Theoretical Overview

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Outline

- I. Electroweak Physics
- II. Electroweak symmetry breaking
- III. Supersymmetry
- IV. Extra dimensions
- V. Final remarks

Good times ahead!

- What we know:

$$\mathcal{L} = \mathcal{L}^{\rm f}_{\rm kinetic} + \mathcal{L}^{\rm GB}_{\rm kinetic} + \mathcal{L}_{\rm ffv} + \mathcal{L}_{\rm vvv} + \mathcal{L}_{\rm vvvv} + \mathcal{L}_{\rm EWSB}$$

- $\mathbf{SU(3)_c \times SU(2)_L \times U(1)_Y}$ gauge interaction between fermions and gauge bosons tested at 0.1% level.

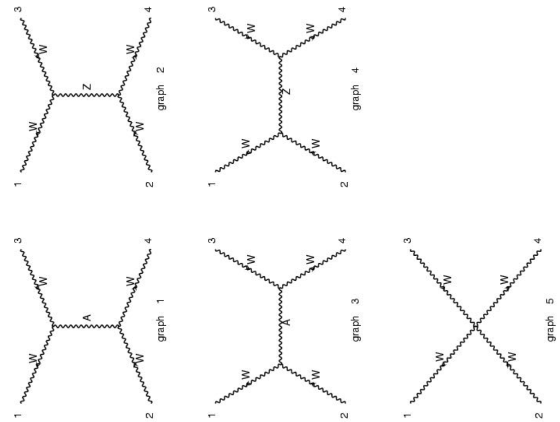
- Some information on the interactions between the gauge bosons

- $\mathcal{L}_{\rm EWSB}$ has not been directly tested: origin of masses, flavor physics, ...

- $\mathbf{SU(2)} \times \mathbf{U(1)}$ symmetry is broken:
  - Without EWSB $\Longrightarrow$ fermions are massless
  - QCD still confines $\Longrightarrow$ $\mathbf{p}$, $\mathbf{n}$, ... with some changes
  - $\mathbf{M_p} > \mathbf{M_n}$ (QED corrections)
  - rapid decay of $\mathbf{p}$ into $\mathbf{n}$ changing completely the world: no atoms, etc
- The EWSB sector has been elusive, but not for long!

EWSB $\times 1$ TeV scale

(Lee, Quigg, Thacker)



- $W_L^+ W_L^- \to W_L^+ W_L^-$ violates unitarity without EWSB

$$T(s,t) = A\left(\frac{p}{M_W}\right)^4 + B\left(\frac{p}{M_W}\right)^2 + C$$

$A = 0$ without the Higgs.

- Including the Higgs: $a_0 = -\frac{M_H^2}{16\pi v^2}\left[2 + \frac{M_H^2}{s-M_H^2} - \frac{M_H^2}{s}\log\left(1+\frac{s}{M_H^2}\right)\right]$

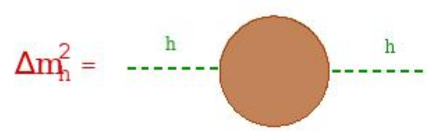
- High energy limit: $a_0 \xrightarrow{M_H^2 \ll s} -\frac{M_H^2}{8\pi v^2} \implies M_H < 870$ GeV ($M_H < 710$ GeV)

- No Higgs limit: $a_0 \xrightarrow{M_H^2 \gg s} -\frac{s}{32\pi v^2} \implies \sqrt{s_c} < 1.2$ TeV

Limitations of the SM

- Even after the Higgs discovery there are unanswered questions:
  - what is the origin of fermion masses?
  - do interactions unify at high energies?
  - what is the dark matter?
  - why is the cosmological constant so small?
  - what is the dark energy?
  - what is the origin of baryon asymmetry? ...
- The SM also has some technical problems: (hierarchy problem)

- Quantum corrections drive scalar masses to high scale $\mathbf{\Delta M_h^2 \propto \Lambda_{UV}^2}$



- This requires new physics in the TeV scale

- There are many solutions, pointing in different directions
  - Supersymmetry
  - Higgs is composite
    * technicolor
    * H is a Goldstone boson (little Higgs)
  - Extra spatial dimensions
    * Large ED
    * Warped ED (Randall-Sundrum)
    * Universal extra dimensions ...

I. Electroweak Physics

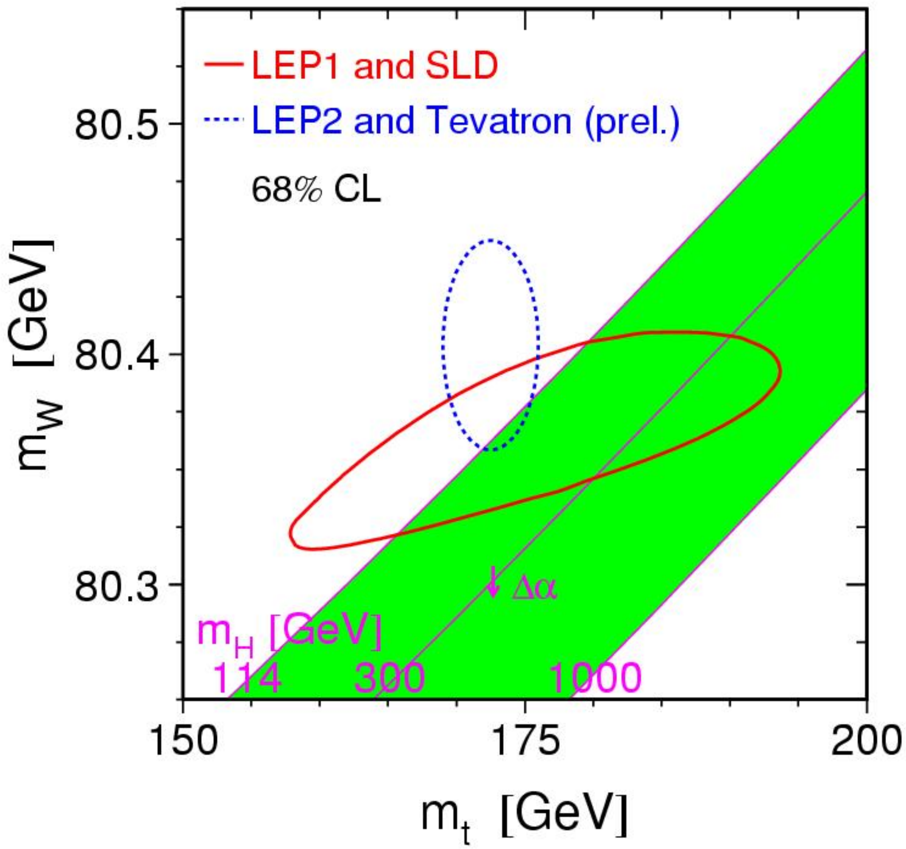
Precison measurements:

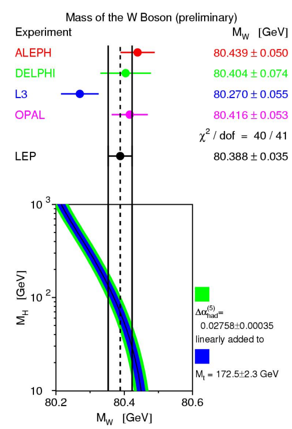
- The parameters of the SM: $\{\mathbf{p}\} \equiv \{\alpha_{\mathbf{em}},\ \alpha_{\mathbf{S}},\ \mathbf{G_F},\ \mathbf{M_Z},\ \mathbf{m_i} \ldots\}$
- In general observables depend upon many parameters after RC

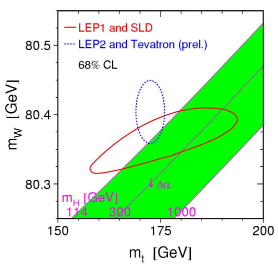
$$\mathcal{O}_{\mathbf{i}}^{\mathbf{theory}}(\{\mathbf{p}\}) = \mathcal{O}_{\mathbf{i}}^{\mathbf{tree}}(\alpha, \mathbf{G_F}, \mathbf{M_Z}) \left[\mathbf{1} + \mathbf{\Delta_i}(\{\mathbf{p}\})\right] \quad \text{e.g.}$$

$$\mathbf{M_W^2} = \frac{\pi\alpha}{\sqrt{\mathbf{2}}\mathbf{G_F}\sin^{\mathbf{2}}\theta_{\mathbf{W}}} \frac{\mathbf{1}}{(\mathbf{1} - \mathbf{\Delta r})}$$

- Precision measurements $\Longrightarrow$ non-trivial tests of the SM


LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
m_W [GeV]
80.5
80.4
80.3
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]


Mass of the W Boson (preliminary)
Experiment
M_W [GeV]
ALEPH
80.439 ± 0.050
DELPHI
80.404 ± 0.074
L3
80.270 ± 0.055
OPAL
80.416 ± 0.053
χ^2 / dof = 40 / 41
LEP
80.388 ± 0.035
10^3
10^2
10
M_H [GeV]
$\Delta\alpha^{(5)}_{had}$=
0.02758±0.00035
linearly added to
M_t = 172.5±2.3 GeV
80.2
80.4
80.6
M_W [GeV]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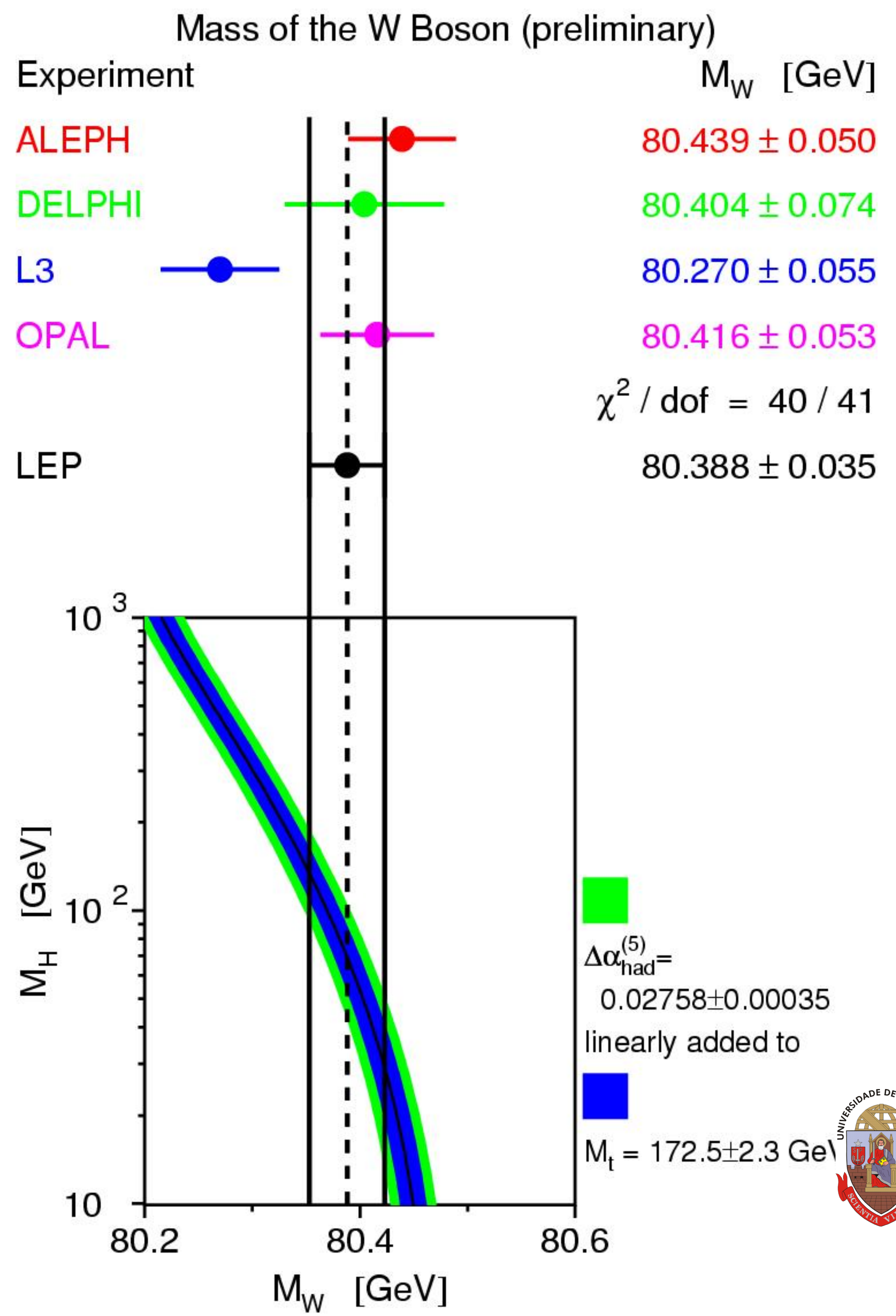
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Δα_had^(5)=
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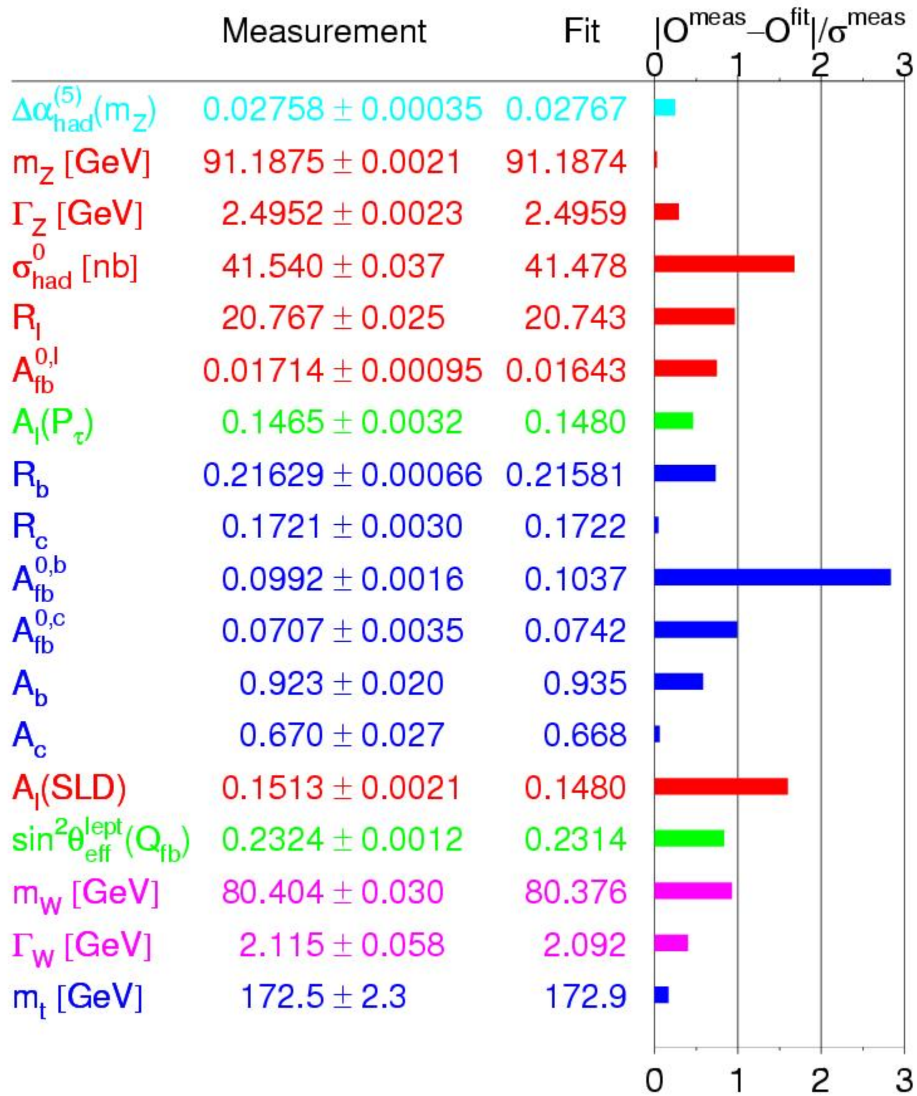
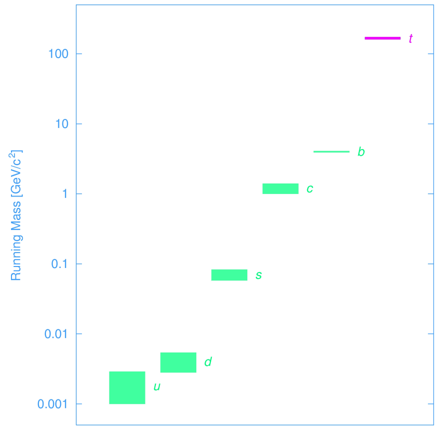
linearly added to
M_t = 172.5±2.3 GeV

❈ The SM is doing rather well





- Presently $\mathbf{m_{top} = 172.5 \pm 2.3}$ GeV
- $\mathbf{M_W = 80.404 \pm 0.030}$ GeV

- How well should we know $\mathbf{M_W}$ and $\mathbf{m_{top}}$?

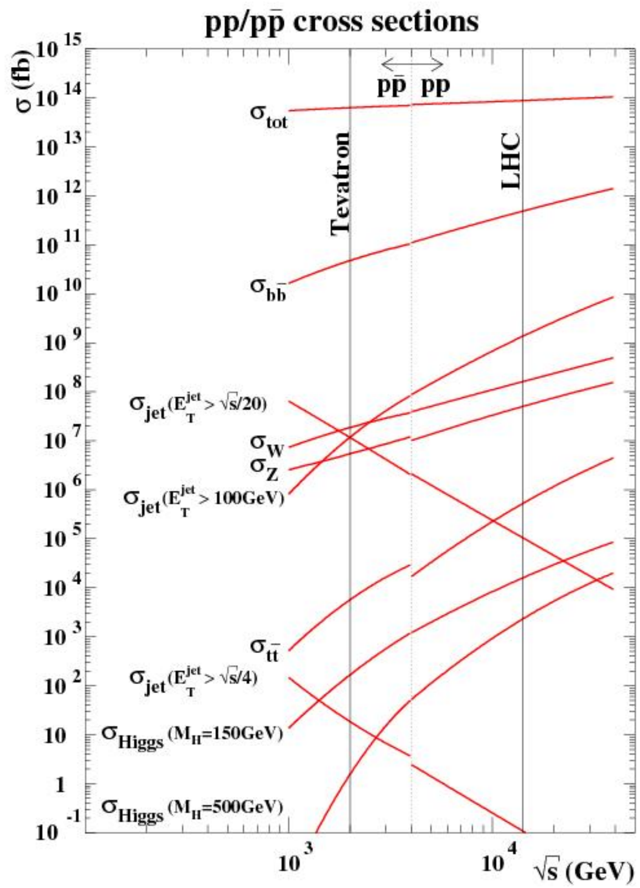
	$\Delta_{\rm theo}$	$\delta(\Delta\alpha_{\rm had}) = 0.00016$	$\Delta m_{top} = 2$ GeV	$\Delta m_{top} = 1$ GeV
$\Delta M_W/{\rm MeV}$	6	3.0	12	6.1
$\Delta \sin^2\theta_{\rm eff}^{\rm lept} \times 10^5$	4	5.6	6.1	3.1

- $\mathbf{\Delta m_{top} \simeq 1}$ GeV is desirable

- $\mathbf{M_W}$ and $\mathbf{m_{top}}$ similar uncertainties to fits $\Longrightarrow$ $\mathbf{\Delta M_W \simeq 7 \times 10^{-3}\, \Delta M_{top}}$

- $\mathbf{\Delta M_W \simeq 10}$ MeV is desirable

Main SM processes



Process	σ (nb)	Evts/year (10 fb^{-1})
Minimum Bias	10^8	$\sim 10^{15}$
Inclus. jets*	100	$\sim 10^9$
$b\bar{b}$	$5\ 10^5$	$\sim 10^{12}$
$W \rightarrow e\nu$	15	$\sim 10^8$
$Z \rightarrow e^+ e^-$	1.5	$\sim 10^7$
$t\bar{t}$	0.8	$\sim 10^7$
Dibosons	0.2	$\sim 10^6$

* p_T>200GeV

$\mathbf{M_W}$ at the LHC

❄ One way of measuring it is

$$\mathbf{m_T^{e\nu}} = \sqrt{\mathbf{2E_T^e} \not{E}_T \left(\mathbf{1} - \cos\phi_{\mathbf{e}\nu}\right)}$$

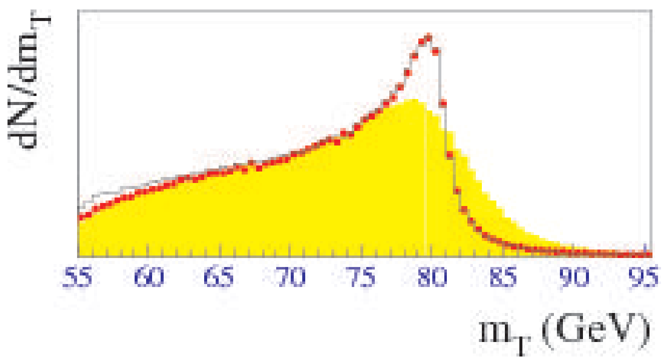
sensitive to $\mathbf{M_W}$ through falling edge

❄ Simple cuts

$$p_T^\ell > 25 \text{ GeV}$$
$$\not{E}_T > 25 \text{ GeV}$$
$$p_T^{veto} = 20 \text{ GeV}$$

$\Longrightarrow$ large sample 30M evts/10 fb^{-1}

❄ 10 fb^{-1} $\Longrightarrow$ $\mathbf{\Delta M_W \simeq 20}$ MeV (stat+syst).

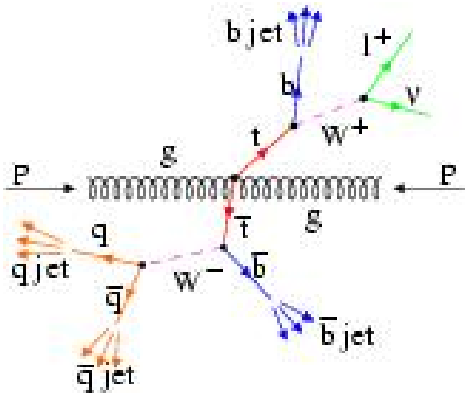


❄ theory is in good shape: NNLO QCD and $\mathcal{O}(\alpha)$

❄ FSR can shft measured masses by $\simeq \mathbf{50}$ MeV

Top quark properties

- $\mathbf{t}$ is produced by $\mathbf{q\bar{q}} \to \mathbf{t\bar{t}}$ (10%) and $\mathbf{gg} \to \mathbf{t\bar{t}}$ (90%) with $\sigma(\mathbf{t\bar{t}}) \simeq \mathbf{830}$ pb
- For $\mathcal{L}= \mathbf{10}$ fb$^{-\mathbf{1}}$ $\implies 10^7\, \mathbf{t\bar{t}} \implies$ LHC is a top factory!
- In the SM $\mathbf{t} \to \mathbf{W^+b} \implies \mathbf{t} \to \ell\nu\mathbf{b}$ (32 %) or $\mathbf{t} \to \mathbf{qq'b}$ (68 %) so
  - $\mathbf{t\bar{t}} \to \mathbf{jjb\; jj\bar{b}}$ (44%)
  - $\mathbf{t\bar{t}} \to \mathbf{jjb}\; (\mathbf{e}/\mu)\nu\mathbf{b}$ (30%)
  - $\mathbf{t\bar{t}} \to (\mathbf{e}/\mu)\nu\mathbf{b}\; (\mathbf{e}/\mu)\nu\mathbf{b}$ (5%)

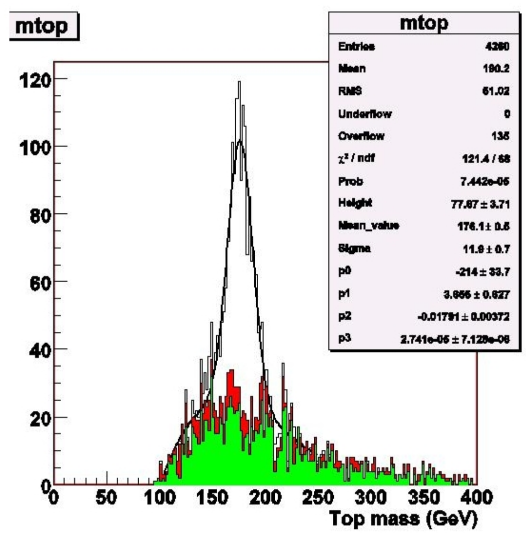


We can study several properties of the top

- $\mathbf{m_{top}}$
- single top production
- $\mathbf{W}$ polarization
- Anomalous $\mathbf{Wtb}$ couplings
- FCNC
- top quantum numbers

Top quark mass

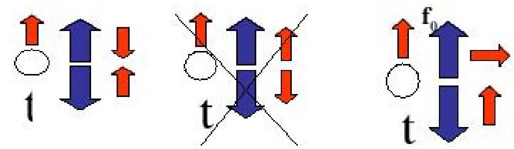
- Channel $\mathbf{t\bar{t}} \to \mathbf{jjb}\ (\mathbf{e}/\mu)\nu\mathbf{b}$: 2 b-tags; 2 extra jets; isolated lepton; $\not{E}_T$
- After cuts $\mathbf{S/B} \simeq \mathbf{78}$ and 87k events for 10 fb^{-1}
- Reconstruct $\mathbf{W} \to \mathbf{jj}$ and then $\mathbf{t} \to \mathbf{bjj}$
- Possible to measure $\mathbf{M_t}$ with a precision $\simeq 1.3$ GeV (systematic) for 10 fb^{-1}



$\mathbf{W}$ polarization

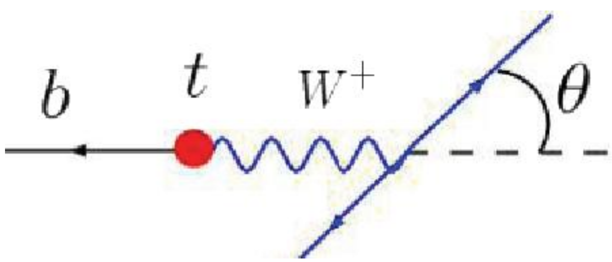
✲ Allows to test the $\mathbf{V-A}$ couplings of the top:

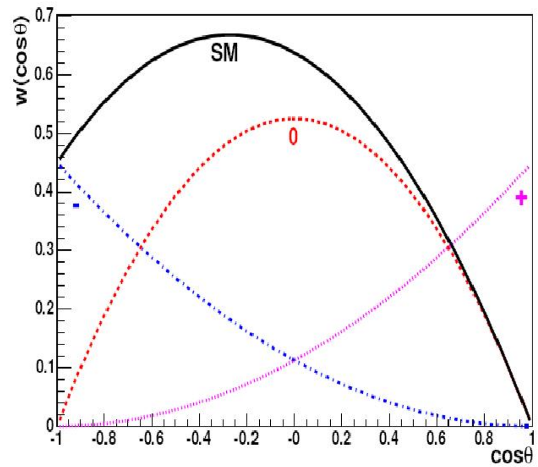
$$\mathbf{F_L^{SM}} = \frac{\mathbf{m_{top}^2}}{\mathbf{m_{top}^2 + 2M_W^2}} \simeq \mathbf{0.703} \quad ; \quad \mathbf{F_0^{SM}} = \frac{\mathbf{2M_W^2}}{\mathbf{m_{top}^2 + 2M_W^2}} \simeq \mathbf{0.297} \quad ; \quad \mathbf{F_R^{SM}} = \mathbf{0}$$



✲ In the $\mathbf{W}$ rest frame

$$\frac{\mathbf{1}}{\mathbf{N}}\frac{\mathbf{dN}}{\mathbf{d}\cos\theta} \propto \mathbf{F_0}\frac{\sin^2\theta}{\mathbf{2}} + \mathbf{F_L}\frac{(\mathbf{1}-\cos\theta)^2}{\mathbf{4}} + \mathbf{F_R}\frac{(\mathbf{1}+\cos\theta)^2}{\mathbf{4}}$$





✲ $\mathbf{10fb^{-1}} \Longrightarrow \mathbf{\Delta F_i} \simeq$ 1–2 $\times\, \mathbf{10^{-2}}$ (at the Tevatron $\mathbf{2}$fb^{-1} $\Longrightarrow$ $\mathbf{\Delta F^{stat}_{0(R)}} \simeq \mathbf{0.03}\ (\mathbf{0.09})$)

FCNC in top decays

- FCNC couplings $\mathbf{Vtc}$ and $\mathbf{Vtu}$ are highly suppressed in the SM:

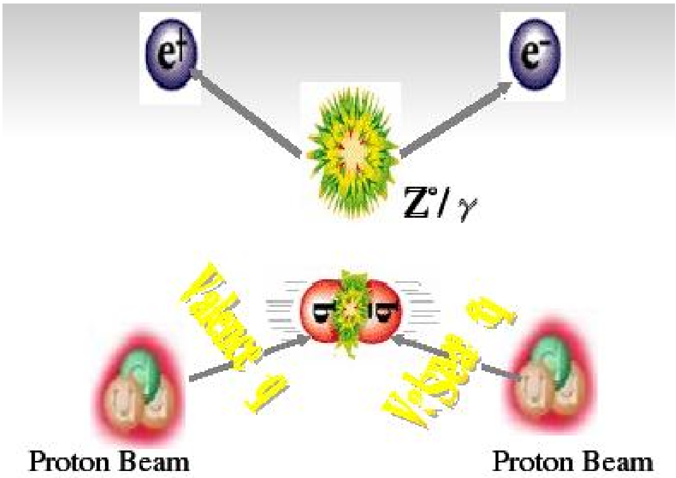
	SM	two-Higgs	SUSY
Br$(t \to qg)$	5×10^{-11}	$\sim 10^{-5}$	$\sim 10^{-3}$
Br$(t \to q\gamma)$	5×10^{-13}	$\sim 10^{-7}$	$\sim 10^{-5}$
Br$(t \to qZ)$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-4}$

- We can describe these terms by effective lagrangians $(\kappa_1 \mathbf{Z}^\mu \bar{\mathbf{t}} \gamma_\mu \mathbf{P_L c})$

Process	95% CL in 2005	ATLAS 5σ (10 fb^{-1})	ATLAS 95% CL (10 fb^{-1})	
$t \to Zq$	~ 0.1	5 10^{-4}	3 10^{-4}	← Reconstruct $t \to Zq \to (l^+l^-)j$
$t \to \gamma q$	0.003	1 10^{-4}	7 10^{-5}	
$t \to gq$	0.3	5 10^{-3}	1 10^{-3}	← Huge QCD background

Improvement $\mathbf{10^2}$–$\mathbf{10^3}$ (Pralavorio, EPS05)

$\sin^2\theta_{\rm eff}^{\rm lept}$



❇ $\sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4}(1 - g_V^\ell/g_A^\ell)$ defined at M_Z

❇ Define the forward direction by the e^+e^- boost direction

❇ can be obtained from $A_{FB} = B(A - \sin^2\theta_{\rm eff}^{\rm lept})$
A and B know in NLO QCD and QED.

❇ $10 {\rm fb}^{-1} \implies 15. \times 10^6\ Z \to e^+e^-$

❇ Large Z sample but there are NLO and PDF uncertainties

❇ 100 $\rm fb^{-1} \implies \Delta \sin^2\theta_{\rm eff}^{\rm lept} \simeq 0.00014$ (LEP 0.00016)

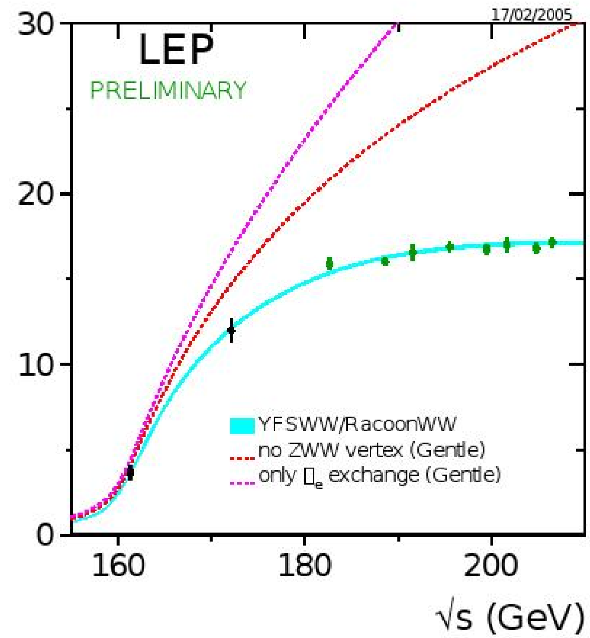
Triple gauge-boson vertices

(hep-ph/0506074)

☆ SM gauge fixes TGV

☆ We have already observed $\mathbf{W^+W^-}\gamma$ and $\mathbf{W^+W^-Z}$

☆ Hypothesis: C and P conservation

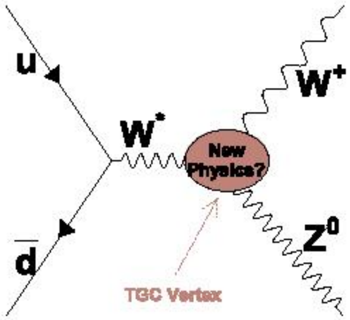


☆ Deviations from SM in terms of 5 new parameters

$$\mathcal{L}_{\rm eff}^{\rm WWV} = -ig_{\rm WWV}\left[g_1^V(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho\right]$$

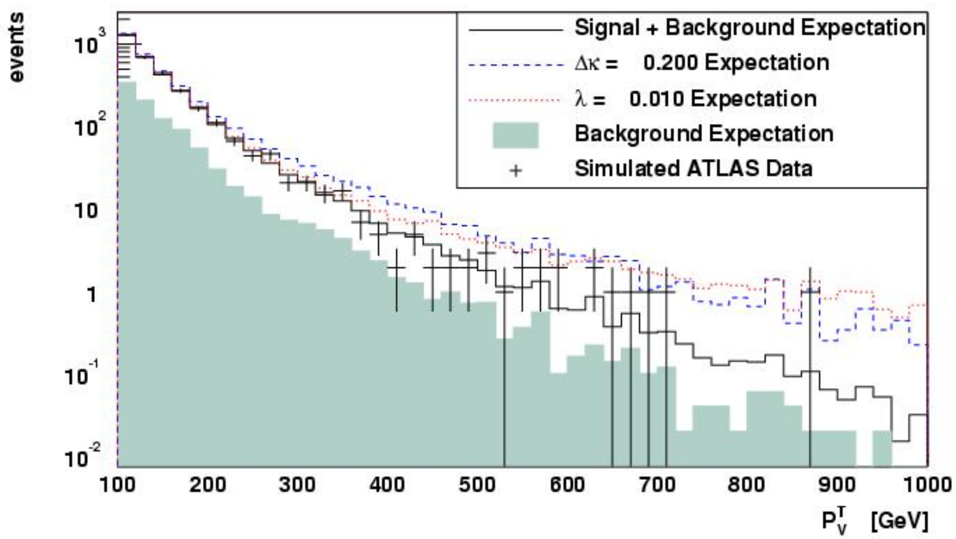
☆ smoking gun: $\hat{\sigma}$ grows with $\sqrt{\hat{s}}$

☆ We must introduce form factors $(1 + Q^2/\Lambda^2)^{-n}$



☆ NLO available; uncertainties PDFs

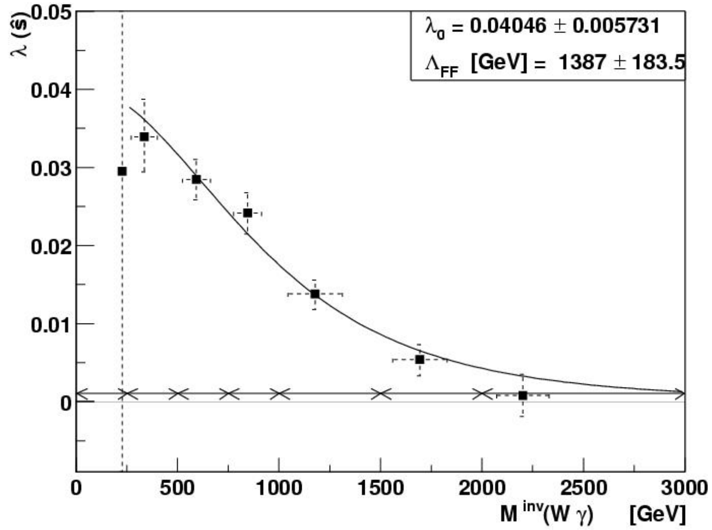
☆ $pp \to W\gamma\ (Z)$: limits fitting p_T^V



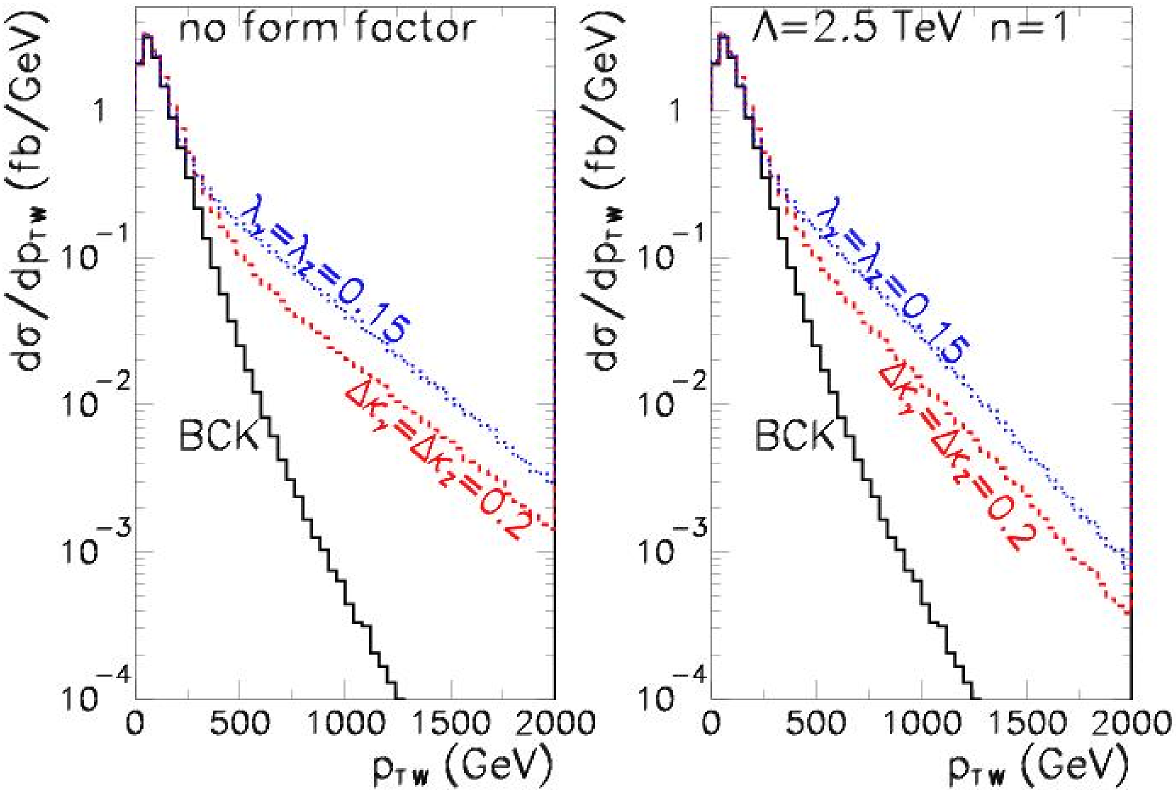
✩ Attainable 95% CL limits

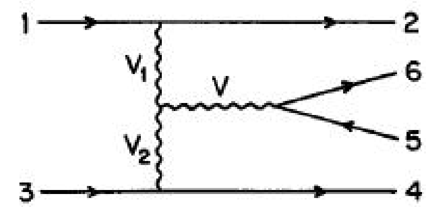
anomalous coupling	direct LEP limits	indirect limits	pair production limits at the LHC
$\Delta\kappa_\gamma$	$[-0.105\ ,\ 0.069]$	$[-0.044\ ,\ 0.059]$	$[-0.034\ ,\ 0.034]$
λ_γ	$[-0.059\ ,\ 0.026]$	$[-0.061\ ,\ 0.10]$	$[-0.0014\ ,\ 0.0014]$
g_1^Z	$[-0.051\ ,\ 0.034]$	$[-0.051\ ,\ 0.0092]$	$[-0.0038\ ,\ 0.0038]$
$\Delta\kappa_Z$	$[-0.040\ ,\ 0.046]$	$[-0.050\ ,\ 0.0039]$	$[-0.040\ ,\ 0.040]$
λ_Z	$[-0.059\ ,\ 0.026]$	$[-0.061\ ,\ 0.10]$	$[-0.0028\ ,\ 0.0028]$

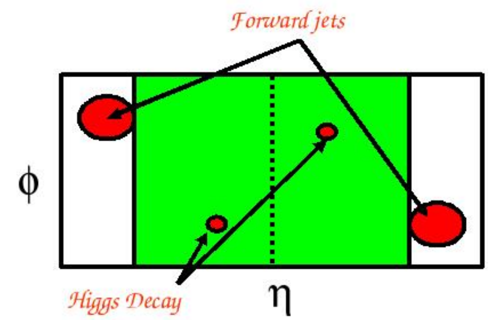
✩ The statistics will be enough to measure the form factors:



- It also possible to use WBF (hep-ph/0405269)
- 2 energetic forward jets $\Longrightarrow$ tagging
- rapidity gap $\Longrightarrow$ reduces QCD contamination
- Signal is enhanced at large $\mathbf{p_T^V}$







★ Limits for $\boldsymbol{\Delta}\kappa_{\mathbf{Z},\gamma}$ similar to VV production

$$-0.066 \leq \Delta\kappa_\gamma \leq 0.052$$

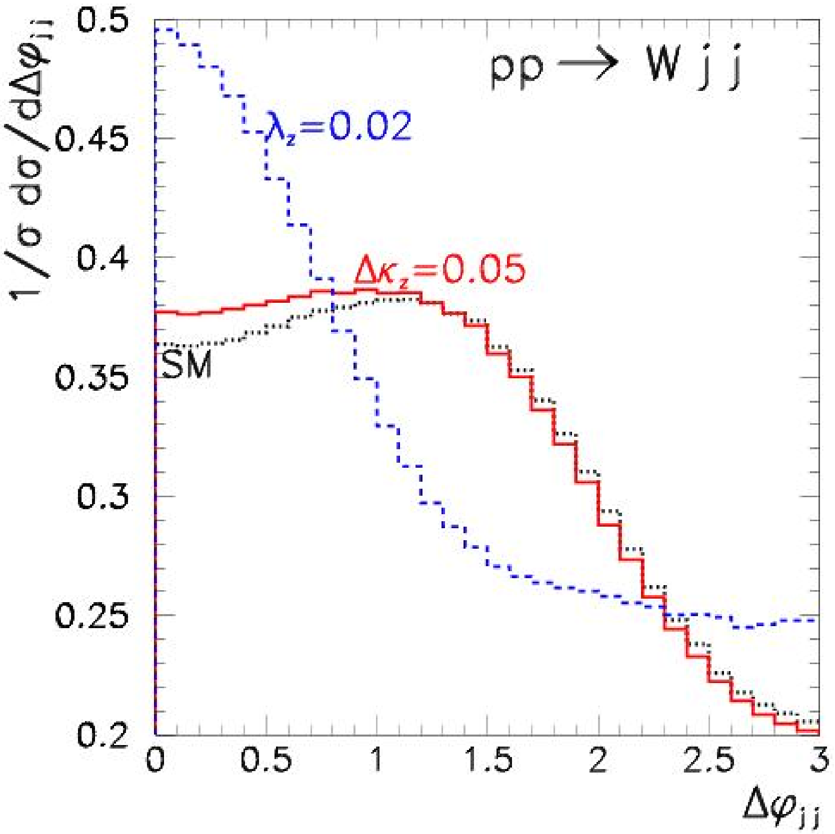
$$-0.038 \leq \lambda_\gamma \leq 0.042$$

$$-0.086 \leq \Delta g_1^Z \leq 0.029$$

$$-0.083 \leq \Delta\kappa_Z \leq 0.034$$

$$-0.024 \leq \lambda_Z \leq 0.030$$

$$-0.13 \leq g_5^Z \leq 0.12$$



★ Single V WBF can be used to completement the VV information on TGV

★ $\boldsymbol{\Delta}\varphi_{\mathrm{jj}}$ good to separate the anomalous TGV

Quartic gauge-boson vertices

(hep-ph/0310141)

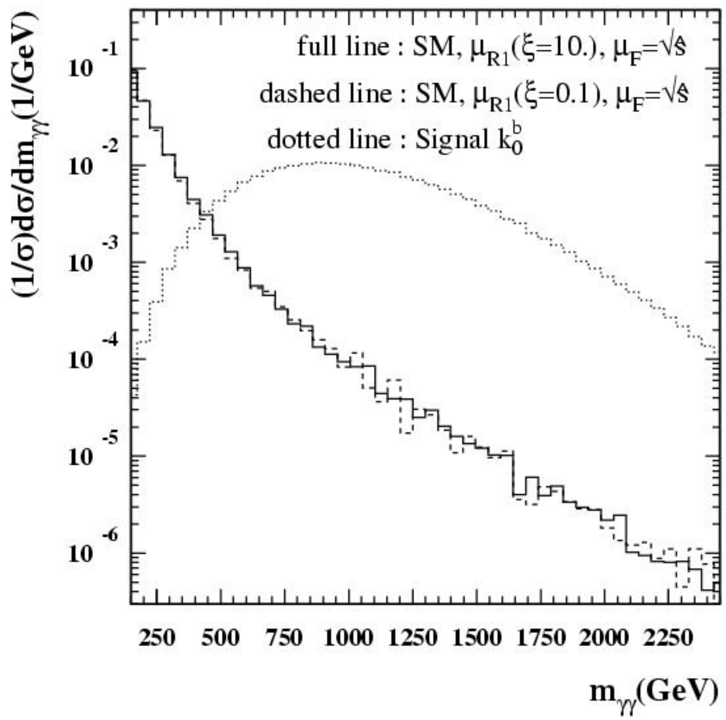
- Anomalous couplings containing photons:

$$\mathcal{W}_{\mathbf{0}}^{\gamma} = -\frac{\mathbf{e^2 g^2}}{\mathbf{2}} \mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu}\mathbf{W}^{+\alpha}\mathbf{W}^{-}_{\alpha} \ , \ \ \mathcal{W}_{\mathbf{c}}^{\gamma} = -\frac{\mathbf{e^2 g^2}}{\mathbf{4}} \mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\alpha}(\mathbf{W}^{+\nu}\mathbf{W}^{-}_{\alpha} + \mathbf{W}^{-\nu}\mathbf{W}^{+}_{\alpha}) \ \ldots$$

- Best channel is VV production via WBF

$$\mathbf{p}+\mathbf{p}\rightarrow \mathbf{q}+\mathbf{q}\rightarrow \mathbf{j}+\mathbf{j}+\gamma+\gamma \quad \text{and} \quad \mathbf{j}+\mathbf{j}+\gamma+(\mathbf{Z}^{*}\mathrm{or}\gamma^{*}\rightarrow)\,\ell^{+}+\ell^{-} \ ,$$

- 2 energetic forward jets with rapidity gap $\Longrightarrow$ tagging
- Signal is enhanced at large $\mathbf{M}_{\gamma\gamma(\ell\ell\gamma)}$
- The background has to be estimated from data



★ Typical limits: LEP $|\frac{k_i^j}{\Lambda^2}| \lesssim \mathcal{O}(\mathbf{10^{-2}}\ \mathrm{GeV}^{-2})$; LHC $|\frac{k_i^j}{\Lambda^2}| \lesssim \mathbf{1\text{–}6} \times \mathbf{10^{-6}}\ \mathrm{GeV}^{-2}$

❁ Quartic couplings without photons (O.E, C Gonzalez-Garcia, J.K. Mizukoshi)

❁ $$\mathcal{O}_0 = g^{\alpha\beta} g^{\gamma\delta} \left[\frac{1}{2} \left(W^+_\alpha W^+_\beta W^-_\gamma W^-_\delta + W^+_\alpha W^+_\gamma W^-_\beta W^-_\delta \right) + \frac{1}{c_W} W^+_\alpha Z_\beta W^-_\gamma Z_\delta + \frac{1}{4c_W^2} Z_\alpha Z_\beta Z_\gamma Z_\delta \right]$$

$$\mathcal{O}_1 = g^{\alpha\beta} g^{\gamma\delta} \left[W^+_\alpha W^-_\beta W^+_\gamma W^-_\delta + \frac{1}{c_W} W^-_\alpha W^+_\beta Z_\gamma Z_\delta + \frac{1}{4c_W^2} Z_\alpha Z_\beta Z_\gamma Z_\delta \right]$$

✷ Best channel is VV production via WBF

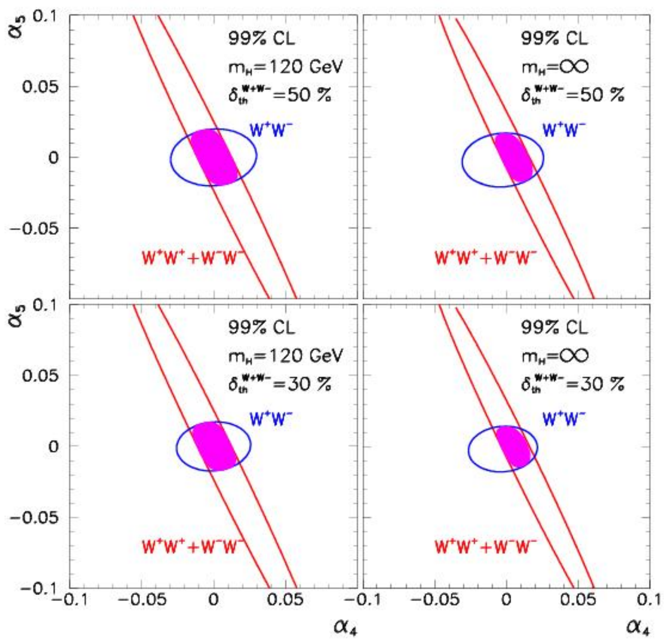
$$p + p \to jjW^+W^- \to jje^\pm\mu^\mp\nu\nu \text{ and } jjW^\pm W^\pm \to jje^\pm\mu^\pm\nu\nu$$

✷ Again: 2 energetic forward jets with rapidity gap, $e\mu$, jet veto, $\not{E}_T$, and large M^T_{WW}

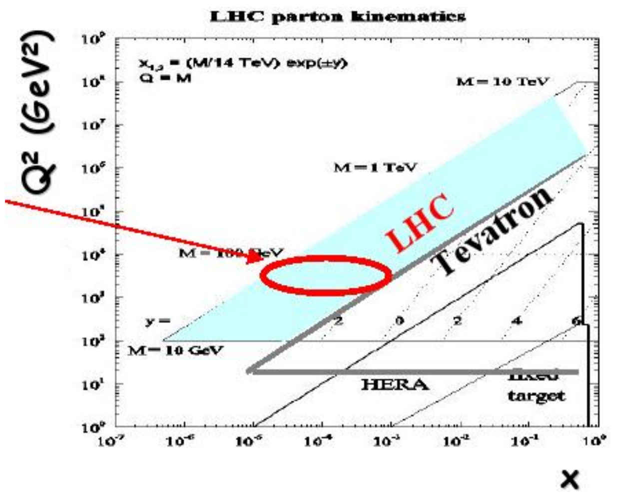
✷ For $e^\pm\mu^\mp$ the largest background is $t\bar{t}j$

✷ Background extracted from data (counting experiment)

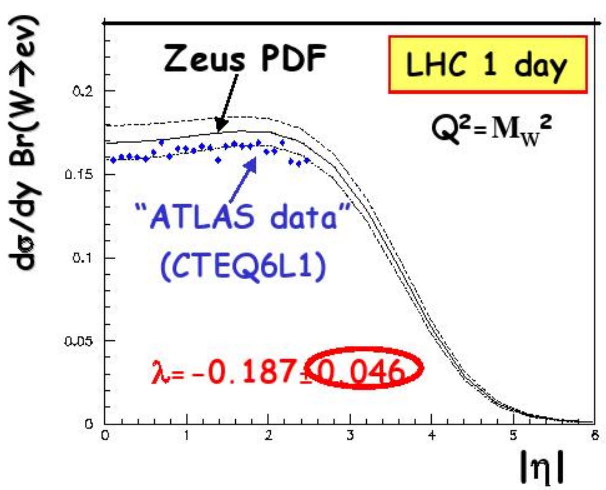
✷ LHC attainable bounds are stronger than the present indirect limits $(-\mathbf{0.27} < \alpha_4 < \mathbf{0.036}\ \ ;\ \ -\mathbf{0.68} < \alpha_5 < \mathbf{0.090})$

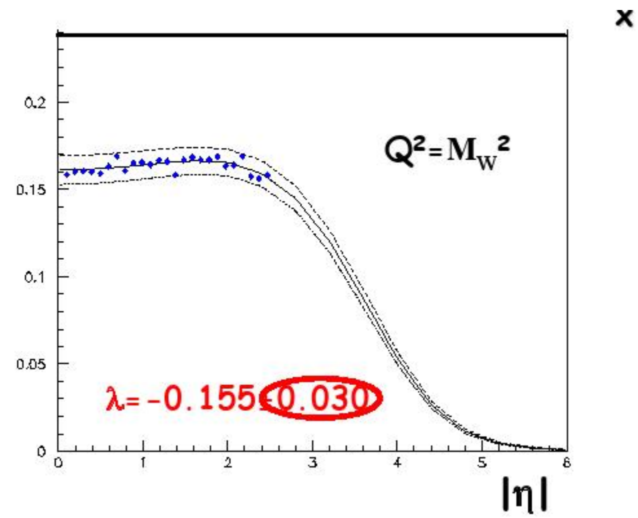


Constraining PDF (Pralavorio, EPS05)



❋ Use the $\mathbf{W} \to e\nu$ rapidity spectrum to constrain $\mathbf{xg(x)} = \mathbf{x}^{-\lambda}$





II. Electroweak symmetry breaking

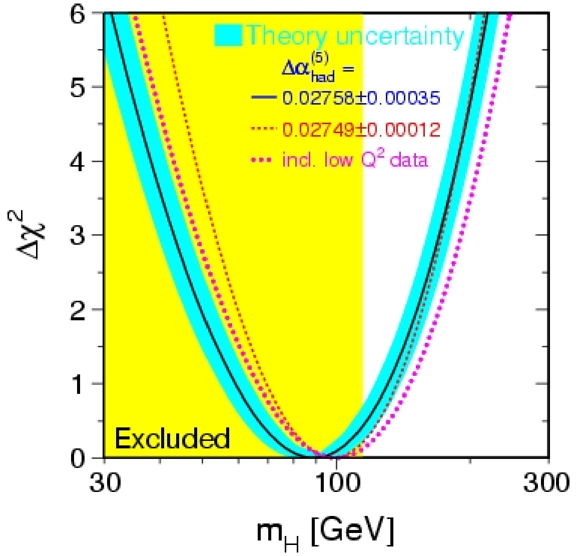
SM Higgs: (minimal scenario)

✻ In the SM there is just one Higgs doublet $\Longrightarrow$ just 1 Higgs boson after EWSB

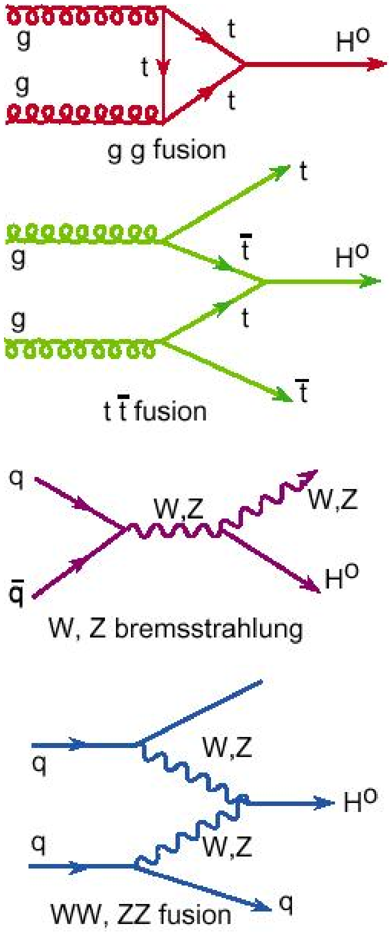
✻ Direct searches at LEP $\Longrightarrow$ $\mathbf{M_H > 114.4}$ GeV at 95% CL

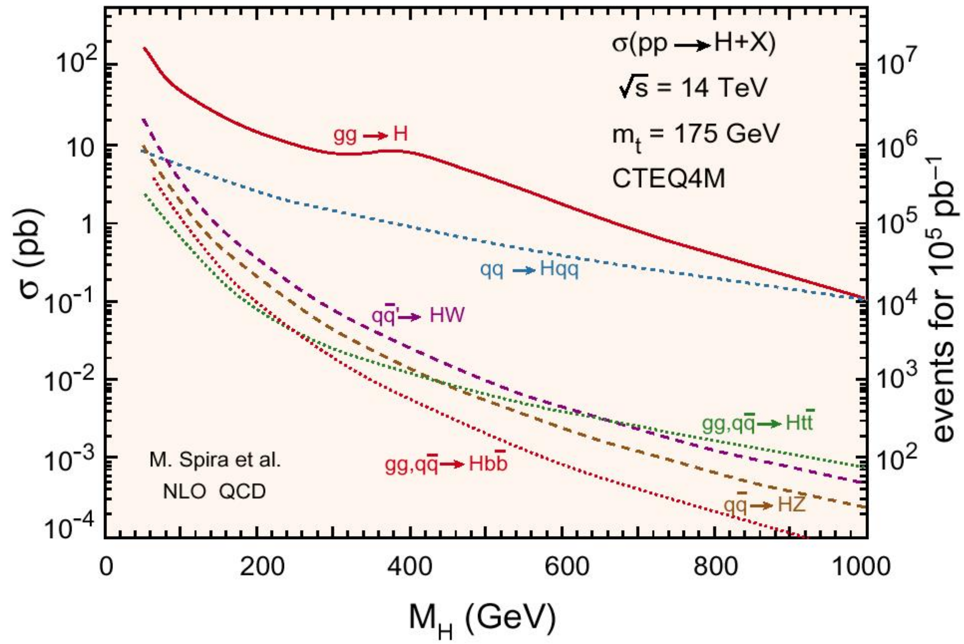
✻ Precision measurements lead to $\mathbf{M_H} <$ 186–219 GeV

✻ is it around the corner?



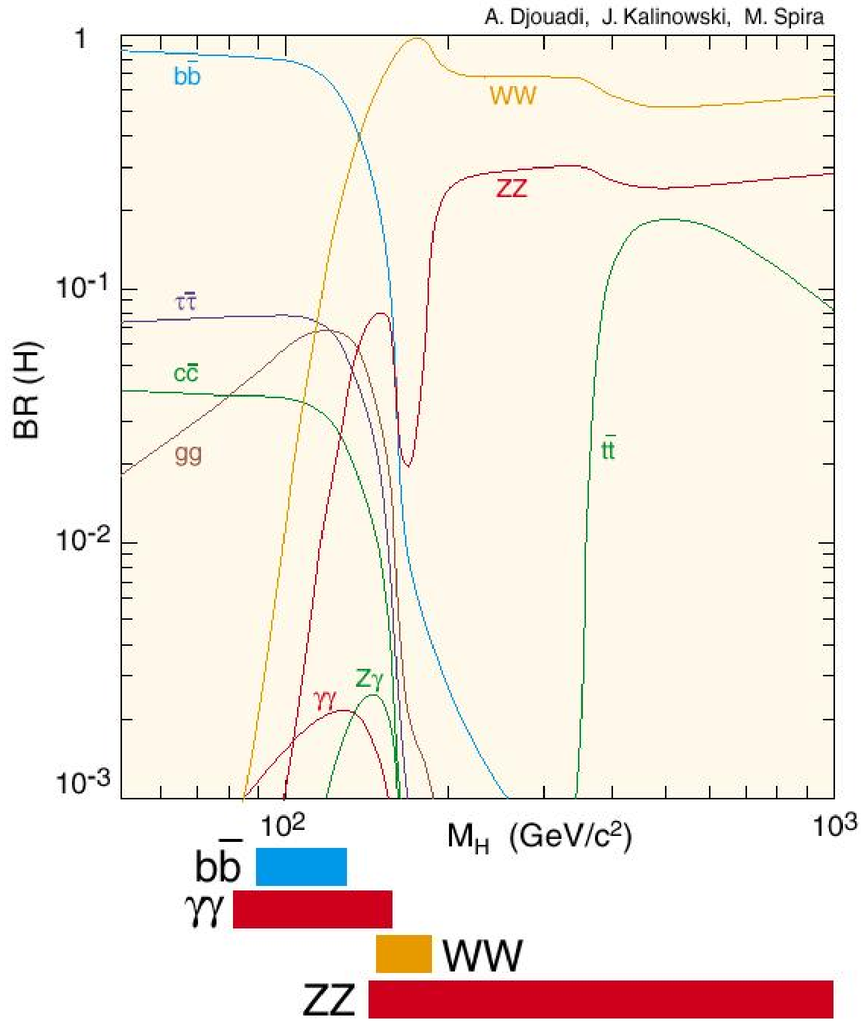
Production Mechanisms:



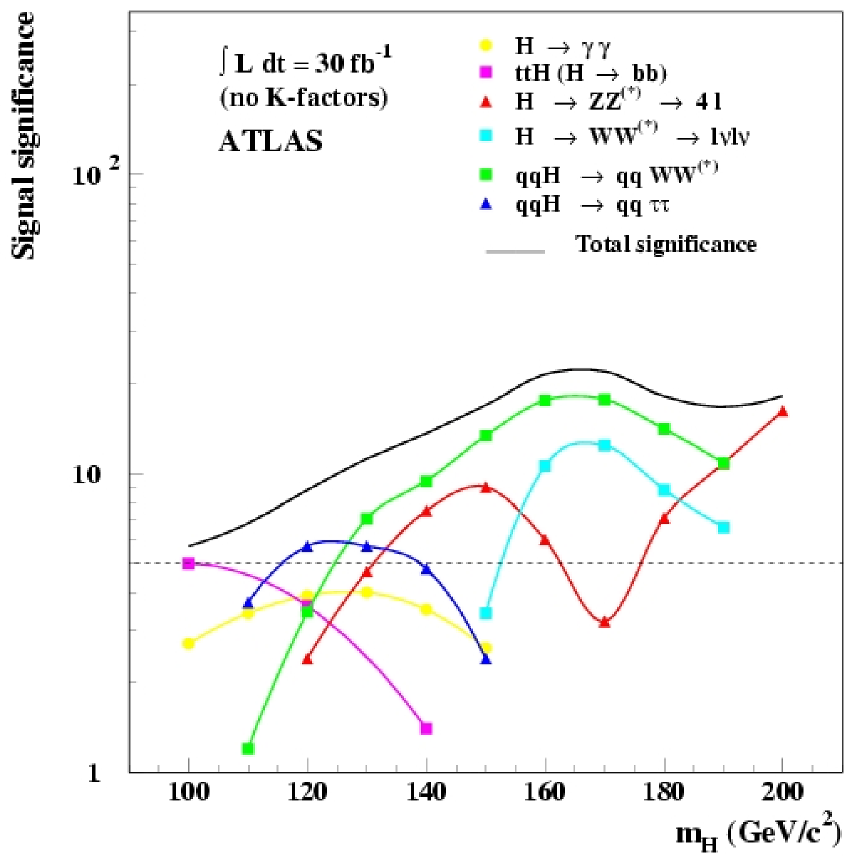


❇ Processes known at least at NLO

❇ The possible decay channels are



❇ What happens when we add all the channels for the SM Higgs?



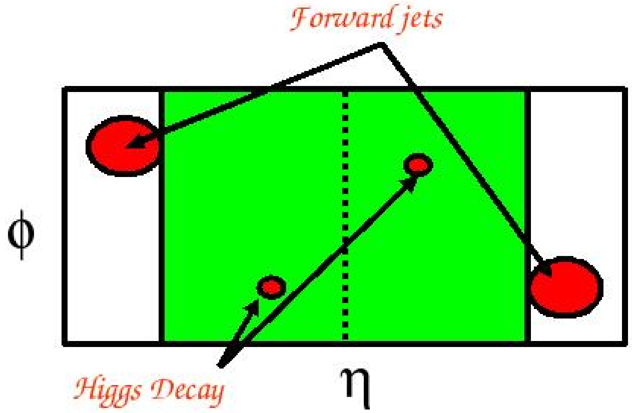
Light Higgs production via WBF

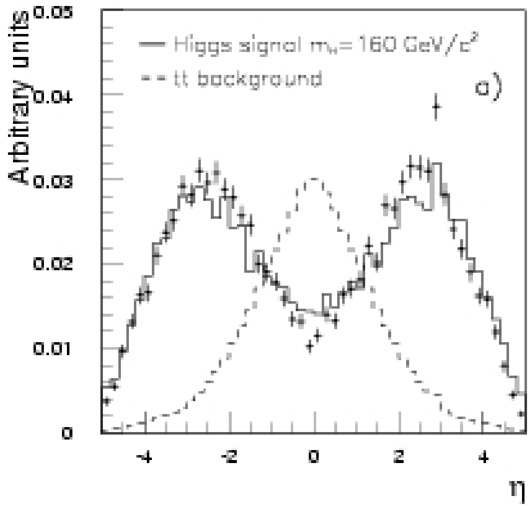
❇ We can tag the final state jets in $\mathbf{qq \to Hqq \to Hjj}$

❇ Let's focus on $\mathbf{H} \to \tau^+\tau^- \to \mathbf{e}^\mp\mu^\pm \not{p}_T$

❇ The main backgrounds are EW and QCD production of $\tau\tau\mathbf{jj}$. $\mathbf{t\bar{t} + n}$ jets can be efficiently eliminated.

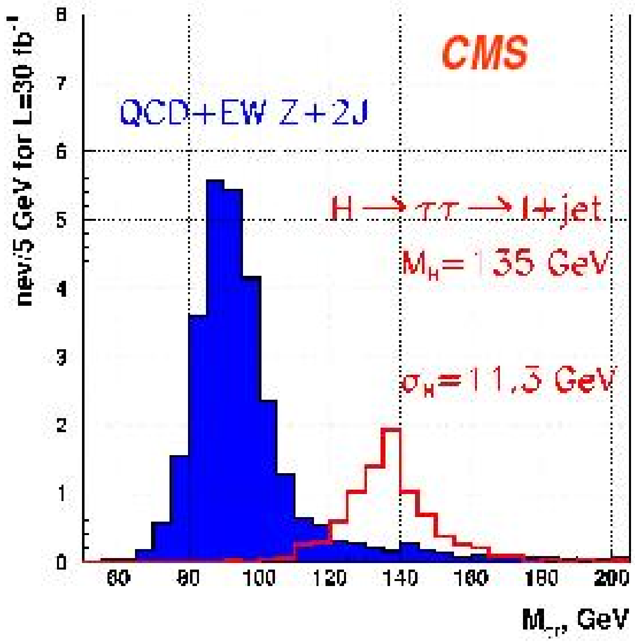
❇ acceptance $\mathbf{p_T}$ and η; rapidity gap; $\tau\tau$ reconstruction and jet veto.





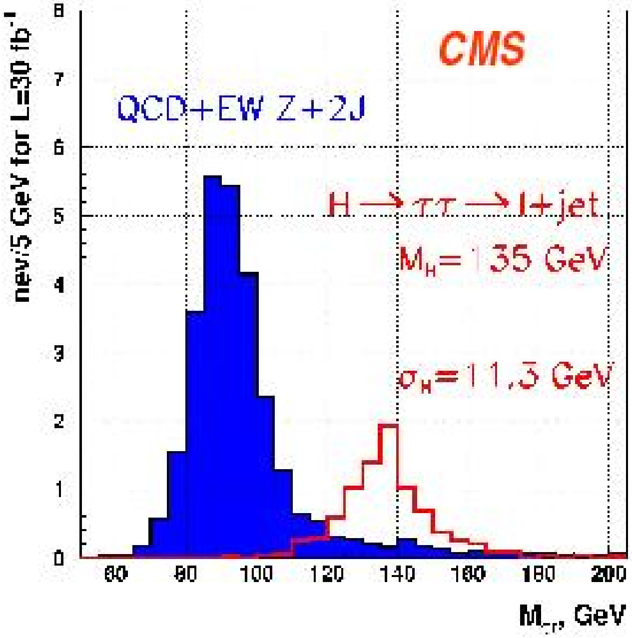
- Even after full simulation the Higgs signal is nice

- $\tau\tau$ channel

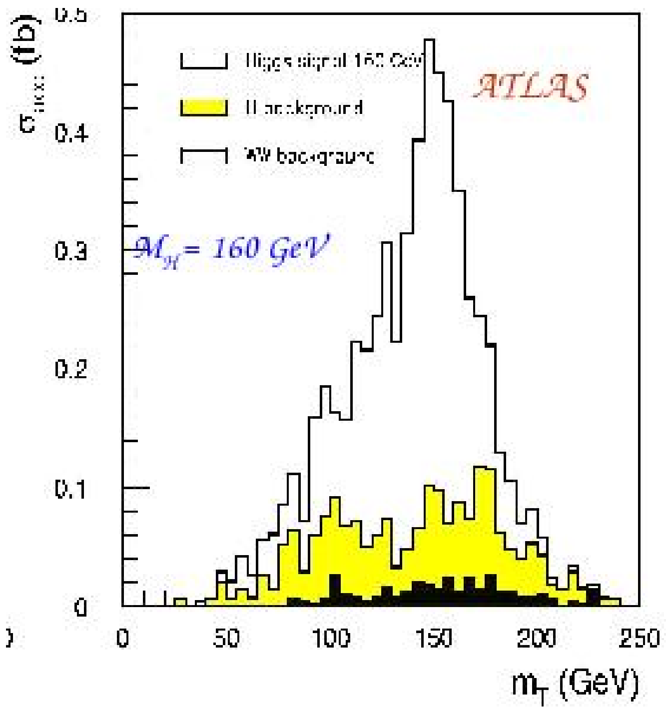


❇ Even after full simulation the Higgs signal is nice

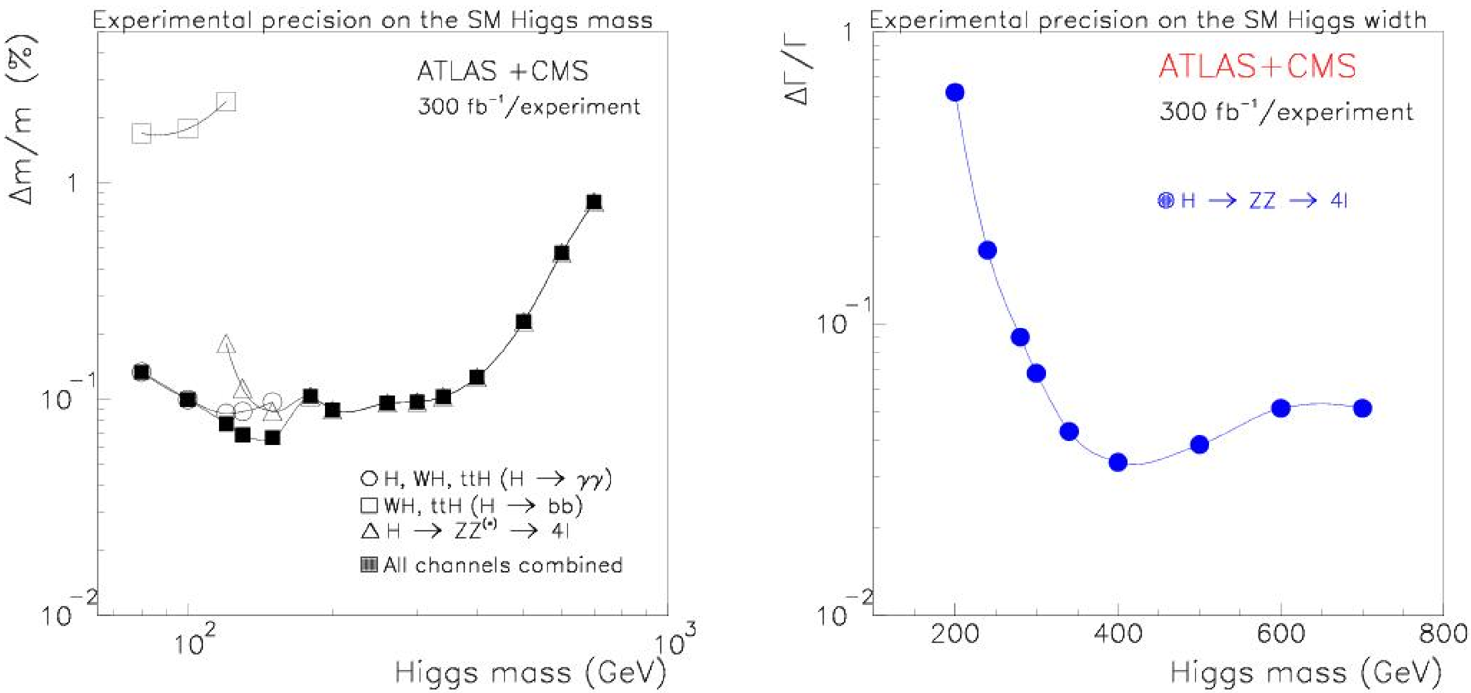
❇ $\tau\tau$ channel



❇ WW channel

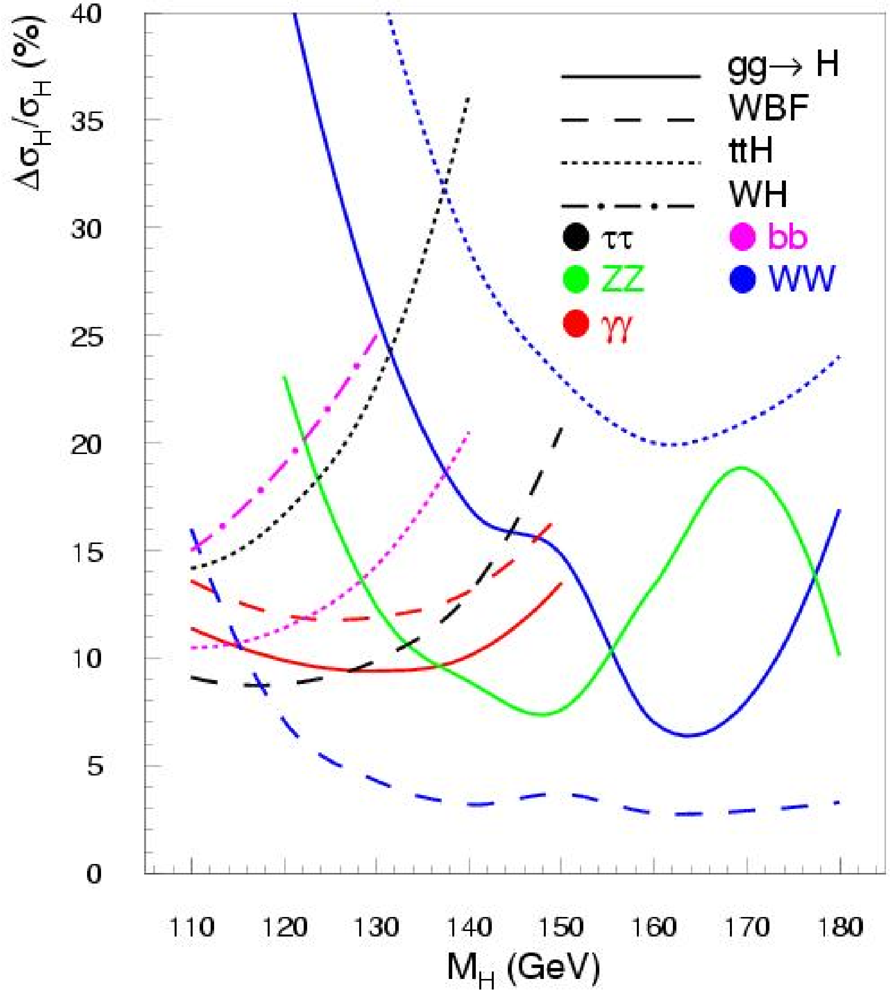


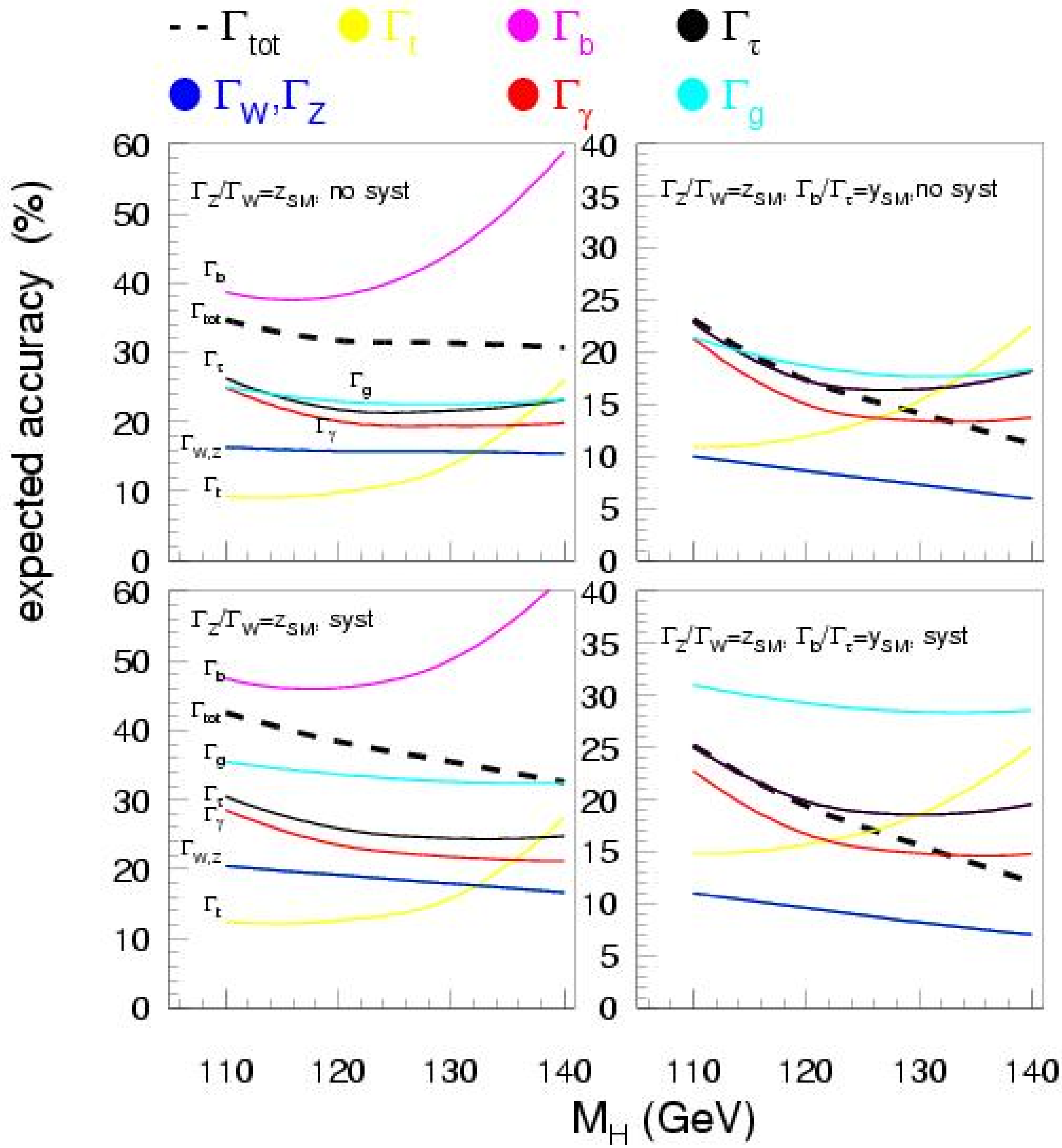
✪ How well can we measure the Higgs properties?



✪ For $\mathbf{M_H \lesssim 200}$ GeV $\Longrightarrow$ Higgs is rather narrow

✪ $\mathbf{M_H \lesssim 200}$ GeV $\Longrightarrow$ combine different channels (hep-ph/0406323)





Γtot
Γt
Γb
Γτ
ΓW,ΓZ
Γγ
Γg
ΓZ/ΓW=zSM, no syst
ΓZ/ΓW=zSM, Γb/Γτ=ySM,no syst
ΓZ/ΓW=zSM, syst
ΓZ/ΓW=zSM, Γb/Γτ=ySM, syst
expected accuracy (%)
MH (GeV)

SUSY Higgses at the LHC

- SUSY requires more than one Higgs doublet

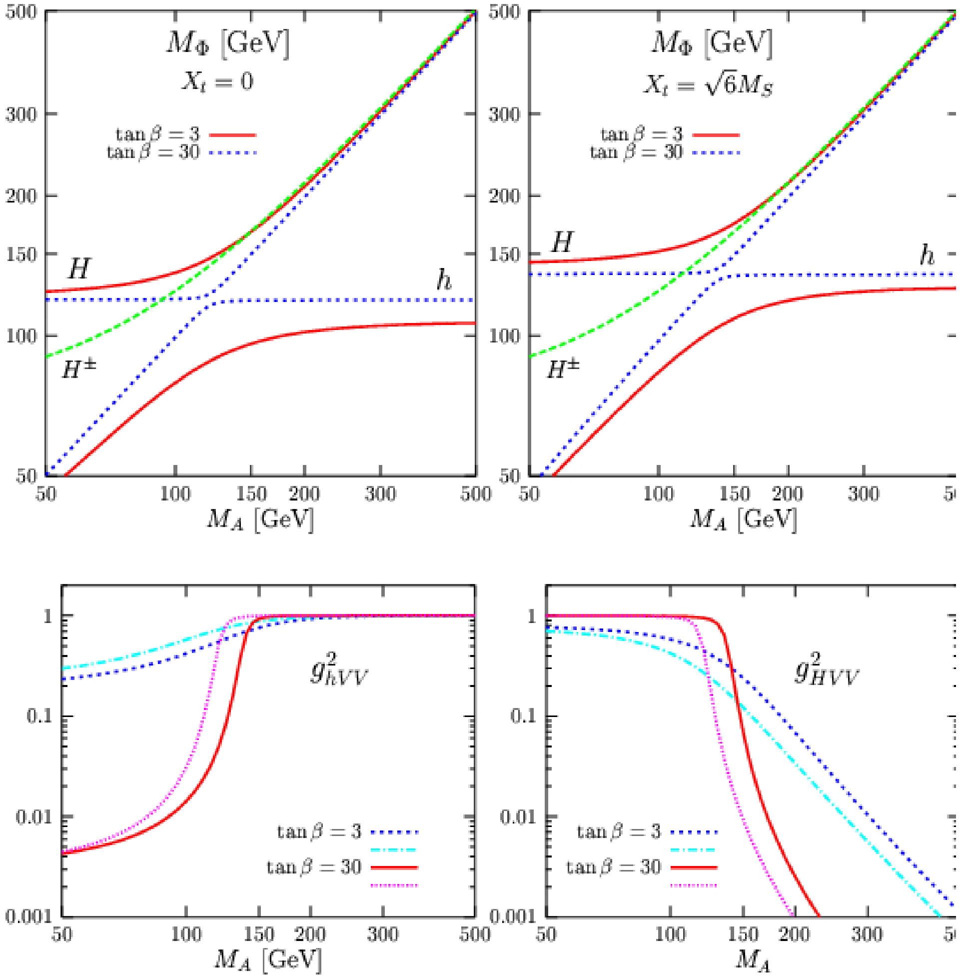
- Physical spectrum: 2 neutral CP-even states $(\mathbf{h},\ \mathbf{H})$, 1 neutral CP-odd $(\mathbf{A})$ and the charged $\mathbf{H}^{\pm}$

- The physical Higgs are mixtures of the initial doublets $\Longrightarrow$ couplings to other particles depend on mixing angles, *e.g.* $\mathbf{G_{hdd} = -i\frac{m_d}{v}\frac{\sin\alpha}{\cos\beta}}$

- At tree level there are only two independent parameters $\mathbf{M_A}$ and $\tan\beta$

$$\mathbf{M^2_{H^\pm} = M^2_A + M^2_W \quad ; \quad M^2_{H,h} = \frac{1}{2}\left(M^2_A + M^2_Z \pm ((M^2_A + M^2_Z)^2 - 4M^2_Z M^2_A \cos^2 2\beta)^{1/2}\right)}$$

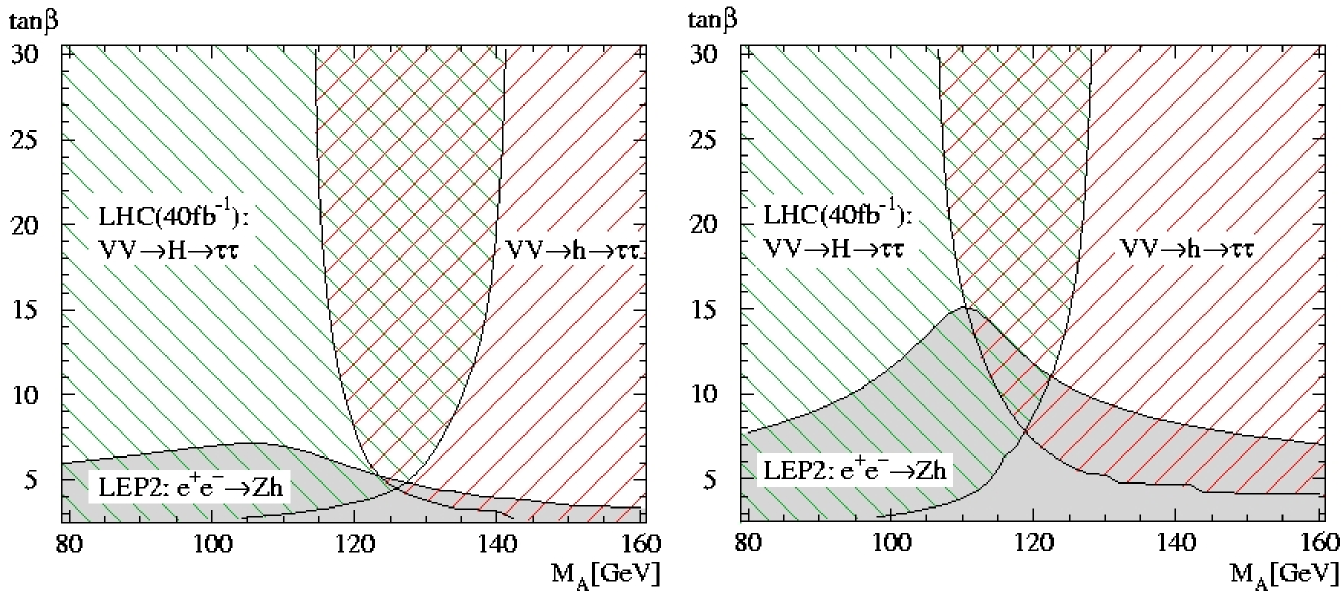
Note that $\mathbf{M_h < M_Z}$. Radiative correction help to evade this limit



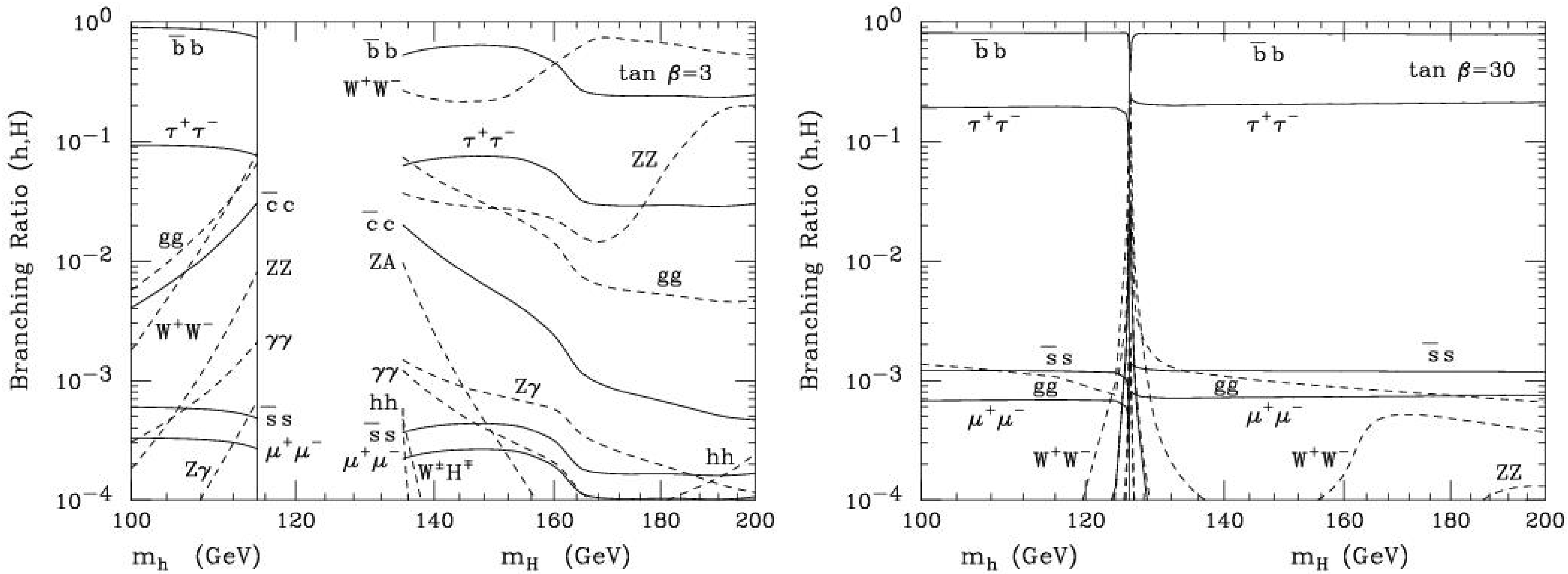
✪ One state similar to a light SM Higgs

No-lose theorem

✪ for a neutral CP–even higgs at the LHC in WBF and $\mathbf{H}/\mathbf{h} \to \tau\tau$ (maximum/no mixing)

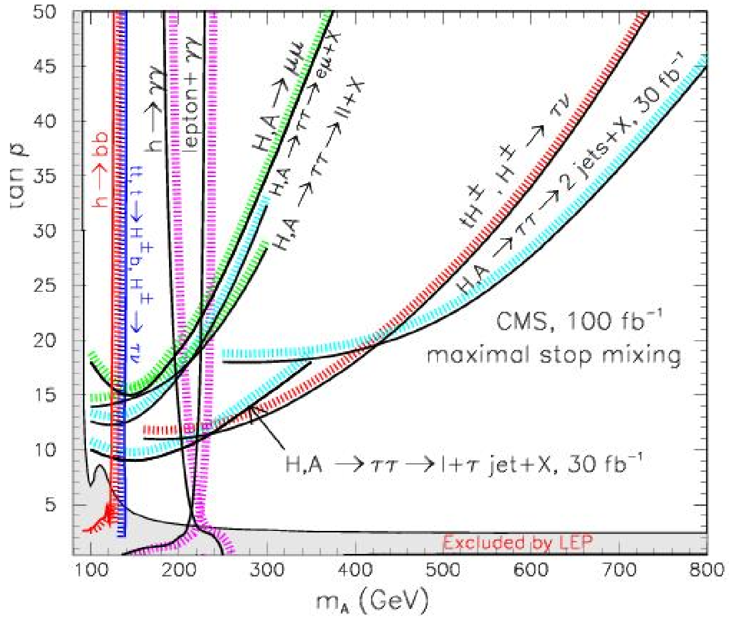


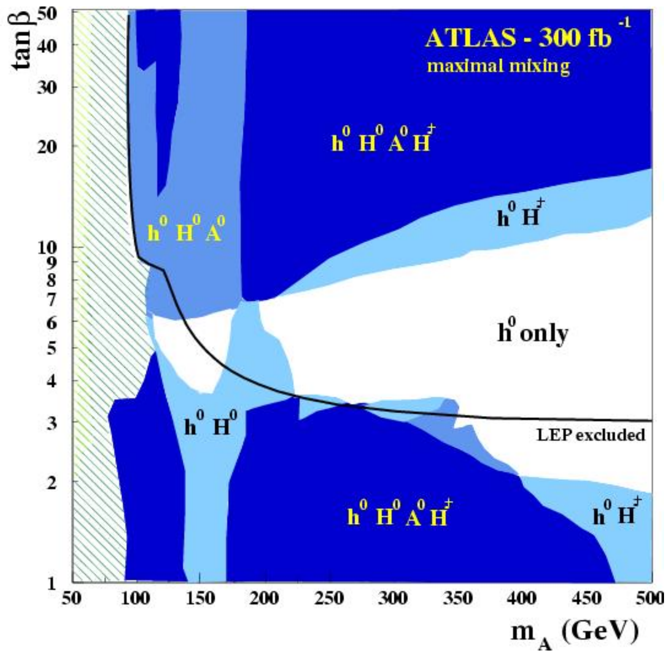
- Branching ratios for heavy SUSY spectrum ($\tan\beta = \mathbf{3}$) and 30



- Signals and cross section vary a lot

✪ Like the branching ratios the importance of the different channels gets modified $\Longrightarrow$ the analysis has to be redone

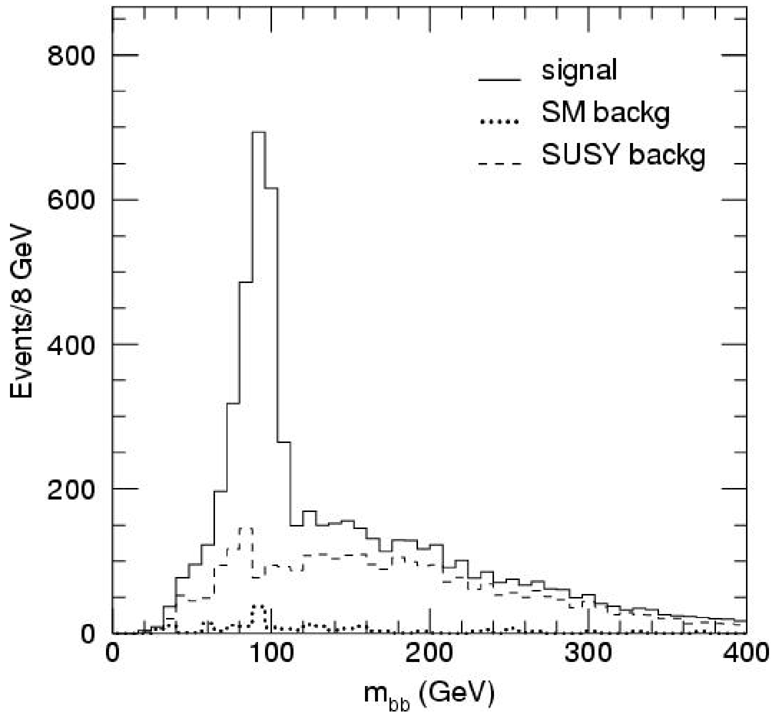


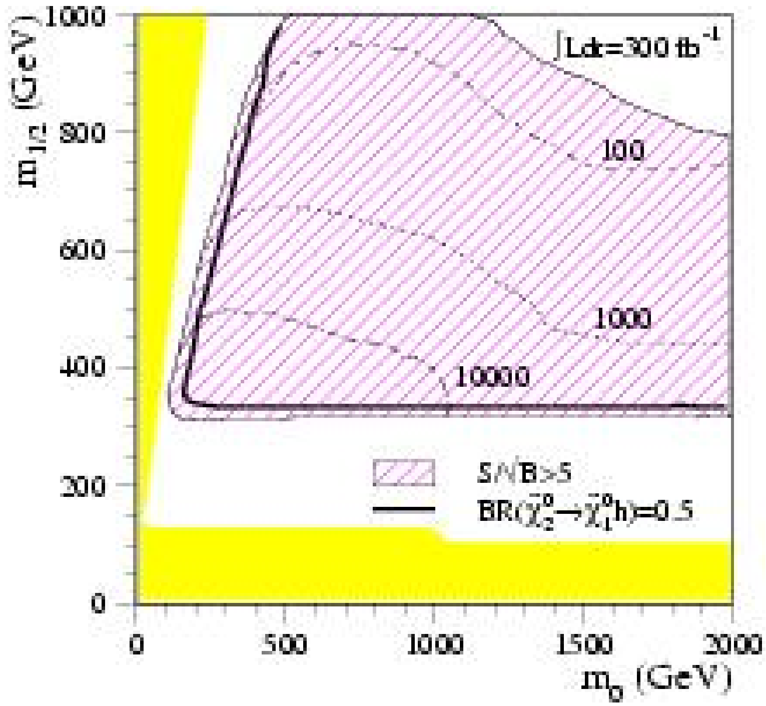


Higgs is decay chain

❈ Depending on the SUSY point, Higgs might be produced copiously in decay chains.

❈ For instance, $\tilde{\chi}_0^2 \to \mathbf{h}\tilde{\chi}_0^1$ versus $\tilde{\chi}_0^2 \to \ell^\pm \tilde{\ell}^\mp \tilde{\chi}_0^1$





Invisible Higgs

* Many models exhibit Higgs bosons that decay into invisible final states:

- SUSY: $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- Majoron models: $h \to JJ$
- Extra dimensions: $Rh^2 \implies h \to G_0^n G_0^n$

* For an intermediate mass Higgs couplings to SM particles are small ($m_b^2/v^2 \lesssim 10^{-3}$) $\implies$ invisible modes can be $\simeq 100\%$

* WBF is a robust way to look for Higgs bosons, even invisible! (hep-ph/0009158)

$$qq \to qqVV \to qqH \quad (V = W \text{ or } Z)$$

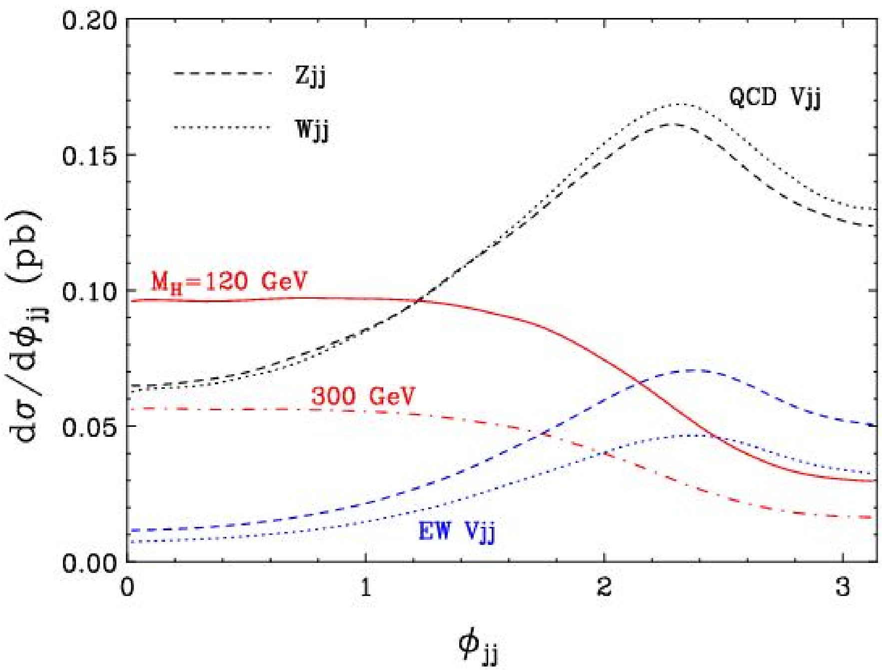
* Signal: two jets at large rapidities and large $\not{p}_T$

* Significant backgrounds: EW and QCD $\mathbf{jjZ}(\rightarrow \nu\bar{\nu})$; EW and QCD $\mathbf{jjW}(\rightarrow \nu[\ell])$; QCD $\mathbf{jj}$; QCD $\mathbf{jjj}$

* Require a rapidity gap; large $\mathbf{M_{jj}}$ and lots of $\not{p}_T$

* This a counting experiment!

* Variable used to estimate backgrounds: $\mathbf{\Delta}\phi_{\mathbf{jj}}$

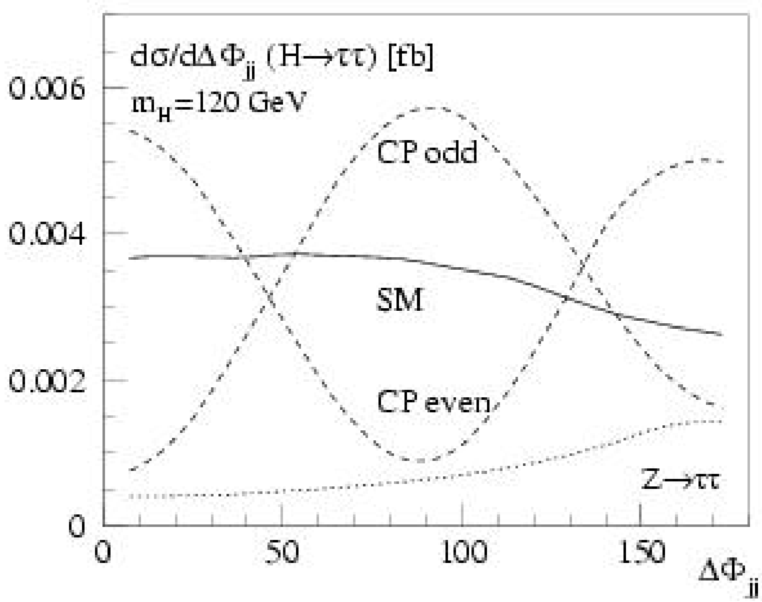


∗ LHC reach in the invisible Br $\times \sigma/\sigma_{\rm SM}$

M_H (GeV)	110	120	130	150	200	300	400
10 fb^{-1}	12.6%	13.0%	13.3%	14.1%	16.3%	22.3%	30.8%
100 fb^{-1}	4.8%	4.9%	5.1%	5.3%	6.2%	8.5%	11.7%

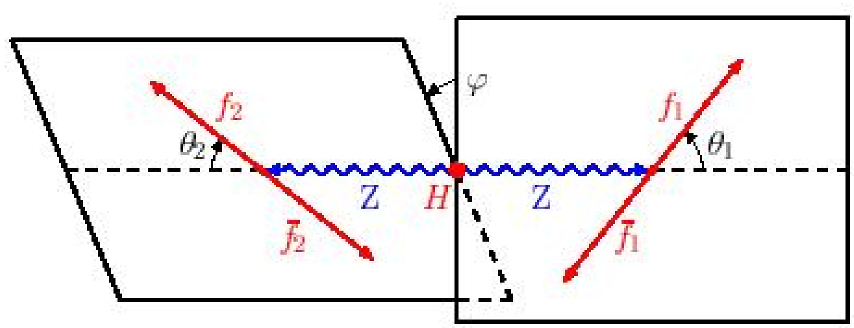
∗ $\phi_{\rm jj}$ carries information on the CP properties of the Higgs

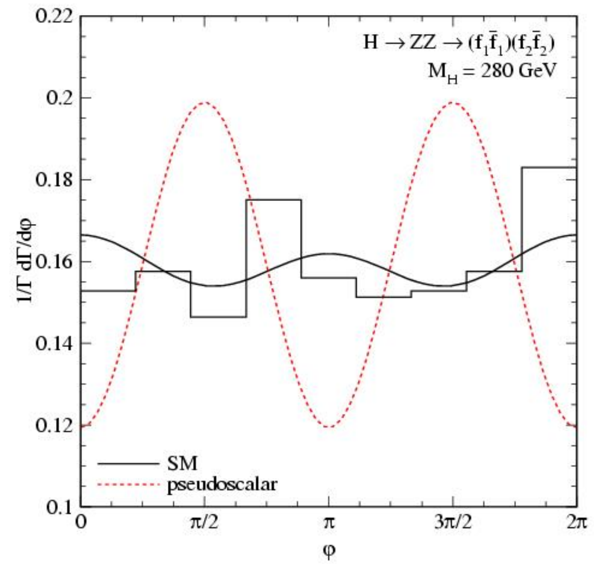
∗ WBF can also reveal the CP nature of the Higgs (hep-ph/0105325)



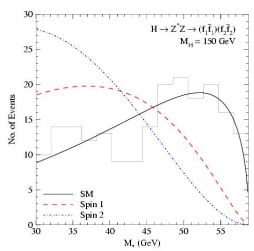
Higgs quantum numbers

❄ $\mathbf{H} \to \mathbf{ZZ} \to \ell\ell\ell\ell$: distributions to determine spin and CP (hep-ph/02100077)





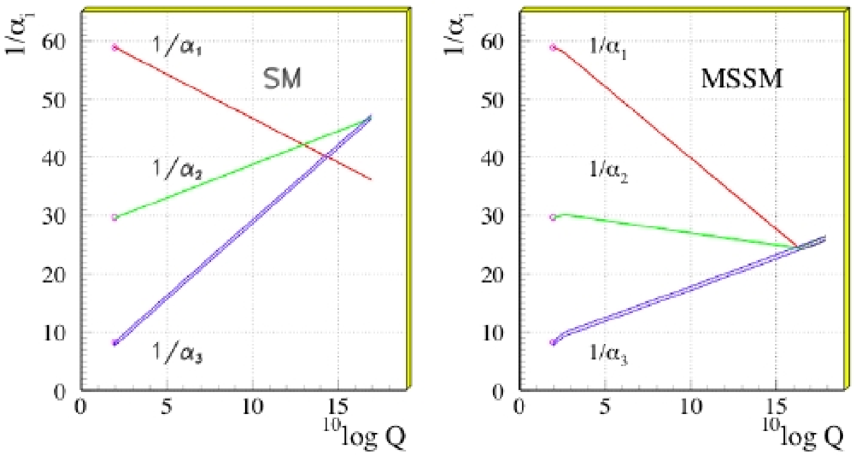
❄ For light Higgs boson $\Longrightarrow$ $\mathbf{m}_{\ell\ell}$ is a good discriminator



III. Supersymmetric models

➪ SUSY has been extensively studied as a candidate for physics BSM:

- the most general extension of the Poincaré group;
- SUSY can lead to coupling unification;
- Weak scale SUSY can solve the hierarchy problem;
- it is perturbative;
- dynamical EWSB
- Many free parameters!
- SUSY has many signals $\Longrightarrow$ good work out



➪ Goal: gather as much information as possible (masses, spin, etc) to reconstruct the low energy SUSY breaking parameters

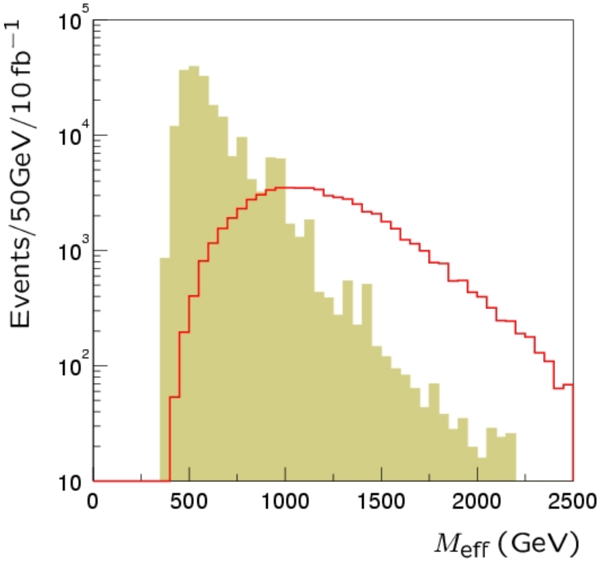
➪ General features: complicated cascade decays with many intermediate states; $\not{E}_T$ if $\mathbf{R = (-1)^{3B+L+2s}}$ is conserved

➪ If R-parity is **not** conserved the signals depend on the LSP decays

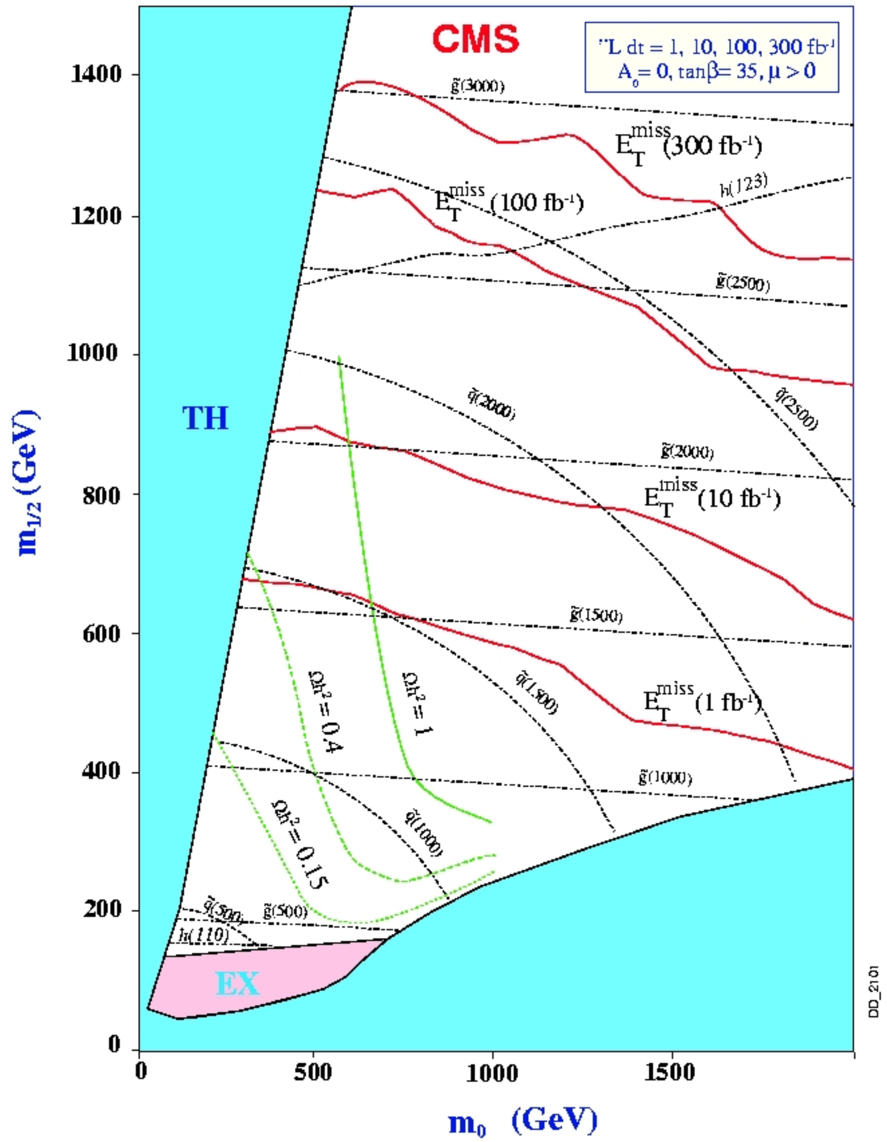
Inclusive SUSY search

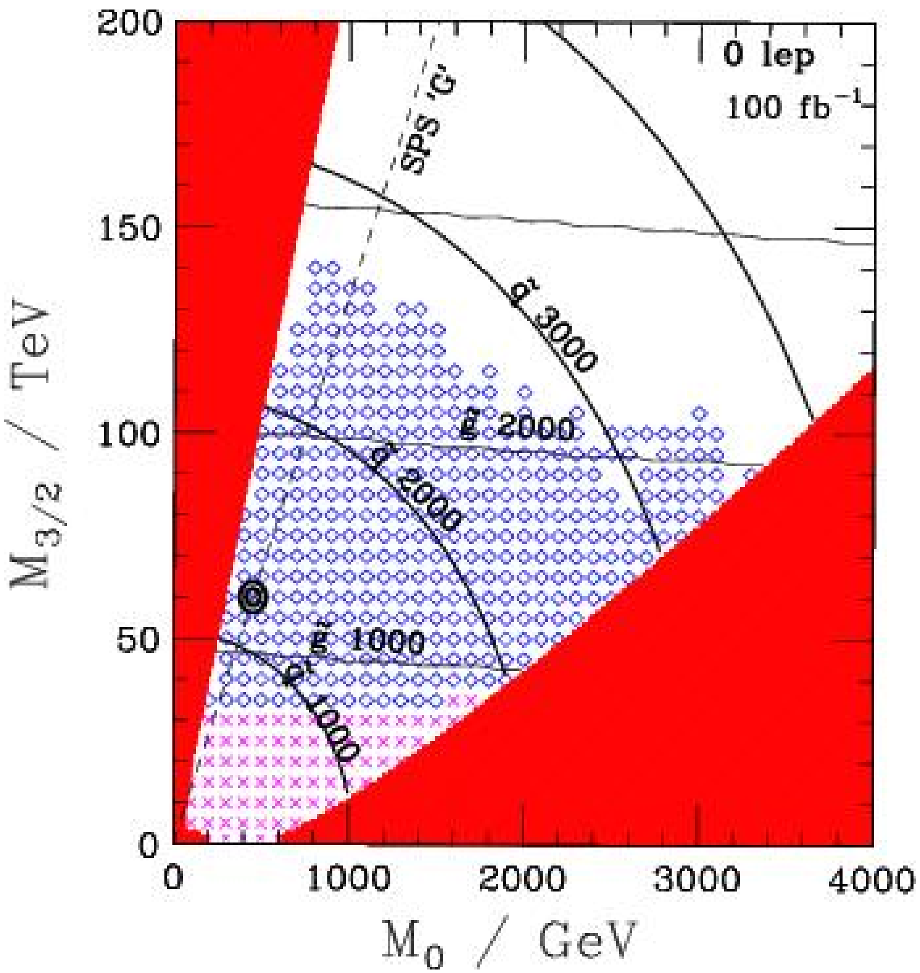
- LHC $\Longrightarrow$ jets and missing $\not{E}_T$
- $\sigma(\mathbf{1}\ \text{TeV}) \simeq \mathcal{O}(\mathbf{10}\ \text{pb})$
- define $\mathbf{M}_{\text{SUSY}} = \min(\mathbf{m}_{\tilde{\mathbf{g}}}, \mathbf{m}_{\tilde{\mathbf{q}}})$

$$\mathbf{M}_{\text{eff}} \equiv \sum_{\mathbf{j=1}}^{\mathbf{4}} \mathbf{p}_{\mathbf{T}}^{\mathbf{j}} + \not{E}_T \ \propto \mathbf{M}_{\text{SUSY}}$$



- Rather simple to rule out/discover gluinos and squarks up to $\simeq \mathbf{2.5}$ TeV

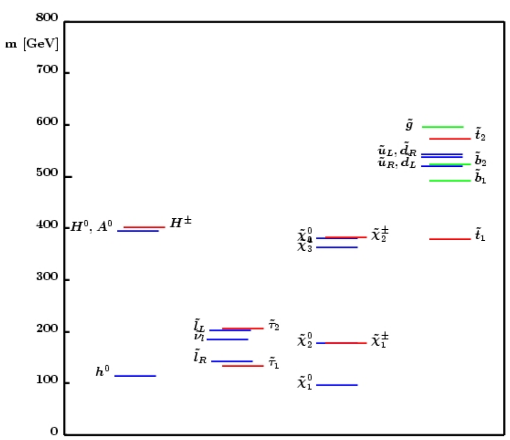

CMS
∫L dt = 1, 10, 100, 300 fb⁻¹
A₀ = 0, tanβ = 35, μ > 0
TH
EX
E_T^{miss} (300 fb⁻¹)
E_T^{miss} (100 fb⁻¹)
E_T^{miss} (10 fb⁻¹)
E_T^{miss} (1 fb⁻¹)
Ωh² = 0.4
Ωh² = 1
Ωh² = 0.15
m1/2 (GeV)
m0 (GeV)
DD_2101

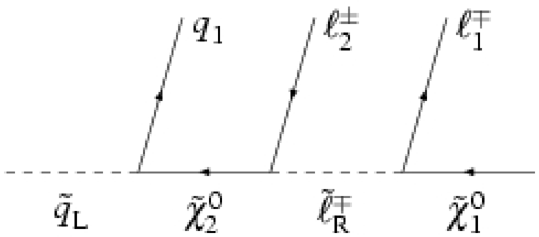

0 lep
100 fb⁻¹
SPS 'G'
M3/2 / TeV
M0 / GeV

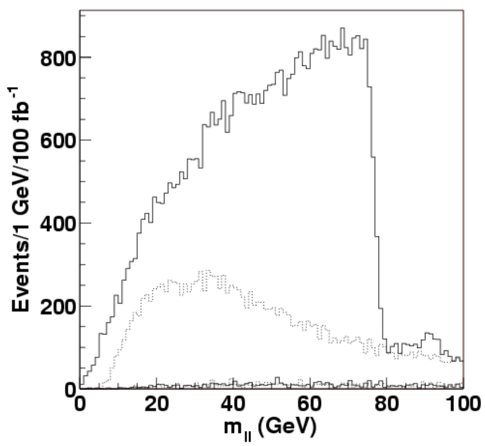
Exclusive SUSY search

❄ Reconstruction is quite involved due to:

- long decay chains $\Longrightarrow$ huge combinatorics
- unknown boost of the subprocess CMS
- Undetectable LSP $\Longrightarrow$ not possible to reconstruct invariant masses event by event $\Longrightarrow$ study distributions

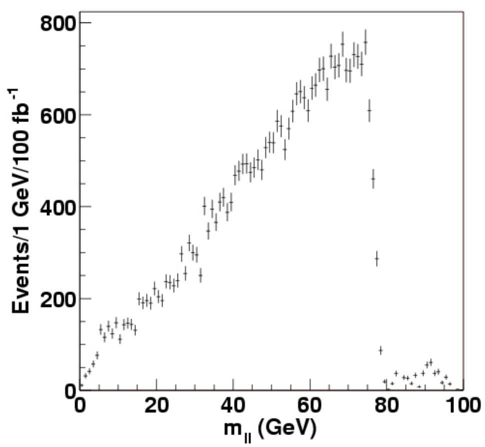






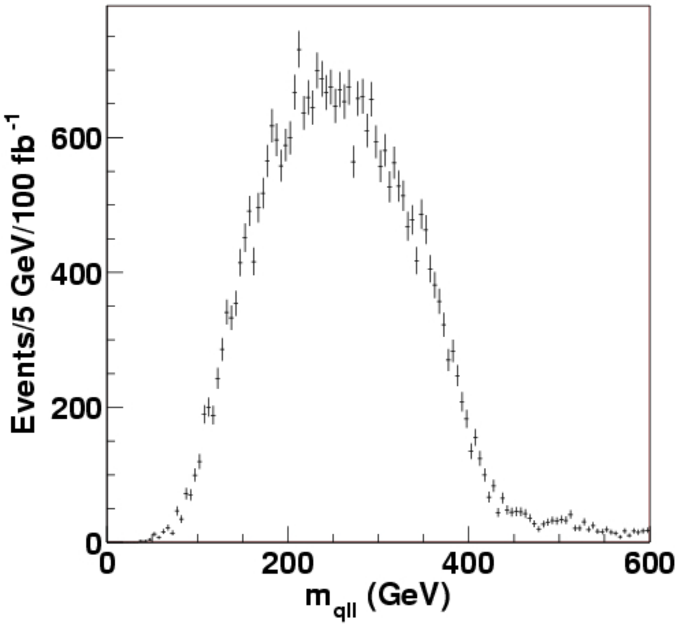
- $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q l_2^\pm \tilde{l}_R^\mp \to q l_2^\pm l_1^\mp \tilde{\chi}_1^0$
- m_{ll} has an edge

$$(m_{ll}^2)^{\text{edge}} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$



- The edge is quite sharp

❄ Long decay chain $\Longrightarrow$ more edges (constraints) available $(\mathbf{m^2_{qll}})^{\rm edge}$, $(\mathbf{m^2_{ql}})^{\rm edge}_{\rm min}$, $(\mathbf{m^2_{ql}})^{\rm edge}_{\rm max}$, $(\mathbf{m^2_{qll}})^{\rm thres}$

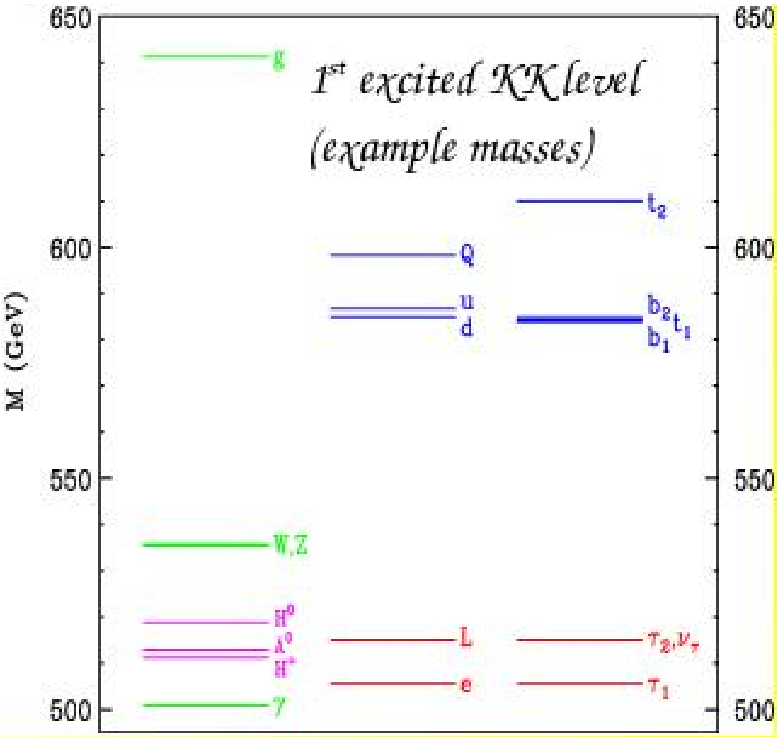


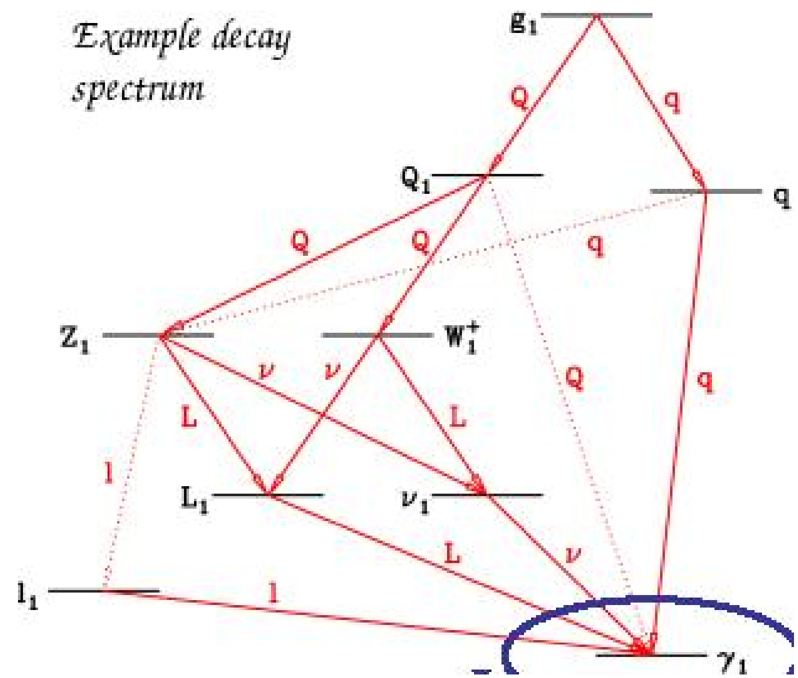
❄ The masses can be obtained with a precision

	LHC
$\Delta m_{\tilde\chi^0_1}$	4.8
$\Delta m_{\tilde l_R}$	4.8
$\Delta m_{\tilde\chi^0_2}$	4.7
$\Delta m_{\tilde q_L}$	8.7
$\Delta m_{\tilde b_1}$	13.2

Unravelling the spin

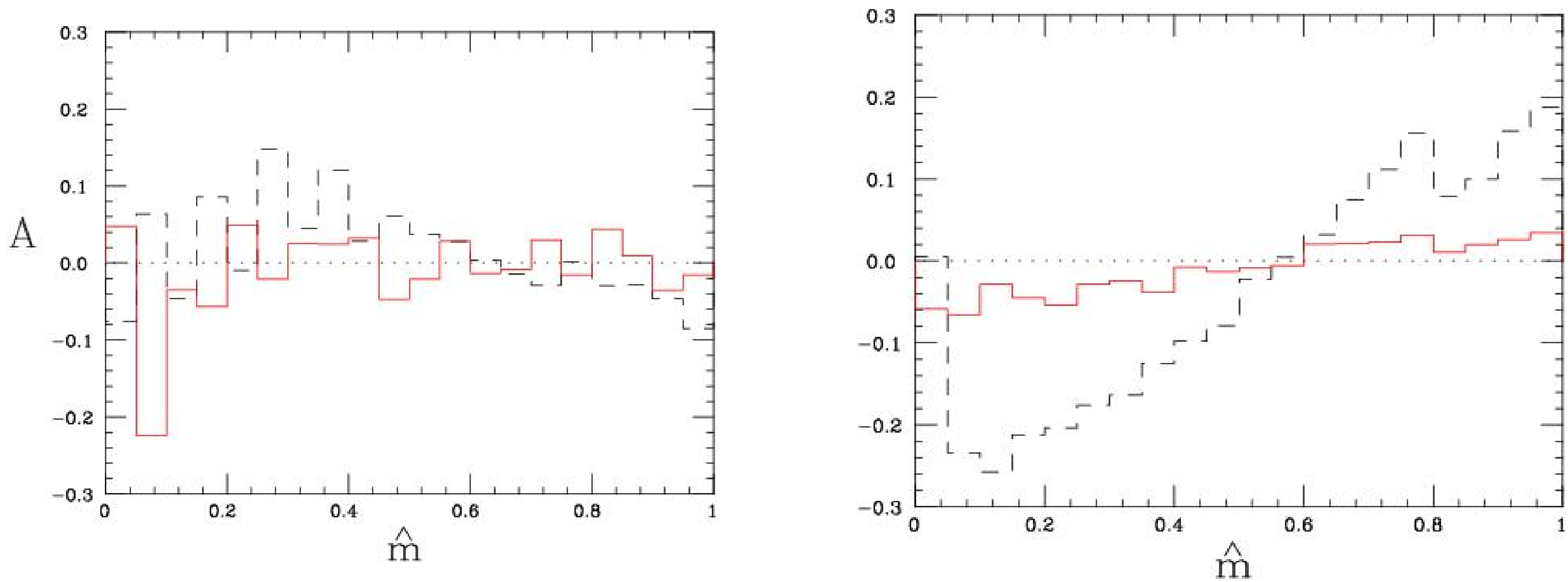
- UED: KK tower with same spin as in the SM
- UED lead to similar signals $\Longrightarrow$ we must probe the spin!





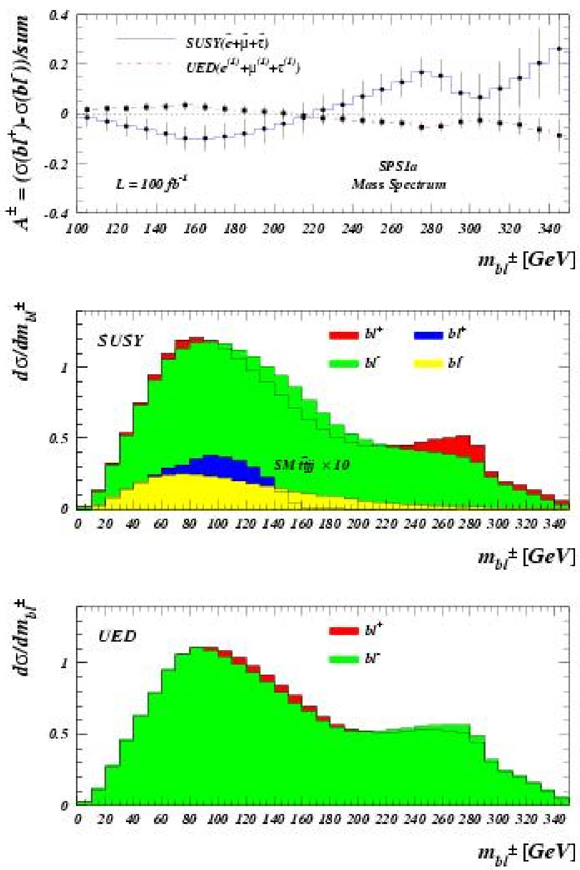
✪ Basic idea: for a decay chain, the structure of interactions and spins lead to correlations between particles $\Longrightarrow$ this can be seen in invariant masses!

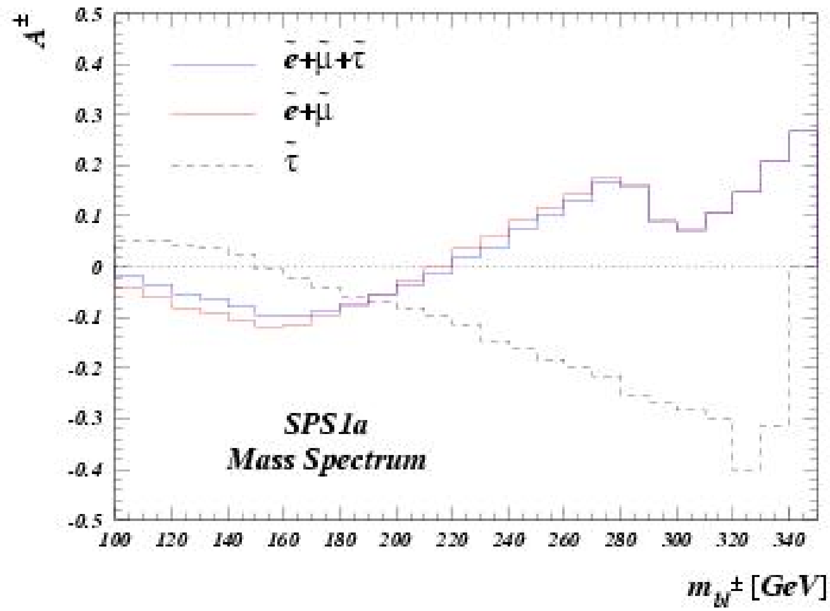
✪ $\mathbf{\tilde{q}_L \to q\tilde{\chi}^0_2 \to q l^\pm_2 \tilde{l}^\mp_R \to q l^\pm_2 l^\mp_1 \tilde{\chi}^0_1}$ (ph/0507170;ph/0405052)



✪ $\mathbf{\hat{m} \equiv m_{\ell q}/m^{max}_{\ell q}}$; $A = \frac{d\sigma/dm_{jl+} - d\sigma/dm_{jl-}}{d\sigma/dm_{jl+} + d\sigma/dm_{jl-}}$

- We can apply the same technique for the gluino (A.Alves, O.E., T.Plehn)
- $\tilde{g} \to \bar{b}\tilde{b}_L \to \bar{b}b\tilde{\chi}^0_2 \to q l^\pm_2 \tilde{l}^\mp_R \to \bar{b}b l^\pm_2 l^\mp_1 \tilde{\chi}^0_1$





IV. Extra dimensions

- Assume that the space has $\mathbf{3} + \mathbf{n}$ dimensions

- The signal is model dependent:
  - one has to define the particles that propagate in ED;
  - geometry of the ED: warped or flat (LED)

- Particles that propagate in the bulk have a Kaluza-Klein (KK) tower in four dimensions: just their “Fourier” modes.

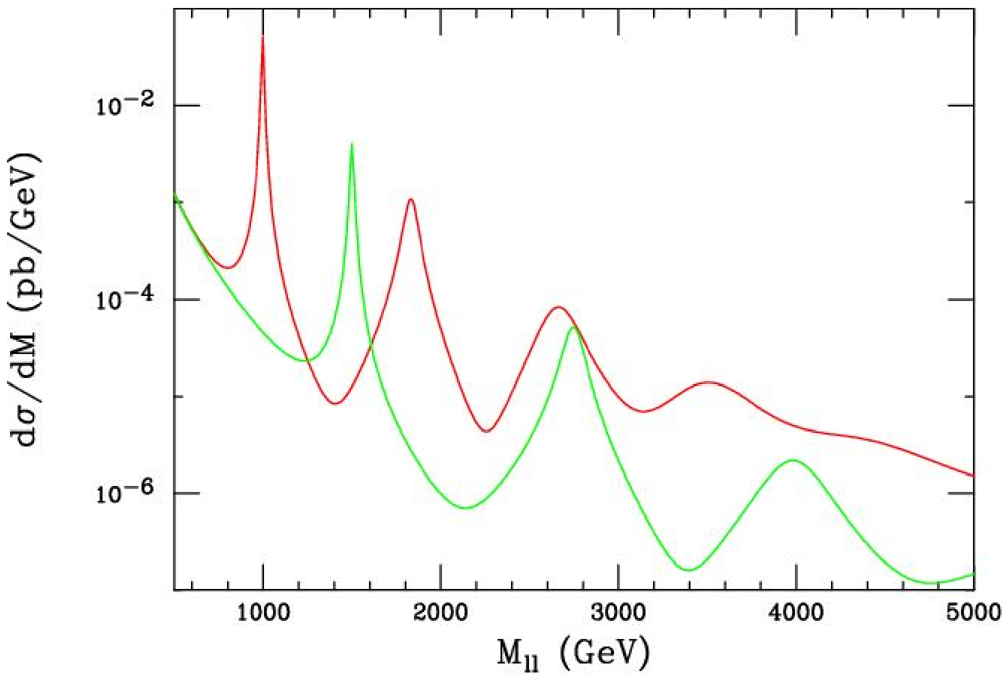
- In LED just gravity in the bulk $\Longrightarrow$ there is a KK tower of gravitons with a small gap $\Longrightarrow$ leads to processes with $\not{E}_T$

- In UED all particle propagate in the bulk $\Longrightarrow$ KK number is conserved $\Longrightarrow$ KK states must be produced in pairs

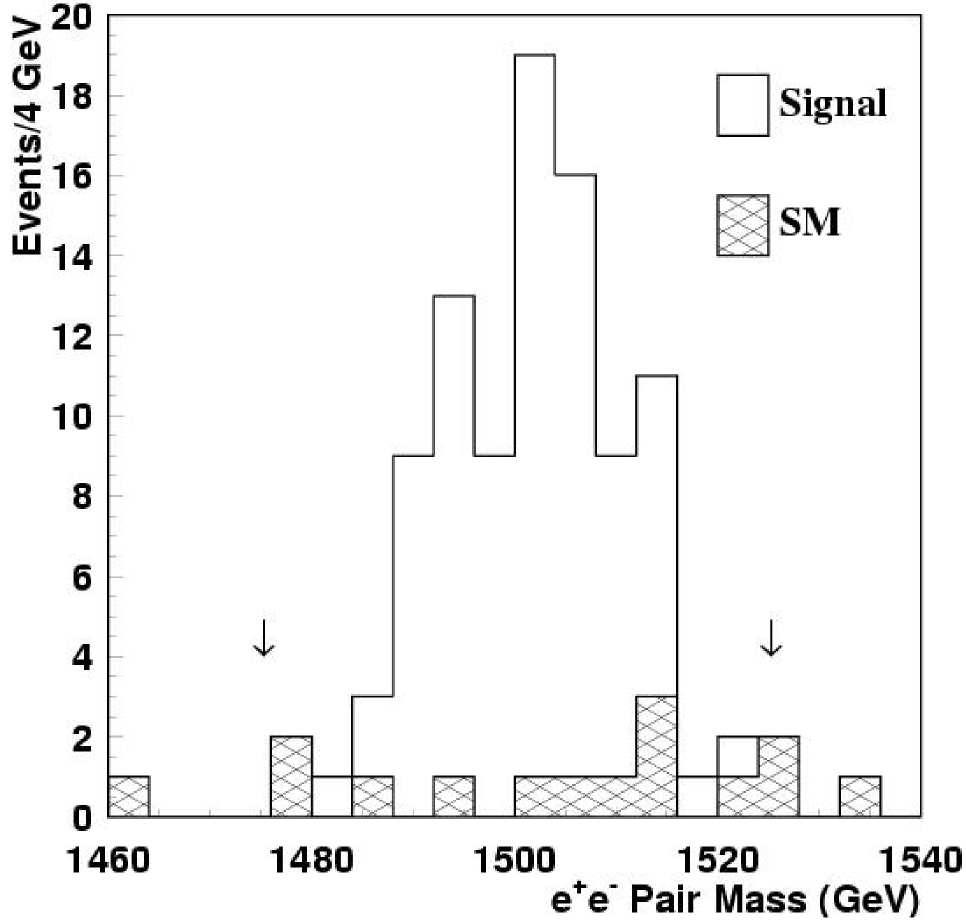
- orbifolding breas KK number conservation, leaving just KK parity

- Let's consider Randall-Sundrum model (warped with only gravity on the bulk) $\Longrightarrow$ new massive spin–2 particles

- There should be a series of resonances in $\mathbf{pp} \to \mathbf{G_n} \to \ell^+\ell^-$



- With mild cuts it is easy to extract the signal

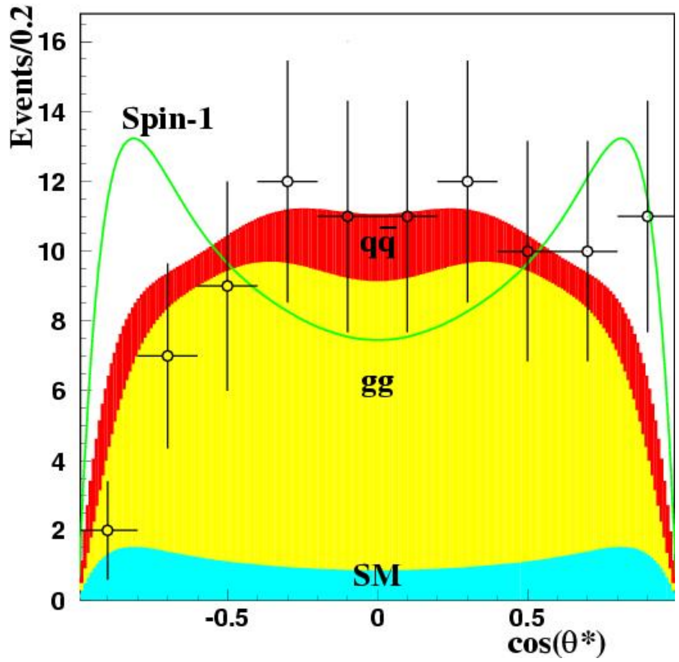


- Can we probe the graviton spin?

- Just use the angular distribution: $\mathbf{1} + \cos^{\mathbf{2}} \theta^*$ for spin1, $\mathbf{1} - \cos^{\mathbf{4}} \theta^*$ ($gg \to G$) and $\mathbf{1} - \mathbf{3} \cos^{\mathbf{2}} \theta^* + \mathbf{4} \cos^{\mathbf{4}} \theta^*$ ($q\bar{q} \to G$)

- Can we probe the graviton spin?

- Just use the angular distribution: $\mathbf{1}+\cos^{\mathbf{2}}\theta^*$ for spin1, $\mathbf{1}-\cos^{\mathbf{4}}\theta^*$ $(gg\to G)$ and $\mathbf{1}-\mathbf{3}\cos^{\mathbf{2}}\theta^*+\mathbf{4}\cos^{\mathbf{4}}\theta^*$ $(q\bar{q}\to G)$



V. Final remarks

- LHC can probe a large number of BSM scenarios
- We don’t know what is out there, but certainly is going to be exciting
- At least, we will discover a new force, the one responsible for EWSB