Higgs boson production in association with a photon via weak boson fusion

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PHYSICS AT THE TERA SCALE
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“Physics at the Terascale”
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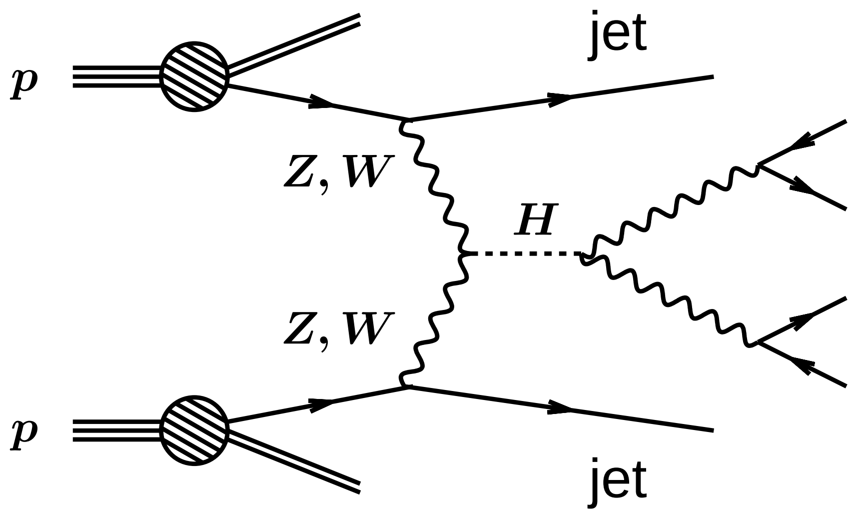
- detailed signal-background analysis:

  Gabrielli, Maltoni, Mele, Moretti, Piccinini, Pittau (2007)

- NLO-QCD calculation of signal process:

  Arnold, Figy, B. J., Zeppenfeld (2010)

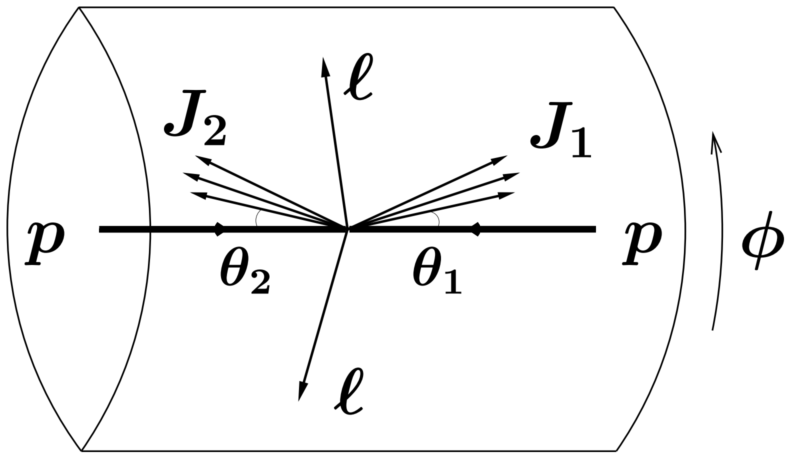
VBF event topology



suppressed color exchange between quark lines gives rise to

- little jet activity in central rapidity region
- scattered quarks $\longrightarrow$ two forward tagging jets
  (energetic; large rapidity)
- Higgs decay products typically between tagging jets

VBF event topology



distinct event topology
of the Higgs signal in VBF
extremely important for
suppression of backgrounds

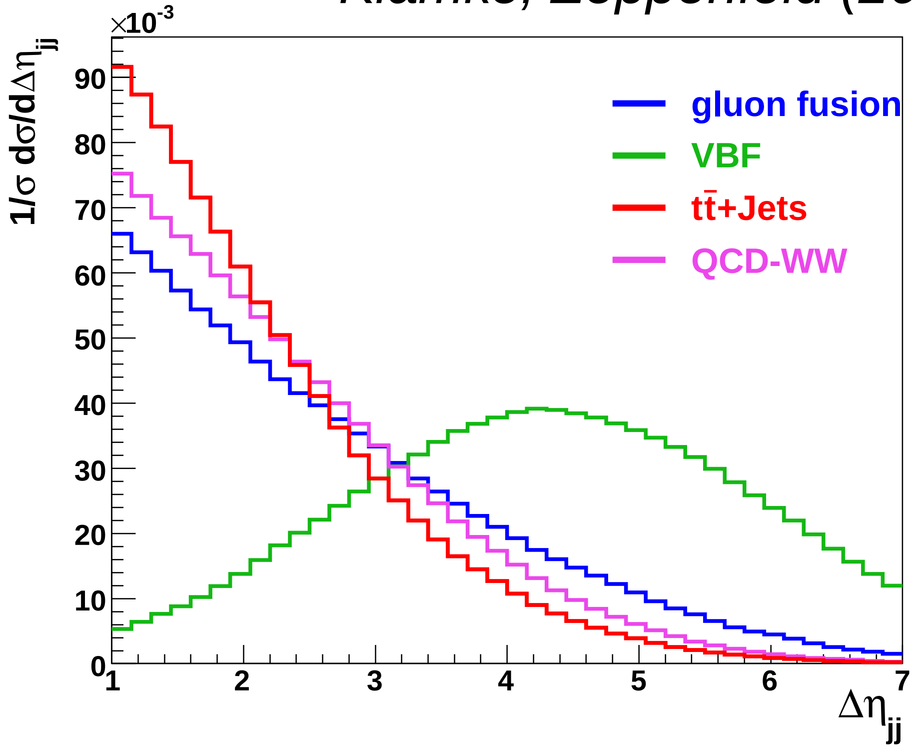
example: backgrounds to $pp \longrightarrow Hjj$ via VBF in the
$H \longrightarrow W^+W^- \longrightarrow e^{\pm}\mu^{\mp}\not{p}_T$ decay mode include

- $t\bar{t} + \text{jets} \longrightarrow b\bar{b}W^+W^- + \text{jets}$
- Hjj production via gluon fusion
- QCD W^+W^-jj production
- EW W^+W^-jj production

tagging jets: properties

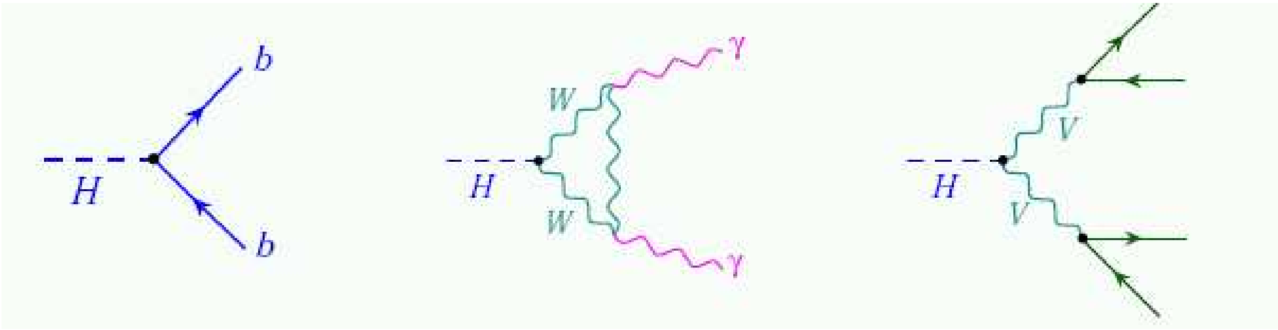
rapidity separation of the tagging jets

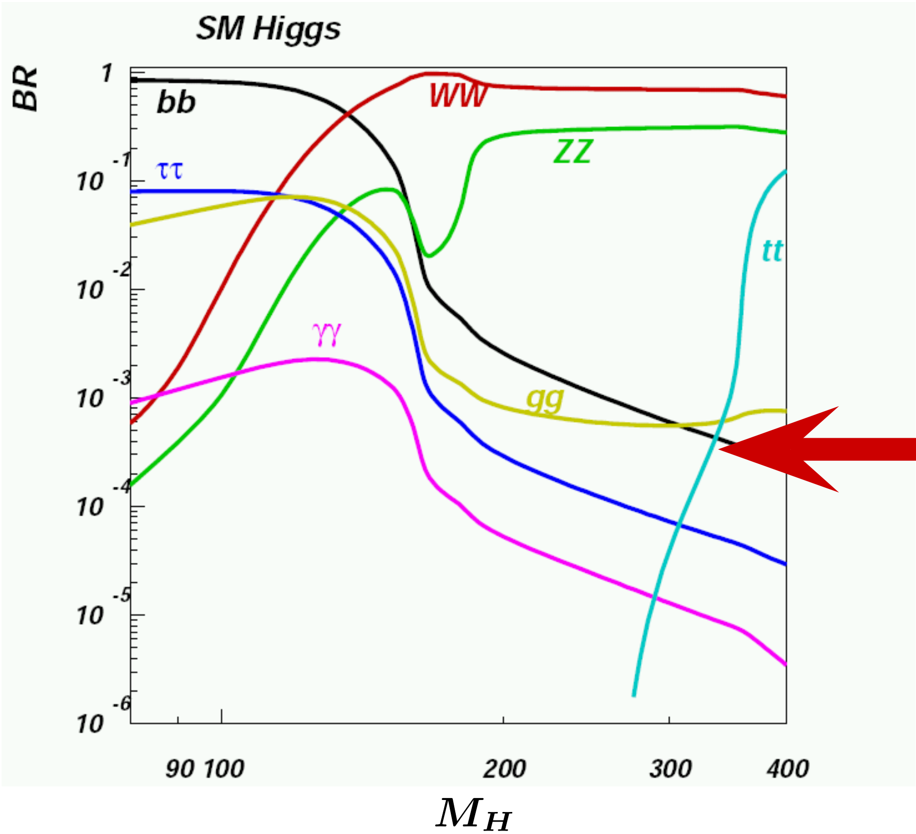
Klämke, Zeppenfeld (2007)



jets more central in QCD- than in EW-induced production processes

Higgs decay





branching fractions

determination of the $Hb\bar{b}$ coupling

$H \longrightarrow b\bar{b}$ is dominant decay mode for $m_H \lesssim 140$ GeV,
but accessing the bottom-quark Yukawa coupling
remains difficult:

- $b\bar{b} \longrightarrow H$ production: overwhelmed by $gg \longrightarrow H$ production and plagued by large theoretical uncertainties

- $b\bar{b} \longrightarrow H + \text{jet}$ production:
  ☞ yesterday's talk by Marius Wiesemann

determination of the $Hb\bar{b}$ coupling

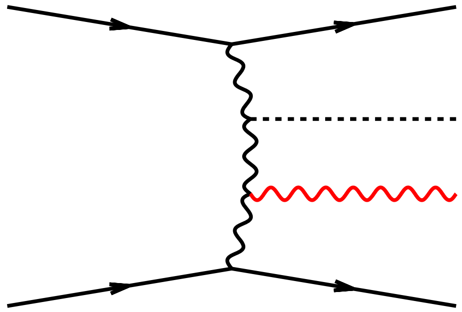
$H \longrightarrow b\bar{b}$ is dominant decay mode for $m_H \lesssim 140$ GeV, but accessing the bottom-quark Yukawa coupling remains difficult:

- $Ht\bar{t}$ production with $H \longrightarrow b\bar{b}$ decay: large backgrounds;
  new approach: accessible by jet-deconstruction techniques?
  [Plehn, Salam, Spannowsky (2009)]

- WBF Hjj production with $H \longrightarrow b\bar{b}$ decay: large backgrounds:
  QCD production of $b\bar{b}jj$, $jjjj$, $t\bar{t}$, $t\bar{t}j$; $(Z^\star/\gamma^\star \longrightarrow b\bar{b})jj$;
  $b\bar{b}jj$ and $jjjj$ production via overlapping events

  [Mangano et al. (2002)]

extra photon radiation in VBF: $pp \longrightarrow H\gamma jj$



Gabrielli et al. (2007):

extra hard, central photon in $pp \longrightarrow Hjj$

powerful tool for suppression of
(gluon-dominated) QCD backgrounds

☞ can the WBF $H \longrightarrow b\bar{b}$ mode be tackled that way?

extra photon radiation in VBF: $pp \longrightarrow H\gamma jj$

effects of hard central photon requirement:

✘ "naive expectation": signal S and background B
suppressed by same factor $\sim \mathcal{O}(\alpha)$

- S/B not much affected:

$$\left(\frac{S}{B}\right)_{Hjj} \sim \left(\frac{S}{B}\right)_{H\gamma jj}$$

- signal significance decreases:

$$\left(\frac{S}{\sqrt{B}}\right)_{H\gamma jj} \sim \sqrt{\alpha}\left(\frac{S}{\sqrt{B}}\right)_{Hjj} \lesssim 1/10\left(\frac{S}{\sqrt{B}}\right)_{Hjj}$$

☞ no advantage?

extra photon radiation in VBF: $pp \longrightarrow H\gamma jj$

effects of hard central photon requirement:

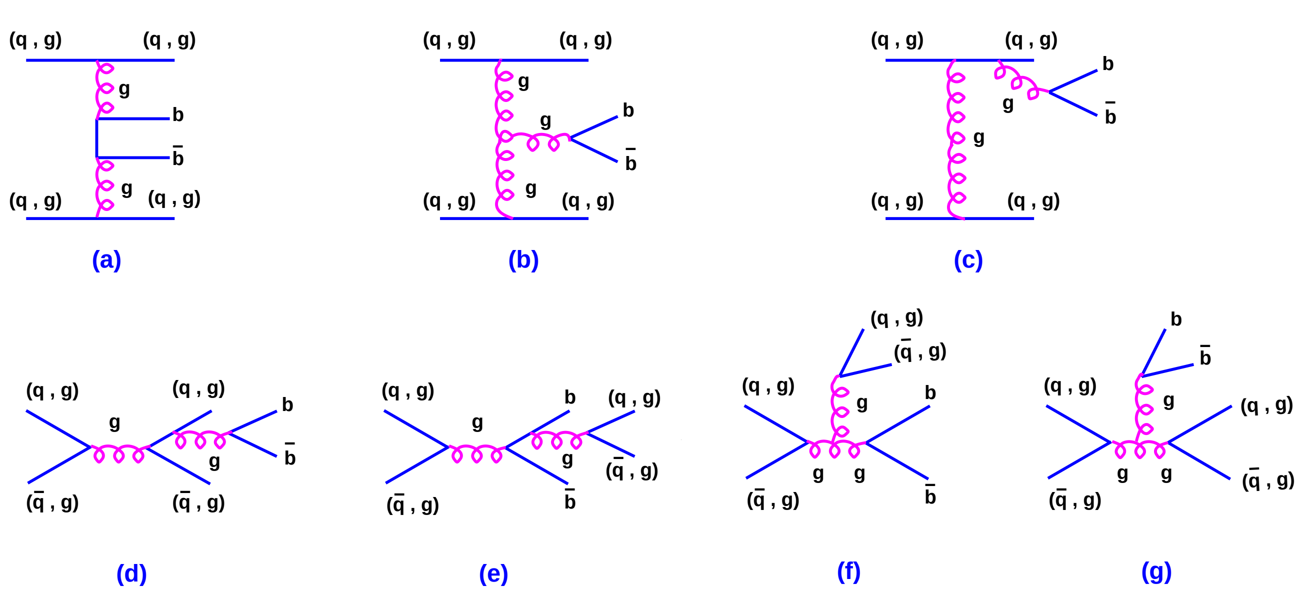
✘ "naive expectation": signal S and background B
suppressed by same factor $\sim \mathcal{O}(\alpha)$

- S/B not much affected
- signal significance decreases

☞ no advantage?

✔ decrease in rate for QCD multi-jet final states

☞ improvement on trigger efficiencies for $b\bar{b}jj$ events



- ✔ large gluonic component in $b\bar{b}jj$ background ($\sim 80\%$ of σ_{bbjj})

  $\longrightarrow$ QCD backgrounds less active in radiating photon than quark-dominated WBF signal

- ✔ WBF-specific selection cuts favor large values of x

  $\longrightarrow$ valence-quarks more relevant than gluons in initial state effects of hard central photon requirement:

✔ destructive interference between photon emission
off initial-state and off final-state quarks
that are linked by neutral t-channel-exchange boson

☞ central photon emission in backgrounds further suppressed

✔ similar interference effects in WBF signal
suppress ZZ fusion, but enhance WW fusion contributions

☞ relative contribution of ZZ fusion depleted w.r.t. WW fusion

extra photon radiation in VBF: $pp \longrightarrow H\gamma jj$

effects of hard central photon requirement:

✘ "naive expectation": signal and background suppressed by same factor $\sim \mathcal{O}(\alpha)$

✔ de facto: reduction factors different for S and B

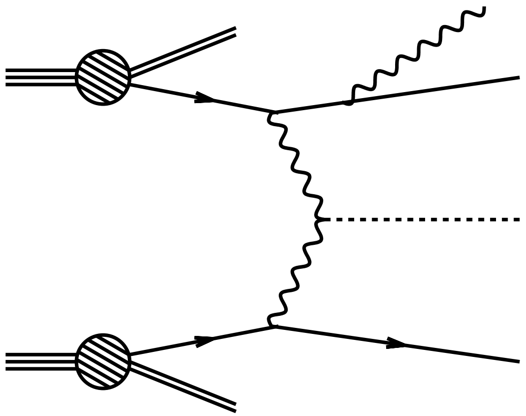
backgrounds: $\sigma_\gamma/\sigma \sim 1/3000$

signal: $\sigma_\gamma/\sigma \sim 1/100$

✔ $\left(S/\sqrt{B}\right)_{H\gamma jj} \lesssim 3$ for $m_H = 120$ GeV, $\mathcal{L} = 100$ fb^{-1} and optimized selection cuts

[Gabrielli et al. (2007)]

the NLO-QCD calculation



need flexible Monte Carlo program which allows for

- computation of various jet observables at NLO-QCD accuracy
- straightforward implementation of cuts

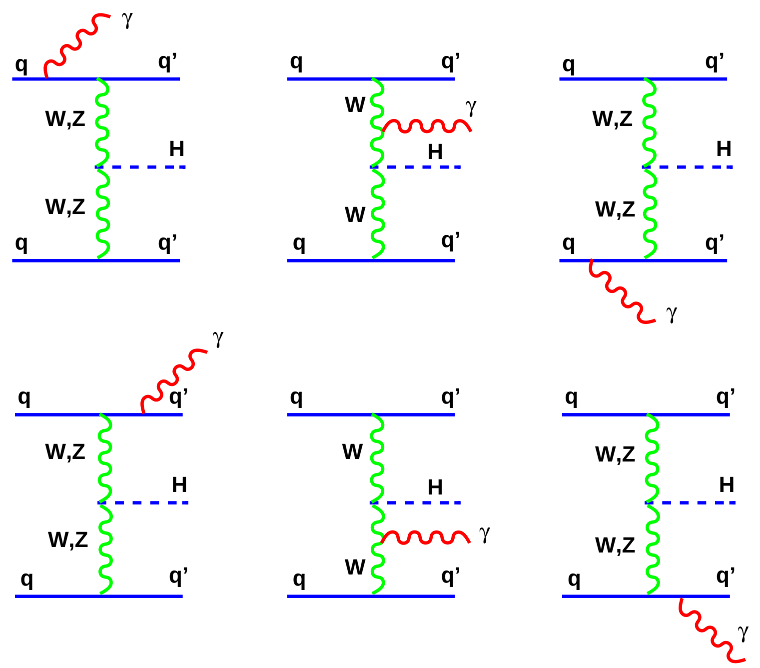
note: QCD structure of the process identical to γjj production via WBF

$\longrightarrow$ recycle elements of previous NLO-QCD calculation *[BJ (2010)]*

elements of the calculation: the leading order

need to compute numerical value for

$$|\mathcal{M}_B|^2 = \left| \quad \right|^2$$



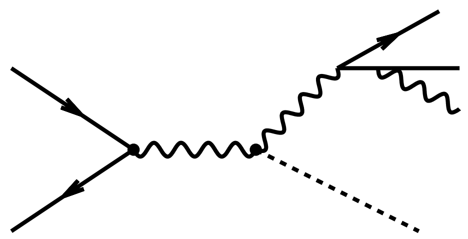
at each generated phase space point in 4 dim (finite)

strategy: develop modular structure with fermionic currents and bosonic tensors (to be recycled at NLO)

elements of the calculation: approximations

neglected:

- interference contributions of t- and u-channel diagrams in processes with identical quarks
- annihilation processes with subsequent decay into quarks and similar contributions like



elements of the calculation: approximations

neglected:

- interference contributions of t- and u-channel diagrams in processes with identical quarks
- annihilation processes with subsequent decay into quarks and similar contributions

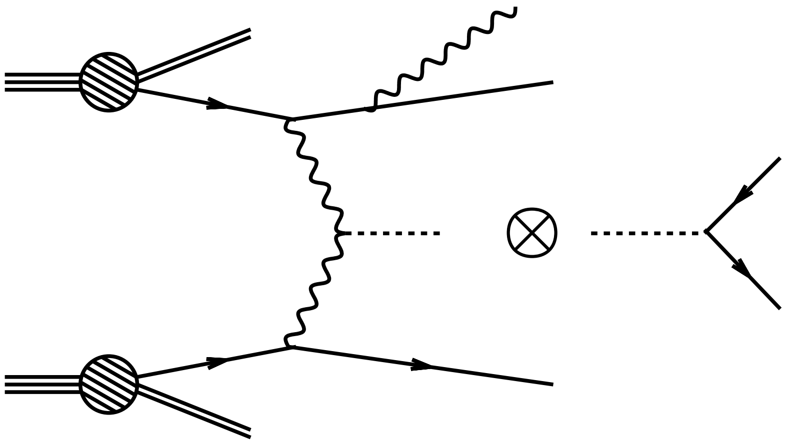
neglected terms strongly suppressed in PS region where VBF can be observed experimentally

(require two widely separated quark jets of large invariant mass)

see, e.g.: *Georg; Andersen et al.;*
Ciccolini, Denner, Dittmaier;
Bredenstein, Hagiwara, B.J.

simulate $H\gamma jj$ production, combined with isotropic Higgs decay into two massless particles d:

$$pp \to H\gamma jj \;\otimes\; H \to dd$$



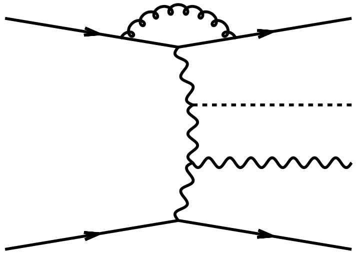
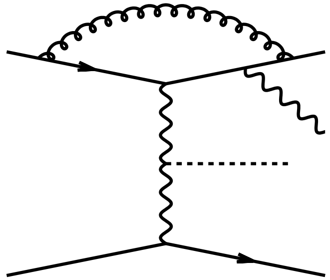
- branching ratio $\mathrm{BR}(H \to dd)$ not included

  [*note:* $\mathrm{BR}(H \to b\bar{b}) \sim 73\%$ *for* $m_H = 120$ *GeV*]

- QCD corrections calculated for production part only

elements of the calculation: virtual corrections

…interference of LO diagrams with

$$\mathcal{M}_V \; = $$  $$+$$  $$+ \; \ldots$$

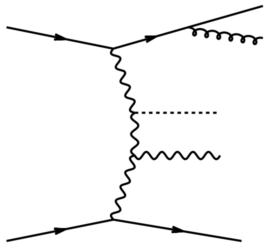
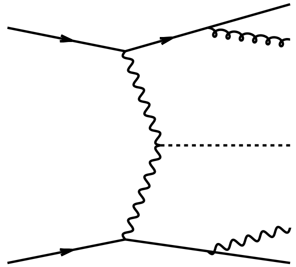
$$= \; \mathcal{M}_B \, F(Q) \left[-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} \right] + \tilde{\mathcal{M}}_V^{finite}$$

$\tilde{\mathcal{M}}_V^{finite}$ … computed via Passarino-Veltman tensor reduction;

need bubbles, triangles, and box-integrals up to rank 3

elements of the calculation: real emission contributions

attach gluon in all possible ways to tree-level graphs
and compute numerical value for

$$|\mathcal{M}_R|^2 = \Bigg|$$  $$+$$  $$+ \ \ldots \Bigg|^2$$

at each generated phase space point in 4 dimensions

infrared-divergent configurations are
handled by dipole subtraction formalism

[Catani, Seymour (1996)]

photon isolation

problem: collinear photon-fermion configurations are singular

cure:

a) compute parton-to-photon fragmentation contributions;
absorb singularities in non-perturbative functions

- ✔ theoretically well-defined
- ✘ introduces poorly known photon fragmentation functions

b) naive photon-jet separation criterion $R_{j\gamma} \geq R_{min}$

- ✔ easy to implement
- ✘ theoretically ill-defined:
  soft-gluon contributions in cone are also removed and can't fully cancel IR singularities of virtual contributions

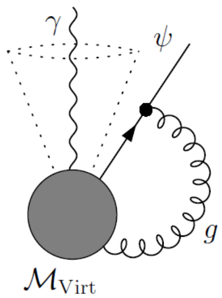
photon isolation

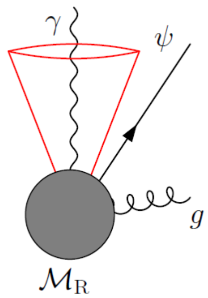
our implementation: cone-isolation criterion of *Frixione (1998)*

idea: veto collinear photon-jet configurations, but allow soft QCD emission

in practice: limit hadronic energy deposited in a cone around the direction of the photon by

$$\sum_{i:R_{i\gamma}<R} p_{Ti} \leq \frac{1-\cos R}{1-\cos\delta_0} p_{T\gamma} \qquad (\forall R \leq \delta_0 = 0.7)$$





checks

- ✔ comparison of LO and real emission amplitudes with `MadGraph`
- ✔ soft / collinear limits: $d\sigma^R \longrightarrow d\sigma^A$
- ✔ QCD gauge invariance of real emission contributions:

$$\mathcal{M} = \varepsilon^\star_\mu(p_g)\mathcal{M}^\mu = \left[\varepsilon^\star_\mu(p_g) + C\, p_{g\,\mu}\right]\mathcal{M}^\mu$$

- ✔ QED gauge invariance of all contributions
- ✔ comparison of LO cross section to `MadEvent` (generic cuts)
- ✔ produce three independent implementations of tree-level, real-emission, and virtual contributions

$pp \to H\gamma jj$ @ LHC: settings

apply k_T jet algorithm and use CTEQ6 parton distributions

inclusive cuts

$$p_{Ti} \geq 20 \text{ GeV},$$
$$|y_j| \leq 5, \;\; |y_{\gamma,b}| \leq 2.5,$$
$$\Delta R_{ik} \geq 0.4,$$
$$M_{jj}^{\text{tag}} > 100 \text{ GeV}$$

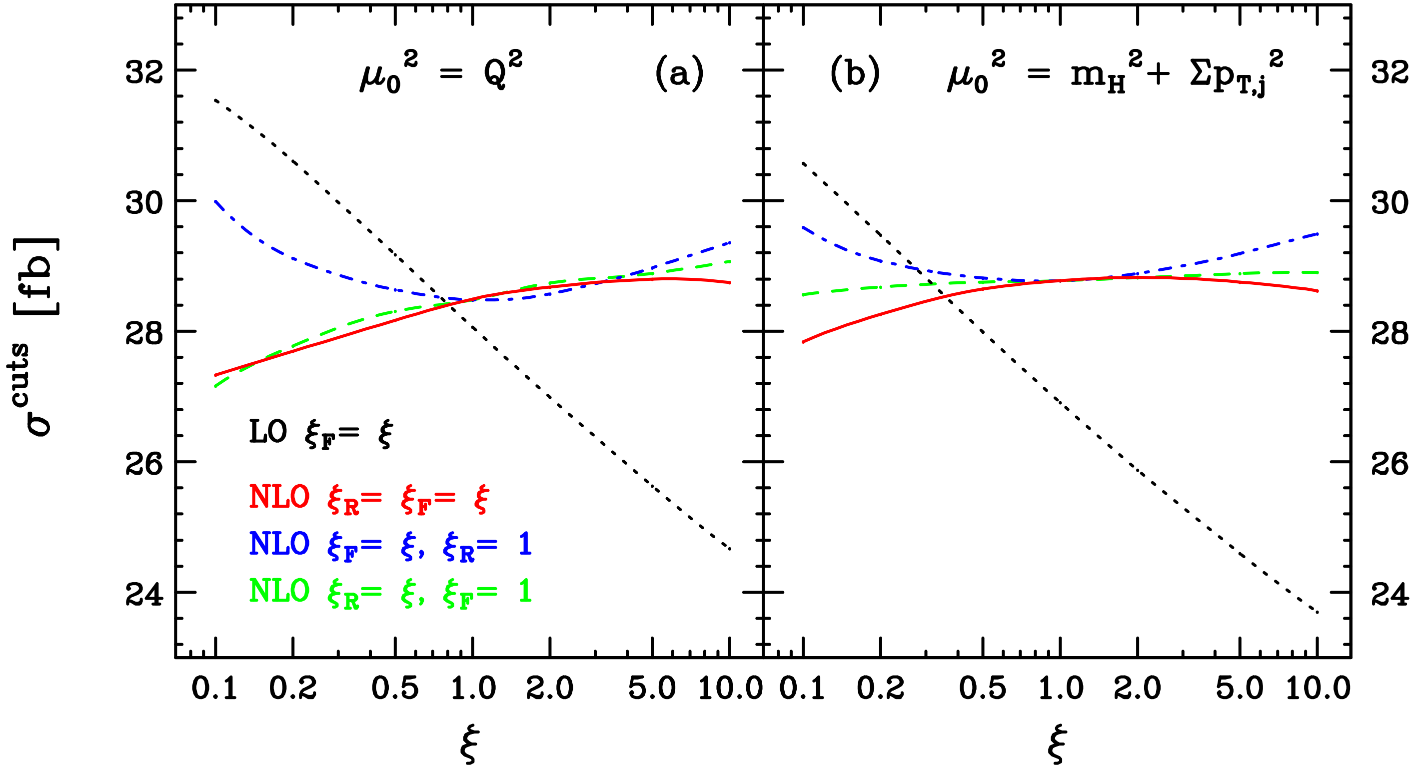
WBF cuts

$$y_j^{\min} < y_\gamma, y_b < y_j^{\max}$$
$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4,$$
$$\Delta R_{ik} \geq 0.7,$$
$$M_{jj}^{\text{tag}} > 600 \text{ GeV}$$

jets located in opposite hemispheres

scale uncertainty

choose default scale $\mu_0^2 = Q_i^2$ or $\mu_0^2 = m_H^2 + \sum p_{Tj}^2$
set $\mu_R = \xi_R \mu_0$ and $\mu_F = \xi_F \mu_0$, with variable ξ



LO: no control on scale
NLO QCD: scale dependence strongly reduced

impact of PDFs and scales

variation of cross section σ^{WBF} for $Q^2/2 \leq \mu^2 \leq 2Q^2$:

CTEQ6

LO: $14.65^{+1.07}_{-0.95}$ fb

NLO: $14.79^{+0.14}_{-0.19}$ fb

MSTW

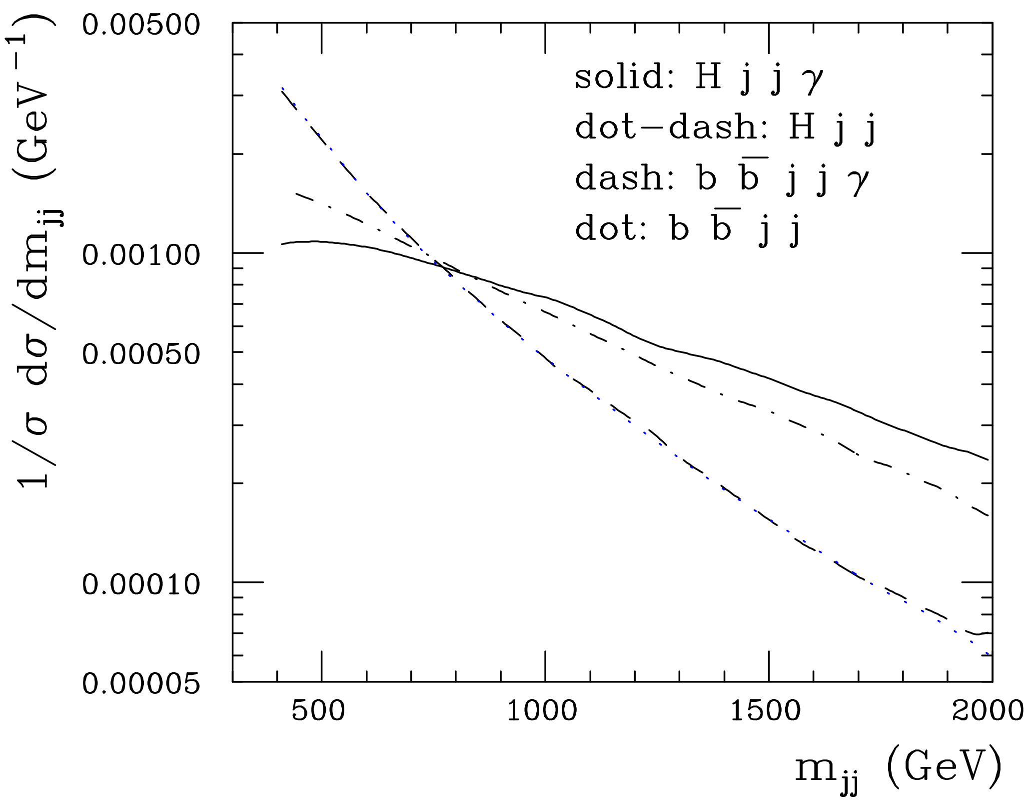
LO: $14.40^{+1.13}_{-1.0}$ fb

NLO: $14.91^{+0.03}_{-0.21}$ fb

☞ $\Delta\sigma^{\mathrm{WBF}}_{\mathrm{LO}} \sim 14\%$ and $\Delta\sigma^{\mathrm{WBF}}_{\mathrm{NLO}} \sim 2\%$

invariant mass of the tagging jets

Gabrielli et al. (2007)

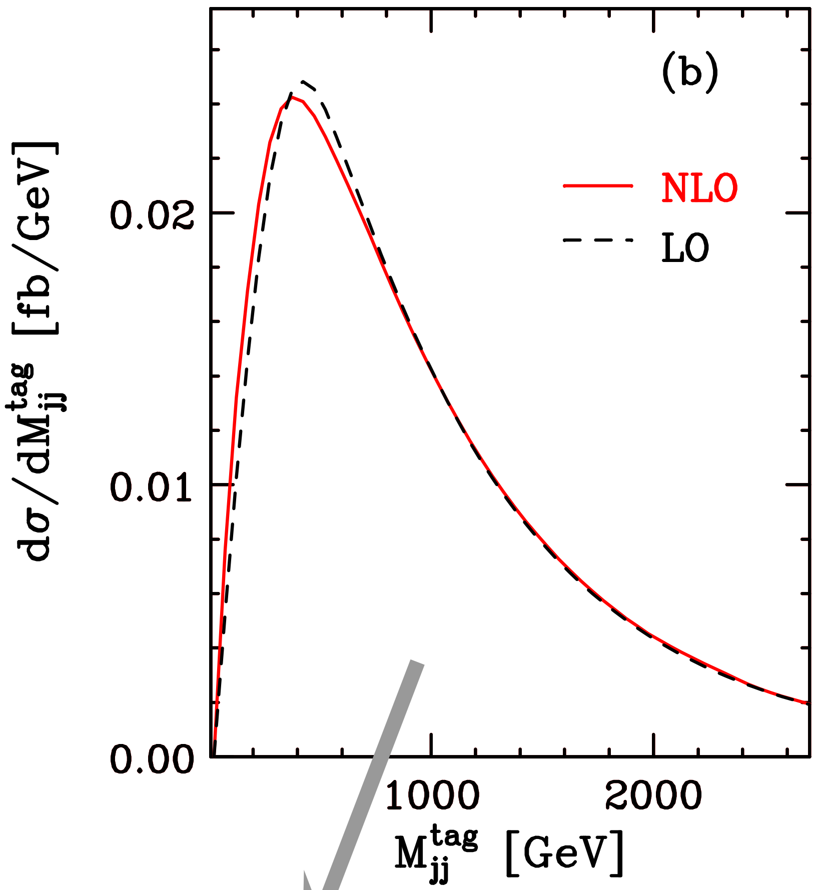


- $d\sigma/dm_{jj}$ slightly flatter for $H\gamma jj$ signal than for Hjj
- $b\bar{b}jj$ and $b\bar{b}\gamma jj$ backgrounds have very similar shapes
- background distributions exhibit much steeper slope than signal

☞ stringent cut on m_{jj} is powerful tool for background suppression

invariant mass of the tagging jets

Arnold, Figy, B. J., Zeppenfeld (2010)



effect of NLO-QCD corrections small

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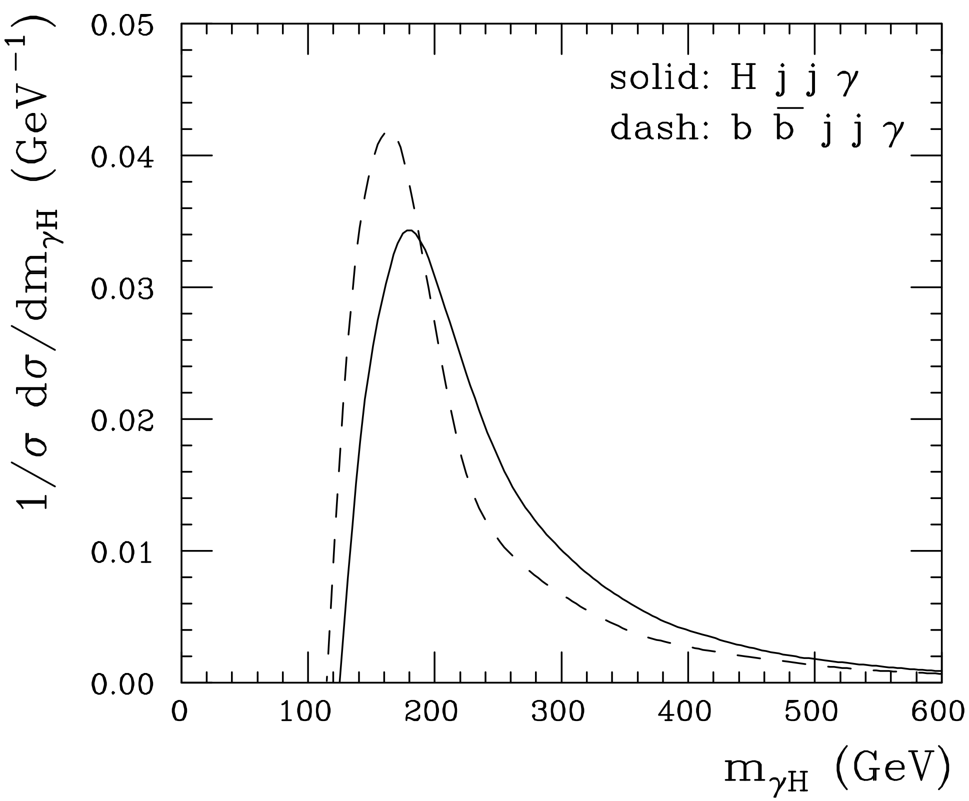
invariant mass of the photon-Higgs system

Gabrielli et al. (2007)



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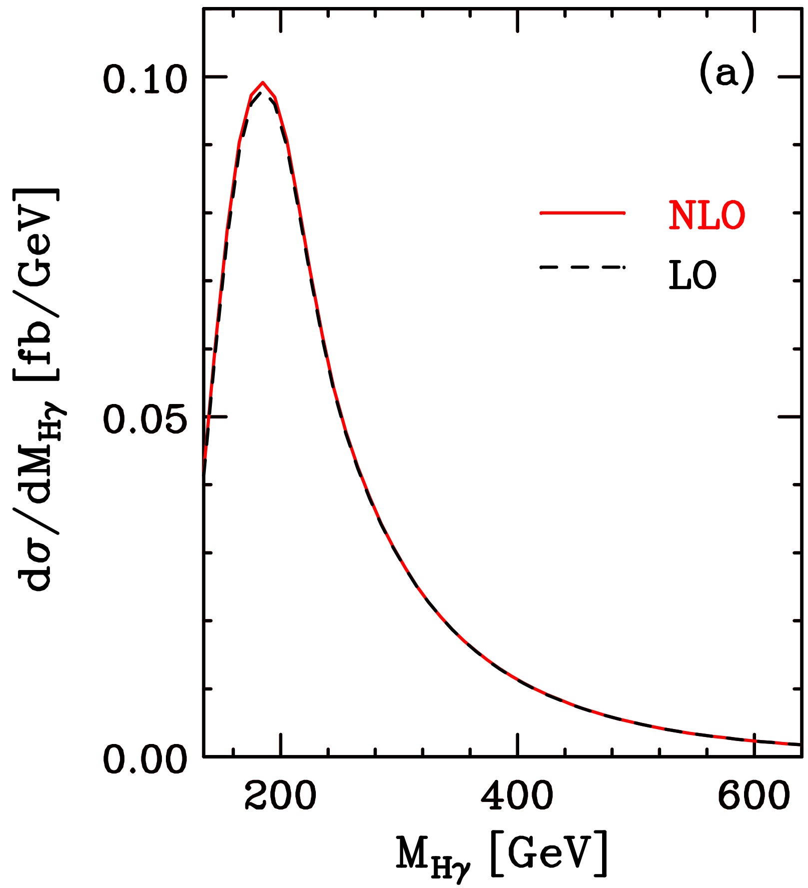
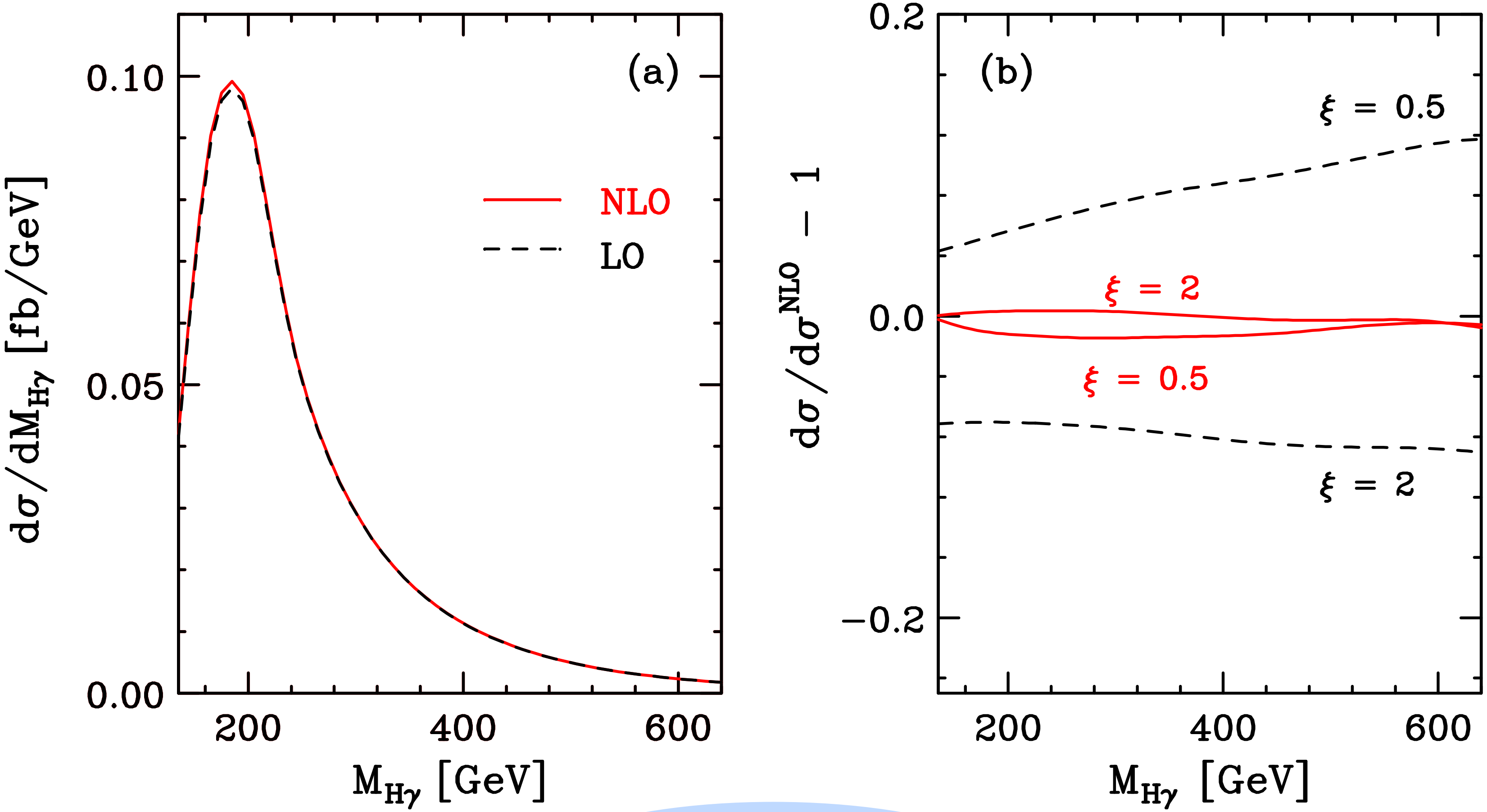


$m_H = 120$ GeV

invariant mass of the photon-Higgs system

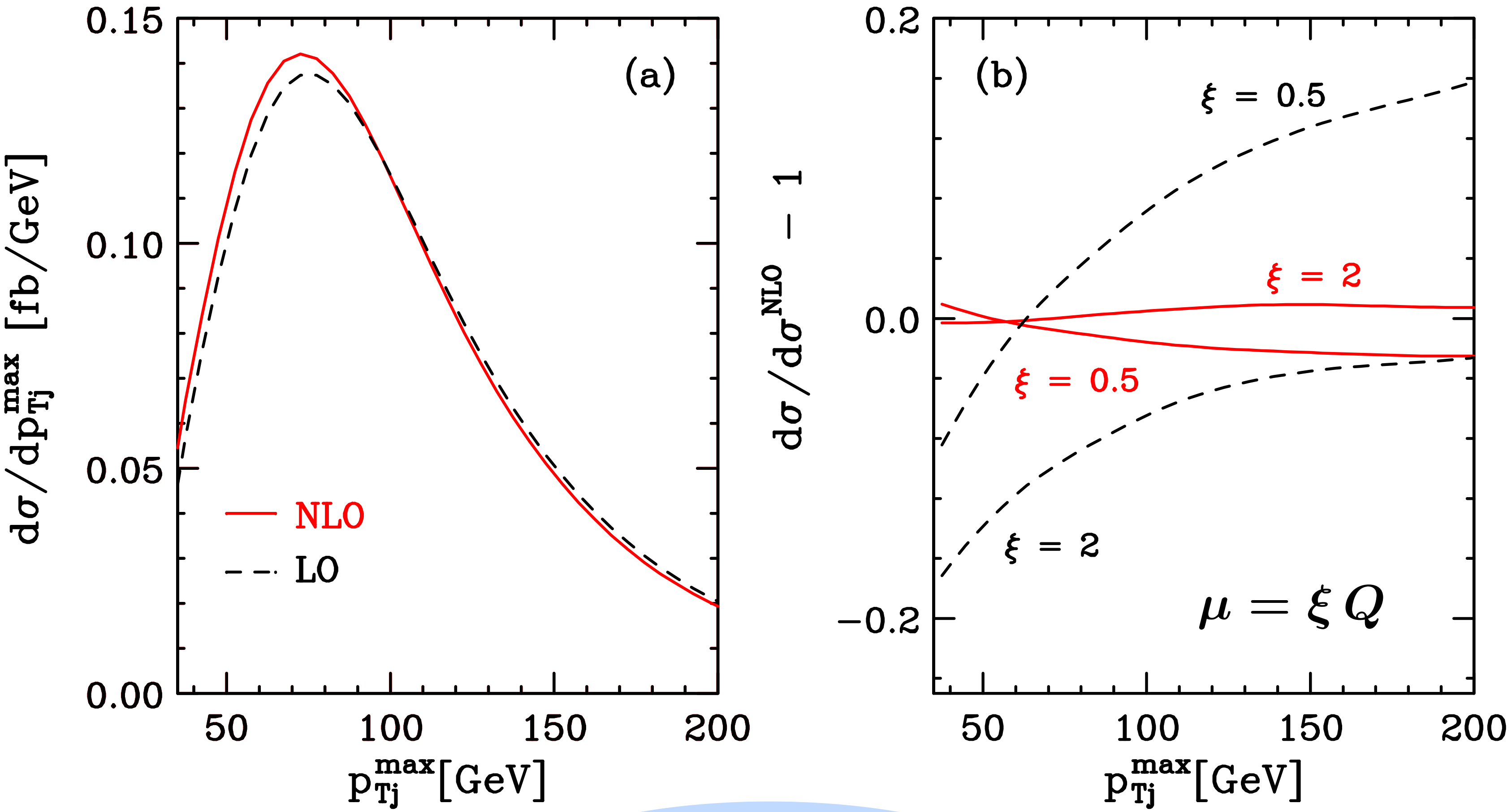
Arnold, Figy, B. J., Zeppenfeld (2010)



$m_H = 120$ GeV

transverse momentum of the hardest jet

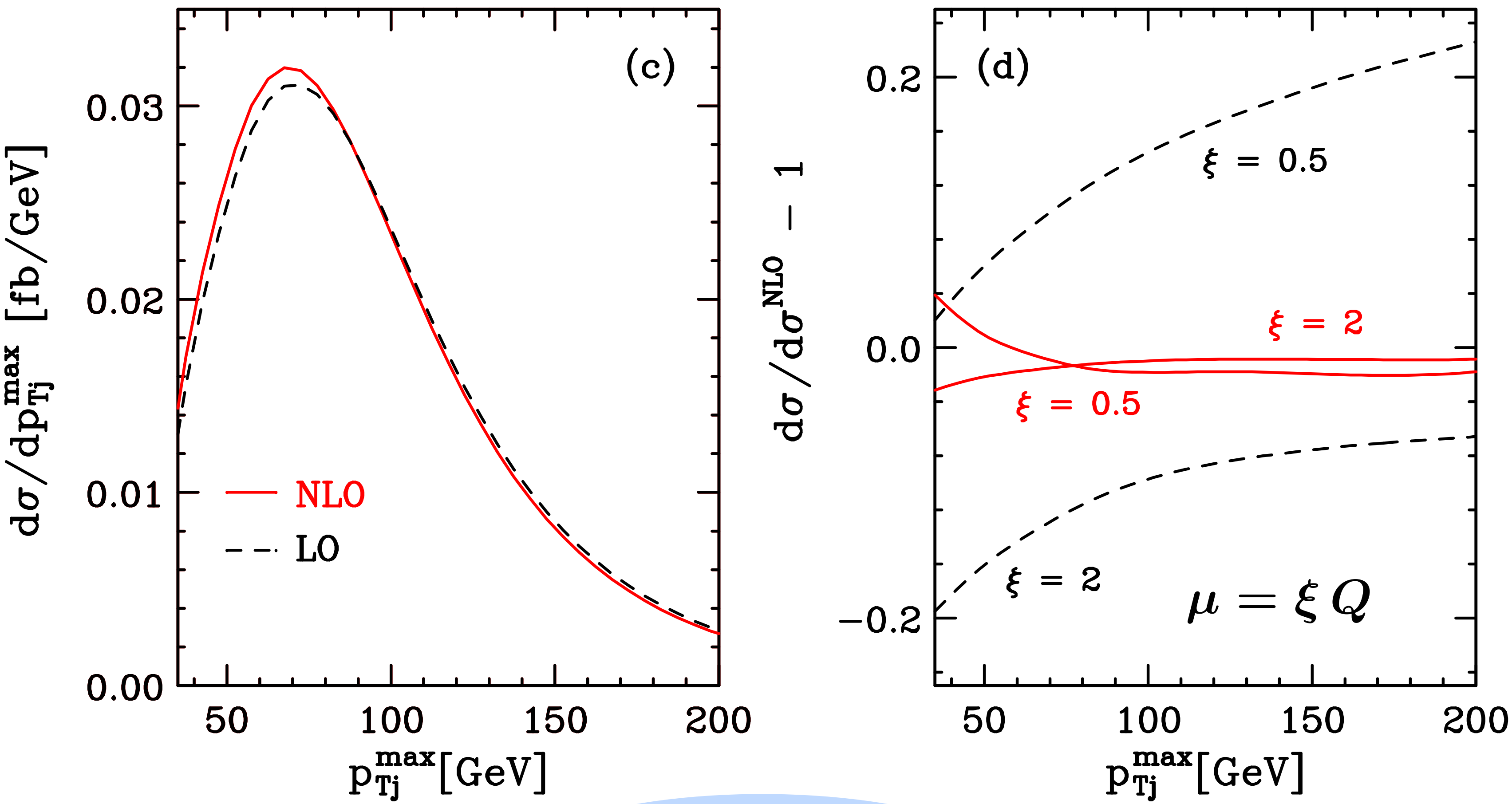
Arnold, Figy, B. J., Zeppenfeld (2010)



$\sqrt{S} = 14$ TeV

transverse momentum of the hardest jet

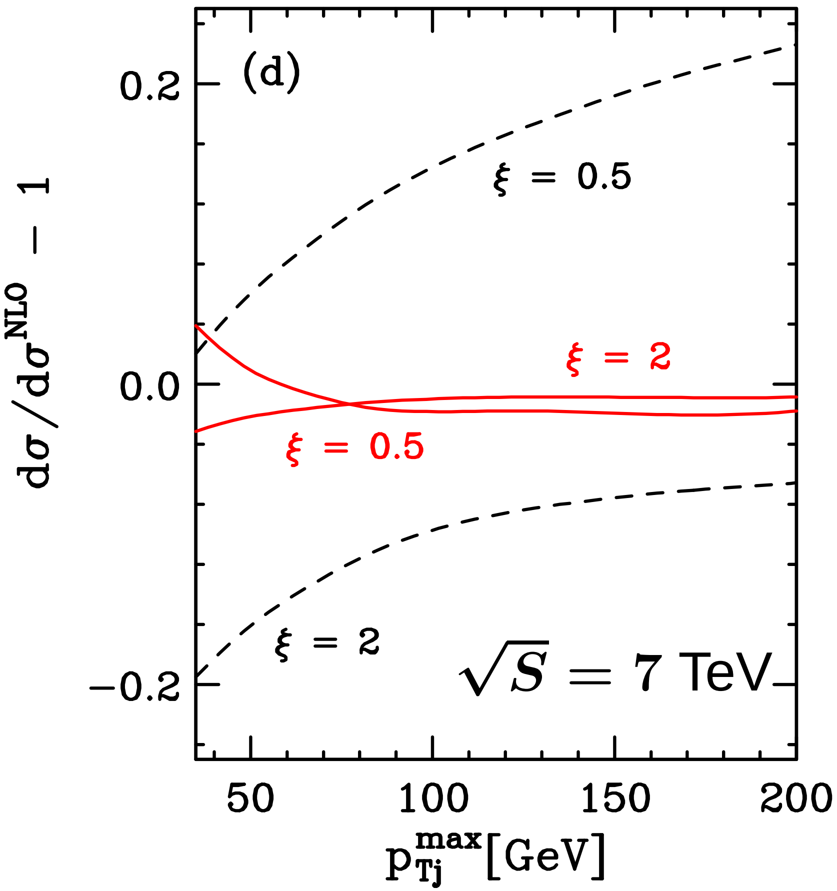
Arnold, Figy, B. J., Zeppenfeld (2010)

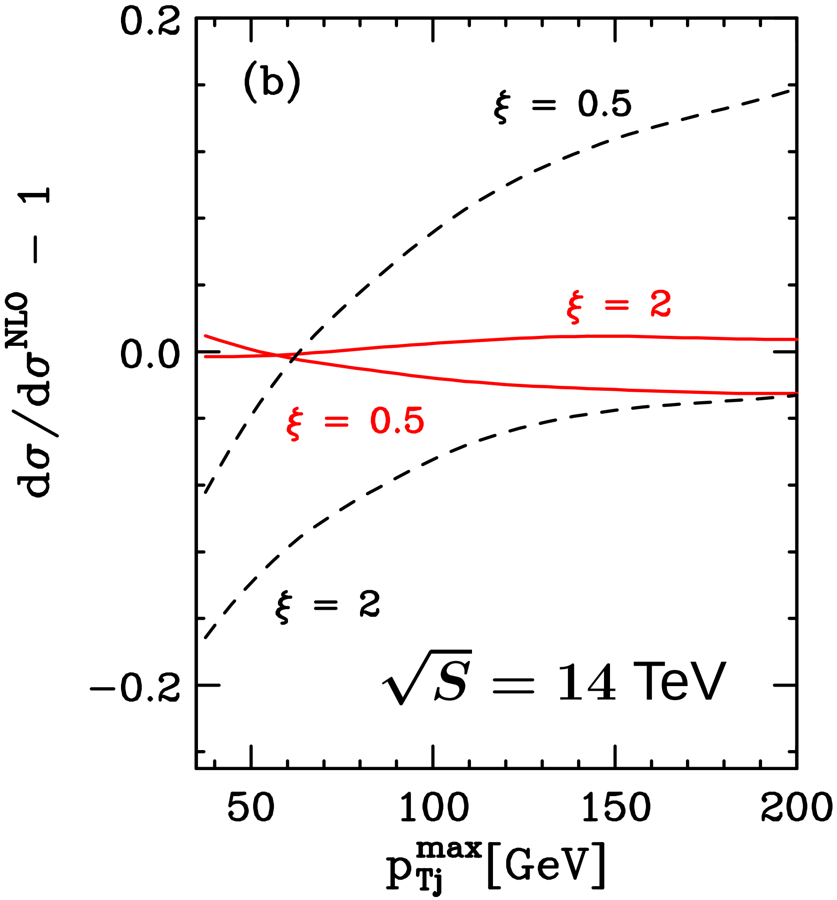


$\sqrt{S} = 7$ TeV

transverse momentum of the hardest jet

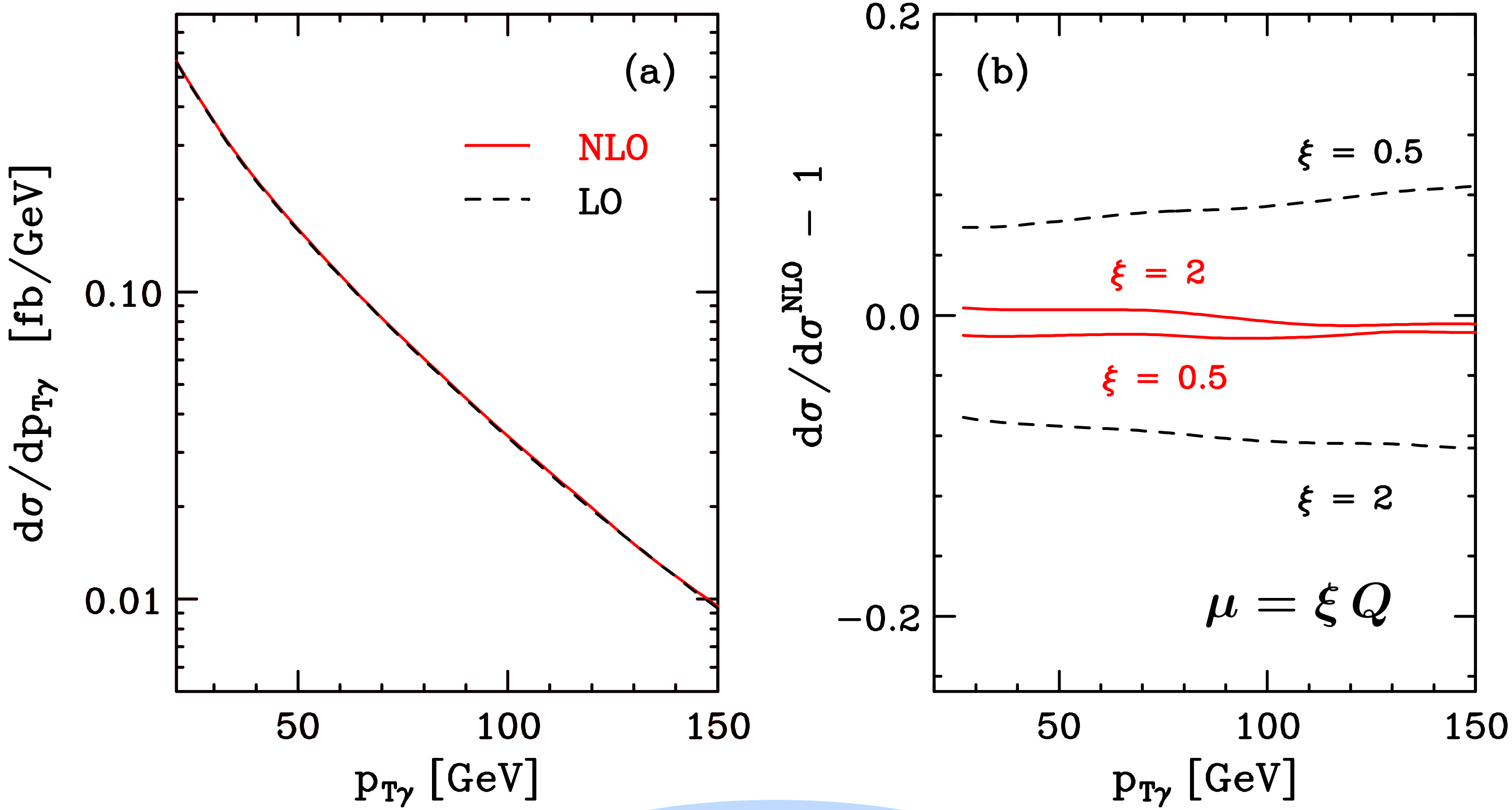
Arnold, Figy, B. J., Zeppenfeld (2010)





transverse momentum of the photon

Arnold, Figy, B. J., Zeppenfeld (2010)



$\sqrt{S} = 14$ TeV

summary & conclusions

- WBF offers promising prospects for Higgs boson search
- $H \longrightarrow b\bar{b}$ mode profits from requirement of hard, central photon:
  - trigger efficiencies improved
  - QCD backgrounds suppressed significantly
  - signal significance $S/\sqrt{B} \sim 3$ for 100 fb^{-1}
- developed fully flexible parton-level Monte-Carlo program with NLO-QCD cross sections and distributions for $pp \longrightarrow H\gamma jj$
- perturbative QCD corrections well under control (modest scale uncertainties & K-factors)
- shape of some distributions sensitive to radiative corrections