Physics Perspectives for a -Super LHC-

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LHC Status/plans

- Date for first beams/collisions: ⇒ **Spring 2007**
- Initial physics run starts in summer/fall 2007
  - ⇒ collect ~10 fb^{-1} /exp ($2.10^{33} cm^{-2} s^{-1}$) by early 2008
- Depending on the evolution of the machine…
  - ⇒ collect 200-300 fb^{-1} /exp ($3.4\text{-}10.10^{33} cm^{-2} s^{-1}$) in 5-6 years time

Already time to think of upgrading the machine

Two options presently discussed/studied

- Higher luminosity ~$10^{35} cm^{-2} s^{-1}$ (SLHC)
  - Needs changes in machine and and particularly in the detectors
  - ⇒ Start change to SLHC mode some time 2013-2016
  - ⇒ Collect ~3000 fb^{-1}/experiment in 3-4 years data taking.
- Higher energy?
  - LHC can reach $\sqrt{s}$ = 15 TeV with present magnets (9T field)
  - $\sqrt{s}$ of 28 (25) TeV needs ~17 (15) T magnets ⇒ R&D needed!

Machine

Large Hadron Collider Project

LHC Project Report 626

LHC Luminosity and Energy Upgrade: A Feasibility Study

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Upgrade in 3 main Phases:

- Phase 0 – maximum performance without hardware changes
  Only IP1/IP5, N_b to beam beam limit→ $L = 2.3 \bullet 10^{34}\ cm^{-2}\ s^{-1}$
- Phase 1 – maximum performance while keeping LHC arcs unchanged
  Luminosity upgrade (β^*=0.25m,#bunches,...)→ $L = 5\text{-}10 \bullet 10^{34}\ cm^{-2}\ s^{-1}$
- Phase 2 – maximum performance with major hardware changes to the LHC
  Energy (luminosity) upgrade → E_{beam} = 12.5 TeV

Machine upgrade

parameter	nom.	ult.	upgrades	
no. of bunches n_b	2808	2808	2808	1
rms bunch length σ_z [cm]	7.6	7.6	7.6, 4.2	7500
rms energy spread σ_δ [10^{-4}]	1.1	1.1	1.1, 3.7	5.8
beta at IP [m] β^*	0.5	0.5	0.25	0.25
crossing angle θ [μrad]	300	315	485	1000
beam current I_b [A]	0.56	0.86	1.3, 1.3	1.0
luminosity L [10^{34} cm^{-2}s^{-1}]	1	2.3	7.3, 9.7	9.0
σ_δ IBS growth time $\tau_{\rm IBS}$ [h]	134	86	56, 674	1712

Latest parameter set:
F. Ruggiero et al.
PAC2003 report
May 2003

A luminosity of 10^{35}cm^{-2} s^{-1} seems possible

(*) Superbunch: 1 bunch of 75 m (rms) in each ring
Good for electron cloud effects/bad for experiments: 50000 events/25 ns slice

Detectors: General Considerations

	LHC	SLHC
$\sqrt{s}$	14 TeV	14 TeV
Luminosity	10^{34}	10^{35}
Bunch spacing Δt	25 ns	12.5/25 ns
σ_{pp} (inelastic)	~ 80 mb	~ 80 mb
N. interactions/x-ing ($N=L\,\sigma_{pp}\,\Delta t$)	~ 20	~ 100/200
$dN_{ch}/d\eta$ per x-ing	~ 150	~ 750/1500
$\langle E_T \rangle$ charg. particles	~ 450 MeV	~ 450 MeV
Tracker occupancy	1	5/10
Pile-up noise in calo	1	~3
Dose central region	1	10

Normalised to LHC values.

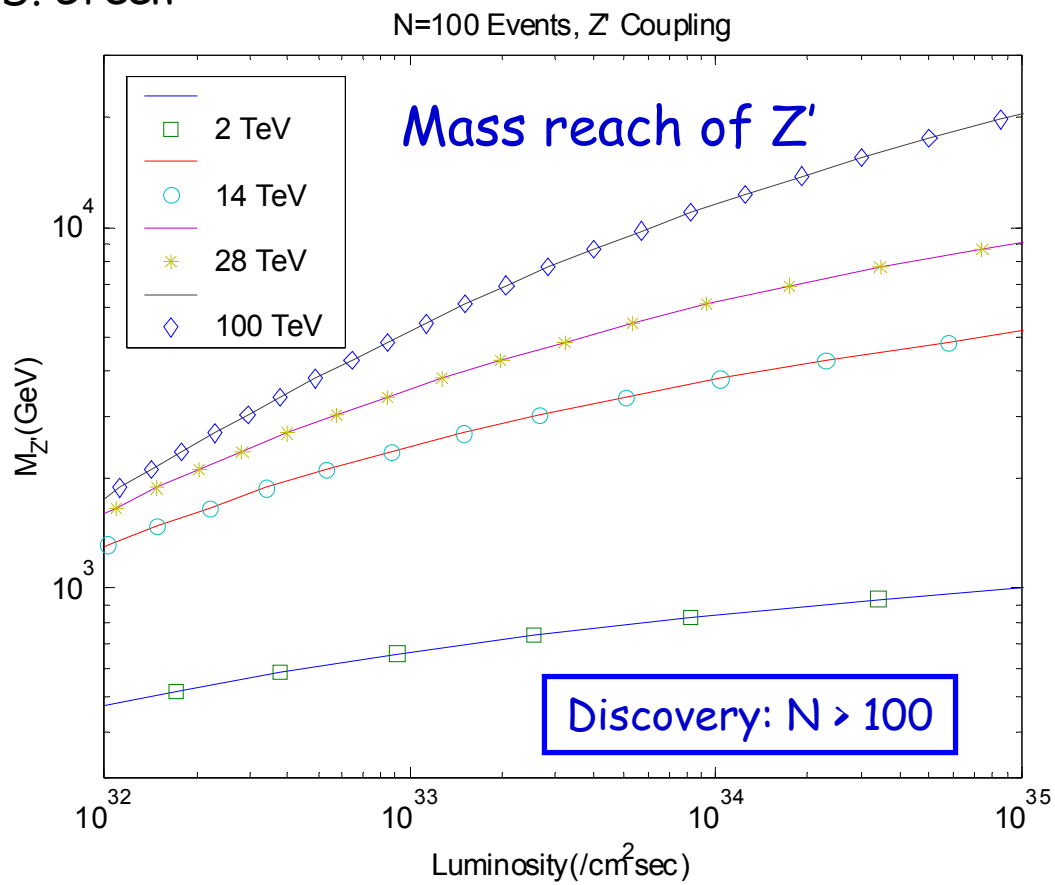
10^4 Gy/year R=25 cm

In a cone of radius = 0.5 there is E_T ~ 80GeV.
This will make low E_t jet triggering and reconstruction difficult.

Extended Reach: General

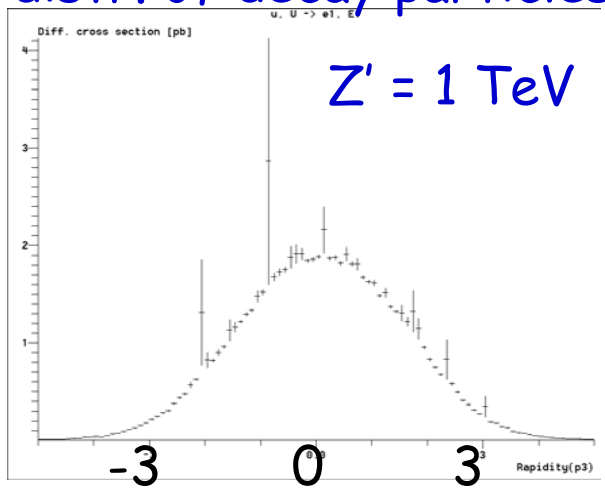
D. Green

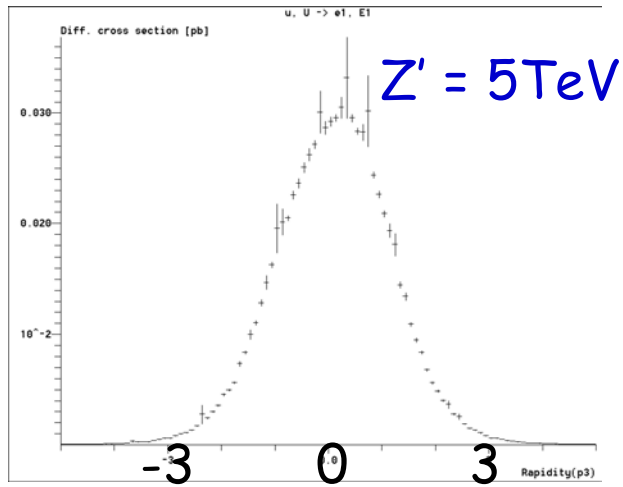
Naïve example: Z'→leptons



Factor 10 in luminosity extends the reach for Z' by 1-1.5 TeV.

η distr. of decay particles



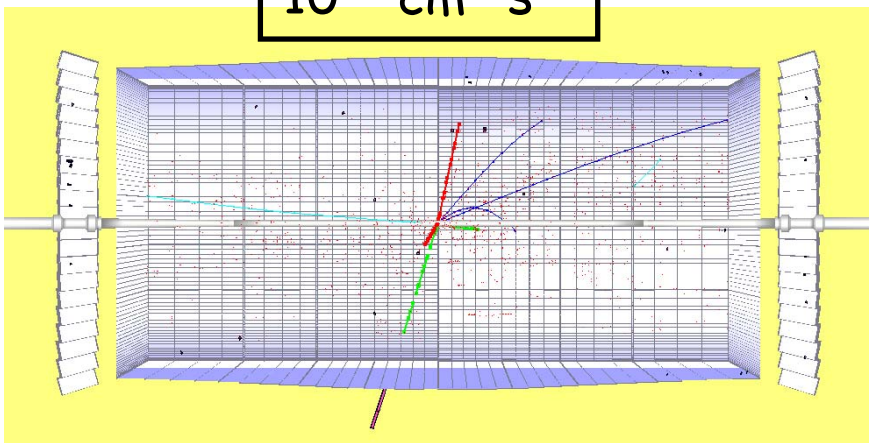


Heavy mass: more central

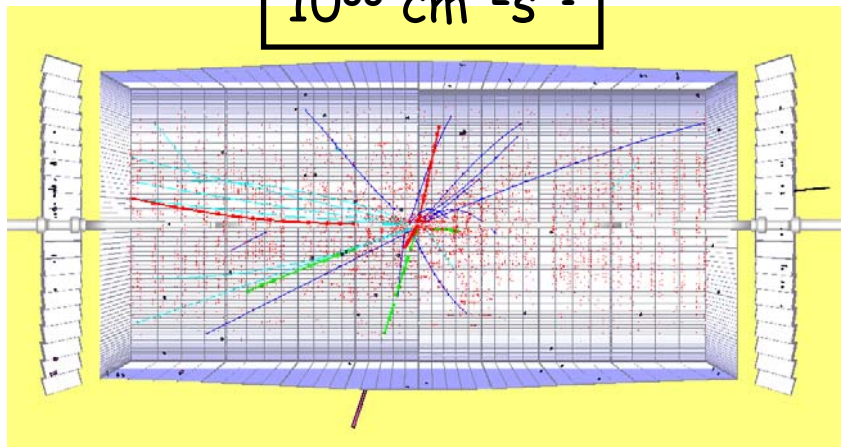
Luminosity effects

$H \rightarrow ZZ \rightarrow \mu\mu ee$ event with M_H= 300 GeV for different luminosities

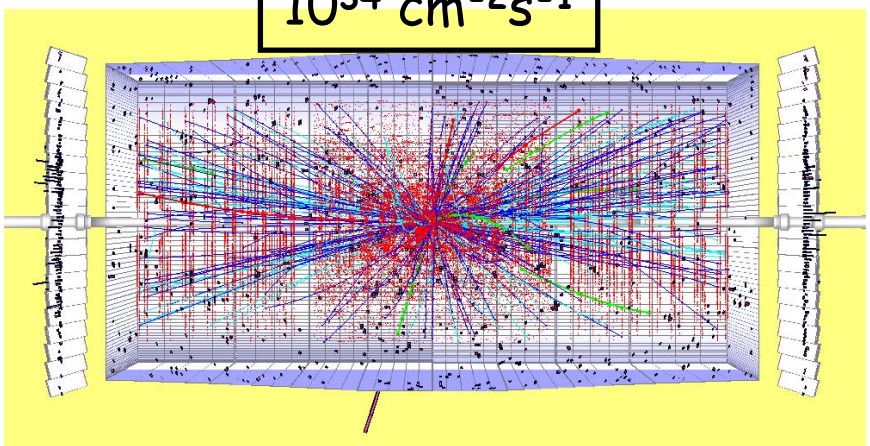
10^{32} cm^{-2}s^{-1}



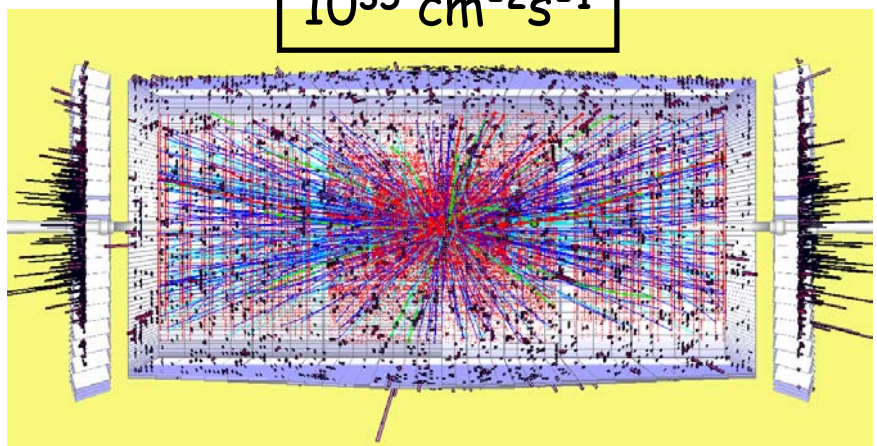
10^{33} cm^{-2}s^{-1}



10^{34} cm^{-2}s^{-1}



10^{35} cm^{-2}s^{-1}



Detectors Upgrades for SLHC

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

Jet E-resolution $\eta = 0$

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

u-jet rejection factor for ε (b)=50%

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

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

R&D necessary
hep-ph/0204087

Assumptions for the study

- **Detector Performance**
  - performance at $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} is comparable to that at 10^{34} cm^{-2}s^{-1} !!
- **Integrated Luminosity per Experiment**
  - 1000 (3000) fb^{-1} per experiment for 1 (3) year(s) of at $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}.

Physics Case for the SLHC

The use/need for for the SLHC will obviously depend on how EWSB and/or the new physics will manifest itself

Likely this will only be answered by LHC itself (except if the Tevatron…)

What will the HEP landscape look like in 2012??

Rough expectation for the SLHC versus LHC

- Improvement of SM/Higgs parameter determination
- Improvement of New Physics parameter determinations, if discovered
- Extension of the discovery reach in the high mass region
- Extension of the sensitivity of rare processes

Extending the Physics Potential of LHC

- **Electroweak Physics**
  - production of multiple gauge bosons ($n_V \geq 3$)
    - triple and quartic gauge boson couplings
  - top quarks/rare decays
- **Higgs physics**
  - rare decay modes
  - Higgs couplings to fermions and bosons
  - Higgs self-couplings
  - Heavy Higgs bosons of the MSSM
- **Supersymmetry**
- **Extra Dimensions**
  - Direct graviton production in ADD models
  - Resonance production in Randall-Sundrum models TeV^{-1} scale models
  - Black Hole production
- **Quark substructure**
- **Strongly-coupled vector boson system**
  - $W_L Z_L$ g $W_L Z_L$, $Z_L Z_L$ scalar resonance, $W^+_L W^+_L$
- **New Gauge Bosons**

Examples studied in some detail

CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

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Include pile up, detector…

Preliminary…

Electroweak Physics

Triple/quartic Gauge couplings

Production of multiple gauge bosons: statistics limited at LHC
E.g. # events with full leptonic decays, Pt>20 GeV/c, $|\eta|<2.5$, 90% eff for 6000 fb^{-1}

Process	WWW	WWZ	ZZW	ZZZ	$WWWW$	$WWWZ$
N(m_H=120 GeV)	2600	1100	36	7	5	0.8
N(m_H=200 GeV)	7100	2000	130	33	20	1.6

quintuple couplings?

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_1^Z	0.0038	0.0024	0.0023	0.0007	0.0050

Triple gauge couplings: $W\gamma$,WZ production

Use only muon and photon final state channels, statistical errors only
$\Rightarrow$ Equal or better than LC for λ type of couplings, worse for κ

Electroweak Physics

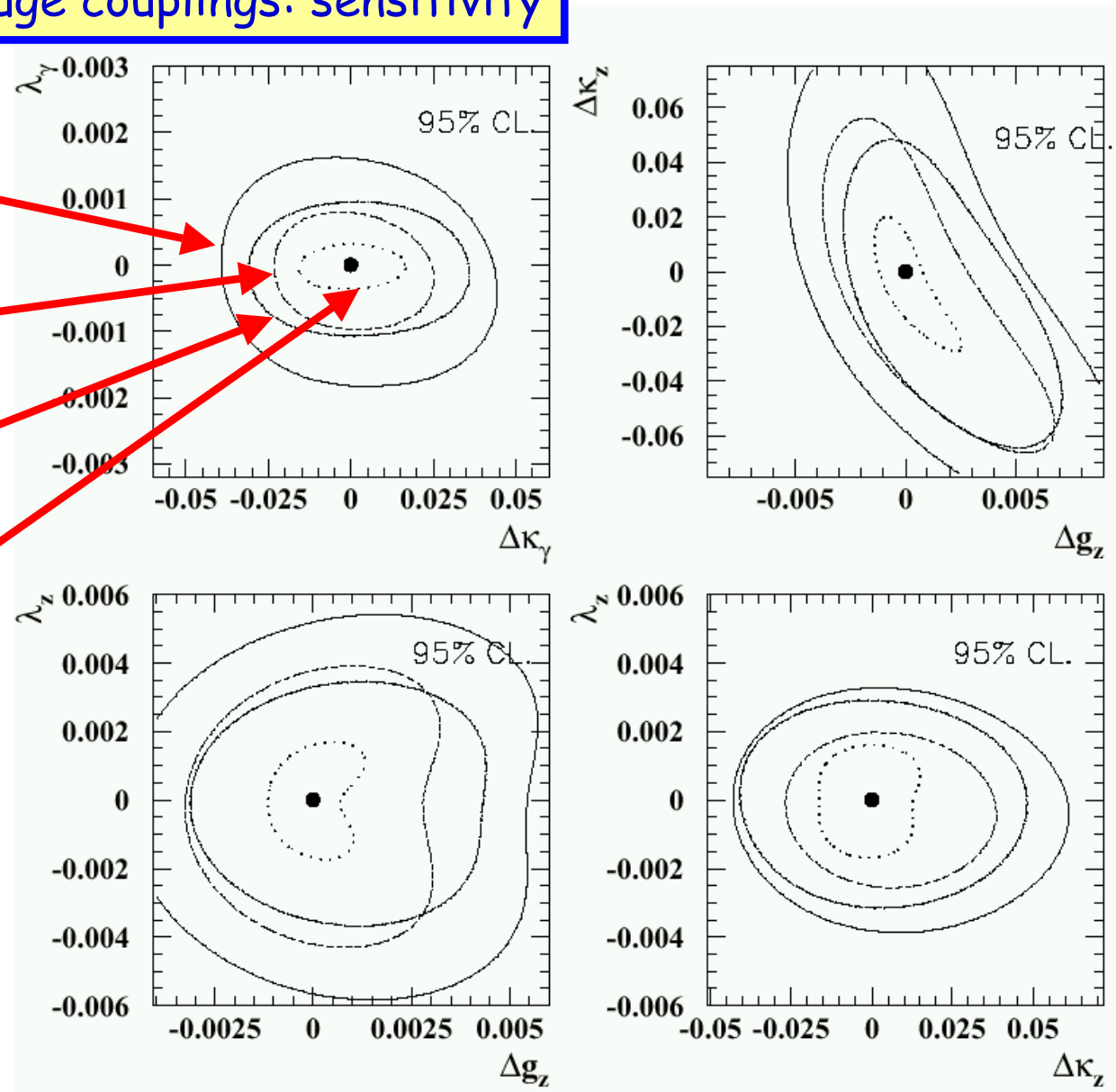
Triple gauge couplings: sensitivity

14 TeV 100 fb^{-1}

14 TeV 1000 fb^{-1}

28 TeV 100 fb^{-1}

28 TeV 1000 fb^{-1}



Sensitivity into the range expected from radiative corrections in the SM

Electroweak Physics

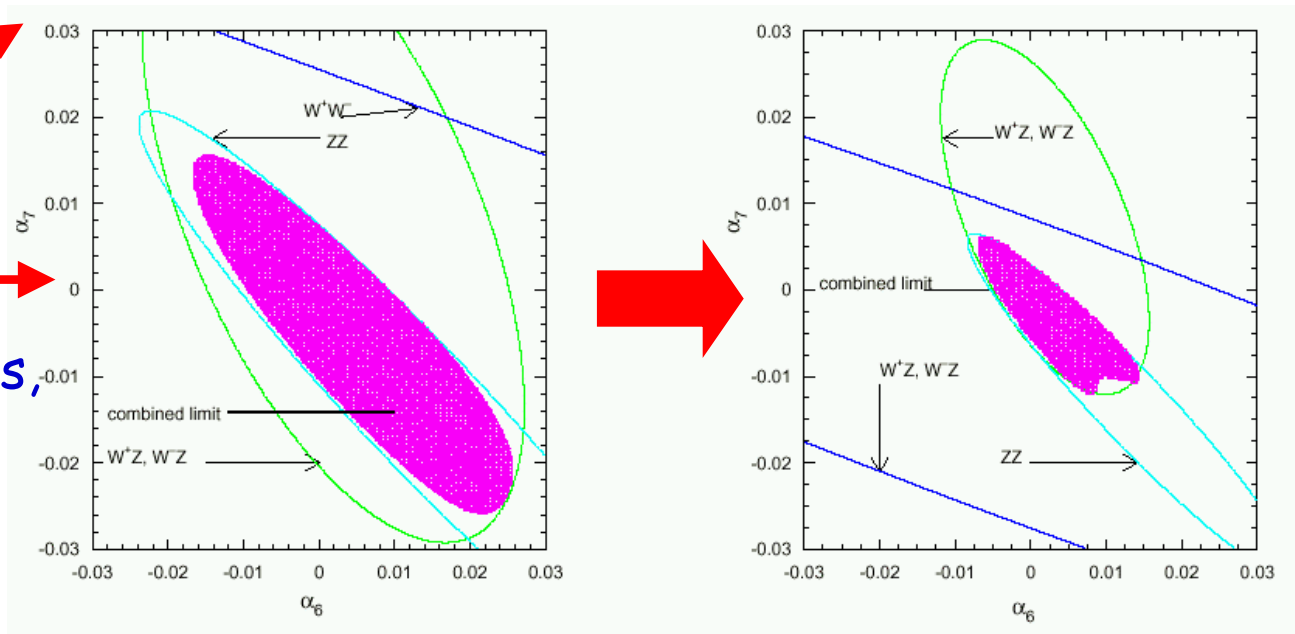
Quartic Gauge Couplings study pp → qqVV →jjVV (V=W,Z)

A. S. Belyaev et al:
Operators leading to genuine quartic vertices

$$\mathcal{L}_4 = \alpha_4 \left[\mathrm{Tr}\,(V_\mu V_\nu)\right]^2 ,$$
$$\mathcal{L}_5 = \alpha_5 \left[\mathrm{Tr}\,(V_\mu V^\mu)\right]^2 ,$$
$$\mathcal{L}_6 = \alpha_6\, \mathrm{Tr}\,(V_\mu V_\nu)\, \mathrm{Tr}\,(TV^\mu)\, \mathrm{Tr}\,(TV$$
$$\mathcal{L}_7 = \alpha_7\, \mathrm{Tr}\,(V_\mu V^\mu) \left[\mathrm{Tr}\,(TV^\nu)\right]^2 ,$$
$$\mathcal{L}_{10} = \frac{\alpha_{10}}{2} \left[\mathrm{Tr}\,(TV_\mu)\ \mathrm{Tr}\,(TV_\nu)\right]^2 .$$

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	$-120. \le \alpha_4 \le 11.$	$-1.1 \le \alpha_4 \le 11.$	$-0.67 \le \alpha_4 \le 0.74$	$-0.92 \le \alpha_4 \le 1.1$
α_5	$-300. \le \alpha_5 \le 28.$	$-2.2 \le \alpha_5 \le 7.7$	$-1.2 \le \alpha_5 \le 1.2$	$-1.7 \le \alpha_5 \le 1.7$
α_6	$-20. \le \alpha_6 \le 1.8$	$-9.6 \le \alpha_6 \le 9.1$	$-3.5 \le \alpha_6 \le 3.2$	$-4.3 \le \alpha_6 \le 3.9$
α_7	$-19. \le \alpha_7 \le 1.8$	$-10. \le \alpha_7 \le 7.4$	$-4.4 \le \alpha_7 \le 2.2$	$-5.4 \le \alpha_7 \le 2.8$
α_{10}	$-21. \le \alpha_{10} \le 1.9$	$-24. \le \alpha_{10} \le 24.$	$-4.1 \le \alpha_{10} \le 4.1$	$-4.8 \le \alpha_{10} \le 4.8$

Results for events with full leptonic decays, P_t>20 GeV/c, |η|<2.5, 90% eff. (conservative)



Top Quark

LHC: $\Delta M(top)$ down to 1.0 GeV (and ΔM_W down to 15 MeV)

⇒Limited by systematics/no significant improvement expected

Statistics can still help for rare decays

$t \to q\gamma$

b-tagging	ideal	real.	μ-tag
600 fb^{-1}	0.48	0.88	3.76
6000 fb^{-1}	0.14	0.26	0.97

$t \to qg$

b-tagging	ideal	real.	μ-tag
600 fb^{-1}	22.3	60.8	210.
6000 fb^{-1}	7.04	19.2	66.2

$t \to qZ$

b-tagging	ideal	real.	μ-tag
600 fb^{-1}	0.46	1.1	83.3
6000 fb^{-1}	0.05	0.11	8.3

Results in units of 10^{-5}

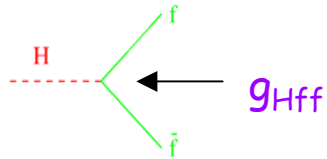
Ideal = MC 4-vector
Real = B-tagging/cuts as for $10^{34} cm^{-2} s^{-1}$
μ-tag = assume only B-tag with muons works at $10^{35} cm^{-2} s^{-1}$

Can reach sensitivity down to ~10^{-6} BUT vertex b-tag a must at $10^{35} cm^{-2} s^{-1}$

Higgs at SLHC

Higgs couplings!

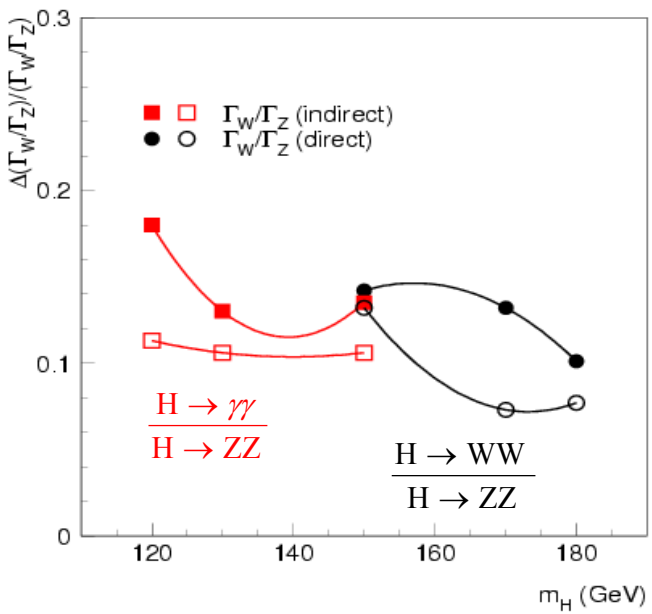
Couplings obtained from measured rate in a given production channel:



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

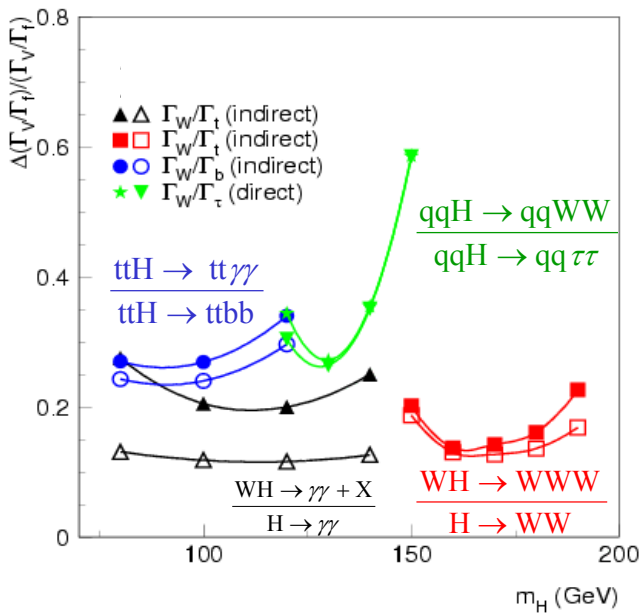
→ deduce $\Gamma_f \sim g^2_{Hff}$

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



Closed symbols:
LHC 600 fb^{-1}

Open symbols:
SLHC 6000 fb^{-1}



SLHC could improve LHC precision by up to ~ 2

Rare Higgs Decays

Channels studied:

- $H \to Z\gamma \to \ell\ell\gamma$
- $H \to \mu\mu$

BR ~ 10^{-4} for these channels!
Cross section ~ few fb

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

3000 fb^{-1}

Channel	m_H	$S/\sqrt{B}$ LHC (600 fb^{-1})	$S/\sqrt{B}$ SLHC (6000 fb^{-1})
$H \to Z\gamma \to \ell\ell\gamma$	~ 140 GeV	~ 3.5	~ 11
$H \to \mu\mu$	130 GeV	~ 3.5 (gg+VBF)	~ 9.5 (gg)

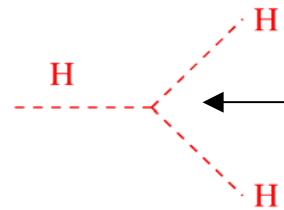
Additional coupling measurements :
e.g. Γ_μ / Γ_W to ~ 20%

Note: also a challenge at a LC: e.g. $\Delta g_{H\mu\mu}$ ~ 16 % for 1 ab^{-1} at 800 GeV

Higgs Self Coupling Measurements

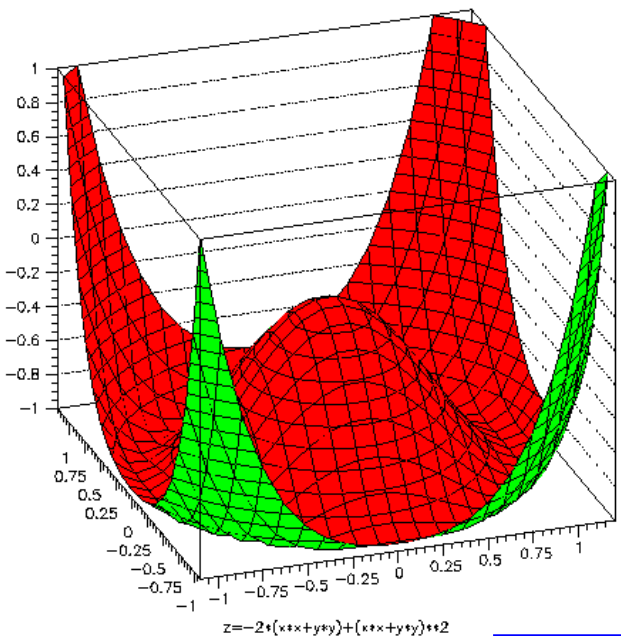
Once the Higgs particle is found, try to reconstruct the Higgs potential

$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

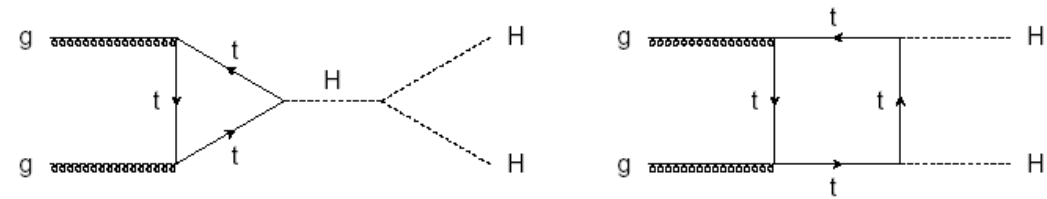


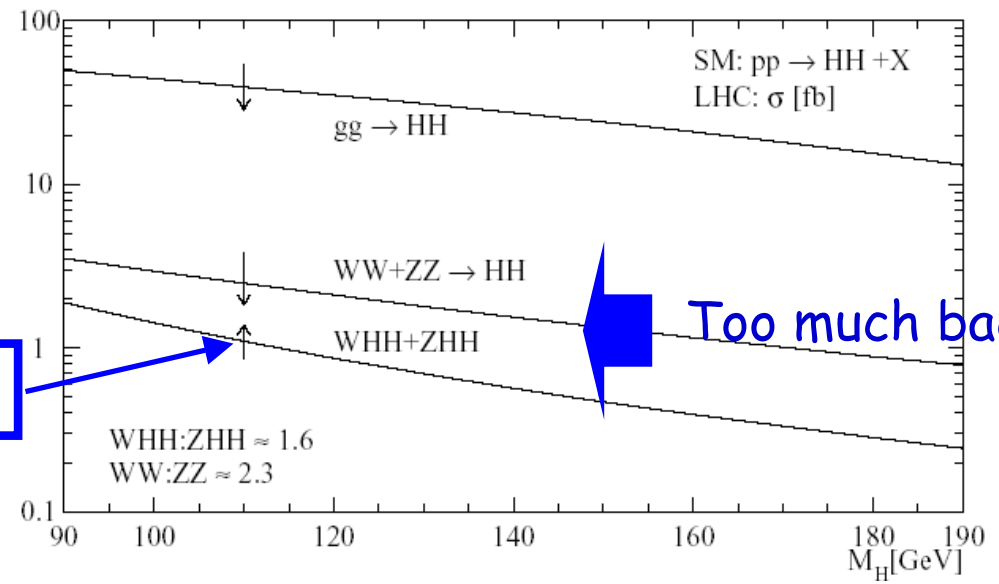
$\sim \lambda v$

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



g g --> H H





Djouadi et al.

Dawson et al.

Too much backgr.

$\lambda/2 < \lambda < 3\lambda/2$

Difficult/impossible at the LHC

Higgs Self Couplings

Atlas Study
Detector Simulation

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

SLHC : HH $\rightarrow$ $W^+ W^- W^+ W^-$ $\rightarrow$ $\ell^\pm \nu jj$ $\ell^\pm \nu jj$ studied

6000 fb^{-1}	S	S/B	S/$\sqrt{B}$
m_H = 170 GeV	350	8%	5.4
m_H = 200 GeV	220	7%	3.1

Mass (GeV)	200	200 (fit)	170
$\frac{d\sigma}{\sigma}$	27%	17%	20%
$\frac{d\lambda}{\lambda}$	25%	15%	19%

-- HH production may be observed for first time at SLHC: ~150 <M_H<200 GeV
-- λ may be measured with statistical error ~ 20-25%

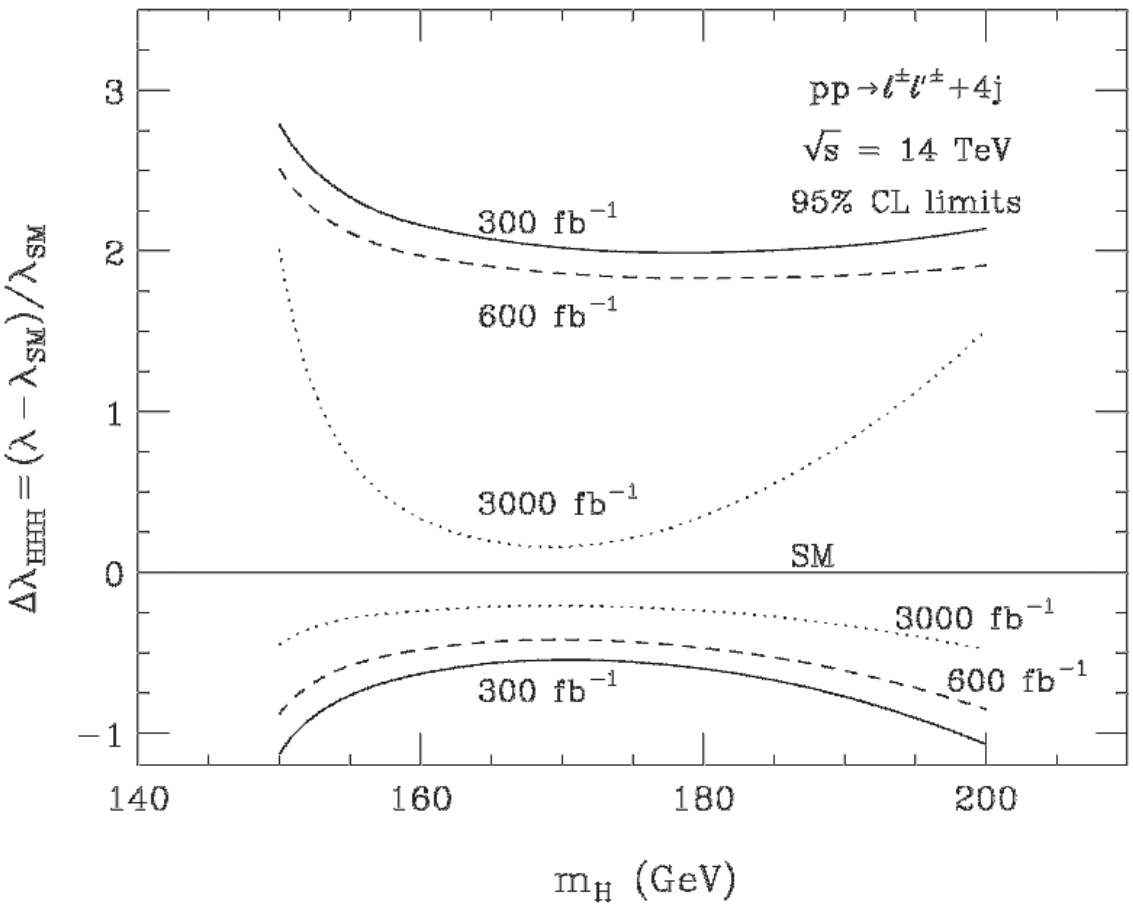
LC : precision up to 20-25% but for M_H < 150 GeV ($\sqrt{s} \geq$ 500-800 GeV, 1000 fb^{-1})
or to ~7-10% for M_H < 200 GeV ($\sqrt{s} \geq$ 3 TeV, 5000 fb^{-1})

Higgs Self Coupling

Baur, Plehn, Rainwater

$HH \rightarrow W^+ W^- W^+ W^- \rightarrow \ell^\pm \nu jj \;\; \ell^\pm \nu jj$

Limits achievable at the 95% CL. for $\Delta\lambda = (\lambda - \lambda_{SM})/\lambda_{SM}$



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

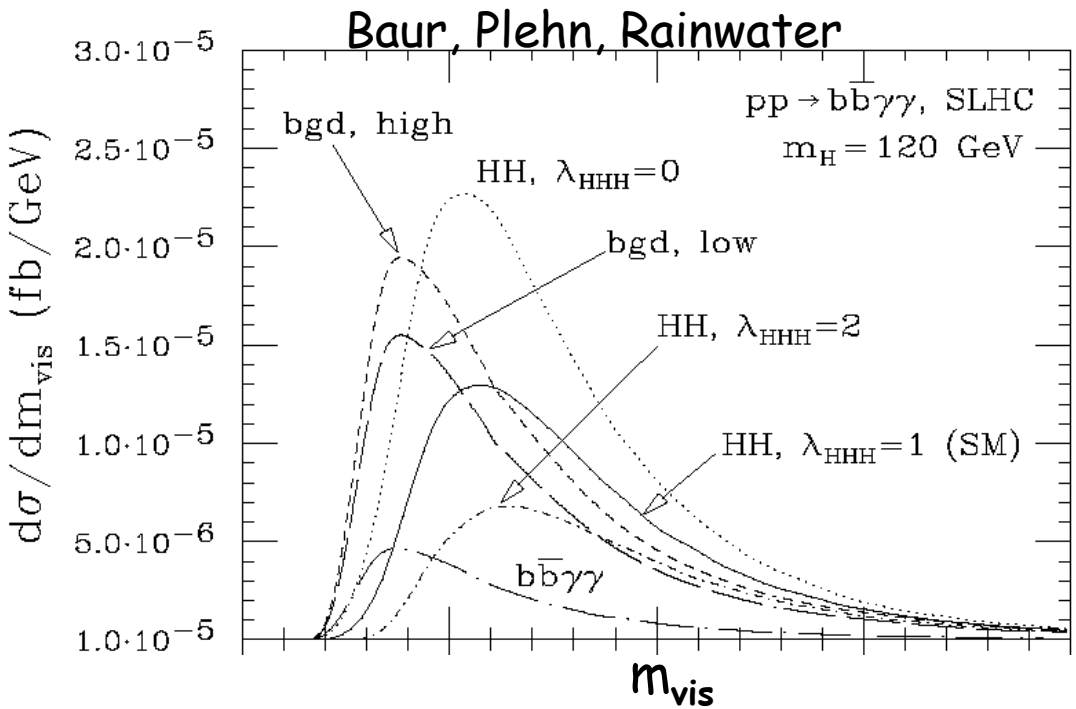
SLHC: λ can be determined to 20-30% (95% CL)

Differences w/t ATLAS study

- Parton level ⇔ Detector Level
- ATLAS includes parton showers
- HO cross sections & effects
- Incorrect simulation ttj in ATLAS study?

⇒ Jury still out… CMS starting

Higgs Self Coupling for low M_H



pp→bbbb not useable
pp→bbττ difficult
pp→bbμμ not useable

New

pp→bbγγ promising

- For m_H=120 GeV and 600 fb^{-1} expect 6 events at the LHC with S/B~ 2 (single b tag)
- Interesting measurement at the SLHC (double b tag)

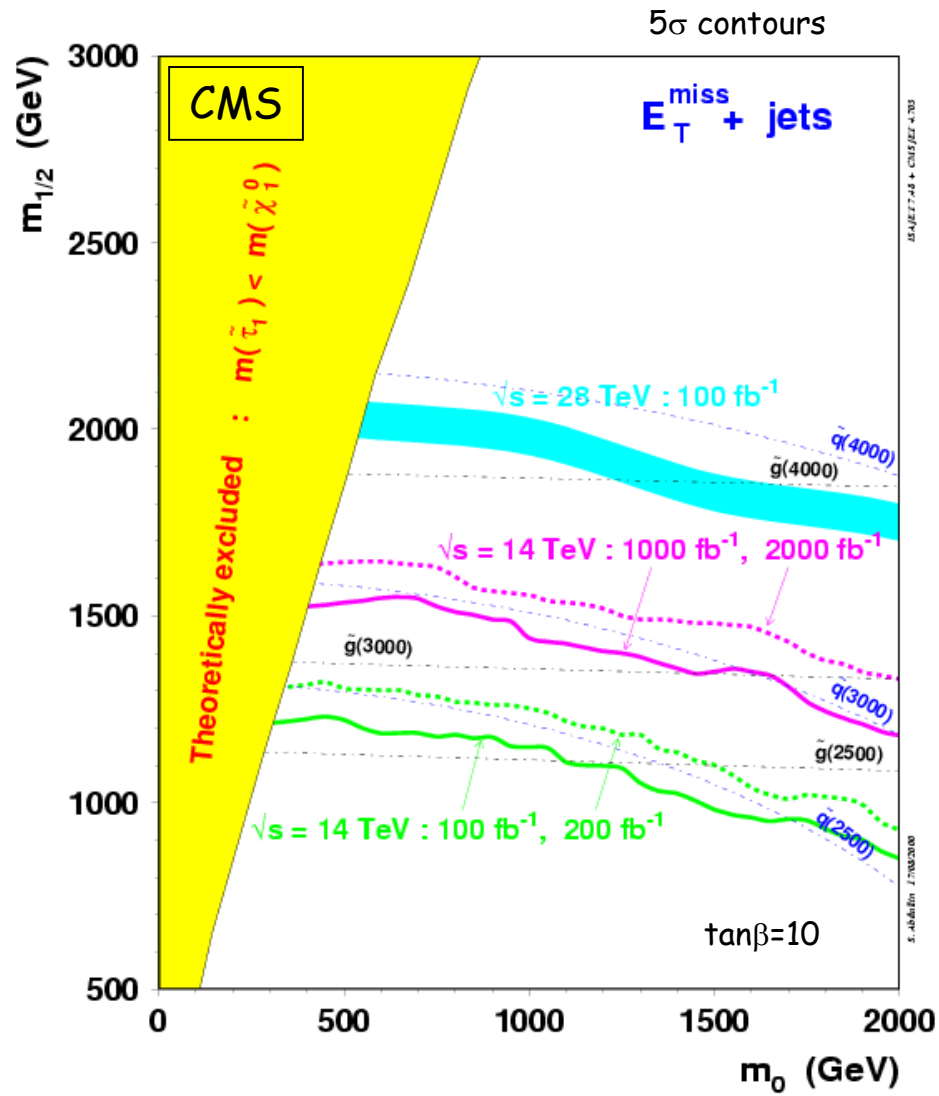
	m_H = 120 GeV			m_H = 140 GeV		
machine	"hi"	"lo"	bkg. sub.	"hi"	"lo"	bkg. sub.
LHC, 600 fb^{-1}	$^{+1.9}_{-1.1}$	$^{+1.6}_{-1.1}$	$^{+0.94}_{-0.74}$	$^{-}_{-}$	$^{-}_{-}$	$^{-}_{-}$
SLHC, 6000 fb^{-1}	$^{+0.82}_{-0.66}$	$^{+0.74}_{-0.62}$	$^{+0.52}_{-0.46}$	$^{+1.7}_{-0.9}$	$^{+1.4}_{-0.8}$	$^{+0.76}_{-0.58}$
VLHC, 600 fb^{-1}	$^{+0.44}_{-0.42}$	$^{+0.42}_{-0.40}$	$^{+0.32}_{-0.30}$	$^{+0.82}_{-0.62}$	$^{+0.66}_{-0.54}$	$^{+0.38}_{-0.34}$
VLHC, 1200 fb^{-1}	$^{+0.32}_{-0.30}$	$^{+0.30}_{-0.28}$	$^{+0.26}_{-0.22}$	$^{+0.76}_{-0.58}$	$^{+0.62}_{-0.50}$	$^{+0.36}_{-0.32}$

Needs accurate prediction of the bbγγ background rate
Needs detector simulation

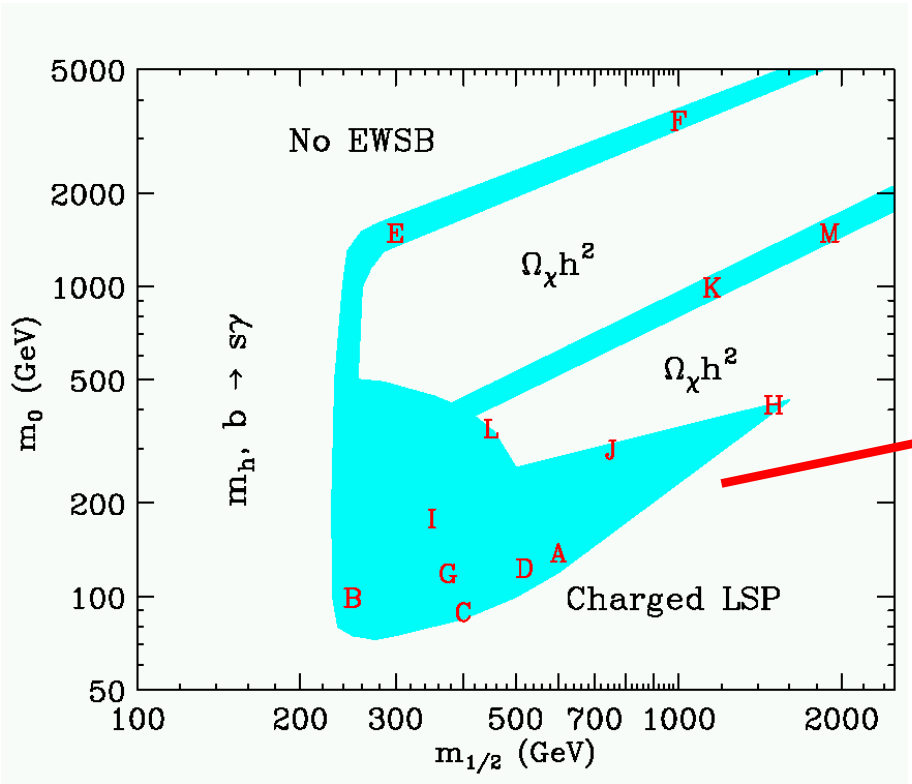
Supersymmetry

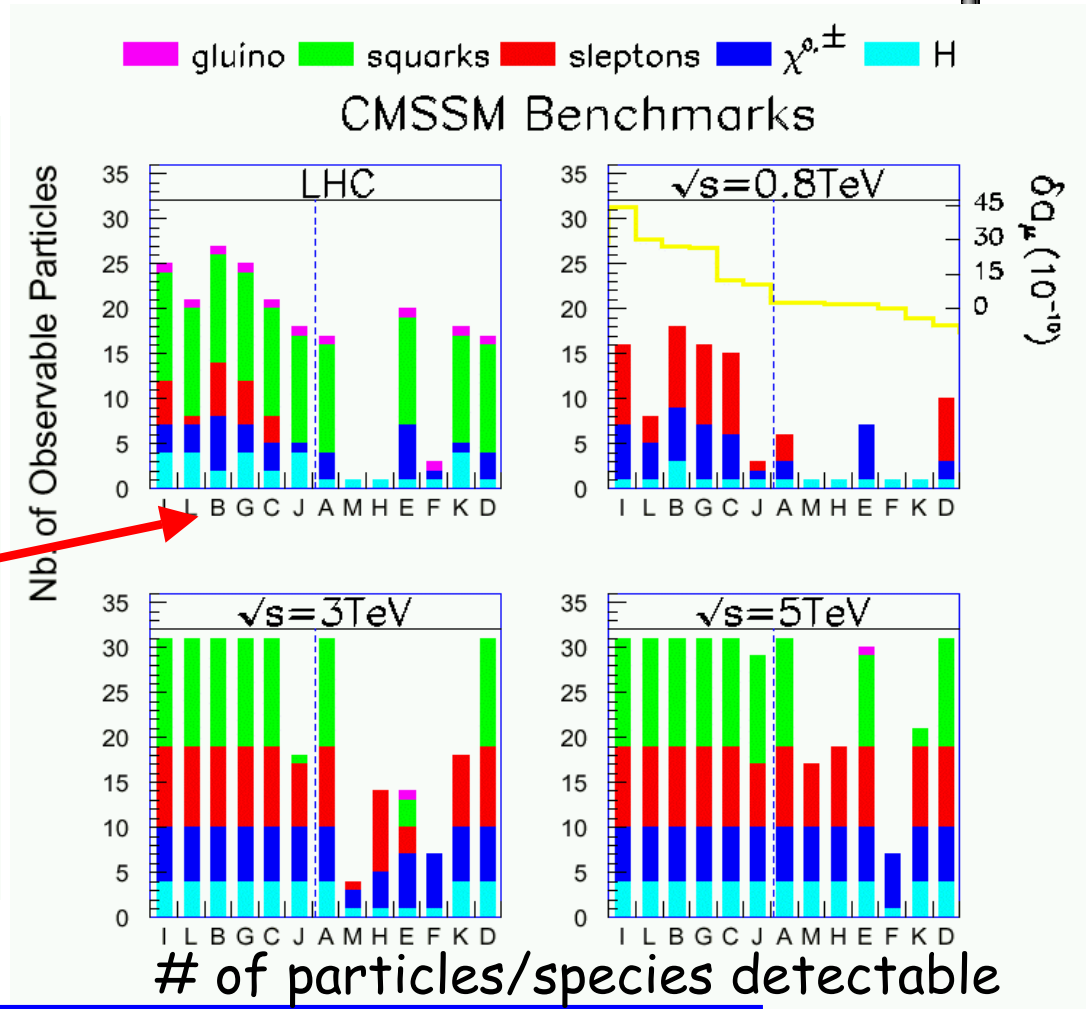
Impact of the SLHC
Extending the discovery region by roughly 0.5 TeV i.e. from
~2.5 TeV → 3 TeV

This extension involved high E_T jets/leptons and missing E_T
⇒ Not compromised by increased pile-up at SLHC



SUSY Measurements





Benchmark points (Battaglia et al./2001)
Difficult points F,H,K, (M) …high masses/low event rate
High Luminosity beneficial to complete further the spectra

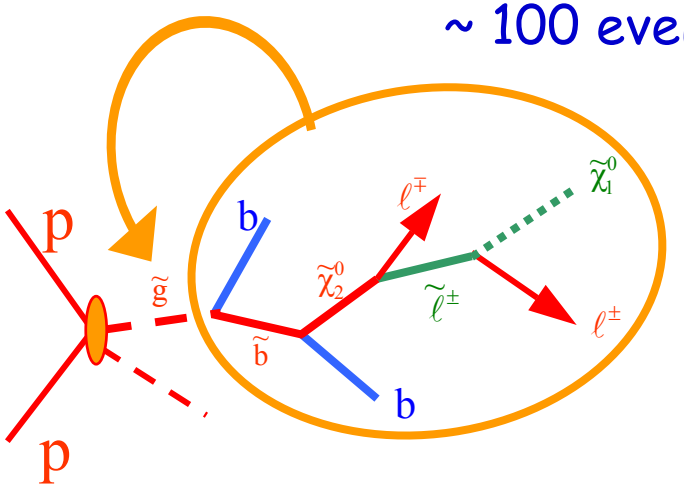
Sparticle Mass Measurements

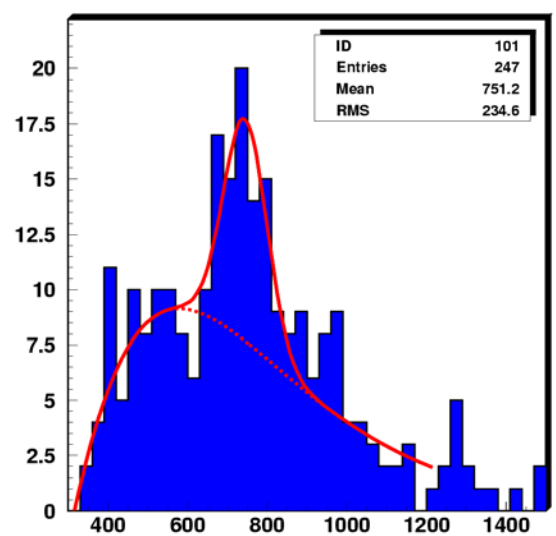
Proposed Post-LEP Benchmarks for Supersymmetry (hep-ph/0106204)

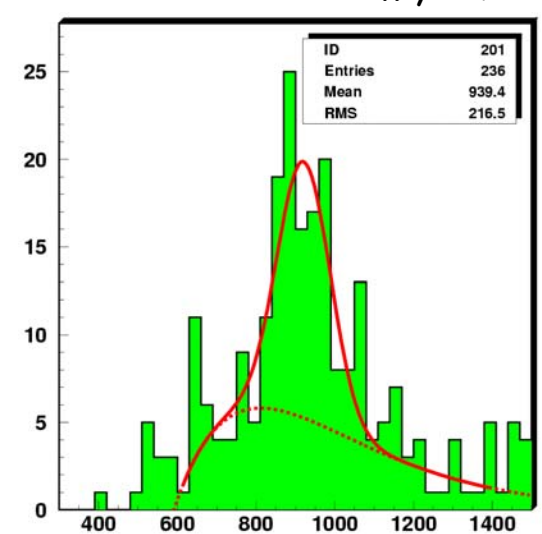
Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
$\mathrm{sign}(\mu)$	+	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	120	123	121	121	123	120	122	117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

After cuts
~ 100 events

Tricomi, Chiorboli







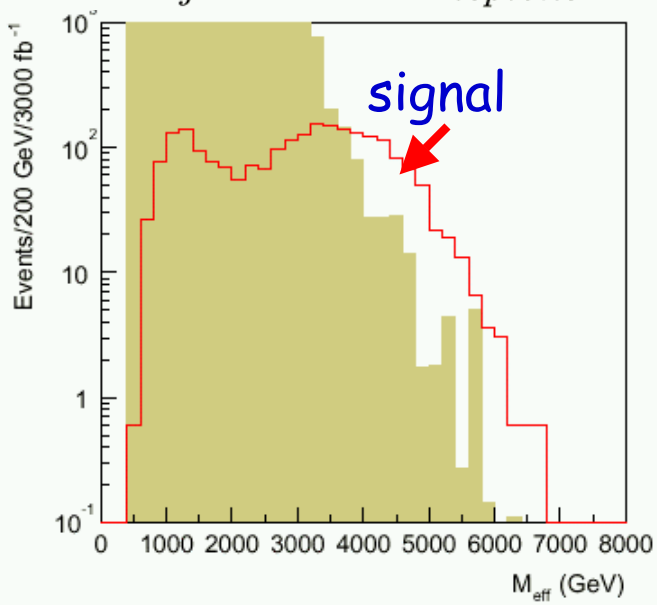
Reconstruction of sbottom (770 GeV) and gluino (920 GeV) for 300 fb^{-1}
$\Rightarrow$ will need more luminosity!

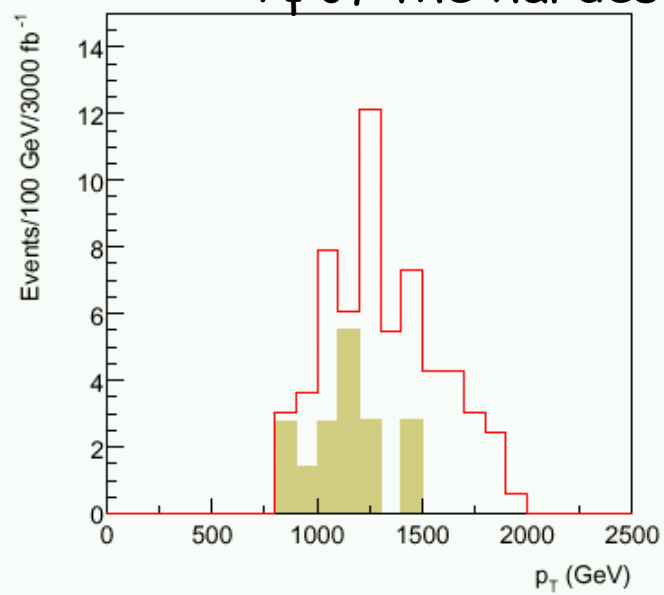
Example: Point K

Squarks: 2.0-2.4 TeV Gluino: 2.5 TeV
Can discover the squarks at the LHC but cannot really study them

$$M_{eff} = E_T^{miss} + \sum_{jets} E_{T,jet} + \sum_{leptons} E_{T,lepton}$$

P_t >700 GeV & E_t^{miss}>600 GeV
P_t of the hardest jet



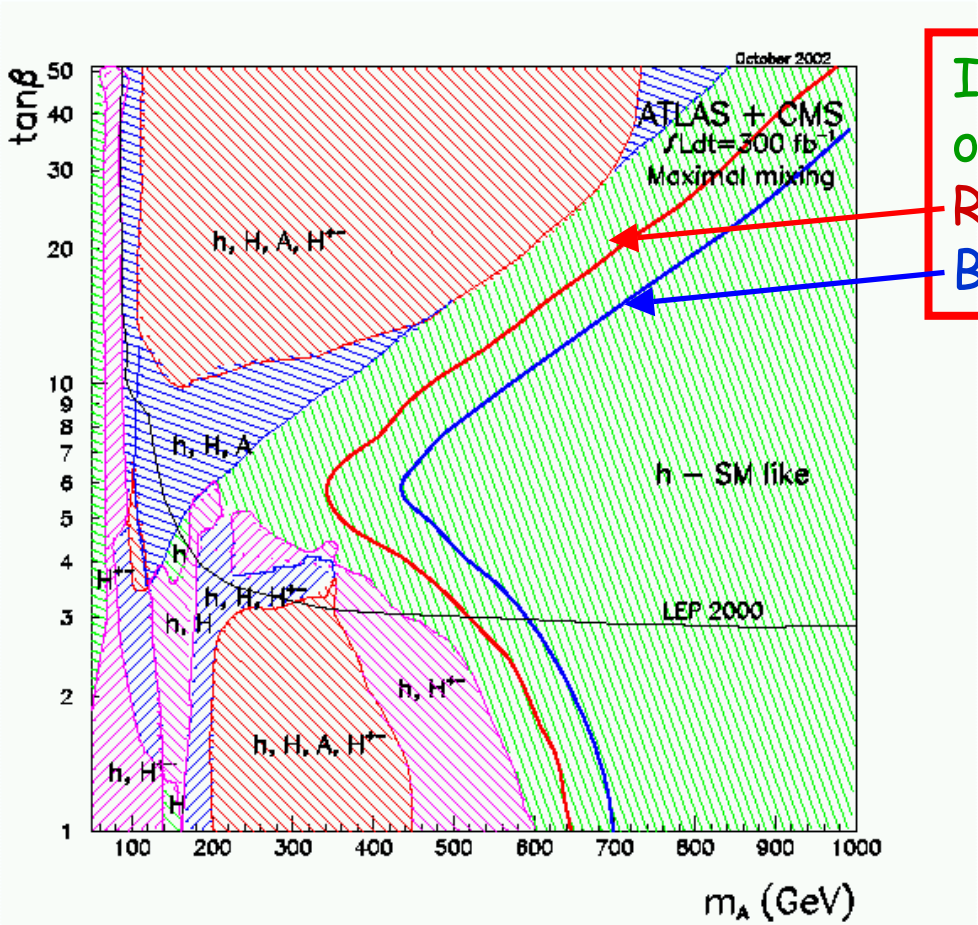


Inclusive: M_{eff} > 4000 GeV
S/B = 500/100 (3000 fb^{-1})

Measurements become possible

Exclusive channel
$\tilde{q}\tilde{q} \rightarrow \chi_1^0 \chi_1^0 qq$
S/B =120/30 (3000 fb^{-1})

MSSM Higgs h,H,A,H±

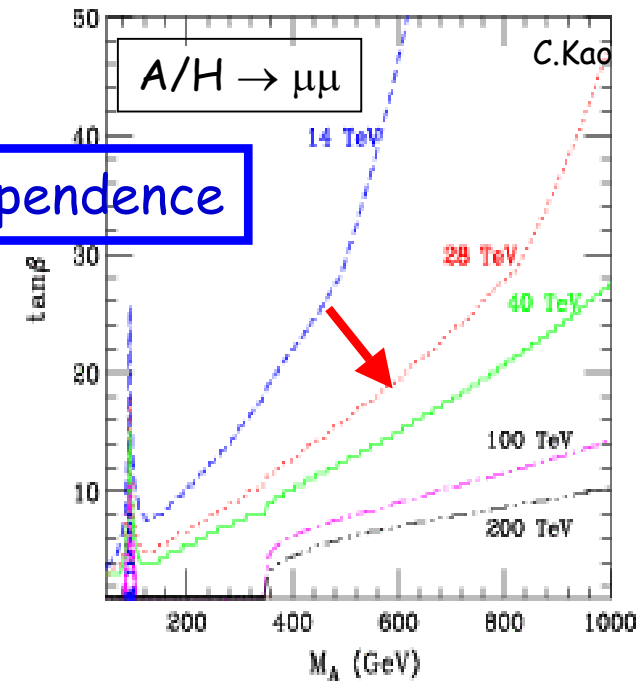


In the green region only SM-like h observable with 300 fb^{-1}/exp

Red line: extension with 3000 fb^{-1}/exp

Blue line: 95% excl. with 3000 fb^{-1}/exp

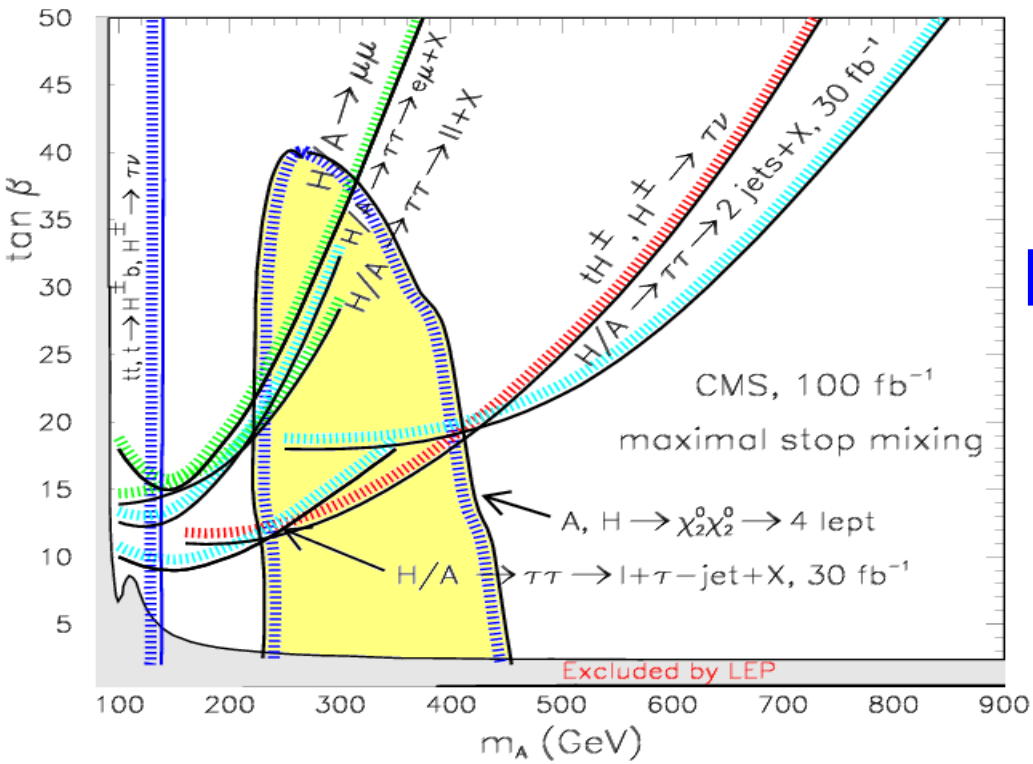
Energy dependence



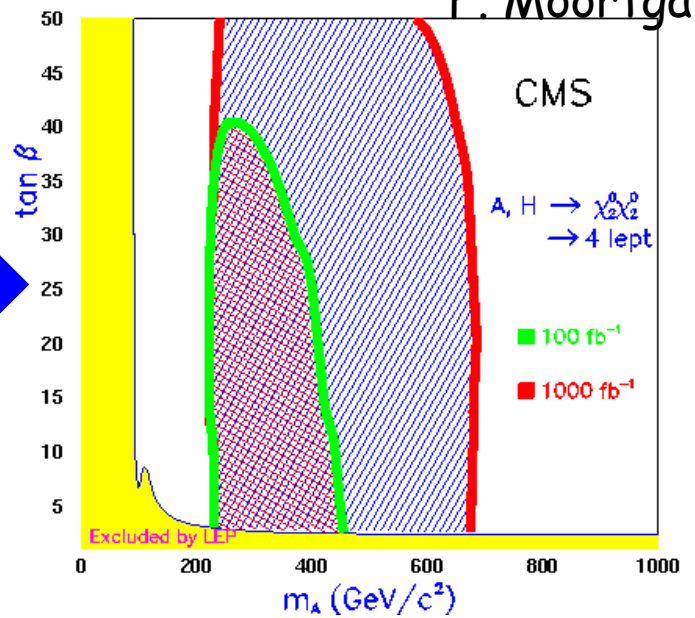
Heavy Higgs observable region increased by ~100 GeV.

Other ways to 'cover the wedge'

Use decays of H,A into SUSY particles, where kin. allowed



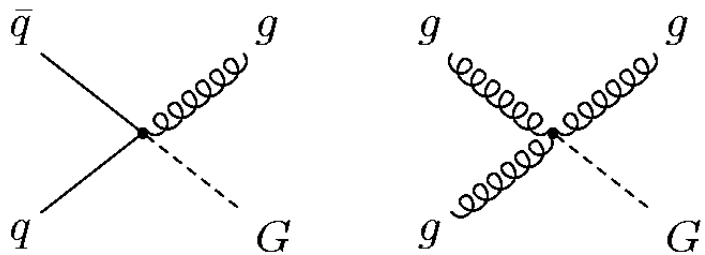
F. Moortgat



$A/H \rightarrow \chi\chi \rightarrow 4$ leptons

Strongly model/MSSM parameter dependent $M_2 = 120$ GeV,
$\mu = -500$ GeV,
$M_{sleptons} = 2500$ GeV,
$M_{squark,\ gluino} = 1$TeV

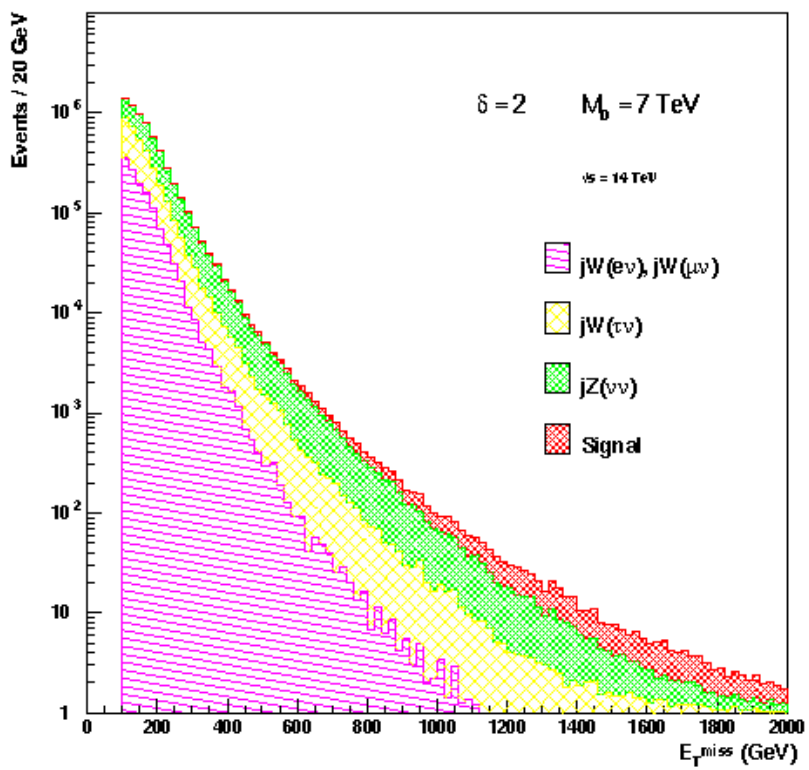
Extra Dimension Signals at the LHC

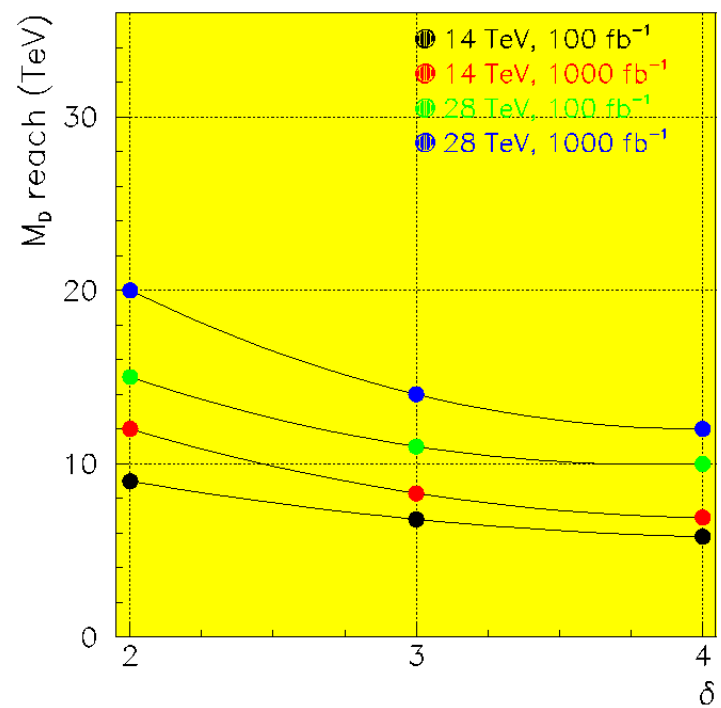


Graviton production!
Graviton escapes detection

ADD type of ED's

Signal: single jet + large missing ET

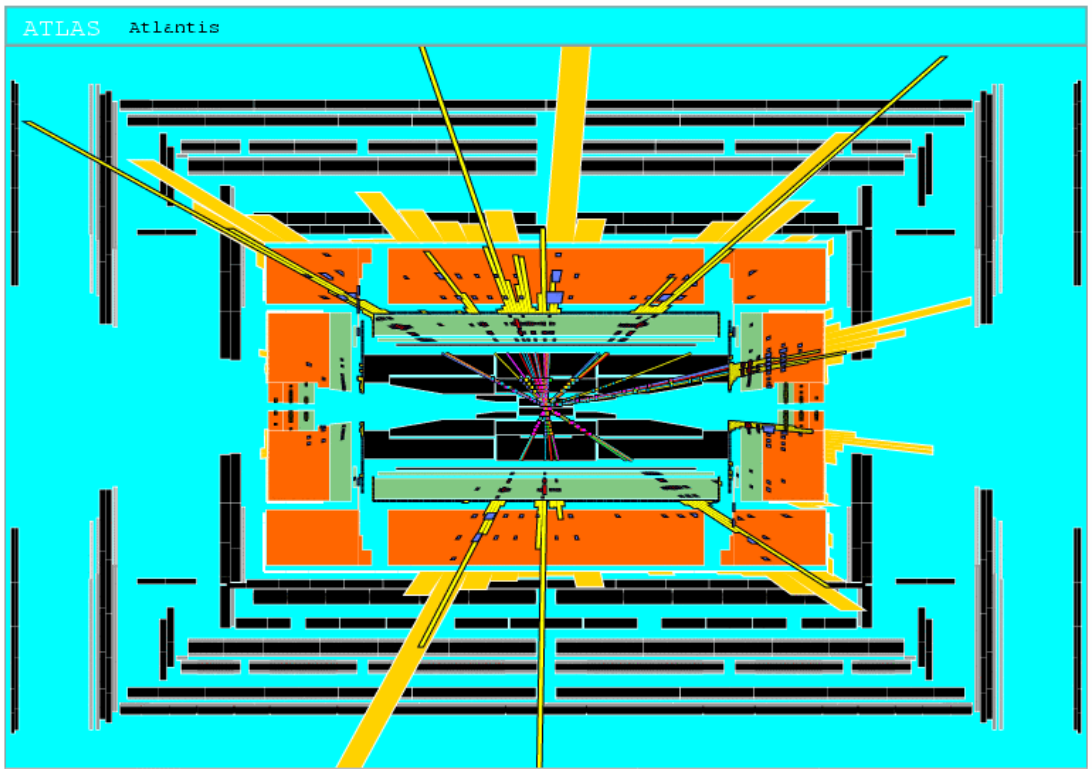




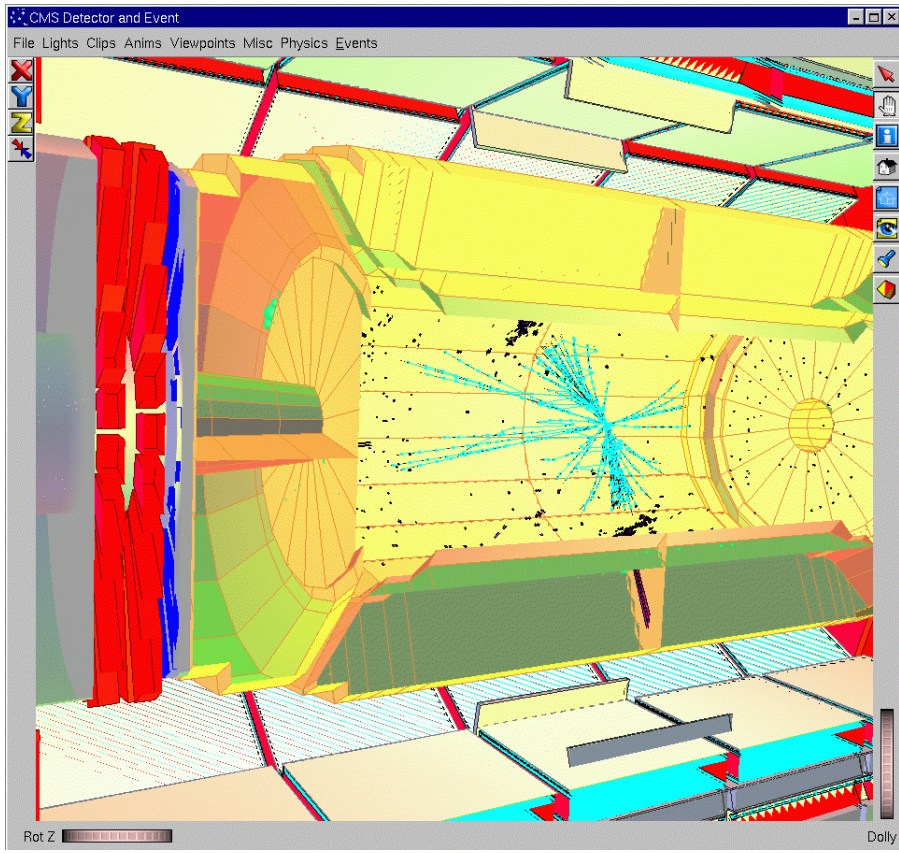
Extra Dimensions at (S)LHC

Large extra dimensions → black holes in the lab?

A **black hole event** with $M_{BH} \sim 8$ TeV in ATLAS
Spectacular signature !

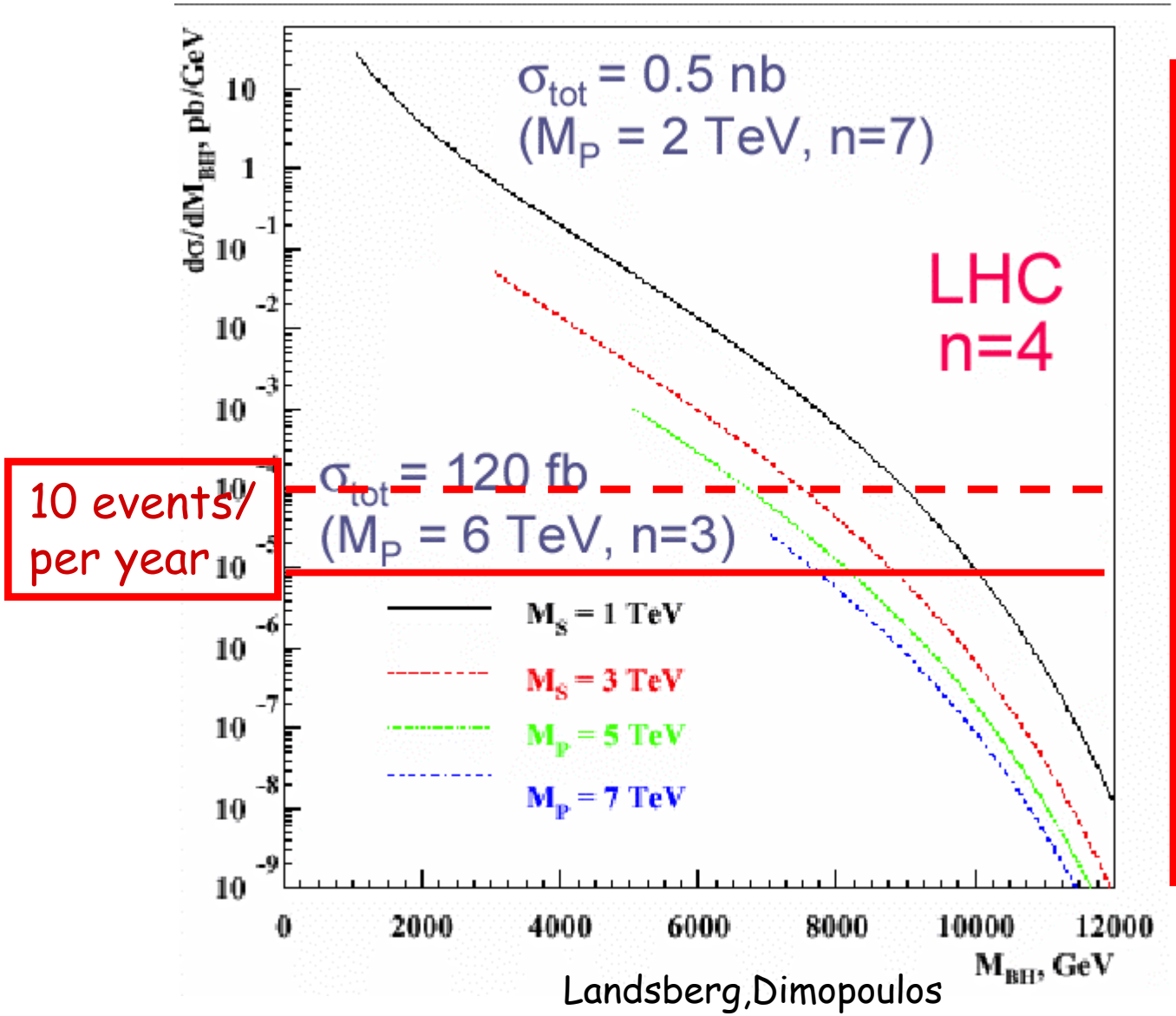


...and in CMS



Black holes decay immediately ($\tau \sim 10^{-26}$ s)
by Hawking radiation (democratic evaporation) :
large multiplicity, small missing E, jets/leptons ~ 5

Black Holes



Example:
Cross sections for black holes can be very large

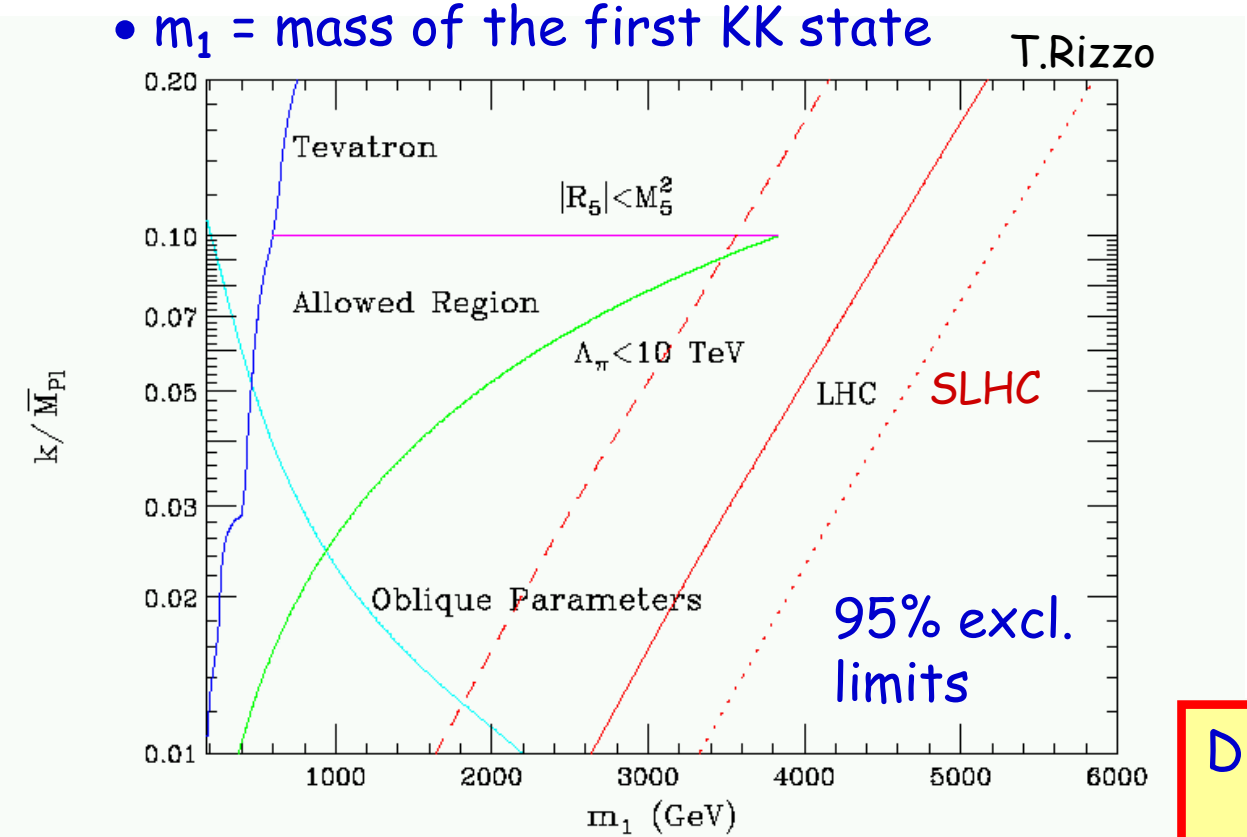
May dominate the particle production at the LHC

But can also be statistics limited for large M_S and M_{BH} (add ~ 1 TeV)

Other Extra Dimension Scenarios

Randall Sundrum model

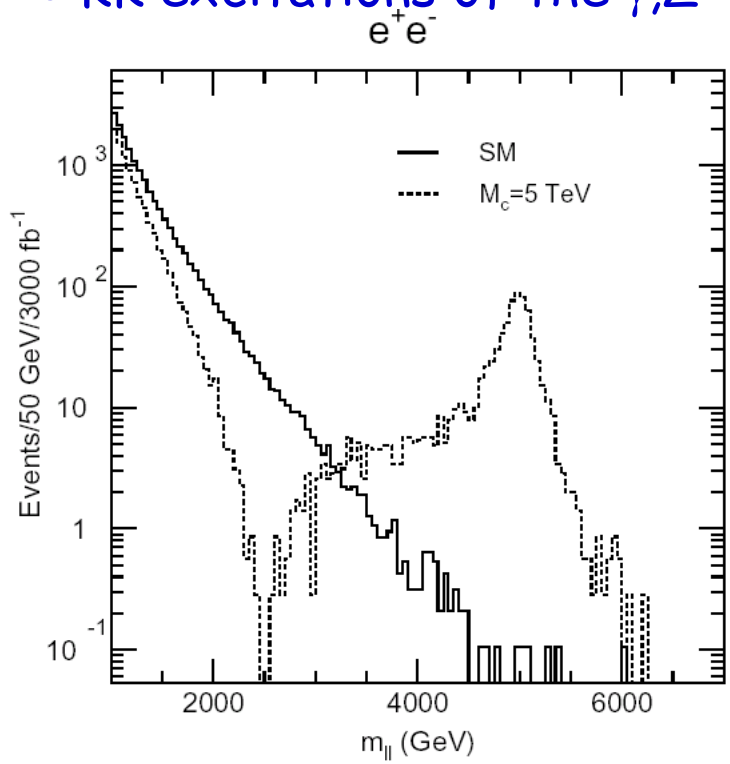
- Predicts KK graviton resonances
- k= curvature of the 5-dim. Space
- m_1 = mass of the first KK state



100→1000 fb^{-1}: Increase in reach by 25%

TeV scale ED's

- KK excitations of the γ,Z

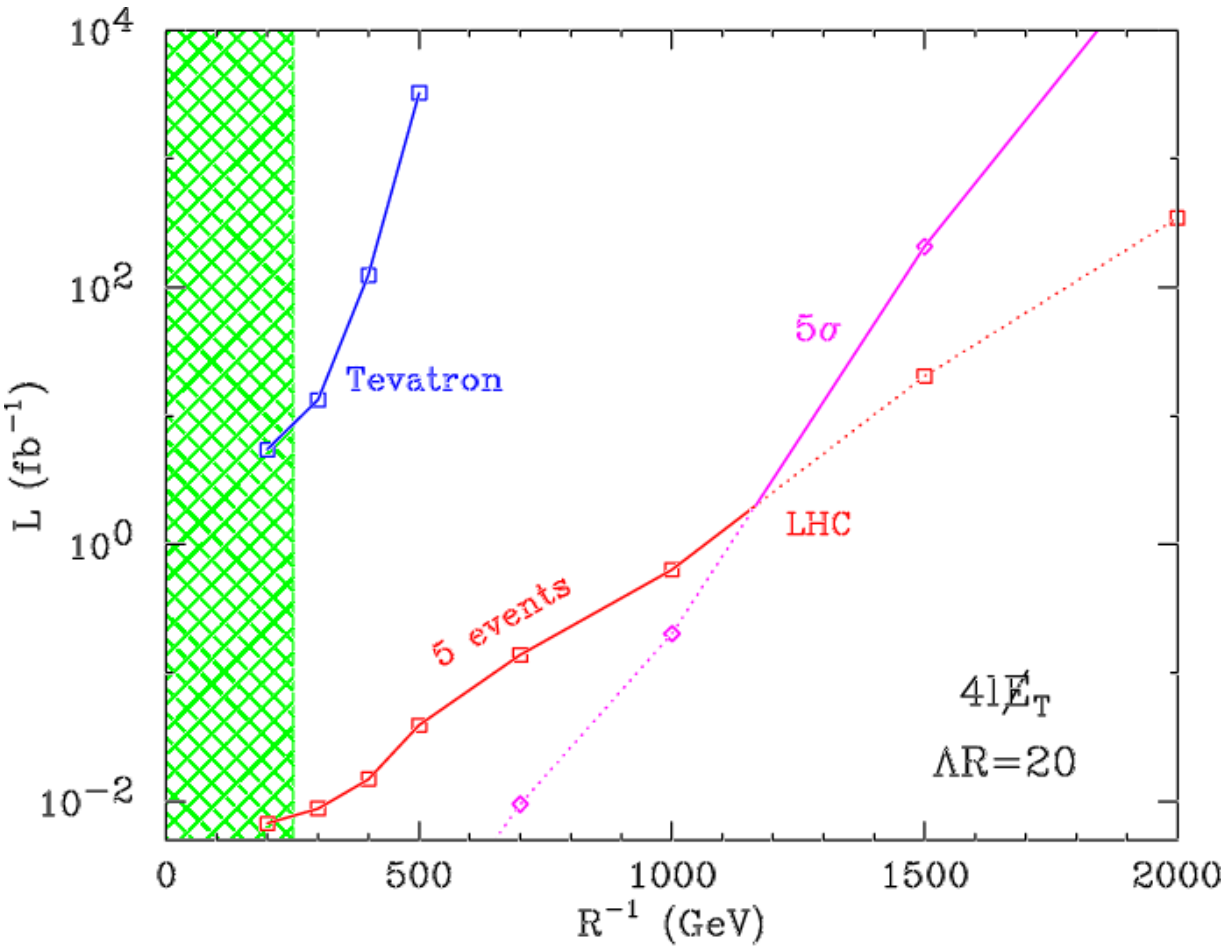


Direct:	LHC/600 fb^{-1}	6 TeV
	SLHC/6000 fb^{-1}	7.7 TeV
Interf:	SLHC/6000 fb^{-1}	20 TeV

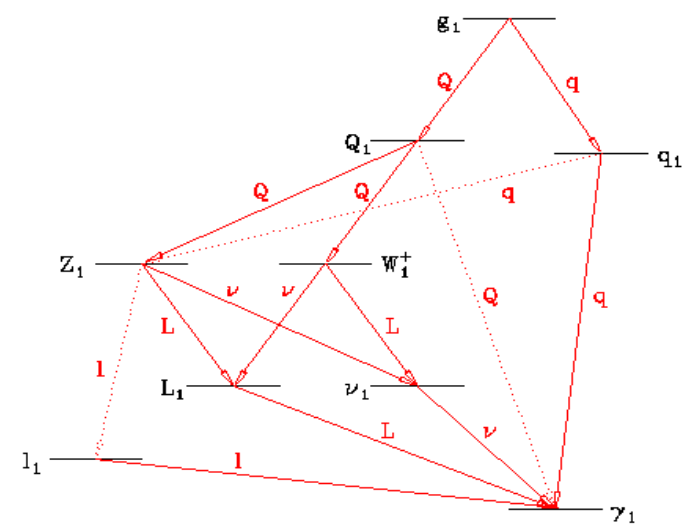
Universal Extra Dimensions

Everybody in the bulk!

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314



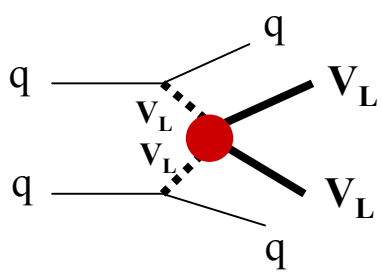
Search: e.g 4 leptons + E_T^{miss}



Increase of the sensitivity to R^{-1} from 1.5 TeV to 2 TeV

Strongly Coupled Vector Boson System

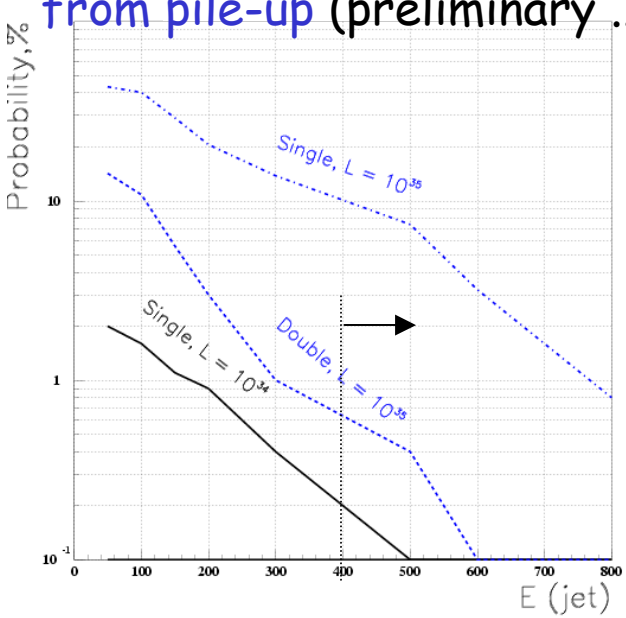
If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at $\sqrt{\hat{s}} \approx \mathrm{TeV}$



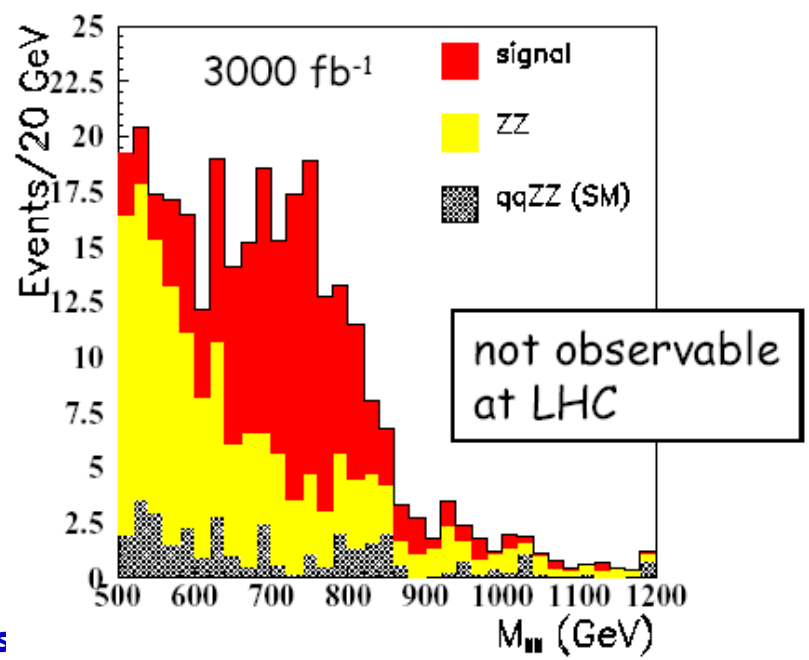
Difficult at LHC. What about SLHC?

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

Fake fwd jet tag ($|\eta| > 2$) probability from pile-up (preliminary ...)



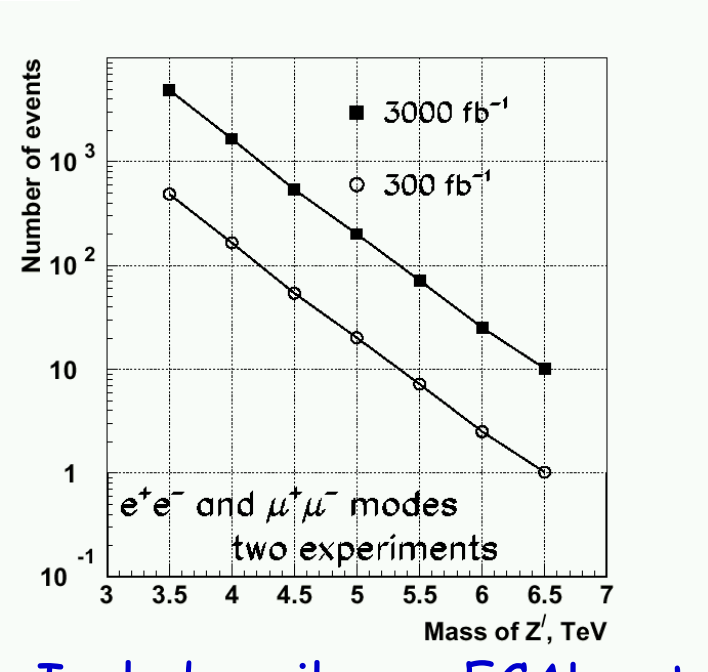
Scalar resonance $Z_L Z_L \to 4\ell$



New Z' Gauge Bosons

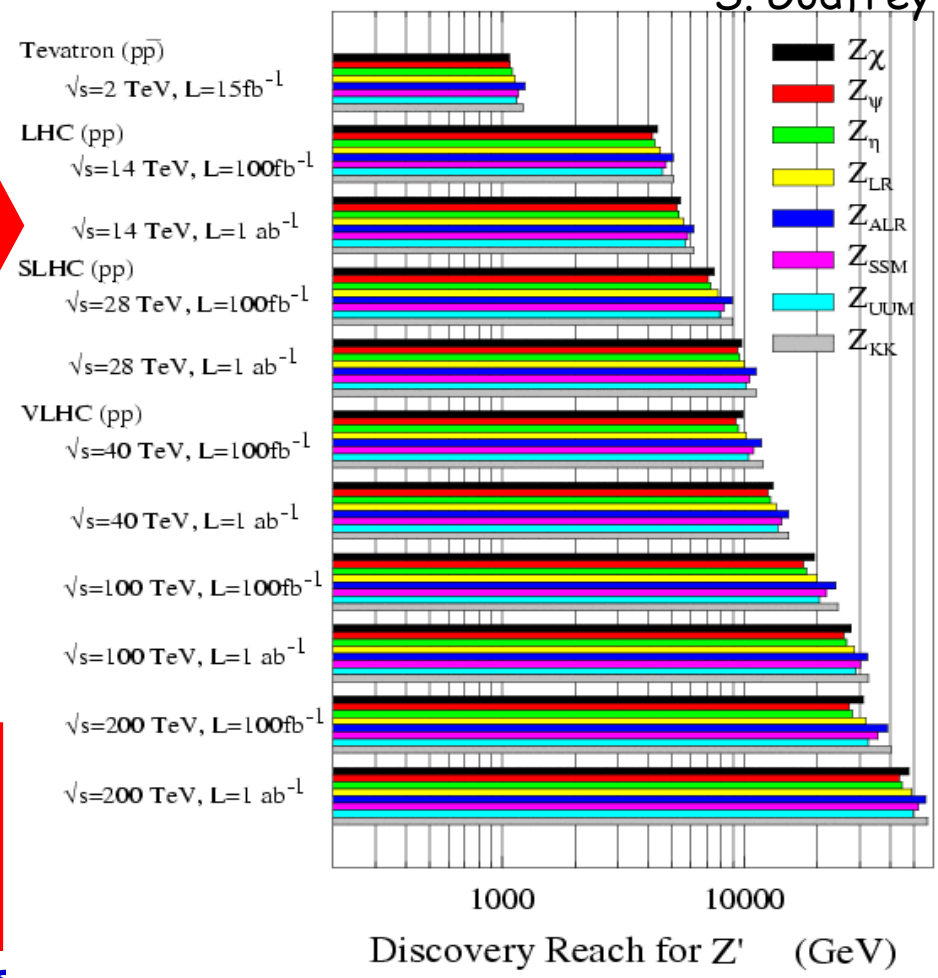
Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

with Z-like couplings



Includes pile-up, ECAL saturation…

S. Godfrey



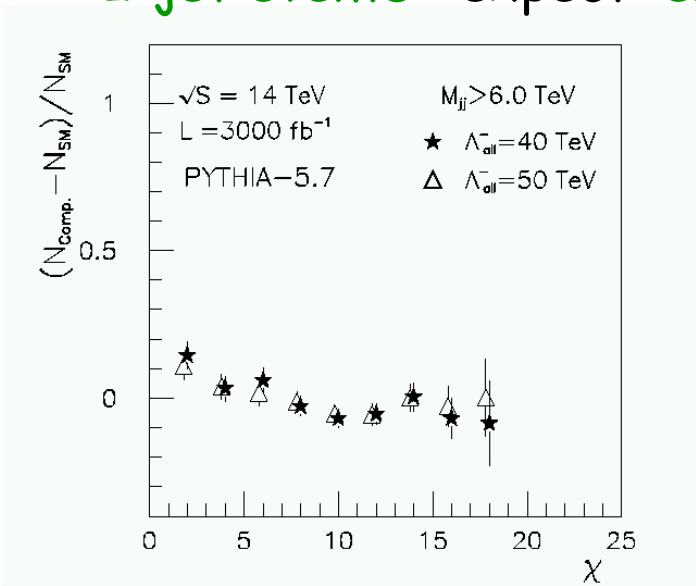
Reach:	LHC/600 fb^{-1}	5.3 TeV
	SLHC/6000 fb^{-1}	6.5 TeV
	LHC-28TeV/600 fb^{-1}	8 TeV

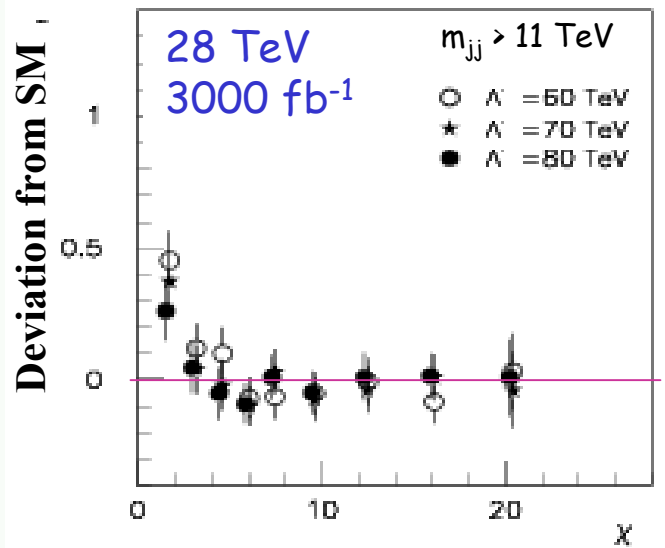
SLHC prospects

Compositeness

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

2-jet events: expect excess of high-E_T centrally produced jets.





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

θ^* angle btw jet & beam
If contact interactions
$\rightarrow$ excess at low χ

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

- For this study, no major detector upgrade needed at SLHC (but b-jet tag may be important)

Indicative Physics Reach

Ellis, Gianotti, ADR
hep-ex/0112004+ updates

Units are TeV (except $W_L W_L$ reach)
✋Ldt correspond to 1 year of running at nominal luminosity for 1 experiment

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	LC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ	7σ	18σ		90σ
Z'	5	6	8	11	35	8†	30†
Extra-dim (δ=2)	9	12	15	25	65	5-8.5†	30-55†
q*	6.5	7.5	9.5	13	75	0.8	5
Λcompositeness	30	40	40	50	100	100	400
TGC (λ_γ)	0.0014	0.0006	0.0008		0.0003	0.0004	0.00008

† indirect reach
(from precision measurements)

Approximate mass reach machines:
$\sqrt{s}$ = 14 TeV, L=10^{34} (LHC) : up to ≈ 6.5 TeV
$\sqrt{s}$ = 14 TeV, L=10^{35} (SLHC) : up to ≈ 8 TeV
$\sqrt{s}$ = 28 TeV, L=10^{34} : up to ≈ 10 TeV

Summary

The LHC luminosity upgrade to 10^{35} cm^{-2}s^{-1} (SLHC)

- Allows to extend the LHC discovery mass/scale range by 25-30%
- Could allow the first measurement of Higgs self-coupling (20-30%)
- Allows further access to rear decays such as $H \rightarrow \mu\mu$, γZ, rare top decays…
- Improved precision on TGCs, Higgs branching ratios,…

It will be a challenge for the experiments/needs detector R&D starting now especially if one wants to be ready to "go" soon after 2013-2014

In general: SLHC looks like giving a good physics return for modest cost.
$\Rightarrow$ Get the maximum out of the (by then) existing machine

An LHC energy upgrade to $\sqrt{s} \sim 28$ TeV

- Will extend the LHC mass range by factor 1.5
- Will be easier to exploit experimentally (at 10^{34} cm^{-2}s^{-1})
- Is generally more powerful than a luminosity upgrade
- Needs a new machine, magnet& machine R&D, and will not be cheap

Expected Detector Performance

The main challenge will be for the detectors

⇒ D. Green

- **Tracking and b-tagging**
  - isolated high p_T (> 20 GeV) tracks - it should be possible to maintain similar efficiency and momentum resolution
  - without a tracker upgrade, for fixed b-tagging efficiency, rejection against light quarks will deteriorate by factor 8-3 (p_T ~ 50-200 GeV)
- **Electron identification and measurement**
  - For electron efficiency of 80% jet rejection decreases by ~ 50%
- **Muon identification and measurement**
  - If enough shielding is provided expect reconstruction efficiency and momentum resolution not to deteriorate much
- **Forward jet-tagging and central veto**
  - Essential handle to increase S/N for WW and ZZ fusion processes
  - Performance will be significantly degraded – though algorithms could be optimised
- **Trigger**
  - high thresholds for inclusive triggers; use of exclusive triggers selecting specific final states, pre-scaling

What if Planck Scale in TeV Range?

- Schwarzschild radius ...within which nothing escapes the gravit. force

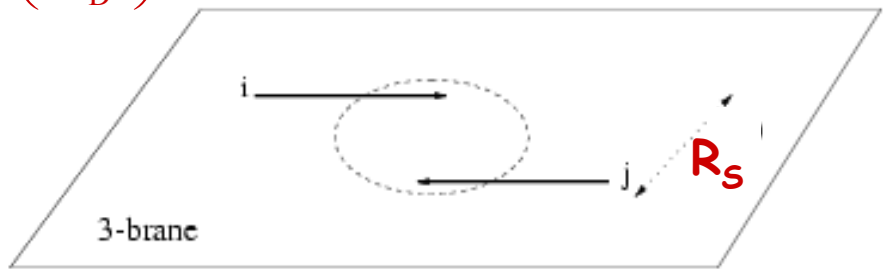
4-dim., $M_{gravity} = M_{Planck}$ $\quad R_S \sim \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$

4 + n-dim., $M_{gravity} = M_D \sim$ TeV $\quad R_S \sim \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$

$R_s \rightarrow << 10^{-35}$ m

$R_s \rightarrow \sim 10^{-19}$ m

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S



- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_S^2$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb – 1 fb

  e.g. For $M_D \sim$1 TeV and n=3, produce 1 event/second at the LHC

- Black holes decay immediately by Hawking radiation (democratic evaporation) :
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

  } expected signature (quite spectacular ...)