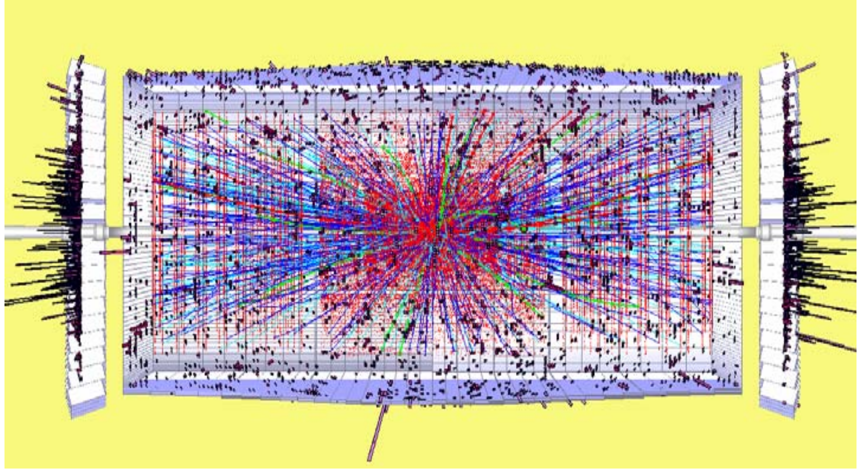
Physics opportunities at the LHC with an improved luminosity

HIF2004, Isola d'Elba, 6/6/2004
Fabiola Gianotti (CERN)

- Motivations
- Environment, detector upgrades
  (machine : see talk by W. Scandale)
- Some examples of physics potential
  (and comparisons with other machines …)

$H \rightarrow ee\mu\mu$ event in CMS at 10^{35} cm^{-2}s^{-1}



Time scale :
-- first LHC collisions : summer 2007
-- reach 10^{34} cm^{-2} s^{-1} in ~ 2010 ?
-- luminosity upgrade to 10^{35} cm^{-2} s^{-1} around 2015 ?

Motivations for a luminosity upgrade of the LHC ("SLHC ≡Super-LHC")

Precise physics case depends on what the LHC will find, but in general:

- **SLHC can extend the LHC mass reach by ~ 30%**
  --> increase/consolidate LHC discovery potential **at the (compelling) TeV-scale**
- **Can improve on precision measurements : parameter determination**
  of e.g. Higgs and New Physics if discovered ….
- **Higher sensitivity to rare processes**

➡ Maximum exploitation of existing tunnel, machine, detectors …

Note:
-- SLHC is not a new machine → physics and cost not comparable to LC, CLIC, MC, VLHC …
-- energy upgrade to $\sqrt{s}$ ~ 28 TeV also considered: requires new machine with ~16T magnets
→ only L upgrade discussed here (but some comparisons with $\sqrt{s}$ = 28 TeV made)

The environment and the main experimental challenges

	LHC	SLHC
$\sqrt{s}$	14 TeV	14 TeV
Luminosity	10^{34}	10^{35}
Bunch spacing Δt	25 ns	12.5 ns *
σ_{pp} (inelastic)	~ 80 mb	~ 80 mb
N. interactions/x-ing (N=L σ_{pp} Δt)	~ 20	~ 100
$dN_{ch}/d\eta$ per x-ing	~ 150	~ 750
$\langle E_T \rangle$ charg. particles	~ 450 MeV	~ 450 MeV
Tracker occupancy	1	10
Pile-up noise in calo	1	~3
Dose central region	1	10

Normalized to LHC values assuming same detector granularity and integration time

e.g. 10^4 Gy/year R=25 cm

* Presently under study:

-- 12.5 ns ok for experiments, bad for machine (e^- cloud)

-- 300 m super-bunch good for machine, bad for experiments (pile-up ~ 20 larger than at LHC)

-- continuous beam may be the solution ...

- Trackers : need to be replaced (radiation, occupancy, response time)
  - -- $R > 60$ cm : development of present Si strip technology ~ ok
  - -- $20 < R < 60$ cm : development of present Pixel technology ~ ok
  - -- $R < 20$ cm : fundamental R & D required (materials, concept, etc.)
  - -- channel number ~ 5 larger (occupancy) → R&D needed for low cost

- Calorimeters : mostly ok
  - -- ATLAS : space-charge problems in LAr fwd calorimeter ?
  - -- CMS : -- radiation resistance of end-cap crystals and electronics ?
    - -- change scintillator or technique in hadronic end-cap
    - -- plastic-clad → quartz-clad quartz fibers in fwd calorimeter

- Muon spectrometers : mostly ok
  - -- increase forward shielding → acceptance reduced to $|\eta| < 2$
  - -- space charge effects, aging ?
  - -- some trigger chambers (e.g. ATLAS TGC) too slow if bunch-crossing is 12.5 ns

- Electronics and trigger : large part to be replaced
  - -- new LVL1 trigger electronics (80 MHz) if bunch-crossing is 12.5 ns
  - -- R&D needed for e.g. tracker electronics (fast, rad hard)
  - -- most calorimeter and muon electronics ~ ok (radiation resistance ?)

Modest upgrades of ATLAS, CMS needed for channels with hard jets, μ, large E_T^{miss}
Major upgrades (new trackers ..) for full benefit of higher L: $e^{\pm}$ ID, b-tag, τ-tag

Preliminary/conservative
(no optimization of algorithms for 10^{35})

Jet E-resolution $\eta = 0$

E_T (GeV)	10^{34}	10^{35}
50	15%	40%
300	5%	8%
1000	3.5%	4%

u-jet rejection factor for ε (b)=50%

p_T (GeV)	10^{34}	10^{35}
30-45	35	4
60-100	190	30
100-200	300	115
200-350	90	40

assuming same 2-track resolution at 10^{35} and 10^{34}

e/jet separation $E_T = 40$ GeV

L (cm^{-2} s^{-1})	Electron efficiency	Jet rejection
10^{34}	81%	10600 ± 2200
10^{35}	78%	6800 ± 1130

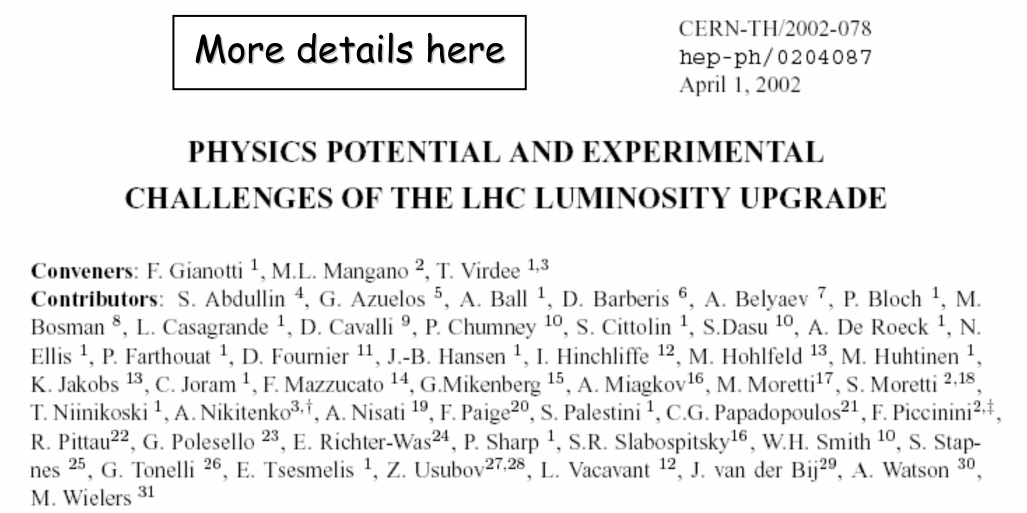
deterioration smaller at higher E

Physics potential of the SLHC …. a few examples …

- Standard Model: multiple Gauge Bosons, top rare decays, …
- Higgs : rare decays, couplings, self-couplings, heavy Higgs MSSM, …
- Beyond SM: strong EWSB, SUSY, Z', compositeness, ….

Detector performance, pile-up included
All results are preliminary

More details here



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PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

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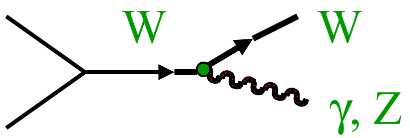
Assumption : $\int L\,dt = 1000\ \mathrm{fb}^{-1}$ per experiment per year of running

Triple Gauge Bosons

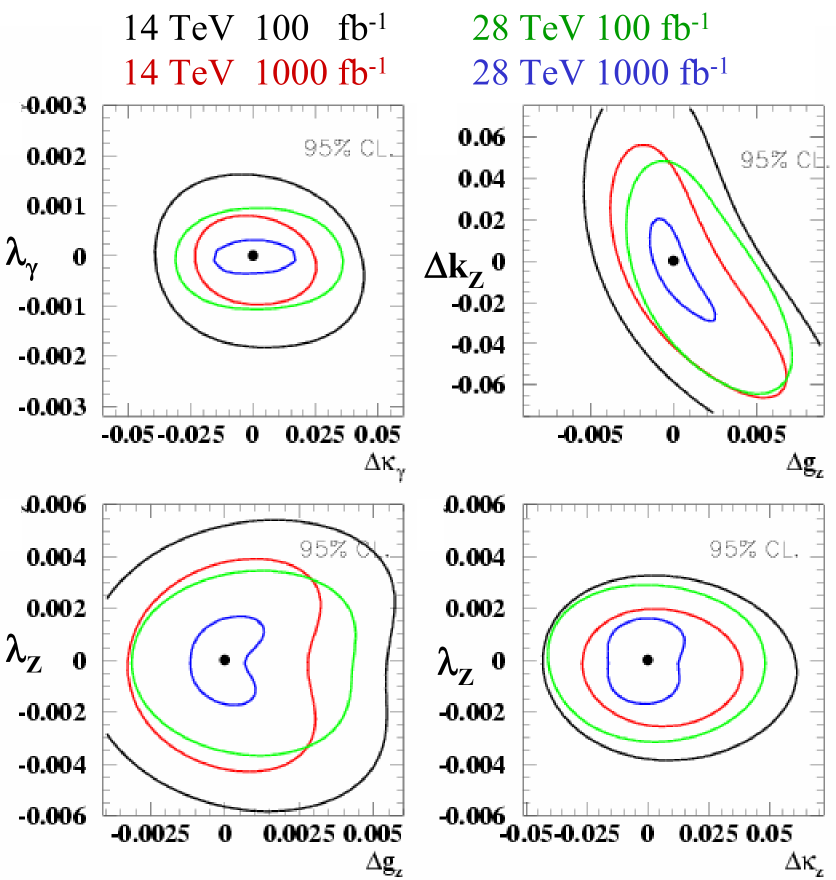


Probe non-Abelian structure of SU (2) and sensitive to New Physics

λ_γ, Δk_γ from $W\gamma \to l\nu\gamma$ } $l = e, \mu$ 10^{34}
λ_Z, Δk_Z, g^1_Z from $WZ \to l\nu\, ll$ } $l = \mu$ 10^{35} (to be conservative ..)

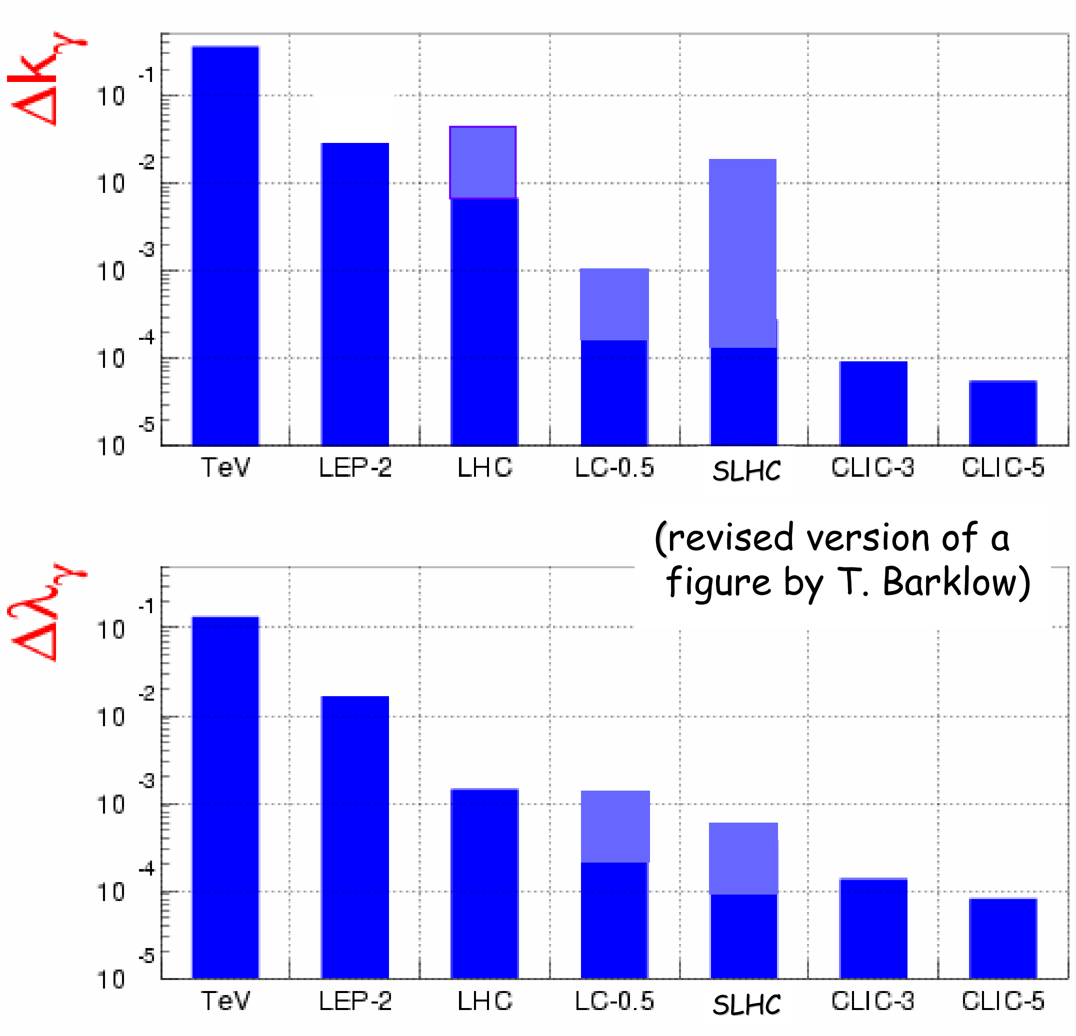
λ-couplings increase as ~ s
→ constrained by σ_{tot}, high-p_T tails
k-couplings : softer energy dependence
→ constrained mainly by angular distributions

95% C.L. constraints for
1 experiment from fits to σ_{tot}, p_T^γ, p_T^Z



- SLHC sensitivity at the level of SM radiative corrections
- Angular distributions not used
  --> pessimistic for k-couplings
- only high-p_T muons and photons used (assuming trackers not replaced)

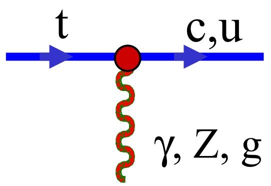
Comparison with other machines …..



(revised version of a figure by T. Barklow)

Anomalous contributions depend on scale of New Physics $\Lambda \rightarrow$ no limit to desired precision

FCNC top decays at SLHC



- Most measurements (e.g. Δm_{top} ~ 1 GeV) limited by systematics
  → ~ no improvement at SLHC

- Exception : FCNC decays
  Some theories beyond SM (e.g. some SUSY models, 2HDM) predict BR $\approx 10^{-5}$- 10^{-6}, which are at the limit of the LHC sensitivity

- Expected limits from Tevatron Run II in 2007 : BR < 10^{-3}

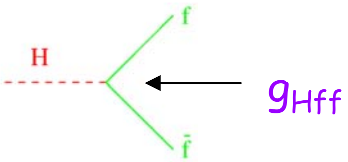
99% C.L. sensitivity to FCNC BR (units are 10^{-5})

Channel	LHC (600 fb^{-1})	SLHC (6000 fb^{-1})
$t \to q\gamma$	0.9	0.25
$t \to qg$	61	19
$t \to qZ$	1.1	0.1

requires b-tagging performance at SLHC similar to that at LHC

LC : worse reach (~ 300 000 tt pairs/year $\sqrt{s}$ = 0.4 TeV compared to 10^9 pairs/year at SLHC)

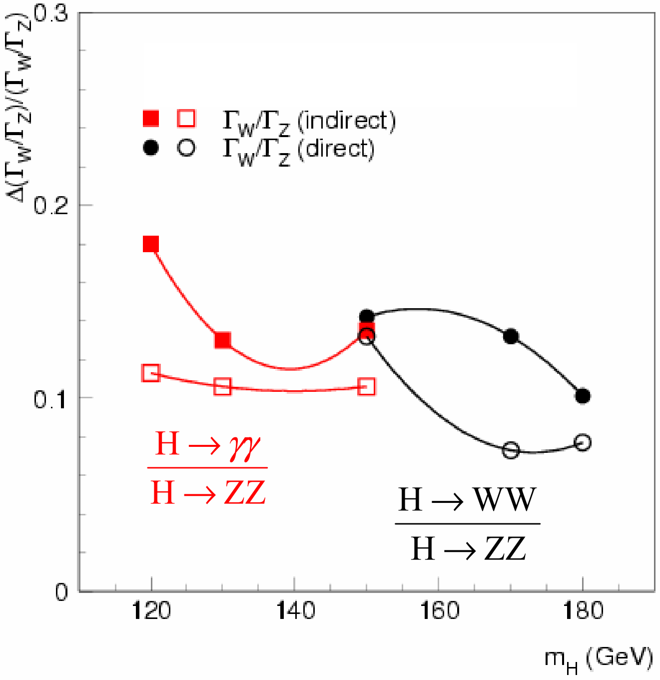
Higgs couplings to fermions and bosons



Can be obtained from measured rate in a given production channel:

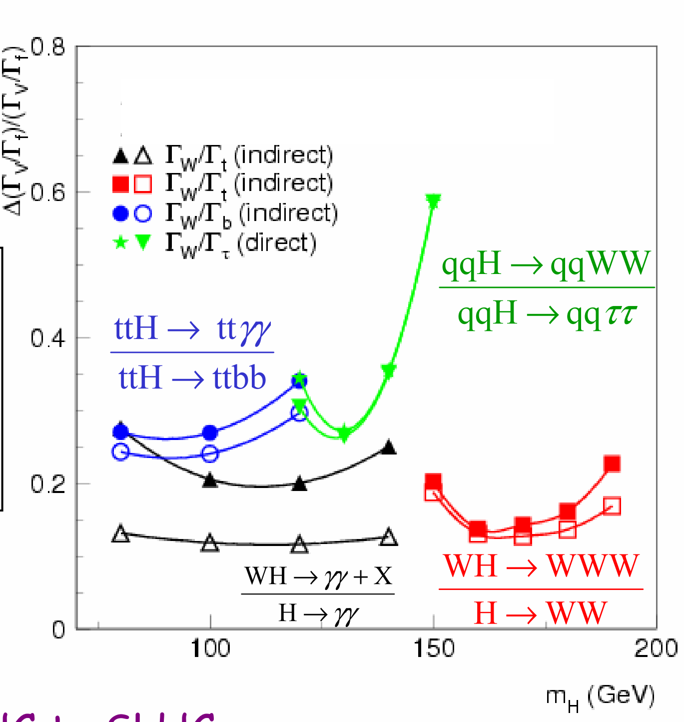
$R_{ff} = \int L\,dt \bullet \sigma(e^+e^-, pp \to H+X) \bullet BR(H \to ff)$ $\quad BR(H \to ff) = \frac{\Gamma_f}{\Gamma_{tot}}$ $\quad \to$ deduce $\Gamma_f \sim g^2_{Hff}$

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



Closed symbols:
LHC 600 fb^{-1}

Open symbols:
SLHC 6000 fb^{-1}



Improvement in precision by up to ~ 2 from LHC to SLHC
(but still not competitive with LC precision of ≈ %)

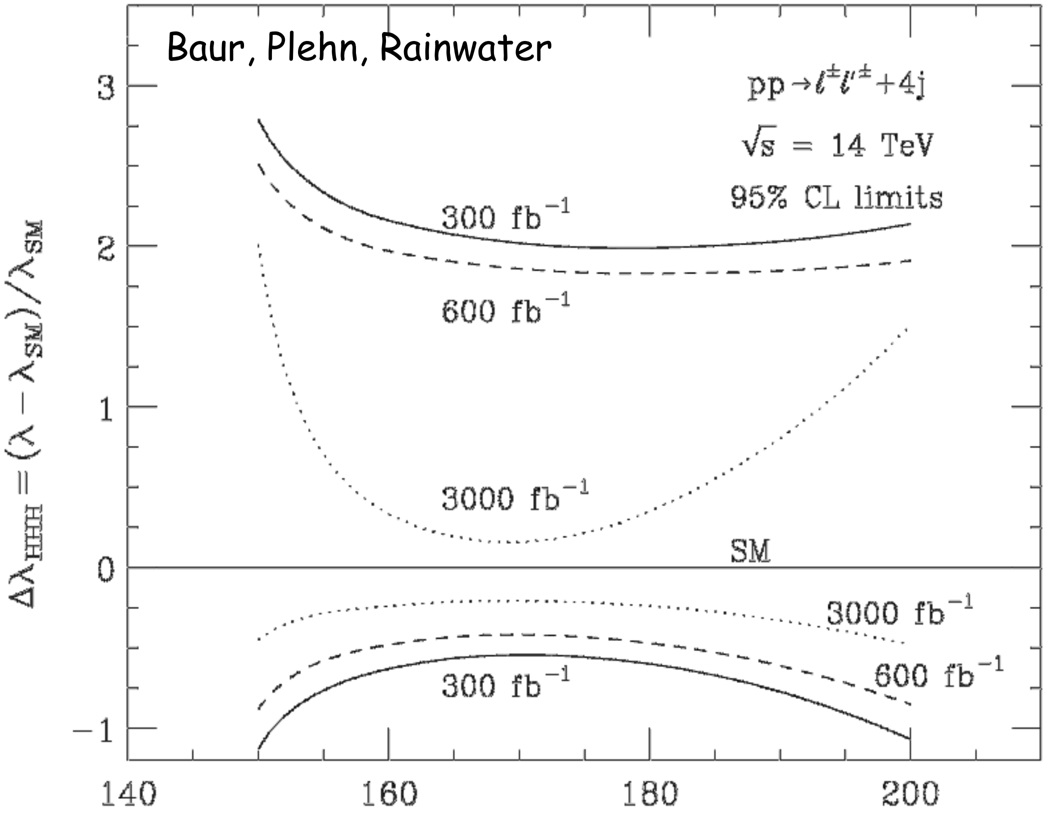
Rare Higgs decays at SLHC

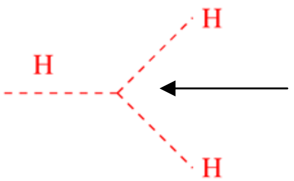
Channel	m_H	$S/\sqrt{B}$ LHC ($600\ fb^{-1}$)	$S/\sqrt{B}$ SLHC ($6000\ fb^{-1}$)
$H \to Z\gamma \to ll\,\gamma$	~ 140 GeV	~ 3.5	~ 11
$H \to \mu\mu$	130 GeV	~ 3.5 (gg+VBF)	~ 7 (gg)

BR ~ 10^{-4} both channels

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

Higgs self-couplings at SLHC ?





~ λv

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

$HH \to W^+ W^- W^+ W^- \to l^\pm\nu\ jj\ l^\pm\nu\ jj$

LHC: $\lambda = 0$ may be excluded at 95% CL.

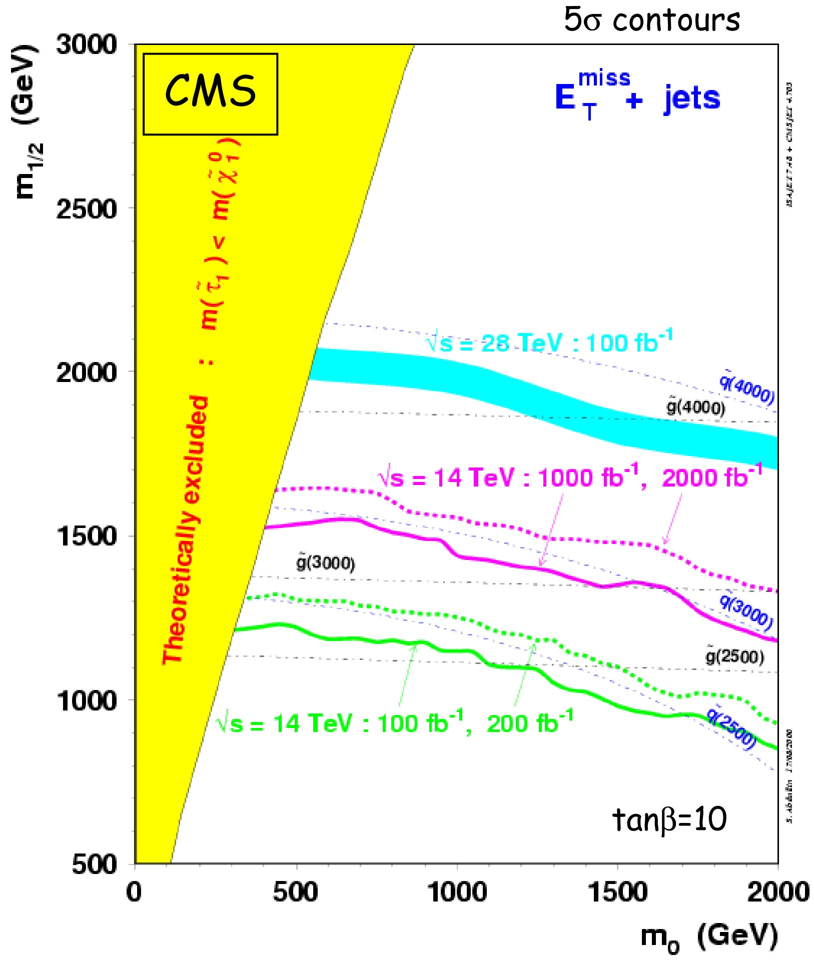
SLHC: λ may be determined to 20-30% (95% CL)

Comparable to $\sqrt{s}$ = 0.5 TeV LC , not competitive with CLIC (precision up to 7%)

Supersymmetry

- If SUSY connected to hierarchy problem, some sparticles should be observed at LHC
- However: no rigorous upper bound → $\tilde{q}, \tilde{g}$ may be at limit of sensitivity
  e.g. inverted hierarchy models : $m(\tilde{q})$ up to several TeV for first two generations
- Expected limits from Tevatron Run II in 2007 : $m(\tilde{q}), m(\tilde{g}) > 400\ \mathrm{GeV}$

5σ contours



5 σ discovery reach on $m(\tilde{q}), m(\tilde{g})$

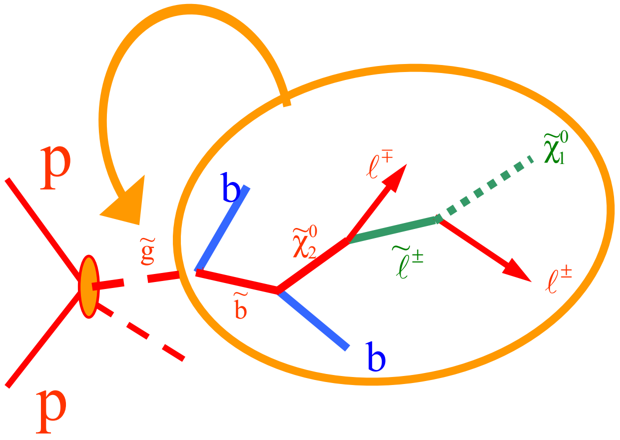
LHC	≈ 2.5 TeV
SLHC	≈ 3 TeV
√s = 28 TeV, 10^{34}	≈ 4 TeV
√s = 28 TeV, 10^{35}	≈ 4.5 TeV

-- No major detector upgrade needed
for discovery : inclusive signatures
with high p_T calorimetric objects
-- Fully functional detectors (b-tag, etc.)
needed for precision measurements
based on exclusive chains

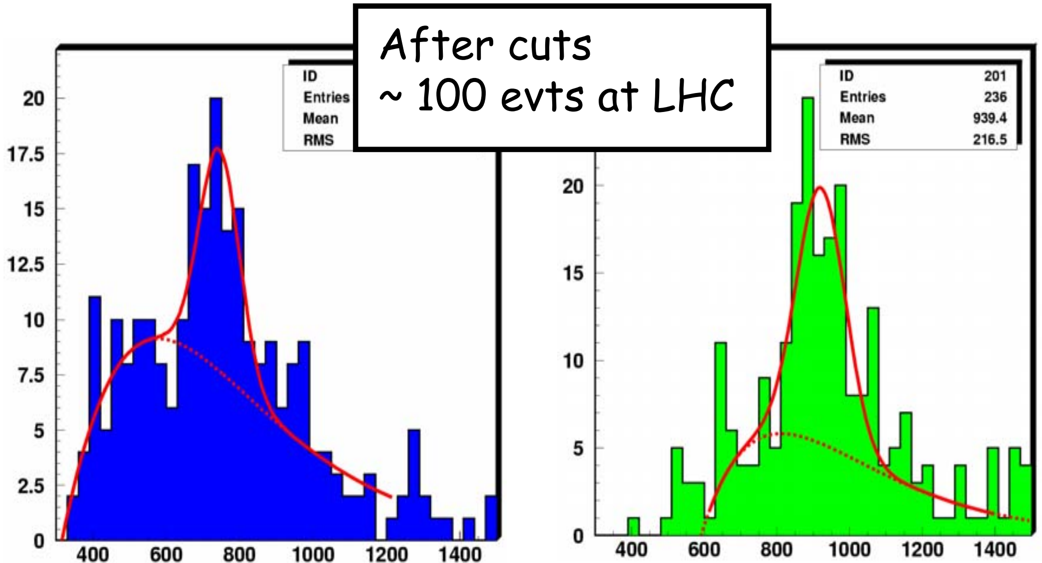
Example of rate-limited (at standard LHC) mass reconstruction ….

Proposed Post-LEP Benchmarks for Supersymmetry (hep-ph/0106204)

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
$\mathrm{sign}(\mu)$	+	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	120	123	121	121	123	120	122	117	122	119	117	121	116
m_t	175	175	175	175	171	171	175	175	175	175	175	175	175



Precise reconstruction of
sbottom (m = 770 GeV) and
gluino (m = 920 GeV)
would benefit from more statistics



After cuts
~ 100 evts at LHC

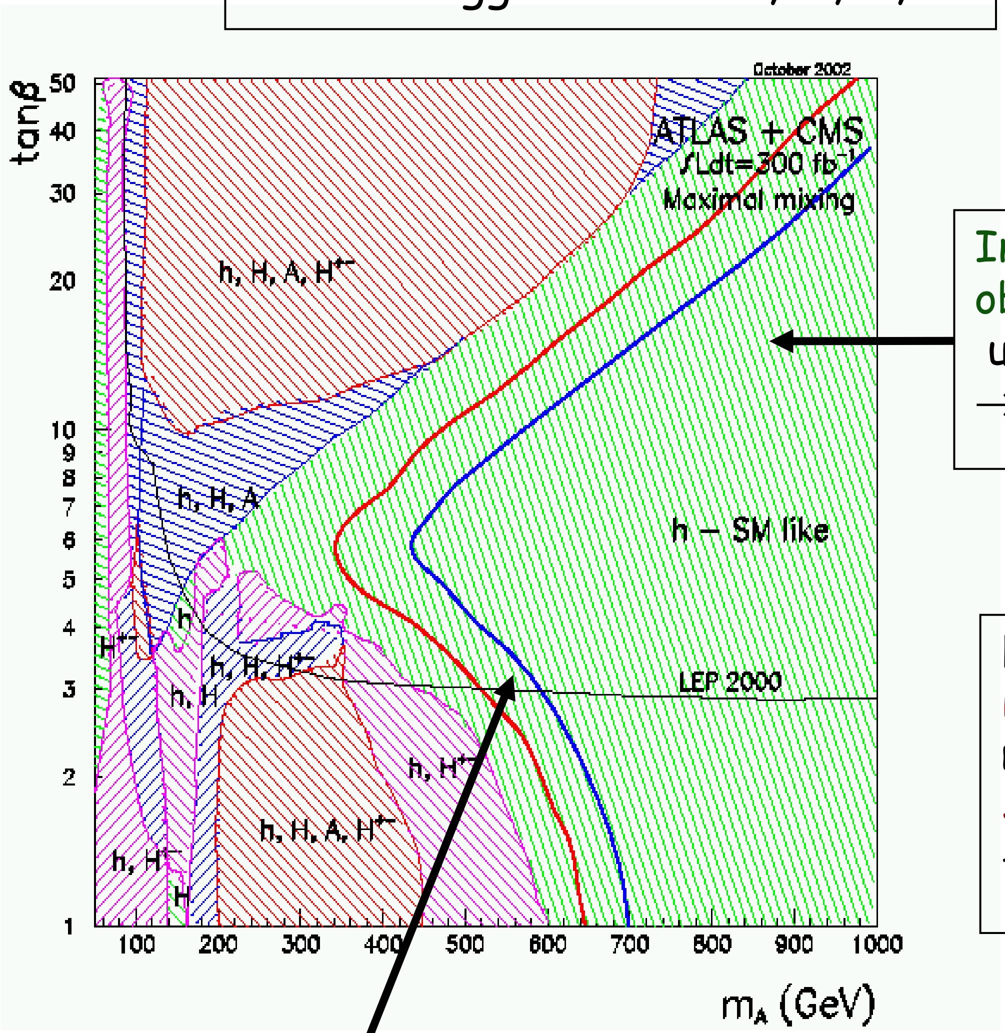
M (sbottom)

M (gluino)

Linear Colliders are best machines to complement (S)LHC (especially if running concurrently): observation and precise measurements (≤ %) of ~ all sparticles with m < √s /2

MSSM Higgs sector : h, H, A, H±

$m_h < 130$ GeV
$m_A \approx m_H \approx m_{H\pm}$



In the green region only SM-like h observable at LHC (300 fb^{-1}/exp), unless A, H, H± → SUSY particles
→ LHC can miss part of MSSM Higgs sector

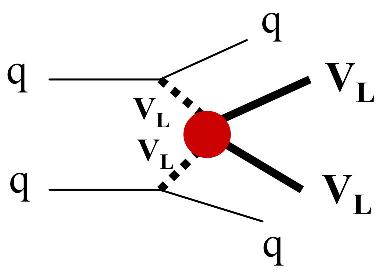
For $m_A < 600$ GeV, TESLA can demonstrate indirectly (i.e. through precision measurements of h properties) SUSY-type Higgs sector at 95%C.L.
--> this region is ~ fully covered at SLHC

Red and blue lines: SLHC extensions for 3000 fb^{-1}/exp.
Regions where ≥ 1 heavy Higgs can be discovered at 5σ or excluded at 95% C.L. at SLHC

Direct observation of complete spectrum may require multi-TeV LC

Strong $V_L V_L$ scattering

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



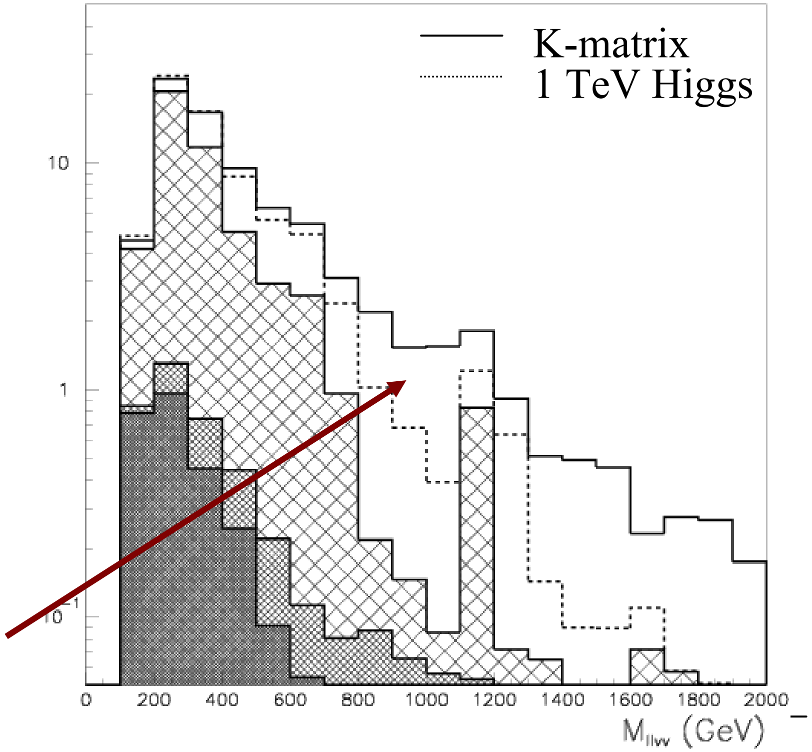
Forward jet tag ($|\eta|>2$) and central jet veto essential tools against background

LHC : difficult …

Best non-resonant channel is
$W^+_L W^+_L \rightarrow W^+_L W^+_L \rightarrow l^+\nu\ l^+\nu$

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

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

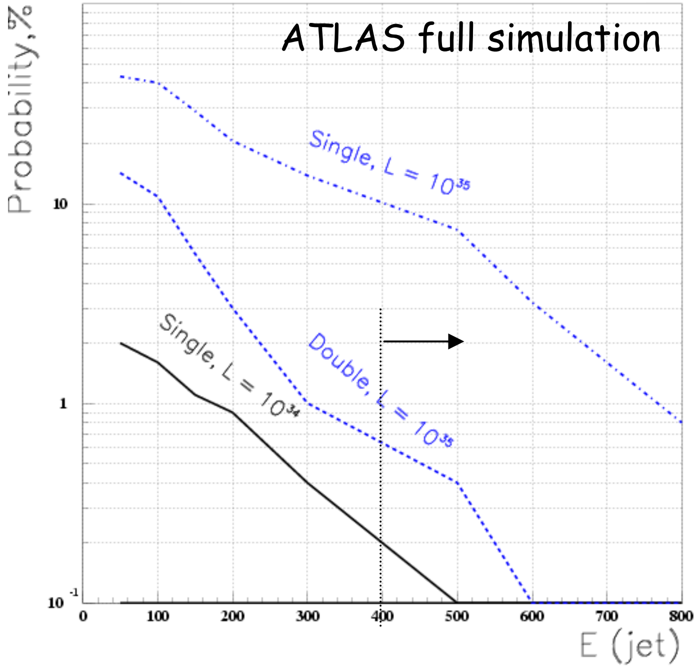


2-3σ excess, S and B have similar shapes

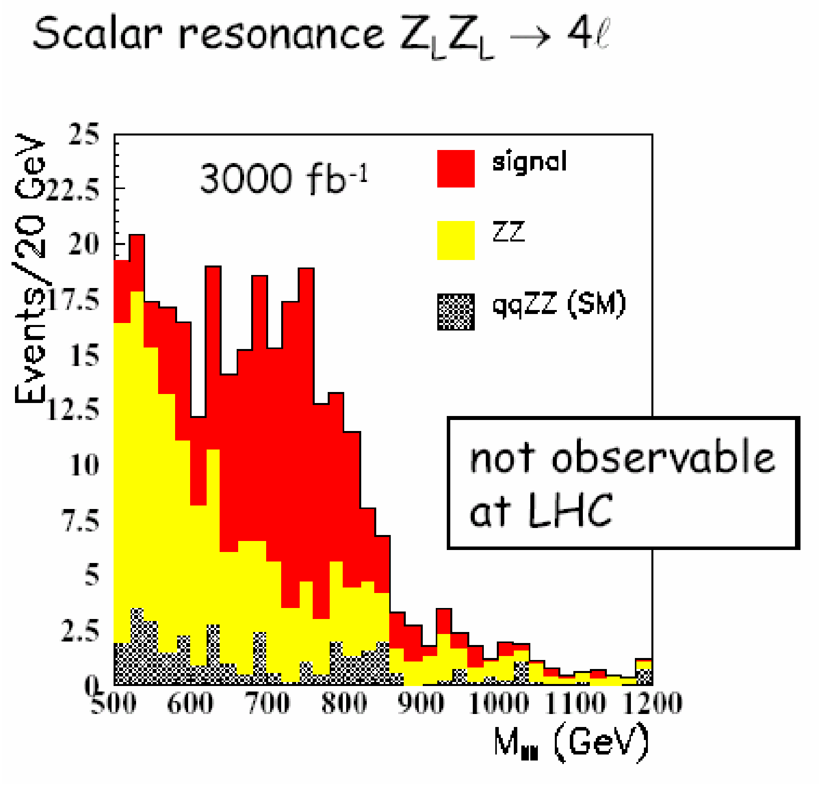
SLHC

-- 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 ...)


ATLAS full simulation

Scalar resonance $Z_L Z_L \rightarrow 4\ell$



not observable at LHC

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
(detailed study may require LC with $\sqrt{s} \geq 1$ 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.

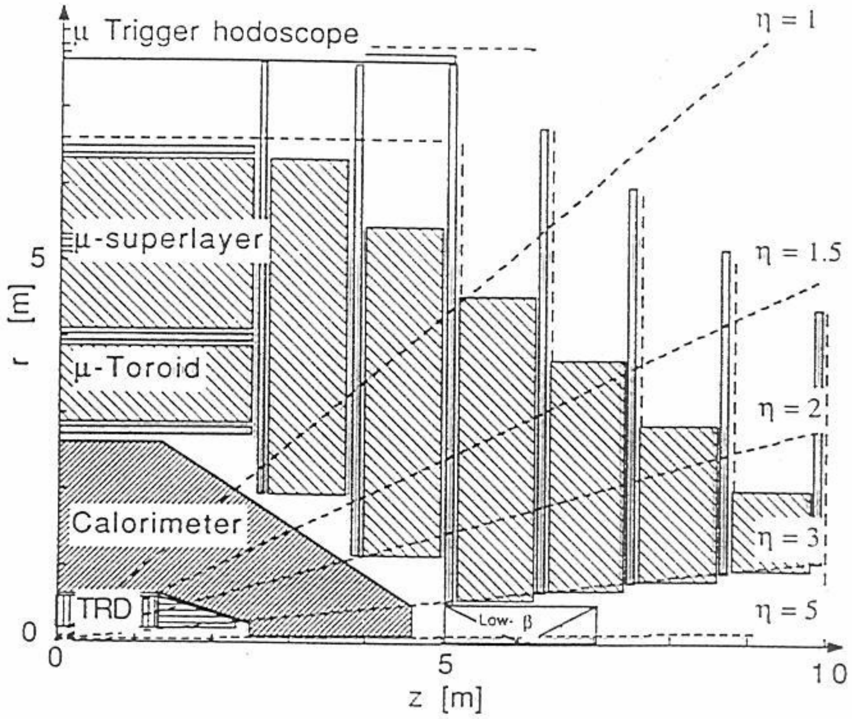


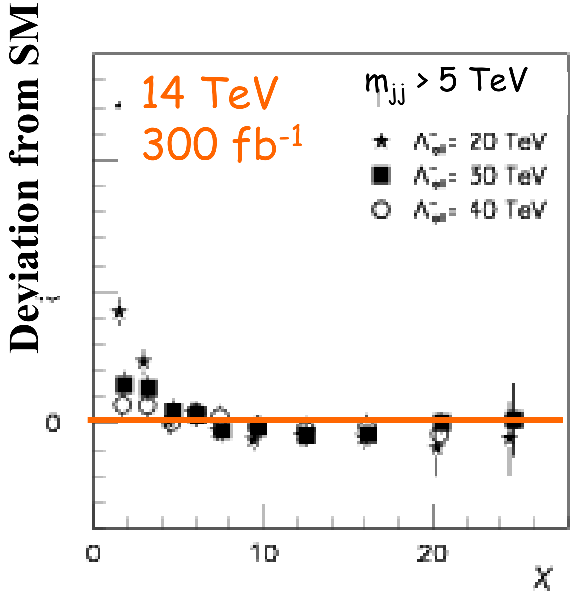
Figure 1. Conceptual design of 'non-magnetic' detector system. Calorimeter coverage for $3 < |\eta| \leq 5$ is not essential for luminosity $> 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$.

?

Quark compositeness

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

Quark sub-structure at a scale $\sqrt{\hat{s}} << \Lambda$ → contact interactions qq → qq
→ modify di-jet angular distributions → expect excess of high-E_T central jets



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

if contact interactions
→ excess at low χ

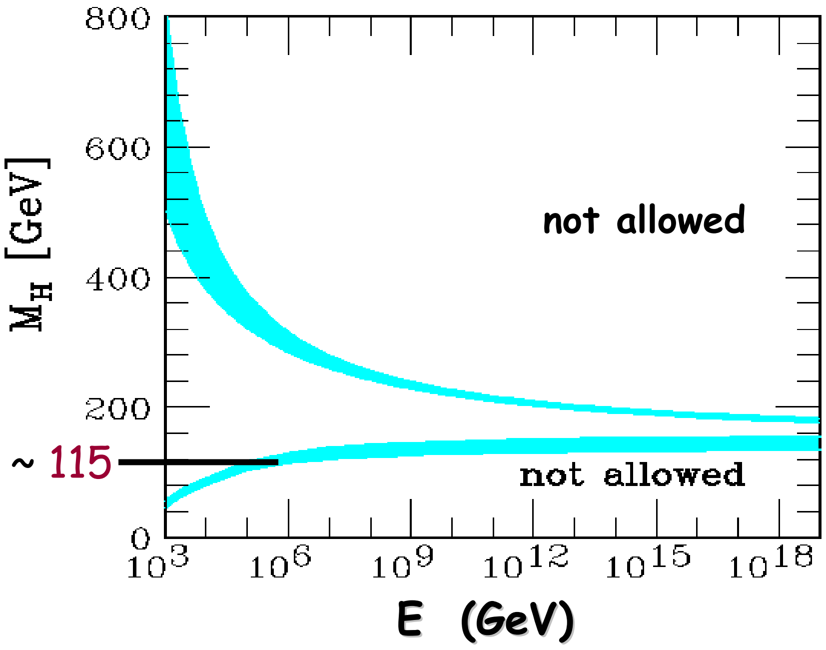
If b-tagging available can measure jet flavour

95% C.L. lower limits on Λ (TeV)

14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	28 TeV 300 fb^{-1}	28 TeV 3000 fb^{-1}
40	60	60	85

LC : sensitive to llqq, llll (complementary) up to ≈ 100-1000 TeV (√s=0.8-5 TeV)

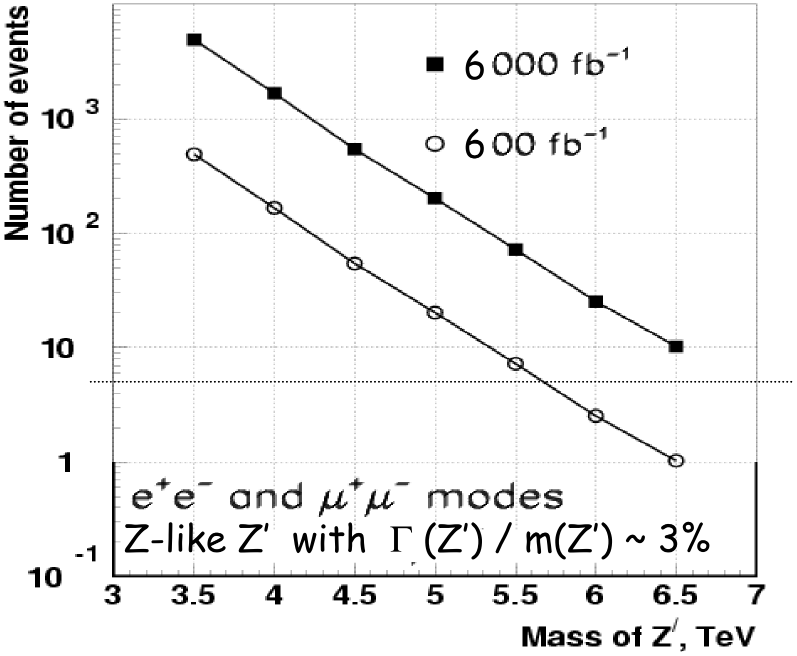
If $m_H \sim 115$ GeV → New Physics at $E < 10^5$-10^6 GeV
→ (S)LHC can probe (directly or indirectly) a large part of this range

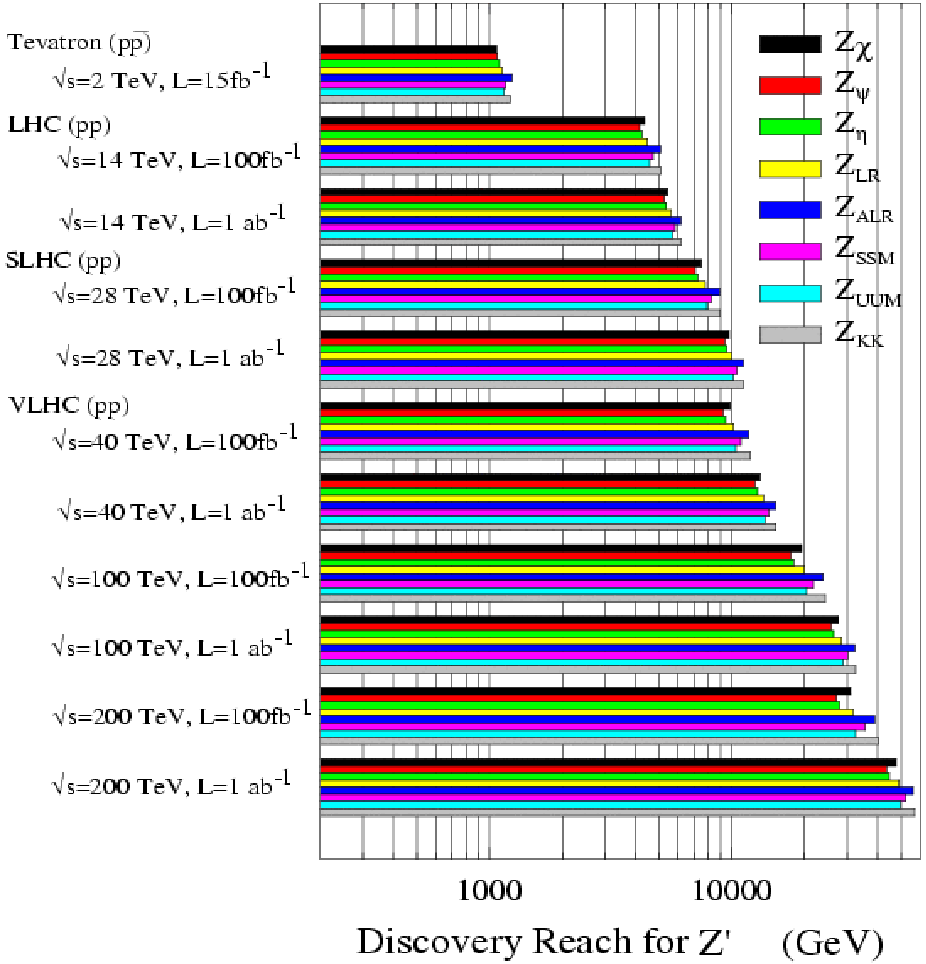


CLIC with $\sqrt{s} = 5$ TeV : probes indirectly up to 10^6 GeV with ultimate luminosity
VLHC with $\sqrt{s} = 200$ TeV : probes directly up to 10^5 GeV with ultimate luminosity

Additional gauge bosons : Z '

SLHC : direct discovery reach up to ~ 7 TeV
mass can be measured to ≤ %





CLIC :
- direct discovery reach up to 3-5 TeV
- mass and width can be measured to 10^{-3} – 10^{-4} from resonance scan
- indirect reach from precise (~ %) EW measurements up to ~ 40 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_LW_L reach)
$\int L dt$ correspond to 1 year of running at nominal luminosity for 1 experiment

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}	CLIC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
W_LW_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
TGC λ_γ (95%)	0.0014	0.0006	0.0008		0.0003	0.0004	0.00008

† indirect reach (from precision measurements)

Approximate direct mass reach :
$\sqrt{s}$ = 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
$\sqrt{s}$ = 28 TeV, L=10^{35} : up to ≈ 11 TeV

CONCLUSIONS

- LHC, although powerful, will not be able to answer all questions and new high energy/luminosity machine(s) will most likely be needed.
  E.g. LHC can discover SUSY but full understanding of new theory requires a complementary machine

- Because we ignore what happens at the TeV scale (although EW data favour a light Higgs and weak EWSB), and in the absence of theoretical preference for a specific energy scale beyond the TeV region, it is not easy to make a choice before LHC data will become available.

- LHC luminosity upgrade to 10^{35} cm^{-2} s^{-1} :
  -- consolidation/extension of LHC (discovery) programme
  -- maximum exploitation of existing tunnel, machine, detectors
  -- "combined studies" if any time overlap with a sub-TeV LC

Not in competition with new machines. Good physics return for "modest" cost ?

- LHC energy upgrade to $\sqrt{s}$ ~ 28 TeV :
  -- larger physics potential than SLHC
  -- easier to exploit experimentally if L=10^{34}
  -- new machine (feasibility, cost ?)

Benefit/cost ratio should be better understood (e.g. if clear physics case from LHC data …), also against other machines

Examples of possible post-LHC scenarii and options (speculative …)

Note : here LC $\equiv$ Lepton Collider

(S)LHC finds SUSY (Higgs, squarks, gluino, and some gauginos and sleptons)
→ (multi)-TeV LC to complete spectrum ?

(S)LHC finds SUSY (Higgs, gluino, stop, some gauginos) but no squarks of first generations
→ 28 TeV (or VLHC) and multi-TeV LC could be equally useful and complementary ?

LHC finds only one SM-like Higgs and nothing else
→ (multi)-TeV LC to study Higgs properties and get clues of next E-scale up to 10^6 GeV ?

(S)LHC finds contact interactions → $\Lambda < 60$ TeV
→ 28 TeV machine or VLHC to probe directly scale Λ ?

(S)LHC finds Extra-dimensions → $M_D < 15$ TeV
→ 28 TeV machine or VLHC to probe directly scale M_D ?

LHC finds nothing → Higgs strongly interacting ?
→ multi-TeV LC to look for new (strong) dynamics and get hints of next E-scale ?

LHC finds less conventional scenarii or totally unexpected physics →

?

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

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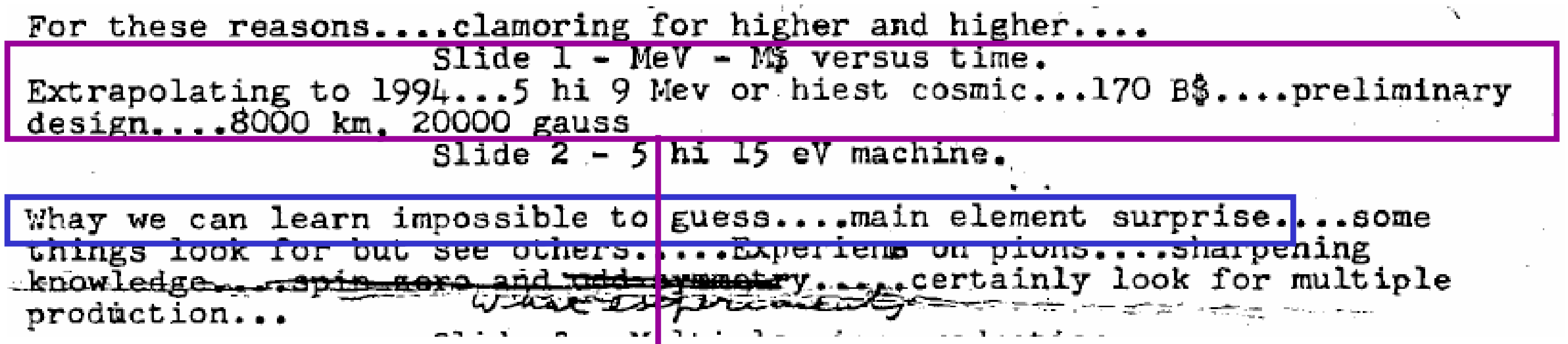

For these reasons....clamoring for higher and higher....

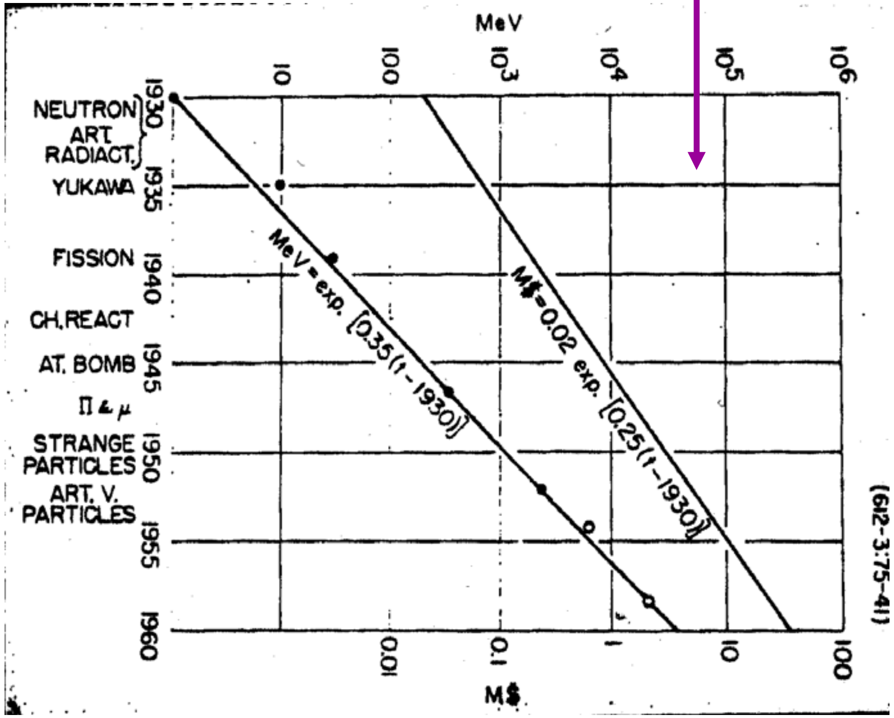
Slide 1 - MeV - M$ versus time.

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.....Experiens on pions....sharpening knowledge....~~spin zero and odd symmetry~~.....certainly look for multiple production...

What is produced



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

We are not doing so bad …

Back-up slides

L = 10^{35} upgrade vs $\sqrt{s}$ ~ 28 TeV upgrade

Easier for machine	Challenging and expensive for machine
Important changes to detectors for full benefit, very difficult environment	Modest changes to detectors
Smaller physics potential: -- mass reach ~30% higher than LHC -- precision measurements possible but -- with major detector upgrades -- challenging due to environment	Larger physics potential: -- mass reach ~1.5 higher than LHC -- many improved measurements (e.g. Higgs) -- higher statistics than LHC -- LHC-like environment

If both : $\sqrt{s}$ ~ 28 TeV + L =10^{35} : LHC mass reach extended by ~ 2

$L = 10^{35}$: experimental challenges and detector upgrades

- If bunch crossing 12.5 ns → LVL1 trigger (BCID) } must work at
  tracker (occupancy) } 80 MHz

- ~ 120 minimum-bias per crossing (compared to ~ 25 at LHC)
- occupancy in tracker ~ 10 times larger than at LHC (for same granularity and response time)
- pile-up noise in calorimeters ~ 3 times larger (for same response time)

- radiation :

—— 500 fb^{-1} = ~ 10 years at LHC
—— 3000 fb^{-1} = ~ 3 years at SLHC

CMS tracker

R (cm)	hadron fluence 10^{14} cm^{-2}	Dose (kGy)
4	30/190	840/5000
11	5/28	190/1130
22	1.5/10	70/420
75	0.3/2	7/40
115	0.2/1	2/11

CMS calorimeters

1 Gy = 1 Joule/Kg

η	ECAL dose (kGy)	HCAL dose (kGy)
0-1.5	3/18	0.2/1
2.0	20/120	4/25
2.9	200/1200	40/250
3.5		100/600
5		1000/6000

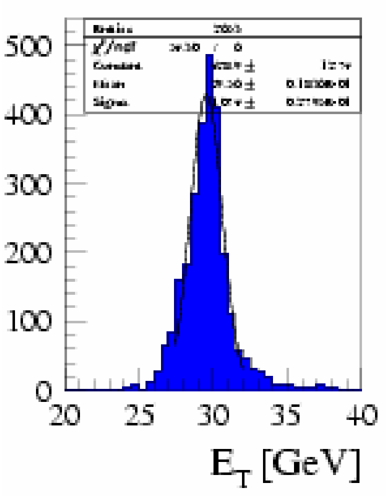
Examples of (ATLAS) performance at 10^{35}

Full Geant simulation
No optimisation done

- EM calorimeter energy resolution:

$e^{\pm}$ E_T= 30 GeV

$\frac{\sigma}{E} \approx 2.5\,\%$ at 10^{34} $\frac{\sigma}{E} \approx 3.6\,\%$ at 10^{35} $\longrightarrow$



- deterioration smaller at higher E ($\sigma_{\text{pile-up}} \sim 1/E$)
- pessimistic : optimal filtering could help

- e/jet separation:

E_T = 40 GeV

L ($cm^{-2}\ s^{-1}$)	Electron efficiency	Jet rejection
10^{34}	81%	10600 ± 2200
10^{35}	78%	6800 ± 1130

deterioration smaller at higher E

- b-tagging:

p_T (GeV)	10^{34}	10^{35}
30-45	33	3.7
60-100	190	27
100-200	300	113
200-350	90	42

Rejection against u- jets for 50% b-tagging efficiency assuming same 2-track resolution at 10^{35} as at 10^{34}

ν Factory and Muon Collider : a 3-step project

excellent physics potential at each step !

❶ ν factory :

-- Superconducting Proton Linac (SPL) : high-intensity p source (10^{16} p/s, 2.2 GeV) using LEP RF cavities. Useful also for LHC, ISOLDE, CNGS (Conceptual Design Rep. ready)

-- μ collection, cooling, acceleration to ~ 50 GeV, decay → ν storage ring

-- high-intensity and well-understood (flux, spectrum) ν_e and ν_μ beams for oscillation/mixing matrix studies

❷ Higgs factory : $\mu^+ \mu^- \to H$

-- $\sqrt{s} \approx 115 \to 1000$ GeV

-- better potential than e^+e^- LC of same $\sqrt{s}$: smaller E-beam spread ($\sim 10^{-5}$), better E-beam calibration (to $\sim 10^{-7}$ from $e^\pm$ spectrum from polarised $\mu^\pm$ decays), $\sigma(\mu^+\mu^- \to H) \sim 40000\ \sigma(e^+e^- \to H)$

e.g. $\Delta m_W \approx 7$ MeV, $\Delta m_{top} \approx$ MeV, H lineshape ($\Delta m_H \approx 0.1$ MeV, $\Delta\Gamma_H \approx 0.5$ MeV at 115 GeV)

❸ High-E Muon Collider :

-- $\sqrt{s} \leq 4$ TeV (ν-radiation ~ E)

-- better potential than e^+e^- LC of same $\sqrt{s}$ (see above), but no $\gamma\mu$, $\gamma\gamma$ options

-- smaller E-beam spread but ν radiation → detector background

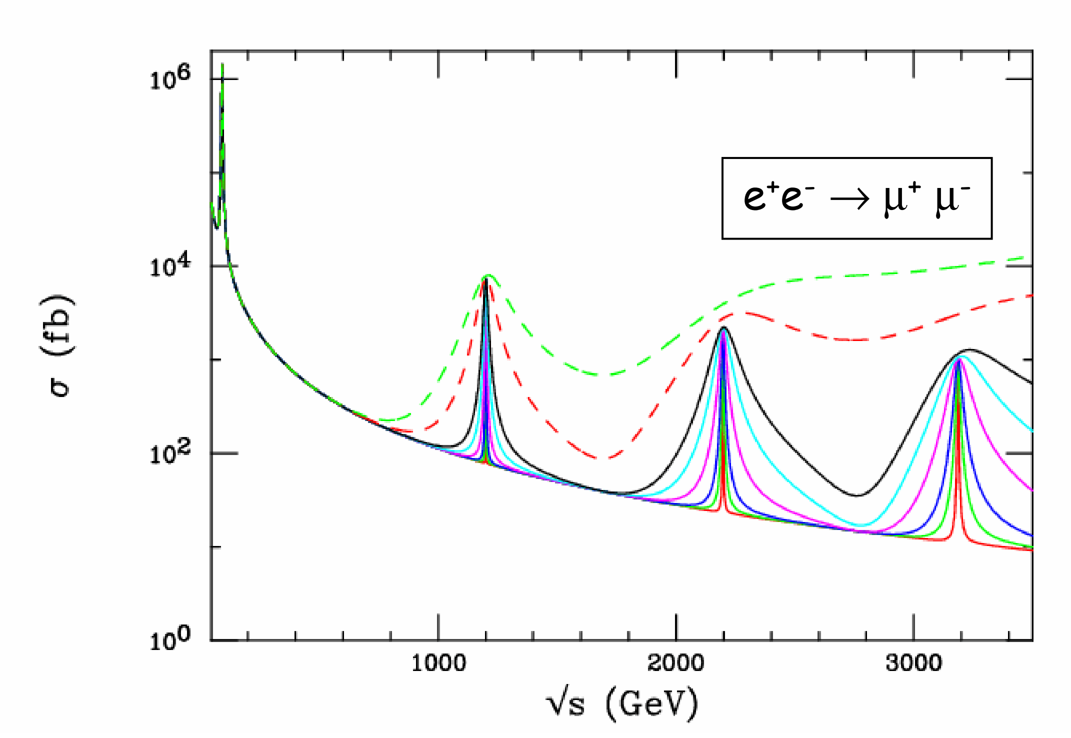
Fundamental questions to be solved for ❷ and ❸ :

μ cooling (fast ionisation cooling ?) and acceleration (re-circulating LINAC)

→

longer time-scale than CLIC

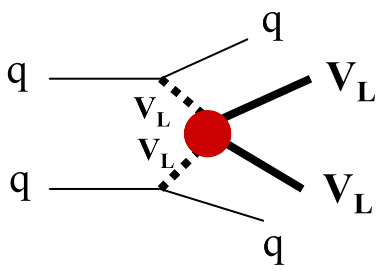
3nd example : Graviton resonance production in RS models at CLIC



CLIC is resonance factory up to kinematic limit.
Precise determination of mass, width, cross-section (from resonance scan `a la LEP1), branching ratios, spin …

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



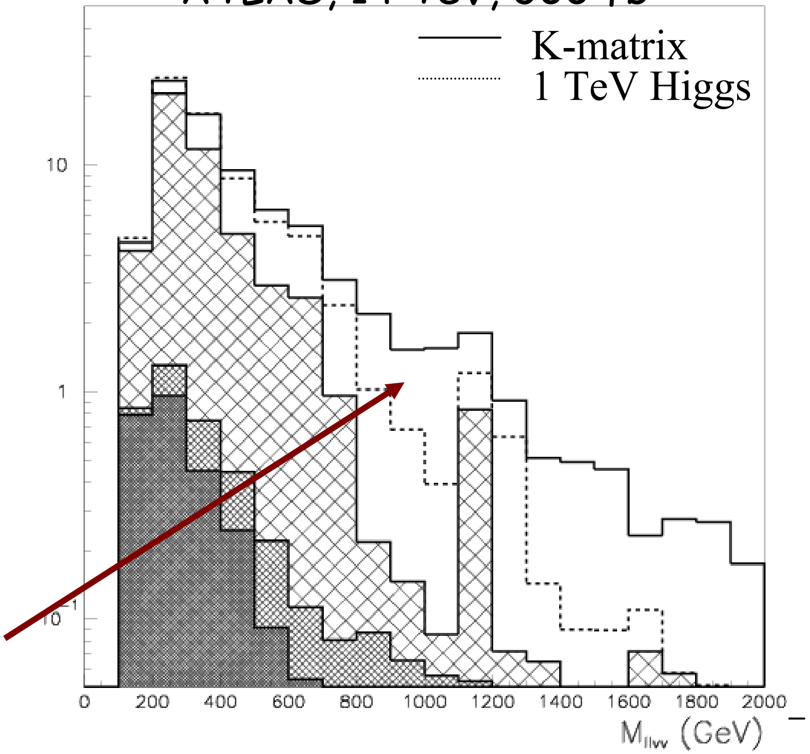
Forward jet tag ($|\eta|>2$) and central jet veto essential tools against background

LHC : difficult …

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

-- 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

From preliminary feasibility studies :

- L upgrade to 10^{35}:
  - -- increase bunch intensity to beam-beam limit → L ~ 2.5×10^{34}
  - -- halve bunch spacing to 12.5 ns (new RF)
  - -- change inner quadrupole triplets at IP1 , IP5
    → halve β^* to 0.25 m

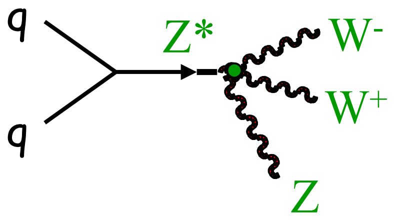
  Other options : upgrade injectors to get more brilliant beams,
  single 300 m long super-bunch, etc.

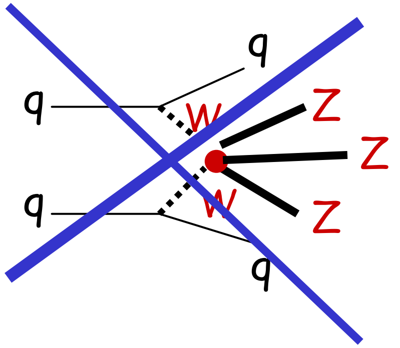
moderate
hardware changes
time scale ≥ 2012 ?

- $\sqrt{s}$ upgrade to 28 TeV :
  - -- ultimate LHC dipole field : B= 9 T → $\sqrt{s}$ = 15 TeV
    → any energy upgrade requires new machine
  - -- present magnet technology up to B ~ 10.5 T
    small prototype at LBL with B= 14.5 T
  - -- magnets with B~16 T may be reasonable target for operation in ~ 2015 provided intense R& D on e.g. high-temperature superconductors (e.g. Nb_3Sn)

major
hardware changes
time scale ≥ 2015 ?

Multiple gauge boson production at SLHC





- Probe ≥ quartic anomalous couplings (e.g. 5-ple vertex = 0 in SM)
- Rate limited at LHC

Process	Expected events after cuts 6000 fb^{-1}
WWW	2600
WWZ	1100
ZZW	36
ZZZ	7
WWWW	5
WWWZ	0.8

$$\left.\begin{array}{l} W \to \ell\nu \\ Z \to \ell\ell \end{array}\right\} \ell = e,\mu$$

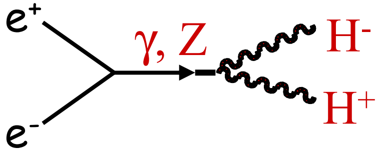
LHC sensitive to some 4-ple vertices

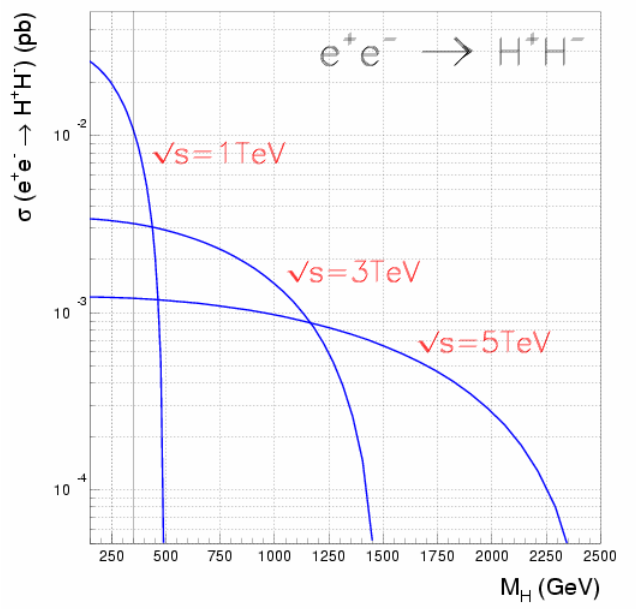
SLHC may be sensitive to 5-ple vertex

Not yet studied at CLIC …

CLIC : sensitive to m (A, H, $H^\pm$) up to ≈ 1 TeV

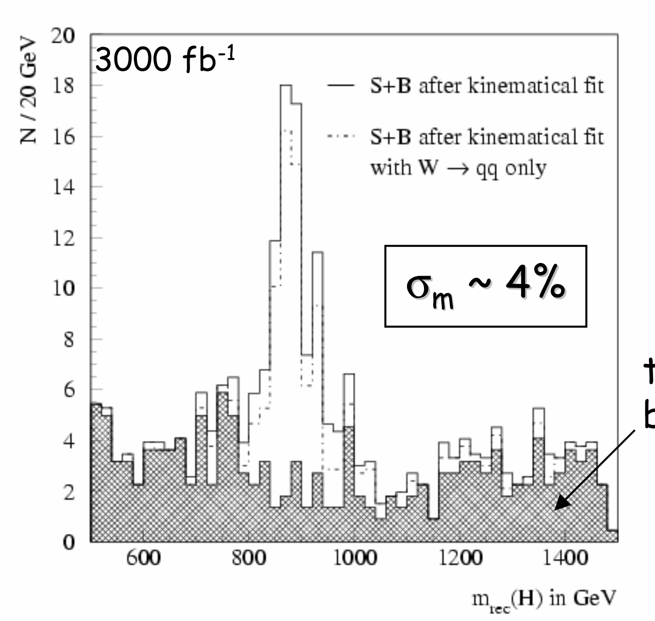
e.g. H^+H^- production





$H^\pm \rightarrow tb \rightarrow Wbb \rightarrow jjbb$

→ 8 jets final state



ttbb
backgound

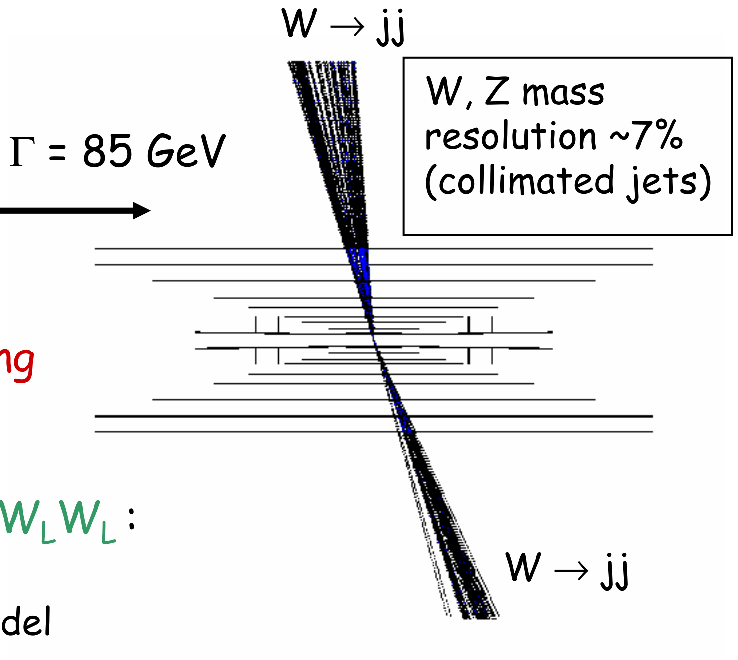
→ full MSSM Higgs spectrum should be observed

Strong V_L V_L scattering at CLIC

Observation of strong EWSB not granted at LHC, SLHC:
- only fully leptonic final states accessible → tiny rates
- non-resonant $W_L W_L$: same shapes for signal and background
- relies on fwd jet tag and jet veto performance

→ observation depends on model parameters

CLIC :
- ~ 4000 events/year at production for m = 2 TeV, Γ = 85 GeV
- fully hadronic final states accessible →
- small backgrounds



W, Z mass resolution ~7% (collimated jets)

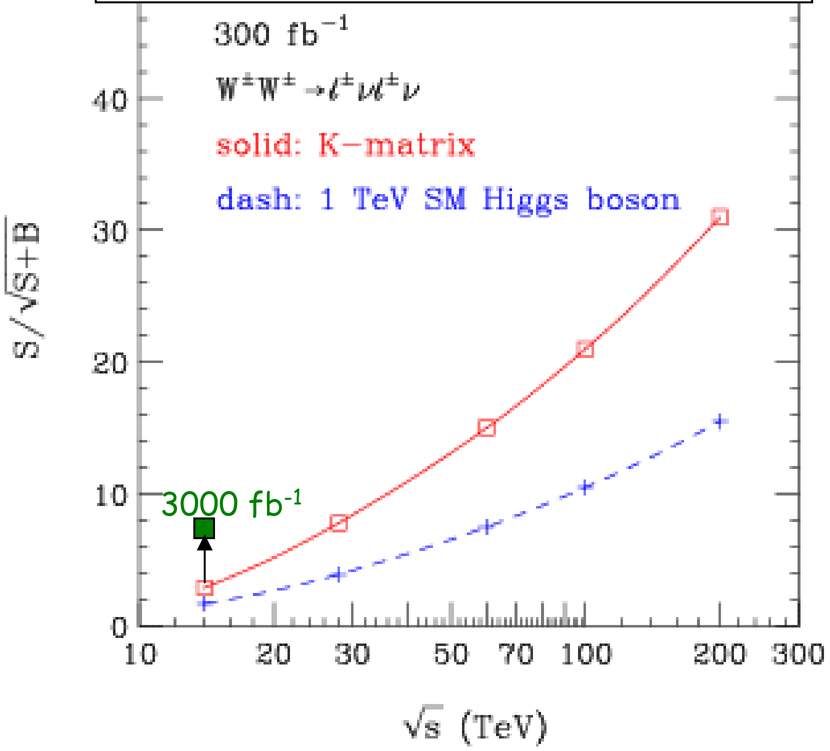
→ observation of resonant and non-resonant scattering up to ~ 2.5 TeV in several models

E.g. expected significance for non-resonant $W_L W_L \rightarrow W_L W_L$:

LHC (300 fb^{-1})	~ 5 σ	K-matrix unitarization model
SLHC (3000 fb^{-1})	~ 13 σ	
CLIC (1000 fb^{-1})	~ 70 σ	

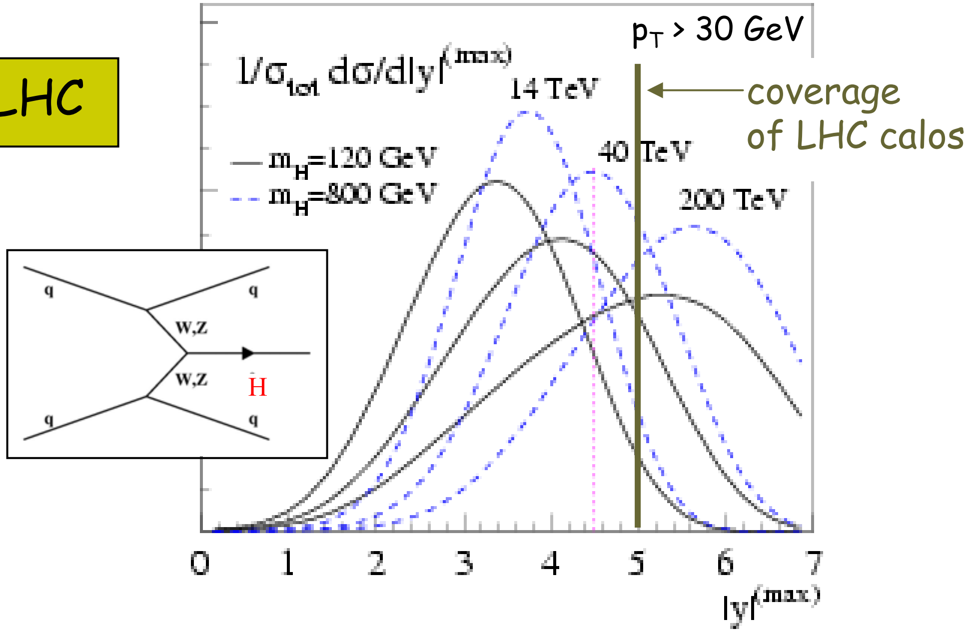
Measurement of resonance parameters at CLIC under study (beam polarisation is additional tool) → strong dynamic should be explored in detail

Non-resonant $W^{+}_{L}W^{+}_{L}$ scattering at pp machines vs √s



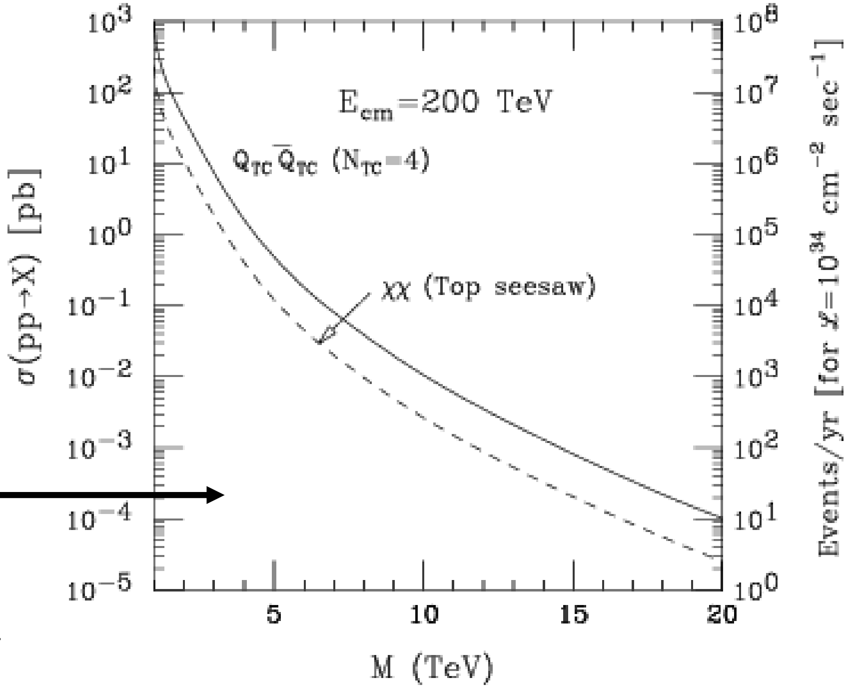
VLHC

Maximum jet rapidity vs √s



Detailed study of new dynamics also possible at LC with √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)

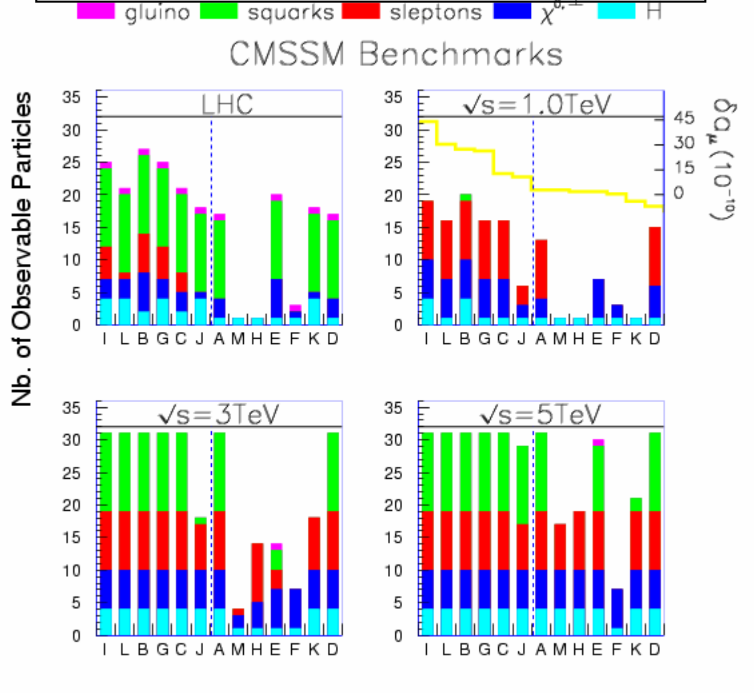


SUSY at CLIC

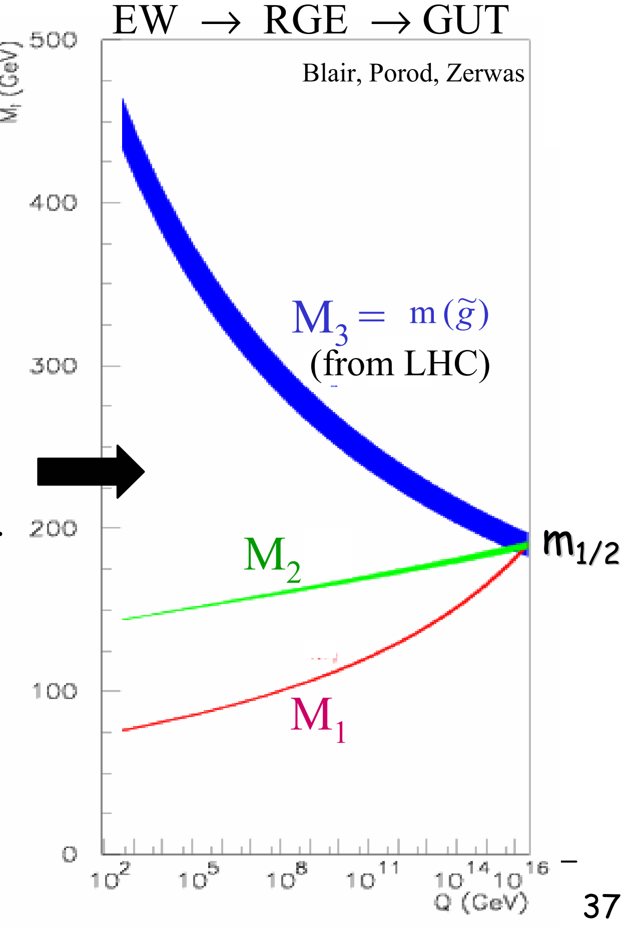
Sensitive to ~ all sparticles up to m ~ 1.5-2.5 TeV

- can complete SUSY spectrum: some sparticles not observable at LHC (small S/B) nor at TESLA (if m > 200-400 GeV)
- precision measurements (e.g. masses to 0.1%, field content) → constrain theory parameters

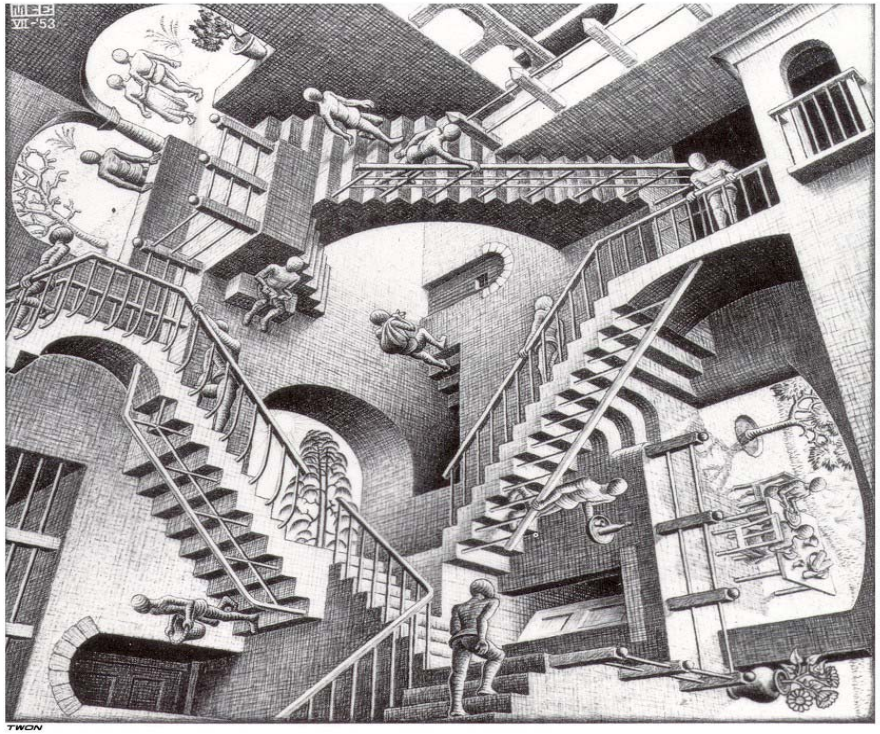
Examples of mSUGRA points compatible with present constraints



from precise measurements of e.g. gaugino masses at EW scale reconstruct theory at high E



Extra-dimensions

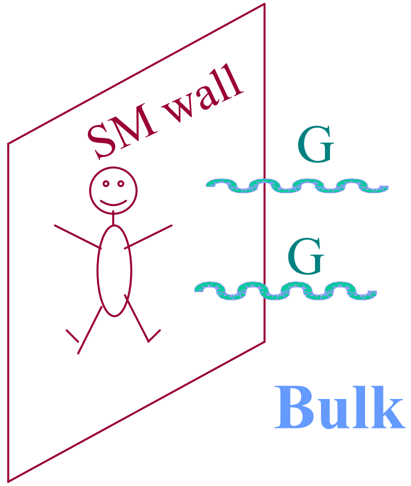


Several models studied :

ADD (≡ Arkani-Hamed, Dimopoulos, Dvali) : direct production or virtual exchange of a continuous tower of gravitons

RS (≡ Randall-Sundrum) : graviton resonances in the TeV region

TeV^{-1} scale extra-dimensions : resonances in the TeV region due to excited states of SM gauge fields



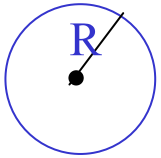
Arkani-Hamed, Dimopoulos, Dvali

If gravity propagates
in $4+\delta$ dimensions,
a gravity scale $\mathbf{M_D \approx 1\ TeV}$ is possible

$$\left.\begin{array}{l} V_4(r) \sim \dfrac{1}{M_{Pl}^2}\,\dfrac{1}{r} \\ V_{4+\delta}(r) \sim \dfrac{1}{M_D^{\delta+2} R^{\delta}}\,\dfrac{1}{r} \end{array}\right\} \text{ at large distance} \Longrightarrow \boxed{M_{Pl}^2 \approx M_D^{\delta+2} R^{\delta}}$$

- If $M_D \approx 1$ TeV :
  $\delta = 1$ $R \approx 10^{13}$ m → excluded by macroscopic gravity
  $\delta = 2$ $R \approx 0.7$ mm → limit of small- scale gravity experiments
  ….
  $\delta = 7$ $R \approx 1$ Fm

$\Longrightarrow$ Extra-dimensions are compactified over R < mm

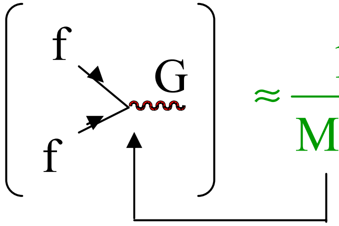


- Gravitons in Extra-dimensions get quantised mass:

$$\left.\begin{array}{ll} m_k \sim \frac{k}{R} & k = 1, \ldots \infty \\ \Delta m \sim \frac{1}{R} & \text{e.g. } \Delta m \approx 400 \text{ eV} \quad \delta = 3 \end{array}\right\} \rightarrow$$

continuous tower
of massive gravitons
(Kaluza - Klein excitations)

σ



$$\approx \frac{1}{M_{Pl}^2} N_{kk} \approx \frac{1}{M_{Pl}^2}\left(\frac{\sqrt{s}}{\Delta m}\right)^{\delta} \approx \frac{1}{M_{Pl}^2}\sqrt{s}^{\,\delta} R^{\delta} \approx \boxed{\frac{\sqrt{s}^{\,\delta}}{M_D^{\delta+2}}}$$

Due to the large number of G_{kk}, the coupling
SM particles - Gravitons becomes of EW strength

➡

- Only one scale in particle physics : EW scale
- Can test geometry of universe and quantum gravity in the lab

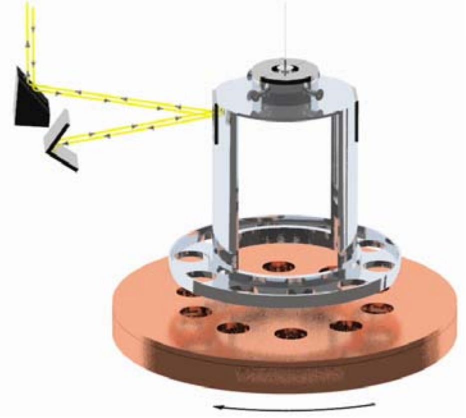
Supernova SN1987A cooling by ν emission (IBM, Superkamiokande) → bounds on cooling via G_{kk} emission:

$M_D > 31\ (2.7)$ TeV $\quad \delta = 2\ (3)$

Distorsion of cosmic diffuse γ radiation spectrum (COMPTEL) due to $G_{kk} \to \gamma\gamma$:

$M_D > 100\ (5)$ TeV $\quad \delta = 2\ (3)$

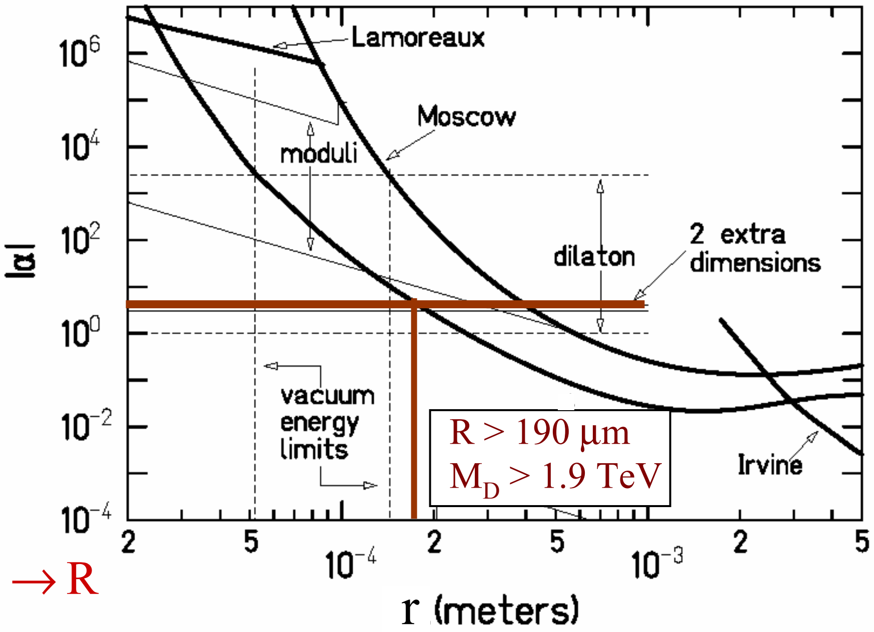
large uncertainties but δ =2 disfavoured



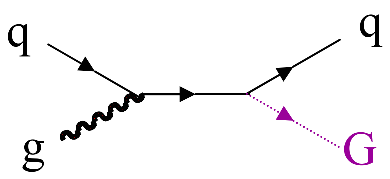
$$V(r) \sim \frac{1}{r^{1+\delta}} \qquad r << R$$

$$V(r) \sim \frac{1}{r}\left[1 + \alpha\, e^{-r/R}\right] \qquad r \to R$$

Seattle experiment, Nov. 2000



1st example : direct G production in ADD models at LHC/SLHC

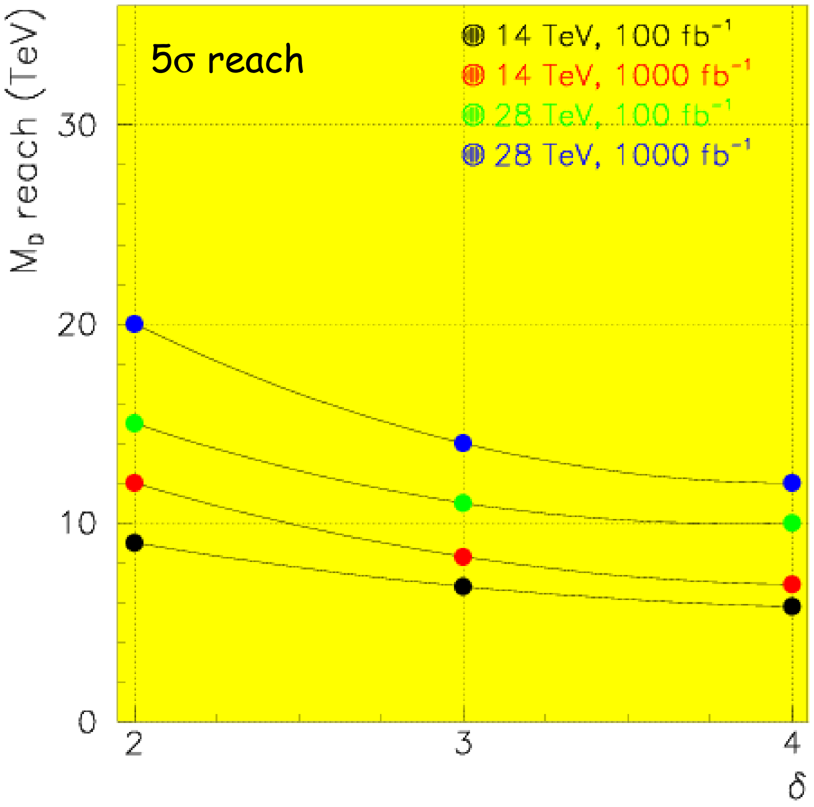


→ topology is
jet(s) + missing E_T

$$\sigma \approx \frac{1}{M_D^{\delta+2}}$$

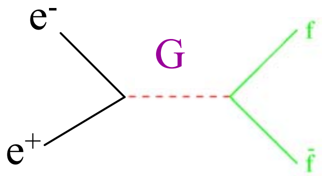
M_D = gravity scale
δ = number of extra-dimensions

Expected limits (Tevatron, HERA) in 2007:
M_D > 2-3 TeV for δ=3

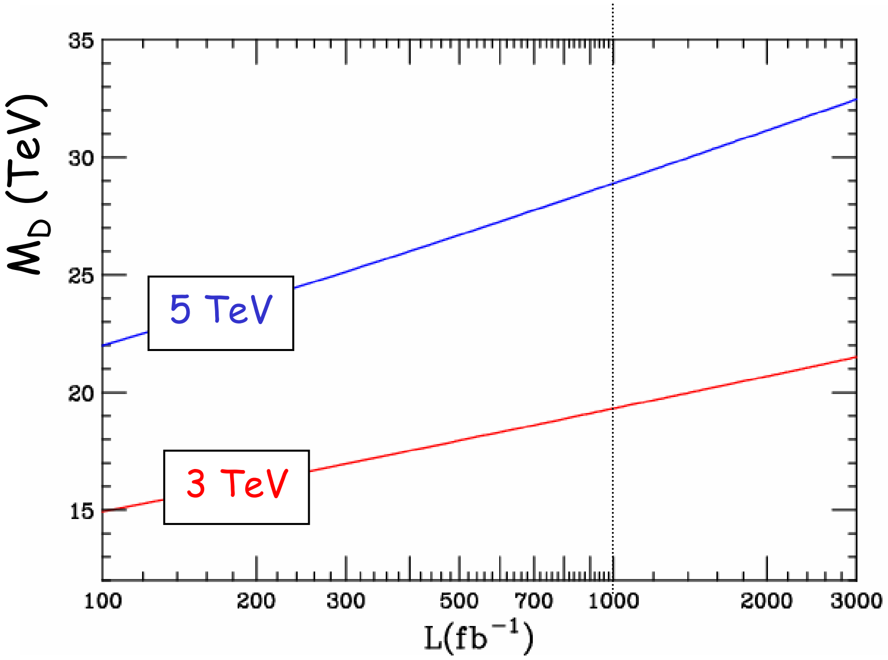


SLHC :
-- no major detector upgrade needed
(high-p_T calorimetric objects)
-- similar reach for virtual G exchange
-- G and γ/Z resonances observable up to 5-8 TeV

2nd example : virtual G exchange in ADD models at CLIC



expect deviations from SM expectation
(e.g. cross-section, asymmetries)
precise measurements at high-E machines are very constraining



Indirect sensitivity up to ~ 80 TeV (depending on model) through precision measurements

Possible options for future machines

① LHC upgrade : luminosity (L = 10^{35} cm^{-2} s^{-1}), maybe energy (√s = 28 TeV ?)

② TeV-range e^+e^- LC (TESLA, NLC, JLC) : √s = 0.5 –1.5 TeV, L = 10^{34} cm^{-2} s^{-1}

③ multi-TeV e^+e^- LC (CLIC) : √s = 3-5 TeV, L = 10^{35} cm^{-2} s^{-1}

$\Big\}$ time scale ≤ 2020

④ Muon Collider : √s ≤ 4 TeV, L ~ 10^{34} – 10^{35} cm^{-2} s^{-1} ?
Three steps : ν factory, Higgs factory, high-E muon collider

⑤ VLHC : √s = 100-200 TeV, L = 10^{34} - 10^{35} cm^{-2} s^{-1} (ring ~ 230 km)

$\Big\}$ time scale > 2020