

CP3, Louvain-La-Neuve, 29-Nov.-2007

Higgs bosons production in association with a photon at LHC

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based on:

E.G, F.Maltoni, B. Mele, M.Moretti, F.Piccinini, R.Pittau, NPB 781 (2007), 64

E.G, B.Mele, J.Rathsman, arXiv:0707.0797

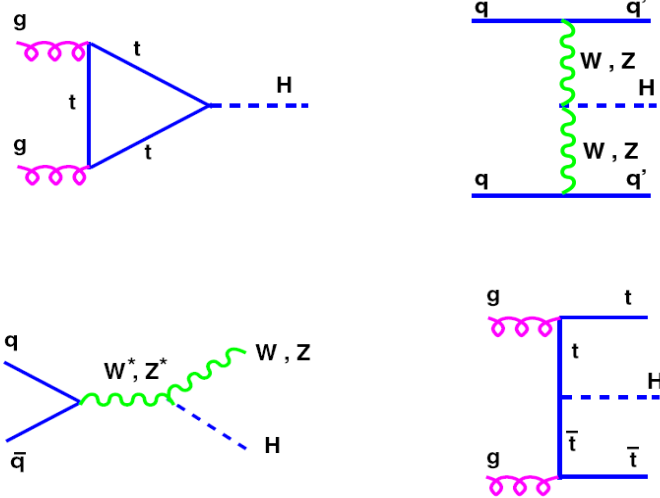
Outlook

- Higgs productions in association with a central photon
- $pp \rightarrow h \, jj + \gamma$ via Vector-Boson-Fusion in the SM
- where $h \rightarrow b\bar{b}$
- allows measurement of bbH and WWH couplings
- $pp \rightarrow H/A + \gamma$ in the MSSM at large $\tan(\beta)$
- where $H/A \rightarrow \tau\tau$
- clean probe of b-quark density in the proton
- allows also measurement of bbH coupling
- Conclusions

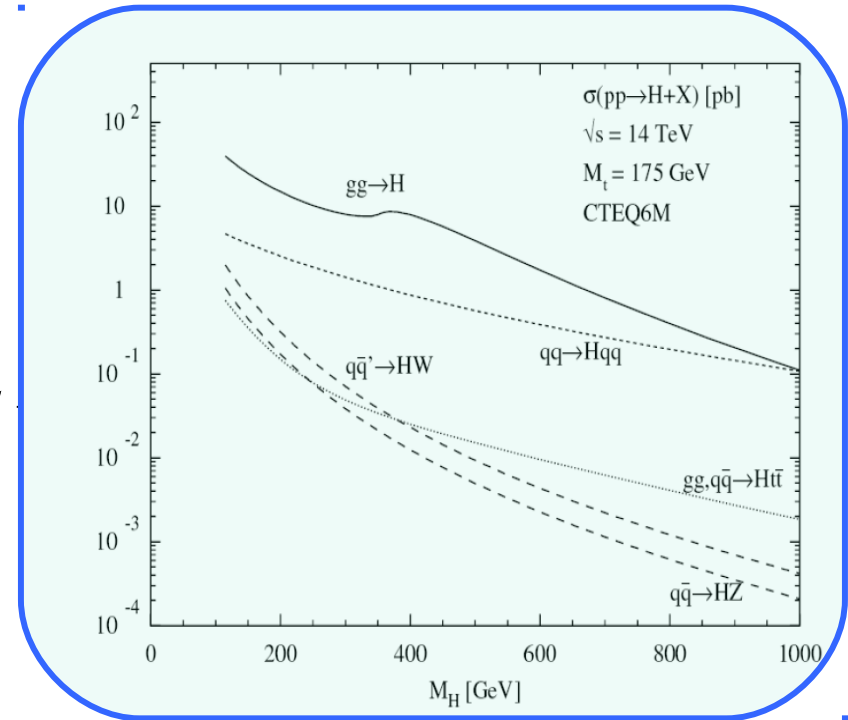
Higgs boson searches at LHC

- Higgs boson search is one of main tasks of LHC
- range of mass is not predicted, varying from LEP limit of 114.5 GeV up to theoretical upper bound $\Lambda \sim 800 \text{ GeV}$
- SM precision tests favor a light Higgs boson, with mass below 200 GeV
- discovery of a light Higgs boson is challenging at LHC due to the huge background (bckg) in $b\bar{b}$
- discovery channels of Higgs boson at LHC strongly depend on the actual Higgs mass

Higgs boson production mechanisms



inclusive x-sections in pb



gluon-gluon fusion, main mechanism in the whole range

- x-section of order of $O(10)$ pb for $m_H < 200$ GeV
- Vector boson fusion is also sizeable
- $t\bar{t}$ interesting at low Higgs masses

Mass range [115-130] GeV

$H \rightarrow \gamma \gamma$

Mass range [130-150] U [180- L] GeV
 $H \rightarrow Z Z \rightarrow 4l$ ($l=\mu, e$) golden channel

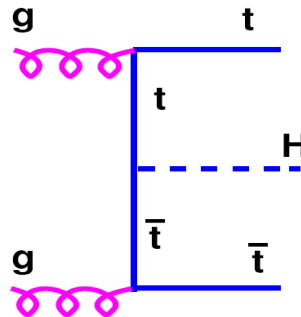
Mass range [150-170] GeV
 $H \rightarrow WW \rightarrow 2l 2\nu$ ($l=\mu, e$) silver channel



for $m(H)=165$ GeV, $\sim 1\text{fb}^{-1}$
necessary for Higgs discovery

Higgs boson decay in $b\bar{b}$

- not a discovery channel, but relevant for measuring the Hbb Yukawa coupling at LHC
- up to now, more serious studies only for $Ht\bar{t}$

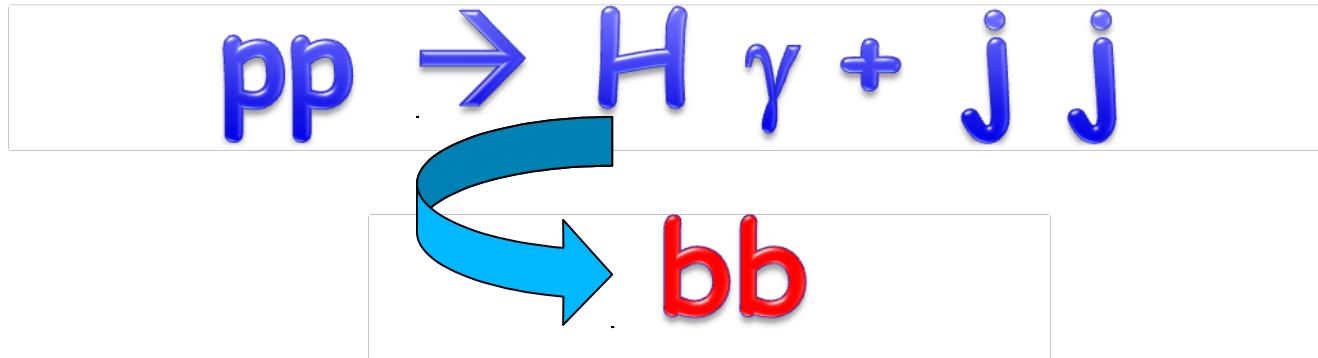


- optimized x-sections of signal are of the order of $O(10 \text{ fb})$. $Ht\bar{t}$ has been disfavored by recent CMS analyses

A new promising channel to measure bbH coupling at the LHC

E.G., F. Maltoni, B. Mele, M. Moretti, F. Piccinini, R. Pittau

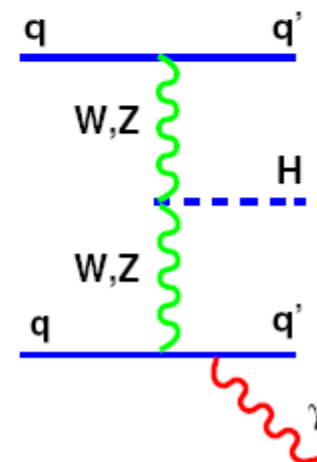
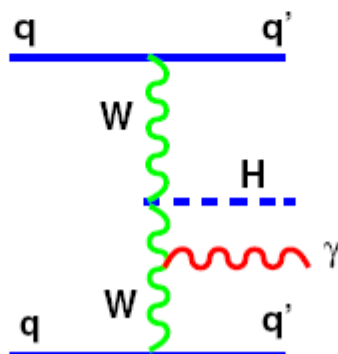
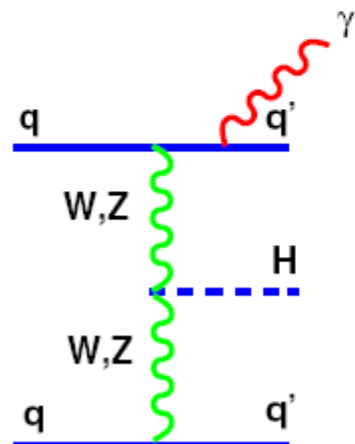
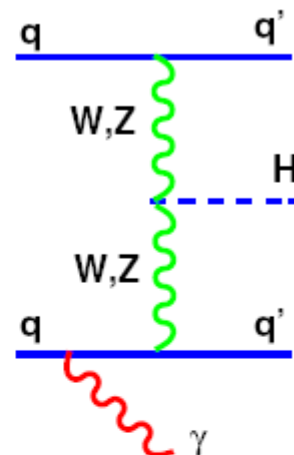
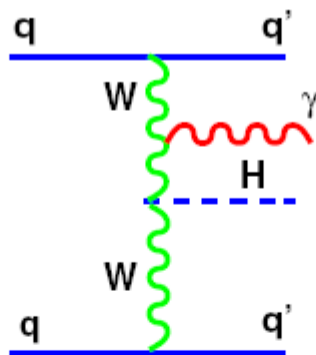
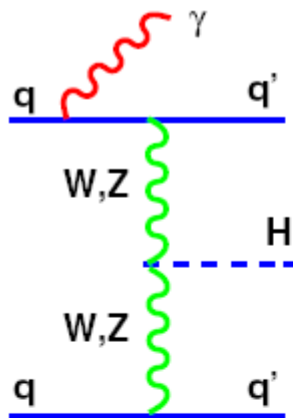
Nucl.Phys. B781 (2007), 64



same mechanism of H production
by Vector Boson Fusion + γ

signal at partonic level

$$qq \rightarrow qq H + \gamma$$



main advantages

- trigger on gamma at high p_T
- the large gluon component in QCD bckg is idle in radiating a photon
- dynamical effects suppress radiation of central photon with respect to signal
- $O(10\text{fb})$ x-section
- could provide a new independent test of Hbb and HWW couplings

signal cross section $pp \rightarrow H \gamma jj$

minimal set of kinematical cuts

$$\Delta R_{ij} > 0.4 \quad p_T^\gamma \geq 20 \text{ GeV} \quad m_{ij} > 100 \text{ GeV}$$

$m_H \text{ (GeV)}$	110	120	130	140
$\sigma(H\gamma jj) \text{ [fb]}$	67.4	64.0	60.4	56.1
$\mathcal{BR}(H \rightarrow b\bar{b})$	0.770	0.678	0.525	0.341

□ Higgs BR to $b\bar{b} \rightarrow H$ DECAY

□ full EW tree-level matrix element
to $pp \rightarrow H \gamma jj$ computed with

□ ALPGEN + MADEVENT
PDF set is CTEQ5L

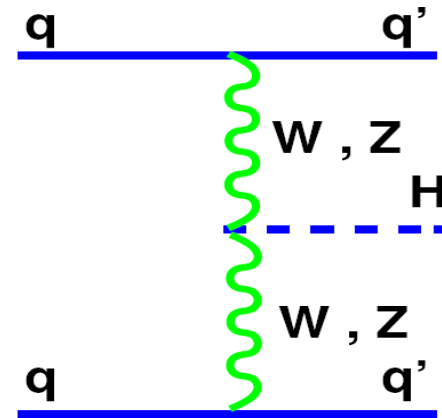
$$\Delta R_{ij} = \sqrt{(\Delta \eta_{ij})^2 + (\Delta \phi_{ij})^2}$$

Higgs production in VBF signal (no photon)

the basic partonic process is $qq \rightarrow qq H$

Mangano, Moretti, Piccinini,
Pittau, Polosa (2003)

$$p_T(j) \approx 40 \text{ GeV}$$

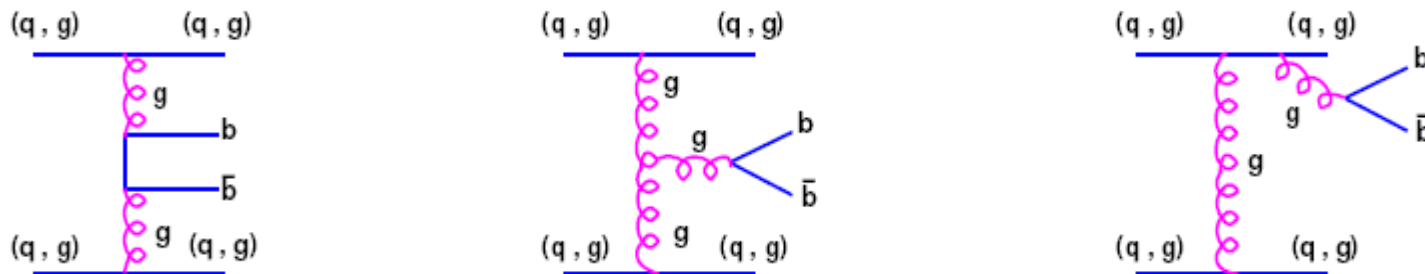


characteristic of the signal: $pp \rightarrow H(\rightarrow b\bar{b}) + 2j$

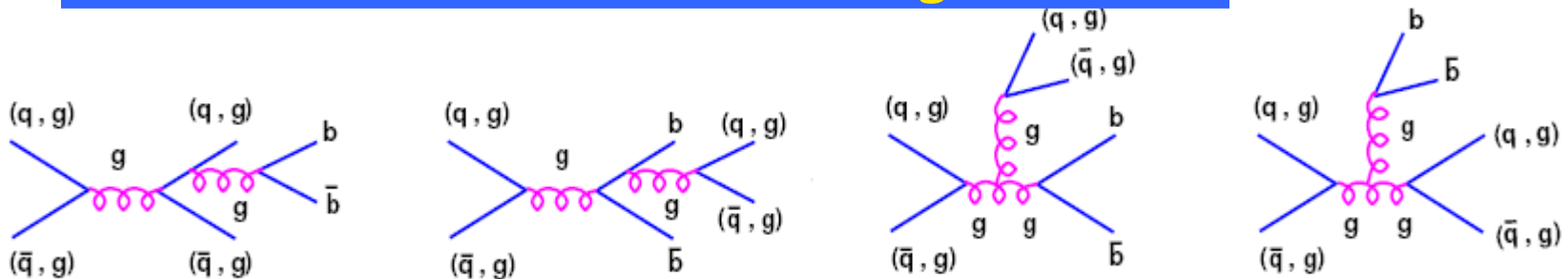
- two Jets with large invariant mass
- widely separated in rapidity (forward/backward)
- typical transverse momentum of jets $p_T(j) \sim 40 \text{ GeV}$
- Higgs decay products lying at intermediate rapidity

QCD background to Higgs boson production via VBF

- the signal has large x-section, BUT it is difficult to measure due to the huge QCD background



a set of t,u-channel diagrams



s-channel diagrams suppressed by $m(jj) > \text{TeV}$

how the emission of a photon affects the background

- one would expect by naive QED rescaling

$$(S/\sqrt{B})|_{H\gamma jj} \sim \sqrt{\alpha} (S/\sqrt{B})|_{Hjj}$$

- if so, then there would be no advantage in considering a photon emission
- QED naive rescaling holds for inclusive processes but not always when restricted regions of phase space are considered !
- requirement of centrality dramatically increases S/B ratio, while signal cross section roughly follows QED naive rescaling

■ cuts made at partonic level (we considered also partonic shower effects)

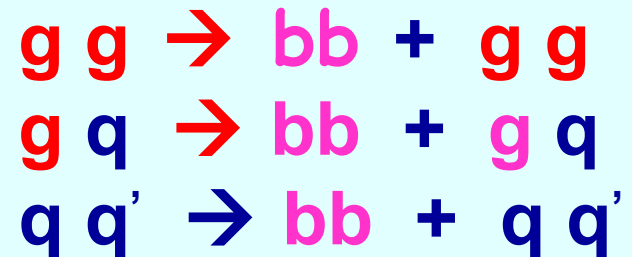
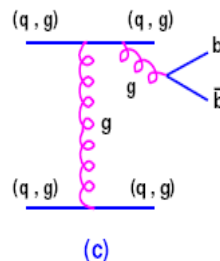
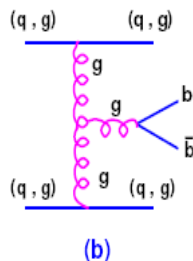
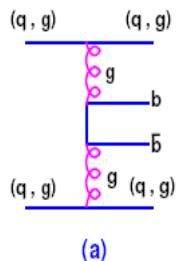
■ optimized **sub-set** of kinematical cuts enhancing S/B

● $m(jj) > 800 \text{ GeV}$

● $mH(1-10\%) < m(bb) < mH(1+10\%)$

● $p_T(\gamma) > 20 \text{ GeV}$

leading contribution to bckg of VVB fusion



sub-processes	σ_i (pb)	σ_i/σ	σ_i^γ (fb)	$\sigma_i^\gamma/\sigma^\gamma$
$gq \rightarrow b\bar{b} gq (\gamma)$	57.2(1)	55.3 %	17.3(1)	51.6 %
$gg \rightarrow b\bar{b} gg (\gamma)$	25.2(1)	24.4 %	3.93(3)	11.7 %
$qq' \rightarrow b\bar{b} qq' (\gamma)$	7.76(3)	7.5 %	4.04(2)	12.1 %
$qq \rightarrow b\bar{b} qq (\gamma)$	6.52(2)	6.3 %	4.49(3)	13.4 %
$q\bar{q}' \rightarrow b\bar{b} q\bar{q}' (\gamma)$	4.60(2)	4.4 %	2.28(2)	6.8 %
$q\bar{q} \rightarrow b\bar{b} q\bar{q} (\gamma)$	2.13(2)	2.1 %	1.21(2)	3.6 %
$gg \rightarrow b\bar{b} q\bar{q} (\gamma)$	0.0332(7)	0.03 %	0.124(3)	0.37 %
$q\bar{q} \rightarrow b\bar{b} gg (\gamma)$	0.0137(2)	0.01 %	0.094(2)	0.28 %
$q\bar{q} \rightarrow b\bar{b} q'\bar{q}' (\gamma)$	0.000080(3)	0.00007 %	0.00080(8)	0.002 %

$\text{bckg}(\gamma) / \text{bckg} \sim 1/3000$

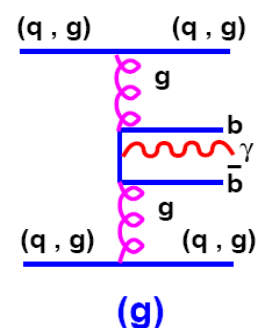
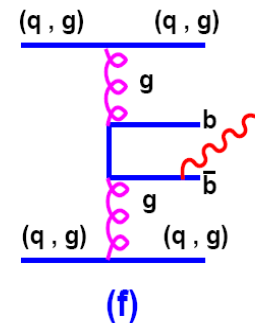
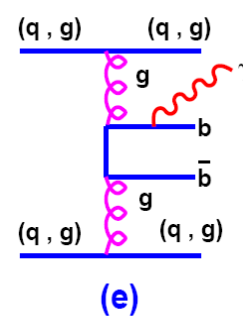
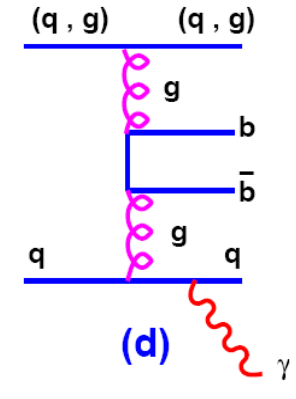
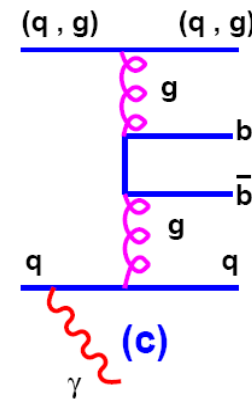
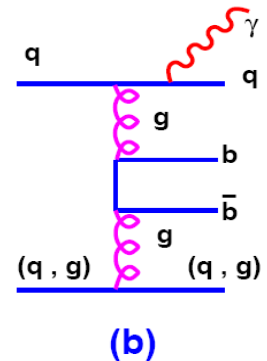
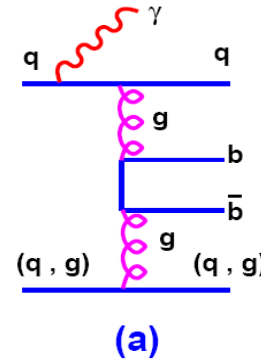
$\text{signal}(\gamma) / \text{signal} \sim 1/100$

main bckg to $pp \rightarrow H \gamma + jj$

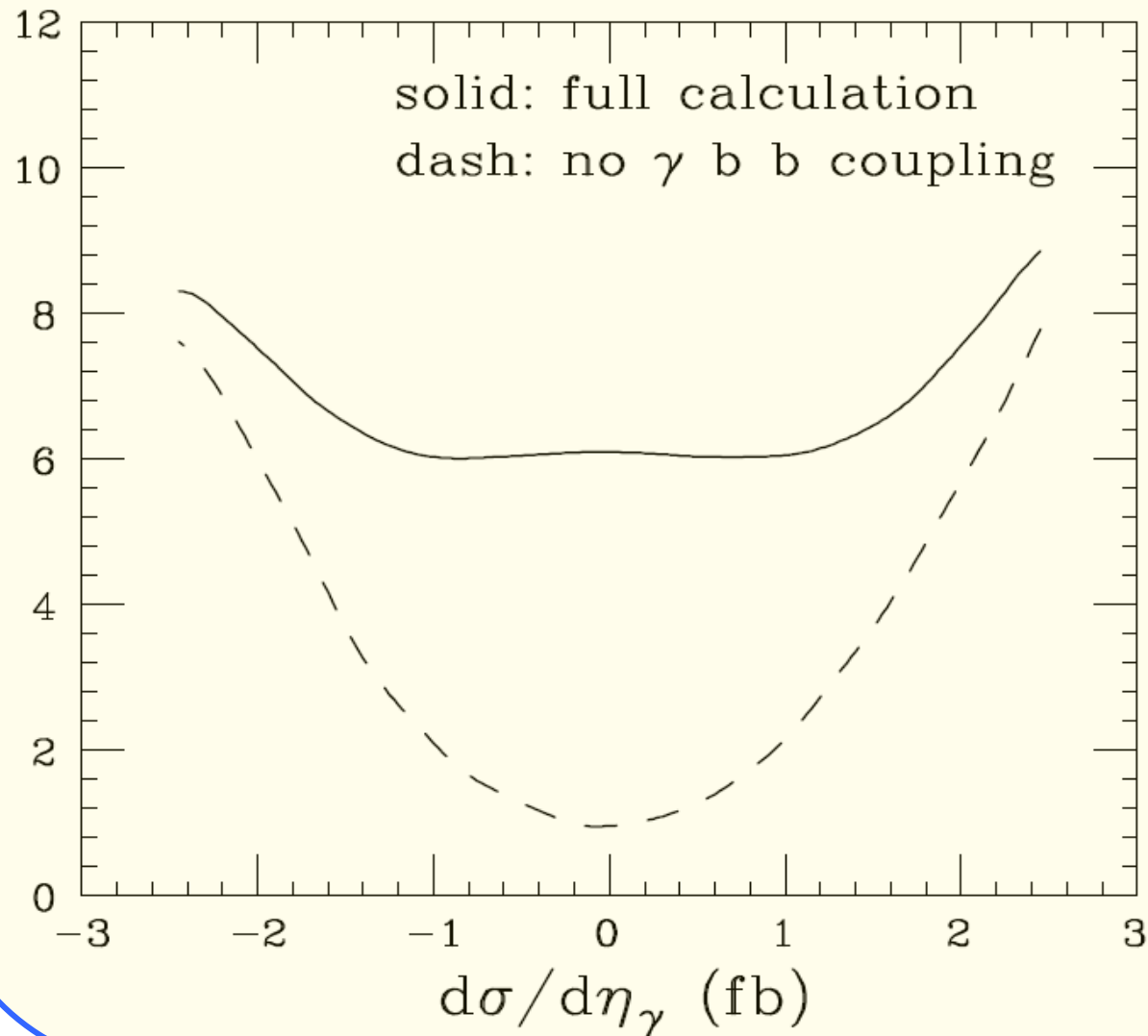
bckg is less active by
requiring a central photon

dynamical effect:
destructive interference
for gamma at large angles
a) + b) and c) + d)

dominant effect, but
suppressed by the b-quark
electric charge



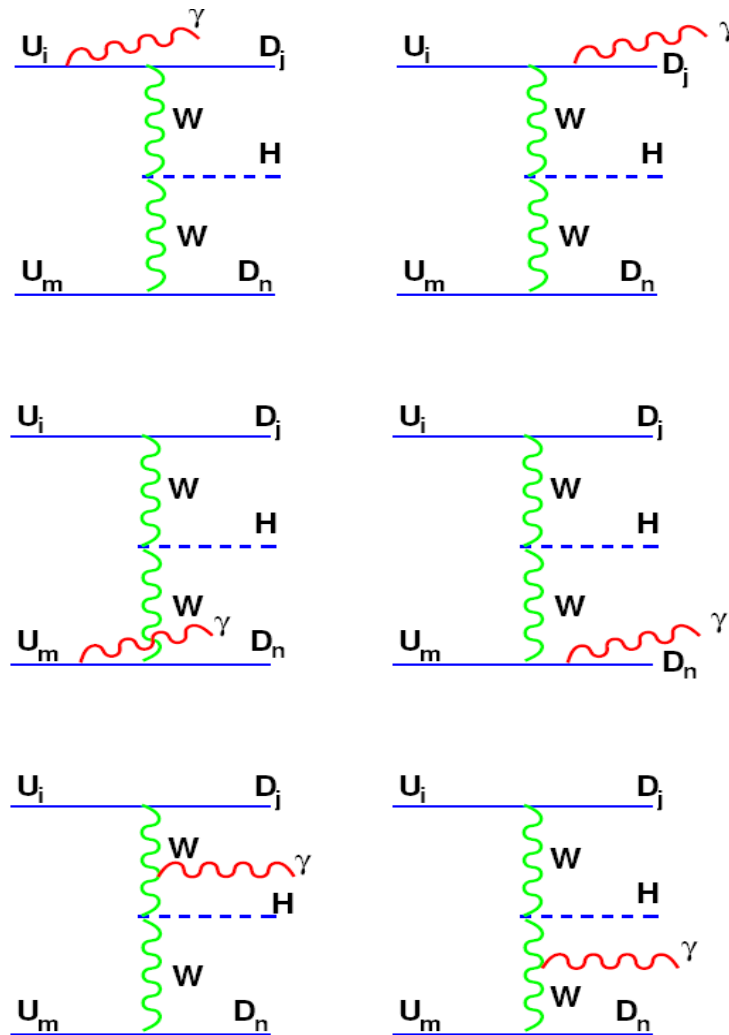
what happens if the radiation of a photon
from b-coupling is switched off



radiation of photon from b-coupling is switched off.
 Partial cross sections

sub-processes	$\sigma_i^\gamma [\text{no } b \text{ rad}] \text{ (fb)}$	$\sigma_i^\gamma [\text{no } b \text{ rad}] / \sigma^\gamma [\text{no } b \text{ rad}]$
$gq \rightarrow b\bar{b} gq\gamma$	8.19(6)	47.8 %
$gg \rightarrow b\bar{b} gg\gamma$	0	0 %
$qq' \rightarrow b\bar{b} qq'\gamma$	2.80(2)	16.4 %
$qq \rightarrow b\bar{b} qq\gamma$	3.49(3)	20.4 %
$q\bar{q}' \rightarrow b\bar{b} q\bar{q}'\gamma$	1.57(2)	9.2 %
$q\bar{q} \rightarrow b\bar{b} q\bar{q}\gamma$	0.87(1)	5.1 %
$gg \rightarrow b\bar{b} q\bar{q}\gamma$	0.10(2)	0.6%
$q\bar{q} \rightarrow b\bar{b} gg\gamma$	0.096(2)	0.6 %
$q\bar{q} \rightarrow b\bar{b} q' \bar{q}' \gamma$	0.0009(1)	0.005 %

SIGNAL
no destructive
interference at large
angle, due to the
charged gauge boson



- different angular photon distribution with respect to bckg

other advantages of requiring a central photon

- depletes **HZZ** amplitudes with respect to **WWH**

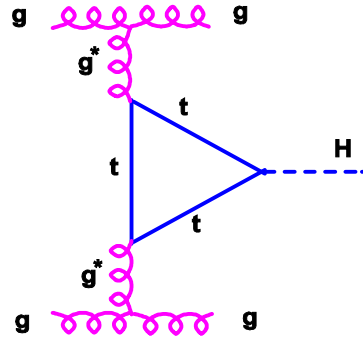

$$\frac{\sigma^{(N)}(H\gamma jj)}{\sigma^{(N)}(Hjj)} = 0.0016$$


$$\frac{\sigma^{(C)}(H\gamma jj)}{\sigma^{(C)}(Hjj)} = 0.013$$

$$p_T^\gamma \geq 20 \text{ GeV}, \quad |\eta_\gamma| \leq 2.5, \quad \text{and} \quad \Delta R_{j\gamma} \geq 0.7$$

- VBF is sensitive to both **WWH** and **ZZH**
- requiring a central photon in VBF increases sensitivity to **WWH**

■ suppresses contaminations from $g^* g^* \rightarrow H$
induced by loop of top



basic kinematical cuts (see next slide)

- ▶ with $p_t > 20 \text{ GeV} \rightarrow$ reduction factor of 8×10^{-4}
for $\sigma(H \gamma jj)$ with respect to $\sigma(H jj)$
(induced by $g^* g^* \rightarrow H$)
- ▶ cross section $\sim 0.21 \text{ fb}$ (negligible !)

basic cuts

$$p_{\text{T}}^j \geq 30 \text{ GeV}, \quad p_{\text{T}}^b \geq 30 \text{ GeV}, \quad \Delta R_{ik} \geq 0.7,$$

$$|\eta_{\gamma}| \leq 2.5, \quad |\eta_b| \leq 2.5, \quad |\eta_j| \leq 5,$$

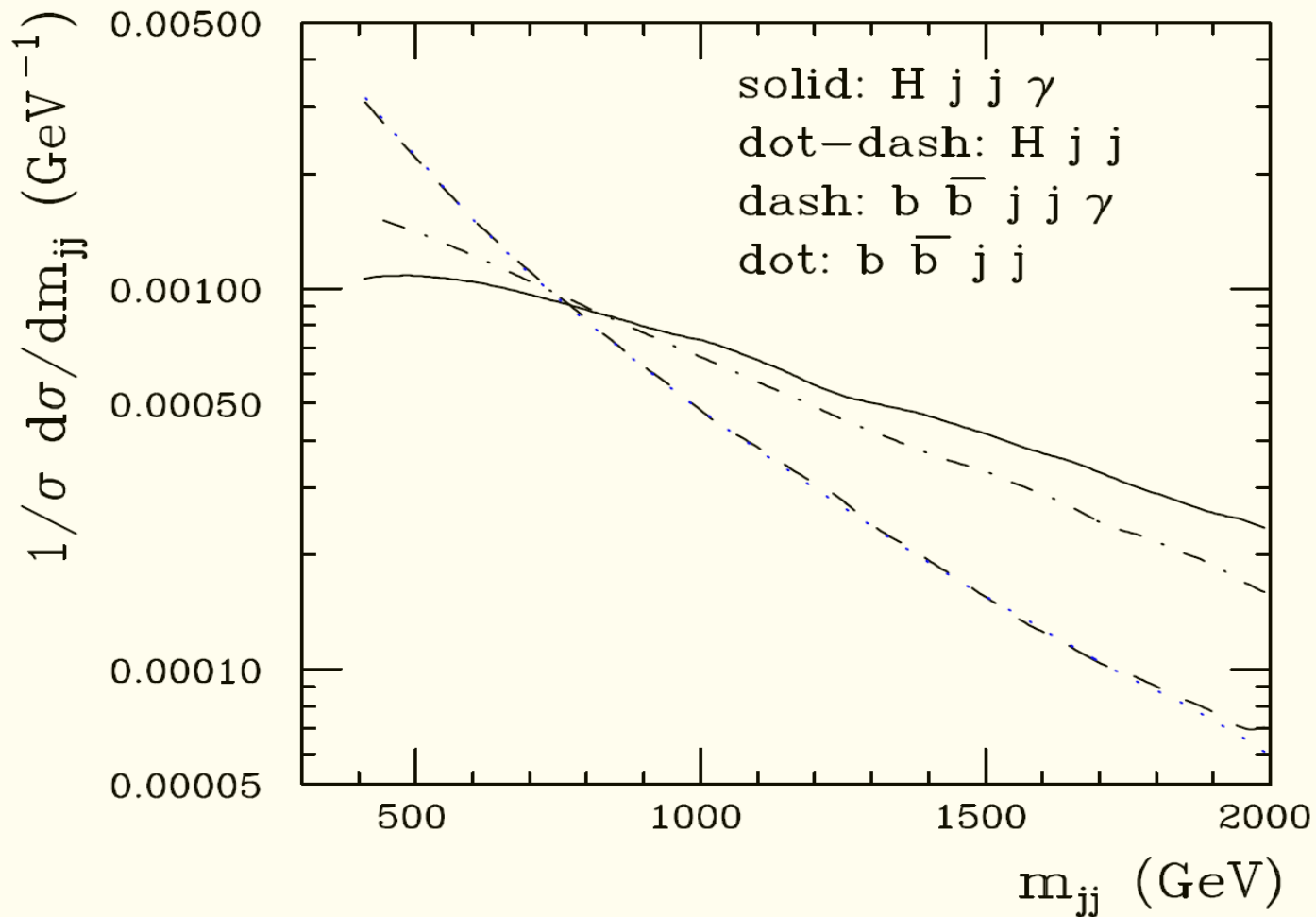
$$m_{jj} > 400 \text{ GeV}, \quad m_H(1 - 10\%) \leq m_{b\bar{b}} \leq m_H(1 + 10\%)$$

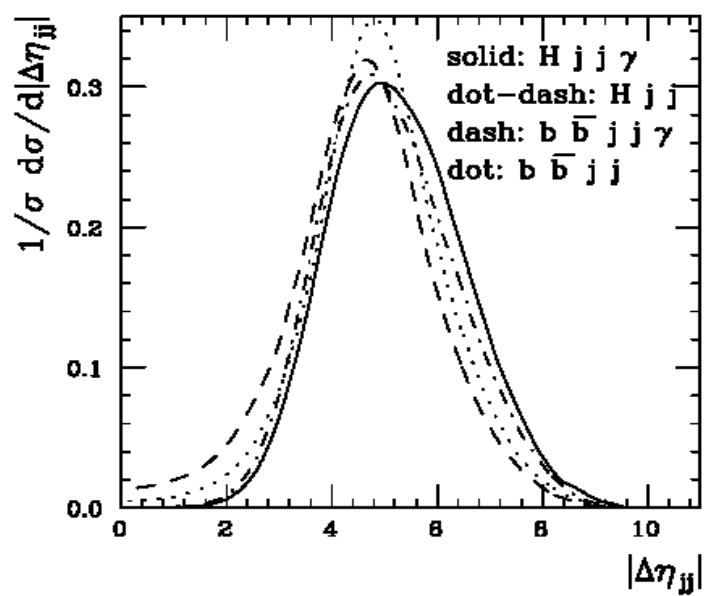
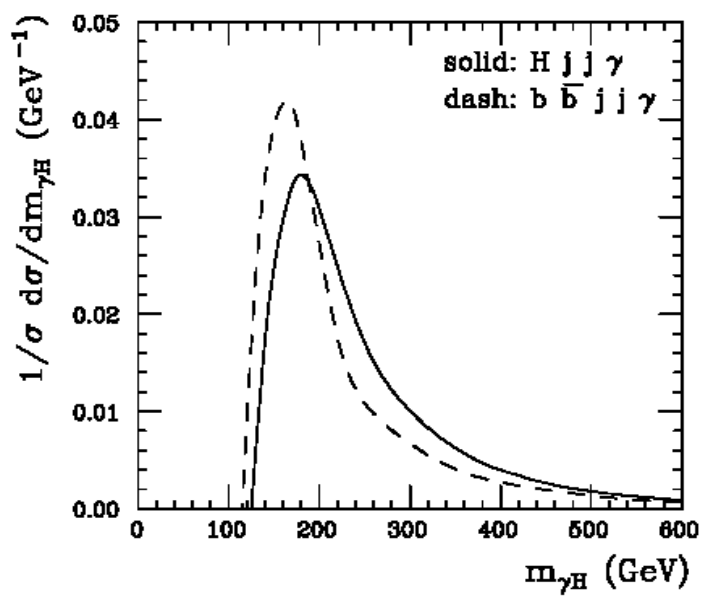
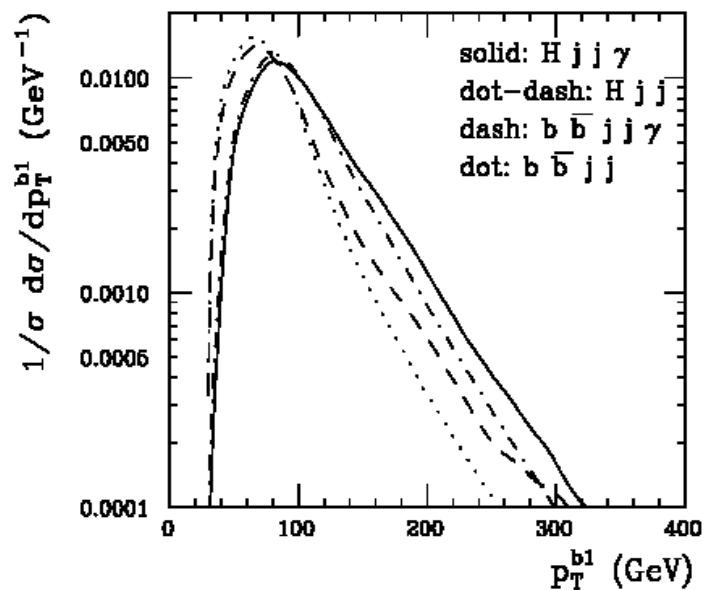
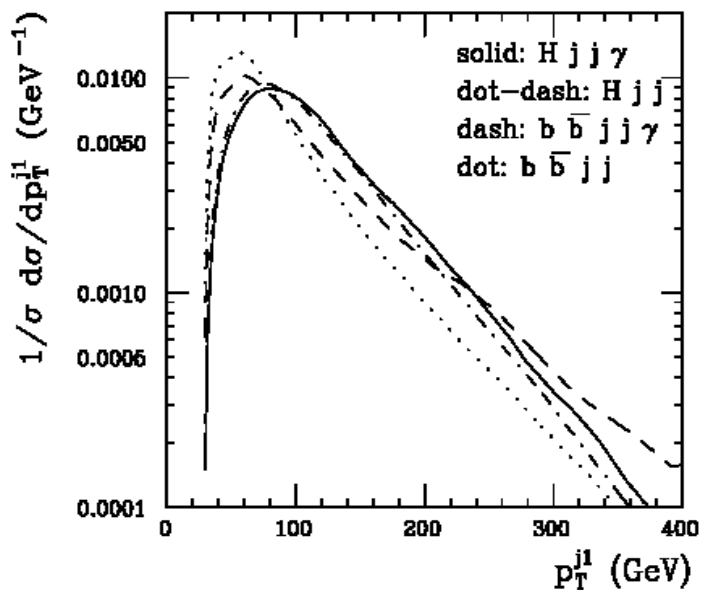
$$1) \quad p_{\text{T}}^{\gamma} \geq 20 \text{ GeV},$$

$$2) \quad p_{\text{T}}^{\gamma} \geq 30 \text{ GeV},$$

$$\frac{d\sigma}{dm_{jj}}, \quad \frac{d\sigma}{dp_{\text{T}}^{j1}}, \quad \frac{d\sigma}{dp_{\text{T}}^{b1}}, \quad \frac{d\sigma}{dm_{\gamma H}}, \quad \frac{d\sigma}{|\Delta\eta_{jj}|},$$

crucial distribution $m(j,j)$





→ optimized cuts follow:

$$m_{jj} \geq 800 \text{ GeV}, \quad p_{\text{T}}^{j1} \geq 60 \text{ GeV}, \quad p_{\text{T}}^{b1} \geq 60 \text{ GeV},$$

$$|\Delta\eta_{jj}| > 4, \quad m_{\gamma H} \geq 160 \text{ GeV}, \quad \Delta R_{\gamma b/\gamma j} \geq 1.2,$$

$$N(B) = L \sigma_B \varepsilon(b) \varepsilon(\bar{b})$$

$$N(S) = L \sigma_S \overset{\bar{b}}{\text{BR}} \varepsilon(b) \varepsilon(\bar{b}) \overset{b}{\text{BR}}$$



$$\text{signf} = \frac{N(S)}{\sqrt{N(B)}}$$

we used

$$L = 100 \text{ fb}^{-1}$$

$$\varepsilon(b) = 60\% \rightarrow \text{eff. b-tag}$$

$$\varepsilon(bb) = 70\% \rightarrow \text{due to } (+/-10\%) \text{ bb mass resolution}$$

pp $\rightarrow$ H γ + j j : optimized cross sections

	$p_T^{\gamma, cut}$	$m_H = 120$ GeV	$m_H = 130$ GeV	$m_H = 140$ GeV
$\sigma[H(\rightarrow b\bar{b})\gamma jj]$	20 GeV	3.59(7) fb	2.92(4) fb	1.98(3) fb
	30 GeV	2.62(3) fb	2.10(2) fb	1.50(3) fb
$\sigma[b\bar{b}\gamma jj]$	20 GeV	33.5(1) fb	37.8(2) fb	40.2(1) fb
	30 GeV	25.7(1) fb	27.7(1) fb	28.9(2) fb
$\sigma[H(\rightarrow b\bar{b})jj]$		320(1) fb	254.8(6) fb	167.7(3) fb
$\sigma[b\bar{b}jj]$		103.4(2) pb	102.0(2) pb	98.4(2) pb

	$p_T^{\gamma, cut}$	$m_H = 120$ GeV	$m_H = 130$ GeV	$m_H = 140$ GeV
$S/\sqrt{B} _{H\gamma jj}$	20 GeV	2.6	2.0	1.3
$S/\sqrt{B} _{H\gamma jj}$	30 GeV	2.2	1.7	1.2
$S/\sqrt{B} _{Hjj}$		3.5	2.8	1.9

$$L=100 \text{ fb}^{-1}$$

$$S/B(\gamma) \sim 1/10$$

$$S/B \sim 1/300$$

Reducible backgrounds

$pp \rightarrow \gamma + 4 \text{ jets}$ where two among the light jets are faked-tagged as b-jets

$pp \rightarrow b\bar{b} + 3 \text{ jets}$ where one of the light jets is misidentified as a photon

$pp \rightarrow 5 \text{ jets}$ where one of the light jets is misidentified as a photon and two light jets are fake-tagged as b-jets

number of events ($m_H=120 \text{ GeV}$)

	$p_T^\gamma \geq 20 \text{ GeV}$	$p_T^\gamma \geq 30 \text{ GeV}$
$pp \rightarrow \gamma H(\rightarrow b\bar{b}) + 2j$	90	66
$pp \rightarrow \gamma b\bar{b} + 2j$	1206	925
$pp \rightarrow \gamma + 4j$	23	17
$pp \rightarrow b\bar{b} + 3j$	440	324
$pp \rightarrow 5j$	14	11
$S/\sqrt{B}$	2.2	1.8

$\epsilon_{\text{fake}} \rightarrow$ for mistagging light-jet as a b-jet

$$\epsilon_{\text{fake}} = 1$$

$$\epsilon_{\gamma j} = 1/5000 \quad (\text{ATLAS})$$

Parton shower effects and central jet veto

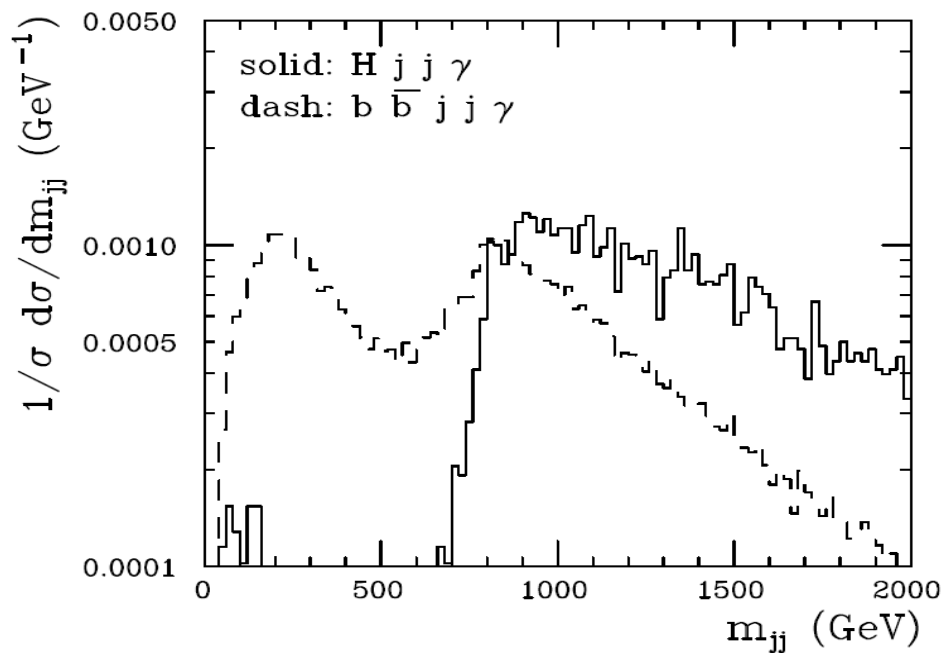
- no color is exchanged in the signal between initial and final fermionic lines
- on the contrary, bckg is characterized by the presence of t-channel virtual gluons
- more QCD radiation is expected for background
- invariant mass and rapidity separation between the tagging jets are expected to decrease in the bckg events with respect to partonic configurations.

algorithms for identification of light tagging jets

- the identification of light tagging jets not uniquely defined, due to extra QCD radiation

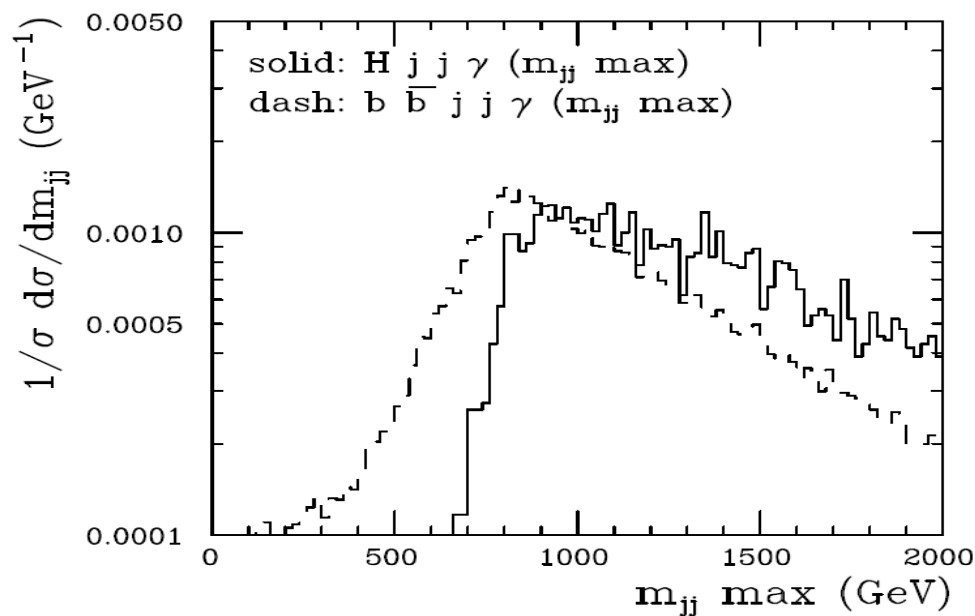
Alg.1 - highest and second highest p_T with
 $p_T(j1) > 60 \text{ GeV}$ $p_T(j2) > 30 \text{ GeV}$

Alg.2 - pair of jets with highest invariant mass, $p_T(j1) > 60 \text{ GeV}$ $p_T(j2) > 30 \text{ GeV}$

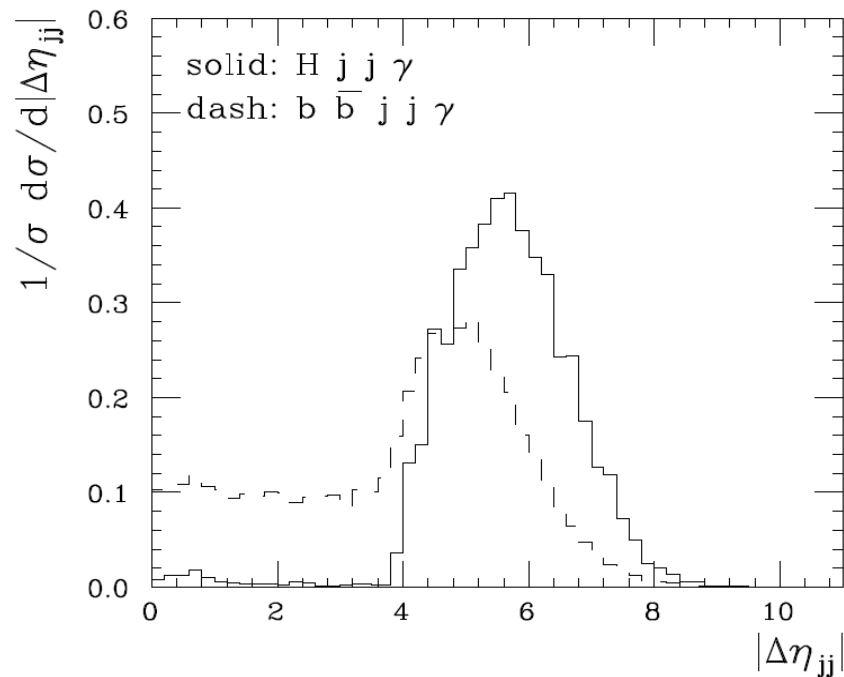


Alg1:
 $m(j1, j2)$
 j1=highest pT
 j2=second highest pT

$pT1 > 60, pT2 > 30$

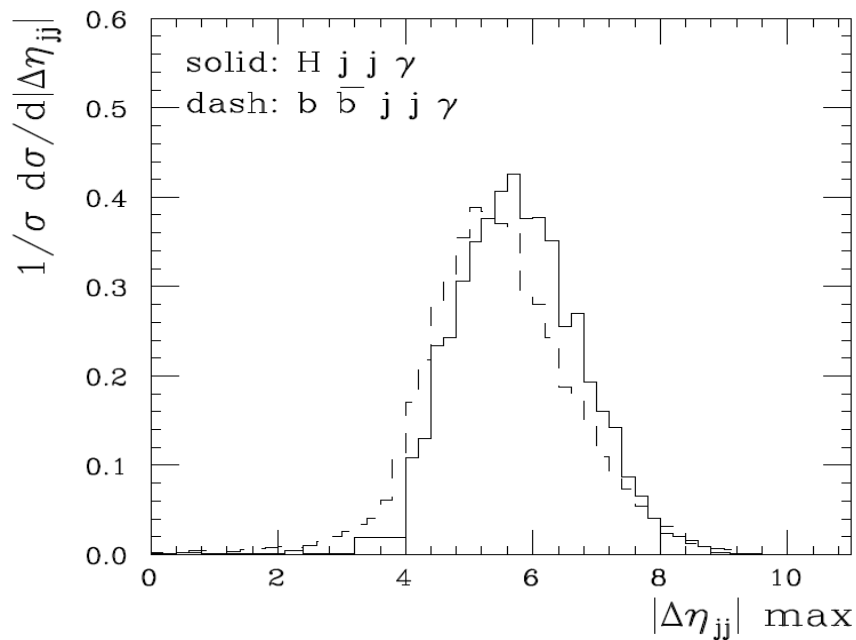


Alg2:
 $\max[m(j1, j2)]$ among
 all jets

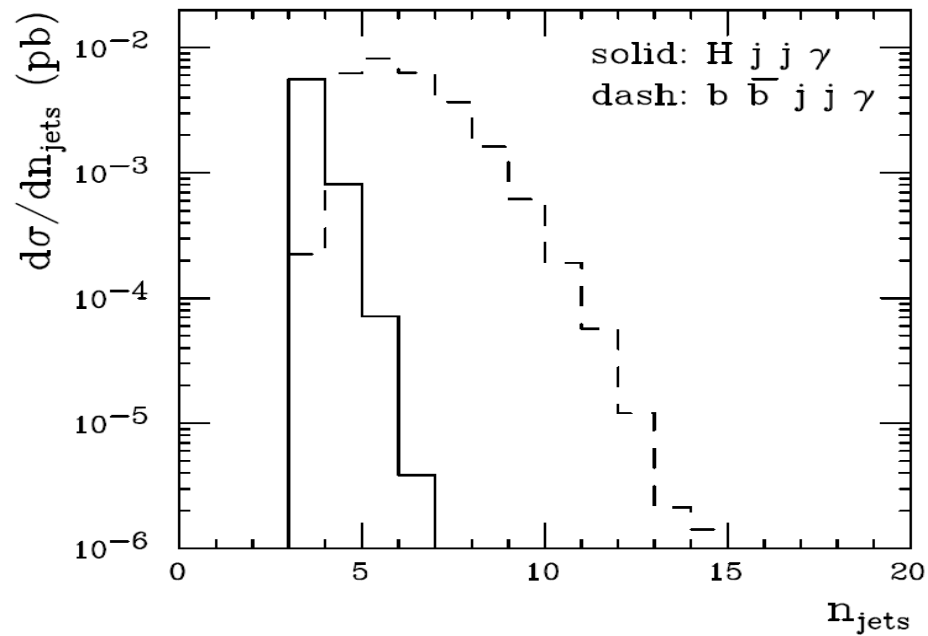


Alg1:
 $\Delta\eta(j1,j2)$
 j1=highest pT
 j2=second highest pT

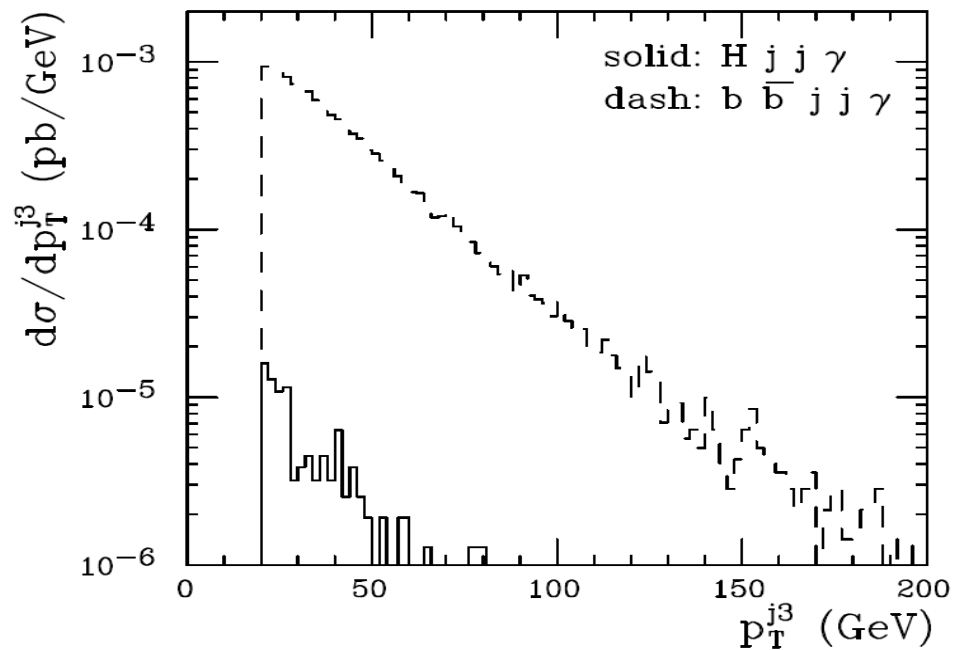
$p_{T1} > 60, \quad p_{T2} > 30$



Alg2:
 $\max[\Delta\eta(j1,j2)]$ among
 all jets



jet multiplicity
distribution



pT distribution
of the third
highest pT jet

- A veto on additional jet activity in the central rapidity region could be very effective in suppressing bckg versus signal
- at least a factor 4 improvement is expected for S/B
- a more refined analysis will be necessary for quantitative statements

what if $\gamma \rightarrow W$: $HW jj$ Rainwater (2001)

 $\nu \quad l=e, \mu$

- it could help in constraining bbH coupling
- however, accurate studies of background and parton shower effects are missing
- relevant cross section is smaller than $H \gamma jj$

with same optimized event selection criteria
(with constraints on photon applied to charged lepton)
for $m_H=120$ GeV and $p_T(\gamma) > 20$ GeV we get

$$\sigma(H \gamma jj) \sim 4.4 \times \sigma(HWjj)$$

 $\nu \quad l=e, \mu$

Higgs sector in the MSSM

Two complex Higgs boson doublets H_U and H_D

■ Spectrum:

two CP-even (h, H) and one CP-odd (A) neutral + a pair of charged Higgs bosons

■ At tree-level, Higgs sector fully specified by two parameters:

$$\tan\beta = \langle H_U \rangle / \langle H_D \rangle$$

m_A = mass of pseudoscalar A .

(radiative corrections depend on other SUSY parameters)

■ Light-Higgs boson mass scenario, naturally predicted in the MSSM

■ Large $\tan\beta$ scenarios are favored:

- ▶ viable dark matter candidate
- ▶ large radiative corrections to lightest Higgs boson mass
- ▶ large SUSY contributions to $(g-2)_\mu$:
needed to accommodate the present 3.4σ deviation
- ▶ H/A Yukawa to b-quarks enhanced by $\tan\beta$

■ CDF and D0 collaborations have recently analyzed $pp \rightarrow (H, A, h) \rightarrow \tau \tau$

- ➡ no evidence of signal observed;
- ➡ only an excess of events in the region $m_H = 140-160$ and $\tan\beta > 45$ observed;
- ➡ limits on m_A and $\tan\beta$ out to be weaker than expected

b-quark fusion process $bb \rightarrow H/A$

- main mechanism for H/A production at large $\tan\beta$
- $bb \rightarrow H/A$ rates comparable with $gg \rightarrow H/A$ rates:
in SM is two order of magnitude smaller than gluon fusion
- particularly sensitive to the composition of proton in terms of b-quarks
- b-quark parton density derived perturbatively from gluon parton density, no direct measurement of it
- no hope in the SM to separate $bb \rightarrow h$ from $gg \rightarrow h$
- in MSSM this is possible for large $\tan\beta$, although a contamination of $gg \rightarrow h$ is unavoidable

$$pp \rightarrow H/A + \gamma$$

- if a high- p_T photon is required then no contamination from gg fusion
- a photon in the final states selects the initial partonic process
- large $\tan\beta$ compensates for EM suppression

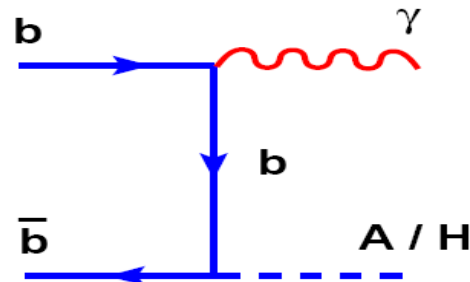
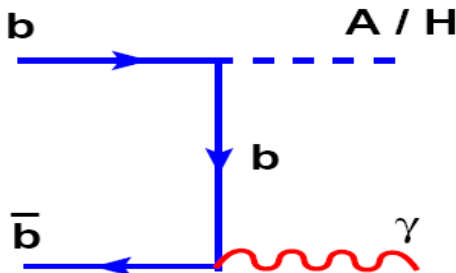


vanishes

forbidden by

$gg \rightarrow H/A + \gamma$
C-parity

cor



the most promising signature is

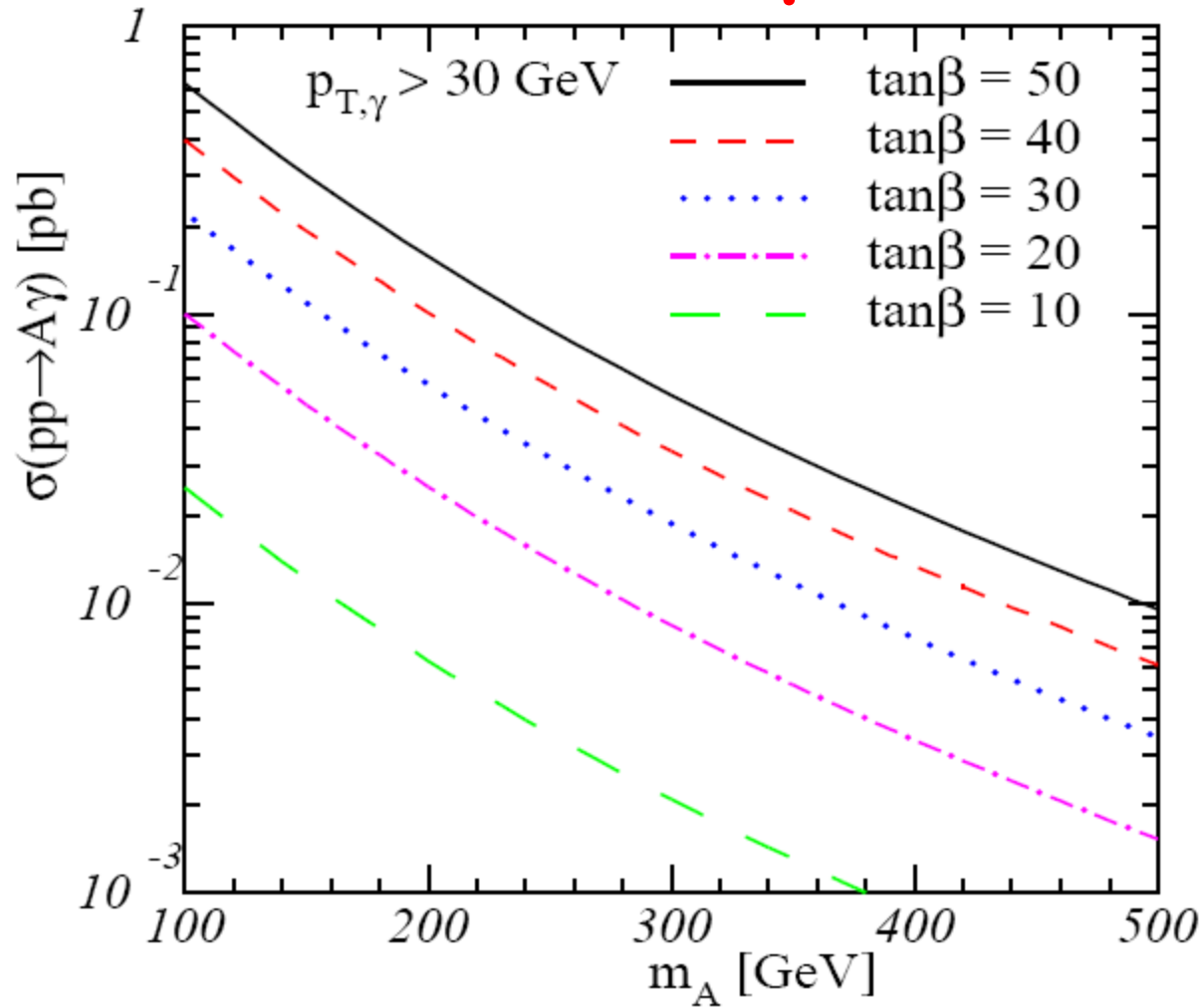
$$H/A \rightarrow \tau \tau$$

- BR~10% for large $\tan\beta$ almost insensitive to m_H
- BCKG for $\tau\tau+\gamma$ final states has an EW origin and is well under control
- tagging tau leptons allows drastic reduction of the BCKG
- tau-tau signature well studied in SM and MSSM. Very promising for Higgs discovery

Note: the complete tau-tau invariant mass can be fully reconstructed, provided the two taus are not neither back-to-back nor collinear in lab frame (due to undetected neutrinos)

Condition satisfied by requiring a large p_T of the photon

signal cross section in pb versus mA



- ◆ Structure functions used : CTEQ6L1 with factorization scale = $m_A/2$
- ◆ Tevatron x-section = 2.5 fb, for $p_T > 20$ GeV, $m_A = 150$, $\tan\beta = 50$

analysis of tau-tau signature

$$pp \rightarrow H/A \rightarrow \tau \tau \gamma$$

- **main irreducible BCKG** is due to tau-pair production via gamma or Z off-shell

also: $pp \rightarrow WW \gamma$ with $W \rightarrow \tau \nu$

negligible: $\sigma \sim 14 \text{ fb}$ for $p_T > 30 \text{ GeV}$

- **only the resonant $H/A \rightarrow \tau \tau$ production associated to a high p_T photon can disentangle the initial bb partonic state**

- **the spurious signal coming from channel**

$bb \rightarrow H/A \rightarrow \tau^* \tau \rightarrow \tau \tau \gamma$, photon radiated by a tau, must be also kept under

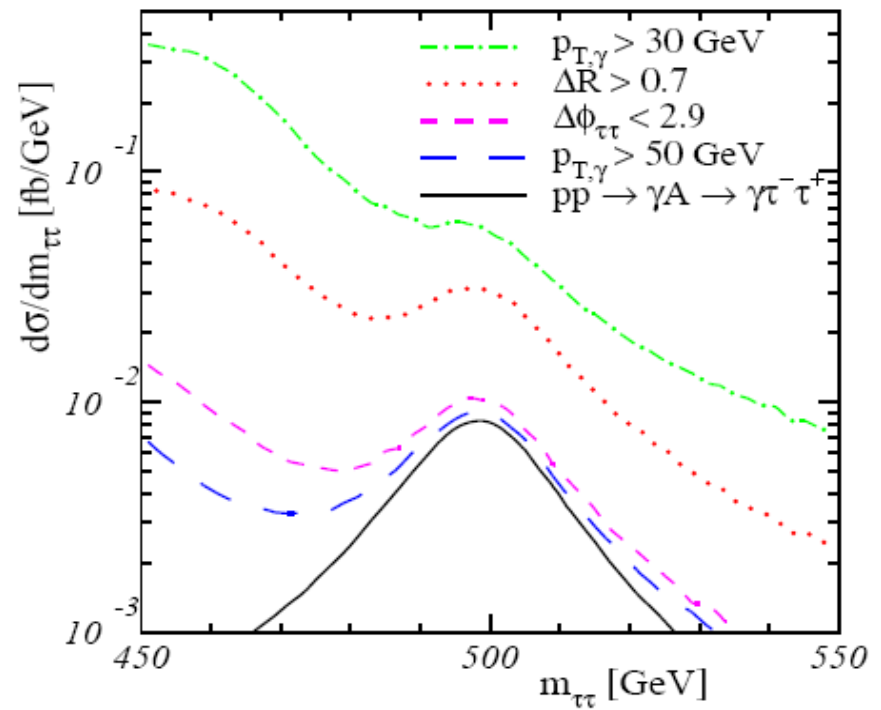
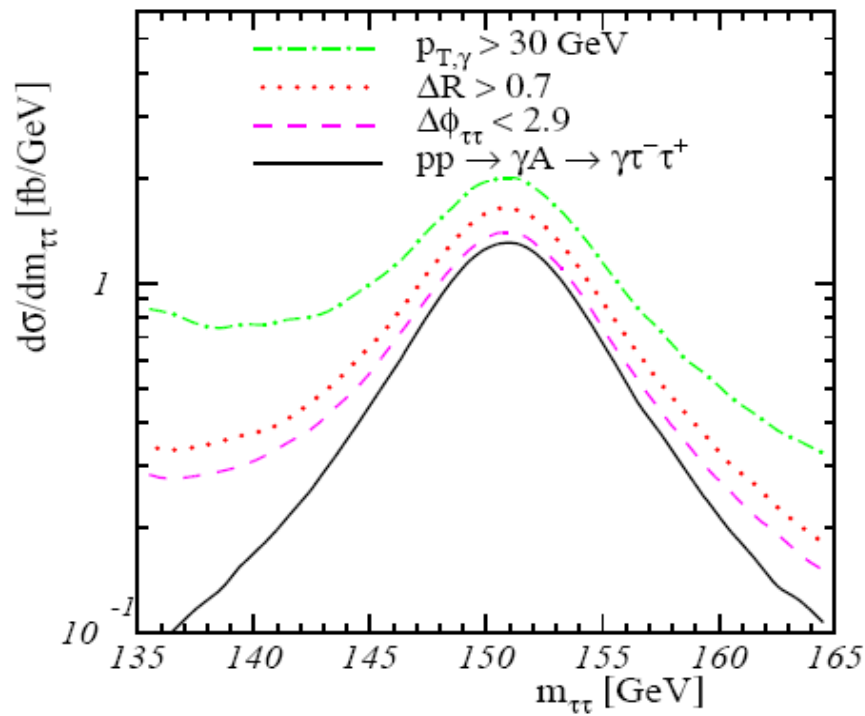
- Large SUSY radiative corrections on b-Yukawa factorizes, residual dependence is small
- in MSSM, $m_A \sim m_H$ (at large $\tan\beta$) gives a factor 2 of enhancement in the σ -section
- assumed tau-pair efficiency = 0.2 comes from
 - $\tau \rightarrow \ell \nu_\tau \nu_\ell$ (35%) ID efficiency = 90%
 - $\tau \rightarrow h \nu$ (50%) ID efficiency = 25%double hadronic decays contribute with 0.016 to 0.2

optimized set of cuts to avoid non-resonant production

- $p_T^\gamma > 30, 30, 40, 50$ GeV, for $m_A = 150, 200, 300, 500$ GeV,
- $0.9 m_A < m_{\tau\tau} < 1.1 m_A$ on the $\tau\tau$ invariant mass ;
- $p_T^{\tau^\pm} > 20\text{GeV}$, $|\eta_\gamma| < 2.5$, $|\eta_{\tau^\pm}| < 2.5$
- $\Delta R_{\gamma\tau^\pm} > 0.7$, $\Delta R_{\tau\tau} > 0.7$, $\Delta\phi_{\tau\tau} < 2.9$.

suppress the kin. configurations where photon is collinear to one of taus: allows tau-tau mass reconstruction

$\Delta\phi_{\tau\tau} < 2.9$ quite effective at larger masses



■ after applying all cuts one gets substantial purity of the signal $bb \rightarrow H/A \gamma$

■ γ -radiation off b's : 83% (66%) of observed rate for $m_A = 150$ (500) GeV at

$\tan\beta = 50$

Signal x-section and corresponding significance S

$\tan \beta$	20		30		40		50	
m_A	σ_S (fb)	S	σ_S (fb)	S	σ_S (fb)	S	σ_S (fb)	S
150	5.58	7.3	12.5	13	22.1	19	34.5	24
200	3.00	5.3	6.81	9.5	12.3	14	19.9	18
300	0.727	2.4	1.67	4.5	3.08	6.7	5.03	9.1
500	0.0981	0.72	0.238	1.5	0.456	2.4	0.768	3.4

$$S = n(S) / \sqrt{n(S) + n(B)}$$

➡ sensitivity to PDF
~ O(20%)

➡ $L=100/\text{fb}$, $\varepsilon(\tau\tau)=0.2$

➡ only irreducible bckg

Conclusions

- the request of an associated high- p_T photon in the Higgs boson production offers great advantages (trigger efficiency improved)

- **SM**

$$pp \rightarrow H \gamma + jj$$

with a light Higgs boson decaying in $H \rightarrow bb$, can help in constraining both Hbb and HWW couplings ($L=100$ /fb)

- **MSSM**

$$pp \rightarrow H/A + \gamma$$

with $H/A \rightarrow \tau \tau$, can provide a clean probe of the b -quark density in the proton at large $\tan\beta$ ($L=100$ /fb up to $m_A=500$)