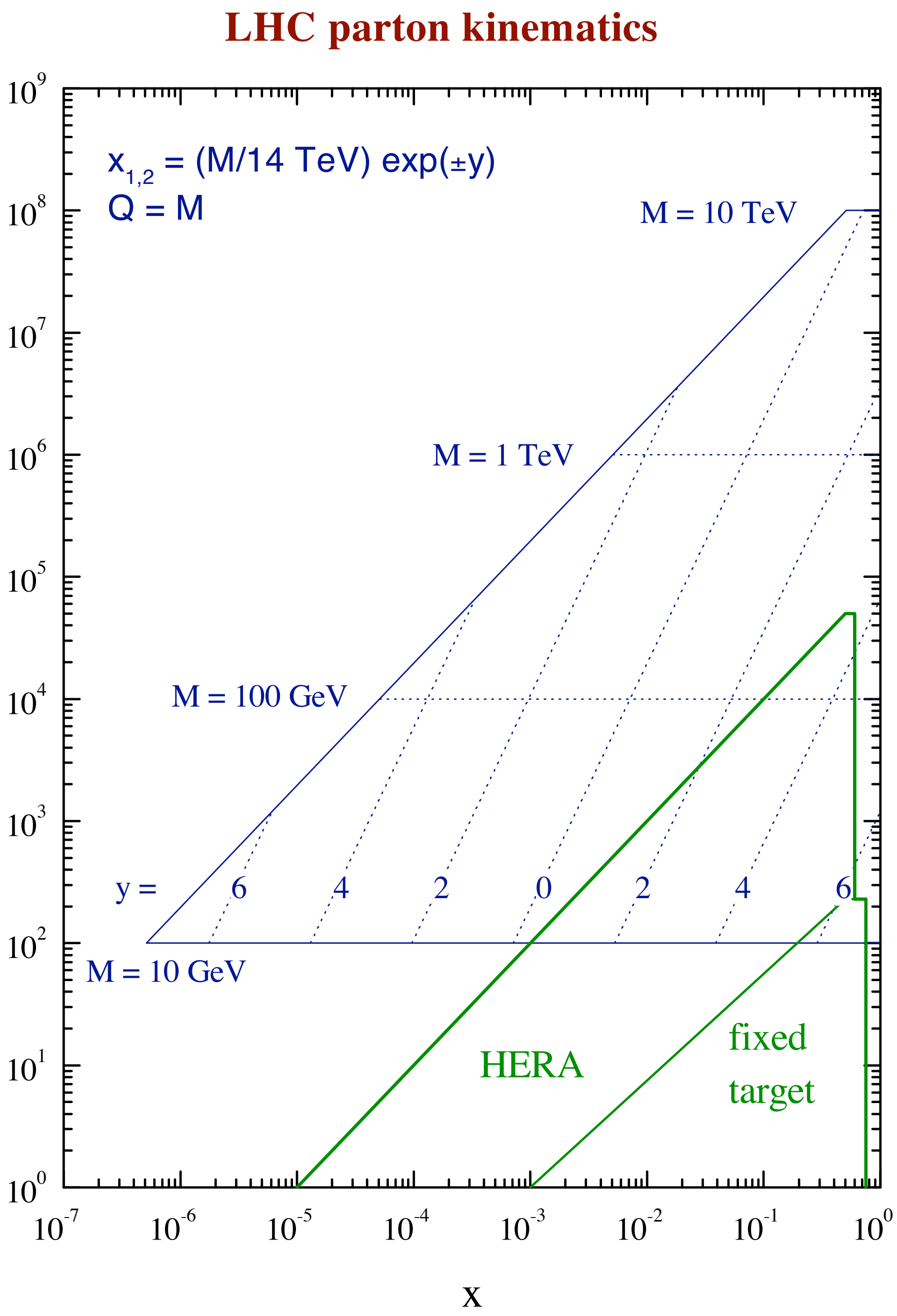
Higgs production in association with jets at the LHC

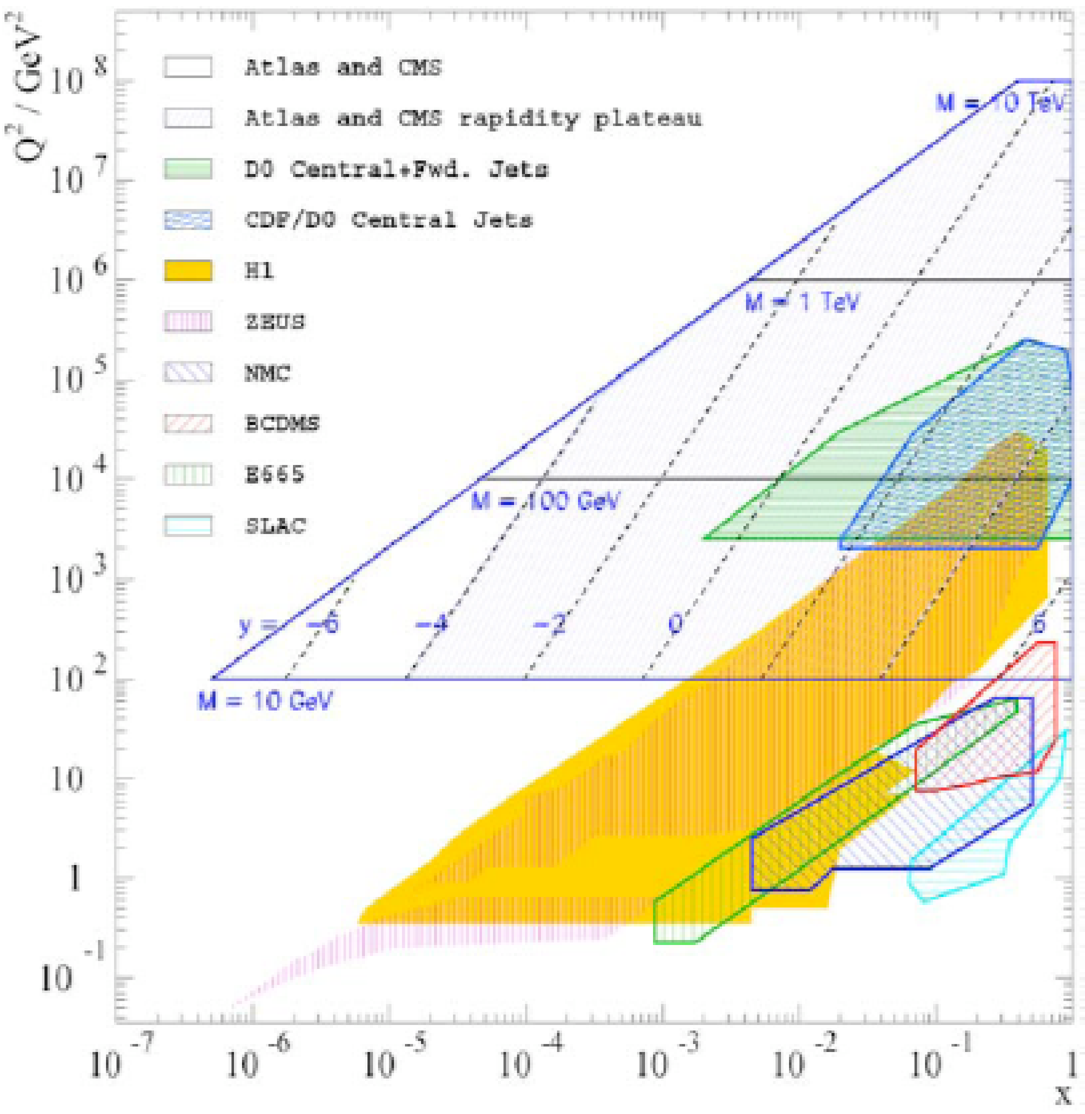
Vittorio Del Duca
INFN LNF

Moriond ``QCD and Hadronic Interactions" La Thuile 21 March 2007

LHC kinematic reach



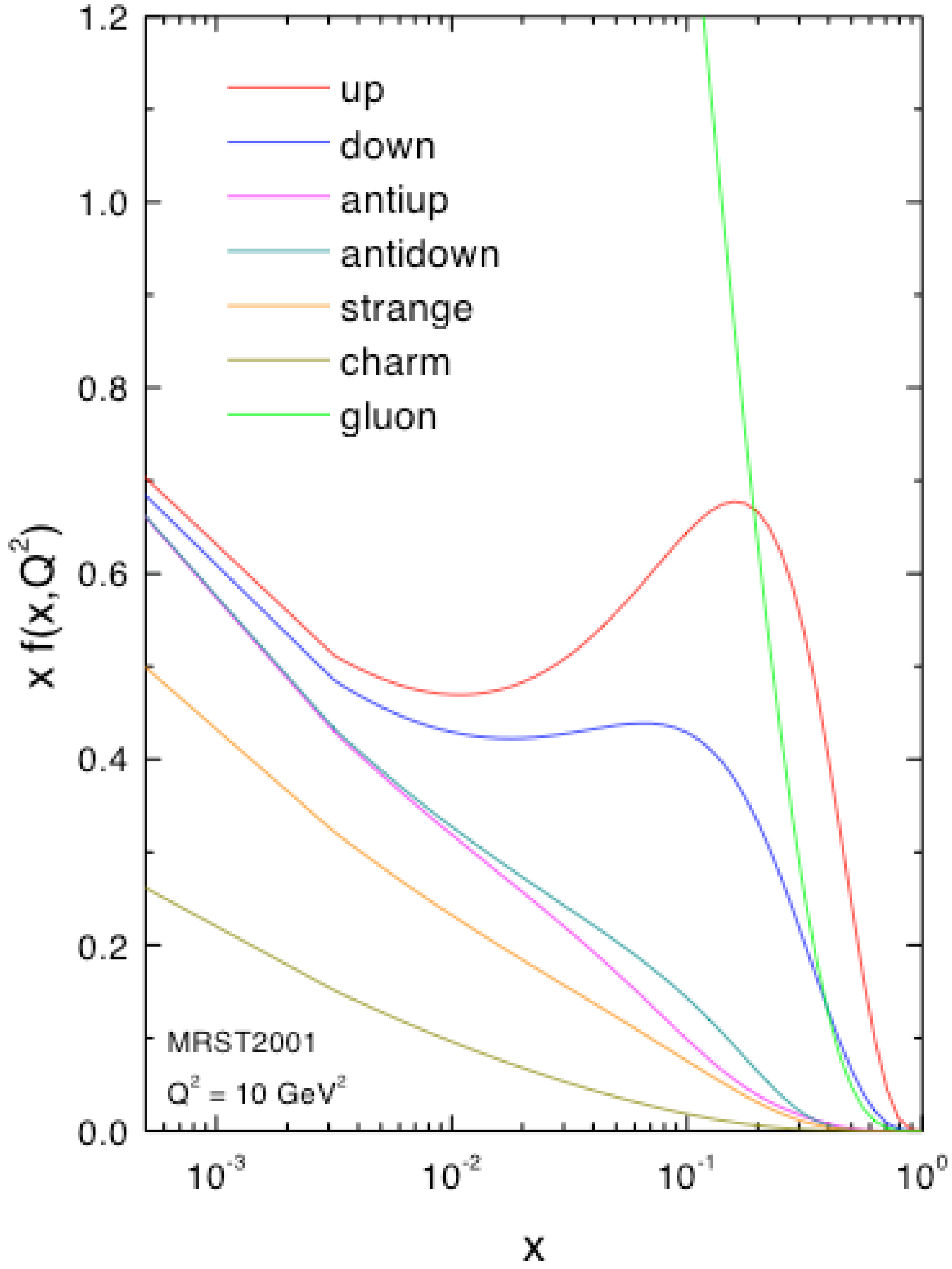
LHC opens up a new kinematic range



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

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

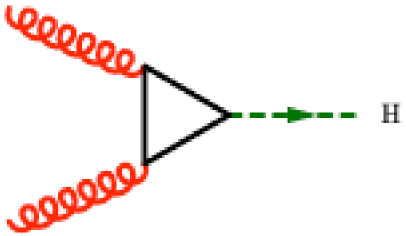
MRST 2001 PDF's



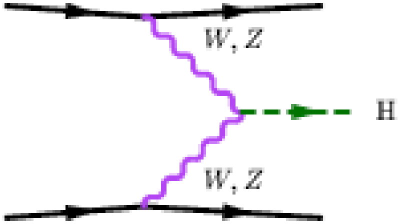
HIGGS PRODUCTION MODES AT LHC

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

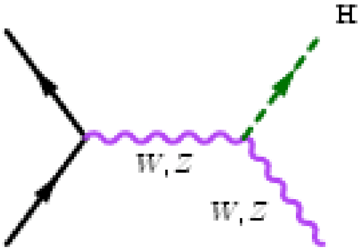
- gluon fusion $gg \to H$
  - largest rate for all M_H
  - proportional to the top Yukawa coupling y_t



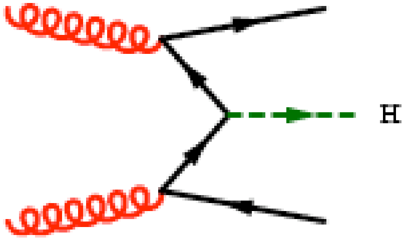
- weak-boson fusion (WBF) $qq \to qqH$
  - second largest rate (mostly $u\,d$ initial state)
  - proportional to the WWH coupling



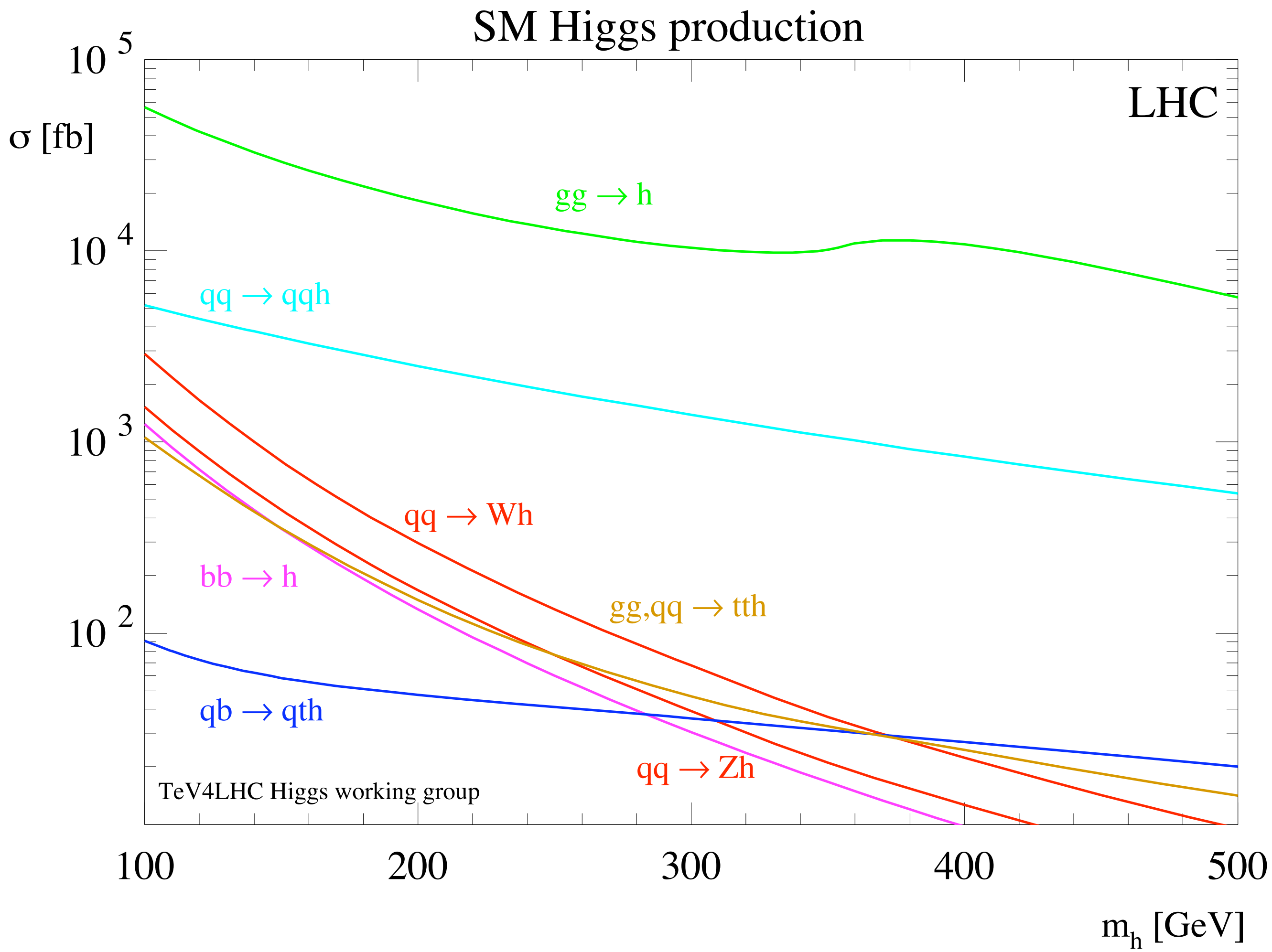
- Higgs-strahlung $q\bar{q} \to W(Z)H$
  - third largest rate
  - same coupling as in WBF



- $t\bar{t}(b\bar{b})H$ associated production
  - same initial state as in gluon fusion, but higher x range
  - proportional to the heavy-quark Yukawa coupling y_Q



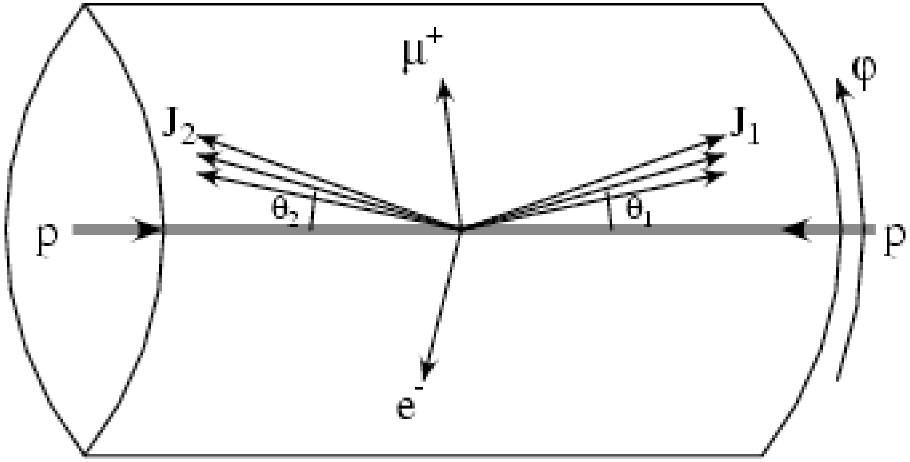
HIGGS PRODUCTION AT LHC



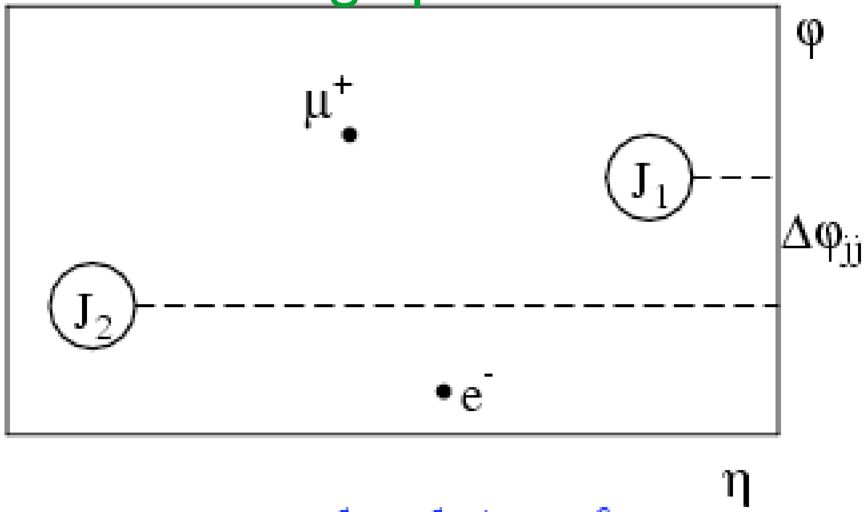
- in the intermediate Higgs mass range $M_H \sim 100 - 200$ GeV
  - gluon fusion cross section is $\sim 20 - 60$ pb
  - WBF cross section is $\sim 3 - 5$ pb
  - $WH, ZH, t\bar{t}H$ yield cross sections of $\sim 0.2 - 3$ pb

WEAK BOSON FUSION: $qq \to qqH$

A WBF event



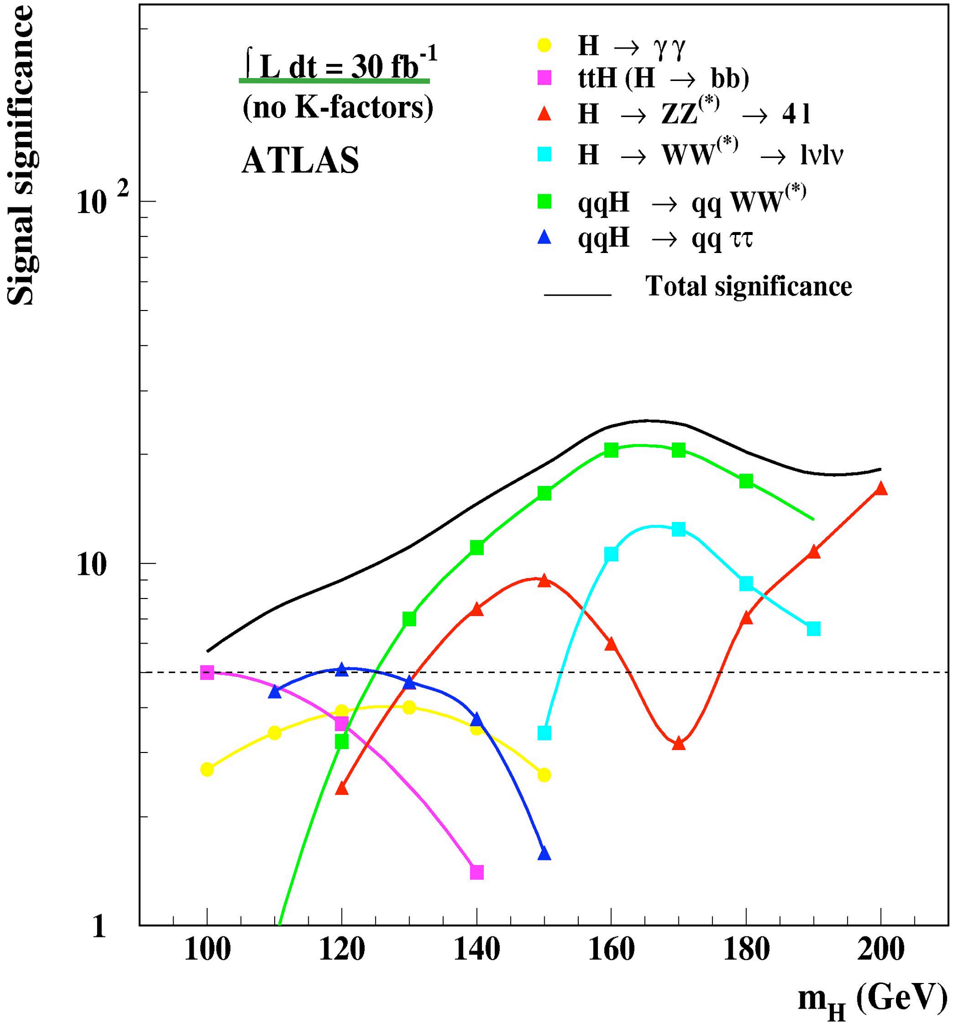
Lego plot

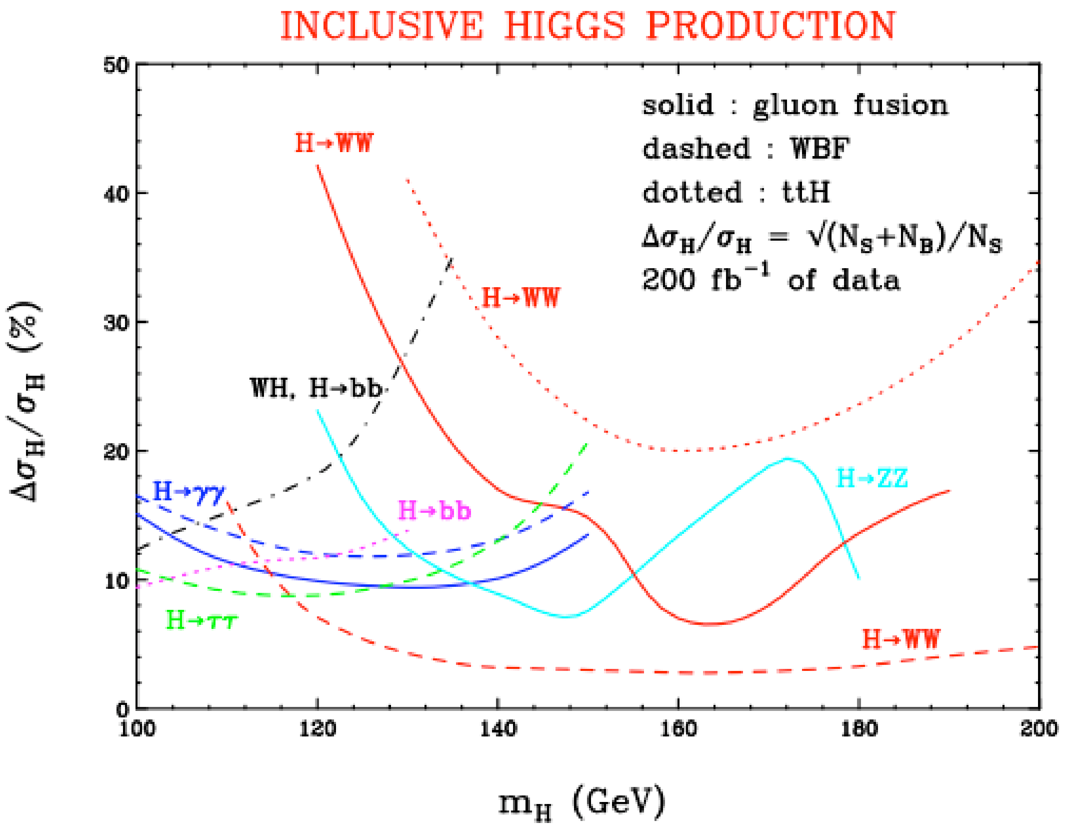


$$\eta = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta}$$

- 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: $\sigma \times \mathrm{BR} \approx \mathcal{O}(10\%)$

SIGNAL SIGNIFICANCE AND (STAT + SYST) ERROR





hep-ph/0203187

QCD/p.d.f. uncertainties:

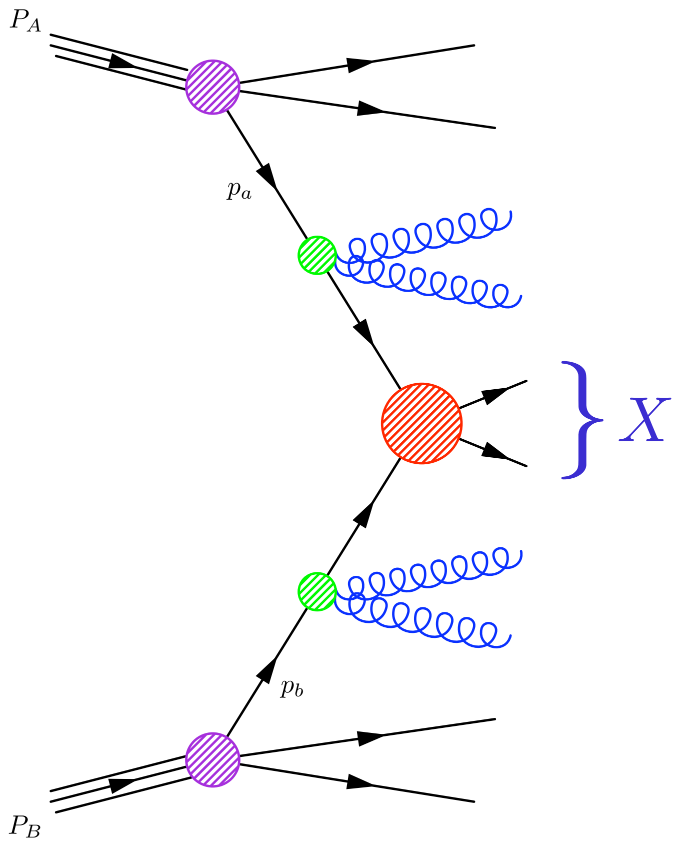
$\mathcal{O}(5\%)$ for WBF

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

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

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

Cross sections at high Q^2



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

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

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

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

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

$c_1 =$ NLO $\qquad c_2 =$ NNLO

or as an all-order resummation

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

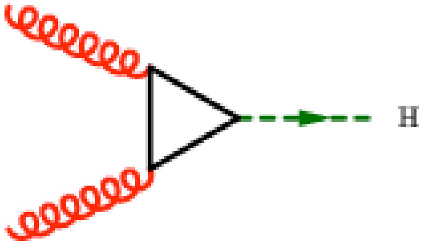
where $L = \ln(M/q_T), \ln(1-x), \ln(1/x), \ln(1-T), \ldots$

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

HIGGS PRODUCTION VIA GLUON FUSION

LEADING ORDER

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

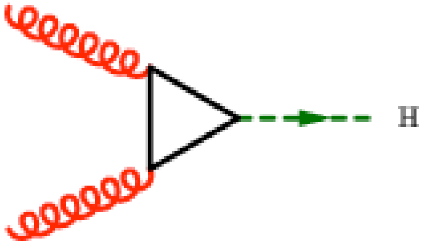


- ☛ energy scales: $\hat{s} = M_{\rm H}^2$ and M_t^2

HIGGS PRODUCTION VIA GLUON FUSION

LEADING ORDER

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

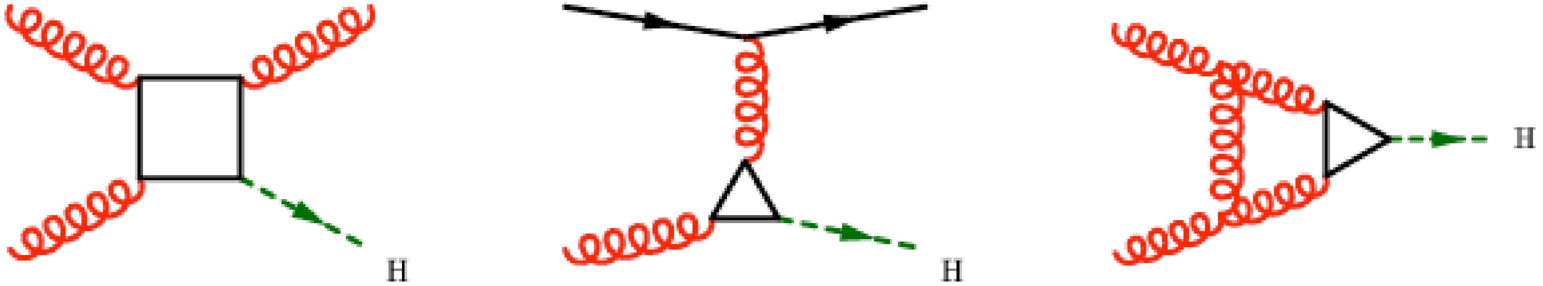


☛ energy scales: $\hat{s} = M_{\rm H}^2$ and M_t^2

NLO CORRECTIONS

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

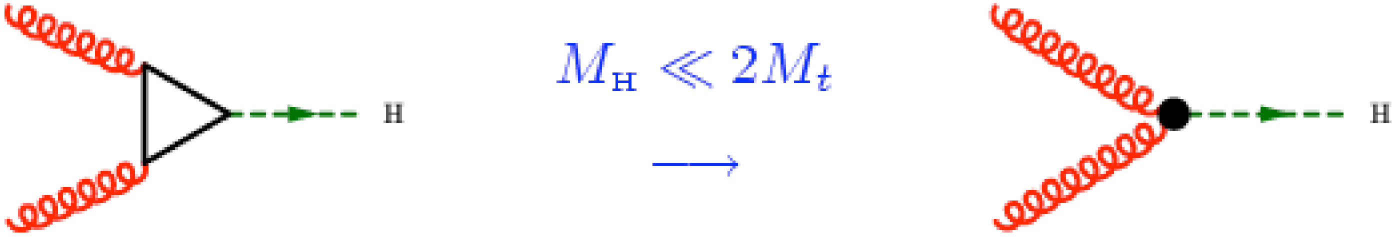
- 2-loop $gg \to H$
- 1-loop $gg \to gH$ $qg \to qH$ $+$ crossings



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

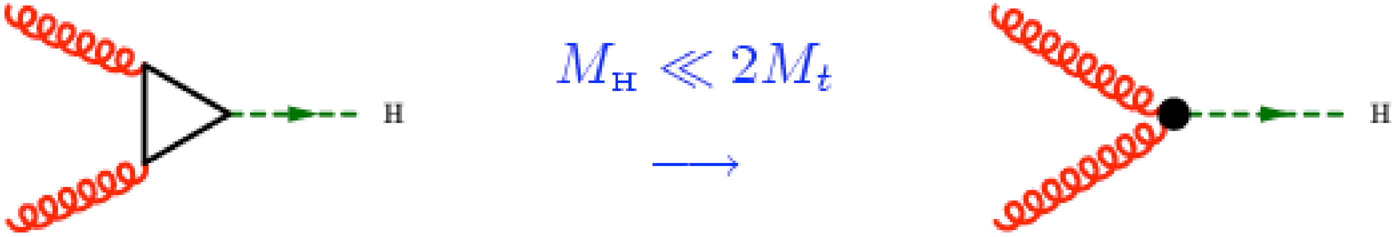
☛ large K factor: $\sigma^{\rm NLO} = K^{\rm NLO}\, \sigma^{\rm LO}$ $\mathcal{O}(40-100\%)$

THE LARGE TOP-MASS LIMIT



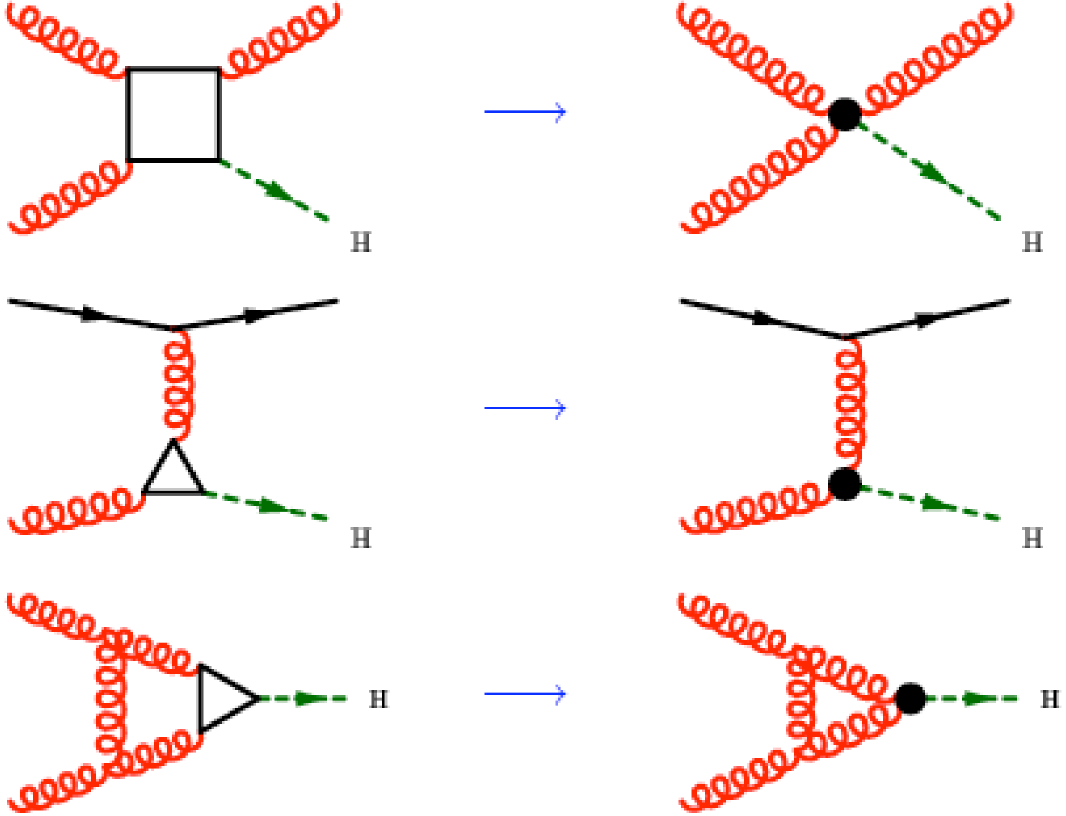
$$\xrightarrow{M_{\mathrm{H}} \ll 2M_t}$$

THE LARGE TOP-MASS LIMIT



$$M_{\rm H} \ll 2M_t \quad \longrightarrow$$

NLO CORRECTIONS



K factor in the large M_t limit

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

NLO rate in the large M_t limit

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

$\sigma_\infty^{\rm NLO}$ is within 10% of $\sigma^{\rm NLO}$ for $M_{\rm H} \lesssim 1$ TeV

$gg \to H$ IN THE LARGE M_t LIMIT

NNLO CORRECTIONS

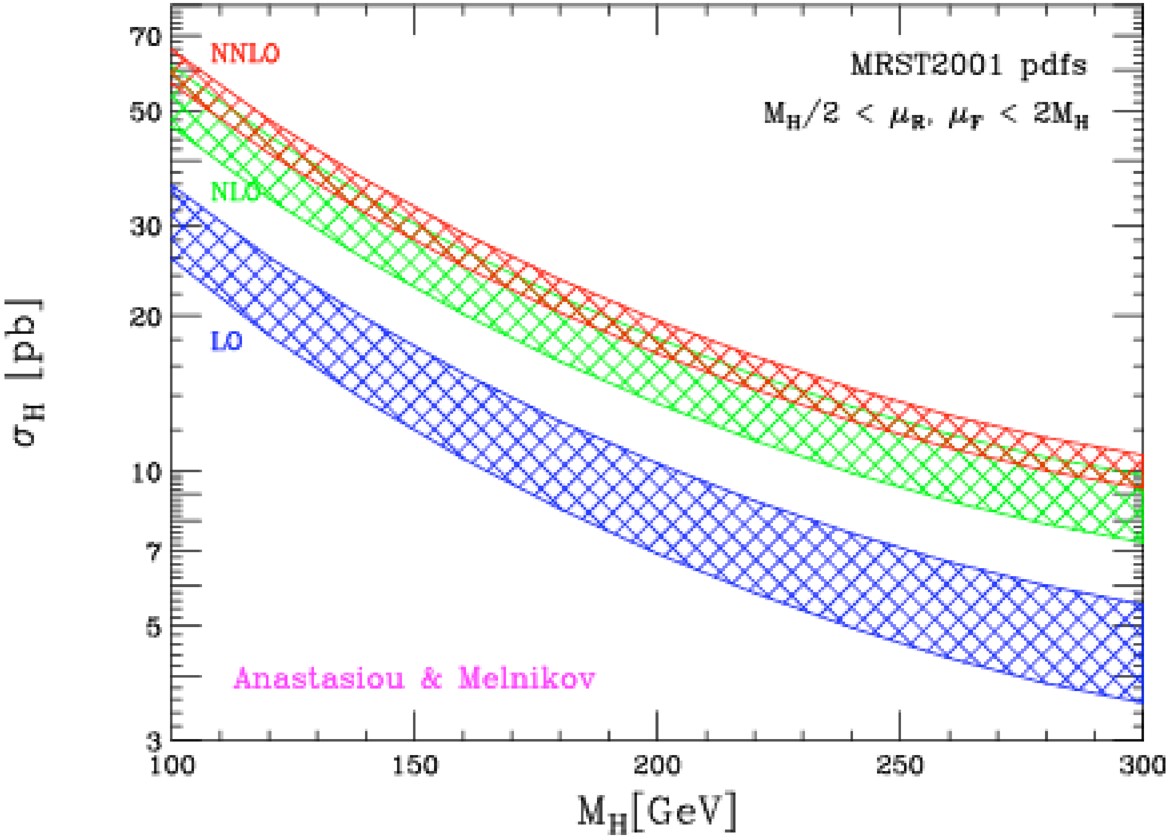
$\mathcal{O}(\alpha_S^4)$

2-loop $gg \to H$

1-loop $gg \to gH \quad qg \to qH \quad +$ crossings

tree $gg \to ggH \quad qg \to qgH \quad qQ \to qQH \quad +$ crossings

R. Harlander hep-ph/0007289



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 $\mu_R = 2M_H \quad \mu_F = M_H/2$

upper $\mu_R = M_H/2 \quad \mu_F = 2M_H$

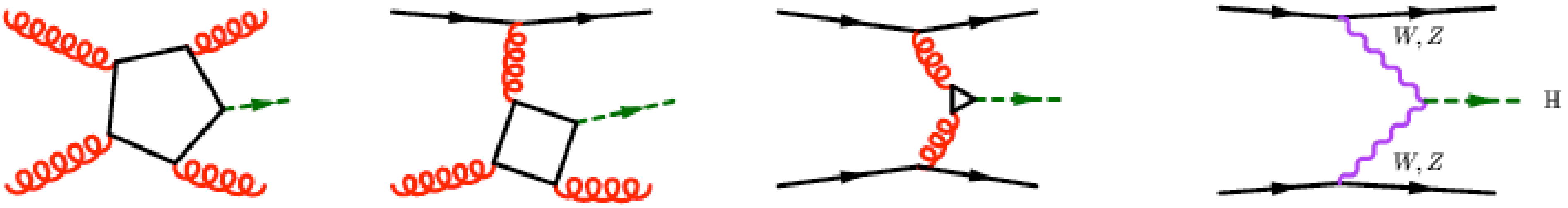
HIGGS COUPLINGS AND QUANTUM NUMBERS

The properties of the Higgs-like resonance are its

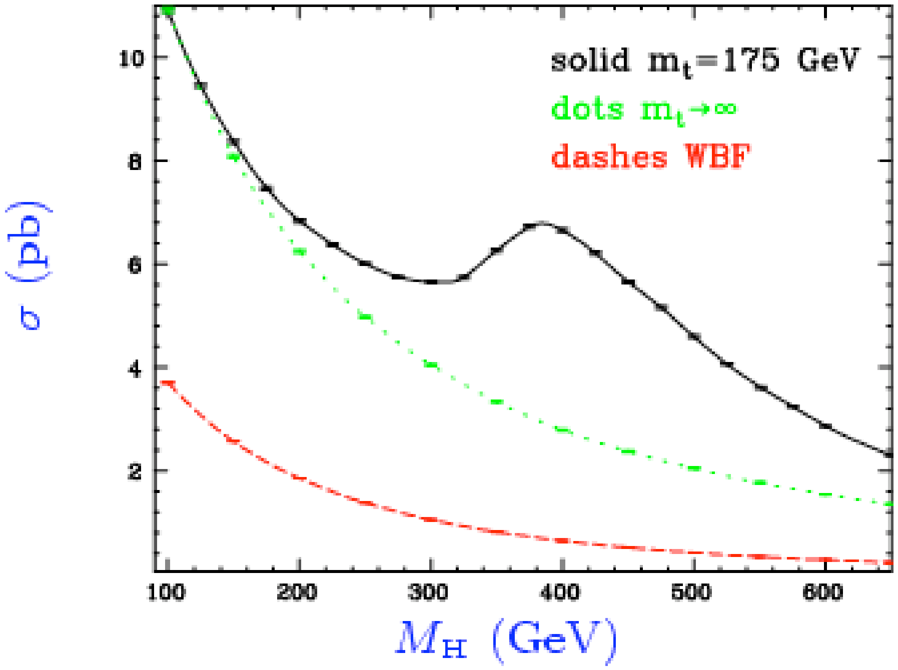
- couplings: gauge, Yukawa, self-couplings
- quantum numbers: charge, colour, spin, CP

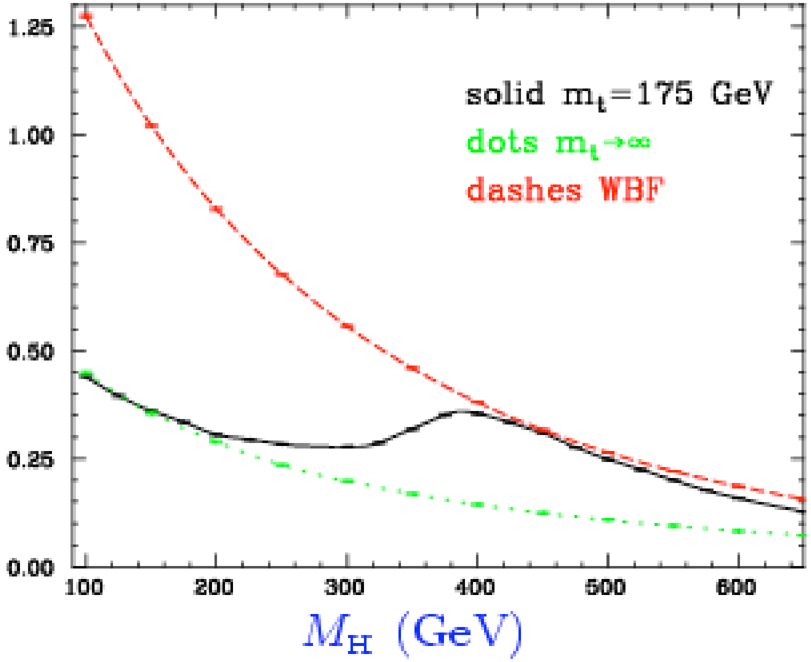
The gauge coupling has also CP properties and a tensor structure. Info on that can be obtained by analysing the final-state topology of Higgs + 2 jet events

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



$\mu_F = \sqrt{p_{j_1\perp} p_{j_2\perp}}\,, \mu_R = M_Z$ Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0105129





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

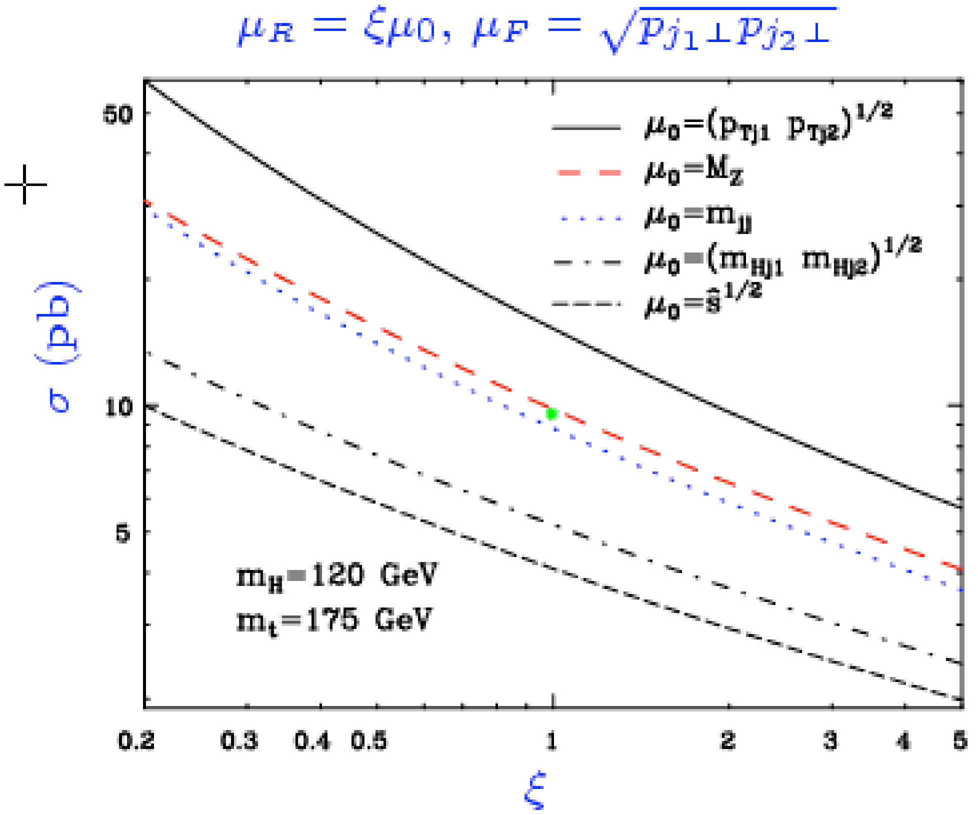
$$\text{WBF cuts: incl. } + \left\{ \begin{array}{l} |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ \eta_{j_1} \cdot \eta_{j_2} < 0 \\ \sqrt{s_{j_1 j_2}} > 600 \text{ GeV} \end{array} \right.$$

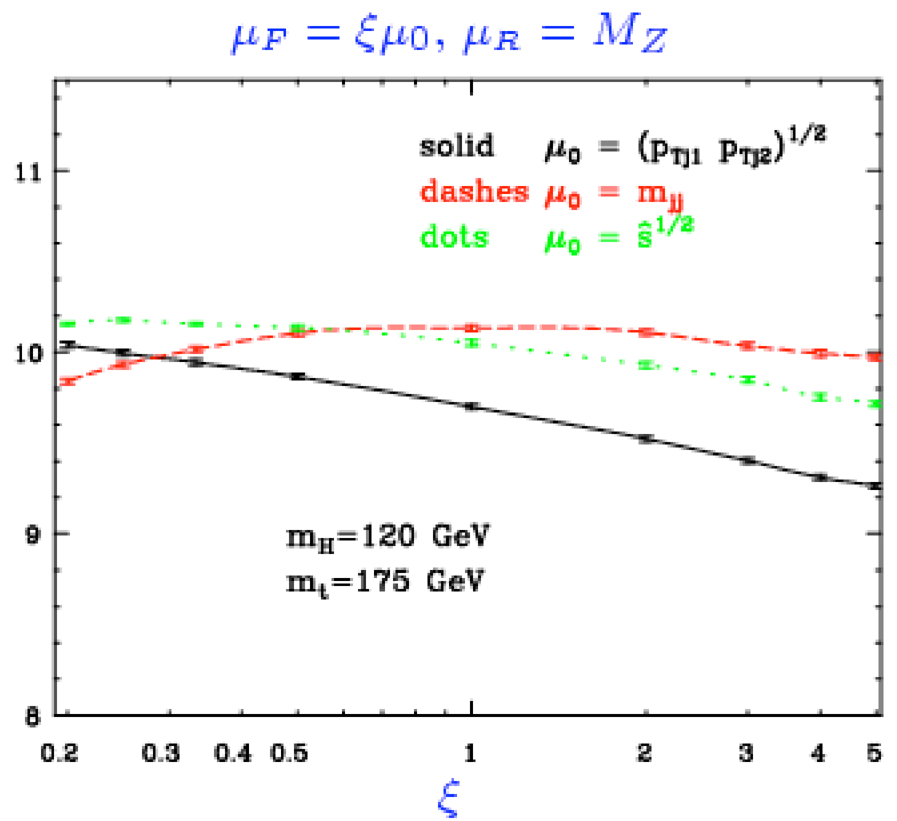
☛ WBF cuts enhance WBF wrt gluon fusion by a factor 10

SCALE DEPENDENCE

renormalisation μ_R & factorisation μ_F scales

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


$\mu_R = \xi\mu_0,\ \mu_F = \sqrt{p_{j_1\perp} p_{j_2\perp}}$


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

- strong μ_R dependence: the calculation is LO and $\mathcal{O}(\alpha_s^4)$
  - a natural scale for α_s ?
    high energy limit suggests $\alpha_s^4 \to \alpha_s(p_{j_1\perp})\alpha_s(p_{j_1\perp})\alpha_s^2(M_H)$
    - 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

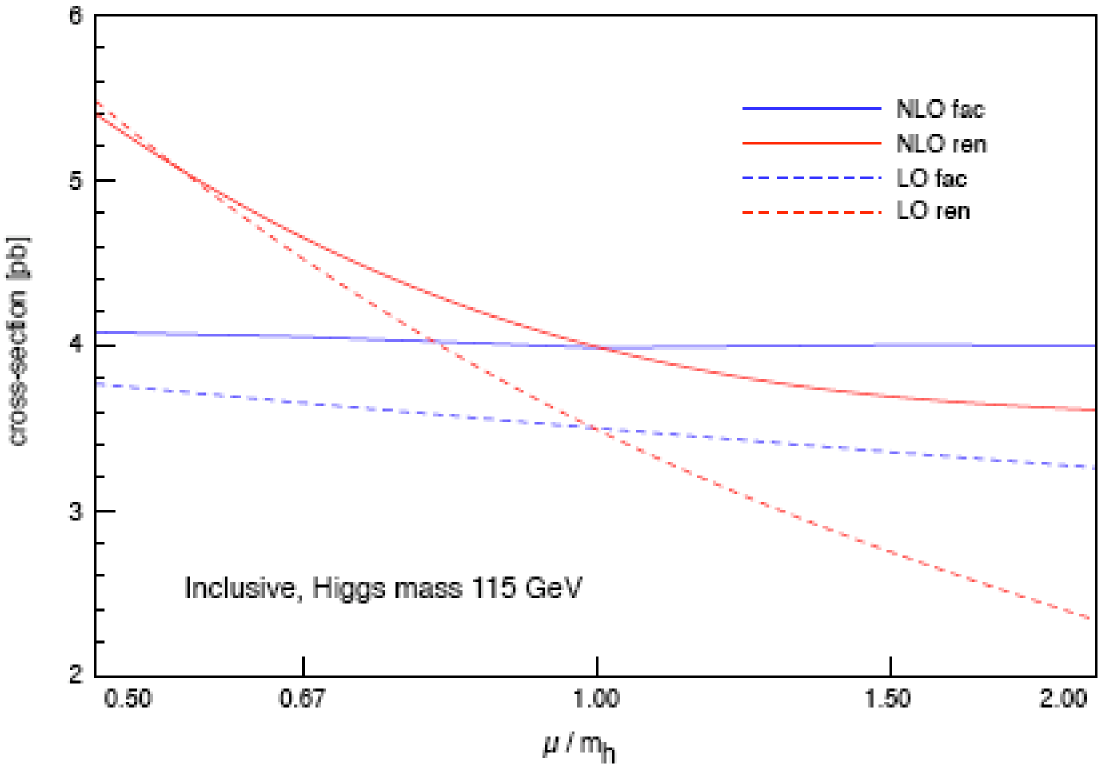
NLO corrections

- 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

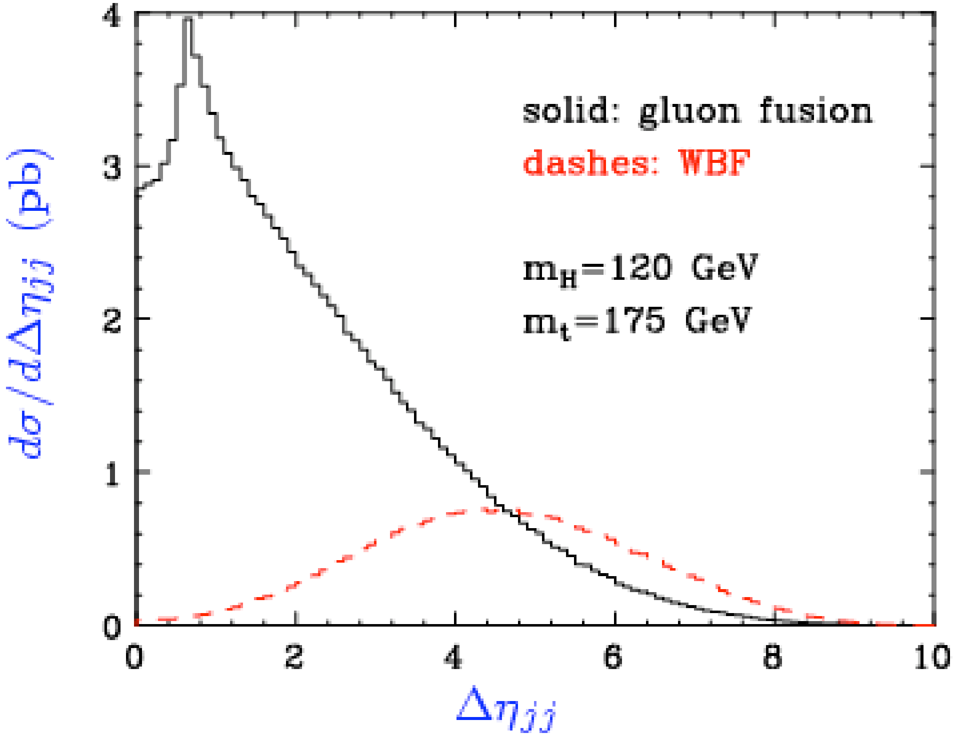
- NLO corrections in the large M_{top} limit increase the gluon fusion production rate by about 15--25 %, but the change under μ_R scale variation is sizeable

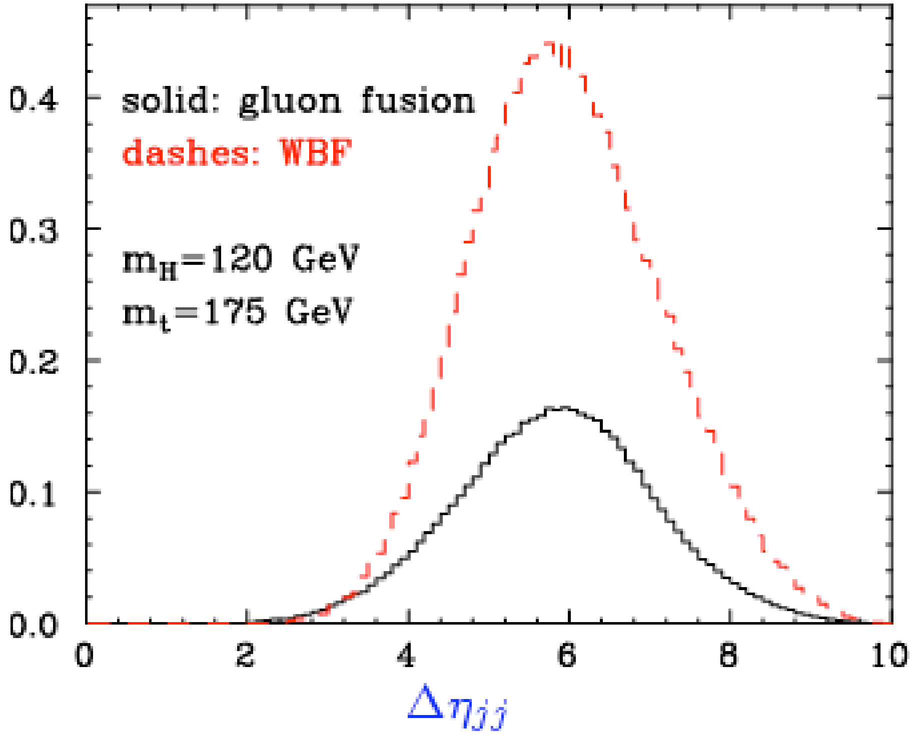
Campbell, Ellis, Zanderighi 2006



RAPIDITY DISTRIBUTIONS

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





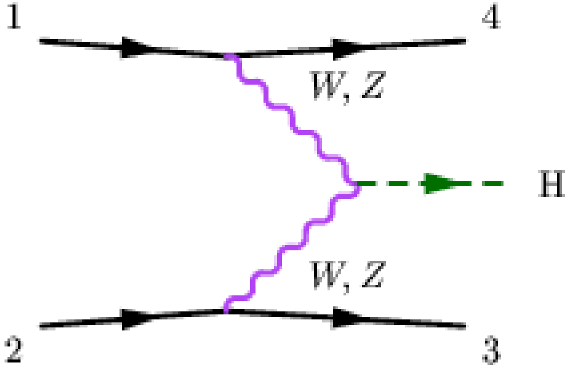
inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

WBF cuts: incl. + $\begin{cases} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ \sqrt{s_{j_1 j_2}} > 600 \text{ GeV} \end{cases}$

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

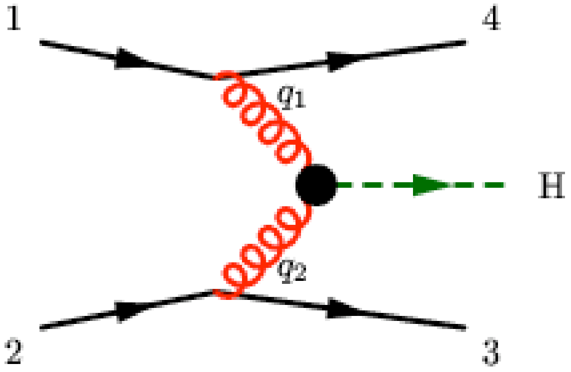
AZIMUTHAL ANGLE CORRELATIONS

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



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

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



gluon fusion in the large M_t limit

$$\mathcal{L}_{eff} = \frac{1}{4} A \; H \; G^a_{\mu\nu} G^{a\,\mu\nu} \qquad A = \frac{\alpha_s}{3\pi v}$$

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

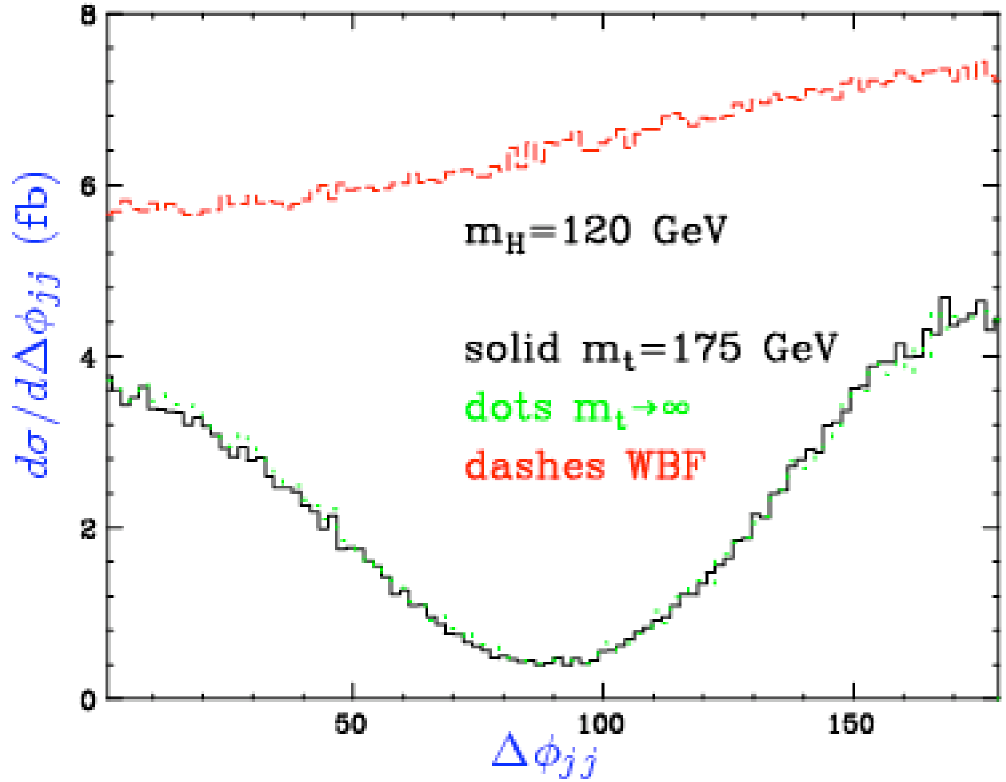
$J^\mu \equiv$ quark-gluon current

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

$$\mathcal{A}_{gluon} \sim (J_1^0 J_2^0 - J_1^3 J_2^3) \; p_{3\perp} \cdot p_{4\perp}$$

➡ zero at $\Delta\phi_{jj} = \dfrac{\pi}{2}$

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

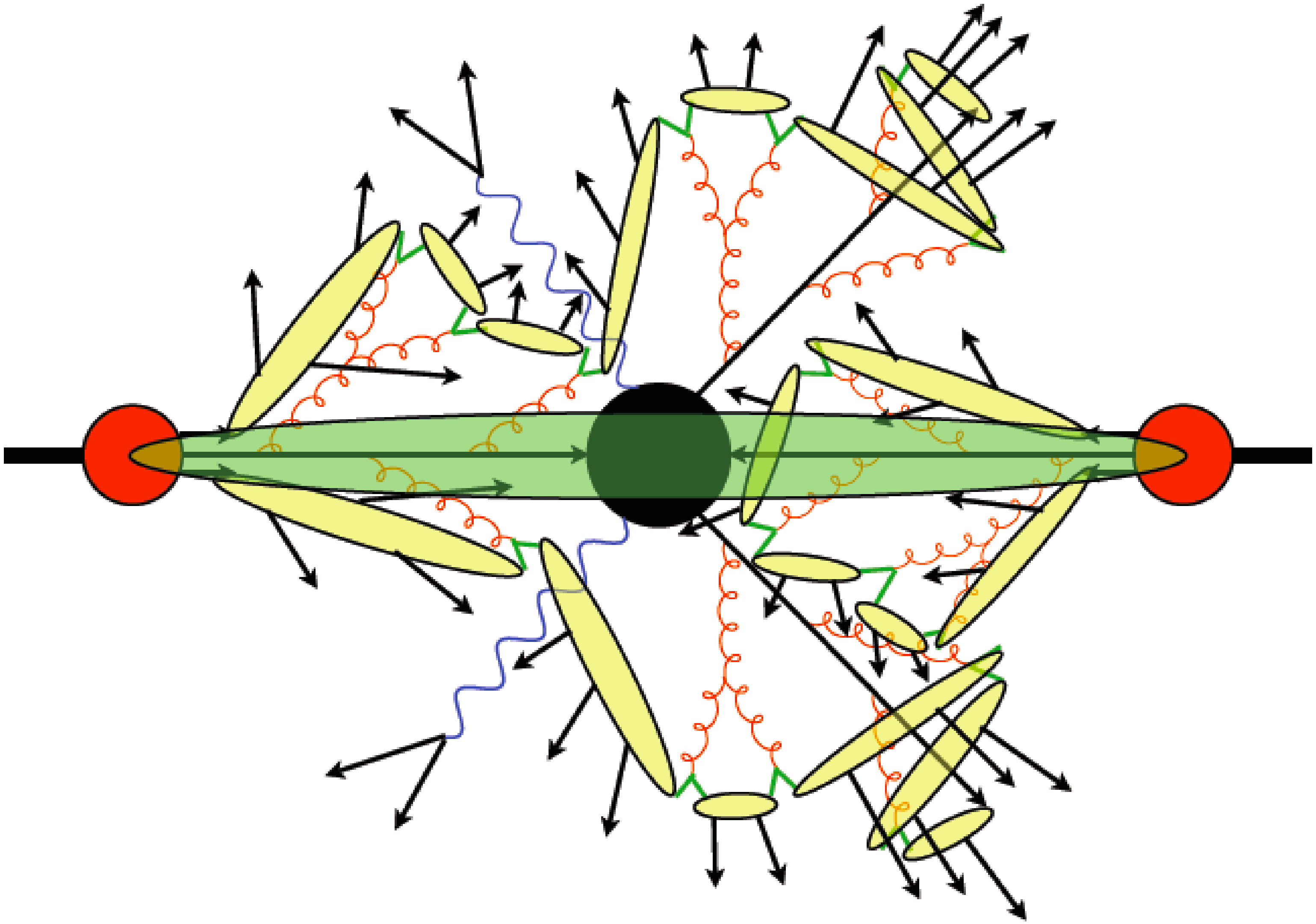
☛ note that the large M_t limit curve approximates very well the exact curve

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)

M.L. Mangano KITP collider conf 2004

LHC Event Simulation



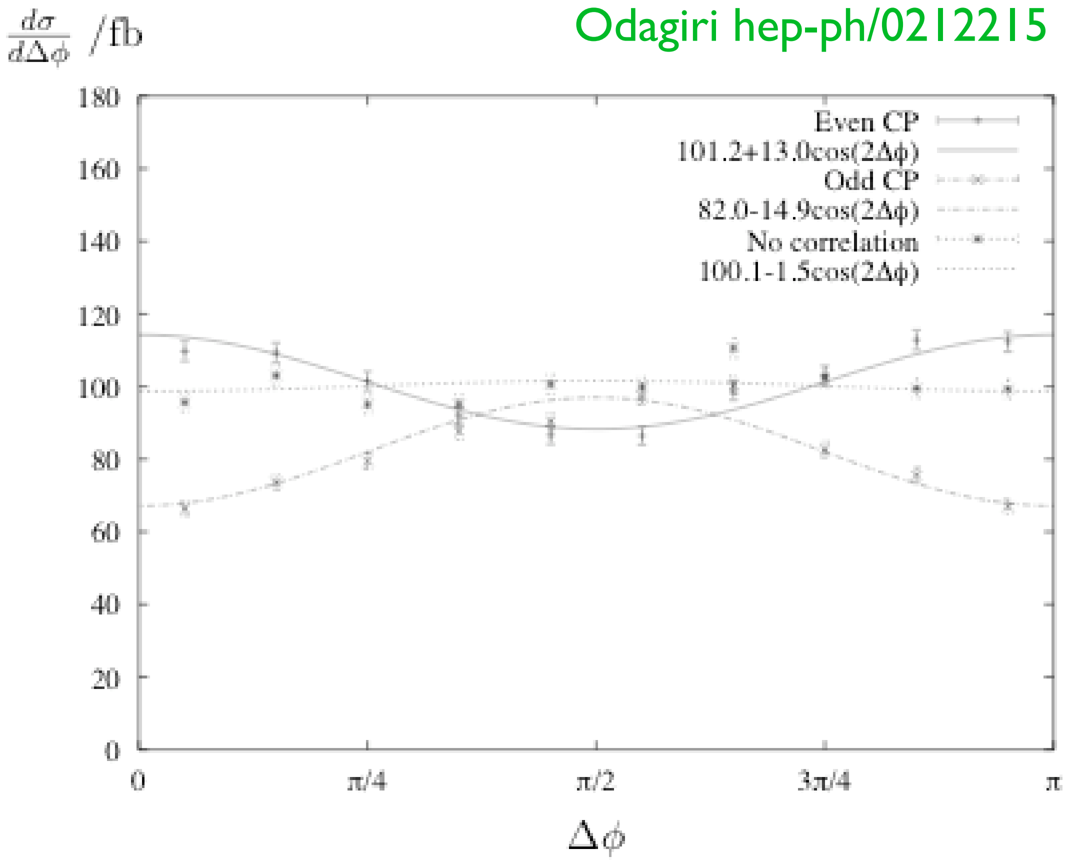
2

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

Azimuthal angle distribution

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

Odagiri hep-ph/0212215



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

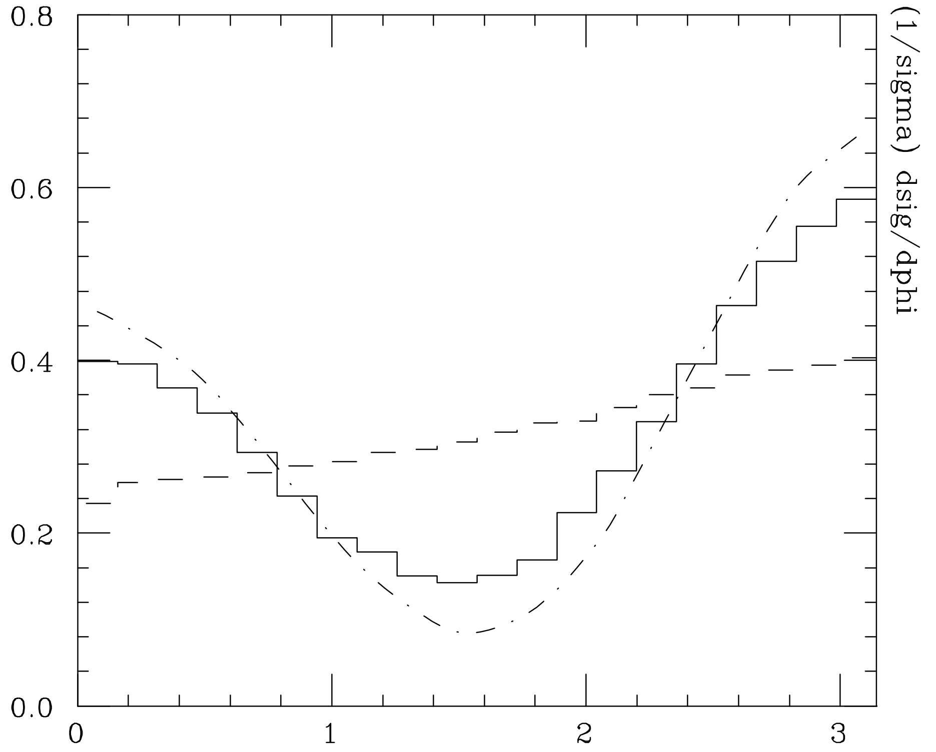
Klamke Mangano Moretti Piccinini Pittau Polosa Zeppenfeld VDD 2006

VBF cuts

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

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

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



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

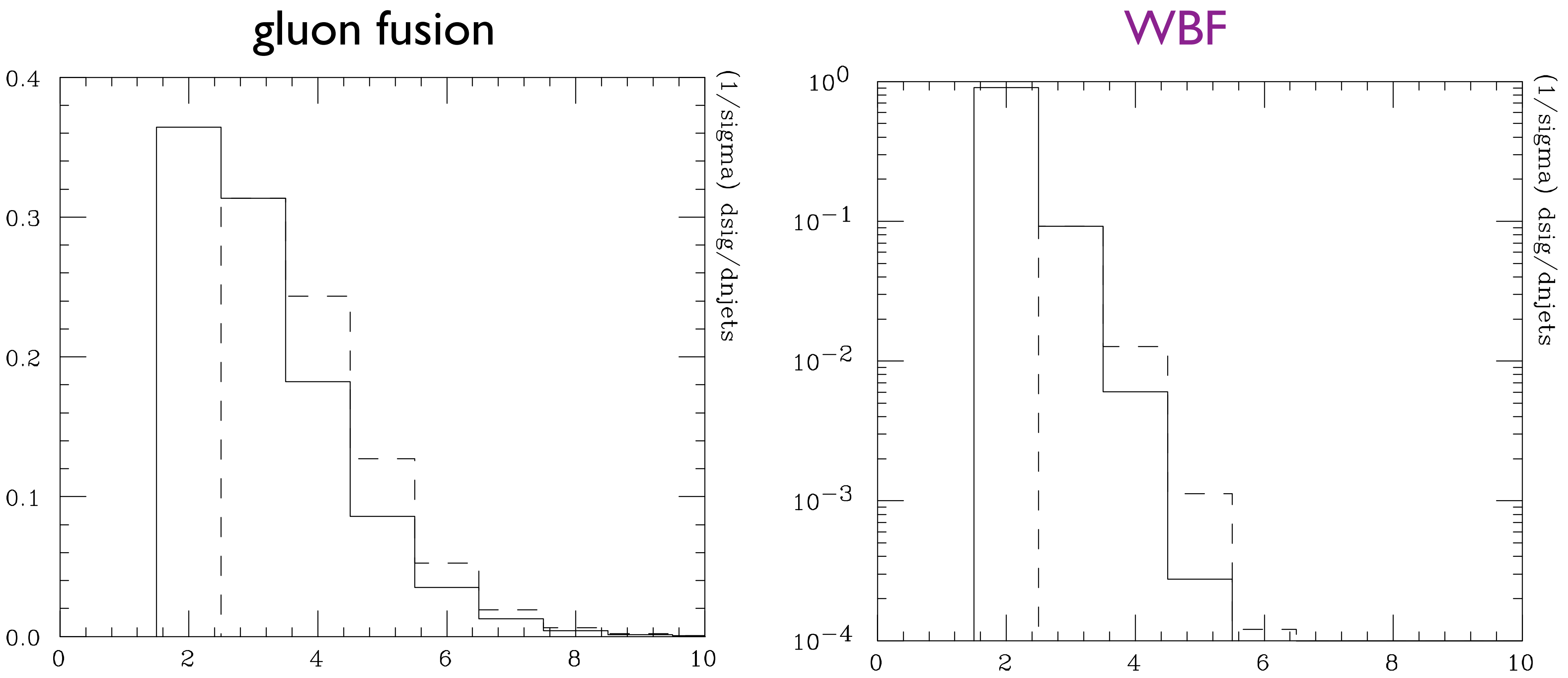
Aφ: a quantity that characterises how deep the dip is

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

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

ΔΦ 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

$$\mathcal{L}_6 = \frac{g^2}{2\Lambda^2_{\mathrm{e},6}} \left(\Phi^\dagger\Phi\right) V_{\mu\nu} V^{\mu\nu} + \frac{g^2}{2\Lambda^2_{\mathrm{o},6}} \left(\Phi^\dagger\Phi\right) \widetilde{V}_{\mu\nu} V^{\mu\nu}$$

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

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

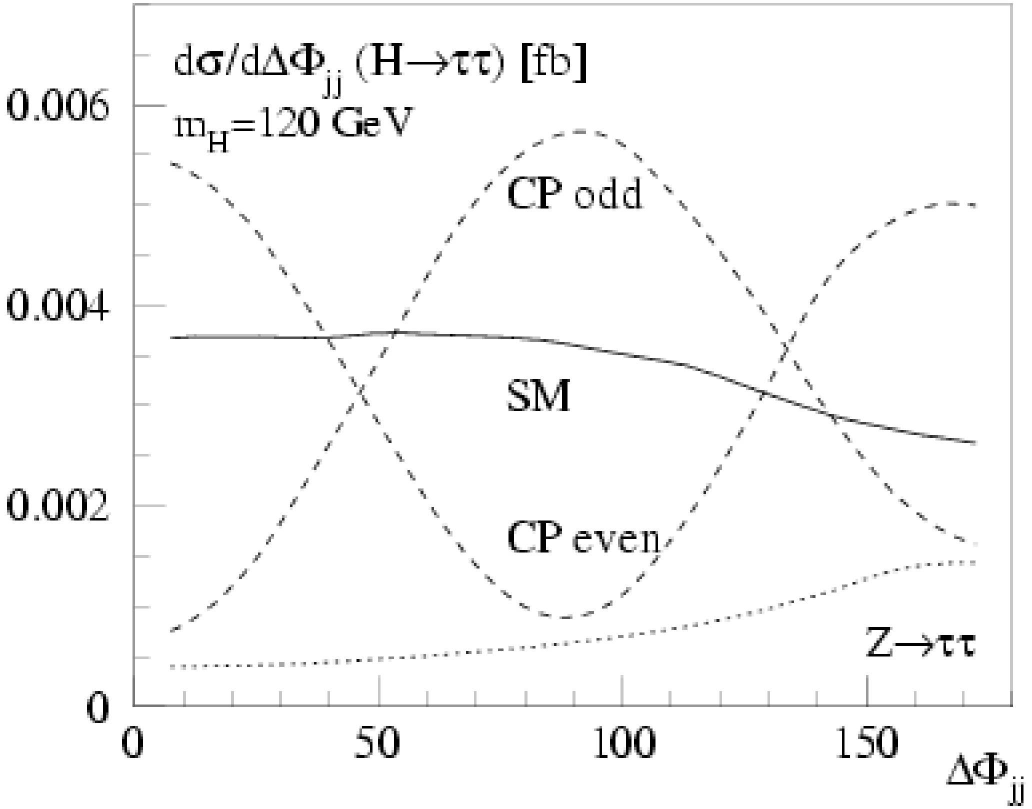
- CP odd D5 operator: $\epsilon^{\mu\nu\alpha\beta}$ tensor in the coupling
  - ➡ zero at $\Delta\phi_{jj} = 0, \pi$

- CP even D5 operator is like the effective ggH coupling

$$\mathcal{A}_{\mathrm{CP\ even}} \sim \frac{1}{\Lambda_{\mathrm{e},5}} J_1^\mu \left(q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2\right) J_2^\nu \qquad \Rightarrow \qquad \text{zero at } \Delta\phi_{jj} = \frac{\pi}{2}$$

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:

$p_{j\perp} > 20$ GeV

$|\eta_j| < 5$

$R_{jj} > 0.6$

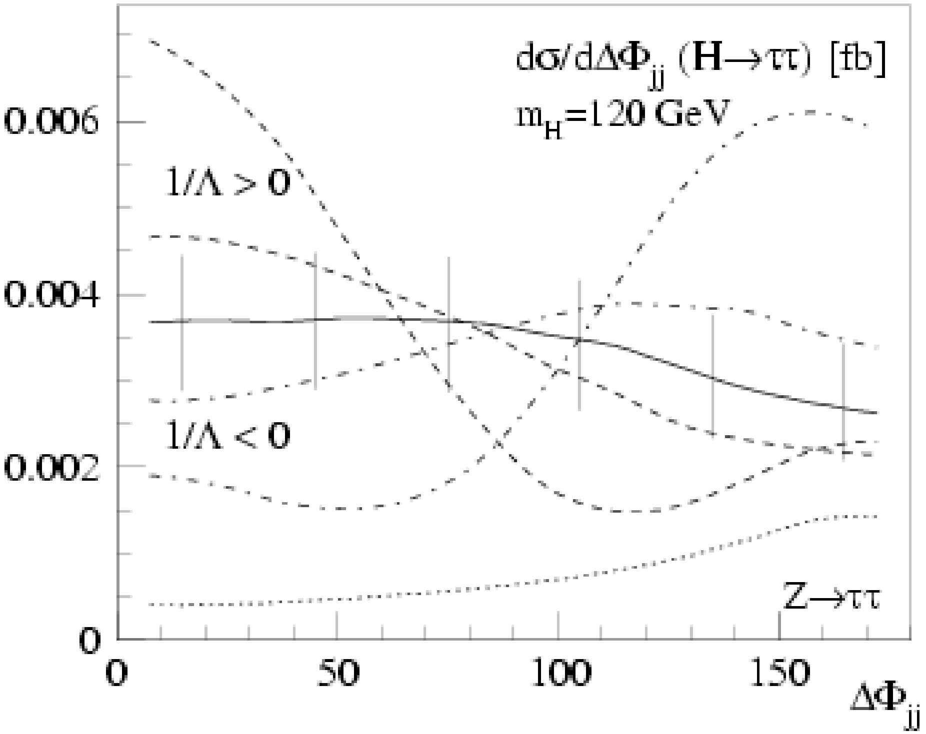
$\eta_{j_1} \cdot \eta_{j_2} < 0$

$|\eta_{j_1} - \eta_{j_2}| > 4.2$

- 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 $\sigma/\sigma_{\rm SM} = 0.04, 1.0$. 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: $|\mathcal{A}|^2 = |\mathcal{A}_{\rm SM} + \mathcal{A}_{e,5}|^2$
  - ☛ all terms, but $|\mathcal{A}_{\rm SM}|^2$, have an approximate zero at $\Delta\phi_{\rm jj} = \pi/2$
  - ☛ 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

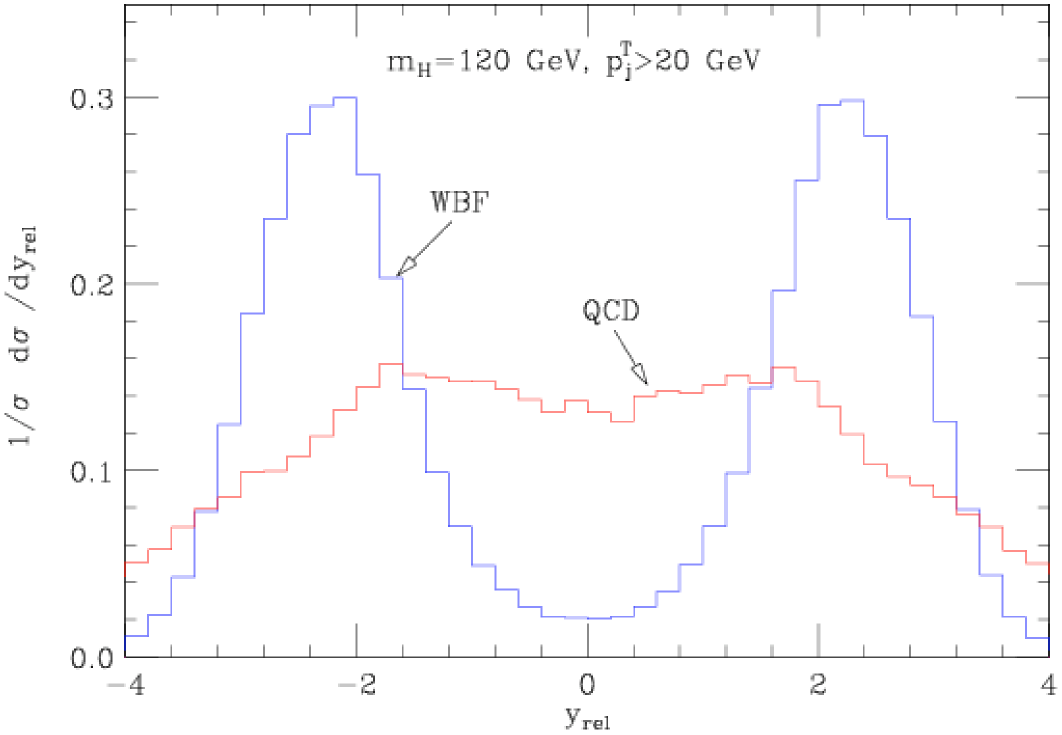
- In WBF no colour is exchanged in the *t* channel

- 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

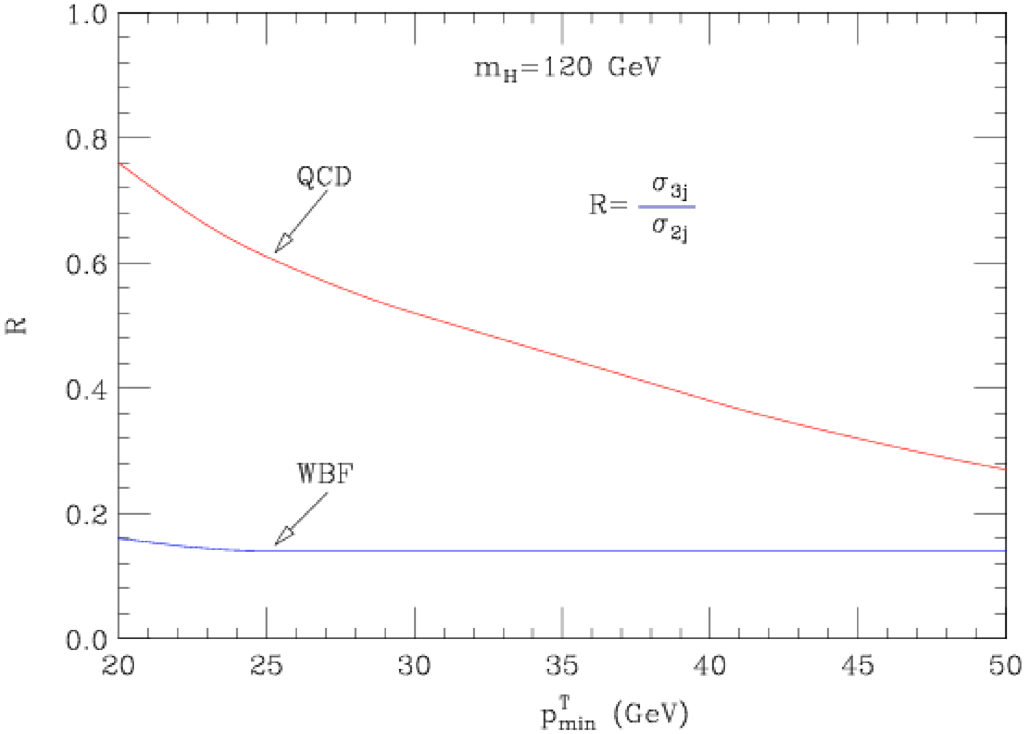
- The central-jet veto can also be used to distinguish between Higgs production via gluon fusion and via WBF

Frizzo, Maltoni, VDD   hep-ph/0404013



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^T_{min}



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 WBF and gluon fusion, and to investigate the tensor structure of the WWH coupling
- Because of the characteristic final-state topology induced by WBF production large-rapidity cuts can be used to deplete gluon fusion wrt WBF
- 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

    → need NLO overall normalisation → MC@NLO