Physics at LHC

13-17 July 2004 . Vienna . Austria

Radion searches in CMS

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Hierarchy problem

1 loop corrections to the Higgs mass in the SM lead to the following result:

$$m_H^2 = m_{H,tree}^2 + \delta m_H^2$$

$$\delta m_H^2 = 3 \frac{G_F}{4\sqrt{2}\pi^2}\left(2 m_W^2 + m_Z^2 + m_H^2 - 4 m_t^2\right)\Lambda_{SM}^2$$
$$= -\left(115\ \text{GeV}\right)^2 \left(\frac{\Lambda_{SM}}{400\ \text{GeV}}\right)^2$$

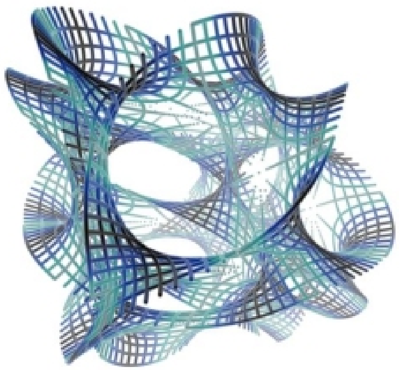
To avoid fine tuning we need: $\Lambda_{SM} \ll M_{GUT}, M_{Pl}$

Which represents the so called: hierarchy problem

How to solve the problem?

- We have to introduce new physics:
  - It must NOT affect too much EWPM
  - The new physics must cut off the Higgs mass corrections at order of (100 GeV)^2

- Few ingredients:
  - SUSY (suppress quadratic divergence in favor of logarithmic divergence)
  - Extradimensions (however needed in string theory)
  - …



Can lead to unify EW to Gravity, thanks to the geometry of the extradimensions

Extra Dimensions, a brief overview

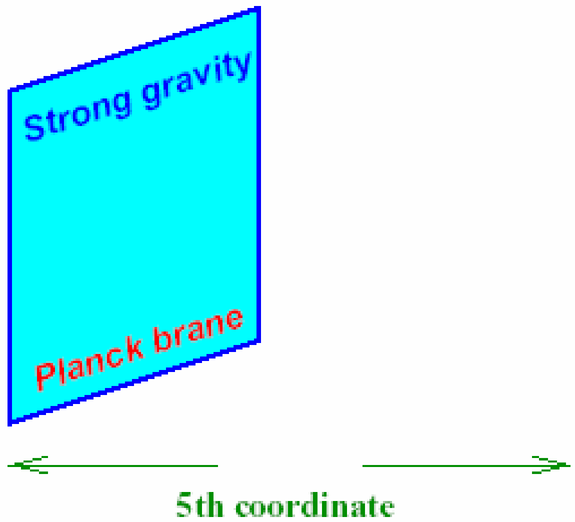
- The model are classified wrt the geometry of the ED:
  - Flat compactified ED (i.e. Flat metric and finite size)
  - Warped ED (warp factor)
- Moreover models can differ on which particles can access the ED:
  - Gravitational ED (only gravity can access the ED)
  - Universal ED (also SM particle can access the ED)

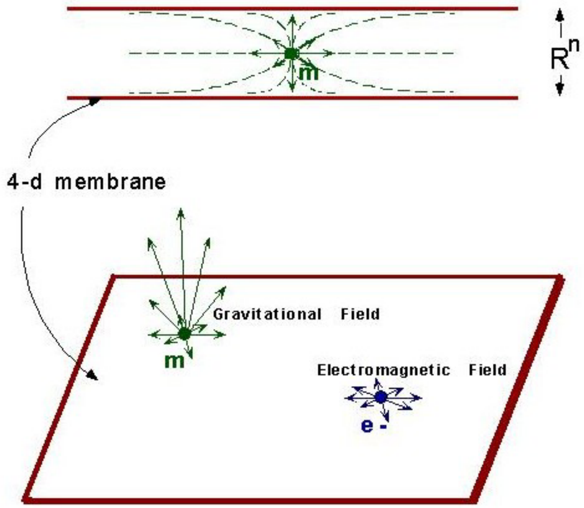
We are interested in this first type.

In particular in the Randall Sundrum Model

How can ED explain the hierarchy problem?

We generally assume that we live on a brane, but it may not be the brane on which gravity is concentrated. Suppose that gravity is highly concentrated near what I'll call the Planck brane. So gravity is concentrated on one brane, the Planck brane, and we live on a second brane, not precisely on top of the first brane but a little apart. Gravity on our second brane would appear to be weak. And that's precisely what we wanted to explain: why gravity appears to be so weak. That's the hierarchy problem-why gravity is so weak. (Lisa Randall)





The warp factor

The hierarchy problem is solved due to the warp factor in the metric:

$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu - \quad dy^2$$

$$\sigma(y) = \quad k \quad |y|$$

Considering the universal scale 5D at ~ $M_{pl,}$ on the scale of EWSB on the EW brane is:

$$\Lambda \equiv \overline{M}_{Pl} e^{-kR_c\pi}$$

(kR_c ~ 10)

Phenomenology of the ED

Assuming, for example, **1** compactified ED (with radius **R**) it is simple to show that particle field can be expanded in series, generating the Kaluza-Klein resonances ...

A scalar field can be expanded in Fourier series in the 5th dimension

$$\Phi(x^\mu, y) = \sum_{n \in \mathbb{Z}} e^{in\frac{y}{R}} \phi_n(x^\mu)$$

With a kinetic part in the Lagrangian

$$\int d^4x\, dy\, (\partial_M \Phi^*\ \partial^M \Phi) = \int d^4x\, dy\, (\partial_\mu \Phi^*\ \partial^\mu \Phi + \partial_5 \Phi^*\ \partial^5 \Phi) =$$

$$= \int d^4x \sum_{n \in \mathbb{Z}} \left(\partial_\mu \phi_n^*\ \partial^\mu \phi_n - \frac{n^2}{R^2} \phi_n^* \phi_n \right)$$

Mass term of orfer 1/R

What is the radion?

Assuming the RS model and representing the 5D graviton field in our 4D world, we obtain spin-2, spin-1 and scalar representation of the graviton.

$$h_{\mu\nu}(x,y) = \sum_{n=0}^{\infty} h^n_{\mu\nu}(x) C^n(y) \ \ (spin-2)$$

$$A_{\mu i}(x,y) = \sum_{n=0}^{\infty} A^n_{\mu i}(x) C^n(y) \ \ (spin-1)$$

$$\phi_{ij}(x,y) = \sum_{n=0}^{\infty} \phi^n_{ij}(x) C^n(y) \ \ (spin-0)$$

→ Here is the radion!

$C^n(y)$ are the corresponding coefficients of the Fourier expansion in the warped fifth dimension

The parameters of the model

$$\xi \qquad \Lambda_\phi \qquad m_h \qquad m_\phi$$

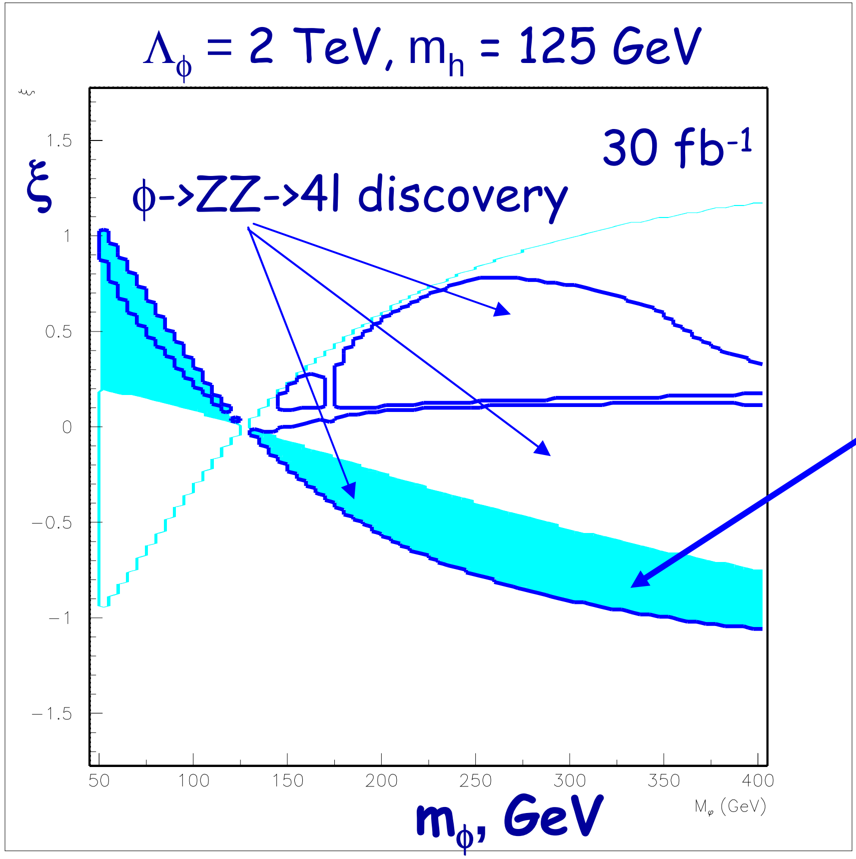
Additional parameter for fixing the phenomenology of KK excitations of the gravitons $h^n_{\mu\nu}$,

$$m_1 = x_1 \frac{m_0}{M_{Pl}} \frac{\Lambda_\phi}{\sqrt{6}}$$

m_1 is the mass of the first KK graviton excitation. $x_1 \sim 3.83$ is the first zero of the Bessel function J_1.

The effect of the mixing

The Higgs boson couplings can change and thus for some regions in the parameters space the mixing may prevent the 5 sigma discovery of the Higgs boson (blue region below).



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h->γγ is lost but
φ->ZZ->4l can be seen

no discovery for h->2γ
σBr(h_{SM}->ZZ->4l) ~= σBr(φ->ZZ->4l)

Observation of X->hh with 30 fb^{-1}
is a hint for radion !

Final states used in the analysis

ATLAS did fast simulation study on
ϕ -> hh ($2\gamma 2b$, 2τ 2b)
G. Azuelos et al . 2002

we take the same mass points: $m_\phi = 300$ GeV, $m_h = 125$ GeV to start with . . .

A. Nikitenko & G. Dewhirst (IC, London)

ϕ -> hh -> 2γ 2b

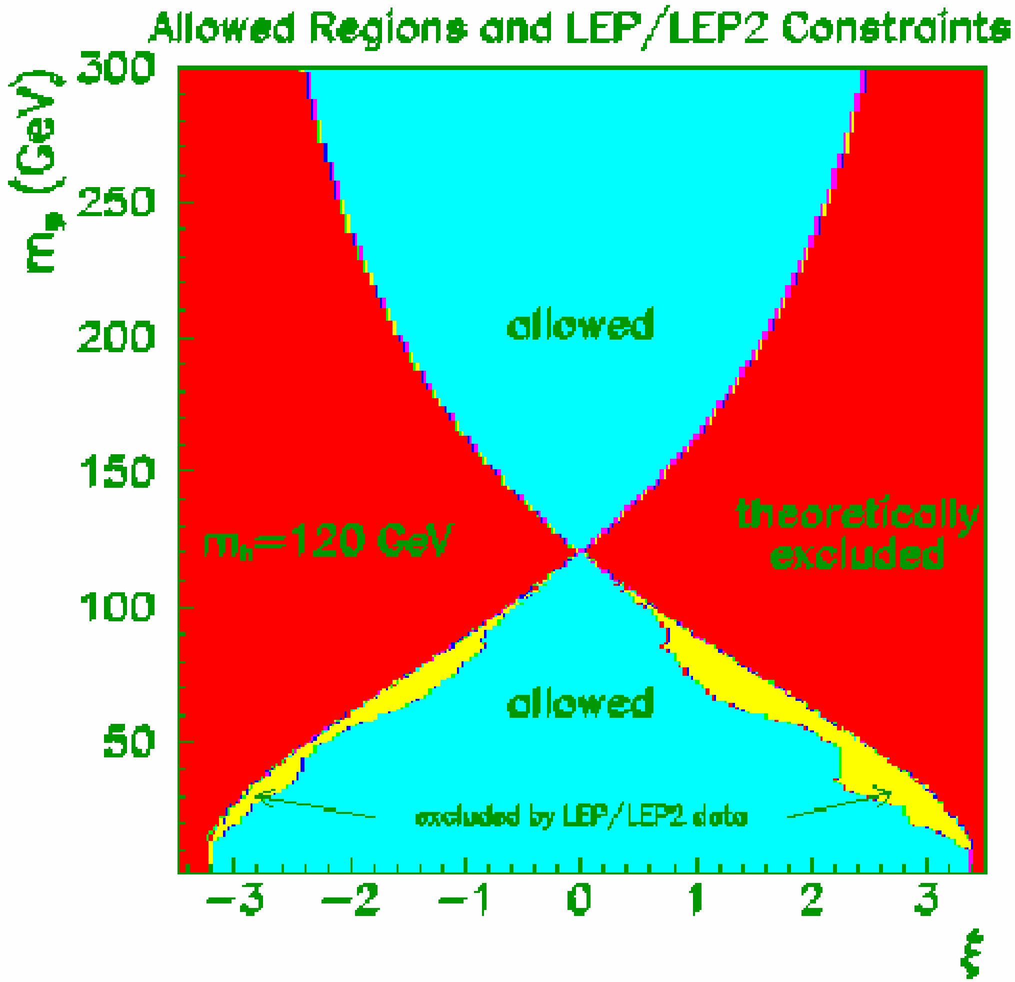
S. Gennai (Pisa)

ϕ -> hh -> 2τ 2b

L. Fano (Perugia)

ϕ -> hh -> 4b

J. Gunion et al. 2002



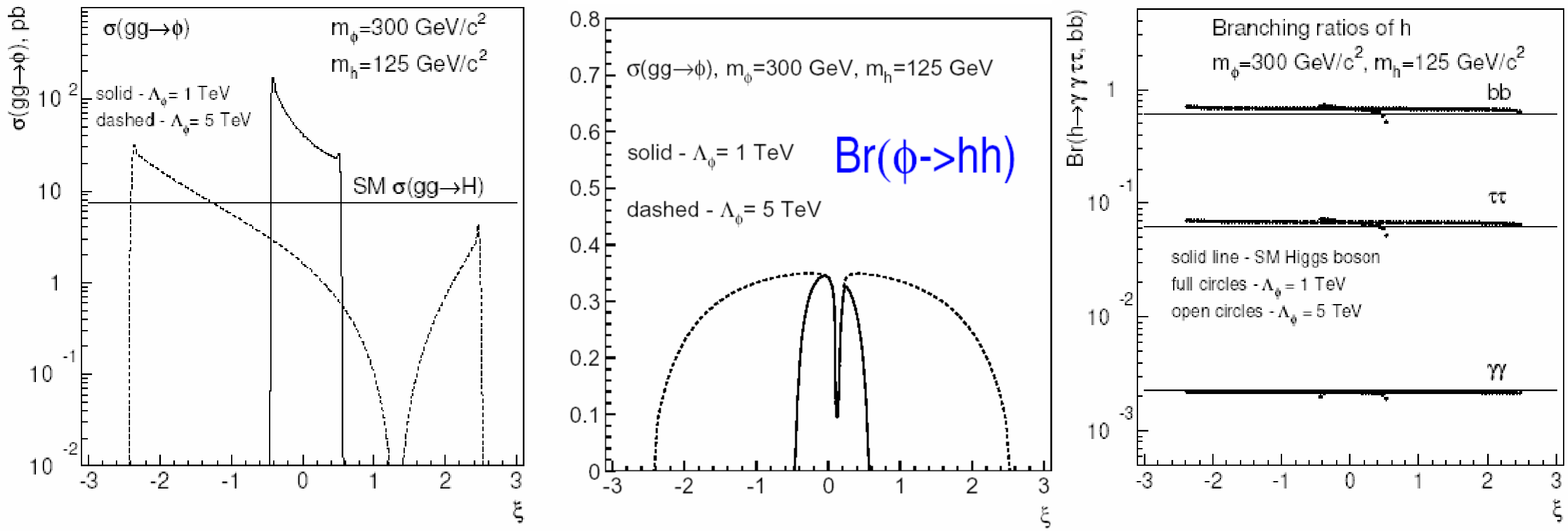
ϕ->hh

In this scenario, it is interested to study the final state where the radion decays in a couple of Higgs bosons.

We have fixed M_R = 300 GeV and M_h = 125 GeV and

we made a scan over (ξ, Λ_ϕ) plane.

$$\sigma(gg \to \phi) = \sigma_{SM}(gg \to h)\frac{\Gamma(\phi)\cdot BR(\phi \to gg)}{\Gamma_{SM}(h)\cdot BR_{SM}(h \to gg)}$$



$\phi \to hh \to \gamma\gamma bb$

M_ϕ =300 GeV, M_h=125 GeV

Λ=1 TeV, ξ=-1/3

-> σxBR~100 fb

Main background:

- Irreducible: $\gamma\gamma$+jj, $\gamma\gamma$+cc, $\gamma\gamma$+bb
- Reducible: γ+jjj, jjjj at LO

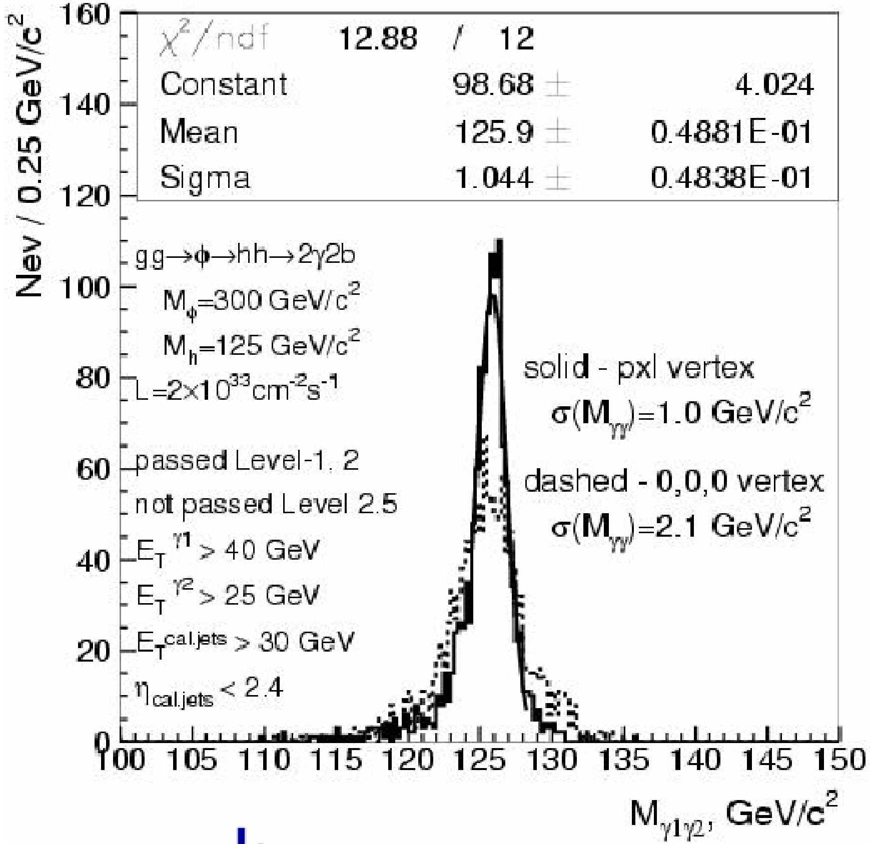
Selection strategy:

- L1 Trigger: double electrons/photons E_T>12 GEV
- HLT : double isolated photons E_T>14.5 GeV, pixel matching cut
- Off-line:
  - 2 isolated (calo+tracker) photons $E_T^{\gamma1,\gamma2}$ >40, 25 GeV
  - 2 calo jets with E_T>30 GeV, $|\eta|$<2.4
  - Tagging at least 1 b jet
  - Invariant mass reconstruction

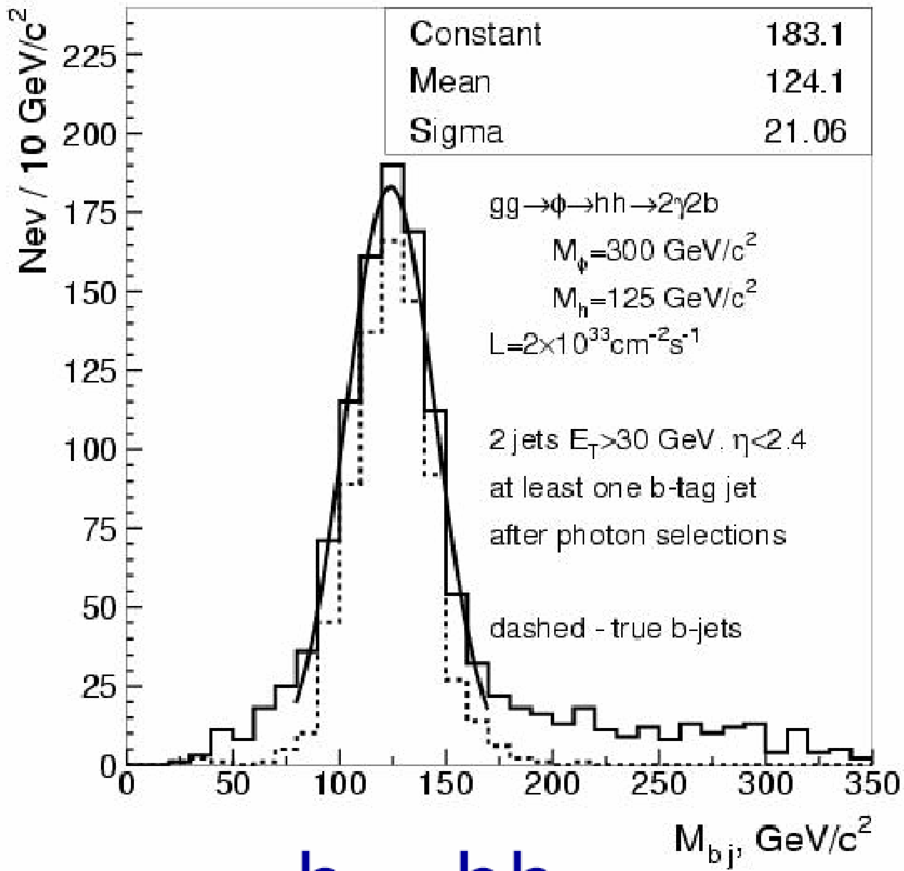
B j and γγ Signal invariant mass

2 jets (iterative cone algorithm, $\Delta R=0.5$) with $E_T>30$ GeV, $|\eta|<2.4$, $R\gamma\text{-}j>0.5$

At least 1 jet b-tagged (>=2 tracks with $\sigma_{IP2D}>3$)



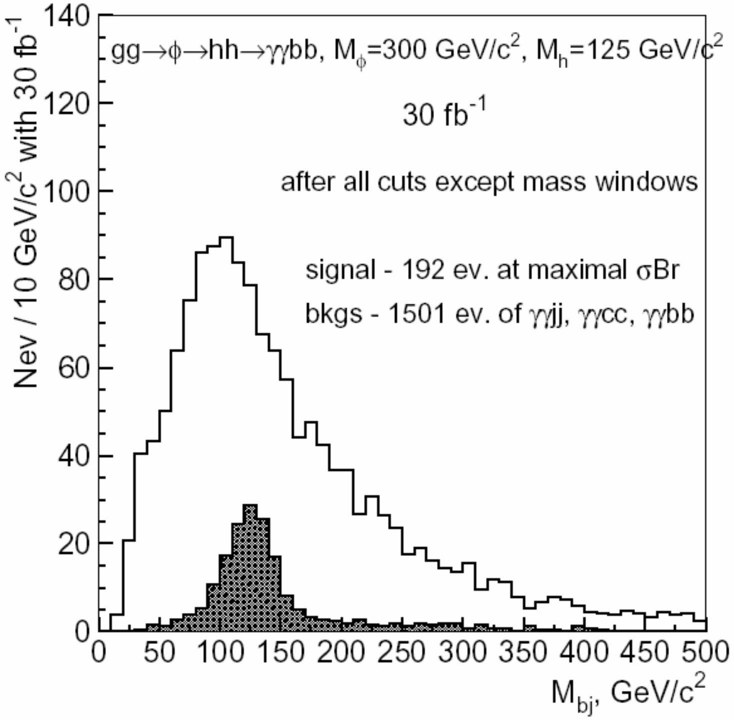
h→γγ



h→ bb

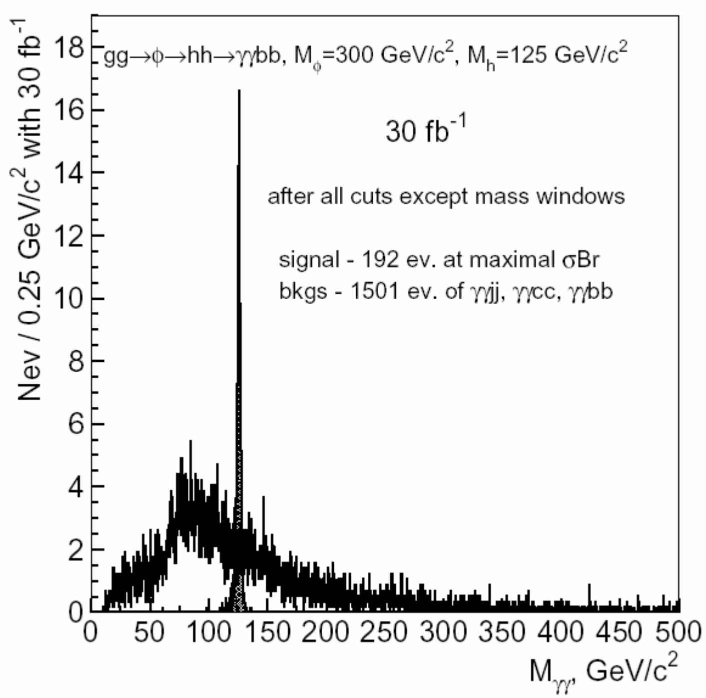
B j and γγ invariant mass

At least 1 jet tagged as b jet.
Correction of the γ direction using the signal vertex



Di-jet invariant mass:white is bkg, black is signal.

(after all selections and b-tagging but before mass windows cut)



γγ invariant mass: Signal is the narrow peak.

(after all selections and b-tagging but before mass windows cut)

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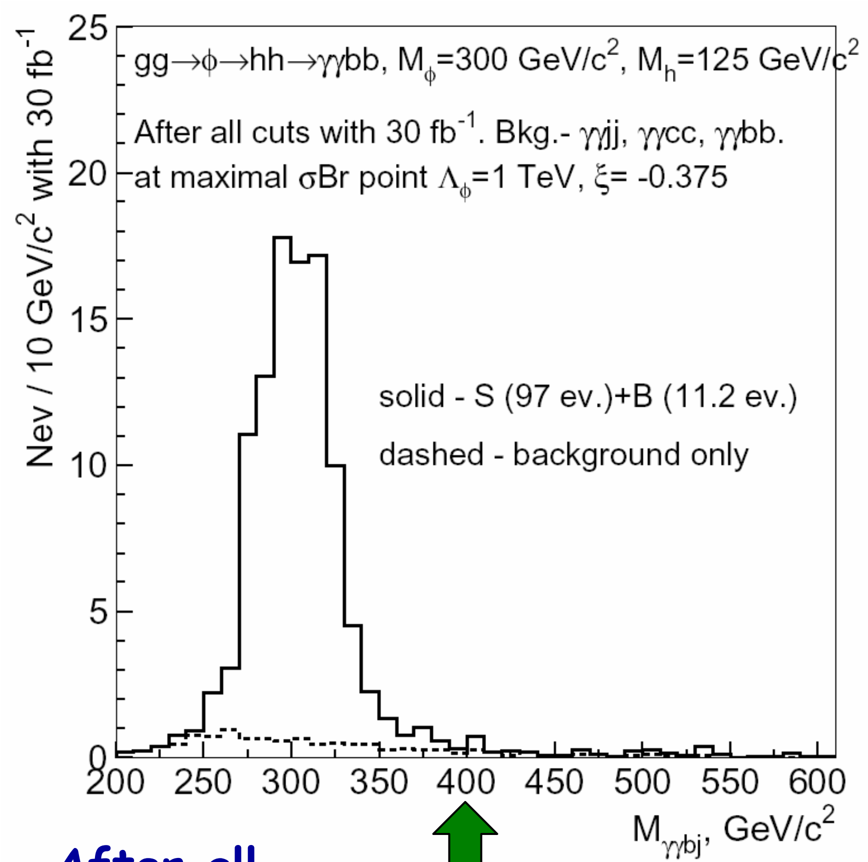
Radion mass distribution



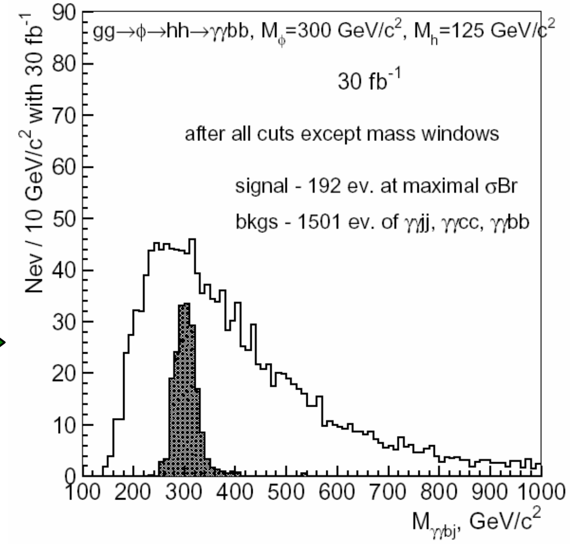
After all selections

Radion invariant mass.

Solid: signal+bkg (max. cross section for signal: Λ=1 TeV, ξ=-0.375)

Dashed: bkg only (irreducible one)

After all selections except mass cut selections



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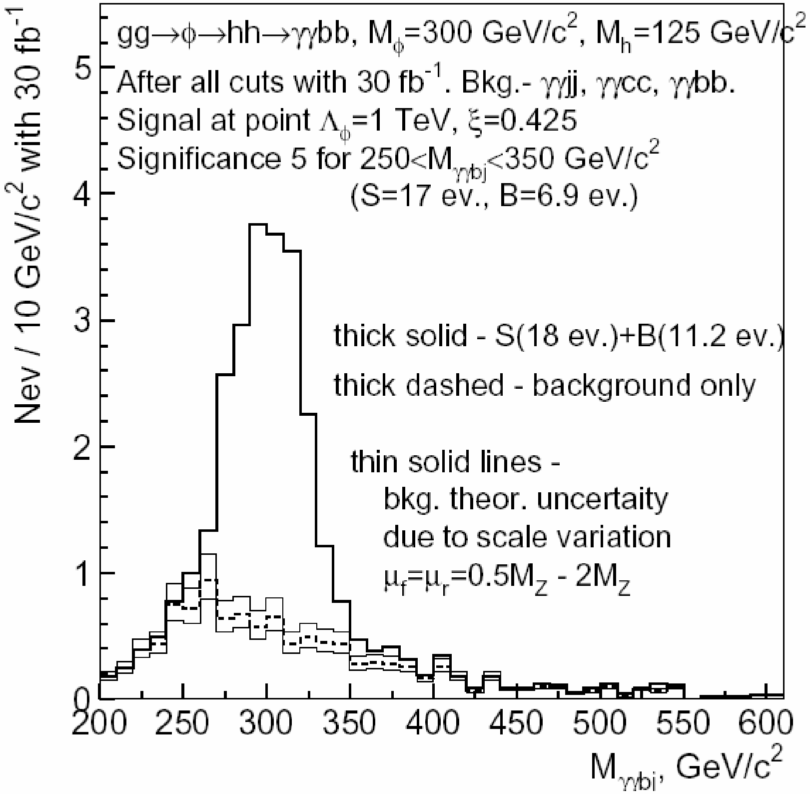
Effect of the bkg scale variation



Radion invariant mass at 5σ point, after all selections

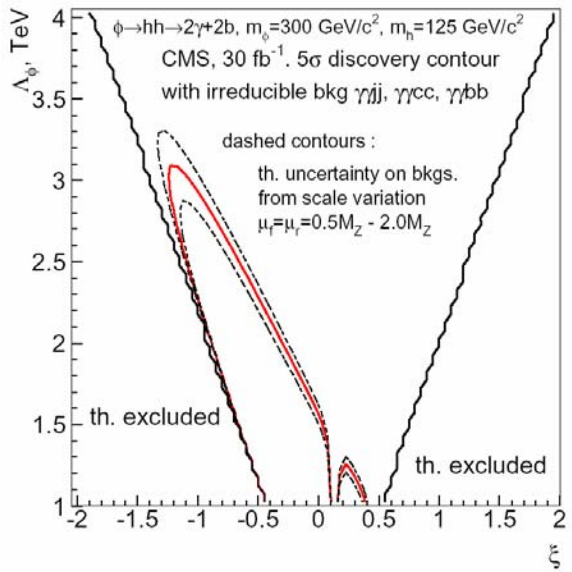
Table 5: Trigger and off-line selection efficiencies for the $\gamma\gamma+b\bar{b}$ signal.

selection criteria	relative efficiency	absolute efficiency
1. Level-1	0.738	0.738
2. Level-2	0.927	0.685
3. Level-2.5 photon stream	0.996	0.683
4. $E_T^{\gamma 1,2} > 40, 25$ GeV	0.871	0.595
5. tracker isolation of photons	0.682	0.406
6. ECAL isolation of photons	0.909	0.369
7. two jets of $E_T > 30$ GeV, $\lvert\eta\rvert < 2.4$	0.341	0.126
8. at least one b jet	0.610	0.077
9. $M_{\gamma\gamma}$ mass window of 4 GeV/c^2	0.779	0.060
10. M_{bj} window 60 GeV/c^2	0.649	0.039
11. $M_{\gamma\gamma bj}$ window 100 GeV/c^2	0.950	0.037

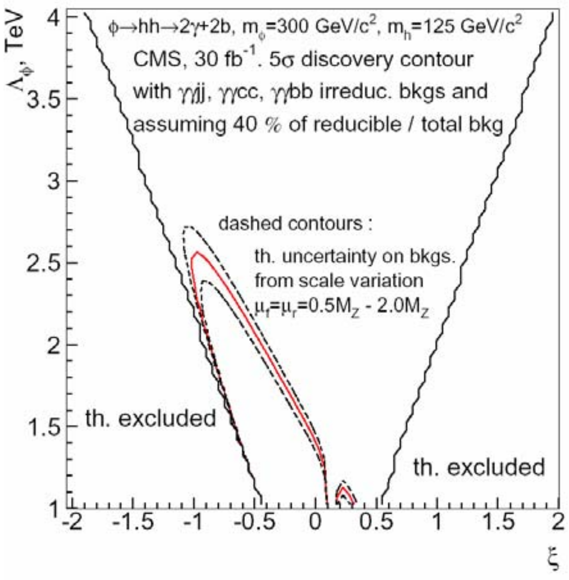
	$\gamma\gamma jj$	$\gamma\gamma c\bar{c}$	$\gamma\gamma b\bar{b}$
selections	efficiency		
1. $E_T^{\gamma 1,2} > 40, 25$ GeV, $\lvert\eta\rvert < 2.5$	0.446	0.466	0.487
2. tracker isolation in cone 0.3	0.328	0.345	0.379
3. two jets $E_T > 30$ GeV, $\lvert\eta\rvert < 2.4$	0.127	0.125	0.133
4. at least one b jet	2.97×10^{-3}	1.76×10^{-2}	9.49×10^{-2}
5. $M_{\gamma\gamma}$ window 4 GeV/c^2	6.50×10^{-5}	3.68×10^{-4}	2.92×10^{-3}
6. M_{bj} window 60 GeV/c^2	2.01×10^{-5}	1.34×10^{-4}	1.02×10^{-3}
7. $M_{\gamma\gamma bj}$ window 100 GeV/c^2	1.05×10^{-5}	8.57×10^{-5}	8.77×10^{-4}
N events after all selections	4.2 ± 0.8	2.0 ± 0.6	2.0 ± 0.6

Signal and background efficiency

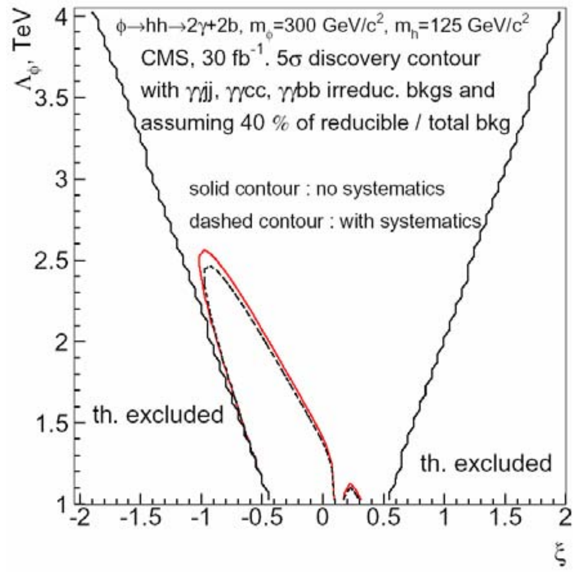
5 sigma plot



Irreducible bkg only + theoretical uncertainties (scale variation of bkg cross section)



Irreducible bkg + reducible bkg (40% of total bkg)*+theoretical uncertainties (scale variation)



Irreducible bkg + reducible bkg (40% of total bkg) + systematics effects on bkg

(*Red. bkg has been assumed from PRELIMINARY inclusive h->γγ studies by S. Shevchenko)

ϕ->hh->$\tau\tau$bb->l τ_{jet} n bb

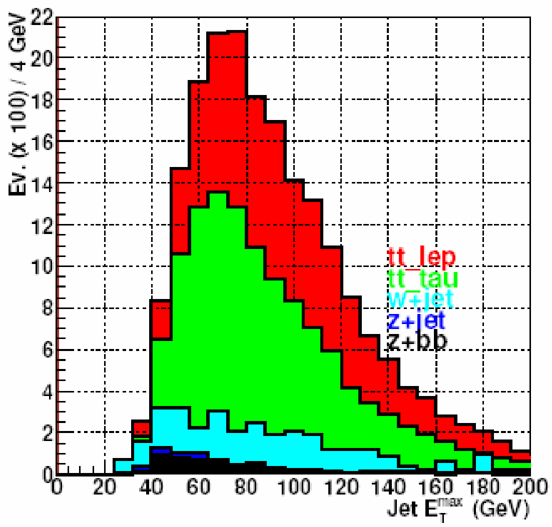
In this analysis we suppose to know the Higgs boson mass value. The Higgs boson discovery can be performed through the ϕ->hh->$\gamma\gamma$bb channel

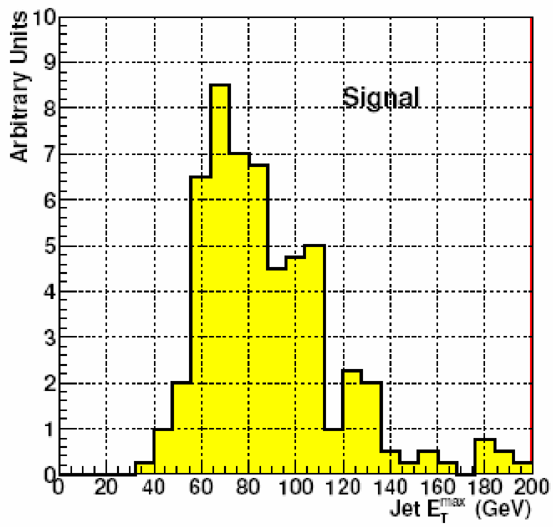
bkg Samples	σ (pb)	$\sigma \times BR$ (pb)	N. of events
$t\bar{t} \rightarrow Wb + W\bar{b} \rightarrow l + \nu + jets + b\bar{b}$ (tt_{had})	825	245	7.3×10^6
$t\bar{t} \rightarrow Wb + W\bar{b} \rightarrow l + \nu + \tau jet + b\bar{b}$ (tt_{tau})	825	27	8×10^5
$Zb\bar{b} \rightarrow \tau\tau + b\bar{b} \rightarrow l + \nu + \tau jet + b\bar{b}$	525	8	2.4×10^5
$Z + jets \rightarrow \tau\tau + jets \rightarrow l + \nu + \tau jet+jets$ ($\hat{p_T} > 20$)	23300	355	10.6×10^6
$W + jets \rightarrow l + \nu + jets$ ($\hat{p_T} > 80$)	4100	900	27×10^6

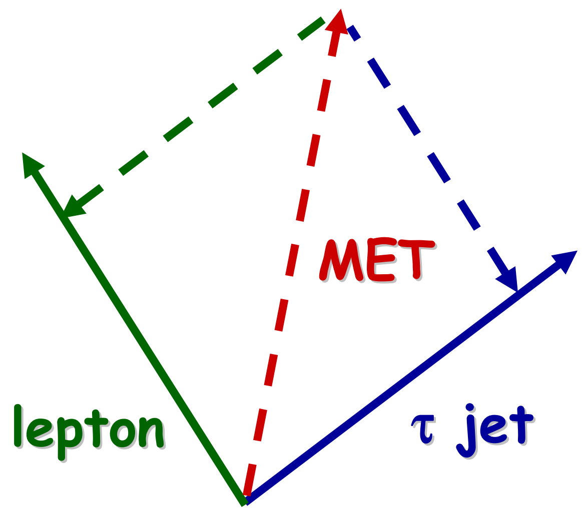
Table 5.3: Cross section (NLO), branching ratios and expected number of events, after 30 fb^{-1}, for the main background samples. See text for more details.

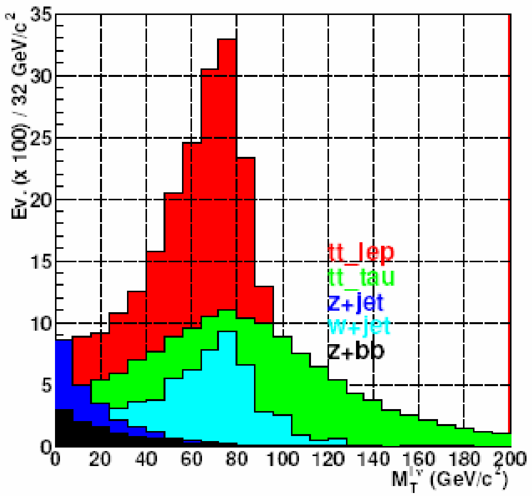
Kinematic distributions

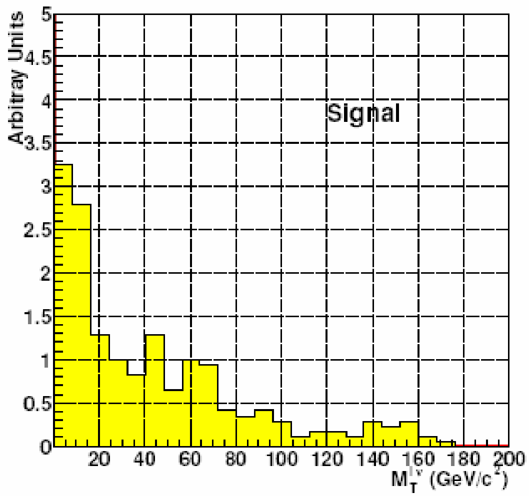
We require to tag at least 1 b jet (p_T jet > 30 GeV).
Selection on the transverse invariant mass of lepton+MET and Max pT of b jet





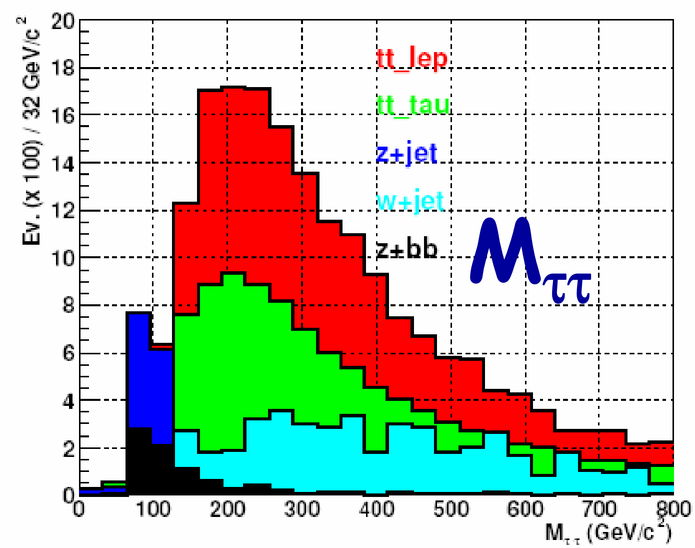


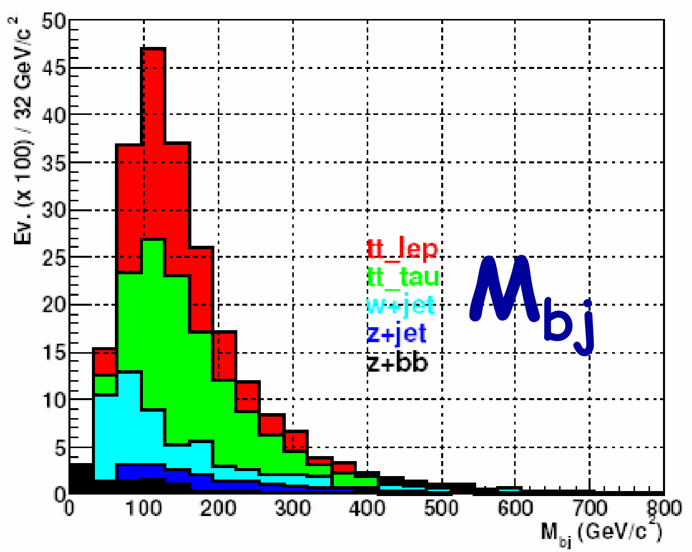


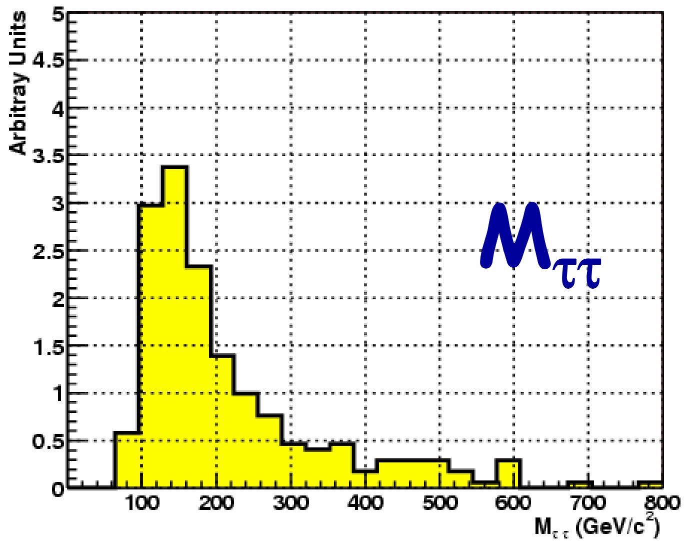


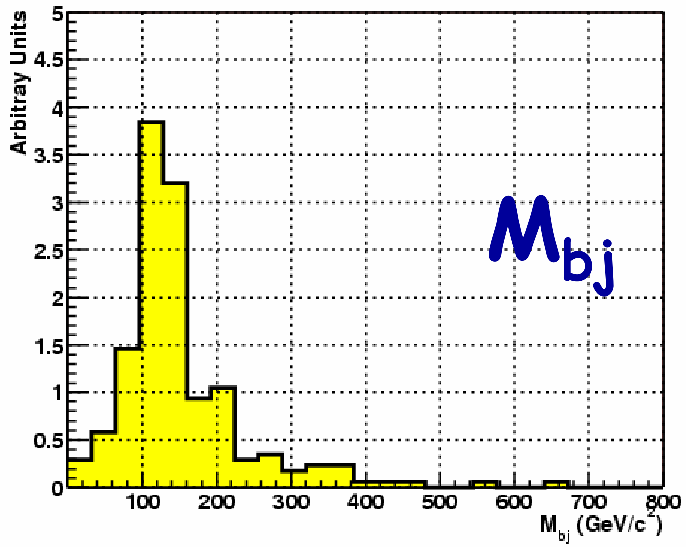
We can reconstruct the nutrinos energy using the collinear approximation

Invariant mass distributions









Kinematic fit

- We can select directly in invariant mass of b and tau jets:
  - 100 < Mbj <150 GeV
  - 100 < $M_{\tau\tau}$ < 160 GeV

- Then apply the kinematic fit in order to rescale the jet energies, no changes in the angle between jets

- Fit the radion invariant mass distribution of signal+background

Kinematic fit, the implementation

The idea is to minimize a Chi-square form:

$$\chi^2 = \left(\frac{E_1 - \omega_1}{\sigma_1}\right)^2 + \left(\frac{E_2 - \omega_2}{\sigma_2}\right)^2 + \lambda\left(m^2 - 2E_1E_2(1-\cos\theta)\right)$$

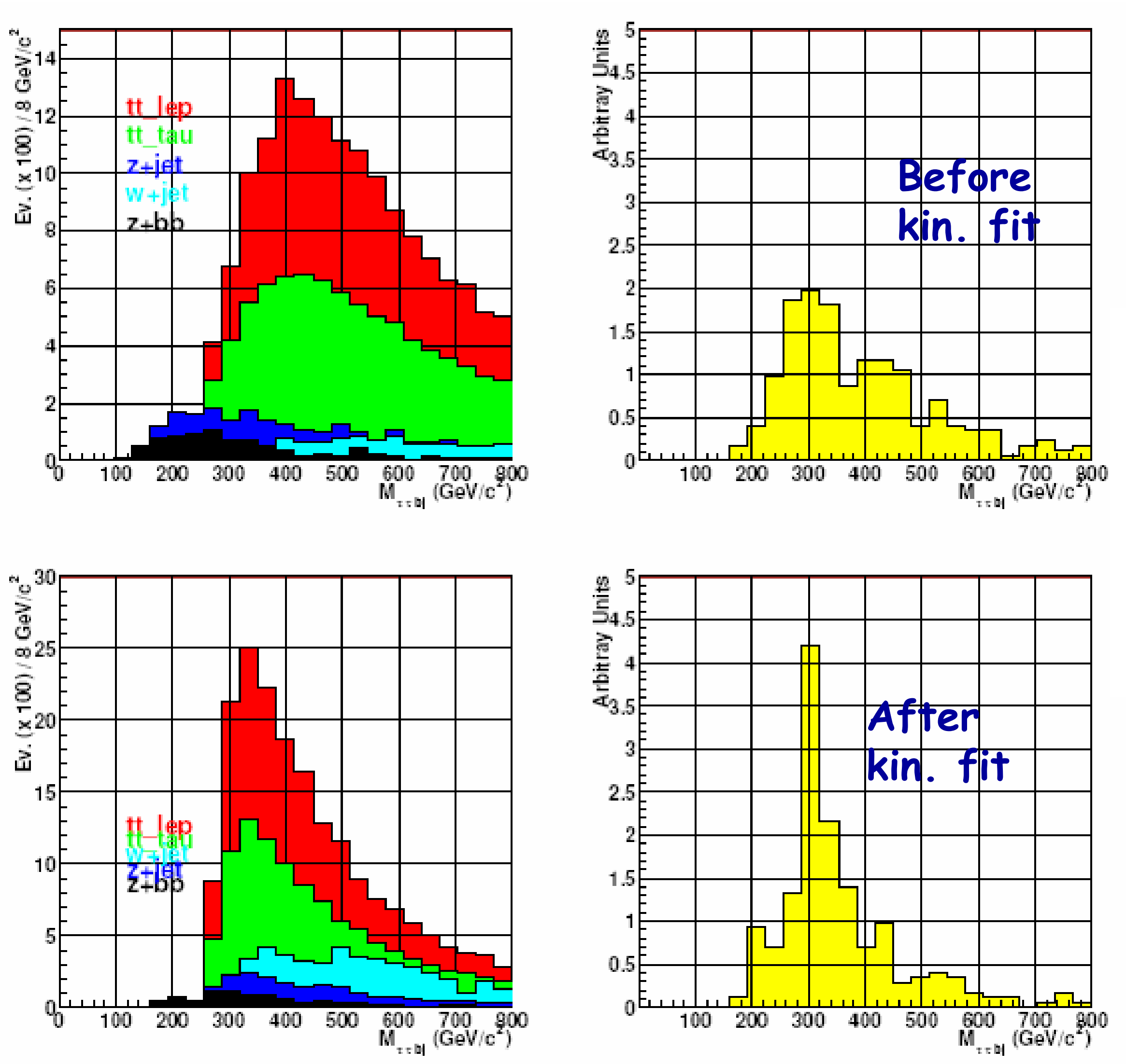
Where:
m = true mass
μ= reconstructed mass
$E_{1,2}$=rescaled energies
$\omega_{1,2}$ = measured energy
λ= Lagrangian multiplier
For what concerns τ, the energies after the neutrino reconstructions have been used.

After some algebra and some assumption on the jet energy resolution we get an approximated formula for the rescaled energies.

$$E_1 = \omega_1 + \left(\frac{m^2 - \mu^2}{\mu^2}\right) \times \frac{\omega_1\omega_2}{\omega_1 + \omega_2};$$

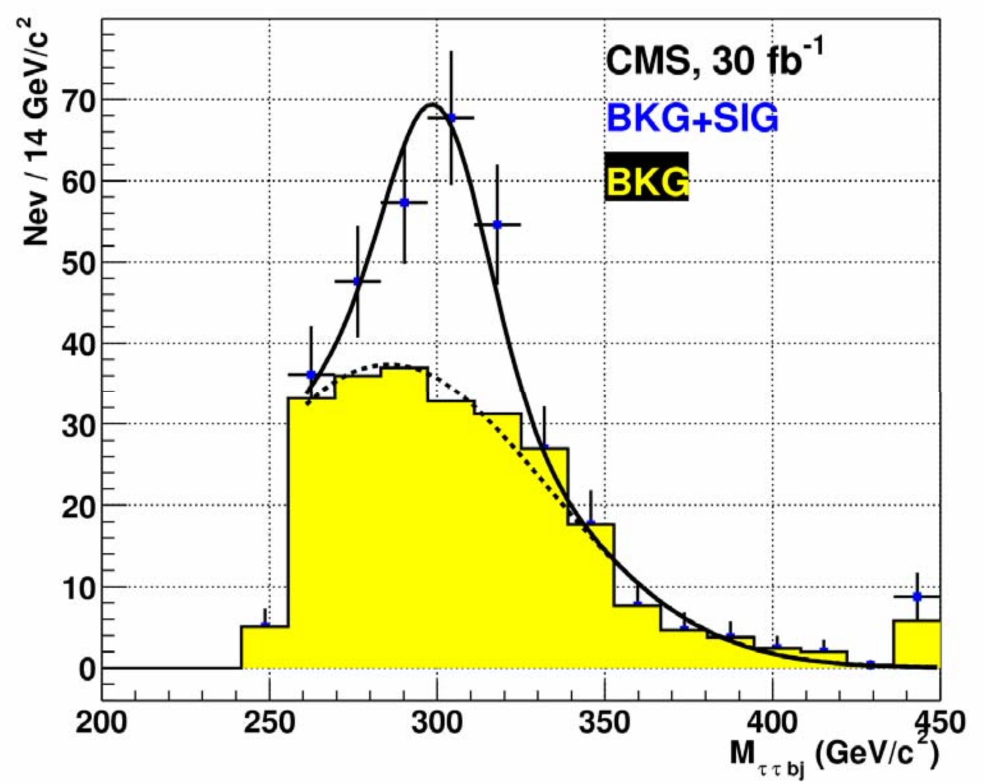
$$E_2 = \omega_2 + \left(\frac{m^2 - \mu^2}{\mu^2}\right) \times \frac{\omega_1\omega_2}{\omega_1 + \omega_2}$$

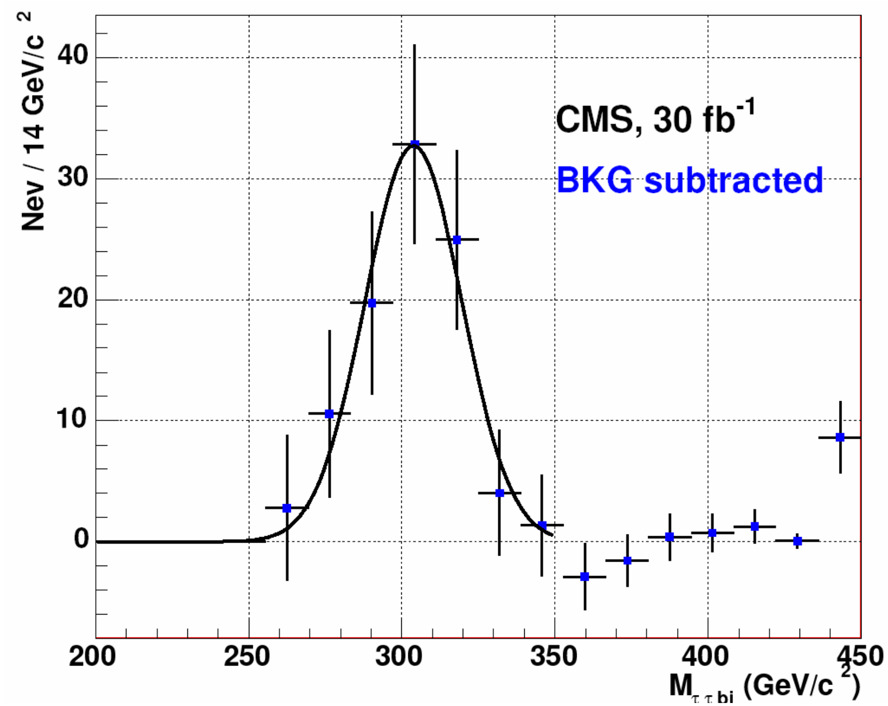
Effect of the kinematic fit



Even if the formula used is an approximation, it yields very good results!

Fitting signal+background





Two gaussian have been used:

Signal: <m> = 300 GeV

σ = 15 GeV

Bkg: <m> = 285 GeV

σ = 45 GeV

5 sigma plot

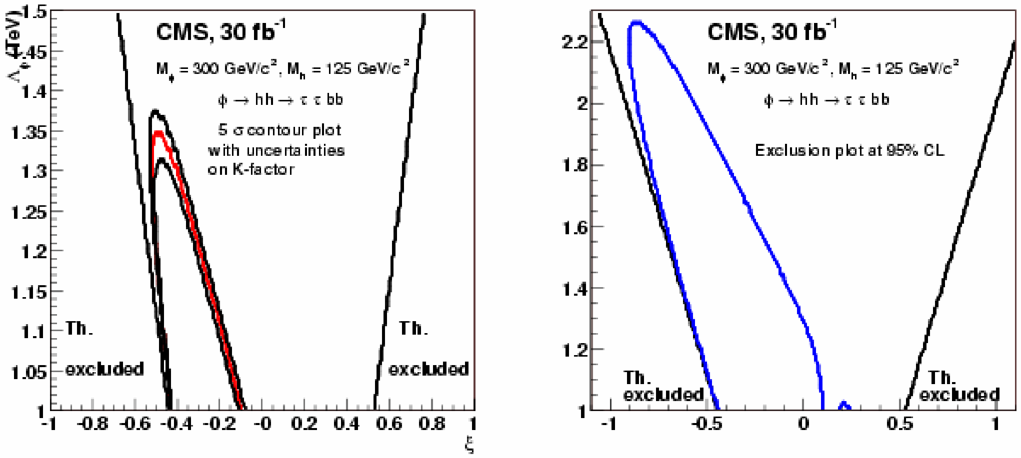


Figure 5.15: 5 σ discovery contour considering the k_{min} and k_{max}-factor, only statistical uncertainties have been considered (upper plot). 95% CL exclusion plot. No NLO uncertainties have been considered in the plot.

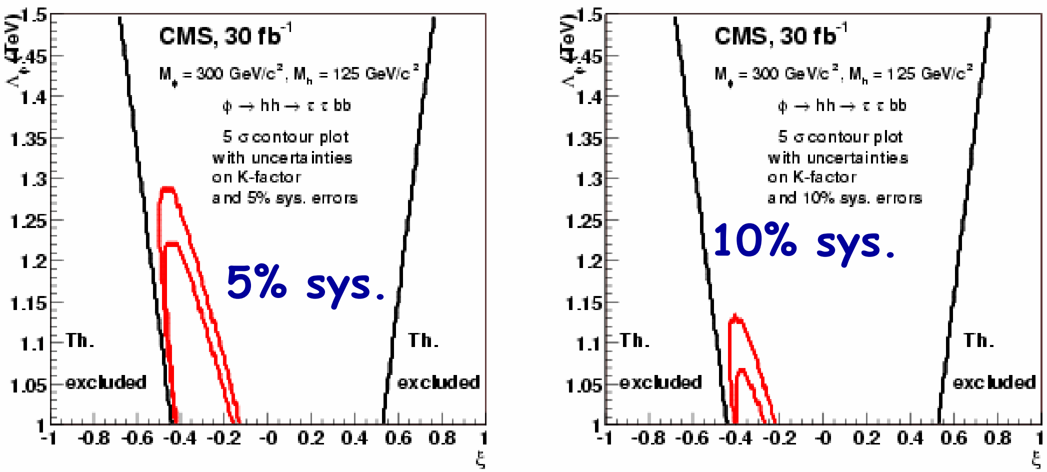


Figure 5.17: 5 σ discovery contour considering the k_{min} and k_{max}-factor and systematical uncertainties of 5% (left plot) and 10% (right plot) on background.

ϕ->hh->bbbb

$\sigma_{gg->\phi} \sim 100$ pb

BR(ϕ->hh) ~ 0.24 BR(h->bb) ~ 0.6

$\sigma_{gg->\phi}$ xBR ~ 10 pb

Non-resonant background:

(strongly dependant on btag performances)

- QCD multijet production JJJJ (+JJJJJ, +JJJJJJ, ...)
  (from 2->2 events + ISR, FSR and gluon splitting)

Main Resonant background:

- tt -> σ ~ 615 pb (NLO 825 pb)
- ttjj -> σ ~ 507 pb
- Zbb -> σ ~ 349 pb

Trigger and off-line strategy

Level 1: .

(Energetic jet trigger Low Lumi)

1 jets E_T> 164 GeV in $|\eta|$<0.8 OR
2 jets E_T> 129 in $|\eta|$<0.8 OR
3 jets E_T> 76 in $|\eta|$<0.8 OR
4 jest E_T> 62 in $|\eta|$<0.8

Corresponding to 95% eff on MC jets 4 kHz rate (L1)

HLT:

at least 4 jets, 2 of which have to be b-tagged (2 trks with SIP2D>2.)

Off line:

Invariant mass reconstruction:

looking for 2 identical object (Higgs bosons)

minimizing (m(i,j)-m(k,l)) -> $m_{h\text{-}rec}$
over all possible combination

radion mass reconstruction

m(i,j,k,l) -> m_ϕ

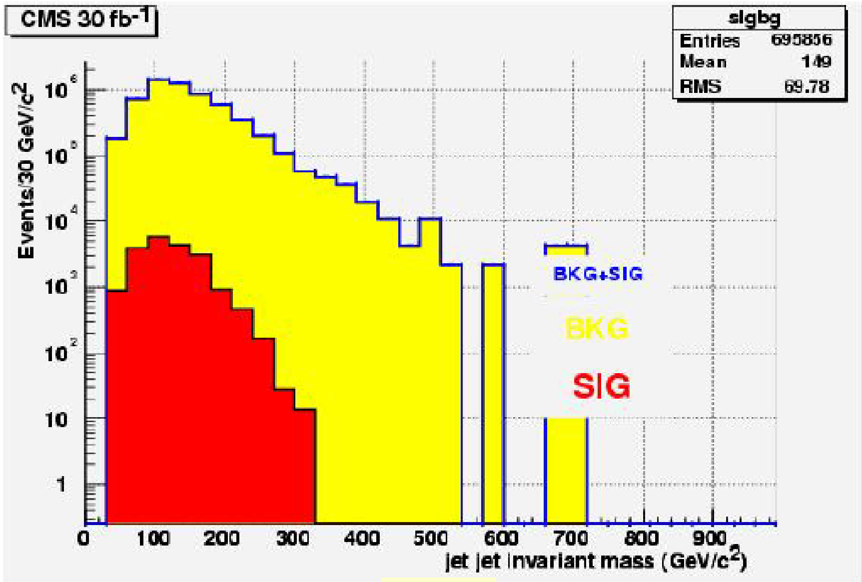
Additional request:

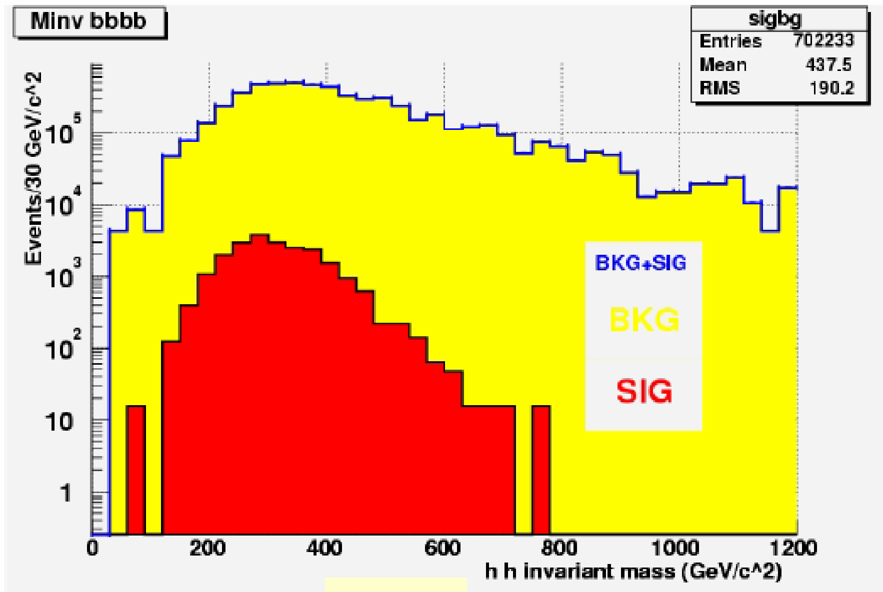
$m_{h\text{-}rec} - 1.5\sigma < m_{inv}(b,b) < m_{h\text{-}rec} + 1.5\sigma$
$m_{\phi\text{-}rec} - 1.5\sigma < m_{inv}(4b) < m_{\phi\text{-}rec} + 1.5\sigma$

Signal and background efficiency

	Cross sec	ε Trigger (A+B)	ε Mass window	Exp events 30 fb^{-1}
Signal	10,3 pb	0.038	0.031	9.5E+3
QCD 30-50 50-80 80-120 120-170	0,1957 mb 0,0258 mb 0,0036 mb 0,0006 mb	<1E-7 (95% CL) <5E-7 (95% CL) 1E-5 1E-4	<1E-7 (95% CL) <5E-7 (95% CL) 7E-6 6.6E-5	<5.7E+5 <3.8E+5 7.5E+5 1.1E+6
tt	614 pb	0.015	0.010	1.8E+5
ttjj	231 pb	0.056	0.026	1.8E+5
Zbb	52 pb	0.002	8E-4	1.2E+3

4 b final state results





M_{jj} M_{jjjj}

Signal and background distribution have the same shape. A counting experiment is the only way to extract signal significance. To still have 5σ discovery at the maximal cross section, the uncertainty on the bkg extrapolation should be less than 0.1%

Conclusions

- The process: $gg \to \phi \to hh$ has been studied. Three different final states have been considered
  - $\gamma\gamma bb$
  - $\tau\tau bb$
  - bbbb
- A radion mass of 300 GeV and a Higgs boson mass of 125 GeV have been considered.
- For $\Lambda \sim 2$ TeV and ξ in the interval [-0.9, -0.4] the $h \to \gamma\gamma$ is not visible, while the $\phi \to hh$ (and $\phi \to ZZ \to 4l$) gives a signal at 5 sigma.
- The $\gamma\gamma bb$ final state offers the best possibilities to discover both the radion and the Higgs up to $\Lambda \sim 2.5$ TeV, the $\tau\tau bb$ can give robust confirm to the radion discovery up to $\Lambda \sim 2$ TeV. They can be used to distinguish between the SM Higgs and the radion.

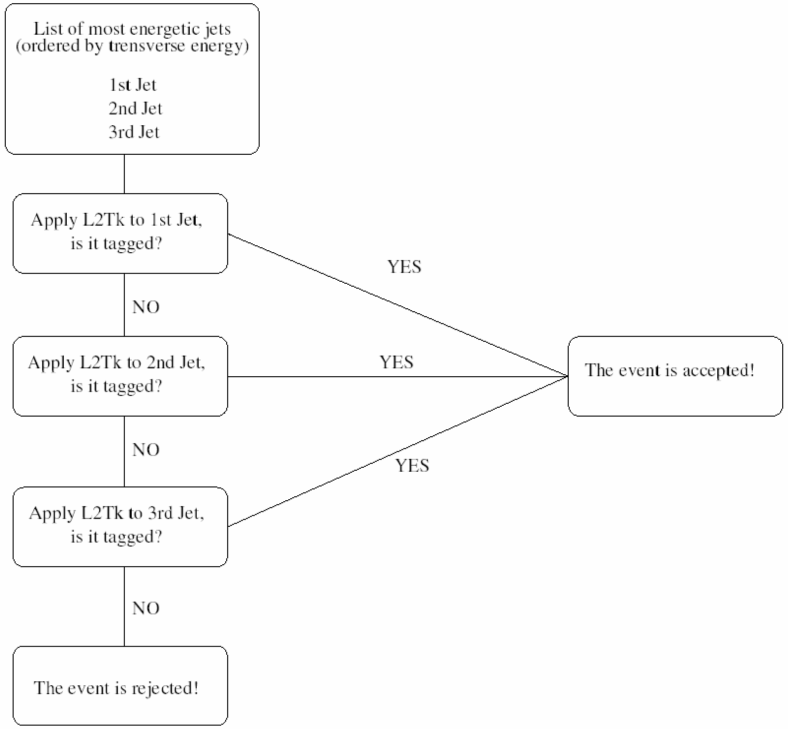
Trigger

- Level1:
  - e/muon+tau

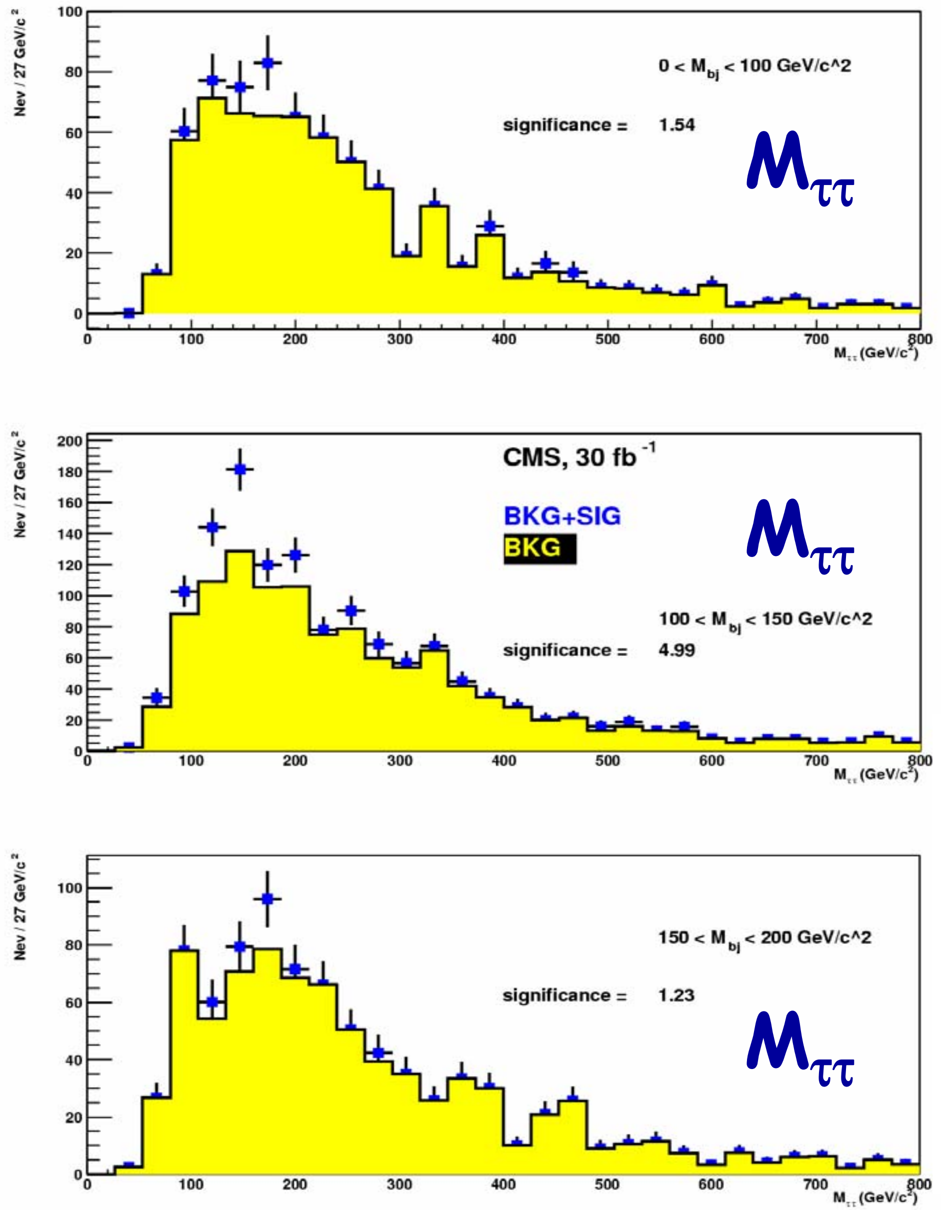
Trigger	Threshold (GeV)
Inlcusive isolated electron/photon	29
Inclusive isolated muon	14
Single tau-jet trigger	86
Electron*Jet	21*45

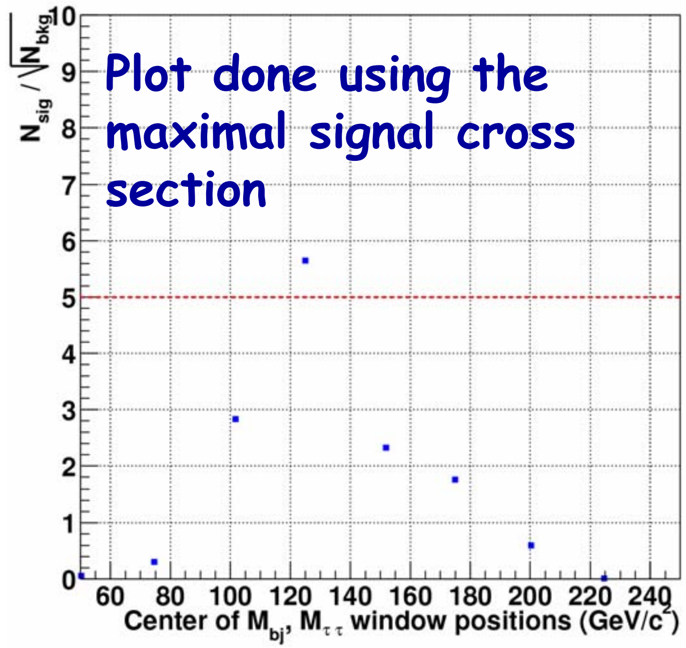
- HLT:
  - e/muon: isolation (calorimeter+Tracker) and refined p_T cut
  - Tau: Isolation (Tracker)

Samples	L1 e*τ (%)	L1 μ*τ (%)	HLT e*τ (%)	HLT μ*τ (%)	Total (%)
$\phi \rightarrow \tau\tau$bb	44.3 $\pm$ 0.7	54.8 $\pm$ 0.7	7.0 $\pm$ 0.3	5.9 $\pm$ 0.3	**6 $\pm$ 0.2**
tt_{had}	28.7 $\pm$ 0.2	32.1 $\pm$ 0.2	0.35 $\pm$ 0.02	0.49 $\pm$ 0.02	**0.57 $\pm$ 0.02**
tt_{tau}	22.6 $\pm$ 0.2	42.5 $\pm$ 0.2	1.4 $\pm$ 0.2	2.8 $\pm$ 0.2	**3.1 $\pm$ 0.2**
Zbb	5.6 $\pm$ 0.2	10.7 $\pm$ 0.2	2.0 $\pm$ 0.2	3.1 $\pm$ 0.2	**1.4 $\pm$ 0.2**
Z+jets	2.6 $\pm$ 0.2	4.6 $\pm$ 0.2	0.55 $\pm$ 0.02	0.74 $\pm$ 0.02	**0.35 $\pm$ 0.02**
W+jets	22.8 $\pm$ 0.2	23.1 $\pm$ 0.2	0.22 $\pm$ 0.02	0.31 $\pm$ 0.02	**0.039 $\pm$ 0.002**



1^{st} analysis, mass scan



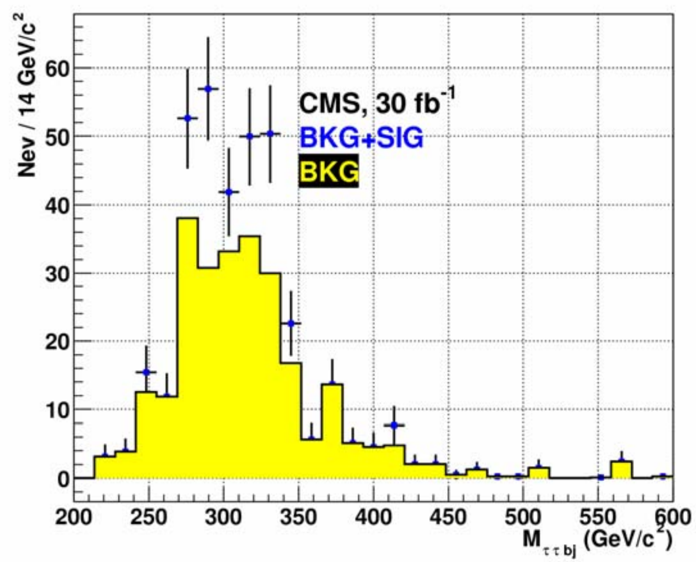


We perform a simultaneus scan in the invariant masses of b and tau jets:

100 < Mbj <150 GeV

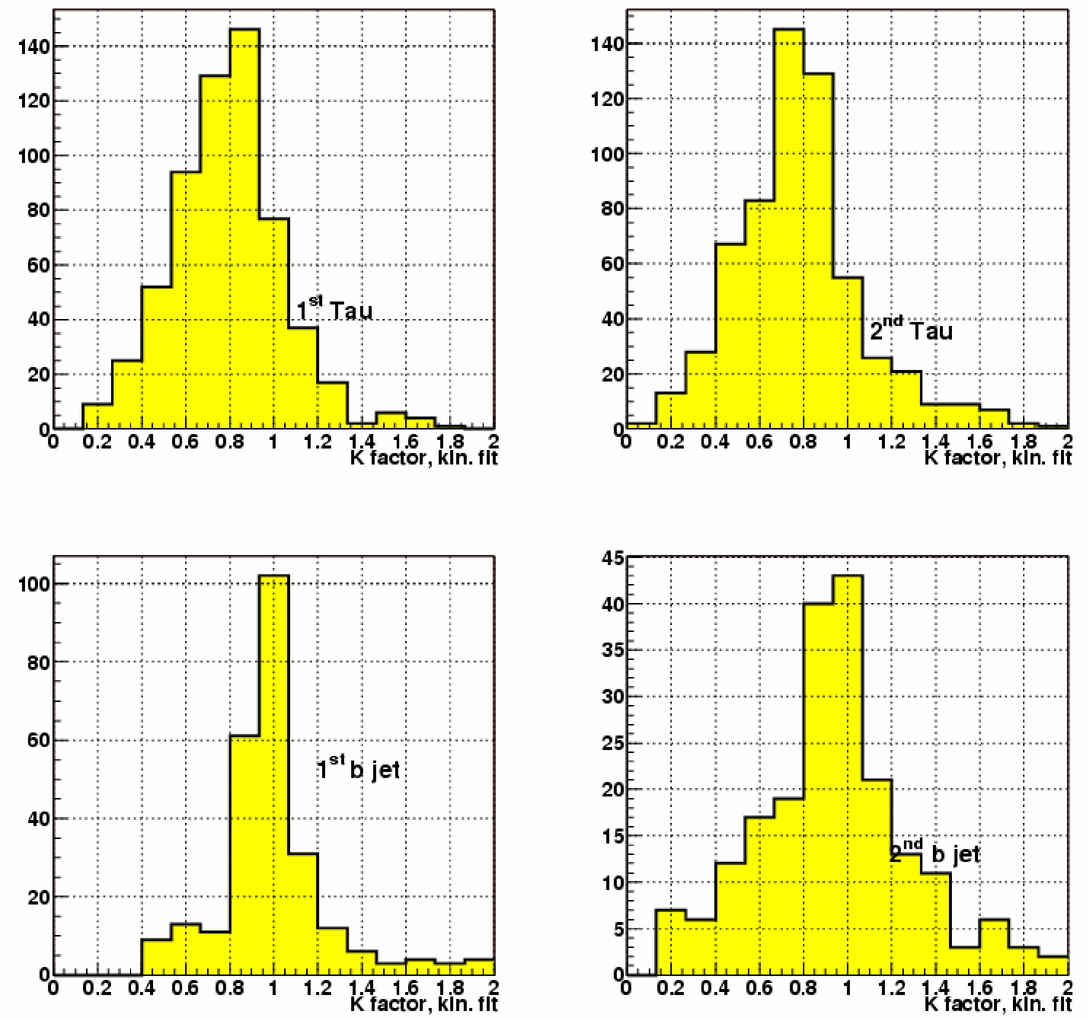
100 < Mtt < 160 GeV

We have taken into account the "else where effect". It has small effect when significance is greater than 5



As signal and background are peaked at the same point, no further information can be extracted from the above plot

Kinematic fit: K-factors



$$k_i = 1 + \frac{m^2 - \mu^2}{\mu^2} \times \frac{\omega_j}{\omega_1 + \omega_2}$$

m = true mass
μ= reconstructed mass
ω = measured energy

The k-factor distributions for τ jets suffer from the long tail on the Mττ invariant mass.

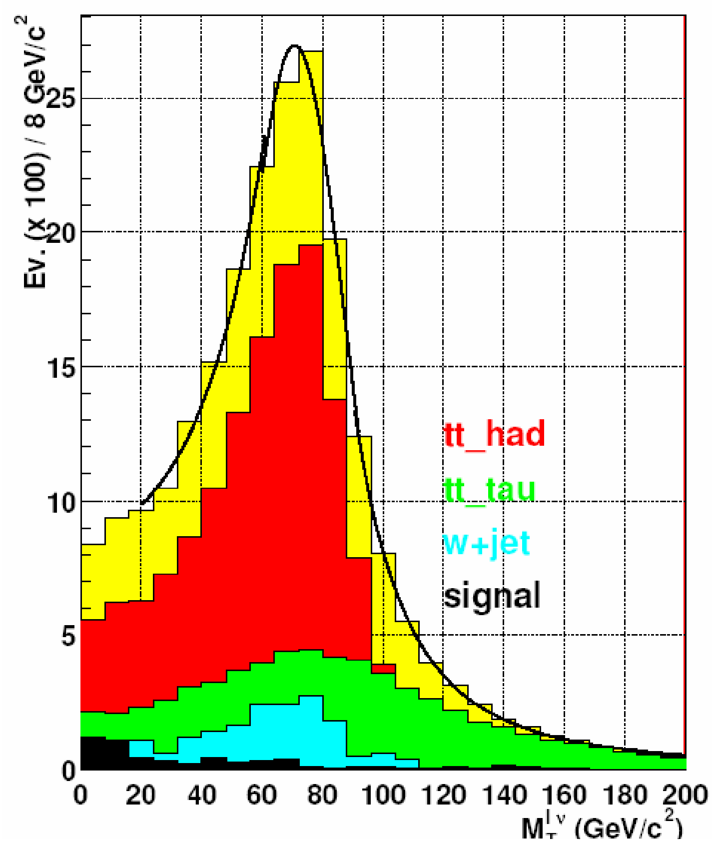
Final efficiency

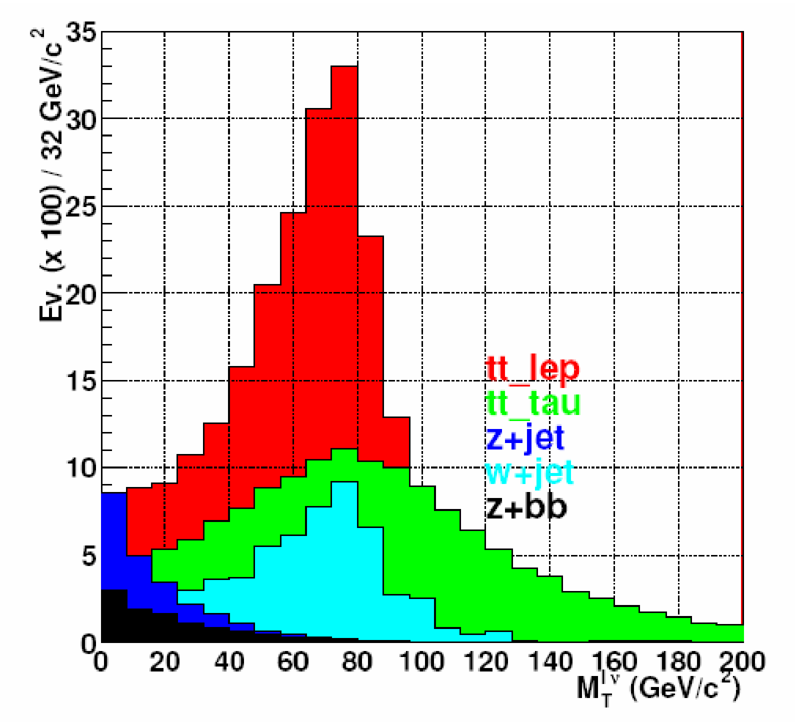
Selection	Samples efficiency (%)					
	$\phi \to$ hh	tt$_{\text{had}}$	tt$_{\text{tau}}$	Z+bb	Z+jets	W+jets
Trigger	6.0± .2	.57±.02	3.1±.2	1.4±.2	.35±.02	.039±.002
b-tagging	2.8±.2	.324±.002	1.740±.005	.44±.02	.0250±.0005	.0084±.0003
$\Delta R_{l\tau}$ >0.1	2.6±.2	.255±.002	1.091±.004	.30±.02	.0188±.0005	.0071±.0003
$p_T^b > 30$ GeV, max(p_T^b)>55 GeV	1.98±.15	.199±.002	.736±.003	.10±.01	.0030±.0002	.0025±.0002
M_T lep+ν < 35 GeV	1.1±.1	.039±.001	.118±.001	.071±.008	.0021±.0001	.0005±.0001
100 GeV < $M_{\tau\tau}$ < 160 GeV	.52±.07	.0054±.0003	.0285±.0006	.0244±.005	.00067±.00008	.00002±.000015
100 GeV < M_{bj} < 150 GeV	.33±.05	.0018±.0002	.0087±.0004	.0090±.003	.00028±.00005	0
290 GeV < $M_{\tau\tau bj}$ < 330 GeV	.27±.05	.00054±.0001	.0030±.0002	.0054±.002	.000063±.00002	0
Number of expected events	**79**	**40**	**24**	**13**	**7**	**0**

Table 1.7: Cumulative efficiency for the overall analysis (trigger and off-line).

S/sqrt(BKG)~8 with signal maximal cross section

How can we get the bkg shape?





We can have a bkg control sample (for the top and W+jets) using the selection on M_T^{ln}. (M_T^{ln} > 30 GeV)
This selection ensure a signal free sample (contamination is <1.5% with the Max cross section).

Few more comments ...

- Fitting the bkg shape (after all cuts) we have a mean value of 285 GeV and a sigma of 46 GeV.

- Fitting the bkg shape using the selection on the M_T^{ln} we get a mean of 292 GeV and a sigma of 46 GeV.

- We can estimate the Z+jets contribution from the lepton decay of the Z.