Mixed QCD-electroweak contributions to Higgs-plus-dijet production at the LHC

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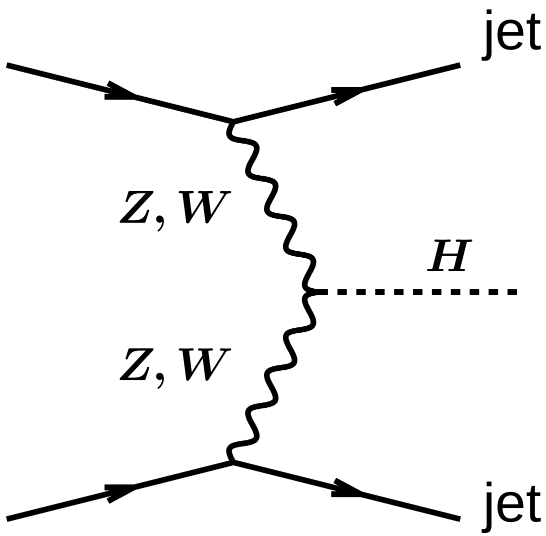
outline

- a brief overview: $\boldsymbol{Hjj}$ production at the LHC
  - ☞ refer to talks by S. Dittmaier and T. Figy
- QCD-EW interference effects in $\boldsymbol{Hjj}$ production beyond tree level:
  - details of the calculation
  - numerical results
- summary & conclusions

Higgs production in WBF

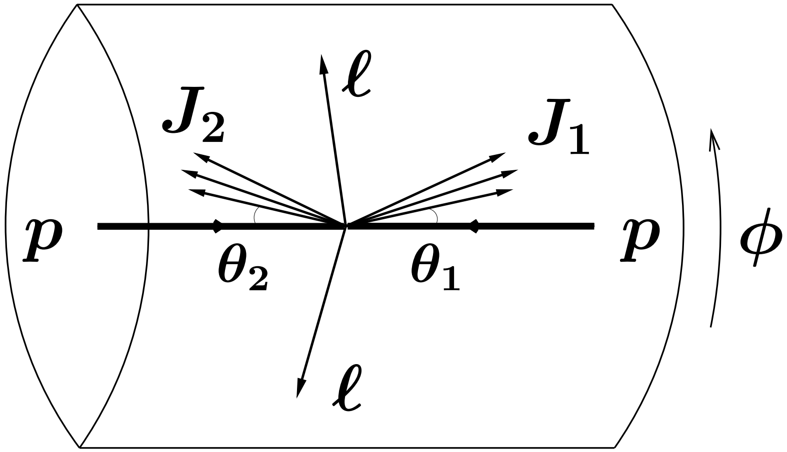


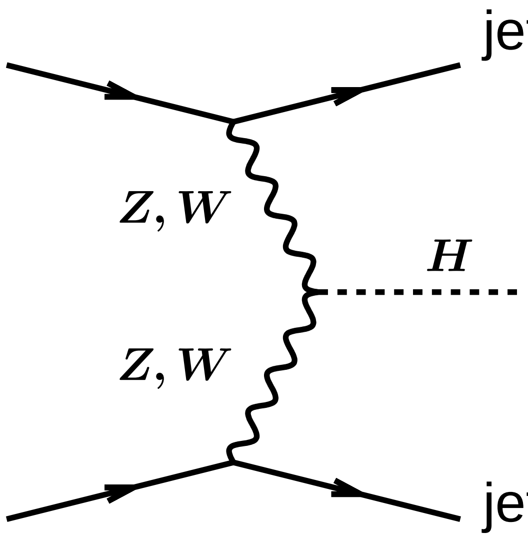
scattered quarks
⟶ two forward tagging jets
(energetic; $p_T > 20$ GeV)

Higgs decay products
typically between tagging jets

little jet activity in
central rapidity region

(colorless V exchange
⟶ gluon radiation suppressed)





inclusive cross section:

Han, Valencia, Willenbrock (1992)

distributions:

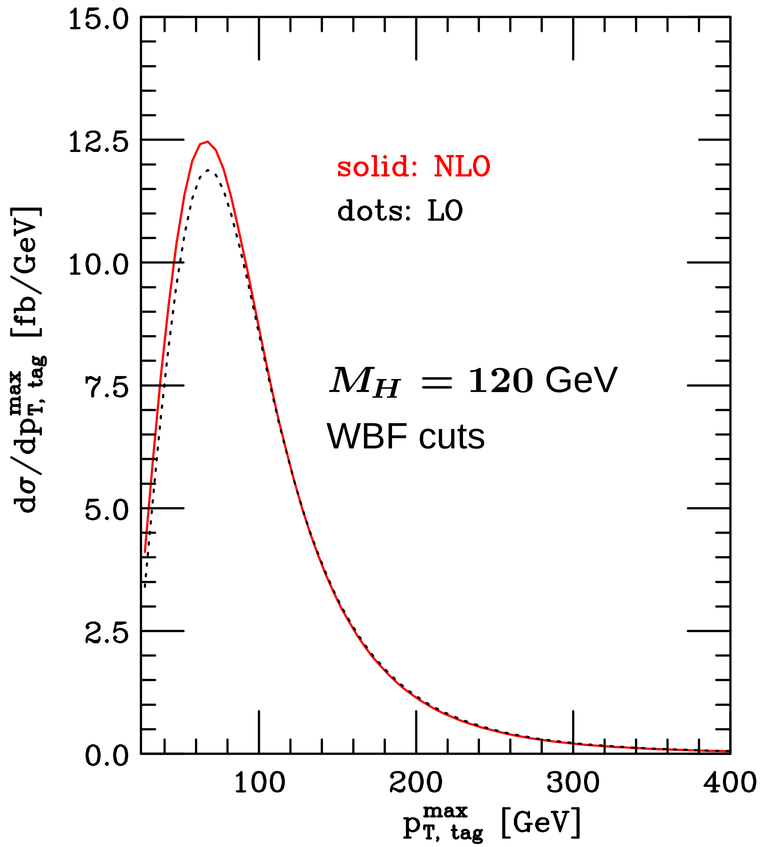
Figy, Oleari, Zeppenfeld (2003)

Berger, Campbell (2004)

Ciccolini, Denner, Dittmaier (2007)

NLO QCD corrections

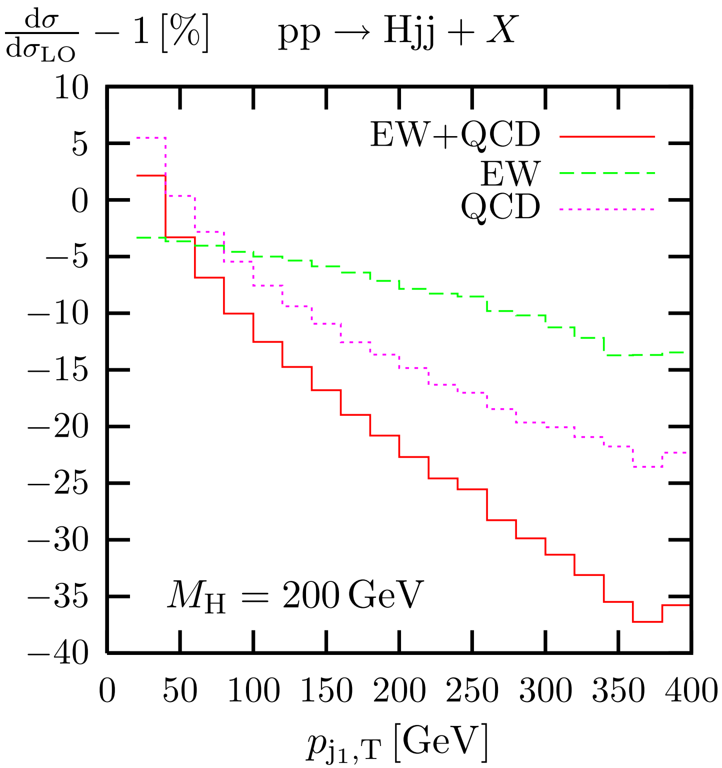
moderate and
theoretically well under control
(order 10% or less)

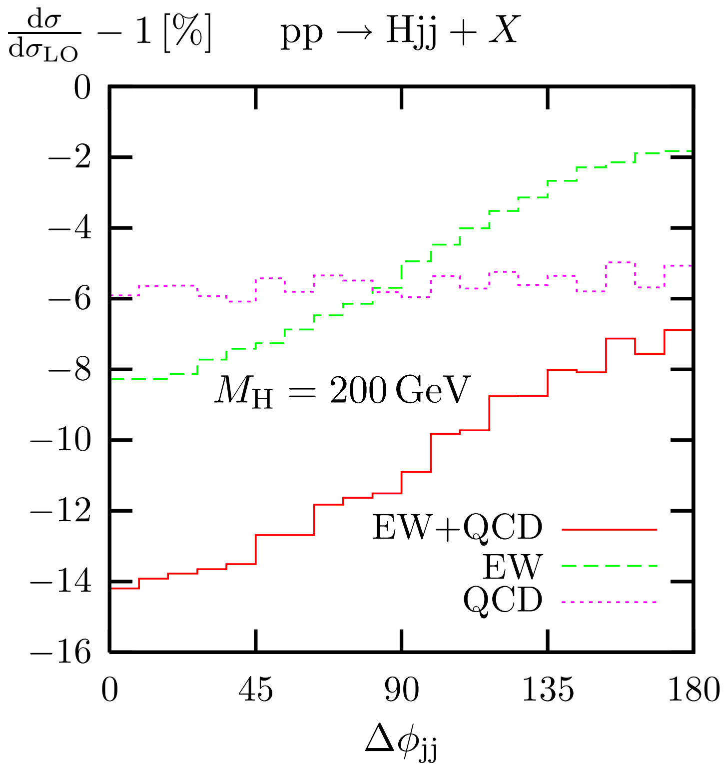


Ciccolini, Denner, Dittmaier (2007):

NLO EW corrections to inclusive cross sections and distributions

☞ NLO EW corrections non-negligible, modify cross sections and distort distributions by up to 10%





and more on WBF beyond the lowest order . . .

$pp \longrightarrow Hjjj$ via WBF @ NLO QCD:

inclusive cross section and distributions:

Figy, Hankele, Zeppenfeld (2007)

➠ refer to Terrance Figy's talk

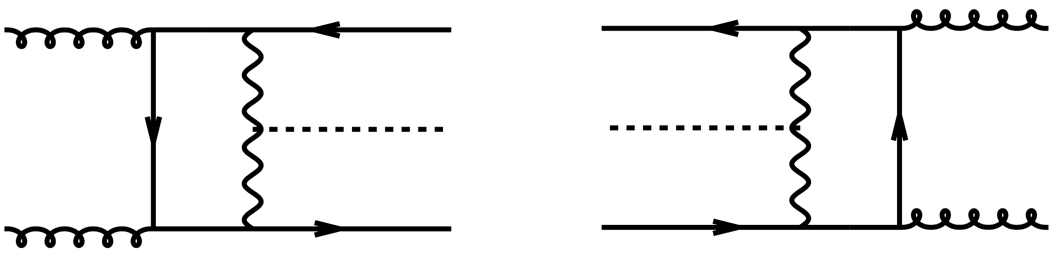
one-loop SUSY corrections to $pp \longrightarrow h^0 jj$ via WBF:

inclusive cross section:

Hollik, Plehn, Rauch, Rzehak (2008)

Harlander, Vollinga, Weber (2007):

gauge invariant, finite sub-class of virtual
two-loop QCD corrections to $pp \longrightarrow Hjj$ via WBF



important due to large gluon luminosity at LHC?

$$gg \longrightarrow q\bar{q}H,\ q\bar{q} \longrightarrow ggH,$$
$$qg \longrightarrow qgH,\ \bar{q}g \longrightarrow \bar{q}gH$$

minimal set of cuts: $\sigma^{2-\text{loop}}_{\text{gluon}} \sim 2\ \%$ of $\sigma^{\text{LO}}_{\text{WBF}}$

WBF cuts: relative suppression by additional order of magnitude

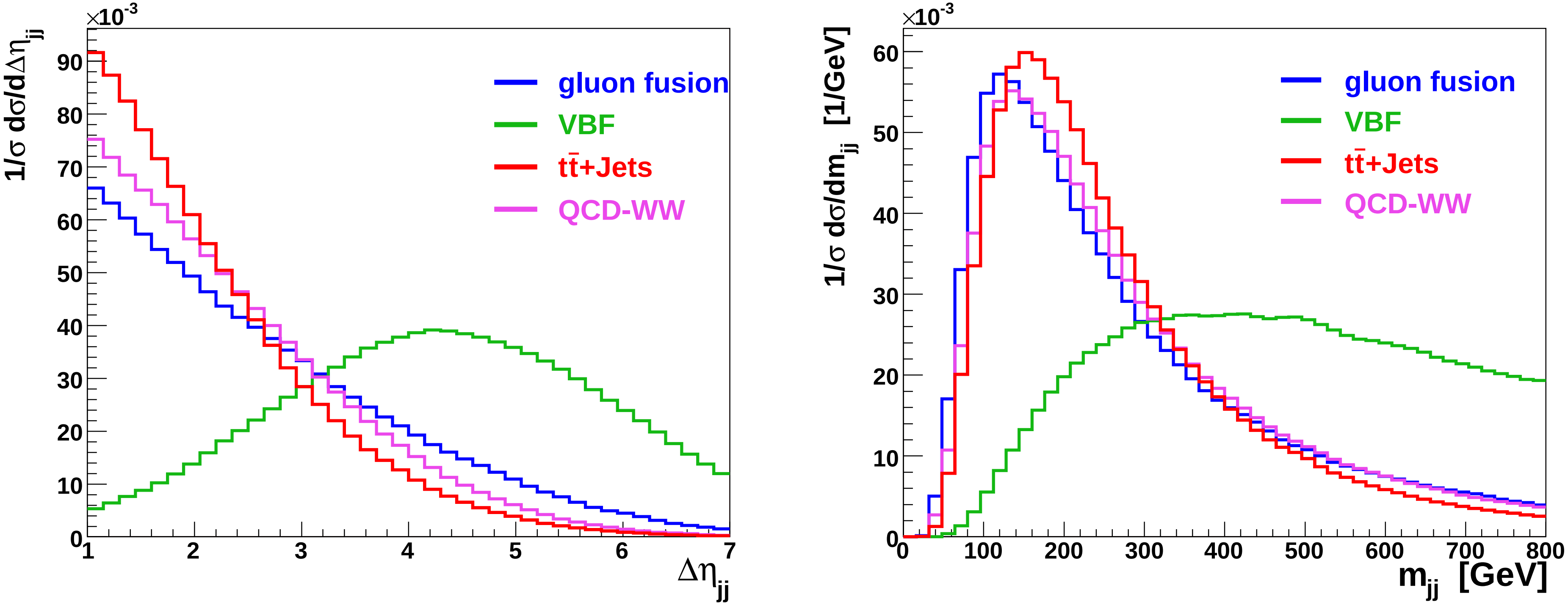
WBF can be faked by double real corrections
to $gg \longrightarrow H$ ("gluon fusion")

complete LO calculation (including pentagons):
Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld (2001)

NLO QCD calculation in $m_t \longrightarrow \infty$ limit:
Campbell, Ellis, Zanderighi (2006)

need to understand phenomenology of both processes to distinguish between them apply cuts to enhance either WBF or gluon fusion (GF)

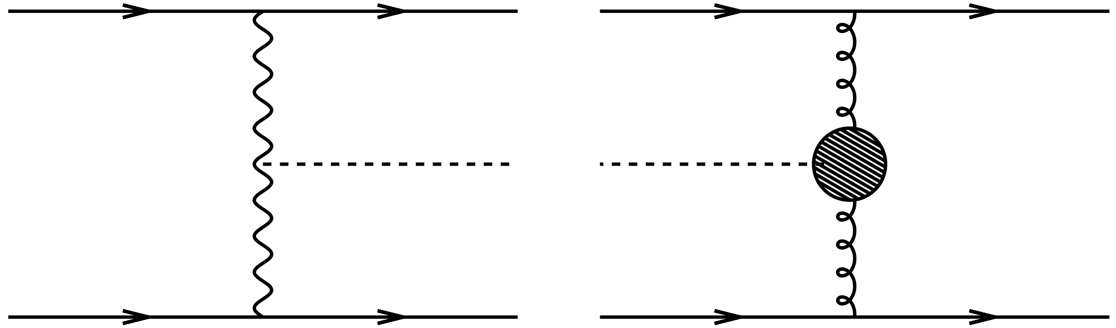
(crucial for measurement of HVV, Htt, Hgg couplings)



Klämke, Zeppenfeld (2007)

$pp \longrightarrow Hjj$ via WBF×GF at tree level

can WBF×GF interference pollute the clean WBF signature?



Georg (2005) & Andersen, Smillie (2006):

tree-level interference possible only for

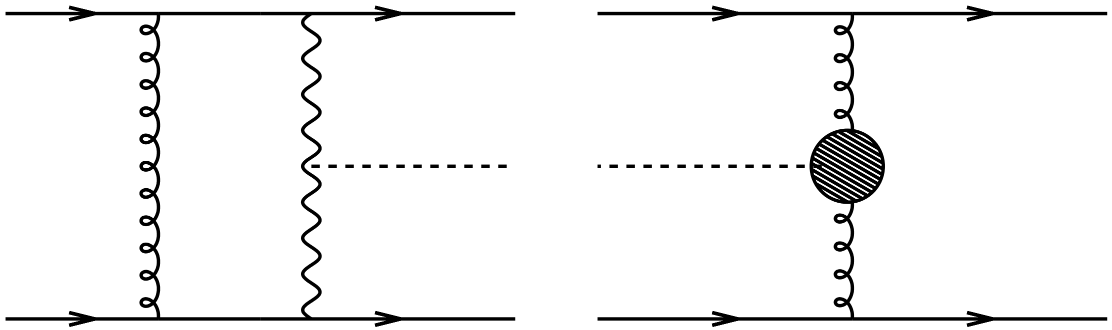
- neutral current graphs (no charged current interference)
- identical quark contributions with $t \leftrightarrow u$ crossing (kinematically suppressed)

☞ completely negligible

$pp \longrightarrow Hjj$ via WBF×GF beyond tree level

additional gluon $\longrightarrow$ WBF×GF interference for $qq' \longrightarrow qq'H$ ✔

(no $t \leftrightarrow u$ crossing necessary)



☞ speculations that the size of the one-loop interference could be comparable to the size of the one-loop NLO-QCD corrections to the WBF and the GF processes

$pp \longrightarrow Hjj$ via WBF×GF beyond tree level

need to check presumption by dedicated loop calculation

☞ *Andersen et al. (2007) & Bredenstein, Hagiwara, B. J. (2008)*

our approach: develop flexible Monte Carlo program allowing for

- computation of various jet observables beyond tree level
- straightforward implementation of cuts

major challenges:

- $2 \longrightarrow 3$ interference process with multiple mass scales
- numerically stable treatment of pentagon contributions

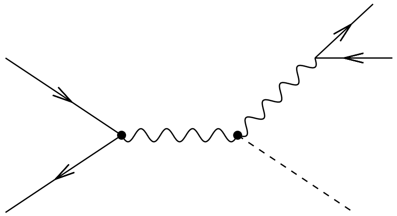
outline of the calculation

$$d\hat{\sigma}_{qq'\to Hjj} \sim \overline{\sum} 2\mathrm{Re}\left[\mathcal{M}_{\mathrm{GF}}\mathcal{M}^{\star}_{\mathrm{WBF}} + \mathcal{M}_{\mathrm{WBF}}\mathcal{M}^{\star}_{\mathrm{GF}}\right] \mathcal{F}_{\mathrm{jet}}\, dPS_f$$

- calculation of $\mathrm{Re}\left[\mathcal{M}_{\mathrm{GF}}\mathcal{M}^{\star}_{\mathrm{WBF}} + \mathcal{M}_{\mathrm{WBF}}\mathcal{M}^{\star}_{\mathrm{GF}}\right]$ at $\mathcal{O}(\alpha^2\alpha_s^3)$
  - dimensional regularization / reduction $(d = 4 - 2\varepsilon)$
  - $\overline{\mathrm{MS}}$-renormalization
- handling of infrared singularities by phase space slicing procedure (need real emission & virtual contributions and “counterterms”)
- phase space integration and convolution with PDFs with Monte Carlo techniques in $d = 4$ dimensions

neglect contributions strongly suppressed for WBF kinematics (two widely separated quark jets of large invariant mass):

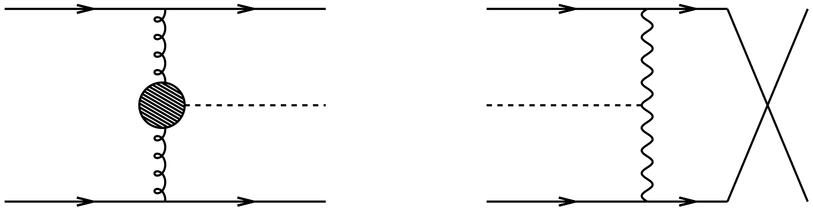
- identical flavor annihilation processes
  with subsequent decay into quarks



see, e.g., *Ciccolini, Denner, Dittmaier (2007)* :

$< \mathbf{0.5\%}$ with WBF cuts

- $t \leftrightarrow u$ channel interference effects
  from diagrams with identical quark flavors

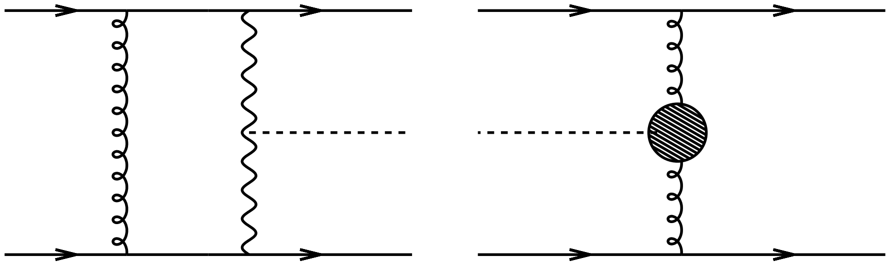


see, e.g., *Georg (2005), Andersen, Smillie (2006)*:

negligible with WBF cuts

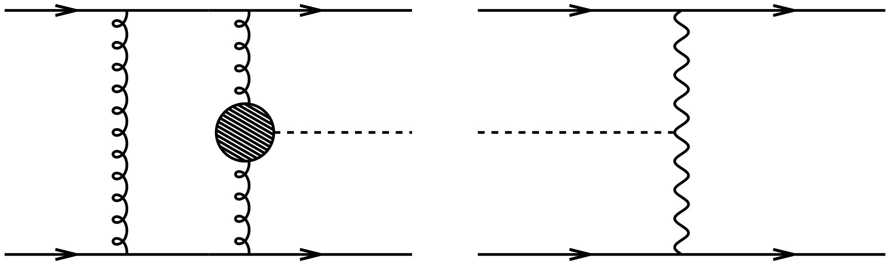
within our approximation need two types of loop contributions:

- interference of WBF@1-loop with GF at LO



$$\mathcal{M}_{\mathbf{WBF}}^{(1-\mathrm{loop})} \cdot \mathcal{M}_{\mathbf{GF}}^{(0)\star}$$

- interference of GF@1-loop with WBF at LO



$$\mathcal{M}_{\mathbf{GF}}^{(1-\mathrm{loop})} \cdot \mathcal{M}_{\mathbf{WBF}}^{(0)\star}$$

all bubble, triangle, and box corrections vanish
due to color conservation ➠ pentagon diagrams only!

$\mathcal{M}^{(1-\text{loop})}_{\text{WBF}}, \ \mathcal{M}^{(1-\text{loop})}_{\text{GF}}$

tensor integrals up to rank two with up to five propagator denominators

↓

expressed in terms of scalar 2-,3-, and 4-point integrals via:

- Passarino-Veltman (PV) tensor reduction
- Denner-Dittmaier (DD) tensor reduction

in numerical implementation DD superior to PV method whenever Gram determinant becomes small

⇒ use PV for checks, but resort to DD reduction for phenomenological studies

virtual contributions

implementation: split loop contributions into finite and singular parts

$$\mathcal{M}^{(1-\text{loop})}_{\text{WBF,GF}} = \frac{1}{\varepsilon^2}\mathcal{M}^{pp,(1-\text{loop})}_{\text{WBF,GF}} + \frac{1}{\varepsilon}\mathcal{M}^{p,(1-\text{loop})}_{\text{WBF,GF}} + \mathcal{M}^{fin,(1-\text{loop})}_{\text{WBF,GF}}$$

singular pieces:

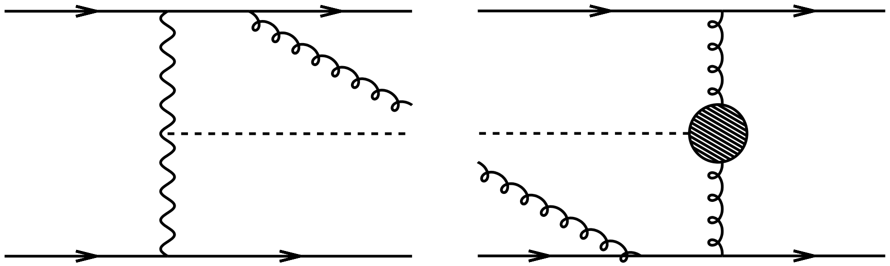
- double poles cancel exactly
- singular interference contribution is proportional to “tree-level” amplitudes:

finite parts:

- compute analytically with `mathematica`
- evaluate numerically with `fortran`

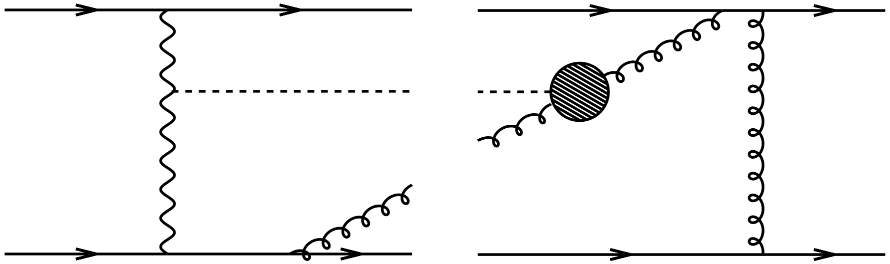
$$\sim -\frac{1}{\varepsilon}\overline{\sum} 2\text{Re}\left[\mathcal{M}^{(0)}_{\text{WBF}}\mathcal{M}^{(0)\star}_{\text{GF}} + \mathcal{M}^{(0)}_{\text{GF}}\mathcal{M}^{(0)\star}_{\text{WBF}}\right]\cdot\left[\ln\frac{s_{ab}}{\mu^2} - \ln\frac{-s_{a2}}{\mu^2} - \ln\frac{-s_{b1}}{\mu^2} + \ln\frac{s_{12}}{\mu^2}\right]$$

- gluons emitted from different fermion lines, Higgs in t-channel



$$\mathcal{M}_{\mathrm{WBF}}^{(\mathrm{real})} \cdot \mathcal{M}_{\mathrm{GF}}^{(\mathrm{real,t})\star}$$

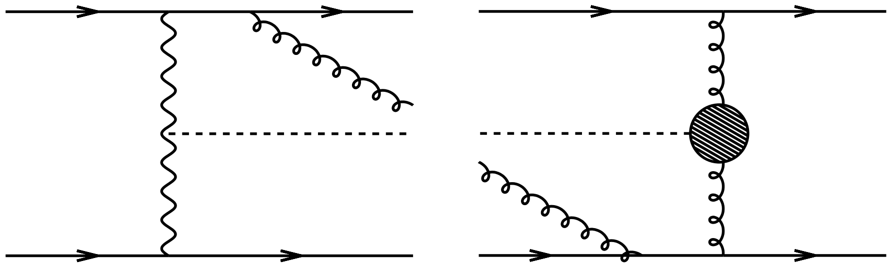
- gluon (WBF) / gluon-plus-Higgs (GF) from different fermion lines



$$\mathcal{M}_{\mathrm{WBF}}^{(\mathrm{real})} \cdot \mathcal{M}_{\mathrm{GF}}^{(\mathrm{real,f})\star}$$

- no contributions from: · gq-scattering diagrams
  · interference of graphs with gluon emission from the same fermion line in WBF and GF

divergence structure



$$\mathcal{M}^{(\mathrm{real})}_{\mathrm{WBF}} \cdot \mathcal{M}^{(\mathrm{real})\star}_{\mathrm{GF}}$$

collinear divergences:

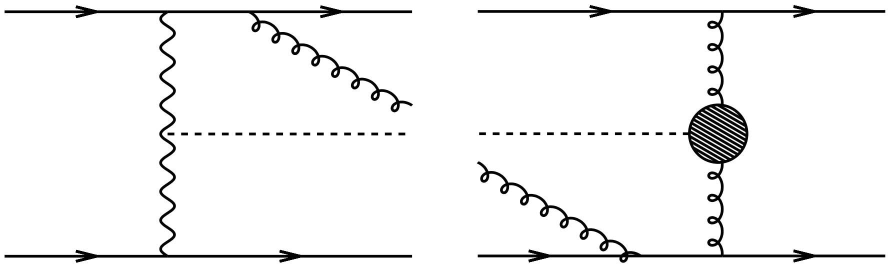
require collinear quark-gluon configuration in $\mathcal{M}^{(\mathrm{real})}_{\mathrm{WBF}}$ and $\mathcal{M}^{(\mathrm{real})\star}_{\mathrm{GF}}$ simultaneously

but no such configurations for WBF×GF interference

soft divergences:

emerge whenever gluon energy becomes small, i.e. $E_g \longrightarrow 0$

divergence structure



$$\mathcal{M}^{(\mathrm{real})}_{\mathrm{WBF}} \cdot \mathcal{M}^{(\mathrm{real})\star}_{\mathrm{GF}}$$

soft divergences:

emerge whenever gluon energy becomes small, i.e. $E_g \longrightarrow 0$

need to isolate soft contributions in real emission contributions and cancel them against respective divergences in virtuals

basic idea:
split real emission
contribution into
soft and hard pieces

$$\hat{\sigma}^{\text{real}} = \hat{\sigma}^{\text{soft}} + \hat{\sigma}^{\text{hard}}$$

- $\hat{\sigma}^{\text{hard}}$ finite ➠ compute entirely numerically (no regularization necessary)

↑

separate by suitable cutoff parameter (s_{min} or E_{min})

↓

- $\hat{\sigma}^{\text{soft}}$ contains all singularities

slicing procedure

for separating soft/hard regions we employ
two conceptually different methods:

- **Lorentz-invariant phase-space slicing:**

[Giele, Glover; Reina et al.]

soft region: $s_{ig} = 2p_i \cdot p_g < s_{min}$ and $s_{jg} = 2p_j \cdot p_g < s_{min}$,
($i, j \ldots$ quarks)

advantage: Lorentz invariant cutoff parameter

- **phase-space slicing with energy cutoff:**

[Denner; Denner et al.]

soft region: $E_g < E_{min}$ in rest frame of two incoming partons

advantage: simple and intuitive interpretation in specific frame

hard real emission contributions

$\hat{\sigma}^{\text{hard}} : \mathcal{M}^{(\text{real})}_{\text{WBF}},\ \mathcal{M}^{(\text{real})}_{\text{GF}}$

↓

in non-singular regions of phase space:
computed numerically in $d = 4$ dimensions by
helicity amplitude formalism of
Hagiwara, Zeppenfeld (1986)

checked against `MadGraph` generated amplitudes

soft contribution

soft region: matrix elements computed by eikonal approximation

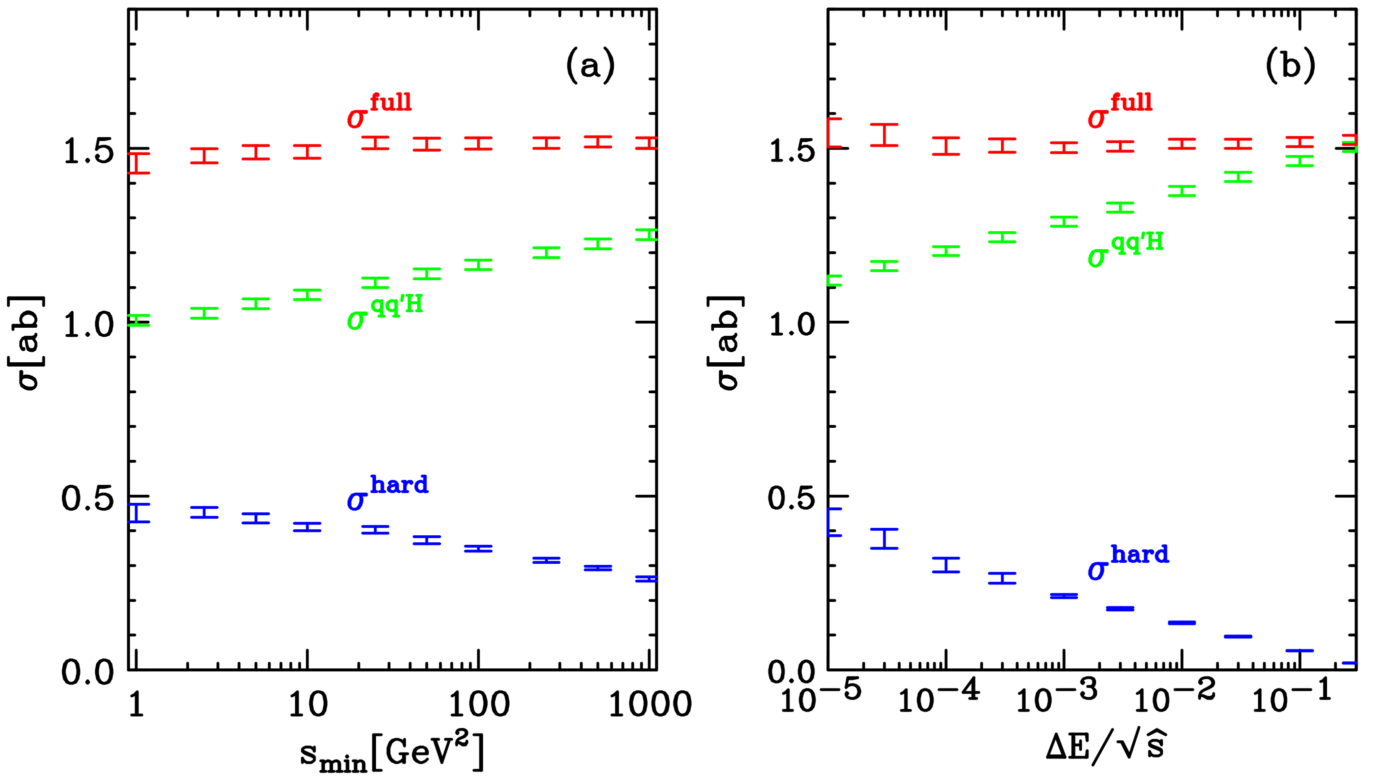
integration over gluon phase space performed analytically

$$\int [d(PS_g)]^{\text{soft}} \overline{\sum} 2\text{Re}\left[\mathcal{M}^{(\text{real})}_{\text{WBF}}\mathcal{M}^{(\text{real})\star}_{\text{GF}} + \mathcal{M}^{(\text{real})}_{\text{GF}}\mathcal{M}^{(\text{real})\star}_{\text{WBF}}\right]_{\text{soft}}$$
$$\sim \overline{\sum} 2\text{Re}\left[\mathcal{M}^{(0)}_{\text{WBF}}\mathcal{M}^{(0)\star}_{\text{GF}} + \mathcal{M}^{(0)}_{\text{GF}}\mathcal{M}^{(0)\star}_{\text{WBF}}\right]$$
$$\times\left\{\frac{1}{\varepsilon}\left[\ln\frac{s_{ab}}{\mu^2} - \ln\frac{-s_{a2}}{\mu^2} - \ln\frac{-s_{b1}}{\mu^2} + \ln\frac{s_{12}}{\mu^2}\right] + f_{\text{fin}}(\text{cutoff})\right\}$$

pole terms match singularities in virtuals exactly

finite rest depends on separation parameter for soft/hard regions in the slicing method important test: dependence on cutoff parameter must drop out in sum of all contributions

$$\hat{\sigma}^{\rm full} = \underbrace{\hat{\sigma}^{\rm virt} + \hat{\sigma}^{\rm soft}}_{\hat{\sigma}^{qq'H}} + \hat{\sigma}^{\rm hard}$$



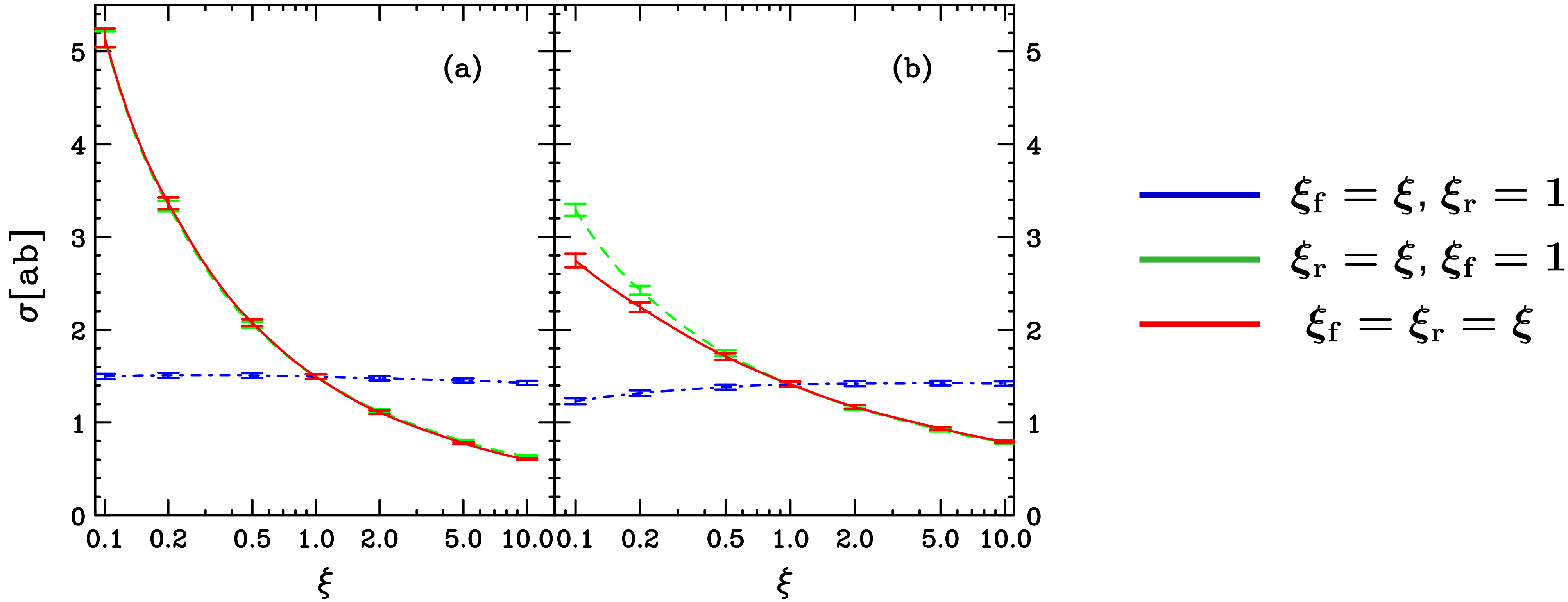
. . . numbers . . .

is clean WBF signature contaminated by interference contribution?

cuts and settings

apply k_T algorithm, CTEQ6 parton distributions, and typical WBF cuts:

tagging jets	$p_{Tj} \geq 20$ GeV, $\lvert y_j \rvert \leq 4.5$, $\Delta y_{jj} = \lvert y_{j_1} - y_{j_2} \rvert > 4$, $M_{jj} > 600$ GeV jets located in opposite hemispheres
for $H \longrightarrow \ell\ell'$ $(\ell = \gamma, b\ldots)$	$p_{T\ell} \geq 20$ GeV, $\lvert \eta_\ell \rvert \leq 2.5$, $\Delta R_{j\ell} \geq 0.6$, $y_{j,min} < \eta_\ell < y_{j,max}$ $m_H = 120$ GeV



study dependence of interference x-sec on choice and value of scale $\longrightarrow$ two settings:

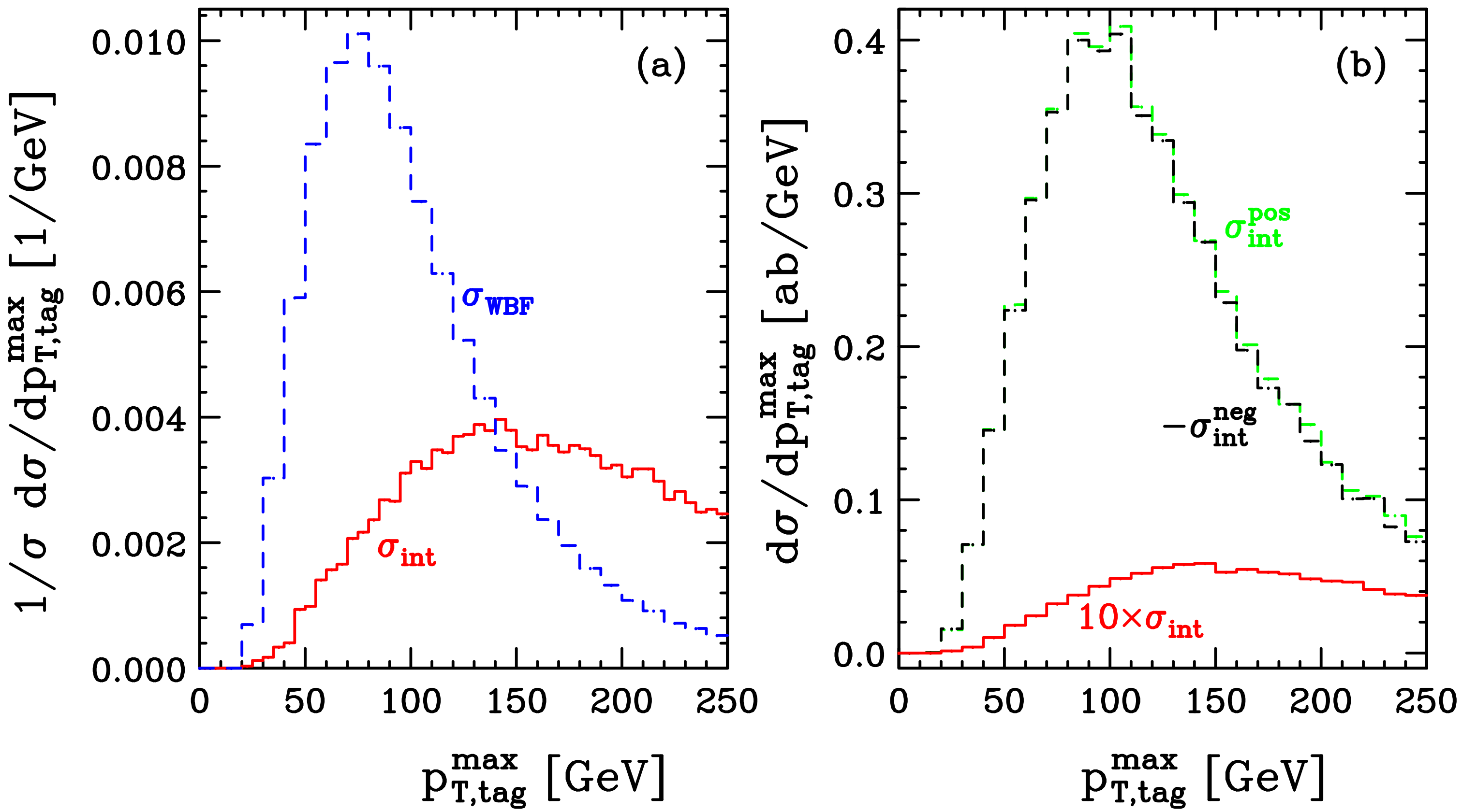
(a) $\mu_{\rm f} = \xi_{\rm f} m_H \,,\, \alpha_s^3(\mu_{\rm r}) = \alpha_s^3(\xi_{\rm r} m_H)$

(b) $\mu_{\rm f} = \xi_{\rm f}\, p_{{\rm T}j} \,,\, \alpha_s^3(\mu_{\rm r}) = \alpha_s(\xi_{\rm r} p_{\rm T1}) \cdot \alpha_s(\xi_{\rm r} p_{\rm T2}) \cdot \alpha_s(\xi_{\rm r} m_H)$

explicit calculation reveals strong cancelation effects
in the total interference cross section

initial state	interaction	isospin	$\sigma_{\rm int}^{\rm cuts}$ [ab]	$\sigma_{\rm WBF}^{\rm cuts}$ [fb]
qq	NC	+ + or - -	51.4	72.3
	NC	+ - or - +	-49.8	70.8
	CC	+ - or - +	–	405.7
$q\bar{q}$	NC	+ - or - +	-3.1	39.3
	NC	+ + or - -	2.2	43.0
	CC	+ + or - -	–	230.7
$\bar{q}\bar{q}$	NC	- - or + +	4.0	5.1
	NC	- + or + -	-3.2	4.3
	CC	- + or + -	–	25.7
sum	NC+CC	all	1.5	896.9

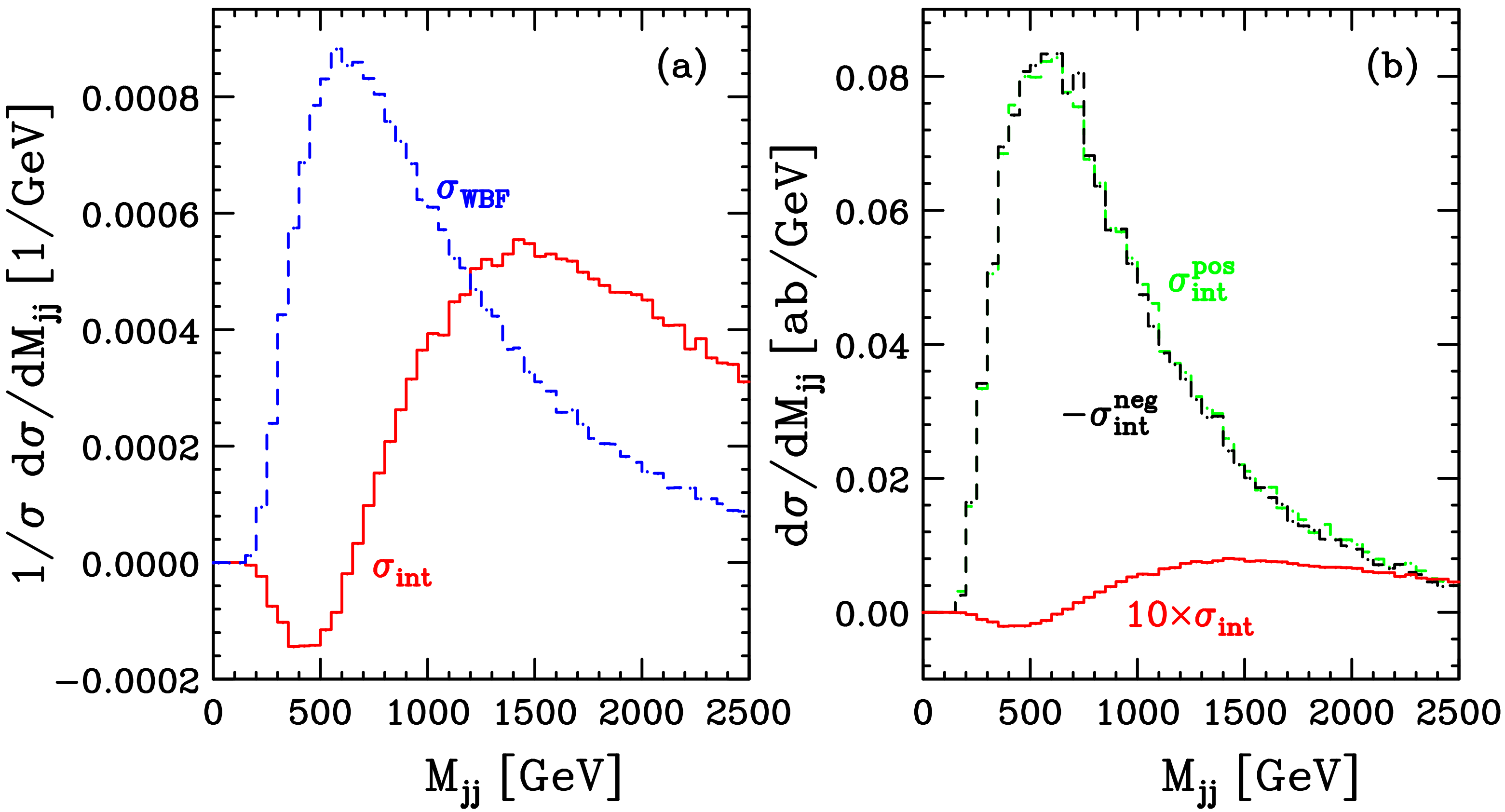
distributions: p_T of tagging jet



cancelations lead to unexpected shapes of distributions

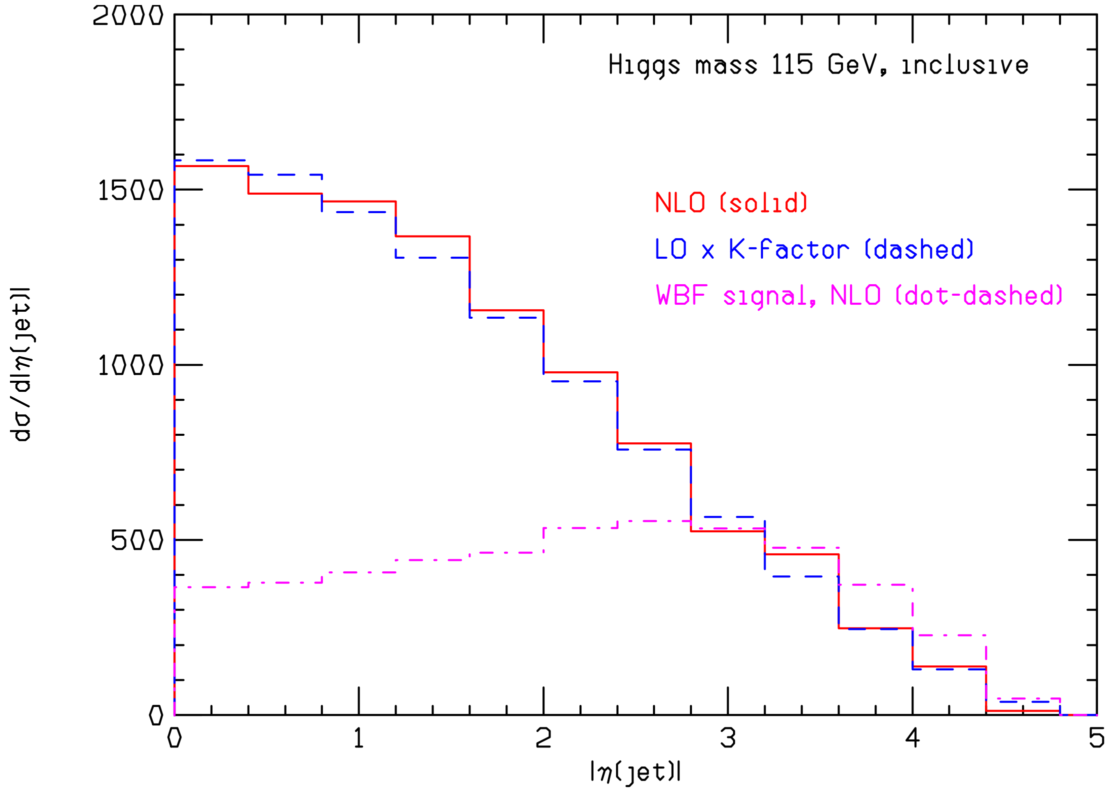
but: $\boldsymbol{\sigma}_{\mathrm{int}}$ tiny $\longrightarrow$ no effect on WBF signal

distributions: dijet invariant mass



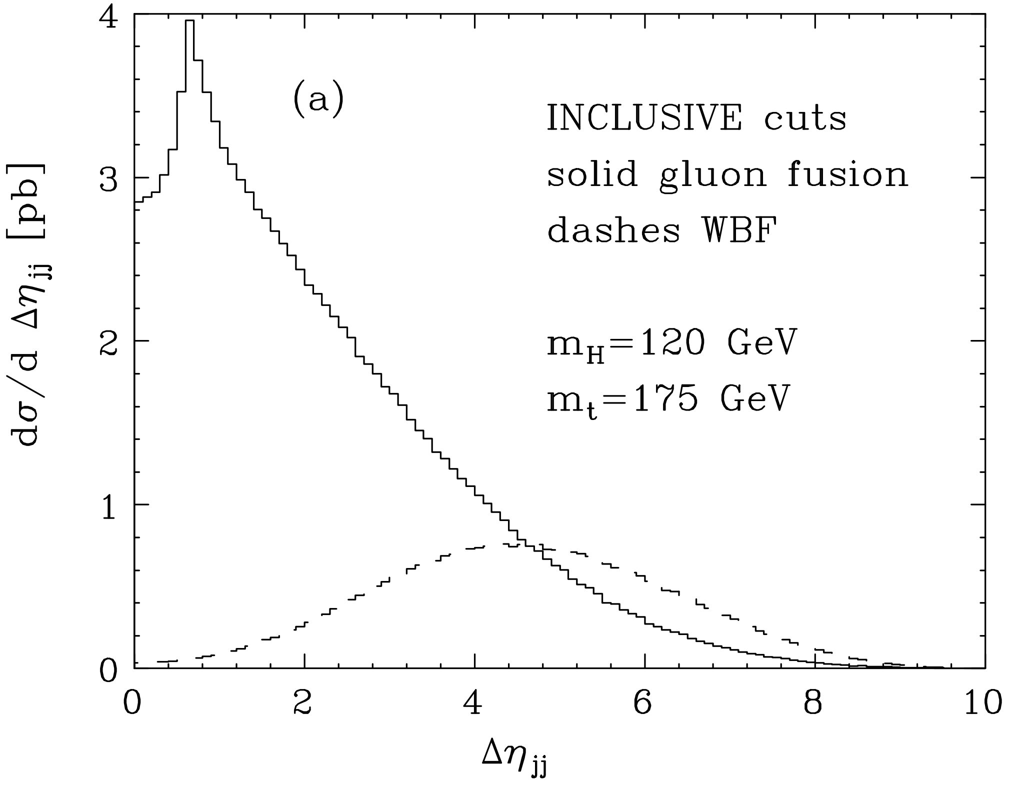
reminder: pure GF . . . softer M_{jj} distribution than pure WBF!

rapidity distribution of tagging jets differs significantly for Hjj final states in $|\text{GF}|^2$ and $|\text{WBF}|^2$ because of color singlet nature of weak boson exchange



Campbell, Ellis, Zanderighi (2006)

rapidity distribution of tagging jets differs significantly
for Hjj final states in $|\mathrm{GF}|^2$ and $|\mathrm{WBF}|^2$
because of color singlet nature of weak boson exchange



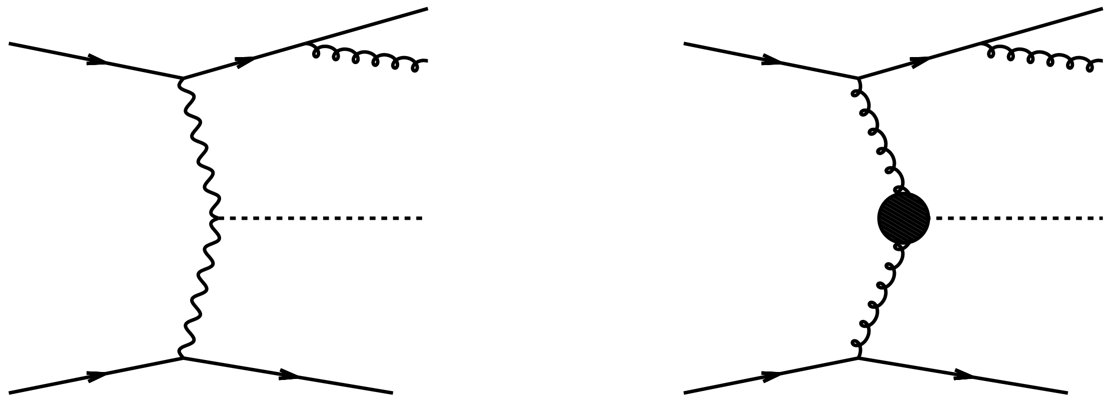
Del Duca et al. (2001)

what about rapidity distribution of
third, non-tagged jet in $Hjjj$ events?

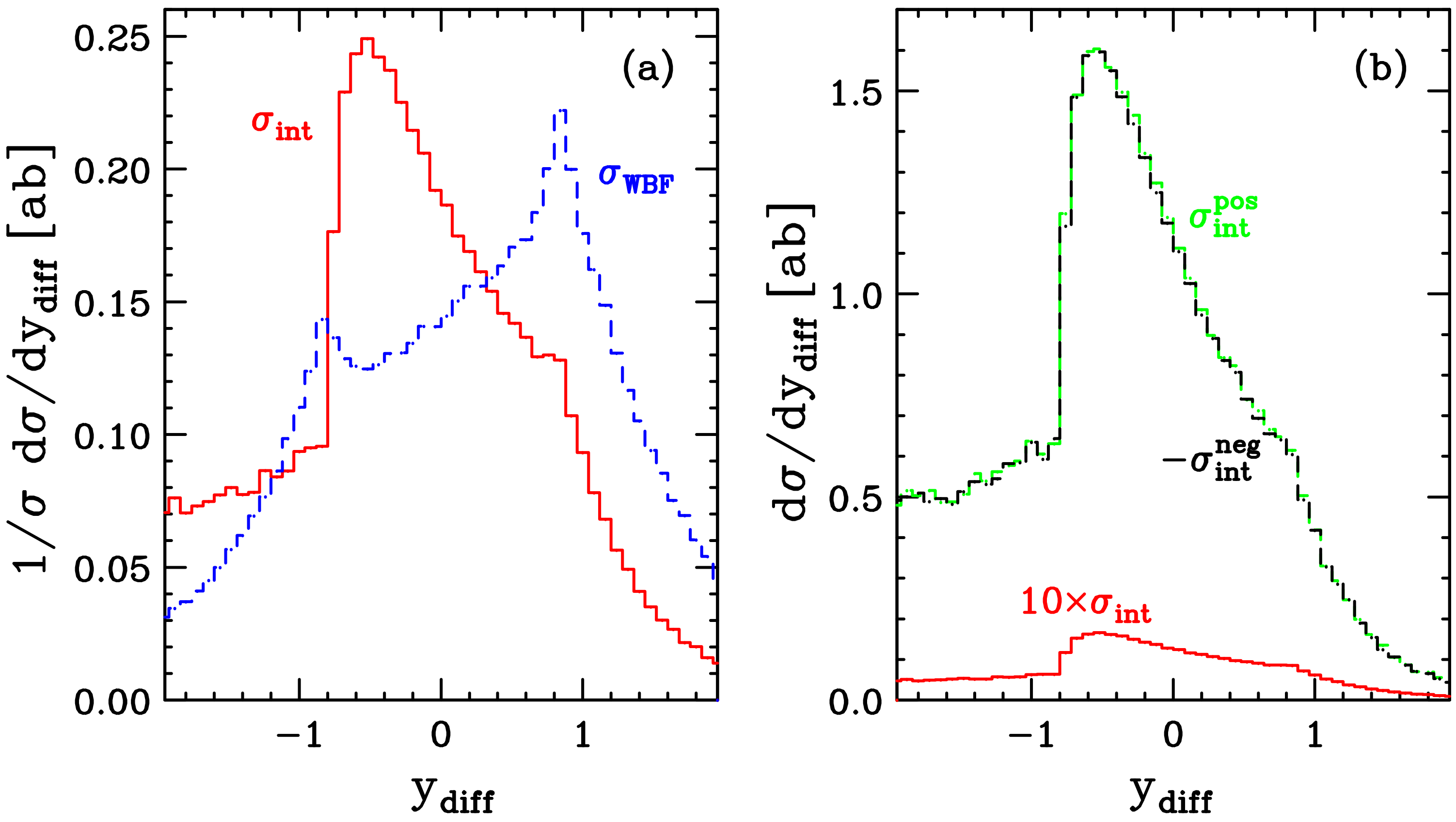
↓

consider separation of third jet from positive-rapidity jet:

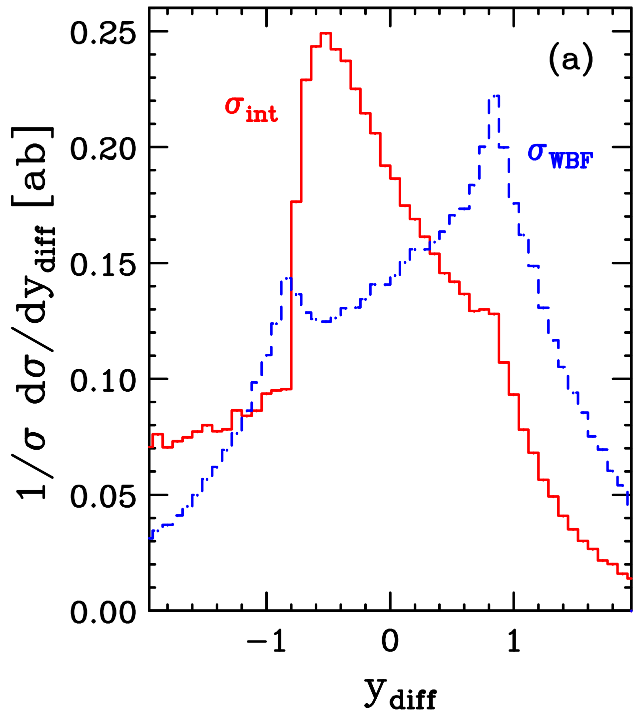
$$y_{\rm diff} = y_3 - \max(y_1, y_2)$$



distributions: rapidity separation



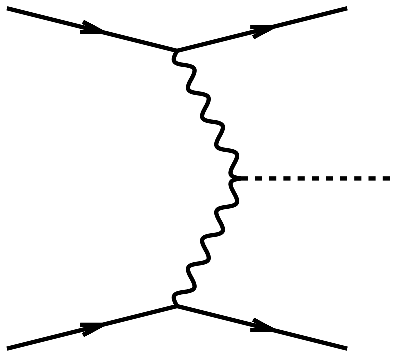
cancelations do not affect shape of $y_{\text{diff}} = y_3 - \max(y_1, y_2)$
as strongly as M_{jj} and p_{Tj} distributions



- $|\mathrm{WBF}|^2$ and WBF× GF peak at small values of $|y_{\mathrm{diff}}| \lesssim 1$
  - ➠ soft jet close to considered hard jet
- $|\mathrm{WBF}|^2$: $y_{\mathrm{soft}} > y_{\mathrm{hard}}$
  - ➠ soft jet located "outside" tag jets
- WBF× GF: $y_{\mathrm{soft}} < y_{\mathrm{hard}}$
  - ➠ soft jet located between tag jets

☞ rapidity gap for color singlet weak boson exchange can be filled by QCD-EW interference contribution

Higgs signal in WBF



- $pp \longrightarrow Hjj$ via WBF under excellent control
- QCD & EW NLO corrections at 10% level
- dominant NNLO QCD corrections small
- SUSY corrections small
- optimized selection cuts allow for
  efficient suppression of GF background
- interference of WBF with
  GF Hjj production negligible

conclusions

- considered loop interference contributions for Hjj production at the LHC exibit interesting features different from WBF (unexpected shapes of distributions due to cancellation effects)

- but: numerical effects on the signal are tiny

- predicting size and shape of higher order corrections by plausibility considerations can be dangerous

- confirming the small impact of higher order contributions and interference effects by explicit calculations strengthens WBF as a promising Higgs boson search channel at the LHC