Physics motivation for a VLHC

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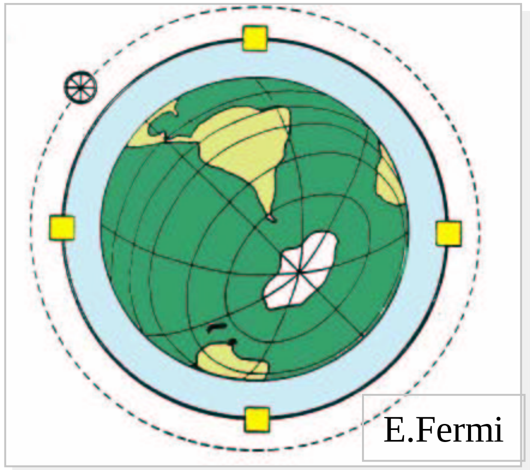


❶ Main experimental challenges
❷ Physics potential (a few examples ….)
❸ Examples of possible scenarios emerging from the LHC data …

Speculative in most cases …

A VLHC is the only "in-principle-feasible" machine which can explore directly the 10-100 TeV energy range

Why is this interesting ?

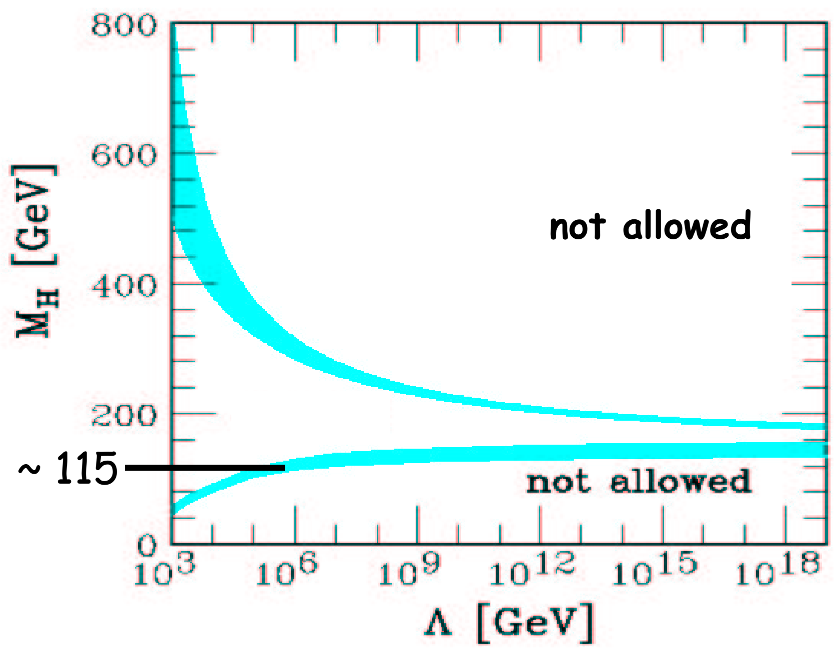
- LHC will most likely not answer all outstanding questions

- Lepton Colliders (LC) : e^+e^- $\sqrt{s}$ = 0.5 –1.5 TeV
  e^+e^- $\sqrt{s}$ = 3-5 TeV
  $\mu^+\mu^-$ $\sqrt{s} \leq 4$ TeV
  } best machines to complement LHC in many scenarios

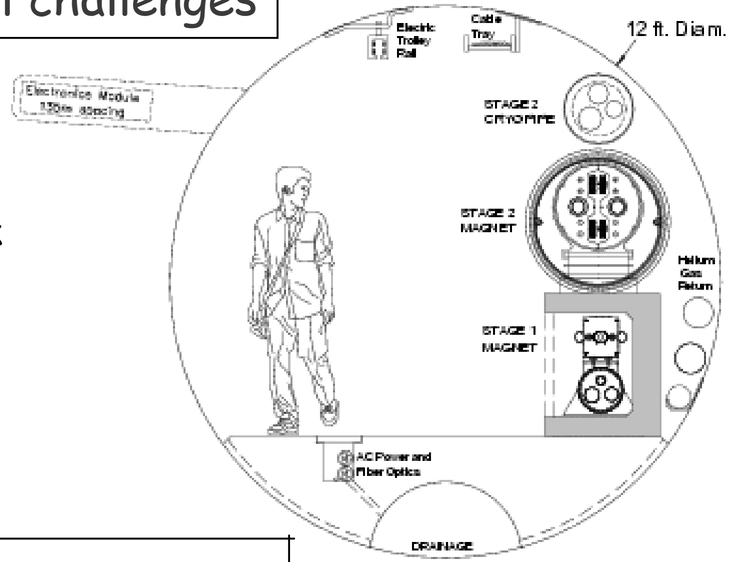
  however : direct observation "limited" to TeV region

- Unlike for TeV scale, no clear preference today for specific E-scale in multi-10 TeV region
  However: indirect evidence for New Physics at 10-100 TeV could emerge from LHC and first LC → compelling arguments for direct exploration of this range

Example : if $m_H \sim 115$ GeV → New Physics at $\Lambda < 10^5$-10^6 GeV → a VLHC can probe directly large part of this range



❶ **The environment and the main experimental challenges**



Recent design study for a
2-stage pp machine at Fermilab
with $\sqrt{s}$ up to 200 TeV
(Fermilab-TM-2149)

→ see P. Limon's talk

	VLHC-I	VLHC-II
$\sqrt{s}$	40 TeV	200 TeV
Ring	233 Km	233 Km
Magnets	2 T super-ferric	~ 11 T
L	1×10^{34} cm^{-2} s^{-1}	$1\text{-}2 \times 10^{34}$ cm^{-2} s^{-1}
Construction time	~ 10 years	~ 7 years (after Stage-I)

→ up to 10^{35} ?

→ direct discovery potential up to m ≈ 70 TeV

	LHC	SLHC	VLHC-I	VLHC-II
$\sqrt{s}$	14 TeV	14 TeV	40 TeV	200 TeV
L	10^{34}	10^{35}	10^{34}	1-2 x 10^{34}
Bunch spacing Δt	25 ns	12.5 ns *	19 ns	19 ns
σ_{pp} (inelastic)	~ 80 mb	~ 80 mb	~ 100 mb	~ 140 mb
N. interactions/x-ing ($N = L\,\sigma_{pp}\,\Delta t$)	~ 20	~ 100	~ 20	~ 25-50
$dN_{ch}/d\eta$ per x-ing	~ 150	~ 750	~ 180	~ 250-500
$\langle E_T \rangle$ charg. particles	~ 450 MeV	~ 450 MeV	~ 500 MeV	~ 600 MeV
Tracker occupancy	1	10	~1	~ 1.5-3
Pile-up noise in calo	1	~3	~1	~ 1.5-2
Dose (central region)	1	10	~1	~ 2.5-5

10^4 Gy/year R=25 cm

Normalized to LHC values, assuming same detector granularity and integration time at SLHC/VLHC as at LHC

* other options (100 super-bunches) being considered as well

→ see Albrow, Denisov, Hauser, Mokhov

Detector and performance requirements for VLHC Stage II

- For $L \leq 2 \times 10^{34}$, environment similar to LHC in central region, harsher in forward regions (dose up to ≈ 10^9 Gy/year compared to ≈ 10^6 Gy/year at LHC)

- Need multi-purpose detector, including in particular:
  - -- e, μ measurements (including charge) up to ≈ 10 TeV with E, p-resolution ≤ 10%
  - -- flavour tagging (b-tag, τ measurement): 3rd family could play special role in New Physics …
  - -- forward jet tagging (Higgs coupling measurements ?, strong EWSB, …)

- Calorimetry : "easiest part" of VLHC detectors, prominent role ($\sigma/E \sim 1/\sqrt{E}$)
  - -- E-resolution dominated by constant term → need compact technique to limit leakage of high-E showers (e.g. q* → jj) at low cost
  - -- Need hadronic response compensation for good linearity up to ~ 10 TeV
  - -- Need good granularity to apply weighting techniques (leakage, compensation)
  - -- Coverage up to |η| ≈ 6-7 desirable (fwd jet tag) → radiation !?

- Tracking : most difficult part of VLHC detectors
  - -- Need muon p-resolution $\Delta p/p \leq$ 10% up to ≈ 10 TeV (Z' asymmetry, E_T^{miss} resolution, new resonance X → μμ and no X → ee, etc.). Will be based on inner detector (most 10 TeV muons shower before Muon Spectrometer)

    ATLAS/CMS $\Delta p/p \sim 50\%$ at 10 TeV

    → need to increase B, L and to improve space resolution

⇨ Room for new ideas and for R&D in detector technology (e.g. dual calorimeter: quartz and scintillator fibres in absorber matrix)

❷

Physics potential of a VLHC

Caveat:
- although present data favour light weakly-coupled Higgs, post-LHC physics scenario remains unknown
- "physics cases" for VLHC more difficult to establish today than for TeV-scale machines (LHC, LC), since it will explore totally unknown territory

⇓

Physics topics shown here are only for illustration of capabilities and main challenges:

-- Standard Model and Higgs
-- SUSY
-- Strong EWSB
-- Compositeness
-- Extra-dimensions

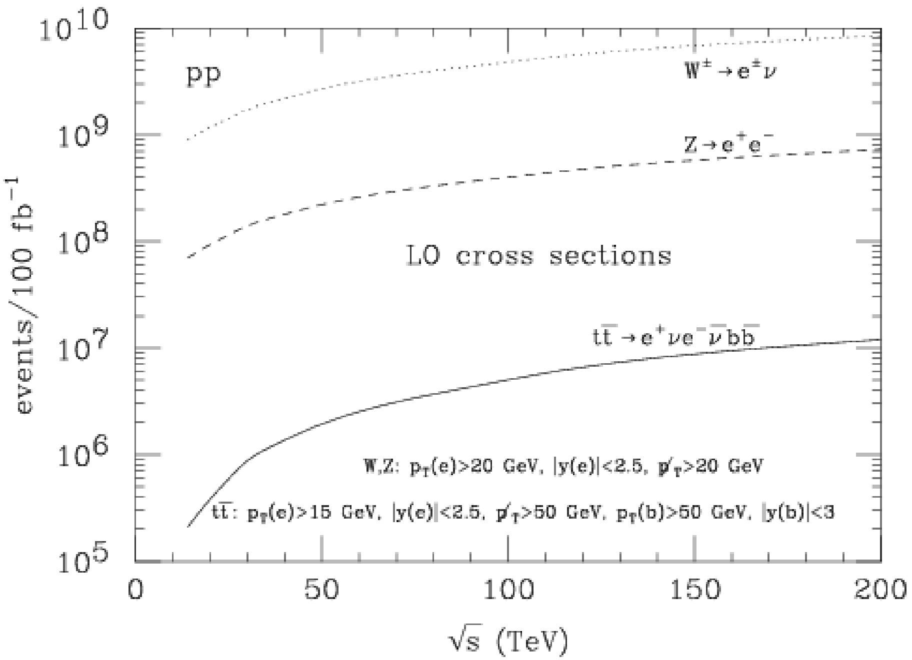
} Preliminary results mainly from hep-ph/0201227
Caveat : large uncertainties

and for some comparison with SLHC, $\sqrt{s}$ = 0.5 –1.5 TeV LC, CLIC

Assumptions :
- integrated luminosities : 100 - 600 fb^{-1} $L \leq 2 \times 10^{34}$
  1000- 6000 fb^{-1} $L = 10^{35}$
- $\sqrt{s}$ = 0.5 –1.5 TeV e^+e^- machine built before VLHC
- LHC-like detectors in most cases (additional performance requirements are mentioned …)

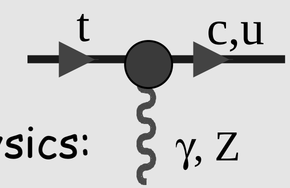
"Standard Model" physics

- Not the primary motivation for the VLHC …
  In general, not competitive with LC for precision measurements
- Exceptions: rate-limited processes, e.g. rare top decays
  (limited tt statistics at LC, huge tt statistics at hadron Colliders)

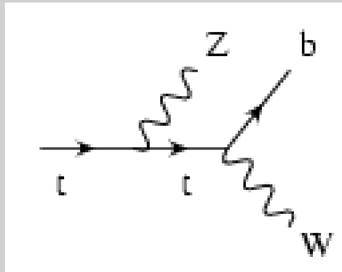


tt cross-section at 200 TeV
is ~ 50 times larger than at 14 TeV
→ > 10^9 tt pairs per year at VLHC

FCNC decays : $t \rightarrow Zq, \gamma q$
-- SM : BR ~ 10^{-13}
-- BR may be larger in New Physics:
e.g. 2HDM : BR ~ 10^{-6} - 10^{-7}
-- SLHC sensitivity : up to 10^{-6}



Radiative decay : $t \rightarrow bWZ$
-- SM : BR ~ 2 x 10^{-6}
-- LHC sensitivity : ≤ 10^{-4}



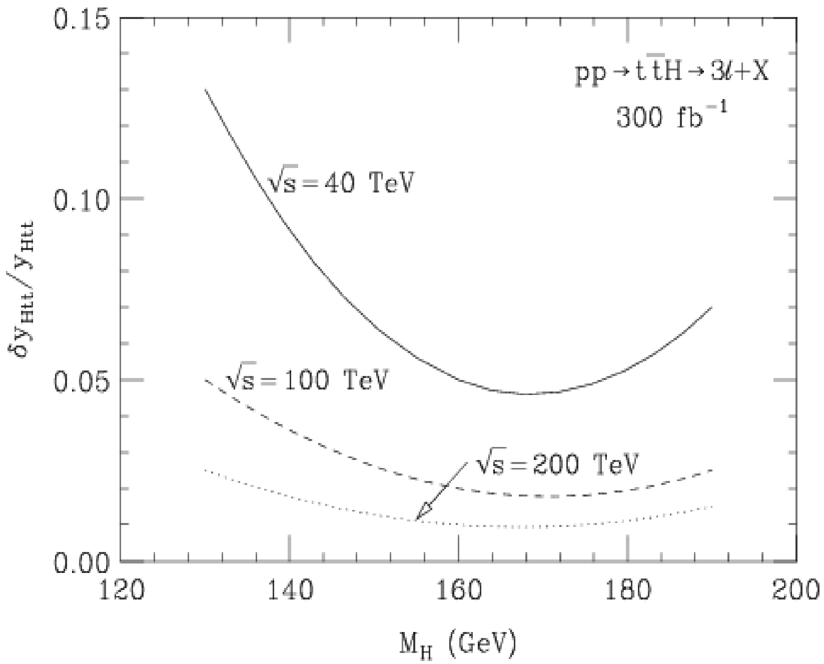
Standard Model Higgs

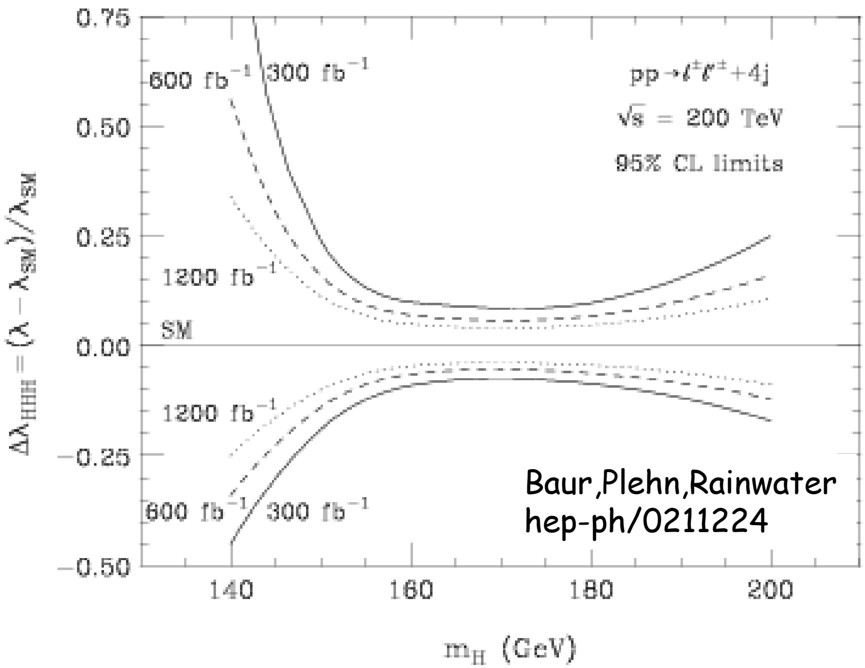
LC are best machines for precise measurements (‰ - % precision) of Higgs sector
→ detailed understanding of EWSB
"Worst-case" measurements : y_{Htt} , $y_{H\mu\mu}$, λ (5-8% precision) → can the VLHC do better ?

y_{Htt} from ttH → tt WW → 3ℓ + X
→ tt $\gamma\gamma$ m_H< 150 GeV

statistical errors only

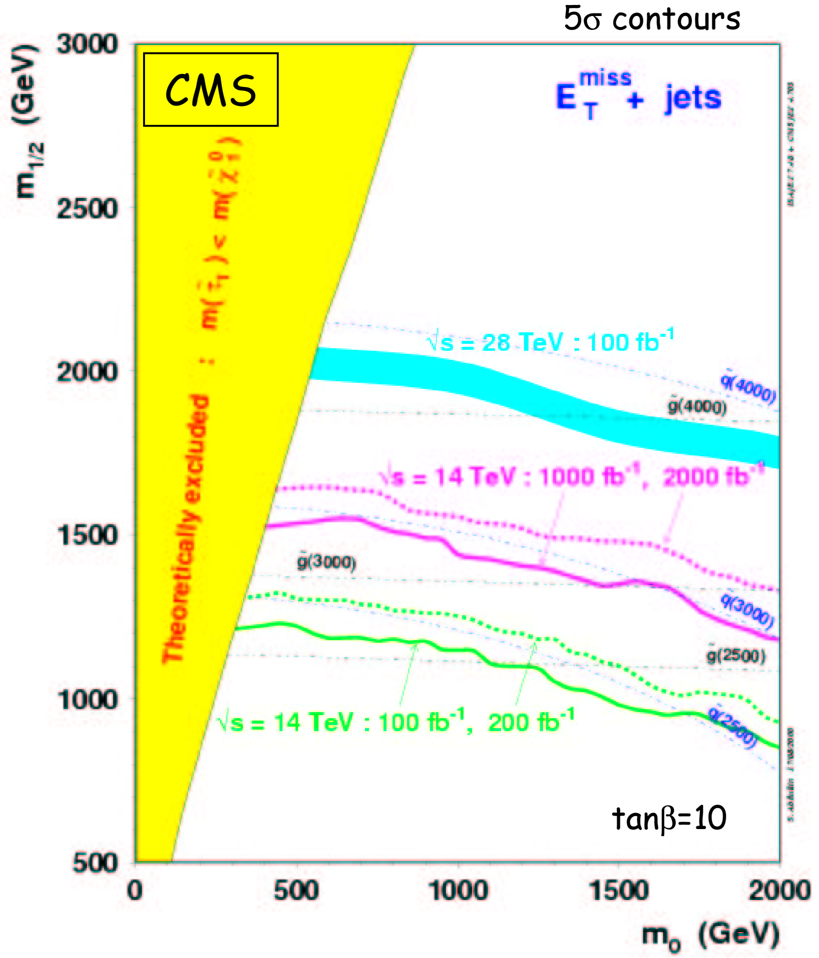
λ from gg→ HH→ WWWW
→ $\ell^{\pm}\nu jj$ $\ell^{\pm}\nu jj$





VLHC has statistical power to reach 1-3% precision [σ (200 TeV) ~ 10^2 σ (14 TeV)]
→ challenge is to control systematics (NLO, PDF, backgrounds, detector ..) to same level …. !?

Supersymmetry



If SUSY stabilizes m_H
→ "easy and fast" discovery at LHC :

-- large $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ cross-sections
-- spectacular signatures: e.g. multijet + E_T^{miss}
-- reach : ≈ 2.5 TeV (squarks, gluino)

In addition : measurements of many sparticle masses to 1-10% → first constraints of underlying theory

However :

- LHC can miss part of SUSY spectrum:
  -- $\tilde{g}$ or (some) $\tilde{q}$ may be at limit of LHC reach
  → SLHC goes up to ≈ 3 TeV

-- $\chi^{\pm}, \chi^0, \tilde{\ell}$ mainly from $\tilde{g}, \tilde{q}$ decays → observation less easy and more model-dependent

- more complete and precise (~‰) measurements of masses, couplings → detailed structure of new theory require cleaner machine

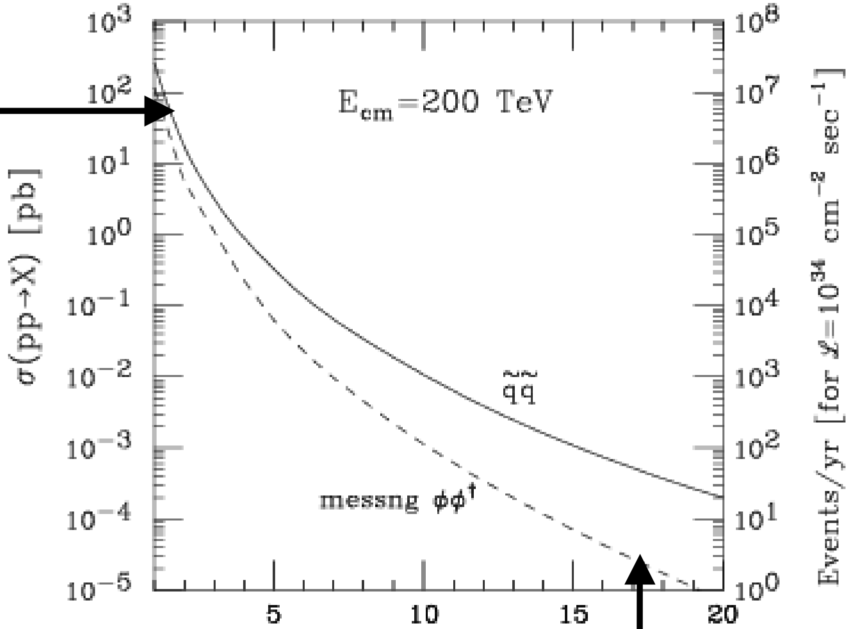
LC are best machines to complement LHC : observation and measurements of ~ all sparticles with m ≤ √s/2

What can the VLHC do for SUSY ?

2 "compelling" examples ...

① Inverted hierarchy models : $\tilde{q}$ of first 2 families heavy (m up to ~ 20 TeV)

→ LHC+ LC observe only part of SUSY spectrum
→ VLHC can observe heavy squarks



② LHC finds GMSB SUSY :

F ≡ SUSY breaking scale (hidden sector)
M ≡ Messenger scale

SUGRA : $M=M_{Pl}$
GMSB : M ~ 10-100 TeV possible

GMSB $LSP \equiv \tilde{G}$ NLSP : $\chi^0_1 \to \gamma \tilde{G}$ non-pointing photons
$\tilde{\ell} \to \ell \tilde{G}$ kinks / displaced vertices in tracker

F can be measured from $c\tau_{NLSP} \approx 100\mu m \left[\frac{100\,GeV}{m_{NLSP}}\right]^5 \left[\frac{F}{100\,TeV}\right]^4$

VLHC L upgrade to 10^{35} useful

→ together with sparticle spectroscopy can constrain M to ≈%-30% (LC or LHC)

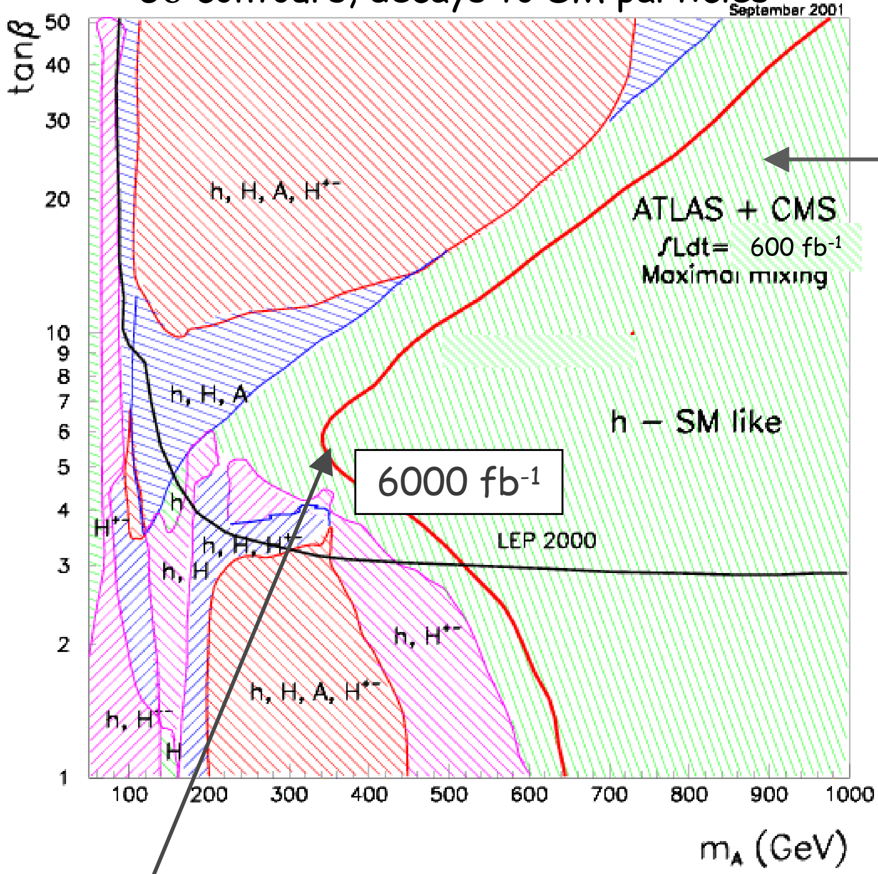
If M < 20 TeV → VLHC can observe GMSB Messenger fields Φ (e.g. $\Phi \to W/Z/\gamma + E_T^{miss}$)

Need good calorimetry (granularity, compensation), b-tag of high-p_T (dense) jets

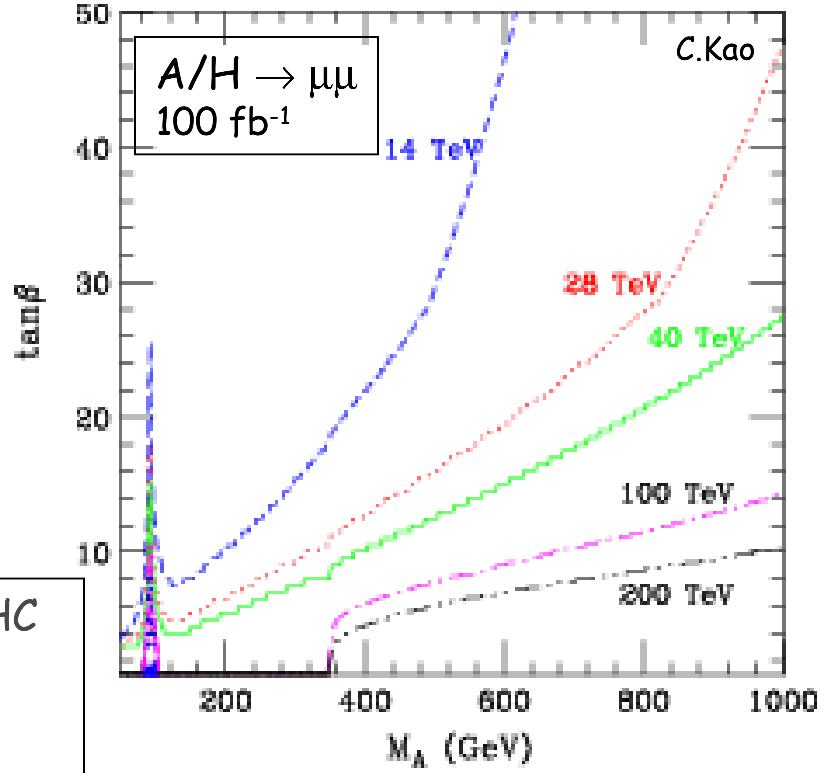
MSSM Higgs sector : h, H, A, $H^{\pm}$

$m_h < 135$ GeV , $m_A \approx m_H \approx m_{H\pm}$

5σ contours, decays to SM particles



In the green region only SM-like h observable, **unless A, H, $H^{\pm} \rightarrow$ SUSY particles**
→ LHC can miss part of MSSM Higgs spectrum

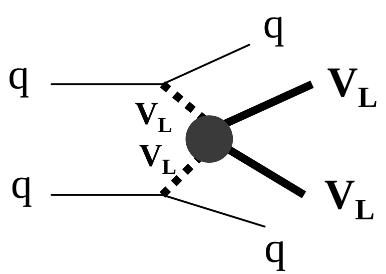


Region where ≥ 1 heavy Higgs observable (5σ) at SLHC
→ green region reduced by up to 200 GeV.
Region m_A < 600 GeV, where √s = 800 GeV LC can demonstrate (at 95% C.L.) existence of heavy Higgs indirectly **(i.e. through precise measurements of h couplings)**, almost fully covered.

Direct observation of whole Higgs spectrum may require √s ≥ 2 TeV LC

Strong $V_L V_L$ scattering

If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at $\sqrt{\hat{s}} \approx$ TeV



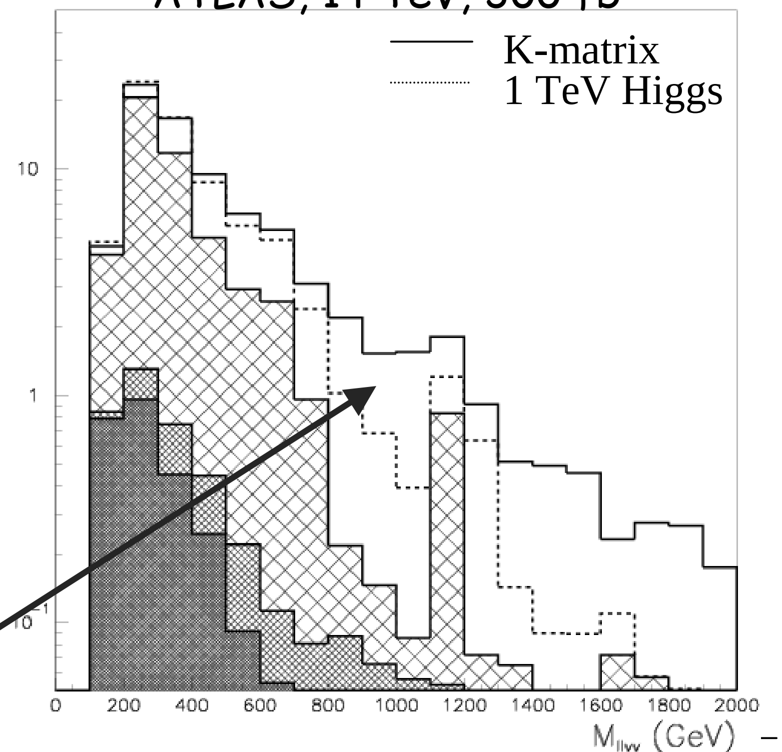
Forward jet tag ($|\eta|>2$) and central jet veto essential tools against background
LHC : σ (signal) $\approx$ fb

LHC : difficult ...

Best non-resonant channel is
$W^+_L W^+_L \to W^+_L W^+_L \to \ell^+\nu \ \ell^+\nu$

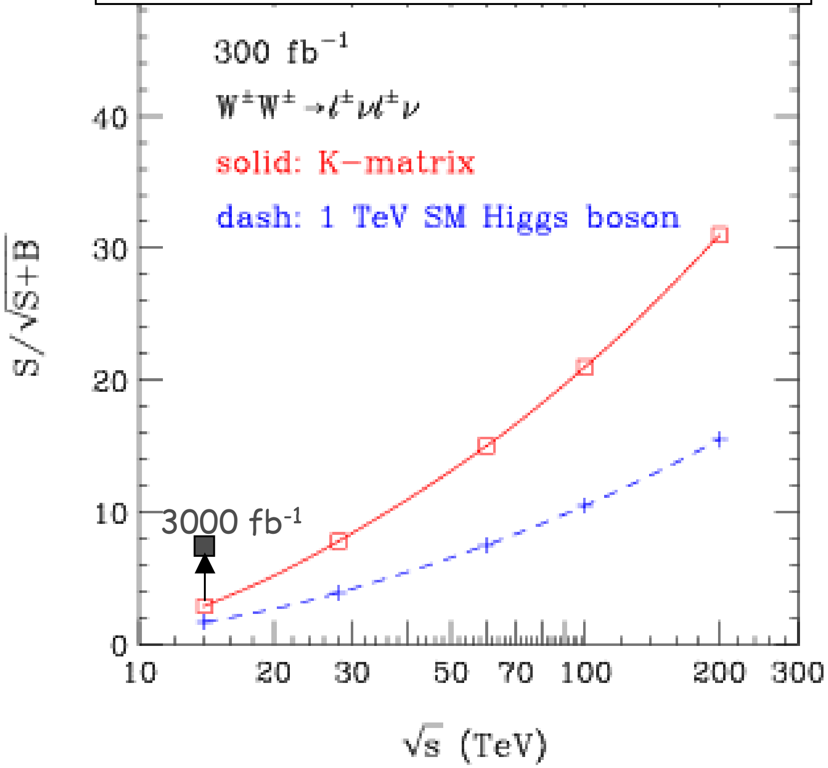
-- Expected potential depends on exact model
-- Lot of data needed to extract signal (if at all possible ...)

ATLAS, 14 TeV, 300 fb^{-1}



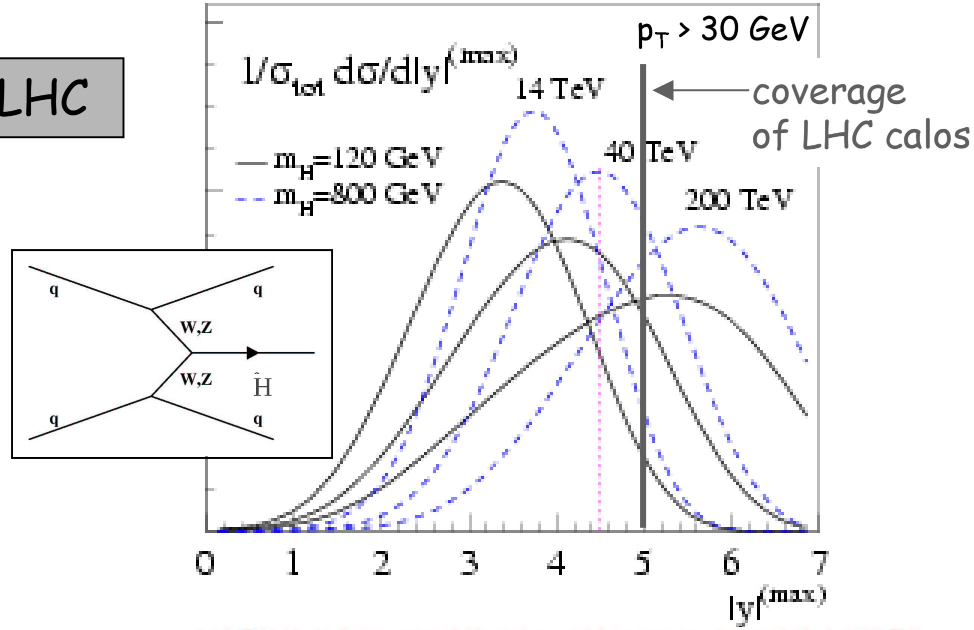
2-3σ excess, S and B have similar shapes

Non-resonant $W^+_L W^+_L$ scattering at pp machines vs $\sqrt{s}$



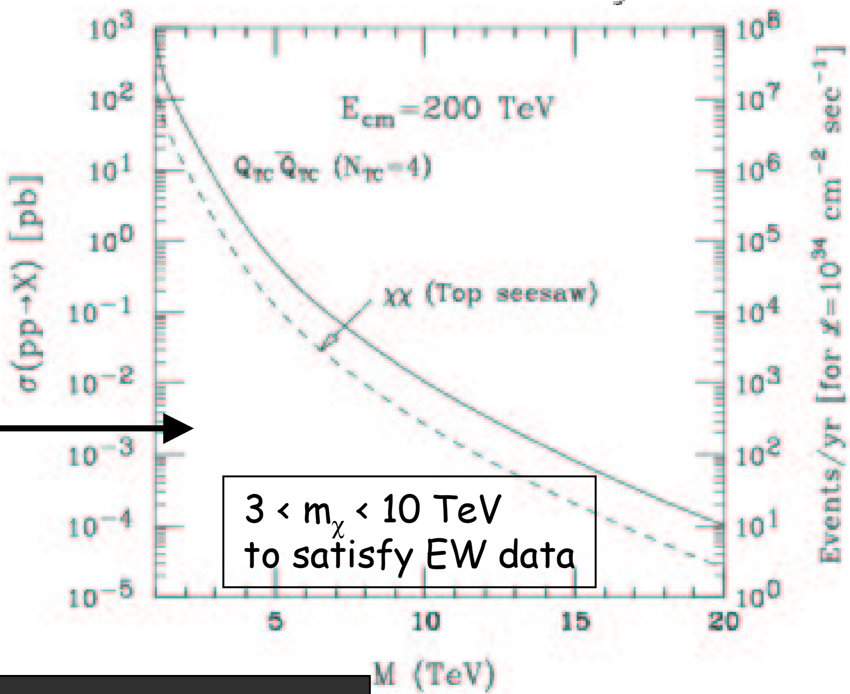
VLHC

Maximum jet rapidity vs $\sqrt{s}$



Detailed study of new dynamics also possible (better ?) at LC with $\sqrt{s}$ > 1 TeV

However : if strong EWSB involves heavy fermions (e.g. Technicolour, top-seesaw models) → only VLHC can observe directly these particles if m >> 1 TeV (up to m ~ 15 TeV)



Need fwd jet tag up to $|\eta|\approx$6-7, ℓ charge measurement up to few TeV

How our views change with time .....

10^{34}

From : "Report of High Luminosity Study Group to the CERN Long-Range Planning Committee", CERN 88-02, 1988.

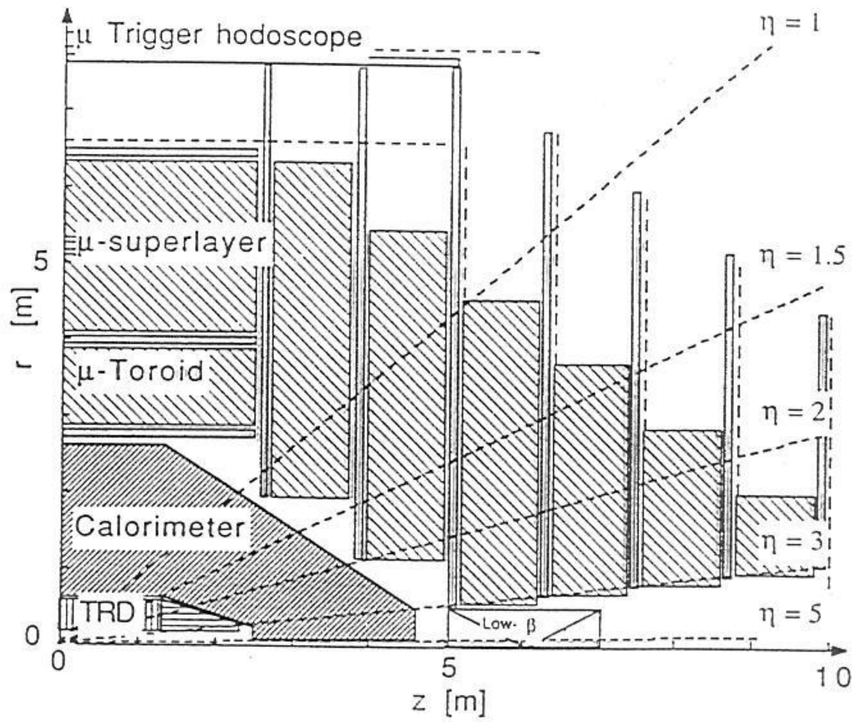


Figure 1. Conceptual design of 'non-magnetic' detector system. Calorimeter coverage for $3 < |\eta| \leq 5$ is not essential for luminosity $> 10^{33} cm^{-2}s^{-1}$.

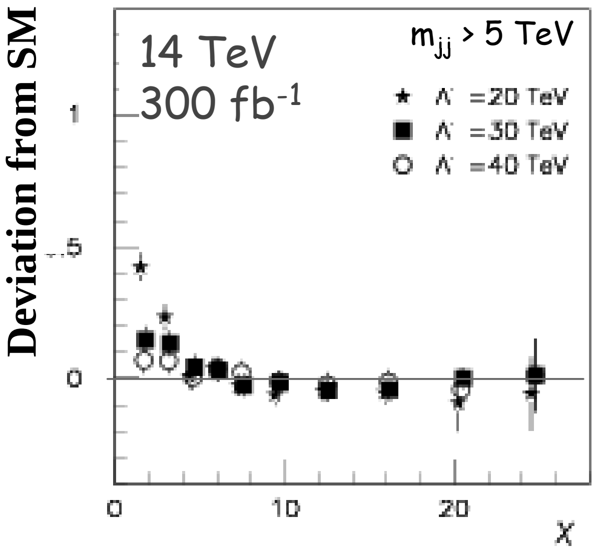
?

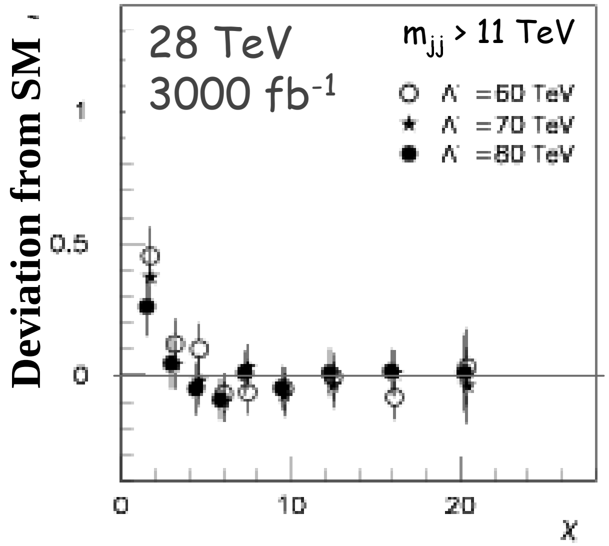
Compositeness

$$L_{CI} = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda^2_{ij}} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma^\mu f_j)$$

① $\sqrt{\hat{s}} << \Lambda$: contact interactions $qq \to qq$

2-jet events: **expect** excess of high-E_T centrally produced jets.
E_T spectrum sensitive to QCD HO corrections, PDF, calorimeter non-linearity, angular distributions ~ insensitive





$$\chi = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

if contact interactions
→ excess at low χ

95% CL	14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	28 TeV 300 fb^{-1}	200 TeV 300 fb^{-1}
Λ (TeV)	40	60	60	≈ 100

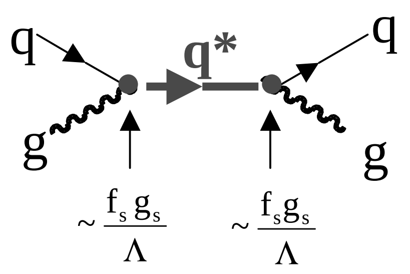
LC : sensitive to $\ell\ell qq$, $\ell\ell\ell\ell$ (complementary) up to ≈ 100-400 TeV (√s=0.8-5 TeV)

Need calorimeter linearity (compensation …) and b-tag (→ flavour-dependence of compositeness) at very high p_T

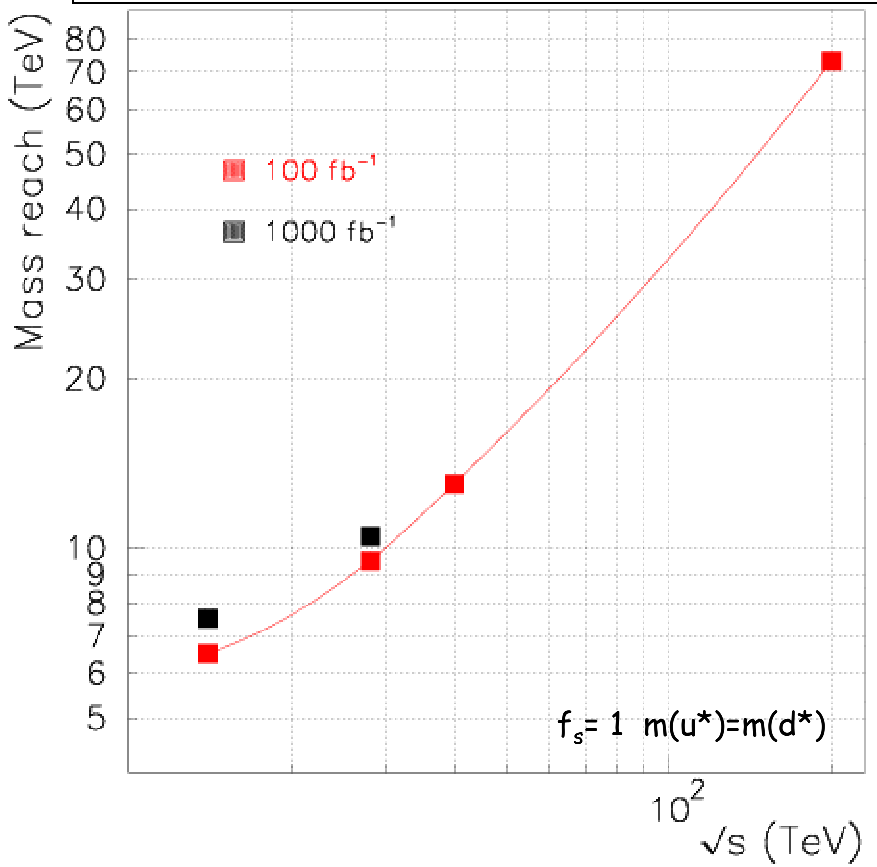
If evidence for compositeness at LHC/SLHC/first LC → VLHC can probe directly scale Λ

② $\sqrt{\hat{s}} \geq \Lambda$: production of excited quarks expected

→ would give conclusive evidence for compositeness



Discovery reach for q* → jj at pp machines



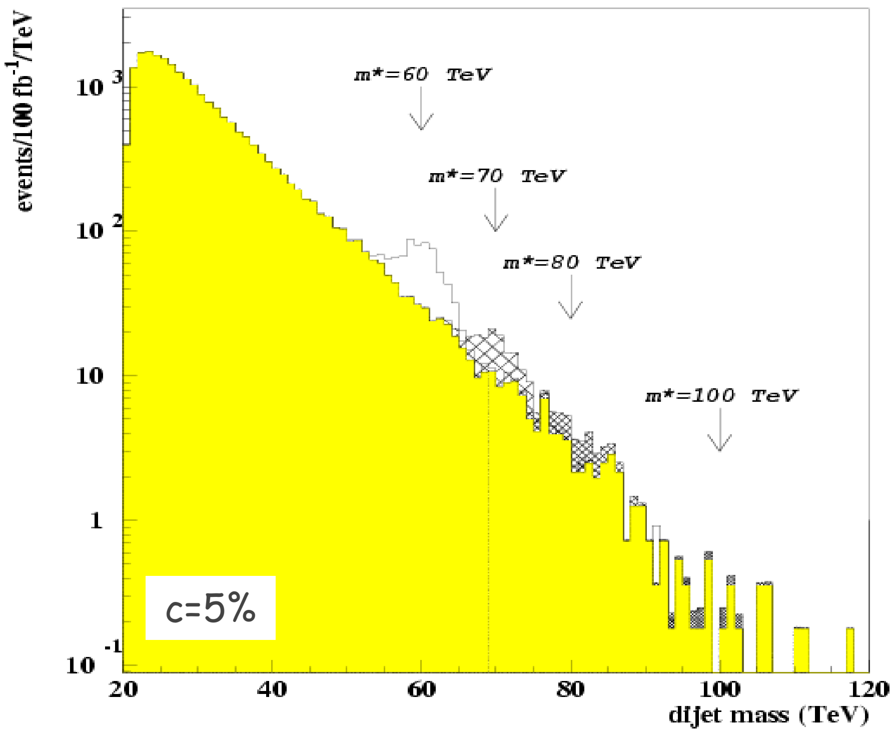
- similar results for q* → qW, qZ, qγ
- f_s = 0.1 : ~ 2 lower mass reach

LC reach : m* ~ √s

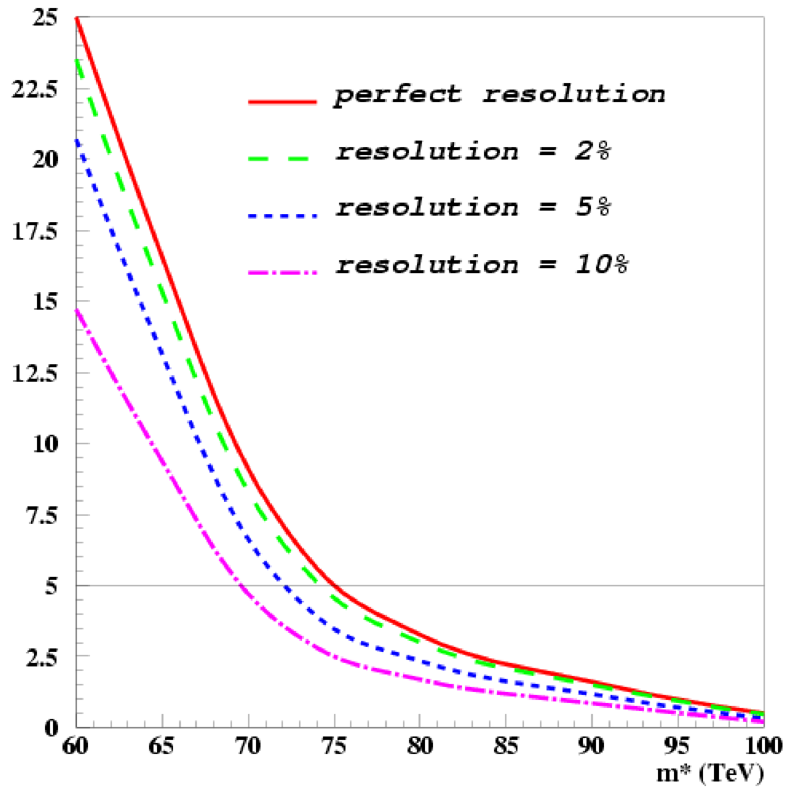
$\Gamma(q^*) \approx 4\% \ m(q^*)$ → small constant term of jet E-resolution crucial to observe "narrow" peaks.

$$\frac{\sigma(\text{jet})}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$\sqrt{s}$ = 200 TeV, 100 fb^{-1}

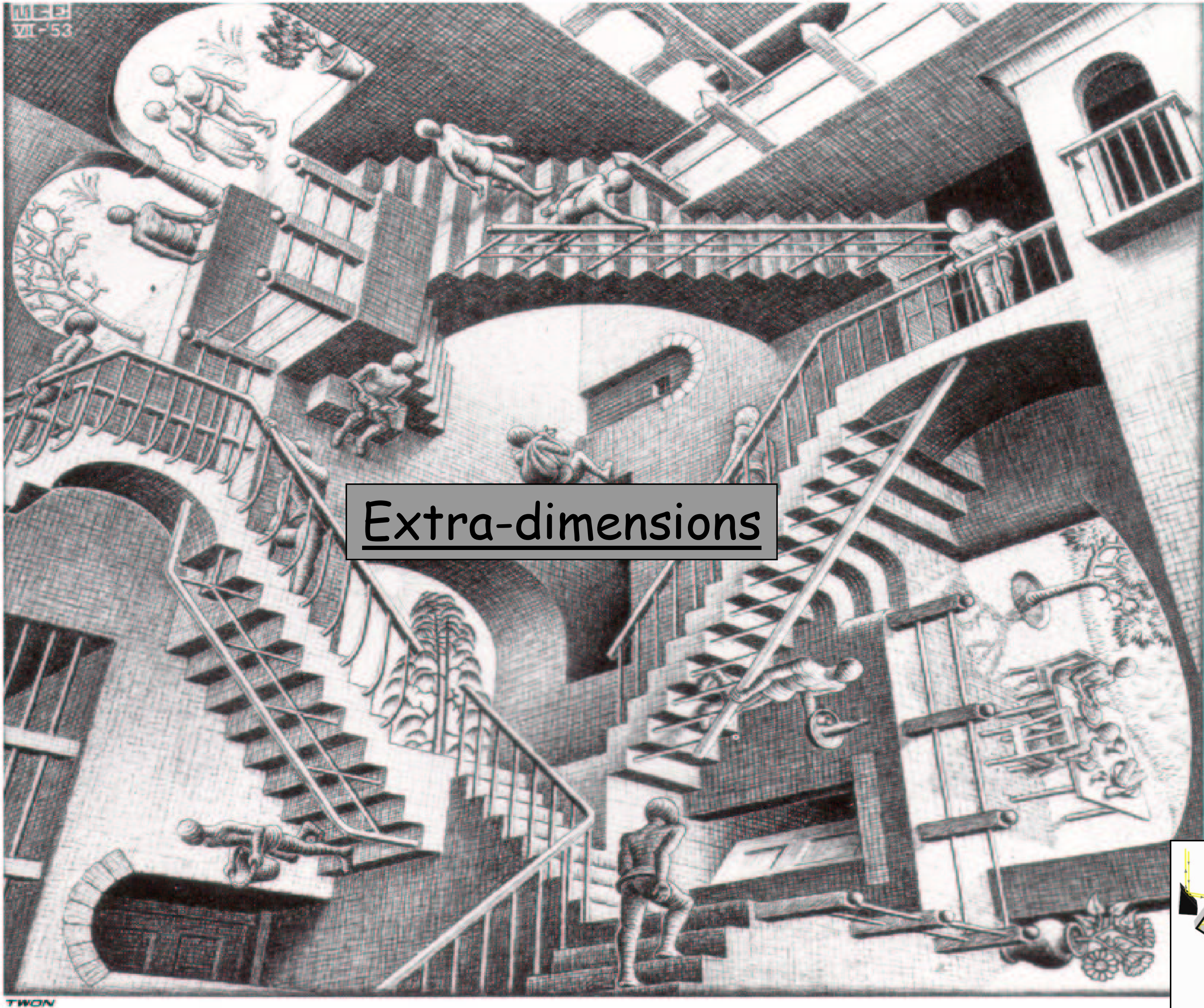


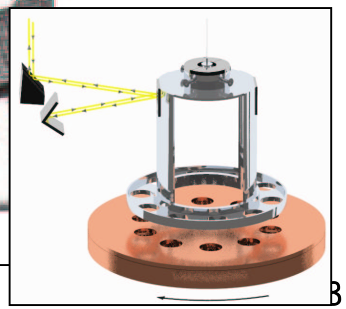
Signal significance for 100 fb^{-1}

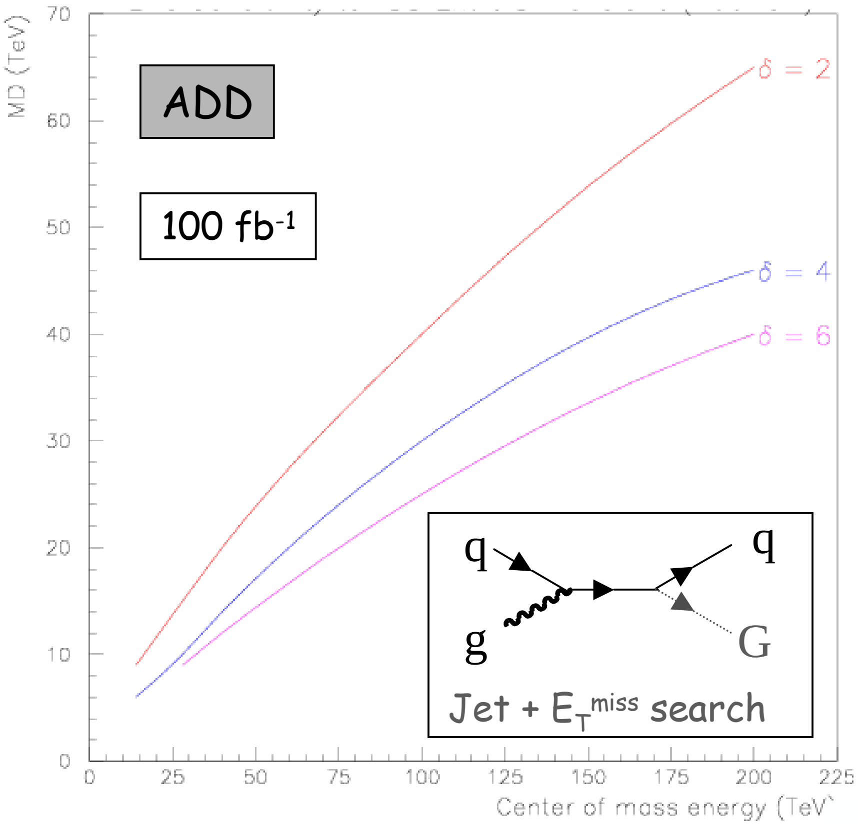


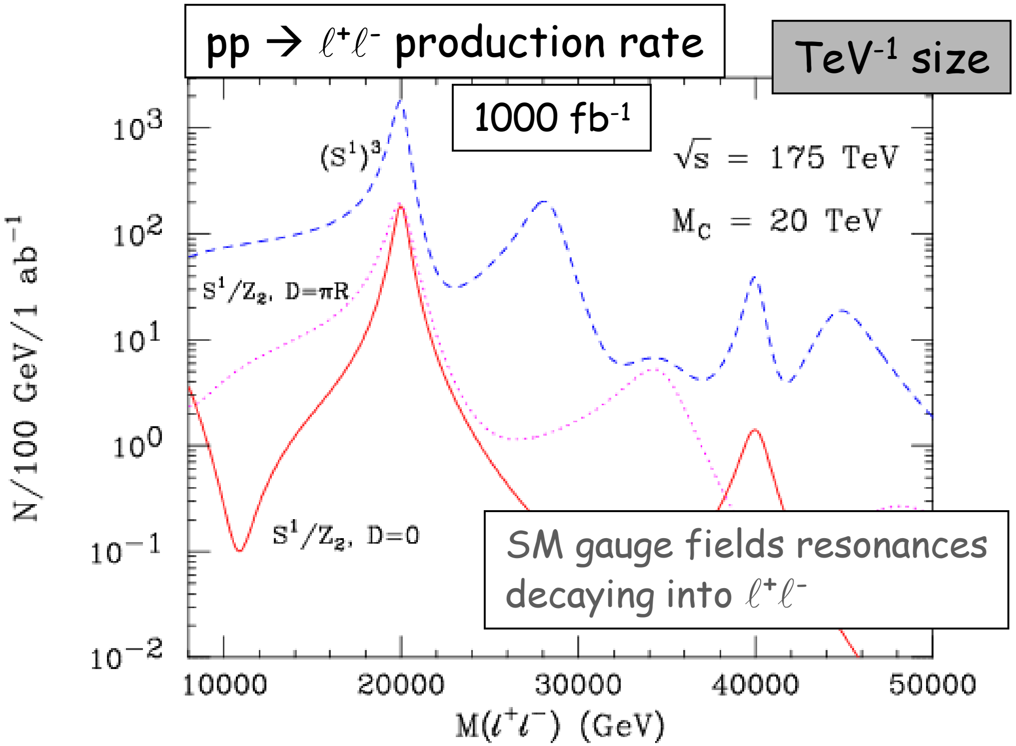
Need good jet energy resolution (i.e. small constant term, i.e. good compensation …)

Extra-dimensions

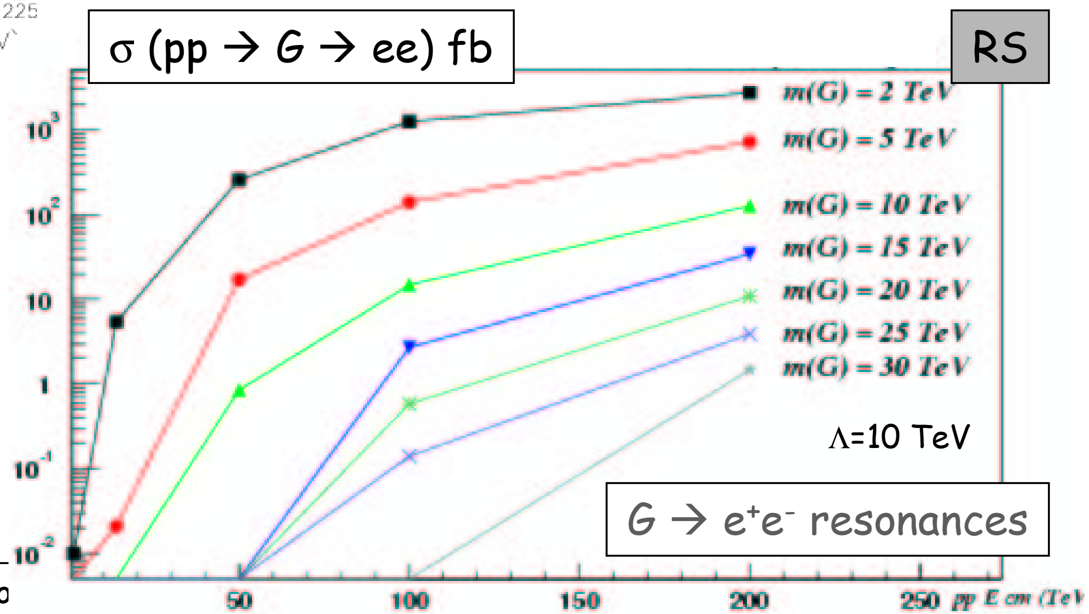








- VLHC reach for resonances: m ~ 20-30 TeV
- LC reach : m ~ √s but more precise measurements of resonance parameters (e.g. from resonance scan)



Need good calorimetry (jets, E_T^{miss}), ℓ p-resolution ≤ 10% up to ~ 10 TeV

Summary of reach and comparison of various machines

Only a few examples ….
In many cases numbers are just indications ….

Units are TeV (except $W_L W_L$ reach)
$\int L dt$ correspond to <u>1 year of running</u> at nominal luminosity for <u>1 experiment</u>

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	LC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ	7σ	18σ	6σ	90σ
Z′	5	6	8	11	35	8†	30†
Extra-dim (δ=2)	9	12	15	25	65	5-8.5†	30-55†
q*	6.5	7.5	9.5	13	75	0.8	5
Λ compositeness	30	40	40	50	100	100	400

† indirect reach (from precision measurements)

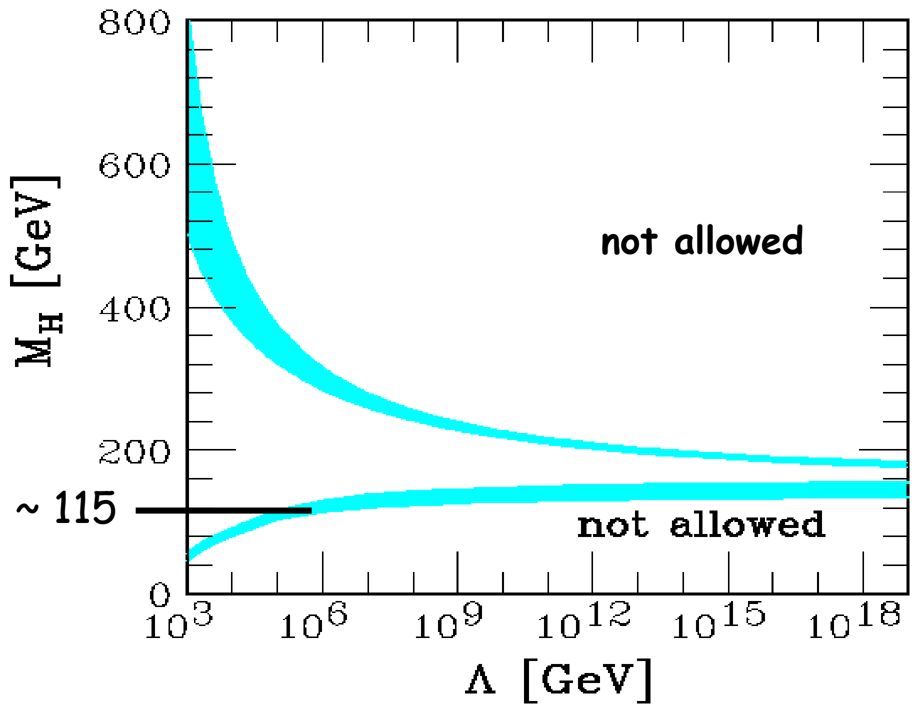
probes directly up to ~100 TeV with ultimate luminosity (VLHC 200 TeV)

probes indirectly up to ~1000 TeV with ultimate luminosity (LC 5 TeV)

Approximate mass reach of pp machines:

$\sqrt{s}$ = 14 TeV, L=10^{34} (LHC) : up to ≈ 6.5 TeV
$\sqrt{s}$ = 14 TeV, L=10^{35} (SLHC) : up to ≈ 8 TeV
$\sqrt{s}$ = 28 TeV, L=10^{34} : up to ≈ 10 TeV
$\sqrt{s}$ = 40 TeV, L=10^{34} (VLHC-I) : up to ≈ 13 TeV
$\sqrt{s}$ = 200 TeV, L=10^{34} (VLHC-II) : up to ≈ 75 TeV

If $m_H \sim 115$ GeV → New Physics at $\Lambda < 10^5$-10^6 GeV
→ a VLHC can probe directly large part of this range



❸ Examples of possible compelling scenarios for a VLHC emerging from LHC data ....

LHC finds some SUSY particles but no squarks of first two generations (as in inverted hierarchy models)
→ VLHC would observe heaviest part of the spectrum

LHC finds GMSB SUSY with Messenger scale M < 20 TeV
→ VLHC would probe directly scale M and observe Messenger fields

LHC finds contact interactions → Λ < 60 TeV
→ VLHC would probe directly scale Λ and observe e.g. q*

LHC finds ADD Extra-dimensions → $M_D \leq 10$ TeV
→ VLHC would probe directly gravity scale M_D and above (e.g. observe black holes)

LHC finds hints of strong EWSB
→ VLHC would see a clear signal and could observe massive particles associated with new dynamics

Conclusions

- LHC, although powerful, will not be able to answer all outstanding questions, and new high energy/luminosity machine(s) will most likely be needed.

- Lepton Colliders are best machine to complement the LHC in most cases, but their direct discovery reach is "limited" to the TeV-range.

- The VLHC is the only machine that in principle we know how to build able to probe directly the 10-100 TeV energy range.

- Because we ignore what happens at the TeV scale, and in the absence of theoretical preference for a specific scale beyond the TeV region, the VLHC physics case is less clear today than that of a LC.

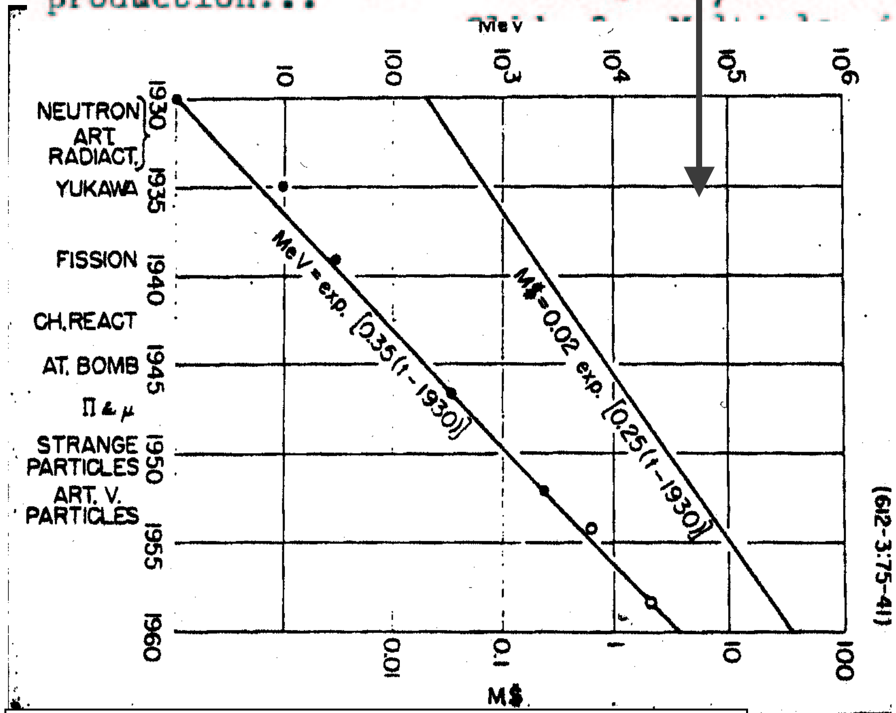
- However, it is likely that at some point we will want to explore the 10-100 TeV range. In particular strong arguments may emerge already from LHC data.
  → it is not too early to start thinking about such a machine … (planning, R&D, etc.)

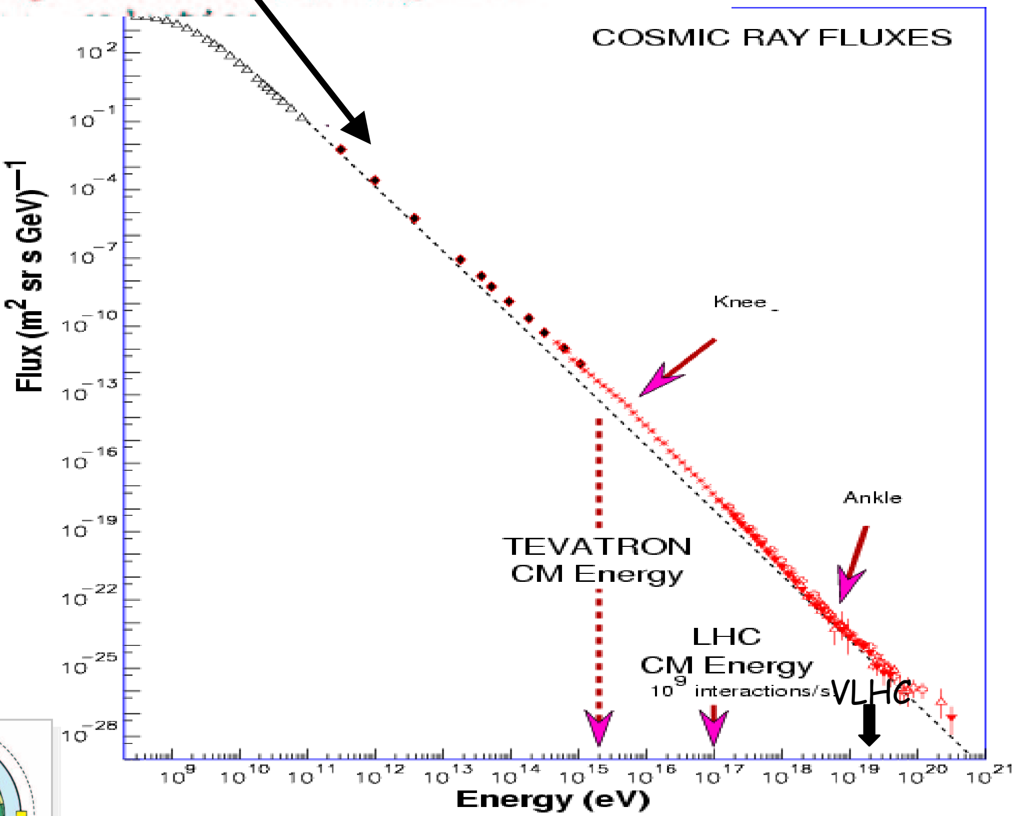
From E. Fermi, preparatory notes for a talk on "What can we learn with High Energy Accelerators ? " given to the American Physical Society, NY, Jan. 29th 1954

University of Chicago Library

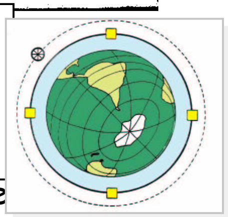
For these reasons....clamoring for higher and higher....
Slide 1 - MeV - M$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss
Slide 2 - 5 hi 15 eV machine.

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experience on pions....sharpening knowledge....spin zero and odd symmetry.....certainly look for multiple production...



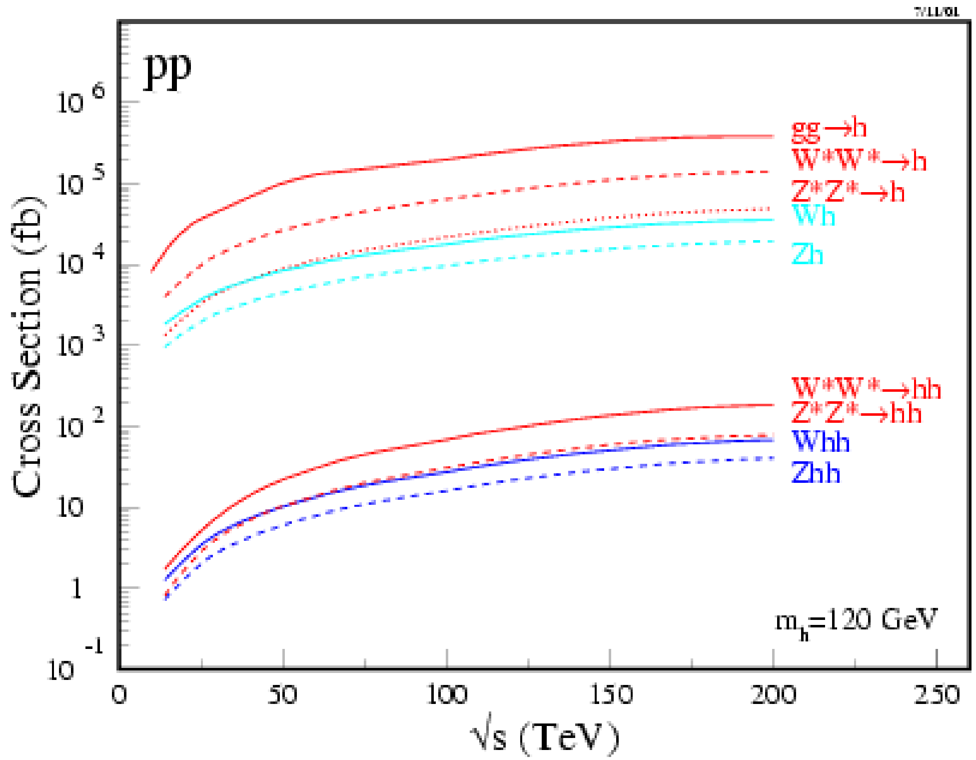


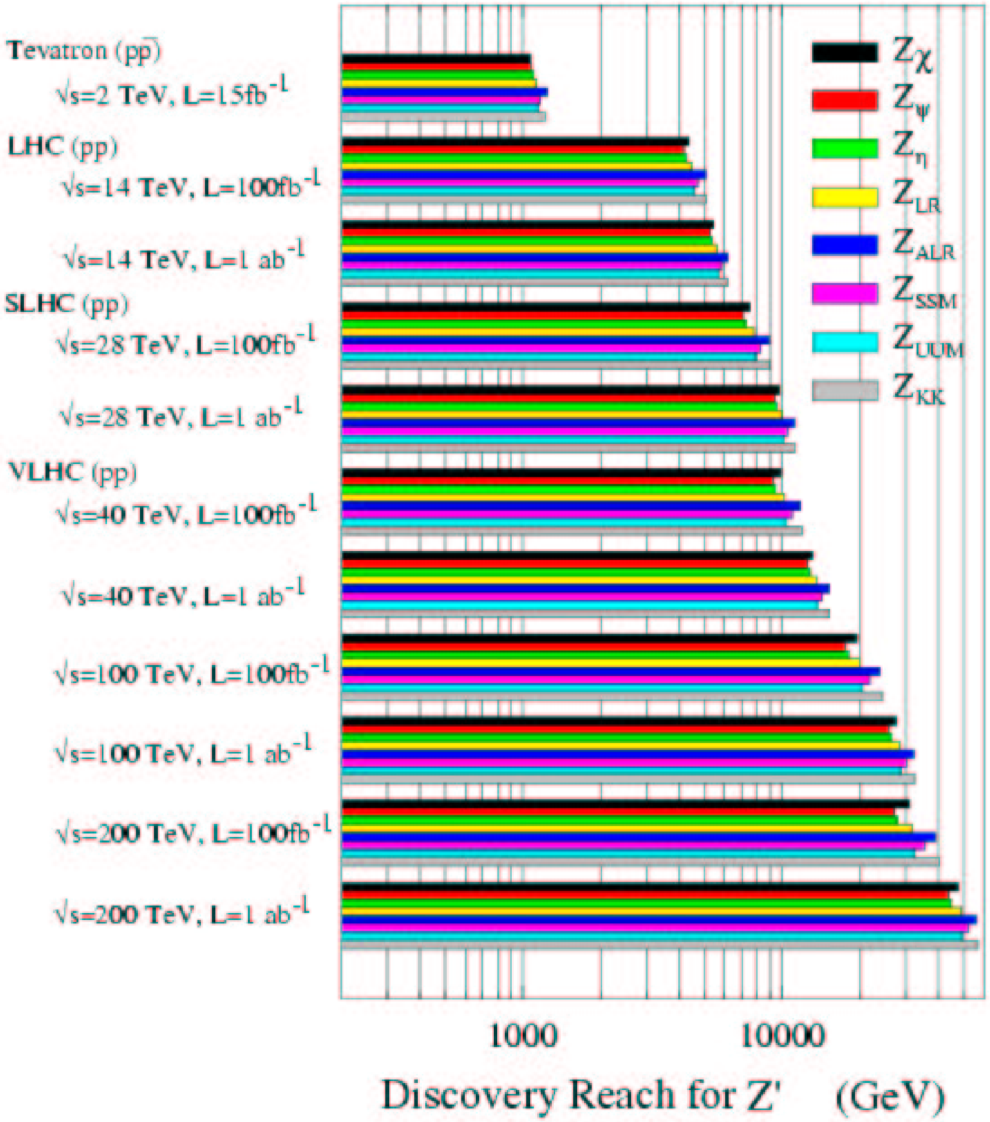
Fermi's extrapolation to year 1994:
2T magnets, R=8000 Km machine
E_{beam} ~ 5×10^3 TeV , cost 170 B$



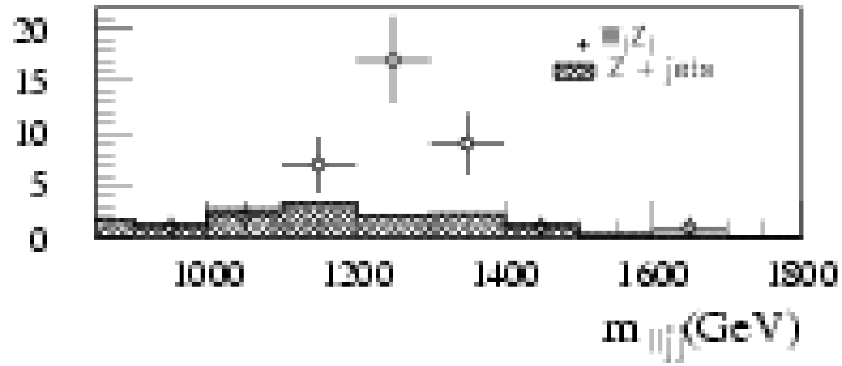
E_{beam} (TeV) ~ 10^3 10^5 10^7 –

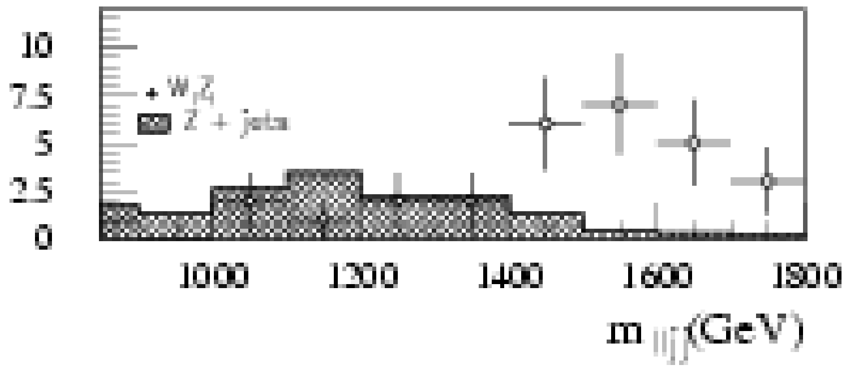
Back-up slides

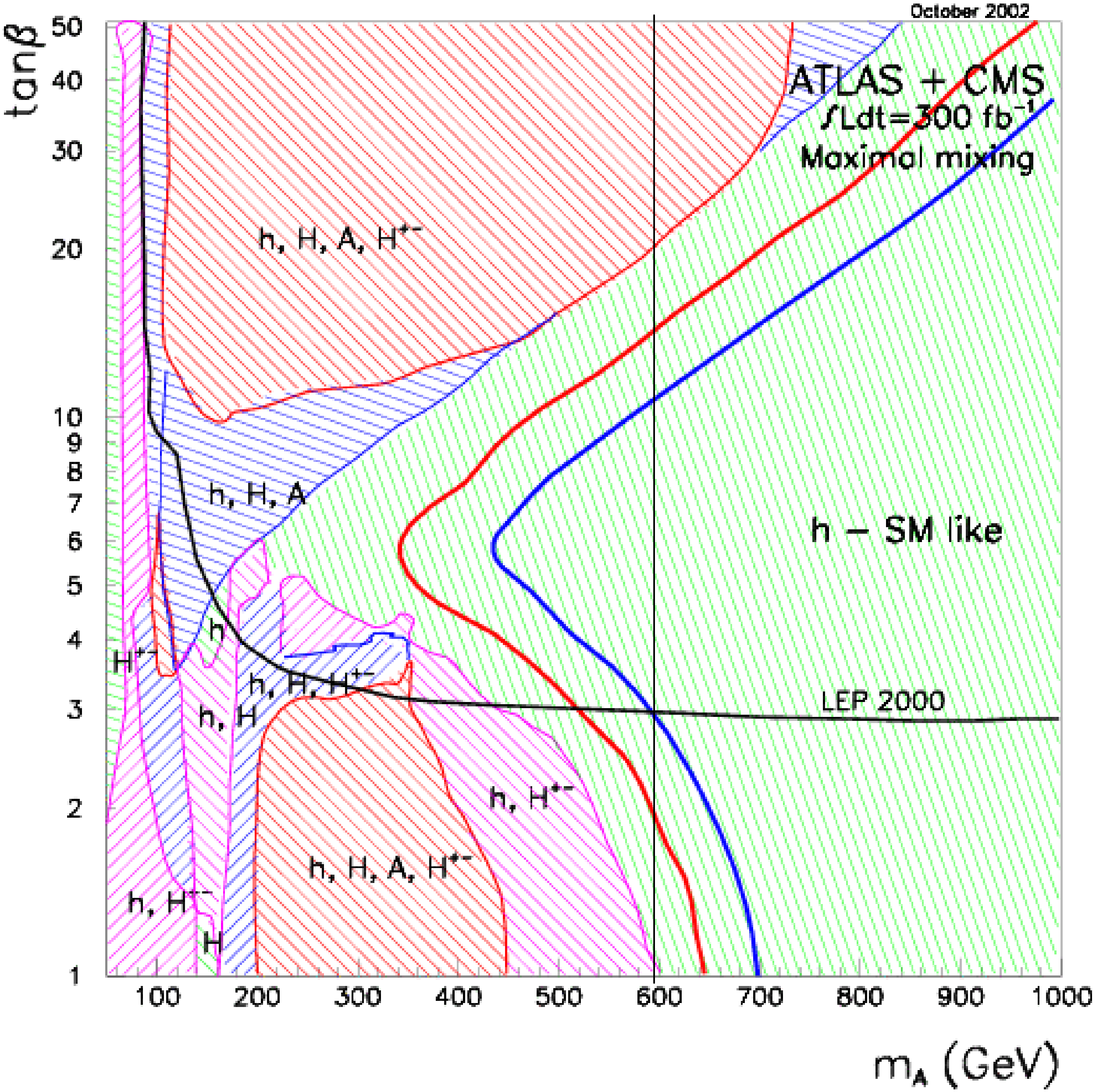

7/11/01
pp
Cross Section (fb)
10 6
10 5
10 4
10 3
10 2
10
1
10 -1
gg→h
W*W*→h
Z*Z*→h
Wh
Zh
W*W*→hh
Z*Z*→hh
Whh
Zhh
m_h=120 GeV
0
50
100
150
200
250
√s (TeV)



Tevatron (pp̄)
√s=2 TeV, L=15fb-1
LHC (pp)
√s=14 TeV, L=100fb-1
√s=14 TeV, L=1 ab-1
SLHC (pp)
√s=28 TeV, L=100fb-1
√s=28 TeV, L=1 ab-1
VLHC (pp)
√s=40 TeV, L=100fb-1
√s=40 TeV, L=1 ab-1
√s=100 TeV, L=100fb-1
√s=100 TeV, L=1 ab-1
√s=200 TeV, L=100fb-1
√s=200 TeV, L=1 ab-1
Zχ
Zψ
Zη
ZLR
ZALR
ZSSM
ZUUM
ZKK
1000
10000
Discovery Reach for Z' (GeV)

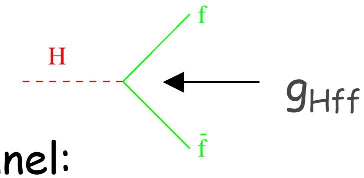

20
15
10
5
0
Z + jets
1000
1200
1400
1600
1800
m lljj(GeV)


10
7.5
5
2.5
0
Z + jets
1000
1200
1400
1600
1800
m lljj(GeV)



October 2002
ATLAS + CMS
∫Ldt=300 fb^{-1}
Maximal mixing
h, H, A, H^{+-}
h, H, A
h
H^{+-}
h, H, H^{+-}
h, H
h, H^{+-}
h, H, A, H^{+-}
h, H^{+-}
H
h – SM like
LEP 2000
tanβ
50
40
30
20
10
9
8
7
6
5
4
3
2
1
100
200
300
400
500
600
700
800
900
1000
m_A (GeV)

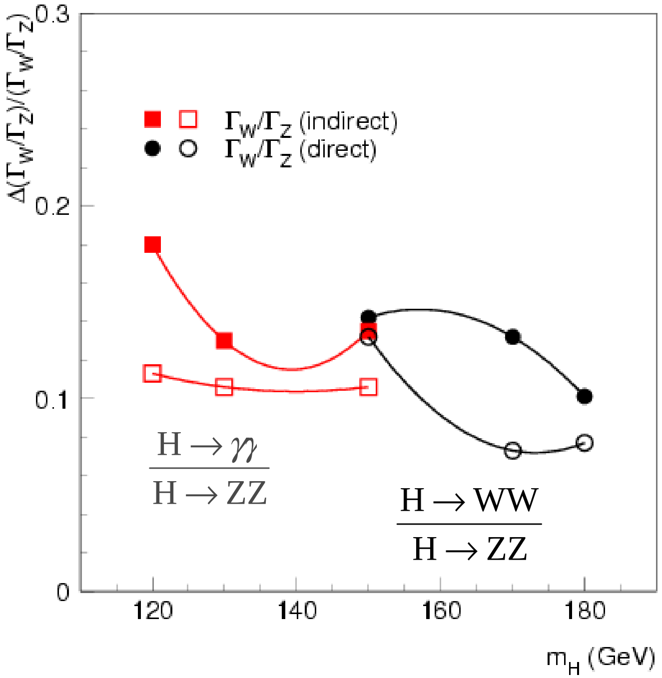
Higgs couplings to fermions and bosons at SLHC



Couplings can be obtained from measured rate in a given production channel:

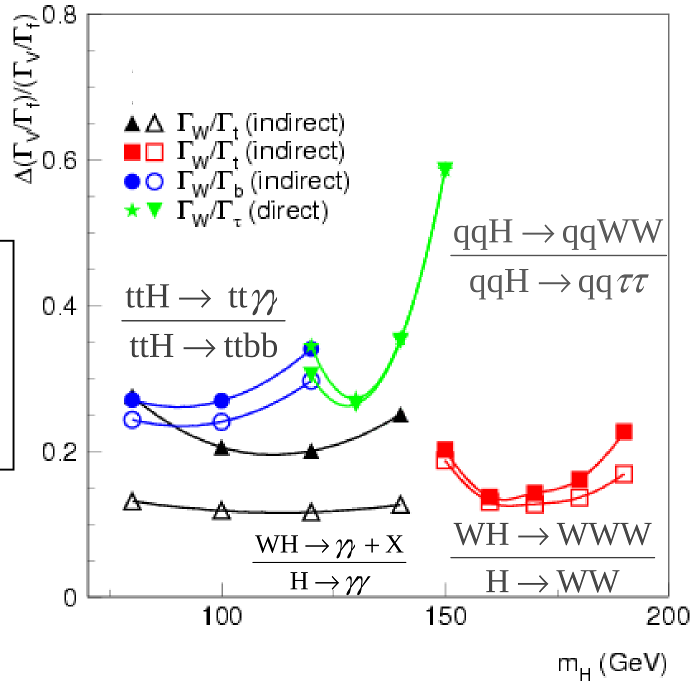
$$R_{ff} = \int L\,dt \bullet \sigma\,(e^+e^-, pp \to H + X) \bullet BR\,(H \to ff) \qquad BR\,(H \to ff) = \frac{\Gamma_f}{\Gamma_{tot}} \qquad \to \text{ deduce } \Gamma_f \sim g^2_{Hff}$$

- LC : Γ_{tot} and σ ($e^+e^- \to H+X$) from data
- Hadron Colliders : Γ_{tot} and σ ($pp \to H+X$) from theory → without theory inputs measure ratios of rates in various channels (Γ_{tot} and σ cancel) → $\Gamma_f/\Gamma_{f'}$ → several theory constraints



Closed symbols: LHC 600 fb^{-1}

Open symbols: SLHC 6000 fb^{-1}



-- SLHC could improve LHC precision by up to ~ 2 before first LC becomes operational

-- Not competitive with LC precision of ≈ %

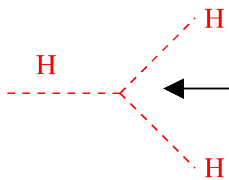
Rare Higgs decays at SLHC

BR ~ 10^{-4} both channels

Channel	m_H	$S/\sqrt{B}$ LHC (600 fb^{-1})	$S/\sqrt{B}$ SLHC (6000 fb^{-1})
$H \to Z\gamma \to \ell\ell\gamma$	~ 140 GeV	~ 3.5	~ 11
$H \to \mu\mu$	130 GeV	~ 3.5 (gg+VBF)	~ 7 (gg)

→ additional coupling measurements : e.g. Γ_μ / Γ_W to ~ 20%

Higgs self-couplings at SLHC ?



~ λv

$m_H^2 = 2 \lambda v^2$

LHC : $\sigma(pp \to HH) < 40$ fb $m_H > 110$ GeV
+ small BR for clean final states → no sensitivity

SLHC : $HH \to W^+ W^- W^+ W^- \to \ell^\pm \nu jj \;\; \ell^\pm \nu jj$
studied (very preliminary)

6000 fb^{-1}	S	S/B	$S/\sqrt{B}$
m_H = 170 GeV	350	8%	5.4
m_H = 200 GeV	220	7%	3.8

If :
- -- $K_B^2 < K_S$
- -- B can be measured with data + MC (control samples)
- -- B systematics < B statistical uncertainty
- -- fully functional detector (e.g. b-tagging)

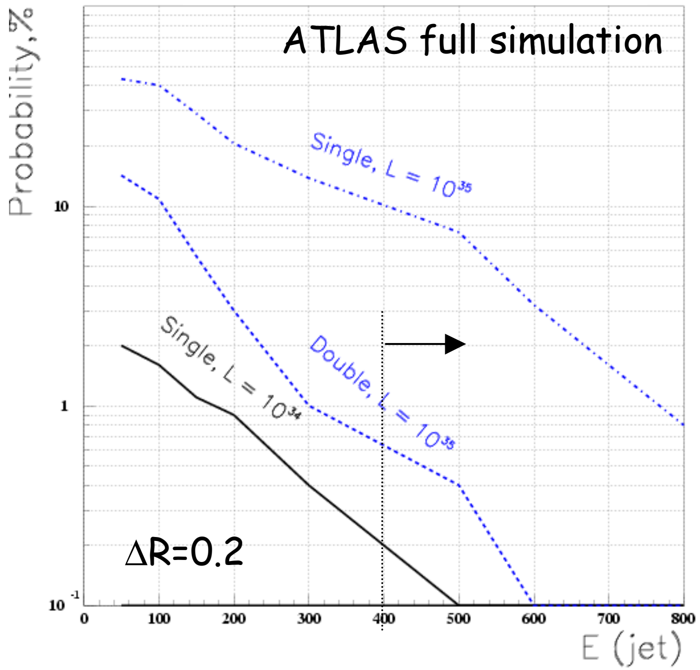
→
- -- HH production may be observed for first time at SLHC
- -- λ may be measured with stat. error ~ 20%

Not competitive with LC : precision up to 7% ($\sqrt{s} \geq 3$ TeV, 5000 fb^{-1})

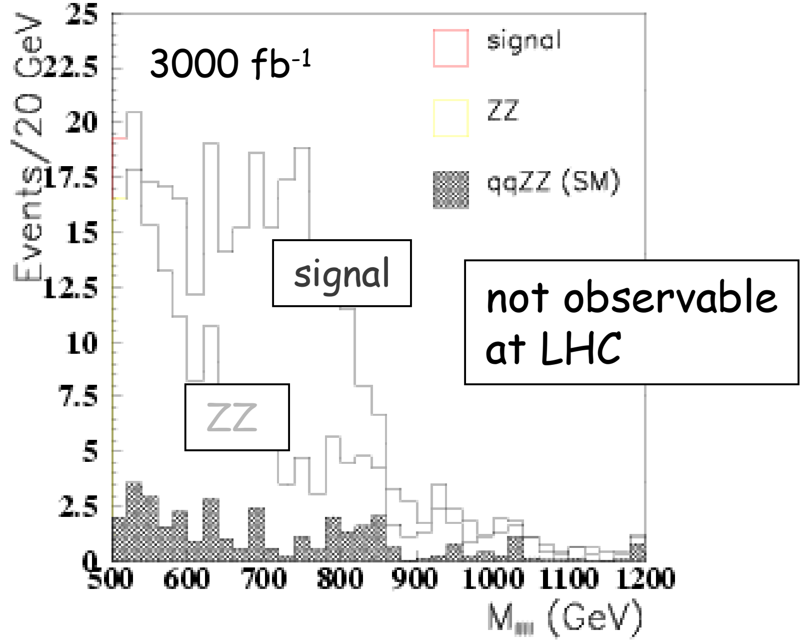
SLHC

-- degradation of fwd jet tag and central jet veto due to huge pile-up
-- **however** : factor ~ 10 in statistics → 5-8σ excess in $W^+_L W^+_L$ scattering
→ other low-rate channels accessible

Fake fwd jet tag (|η| > 2) probability
from pile-up **(preliminary ...)**



Scalar resonance $Z_L Z_L \rightarrow 4\ell$



Study of several channels ($W_L W_L$, $Z_L Z_L$, $W_L Z_L$) may be possible at SLHC
→ insight into the underlying dynamics