

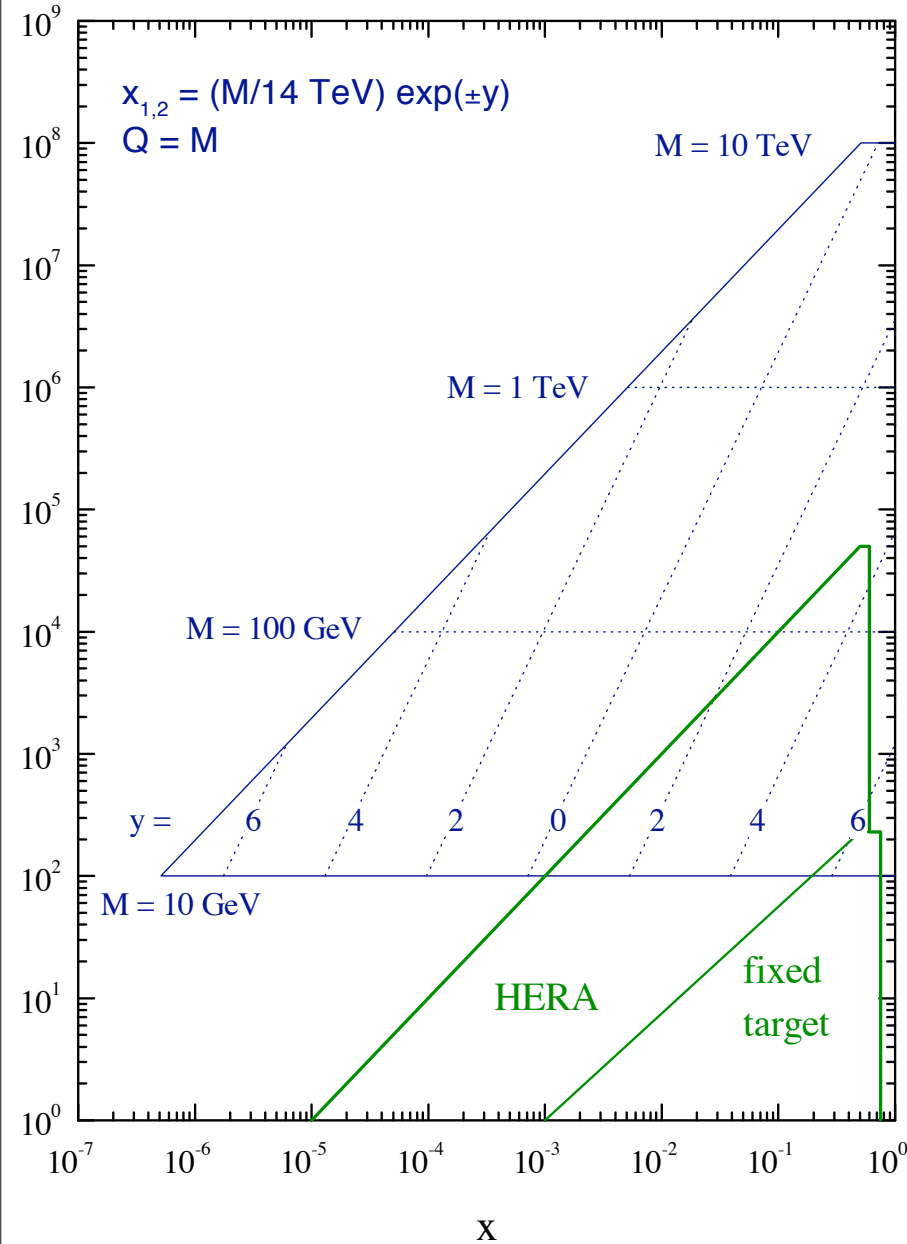
Higgs production in association with jets at the LHC

Vittorio Del Duca
INFN LNF

LHC kinematic reach

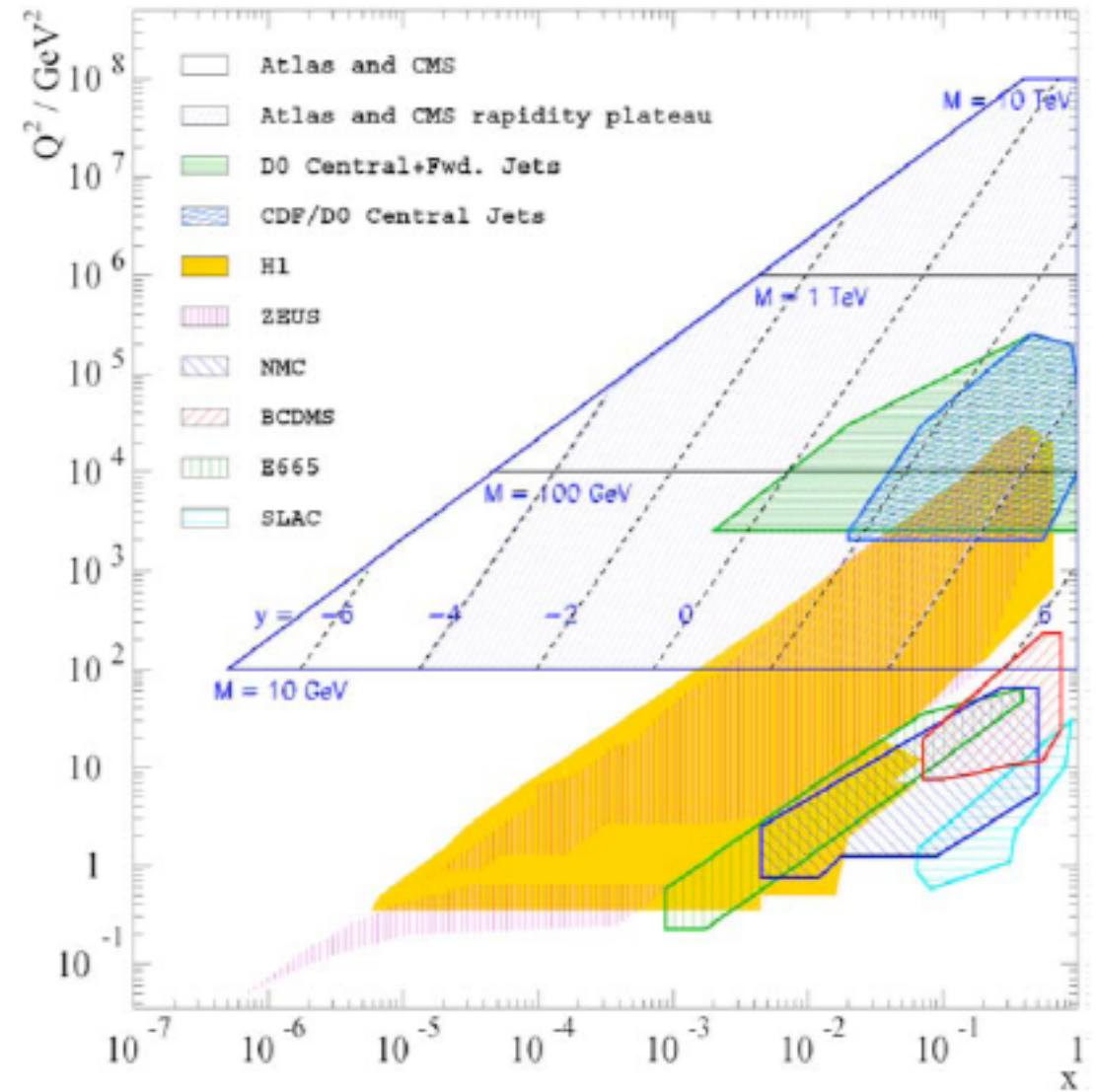
LHC parton kinematics

LHC opens up a new kinematic range



Feynman x's for the production of a particle of mass M

$$x_{1,2} = \frac{M}{14 \text{ TeV}} e^{\pm y}$$



HIGGS PRODUCTION MODES AT LHC

In proton collisions at **14 TeV**, and for $M_H > 100$ GeV the **Higgs** is produced mostly via

🏆 **gluon fusion** $gg \rightarrow H$

🥈 largest rate for all M_H

🥉 proportional to the top Yukawa coupling y_t

🏆 **weak-boson fusion (VBF)** $qq \rightarrow qqH$

🥈 second largest rate (mostly ud initial state)

🥉 proportional to the **VVH** coupling

🏆 **Higgs-strahlung** $q\bar{q} \rightarrow W(Z)H$

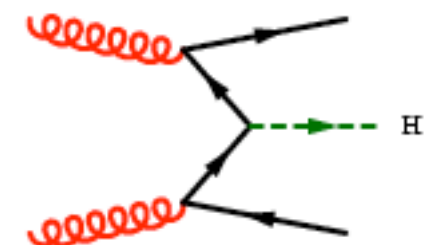
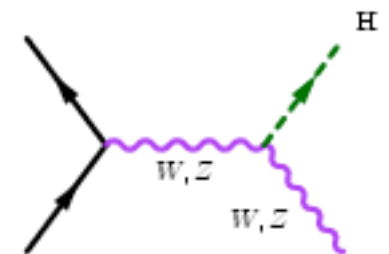
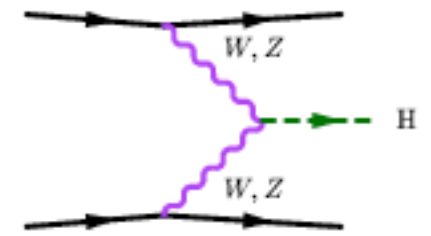
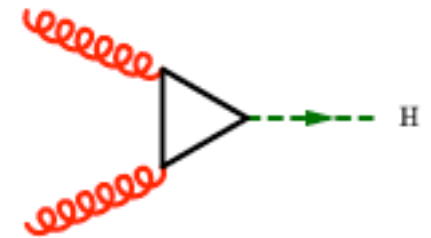
🥈 third largest rate

🥉 same coupling as in **VBF**

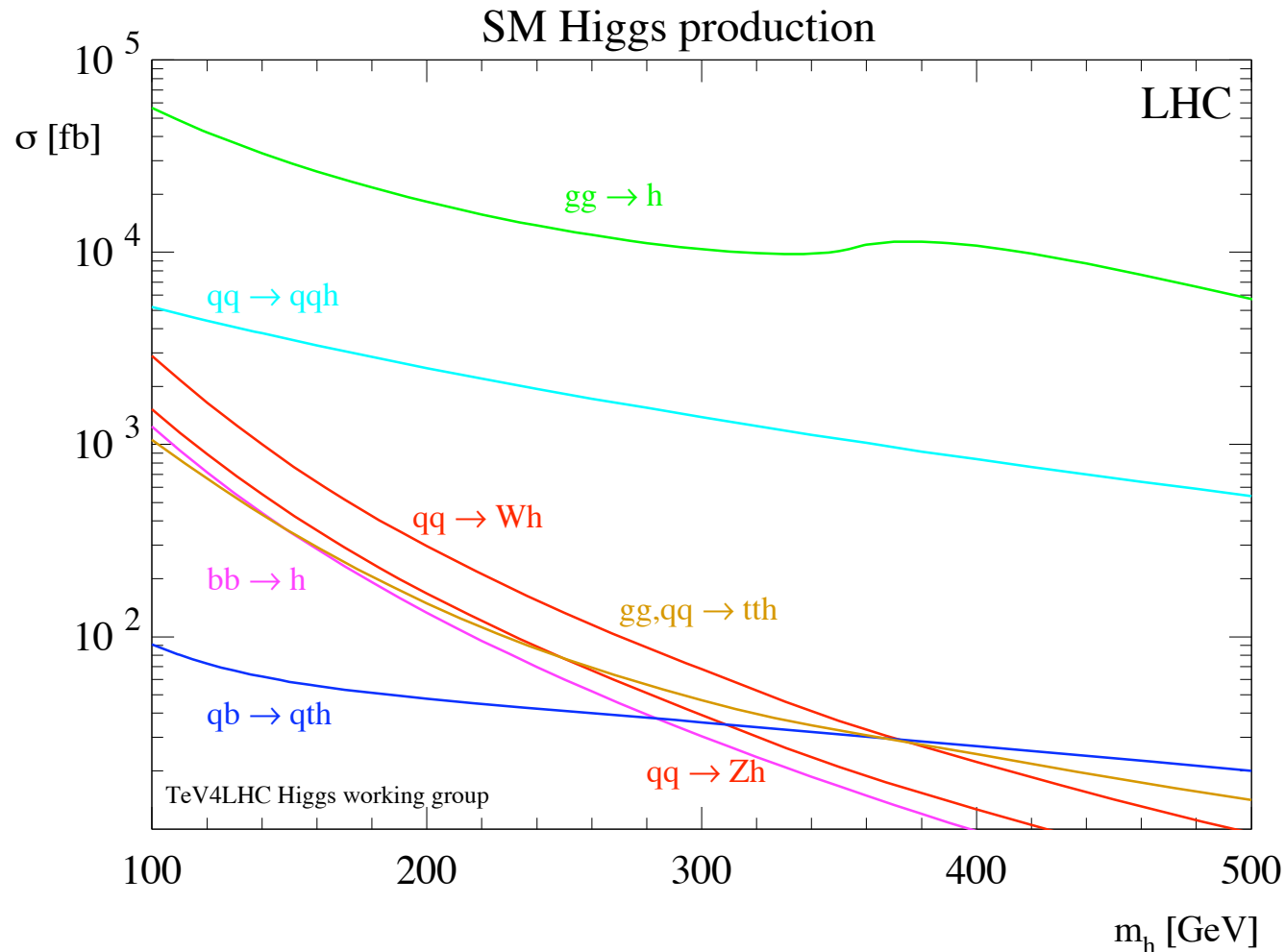
🏆 $t\bar{t}(b\bar{b})H$ associated production

🥈 same initial state as in **gluon fusion**, but higher x range

🥉 proportional to the heavy-quark Yukawa coupling y_Q



HIGGS PRODUCTION AT LHC



in the intermediate Higgs mass range $M_H \sim 100 - 200$ GeV

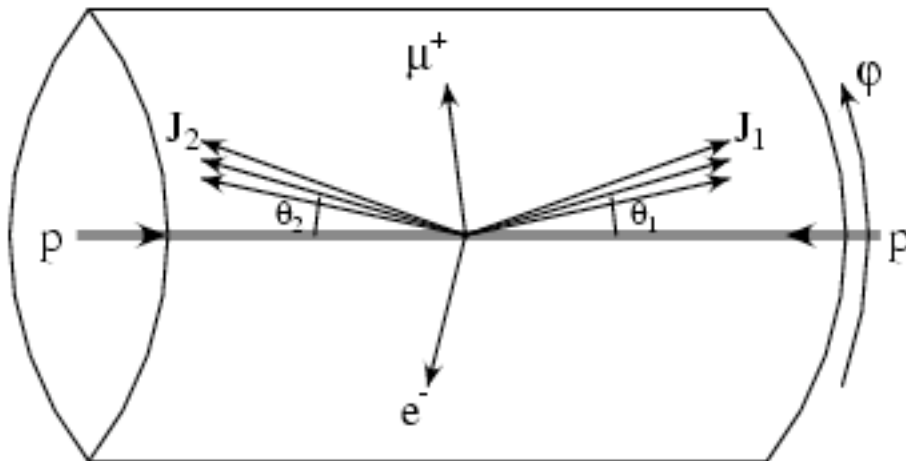
gluon fusion cross section is $\sim 20 - 60$ pb

WBF cross section is $\sim 3 - 5$ pb

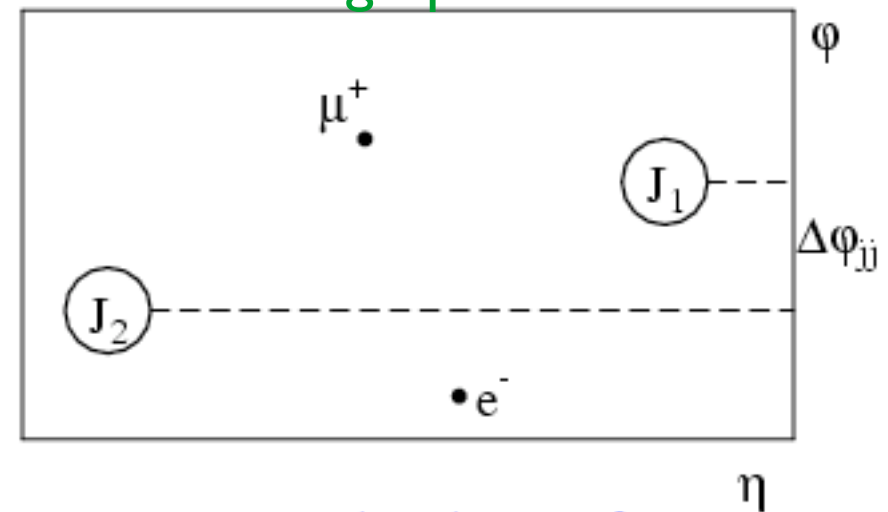
$WH, ZH, t\bar{t}H$ yield cross sections of $\sim 0.2 - 3$ pb

WEAK BOSON FUSION: $qq \rightarrow qqH$

A WBF event



Lego plot

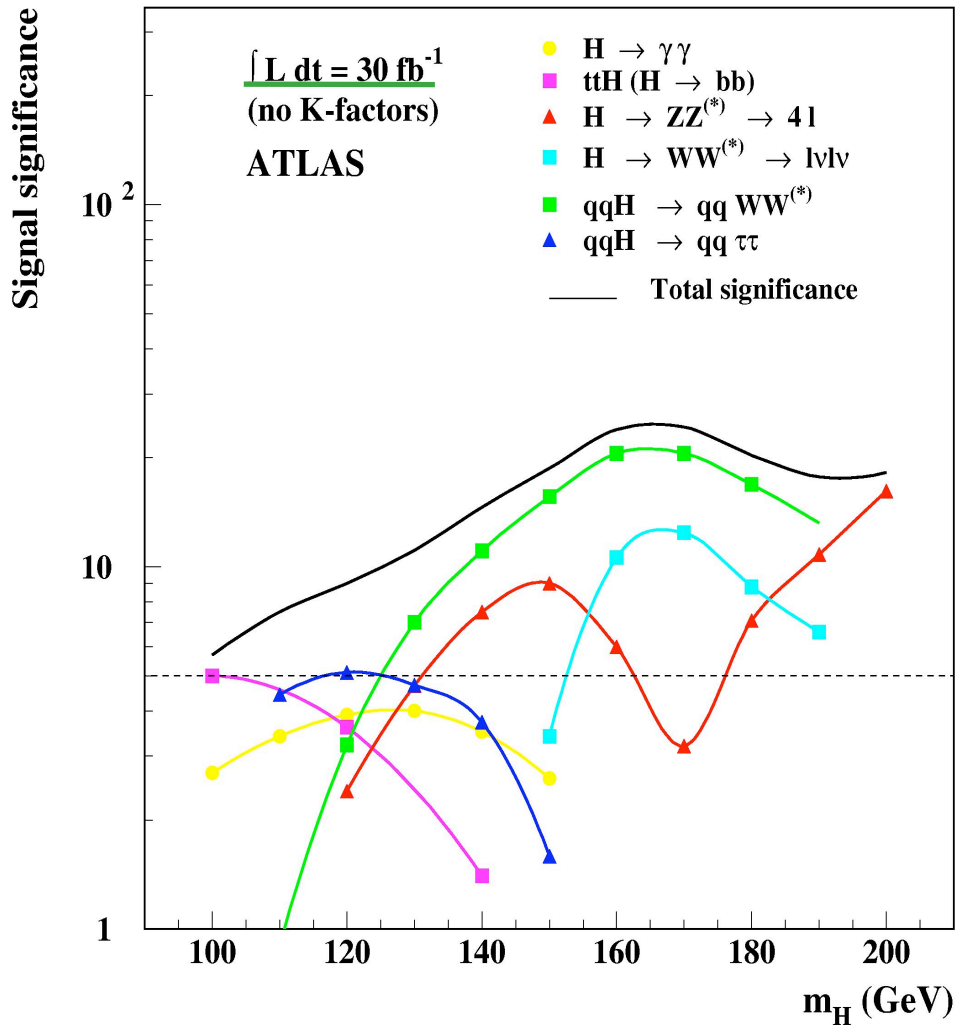


$$\eta = \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta}$$

WBF features

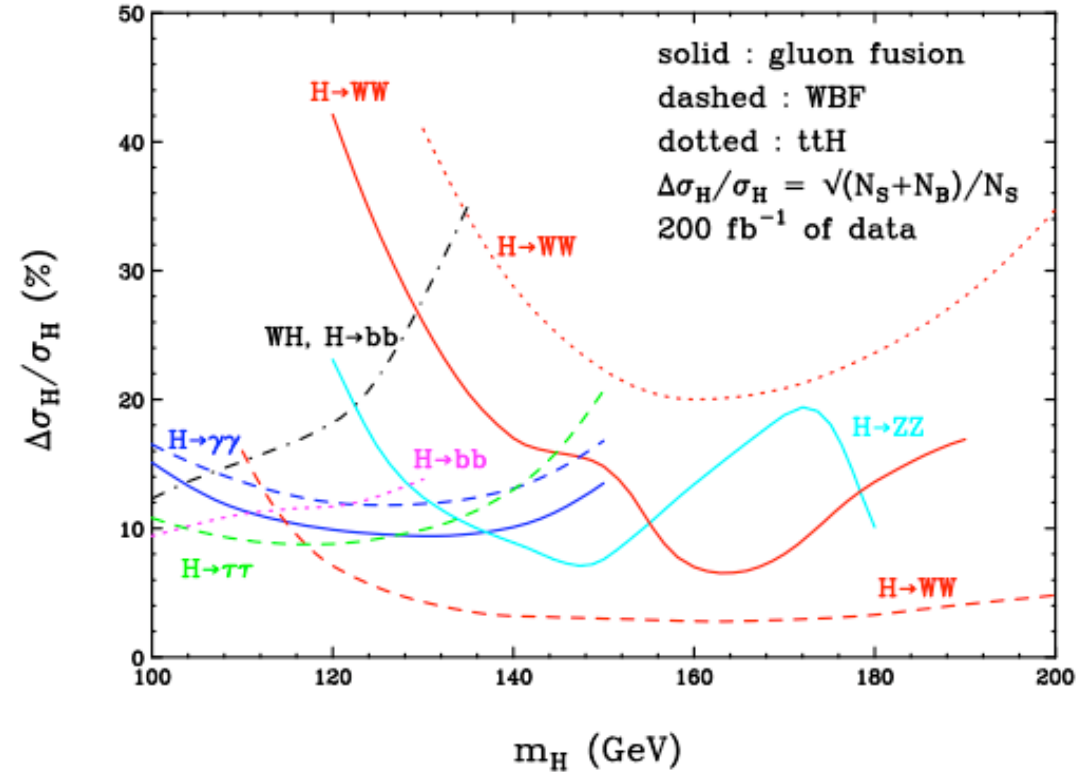
- energetic jets in the forward and backward directions
- Higgs decay products between the tagging jets
- sparse gluon radiation in the central-rapidity region, due to colourless W/Z exchange
- NLO corrections increase the WBF production rate by about 10%, and thus are small and under control
- WBF can be measured with good statistical accuracy: $\sigma \times \text{BR} \approx \mathcal{O}(10\%)$

SIGNAL SIGNIFICANCE AND (STAT + SYST) ERROR



Statistical significance:
$$\frac{N_S}{\sqrt{N_S + N_B}}$$

INCLUSIVE HIGGS PRODUCTION



hep-ph/0203187

QCD/p.d.f. uncertainties:

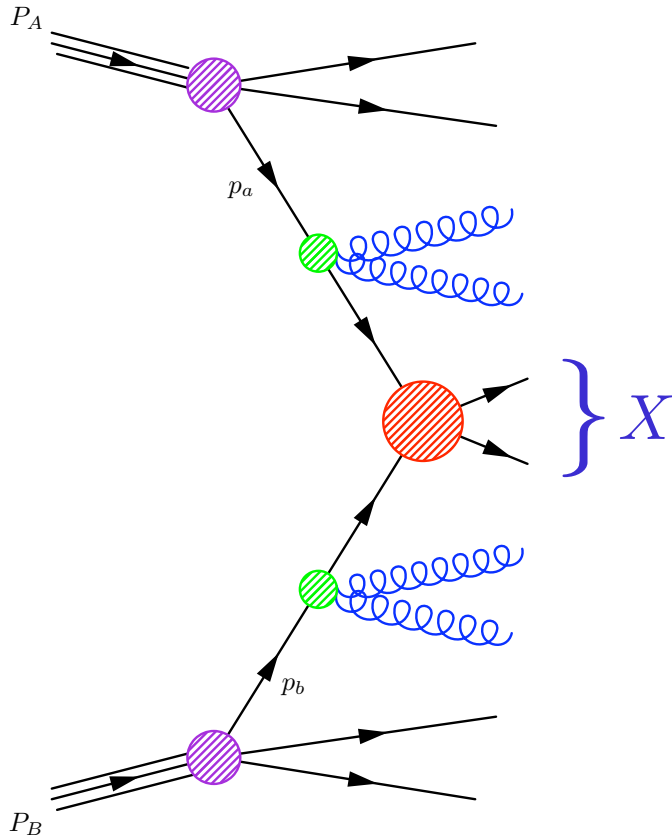
$\mathcal{O}(5\%)$ for WBF

$\mathcal{O}(20\%)$ for gluon fusion

luminosity uncertainties: $\mathcal{O}(5\%)$

Cross sections at high Q^2

separate the short- and the long-range interactions through factorisation



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a/A}(x_1, \mu_F^2) f_{b/B}(x_2, \mu_F^2) \times \hat{\sigma}_{ab \rightarrow X} \left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)$$

$X = W, Z, H, Q\bar{Q}, \text{high-}E_T \text{jets}, \dots$

$\hat{\sigma}$ is known as a fixed-order expansion in α_S

$$\hat{\sigma} = C \alpha_S^n (1 + c_1 \alpha_S + c_2 \alpha_S^2 + \dots)$$

$c_1 = \text{NLO}$ $c_2 = \text{NNLO}$

or as an all-order resummation

$$\hat{\sigma} = C \alpha_S^n [1 + (c_{11}L + c_{10})\alpha_S + (c_{22}L^2 + c_{21}L + c_{20})\alpha_S^2 + \dots]$$

where $L = \ln(M/q_T), \ln(1-x), \ln(1/x), \ln(1-T), \dots$

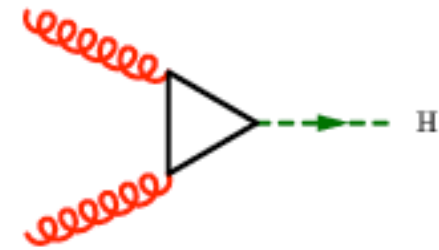
$c_{11}, c_{22} = \text{LL}$ $c_{10}, c_{21} = \text{NLL}$ $c_{20} = \text{NNLL}$

HIGGS PRODUCTION VIA GLUON FUSION

LEADING ORDER

$$\mathcal{O}(\alpha_s^2)$$

$$gg \rightarrow H$$

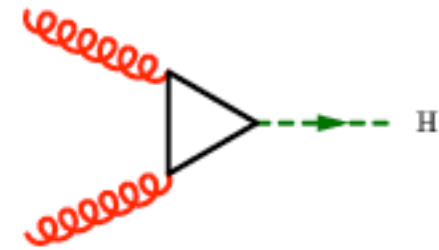


energy scales: $\hat{s} = M_H^2$ and M_t^2

HIGGS PRODUCTION VIA GLUON FUSION

LEADING ORDER

$$\mathcal{O}(\alpha_s^2) \quad gg \rightarrow H$$

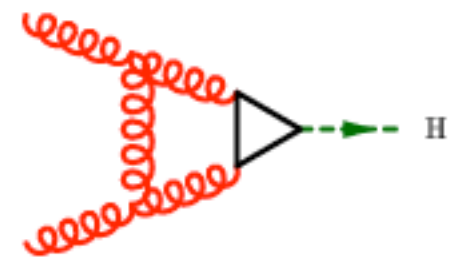
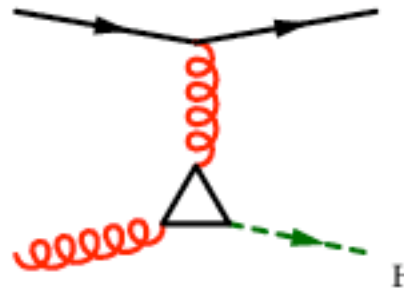
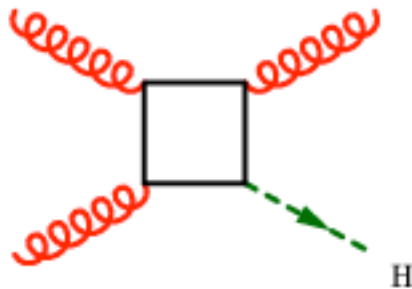


energy scales: $\hat{s} = M_H^2$ and M_t^2

NLO CORRECTIONS

$$\mathcal{O}(\alpha_s^3)$$

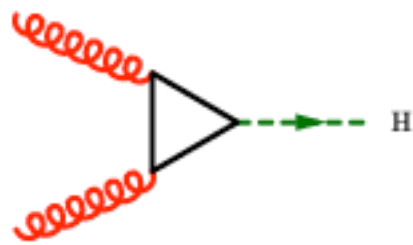
- 2-loop $gg \rightarrow H$
- 1-loop $gg \rightarrow gH$ $qg \rightarrow qH$ + crossings



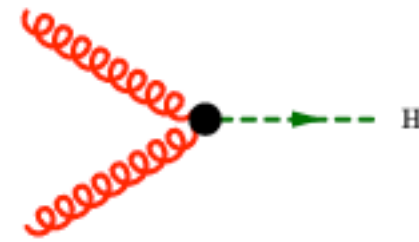
Djouadi, Graudenz, Spira, Zerwas, '93-'95

large K factor: $\sigma^{\text{NLO}} = K^{\text{NLO}} \sigma^{\text{LO}} \quad \mathcal{O}(40 - 100\%)$

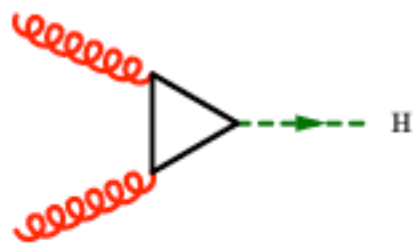
THE LARGE TOP-MASS LIMIT



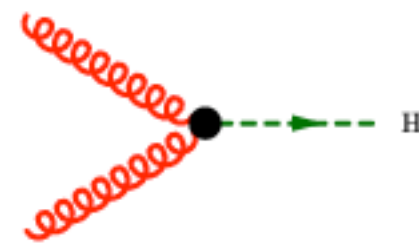
$$M_H \ll 2M_t$$



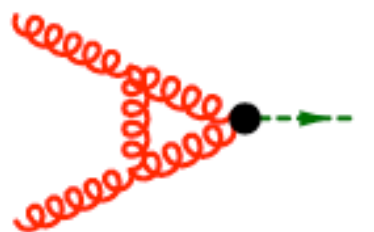
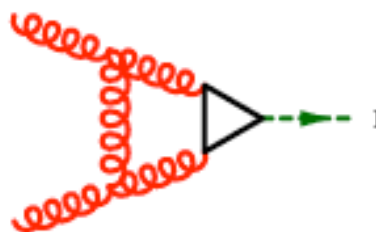
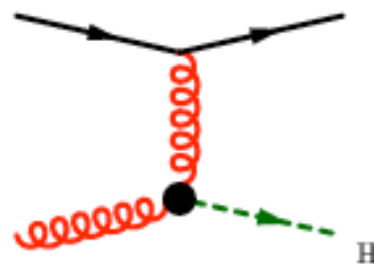
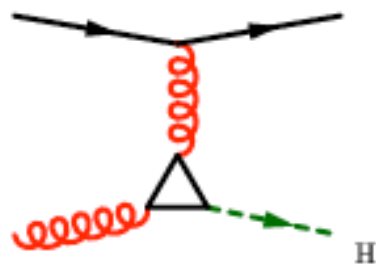
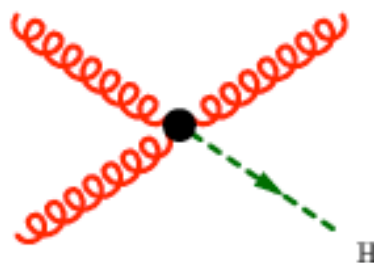
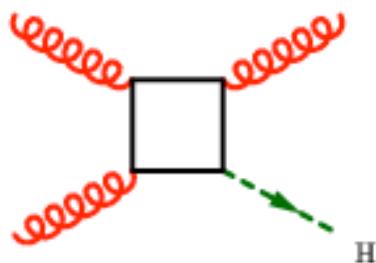
THE LARGE TOP-MASS LIMIT



$$M_H \ll 2M_t$$



NLO CORRECTIONS



K factor in the large M_t limit

$$K_\infty = \lim_{M_t \rightarrow \infty} K$$

NLO rate in the large M_t limit

$$\sigma_\infty^{\text{NLO}} = K_\infty^{\text{NLO}} \sigma^{\text{LO}}$$

$\sigma_\infty^{\text{NLO}}$ is within 10% of σ^{NLO}
for $M_H \lesssim 1 \text{ TeV}$

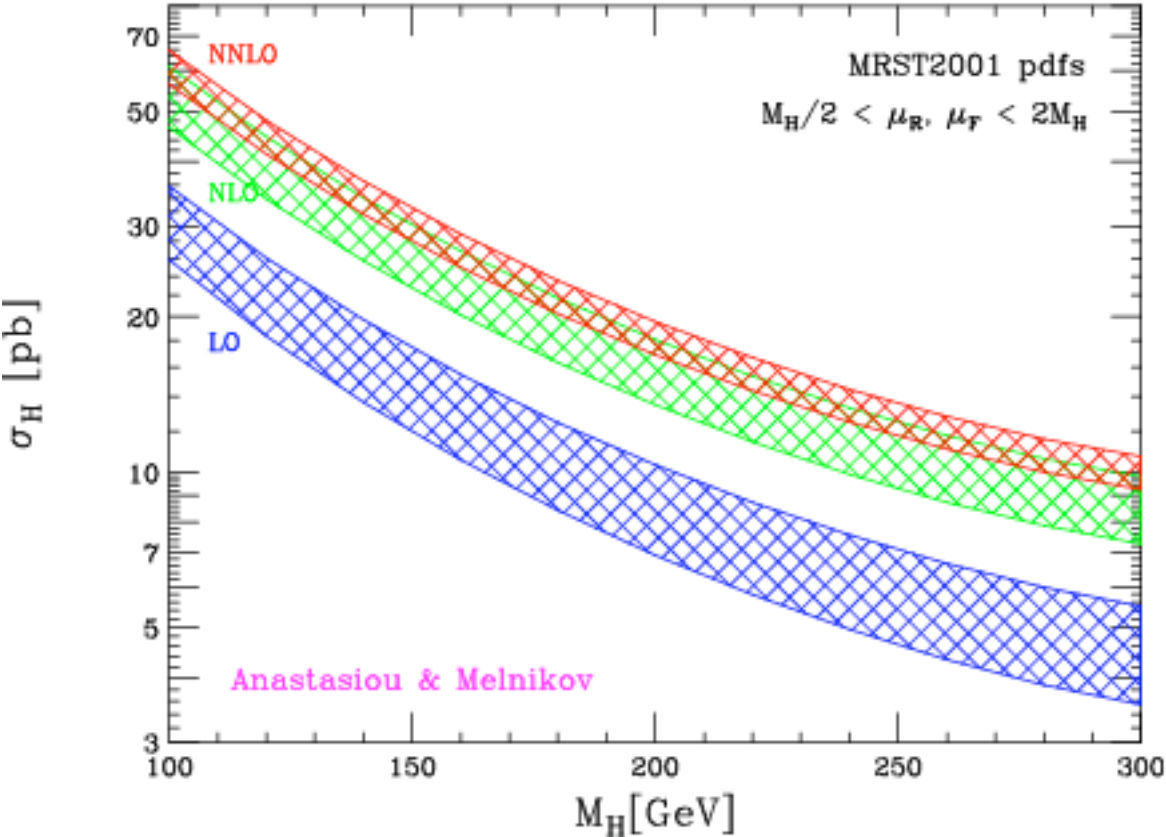
$gg \rightarrow H$ IN THE LARGE M_t LIMIT

NNLO CORRECTIONS

$\mathcal{O}(\alpha_s^4)$

R. Harlander hep-ph/0007289

- 2-loop $gg \rightarrow H$
- 1-loop $gg \rightarrow gH$ $qg \rightarrow qH$ + crossings
- tree $gg \rightarrow ggH$ $qg \rightarrow qgH$ $qQ \rightarrow qQH$ + crossings



total cross section for
inclusive **Higgs** production
at **LHC**

Harlander Kilgore 02
Anastasiou Melnikov 02
Ravindran Smith van Neerven 03

The band contours are

- lower $\mu_R = 2M_H$ $\mu_F = M_H/2$
- upper $\mu_R = M_H/2$ $\mu_F = 2M_H$

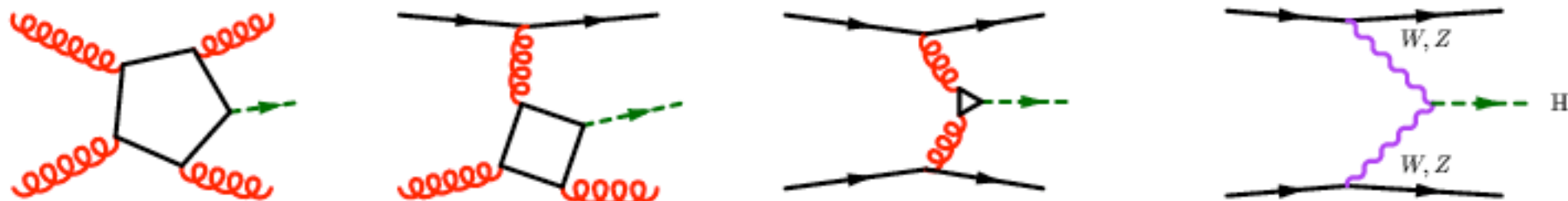
HIGGS COUPLINGS AND QUANTUM NUMBERS

The properties of the Higgs-like resonance are its

- couplings: gauge, Yukawa, self-couplings
- quantum numbers: charge, colour, spin, CP

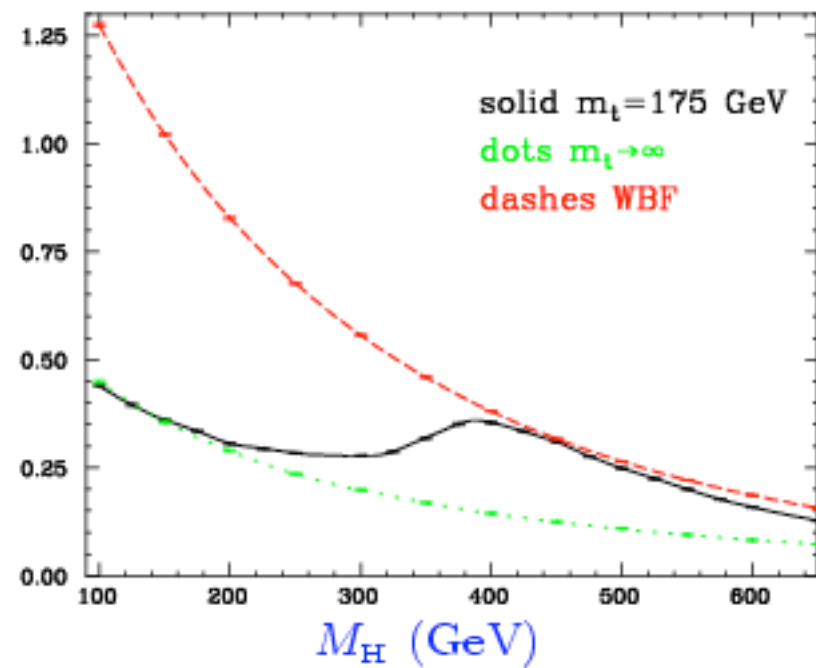
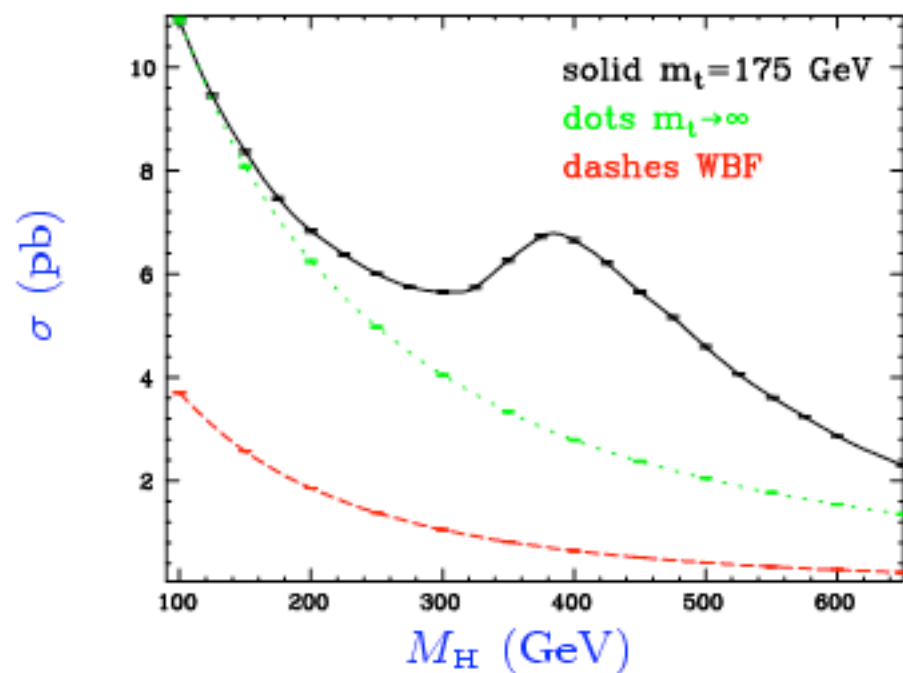
The gauge coupling has also CP properties and a tensor structure. Info on that can be obtained by analysing the final-state topology of Higgs + 2 jet events

$H + 2$ JETS RATE as a function of M_H



$$\mu_F = \sqrt{p_{j1\perp} p_{j2\perp}}, \mu_R = M_Z$$

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0105129



inclusive cuts: $\left\{ \begin{array}{l} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{array} \right.$

WBF cuts: incl. + $\left\{ \begin{array}{l} |\eta_{j1} - \eta_{j2}| > 4.2 \\ \eta_{j1} \cdot \eta_{j2} < 0 \\ \sqrt{s_{j1j2}} > 600 \text{ GeV} \end{array} \right.$

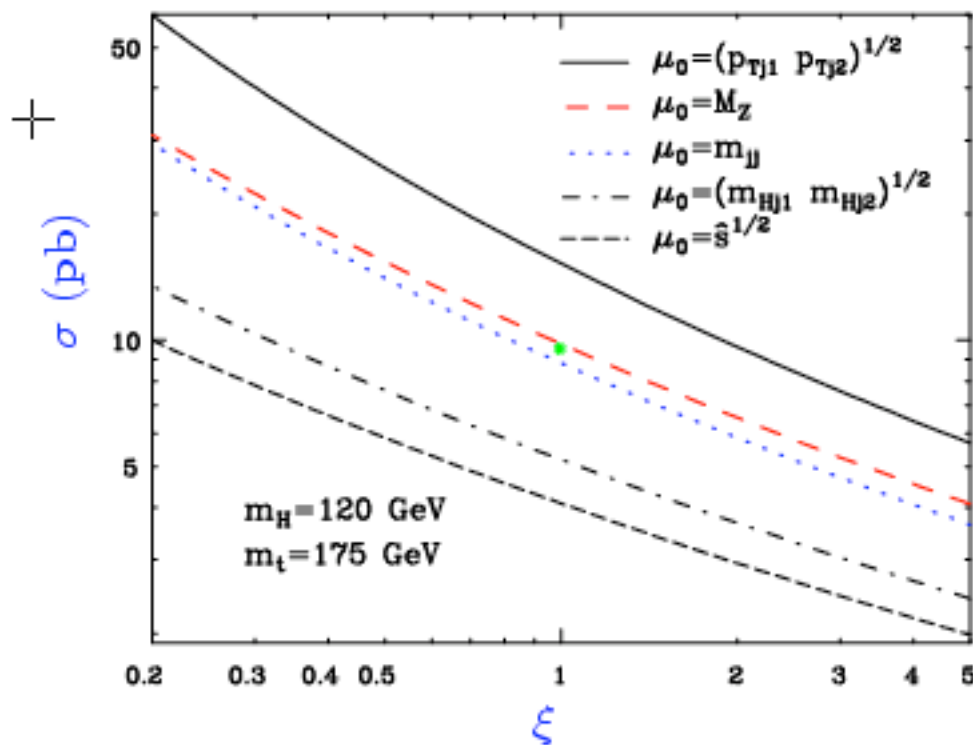
👁 WBF cuts enhance WBF wrt gluon fusion by a factor 10

SCALE DEPENDENCE

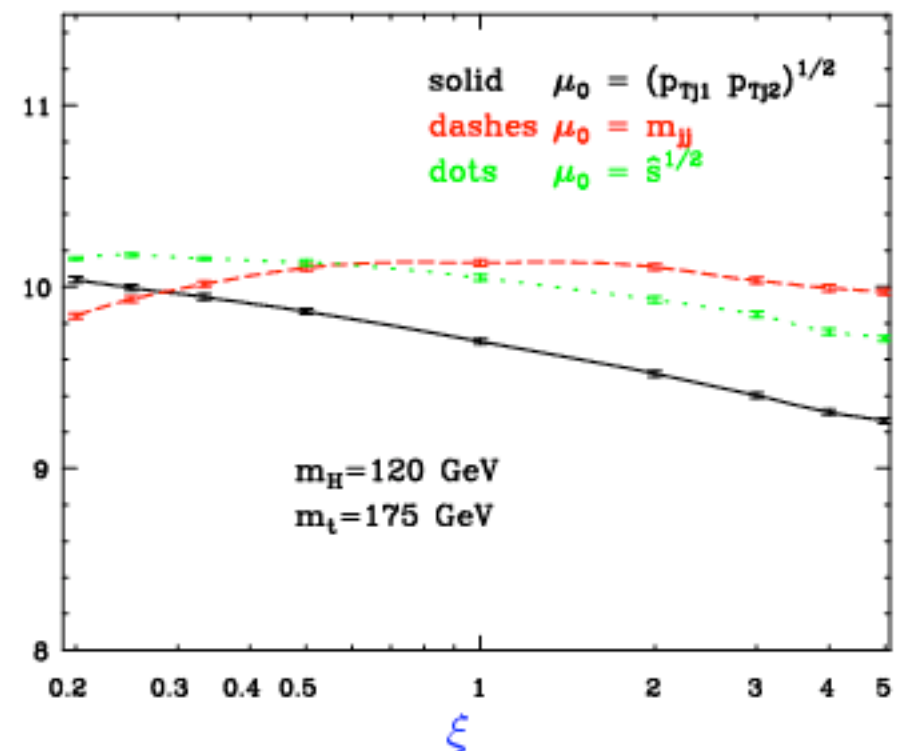
renormalisation μ_R & factorisation μ_F scales

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0108030

$$\mu_R = \xi \mu_0, \mu_F = \sqrt{p_{j1\perp} p_{j2\perp}}$$



$$\mu_F = \xi \mu_0, \mu_R = M_Z$$



☛ strong μ_R dependence: the calculation is LO and $\mathcal{O}(\alpha_s^4)$

☛ a natural scale for α_s ?

high energy limit suggests $\alpha_s^4 \rightarrow \alpha_s(p_{j1\perp}) \alpha_s(p_{j1\perp}) \alpha_s^2(M_H)$

☛ σ varies by a factor 2.5 for $\mu_0/2 < \mu_R < 2\mu_0$

☛ mild μ_F dependence: $\mathcal{O}(10\%)$ over the $\mu_0/5 < \mu_R < 5\mu_0$ range

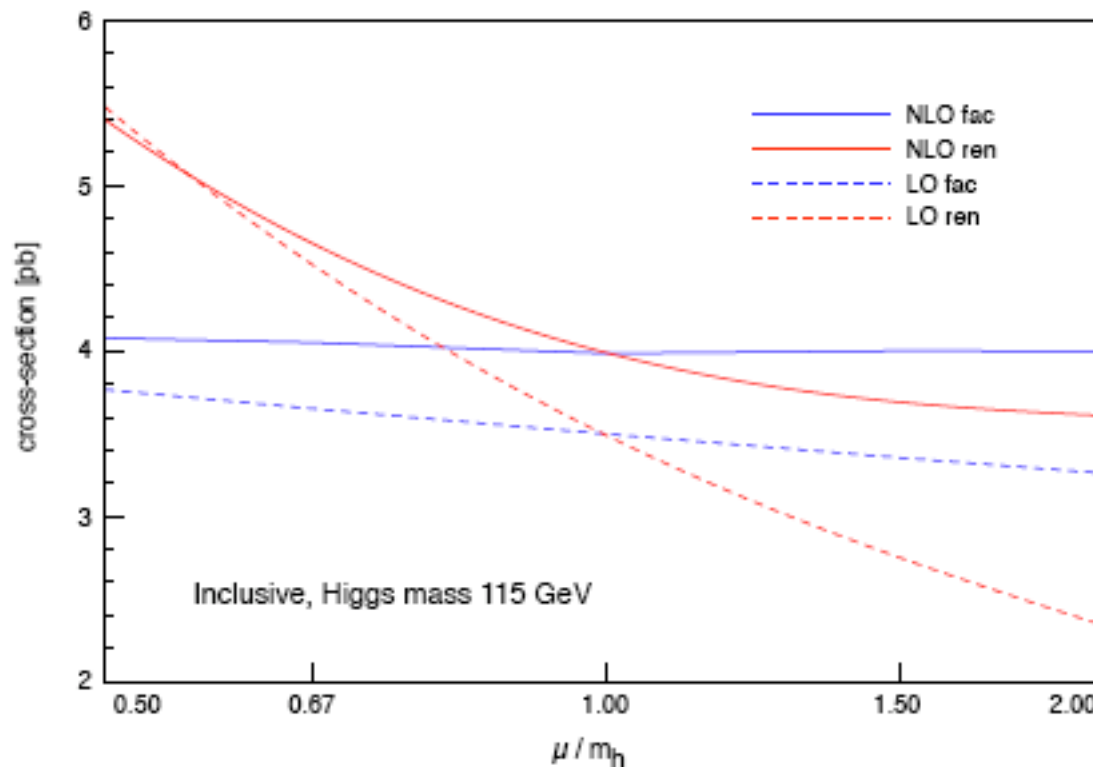
NLO corrections

- NLO corrections increase the **WBF** production rate by about **10 %**, with a few % change under μ_R scale variation

Campbell, Ellis; Figy, Oleari, Zeppenfeld 2003
Berger Campbell 2004

- NLO corrections in the large M_{top} limit increase the **gluon fusion** production rate by about **15--25 %**, but the change under μ_R scale variation is sizeable

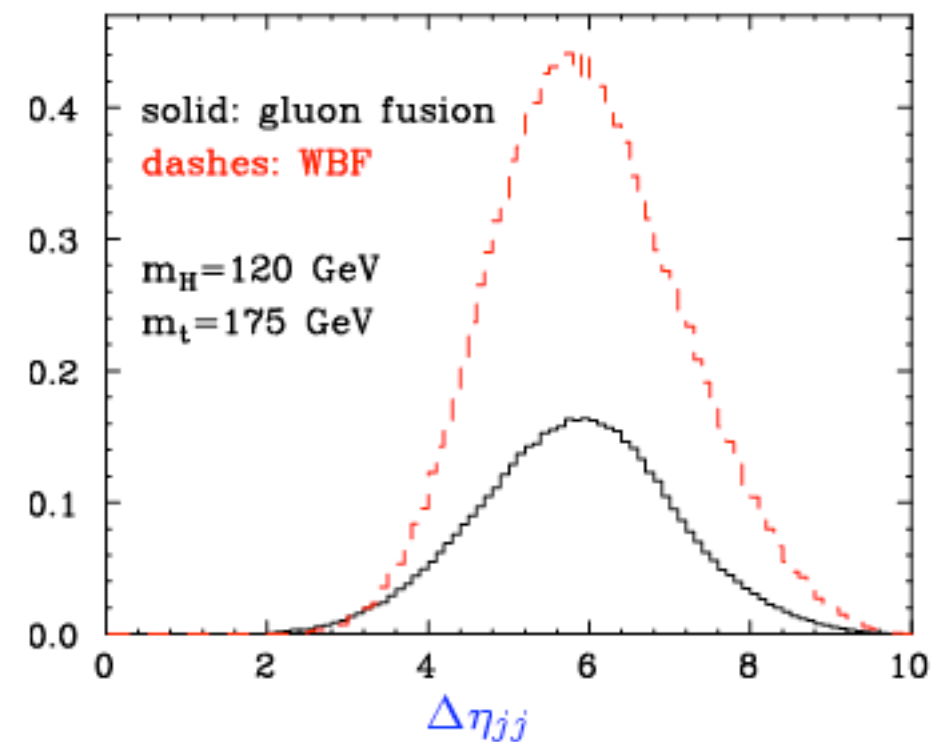
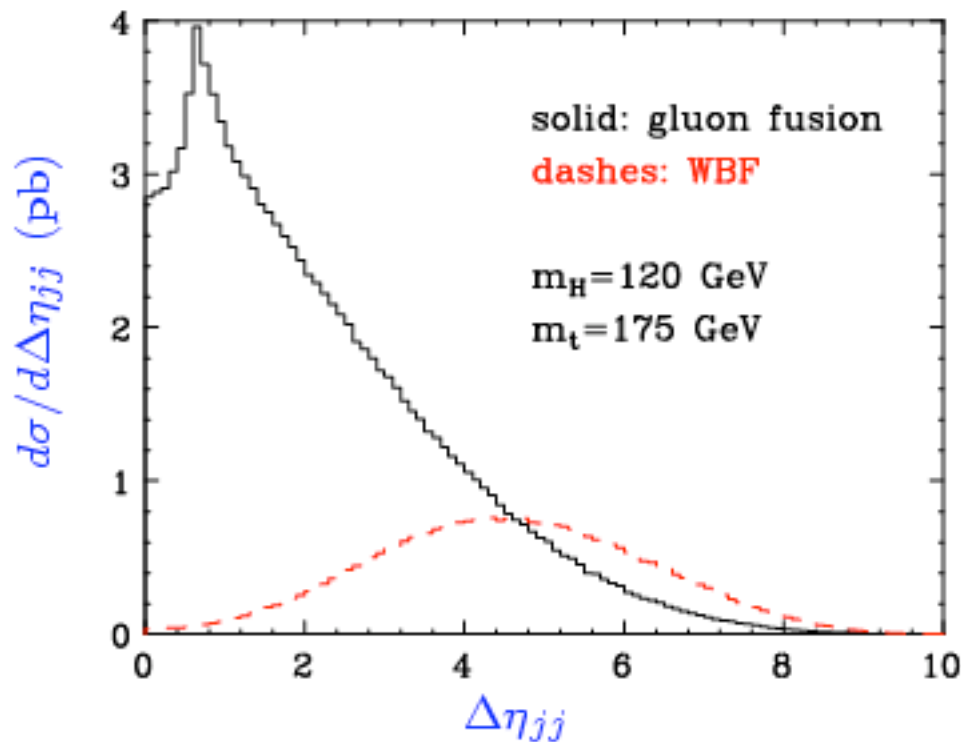
Campbell, Ellis, Zanderighi 2006



RAPIDITY DISTRIBUTIONS

+

$\Delta\eta_{jj}$: rapidity difference between the two jets



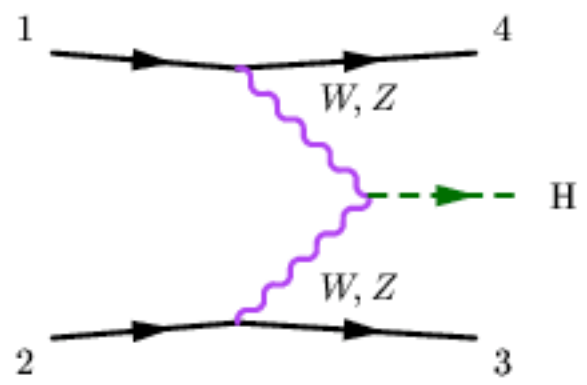
inclusive cuts: $\left\{ \begin{array}{l} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{array} \right.$

WBF cuts: incl. + $\left\{ \begin{array}{l} \eta_{j1} \cdot \eta_{j2} < 0 \\ \sqrt{s_{j1j2}} > 600 \text{ GeV} \end{array} \right.$

- WBF events spontaneously have a large $\Delta\eta_{jj}$
- dip in gluon fusion at low $\Delta\eta_{jj}$ is unphysical: $R_{jj} = \sqrt{\Delta\eta_{jj} + \Delta\phi_{jj}} > 0.6$

AZIMUTHAL ANGLE CORRELATIONS

$\Delta\phi_{jj} \equiv$ the azimuthal angle between the two jets

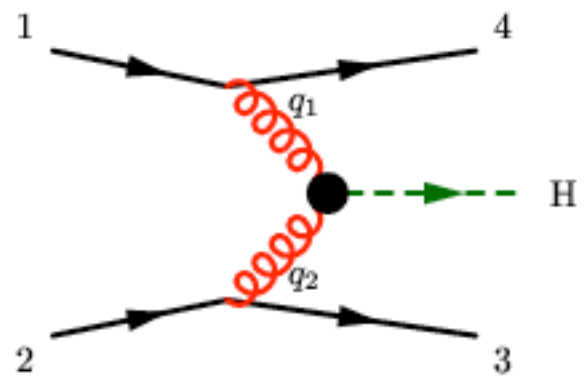


$$A_{WBF} \sim \frac{1}{2p_1 \cdot p_4 - M_W^2} \frac{1}{2p_2 \cdot p_3 - M_W^2} \hat{s} m_{jj}^2$$

→ a flat $\Delta\phi_{jj}$ distribution

gluon fusion in the large M_t limit

$$\mathcal{L}_{eff} = \frac{1}{4} A H G_{\mu\nu}^a G^{a\mu\nu} \quad A = \frac{\alpha_s}{3\pi v}$$



$$A_{gluon} \sim J_1^\mu (q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2) J_2^\nu$$

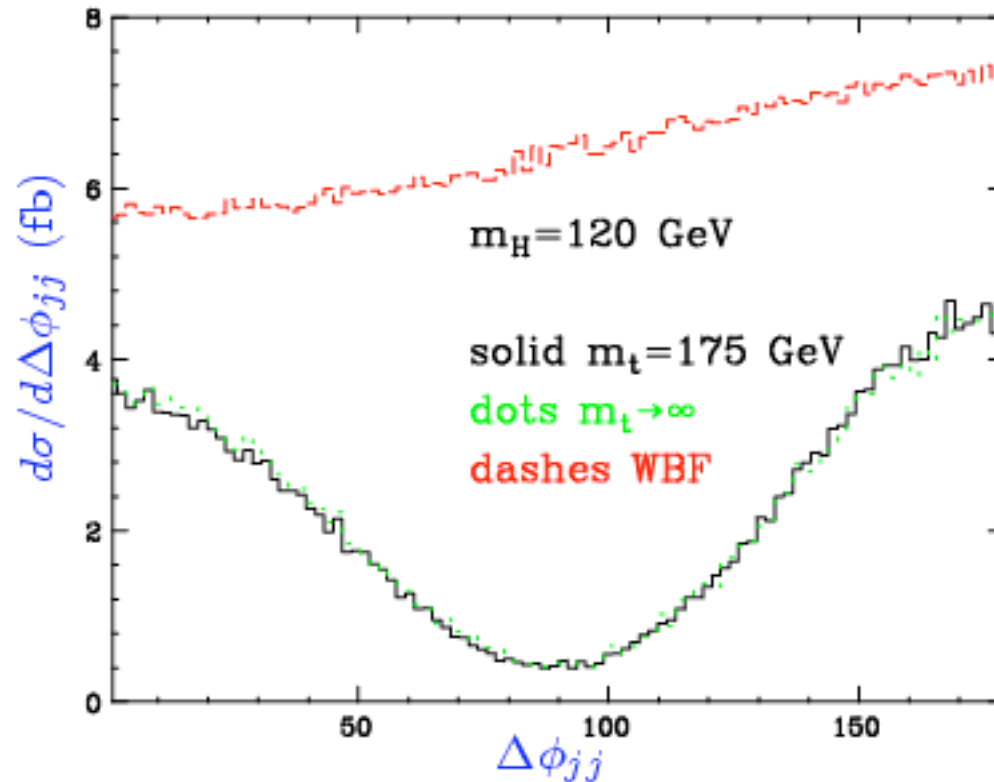
$J^\mu \equiv$ quark-gluon current

for $|p_i^z| \gg |p_i^{x,y}| \quad i = 3, 4$: forward jets

$$A_{gluon} \sim (J_1^0 J_2^0 - J_1^3 J_2^3) p_{3\perp} \cdot p_{4\perp}$$

→ zero at $\Delta\phi_{jj} = \frac{\pi}{2}$

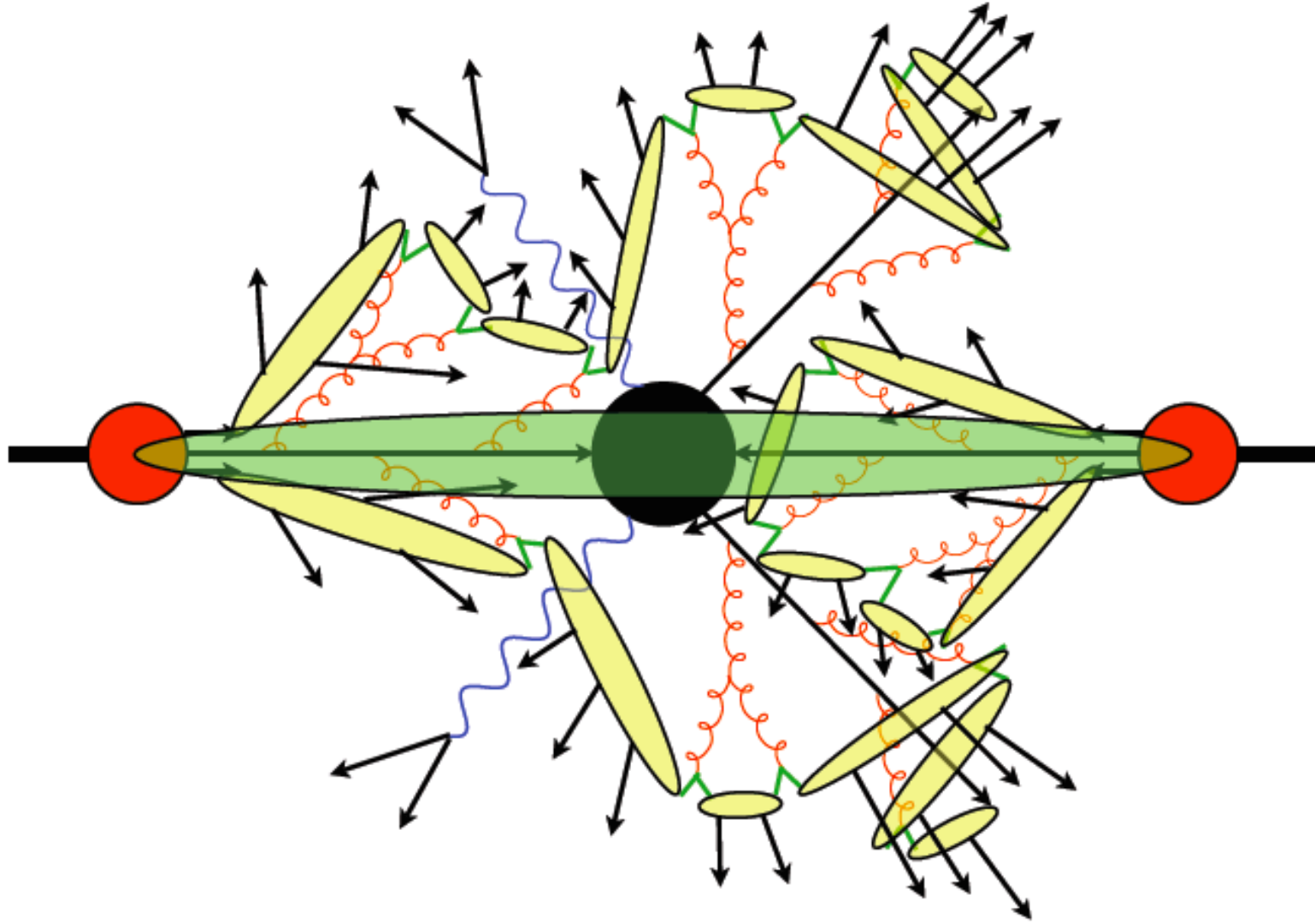
AZIMUTHAL ANGLE DISTRIBUTION



WBF cuts: $\left\{ \begin{array}{l} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{array} \right. + \left\{ \begin{array}{l} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ m_{jj} > 600 \text{ GeV} \end{array} \right.$

- ☛ the azimuthal angle distribution discriminates between WBF and gluon fusion
- ☛ note that the large M_t limit curve approximates very well the exact curve

LHC Event Simulation



2

Parton showering and hadronisation are modelled through shower Monte Carlos (HERWIG o PYTHIA)

3 complementary approaches to $\hat{\sigma}$

	matrix-elem MC's	fixed-order x-sect	shower MC's
final-state description	hard-parton jets. Describes geometry, correlations, ...	limited access to final-state structure	full information available at the hadron level
higher-order effects: loop corrections	hard to implement: must introduce negative probabilities	straightforward to implement (when available)	included as vertex corrections (Sudakov FF's)
higher-order effects: hard emissions	included, up to high orders (multijets)	straightforward to implement (when available)	approximate, incomplete phase space at large angles
resummation of large logs	?	feasible (when available)	unitarity implementation (i.e. correct shapes but not total rates)

Shower MonteCarlo generators

- **HERWIG** B. Webber et al. 1992
being re-written as a C++ code (HERWIG++)

- **PYTHIA** T. Sjostrand 1994

and more

- **CKKW** S. Catani F. Krauss R. Kuhn B. Webber 2001

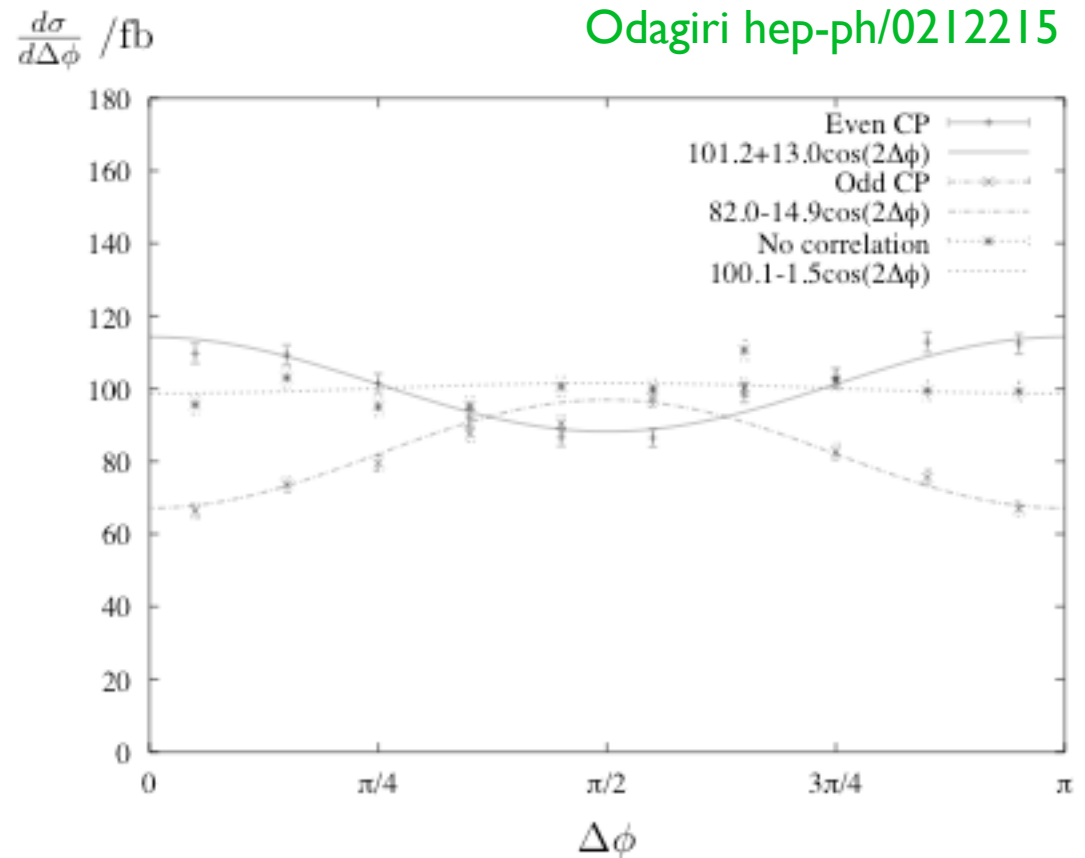
a procedure to interface parton subprocesses with a different number of final states to parton showers

- **MC@NLO** S. Frixione B. Webber 2002

a procedure to interface NLO computations to shower MC's

Azimuthal angle distribution

Including **parton showers** and **hadronisation** through **HERWIG**, Odagiri finds much less correlation between the jets



Caveat !

the plot has been obtained by generating also the jets through the showers

Matrix-element MonteCarlo generators

- multi-parton generation: processes with many jets (or W/Z/H bosons)
 - ALPGEN M.L.Mangano M. Moretti F. Piccinini R. Pittau A. Polosa 2002
 - MADGRAPH/MADEVENT W.F. Long F. Maltoni T. Stelzer 1994/2003
 - COMPHEP A. Pukhov et al. 1999
 - GRACE/GR@PPA T. Ishikawa et al. K. Sato et al. 1992/2001
 - HELAC C. Papadopoulos et al. 2000
- processes with 6 final-state fermions
 - PHASE E.Accomando A. Ballestrero E. Maina 2004
- merged with parton showers
 - all of the above, merged with HERWIG or PYTHIA
 - SHERPA F. Krauss et al. 2003

Azimuthal angle distribution

 **ALPGEN**: $H + 2$ jets at parton level + parton shower by **HERWIG**

Klamke Mangano Moretti Piccinini Pittau Polosa Zeppenfeld VDD 2006

VBF cuts

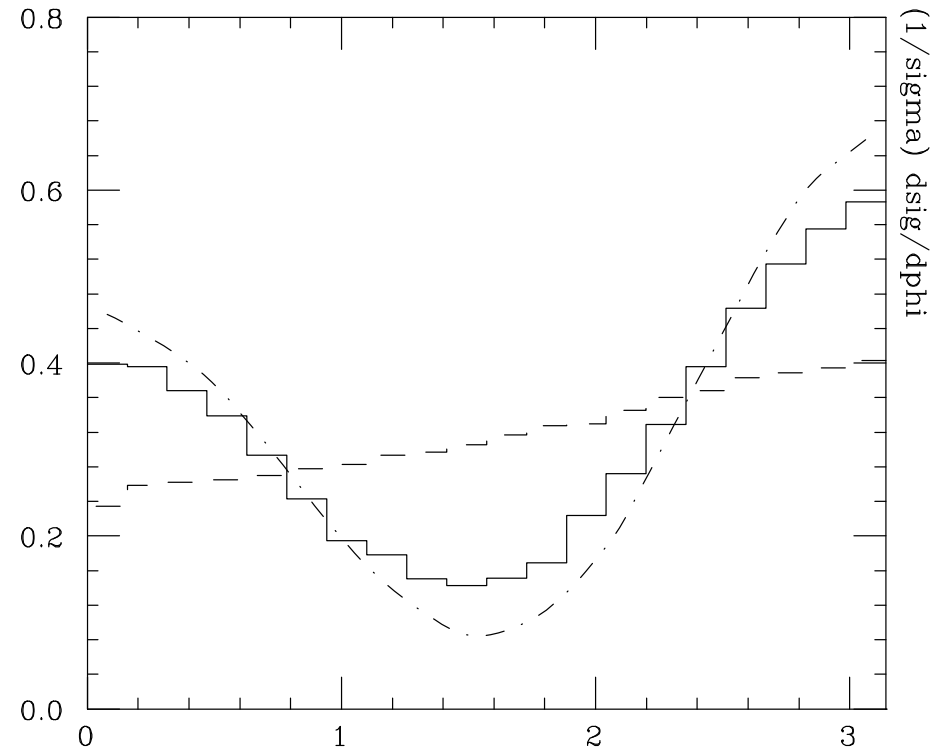
$$p_{Tj}^{tag} > 30 \text{ GeV} \quad |\eta_j| < 5 \quad R_{jj} > 0.6$$

$$|\eta_{j1} - \eta_{j2}| < 4.2 \quad \eta_{j1} \cdot \eta_{j2} < 0$$

$$m_{jj} > 600 \text{ GeV}$$

A_ϕ : a quantity that characterises how deep the dip is

A_ϕ	parton level	shower level
$ggH + 2$ jets	0.474(3)	0.357(3)
$VBF + 2$ jets	0.017(1)	0.018(1)



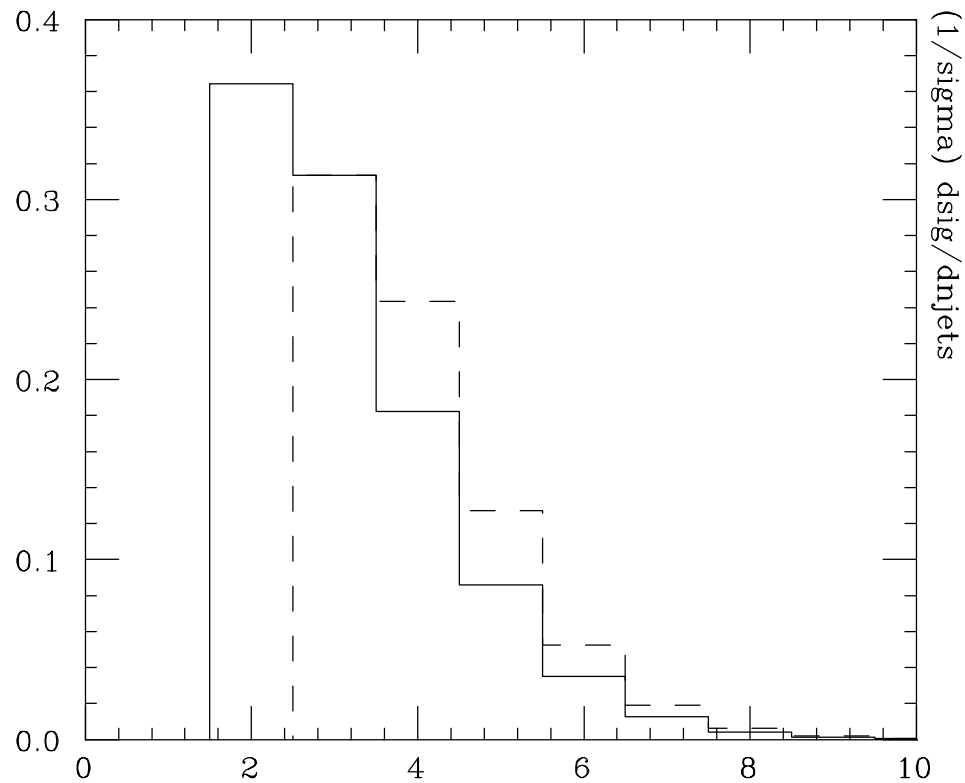
dash: VBF
solid: gluon fusion w/ PS
dot-dash: ditto w/o PS

$$A_\phi = \frac{\sigma(\Delta\phi < \pi/4) - \sigma(\pi/4 < \Delta\phi < 3\pi/4) + \sigma(\Delta\phi > 3\pi/4)}{\sigma(\Delta\phi < \pi/4) + \sigma(\pi/4 < \Delta\phi < 3\pi/4) + \sigma(\Delta\phi > 3\pi/4)}$$

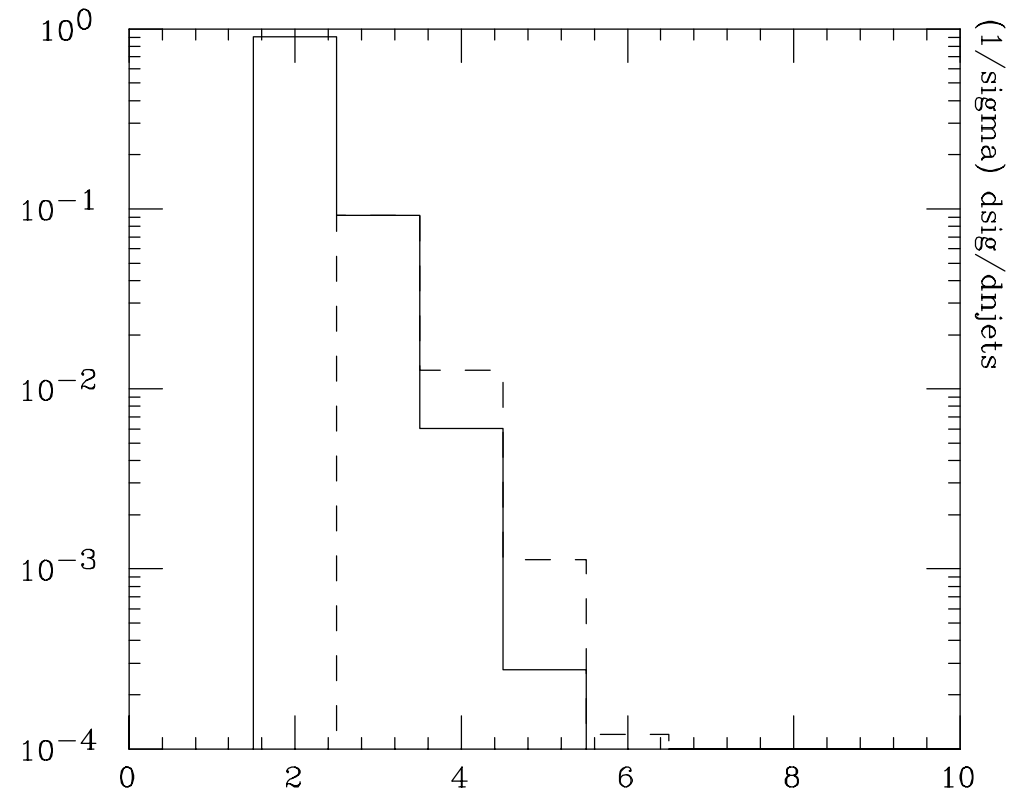
$\Delta\Phi$ is the azimuthal angle between the tagging jets

Jet multiplicity

gluon fusion



WBF



Normalised jet multiplicity after parton shower for H + 2 (solid) and 3 (dashes) partons. Solid curve is normalised to the total x-sect for H + 2 jets.

Note the log scale on the rhs panel

VBF cuts

$$p_{Tj}^{tag} > 30 \text{ GeV} \quad p_{Tj} > 20 \text{ GeV} \quad |\eta_j| < 5 \quad R_{jj} > 0.6$$
$$|\eta_{j1} - \eta_{j2}| < 4.2 \quad \eta_{j1} \cdot \eta_{j2} < 0 \quad m_{jj} > 600 \text{ GeV}$$

WWH COUPLING

- the azimuthal angle $\Delta\phi_{jj}$ between the jets can be used as a tool to investigate the tensor structure of the WWH coupling

Plehn, Rainwater, Zeppenfeld hep-ph/0105325

- take a gauge-invariant effective Lagrangian with dim. 6 operators (CP even and CP odd) describing an anomalous WWH coupling

$$\mathcal{L}_6 = \frac{g^2}{2\Lambda_{e,6}^2} (\Phi^\dagger \Phi) V_{\mu\nu} V^{\mu\nu} + \frac{g^2}{2\Lambda_{o,6}^2} (\Phi^\dagger \Phi) \tilde{V}_{\mu\nu} V^{\mu\nu}$$

- expand Φ about the vev (get dim. 5 (D5) operators)

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}} H W_{\mu\nu}^+ W^{-\mu\nu} + \frac{1}{\Lambda_{o,5}} H \tilde{W}_{\mu\nu}^+ W^{-\mu\nu} \quad \text{with} \quad \frac{1}{\Lambda_5} = \frac{g^2 v}{\Lambda_6^2}$$

- CP odd D5 operator: $\epsilon^{\mu\nu\alpha\beta}$ tensor in the coupling

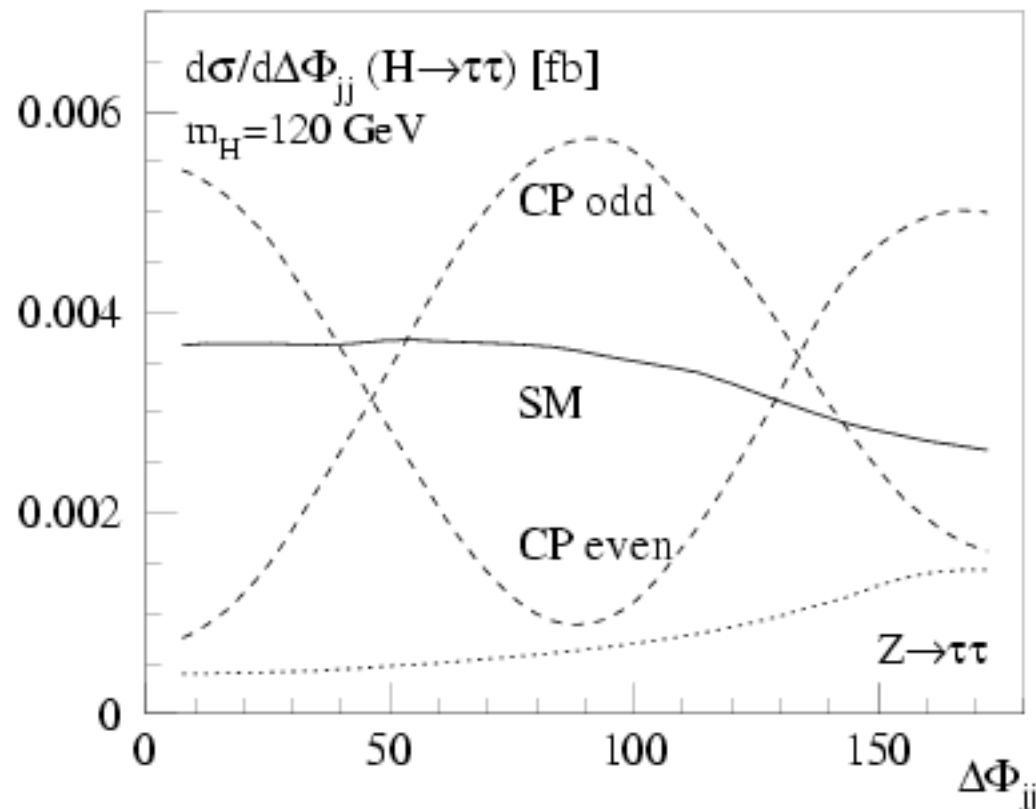
➔ zero at $\Delta\phi_{jj} = 0, \pi$

- CP even D5 operator is like the effective ggH coupling

$$A_{\text{CP even}} \sim \frac{1}{\Lambda_{e,5}} J_1^\mu (q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2) J_2^\nu \quad \Rightarrow \quad \text{zero at } \Delta\phi_{jj} = \frac{\pi}{2}$$

AZIMUTHAL ANGLE DISTRIBUTION FOR WWH COUPLINGS

- assume a Higgs-like scalar signal is found at LHC at the SM rate (for D5 operators: $\Lambda_5 \sim 500$ GeV)



WBF cuts:

$$p_{j\perp} > 20 \text{ GeV}$$

$$|\eta_j| < 5$$

$$R_{jj} > 0.6$$

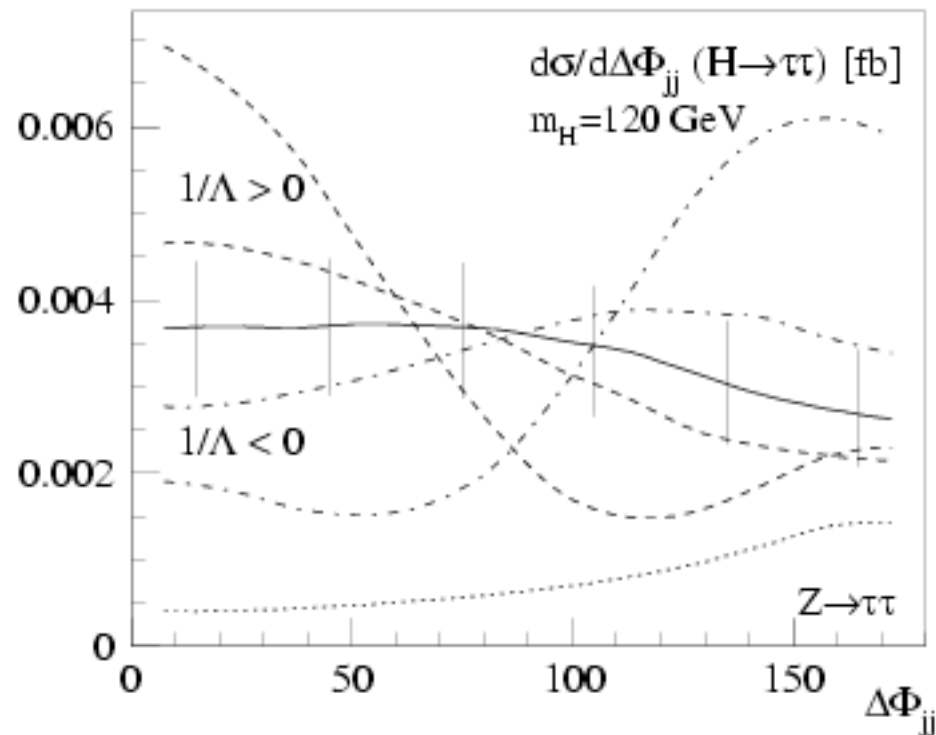
$$\eta_{j1} \cdot \eta_{j2} < 0$$

$$|\eta_{j1} - \eta_{j2}| > 4.2$$

- the $\Delta\phi_{jj}$ distribution
 - discriminates between different WWH couplings
 - is independent of the particular decay channel and the Higgs mass range

INTERFERENCE EFFECTS IN THE $\Delta\phi_{jj}$ DISTRIBUTION

- assume a **Higgs** candidate is found at **LHC** with a predominantly **SM** $g^{\mu\nu}$ + coupling. How sensitive are experiments to any **D5 terms** ?
- no **interference** between **SM** and **CP odd D5 operator**

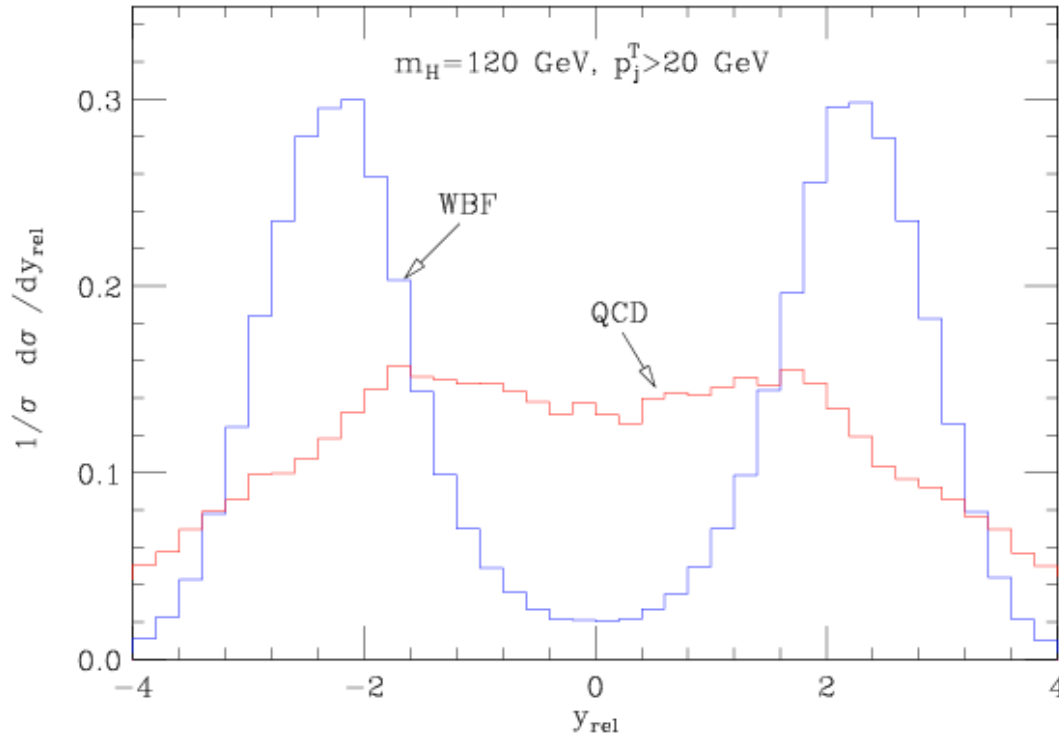


$\Delta\phi_{jj}$ distribution for the **SM** and **interference** with a **CP even D5 coupling**. The two curves for each sign of the operator correspond to values $\sigma/\sigma_{\text{SM}} = 0.04, 1.0$. Error bars correspond to an integrated luminosity of 100 fb^{-1} per experiment, distributed over 6 bins, and are **statistical** only

- **interference** between **SM** and **CP even D5 operator**: $|\mathcal{A}|^2 = |\mathcal{A}_{\text{SM}} + \mathcal{A}_{e,5}|^2$
 - ☛ all terms, but $|\mathcal{A}_{\text{SM}}|^2$, have an approximate zero at $\Delta\phi_{jj} = \pi/2$
 - ☛ **systematic** uncertainty induced by $H + 2$ jet rate from **gluon** fusion
 - ☛ $HG_{\mu\nu}G^{\mu\nu}$ is a **CP even D5 operator**

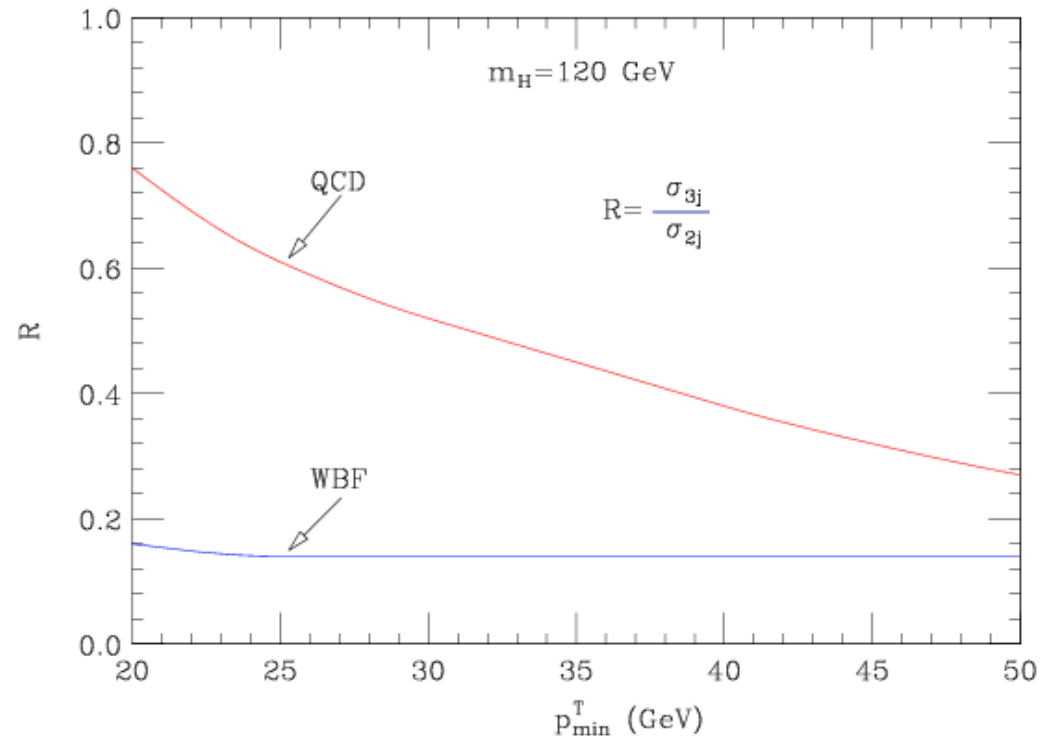
THE CENTRAL JET VETO

- In **WBF** no **colour** is exchanged in the t channel
- The central-jet veto is based on the different radiation pattern expected for **WBF** versus its major backgrounds, i.e. $t\bar{t}$ production and **WW + 2 jet** production
Barger, Phillips & Zeppenfeld hep-ph/9412276
- The central-jet veto can also be used to distinguish between **Higgs** production via gluon fusion and via **WBF**



Distribution in **rapidity** of the **third jet** wrt to the rapidity average of the tagging jets

Ratio of **Higgs + 3 jet** to **Higgs + 2 jet** production as a function of p_{min}^T



CONCLUSIONS

- Once a Higgs-like resonance is found at the LHC, we shall want to study its couplings and quantum numbers
- In Higgs + 2 jets, the azimuthal angle correlation between the two jets can be used as a tool to distinguish between VBF and gluon fusion, and to investigate the tensor structure of the WWH coupling
- Because of the characteristic final-state topology induced by VBF production large-rapidity cuts can be used to deplete gluon fusion wrt VBF
- We examined Higgs + 2 jet-production through matrix-element MC's, which include shower effects.
 - the analysis confirms the one at the parton level
 - however, in gluon fusion large fraction of events with 3 or more jets
 - need a CKKW-type analysis