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CMS workshop on detectors and electronics for SLHC

Physics potential of a SLHC (10^{35} cm^{-2} s^{-1})

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Physics potential of the LHC at 10^{35} cm^{-2} s^{-1} (SLHC)

What improvements in the physics reach could we expect from operating the LHC at a luminosity of ~ 10^{35} cm^{-2} s^{-1} with an integrated luminosity ~ 1000 fb^{-1} per year at $\sqrt{s} \approx 14$ TeV i.e. retaining present LHC magnets/dipoles

This is a very partial review, topics addressed:

- some experimental requirements/desirability, expected performances (forward jet tagging, central jet vetoing)
- triple and quartic gauge boson couplings
- new SM/MSSM Higgs modes and improvements in MSSM Higgs reach
- Higgs self coupling - reachable?
- strongly interacting W,Z schemes
- SUSY/sparticle reach/ spectrum
- new gauge bosons
- extra dimension models

Nominal LHC and upgrades

Nominal LHC: 7 TeV,

- injection energy: 450 GeV, ~ 2800 bunches, spacing 7.5 m, bunch length 7.5 cm
- 1.1 *10^{11} protons per bunch, β^* at IP : 0.5 m $\Rightarrow$ 10^{34} cm^{-2} s^{-1} (lumi-lifetime 10h)

Upgrades/steps considered:

-increase up to 1.7 *10^{11} protons per bunch (beam-beam limit) $\Rightarrow$ 2*10^{34} cm^{-2} s^{-1}

- increase operating field from 8.3T to 9T (ultimate field) $\Rightarrow$ $\sqrt{s} \approx 15$ TeV

minor hardware changes to LHC insertions or injectors:

- modify insertion quadrupoles (larger aperture) for $\beta^* = 0.5 \rightarrow 0.25$ m
- increase crossing angle 300 μrad $\rightarrow$ 424 μrad
- halving bunch spacing (12.5nsec), with new RF system

$\Rightarrow L \approx 5 * 10^{34}$ cm^{-2} s^{-1}

major hardware changes in arcs or injectors:

- SPS equipped with superconducting magnets to inject at ≈ 1 TeV

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

- new superconducting dipoles at B ≈ 16 Tesla for beam energy ≈ 14 TeV i.e. $\sqrt{s} \approx 28$ TeV

Experimental conditions at 10^{35} cm^{-2} s^{-1}

~ 100 pile-up events per bunch crossing - if 12.5 nsec bunch spacing - compared to ~ 20 for operation at 10^{34}cm^{-2}s^{-1} and 25 nsec (LHC regime), $dn^{ch}/d\eta$/crossing ≈550 and ≈2500 tracks in tracker acceptance

⇒ reduced efficiency for selection of isolated objects (μ, e, γ, τ….)

⇒ degraded energy resolution due to pile-up for e, γ, jets, missing $E_{t,}$ effect decreases with E_t, negligible beyond ~ 50 (e,γ) - 100 (jets) GeV

⇒ reduced selectivity of missing E_t cuts (below ~ 100 GeV)

⇒ reduced efficiency and purity of forward jet tagging and central jet vetoing techniques to improve S/B

⇒ somewhat reduced muon acceptance,(to $|\eta| < \sim 2.0$) due to need for increased forward shielding

…….

Triggers

High thresholds for inclusive triggers: e/γ, μ, jets, E_t^{miss} etc and combined for high mass searches/reach, as dileptons, $\gamma\gamma$ /R-S Graviton, lepton-γ for TGC, lepton-jet/LQ, jets + E_t^{miss} /SUSY …..)

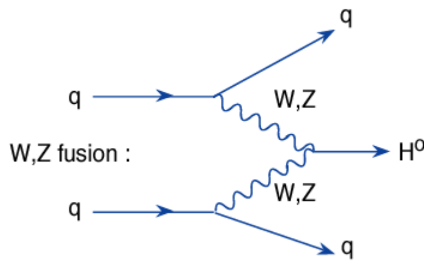
Prescaled lower p_t triggers - for control samples Z $\rightarrow l^+l^-$, $t\bar{t} \rightarrow$ 1or 2 leptons, QCD jets and direct photons etc.

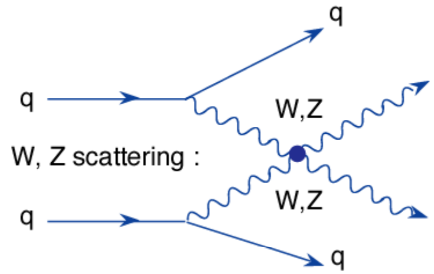
Menu of selective triggers for well defined final states:

$t\bar{t} \rightarrow$ 3 leptons, $\chi^0\chi^\pm \rightarrow$ 3 leptons, $\chi^0\chi^0 \rightarrow$ 4 leptons,
3 and 4 leptons for TGC and QGC
$\tau^\pm \rightarrow 3\mu^\pm$, $\mu^+\mu^-e^\pm$, $\mu^\pm e^+e^-$ etc, $\Upsilon \rightarrow \mu^+\mu^-$, $B^0_{d,s} \rightarrow \mu^+\mu^-$
slepton pairs $\rightarrow$ 2 leptons, A/H $\rightarrow \mu\mu$, A/H $\rightarrow \tau\tau \rightarrow e\mu$, A/H $\rightarrow \tau\tau \rightarrow$ lepton-jet,
A/H $\rightarrow \tau\tau \rightarrow$ jet-jet (possibly)
ttH(t $\rightarrow$ lept,H $\rightarrow \gamma\gamma$), W/ZH(W/Z $\rightarrow$ lept,H $\rightarrow \gamma\gamma$) channels limited by event rate at LHC, etc.

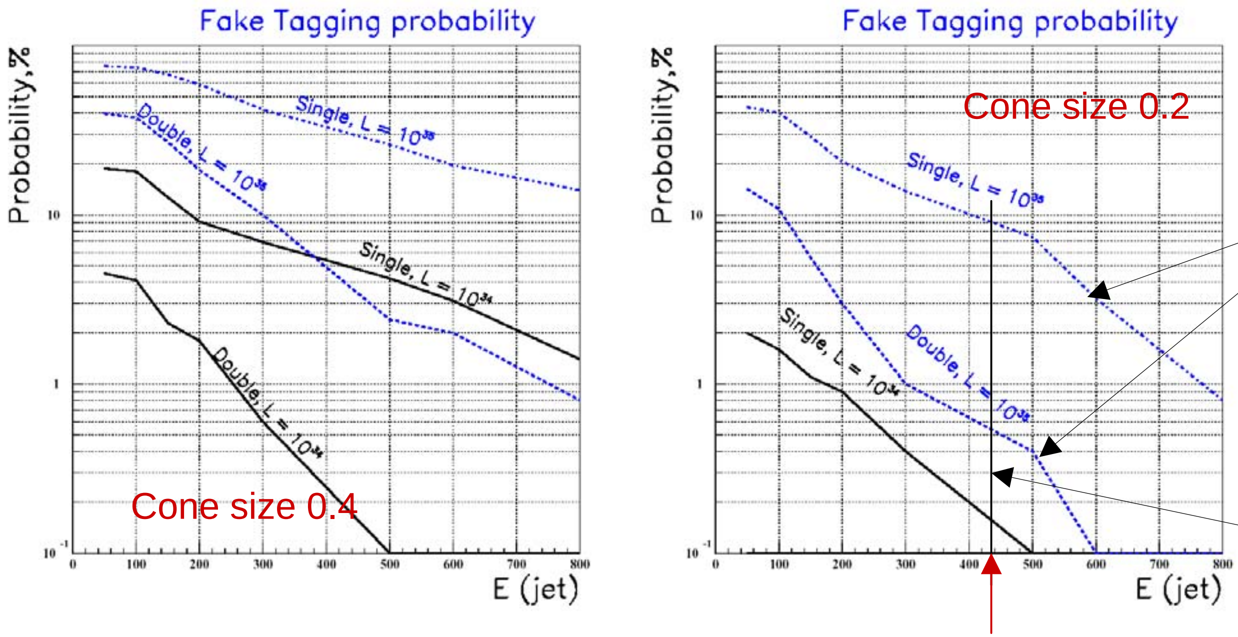
Forward jet tagging

Forward jet tagging needed to improve S/B in VB fusion/scattering processes pp $\rightarrow$ qqH, qqVV ....





Fake single and double forward jet tagging probabilities from pile up - crossings with only min bias interactions, at 10^{34} and 10^{35} cm^{-2} s^{-1}, jets at $|\eta| > 2$, two jet cone sizes:



SLHC regime

ATLAS full simulation - preliminary
with present ATLAS granularity

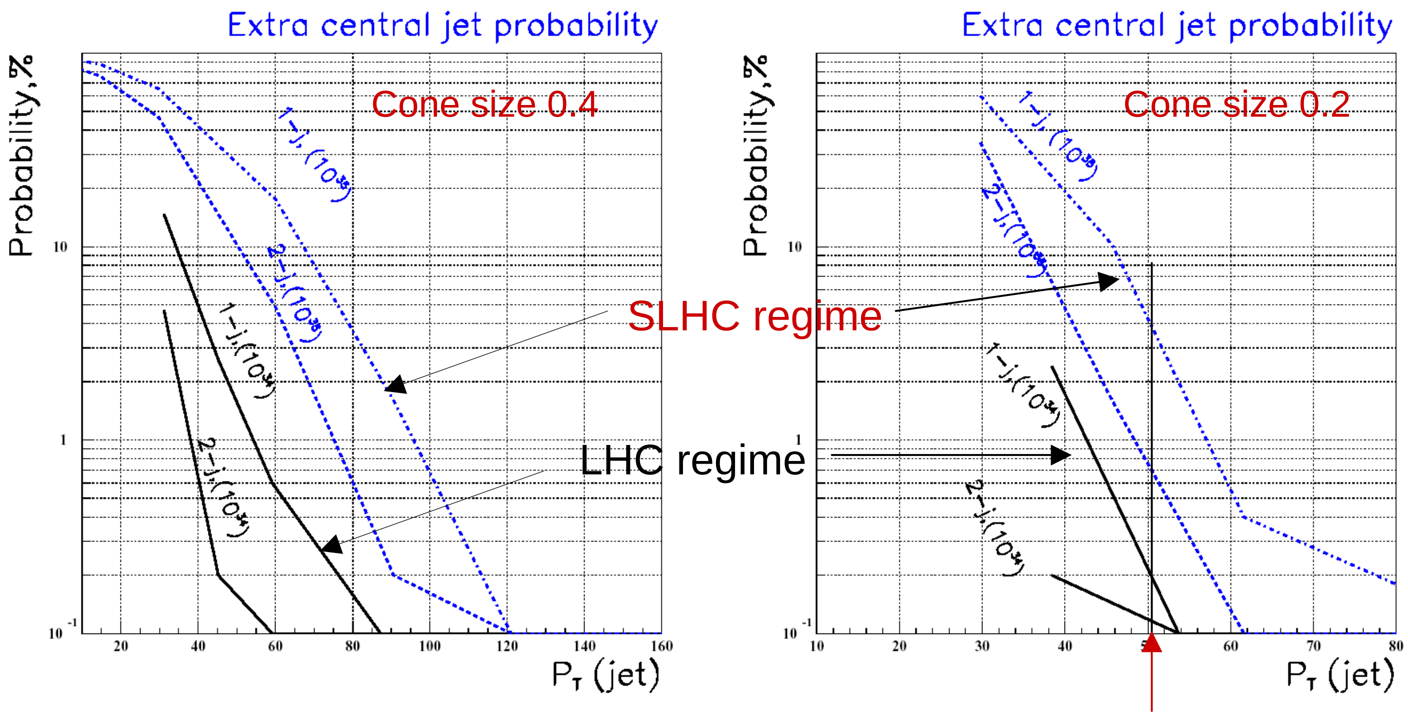
cut at > ~ 400 GeV

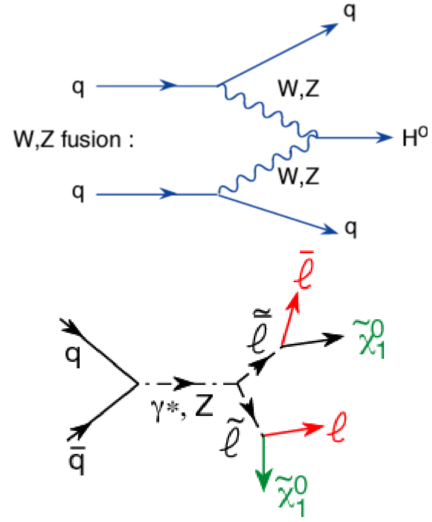
$\Rightarrow$ Method should still work at 10^{35}: increase forward calo granularity, reduce jet reconstruction cone, optimise jet algorithms to minimize energy pile-up (false jets)

Extra central jets from pile-up

"Central jet vetoing" is used to enhance ew production vs QCD type bkgds, ex. in pp $\rightarrow$ qqH, qqVV vs tt, in DY production of slepton pairs, chargino-neutralino pairs vs squark/gluino production etc, jets from event pile-up spoil the method

Probability of having 1 or 2 extra central jets ($|\eta| < 2$) from pile-up vs jet E_t for two cone sizes





ATLAS full simulation - preliminary jets at $|\eta| < 2$

$\Rightarrow$ Method should still work at 10^{35} provided jet threshold increased from ~ 30 GeV at LHC to ~ 50 GeV at SLHC - but loss of efficiency on signals

Some expectations for detector performances at 10^{35} cm^{-2} s^{-1}

- Electron identification and rejections against jets, E_t = 40 GeV, ATLAS full simulation

L (cm^{-2} s^{-1})	Electron efficiency	Jet rejection
10^{34}	81%	10600±2200
10^{35}	78%	6600±1130

- Electron resolution degradation due to pile-up, at 30 GeV: 2.5% (LHC) → 3.5% (SLHC)

- b-jet tagging performance: rejection against u-jets for a 50% b-tagging efficiency

p_T (GeV)	R_u at 10^{34} cm^{-2}s^{-1}	R_u at 10^{35} cm^{-2}s^{-1}
30-45	33	3.7
45-60	140	23
60-100	190	27
100-200	300	113
200-350	90	42

Preliminary study, ATLAS

⇒ performance degradation at 10^{35} factor of ~ 8 - 2 depending on E_t

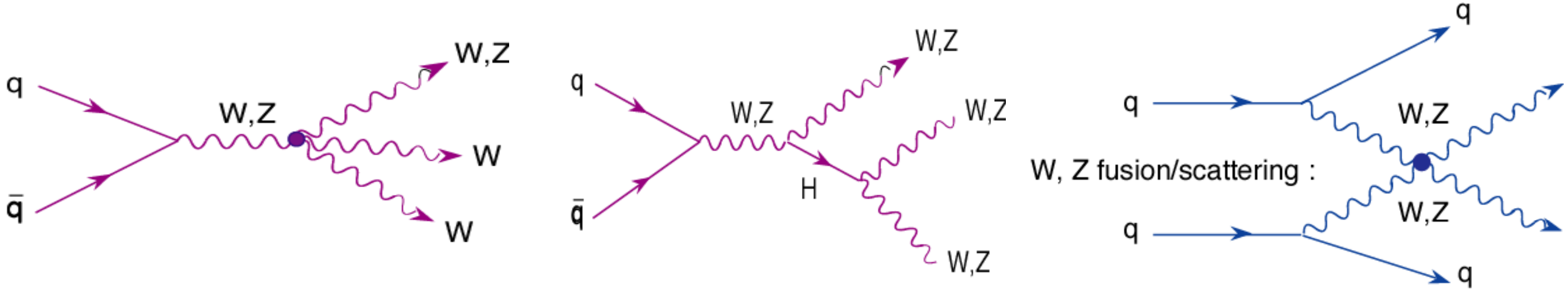
- Forward jet tagging and central jet vetoing still possible - albeit at reduced efficiencies reducing the cone size to ≈ 0.2

probability of double forward tag is ~ 2% for E_{jet} > 300 GeV (|η| > 2)

probability of 10% for additional central jet for E_t > 50 GeV (|η| < 2)

Multiple gauge boson production at SLHC

Test of high energy behaviour of weak interactions



+......

W,Z $\rightarrow$ leptons cleanest, but rate limited at LHC, obvious topic for SLHC!

Expected numbers of events in purely leptonic final states, 3 and 4 VB production, SLHC 6000 fb^{-1}

lepton cuts: $p_t > 20$ GeV, $|\eta| < 2.5$, assumed reconstruction efficiency 90%

(LO rates, CTEQ5M, k ~ 1.5 expected for these final states)						
Process	WWW	WWZ	ZZW	ZZZ	$WWWW$	$WWWZ$
N(m_H = 120 GeV)	2600	1100	36	7	5	0.8
N(m_H = 200GeV)	7100	2000	130	33	20	1.6

On-shell decays

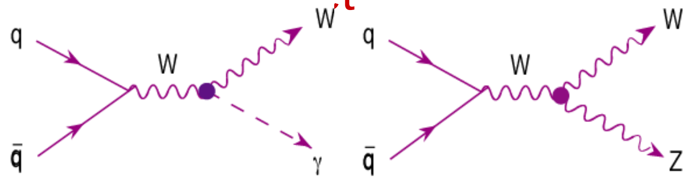
$\Rightarrow$ WZZ $\rightarrow$ 5 leptons, ZZZ $\rightarrow$ 6 leptons accessible at SLHC (not at LHC)

WWWW $\rightarrow$ 4 leptons could allow to put limits on 5-ple coupling (zero in SM)

ew physics, triple gauge boson couplings (I)

In the SM TGC uniquely fixed, extensions to SM (for ex. non-elementary VBs) induce deviations (form factors are introduced, Λ = scale new physics)

At LHC the best channels are: $W\gamma \rightarrow l\nu\gamma$ and $WZ \rightarrow l\nu ll$ (need central jet veto)



5 parameters are introduced to describe TGCs:

g_1^Z (1 in SM), $\Delta\kappa_Z$, $\Delta\kappa_\gamma$, λ_γ, λ_Z (all 0 in SM)

$W\gamma$ final state probes $\Delta\kappa_\gamma$, λ_γ and WZ probes g_1^Z, $\Delta\kappa_Z$, λ_Z

Sensitivity to λ-couplings in events rates/σ_{tot}, to κ-couplings in angular distributions

Expected sensitivity to TGC, 95% CL constraints, ATLAS

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g^Z_1	0.0038	0.0024	0.0023	0.0007	0.0050

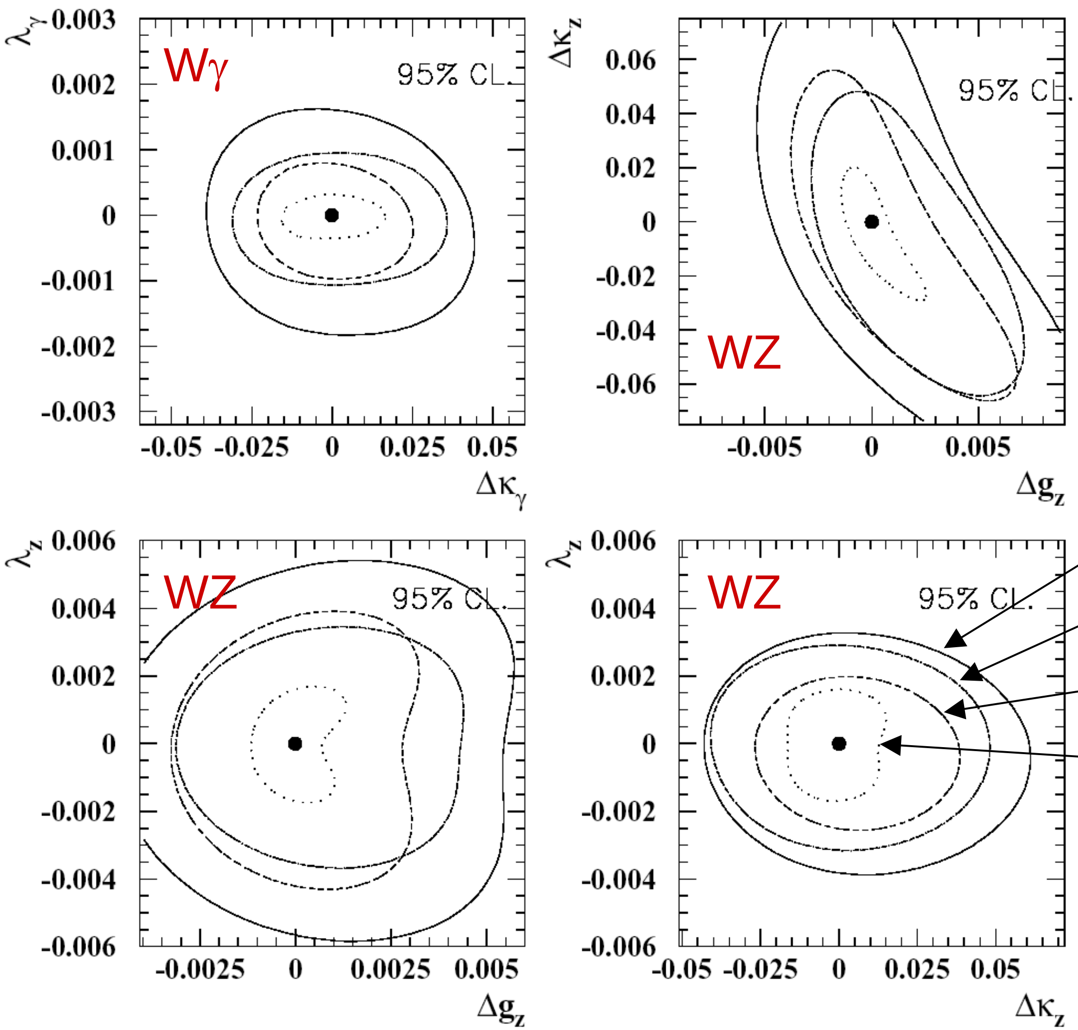
Only one coupling at a time varied relative to SM value (Λ = 10 TeV) μ,γ only, no electrons

LHC SLHC

$\Rightarrow$ SLHC can bring sensitivity to λ_γ, λ_Z and g_1^Z to the ~ 0.001 level (of SM rad.corrections)

ew physics, triple gauge boson couplings (II)

Correlations among parameters



TGCs: a case where a luminosity increase by a factor ~10 is better than a cm energy increase by a factor ~ 2 (jet vetoing needed….)

95 % CL on TGC

14 TeV, 100 fb^{-1} -solid

28 TeV, 100 fb^{-1} -dot-dashed

14 TeV, 1000 fb^{-1} -dashed

28 TeV, 1000 fb^{-1} -dotted

Higgs physics - generalities

Increased statistics would allow to look for modes not observable at the LHC for example:

$H_{SM} \to Z\gamma$ (BR ~ 10^{-3}), $H_{SM} \to \mu^+\mu^-$ (BR ~ 10^{-4}) - the muon collider mode!

$H^{\pm} \to \mu\nu$

. . . . β.

in channels like:

A/H $\to \mu\mu$, A/H $\to \tau\tau \to \mu$, A/H $\to \tau\tau \to$ /$\mu + \tau-$

A/H $\to \chi^0\ \chi^0 \to 4$ /μ

Specific examples:

$H_{SM} \to Z\gamma \to l^+l^-\gamma$ 120 < M_H < 150 GeV, LHC with 600 fb^{-1} signal significance: 3.5σ

SLHC with 6000 fb^{-1} signal of 11σ

$H_{SM} \to \mu^+\mu^-$ 120 < M_H < 140 GeV, LHC (600 fb^{-1}) significance: < 3.5σ, at SLHC > 5σ

m_H (GeV)	$S/\sqrt{B}$	$\frac{\delta\sigma\times BR(H\to\mu\mu)}{\sigma\times BR}$
120 GeV	7.9	0.13
130 GeV	7.1	0.14
140 GeV	5.1	0.20
150 GeV	2.8	0.36

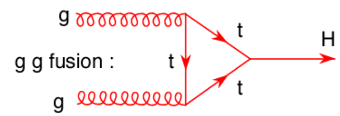
Expected signal significance,

two experiments, each with 3000 fb^{-1}

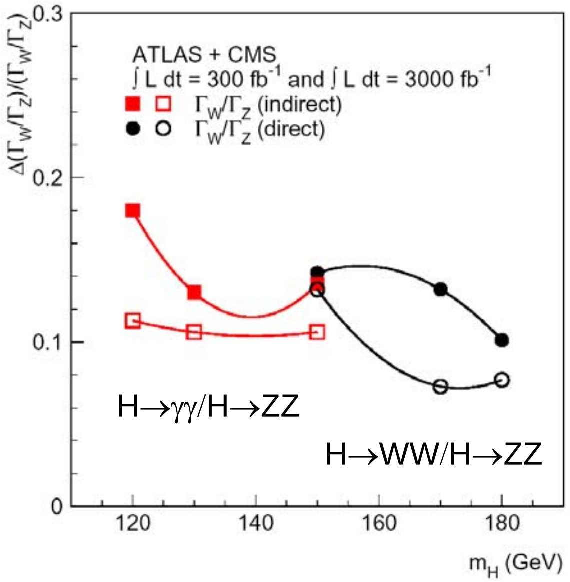
Higgs physics - SM Higgs couplings

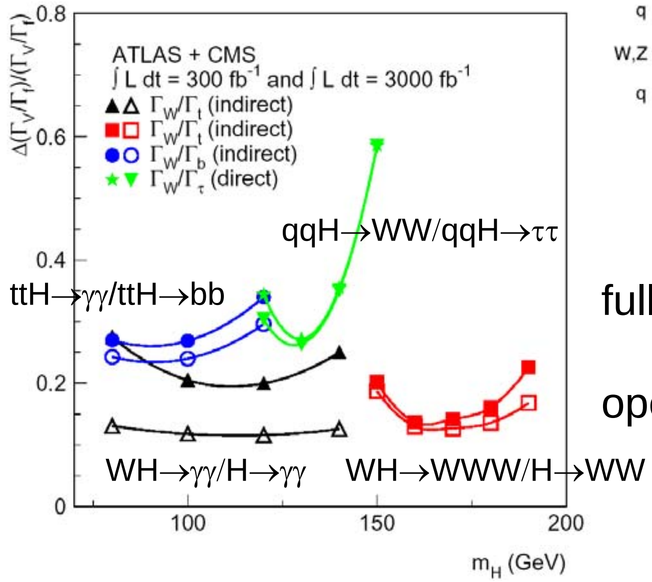
Combining different production mechanisms and decay modes get ratios of Higgs couplings to bosons and fermions - this is independent of σ_{tot}^{Higgs}, Γ_H and integrated luminosity L_{int}, it is mostly statistics limited at LHC

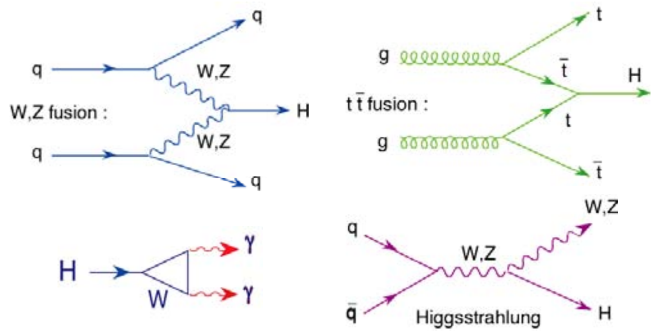
$\Rightarrow$ should benefit from LHC $\rightarrow$ SLHC luminosity increase, provided detector performances are not significantly reduced



Uncertainties on the ratios of Higgs partial rates to bosons and fermions, LHC and SLHC expectations







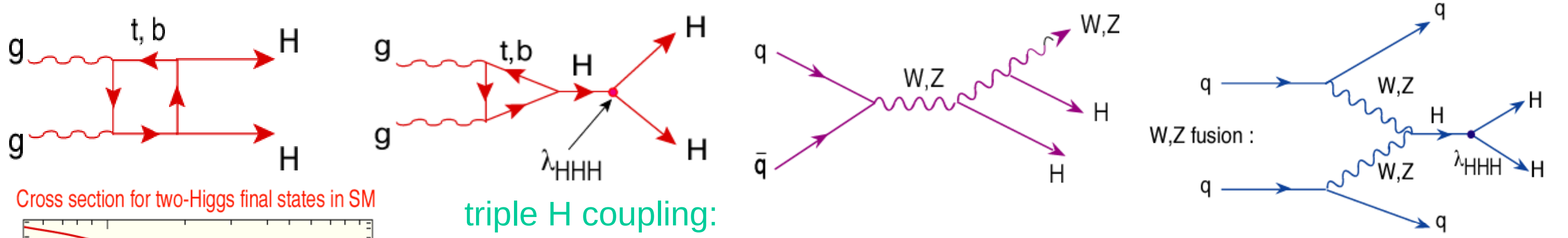
full symbols:
LHC, 300 fb^{-1} per experiment
open symbols:
SLHC, 3000 fb^{-1} per experiment

At the SLHC the ratios of Higgs couplings should be measurable with a ~ 10% precision

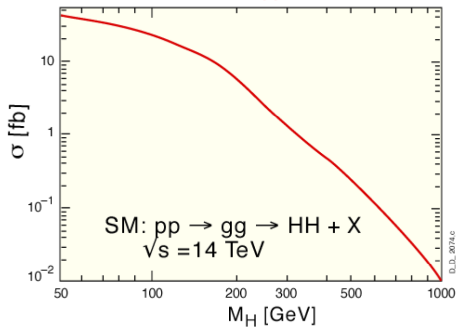
Higgs pair production and self coupling (I)

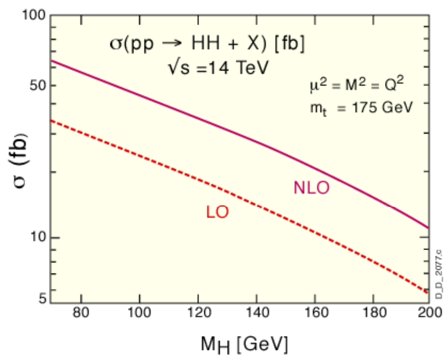
Higgs pair production can proceed through two Higgs bosons radiated independently (from VB, top) and from trilinear self-coupling terms proportional to λ_{HHH}^{SM}

In pp collisions we have: gg → HH, qq → qqVV → qqHH ,qq →VHH, gg,qq → ttHH etc



Cross section for two-Higgs final states in SM



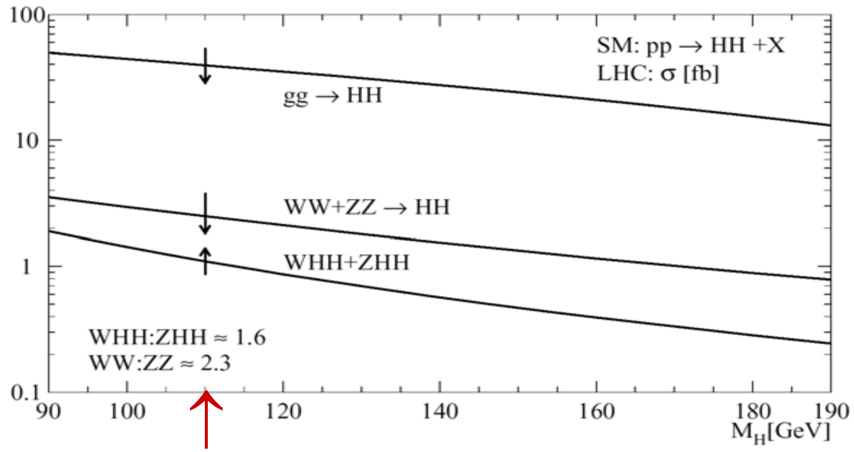


triple H coupling:
$\lambda_{HHH}^{SM} = 3m_H^2/v$
there is also a quartic H coupling λ_{HHHH}^{SM}

→very small cross sections, hopeless at LHC (10^{34}), some hope at SLHC

→ very significant NLO corrections

cross sections for Higgs boson pair production in various production mechanisms and sensitivity to λ_{HHH} variations



arrows correspond to variations of λ_{HHH} from 1/2 to 3/2 of its SM value

Higgs self couplings (II)

ATLAS made a preliminary study for SLHC (10^{35} cm^{-2} s^{-1}) indicating that a first measurement of λ_{HHH} is possible - provided detector performances are comparable to the expectations for LHC detectors - for a Higgs in the $170 < m_H < 200$ GeV range

Channel considered: $gg \rightarrow HH \rightarrow W^+ W^- W^+ W^- \rightarrow l^{\pm}\nu jj\ l^{\pm}\nu jj$ with same-sign dileptons

Backgrounds considered: $t\bar{t}$ + jets, WZ+ jets, $t\bar{t}$ W, WWWjj, $t\bar{t}$ $t\bar{t}$

lepton cuts: $p_t > 20$ GeV, $|\eta| < 2.4$
jet cuts: ≥ 4 jets with $E_t > 20$ GeV, of which two with $E_t > 30$ GeV, $|\eta| < 2.4$
veto b-tagged events
veto events with more than 6 jets with $E_t > 30$ GeV

expected number of signal and background events for 6000 fb^{-1}

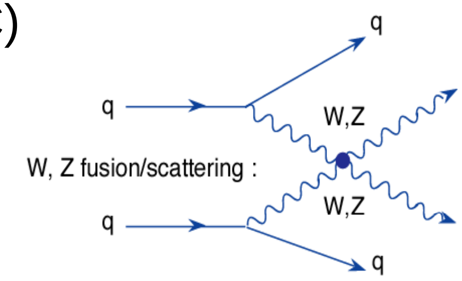
m_H	signal	$t\bar{t}$	$W^{\pm}Z$	$W^{\pm}\ W^{+}\ W^{-}$	$t\bar{t}W^{\pm}$	$t\bar{t}\ t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8

$\Rightarrow$ total cross section and λ_{HHH} determined with ~ 25% statistical error
this is a counting experiment, thus requires very good knowledge of backgrounds

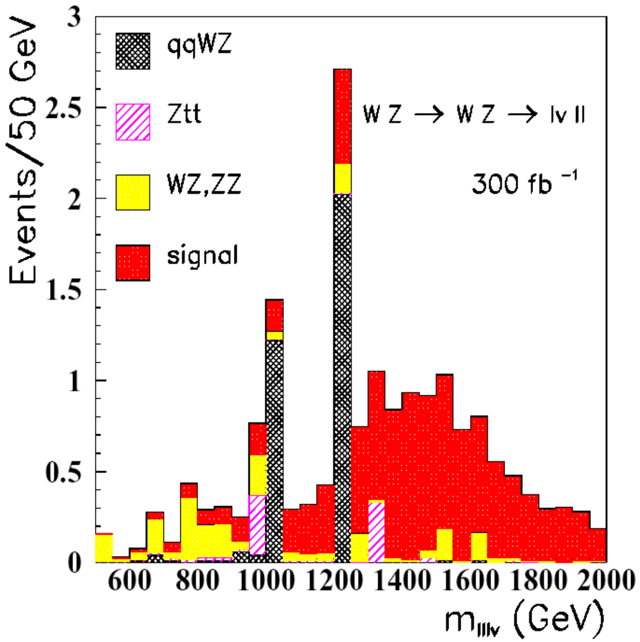
WZ vector resonance in VB scattering

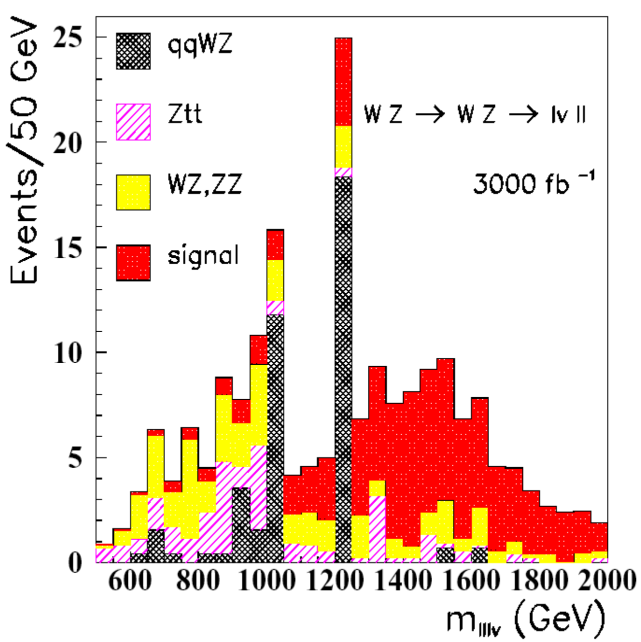
If no (light) Higgs, anomalies should appear in VB scattering, possible onset of a new strong interaction regime in $V_L V_L$ scattering;
example:

Vector resonance (ρ-like) in $W_L Z_L$ scattering from Chiral Lagrangian model
M = 1.5 TeV, leptonic final states, 300 fb^{-1} (LHC) vs 3000 fb^{-1} (SLHC)



lepton cuts: p_{t1} > 150 GeV, p_{t2} > 100 GeV, p_{t3} > 50 GeV; E_t^{miss} > 75 GeV





These studies require both forward jet tagging and central jet vetoing!

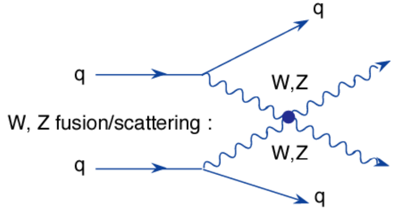
Note event numbers!

at LHC: S = 6.6 events, B = 2.2 events

at SLHC: $S/\sqrt{B} \sim 10$

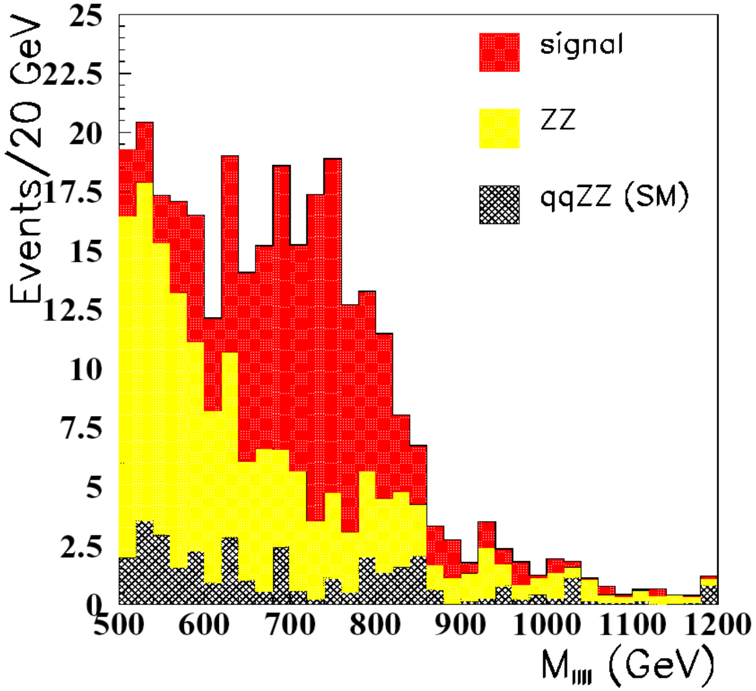
Scalar resonance in VB scattering

Scalar resonance in $W_L W_L$, $Z_L Z_L \rightarrow Z_L Z_L$ scattering from Chiral Lagrangian model
M = 0.75 TeV, 4-lepton final states, 3000 fb^{-1} (SLHC)



SM backgrounds: $qq \rightarrow qqZZ$, $qq \rightarrow ZZ$, $gg \rightarrow ZZ$

leptons: 4 leptons p_t > 30 GeV, two Z-compatible masses; 2 tagging jets with E_t > 400 GeV



3000 fb^{-1} (SLHC)

SLHC: improved reach for heavy MSSM Higgs bosons (I)

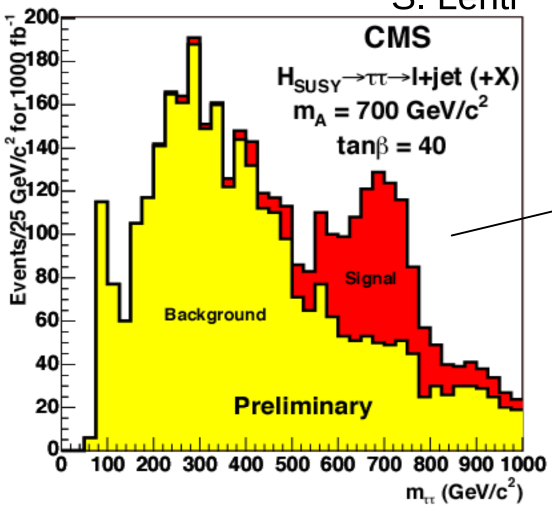
The order of magnitude increase in statistics with the SLHC should allow to extend the discovery domain for massive MSSM Higgs bosons A,H,$H^{\pm}$

Example: A/H $\rightarrow \tau\tau \rightarrow$ lepton + τ-jet, produced in bbA/H; fast simulation, preliminary

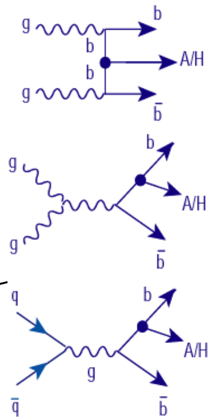
p_t(lept) > 30 GeV, E_t(τ-jet) > 100 GeV
E_t(b-jet) > 50 GeV, CMS b-tagging performance
no additional jets with E_t > 50 GeV,

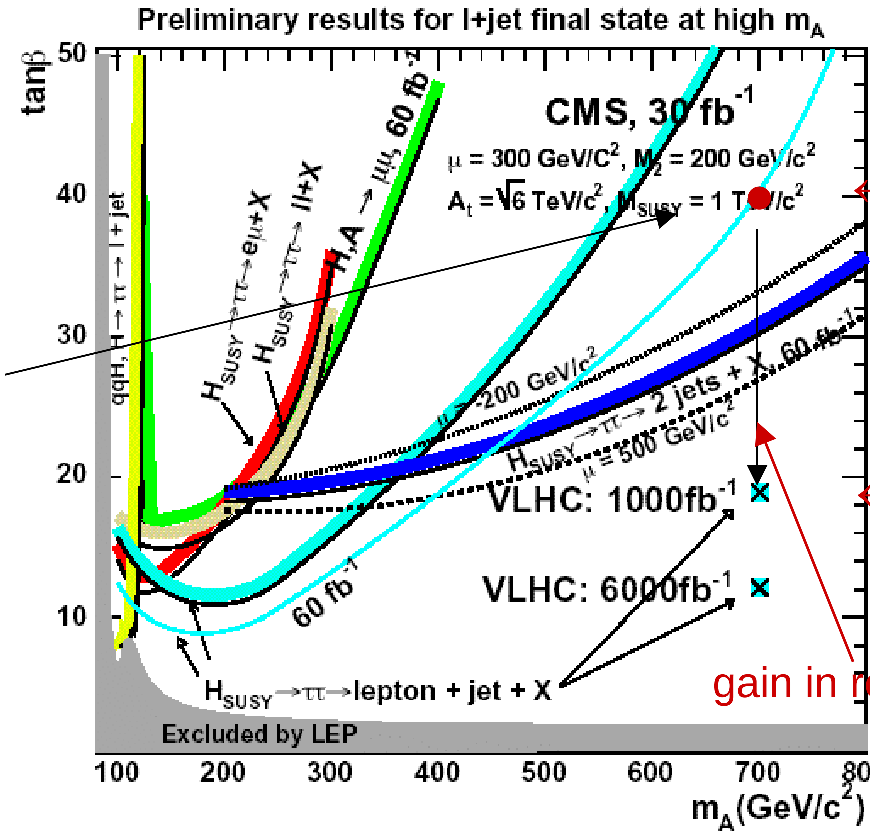
no missing E_t cut

S. Lehti



← SLHC
1000 fb^{-1}



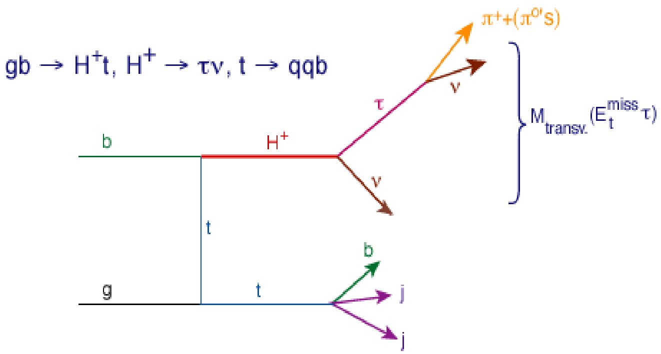


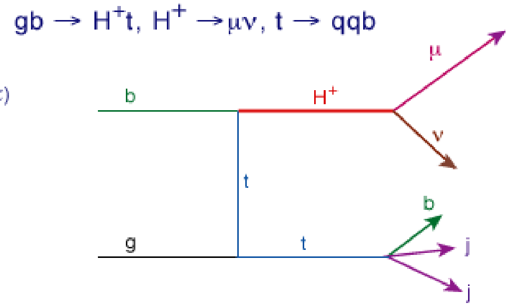
←LHC
60 fb^{-1}

←SLHC
1000 fb^{-1}

$H^{\pm} \to \mu\nu$

Some remarks on $H^{\pm}$





← under study

not observable at LHC with 300 fb^{-1} (m_A = 200 GeV, tgβ = 50, signal ~ 20 events, bkgd ~ 20000 events in full transverse mass range)

Comparison of these two rates should give $g_{H\tau\nu}/g_{H\mu\nu} = m_\tau/m_\mu \Rightarrow$ . .f . $\propto m_{fermion}$

the main expected bkgds in $H^+ \to \mu\nu$ are from tt/Wtb → W → μν and tt/Wtb → W → τν → μνν but for SM-W BR(W → μν) = BR(W → τν) ⇒ large bkgd, but H mass known (from $H^+ \to \tau\nu$) and W- gen and magnitude in μν mode known from W → eν (where no H^+ contribution is expected)

Preliminary results (R. Kinnunen):

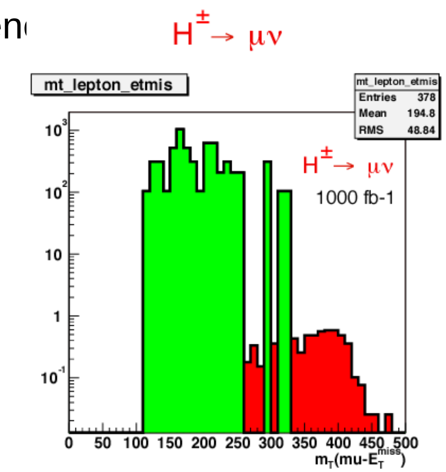
for $m(H^{\pm})$ = 400 GeV, tgβ = 40, 1000 fb^{-1}

$\sigma(H^{\pm})$ = 219 fb (T. Plehn), BR = 0.00049, σ*BR = 0.073fb (including t → W → hadrons)

for p_t^{μ} > 100 GeV, E_t^{miss} > 150 GeV, muon isolation, W mass,

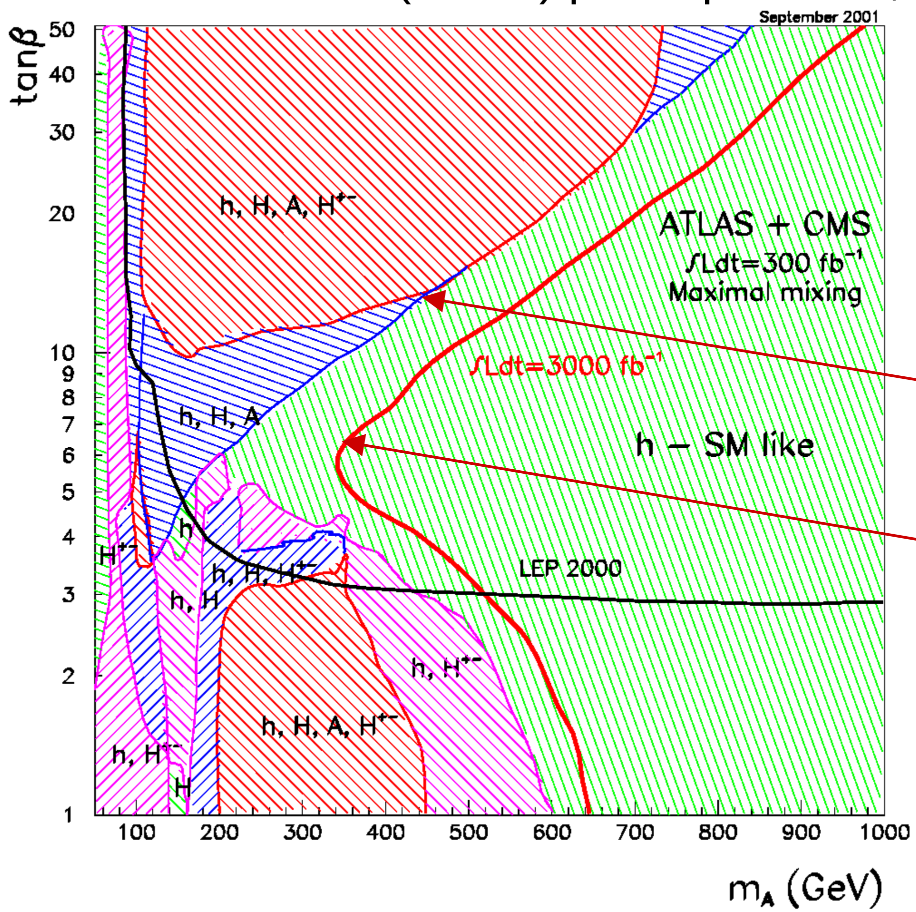
one b-jet tag, veto on 4th central jet:

⇒ 5 events left, no bkgd from tt and W+jets - hopeful! (more studies of bkgd needed)



SLHC: improved reach for MSSM Higgs bosons (II)

MSSM parameter space regions for > 5σ discovery for the various Higgs bosons, 300 fb^{-1} (LHC), and expected improvement - at least two discoverable Higgs bosons - with 3000 fb^{-1} (SLHC) per experiment, both experiments combined.



green area: region where only one (the h, SM-like) among the 5 MSSM Higgs bosons can be found (assuming only SM decay modes)

LHC contour, 300 fb^{-1}

SLHC contour, 3000 fb^{-1}

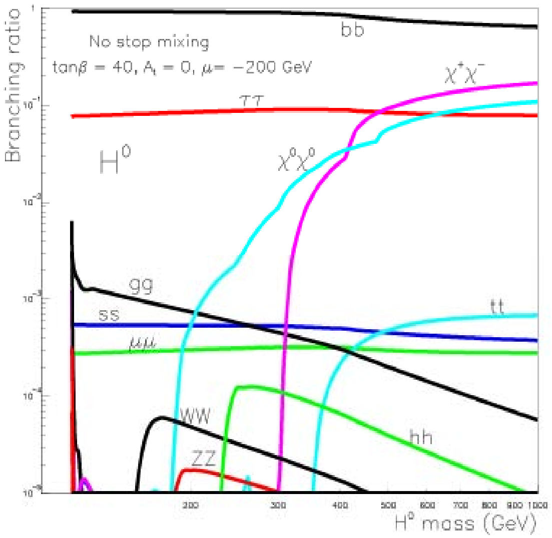
Improved reach for A/H decaying to neutralinos to 4 isolated leptons (III)

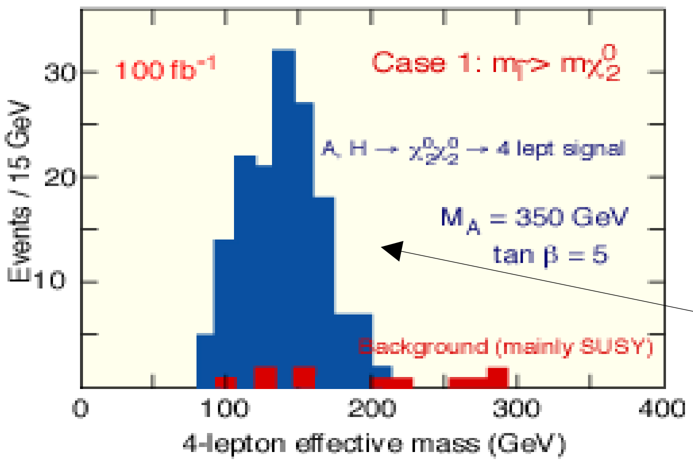
$A/H \rightarrow \chi^0_2 \chi^0_2 \rightarrow 4\ l^{\pm}_{isol}$ ⇒ trigger should be easy

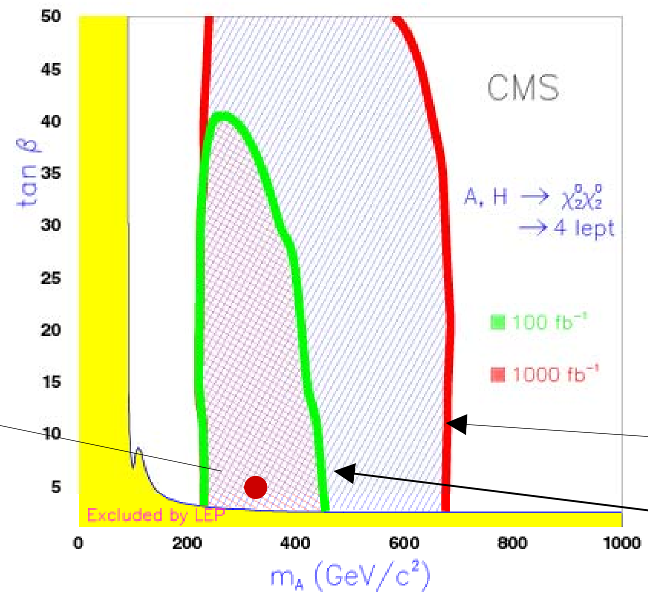
Signal: 4 isolated leptons (+ E_t^{miss}),
main bkgd: SUSY, reducible by jet multiplicity, E_t^{miss}, p_t^{lept} etc
cuts to be optimized in different parameter space regions

example:
MSSM parameters: M_2 = 120 GeV, M_1 = 60 GeV, μ = -500 GeV,
m(sleptons) = 250 GeV, m(squarks, gluinos) = 1 TeV

Branching ratios of $H^0 \rightarrow \tilde{\chi}^0\tilde{\chi}^0 / \tilde{\chi}^+\tilde{\chi}^-$







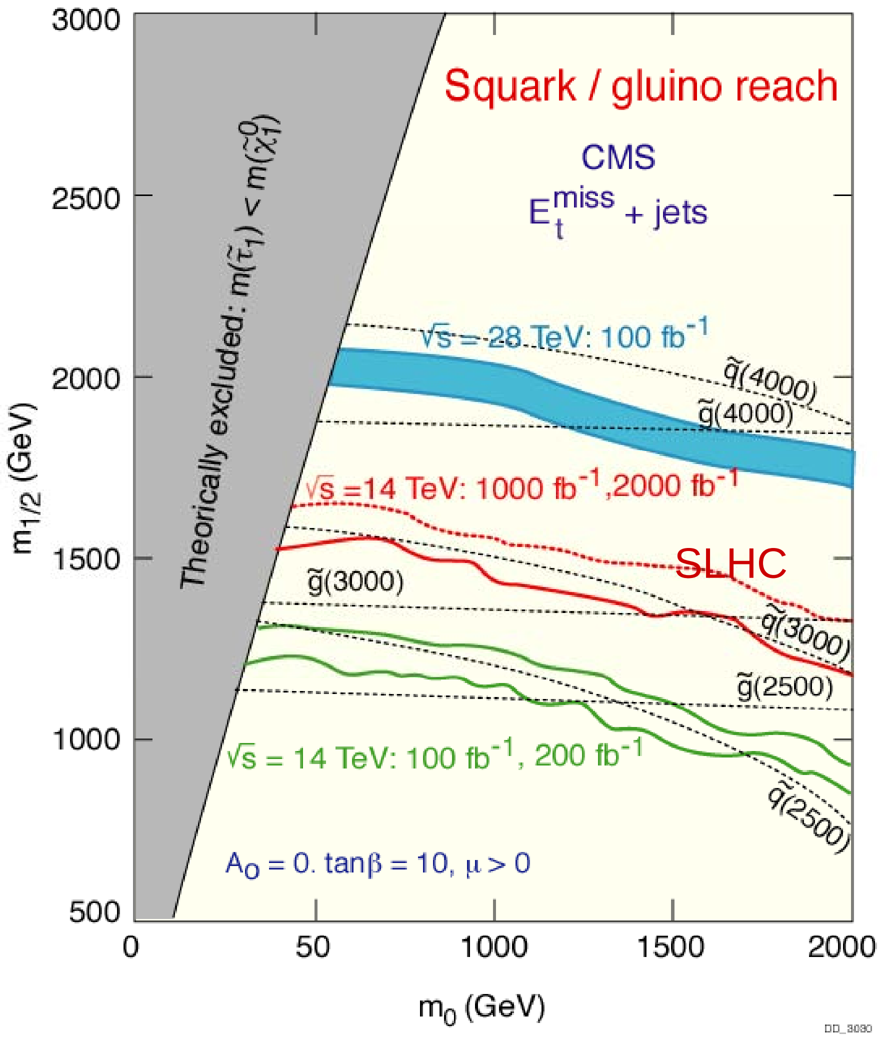
F. Moortgat

CMS, very preliminary
important as complements
param. space explorable
through SM decay modes!

SLHC, 1000 fb^{-1}

LHC, 100 fb^{-1}

SUSY at SLHC (I)



Notice advantage of a 28 TeV machine….

Higher integrated luminosity brings an obvious increase in mass reach in squark, gluino searches, i.e. in SUSY discovery potential; this is not too demanding on detectors as very high E_t jets, E_t^{miss} are involved, large pile-up not so detrimental

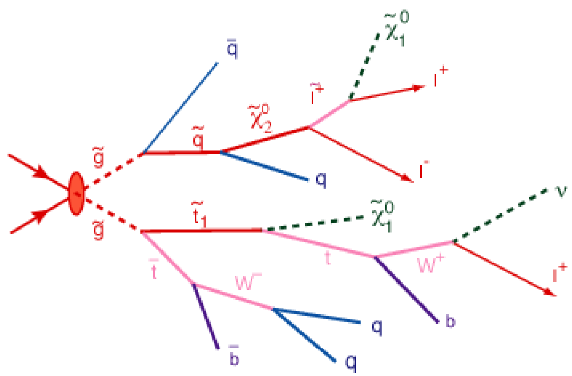
⇒ with SLHC the SUSY reach is increased by ~ 500 GeV, up to ~ 3 TeV in squark and gluino masses

but this is just "the reach", the main advantage of increased statistics should be in the sparticle spectrum reconstruction possibilities, larger fraction of spectrum, more precision, but this would require detectors of comparable performance to "present ones"

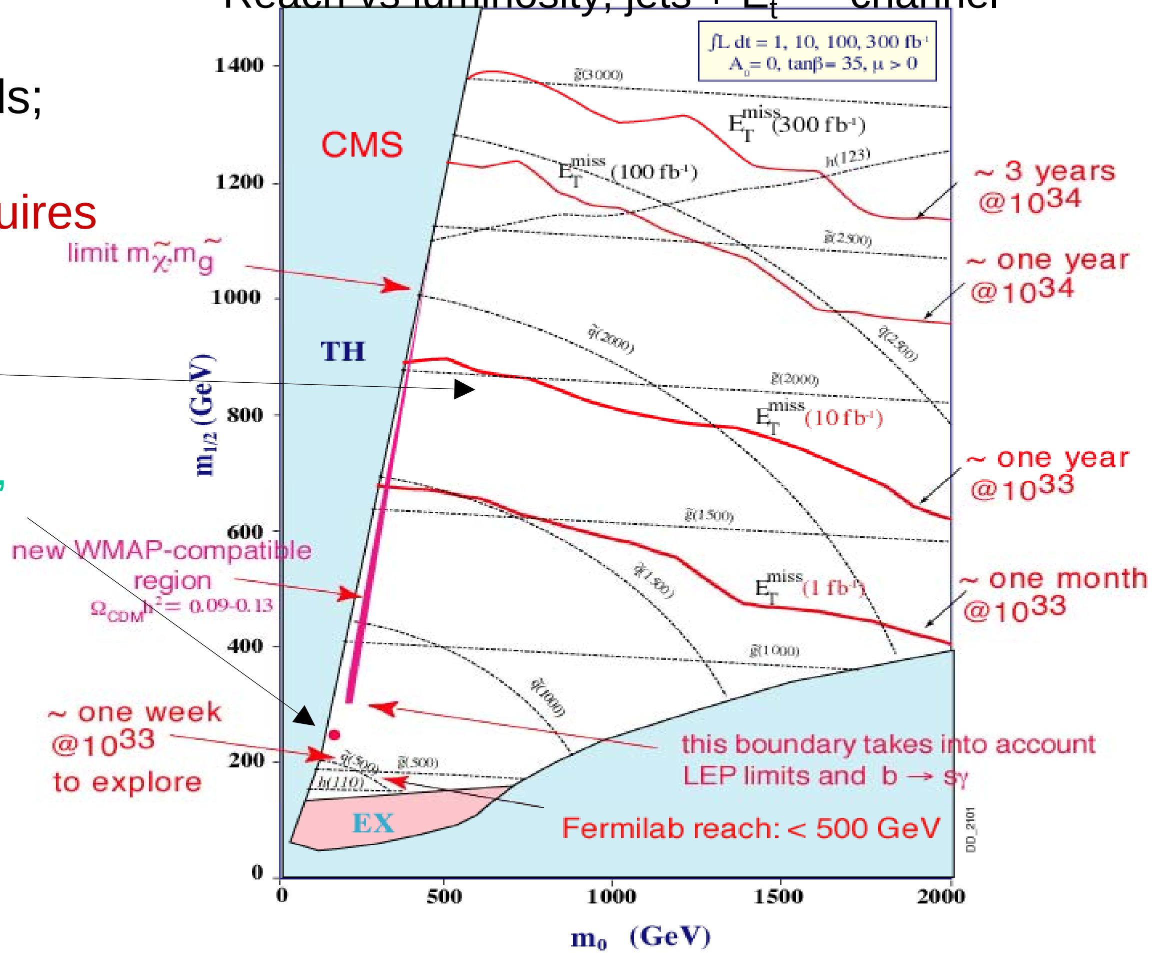
SUSY at SLHC (II)

“Reach” means a > 5σ excess of events over known (SM) and assumed controlled backgrounds; discovering SUSY is one thing, understanding what is seen requires much more statistics!

Compare for ex. 10 fb^{-1} reach and sparticle reconstruction stat limited at 10 fb^{-1} at “point B” (tgβ = 10), as many topologies required, leptons, b-tagging…



Reach vs luminosity, jets + E_t^{miss} channel

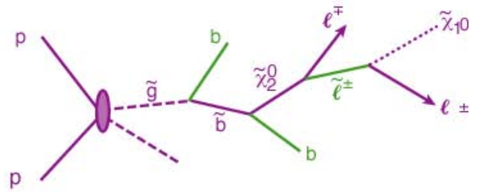


This is domain where SLHC statistics may be decisive!
but LHC-type detector performance needed

Sparticle reconstruction

SUSY point B ($m_{1/2}$ = 250 GeV, m_0 = 100 GeV, $\tan\beta$ = 10, $\mu > 0$)

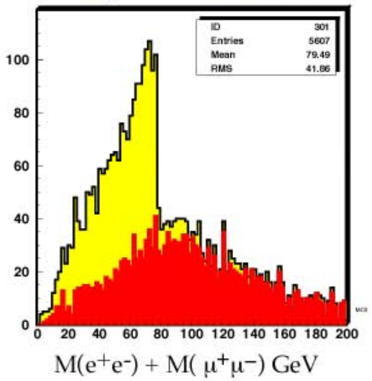
fast simulation+parametrized full b-tagging



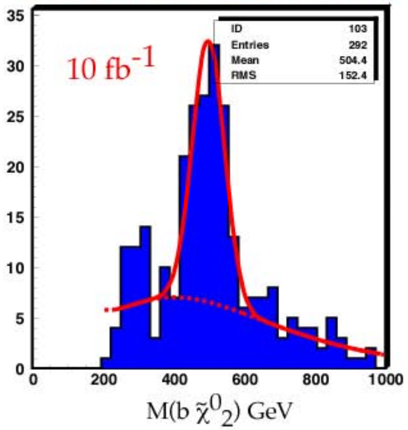
main cuts: $E_t^{miss} > 150$ GeV E(ll) > 100 GeV $E_{b\text{-}jet} > 250$ GeV, b-tagging

Dilepton edge

$E_t^{miss} > 100$ GeV



Sbottom reconstruction

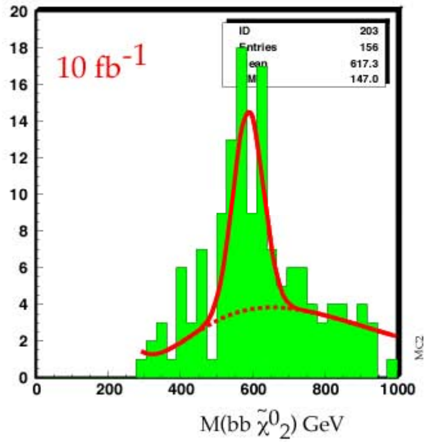


fit:

M(b $\tilde{\chi}^0_2$) GeV = 499 ± 7 GeV
σ = 48 GeV

generated: M($\tilde{b}_L$) = 496 GeV
M($\tilde{b}_R$) = 524 GeV

Gluino reconstruction



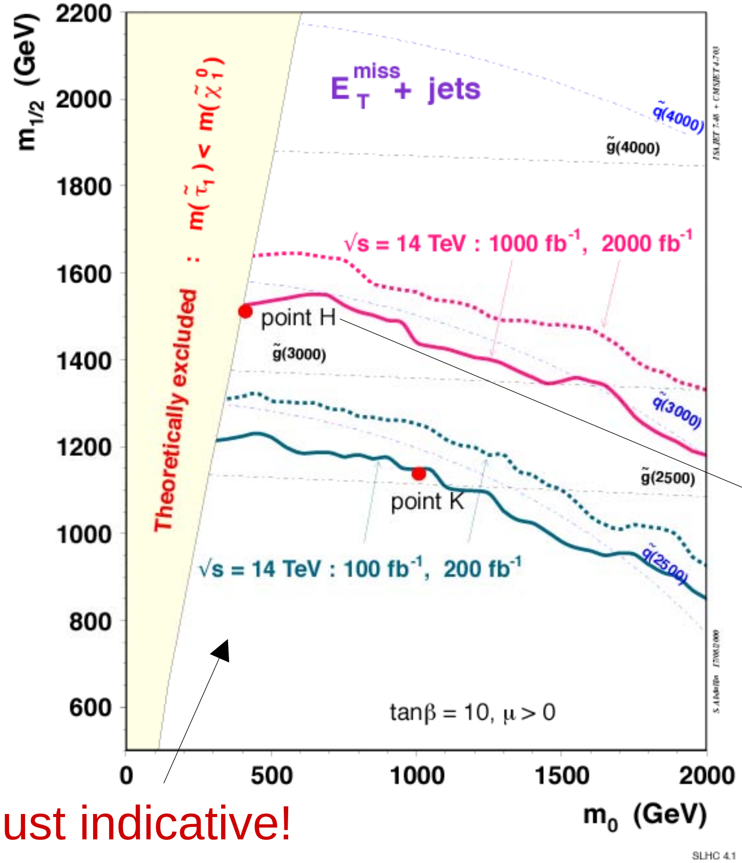
fit:

M(bb$\tilde{\chi}^0_2$) GeV = 587 ± 11 GeV
σ = 41GeV

generated mass: M($\tilde{g}$) = 595 GeV

Point B is far inside the "10 fb^{-1} reach", nonetheless sparticle reconstruction/spectroscopy obviously statistically limited!

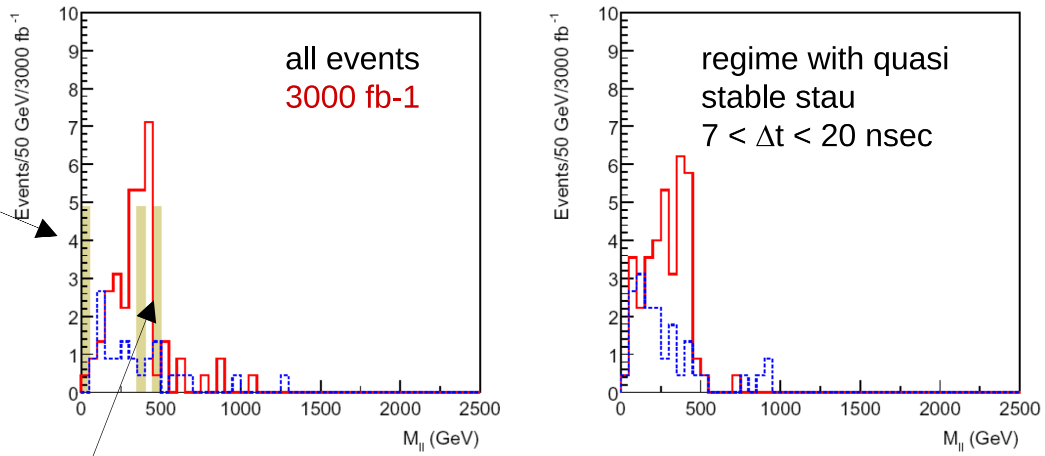
SUSY at LHC/SLHC, dilepton edges



just indicative!

Dilepton effective mass, benchmark point H
(m_0 = 419 GeV, $m_{1/2}$ = 1500, tgβ = 20, μ > 0), 3000 fb^{-1}

$m(\tilde{q},\tilde{g}) \sim 2.5$ TeV, $\tilde{\tau}_1$ and $\tilde{\chi}^0_1$ almost degenerate,
$\tilde{\tau}_1$ long lived and "heavy muon like"
large rate for $\tilde{q}_L \rightarrow q\tilde{\chi}^0_2 \rightarrow q\, l^+l^-\tilde{\chi}^0_1$
thus dileptons with "edge" structure

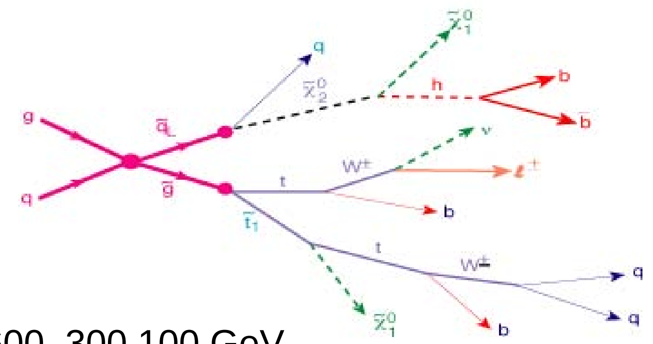


red: same flavor leptons, blue: different flavors;
shaded: SM bkgd

High momentum leptons, but lot of stat needed to reconstruct sparticle mass peaks from edge regions! SLHC luminosity should be crucial, but also need for jets, b-tagging, missing E_t i.e. adequate detector performances (calorimetry, tracker) to really exploit the potential of increased statistics at SLHC…..

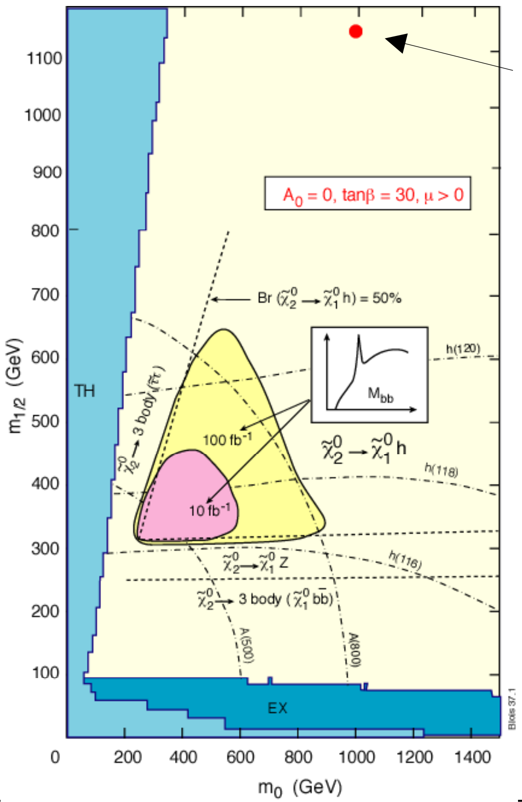
$h \rightarrow$ bb in squark/gluino decay chains

$h \rightarrow$ bb in squark/gluino decay chains,
benchmark point K (m_0 = 1000 GeV, $m_{1/2}$ = 1150, tgβ = 35, μ < 0)



at point K $\tilde{\chi}^0_2 \longrightarrow h\tilde{\chi}^0_1$ is dominant,
thus h could appear in decay chains

$\tilde{q}_L \rightarrow q\tilde{\chi}^0_2 \rightarrow q\, h\tilde{\chi}^0_1 \rightarrow q\, bb\tilde{\chi}^0_1$

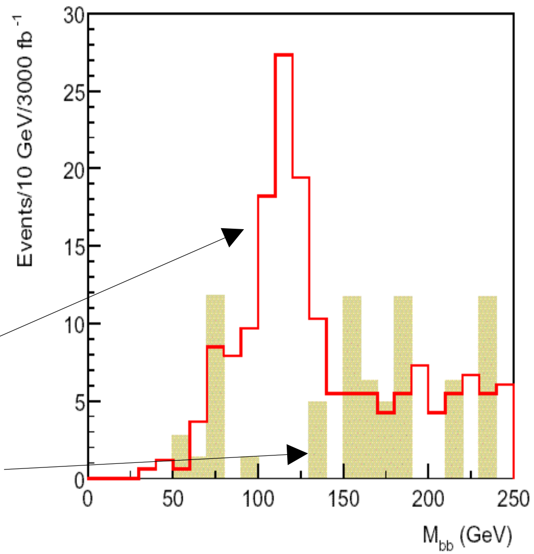


"point K"
but for
tgβ = 35, μ < 0

main cuts:
≥ 3 jets with E_t > 600 ,300,100 GeV
E_t^{miss} > 400 GeV
M_{eff} > 2500 GeV
b-tagging efficiency assumed: 60%
rejection against light quark jets ~ 100

h → bb
signal

SM bkgd



SLHC
3000 fb^{-1}

b-tagging is essential
for this type of study
and jet resolution for
jet spectroscopy,

New gauge bosons, SLHC vs LHC (I)

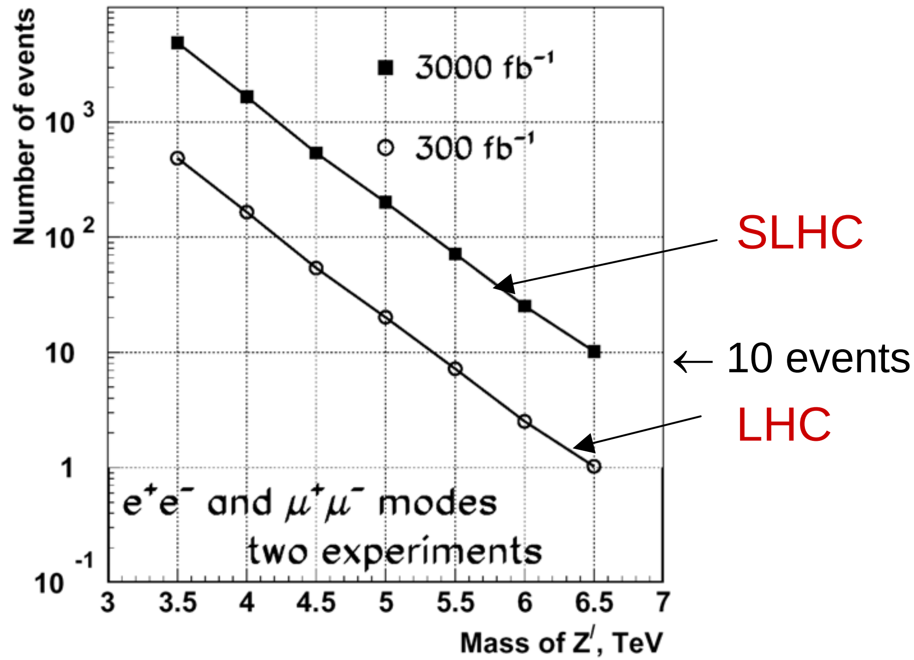
Additional heavy gauge bosons (W,Z-like) are expected in various extensions of the SM symmetry group (LR,ALR,E_6,SO10…..), with couplings to leptons ~ similar to SM W,Z

Ex. sequential Z' model, Z' production - assuming same BR as for SM Z - and Z' width

Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

Acceptance, e/μ reconstruction eff., resolution, pile-up noise, ECAL saturation included

For high mass objects electrons more usefull than muons -thanks to better resolution



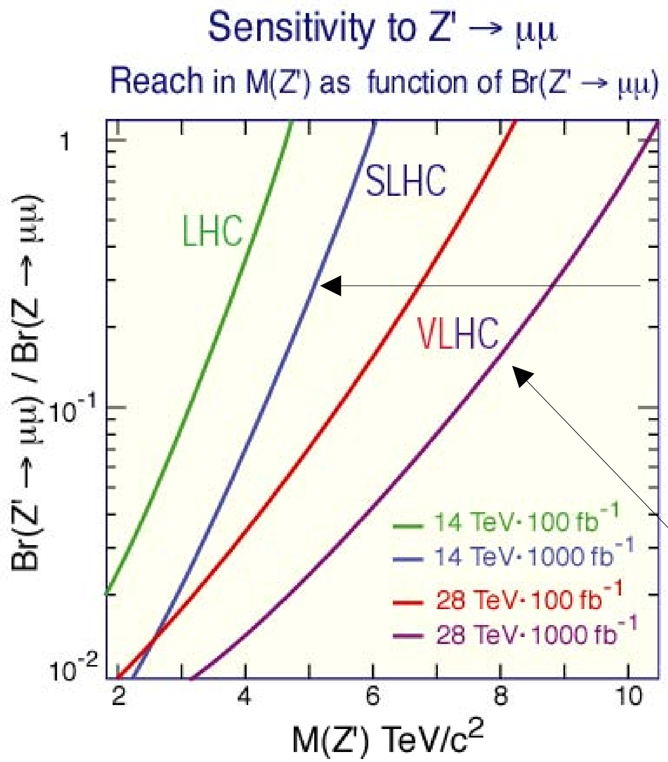
Expected backgrounds from Drell-Yan and tt production at the few % level

With 10 events to claim discovery, reach improves from ≈ 5.3 TeV (LHC, 600 fb^{-1})

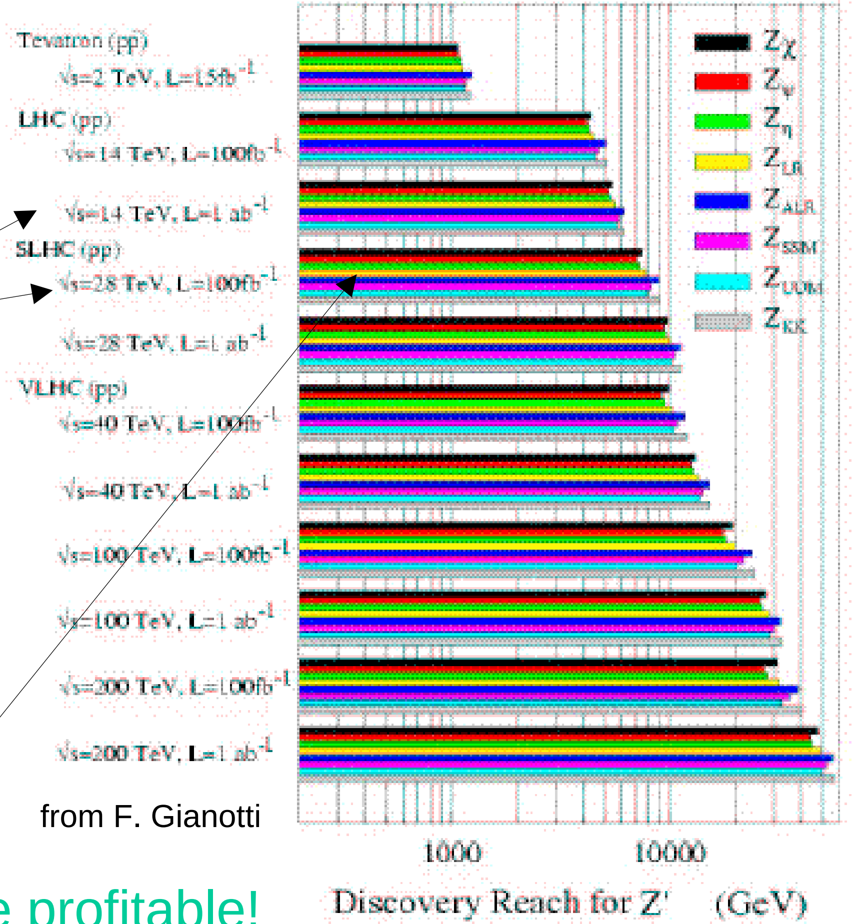
to ≈ 6.5 TeV (SLHC, 6000 fb^{-1})

New gauge bosons, SLHC vs LHC (II)

For new heavy gauge bosons (Z') expected in various extensions of the SM (L-R,A_{LR},E6,SO10…..), sensitivity to couplings to lepton pairs relative to SM Z-couplings and mass reach at SLHC



Gain in reach ~ 30%
LHC (100 fb^{-1}) vs
SLHC (1000 fb^{-1})

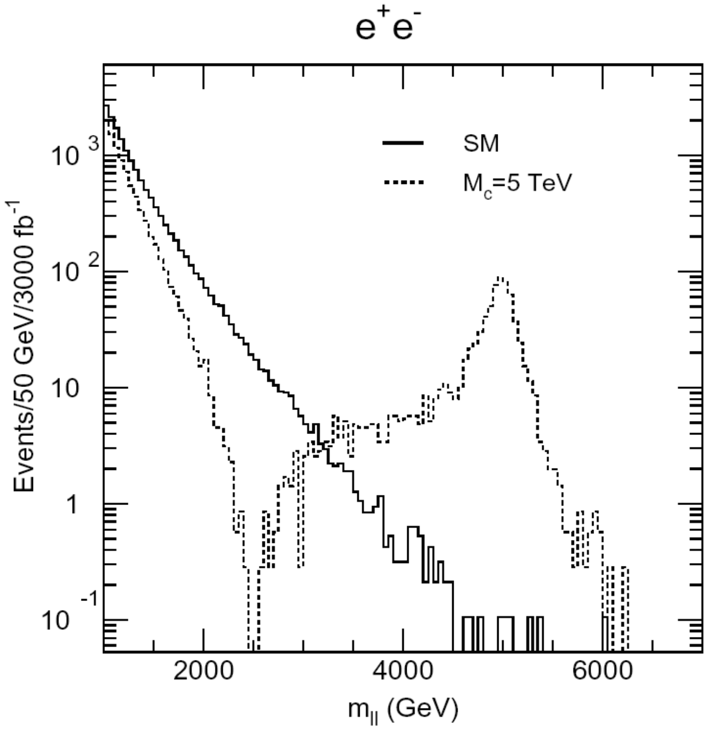


from F. Gianotti

for massive objects larger cm energy is more profitable!

Extra dimensions, TeV^{-1} scale model

Theories with extra dimensions - with gravity scale ~ ew scale - lead to expect characteristic new signatures/signals at LHC/SLH; various models: ADD, ABQ, RS…



Some signatures: escaping gravitons /E_t^{miss}(ADD), TeV scale KK excitations of SM gauge bosons (ABQ), TeV-Dilepton/diphoton mass peaks of RS gravitons…

Example: two-lepton invariant mass, TeV^{-1} scale extra dim model (ABQ-type, one "small" extra dim. $R_c = 1/M_c$) with M_c = 5 TeV, 3000 fb^{-1}

(LEP - indirect limit: M_c > 4 TeV)

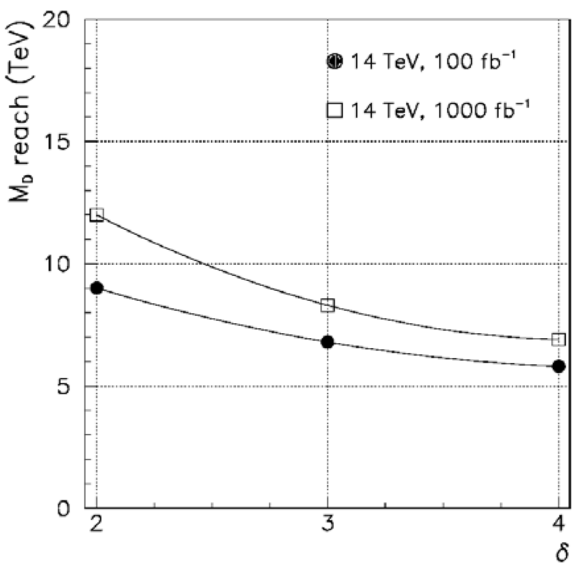
peak due to first γ, Z excitation at ~ M_c ; note also interference between γ, Z and KK excitations $\gamma^{(\ )}$, $Z^{(n)}$, thus sensitivity well beyond direct peak observation from $d\sigma/dM$ and angular distributions

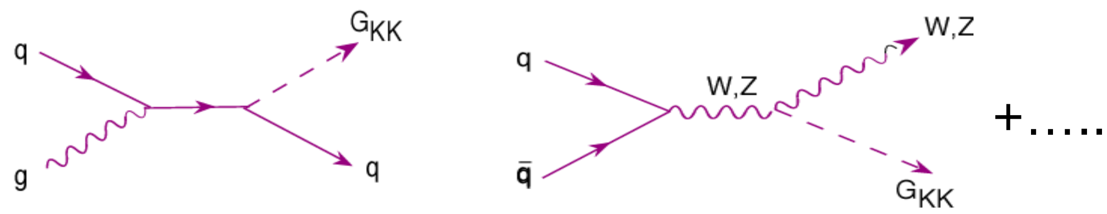
reach ~ 6 TeV for 300 fb^{-1} (LHC), ~ 7.7 TeV for 3000 fb^{-1} from direct observation

indirect reach (from interference) - requiring good control of SM bkgd magnitude - to ~ 14 TeV for SLHC, 3000 fb^{-1}, e + μ 10σ , as compared to ~ 10 TeV reach at LHC, 100 fb^{-1}, for a 5σ discrepancy vs SM expectations

Extra dimensions, ADD model

In ADD-type models large extra dimension compactified at < ~ 100 μm, only gravity propagates in them ⇒ tower of nearby KK excitations of gravitons (quasi continuum) escaping detection (missing E_t);
at LHC/SLHC best signature is production of KK gravitons + quark/gluon jet, i.e. a monojet topology;
cross section depends on the gravity scale M_D and number of extra dimensions δ ($\delta \geq 2$);
($\delta < 2$ excluded, $\delta > 6$ not observable as $\sigma \propto 1/M_D^{\delta+2}$ too small);
production: $qg \to qG$, $gg \to gG$, $q\bar{q} \to gG$ …..; bkgds: $Z(\to \nu\nu)$ + jet(s), $W(\to \tau\nu)$ + jet
typical cuts: $E_t^{miss} > 1$ TeV, $E_t^{jet} > 400$ GeV





Expected 5σ discovery reach, in M_D vs δ, LHC and SLHC, ATLAS study
for $\delta = 2$: 9 TeV (LHC) → 12 TeV (SLHC)

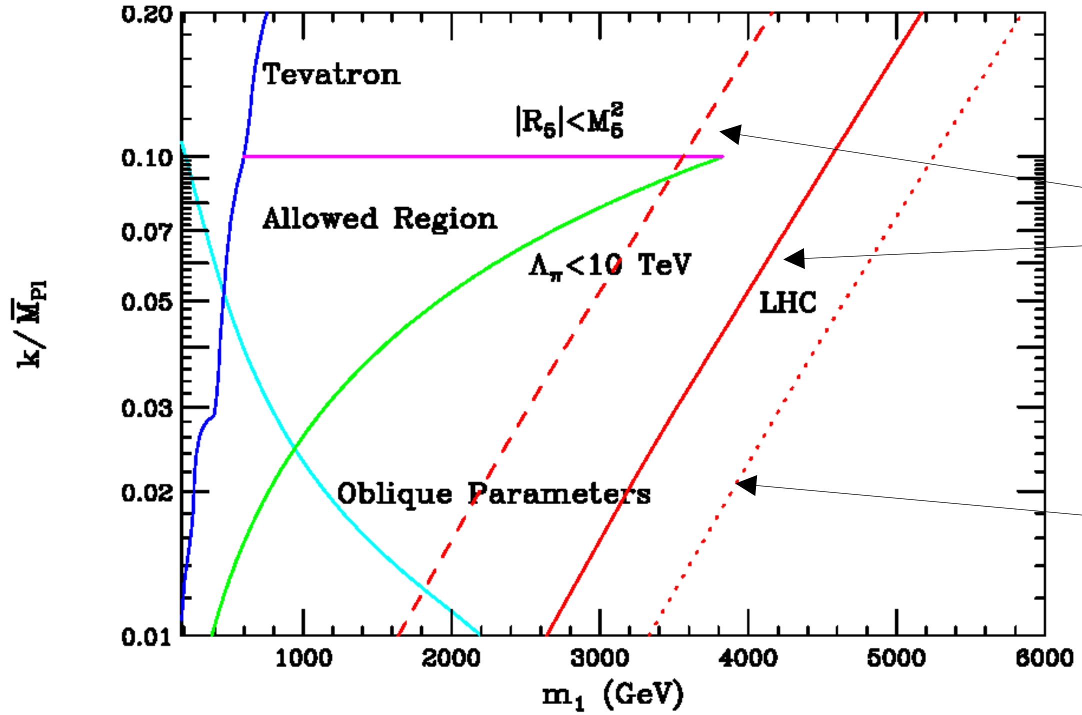
⇒ LHC to SLHC luminosity upgrade allows a <~ 30% increase in reach

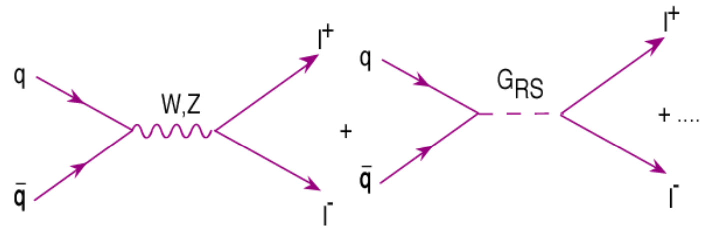
Extra dimensions, RS model

Direct production of a R-S graviton at weak-scale mass could result in a striking heavy (and narrow - depending on coupling) dilepton or diphoton signal;

prod.: pp → G_{RS} → ee/μμ/γγ (2!); ee and γγ has much better resolution than μμ;

Exclusion limit in m_1 vs c-parameter plane





LHC,
10 fb^{-1}
100 fb^{-1}

at LHC RS gravitons can be looked for in the ~ 2-4 TeV range, depending on the coupling,
SLHC with 1000 fb^{-1} extends the reach by ~ 1 TeV

Conclusions, physics, SLHC vs LHC (I)

- ew physics:

multiple VB production, TGC, QGC, SM Higgs….this becomes “precision physics”, the most sure/assured one of being at the rendez-vous, TGC testable at level SM rad corrections,

ratios of SM Higgs BRs to bosons and fermions measurable to ~ 10% level,

Higgs self-couplings, first observation possible only at SLHC, of fundamental importance as a test of ew theory,

these measurements however require full performance detectors

- strongly coupled VB regime :

getting within reach really only at SLHC

but requires full performance calorimetry, forward one in particular

- SUSY:

MSSM Higgs (A/H,$H^{\pm}$) parameter space coverage significantly improved (A/H $\to \tau\tau, \mu\mu$), new modes become accessible ($H^{\pm} \to \mu\nu$);

SUSY discovery and sparticle mass reach augmented by ~ 20-25%, spectrum coverage and parameter determination improved

some of these measurements (sparticle spectrum reconstruction) require full performance detectors

Conclusions SLHC vs LHC (II)

- search for massive objects :
  new heavy gauge bosons, manifestations of extra dimensions as KK-recurencies of γ, W, Z, gluon, R-S gravitons, LQ's, q*,……
  reach improved by 20-30%,
  but these are much more speculative/unsure topics, maybe only limits to be set…..
  these measurements least demanding in terms of detector performances
- rare/forbidden decays:
  of top in $t \rightarrow u/c + \gamma/Z$, sensitivity down to BR ~ 10^{-6}; tau in $\tau^{\pm} \rightarrow 3\mu^{\pm}, \mu^{+}\mu^{-}e^{\pm}, \mu^{\pm}e^{+}e^{-}$…
  possibly to BR ~ 10^{-8} (to be studied!), B-hadrons etc
  requires full performance detectors
- SLHC as a ν_{τ} factory - source of F-B collimated c and b production - to be revisited?

In conclusion the SLHC ($\sqrt{s} \approx 14$ TeV, L ≈ 10^{35} cm^{-2} s^{-1}) would allow to extend significantly the LHC physics reach whilst keeping the same tunnel, machine dipoles, a large part of "existing" detectors, but to exploit fully its potential inner/forward parts of detectors must be changed/hardened/upgraded, trackers in particular, to maintain performances similar to "present ones"; forward calorimetry of higher granularity would be highly desirable for jet tagging

Backups/alternatives

General remarks on desirability for detector upgrades (I)

- High mass searches/TeV scale reach studies such as:
SUSY reach (squarks, gluinos), W', Z', Z_{KK}, R-S gravitons, LQ, extra dim monojets etc not much affected by instantaneous luminosity increase/higher pile-up, nor by some reduction in acceptance for leptons, say, $|\eta| < 2.5 \rightarrow < 2.0$, as heavy objects are centrally produced; good tracker still needed for muon momentum resolution and electron identification (E/p)

- There are however important topics which would benefit greatly from the ~ 300 fb^{-1} to 3000 fb^{-1} increase, but depend on forward jet tagging and/or central jet veto techniques to suppress backgrounds:

  $pp \rightarrow qqH$, qqVV (heavy Higgs, MSSM Higgs, resonant or non-resonant W_L , Z_L scattering)

  direct slepton pair production ($\rightarrow$ 2 leptons), mass reach potentially increases from ~ 350 GeV $\rightarrow$ 450 GeV

  chargino-neutralino direct pair production ($\rightarrow$ 3 leptons)

  precision measurements of TGC, QGC …….

this requires maintaining present calorimetric angular coverage but with preferably improved granularity and new detector techniques (quartz fibers and clading? or…) to sustain radiation damage

General remarks on desirability for detector upgrades (II)

- b-tagging capability - probably most difficult to maintain at present (expected) level of performance would be most desirable,

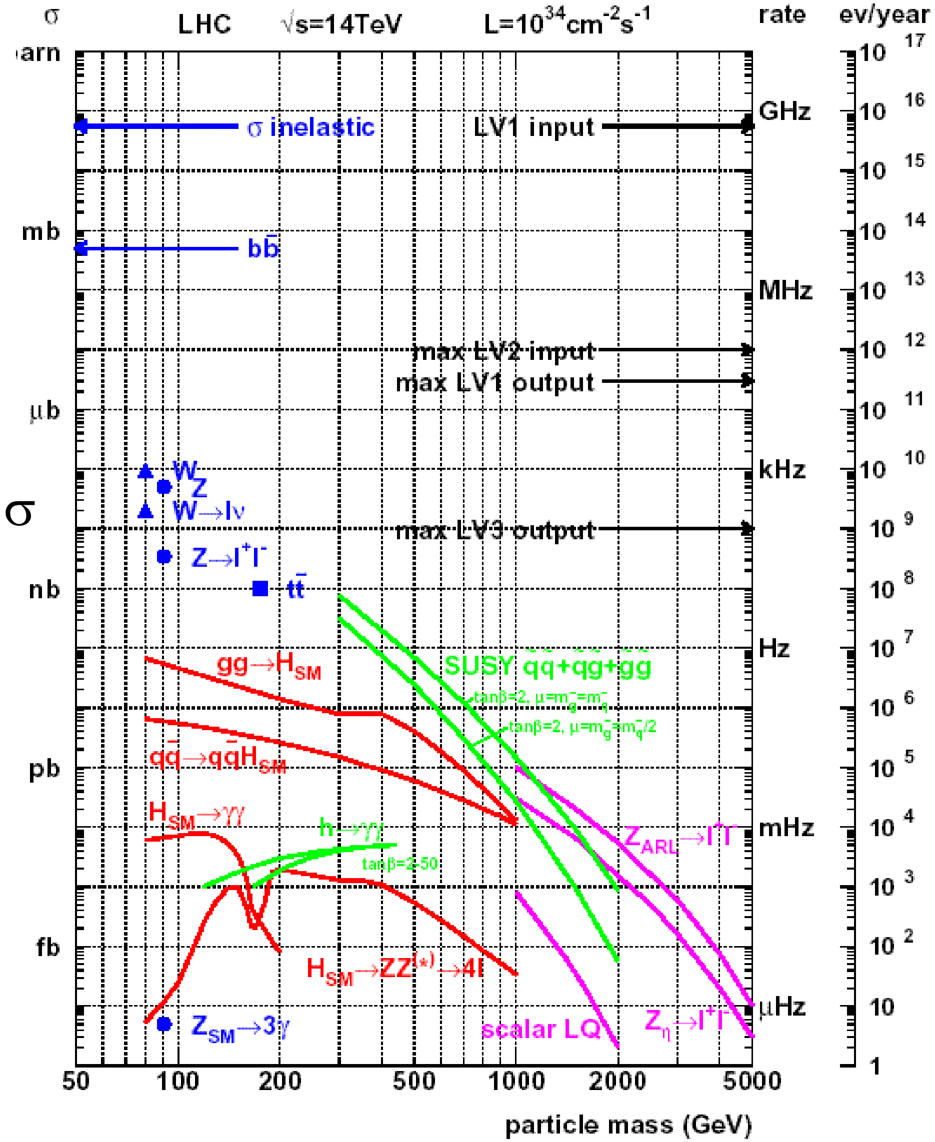
  to increase the SUSY spectrum coverage, for stop, sbottom (especially in case of "inverted mass hierarchy" where these could be the only observable sparticles….),
  for precision measurements on SM Higgs BR's,
  to extend MSSM Higgs searches in bbA/H, $tbH^{\pm}$ etc final states
  rare top decays (FCNC) $t \rightarrow u/c + \gamma/Z$, rare $B^{o}_{s,d}$ decays……

- τ-tagging capability, even more demanding on tracker/impact parameter/sec vertex measurements,

  for $A/H \rightarrow \tau\tau$, $H^{\pm} \rightarrow \tau\nu$;
  for SUSY/stau spectroscopy (at large tgβ neutralinos largely decay to tau-stau);
  GMSB with $\tilde{\tau}_1 \rightarrow \tau\ G_{3/2}$ (scenario with $\tilde{\tau}_1$NLSP)
  $\tau^{\pm} \rightarrow 3\mu^{\pm}, \mu^{+}\mu^{-}e^{\pm}, \mu^{\pm}e^{+}e^{-}$…….

Both these topics require a high performance tracker, measurements close to beam pipe for impact parameter/sec. vertices; τ-related physics requires also understanding hadronic τ triggering need and capability at high luminosity

Cross sections, rates at LHC

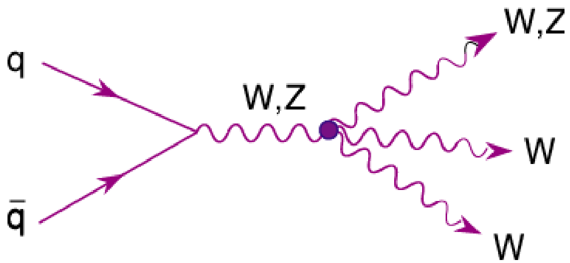


Event rates and events per year for 10^{34} cm^{-2} s^{-1}

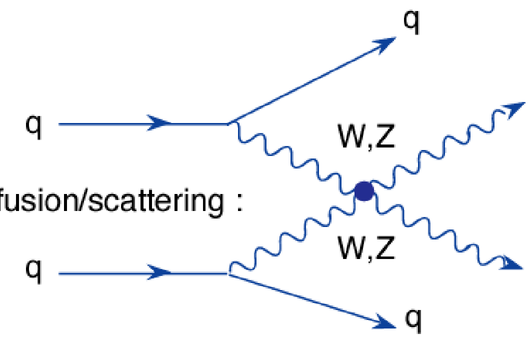
ew physics, quartic couplings (I)

In the SM QGC completely specified

Quartic couplings can be tested in triple VB production or VB scattering/fusion:



W, Z fusion/scattering :



+......

deviations from SM expressed in terms of anomalous couplings α_4, α_5, α_6, α_7, α_{10}

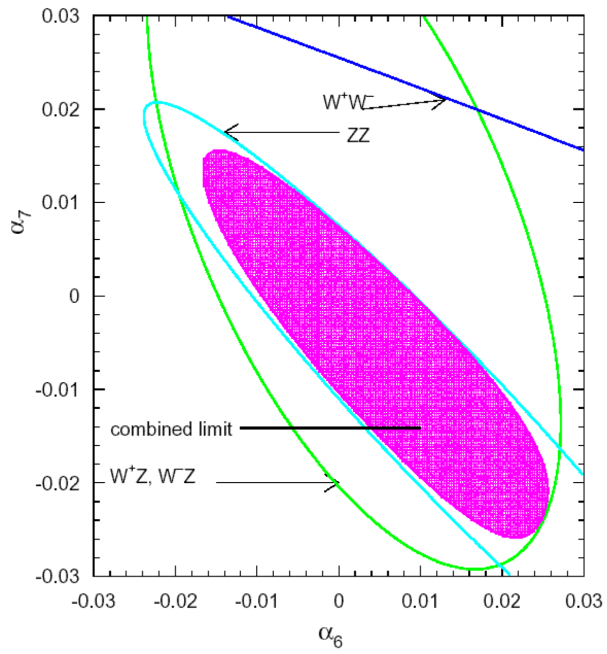
1σ limits on anomalous quartic couplings (Belyaev et al.)

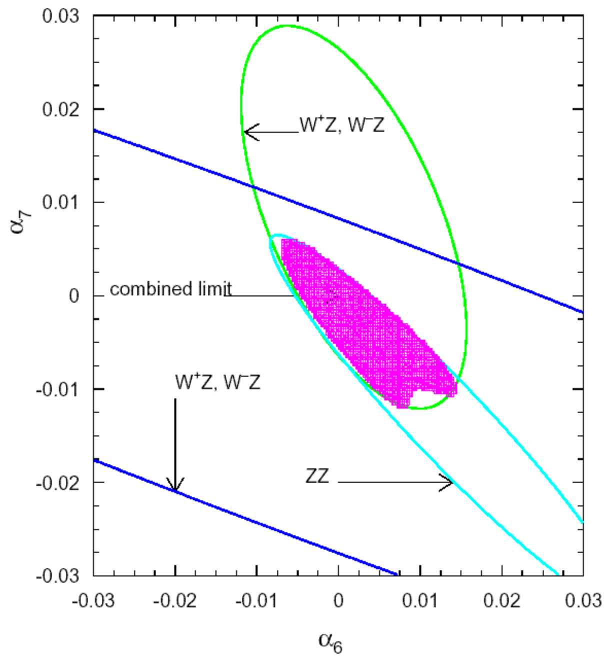
Coupling	Indirect Limits (1σ) $(\times 10^{-3})$	LHC, 100 fb^{-1} (1σ) $(\times 10^{-3})$	LHC, 6000 fb^{-1} (1σ) $(\times 10^{-3})$	LHC, 6000 fb^{-1} 95% C.L. $(\times 10^{-3})$
α_4	$-120. \leq \alpha_4 \leq 11.$	$-1.1 \leq \alpha_4 \leq 11.$	$-0.67 \leq \alpha_4 \leq 0.74$	$-0.92 \leq \alpha_4 \leq 1.1$
α_5	$-300. \leq \alpha_5 \leq 28.$	$-2.2 \leq \alpha_5 \leq 7.7$	$-1.2 \leq \alpha_5 \leq 1.2$	$-1.7 \leq \alpha_5 \leq 1.7$
α_6	$-20. \leq \alpha_6 \leq 1.8$	$-9.6 \leq \alpha_6 \leq 9.1$	$-3.5 \leq \alpha_6 \leq 3.2$	$-4.3 \leq \alpha_6 \leq 3.9$
α_7	$-19. \leq \alpha_7 \leq 1.8$	$-10. \leq \alpha_7 \leq 7.4$	$-4.4 \leq \alpha_7 \leq 2.2$	$-5.4 \leq \alpha_7 \leq 2.8$
α_{10}	$-21. \leq \alpha_{10} \leq 1.9$	$-24. \leq \alpha_{10} \leq 24.$	$-4.1 \leq \alpha_{10} \leq 4.1$	$-4.8 \leq \alpha_{10} \leq 4.8$

ew physics, quartic couplings (II)

Correlations among α-parameters, 1σ contours from VV production
LHC (100 fb^{-1}) vs SLHC (6000 fb^{-1}) sensitivity

Belyaev et al.





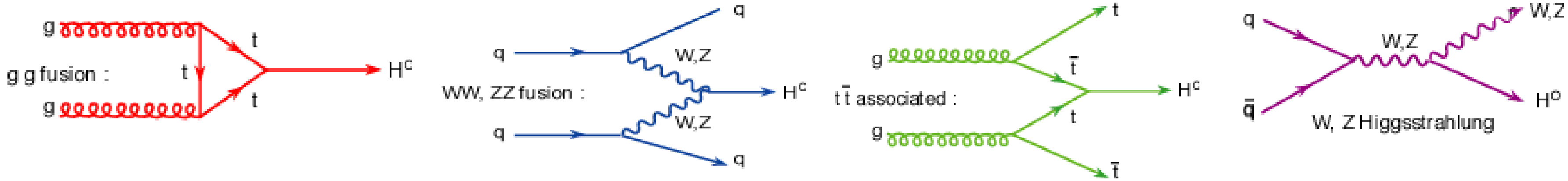
$\alpha_4, \alpha_5, \alpha_{10} = 0$

↑ LHC

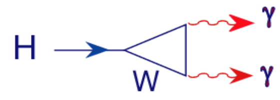
↑ SLHC

Precisions on SM Higgs couplings, LHC

Using the various Higgs production mechanisms:



and the Higgs decays: $H \to bb$, $\tau\tau$, $WW \to l\nu l\nu$, $ZZ \to 4l^{\pm}$, and $H \to \gamma\gamma$



taking ratios of final states where uncertainties (σ_H, luminosity) cancel, ratios of BR's and couplings can be determined in various m_H intervals; expectations for 300 fb^{-1}

$$\frac{\sigma \cdot B\,(ttH+WH \to \gamma\gamma)}{\sigma \cdot B\,(ttH+WH \to bb)} \Rightarrow \frac{BR\,(H \to \gamma\gamma)}{BR\,(H \to b\bar{b})}$$

known to ~ 15% stat. limited

only for: $80 \lesssim m_H \lesssim 120$ GeV

$$\frac{\sigma \cdot B\,(H \to WW^*/W)}{\sigma \cdot B\,(H \to ZZ^*/Z)} \Rightarrow \frac{g^2_{H\,WW}}{g^2_{H\,ZZ}}$$

known to ~ 20% stat. (ZZ*) limited

only for: $140 \lesssim m_H \lesssim 190$ GeV

$$\frac{\sigma \cdot B\,(H \to \gamma\gamma)}{\sigma \cdot B\,(H \to ZZ^*)} \Rightarrow \frac{BR\,(H \to \gamma\gamma)}{BR\,(H \to ZZ^*)}$$

known to ~ 10% stat. limited

only for: $125 \lesssim m_H \lesssim 155$ GeV

$$\frac{\sigma \cdot B\,(t\bar{t}H \to \gamma\gamma/b\bar{b})}{\sigma \cdot B\,(WH \to \gamma\gamma/b\bar{b})} \Rightarrow \frac{g^2_{H\,tt}}{g^2_{H\,WW}}$$

known to ~ 20% stat. limited

only for: $80 \lesssim m_H \lesssim 130$ GeV

. . . .

precisions on ratios are stat limited, thus would benefit from SLHC stat increase
- provided detectors perform as at LHC -
case where stat increase factor ~10 could

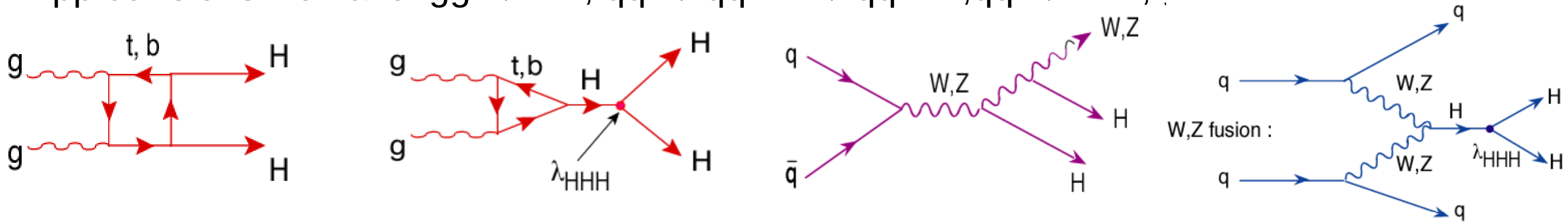
be more valuable than factor ~ 2 in energy!

Higgs pair production and self coupling (I')

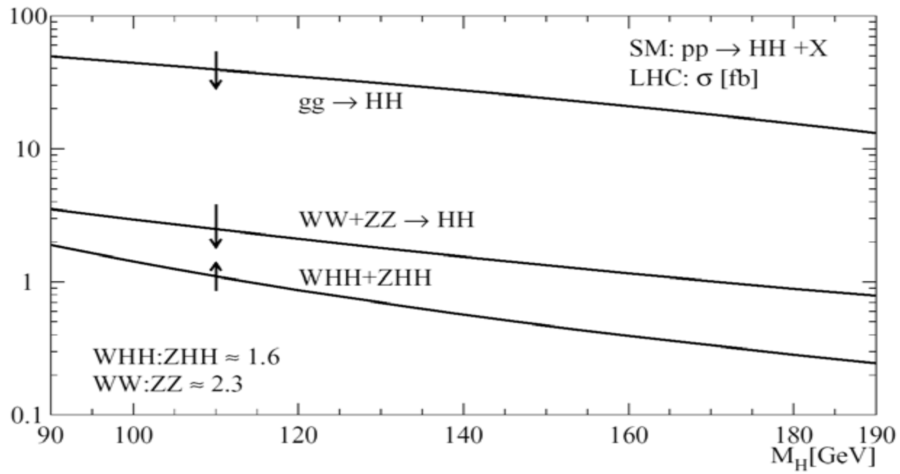
Higgs pair production can proceed through two Higgs bosons radiated independently (from VB, top) and from trilinear self coupling terms proportional to λ_{HHH}^{SM}

triple H coupling: $\lambda_{HHH}^{SM} = 3m_H^2/v$ there is also a quartic H coupling λ_{HHHH}^{SM}

In pp collisions we have: gg → HH, qq → qqVV → qqHH ,qq →VHH, qq qq → ttHH etc



cross sections for Higgs boson pair production in various production mechanisms



arrows correspond to variations of λ_{HHH} from 1/2 to 3/2 of its SM value

→ very small cross sections hopeless at LHC (10^{34})

exploitable H decay modes: H → bb, WW, ZZ ...

SLHC: improved reach for heavy MSSM Higgs bosons (I)

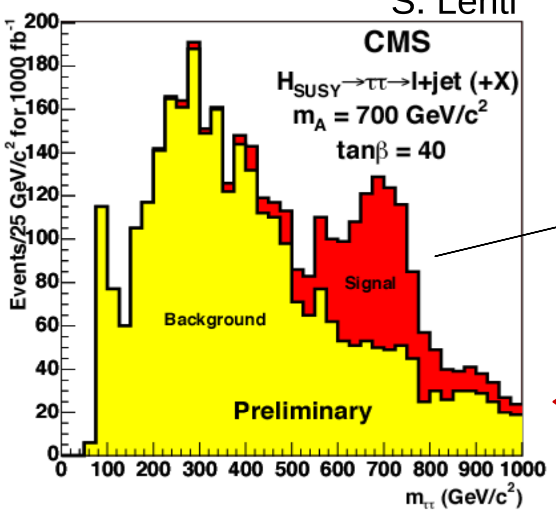
The order of magnitude increase in statistics with the SLHC should allow to extend the discovery domain for massive MSSM Higgs bosons, A,H,$H^{\pm}$

Example: A/H $\rightarrow \tau\tau \rightarrow$ lepton + τ-jet, produced in bbA/H; fast simulation, preliminary

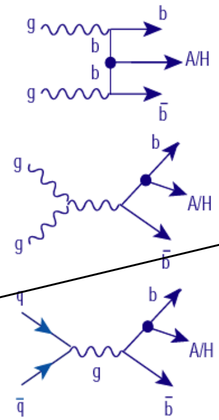
p_t(lept) > 30 GeV, E_t(τ-jet) > 100 GeV
E_t(b-jet) > 50 GeV, CMS b-tagging performance
no additional jets with E_t > 50 GeV,

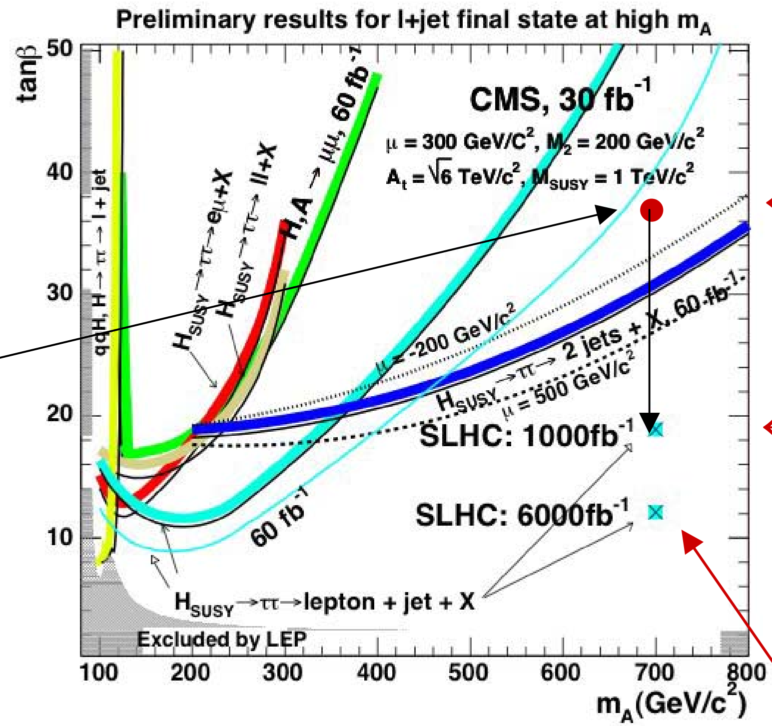
no missing E_t cut

S. Lehti



← SLHC
1000 fb^{-1}





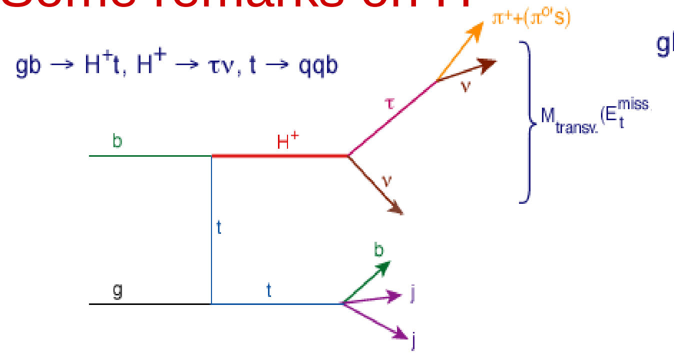
←LHC
60 fb^{-1}

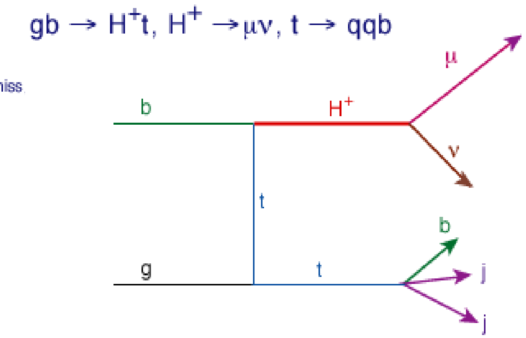
←SLHC
1000 fb^{-1}

gain in reach

$H^{\pm} \rightarrow \mu\nu$, $A/H \rightarrow \mu\mu$.

Some remarks on $H^{\pm}$





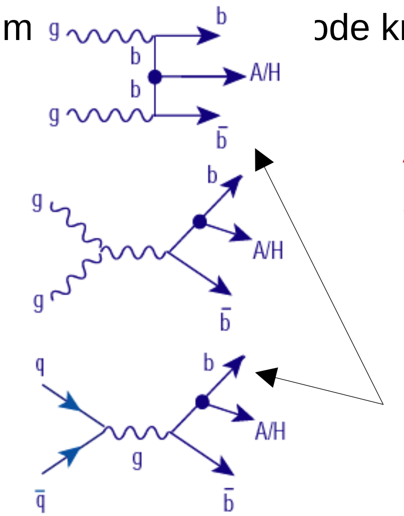
← under study

not observable at LHC with 300 fb^{-1} (m_A = 200 GeV, tgβ = 50, signal ~ 20 events, bkgd ~ 20000 events in full transverse mass range)
but should be at SLHC with 3000 fb^{-1}

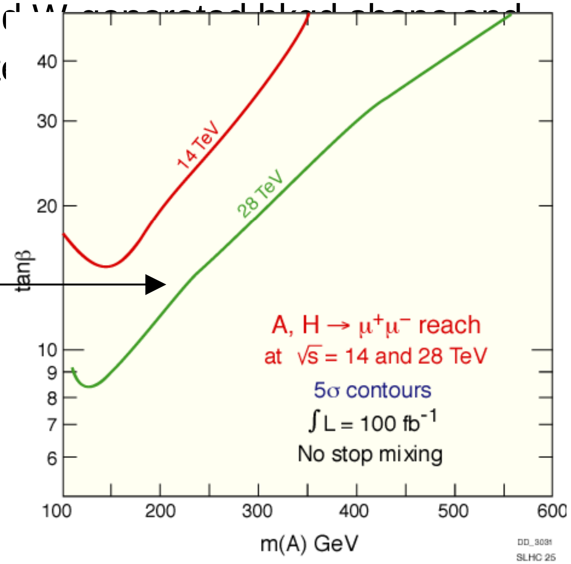
Comparison of these two rates should give $g_{H\tau\nu}/g_{H\mu\nu} = m_\tau/m_\mu$ ⇒ . .f . $\propto m_{fermion}$

the main expected bkgds in $H^+ \rightarrow \mu\nu$ are from tt/Wtb → W → μν and tt/Wtb → W → τν → μννν but for SM-W BR(W → μν) = BR(W → τν) ⇒ large bkgd, but H mass known (from $H^+ \rightarrow \tau\nu$) anc

m ode known from W → eν (where no H^+ contribution is expect

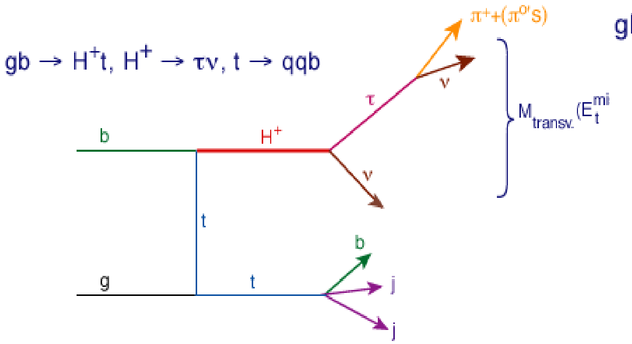


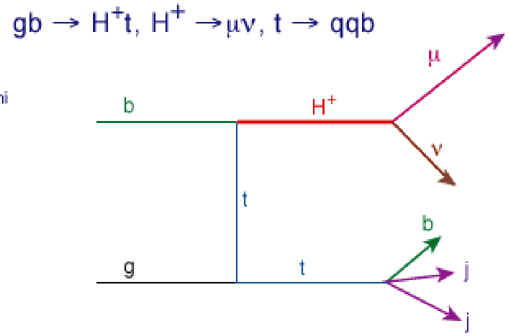
A/H → μμ - channel which most obviously should benefit from increased statistics at SLHC (and increased cm energy/ VLHC)
- easy to trigger -
but as main production mechanism is associated bbA/H production, good b-tagging performance highly desirable



$H^{\pm} \to \mu\nu$, $A/H \to \mu\mu$.

Some remarks on $H^{\pm}$





not observable at LHC: with 300 fb^{-1} (m_A = 200 GeV, tgβ = 50, signal ~ 20 events, bkgd ~ 20000 events in full transverse mass range)

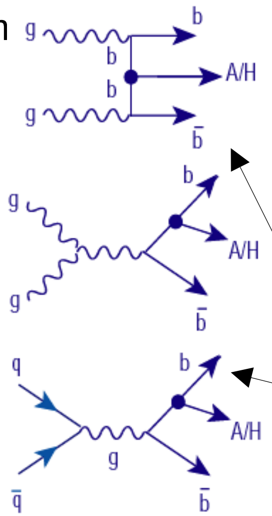
at SLHC, m_A = 400 GeV,tgβ = 40, 3000 fb^{-1}, signal ~ 15 events, no tt, W+jets bkgd after hard cuts (preliminary, R. Kinnunen)

Comparison of these two rates should give $g_{H\tau\nu}/g_{H\mu\nu} = m_\tau/m_\mu$ ⇒ . .f .

$\propto m_{fermion}$

the main expected bkgds in $H^+ \to \mu\nu$ are from tt/Wtb → W → μν and tt/Wtb → W → τν → μννν but for SM-W BR(W → μν) = BR(W → τν) ⇒ large bkgd, but H mass known (from $H^+ \to \tau\nu$) and W-generated bkgd shape and

m ode known from W → eν (where no H^+ contribution is expect



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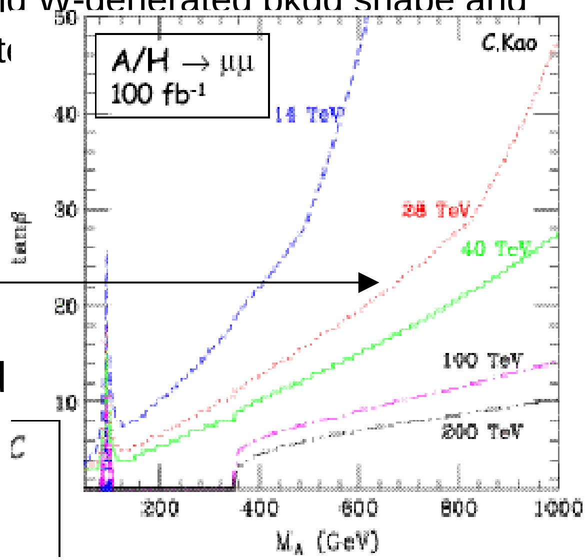
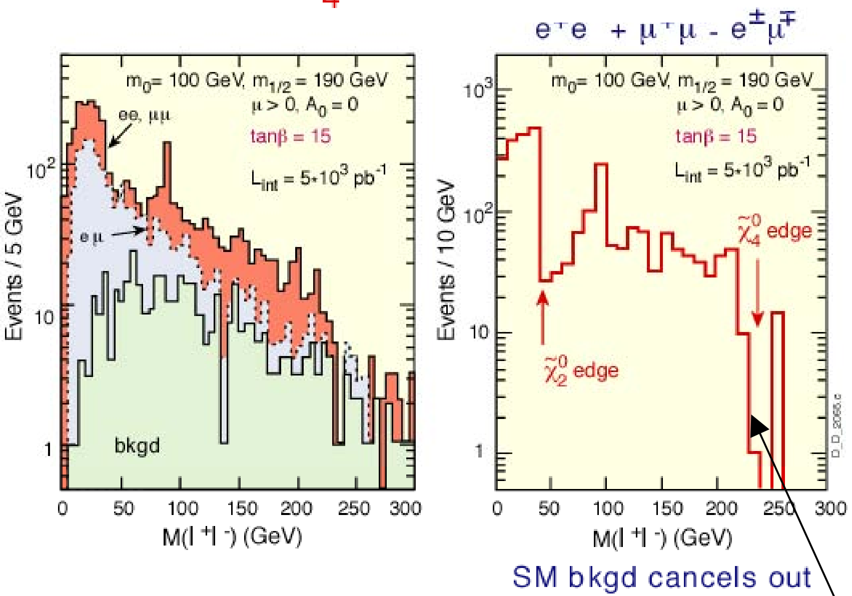


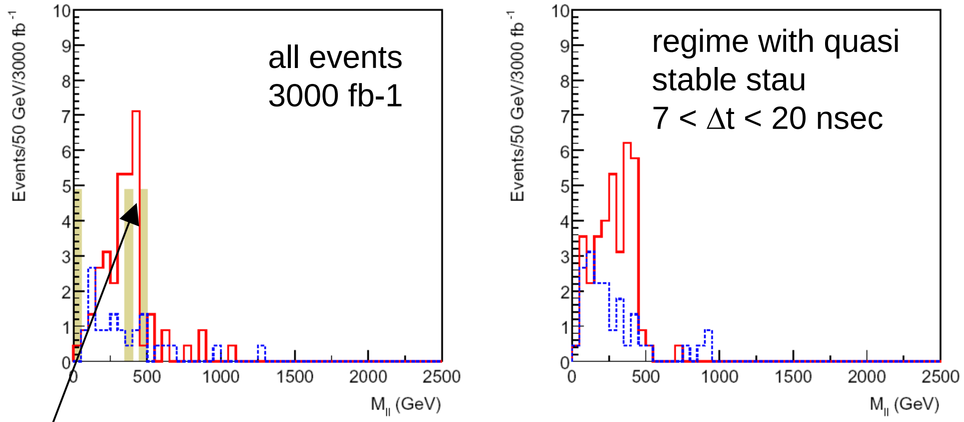
SUSY at LHC/SLHC, dilepton edges'

Evidence for $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$ (in eμ) with $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_4$ dilepton edges



Dilepton effective mass, benchmark point H
(m_0 = 419 GeV, m $_{1/2}$ = 1500, tgβ = 20), 3000 fb^{-1}

$m(\tilde{q},\tilde{g}) \sim 2.5$ TeV, $\tilde{\tau}_1$ and $\tilde{\chi}^0_1$ almost degenerate,
$\tilde{\tau}_1$ long lived and "heavy muon like"
large rate for $\tilde{q}_L \rightarrow q\tilde{\chi}^0_2 \rightarrow q\, l^+l^-\tilde{\chi}^0_1$
thus dileptons with "edge" structure



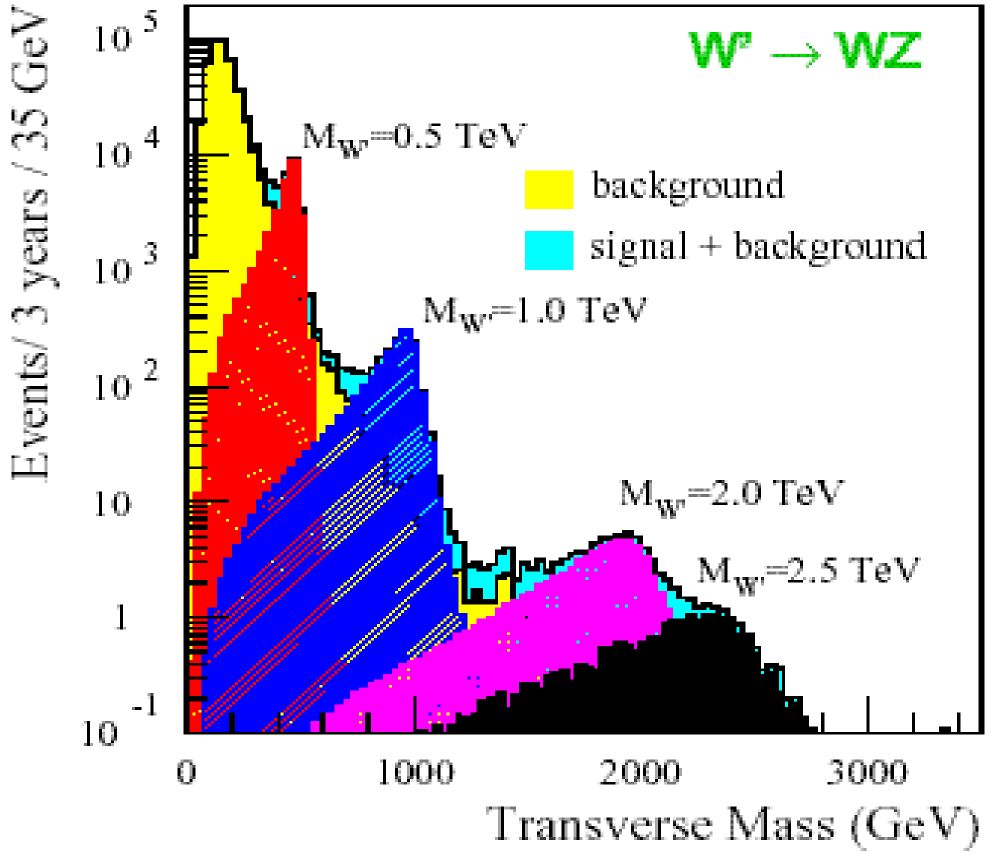
red: same flavor leptons, blue: different flavors;
shaded: SM bkgd

High momentum leptons, but lot of stat needed to reconstruct sparticle mass peaks from edge regions! SLHC luminosity should be crucial, but also need for jets, b-tagging, missing E_t i.e. adequate detector performances (calorimetry, tracker) to really exploit the potential of increased

statistics at SLHC…..

New gauge bosons, W’ → WZ (III)

Extensions of the SM and the possible new heavy gauge bosons,
W’, Z’ decays to VB pairs, for example W’ → WZ → 3 leptons

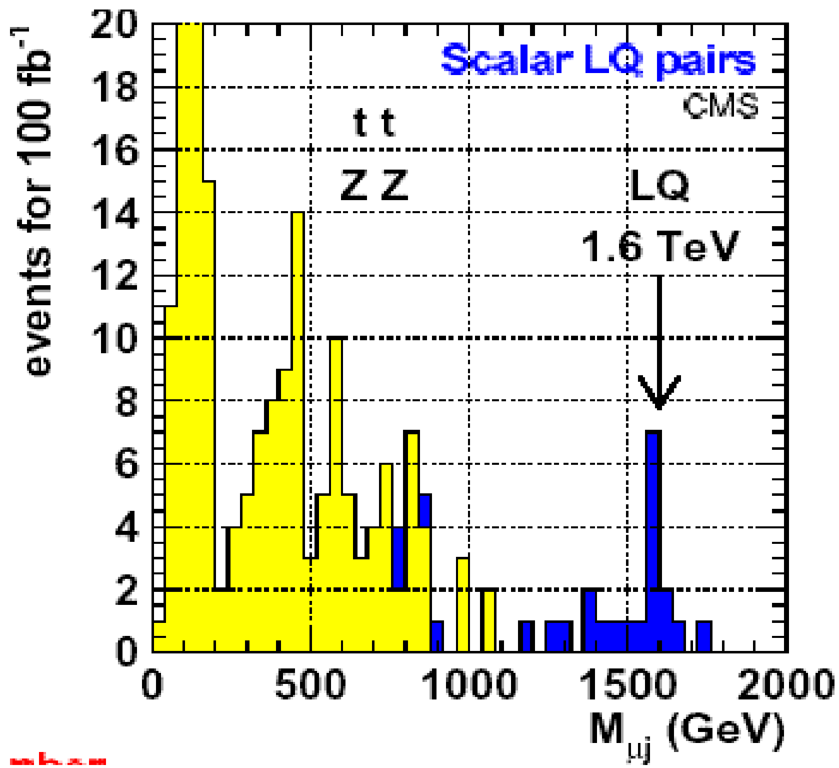


W’ → WZ → 3 leptons
typical channel where the SLHC statistics would allow to extend the mass reach by ~ 25 - 30% as compared to LHC,
easy trigger, not too demanding on detector performance,
tracker still important for lepton isolation suppressing tt bkgd

LHC, 300 fb^{-1}

Leptoquarks

In models with symmetries connecting quarks and leptons leptoquarks can appear; they carry both leptonic and quark quantum numbers
production: qq → LQ LQ, qg → LQ,
decay: LQ → lepton + quark/jet ⇒ triggering on a high-pt lepton-jet pair



At LHC leptoquarks can be searched for masses up to ~ 2. TeV (300 fb^{-1})
At SLHC the reach should be ~ 2.5 TeV