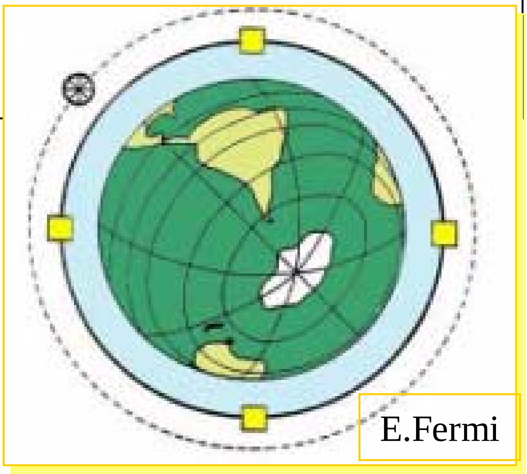
PHYSICS AT FUTURE HADRON COLLIDERS

(beyond LHC)



1. Options for future Hadron Colliders
2. Main challenges
3. Physics potential
4. Examples of possible scenarii and questions emerging from LHC

Speculative in most cases ….

Fabiola Gianotti, EP-TH Faculty, 17/1/2001

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Options for Hadron Colliders beyond LHC

① LHC upgrade : Super-LHC (SLHC) (from L.Evans)

- $L = 5 \times 10^{34}$ cm^{-2} s^{-1} - 10^{35} cm^{-2} s^{-1}
  - -- increasing bunch intensity to beam-beam limit
  - -- changing inner quadrupole triplets at IP with larger aperture magnets → reduce β by ~ 2
  - -- bunch spacing 12.5 ns → same number of interactions per crossing with double L → preserve L lifetime

→ extend LHC mass reach by ≈ 20%

- $\sqrt{s} = 15$ TeV since present dipoles designed for 9 T

Time scale : ≥ 5 years after LHC start-up

Higher-energy machine in LHC ring ?

-- justified (my opinion ...) if significant energy jump (factor ~2)

-- magnets: present technology up to B=10.5 T ($\sqrt{s} \sim 18$ TeV)

-- synchrotron radiation problems (beam screen):
B=10.5 T not impossible, much higher is excluded (according to experts).

② New machine with ~ 10 times more energy

E.g. US Very Large Hadron Collider, INFN/ELN

$\sqrt{s}$ =100-200 TeV   L =10^{33}-10^{36} cm^{-2} s^{-1}

→ explore the ≈ **10 TeV** energy scale

$\sqrt{s}$ =100 TeV, L = 10^{34} cm^{-2} s^{-1} : **mass reach up to ≈ 30 TeV**

Time scale : > 2020

May not be an option for CERN site (ring > 100 Km)

However, US VLHC discussed here (as an example) because:
-- one of the options for future big high-energy projects
   (complementary to multi-TeV Lepton Colliders)
   → useful inputs to our discussion
-- CERN could participate to world-wide project ?

VLHC main parameters

$\sqrt{s} = 100$ TeV $L = 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
from Snowmass 1996

	low field	high field known technology	high field new technology	LHC
Dipole field (T)	1.8	9.5 (Nb_3Sn)	12.5	8.4
Circumference (Km)	646	138	104	27
Bunch spacing (ns)	16.7	16.7	16.7	25
Number of bunches	129240	27522	20794	2835
Stored beam energy (GJ)	9.7	1.2	0.9	0.3
E loss per turn (MeV)	0.5	2.8	3.7	0.007
Synchrotron radiation (kW)	48	143	189	3.7

Main challenges: find economically and technically viable solutions

- -- low field : tunneling, beam stability, stored beam energy
- -- high field known technology : cryogenics, tunneling, synchrotron radiation
- -- high field new technology : magnets (high-T superconductors ?), tunneling, synchrotron radiation

Drell Panel '94 : "The **LHC** technology does not exhaust the possibilities for proton storage rings. Preliminary investigations indicate that it may be technically feasible to build a proton collider with beam energies up to 10 times those of the **LHC** with technology that could be developed during the next decade"

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Main challenges

SLHC challenge : running at L = 10^{35}

Major impact on LHC detectors (see J.Virdee's talk):

- occupancy and radiation ~ 10 times larger:
  → replace large part of trackers (or lose b-tag, electron identification, etc.); increase shielding of Muon Spectrometer at the price of reduced forward acceptance; etc.

- pile-up noise in calorimeters ~ 3 larger:
  → acceptable for e/γ / jet measurements (high-p_T physics) but degradation of forward jet tag and low-p_T jet veto (needed e.g. for strong WW scattering)
  → worse S/B for some channels

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For L ≈ 10^{35} performance of LHC detectors is degraded even with major upgrades.
Similar problems at any Hadron Collider running at L >> 10^{34}
→ in general $\sqrt{s}$ increase much easier to exploit

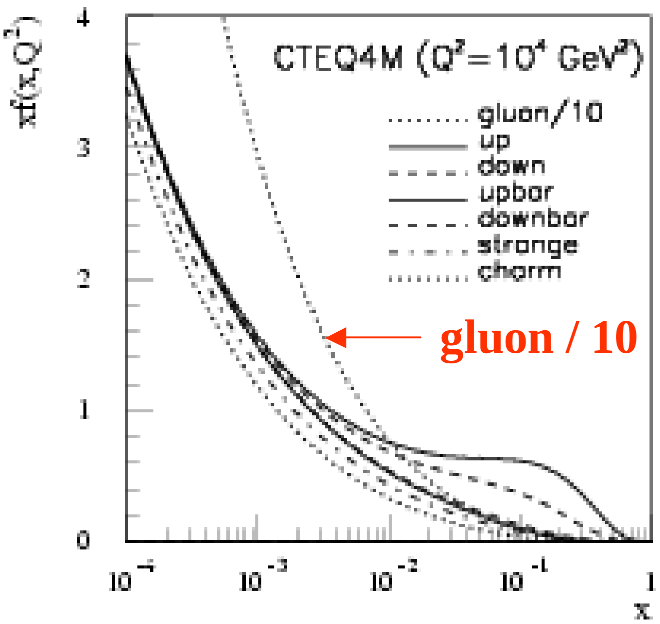
Note : elementary cross-section $\hat{\sigma} \sim 1/s$

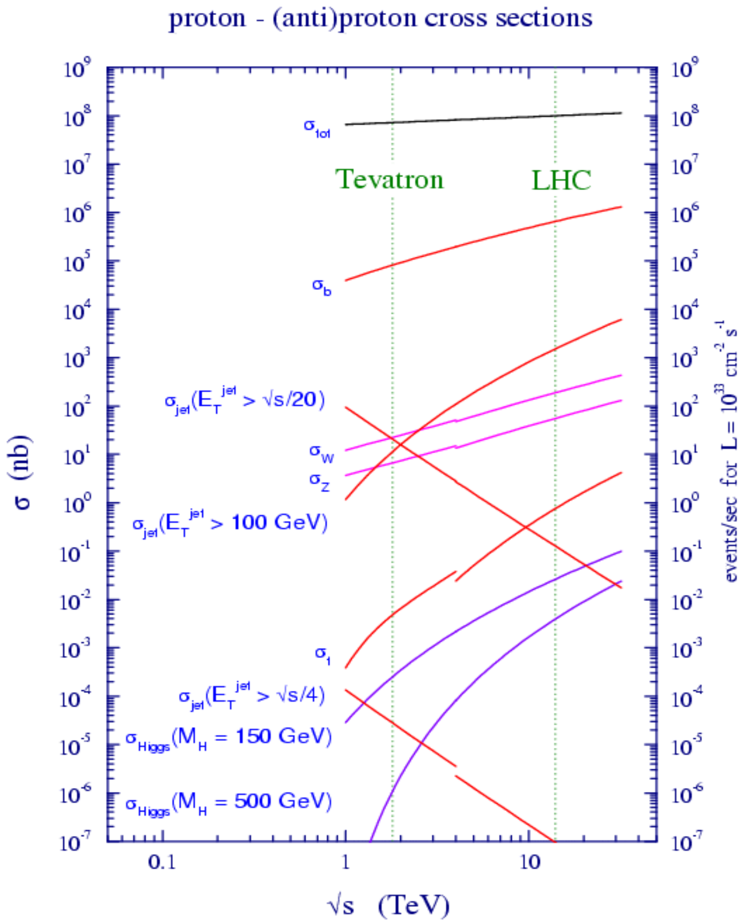
→ thumb rule : √s increase by a factor N requires luminosity increase by factor N^2 to get the same number of events. This is not true at high-energy hadron colliders.

Production cross-section for a particle of mass m (fixed):

$$\sigma \sim \frac{1}{s} \sum_{a,b} \int_{x_a x_b = m^2/s}^{1} \hat{\sigma}_{ab}\, dx_a\, dx_b\, F_a(x_a, Q^2)\, F_b(x_b, Q^2)$$

The larger √s, the smaller the Bjorken-x values of colliding partons → big increase in cross-secti due to increase of PDF's at low x





In general factor ~ 2 increase in √s equal / better to/than factor 10 increase in L

However: usually QCD backgrounds grow faster with √s than "Electroweak signals"

VLHC experimental environment

For L = 10^{34}, $\sqrt{s}$ = 100 TeV : very similar to LHC

	LHC 14 TeV, 10^{34}	VLHC 100 TeV, 10^{34}
σ_{pp} (inelastic)	~ 80 mb	~ 130 mb
Bunch spacing Δt	25 ns	17 ns
Interactions/crossing ($N= \sigma_{pp} L \Delta t$)	~ 20	~ 20
N_{ch} $\lvert\eta\rvert < 3$ per crossing	~ 900	~ 1400
$< E_T >$ charged particles	~ 450 MeV	~ 600 MeV
Tracker occupancy *	1	~ 1.5
Pile-up noise calorimeter *	1	~ 1.5
Dose *	1 (up to 10^6 Gy / year)	~ 2

* relative to LHC

- Larger σ_{pp} but shorter bunch spacing at VLHC → same number of interactions per crossing as LHC
- 1.5-2 higher occupancy, pile-up, radiation due to 50% larger particle multiplicity and slightly higher E_T at VLHC
- Calorimeter pile-up ($E_T \approx$ 400 MeV in EM cluster, $E_T \approx$ 10 GeV in jet cone ΔR=0.4) is not a concern at high energy.

Main detector requirements at VLHC (see J.Virdee's talk)

- e , μ identification and measurement (E, p, charge) up to ≈ 10 TeV with resolution ≤ 10% → challenging for muons

ATLAS, CMS : $\frac{\sigma}{p} \approx 50\%$ 10 TeV muons

- Similar radiation resistance as LHC detectors at 10^{34}. Operation at 10^{35} much more challenging.

Tracker:

-- need good momentum resolution up to ~ 10 TeV

-- need b-tagging and τ identification/measurement: top and tau could play special role in New Physics (e.g. τ for Lepton Flavour Violation)

Calorimeters:

-- "easiest" part of VLHC detectors, prominent role: $\sigma/E \sim 1/\sqrt{E}$

-- need very good constant term, granularity, fast response (LHC technology is ~ ok for 10^{34})

-- need forward jet tag

-- electron energy scale calibration up to ~ 10 TeV is challenging

Muon spectrometer:

-- must contribute to good momentum resolution up to ~ 10 TeV

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❸ Physics potential of SLHC and VLHC

Few "conventional" examples and results (for illustration only ….)

- SM physics
- Higgs
- SUSY
- Strong Eletroweak Symmetry Breaking
- New gauge bosons (W', Z')
- Compositeness
- Extra-dimensions

-- SLHC : $\sqrt{s}$ = 14 TeV $L = 10^{35}$
-- machine with $\sqrt{s}$ = 28 TeV $L = 10^{34}, 10^{35}$
} studied by ATLAS and CMS
-- VLHC : $\sqrt{s}$ = 50, 100, 200 TeV $L = 10^{34}, 10^{35}$
(e.g. FERMILAB-CONF-97/318-T)

Considered integrated luminosities:
100 fb^{-1} - 300 fb^{-1} : at 10^{34}
1000 fb^{-1} - 3000 fb^{-1} : at 10^{35}

Note : large uncertainties : in some cases extrapolations, not same assumptions and same maturity in all studies

For comparisons with Lepton Colliders I have assumed:
CLIC : $\sqrt{s}$ = 5 TeV
Muon Collider : $\sqrt{s}$ = 4 TeV

Standard Model physics

Not primary motivation for a future Hadron Collider ....

- Electroweak, B-physics, top physics, etc. well known from previous machines → not easy to improve

- For measurements where Hadron Colliders competitive (e.g. W mass, top mass) ultimate LHC precision ($\Delta m_W \sim 15$ MeV, $\Delta m_{top} \sim 1.5$ GeV) dominated by systematic uncertainties (e.g. lepton and jet energy scale) not easily reducible at a Hadron Collider

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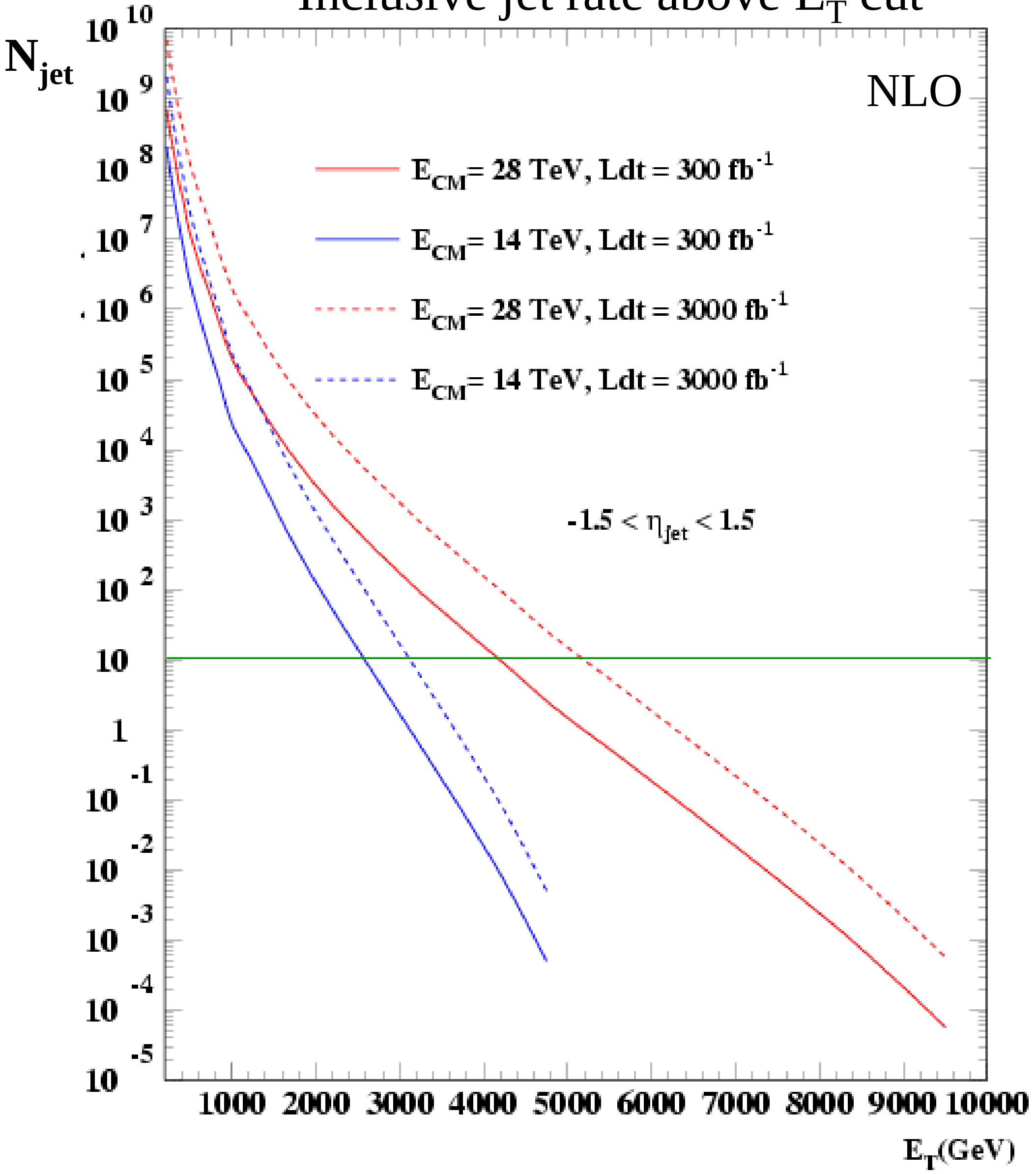
In general future Hadron Collider not competitive to refine SM precision measurements

However, some issues benefit from higher $\sqrt{s}$ and L:

-- QCD : increased $\{x, Q^2\}$ reach,
W, Z, γ, b, top, jet production at high $\sqrt{s}$, etc.

-- Triple Gauge Couplings: anomalous contributions to $WW\gamma$ and WWZ vertices have strong energy dependence.
E.g. λ_γ , λ_Z $\sim s$

Reach of QCD studies

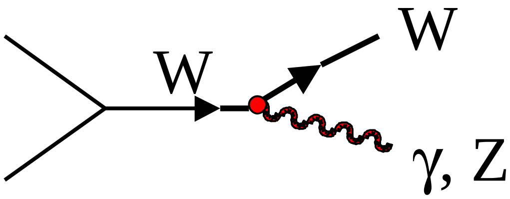

Inclusive jet rate above E_T cut

1 experiment

LHC 14 TeV 300 fb^{-1} : $E_T^{max} \sim$ 2.6 TeV
SLHC 14 TeV 3000 fb^{-1} : $E_T^{max} \sim$ 3.1 TeV
28 TeV 300 fb^{-1} : $E_T^{max} \sim$ 4.2 TeV
28 TeV 3000 fb^{-1} : $E_T^{max} \sim$ 5.2 TeV
VLHC 100 TeV up to $E_T^{max} \sim$ 20 TeV ?

Possible at 10^{35} with small changes to LHC detectors (high-p_T jets)

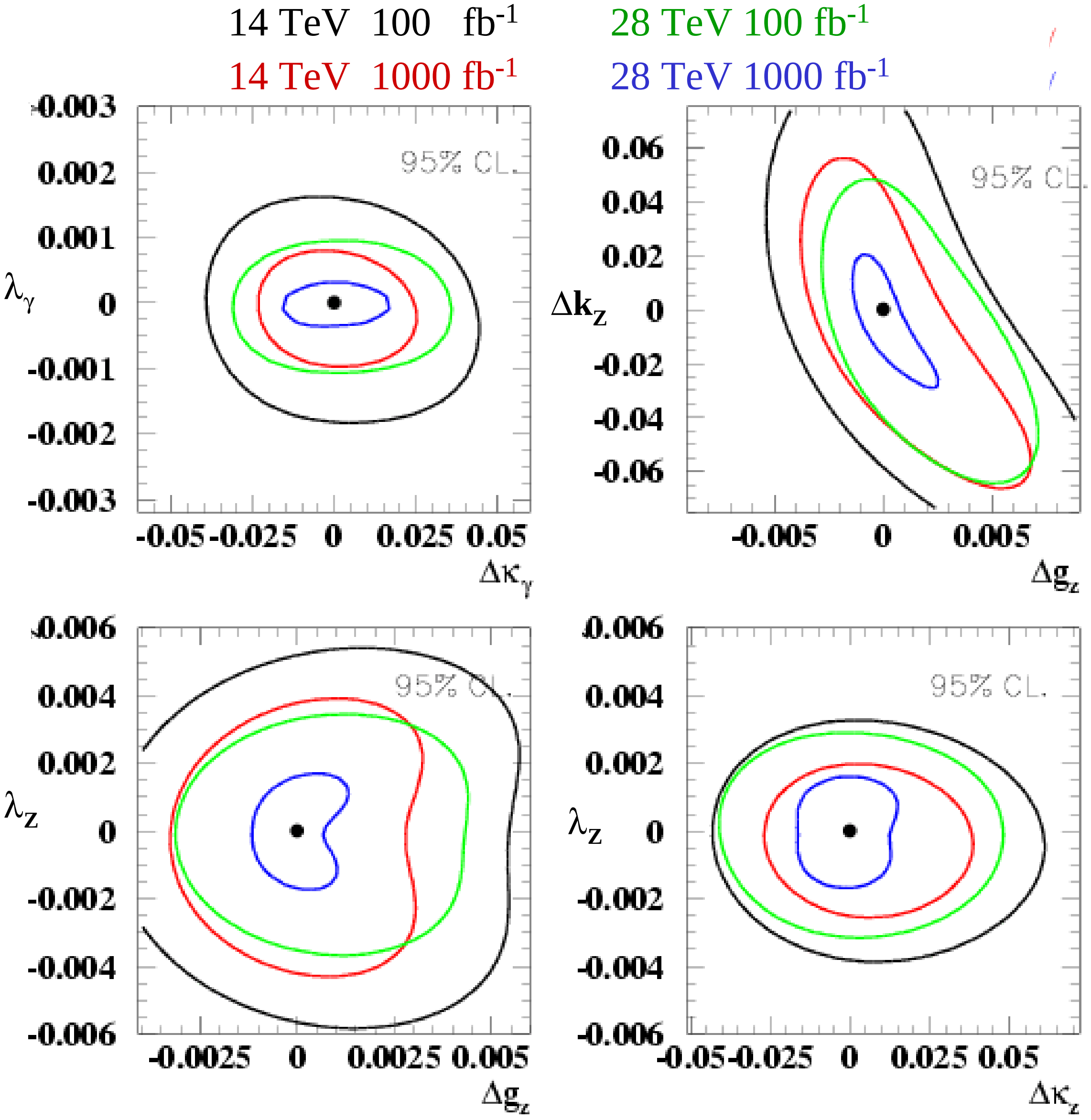
Triple Gauge Couplings



λ_γ, Δk_γ from $W\gamma \to \ell\nu\gamma$ } ℓ =e, μ 10^{34}
λ_Z, Δk_Z, g^1_Z from $WZ \to \ell\nu\,\ell\ell$ } ℓ = μ 10^{35}

From fits to cross-section, p_T^γ, p_T^Z :

14 TeV 100 fb^{-1}
14 TeV 1000 fb^{-1}
28 TeV 100 fb^{-1}
28 TeV 1000 fb^{-1}



95% C.L. constraints
for 1 experiment

	NLC 500 GeV 500 fb^{-1}	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	28 TeV 1000 fb^{-1}
λ_γ	0.0014	0.0014	0.0006	0.0002
λ_Z	0.0013	0.0028	0.0018	0.0009
Δk_γ	0.0010	0.034	0.020	0.013
Δk_Z	0.0016	0.040	0.034	0.013
g^1_Z	0.0050	0.0038	0.0024	0.0007

-- Angular distributions not used → pessimistic for Δk_γ, Δk_Z
-- Precision for λ_γ, λ_Z (≈ SM radiative corrections)
similar to 500 GeV NLC
-- Only muon channels included at 10^{35} (50% of Wγ and
25% of WZ) → conservative

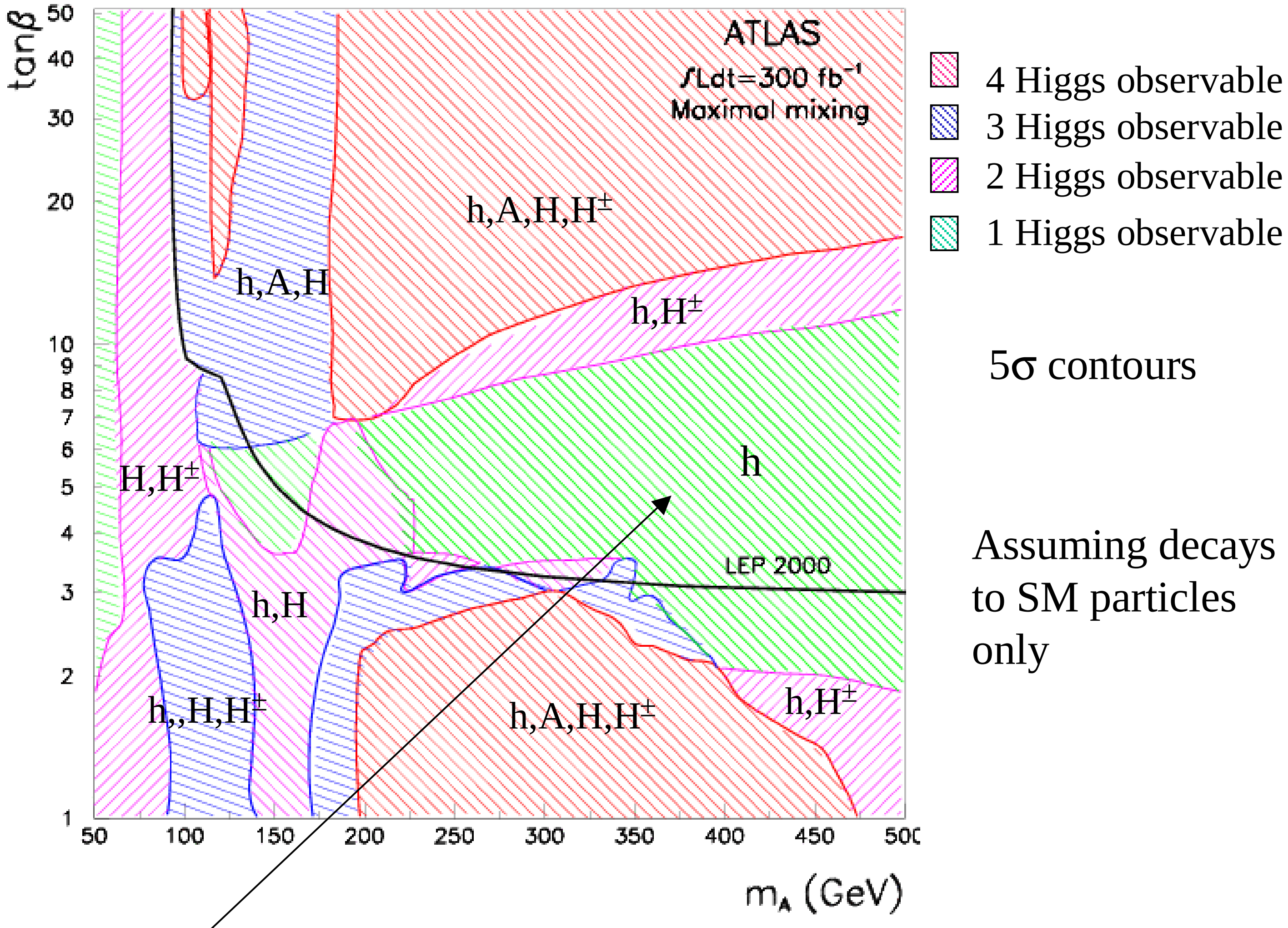
→ LHC luminosity upgrade has significant impact

-- CLIC : ≈ 10^{-4}
VLHC ≈ 10^{-4} for λ -type ?

HIGGS

SM Higgs will be discovered/confirmed or excluded by Tevatron and/or LHC over full allowed mass region

MSSM Higgs bosons



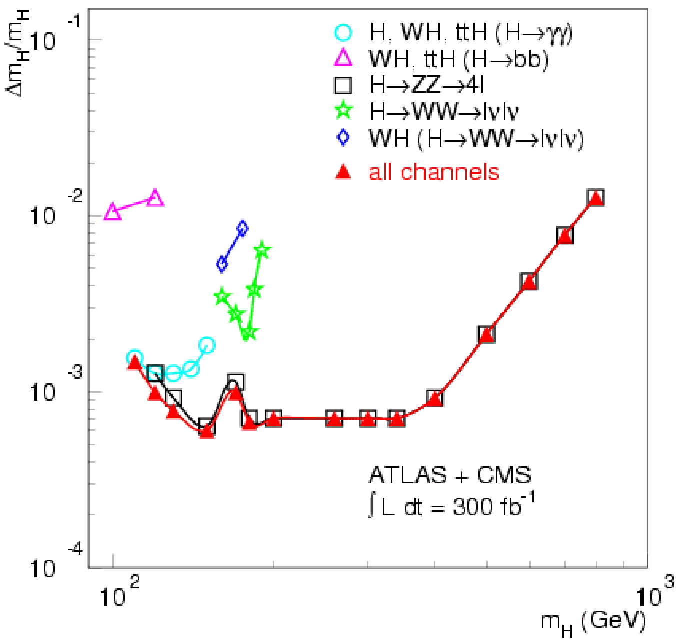
5σ contours

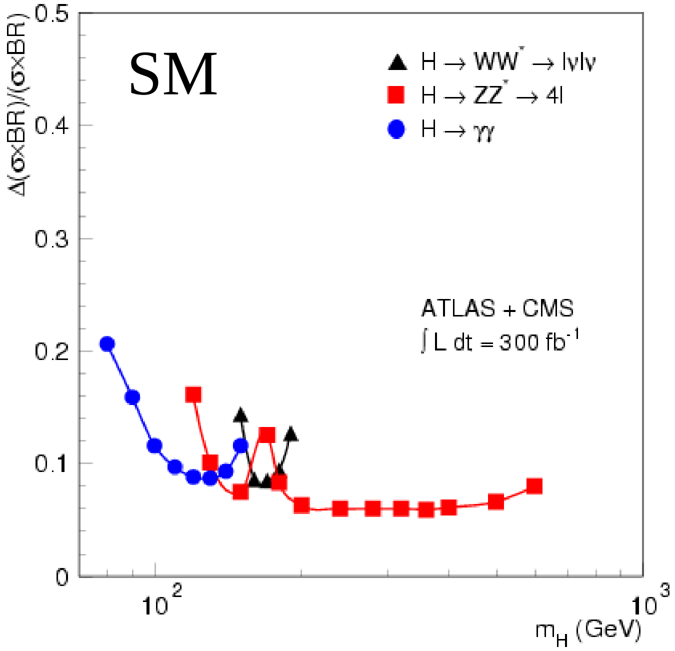
Assuming decays to SM particles only

Here A/H/H± → SUSY particles observable over limited region and for m < 600 GeV. No big improvement expected at SLHC.

Discovery reach for A/H/ H± should increase at VLHC but full sensitivity may require > 2 TeV Lepton Collider

Measurement of the SM Higgs parameters at LHC:
mass to ~0.1%, width to ≤ 10%, rates (σ x BR) to ~10%,
ratios of couplings (WWH, ZZH, ttH, bbH) to 10-20%





Precision on coupling ratios (in many cases dominated by statistical error at LHC) might improve to 5-10% at SLHC (if detector fully functional) and VLHC.
→ Not competitive with Lepton Colliders : ~ all couplings to ≈ %.

Possible scenarii

-- No Higgs found at LHC → strongly interacting (see later), or invisible ? …. or … **?** ….

-- SM -like Higgs found, no sparticles → Lepton Collider for precise Higgs measurements and VLHC for high-mass SUSY ?

-- MSSM h, sparticles, and maybe some heavy Higgs found → ≥ 2 TeV Lepton Collider to find $H/A/H^{\pm}$ and for precise Higgs measurements

SUSY

LHC potential :

-- $\tilde{q}, \tilde{g}$ mass reach $\approx$ 2.5 TeV (~ model independent)

-- other sparticles (e.g. $\tilde{\chi}, \tilde{\ell}$) mainly from cascade decays of squarks and gluinos → observation is more model dependent (but many should be observed)

-- several precise measurements (e.g. sparticle masses) possible → constrain theory parameters to $\leq 10\%$ (mSUGRA, mGMSB)

Possible scenarii

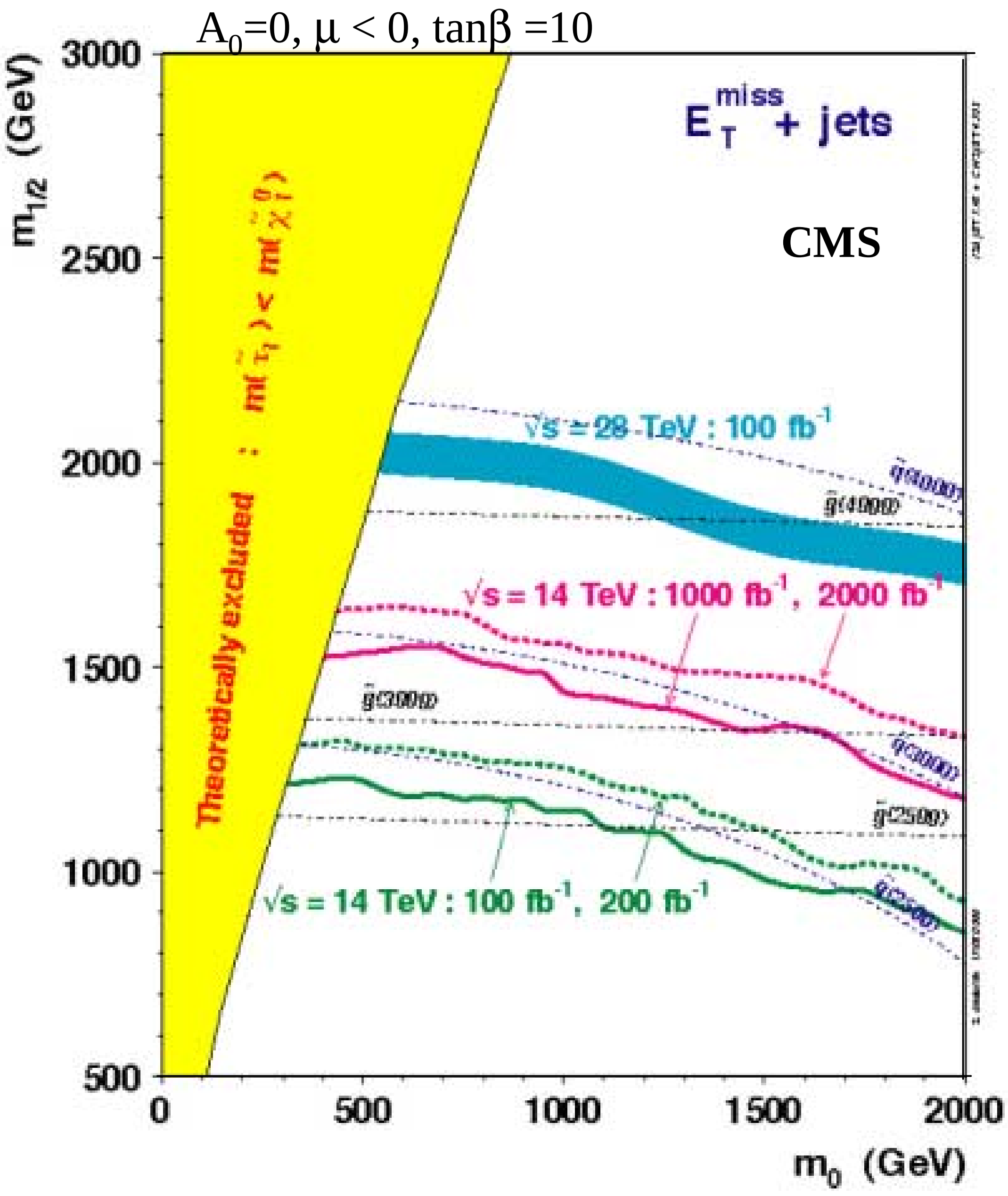
❶ LHC finds no sparticles (only SM - like h) → does SUSY exist ? give SUSY a last chance with a VLHC ?

❷ LHC finds $\tilde{q}, \tilde{g}$ but misses many $\tilde{\chi}^{\pm}, \tilde{\chi}^{0}, \tilde{\ell}$, Higgs

2-5 TeV Lepton Collider to complete SUSY spectrum and perform precision SUSY measurements

❸ LHC finds $\tilde{t}, \tilde{g}, \tilde{\chi}_i$ but misses first two generation squarks
(inverted hierarchy models : squark masses → ≈ 10 TeV)

VLHC should find missing squarks



mSUGRA

VLHC reach :
> 10 TeV on
squark and
gluino masses

SLHC : reach ≈ 3 TeV (LHC detectors ~ ok for Jets + E_T^{miss} discovery, but need to replace trackers for precision measurements)

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❹ LHC finds SUSY and it is low-E GMSB

F ≡ SUSY breaking scale (hidden sector)

M ≡ Messenger scale

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

- **M** scale measured from sparticle spectroscopy : expected precision at LHC ≈ 30% (log dependence)
- **F** scale from measurements of NLSP lifetime and mass

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

NLSP : $\chi^0{}_1 \rightarrow \gamma\,\tilde{G}$ non-pointing photons

$\tilde{\ell} \rightarrow \ell\,\tilde{G}$ kinks / displaced vertices in tracker

(~10% precision on **F** obtained, but for long lifetimes)
→ **F** gives upper bound on **M**

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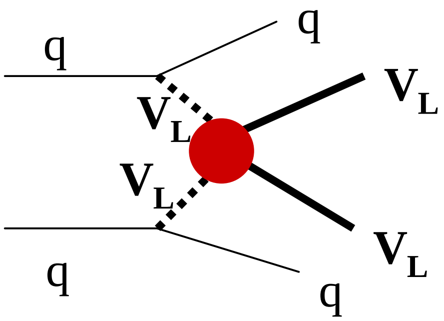
If LHC finds GMSB with **M < 100 TeV** → VLHC can probe directly the Messenger sector

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

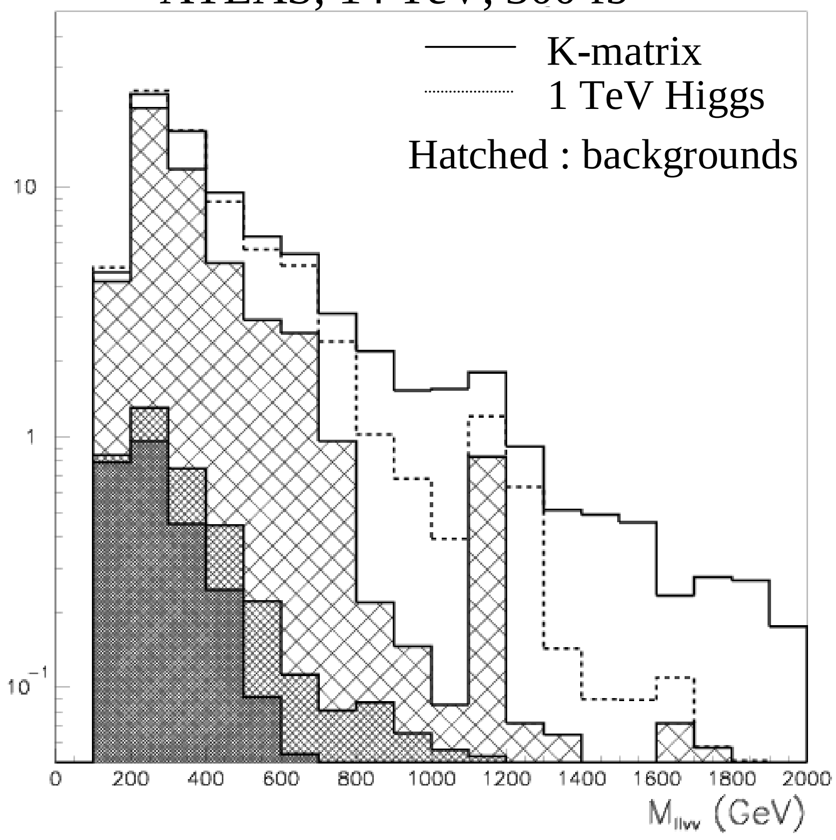


LHC : $\sigma \approx$ fb

Forward jet tag and central jet veto powerful tools against background

Non-resonant scattering (most difficult case):
best channel $W^+_L W^+_L \rightarrow W^+_L W^+_L \rightarrow \ell^+\nu\ \ell^+\nu$

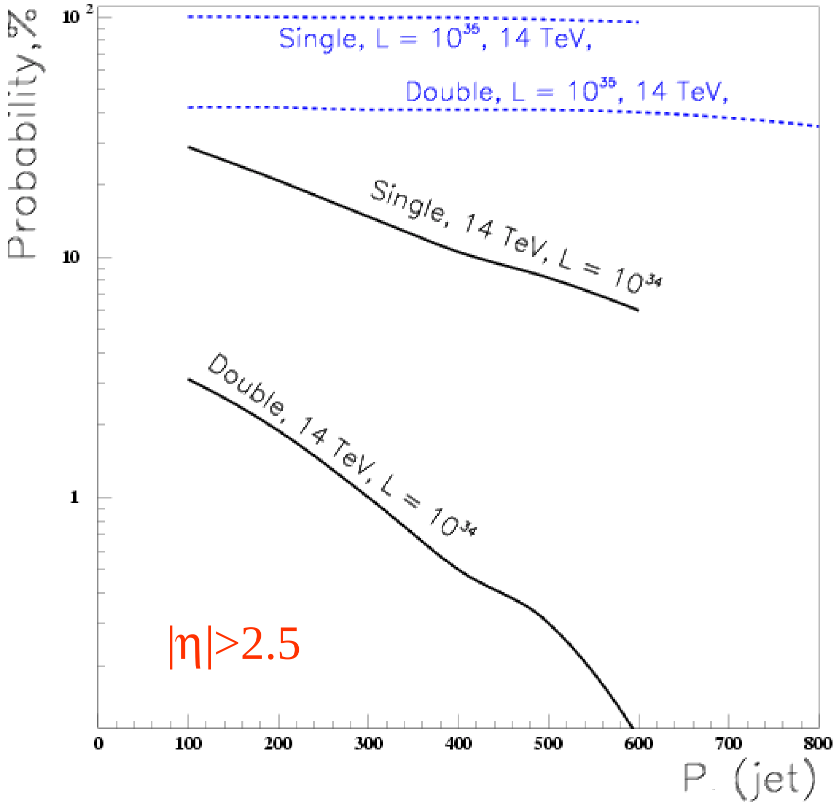
ATLAS, 14 TeV, 300 fb^{-1}



Signal and background (W^+W^+ continuum) ~ same shape → lot of data needed for a convincing signal

SLHC: degradation of forward jet tag and central jet veto due to pile-up at 10^{35}

Fake tag probability from pile-up



More study (and optimisation) needed

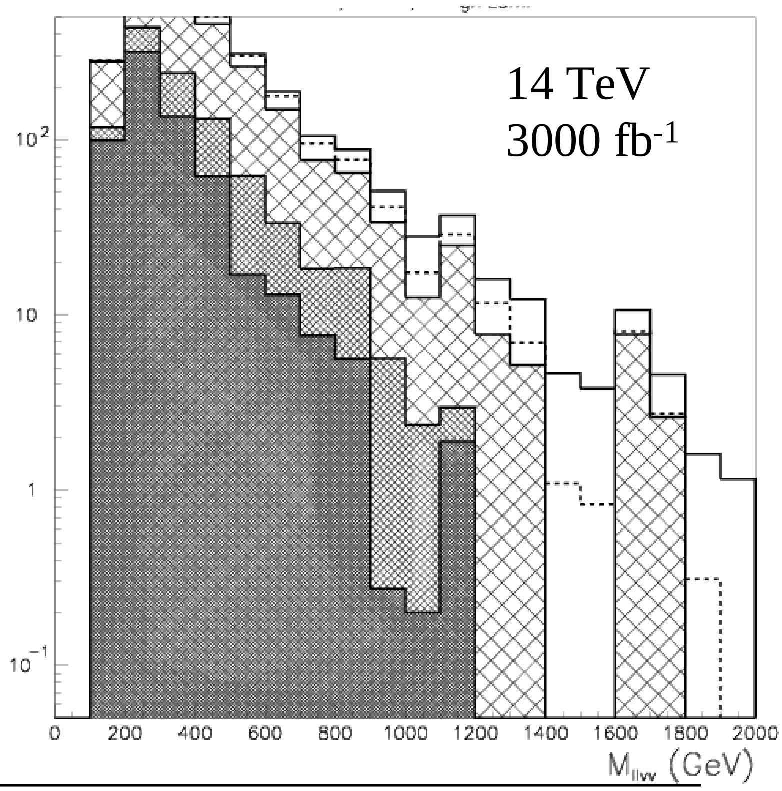
S/B < 1

However: can profit from higher L to study/compare many (low-rate) channels: WW, WZ, ZZ scattering

→ possibly get clues to underlying dynamics

For this need fully functional detector (e.g. charge measurement)

More study needed ...



➡ **Possible scenarii**

-- LHC finds strong EWSB → first exploration of strong dynamics
-- LHC gets only hints of strong EWSB
-- No evidence for strong EWSB at LHC (given the theoretical and experimental uncertainties this does not mean it is not there …..)

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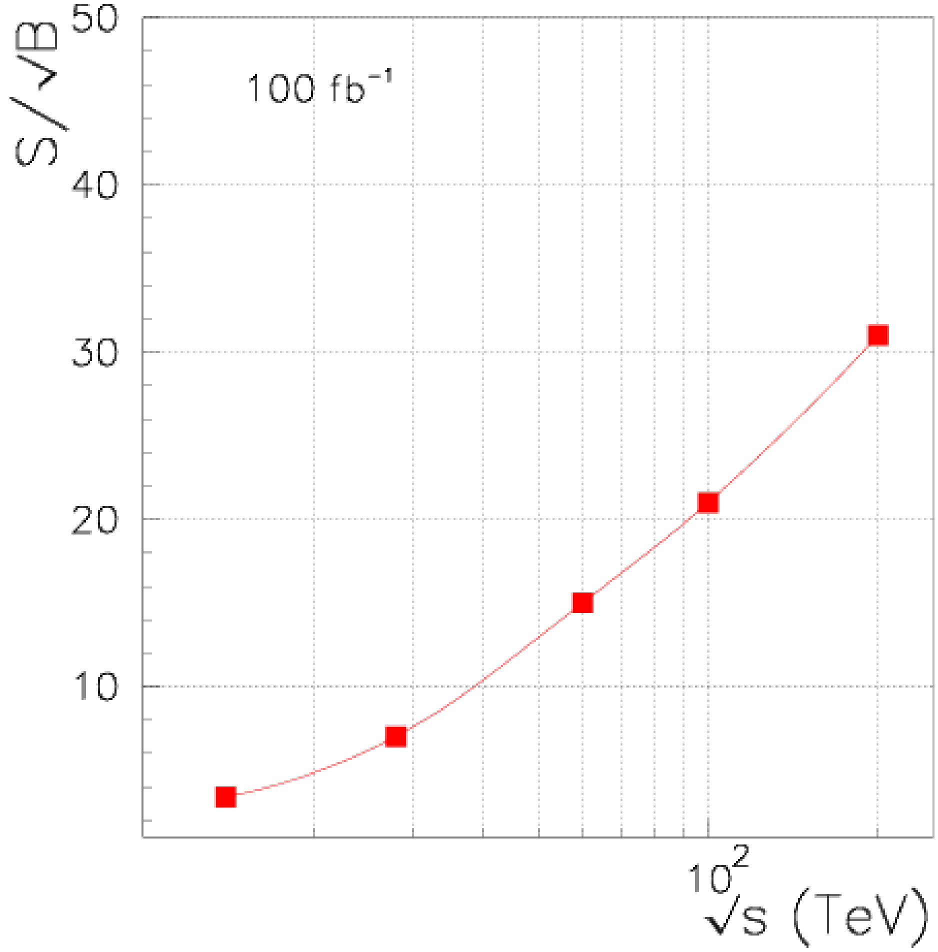
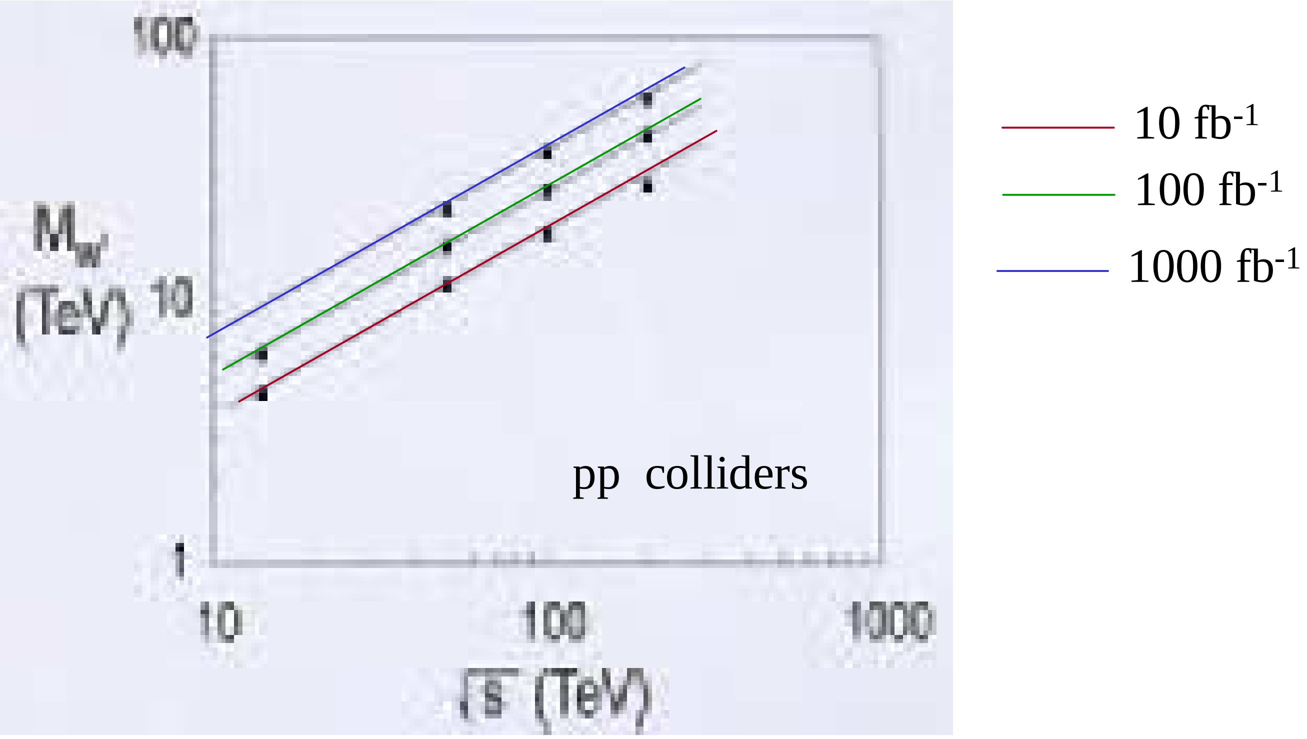
Most likely in all cases need another machine to fully explore/understand strong dynamics up to few TeV.
VLHC (mass reach) or Lepton Collider (polarization measurements) ?

$W^{\pm} W^{\pm} \to \ell\nu\ \ell\nu$ non-resonant scattering vs $\sqrt{s}$ at pp colliders



New gauge bosons : W’, Z’

Mass reach for W’ → eν (W-like couplings)

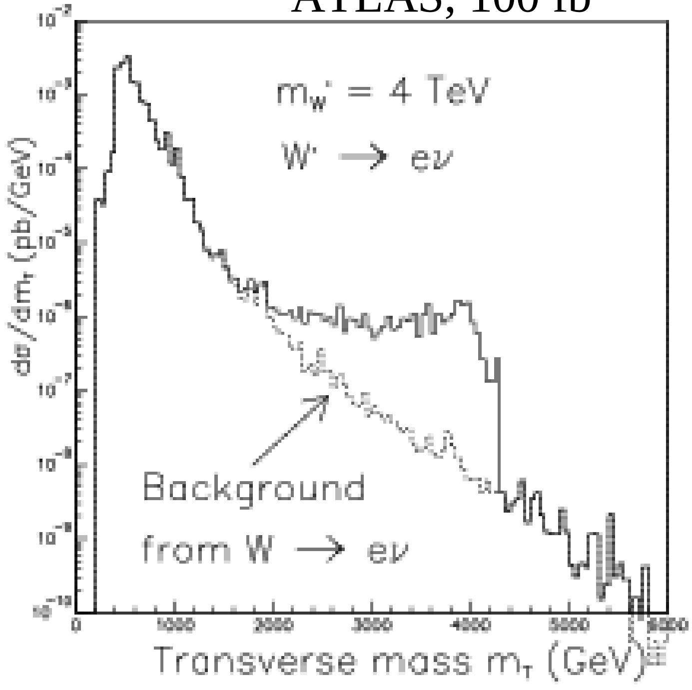


Discovery in W’ → ℓν channels.
Other channels (e.g. W’ → WZ)
for coupling measurements.

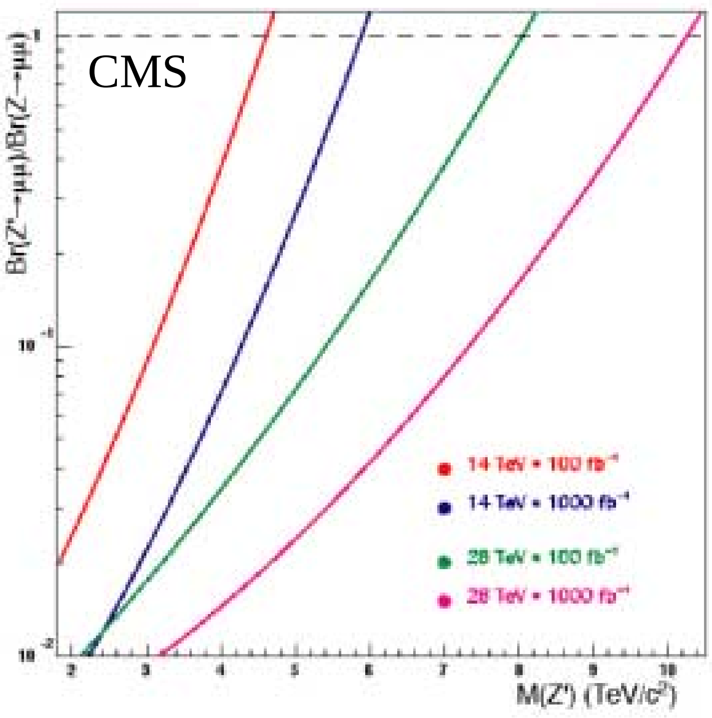
W’ mass can be measured to ≈ 2%

$\Gamma_W/W \approx 2.5\ \%$

ATLAS, 100 fb^{-1}

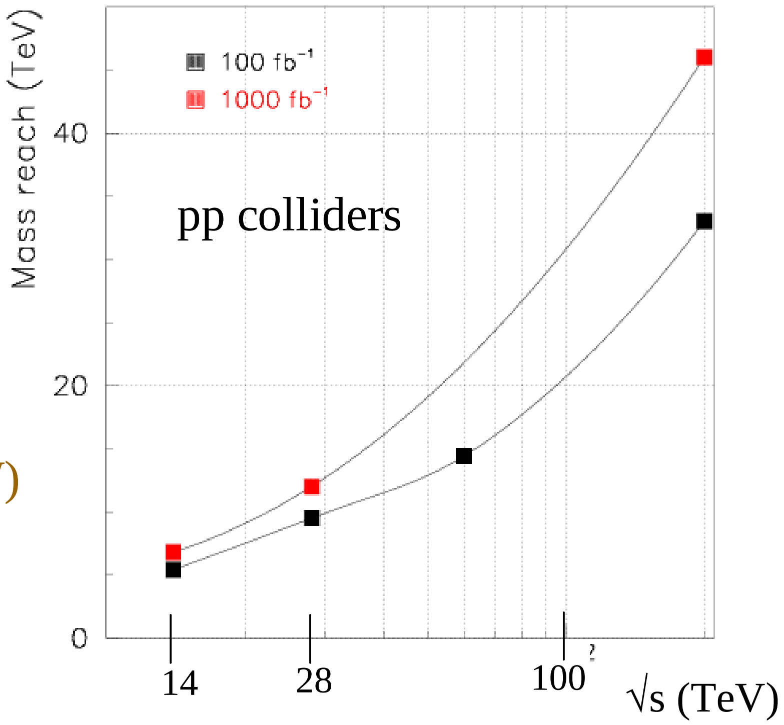


Z’ mass reach (5σ) vs BR (Z’ → μμ)



Largest reach for Z’ → ee

Z’ → ℓℓ (Z-like couplings)



Parameter measurements:

- mass to < 1%
- width to 1-5%
- σ x BR to 5-30%

Other channels (Z’ → jj, WW) for coupling measurements

Reach of indirect measurements at Lepton Colliders:
CLIC ≈ 30 TeV, M C ≈ 25 TeV

Compositeness

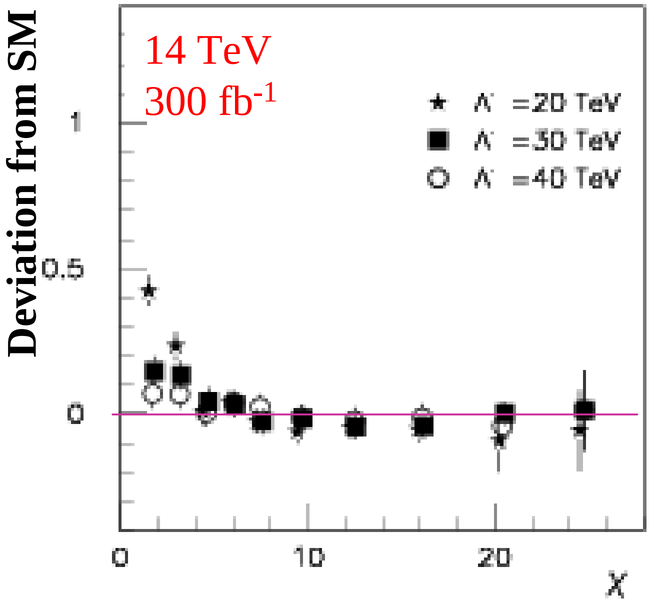
$\sqrt{\hat{s}} << \Lambda$

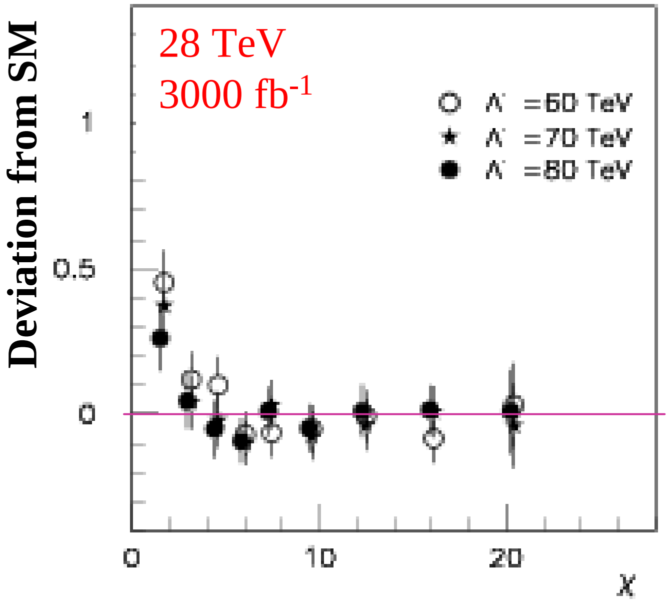
❶ Contact interactions in qq → qq:

2-jet events: expect excess of high-E_T centrally produced jets compared to SM (E_T spectrum sensitive to QCD corrections, calorimeter non-linearities, etc., angular distributions ~ insensitive)

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

If contact interactions expect excess above QCD at low χ

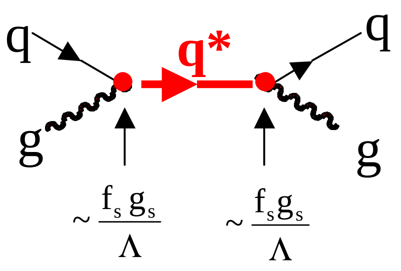




	14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	28 TeV 3000 fb^{-1}
Λ (95% CL)	40	60	85

CLIC, MC (complementary) : sensitive to $\ell\ell\ell\ell$, qq$\ell\ell$ up to ≈ 150 TeV

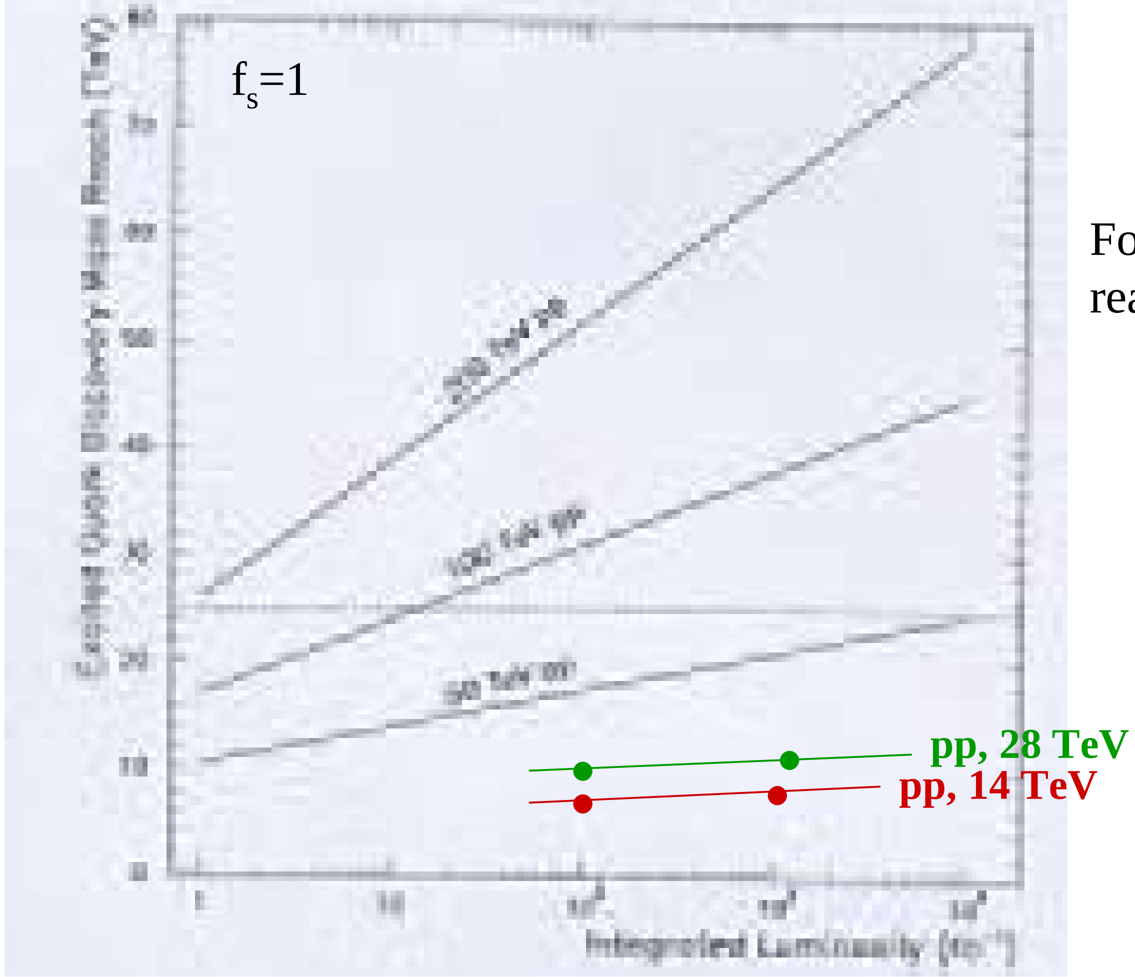
❷ Excited quarks : $\sqrt{\hat{s}} \geq \Lambda$



Could give conclusive evidence of compositeness

q* → qγ, qW, qZ also observable

5σ reach for u*,d* → jj at pp colliders



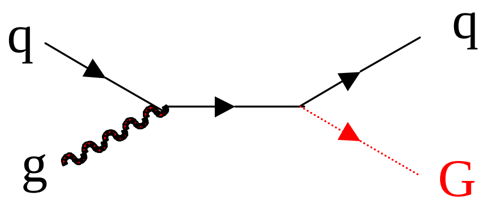
For $f_s = 0.1$
reach ~ 2 smaller

SLHC : gain ~ 10% compared to LHC (present detectors ~ ok)

Possible scenario : LHC / SLHC see contact interactions (Λ≤ 60 TeV)
→ VLHC probe directly the scale Λ
(CLIC, MC reach ≈ 2 TeV from direct searches)

Fabiola Gianotti, EP-TH Faculty, 17/1/2001

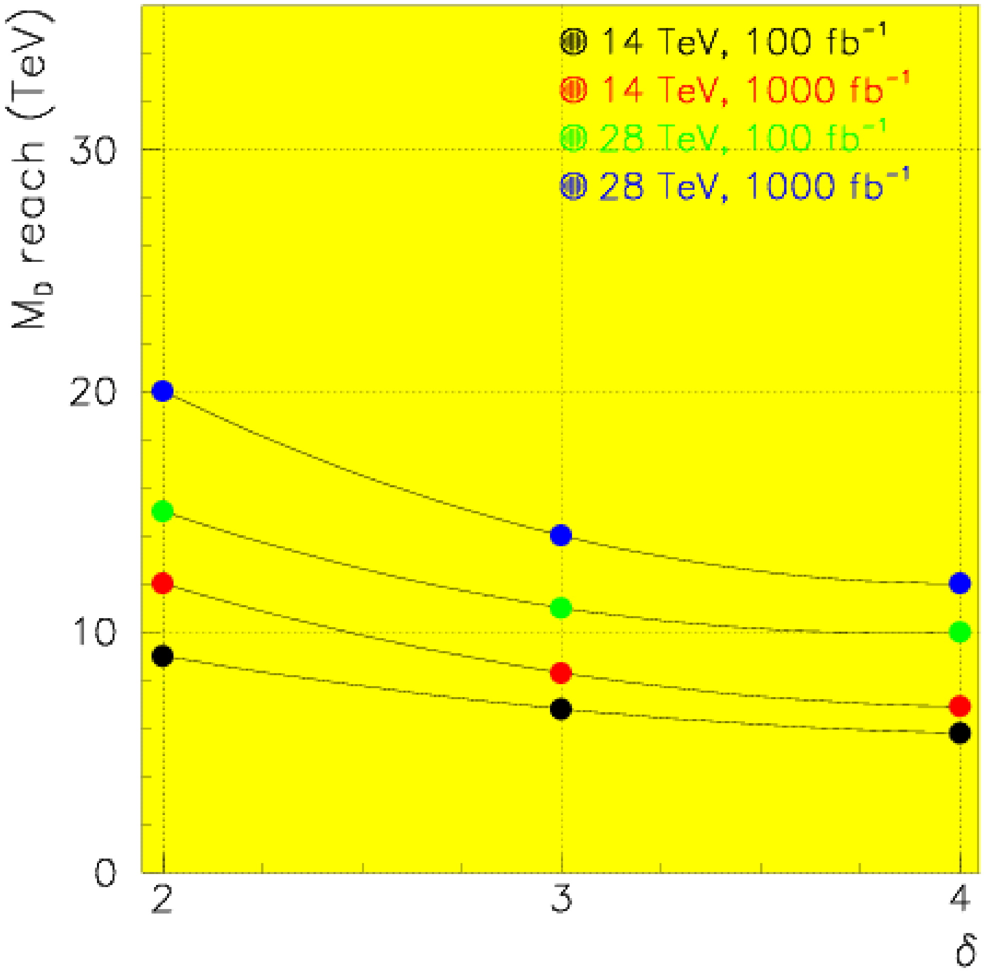
Extra-dimensions



→ topology is jet(s) + missing E_T

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

M_D = gravity scale
δ = number of extra-dimensions



5σ reach

SLHC : gain 30% in mass reach compared to LHC

VLHC $\sqrt{s}$=100 TeV : $M_D \approx$ 45 TeV for δ=2

- Ratios of σ at different $\sqrt{s}$ give δ → disentangle M_D and δ
- Combinations of various signatures might constrain model (need full detector functionality)

SUMMARY of REACH

Non exhaustive, ….. large uncertainties ….

Channel / particle	LHC 14 TeV, 10^{34}	SLHC 14 TeV, 10^{35}	28 TeV 10^{34}	VLHC 100 TeV 10^{34}
Jet E_T (TeV)	≈ 2.5	≈ 3	≈ 4	≈ 20
$\tilde{q}, \tilde{g}$ (TeV)	≈ 2.5	≈ 3	≈ 4	> 10
W' (TeV)	≈ 6	≈ 7	≈ 10	≈ 20
Z' (TeV)	≈ 4.5	≈ 5.5	≈ 9.5	≈ 20
q* (TeV)	≈ 6.5	≈ 7.5	≈ 9.5	≈ 30
Λ comp. (TeV)	≈ 40	≈ 60	≈ 65	?
Extra-dim. (TeV)	≈ 9	≈ 12	≈ 15	≈ 45
Strong $W_L W_L$ ($\int$ Ldt for 5σ)	~ 300 fb^{-1}	> 300 fb^{-1}	~ 50 fb^{-1}	~10 fb^{-1}
TGC (λ_γ)	0.0014	0.0006	0.0008	?

Broad conclusion on mass reach for singly-produced particles:

LHC (14 TeV, 10^{34})	~ 5-6 TeV
SLHC (14 TeV, 10^{35})	~ 6-7 TeV
28 TeV, 10^{34}	~ 10 TeV
VLHC (100 TeV, 10^{34})	up to ~ 30 TeV

SLHC results assume no major changes to LHC detectors (only high-p_T jets or muon final states included conservatively). Major changes (e.g. trackers replaced): improve mass reach for lepton final states by ~20%, improve measurements of TGC, Higgs, SUSY, more solid results at the limit of reach.

❹

Examples of possible scenarii and possible options (provocative …. as input to discussion)

- LHC finds only one Higgs and nothing else
  → machine to study Higgs properties (e.g. Muon Collider)
  and VLHC (to get indications for next scale) **?**

- LHC finds h, heaviest sparticles (squarks, gluinos) and
  some light sparticles (some gauginos, sleptons)
  → multi-TeV Lepton Collider to complete spectrum **?**

- LHC finds SUSY (Higgs boson(s), gluino, stop and
  some gauginos) but no squarks of the first two generations
  → multi-TeV Lepton Collider and VLHC could be equally useful
  (and complementary) **?**

- LHC finds GMSB with Messenger scale $M < 100$ TeV
  → VLHC to probe directly scale M **?**

- LHC finds contact interactions (→ $\Lambda < 60$ TeV)
  → VLHC to probe directly scale Λ **?**

- LHC finds Extra-dimensions (→ $M_D < 15$ TeV)
  → VLHC to probe directly scale M_D **?**

- LHC finds nothing → Higgs strongly interacting or invisible ?
  → Lepton Collider or VLHC **?**

- LHC finds less conventional scenarii or
  totally unexpected physics → **?**

Conclusions

LHC upgrade to L ≈ 10^{35} could push mass reach for Physics Beyond SM by typically 20% (up to ≈ 7 TeV) with no major detector changes . However, with upgraded detectors could fully benefit from luminosity increase → more convincing conclusions for signals at the limit of the sensitivity.

Significant LHC energy upgrade seems excluded (L.Evans).

VLHC with $\sqrt{s} \approx 100$ TeV :

- -- CERN site may be difficult
- -- machine and cost are big challenges
  (LHC-type detectors ~ ok for 10^{34})
- -- not competitive with multi-TeV Lepton Colliders
  for precise measurements and/or to fill "LHC holes"
  in particle spectrum at ≤ TeV scale (e.g. SUSY, Higgs).

However: only conceivable machine today
to explore the ≈ 10 TeV energy scale (up to ≈ 30 TeV).

No compelling scenario today for Physics at ≈ 10 TeV,
but clues to next energy scale could emerge from LHC data:
if evidence for e.g. GMSB, contact interactions,
Extra-dimensions at scales < 100 TeV, then
VLHC could probe directly the scale of New Physics.