{-2}s^{-1}$ HAS EXTENDED PHYSICS REACH (cf LHC)

- OCCUPANCY, RADIATION LEVELS GROW SLOWLY ($\ln s$) WITH $\sqrt{s}$ ($\sim \times 2$)

- VAST R & D EFFORT FOR SSC, LHC IS APPLICABLE. REASONABLE EXTRAPOLATION (+ CONT. R & D!) → VLHC (10^{34}) ✓

  ~ "EXISTENCE PROOF"

- AS ALWAYS (?) HAPPENS LATER DEVELOPMENTS MAY PUSH – MACHINE, – DETECTORS → 10^3 ??

ACCELERATOR PEOPLE ALREADY BELIEVE 10^{35} $cm^{-2}s^{-1}$ POSSIBLE.

DETECTORS

* CDF-DØ-CMS-ATLAS TRADITION

DESIGN: $\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$, 50+50 TeV, $\Delta t = 19$ ns
→ ev/x ~20

JETS, $\not{E}_T$, e, μ, W, Z, b, t ...
→ CALO (em + had), TRACKING < μVTX / MUONS

μ ~10 TeV EXPENSIVE TO MEASURE WELL

GENERIC W ($p_T \leq 50$ GeV) DIFFICULT IN ENVIRONMENT
+ LOW E_T JETS (").

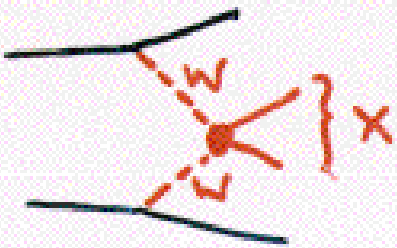
ASIDE: 5 TeV B-MESON TRAVELS ~30cm TYPICALLY

* COMPLEMENTARY DETECTOR ±12 UNITS y
(cf ±4 or 5)

~1 ev/x ⟹ $\mathcal{L} = 5.10^{32}\ cm^{-2}s^{-1}$ (not "Low")

CENTRAL DETECTOR ON CDF', DØ' SCALE
+FORWARD MAGNETS/TRACKING/CALOS ~±1 km.

- CLEANER MEASUREMENTS OF HIGHER σ PROCESSES (INCL. MULTI-W, top PRODN)
- COLOR SINGLET EXCHANGE CAN LEAVE RAPIDITY GAPS, SPOILT BY OTHER INTNS.



W + DIFFRACTION

DETECTOR TECHNIQUES

TRACKING & CALORIMETRY

$\rightsquigarrow 10^{34}\ cm^{-2}s^{-1}$ @ LHC

VLHC ↑ R & D ... START IN 3-5 YEARS
DETECTOR POST LHC R & D (CONT...

RESOLUTION 10-20 μm PIXELS INSIDE
~ 20μm ~ 40 μm STRIPS OUTER

FAST (20ns) & RAD-HARD (MRads)

R/O ELECTRONICS, COMPUTING → MAJOR ADVANCES EXPECTED

NO SHOW-STOPPERS,
BUT NOVEL CONCEPTS WELCOME.
(IN DETECTORS AS IN ACCELERATORS)

HAVE DISCUSSED $\boxed{\text{VLHC}}$ AS 50+50p

→ 70+70??

OTHER POSSIBILITIES IN TUNNEL

- e^+e^- $\sqrt{s} \sim 500-600$ GeV

  $\mathcal{L} \sim 10^{33}\,cm^{-2}s^{-1}$ @ 360, ~$t\bar{t}$ THRESHOLD

- ep 300 GeV → ← 50 TeV

  cf LEP×LHC 90 GeV → ← 7 TeV

  cf HERA 30 GeV → ← 0.8 TeV

  ×25 $\sqrt{s}$

- FIXED TARGET ? $\nu/\bar{\nu}$ FROM 50 TeV p ?

  (NOT YET STUDIED)

- AA COLLISIONS $\sqrt{s_{AA}} \gtrsim 5000$ TeV

  (5 PeV)

"OMNITRON"

.... t'Hooft

+ IF LOW FIELD-HIGH R,

UPGRADE PATH → HIGHER $\sqrt{s}$?

SUMMARY (GILMAN PANEL JULY '97)

A $\sqrt{s}$ - STEP IN $p\overset{(-)}{p}$ COLLIDER $\gtrsim \times 5(7)$

ALWAYS LED TO NEW WONDERS.

VLHC MUCH SUPERIOR [fn(M)] TO LHC $\gtrsim 1$ TeV

PROBABLY RICH PHYSICS THERE, IF

→ LHC IS COVERING SUSY, HIGGS THRESHOLDS

→ LHC IS NOT " " " "

EVEN WITH OUR LIMITED IMAGINATION:

SUSY, WW, TECHNICOLOR, INSTANTONS, W', Z', COMPOSITENESS etc. + GUTS

FOR 50 TeV + 50 TeV $\mathcal{L}_{DESIGN} = 10^{34}\ cm^{-2}s^{-1}$

NO SHOW-STOPPERS IN DETECTOR TECHNOLOGY

ALLOWING REASONABLE DEVELOPMENT

μ-TRACKING, TRACKING, EMCALS, HADCALS, MUONS, DAQ, TRIG

LHC GROUPS ARE BUSY WITH ALL THIS.

KEY IS R&D ON COLLIDER !!