Higgs + 2 Jets
via
Gluon Fusion

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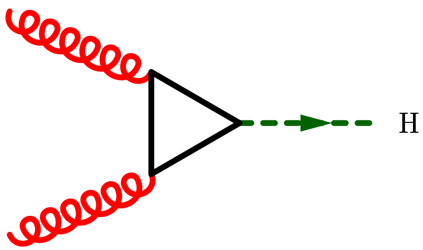
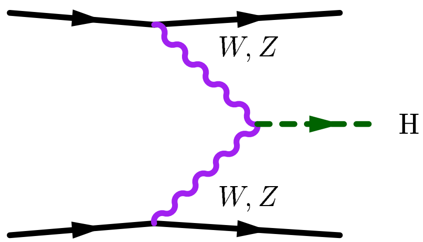
I.N.F.N. Torino

Theory Colloquium CERN, July 31, 2002

THEORY in pp collisions, the Higgs is produced mostly via

- gluon fusion $gg \to H$
- weak-boson fusion (WBF) $qq \to qqH$





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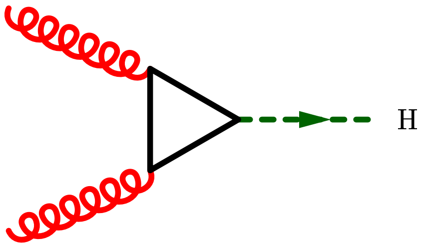
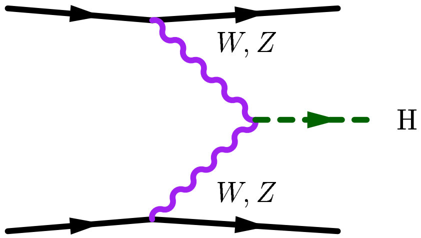




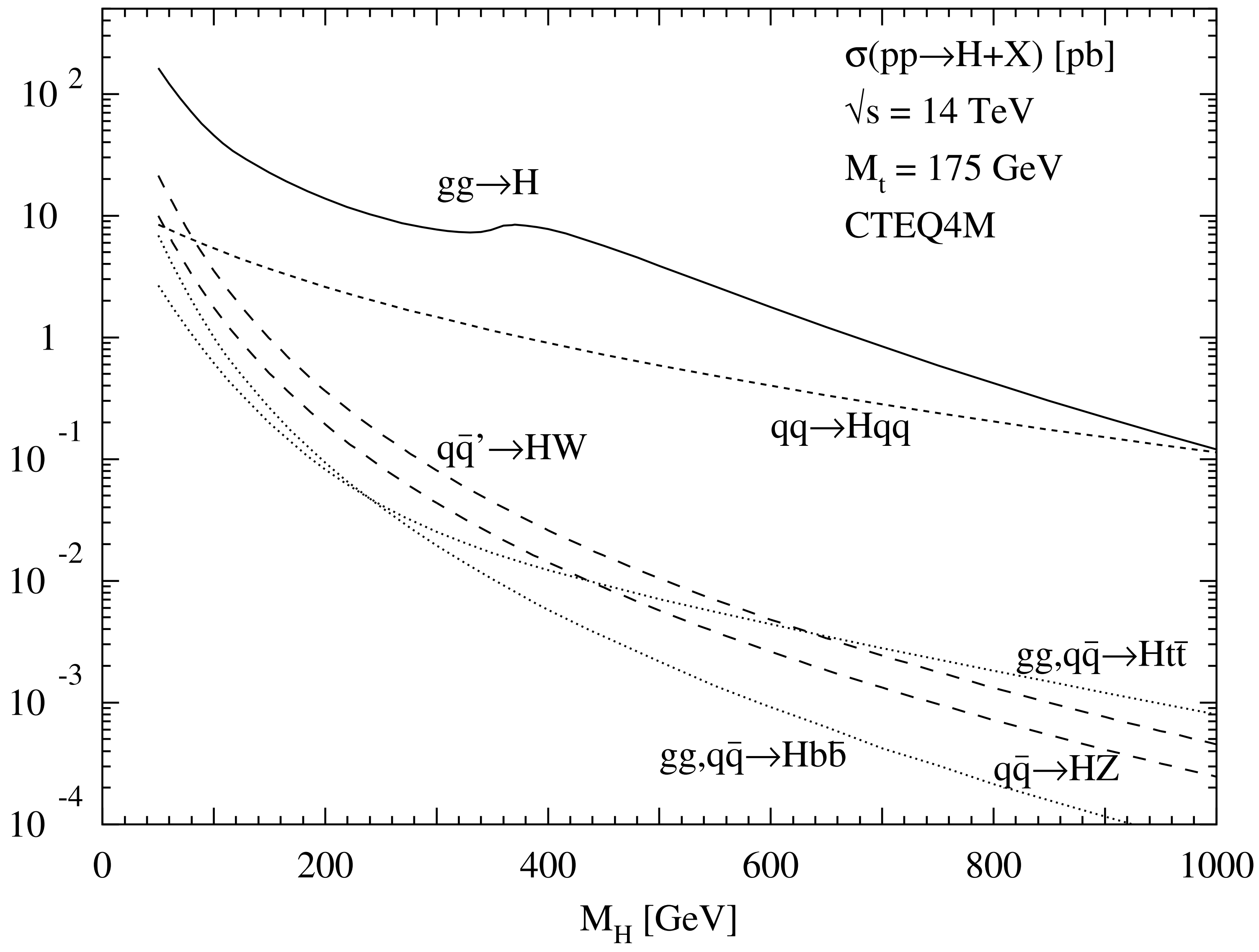
GOALS we wish to:

- distinguish between gluon and WBF
- investigate approximations that make gluon fusion simpler
- measure the WWH coupling

METHOD detect a Higgs and two jets
and use the topology of the final state

Higgs Production at the LHC

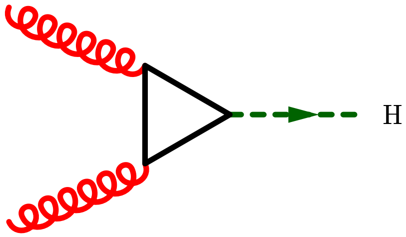
Spira hep-ph/9705337



Higgs Production via Gluon Fusion

Leading Order

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

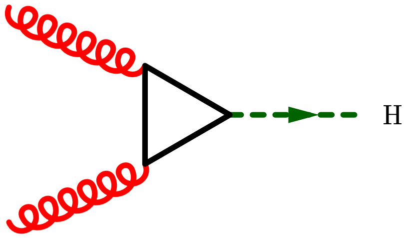


- energy scales: $\hat{s} = M_{\mathrm{H}}^2$ and M_t^2

HIGGS PRODUCTION VIA GLUON FUSION

LEADING ORDER

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

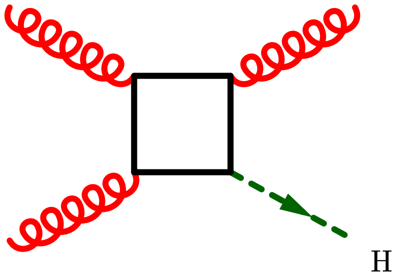


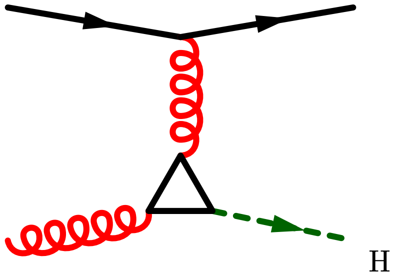
☛ energy scales: $\hat{s} = M_{\rm H}^2$ and M_t^2

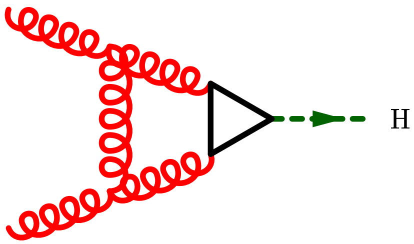
NLO CORRECTIONS

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

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



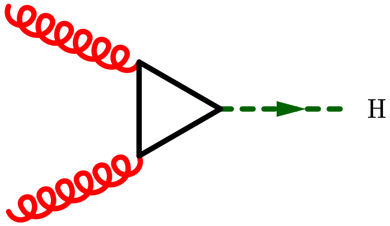




Djouadi, Graudenz, Spira, Zerwas, '93-'95

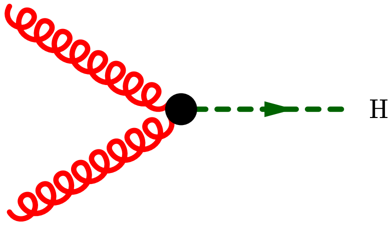
☛ large K factor: $\sigma^{\rm NLO} = K^{\rm NLO}\ \sigma^{\rm LO}$

The Large Top-mass Limit

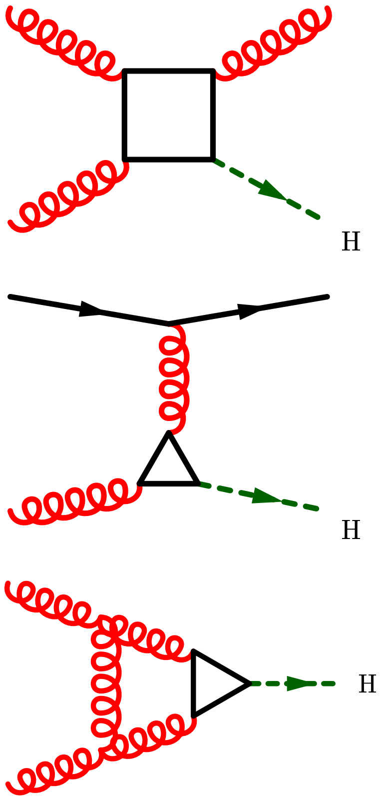


$M_H \ll 2M_t$

$\longrightarrow$



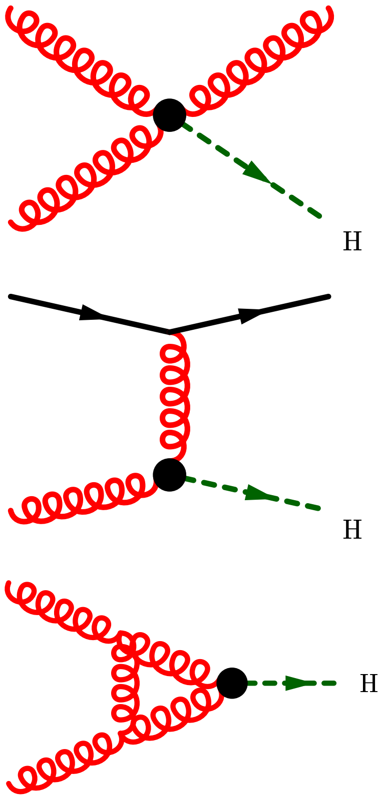
NLO corrections



$\longrightarrow$

$\longrightarrow$

$\longrightarrow$



K factor in the large M_t limit

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

NLO rate in the large M_t limit

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

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

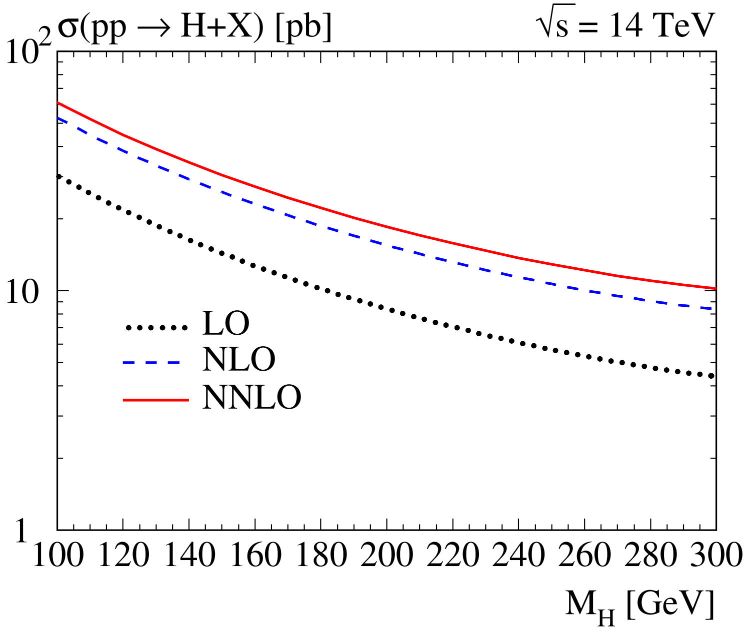
$gg \to H$ IN THE LARGE M_t LIMIT

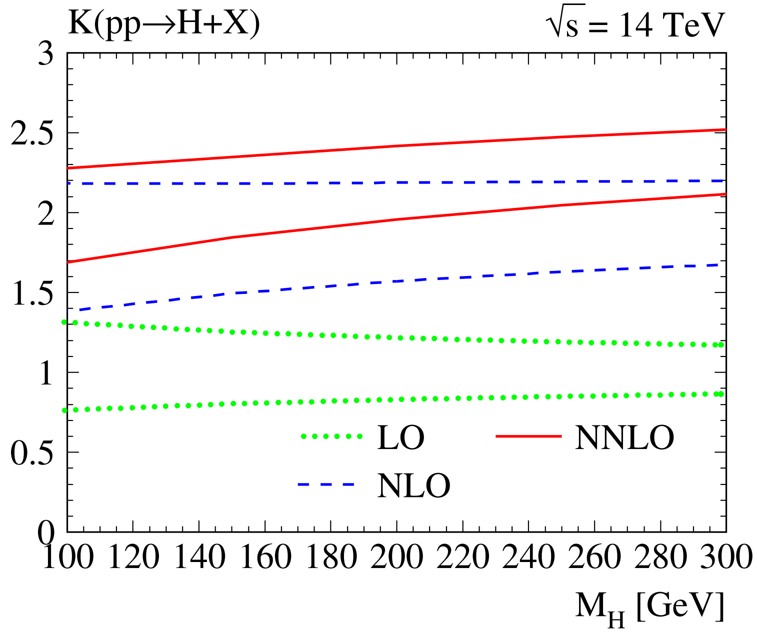
NNLO CORRECTIONS

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

- 2-loop $gg \to H$ — Harlander hep-ph/0007289
- 1-loop $gg \to gH$ $qg \to qH$ + crossings
- tree $gg \to ggH$ $qg \to qgH$ $qQ \to qQH$ + crossings

Harlander, Kilgore hep-ph/0201206





$$\sigma_\infty^{\mathrm{N(N)LO}} = K_\infty^{\mathrm{N(N)LO}}\ \sigma^{\mathrm{LO}}$$

for $\mu_R = \mu_F = M_\mathrm{H}$

Scale dependence of the K factor

Lower curves: $\mu_R = 2M_\mathrm{H}$ $\mu_F = M_\mathrm{H}/2$

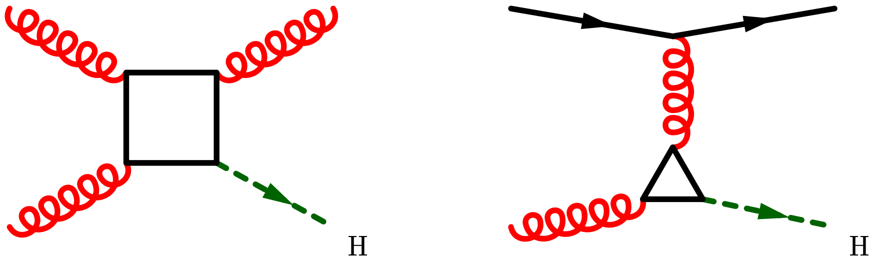
Upper curves: $\mu_R = M_\mathrm{H}/2$ $\mu_F = 2M_\mathrm{H}$

K factor is computed wrt to σ^{LO} at $\mu_R = \mu_F = M_\mathrm{H}$

Higgs + 1 Jet via Gluon Fusion

Leading Order

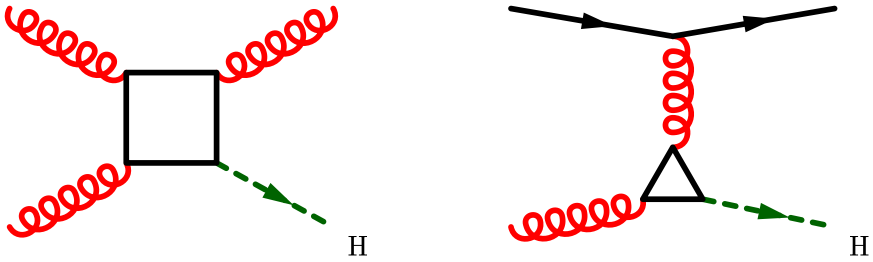
$\mathcal{O}(\alpha_s^3)$



- 1-loop $\quad gg \to gH \quad qg \to qH \quad + \quad$ crossings
- energy scales: $\hat{s} = s_{j\mathrm{H}}$ and $M_{\mathrm{H}}^2\,, M_t^2$, with $\hat{s} + \hat{t} + \hat{u} = M_{\mathrm{H}}^2$

HIGGS + 1 JET VIA GLUON FUSION

LEADING ORDER $\mathcal{O}(\alpha_S^3)$



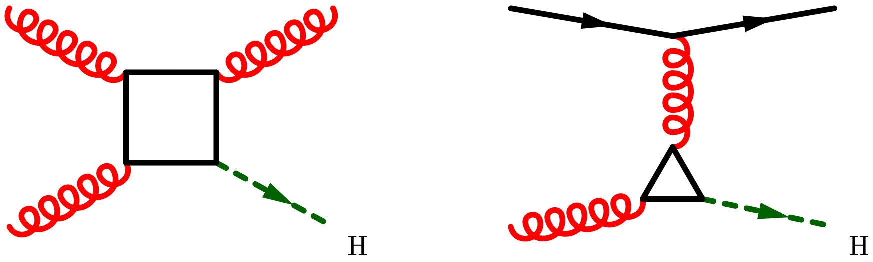
- 1-loop $gg \to gH \quad qg \to qH \quad +$ crossings
- energy scales: $\hat{s} = s_{j\mathrm{H}}$ and $M_{\mathrm{H}}^2\,, M_t^2$, with $\hat{s} + \hat{t} + \hat{u} = M_{\mathrm{H}}^2$

LARGE M_t LIMIT is accurate if $M_{\mathrm{H}} \ll 2M_t$ and $p_\perp \ll M_t$

is valid even when $s_{j\mathrm{H}} \gg M_t^2$

HIGGS + 1 JET VIA GLUON FUSION

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



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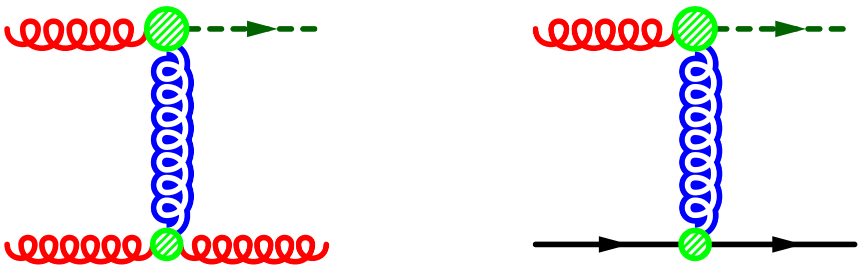
LARGE M_t LIMIT is accurate if $M_{\mathrm{H}} \ll 2M_t$ and $p_\perp \ll M_t$

is valid even when $s_{j\mathrm{H}} \gg M_t^2$

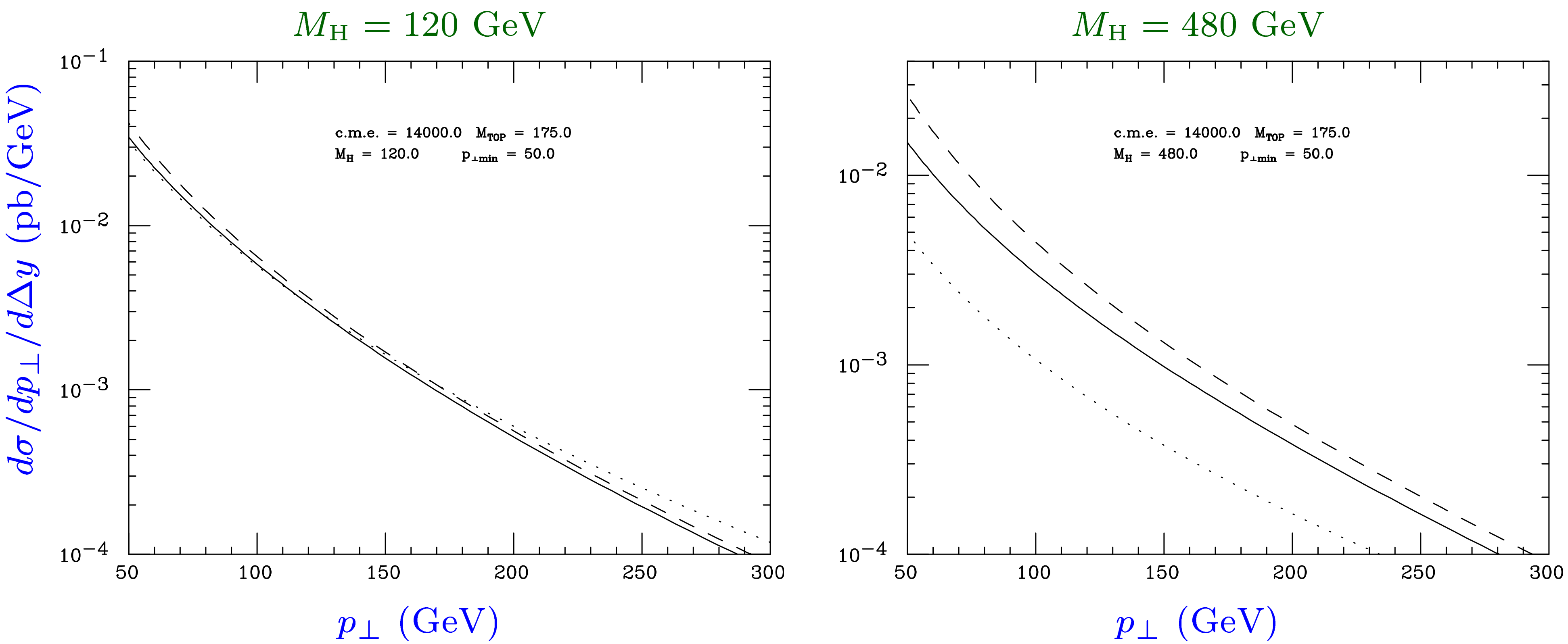
HIGH ENERGY LIMIT is valid if $s_{j\mathrm{H}} \gg |\hat{t}|, M_{\mathrm{H}}^2$

the scattering is dominated by the sub-processes with gluon exchange in the t channel



- the large M_t limit and the high energy limit commute

$p_\perp$ DISTRIBUTION at $\Delta y = 3$ for $M_t = 175$ GeV



—— :exact

$\cdots$:large M_t limit

- - - :high energy limit

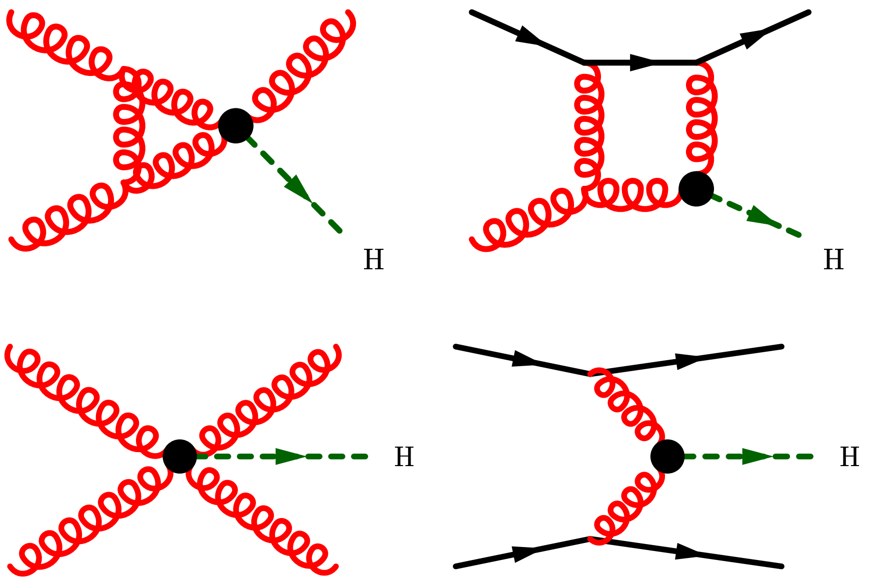
- for $M_{\rm H} = 120$ Gev and $p_\perp \geq 50$ GeV, the jet-Higgs mass is $\sqrt{s_{j{\rm H}}} \gtrsim 390$ GeV: the large M_t limit performs well for $p_\perp \lesssim M_t$, and irrespective of $s_{j{\rm H}}$
- for $M_{\rm H} = 480$ GeV, the large M_t limit does not apply, the high energy limit only gets slightly worse

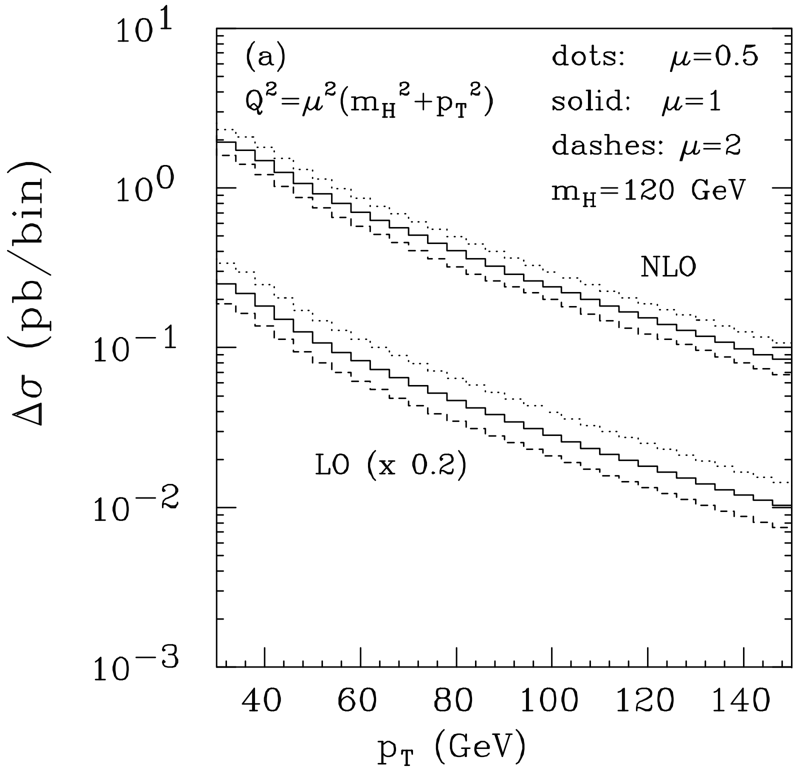
HIGGS + 1 JET IN THE LARGE M_t LIMIT

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

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

de Florian, Grazzini, Kunszt hep-ph/9902483



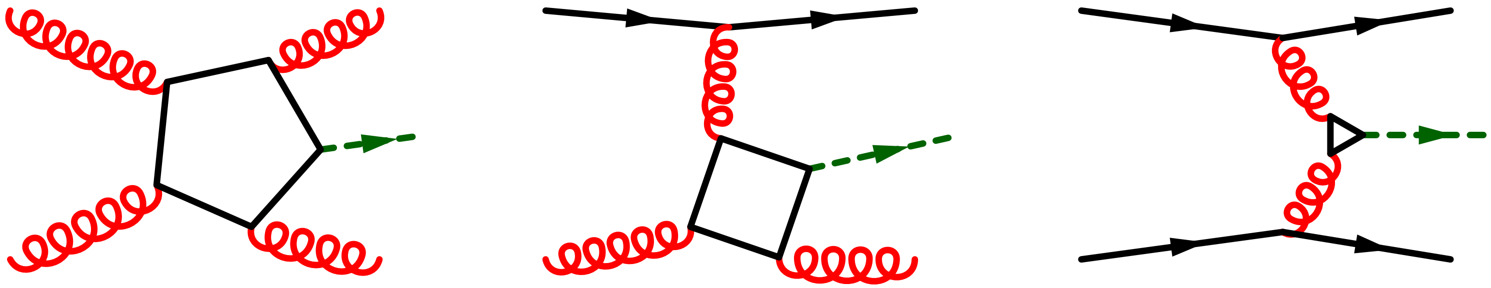


- large K factor: $K_\infty^{\mathrm{NLO}} \simeq 1.6$
- variation of $\mu_R = \mu_F = \mu = 0.5 \to 2$: $\pm 35\%$ at LO; $\pm 20\%$ at NLO

Higgs + 2 Jets via Gluon Fusion

Leading Order

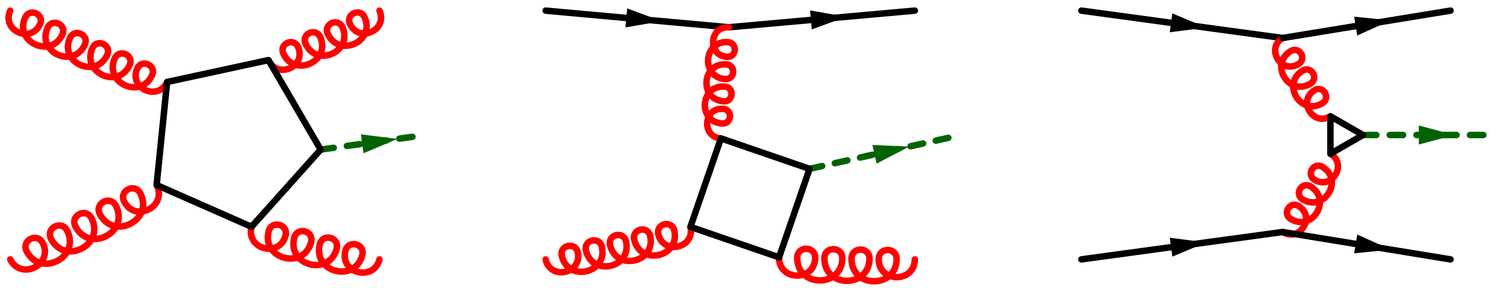
$\mathcal{O}(\alpha_s^4)$



- tree $\quad gg \to ggH \quad qg \to qgH \quad qQ \to qQH \quad +$ crossings
- energy scales: $\hat{s}\,, s_{j_1\mathrm{H}}, s_{j_2\mathrm{H}}, s_{j_1 j_2}, M_{\mathrm{H}}^2, M_t^2$, with $\hat{s} = s_{j_1 j_2} + s_{j_1\mathrm{H}} + s_{j_2\mathrm{H}} - M_{\mathrm{H}}^2$

Higgs + 2 Jets via Gluon Fusion

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



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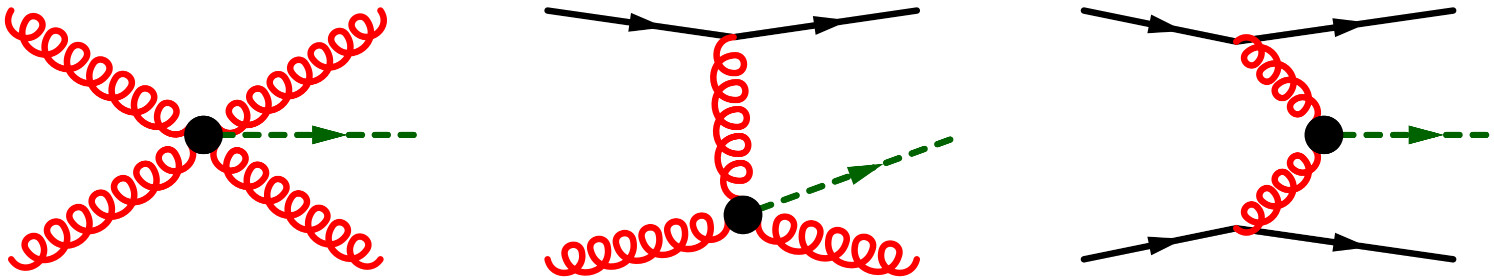
- energy scales: $\hat{s}\,, s_{j_1 \mathrm{H}}, s_{j_2 \mathrm{H}}, s_{j_1 j_2}, M_{\mathrm{H}}^2, M_t^2$, with $\hat{s} = s_{j_1 j_2} + s_{j_1 \mathrm{H}} + s_{j_2 \mathrm{H}} - M_{\mathrm{H}}^2$

Large M_t limit

is accurate if $M_{\mathrm{H}} \ll 2M_t$ and $p_{j_1 \perp}, p_{j_2 \perp}, p_{\mathrm{H} \perp} \ll M_t$

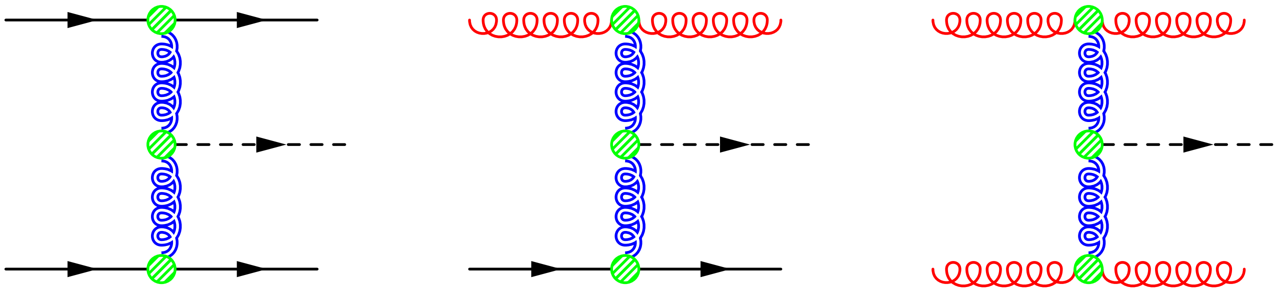
is valid even when $s_{j_1 j_2}, s_{j_1 \mathrm{H}}, s_{j_2 \mathrm{H}} \gg M_t^2$



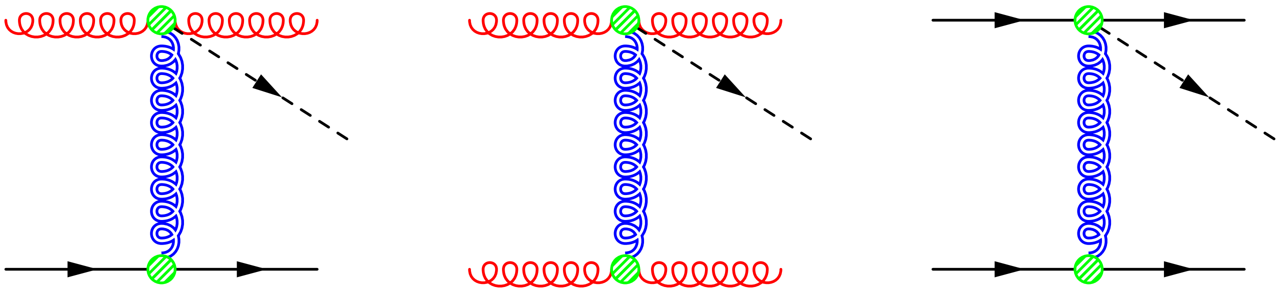
HIGH ENERGY LIMITS commute with the large M_t limit

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0301013

- $s_{j_1 j_2} \gg s_{j_1 \mathrm{H}}\,, s_{j_2 \mathrm{H}} \gg M_{\mathrm{H}}^2$

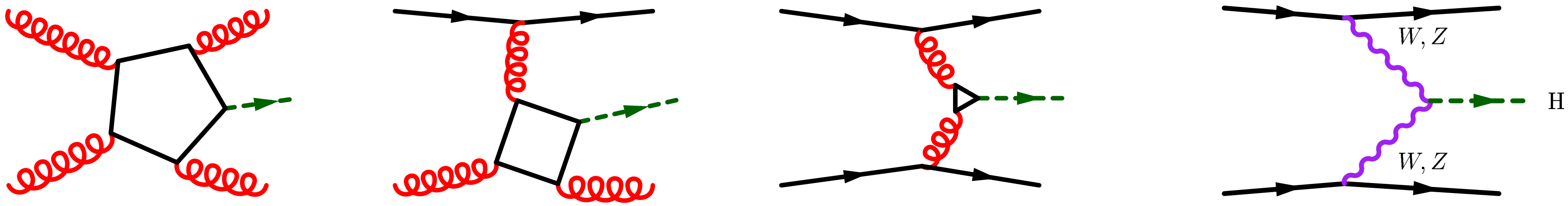


- $s_{j_1 j_2}\,, s_{j_2 \mathrm{H}} \gg s_{j_1 \mathrm{H}}\,, M_{\mathrm{H}}^2$

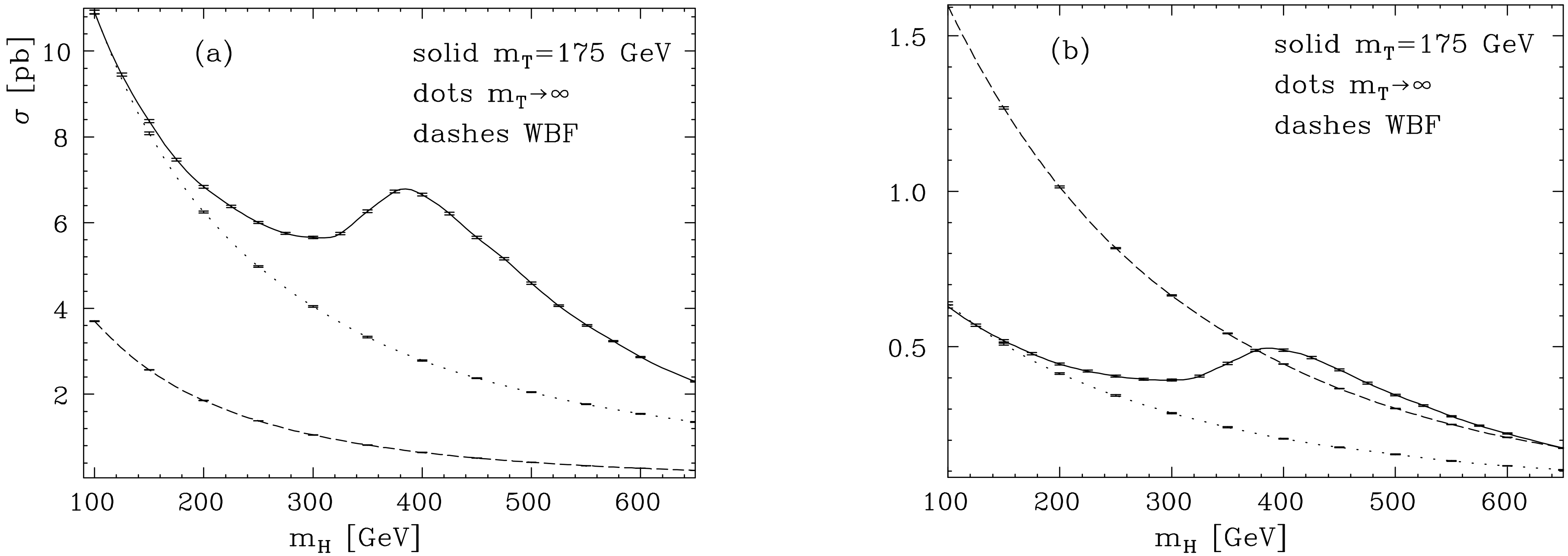


- the large M_t limit does not modify the high-energy factorization, but only the impact factor for Higgs production. In the high-energy limit, the sensitivity to the full M_t dependence does not occur globally at the level of the entire amplitude, but locally (in rapidity) at the level of the impact factor for Higgs production.

$H+$ 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



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

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

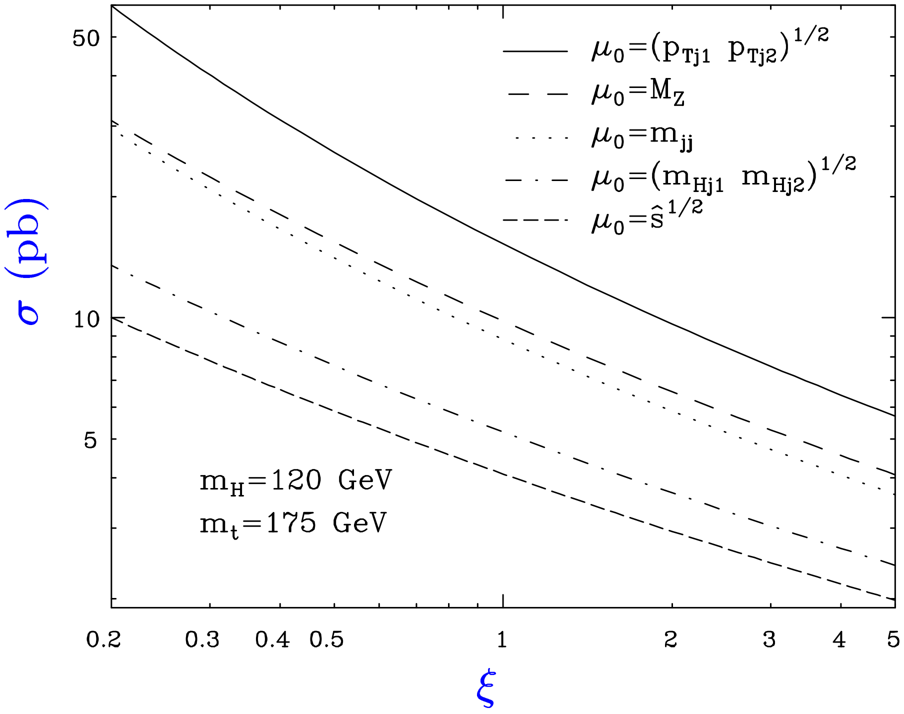
☛ WBF cuts enhance WBF wrt gluon fusion by a factor 10

Scale dependence

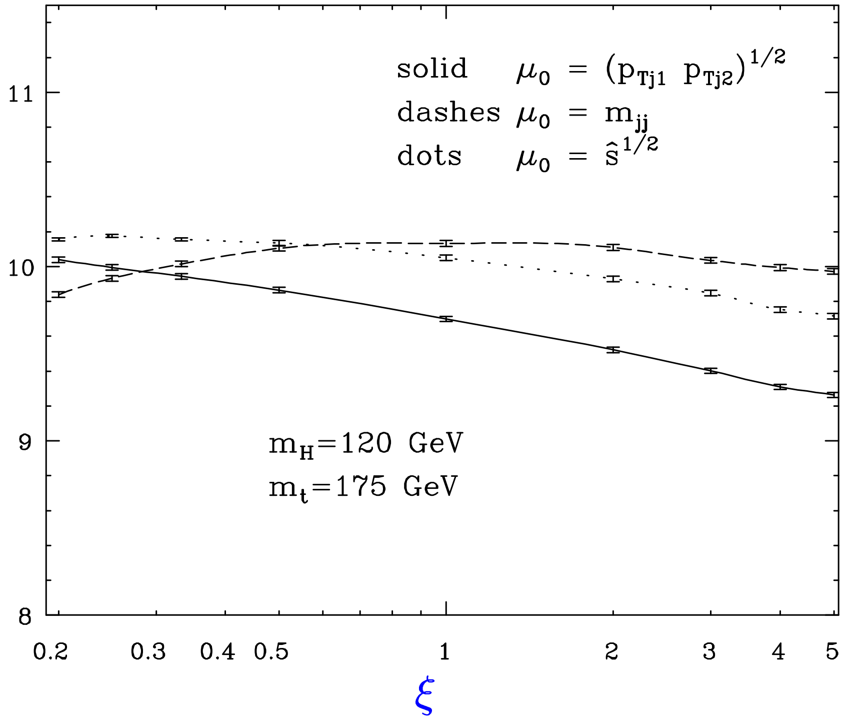
renormalisation μ_R & factorisation μ_F scales

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

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



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

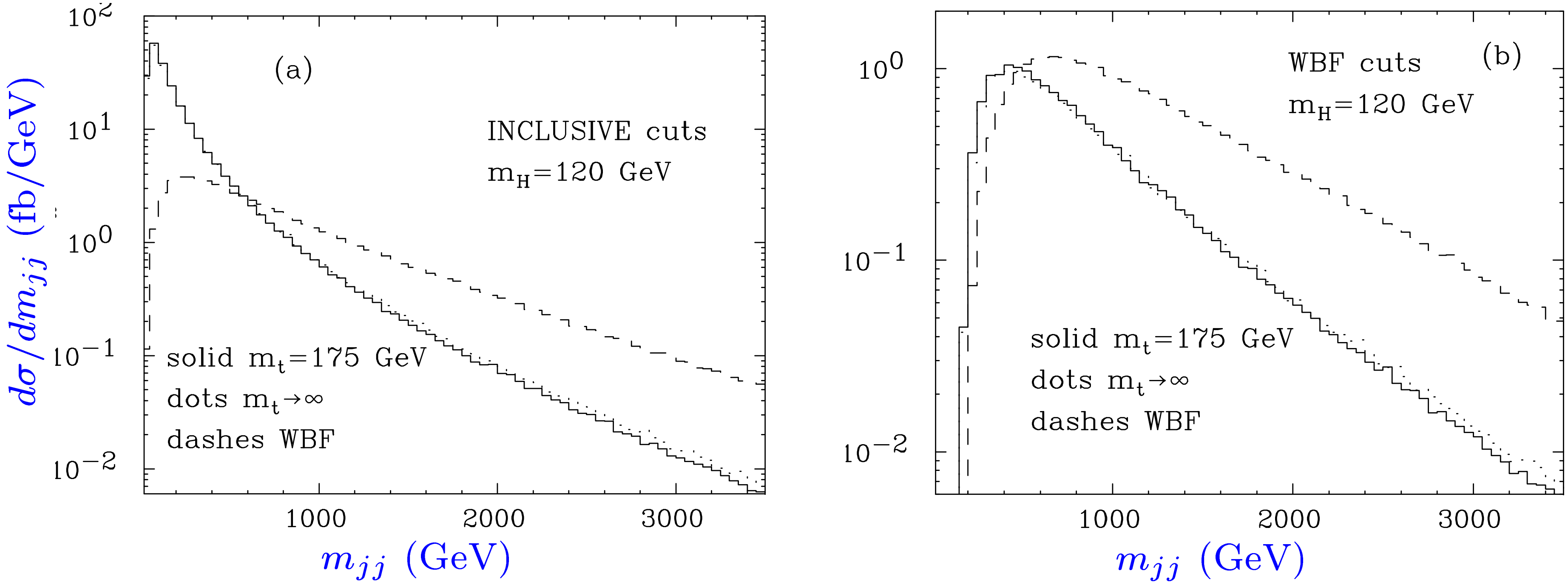


- strong μ_R dependence: the calculation is LO and $\mathcal{O}(\alpha_S^4)$
  - a natural scale for α_S ?

    high energy limit suggests $\alpha_S^4 \to \alpha_S(p_{j_1\perp})\alpha_S(p_{j_1\perp})\alpha_S^2(M_{\rm H})$
    - 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

DIJET MASS DISTRIBUTIONS

$\sqrt{s_{jj}} \equiv m_{jj}$: dijet invariant mass



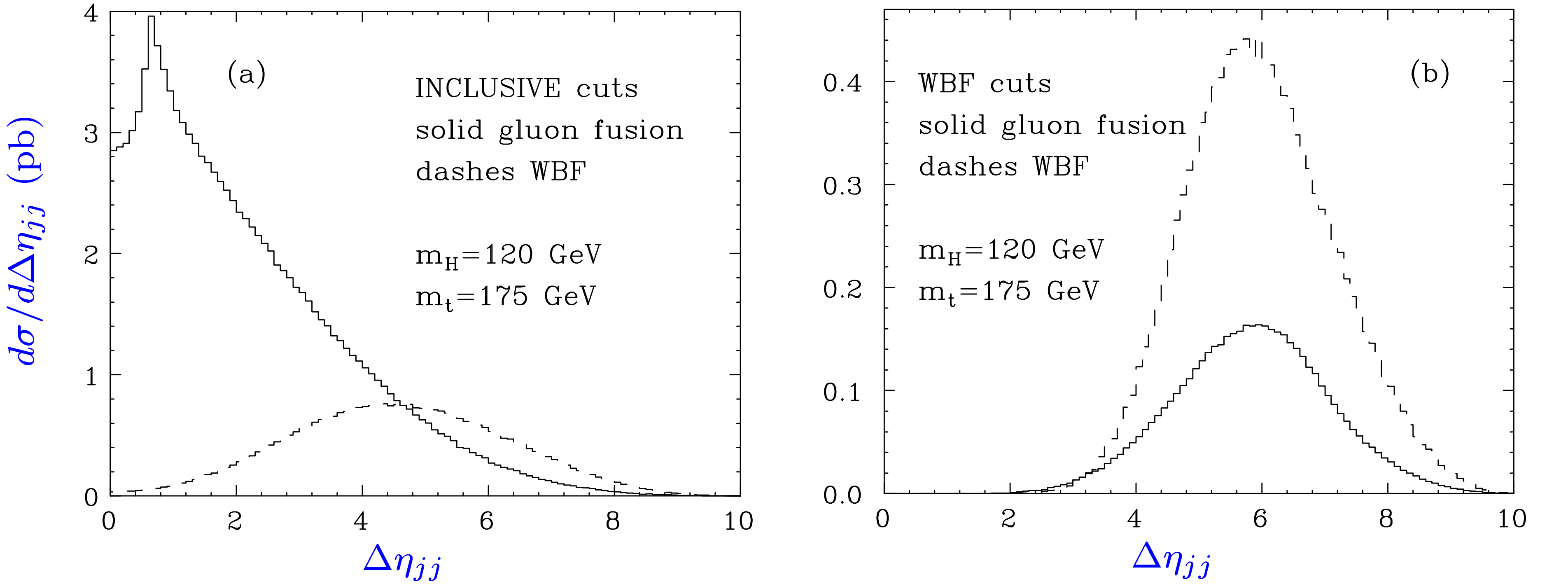
inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

WBF cuts: incl. + $\begin{cases} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ |\eta_{j_1} - \eta_{j_2}| > 4.2 \end{cases}$

- high dijet mass region ($m_{jj} \gtrsim 1$ TeV) is dominated by WBF
- large dijet masses do not invalidate the large M_t limit (as long as $p_{j_1\perp}, p_{j_2\perp} \ll M_t$)

Rapidity distributions

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



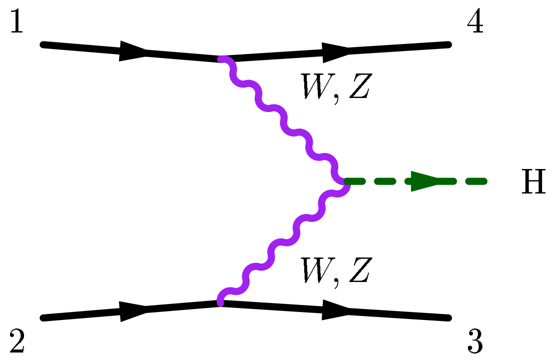
inclusive cuts: $\begin{cases} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{cases}$

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: $R_{jj} = \sqrt{\Delta\eta_{jj} + \Delta\phi_{jj}} > 0.6$

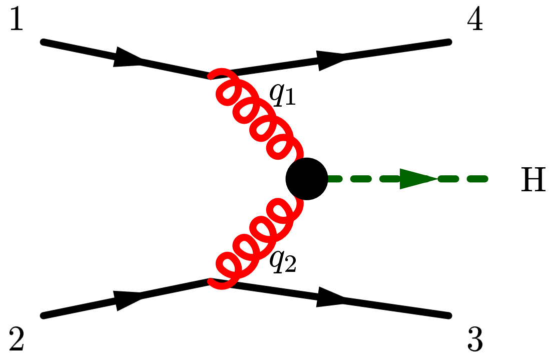
Azimuthal angle correlations

$\Delta\phi_{jj} \equiv$ 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

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

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

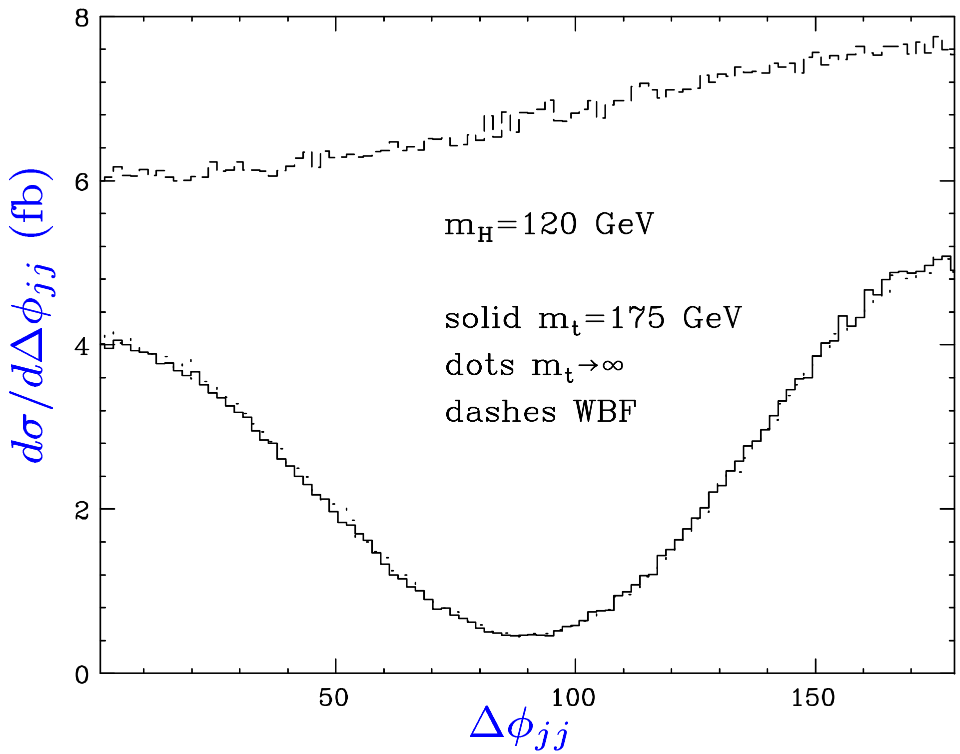
$J^\mu \equiv$ quark-gluon current

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 $\Delta\phi_{jj} = \frac{\pi}{2}$

Azimuthal angle distribution



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

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

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

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

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

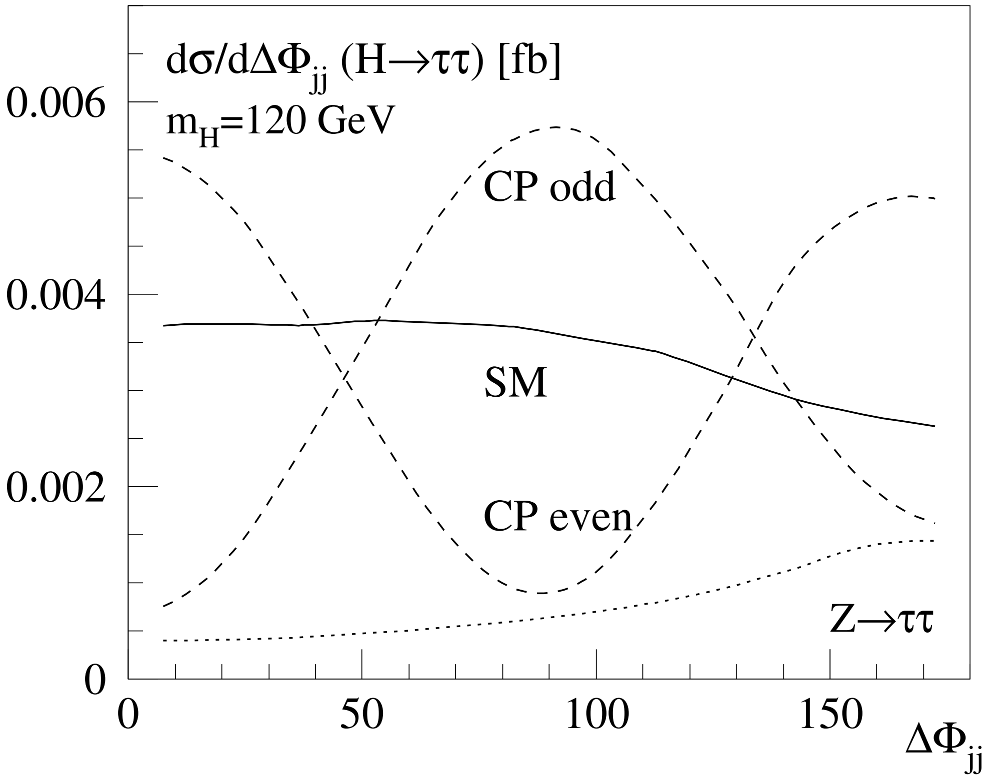
- CP odd D5 operator: $\epsilon^{\mu\nu\alpha\beta}$ tensor in the coupling
  - ➥ zero at $\Delta\phi_{jj} = 0, \pi$

- CP even D5 operator is like the effective ggH coupling

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

Azimuthal angle distribution for WWH couplings

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



WBF cuts:

$p_{j\perp} > 20$ GeV

$|\eta_j| < 5$

$R_{jj} > 0.6$

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

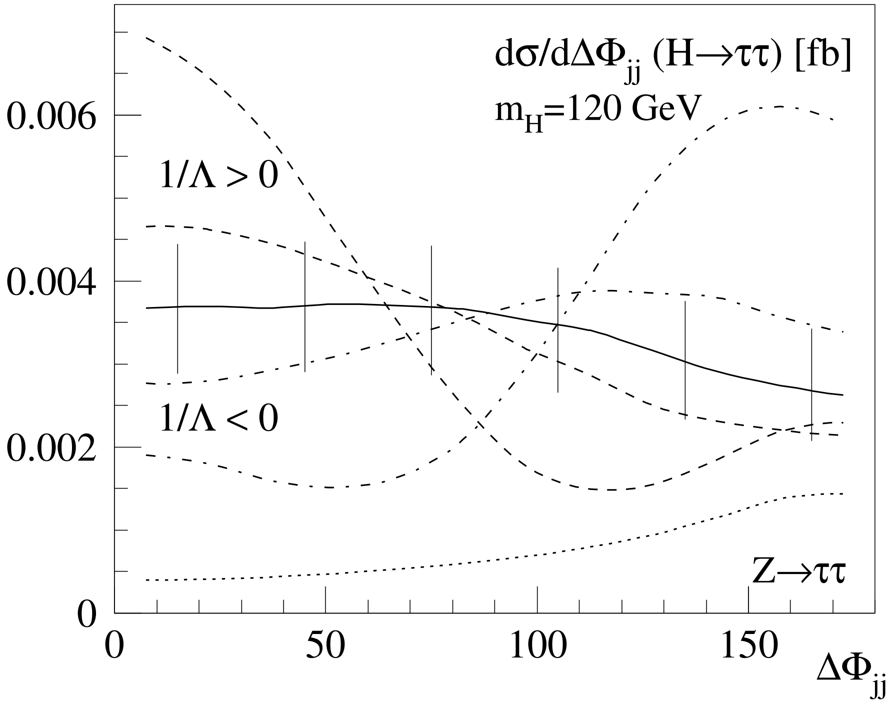
$|\eta_{j_1} - \eta_{j_2}| > 4.2$

- 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 the 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



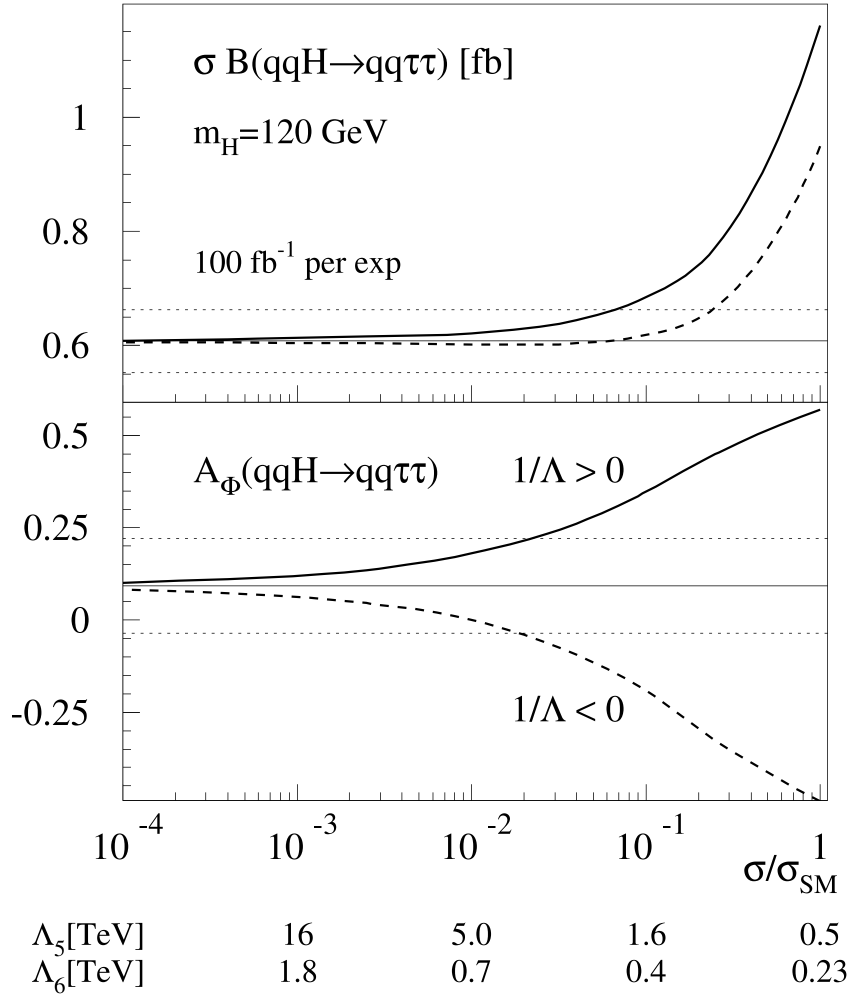
$\Delta\phi_{jj}$ distribution for the SM and interference with a CP even D5 coupling. The two curves for each sign of the operator correspond to values $\sigma/\sigma_{\rm SM} = 0.04, 1.0$. Error bars correspond to an integrated luminosity of 100 fb^{-1} per experiment, distributed over 6 bins, and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

AZIMUTHAL ANGLE ASYMMETRY

$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \pi/2) - \sigma(\Delta\phi_{jj} > \pi/2)}{\sigma(\Delta\phi_{jj} < \pi/2) + \sigma(\Delta\phi_{jj} > \pi/2)}$$

comparison of the sensitivity of a total cross section (counting) experiment and the azimuthal angle asymmetry, A_ϕ, to the presence of a CP even D5 coupling. The horizontal lines represent one sigma statistical deviations from the SM value. The secondary axes show the corresponding values of Λ_5 and Λ_6



At the 1-σ level (statistical errors only), with $100\ \mathrm{fb}^{-1}$ per experiment,

- the total cross section is sensitive to $\Lambda_{e,6} < 510$ GeV $(1/\Lambda > 0)$ or 290 GeV $(1/\Lambda < 0)$
- with A_ϕ the reach in the leptonic $\tau\tau$ channel is ~ 690 GeV, which goes up to $\Lambda_6 \sim 1$ TeV, after adding the statistics of $\tau\tau$, WW, and $\gamma\gamma$ WBF channels.

Conclusions

- Higgs + 2 Jets via gluon fusion has been computed at leading order, including the full top mass dependence
- the large M_t limit is accurate if $M_{\mathrm{H}} \ll 2M_t$ and $p_\perp \ll M_t$, and is valid even when the dijet (or jet-Higgs) invariant masses are much larger than M_t
- with inclusive cuts, Higgs + 2 Jets via gluon fusion is about 3 times as large as the same via WBF; the reverse is true if WBF cuts are used
- Higgs + 2 Jets via gluon fusion has a strong renormalisation scale dependence
- the azimuthal angle correlation between the two jets can be used as a tool to distinguish between gluon fusion and WBF, and to investigate the tensor structure of the WWH coupling
  - ➥ systematic uncertainty is affected by $H + 2$ jet rate from gluon fusion, and is limited by lack of knowledge of NLO corrections