The Search for New States and Forces of Nature

GGI, Florence, 28 Oct. 2009

Asking for a *high-p_T* photon in Higgs *production* at LHC

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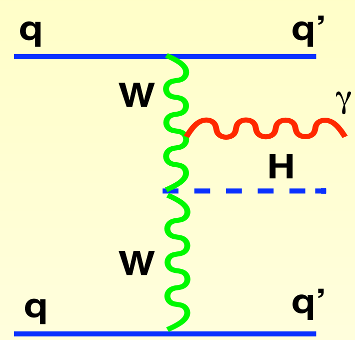
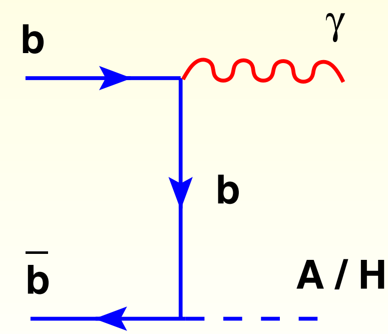
focus on two processes :

- pp → H (→ bb) 2j + γ (in the SM)



Gabrielli, Maltoni, B.M., M.Moretti, Piccinini, Pittau, NPB 781 (2007) 64

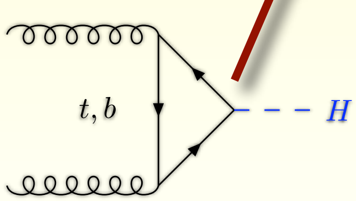
- pp → H / A (→ ττ) + γ (in the MSSM)

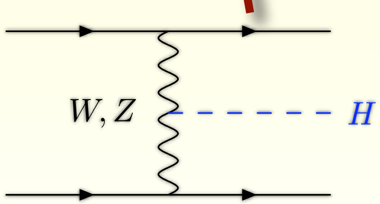


Gabrielli, B.M., Rathsman, PRD 77 (2008) 015007

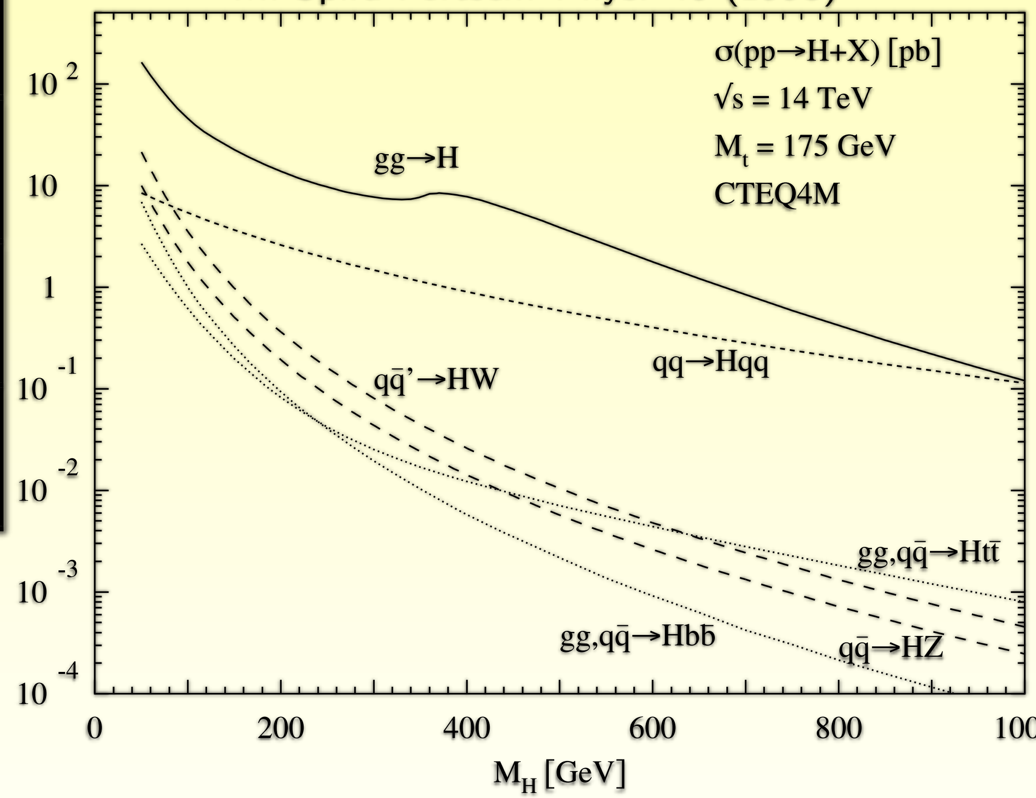
HIGGS TOTAL CROSS SECTIONS

m_H (GeV)	σ_{gg} [pb]	σ_{VBF} [pb]
120	42	4.4
140	33	3.8
200	18	2.5
300	10	1.4





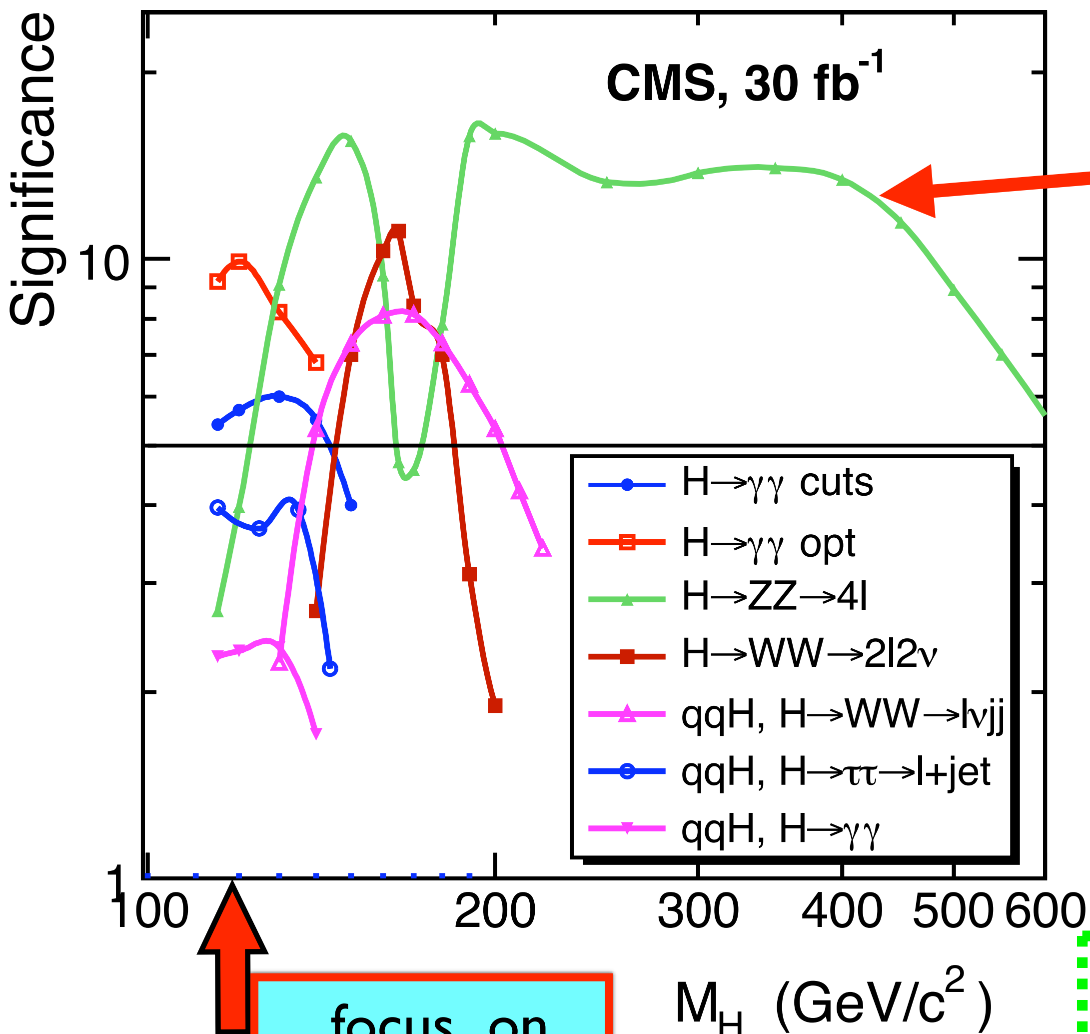
M. Spira Fortsch. Phys. 46 (1998)



different final states !

but interesting σ's are of the order of few fb's

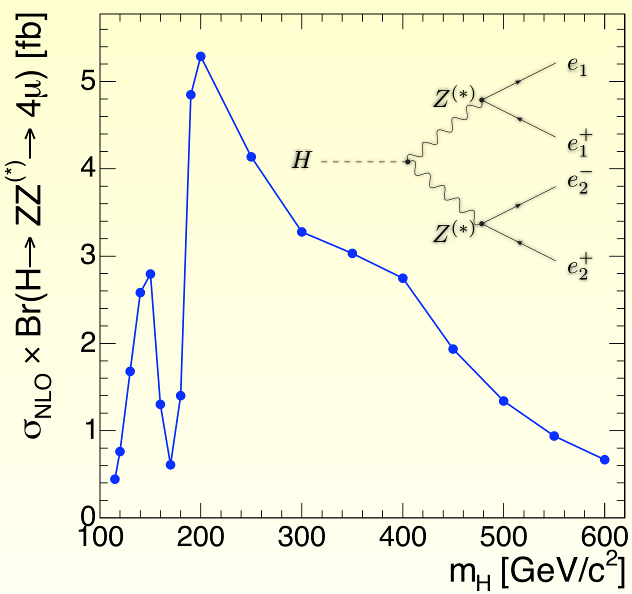
(after BR's + cuts for enhancing signal/bckg)



focus on $m_H \sim 120$ GeV

GOLDEN CHANNEL !

$$H \to ZZ \to 4l$$



$\sigma \times BR\ (H \to 4\ \mu) < 6$ fb

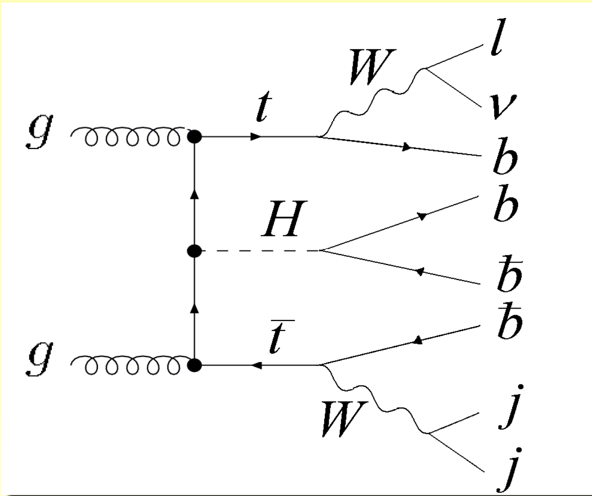
Hbb coupling dominant in light-H decay !

[BR($H \to bb$) ~ 70% at m_H ~ 120 GeV]

but QCD bb continuum tends to swamp any EW bb resonance at hadron colliders !

Can one constrain the Hbb coupling at all ?

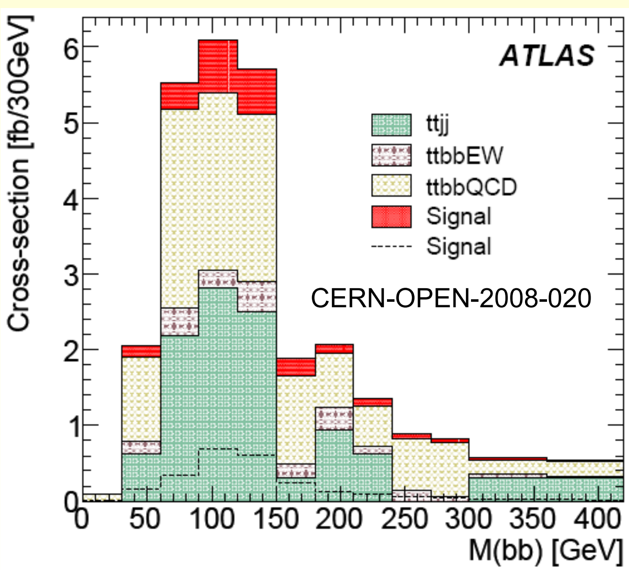
Constraining Hbb coupling for light H

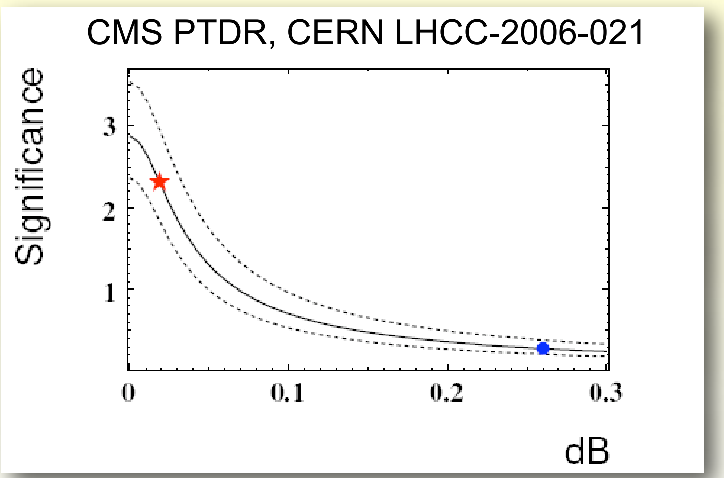


most studied channel :

pp → ttH → ttbb

after including detector simulation, initial "optimistic" expectations vanished !





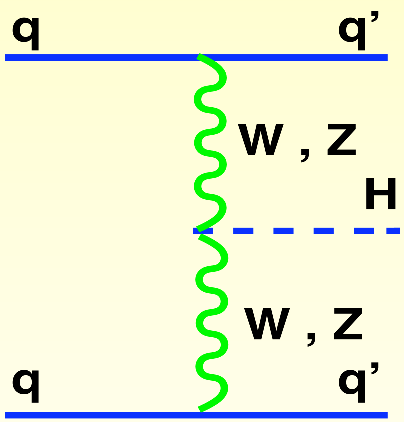
Also, an expected k~1.8 factor on bckgd at NLO*** makes everything even worse !

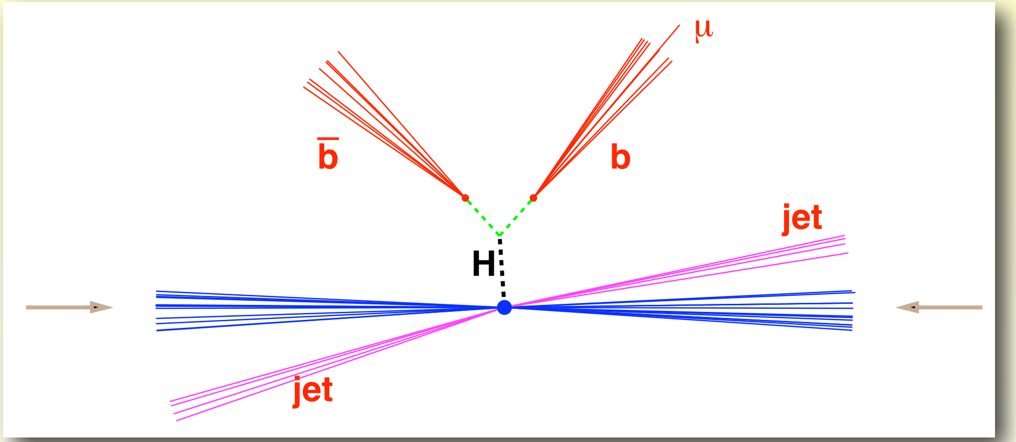
(***Bredenstein, Denner, Dittmaier, Pozzorini, arXiv:0905.0110)

Alternatives :

pp → H (→bb) + 2j (VBF fusion)

- light Jets with large invariant mass $p_T(j) \approx 40\,\mathrm{GeV}$
- widely separated in rapidity (forward/backward)
- Higgs decay products lying at intermediate rapidity





- potential <u>difficult</u> to assess (4-jet final state...???)

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

recent proposal :

Butterworth, Davison, Rubin and Salam, 2008

new strategy for pp → H (→ bb) W,Z (→ℓℓ')

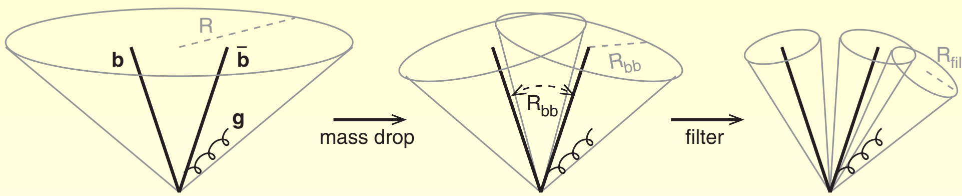
❄ increase (tiny) S/B for pp → HW(Z) → bbℓℓ'

by looking to events with **very high-p_T** H and W(Z) (p_T>200,300 GeV)

→ S/B improves (but σ drops ...) !

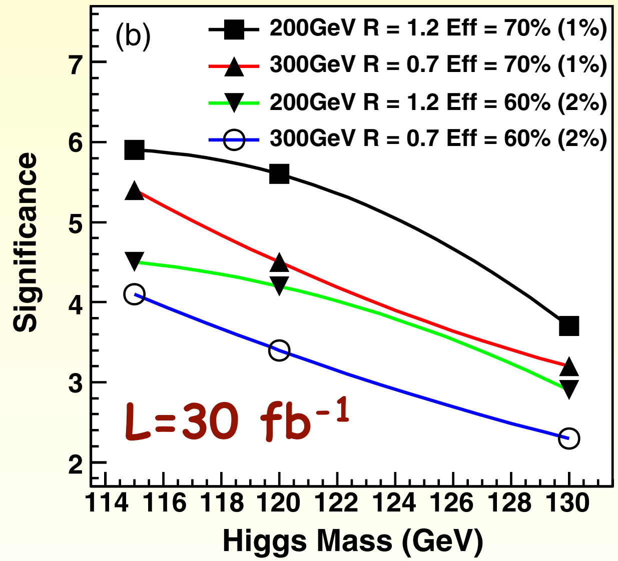
challenge : high-p_T H→bb quite collimated → may give a single jet

→ using a (QCD-motivated) subjet analysis could help !



Jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B\cdot \text{fb}}$
CA, $R = 1.2$, MD-F	0.57	0.51	0.80
$K_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	0.22
SISCONE, $R = 0.8$	0.49	1.33	0.42

TABLE I. Cross section for signal and the Z + jets background in the leptonic Z channel for $200 < p_{TZ}/\text{GeV} < 600$ and $110 < m_J/\text{GeV} < 125$, with perfect b-tagging; shown for our jet definition, and other standard ones at near optimal R values.

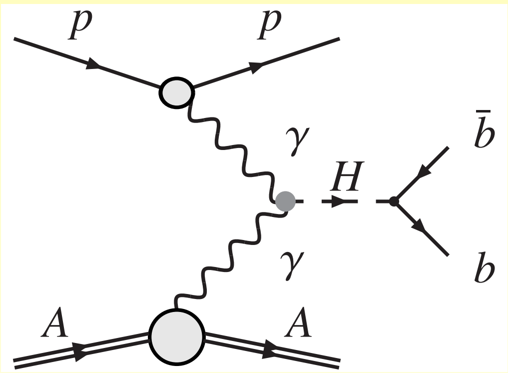


to be validated by complete detector simulation !

$\gamma\gamma$ collisions in p Pb → p H (→ bb) Pb

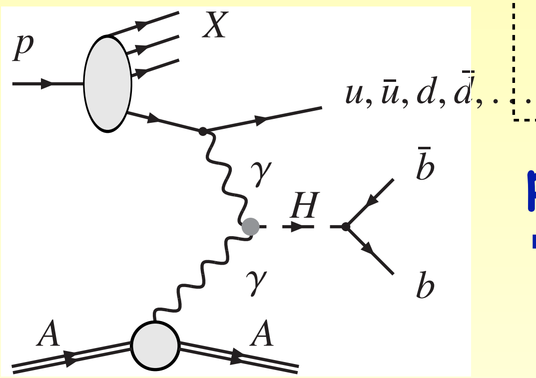
d'Enterria and Lansberg arXiv:0909.3047

$$p\,\mathrm{Pb} \xrightarrow{\gamma\gamma} p\,H\,\mathrm{Pb}$$



(a) Elastic case

$$p\,\mathrm{Pb} \xrightarrow{\gamma\gamma} X\,H\,\mathrm{Pb}$$

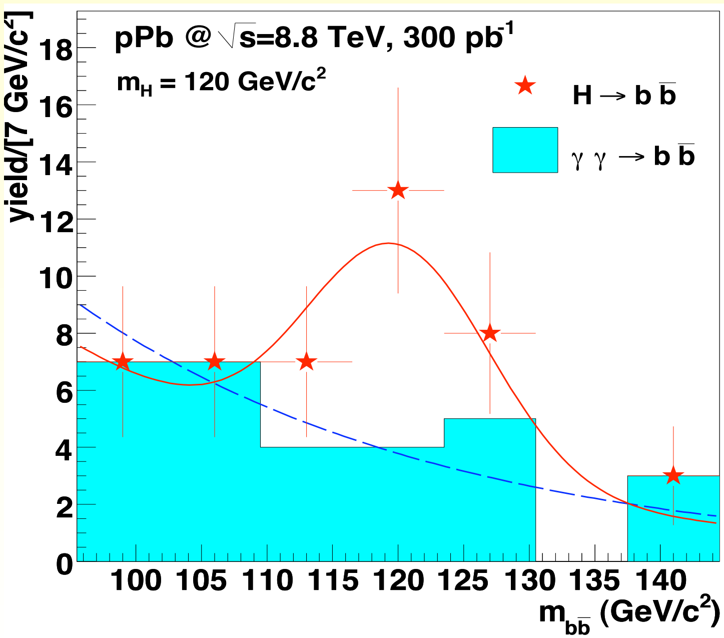


(b) Semielastic case

given E_p ~ 7 TeV (B~8.3 T)
→ $E_{N(Z,A)}$ ~ Ep x Z/A

p-Pb → $\sqrt{s_{NN}} = 8.8$ TeV

$$\mathcal{L}_{pPb} \sim 10^{31}\ \mathrm{cm^{-2}s^{-1}}$$



- Pb increases γ flux (~Z^2), and kills pile-up (low lumi)
- p increases γ-flux end-point and lumi

m_H=120 GeV Higgs observed with $S/\sqrt{B}$ ~ 3 after 3-year run

summing up

measurement of g_{Hbb} challenging at LHC !

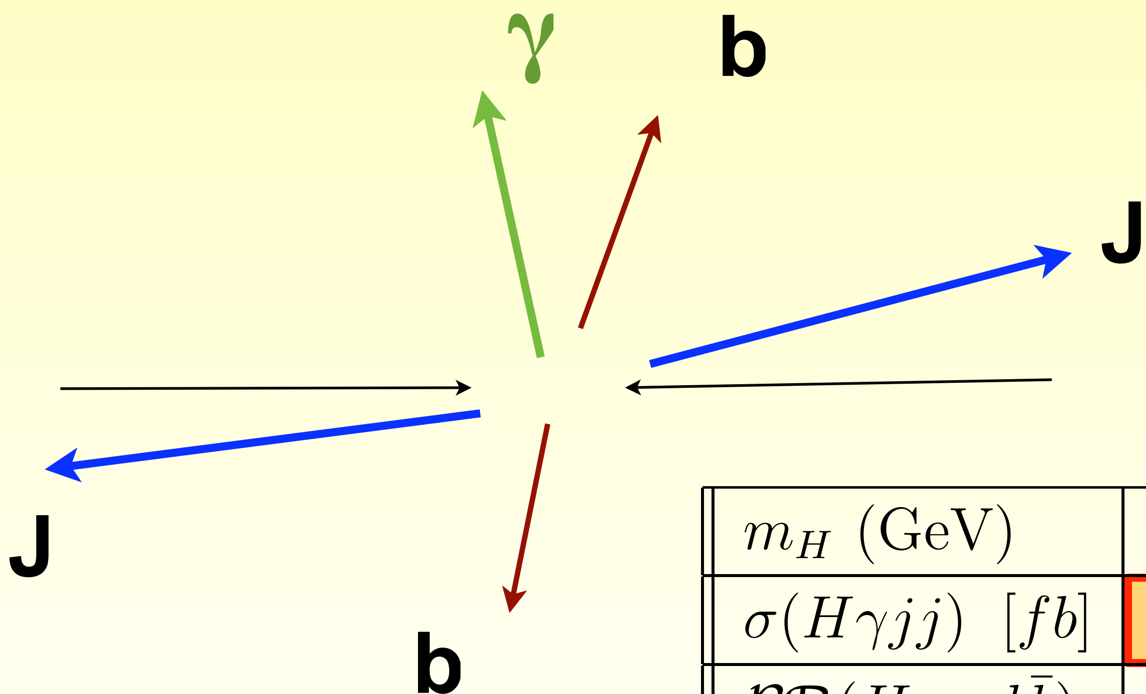
LHC potential not yet really established !

New Channel :

(Gabrielli, Maltoni, B.M., M. Moretti, Piccinini, Pittau, 2007)

- require a further **central photon** from **VBF**

pp → H (→bb) + 2j + γ

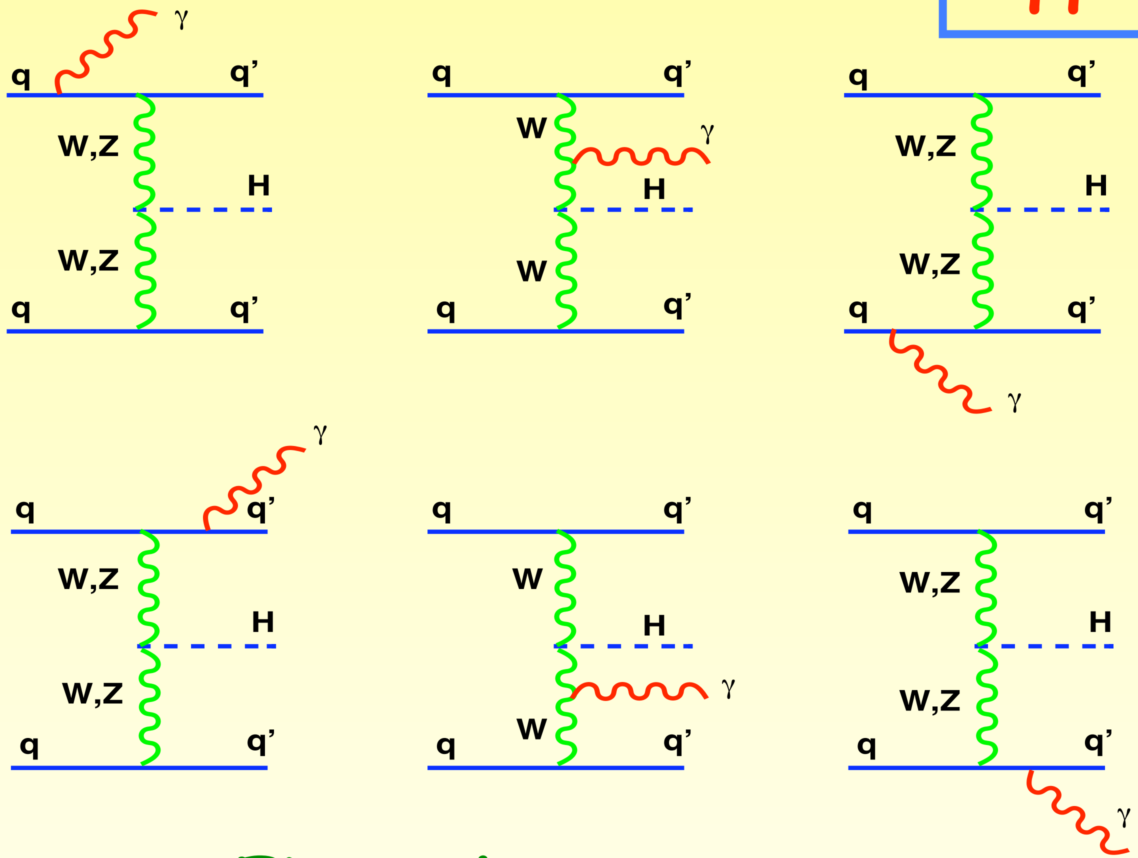


increases triggering efficiency !

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

$(\Delta R_{\gamma j} > 0.4,\ p_T^{\gamma} \geq 20\ \mathrm{GeV},\ \text{and}\ m_{jj} > 100\ \mathrm{GeV})$

$qq \to qq\, H + \gamma$



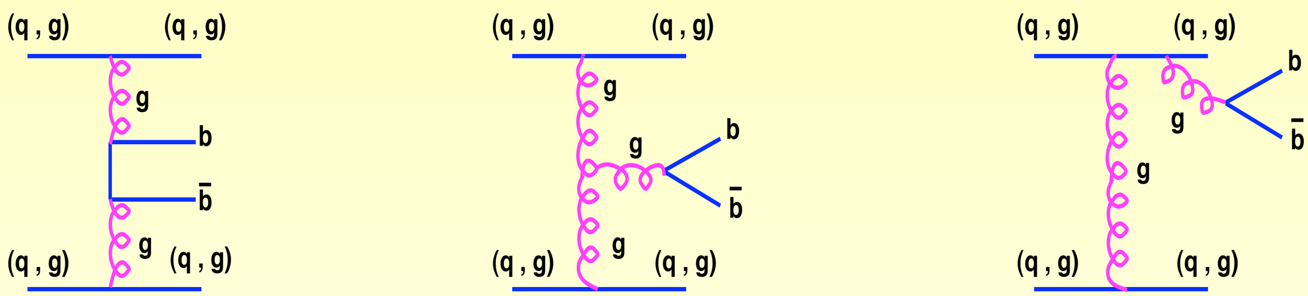
from naive QED scaling :

$$(S/\sqrt{B})|_{H\gamma\, jj} \sim \sqrt{\alpha}\,(S/\sqrt{B})|_{H\, jj} \lesssim 1/10\,(S/\sqrt{B})|_{H\, jj}$$

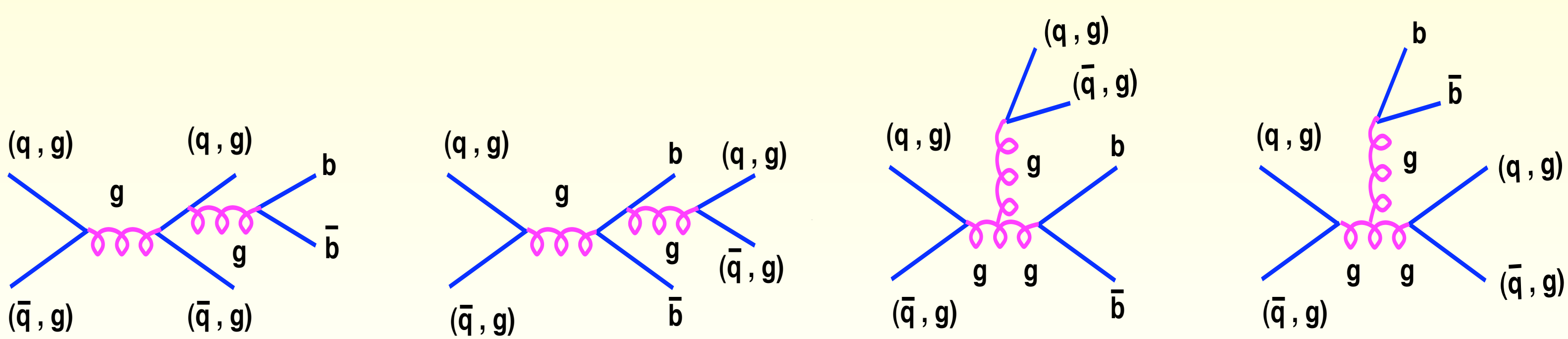
Actual S/√B much better than this !!!!

IRREDUCIBLE BCKGD

add a photon to ⬇ (gluons are idle !)



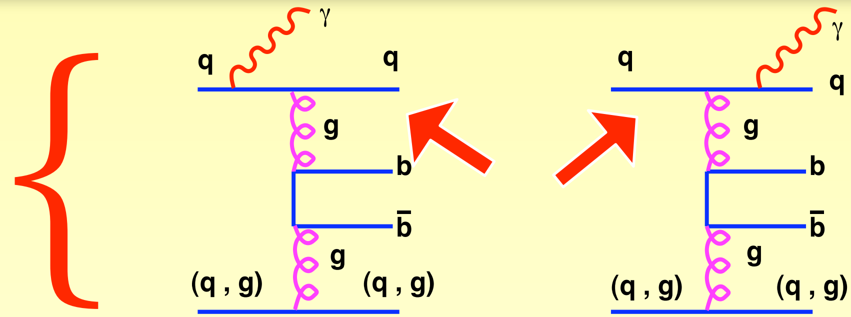
t,u-channel (most relevant !)



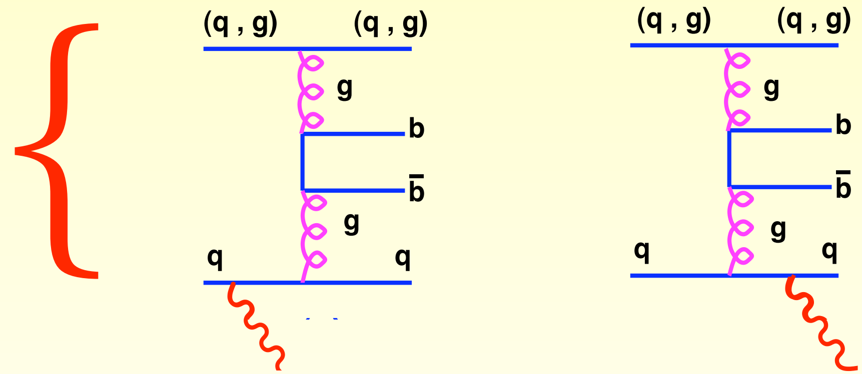
s-channel (suppressed at M_{jj} ~ 1TeV)

Also, destructive interf.s in central γ emissions off q_{in} and q_{fin} in a t-channel gluon diagram

("coherence" effect)

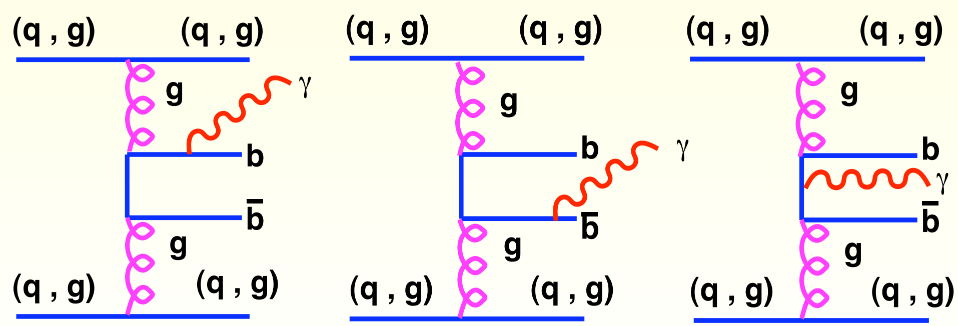


→ bckg suppressed by requiring a central photon by O(1/10) compared to naive QED scaling!

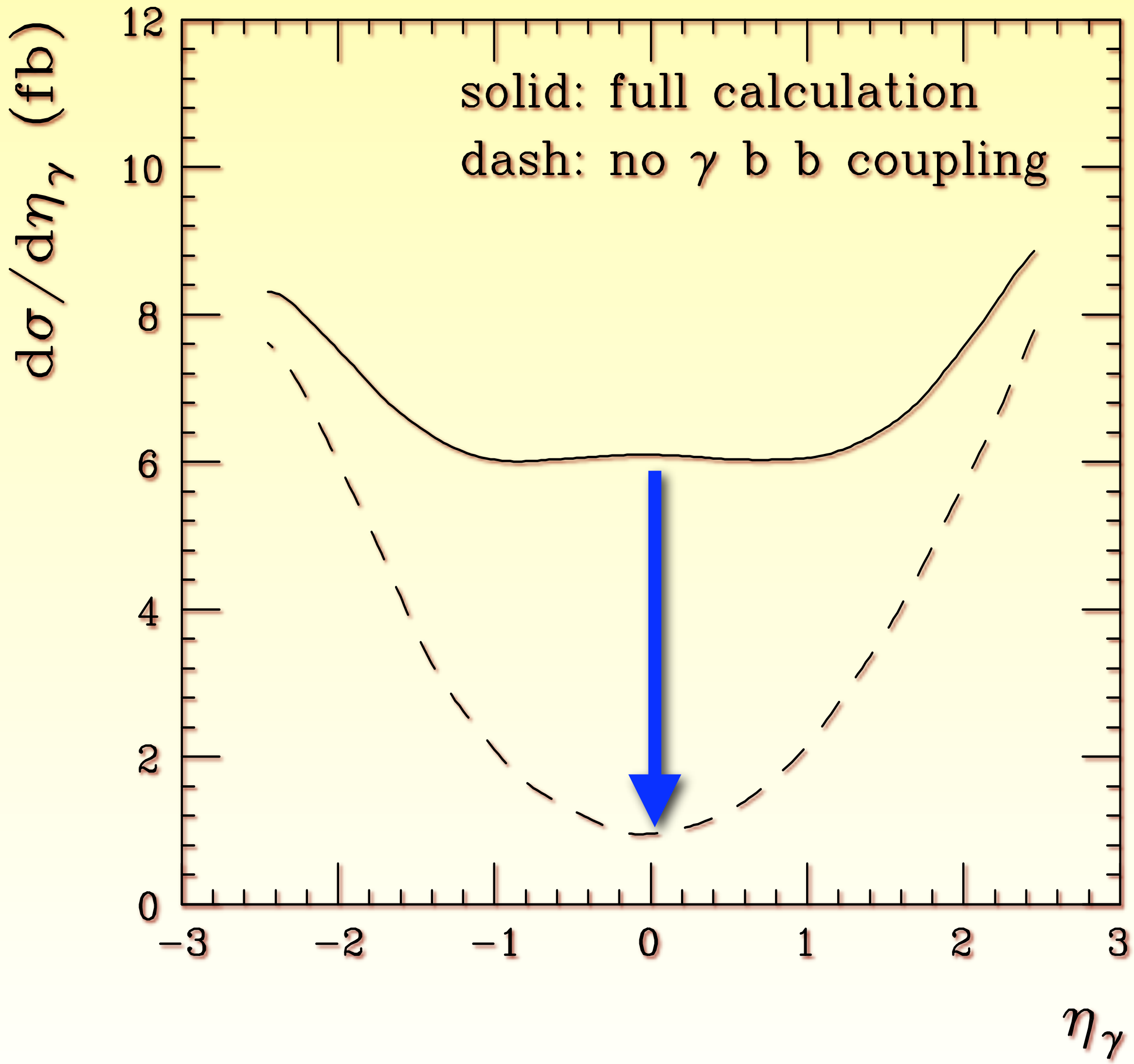


dominant contribut. →

(suppressed by b-quark electric charge)



switching off the γbb coupling in irred. bckg



photon rapidity distr.s

(optimized cuts)

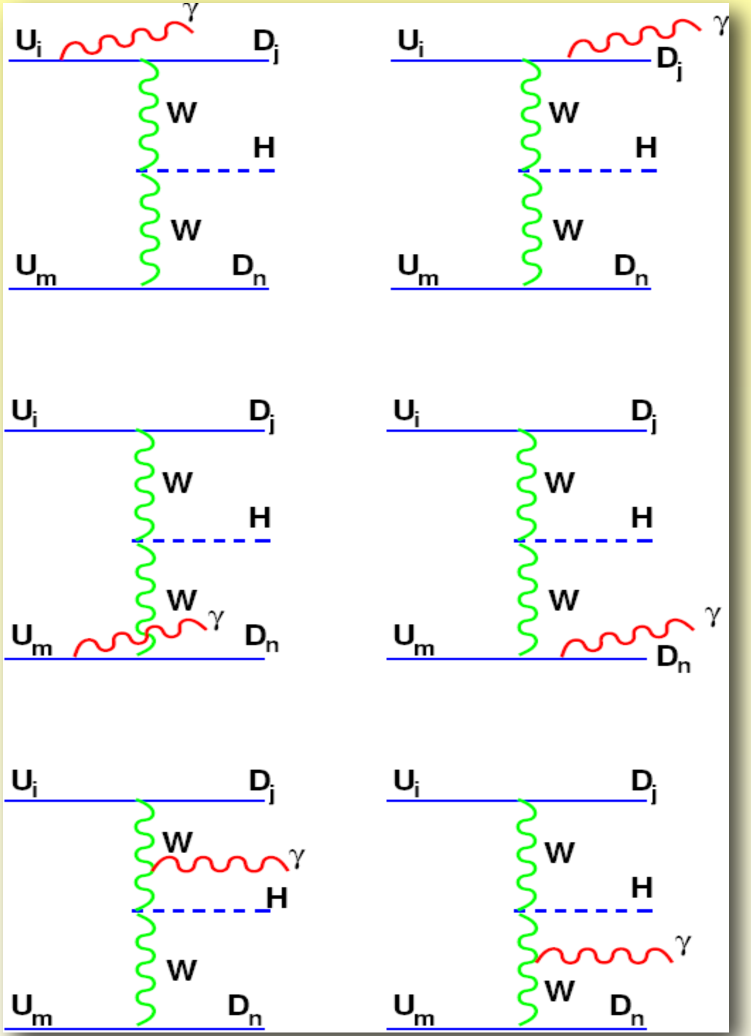
what about signal ?

W charged current spoils destructive interference at large angle !

(WW→H) $$\frac{\sigma^{(C)}(H\gamma\, jj)}{\sigma^{(C)}(H\, jj)} = 0.013$$

but Z neutral current follows BCKG pattern !!!

(ZZ→H) $$\frac{\sigma^{(N)}(H\gamma\, jj)}{\sigma^{(N)}(H\, jj)} = 0.0016$$



$p_T^\gamma \geq 20\,\mathrm{GeV}$
$|\eta_\gamma| \lesssim 2.5$
$\Delta R_{j\gamma} \geq 0.7$

central photon singles out WW over ZZ fusion !!!

basic cuts :

EVENT SELECTION

$$p_T^j \geq 30\,\mathrm{GeV}, \quad p_T^b \geq 30\,\mathrm{GeV}, \quad \Delta R_{ik} \geq 0.7,$$

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

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

$$\begin{cases} 1)\ p_T^\gamma \geq 20\,\mathrm{GeV}, \\ 2)\ p_T^\gamma \geq 30\,\mathrm{GeV}, \end{cases}$$

then, look at distrib's :

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

→ **add optimized cuts :**

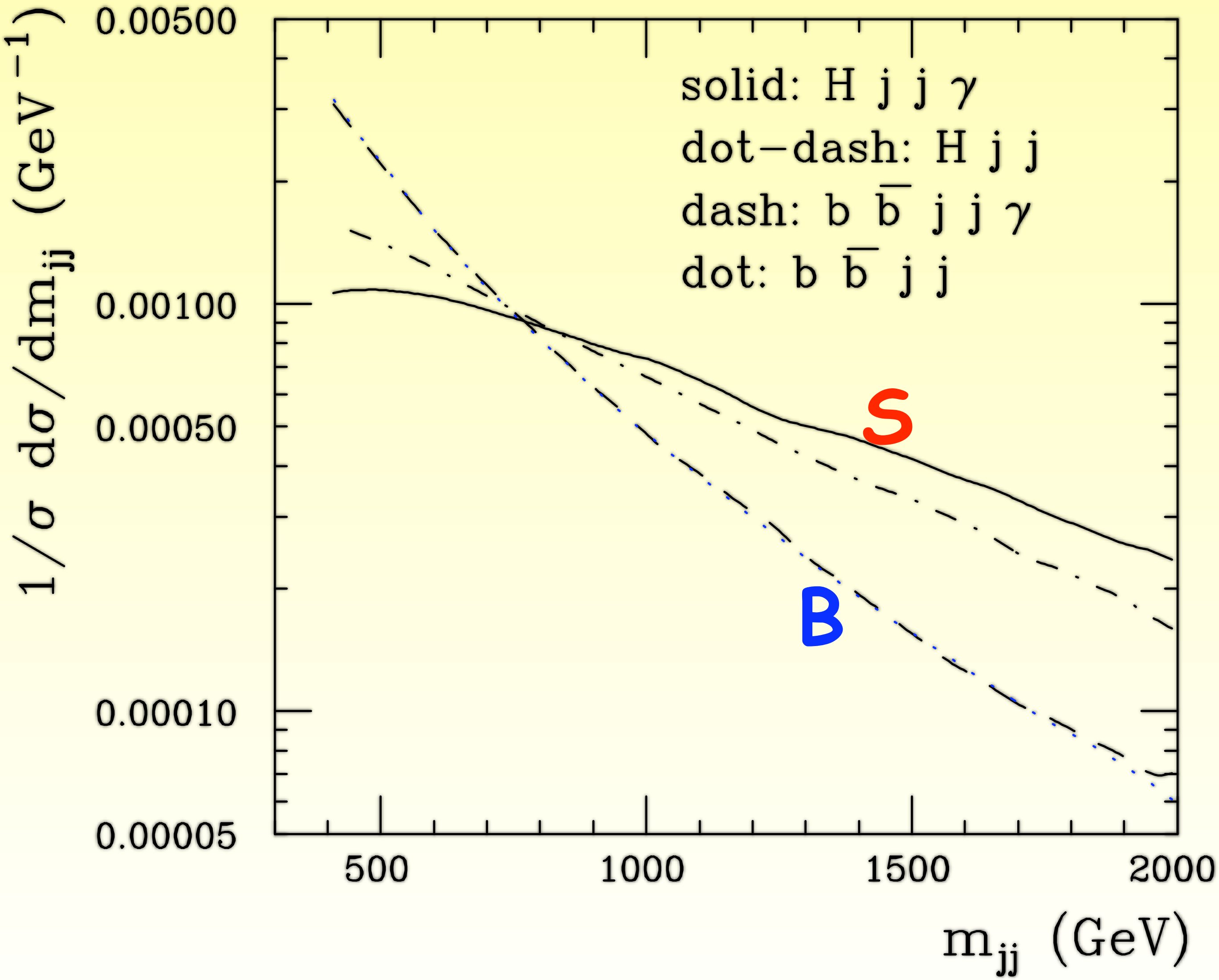
$$m_{jj} \geq 800\,\mathrm{GeV}, \quad p_T^{j1} \geq 60\,\mathrm{GeV}, \quad p_T^{b1} \geq 60\,\mathrm{GeV},$$

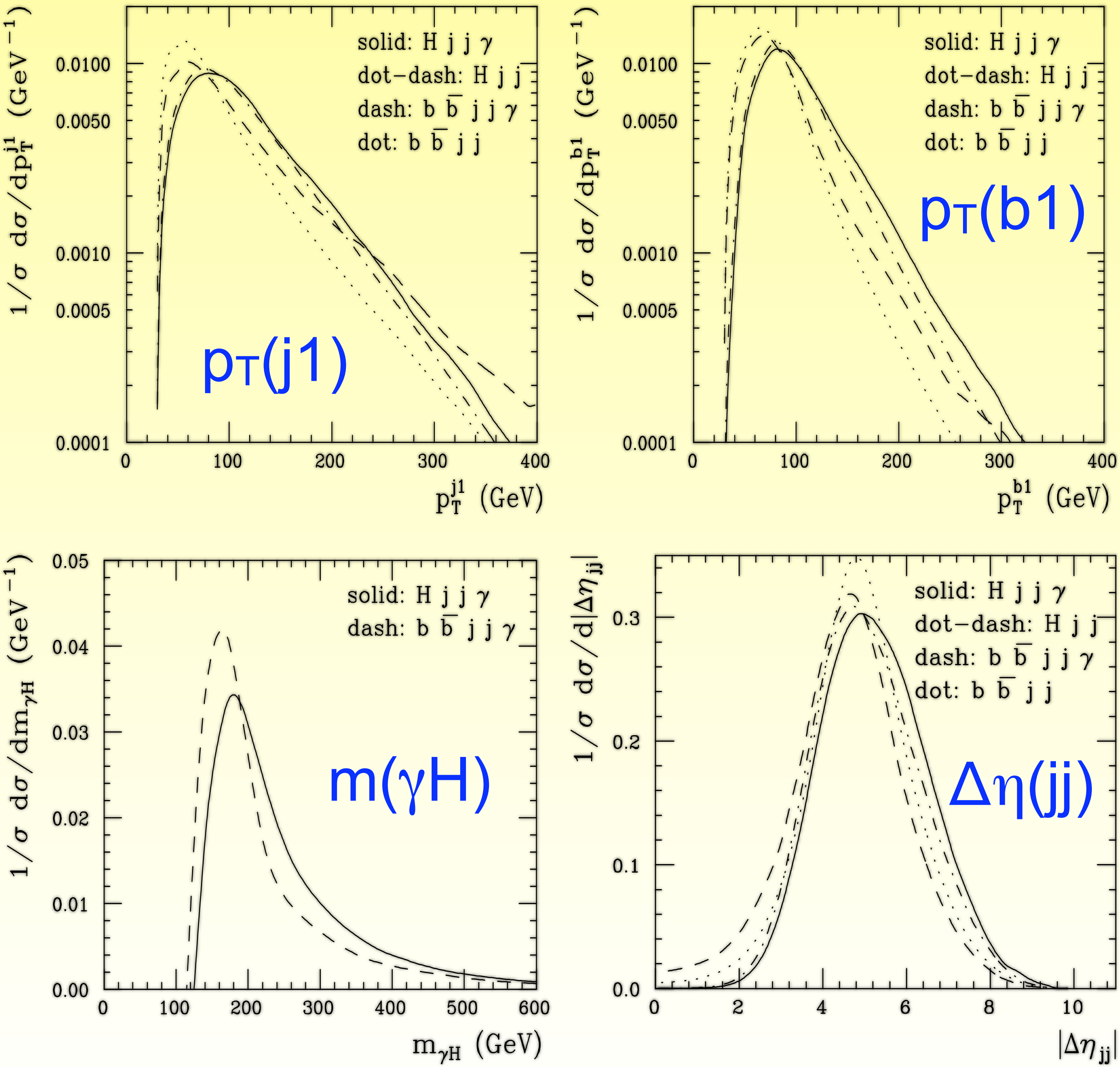
$$|\Delta\eta_{jj}| > 4, \quad m_{\gamma H} \geq 160\,\mathrm{GeV}, \quad \Delta R_{\gamma b/\gamma j} \geq 1.2\,.$$

well isolated photon ↑

m_{jj} distribution critical to enhance S/B

(even more than in plain VBF !!!)




solid: H j j γ
dot−dash: H j j
dash: b b̄ j j γ
dot: b b̄ j j
pT(j1)
$1/\sigma \, d\sigma/dp_T^{j1}$ (GeV^{-1})
p_T^{j1} (GeV)
pT(b1)
$1/\sigma \, d\sigma/dp_T^{b1}$ (GeV^{-1})
p_T^{b1} (GeV)
solid: H j j γ
dash: b b̄ j j γ
m(γH)
$1/\sigma \, d\sigma/dm_{\gamma H}$ (GeV^{-1})
$m_{\gamma H}$ (GeV)
solid: H j j γ
dot−dash: H j j
dash: b b̄ j j γ
dot: b b̄ j j
Δη(jj)
$1/\sigma \, d\sigma/d|\Delta\eta_{jj}|$
$|\Delta\eta_{jj}|$

irreducible bckgr σ's (optimized cuts) $p_T^\gamma \geq 20\,\mathrm{GeV}$

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

(m_H=120 GeV)

bckg(γ) / bckg ~ *33 fb / 103 pb* ~ 1/3000

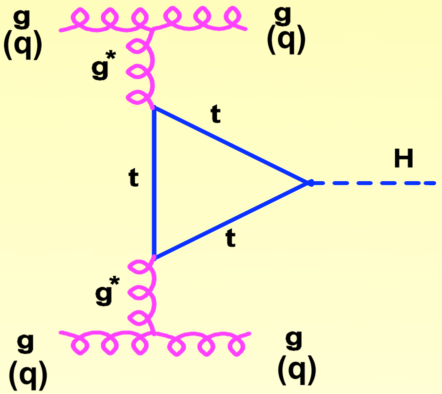
cf. signal(γ) / signal ~ 1/100

note : conservative choice of QCD scales in the bckg evaluation !

- requirement of a central photon also suppresses contamination from $g^*g^* \to H\, jj\, \gamma$

(induced by top loop)

("bckg" to Higgs via VBF)



- $\sigma(H\,\gamma\,jj)_{g^*g^*\to H} \sim 8\times10^{-4}\ \sigma(H\,jj)_{g^*g^*\to H}$

- $\sigma(H\,\gamma\,jj)_{g^*g^*\to H} \sim 0.21$ fb   negligible !

(basic cuts, p_T^γ >20 GeV)

σ's : pp → H γ j j vs irrid. bckgr

PDF : CTEQ5L

(ALPGEN + MADEVENT)

	$p_T^{\gamma,cut}$	$m_H = 120$ GeV	$m_H = 130$ GeV	$m_H = 140$ GeV
$\sigma[H(\to b\bar{b})\gamma jj]$	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
$\sigma[H(\to b\bar{b})jj]$		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

for m_H=120 GeV : **S/B(γ) ~ 1/10 ~ 30 S/B$_0$!**

$\epsilon_b = 60\%$ (b tagging eff.)
$\epsilon_{b\bar{b}} \simeq 70\%$ (finite m_{bb} resolution)

cf. S/B (gg→ H → $\gamma\gamma$) ~ 1/20

L=100 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
$S/\sqrt{B}\|_{H jj}$		3.5	2.8	1.9

N_{events} for red. vs irred. bckgs (m_H=120 GeV)

$\epsilon_b = 60\%$
$\epsilon_{b\bar{b}} \simeq 70\%$

L=100 fb^{-1}

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

$\varepsilon_{fake} = 1\%$

eff for mistagging light-jet as a b-jet

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

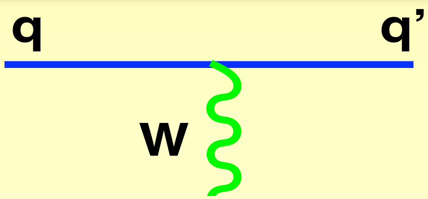
γj rejection factor

(CMS can do better than this !)

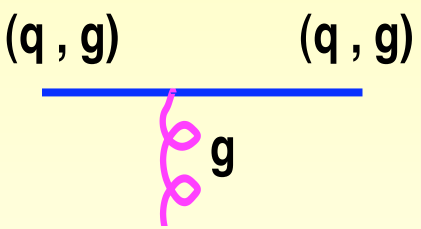
irred. bckg is dominant !

Parton shower effects and central-jet veto help S/B

- no color exchanged in the signal between up and down fermionic lines



- on the contrary, in bckg t-channel virtual gluons



- higher-order QCD radiation much more relevant for bckg than for signal !

- in bckg, m_{jj} and $|\Delta\eta_{jj}|$ for light tagging jets expected to decrease with respect to partonic configurations

ALPGEN + HERWIG

jet cone as in GETJET $p_T^j > 20\,\mathrm{GeV} \quad |\eta_j| < 5 \quad R = 0.7$

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

2 different algorithms for jets :

a_1-highest and second highest p_T with

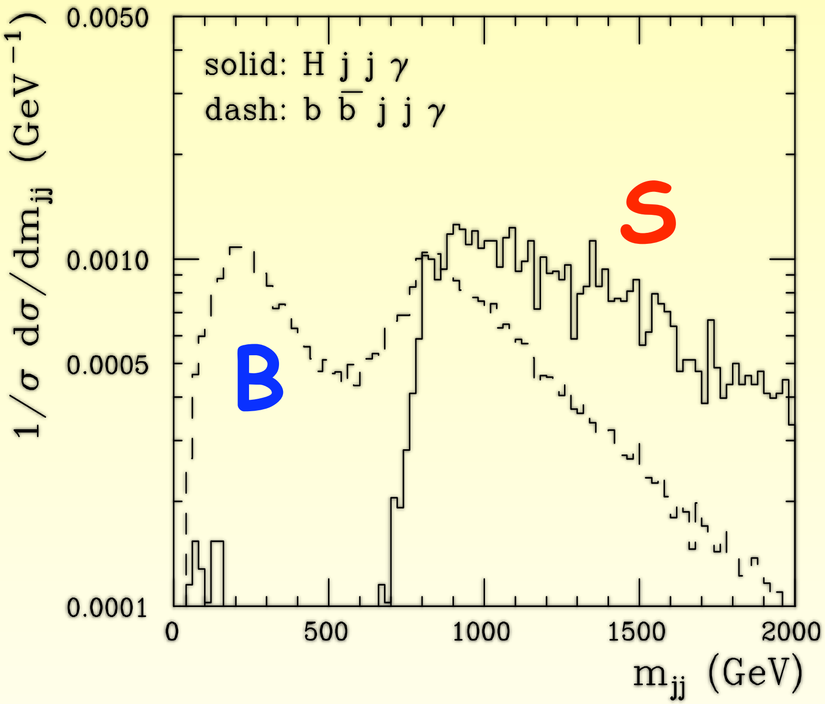
$p_T(j_1) > 60$ GeV $p_T(j_2) > 30$ GeV

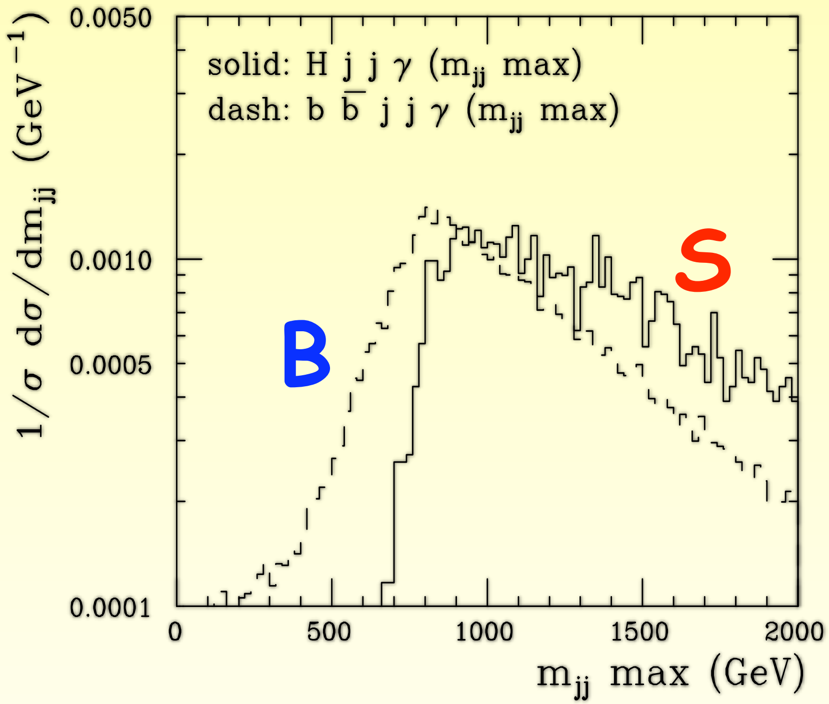
a_2-pair of jets with highest invariant mass, $pT(j_1) > 60$ GeV $pT(j_2) > 30$ GeV

distributions after parton shower

(j_1,j_2) invariant mass distribution

p_{T1} > 60 GeV, p_{T2} >30 GeV





a_1

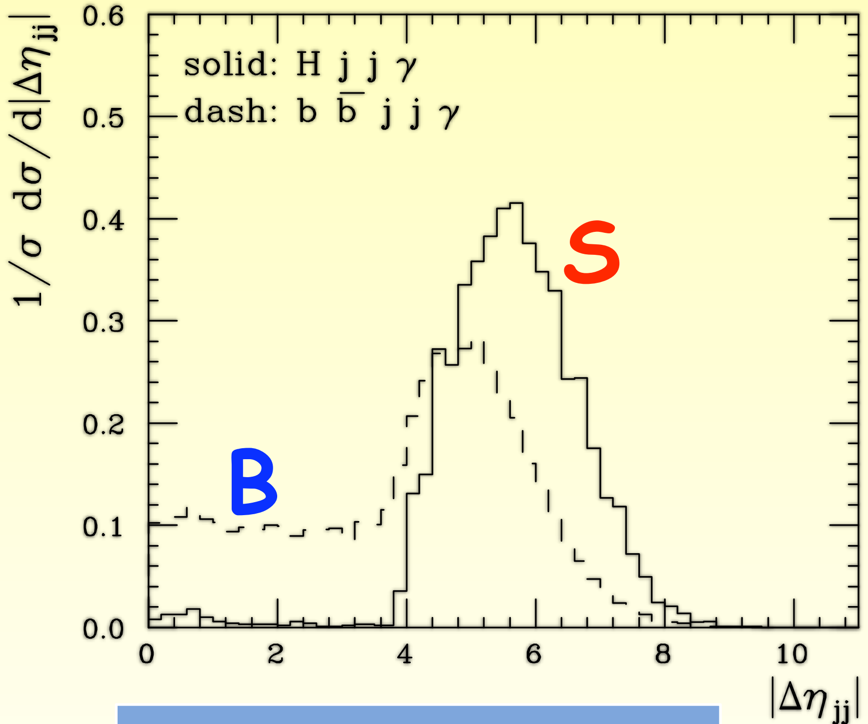
m(j_1,j_2)
j_1=highest p_T
j_2=second highest p_T

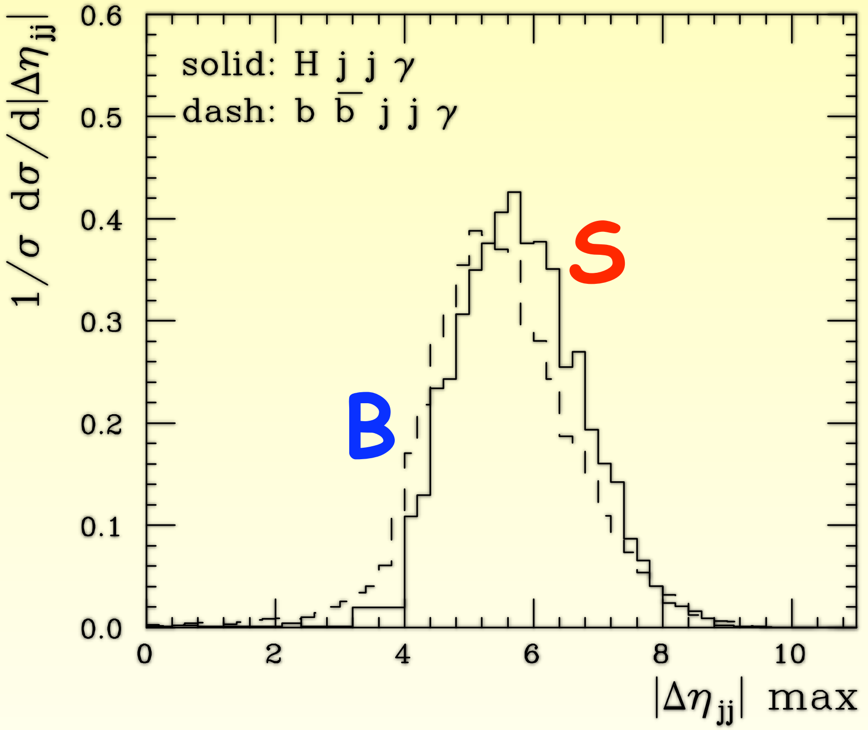
a_2

max[m(j_1,j_2)] among all jets

(j_1,j_2) rapidity difference distribution

$p_{T1} > 60$ GeV, $p_{T2} > 30$ GeV



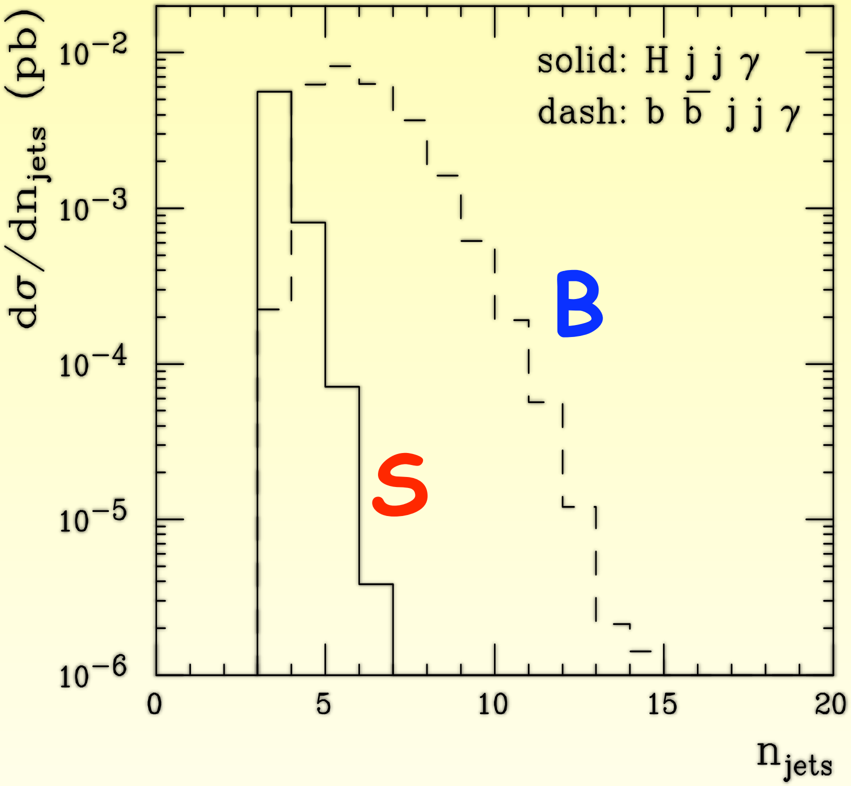


$\Delta\eta(j_1,j_2)$

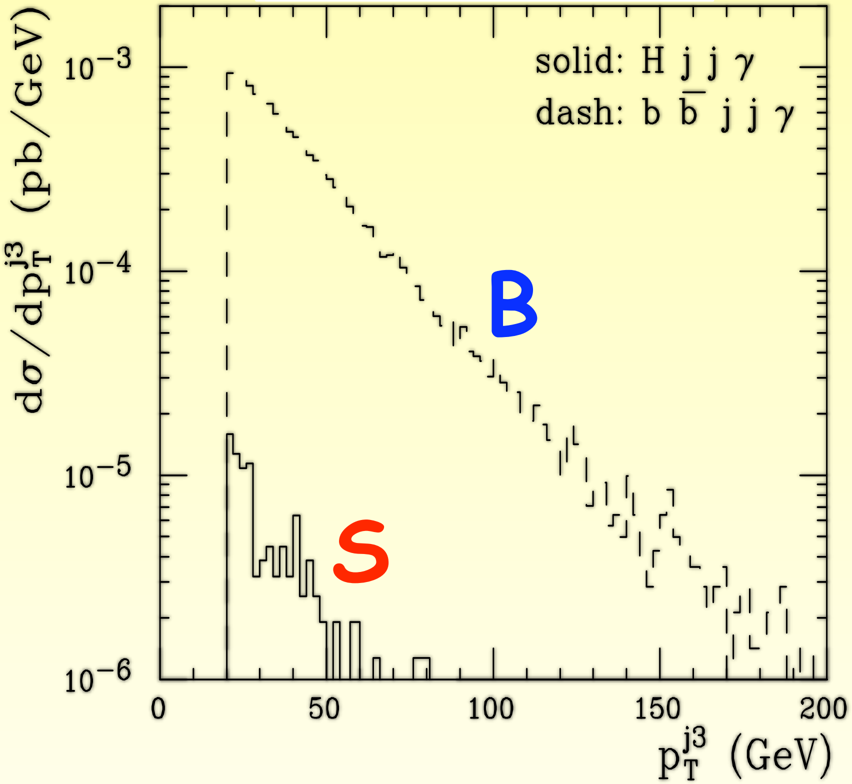
j_1=highest p_T

j_2=second highest p_T

max[$\Delta\eta(j_1,j_2)$] among all jets jet multiplicity distribution



p_T distribution of the third highest p_T jet



COMBINING ALL :

⇒ bckg drops by a factor ~ **4**
(signal almost unaffected !)

⇒ { factor ~ **2** gain in $S/\sqrt{B}$!
$S/\sqrt{B}$ ~ **5** (m_H=120 GeV) !

what if $\gamma \to W$? $pp \to HW\, jj$

$\searrow$ $\nu\, \ell = e, \mu$

Rainwater (2001)
Ballestrero, Bevilacqua, Maina "BBM" (2008)

- could also help in constraining bbH coupling
- cross section smaller than for $pp \to H\gamma\, 2j$

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

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

$\searrow$ $\nu\, \ell = e, \mu$

- "BBM" obtains $S/\sqrt{B} \sim 1.8$ at parton level ($S/B \sim 1/25$)

  ($L = 100$ fb^{-1}, m_H= 120 GeV)

summary on $pp \to H (\to bb)\ 2j + \gamma$

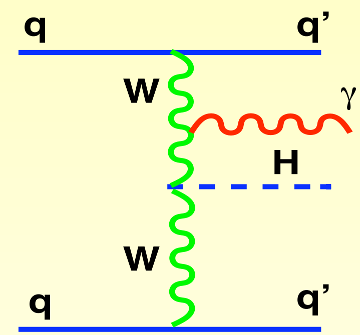
- measurement of g_{Hbb} not yet established at LHC
- $pp \to H\, jj + \gamma$ offers

  a) trigger on γ b) improved S/B

- $S/\sqrt{B} \sim 2.5$ at parton level $\to$ $S/\sqrt{B} \sim 5$ expected after central-jet veto , ($L=100\ fb^{-1}$, $m_H = 120$ GeV)
- could provide a new independent test of Hbb and HWW couplings (sensitivity to HZZ drops) !
- if problems with $H \to \gamma\gamma$, could even have a crucial role in light Higgs searches !
- $pp \to H\, jj + \gamma$ deserves complete detector effect simulation . . . (now ongoing in both ATLAS and CMS)

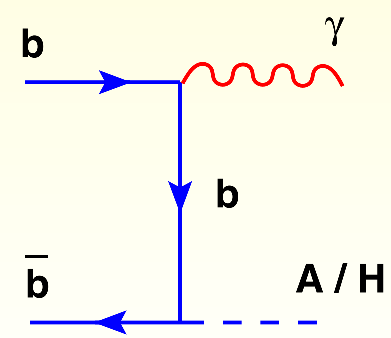
focus on two processes :

- pp → H (→ bb) 2j + γ (in the SM)



Gabrielli, Maltoni, B.M., M.Moretti, Piccinini, Pittau, NPB 781 (2007) 64

- pp → H / A (→ ττ) + γ (in the MSSM)

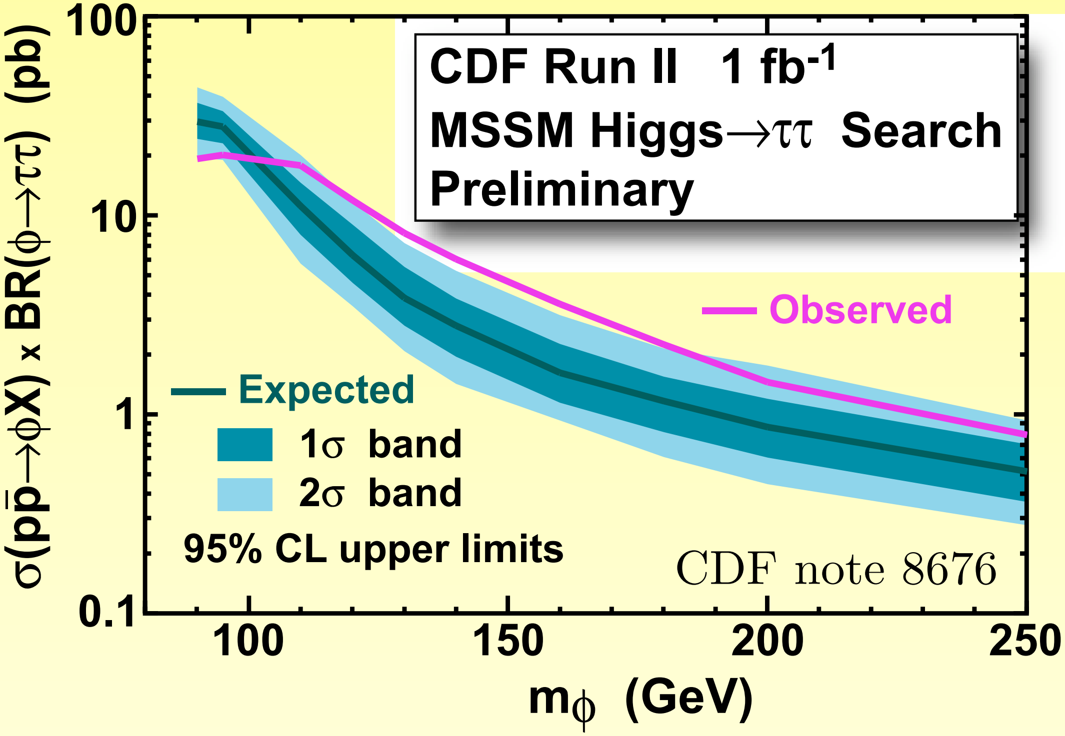


Gabrielli, B.M., Rathsman, PRD 77 (2008) 015007

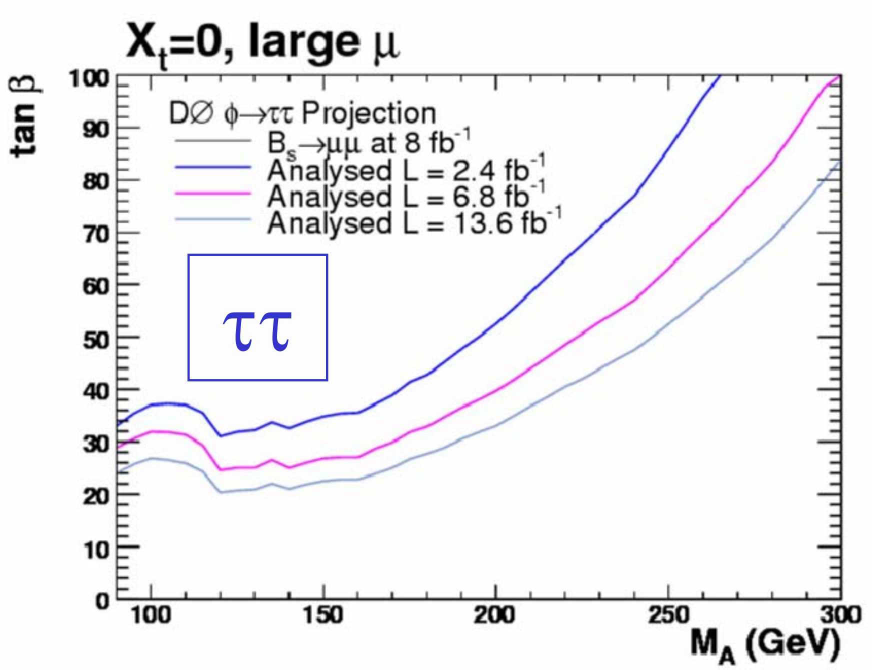
Search for a MSSM Higgs at TeVatron

$$p\bar{p} \to \phi \to \tau^+\tau^-$$

$$\phi = \{h, H, A\}$$



robust prediction in H/A→ $\tau^+\tau^-$ channel !



strong SUSY parameter dependence in Rad. Corrs (Δ_b) [present in H/A→ bb channel] drops in H/A→ $\tau^+\tau^-$ channel :

$$\sigma(gg, b\bar{b} \to A) \quad \mathrm{BR}(A \to \tau^+\tau^-)$$

$$\simeq \quad \sigma(gg, b\bar{b} \to A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \frac{(1+\Delta_b)^2}{(1+\Delta_b)^2+9}$$

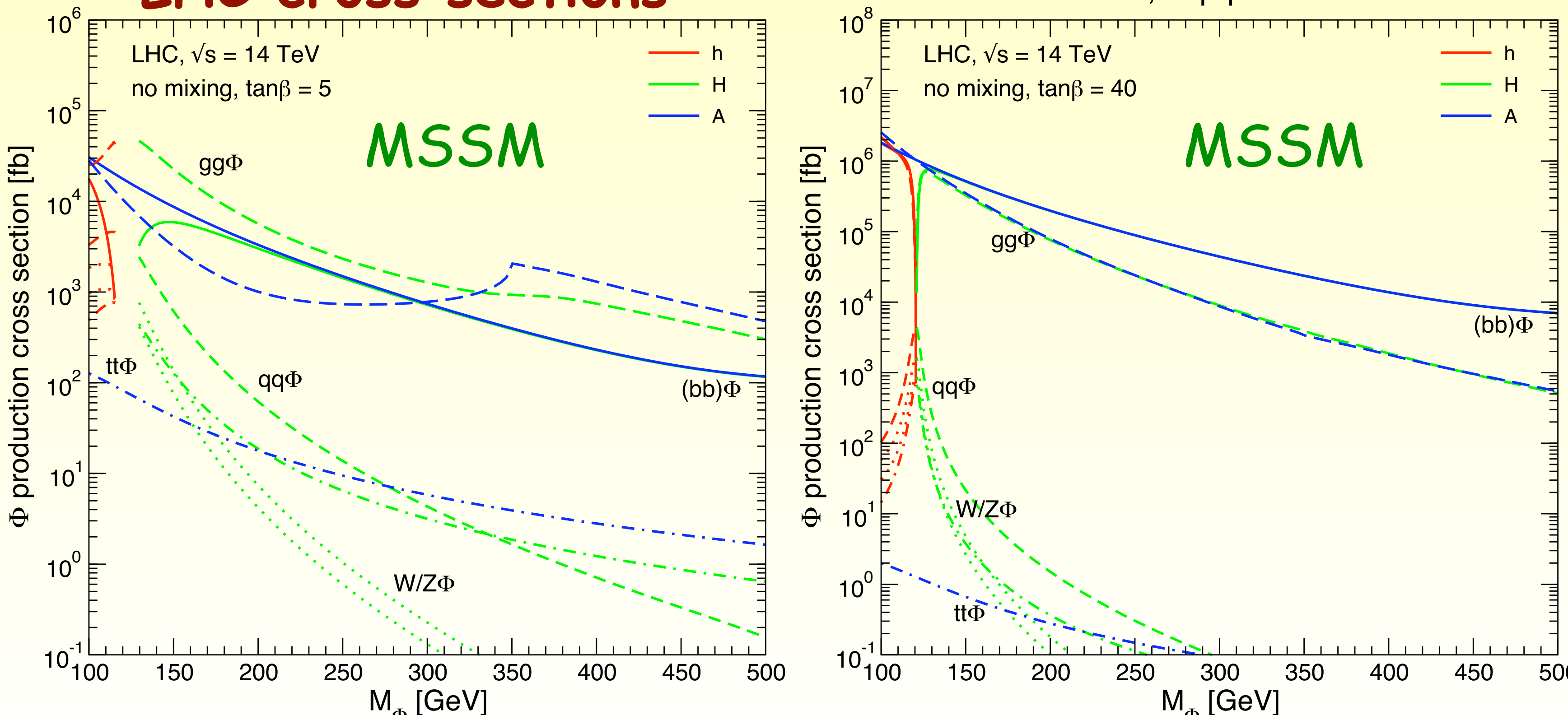
at large $\tan\beta = v_2/v_1$ enhanced couplings to down quarks and leptons !

in MSSM σ($b\bar{b} \to A/H$) ≈ σ($gg \to A/H$) (at moderate tanβ, too)

[in SM σ($b\bar{b} \to h$) $\ll$ σ($gg \to h$)]

LHC cross sections

Hahn et al, hep-ph/0607308



$b\bar{b} \longrightarrow A/H$ sensitive to $y_{bbA/H}$ coupling and
to b-quark parton densities

in b-quark parton density presently derived perturbatively by g(x) !
[no direct measurement of b(x)]

⇒ Δg(x) propagates to Δb(x)

in SM one plans to determine b(x) studying $bg \longrightarrow bZ/b\gamma$

$b\bar{b} \longrightarrow h$ would be more sensitive to b(x),
but swamped by $gg \longrightarrow h$

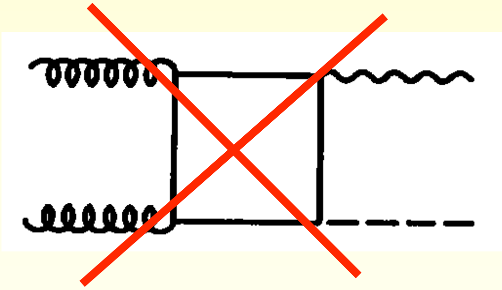
in MSSM $\sigma(b\bar{b} \to A/H) \approx \sigma(gg \to A/H)$

but how to disentangle bb from gg ?

ask for a high p_T photon !

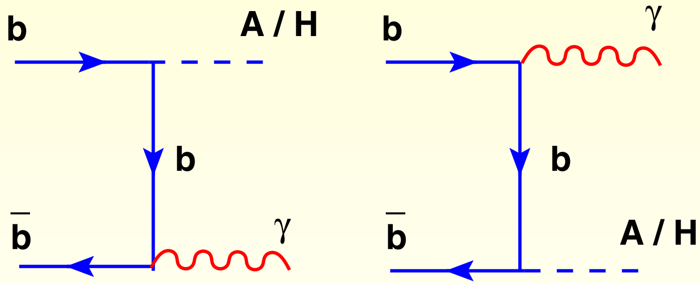
$$\phi = \{h, H, A\}$$

$$gg \to \phi\gamma$$



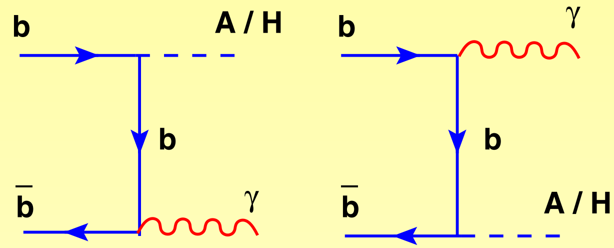
by C-parity

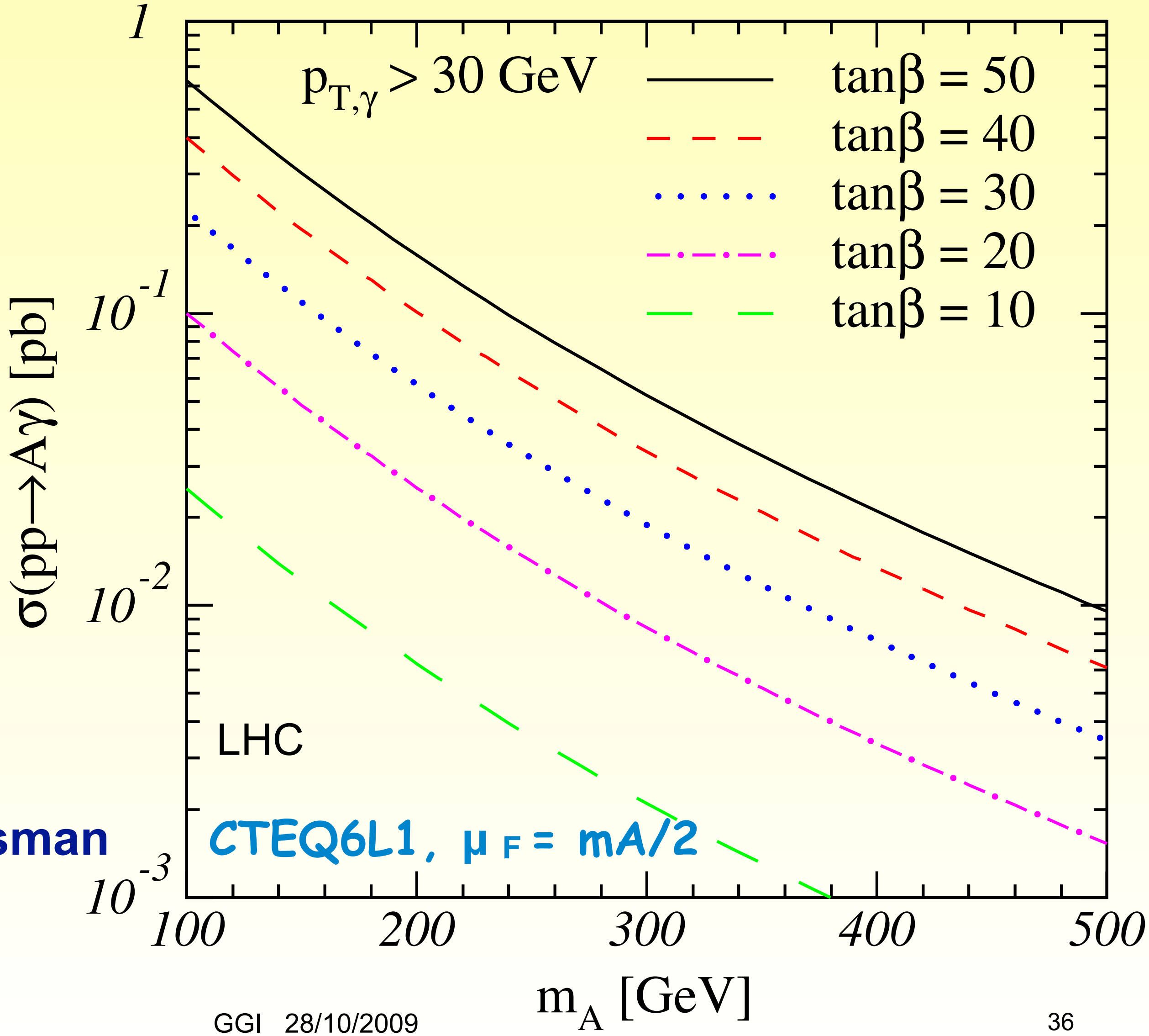
$$b\bar{b} \to \phi\gamma$$



only contribution to $pp \to \phi\gamma$

σ suppressed by α_{em} and $Q_b^2 = 1/9$, but still quite large at large tanβ !





Gabrielli, B.M., Rathsman

we consider : $b\bar{b} \to \phi\gamma \to \tau\tau\gamma$

$\mathrm{BR}(A/H \to \tau\tau) \simeq 10\%$ for large tanβ, almost insensitive to m_H

- irreducible BCKGs have EW origin (manageable !)

- tau-tau signature extensively studied in SM and MSSM (can help in Higgs discovery)

Note: the complete tau-tau invariant mass can be fully reconstructed, provided the two taus are neither back-to-back nor collinear in lab frame (due to undetected neutrinos)

a large-p_T photon naturally satisfies the above condition !

- Large SUSY radiative corrections on b-Yukawa factorizes, residual dependence is small

- in MSSM, mA ~ mH (at large tanβ)
- gives a factor 2 of enhancement in the x-section

- assumed tau-pair efficiency = 0.2
- comes from
- $\tau \to \ell \, \nu_\tau \nu_\ell \; (35\%)$ ID efficiency = 90%
- $\tau \to h\nu \; (50\%)$ ID efficiency = 25%
- double hadronic decays contribute with
- 0.016 to 0.2

$b\bar{b} \to \phi\gamma \to \tau\tau\gamma$

main irred. bckgs :

$pp \to Z^*/\gamma^*\,\gamma \to \tau\tau\gamma$

$gg,\; bb \to \phi \to \tau^*\tau \to \tau\tau\gamma$

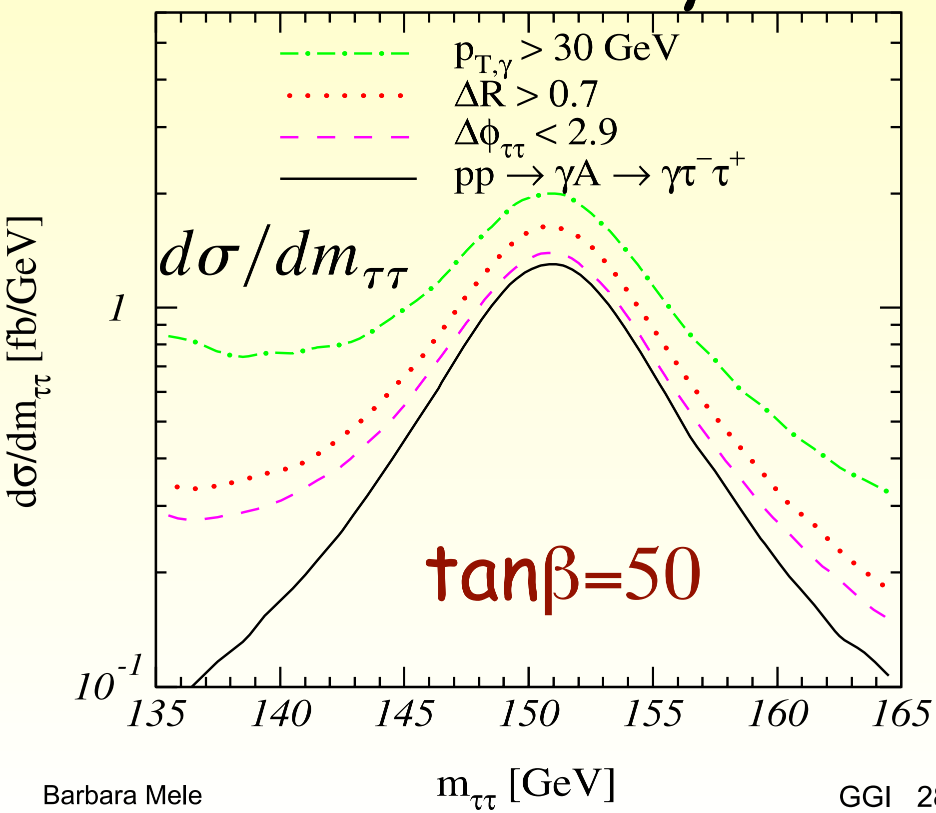
$(\sigma_A + \sigma_H \approx 2\,\sigma_A)$

$0.9 m_A < m_{\tau\tau} < 1.1 m_A$

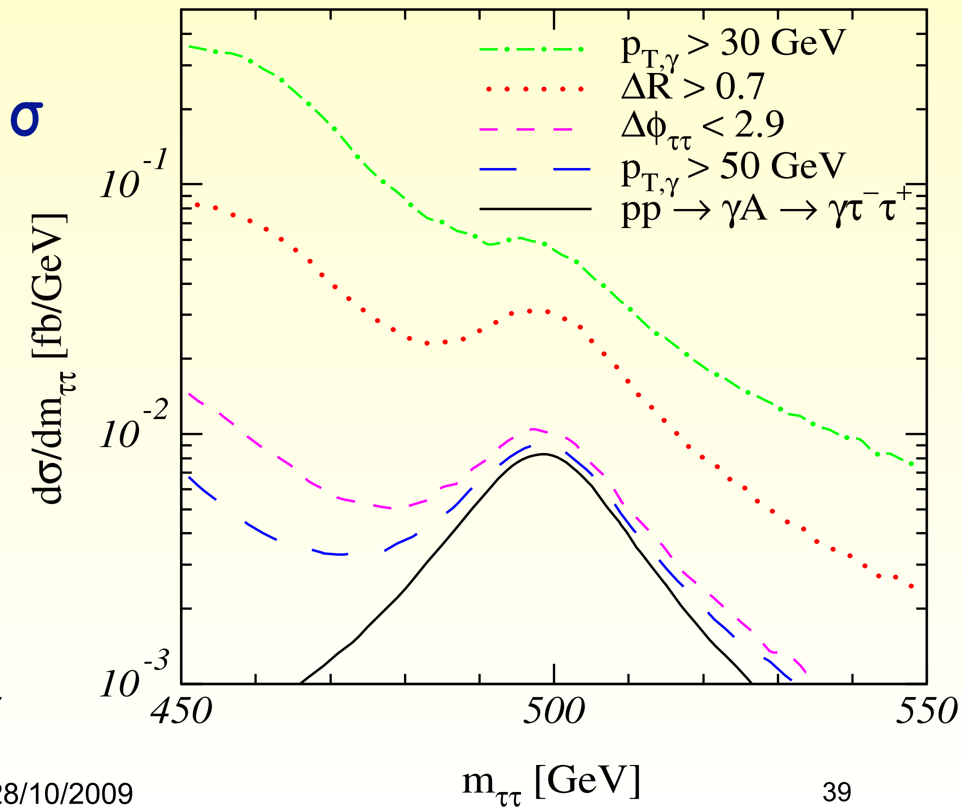
$p_T^{\tau^\pm} > 20$ GeV, $|\eta_\gamma| < 2.5$, $|\eta_{\tau^\pm}| < 2.5$

$\Delta R_{\gamma\tau^\pm} > 0.7$, $\Delta R_{\tau\tau} > 0.7$, $\Delta\phi_{\tau\tau} < 2.9$

$b\bar{b} \to \tau\tau\gamma$



σ



$$pp \longrightarrow \tau^+ \tau^- \gamma$$

$(\sigma_A + \sigma_H \approx 2\,\sigma_A)$

n(S) ⇒ $b\bar{b} \longrightarrow \phi\gamma \longrightarrow \tau\tau\gamma$

n(B) ⇒ irred. bckgs

$\tan\beta$	20		30		40		50	
m_A	σ_S (fb)	$\mathcal{S}$	σ_S (fb)	$\mathcal{S}$	σ_S (fb)	$\mathcal{S}$	σ_S (fb)	$\mathcal{S}$
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

$\epsilon_{\tau\tau} \simeq 0.2$

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

$\mathcal{S} = n(S)/\sqrt{n(S)+n(B)} \gtrsim 5$

for $m_A \lesssim 300$ GeV **and** $\tan\beta \gtrsim 30$

comments on pp → H / A (→ ττ) + γ

- cross section varies by 20% within LHAPDF; actual uncertainty on b(x) could well be larger than that (see e.g. Thorne, arXiv:0711.2986)
- Hbb coupling (tanβ) can be determined via complementary processes ($\mathrm{gg} \to \mathrm{bbH/A}$) ; then $b\bar{b} \to \phi\gamma$ cleaner probe of b(x) densities
- needs inclusion of QCD corrections

  (Carloni Calame, Gabrielli, BM, Piccinini, in progress)
- needs full exp simulation to assess its actual potential