(Forward Look at) Physics at the LHC

Paris Sphicas
CERN and Univ. of Athens
International Conference for High Energy Physics
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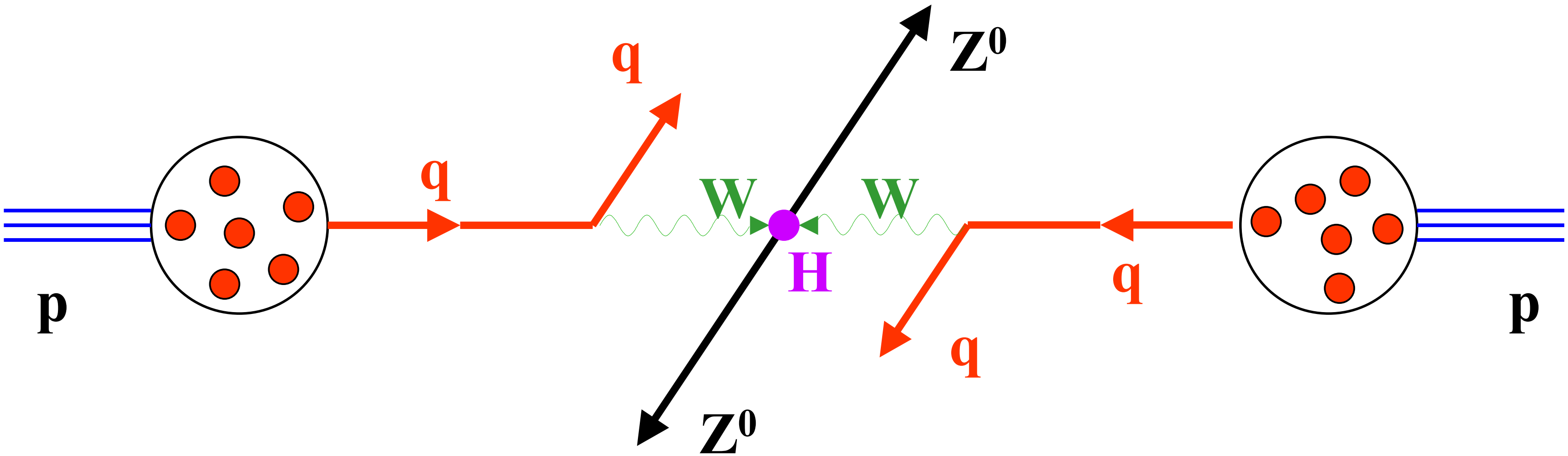
Outline

- The LHC – quick introduction/reminder
- Higgs search; reach, properties
- SUSY:
  - Sparticles (squarks/gluinos/gauginos)
  - Precision measurements
- Other (possible) new physics
- TeV-scale gravity
- Summary

EWK Symmetry Breaking (EWSB)

- EWSB requires (at least) one new particle
  - And energy scale of EWSB must be ~ TeV
    - To preserve unitarity of V-V (V=W, Z) scattering matrix
- Current wisdom: SB mechanism generates Goldstone bosons → longitudinal degrees of freedom for W & Z
  - But underlying nature of dynamics not known → two possibilities: weakly-coupled and strongly-coupled dynamics
- Weakly-coupled: self-interacting scalar fields
  - Self-interaction → non-vanishing vev
  - Then: interactions with bosons/fermions → mass to them
  - Must stabilize mass of the field. Embed in SUSY.
- Strongly-coupled: new strong interaction at ~TeV scale
  - Fermion-antifermion pair condensates; repeat exercise
- Recently, whole new "world": extra space dimensions

Higgs Production in pp Collisions



$M_H \sim 1000$ GeV

$E_W \geq 500$ GeV

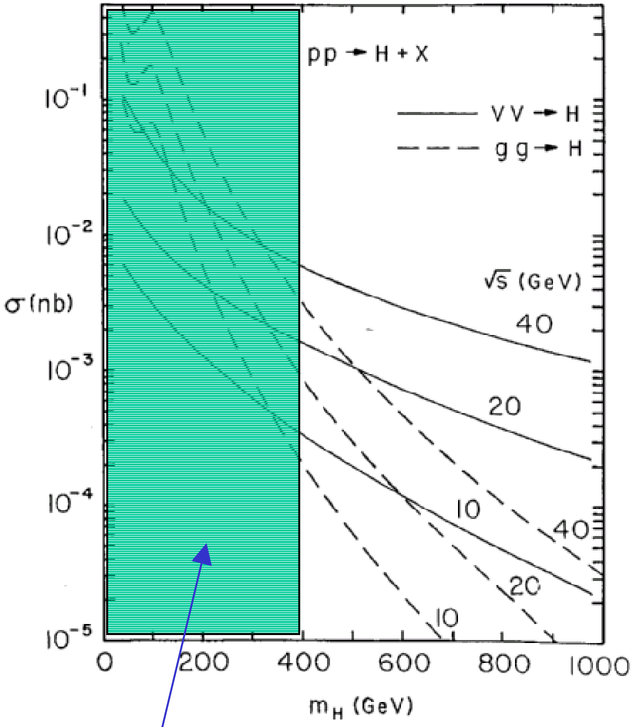
$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

→ Proton Proton Collider with $E_p \geq 7$ TeV

A machine for EWK Symmetry Breaking

- Superconducting SuperCollider (SSC)
  - Would have 2nd-generation results
- Large Hadron Collider
  - Use existing LEP tunnel



D.Dicus, S. Willenbrock

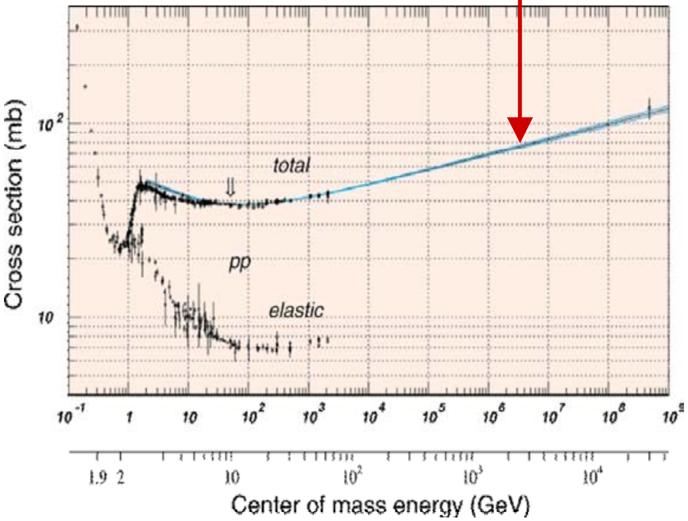
Phys.Rev.D32:1642,1985

Not true any more (M_T=175 GeV)

pp cross section and min. bias

- # of interactions/crossing:
  - Interactions/s:
    - Lum = 10^{34} cm^{-2}s^{-1}=10^{7}mb^{-1}Hz
    - σ(pp) = 70 mb
    - Interaction Rate, R = 7×10^{8} Hz
  - Events/beam crossing:
    - Δt = 25 ns = 2.5×10^{-8} s
    - Interactions/crossing=17.5
  - Not all p bunches are full
    - Approximately 4 out of 5 (only) are full
    - Interactions/"active" crossing = 17.5 x 3564/2835 = 23

σ(pp)≈70 mb



Operating conditions (summary):

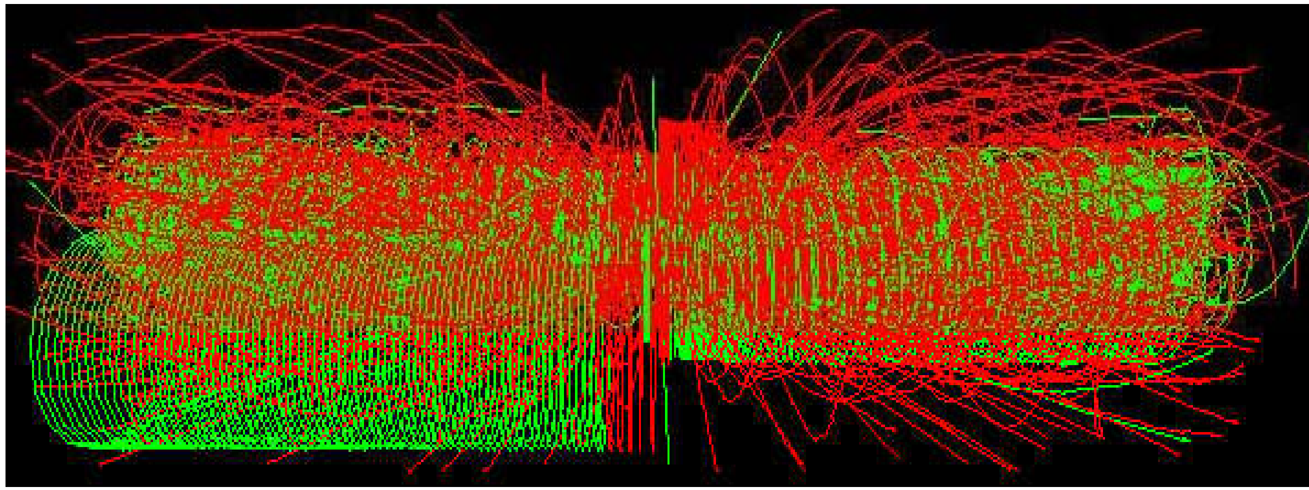
1) A "good" event containing a Higgs decay +
2) ≈ 20 extra "bad" (minimum bias) interactions

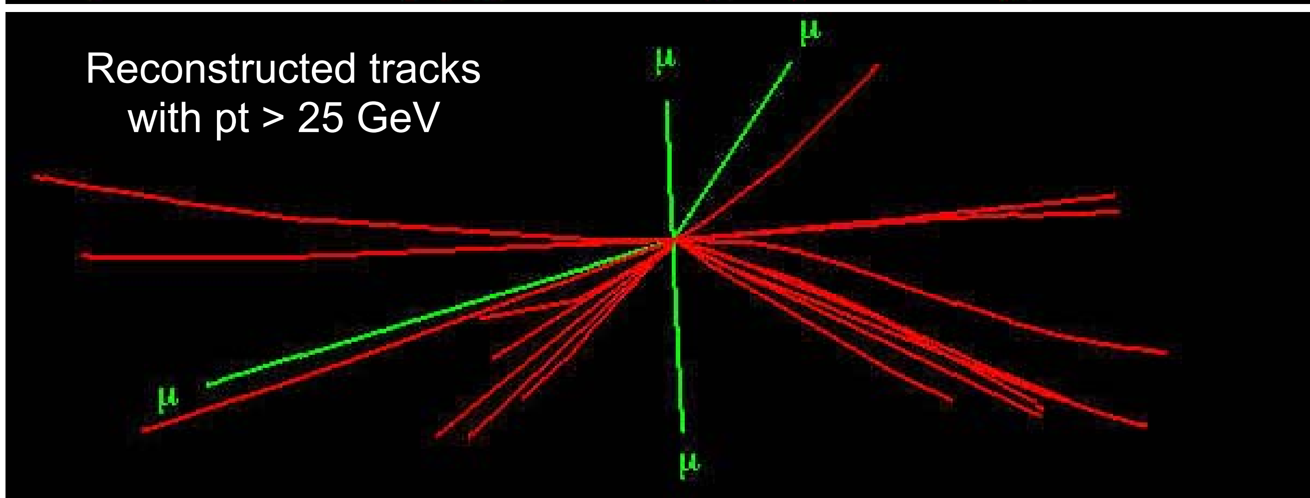
pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}

- 20 min bias events overlap
- H→ZZ

Z →μμ

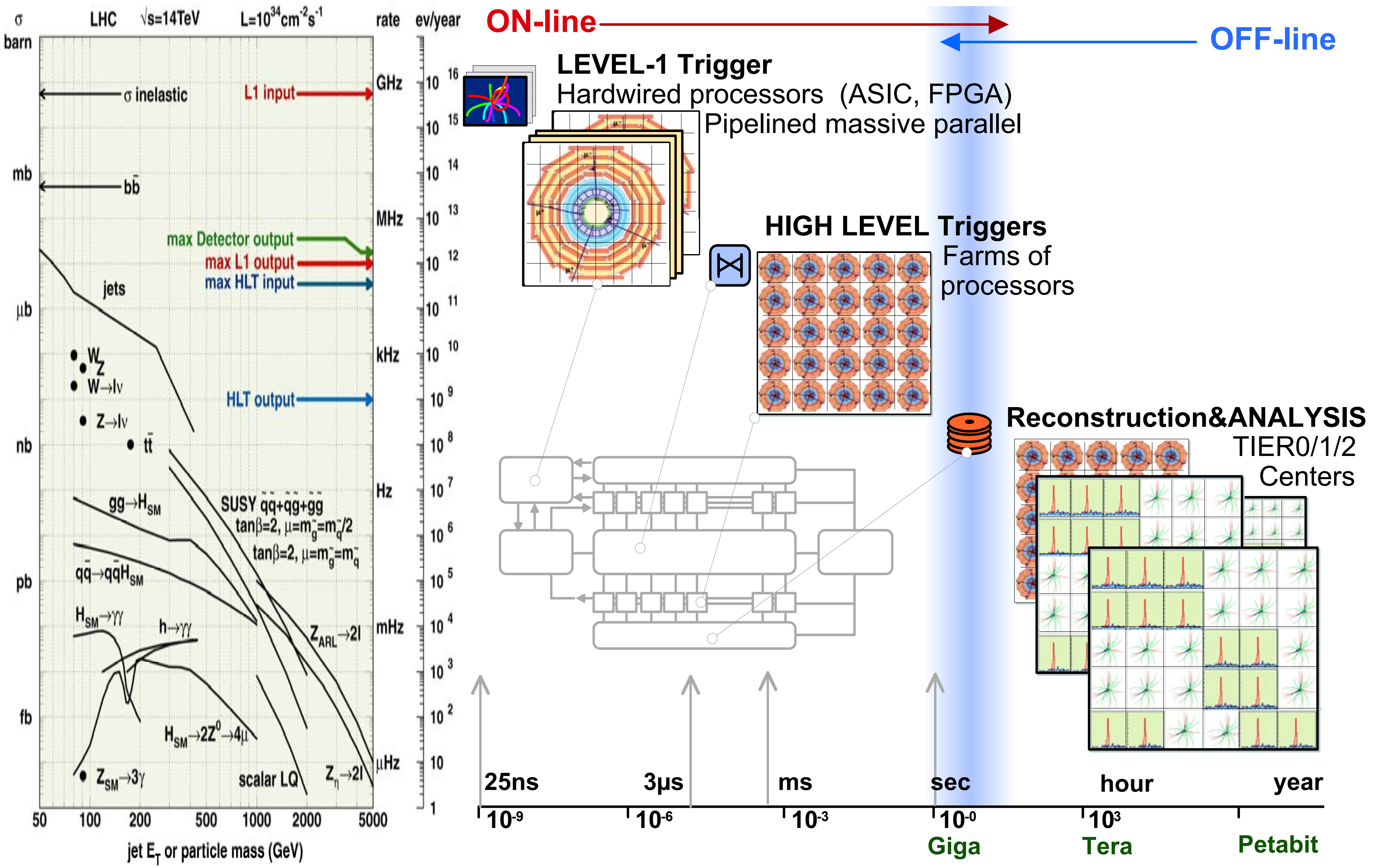
H→ 4 muons: the cleanest ("golden") signature





And this (not the H though…) repeats every 25 ns…

Physics selection at the LHC



Standard Model Higgs

Information (limits) on M_H: summary

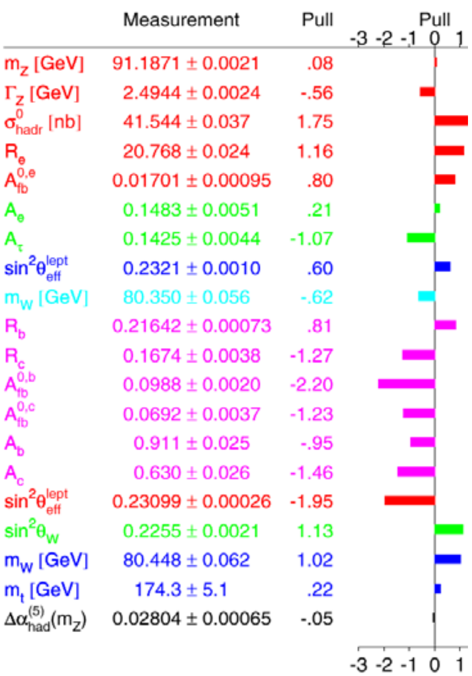
- Triviality bound

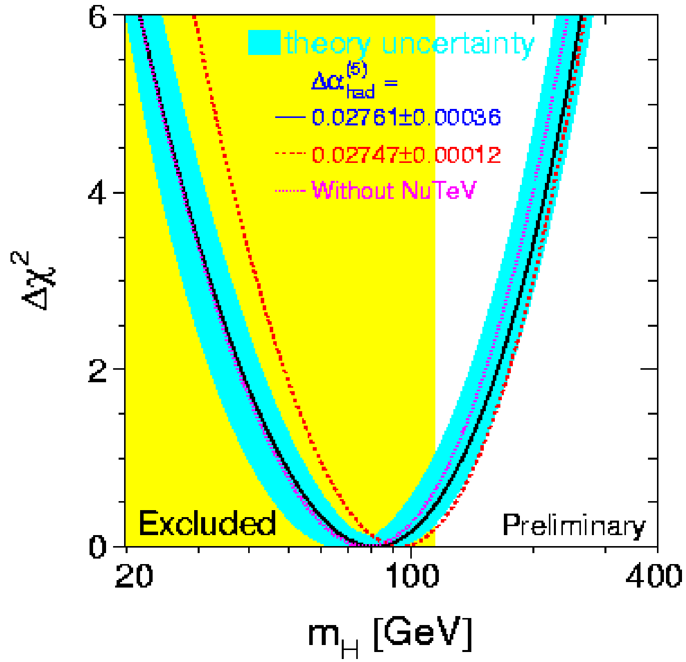
$$\Lambda \le M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

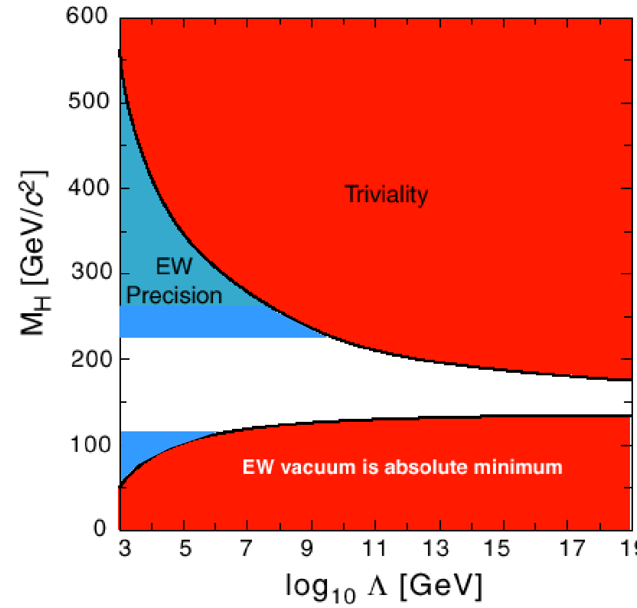
- $<\phi_0>\neq 0$

$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2} F \log\left(\Lambda^2 / v^2\right)$$

- Precision EWK measurements



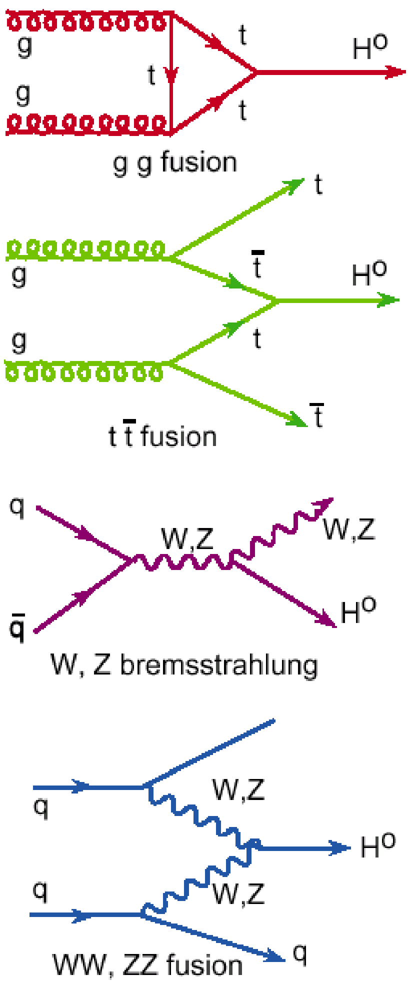


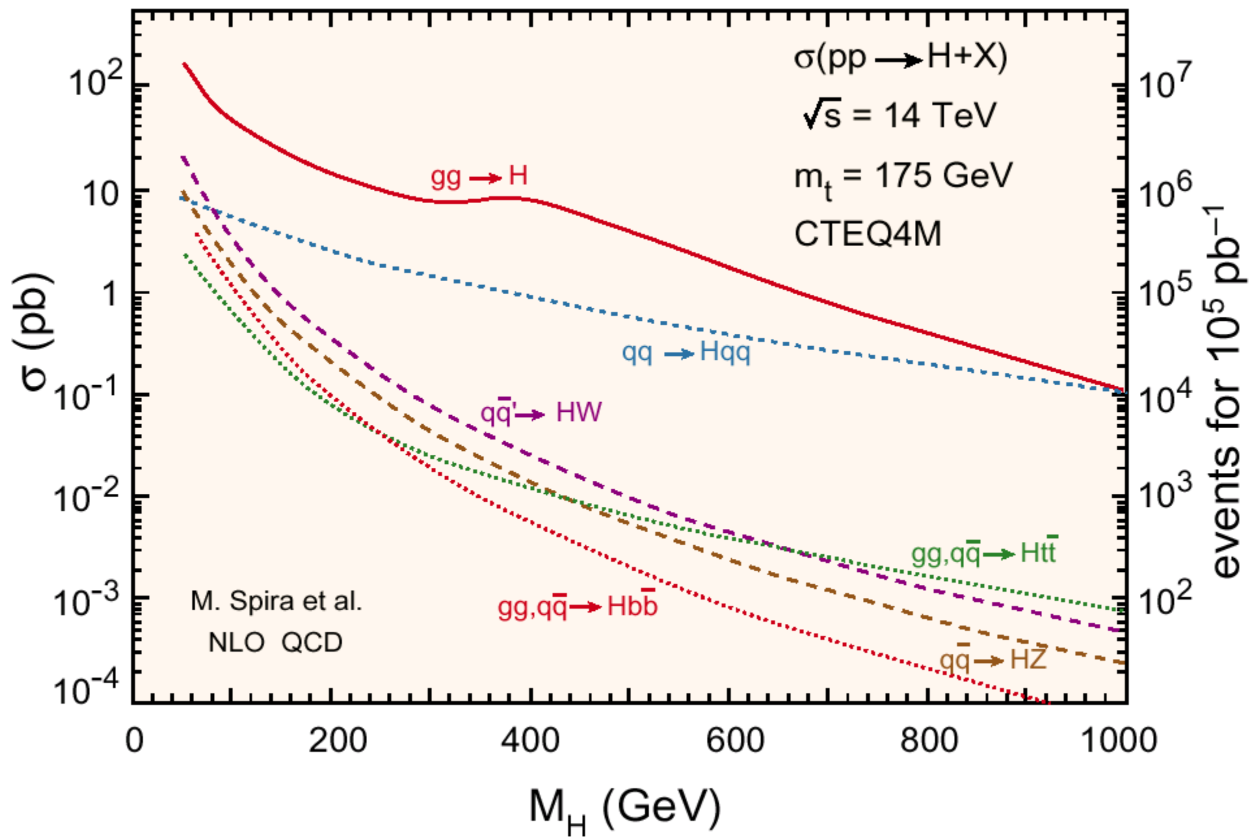


LEP direct search:
M_H>114 GeV/c^2

SM Higgs at the LHC

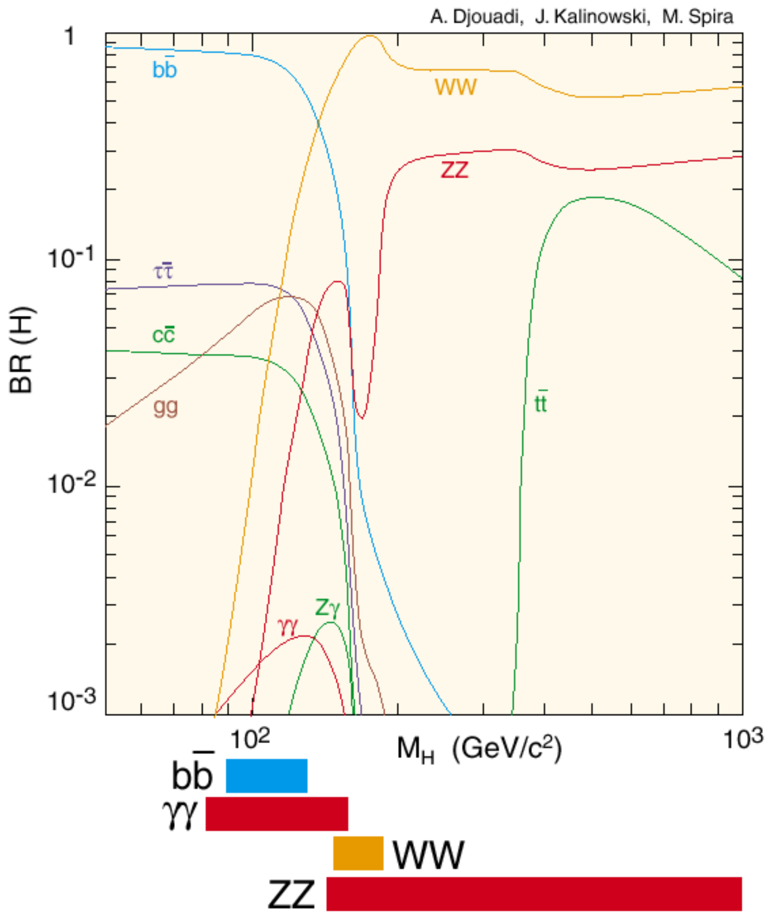
- Production mechanisms & cross section





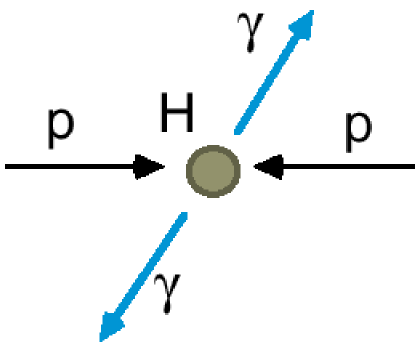
SM Higgs

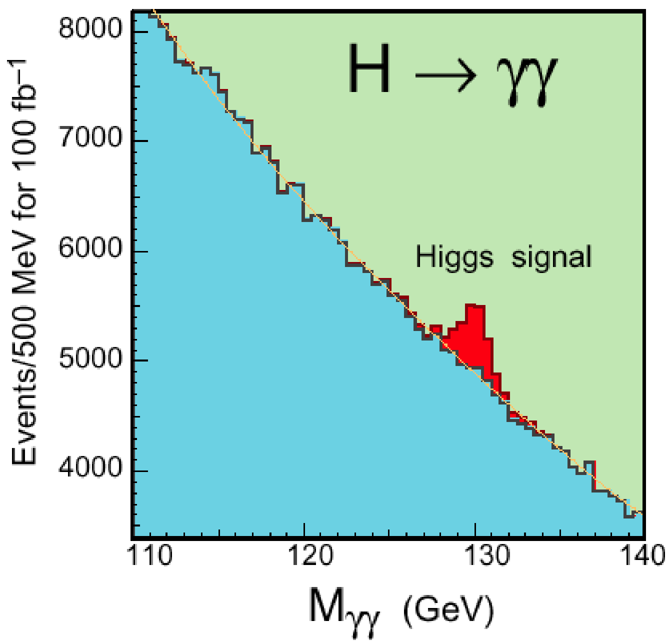
- Decays & discovery channels
  - Higgs couples to m_f^2
    - Heaviest available fermion (b quark) always dominates
    - Until WW, ZZ thresholds open
  - Low mass: b quarks$\rightarrow$ jets; resolution ~ 15%
    - Only chance is EM energy (use $\gamma\gamma$ decay mode)
  - Once M_H>$2M_Z$, use this
    - W decays to jets or lepton+neutrino (E_T^{miss})

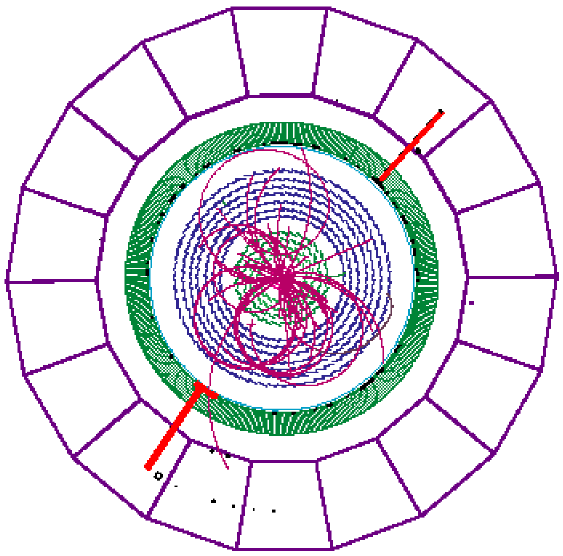


Low mass Higgs (M_H<140 GeV/c^2)

- $H \rightarrow \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)
  - But with good resolution, one gets a mass peak
  - Motivation for LAr/$PbWO_4$ calorimeters
  - Resolution at 100 GeV, $\sigma \approx$1GeV
    - S/B $\approx$ 1:20

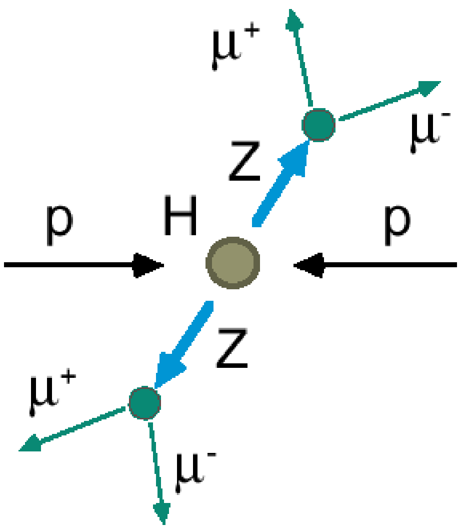


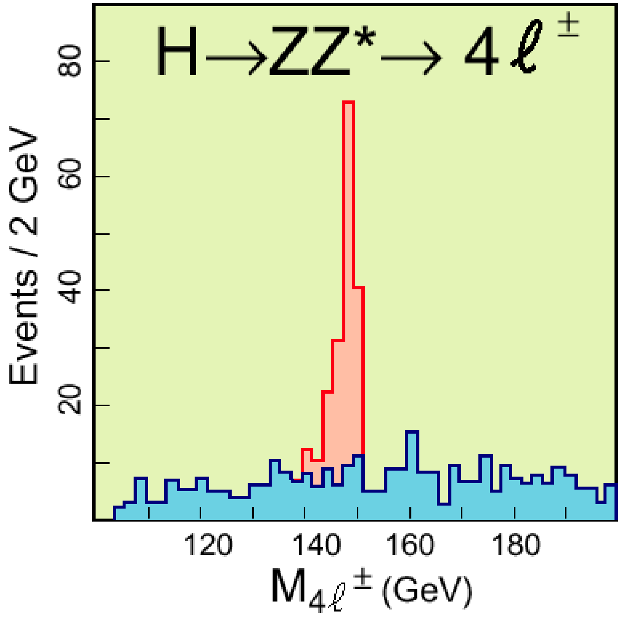


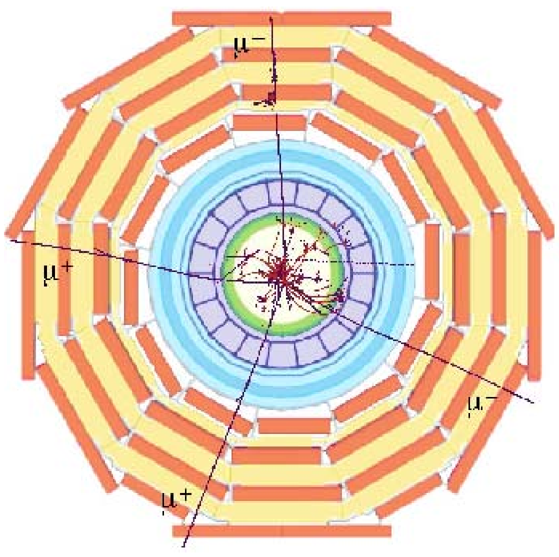


Intermediate mass Higgs

- $H \to ZZ \to \ell^+\ell^- \ \ell^+\ell^-$ (ℓ =e,μ)
  - Very clean
    - Resolution: better than 1 GeV (around 100 GeV mass)
  - Valid for the mass range $130 < M_H < 500\ \mathrm{GeV}/c^2$

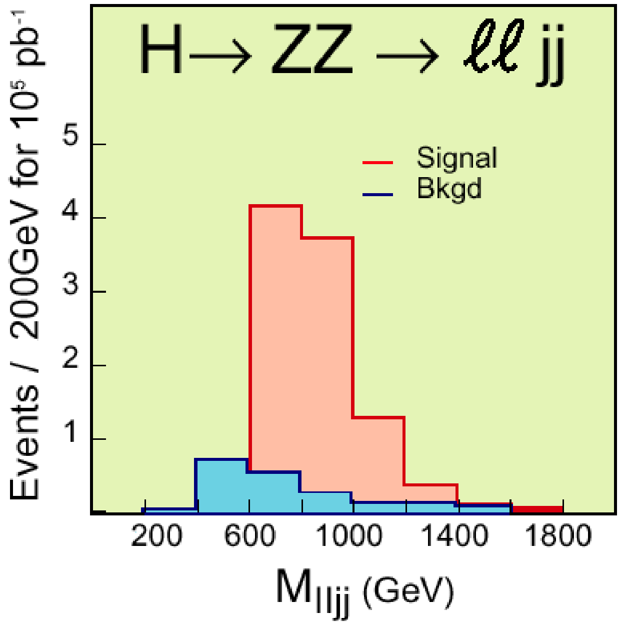


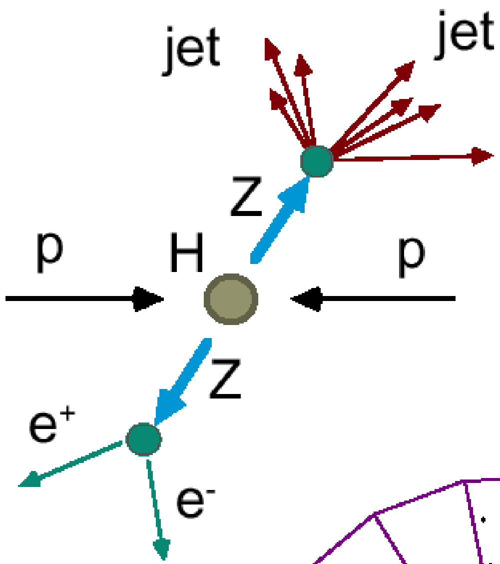


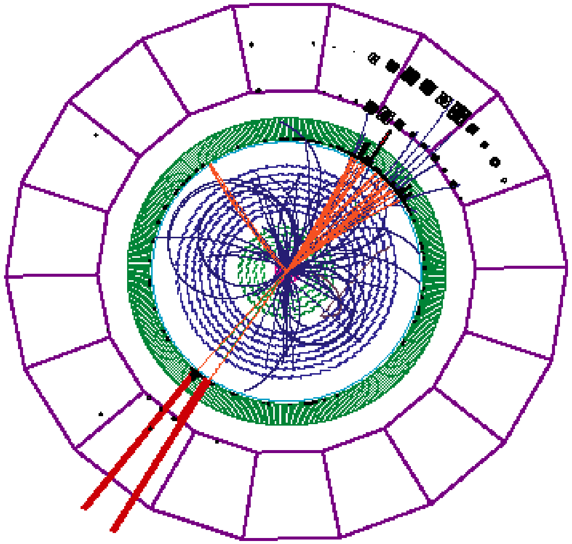


High mass Higgs

- $H \to ZZ \to \ell^+\ell^-$ jet jet
  - Need higher Branching fraction (also $\nu\nu$ for the highest masses ~ 800 GeV/c²)
  - At the limit of statistics

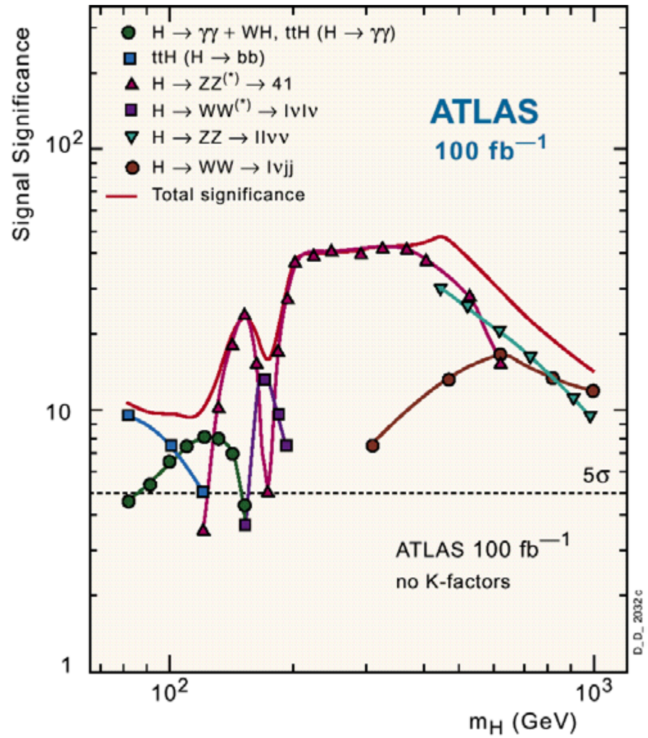


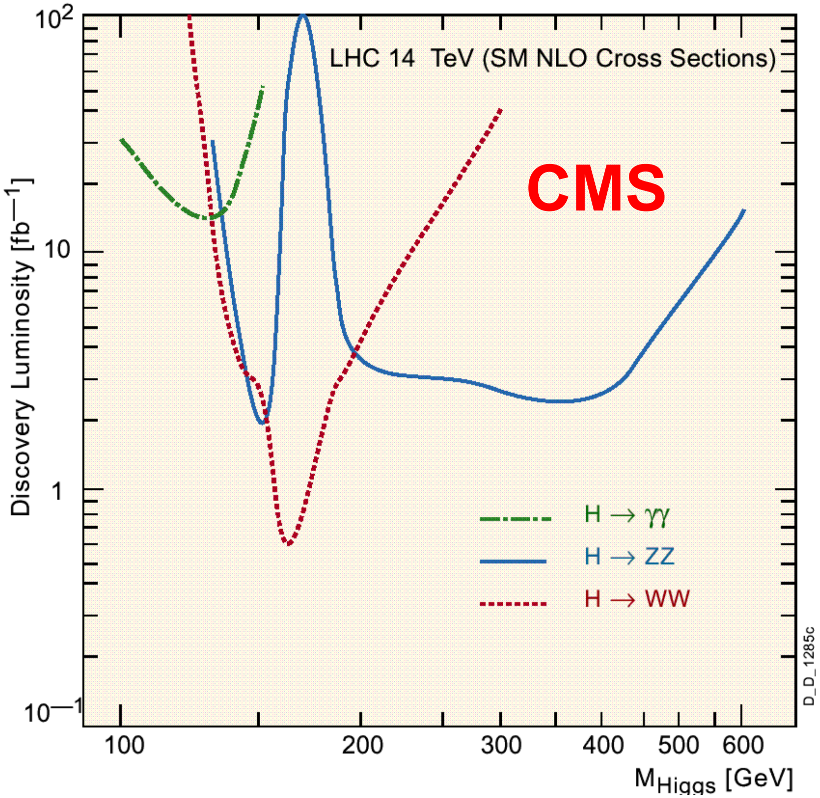




Higgs discovery prospects @ LHC

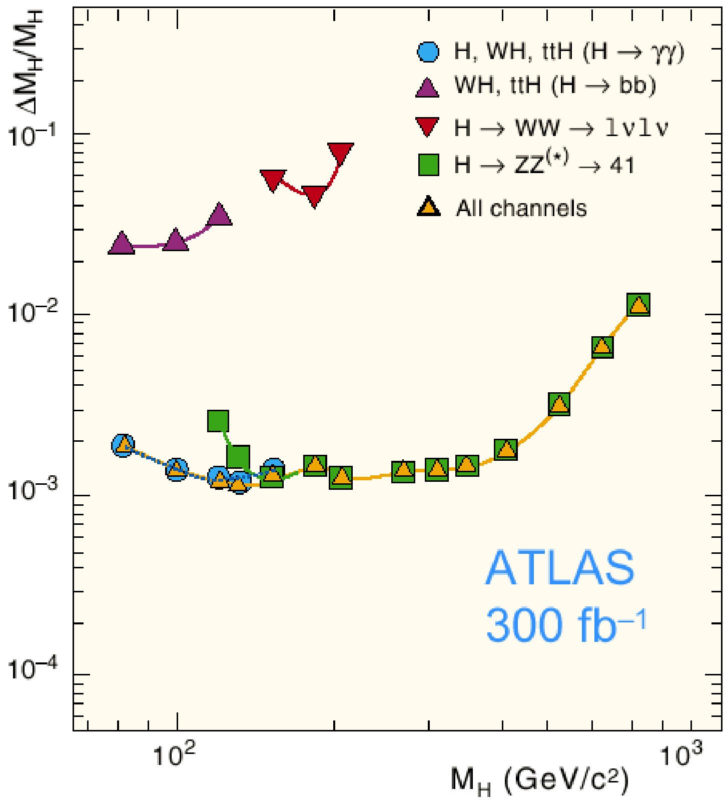
- The LHC can probe the entire set of "allowed" Higgs mass values
  - in most cases a few months at low luminosity are adequate for a 5σ observation





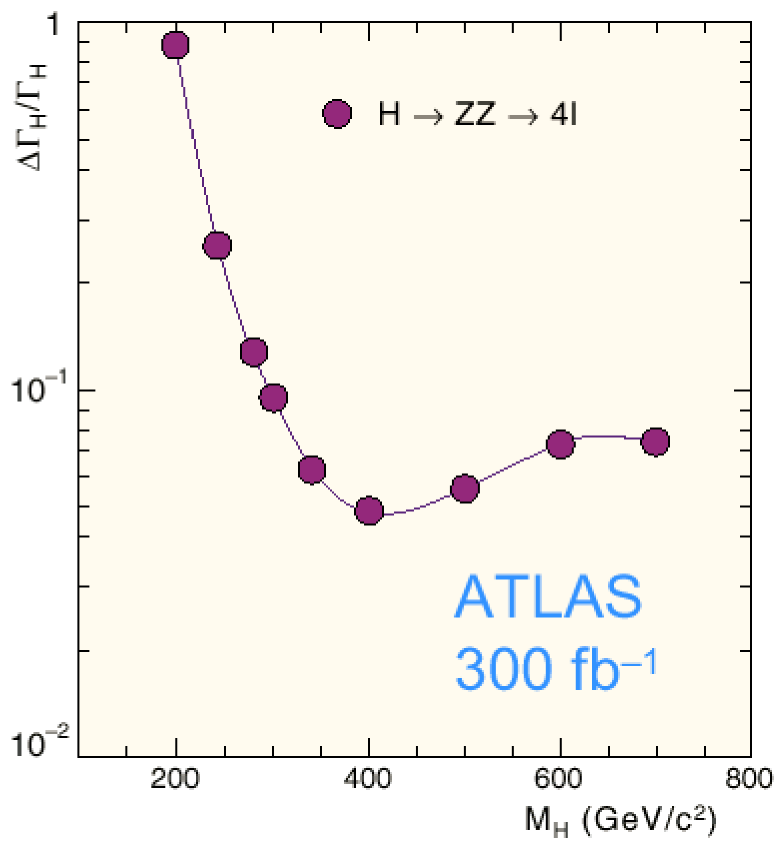
SM Higgs properties (I): mass

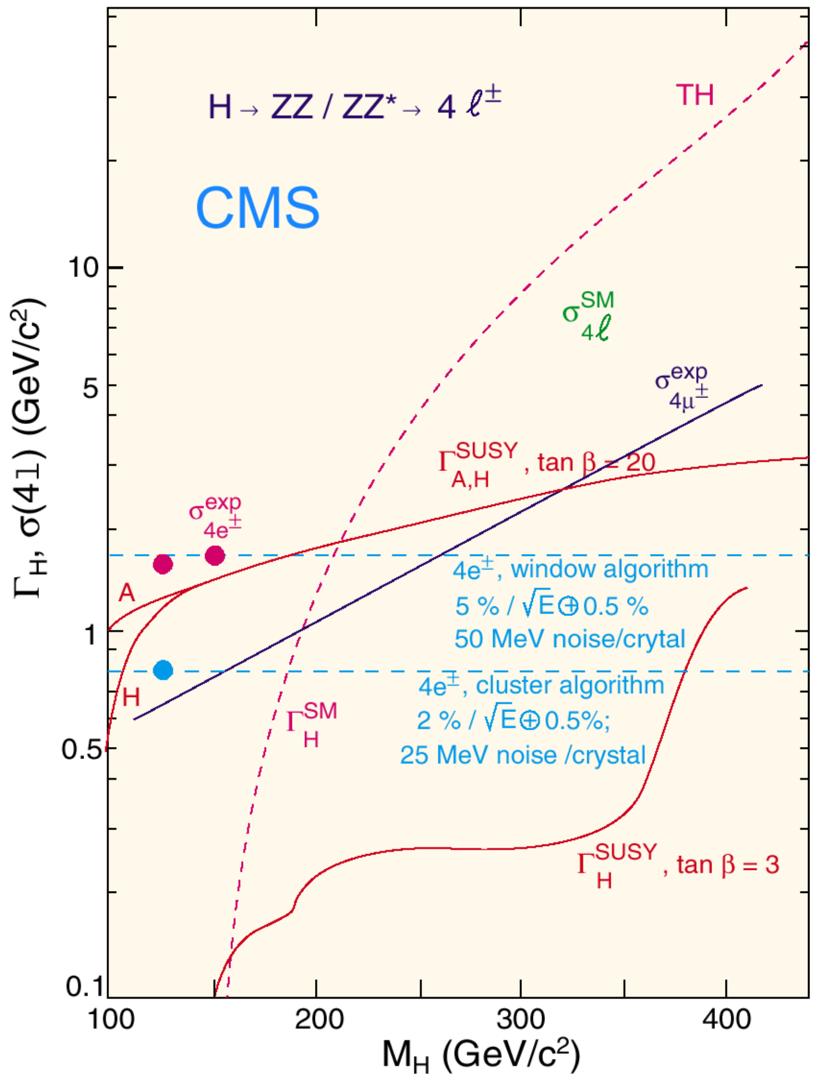
- Mass measurement
  - Limited by absolute energy scale
    - leptons & photons: 0.1% (with Z calibration)
    - Jets: 1%
  - Resolutions:
    - For $\gamma\gamma$ & $4\ell \approx 1.5$ GeV/c^2
    - For bb ≈ 15 GeV/c^2
  - At large masses: decreasing precision due to large Γ_H
  - CMS ≈ ATLAS



SM Higgs properties (II): width

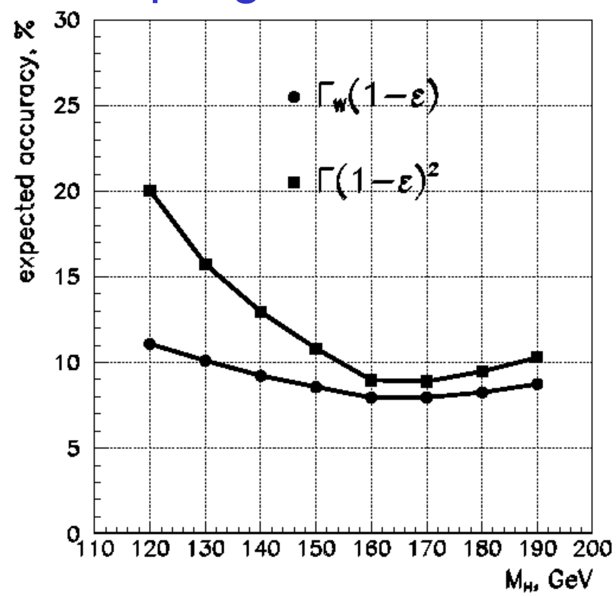
- Width; limitation:
  - Possible for M_H>200
    - Using golden mode (4ℓ)





SM Higgs; (indirect) width for $M_H<2M_Z$

- Basic idea: use qq$\rightarrow$qqH production (two forward jets+veto on central jets)
  - Can measure the following: $X_j = \Gamma_W\Gamma_j/\Gamma$ from qq$\rightarrow$qqH $\rightarrow$qqjj
    - Here: j = γ, τ, W(W*); precision~10-30%
  - One can also measure $Y_j = \Gamma_g\Gamma_j/\Gamma$ from gg$\rightarrow$H$\rightarrow$jj
    - Here: j = γ, W(W*), Z(Z*); precision~10-30%
  - Clearly, ratios of X_j and Y_j (~10-20%) $\rightarrow$ couplings
  - But also interesting, if Γ_W is known:
    - $\Gamma = (\Gamma_W)^2/X_W$
    - Need to measure H $\rightarrow$ WW*
    - $\varepsilon=1-(B_b+B_\tau+B_W+B_Z+B_g+B_\gamma)<<1$
    - $(1-\varepsilon)\Gamma_W= X_\tau(1+y)+X_W(1+z)+X_\gamma+X_g$
    - $z= \Gamma_W/\Gamma_Z$; $y= \Gamma_b/\Gamma_\tau=3\eta_{QCD}(m_b/m_\tau)^2$

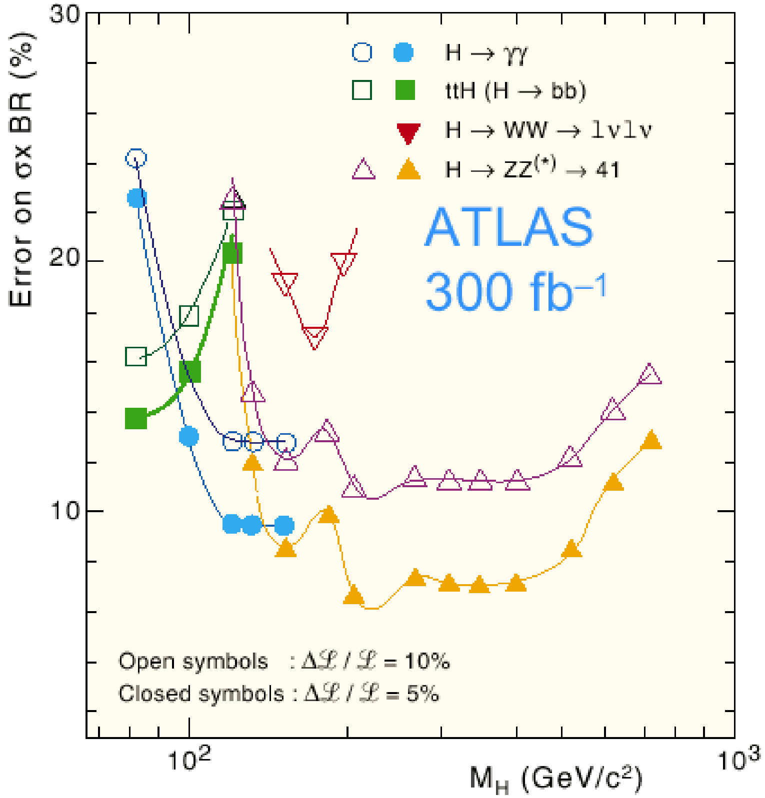


Zeppenfeld, Kinnunen, Nikitenko, Richter-Was

SM Higgs properties (III)

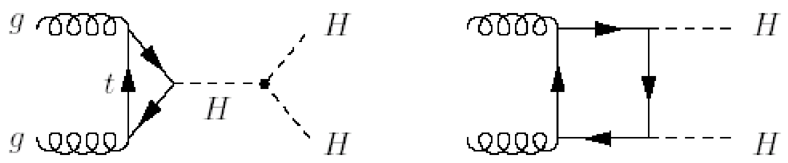
- Biggest uncertainty(5-10%): Luminosity
  - Relative couplings statistically limited
    - Small overlap regions

Measure	Error	M_H range
$\frac{B(H \to \gamma\gamma)}{B(H \to b\bar{b})}$	30%	80–120
$\frac{B(H \to \gamma\gamma)}{B(H \to ZZ^*)}$	15%	125–155
$\frac{\sigma(t\bar{t}H)}{\sigma(WH)}$	25%	80–130
$\frac{B(H \to WW^{(*)})}{B(H \to ZZ^{(*)})}$	30%	160–180

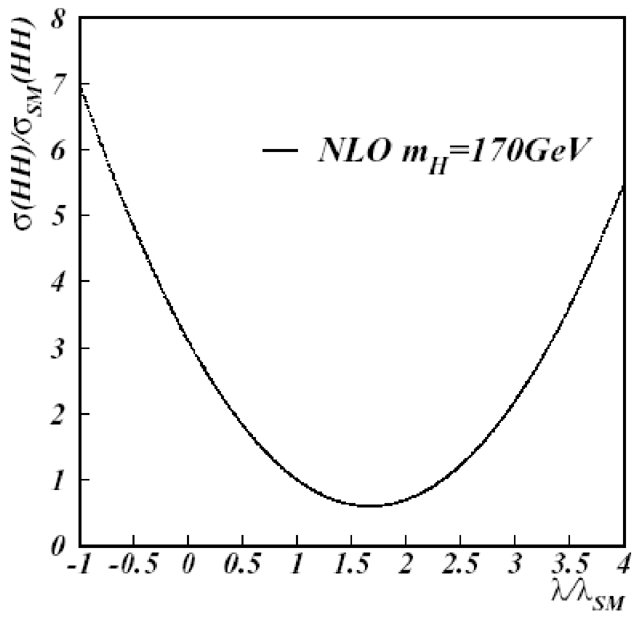


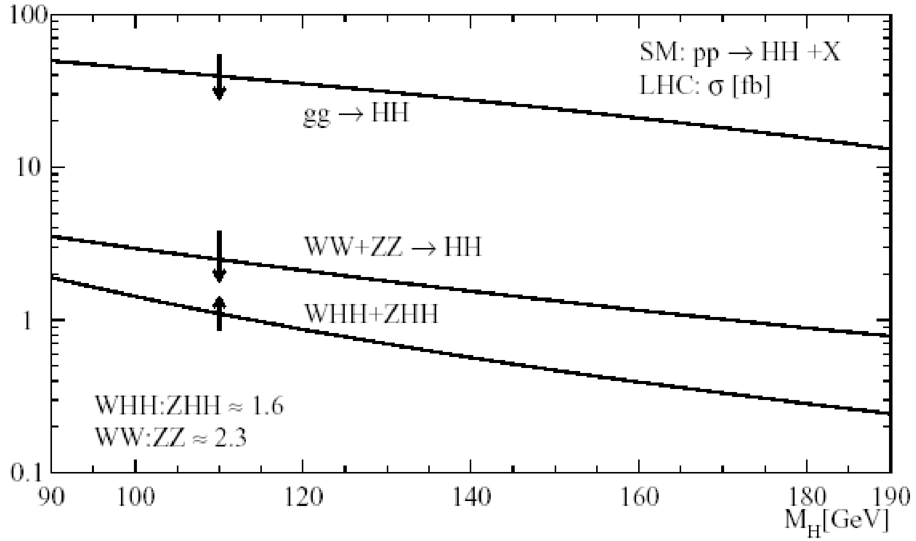
SM Higgs: properties (IV)

- Self-coupling
  - From HH production



  - Cross sections are low
    - Relevant for M_H<200 GeV/c^2





Need higher statistics, i.e. luminosities; for example, $WW^{(*)}$ with $\ell\nu$+jetjet channel visible *(with 10x the statistics)*
Measures λ to 20-25%

MSSM Higgs(es)

MSSM Higgs(es)

- Complex analysis; 5 Higgses ($\Phi \equiv H^{\pm}; H^0, h^0, A^0$)
  - At tree level, all masses & couplings depend on only two parameters; tradition says take M_A & $\tan\beta$
  - Modifications to tree-level mainly from top loops
    - Important ones; e.g. at tree-level, $M_h < M_z \cos\beta$, $M_A < M_H$; $M_W < M_{H^+}$; radiative corrections push this to 135 GeV.
  - Important branch 1: SUSY particle masses

    (a) M>1 TeV (i.e. no Φ decays to them); well-studied

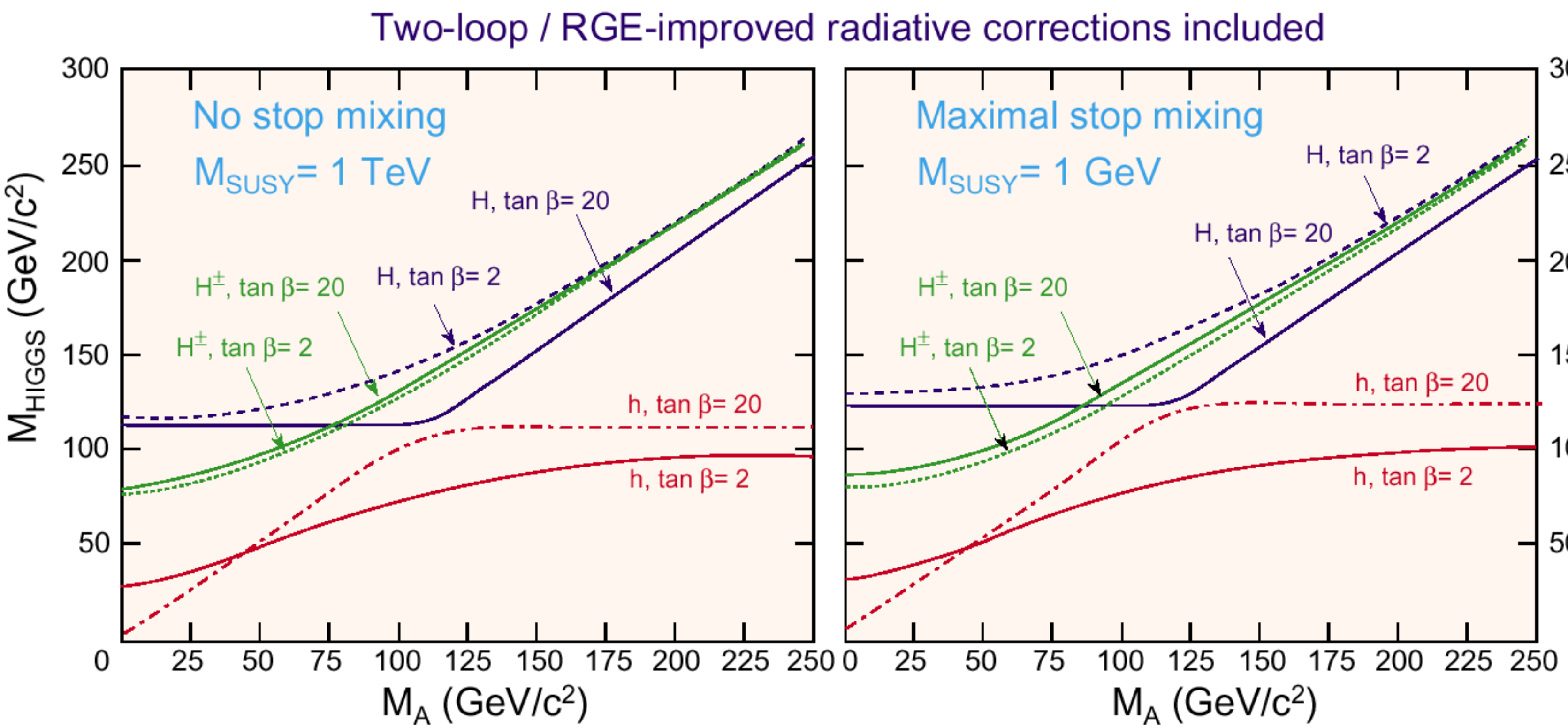
    (b) M<1 TeV (i.e. allows Φ decays); “on-going”
  - Important branch 2: stop mixing; value of $\tan\beta$

    (a) Maximal–No mixing

    (b) Low (1.5) and high (≈30) values of $\tan\beta$

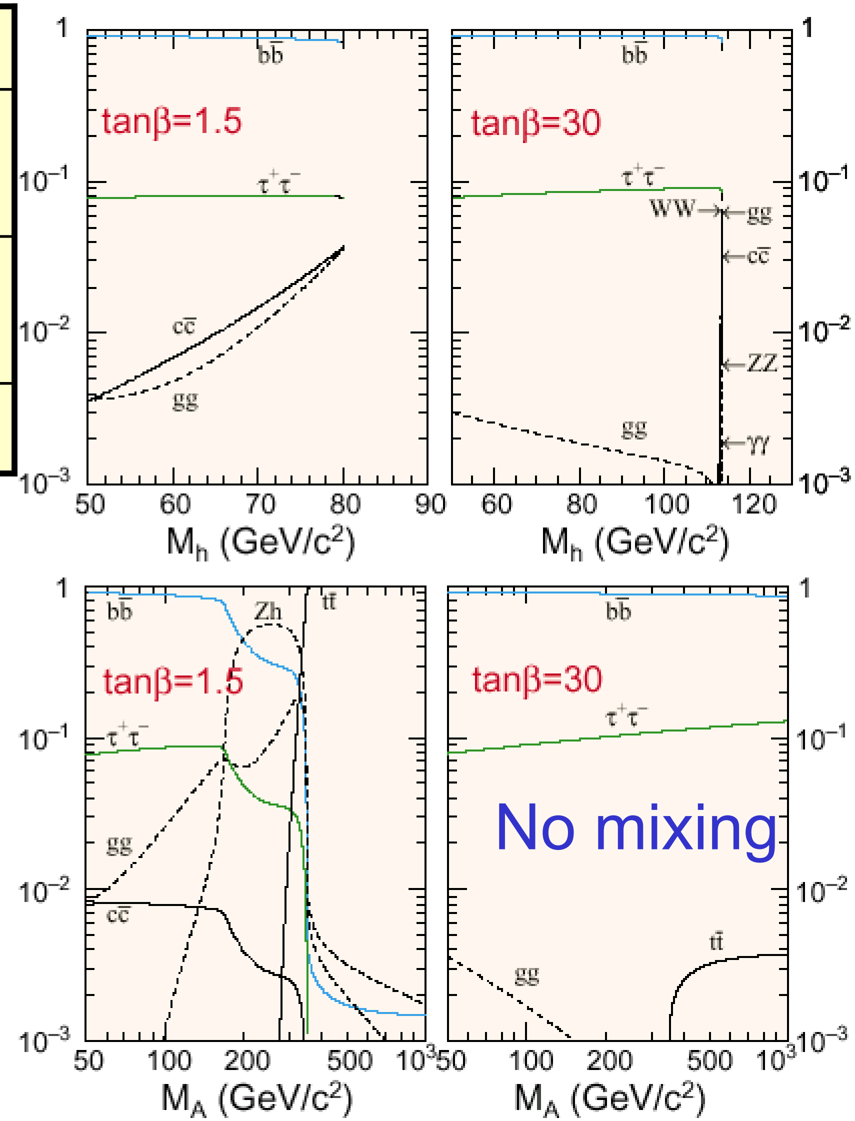
MSSM Higgses: masses

- Mass spectra for M_{SUSY}>1TeV
  - The good news: M_h<135 GeV/c^2



MSSM: h/A decay

Φ	$g(\Phi uu)$	$g(\Phi dd)$	$g(\Phi VV)$
h	$\cos\alpha/\sin\beta$ $\to 1$	$-\sin\alpha/\cos\beta$ $\to 1$	$\sin(\beta-\alpha)$ $\to 1$
H	$\sin\alpha/\sin\beta$ $\to 1/\tan\beta$	$\cos\alpha/\cos\beta$ $\to \tan\beta$	$\cos(\beta-\alpha)$ $\to 1$
A	$1/\tan\beta$	$\tan\beta$	0



- h is light
  - Decays to $b\bar{b}$ (90%) & $\tau\tau$ (8%)
    - cc, gg decays suppressed
- H/A "heavy"
  - Decays to top open (low $\tan\beta$)
  - Otherwise still to $b\bar{b}$ & $\tau\tau$
  - But: WW/ZZ channels suppressed; lose golden modes for H

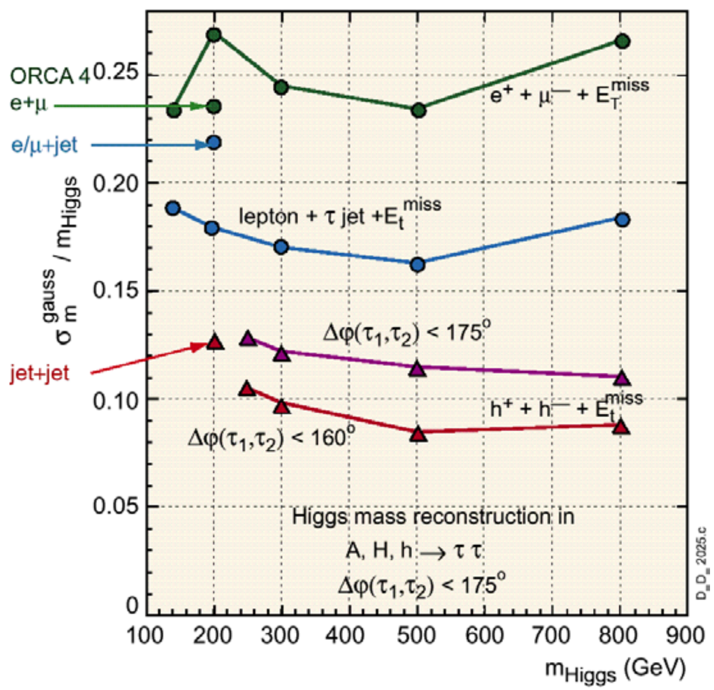
Higgs channels considered

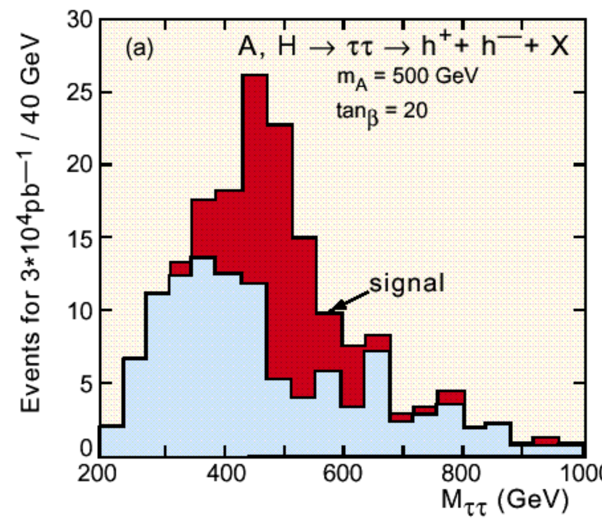
- Channels currently being investigated:
  - H, h$\rightarrow\gamma\gamma$, $b\bar{b}$ (H$\rightarrow b\bar{b}$ in WH, $t\bar{t}$H) — (very) important and hopeful
  - h$\rightarrow\gamma\gamma$ in WH, $t\bar{t}h \rightarrow \ell\gamma\gamma$
  - h, H $\rightarrow$ ZZ*, ZZ $\rightarrow 4\ell$
  - h, H, A$\rightarrow \tau^+\tau^- \rightarrow (e/\mu)^+ + h^- + E_T^{miss}$
    $\rightarrow e^+ + \mu^- + E_T^{miss}$
    $\rightarrow h^+ + h^- + E_T^{miss}$ — inclusively and in $b\bar{b}H_{SUSY}$
  - $H^+ \rightarrow \tau^+\nu$ from $t\bar{t}$
  - $H^+ \rightarrow \tau^+\nu$ and $H^+ \rightarrow t\bar{b}$ for $M_H > M_{top}$
  - A $\rightarrow$ Zh with h $\rightarrow b\bar{b}$; A $\rightarrow\gamma\gamma$
  - H, A $\rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^0_i\tilde{\chi}^0_j, \tilde{\chi}^+_i\tilde{\chi}^-_j$
  - $H^+ \rightarrow \tilde{\chi}^+_2\tilde{\chi}^0_2$ — fairly new and promising
  - qq $\rightarrow$qqH with H $\rightarrow\tau^+\tau^-$
  - H $\rightarrow\tau\tau$, in WH, $t\bar{t}$H

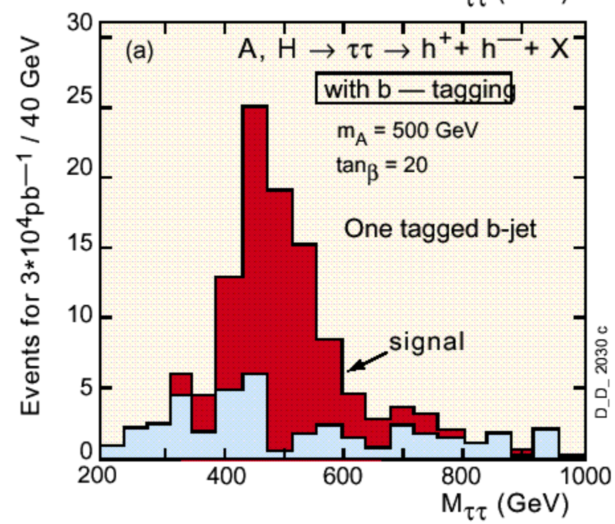
H,A→ττ; 3rd-generation lepton the LHC

- Most promising modes for H,A
  - τ's identified either in hadronic or leptonic decays
  - Mass reconstruction: take lepton/jet direction to be the τ direction

Higgs mass resolution in $H \to \tau^+ \tau^-$

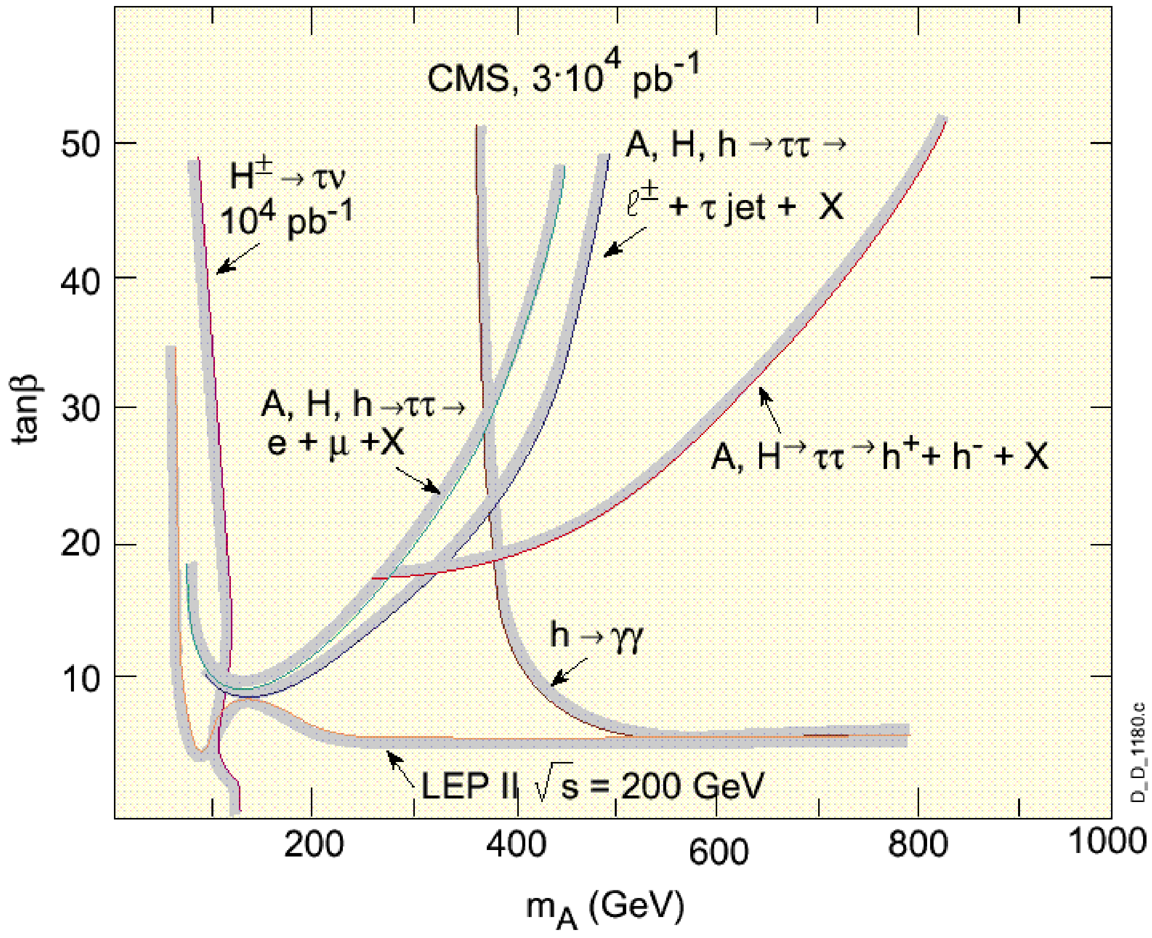






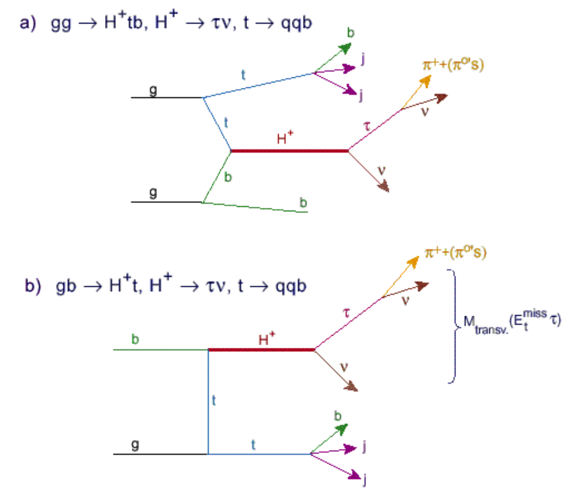
H, A reach via τ decays

- Contours are 5σ; M_{SUSY}=1 TeV



H^+ detection

- Associated top-H^+ production:
  - Use all-hadronic decays of the top (leave one "neutrino")
  - H decay looks like W decay $\rightarrow$ Jacobian peak for τ-missing E_T
  - In the process of creating full trigger path + ORCA analysis

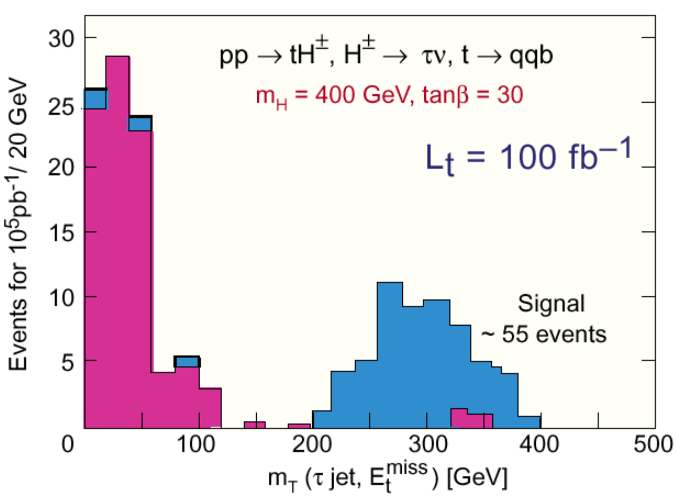


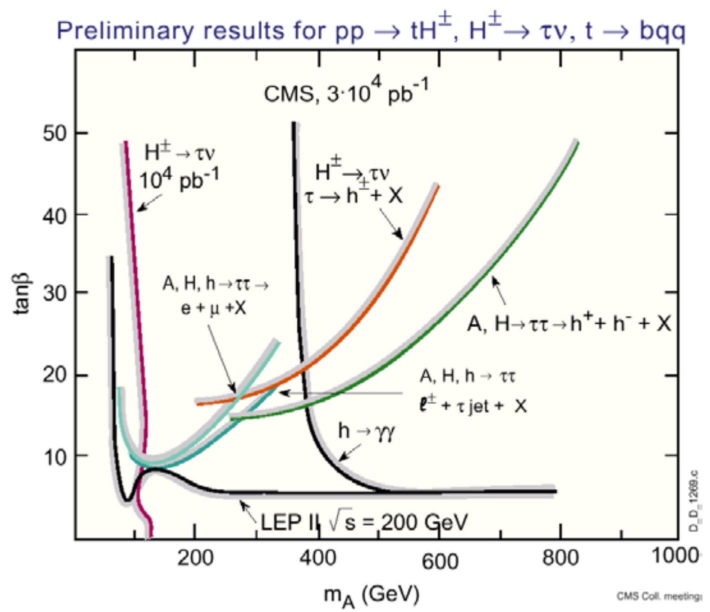
E_T(jet)>40

$|\eta|$<2.4

Veto on extra jet, and on second top

Bkg: $t\bar{t}H$





SUSY reach on tanβ-M_A plane

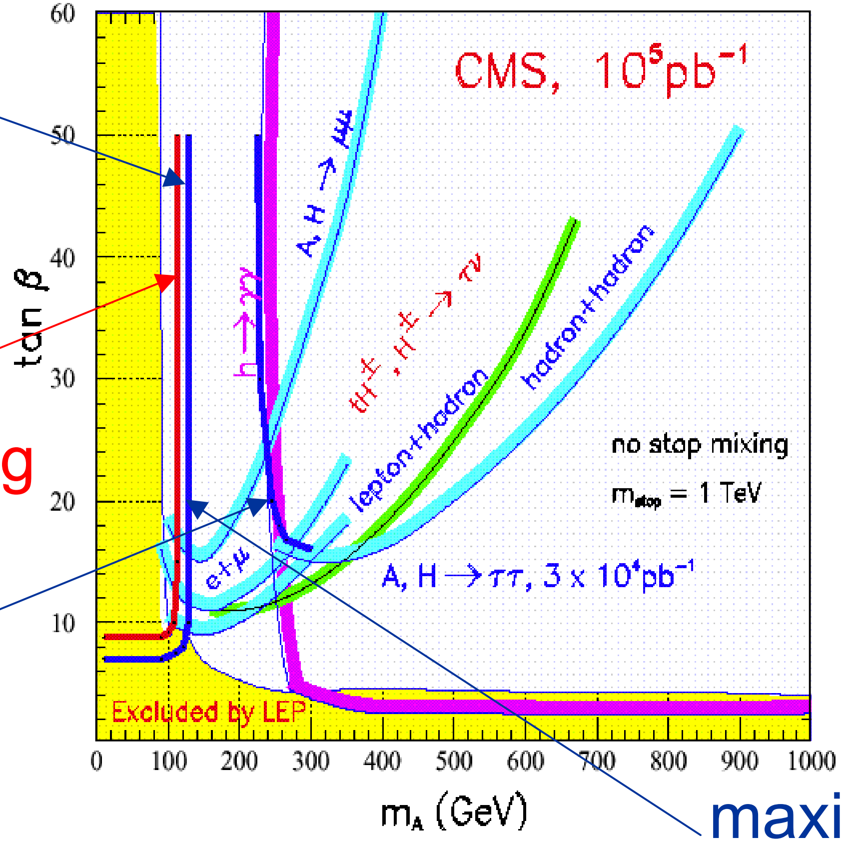
- Adding $b\bar{b}$ on the τ modes can “close” the plane

Wh

(e/μ)ν $b\bar{b}$

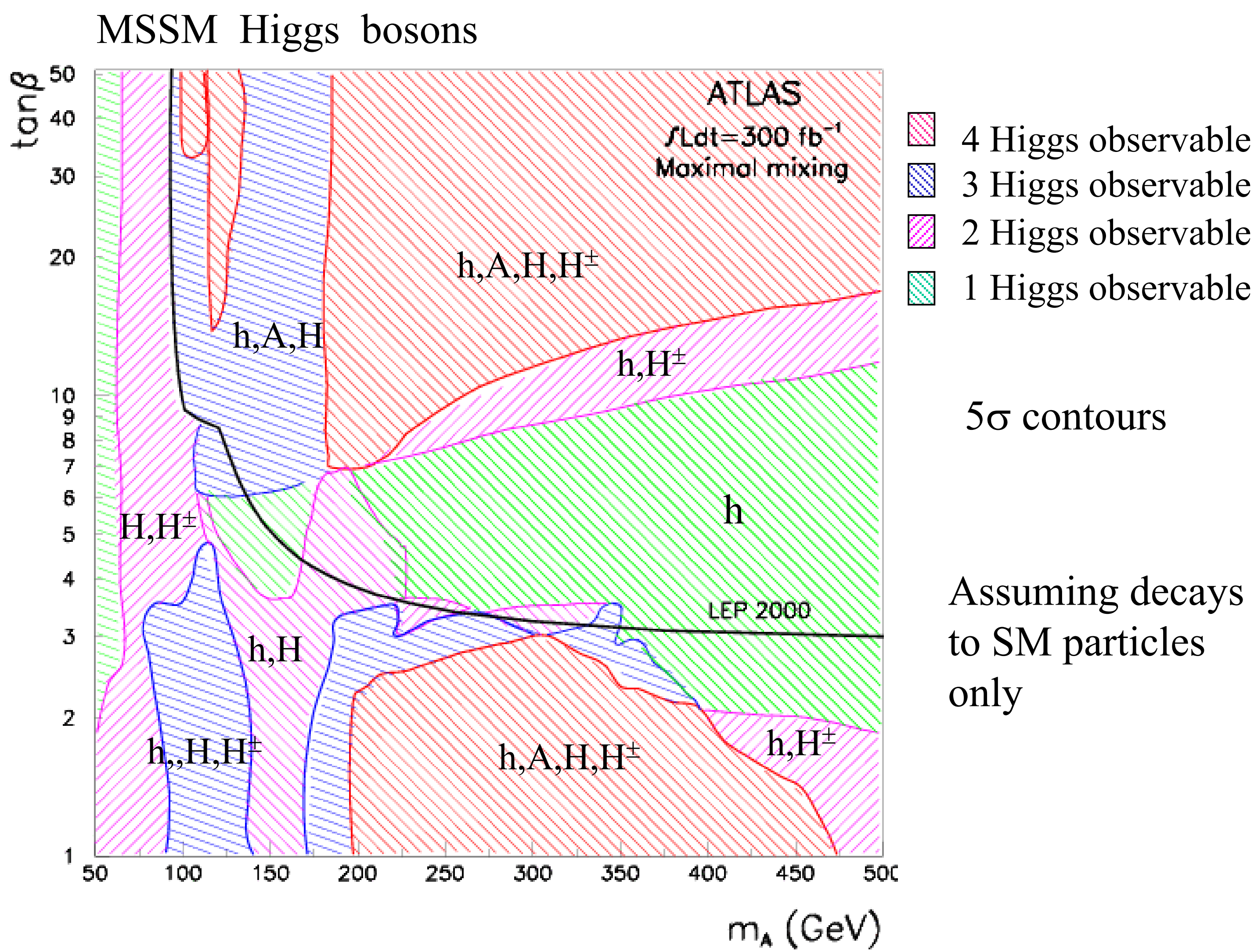
No stop mixing

maximal stop mixing with 30 fb^{-1}



maximal stop mixing with 300 fb^{-1}

Observability of MSSM Higgses

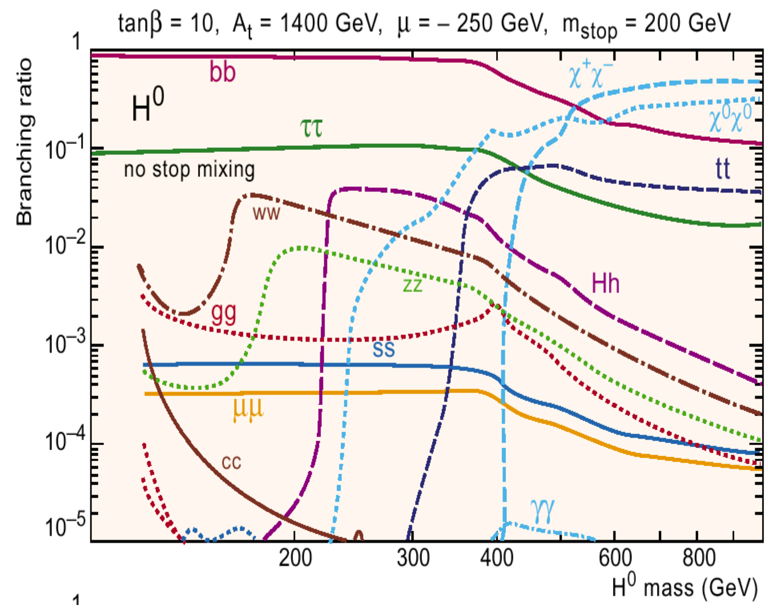


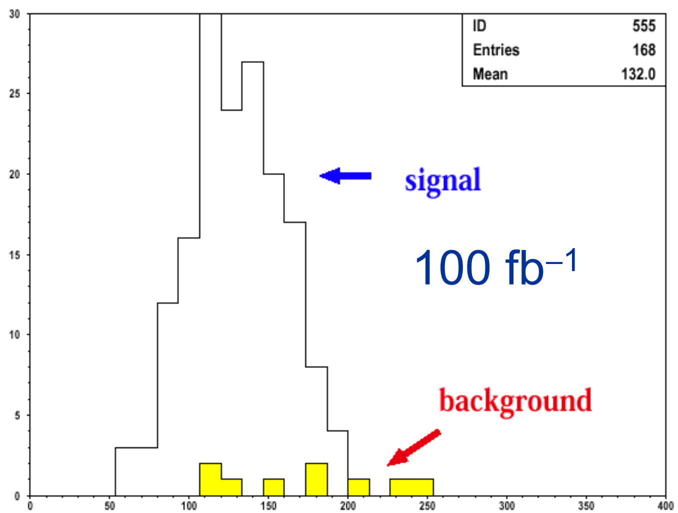
5σ contours

Assuming decays to SM particles only

If SUSY charg(neutral)inos < 1 TeV (I)

- Decays $H^0 \to \tilde{\chi}^0_2\tilde{\chi}^0_2$, $\tilde{\chi}^+_i\tilde{\chi}^-_j$ become important
  - Recall that $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+\ell^-$ has spectacular edge on the dilepton mass distribution
  - Example: $\tilde{\chi}^0_2\tilde{\chi}^0_2$. Four (!) leptons (isolated); plus two edges





Four-lepton mass

Central point in MSSM parameter space :

$M_{A,H} = 350$ GeV $\tan\beta = 5$

$M_{\tilde{l}} = 250$ GeV $\mu = -500$ GeV

$M_{\tilde{\chi}^0_1} = 60$ GeV $M_{\tilde{\chi}^0_2} = 110$ GeV

$M_{\tilde{q}} = M_{\tilde{g}} = 1$ TeV

If SUSY charg(neutral)inos < 1 TeV (II)

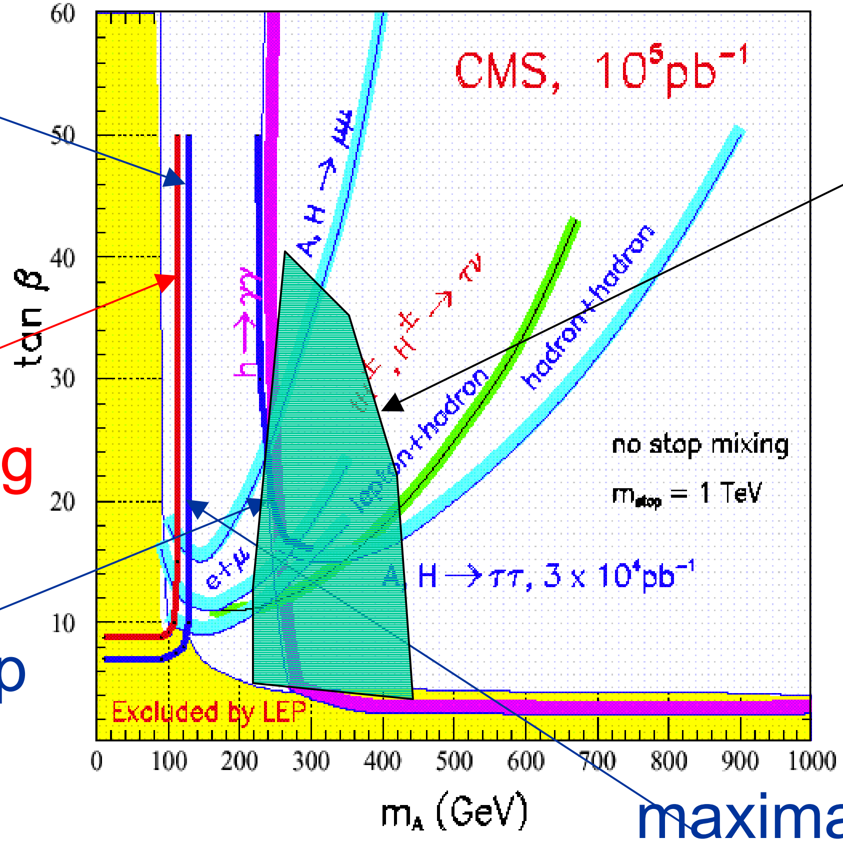
- Helps fill up the "hole"

Wh

$(e/\mu)\nu$ $b\bar{b}$

No stop mixing

maximal stop mixing with 30 fb^{-1}



Area covered by $H^0 \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2$, $\rightarrow 4\ell$eptons 100 fb^{-1}

maximal stop mixing with 300 fb^{-1}

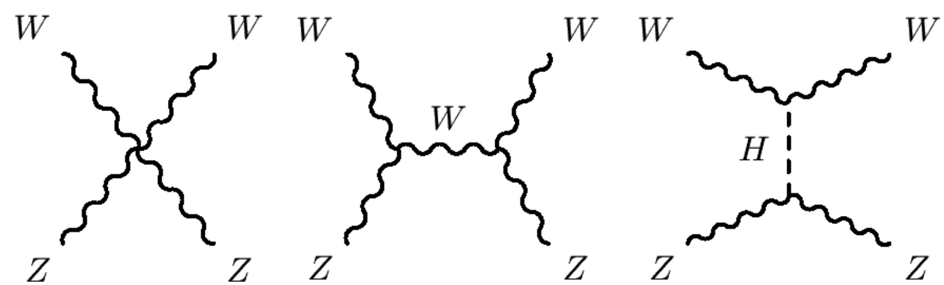
MSSM: Higgs summary

- At least one ϕ will be found in the entire M_A-tanβ plane
  - latter (almost) entirely covered by the various signatures
  - Full exploration requires 100 fb^{-1}
  - Difficult region: $3<\tan\beta<10$ and $120<M_A<220$; will need:
    - > 100 fb^{-1} or $h \rightarrow bb$ decays
    - Further improvements on τ identification?
  - Intermediate tanβ region: difficult to disentangle SM and MSSM Higgses (only h is detectable)
- Potential caveats (not favored)
  - Sterile (or "invisible") Higgs
  - Light gluino (~10 GeV), decays to sbottom (~few GeV), does not couple to Z, etc
    - Leads to hadronic (but non-b) decays of the H; e.g. Berger et al, hep-ph0205342

Strong “EWK” interactions

Strong boson-boson scattering

- Example: $W_L Z_L$ scattering
  - W, Z polarization vector ε^{μ} satisfies: $\varepsilon^{\mu} p_{\mu}=0$;
    - for $p_{\mu}=(E,0,0,p)$, $\varepsilon^{\mu}=1/M_V(p,0,0,E) \approx P^{\mu}/M_V+O(M_V/E)$
  - Scattering amplitude ~ (p_1/M_W) (p_2/M_Z) (p_3/M_W) (p_4/M_Z), i.e. $\sigma \sim s^2/M_W^2 M_Z^2$

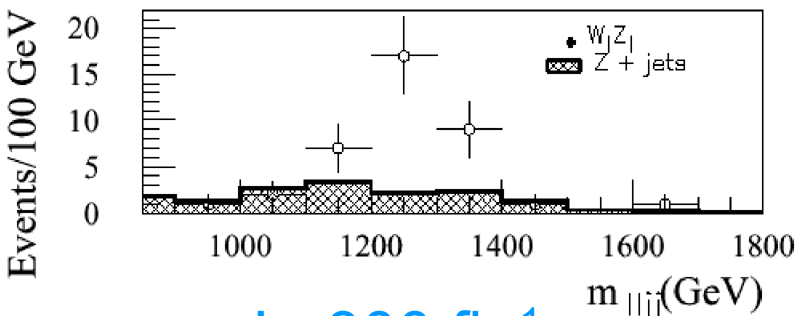


  - Taking $M_H \to \infty$ the H diagram goes to zero (~ $1/M_H^2$)
  - Technicalities: diagrams are gauge invariant, can take out one factor of s
    - but the second always remains (non-abelian group)
  - Conclusion: to preserve unitarity, one must switch on the H at some mass
    - Currently: $M_H \leq 700$ GeV

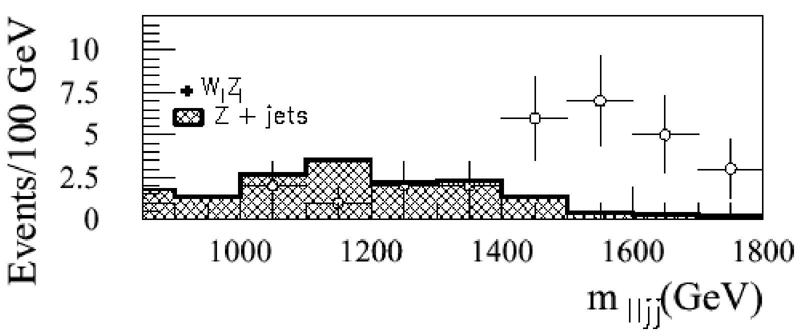
The no Higgs case: $V_L V_L$ scattering

- Biggest background is Standard Model VV scattering
  - Analyses are difficult and limited by statistics

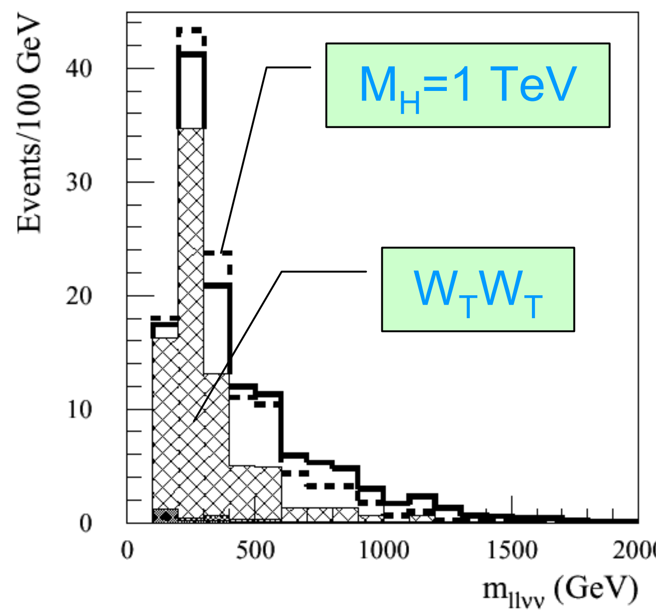
Resonant WZ scattering at 1.2 & 1.5 TeV



L=300 fb^{-1}



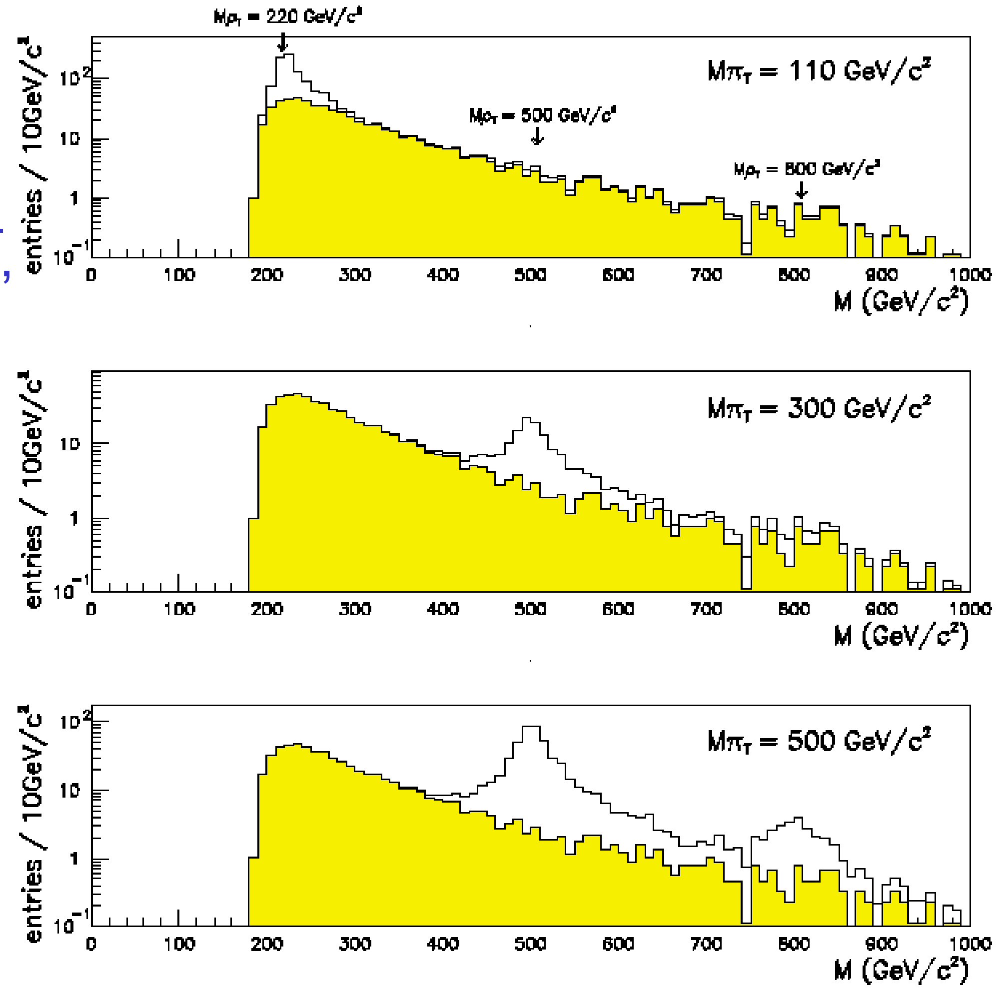
Non-resonant W^+W^+ scattering



Other resonances/signatures

- Technicolor; many possibilities
  - Example: $\rho_T^{\pm} \to W^{\pm}Z^0 \to \ell^{\pm}\nu\ell^{+}\ell^{-}$ (cleanest channel…)
  - Many other signals ($b\bar{b}$, $t\bar{t}$ resonances, etc…)
  - Wide range of observability

ATLAS; 30 fb^{-1}



Supersymmetry

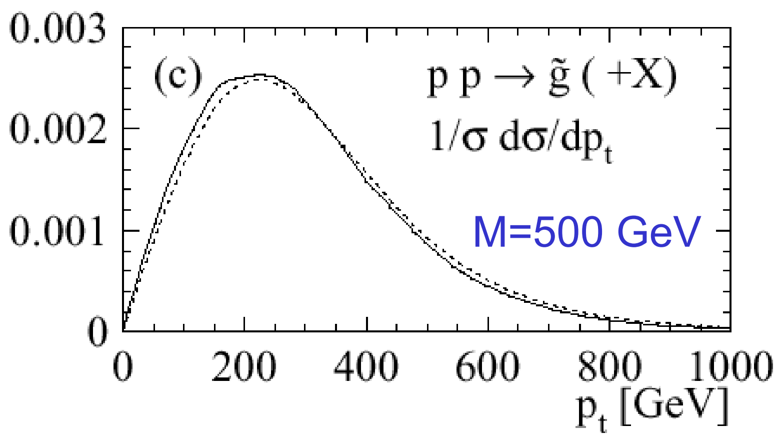
Sparticles

SUSY @ LHC

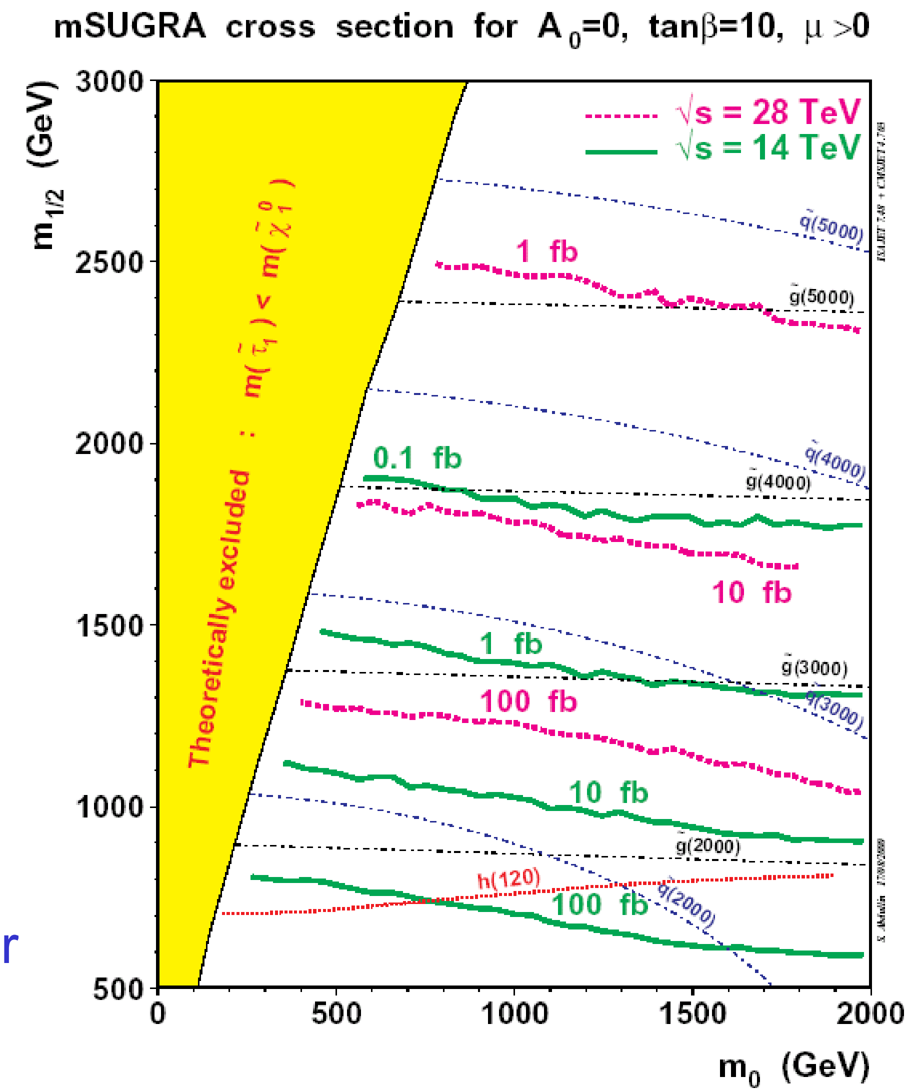
Simplest SUSY

- A SUSY factory

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3



- Gauginos produced in their decay; example: $q_L \to \chi_2^0 q_L$

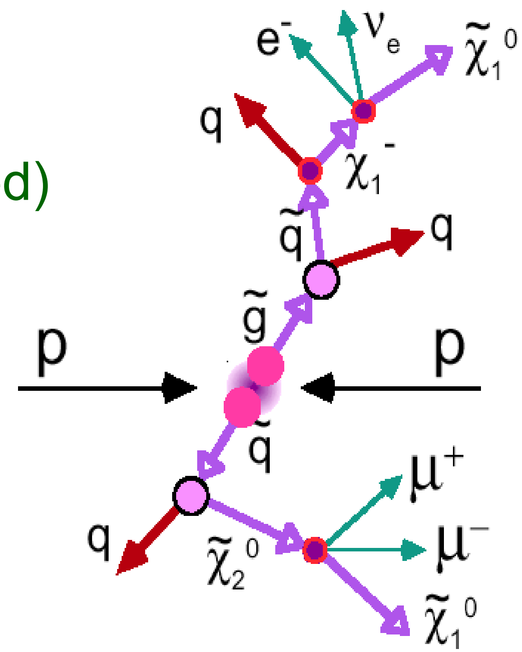


SUSY decays

- Squarks & gluinos produced together with high σ
  - Gauginos produced in their decays; examples:
    - $\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q_L$ (SUGRA P5)
    - $\tilde{q} \rightarrow \tilde{g}\, q \rightarrow \tilde{\chi}_2^0 q \bar{q}$ (GMSB G1a)
  - Two "generic" options with χ^0:

    (1) $\chi_2^0 \rightarrow \chi_1^0 h$ (~ dominates if allowed)

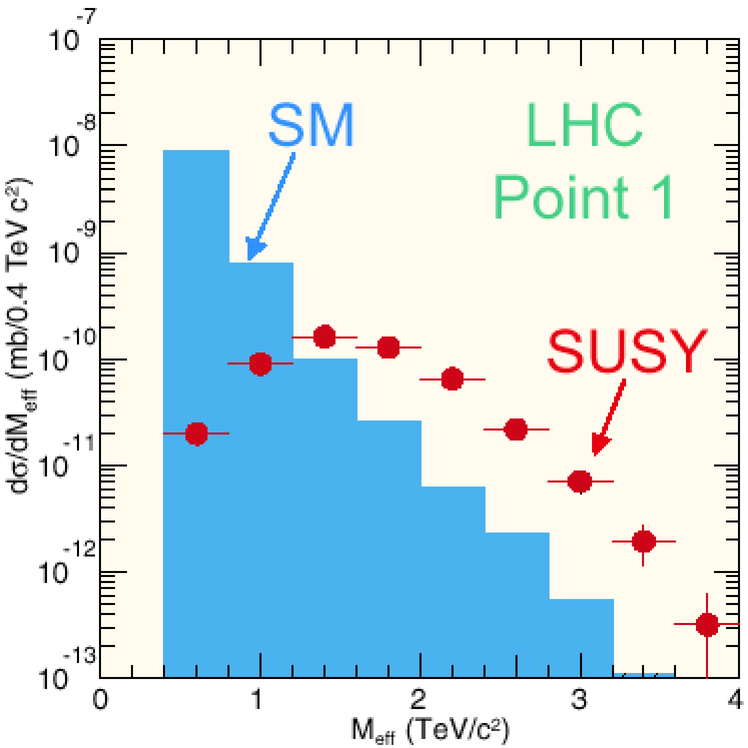
    (2) $\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$ or $\chi_2^0 \rightarrow \ell^+ \ell^-$
  - Charginos more difficult
    - Decay has ν or light q jet
  - Options:
    - Look for higgs (to $b\bar{b}$)
    - Isolated (multi)-leptons



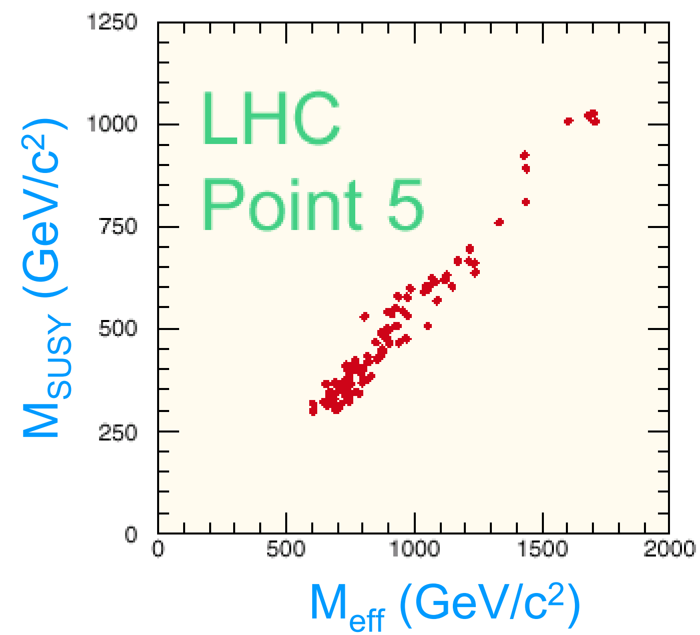
SUSY mass scale

- Events with ≥ 4jets + E_T^{miss}
  - Clean: S/B~10 at high M_{eff}
  - Establish SUSY scale ($\sigma \approx 20\%$)

$$M_{\text{eff}} = \sum_{j=1}^{4} P_{\text{T},j} + E_{\text{T}}^{\text{miss}}$$



Effective mass “tracks” SUSY scale well



SUSY

- Huge number of theoretical models
  - Very complex analysis; MSSM-124
  - Very hard work to study particular scenario
    - assuming it is available in an event generator
  - To reduce complexity we have to choose some “reasonable”, “typical” models; use a theory of dynamical SYSY breaking
    - mSUGRA
    - GMSB
    - AMSB (studied in less detail)
  - Model determines full phenomenology (masses, decays, signals)

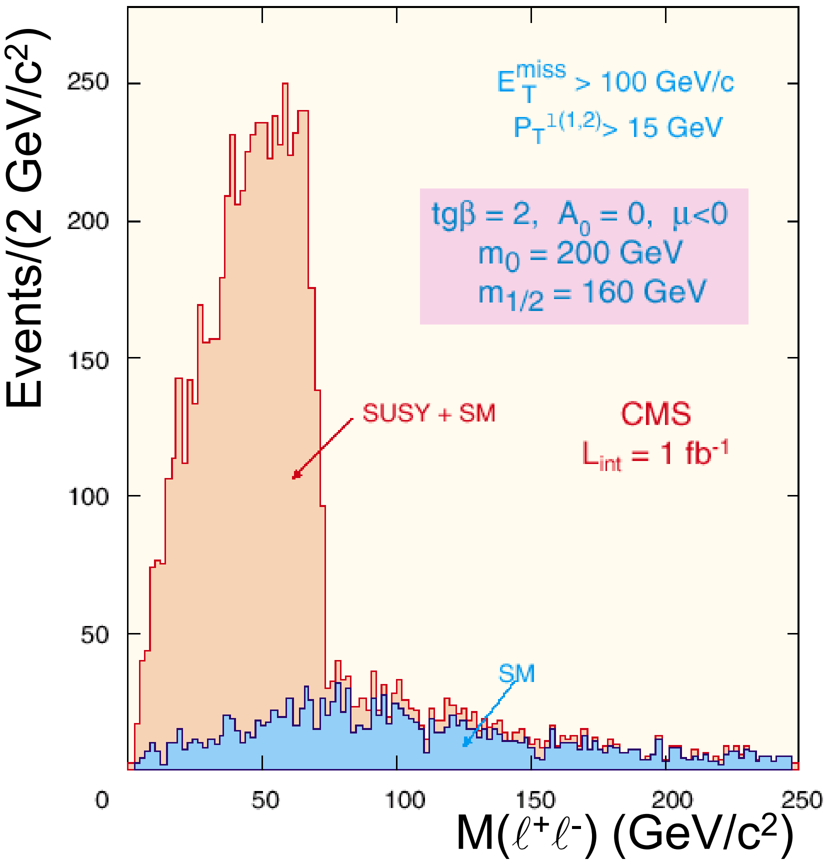
SUGRA: the (original) five LHC points

- Defined by LHCC in 1996
  - Most of them excluded by now…
    - Easy to bring them back
  - Points 1,3,5: light Higgses
    - LEP-excluded (3; less for 1,5)
    - Restore with larger $\tan\beta$
  - Points 1&2:
    - Squark/gluinos ≈ 1TeV
  - Point 4: at limit of SB
    - Small μ^2, large χ,ϕ mixing
    - Heavy squarks
  - Point 5: cosmology-motivated
    - Small $m_0 \rightarrow$ light sleptons
      $\rightarrow$ increase annihilation of χ_1^0
      $\rightarrow$ reduce CDM

P	M_0	$M_{1/2}$	A_0	$\tan\beta$	$s(\mu)$
1	400	400	0	2	+
2	400	400	0	10	+
3	200	100	0	2	–
4	800	200	0	10	+
5	100	300	300	2.1	+

Experimentally: spectacular signatures

- "Prototype": $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$
  - Straightforward:
    dileptons + E_T^{miss}
  - Example from P3
    - SM even smaller with b's
    - Also works at other points
    - But additional SM (e.g. Z^0)
  - ΔM measurement easy
    - Position of edge; accurate
  - Point excluded, but main point (dilepton-edge) still valid at other points



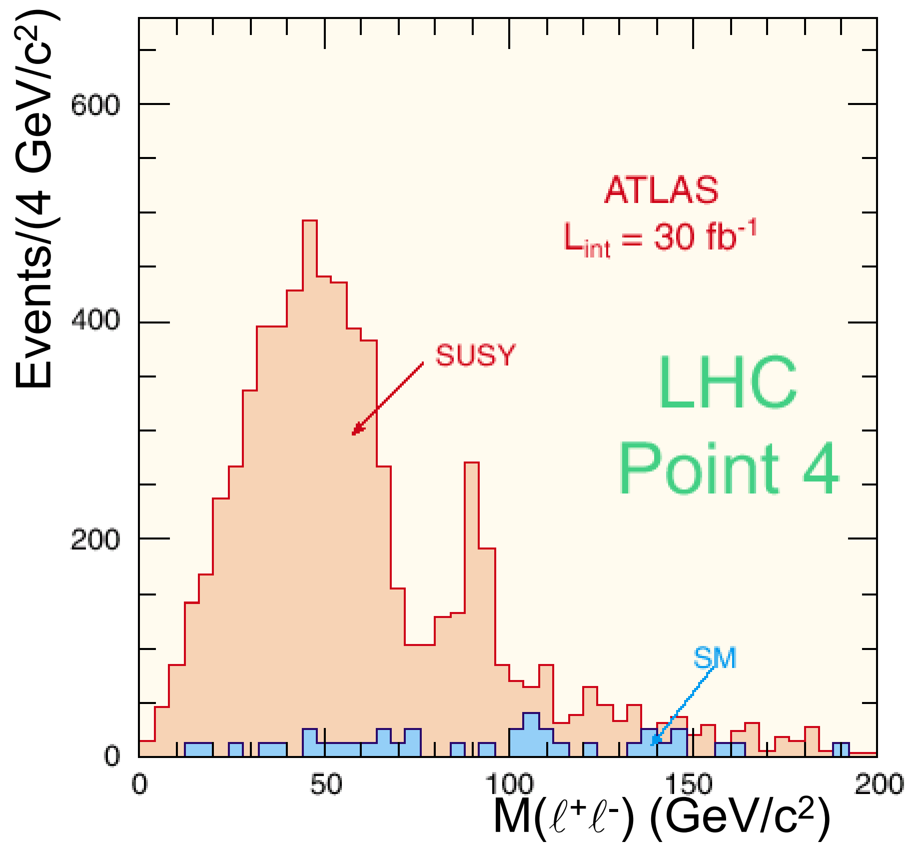
Dileptons @ other points

- Multi-observations
  - Main peak from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$
    - Measure Δm as before
  - Also peak from Z^0 through $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^0$
    - Due to heavier gauginos
    - P4 at "edge" of SB

      $\rightarrow$ small μ^2 $\rightarrow$

      (a) $\chi^\pm$ and $\tilde{\chi}^0$ are light

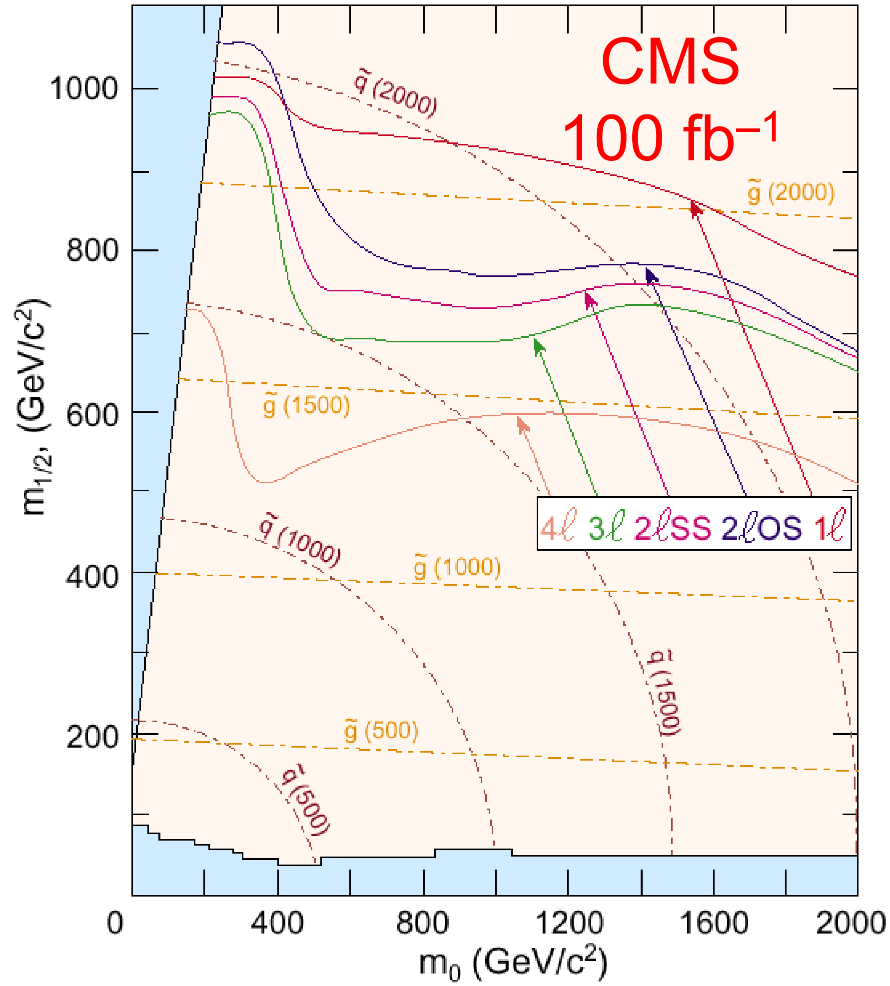
      (b) strong mixing between gauginos and Higgsinos



- At P4 large Branching fractions to Z decays:
  - e.g. $B(\tilde{\chi}_3 \rightarrow \tilde{\chi}_{1,2} Z^0) \approx 1/3$; size of peak/$P_T(Z) \rightarrow$ info on masses and mixing of heavier gauginos (model-dependent)

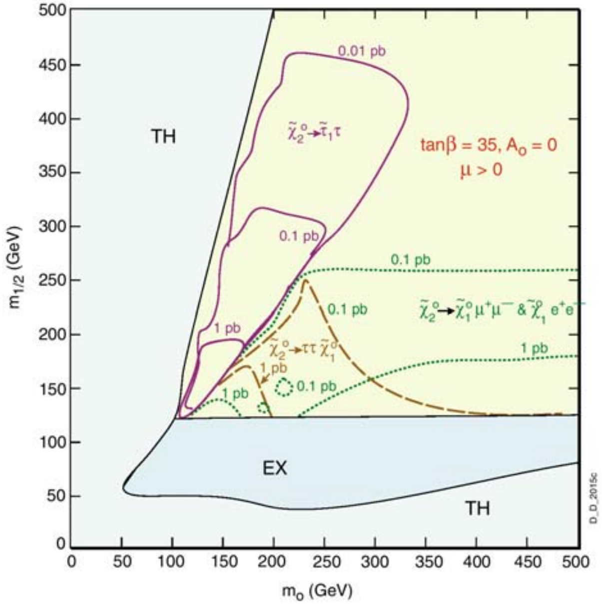
SUGRA reach

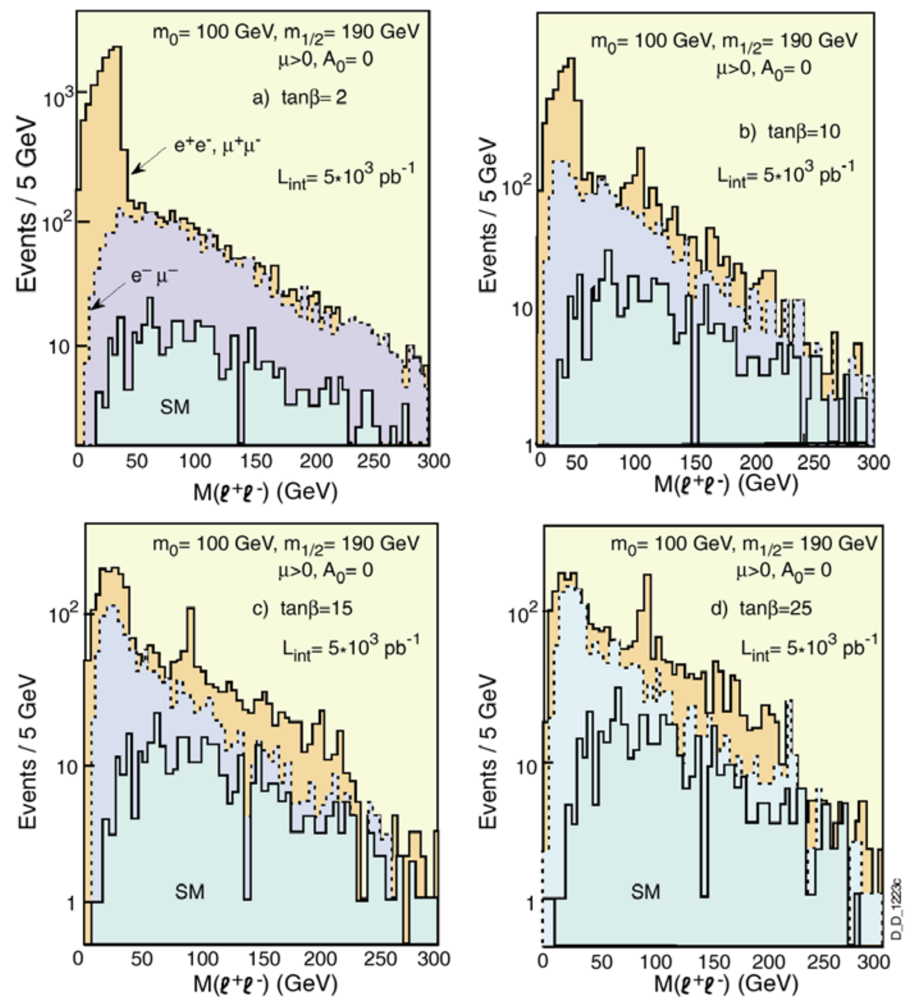
- Using all signatures
  - $\tan\beta=2; A_0=0; \mathrm{sign}(\mu)=-$
  - But look at entire m_0-$m_{1/2}$ plane
  - Example signature:
    - N (isolated) leptons + ≥ 2 jets + E_T^{miss}
    - 5σ (σ=significance) contours
- Essentially reach is ~2 (1) TeV/c^2 for the m_0 ($m_{1/2}$) plane



Varying tanβ

- τ modes eventually become important



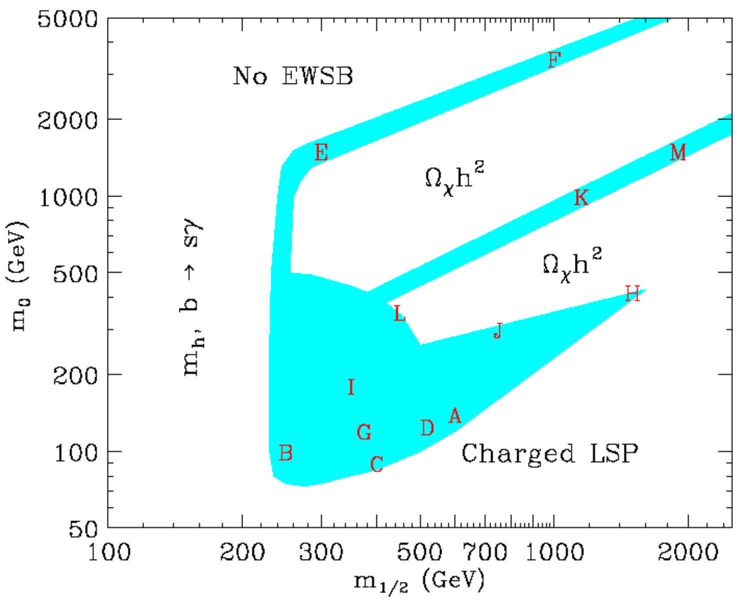


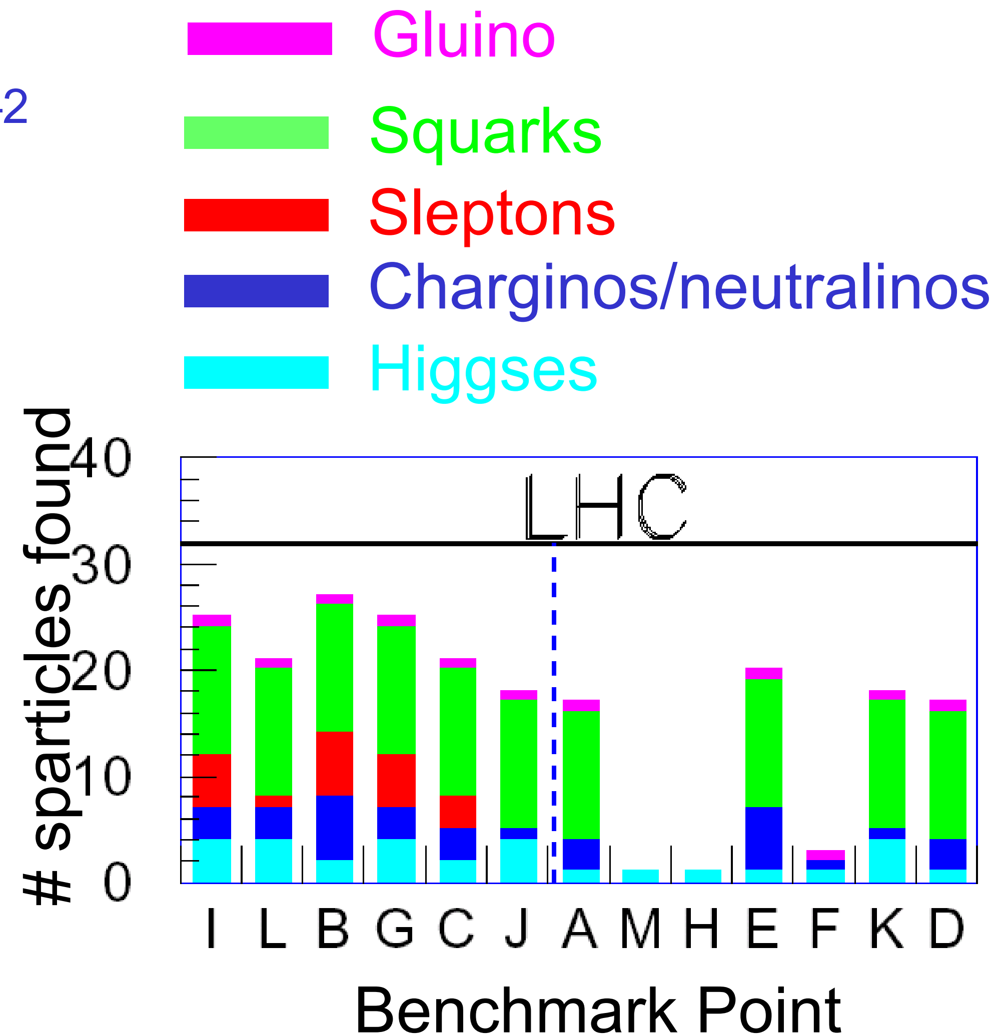
  - At tanβ>>1 only 2-body $\tilde{\chi}_2^0$ decays (may be): $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau \to \tau\tau\tilde{\chi}_1^0$
- Visible eμ excess over SM; for dilepton edge: need ττ mass

Overall reach

- New set of benchmarks currently in use
  - Account for LEP, $b \to s\gamma$, $g_\mu - 2$ and cosmology
  - Example: “BDEGMOPW”

    (Battaglia et al, hep-ph/0112013)





SUSY parameters; SUGRA

Point/Lumi	m_0 (GeV)	$m_{1/2}$ (TeV)	$\tan\beta$	$s(\mu)$
P1 @100fb^{-1}	400±100	400±8	2.00±0.08	ok
P2 @100fb^{-1}	400±100	400±8	10±2	ok
P4 @100fb^{-1}	800±50	200±2	10±2	ok
P5 @10fb^{-1}	100±4	300±3	±0.1	ok

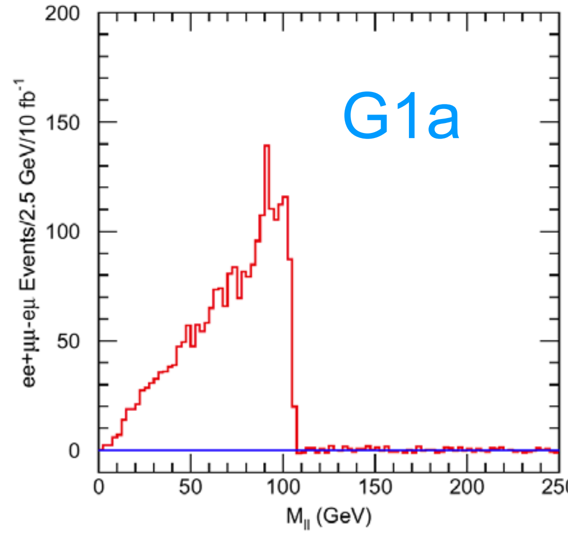
Essentially no information on A_0

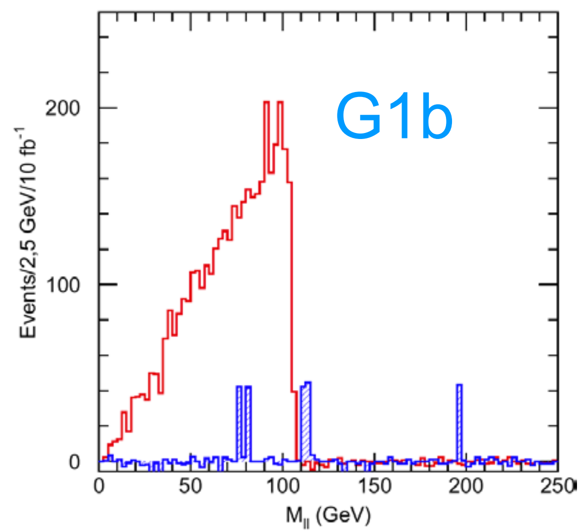
(A_{heavy} evolve to fixed point independent A_0)

SUSY: precision measurements

GMSB observation

- Example: G1a; same dilepton edge
  - Decay observed:
    $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\, \ell^{\pm}\ell^{\mp} \to \tilde{G}\gamma\ell^{+}\ell^{-}$
  - Selection is simple:
    - M_{eff}>400 GeV
    - E_T^{miss}>0.1M_{eff}
    - Demand same-flavor leptons
    - Form $e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mp}$
- G2b: very similar to SUGRA
  - χ_1^0 is long-lived, escapes
  - Decay observed:
    $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\, \ell^{+}\ell^{-}$
  - M_{eff}>1 TeV; rest of selection as in G1a





SUSY parameter measurements (G1a)

- G1a: endpoint in $M(\ell\ell) \rightarrow$ 3 parameters

$$M_{\max}^{\ell^+\ell^-} = M(\tilde{\chi}_2^0)\sqrt{1-\left(\frac{M(\tilde{\ell}_R)}{M(\tilde{\chi}_2^0)}\right)^2}\sqrt{1-\left(\frac{M(\tilde{\chi}_1^0)}{M(\tilde{\ell}_R)}\right)^2}$$

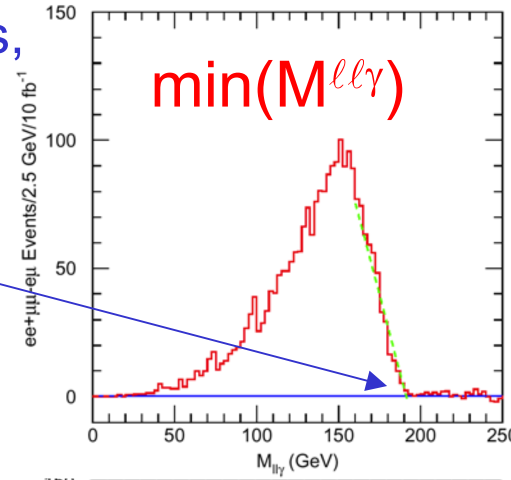
  - Events with two leptons and two photons, plot min($M(\ell\ell\gamma)$) yields second relation:

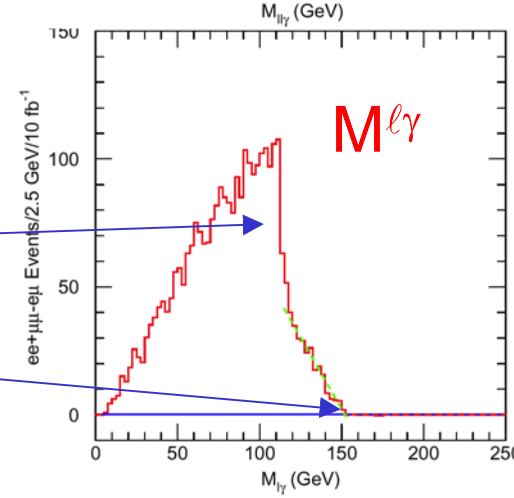
$$M_{\max}^{\ell^+\ell^-\gamma} = \sqrt{M^2(\tilde{\chi}_2^0) - M^2(\tilde{\chi}_1^0)}$$

  - Next: evts with only one $M(\ell\ell\gamma)$ smaller than endpoint mass
    - Unambiguous id of *χ_2^0 decay*
    - Plot lepton-photon mass, two more structures:

$$\sqrt{M^2(\tilde{\ell}_R) - M^2(\tilde{\chi}_1^0)} = 112.7\,\mathrm{GeV}$$

$$\sqrt{M^2(\tilde{\chi}_2^0) - M^2(\tilde{\ell}_R)} = 152.6\,\mathrm{GeV}$$

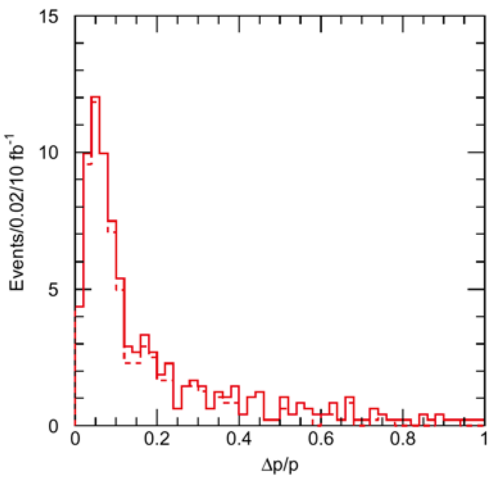




SUSY mass measurements (G1a)

- Measurement of edge positions: very accurate
  - Worse resolution on linear fit (e.g. min(M($\ell\ell\gamma$)) $\rightarrow$
    - Low luminosity: ±0.5 GeV; High lumi: ±0.2 GeV (syst).
  - One can extract masses of $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$, $\tilde{\ell}_R$
    - Model-independent (except for decay, rate and interpretation of slepton mass as mass of $\tilde{\ell}_R$)
- Next step: reconstruct G momentum
  - Motivation: can then build on $\tilde{\chi}_2^0$ to reconstruct M_q and M_g
    - 0C fit to $\tilde{\chi}_2^0 \rightarrow \tilde{G}\gamma\ell^+\ell^-$ (with $M_{\tilde{G}}$=0)
      - Momentum to 4-fold ambiguity
    - Use evts with 4 leptons + 2 photons
      - E_T^{miss} fit to resolve solns: min(χ^2):

$$\chi^2 = \left(\frac{E_x^{miss} - P_{1x} - P_{2x}}{\Delta E_x^{miss}}\right)^2 + \left(\frac{E_y^{miss} - P_{1y} - P_{2y}}{\Delta E_y^{miss}}\right)^2$$



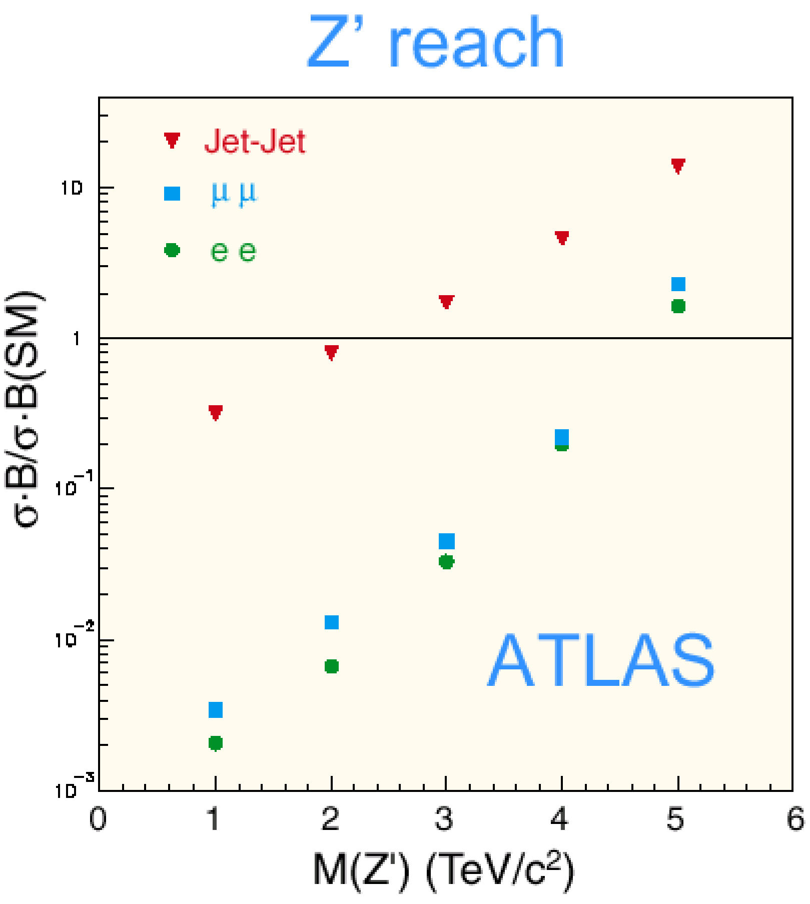
SUSY Summary

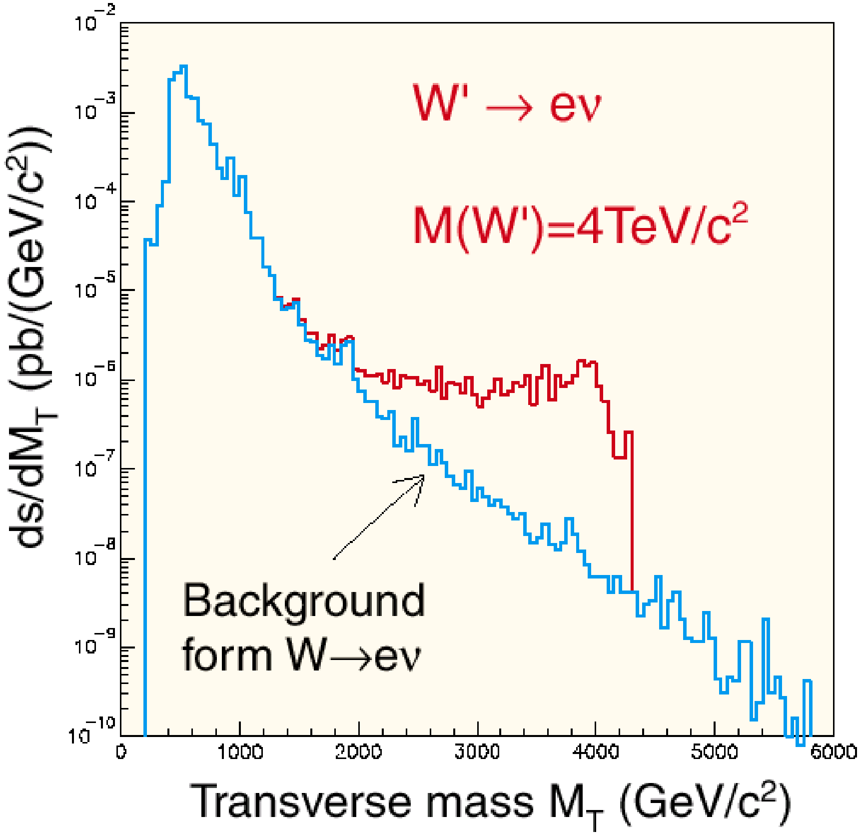
- SUSY discovery (should be) easy and fast
  - Expect very large yield of events in clean signatures (dilepton, diphoton).
    - Establishing mass scale is also easy (M_{eff})
- Squarks and gluinos can be discovered over very large range in SUGRA space $(M_0,M_{1/2})\sim(2,1)$TeV
  - Discovery of charginos/neutralinos depends on model
  - Sleptons difficult if mass > 300 GeV
  - Evaluation of new benchmarks (given LEP, cosmology etc) in progress
- Measurements: mass differences from edges, squark and gluino masses from combinatorics
- Can extract SYSY parameters with ~(1-10)% accuracy

Other new Physics BSM

Other resonances/signatures (I)

- New vector bosons



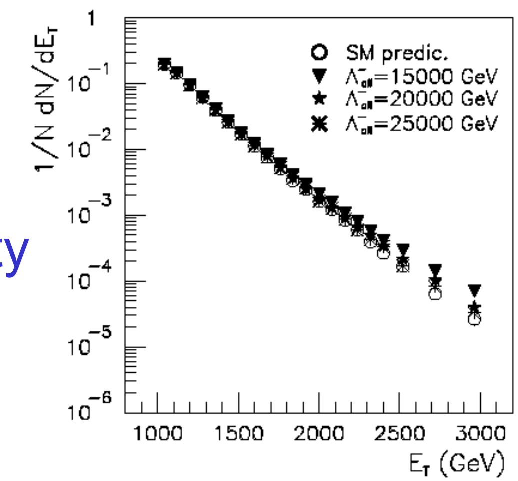


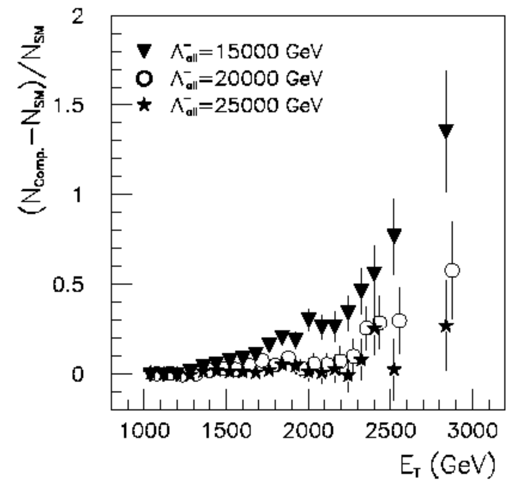
Compositeness

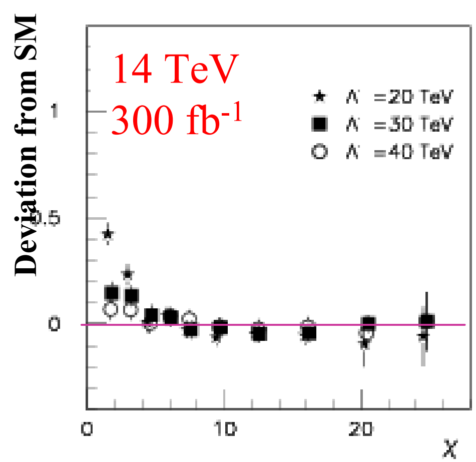
- Usual excess @ high P_T(jet) expected
  - Tricky issue: calorimeter (non)linearity
  - Analysis proceeds via angular distribution

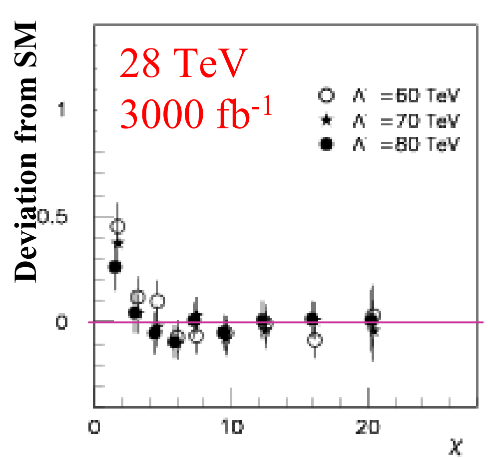
$$\chi = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

  - Ultimate reach: Λ_{comp} ~ 40 TeV (depends on understanding non-linearity @ 1-2% level)



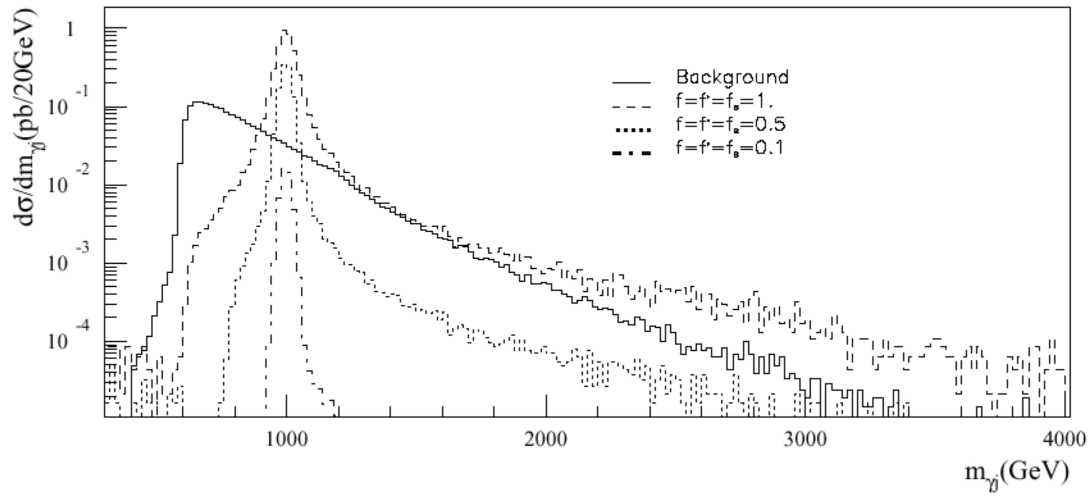


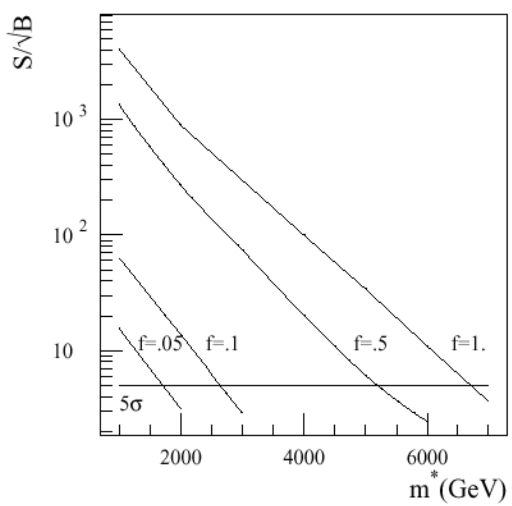


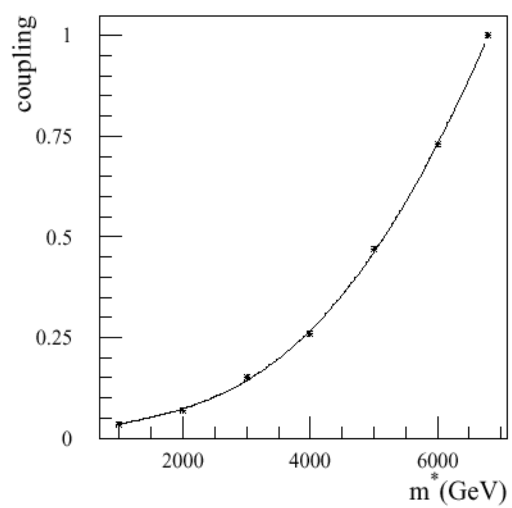


Excited quarks

- Search for q*→qγ







TeV-scale gravity

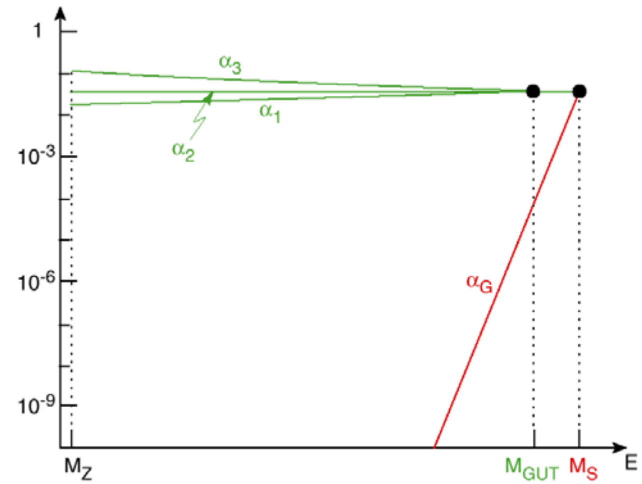
Naturalness

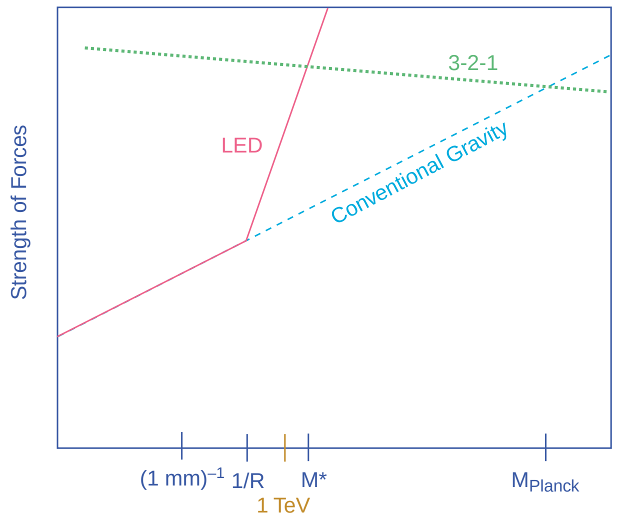
- SUSY: the mass protector
  - $\delta M_W^2 \sim (\alpha/\pi)\Lambda^2 >> (M_W)^2$; But with SUSY $\delta M_W^2 \sim (\alpha/\pi)|M_{SP} - M_P|^2$
    - The pro-LHC argument: correction small$\rightarrow M_{SP} \sim 1$TeV
    - Lots of positive side-effects:
      - LSP a great dark-matter candidate;
      - unification easier;
      - poetic justice: why would nature miss this transformation? (complete transforms in the Poincare group – only SUSY escapes Coleman-Mandula no-go theorem)

- SUSY does not answer why $G_F \sim (M_W)^{-2} >> (M_{PL})^{-2} \sim G_N$
  - But it (at least) allows it

TeV-scale gravity

- The idea of our times: that the scale of gravity is actually not given by M_{PL} but by M_W
  - Strings live in >4 dimensions. Compactification → 4D "SM". M_{PL-4} related to $M_{PL-(4+d)}$ via volume of xtra dimensions:
    - $M_{PL-4}^2 \sim V_d \, M_{PL-(4+d)}^{2+d}$
  - Conventional compactification: very small curled up dims, $M_{PL-4} \sim M_{PL-(4+d)}$
    - $V_d \sim (M_{PL-4})^{-d}$
  - Alternative: volume is large; large enough that $V_d >> (M_{PL-(4+d)})^{-d}$
    - Then $M_{PL-(4+d)}$ can be ~ TeV (!)
    - "our" Planck mass at log(Λ)~19: an artifact of the extrapolation



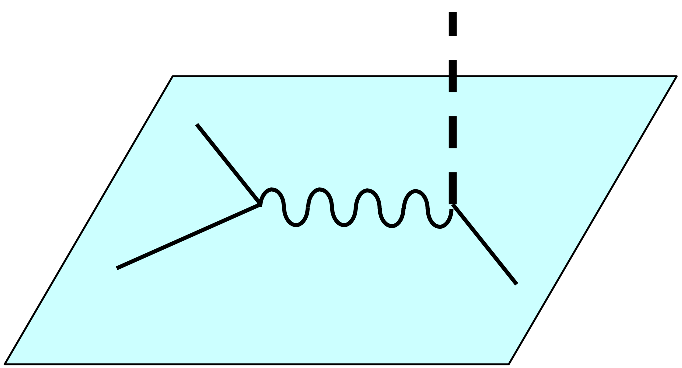


Getting M_{PL-4}~1TeV

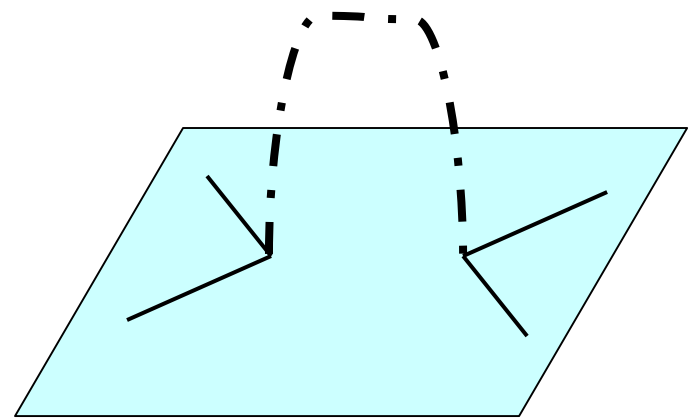
- Can be, if V_d is large; this can be done in two ways:
  - By hand: large extra dimensions (Arkani-Hamed,Dimopoulos,Dvali)
    - Size of xtra dimensions from ~mm for d=2 to ~fm for d=6
    - But gauge interactions tested to ~100 GeV
      - Confine SM to propagate on a brane (thanks to string theory)
    - Rich phenomenology
  - Via a warp factor (Randall-Sundrum)
    - $ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}(y) dy^m dy^n$
      - (x: SM coordinates; y: d xtra ones)
    - Generalize: dependence on location in xtra dimension
    - $ds^2 = e^{2A(y)}\, g_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}(y) dy^m dy^n$
      - Large exp(A(y)) also results in large V_d
      - As an example (RS model), two 4-D branes, one for SM, one for gravity, "cover" a 5-D space – with an extra dim in between

Extra (large) dimensions

- Different models, different signatures:
  - Channels with missing E_T: E_T^{miss}+(jet/γ) (back-to-back)
  - Direct reconstruction of KK modes
    - Essentially a W', Z' search
  - Warped extra dimensions (graviton excitations)



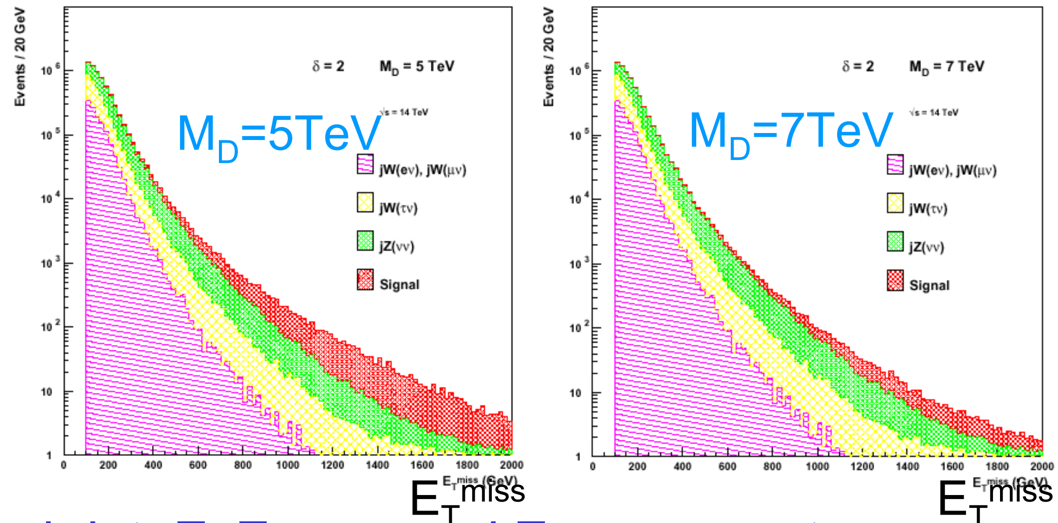
e.g. in Giudice, Ratazzi, Wells (hep-ph/9811291)

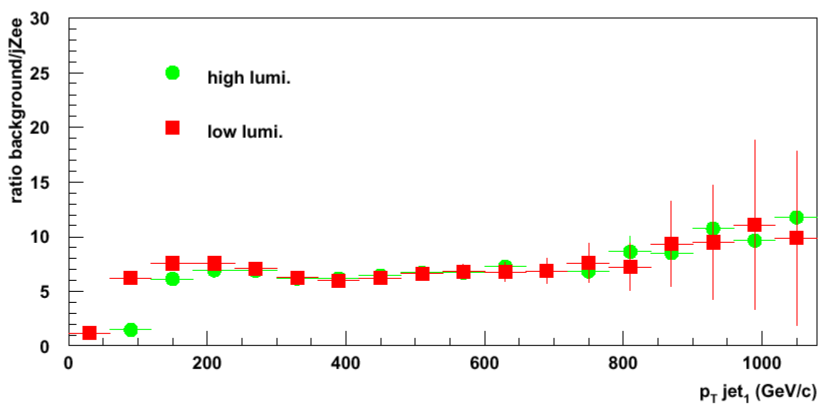


e.g. in Hewett (hep-ph/9811356)

Extra dimensions (I): E_T^{miss}+Jet

- Issue: signal & bkg topologies same; must know shape of bkg vs e.g. E_T^{miss}
  - Bkg: jet+W/Z; $Z \to \nu\nu$; $W \to \ell\nu$.
  - Bkg normalized through jet+Z, $Z \to ee$ and $Z \to \mu\mu$ events





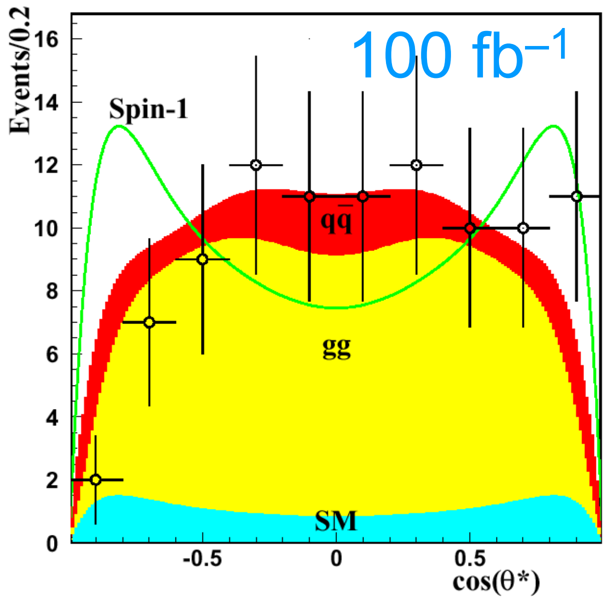
Reach @ 5σ

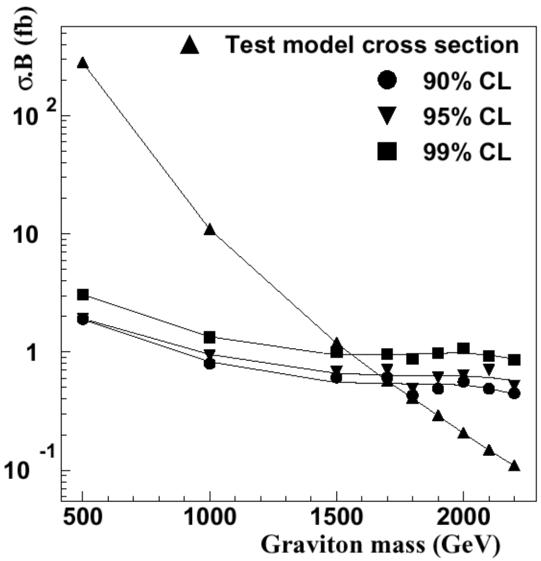
δ	M_D (TeV)	R_D
2	7.5	10 μm
3	5.9	200 pm
4	5.3	1 pm

- Also $E_T^{miss}+\gamma$; M_D reach smaller

KK resonances+angular analysis

- If graviton excitations present, essentially a Z' search.
  - Added bonus: spin-2 (instead of spin-1 for Z)
    - Case shown*: $G \rightarrow e^+e^-$ for M(G)=1.5 TeV
    - Extract minimum σ.B for which spin-w hypothesis is favored (at 90-95%CL)





* B.Allanach,K.Odagiri,M.Parker,B.Webber JHEP09 (2000)019

En passant

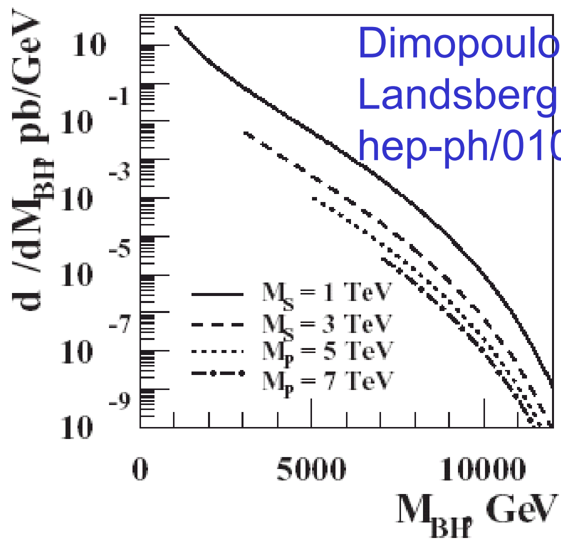
- TeV-scale gravity is attracting a lot of interest/work
  - Much is recent, even more is evolving
  - Turning to new issues, like deciding whether a new dilepton resonance is a Z' or a KK excitation of a gauge boson
    - In the latter case we know photon, Z excitations nearly degenerate
      - One way would be to use W' (should also be degenerate, decays into lepton+neutrino)
        - » But this could also be the case for additional bosons…
  - Example: radion phenomenology
    - Radion: field that stabilizes the brane distance in the RS scenario. Similar to Higgs. Recent work suggests it can even mix with the Higgs.
      - Can affect things a lot
  - Stay tuned, for this is an exciting area

Black Holes at the LHC (?) (I)

- Always within context of "TeV-scale gravity"
  - Semi-classical argument: two partons approaching with impact parameter < Schwarzschild radius, $R_S \rightarrow$ black hole
    - $R_S \sim 1/M_P\,(M_{BH}/M_P)^{(1/d+1)}$ (Myers & Perry; Ann. Phys 172, 304 (1996)
  - From dimensions: $\sigma(M_{BH}) \sim \pi R_S^2$; $M_P \sim 1$TeV $\rightarrow \sigma \sim 400$ pb (!!!)
    - Absence of small coupling like α
  - LHC, if above threshold, will be a Black Hole Factory:
    - At minimum mass of 5 TeV: 1Hz production rate

Giddings & Thomas
hep-ph/0106219

Dimopoulos & Landsberg
hep-ph/0106295



Assumptions:

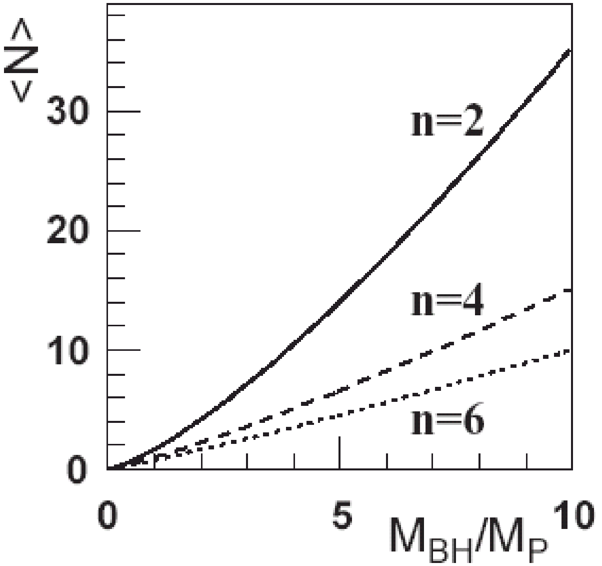
$M_{BH} >> M_P$; in order to avoid true quantum gravity effects… clearly not the case at the LHC – so caution

Black Holes at the LHC (II)

- Decay would be spectacular
  - Determined by Hawking temperature, $T_H \propto 1/R_S \sim M_P(M_P/M_{BH})^{(1/n+1)}$
    - Note: wavelength of Hawking T_H $(2\pi/T_H) > R_S$
      - BH a point radiator emitting s-waves
  - Thermal decay, high mass, large number of decay products
    - Implies democracy among particles on the SM brane
      - Contested (number of KK modes in the bulk large)

Picture ignores time evolution

…as BH decays, it becomes lighter hotter and decay accelerates (expect: start from asymmetric horizon $\rightarrow$symmetric, rotating BH with no hair $\rightarrow$spin down $\rightarrow$Schwarz-schild BH, radiate until $M_{BH} \sim M_P$. Then? Few quanta with $E \sim M_P$?



More generally: "transplackian physics"; see: Giudice, Ratazzi&Wells, hep-ph0112161

Beyond the LHC

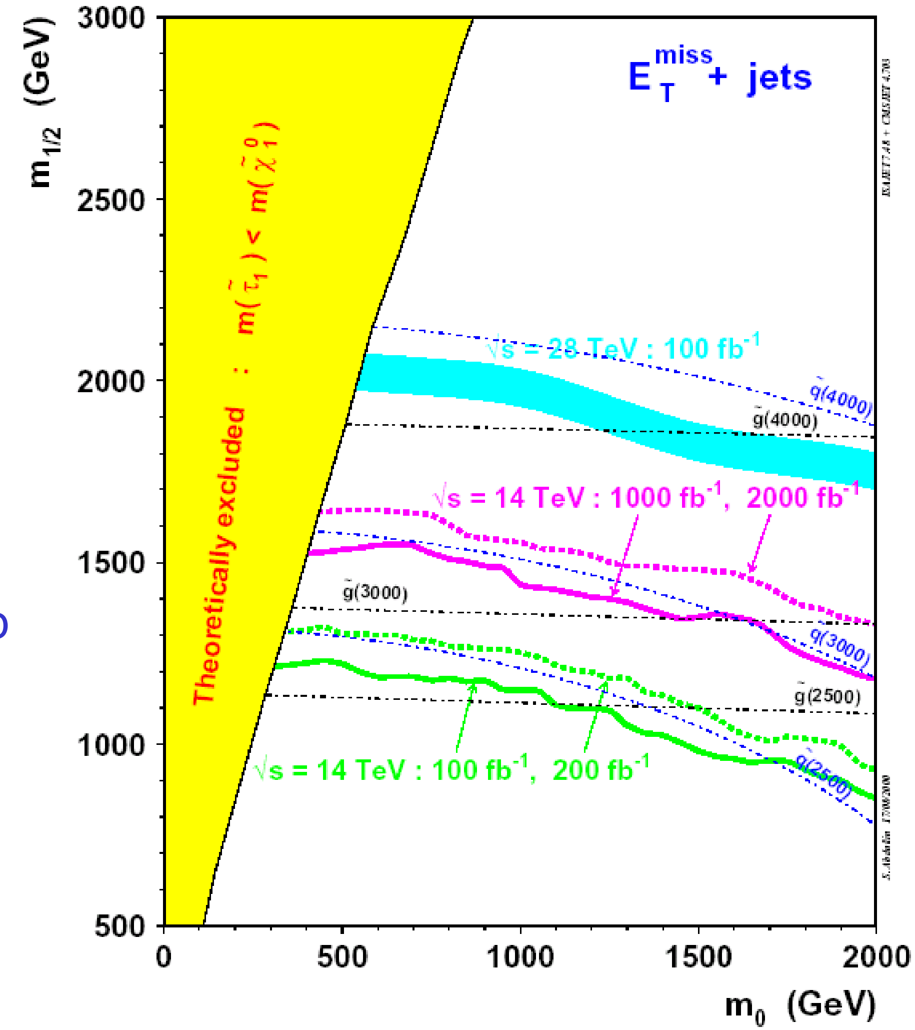
LHC++

Beyond LHC; LHC++?

- Clearly, a Linear Collider is a complementary machine to the LHC
  - Will narrow in on much of what the LHC cannot probe
  - Still a lot to do; e.g. see (and join/work!) LHC-LC study group http://www.ippp.dur.ac.uk/~georg/lhclc
- As for LHC, a very preliminary investigation of
  - LHC at $10^{35}cm^{-2}s^{-1}$; LHC at 28 TeV; LHC with both upgrades
  - First look at effect of these upgrades
    - Triple Gauge Couplings
    - Higgs rare decays; self-couplings;
    - Extra large dimensions
    - New resonances (Z')
    - SUSY
    - Strong VV scattering
  - Clearly, energy is better than luminosity
    - Detector status at 10^{35} needs careful evaluation

Supersymmetry reach @ LHC++

- mSUGRA scenario
  - Assume R_P conservation
  - Generic E_T^{miss}+Jets
  - Cuts are optimized to get best $S^2_{SUSY}/(S_{SUSY}+B_{SM})$
    - In some cases 0-2 leptons could be better
  - Shown: reach given
    - $A_0 = 0$; $\tan\beta=10$; $\mu>0$
  - For 28 TeV @ $10^{34}\text{cm}^{-2}\text{s}^{-1}$ probe squarks & gluinos up to ~ 4 TeV/c^2
  - For 14 TeV @ $10^{35}\text{cm}^{-2}\text{s}^{-1}$ reach is ~ 3 TeV/c^2



(Grand) Summary

- Symmetry Breaking in the SM (and beyond!) still not really understood
  - Higgs missing; LHC (and ATLAS/CMS) designed to find it
- Physics at the LHC will be extremely rich
  - SM Higgs (if there) in the pocket
    - Turning to measurements of properties (couplings, etc.)
  - Supersymmetry (if there) ditto
    - Can perform numerous accurate measurements
  - Large com energy: new thresholds
    - TeV-scale gravity? Large extra dimensions? Black Hole production? The end of small-distance physics?
    - And of course, compositeness, new bosons, excited quarks…
    - There might be a few physics channels that could benefit from more luminosity… LHC++?
- We just need to build the machine and the experiments