

Higgs boson production in association with a photon

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based on:

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

Nucl. Phys. B 781 (2007), 64; hep-ph/0702119

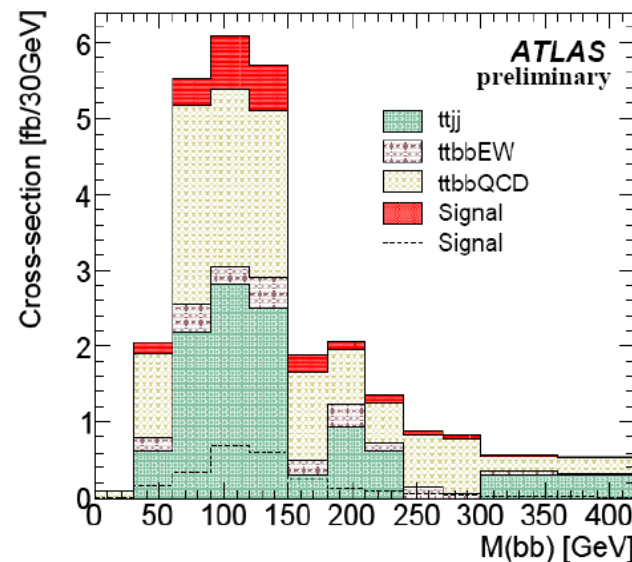
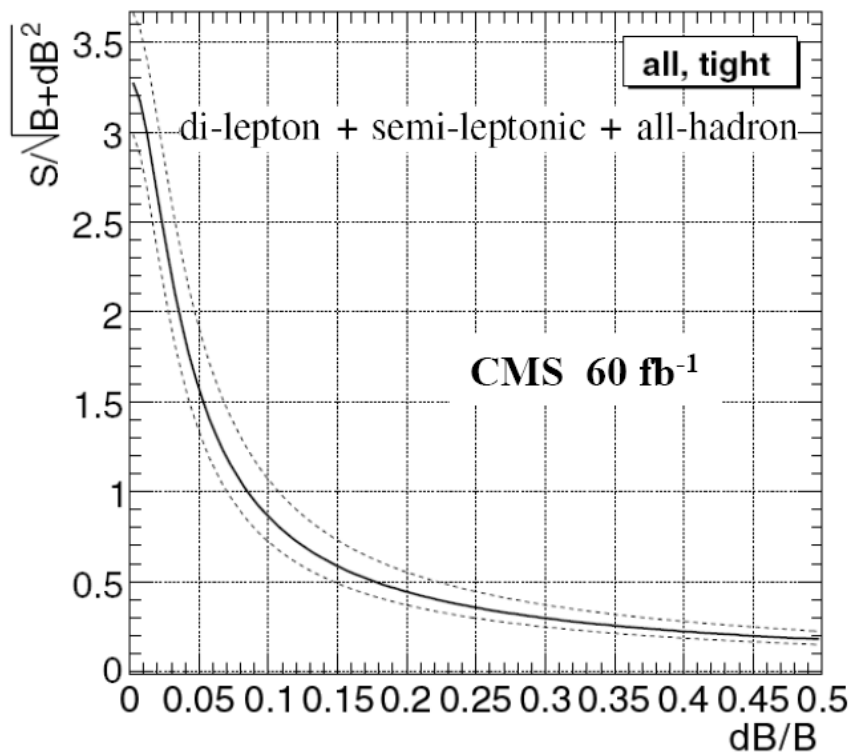
Introduction

- Information on Higgs couplings to fermions and gauge bosons is crucial for unravelling the origin of the Higgs mechanism (SM, MSSM, technicolor, extra-dimensions)
- at low m_H , important to determine both Hbb and $H\tau\tau$ couplings, e.g. $Hbb/H\tau\tau$ is sensitive to the nature of the SM extension
- discovery channels for $m_H=115-130$ GeV:
 $H \rightarrow \gamma\gamma$ (and $H \rightarrow \tau\tau$)
- $H\gamma\gamma$ coupling: 1-loop vertex (as ggH) $\Rightarrow$ sensitive to the ultraviolet sector of the theory $\Rightarrow$ problems ?
- however, discovery channels don't constrain Hbb coupling
- difficult to measure Hbb due to the large QCD bckg

ttH, H → bb

new ATLAS I.Ludwig ← **semileptonic top decay**
CMS TDR S.Cucciarelli, A.Schmidt, C.Weiser,
C.Riccardi, P.Torre, D.Benedetti, A.Santocchia, C.Hill, ← **semileptonic ,**
J.Incandela and S.Koay CMS note 2006/119 **dileptonic and**
J.Phys.G:Nucl.Part.Phys. 34 (2007) N221-N250 **all hadronic**
channels

Very difficult
large background , similar to signal

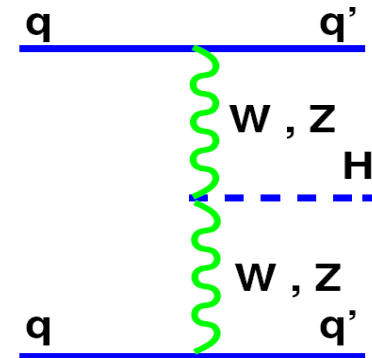


$H \rightarrow bb$ in VBF

the basic partonic process is $qq \rightarrow qq H(\rightarrow bb)$

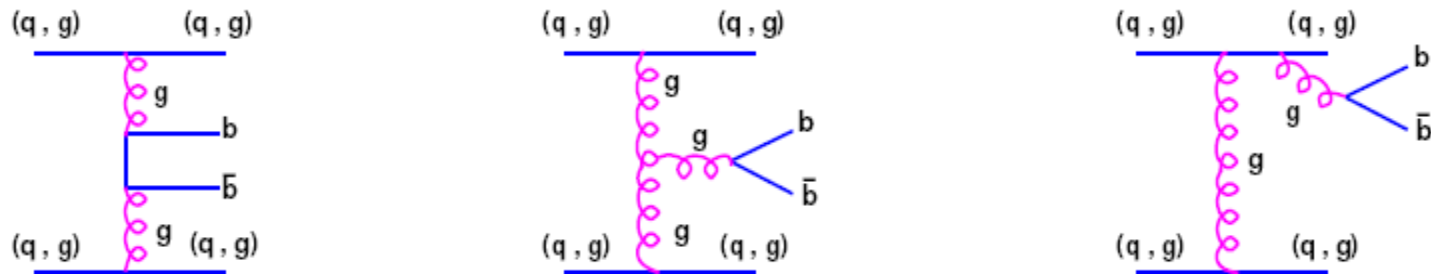
Mangano, Moretti, Piccinini,
Pittau, Polosa (2003)

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

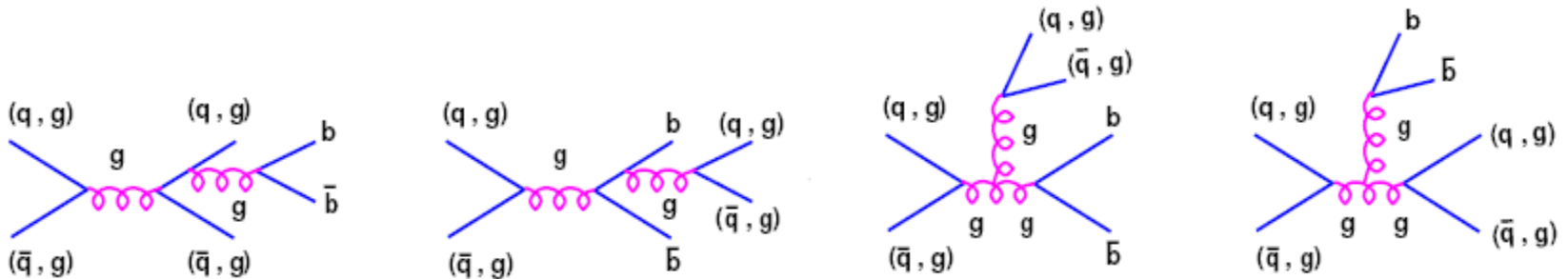


- signature: $pp \rightarrow H(\rightarrow bb) + jj$
- large x-section, but...
- **VERY DIFFICULT** to control the huge QCD bckg
- potential problems with trigger efficiency

QCD bckg at partonic level for $pp \rightarrow bb \, jj$



a set of t,u-channel diagrams



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

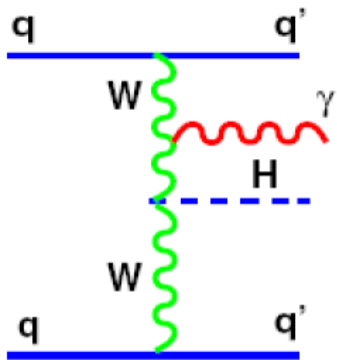
- large contribution of gluons in external legs

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

VBF



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

↓

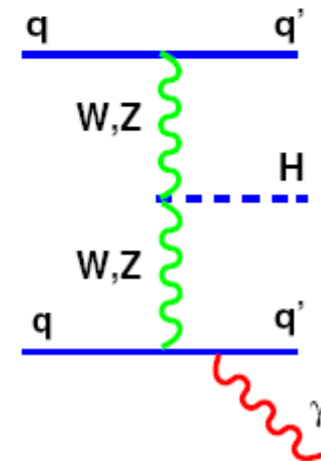
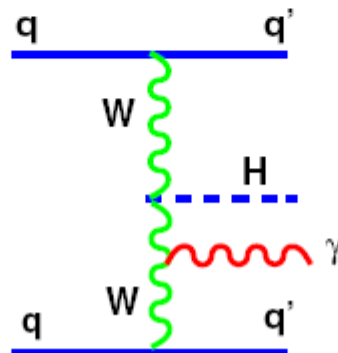
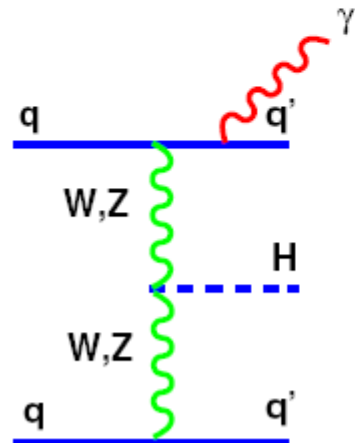
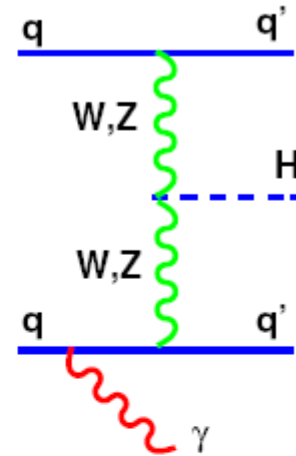
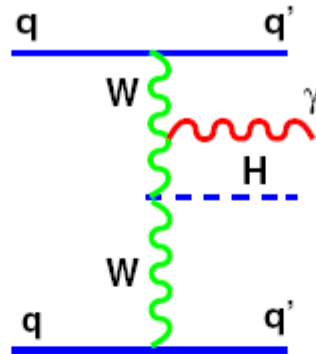
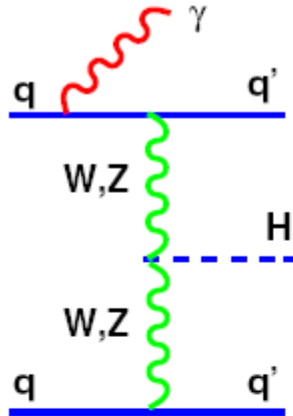
$$bb$$

the following characteristics still hold !

- 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

signal at partonic level

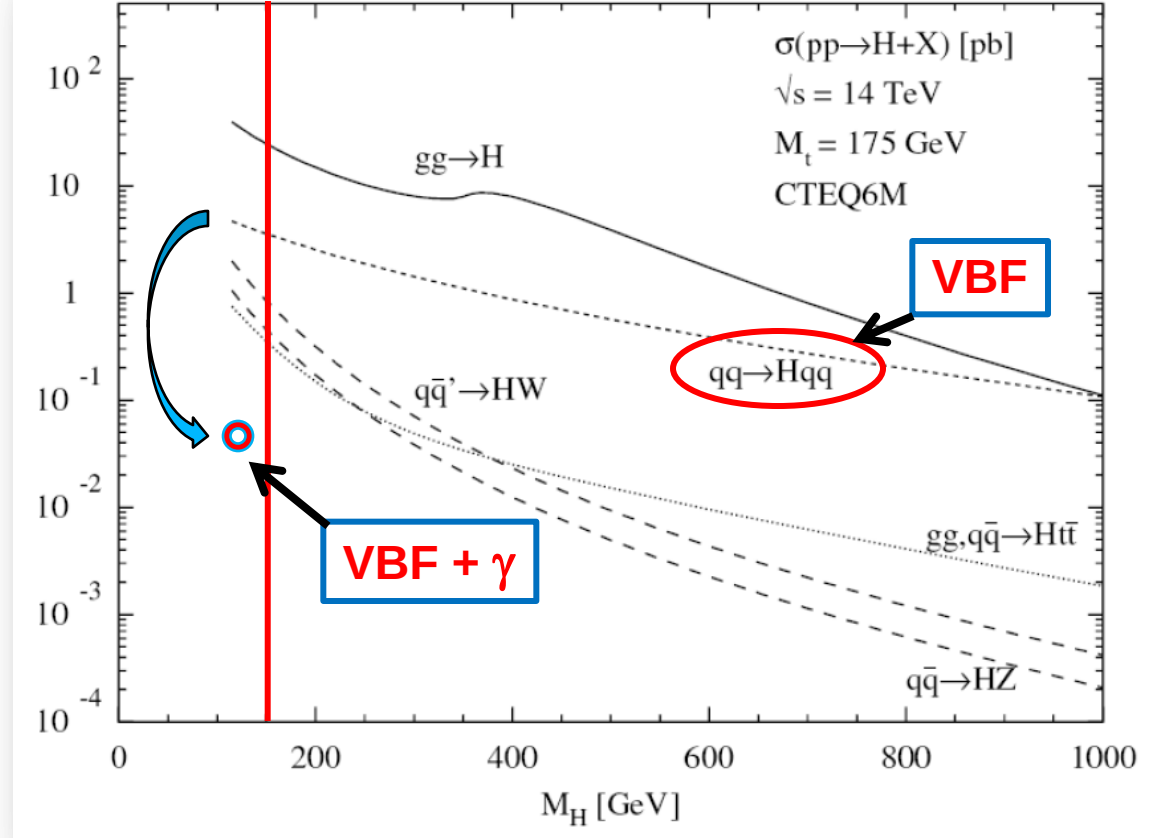
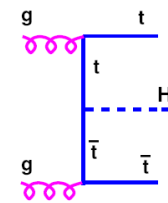
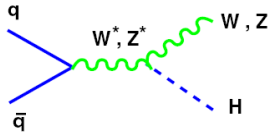
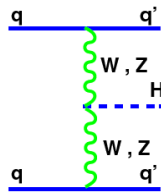
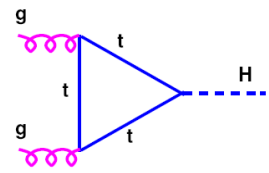
$$qq \rightarrow qq H + \gamma$$



main advantages

- trigger on photon at high p_T
- the large gluon component in QCD bckg is idle in radiating a photon
- dynamical effects (coherence) **dramatically suppress** radiation of central photon in QCD bckg
- **x-section ~ 65 fb** with $p_T(\gamma) > 20$ GeV
- could provide a new independent test not only of **Hbb** but also of **HWW** coupling

Higgs production: inclusive x-sections in pb



■ $\sigma(H+jj+\text{gamma}) \sim 1/100 \times \sigma(H+qq)$ $p_T(\gamma) > 20$ GeV

■ BUT: **VBF + γ** doesn't pay any suppression for $\text{BR}(H \rightarrow b\bar{b})$ (cfr **$\text{BR}(H \rightarrow \gamma\gamma) \sim 0.002$**)

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

minimal set of kinematical cuts

$$\Delta R_{ij} > 0.4$$

$$p_T^\gamma \geq 20 \text{ GeV}$$

$$m_{ij} > 100 \text{ GeV}$$

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

- ❑ full EW tree-level matrix element to $pp \rightarrow H \gamma jj$
computed with both ALPGEN and MADEVENT
- ❑ PDF set is CTEQ5L

how a γ emission affects the bckg

- one would expect by naive QED rescaling

$$S(\gamma Hjj) \sim \alpha S(Hjj) \quad (\alpha = \text{fine structure constant})$$

$$B(\gamma Hjj) \sim \alpha B(Hjj)$$

$$(S/\sqrt{B})|_{H\gamma jj} \sim \sqrt{\alpha} (S/\sqrt{B})|_{Hjj} \quad \sqrt{\alpha} \approx 1/10$$

- if so $\longrightarrow$ no interest in requiring γ emission

...but this is not the case

- QED naive rescaling holds for **inclusive processes**
 $\longrightarrow$ not always for restricted regions of phase space !
- requirement of centrality **dramatically suppresses bckg**

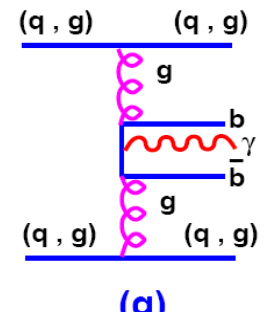
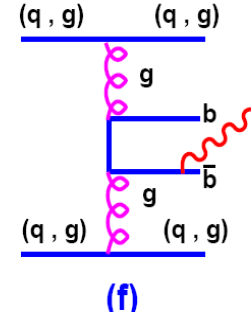
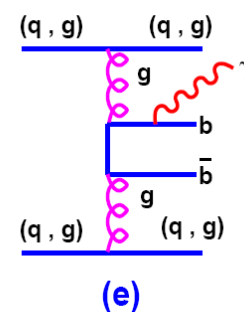
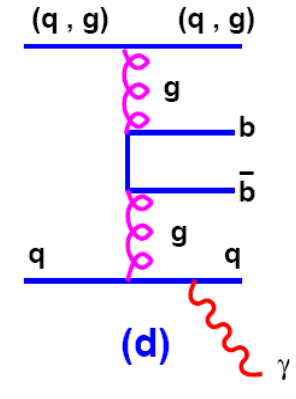
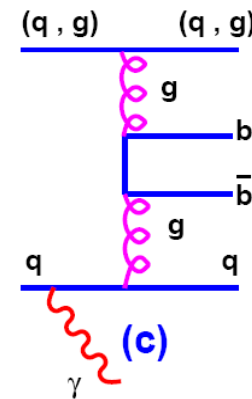
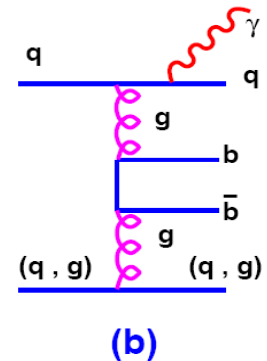
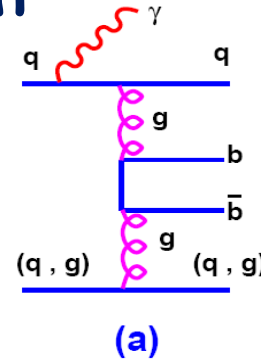
main bckg to $pp \rightarrow H \gamma + jj$

■ t and u type diagrams dominant

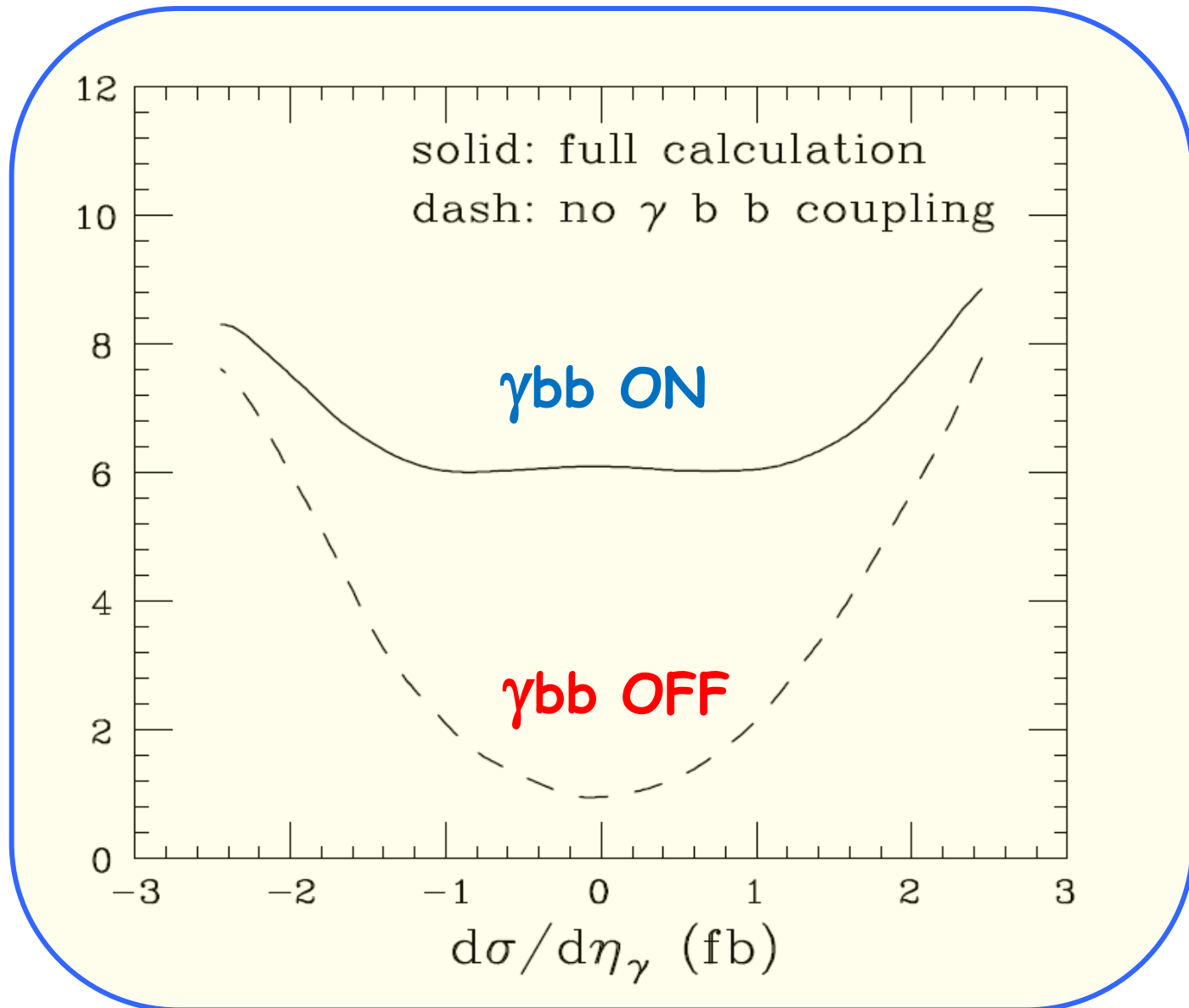
bckg is less active by requiring a central photon

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

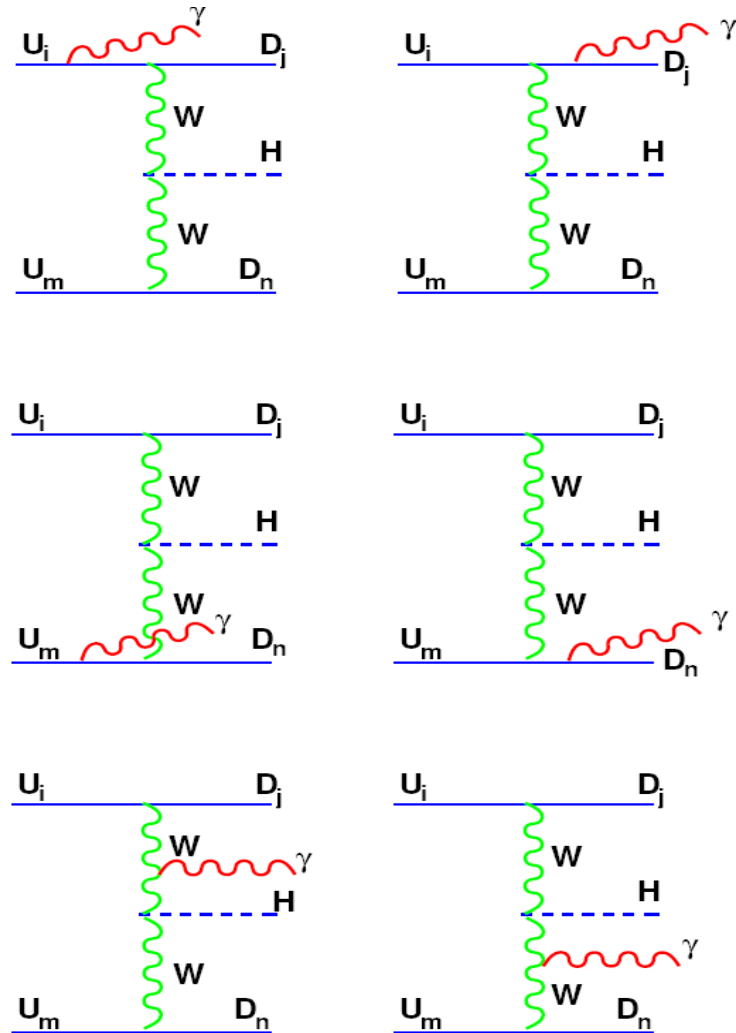
dominant contribution
(suppressed by b-quark
electric charge)



what if the $\gamma b b$ coupling is switched off in the BCKG ?



on the contrary
SIGNAL
 has no destructive
 interference at large
 angle, due to the
 charged currents



• no suppression at large angle for the signal

S/B versus optimization of kinematical cuts

- cuts made at partonic level (partonic shower effects added in a second stage)
- we obtained (optimized cuts follow)

$$B(\gamma bbjj) / B(bbjj) \sim 1/3000$$

$$S(\gamma bbjj) / S(bbjj) \sim 1/100$$

$$S(\gamma) / B(\gamma) \sim 30 \text{ S/B}$$

basic cuts

$$\begin{aligned} p_{\text{T}}^j &\geq 30 \text{ GeV}, & p_{\text{T}}^b &\geq 30 \text{ GeV}, & \Delta R_{ik} &\geq 0.7, \\ |\eta_{\gamma}| &\leq 2.5, & |\eta_b| &\leq 2.5, & |\eta_j| &\leq 5, \\ m_{jj} &> 400 \text{ GeV}, & m_H(1-10\%) &\leq m_{b\bar{b}} \leq m_H(1+10\%) \\ 1) \quad p_{\text{T}}^{\gamma} &\geq 20 \text{ GeV}, \\ 2) \quad p_{\text{T}}^{\gamma} &\geq 30 \text{ GeV}, \end{aligned}$$

after looking at:

$$\frac{d\sigma}{dm_{jj}}, \quad \frac{d\sigma}{dp_T^{j1}}, \quad \frac{d\sigma}{dp_T^{b1}}, \quad \frac{d\sigma}{dm_{\gamma H}}, \quad \frac{d\sigma}{|\Delta\eta_{jj}|};$$

optimized cuts follow:

$$m_{jj} \geq 800 \text{ GeV}, \quad p_T^{j1} \geq 60 \text{ GeV}, \quad p_T^{b1} \geq 60 \text{ GeV}, \\ |\Delta\eta_{jj}| > 4, \quad m_{\gamma H} \geq 160 \text{ GeV}, \quad \Delta R_{\gamma b/\gamma j} \geq 1.2,$$

$$\text{signf} = \frac{S}{\sqrt{B}}$$

we used

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

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

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

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

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

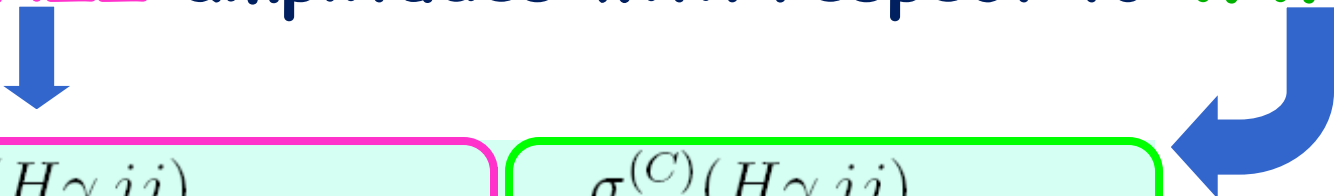
partonic contributions to bckg

	no photon		with photon	
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 %

further advantages of requiring a central photon

- VBF is sensitive to both WWH and ZZH

γ depletes HZZ amplitudes with respect to WWH


$$\frac{\sigma^{(N)}(H\gamma jj)}{\sigma^{(N)}(H jj)} = 0.0016, \quad \frac{\sigma^{(C)}(H\gamma jj)}{\sigma^{(C)}(H jj)} = 0.013$$

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

- requiring a central photon in VBF increases sensitivity to WWH coupling

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

$L=100 \text{ fb}^{-1}$	$p_T^{\gamma, cut}$	$m_H = 120$ 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

(before shower)

$H(\rightarrow b\bar{b})+jj+ \gamma$

$S/B \sim 1/10$

$H(\rightarrow b\bar{b})+jj$

$S/B \sim 1/300$

cfr.

$gg \rightarrow H(\rightarrow \gamma\gamma)$

$S/B \sim 1/20$

Reducible backgrounds

- $pp \rightarrow \gamma + 4 \text{ jets}$ with two light jets tagged as b-jets
- $pp \rightarrow bb + 3 \text{ jets}$ with one light jet misidentified as γ
- $pp \rightarrow 5 \text{ jets}$ with one light jet misidentified as γ and two light jets tagged as b-jets

Efficiencies of mistagging

$$\varepsilon_{bj} = 1/100$$

$$\varepsilon_{\gamma j} = 1/5000$$

(ATLAS)

number of events ($m_H=120$ GeV) Signal versus Bckg

	$p_T^\gamma \geq 20$ GeV	$p_T^\gamma \geq 30$ 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

(before shower)

Irreducible bckg has a dominant role !

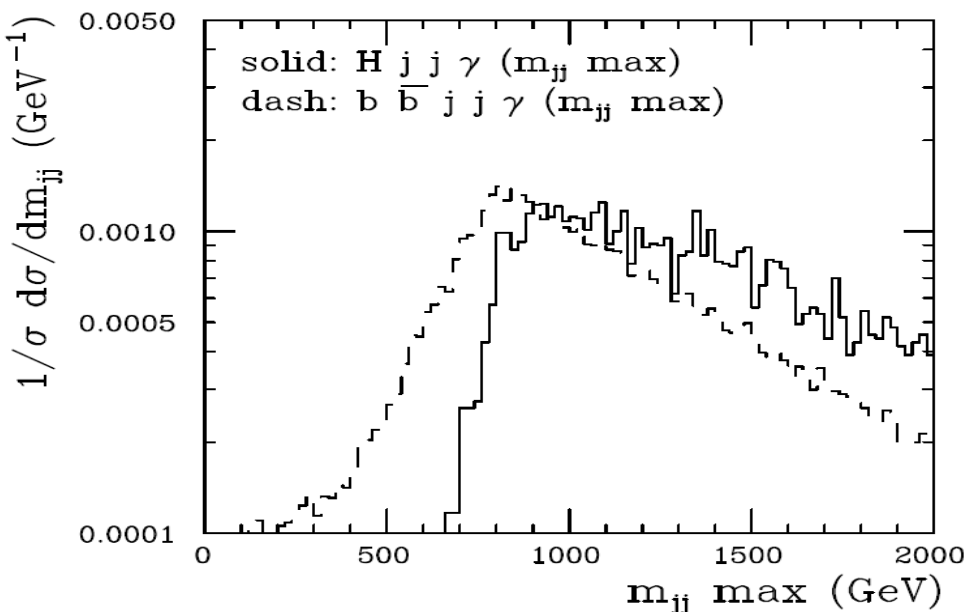
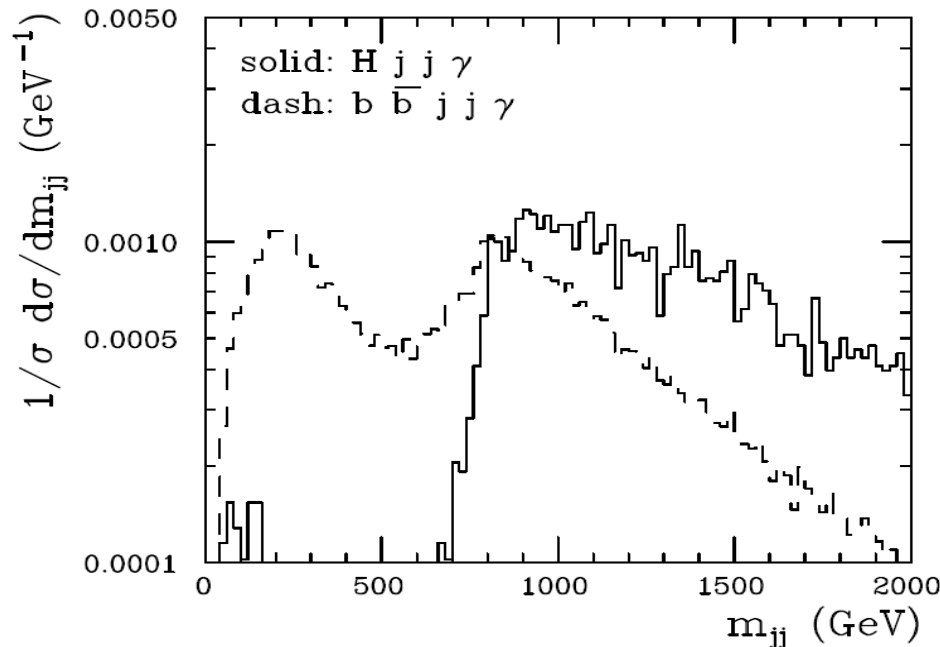
Parton shower effects and central jet veto

■ QCD radiation pattern is similar to the plane VBF process → central jet veto drastically enhances S/B

→ in the QCD bckg $\Delta M(j1, j2)$ and $\Delta \eta(j1, j2)$ decrease with respect to partonic configurations (smaller effects in the signal)

→ kinematical cuts get more effective in enhancing S/B

Parton shower effects

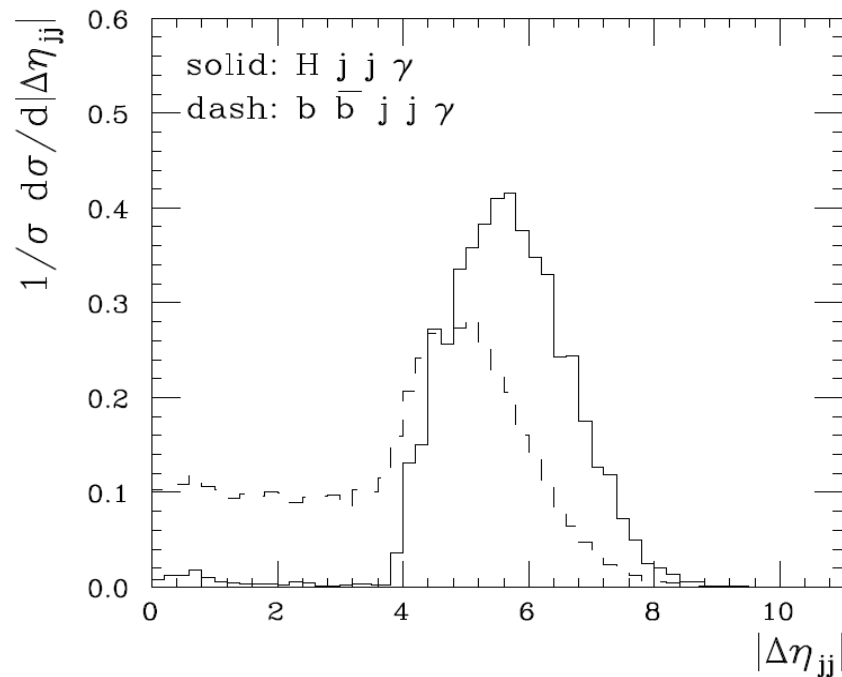


Algorithm1:
 $m(j1, j2)$
 j1=highest pT
 j2=second highest pT

$pT(j1) > 60 \, \text{GeV}$

$pT(j2) > 30 \, \text{GeV}$

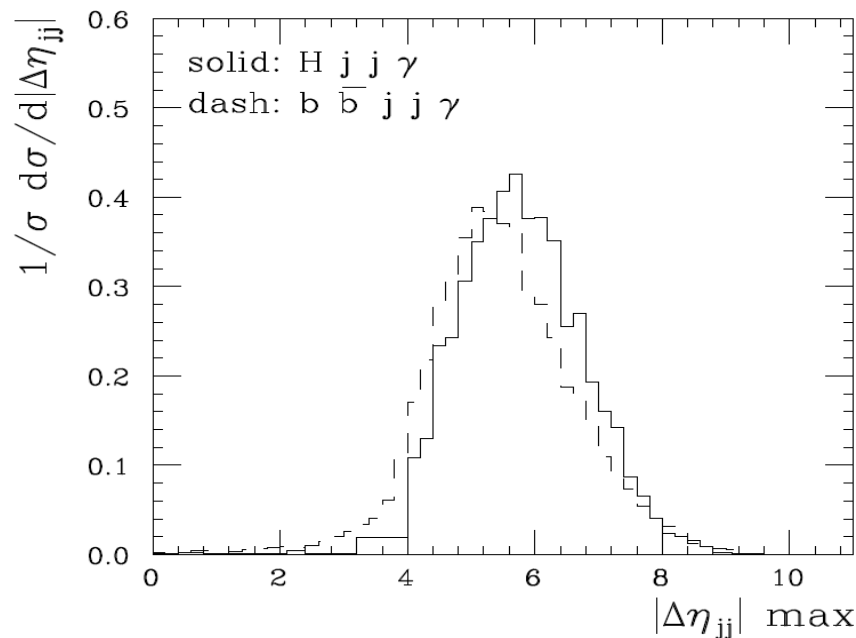
Algorithm2:
 $\max[m(j1, j2)]$ among
 all jets



Algorithm1:
 $\Delta\eta(j1,j2)$
 $j1 = \text{highest } p_T$
 $j2 = \text{second highest } p_T$

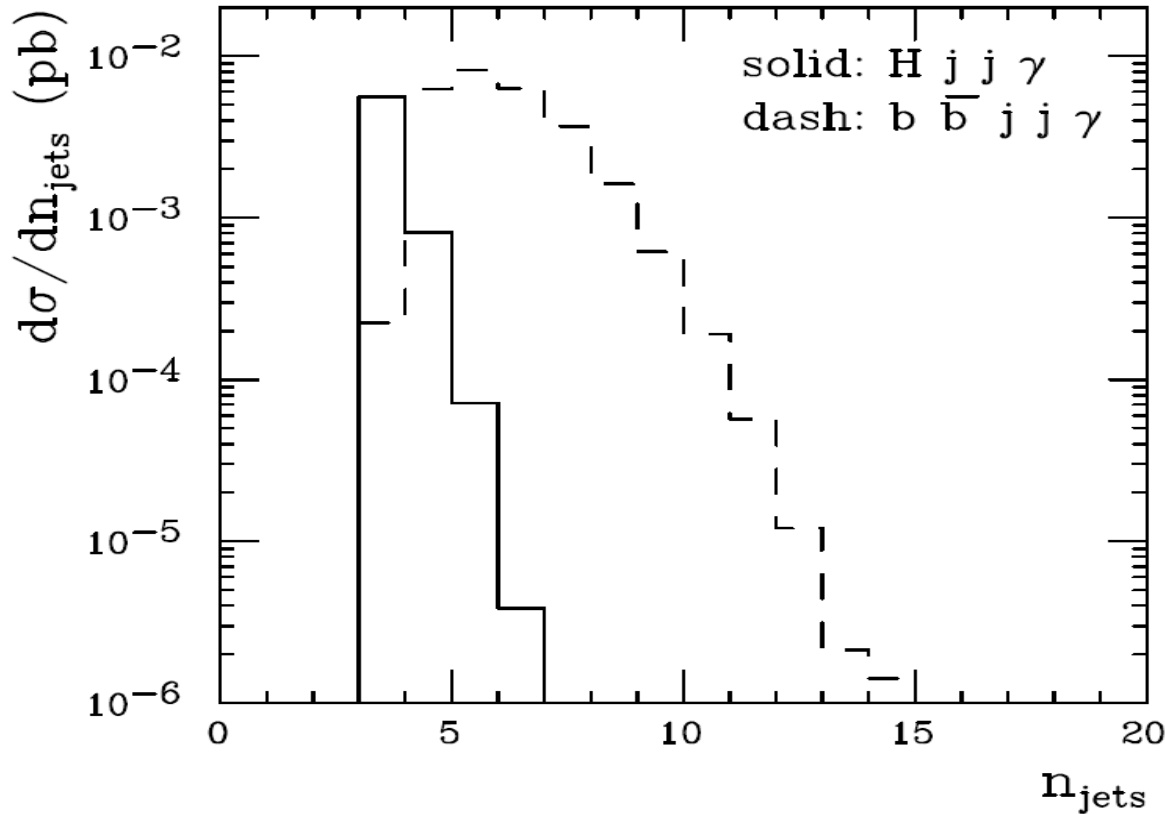
$p_T(j1) > 60 \text{ GeV}$

$p_T(j2) > 30 \text{ GeV}$



Algorithm2:
 $\max[\Delta\eta(j1,j2)]$ among
all jets

jet multiplicity distribution



- at least a factor 4 improvement is expected for S/B when parton shower effects are included



GAIN factor 2 in significance

Conclusions

- Requiring an associated central photon in the Higgs production via VBF offers great advantages:
 - **trigger efficiency**
 - strong suppression of QCD bckg
 - **$S/B \sim 1/10$**
 - sensitivity to Hbb & HWW couplings
- factor 2 improvement in significance when parton shower effects are included

CRUCIAL that ATLAS trigger does not loose this kind of events

Backup

Signal and background events at 30 fb^{-1} (fast simulation)

Expected $qqH, H \rightarrow b\bar{b}$ signal and background events in $m_{b\bar{b}}$ mass window of $\pm 30 \text{ GeV}/c^2$

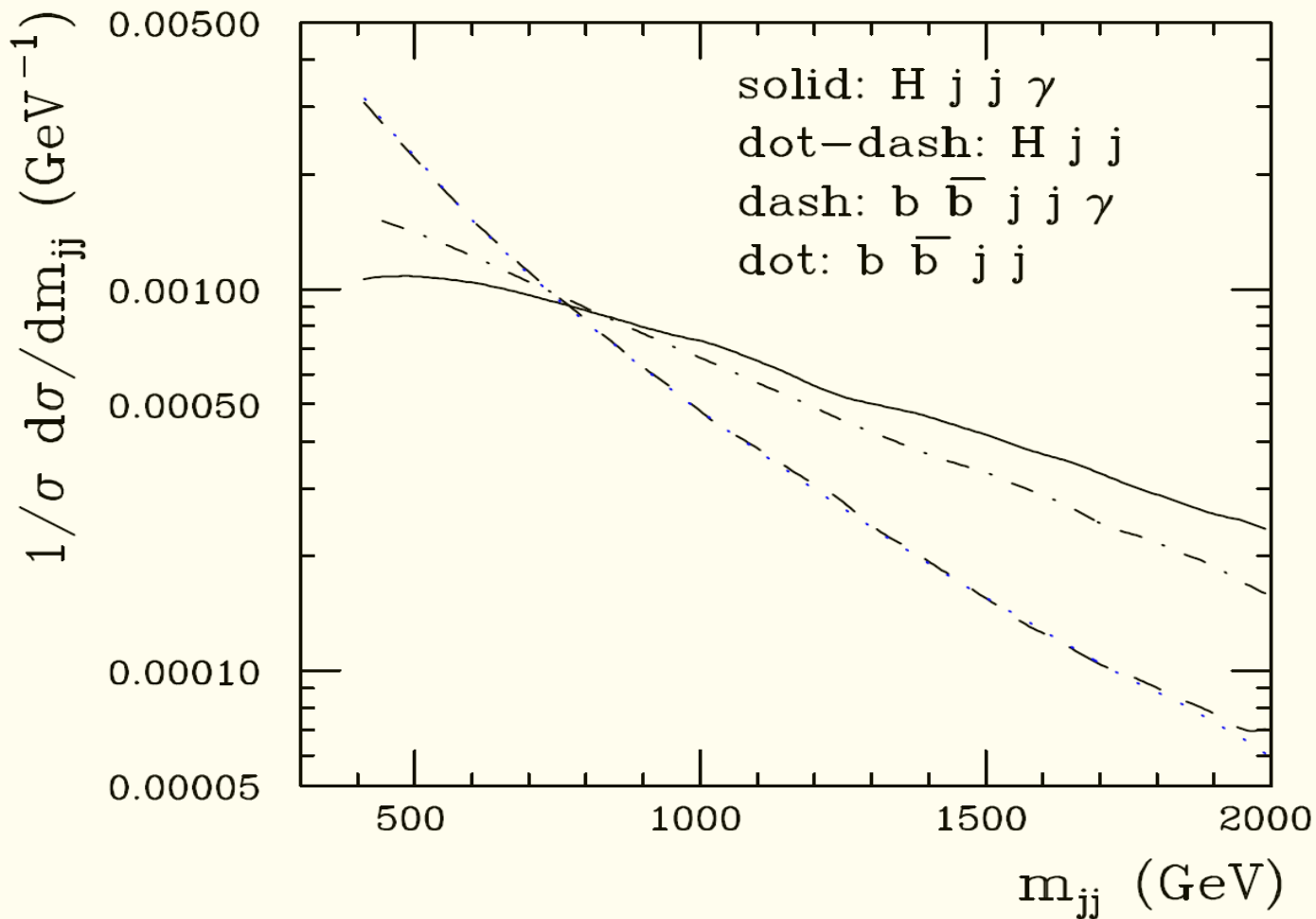
Decay channel	$N_{\text{final events}}$		Efficiencies		$N_{\text{normalized to } \mathcal{L} = 30 \text{ fb}^{-1}}$	
	Fast	Full	Fast	Full	Fast	Full
$qqH \ H \rightarrow b\bar{b}$	5354	365	4.5×10^{-3}	3.2×10^{-3}	328	243
single t	2689	-	9.0×10^{-5}	-	881	-
$b\bar{b}$	25	-	2.5×10^{-8}	-	315000	-
W+jets	18	-	3.2×10^{-8}	-	331	-
Z+jets	311	-	1.2×10^{-6}	-	681	-
$t\bar{t} \rightarrow WWb\bar{b}$	404	-	1.4×10^{-5}	-	203	-
Total Background					317096	-
$S/\sqrt{B}$					0.6	-

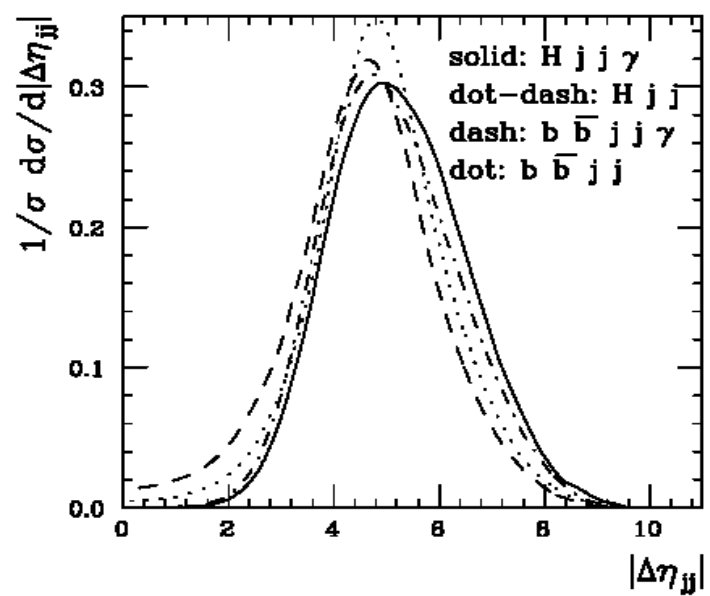
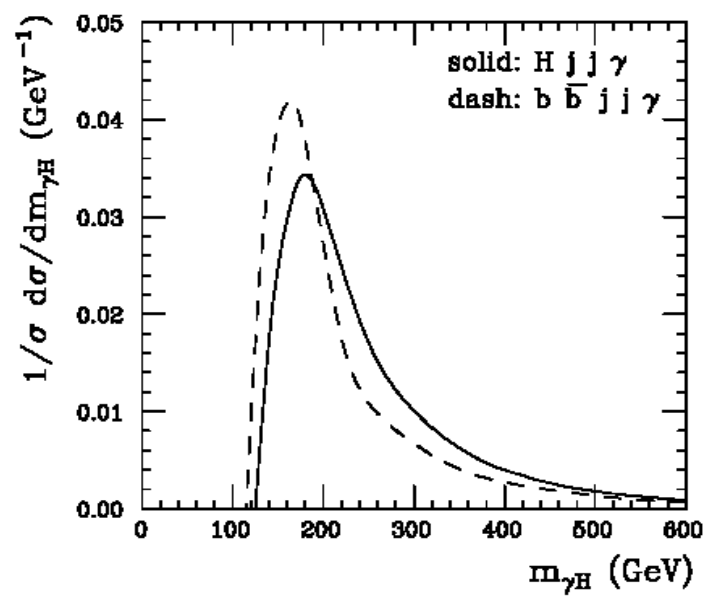
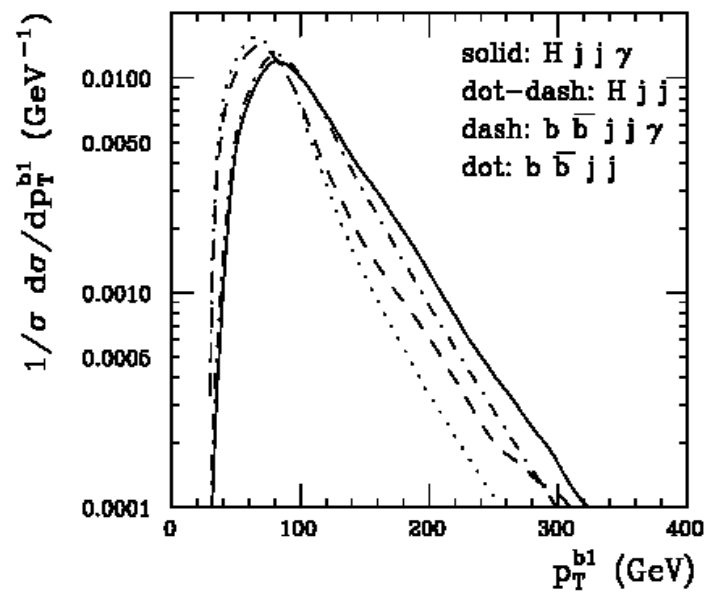
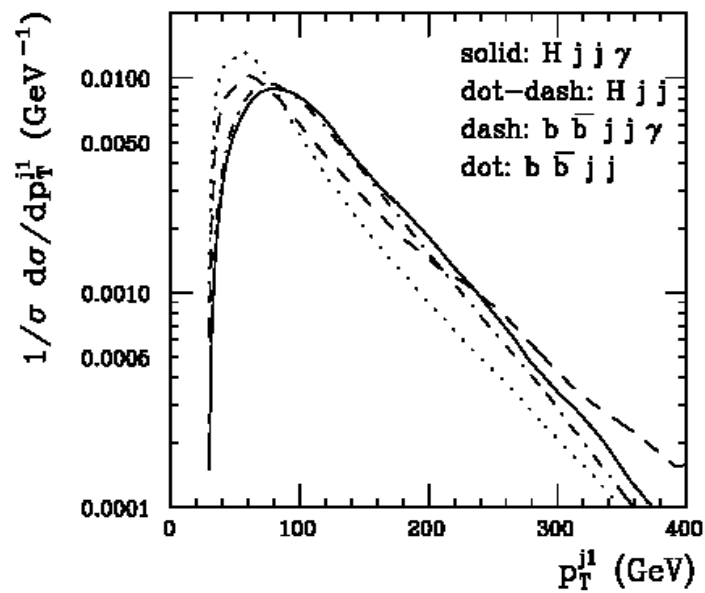
HLT efficiency after all reconstruction cut

Trigger menu	trigger efficiency (%)
e25i	0.0
2e15i	0.0
$\mu 6$	79.7(after prescale: 4.0)*
$\mu 20i$	21.9
1j400	1.6
3j165	0.0
4j110	0.0
Any trigger	80.0(25.6)

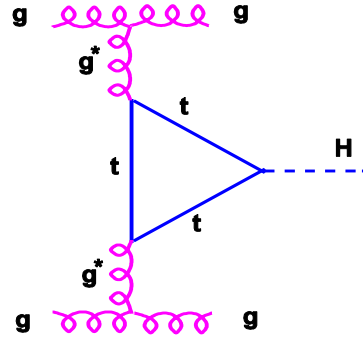
* Assuming the prescale factor of 20,
 from John Baines slide of the TAPM open
 meeting on 13th of February

crucial distribution $m(j,j)$





- 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 !)