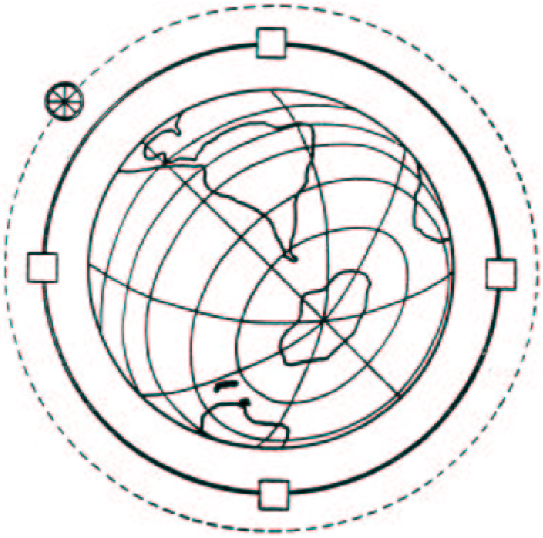
Physics at the VLHC



1. Future Colliders
2. VLHC detector issues
3. Physics Potential of the VLHC
4. Summary

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1 – Future Colliders

- e^+e^- Linear Colliders

  ☞ TESLA/NLC: $\sqrt{s} = 500$ GeV – 1.5 TeV

  $\mathcal{L} = \text{few} \times 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$

  ☞ CLIC (CERN): $\sqrt{s} = 3$ TeV – 5 TeV

  $\mathcal{L} \approx 10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$

- Muon Collider

  ☞ $\sqrt{s} = 400$ GeV – 3 TeV

  ☞ $\mathcal{L} = 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1} - 5 \cdot 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$

- LHC upgrade scenarios (SLHC)
  studied by ATLAS (ATL-PHYS-2001-002)
  and CMS:

  ☞ luminosity upgrade to
  $\mathcal{L} = 5 \cdot 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} - 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  ☞ and/or energy upgrade: $\sqrt{s} = 28$ TeV
  requires ~ 17 T magnets (do not exist yet)
  ☞ remarks
  → for $\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ the performance of LHC detectors is degraded, even with major upgrades (occupancy and radiation, pile-up)
  → similar problems at any hadron collider running at $\mathcal{L} \gg 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  → in general, an increase in $\sqrt{s}$ is easier to exploit than an increase in luminosity

- VLHC (Fermilab-TM-2149)

  ☞ stage 1: $\sqrt{s} = 40$ TeV, $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1}

  ☞ stage 2:

$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2} s^{-1})
125	$5.1 \cdot 10^{34}$
150	$3.6 \cdot 10^{34}$
175	$2.7 \cdot 10^{34}$
200	$2.1 \cdot 10^{34}$

  up to 50 interactions/crossing (cf. LHC: 20)

- remarks

  ☞ TESLA/NLC give access to the same energy regime as the LHC. They complement the LHC

  ☞ CLIC uses a technology (two beam acceleration) very different from that used by TESLA/NLC and is a post TESLA/NLC machine

  ☞ CLIC begins to give access to energies which the LHC (without upgrade in energy) cannot reach

- remarks (cont.)

  ☞ stage 2 of the the VLHC is a post LHC and post TESLA/NLC machine

  ☞ stage 2 of the VLHC breaks completely new ground

- rest of this talk

  ☞ remarks on detector requirements

  ☞ compare LHC upgrade scenarios with stage 1 of the VLHC where appropriate

  ☞ discuss physics reach of stage 2 of the VLHC

  ☞ all estimates/extrapolations carry substantial uncertainties. More precise results should be available after Snowmass

- Result:

  regardless of what we will find at the LHC we will eventually want to have a hadron collider operating in the 100 TeV range

VLHC: UV fixed point of HEP program

2 – VLHC Detector Issues

- Physics should drive the needed detector technologies
- LHC technology should be ok for VLHC stage 1 detectors
- need serious R&D for stage 2 detectors

☞ electron detection

→ high charged track multiplicity is a potential problem

→ isolation is messy: many interactions/crossing

☞ muon detection

momentum measurement for multi-TeV μ's is difficult and requires a very large, many Tesla magnet

☞ $\not\!\!E_T$

difficult due to many interactions/crossing

☞ jets

→ need small constant term ($\sigma/E \sim 1/\sqrt{E}$)

→ need to understand how many interactions/crossing influence jet energies (similar to LHC)

→ need forward jet tag (up to $|\eta| = 6 - 7$?)

☞ b-tagging

radiation environment and track multiplicity pose problems

3 – Physics Potential of the VLHC

To illustrate the physics potential of the VLHC we consider a few more or less representative examples:

- precision SM physics and anomalous WWV ($V = \gamma,\ Z$) couplings
- Higgs boson physics
- supersymmetry
- strong electroweak symmetry breaking
- new gauge bosons
- compositeness (excited quarks and leptons)
- extra dimensions

Precision SM Physics

- this is not the primary reason for building the VLHC!
- well known from previous machines; many areas of the SM will have been tested at the 1-loop level
- for measurements where LHC is competitive (M_W, m_{top}), the ultimate precision is limited by systematic uncertainties. These are difficult to reduce
- special case: anomalous gauge boson couplings

  ☞ concentrate on trilinear WWV ($V = \gamma, Z$) couplings: κ_V, λ_V, g_1^Z

  ☞ non-SM contributions grow with energy ($\sim \sqrt{s}$ or $\sim s$); details depend on coupling and process considered

  ☞ need form factor to guarantee S-matrix unitarity

  ☞ limits depend on form factor scale Λ_{FF}

  ☞ limits scale roughly with $(\int \mathcal{L} dt)^{1/4}$

  → increasing $\int \mathcal{L} dt$ by a factor 10, strengthens bounds by about a factor 2 – 3

- 95% CL limits:

☞ $\Delta\kappa_\gamma$, λ_γ from $pp \to W(\to \ell\nu)\gamma$

☞ $\Delta\kappa_Z$, λ_Z, Δg_1^Z from $pp \to WZ \to \ell_1\nu\ell_2^+\ell_2^-$

☞ dipole form factor (similar to proton form factor) with $\Lambda_{FF} = 10$ TeV

$\sqrt{s}$	14 TeV	28 TeV	40 TeV	200 TeV	CLIC (5 TeV)
$\int\mathcal{L}dt$	100 fb^{-1}	100 fb^{-1}	100 fb^{-1}	200 fb^{-1}	1 ab^{-1}
$\Delta\kappa_\gamma$	0.034	0.027	0.023	0.013	$6 \cdot 10^{-5}$
λ_γ	0.0014	$8 \cdot 10^{-4}$	$6 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$8 \cdot 10^{-5}$
$\Delta\kappa_Z$	0.040	0.036	0.035	0.020	$7 \cdot 10^{-5}$
λ_Z	0.0028	0.0023	0.0020	0.0011	$6 \cdot 10^{-5}$
Δg_1^Z	0.0038	0.0023	0.0020	0.0011	$2 \cdot 10^{-4}$

☞ for larger values of Λ_{FF}, the limits improve substantially: $\sqrt{s} = 200$ TeV, $\Lambda_{FF} = 50$ TeV: $|\lambda_\gamma| < 0.0001$

☞ SM radiative corrections are $\mathcal{O}(\text{few} \times 10^{-4})$

- hadron and e^+e^- colliders are complementary

☞ hadron colliders probe high energy behaviour of helicity amplitudes

☞ e^+e^- colliders test angular distributions

Higgs boson physics

- the SM Higgs boson will be discovered, if it exists, at the Tevatron/LHC over the entire allowed mass range (< 1 TeV)
- measurement of SM Higgs parameters at the LHC:

☞ M_H to 0.1%

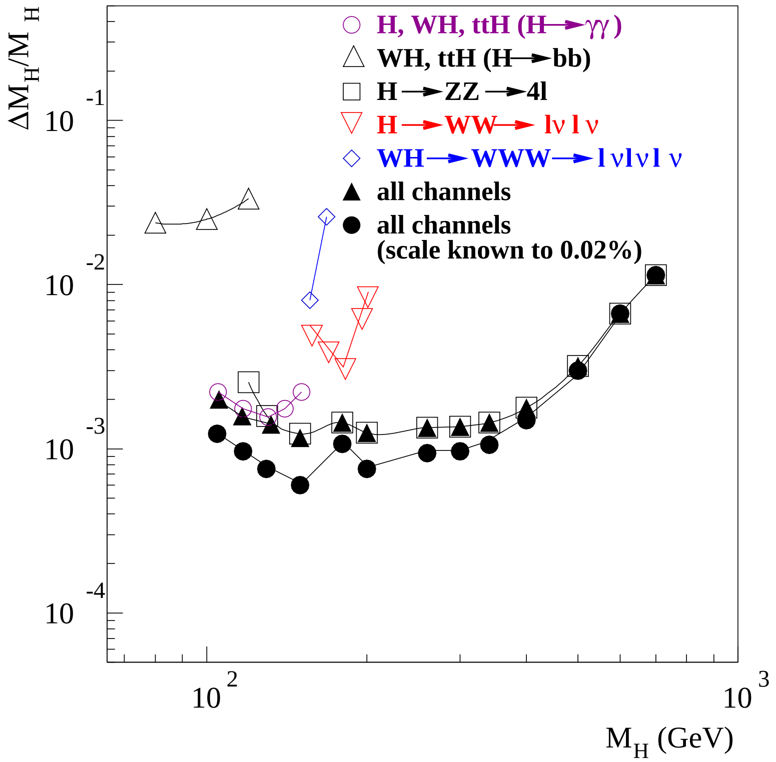
☞ Γ_H to $\leq 10\%$

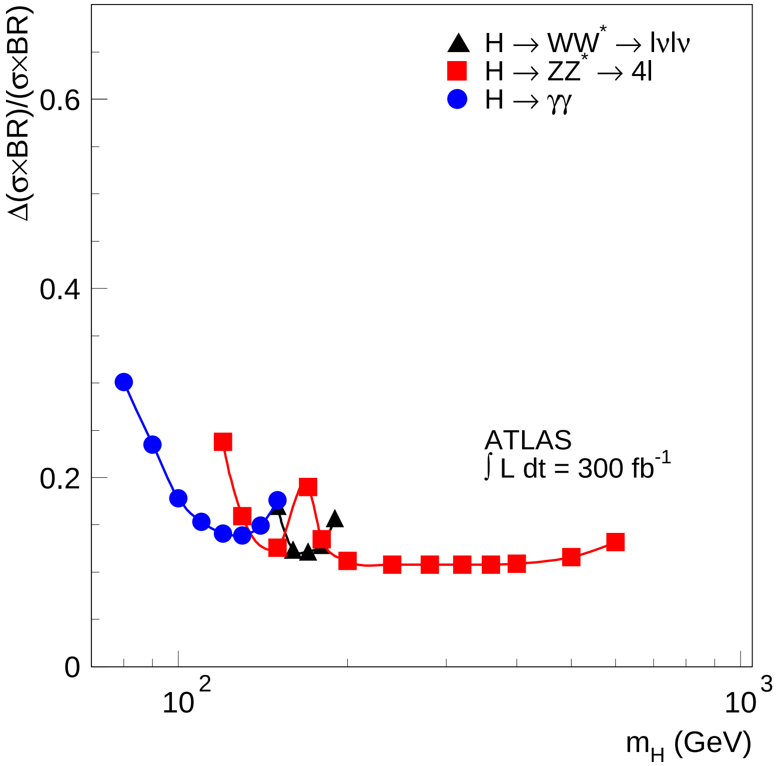
☞ $\sigma\times$ Br to 10%

☞ ratios of couplings (WWH, ZZH, $\bar{t}tH$, $\bar{b}bH$) to $10-20\%$, in many cases dominated by statistics

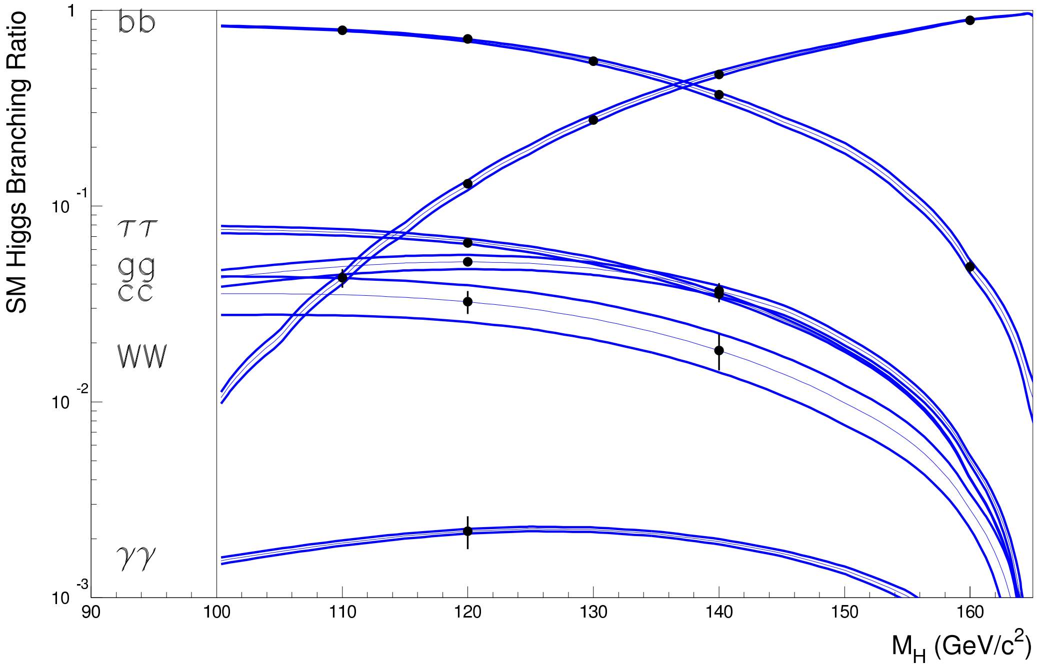
☞ weak boson fusion and forward jet tagging crucial to measure Higgs couplings

☞ no information on HHH coupling (rate and/or background limited)


ΔM_H/M_H
10^-1
10^-2
10^-3
10^-4
10^2
10^3
M_H (GeV)
○ H, WH, ttH (H→γγ)
△ WH, ttH (H→bb)
□ H→ZZ→4l
▽ H→WW→ lν l ν
◇ WH→WWW→l νlνl ν
▲ all channels
● all channels
(scale known to 0.02%)

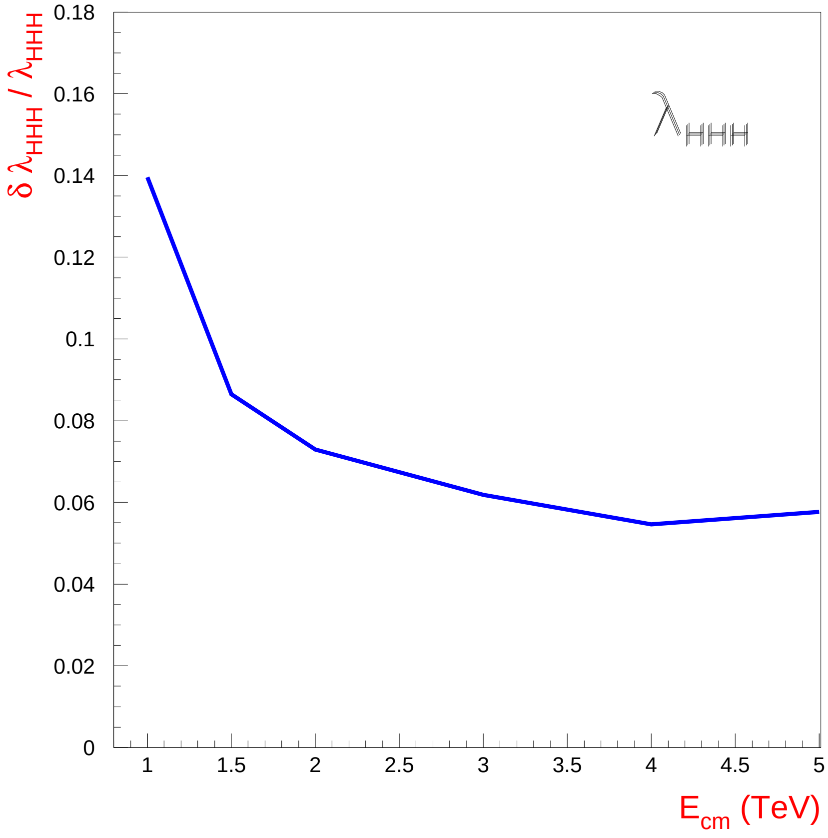

Δ(σ×BR)/(σ×BR)
0.6
0.4
0.2
0
10^2
10^3
m_H (GeV)
▲ H → WW* → lνlν
■ H → ZZ* → 4l
● H → γγ
ATLAS
∫ L dt = 300 fb^-1

- precision of ratios of couplings might (need more studies!) improve by about a factor 2 at SLHC
- TESLA/NLC $H\bar{f}f$ couplings (Battaglia):



☞ similar precision for VVH ($V = W$, Z) couplings

- HHH coupling in e^+e^- collisions:



- linear colliders can measure all couplings to $\mathcal{O}(10^{-2})$
- VLHC:

☞ tagging jets in weak boson fusion become more forward with increasing $\sqrt{s}$

→ easier to suppress bgd.

☞ significantly improve LHC measurement of Higgs couplings at the VLHC (stage 1)? Measure λ_{HHH}?

→ need detailed study

what if . . .

- no Higgs boson is found at the LHC:

  ☞ strongly interacting Higgs sector?

  → VLHC (stage 1 may give hints already)

- Higgs boson compatible with a SM interpretation is found at the LHC, but no sparticles:

  → TESLA/NLC and/or CLIC for precision Higgs boson physics

  → VLHC for high mass sparticles search (and precision Higgs boson physics?)

- MSSM, Higgs boson(s) and some sparticles are found at the LHC:

  → CLIC and/or VLHC complete sparticle spectrum and for precision Higgs boson physics

Supersymmetry

- with 100 fb^{-1}, the LHC can find squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) if their masses are ≤ 2 TeV
- increasing the LHC luminosity by a factor 10 extends the mass reach by about 20%.
- doubling the LHC energy to $\sqrt{s} = 28$ TeV provides access to $\tilde{q}$ and $\tilde{g}$ with masses up to $3-4$ TeV

  ➞ at stage 1 of the VLHC one can detect squarks and gluinos with masses up to $4-5.5$ TeV
- LHC: other sparticles are mainly detected from $\tilde{q}$ and $\tilde{g}$ cascade decays

  ☞ for many mSUGRA models, the LHC will miss most of the sleptons, charginos and neutralinos, and the heavy Higgs bosons
- one can construct inverted hierarchy models (IHM) where none of the sparticles can be discovered ($5\,\sigma$) at the LHC (Baer et al.)

- stage 2 of the VLHC might be able to probe the dynamics of SUSY breaking

☞ any SUSY theory must contain a mechanism for breaking SUSY

☞ and a method (messengers) for communicating SUSY breaking to the sparticles

☞ two scales:

→ SUSY breaking vev F

→ messenger scale M

☞ sparticle mass:

$$\tilde{m} \sim \eta \, \frac{F}{M}$$

η: dimensionless suppression factor from coupling constants

☞ GMSB: M is replaced by vector-like messenger field; $\eta \sim \alpha/4\pi$

→ for $\sqrt{F} \sim M$, both messenger fields and SUSY breaking scale could be as low as $10 - 100$ TeV

→ could be accessible at stage 2 of the VLHC

☞ M can be measured from sparticle spectroscopy

→ expected precision at the LHC: $\sim 30\%$

☞ F from NLSP lifetime and mass

- SUSY mass scales:

  ☞ electroweak scale protected if superpartners coupling most strongly to Higgs boson have masses < 1 TeV

  ☞ $\tilde{t}, \tilde{b}_L$, weak gauginos, higgsinos have $m < 1$ TeV

  ☞ other squarks/sleptons contribute to weak scale at two loop

  → $m < 20$ TeV

what if . . .

- the LHC finds $\tilde{q}$ and $\tilde{g}$ and maybe a few other sparticles

  → VLHC and CLIC have a good chance to fill in the gaps of the sparticle spectrum

- the LHC finds $\tilde{t}$ and $\tilde{g}$ but misses the first two generation squarks

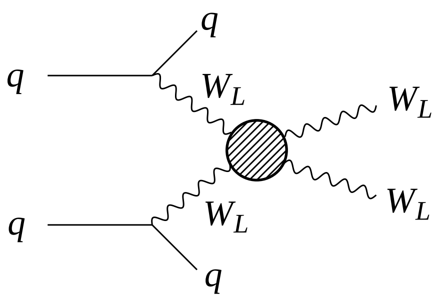
  → VLHC (maybe stage 1, but certainly stage 2) should find the missing squarks (no quantitative estimates so far)

- the LHC discovers SUSY and finds it is low energy GMSB

  → stage 2 of the VLHC can probe messenger sector

strong electroweak symmetry breaking

- if no Higgs boson exists, one expects that longitudinal W's and Z's interact strongly for $\sqrt{\hat{s}} \geq$ 1 TeV
- vector boson scattering, eg:

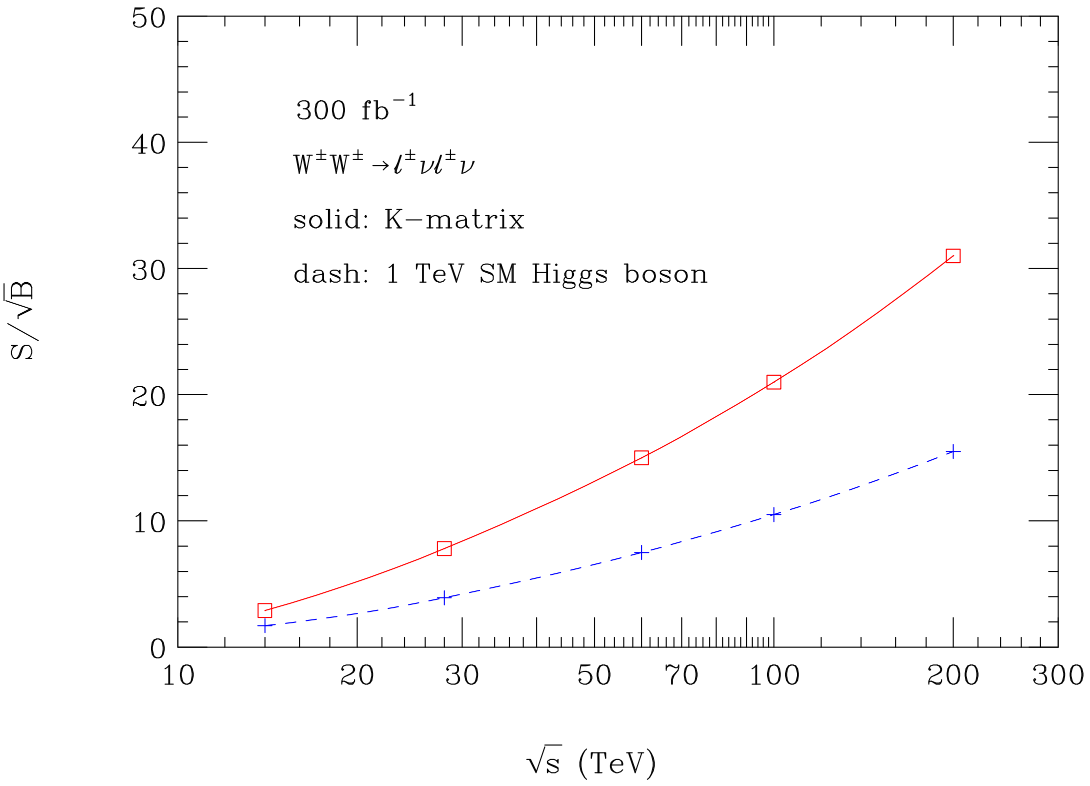


- forward jet tagging and central jet veto are powerful tools to reduce background
- example:
  ☞ non-resonant scattering
  ☞ most difficult case
  ☞ best channel: $W^{\pm}W^{\pm} \to \ell_1^{\pm}\nu\ell_2^{\pm}\nu$
  ☞ compare 1 TeV SM Higgs boson with K-matrix unitarization model (Bagger et al.)

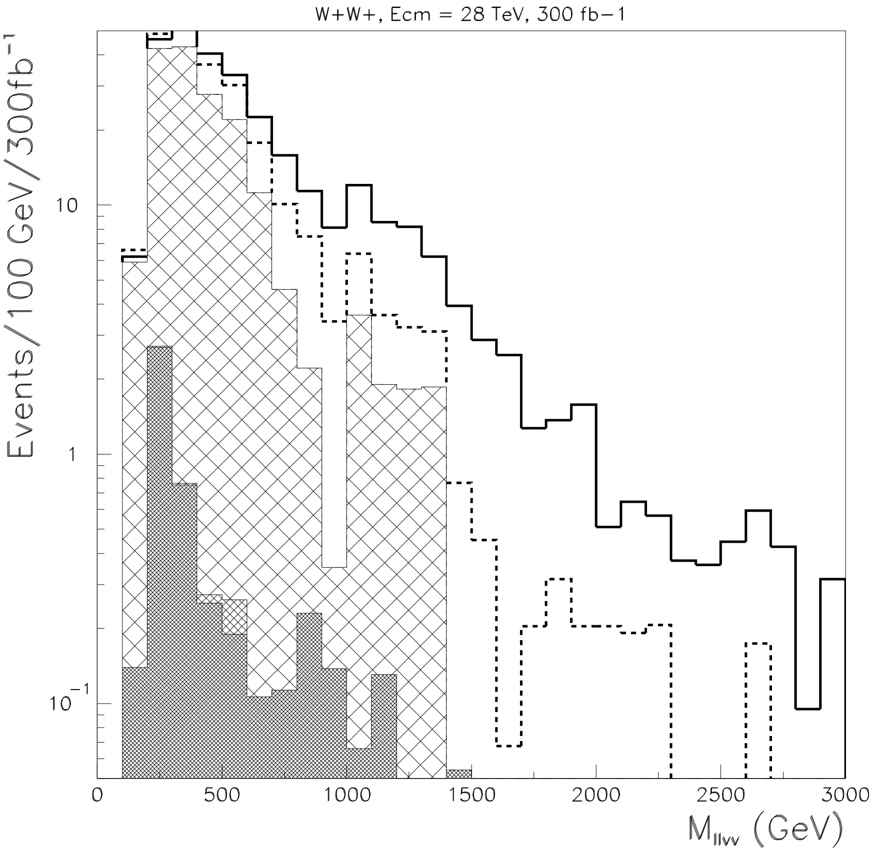
☞ K-matrix unitarization: replace partial wave amplitudes a_l^I by

$$t_l^I = \frac{a_l^I}{1 - i a_l^I}$$

- significance versus $\sqrt{s}$:



- signal and background have same shape
  → large statistics needed for a convincing signal (ATLAS)



☞ hatched: WW and WZ background

☞ solid: K-matrix unitarization

☞ dashed: 1 TeV SM Higgs boson

- LHC, at $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}:

  ☞ degradation of forward jet tag and central jet veto due to pile-up

  ☞ large ($\approx 50\%$) probability for fake jet tags even at momenta of a few hundred GeV

  → luminosities $\mathcal{L} > 10^{34}$ cm^{-2} s^{-1} do not help much

what if . . .

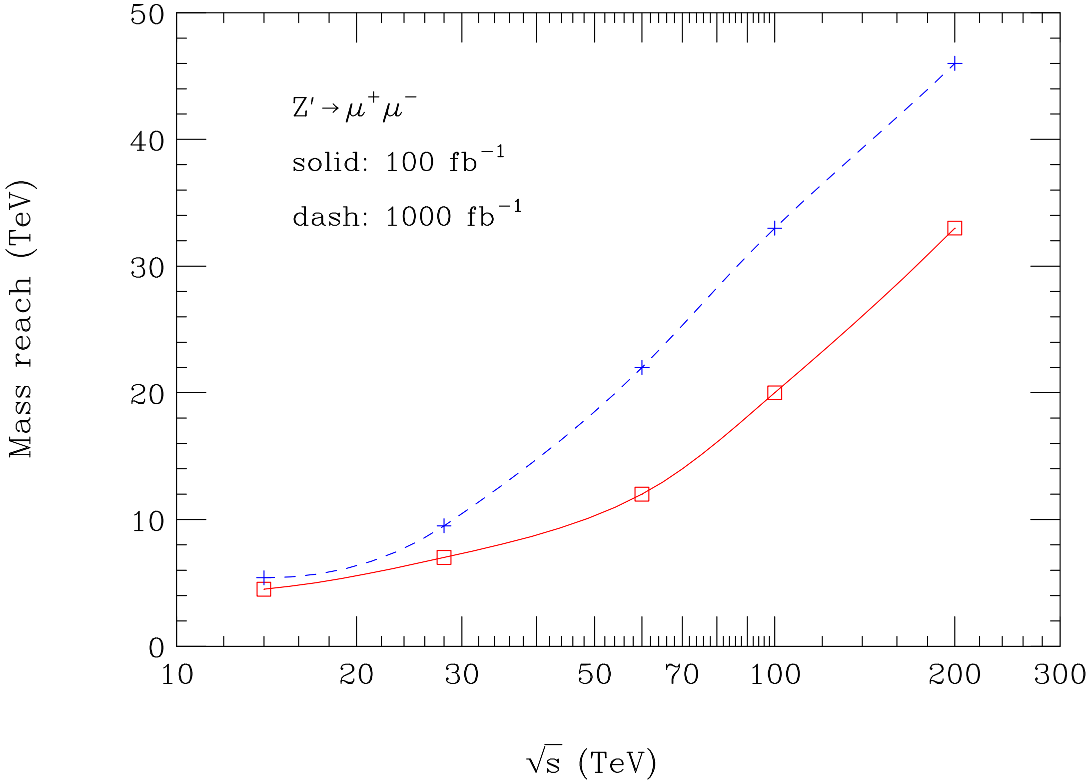
- LHC does not find a Higgs boson but observes hints for strong electroweak symmetry breaking

  → stage 1 of the VLHC should find convincing signal

  → fully explore strong dynamics at stage 2 of the VLHC

Extra gauge bosons

- additional gauge bosons, W' and Z', appear in many GUT models ($E_6, \ldots$)
- the reach depends on the W', Z' couplings to quarks and charged leptons
- concentrate on $Z' \to \mu^+\mu^-$ with SM couplings here (classic benchmark)



☞ similar reach for W''s

- can measure:
  - ☞ Z' mass at (energy or luminosity upgraded) LHC to $< 1\%$
  - ☞ Z' width to a few percent
  - ☞ couplings using other channels: $Z' \to jj$, $Z' \to W^+W^-$
- CLIC: from indirect measurements: sensitivity up to $M_{Z'} = 30$ TeV
- direct search at CLIC: only for $M_{Z'} < \sqrt{s}$
  - ☞ can measure Z' mass to $< 10^{-4}$
  - ☞ Z' width and peak cross section to better than 1%

Compositeness

- if quarks and/or leptons are composite with a scale Λ (scale of interactions which binds constituents):

  ☞ for $\sqrt{\hat{s}} \ll \Lambda$: contact interactions

  ☞ for $\sqrt{\hat{s}} \geq \Lambda$: production of excited quarks (q^*) and leptons (ℓ^*)

- contact interactions: example: 2-jet events

  ☞ expect excess of high E_T centrally produced jets

  ☞ maximum scale probed for 300 fb^{-1}:

$\sqrt{s}$ (TeV)	Λ (TeV)
14	40
28	60
40	~ 75
100	~ 115
200	~ 130

- excited quarks:

  ☞ produced via qg fusion in s-channel: $qg \to q^*$

  ☞ decays: $q^* \to qg,\ q\gamma,\ qW,\ qZ$

  ☞ effective Lagrangian for $q^* q\gamma$ coupling is of magnetic moment type

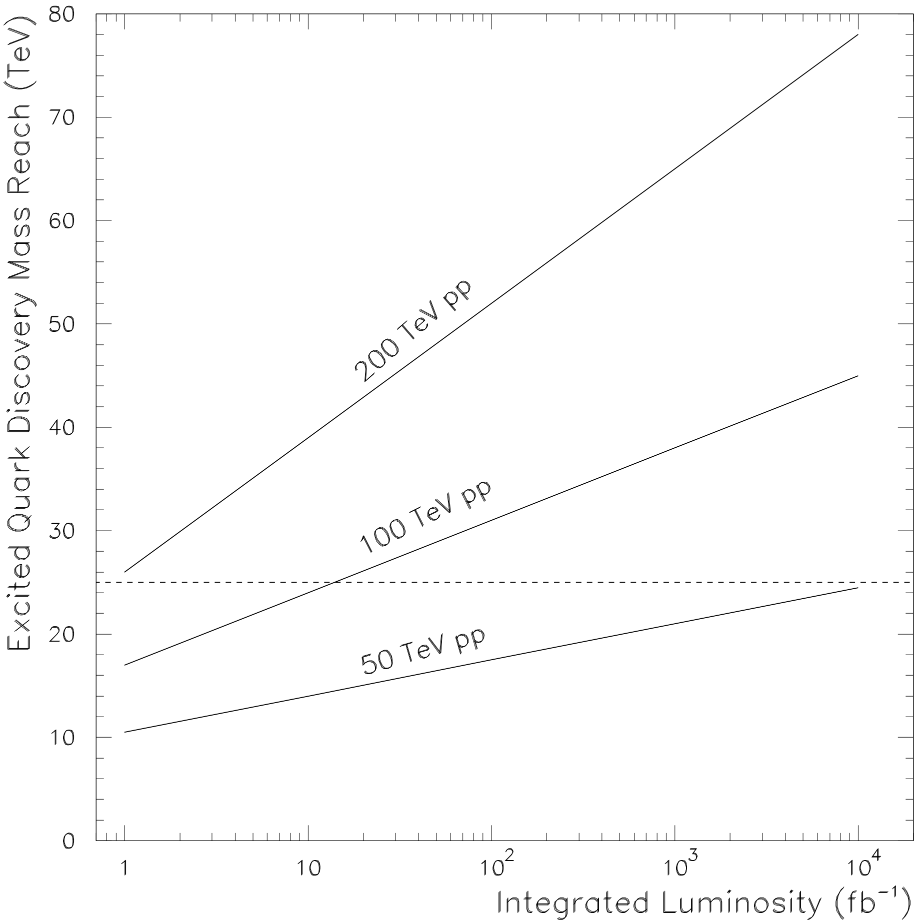
$$\mathcal{L} \sim \frac{f_s g}{\Lambda}\, q^* \sigma_{\mu\nu} F^{\mu\nu} q$$

- mass reach for $q^* \to jj$, $f_s = 1$, $M_{q^*} = \Lambda$:

  ☞ LHC, 100 fb^{-1} (1000 fb^{-1}): 7 TeV (8 TeV)

  ☞ $\sqrt{s} = 28$ TeV, 100 fb^{-1} (1000 fb^{-1}): 10 TeV (11 TeV)

☞ VLHC: 5σ reach for $f_s = 1$, $M_{q^*} = \Lambda$:



☞ for $f_s = 0.1$ the reach is about a factor 2 smaller

what if . . .

- the LHC finds evidence for contact interactions?

→ $\Lambda < 60$ TeV

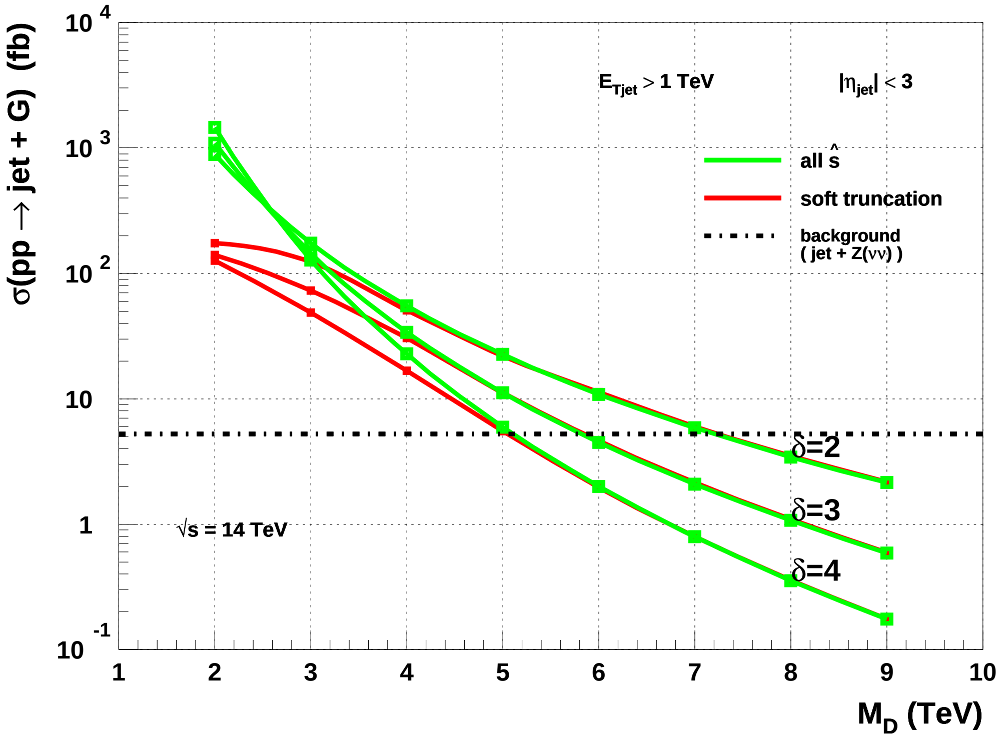
→ find excited quarks and/or leptons at the VLHC (stage 2)

Extra dimensions

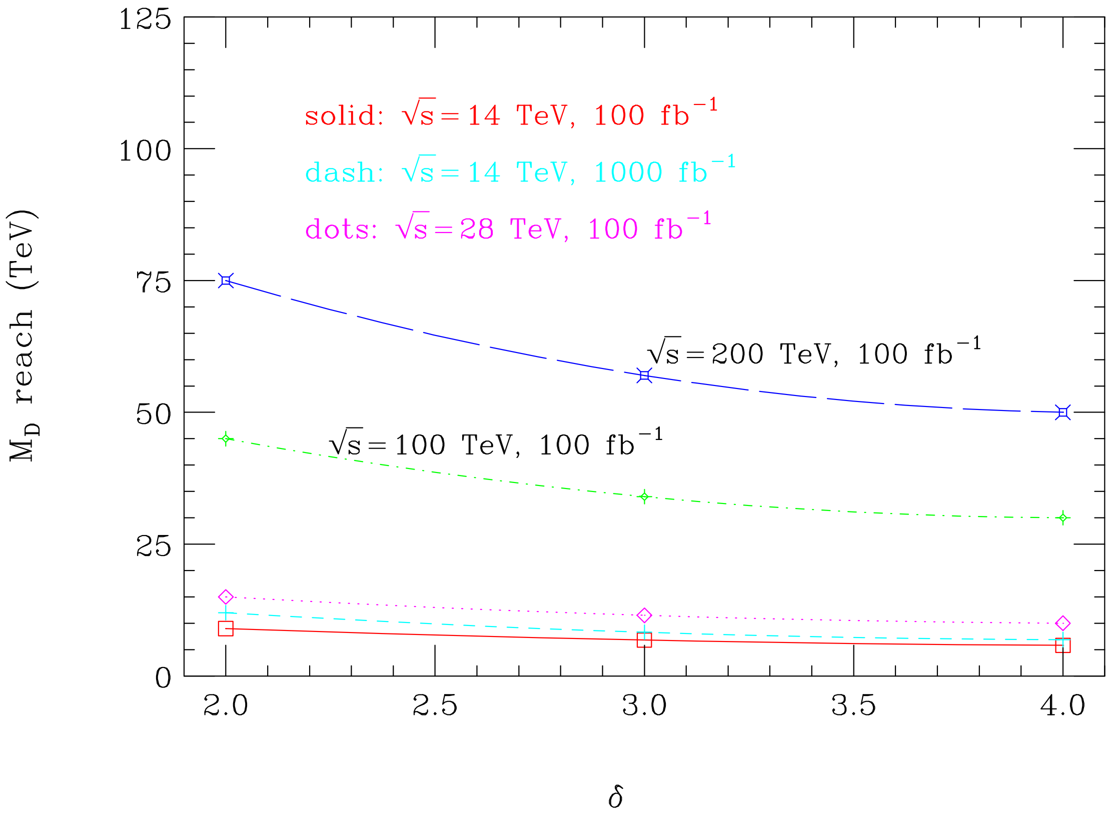
- Fields propagating in more than 4 dimensions lead to Kaluza-Klein (KK) excitations, modifications to cross section, or $\not\!\!E_T$ signatures
- example: $jet{+}graviton$ production in ADD model; graviton manifests as $\not\!\!E_T$

☞ cross section depends on M_D, the scale of gravity and δ, the number of extra dimensions ($\delta = 1$ ruled out by celestial mechanics)

☞ main background: $Z(\rightarrow \bar{\nu}\nu){+}jets$ (Hinchliffe)



- M_D reach of the (upgraded) LHC and VLHC:



- warped extra dimensions (RS models):

  ☞ SM gauge and fermion fields live on the TeV-brane

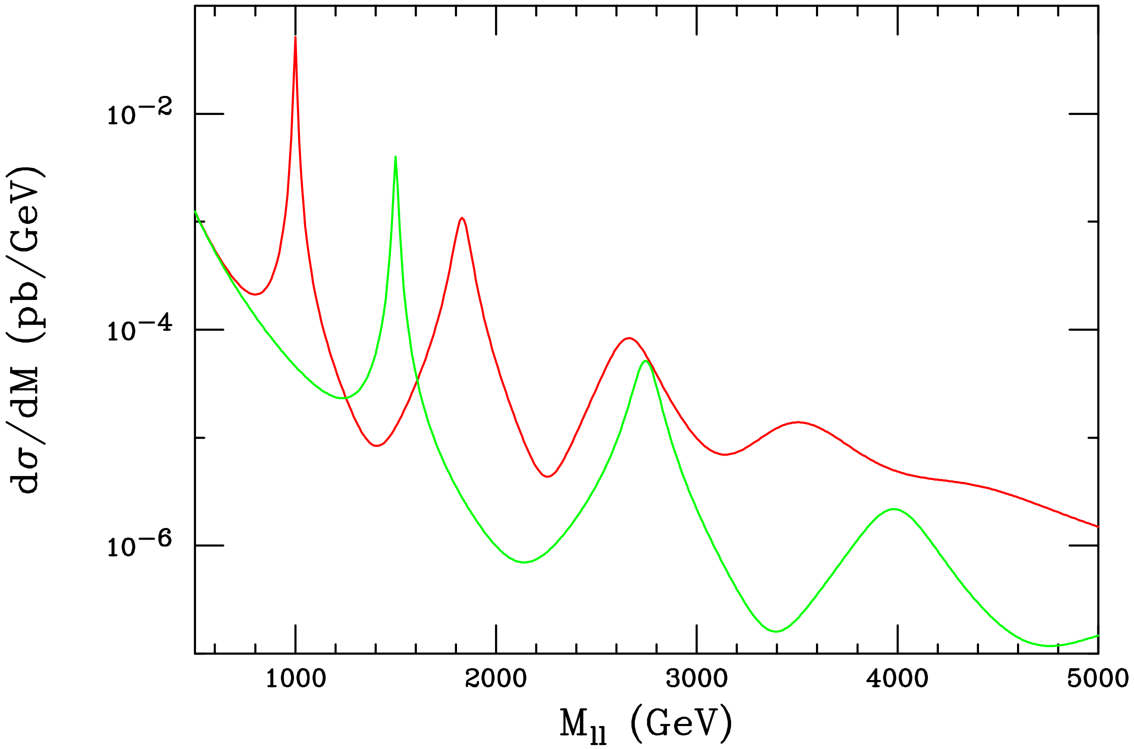
  ☞ or they may propagate in the bulk

- SM fields constrained to the TeV brane:

  ☞ colliders are KK resonance factories

  ☞ production of graviton KK excitations ($G^{(n)}$): $\bar{q}q,\ gg \to G^{(n)} \to \ell^+\ell^-$

- example: LHC (Davoudiasl et al.)



  ☞ red: $m_{G^{(1)}} = 1$ TeV, $k/\bar{M}_{Pl} = 0.1$

  ☞ green: $m_{G^{(1)}} = 1.5$ TeV, $k/\bar{M}_{Pl} = 0.2$

  → k: AdS_5 curvature scale

- the LHC with 100 fb^{-1} can determine the spin-2 nature of a KK graviton for $m_{G^{(1)}} \leq 4.2$ TeV

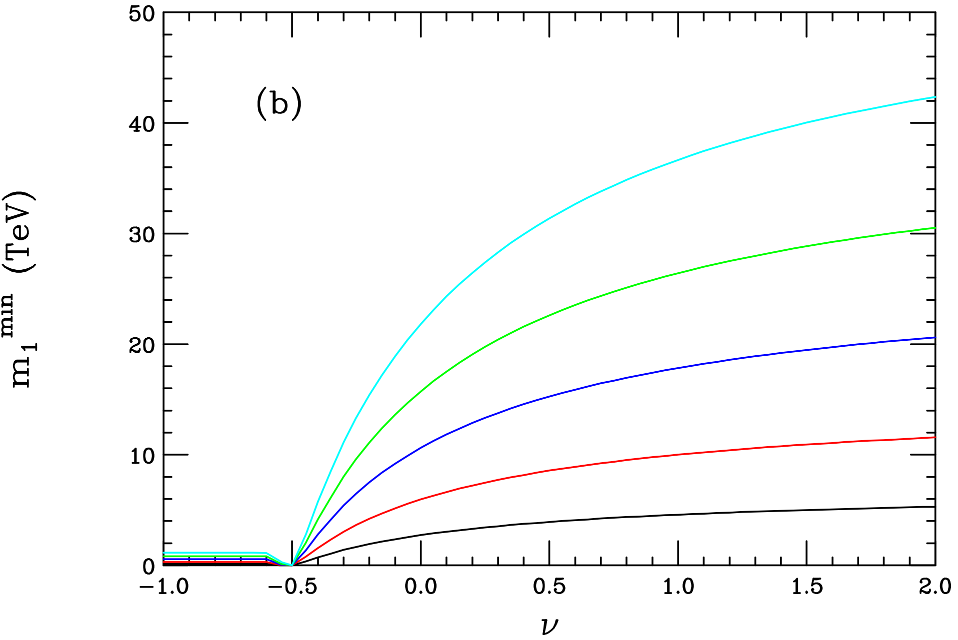
  → no VLHC studies yet (after Snowmass?)

  ☞ CLIC: sensitive to $G^{(1)}$ up to kinematic limit

- if no evidence for new particles at LHC or TESLA/NLC:

  ☞ search for indirect effects of KK excitations through contact like interactions

  ☞ example (SM fields propagating in the bulk) 95% CL, Drell-Yan production (Davoudiasl et al.):



  ☞ $m_1^{\rm min}$: mass of lightest KK excitation

  ☞ ν: bulk mass parameter; controls how far off the TeV-brane ($\nu \to \infty$) the wave function is located

  ☞ black: Tevatron, Run I, red: Tevatron, 2 fb^{-1}, blue: Tevatron, 30 fb^{-1}, green: LHC, 10 fb^{-1}, cyan: LHC, 100 fb^{-1}

  → no VLHC studies yet (after Snowmass?)

what if . . .

- the LHC finds evidence for extra-dimensions?
  - → the VLHC (stage 2) will directly probe M_D
  - → VLHC could find totally unexpected physics

VLHC Pocket Guide

channel particle	LHC 100 fb^{-1}	LHC 1 ab^{-1}	28 TeV 100 fb^{-1}	40 TeV 100 fb^{-1}	200 TeV 100 fb^{-1}
$\tilde{q}$, $\tilde{g}$	2	2.5	4	5.5	> 10
W' Z'	4.5	5.4	7	8.5	33
q^*	7	8	10	13	50
Λ comp.	33	50	60	75	130
M_D $(\delta = 2)$	9	12	15	20	75

- large uncertainties
- not exhaustive
- all masses in TeV

4 – Summary

- Upgrading the LHC luminosity by a factor 10 increases the reach by 20%
- Doubling the LHC energy to $\sqrt{s} = 28$ TeV increases the reach by up to a factor 2
- stage 1 of the VLHC only insignificantly increases the reach of a 28 TeV LHC

  → makes only sense if LHC is not significantly upgraded in energy
- At some point we will, inevitably, want to go to the 100 TeV region
- the VLHC is the only machine which can directly discover new physics in the multi 10 TeV region
- most of the what if . . . scenarios discussed suggest that we need the VLHC

  → we don't need to wait for LHC results to decide
- need a coordinated and coherent international plan for the VLHC which is part of a comprehensive and global HEP program