Next-to-leading order QCD corrections in Higgs boson production in association of a photon via VBF

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Heavy Particles at the LHC
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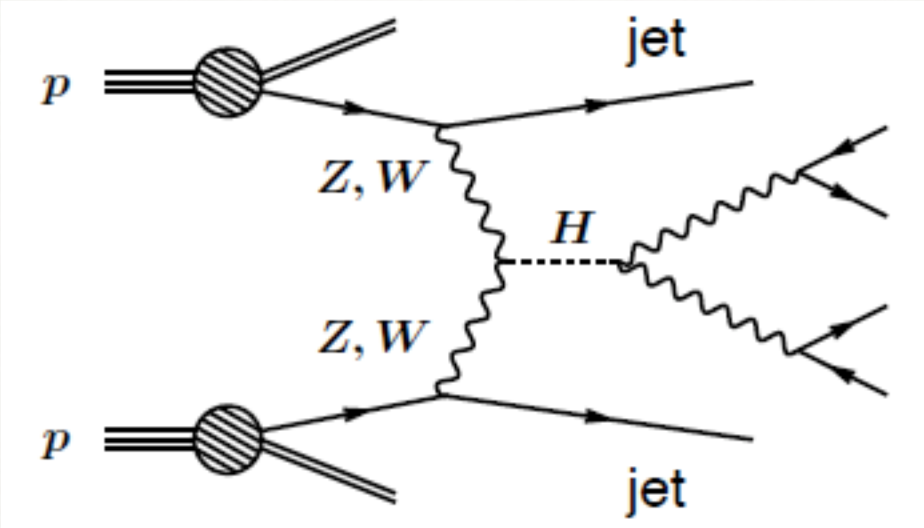
References

- ★ detailed signal-background analysis: Gabrielli, Maltoni, Mele, Moretti, Piccinini, Pittau (2007) [Spires]
- ★ NLO-QCD calculation of signal process: Arnold, TF, Jager, Zeppenfeld (2010) [Spires]
- ★ See Barbara Jagar's slides

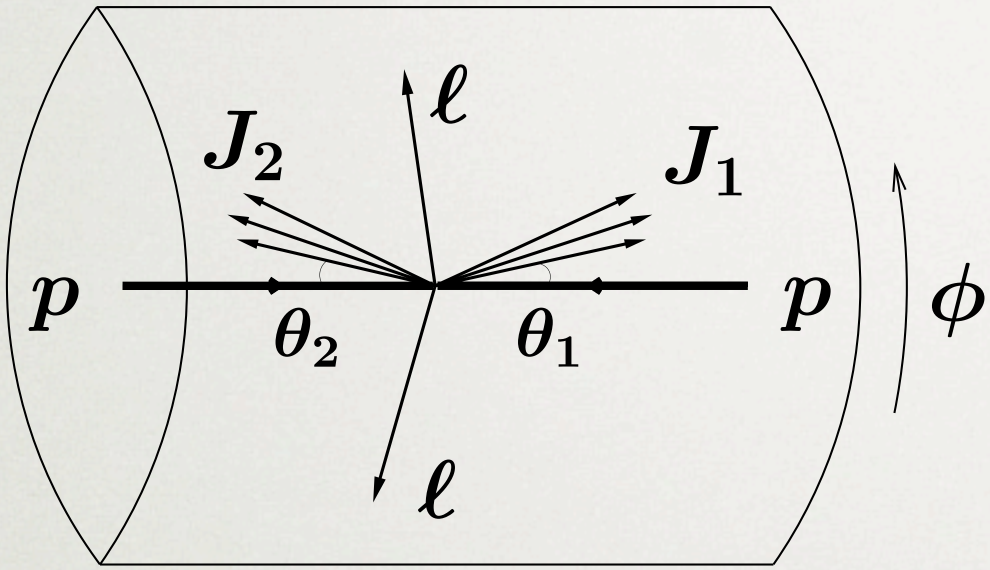
VBF event topology



Suppressed color exchange between quark lines gives rise to

- ★ Little jet activity in central rapidity region
- ★ Scattered quarks: 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

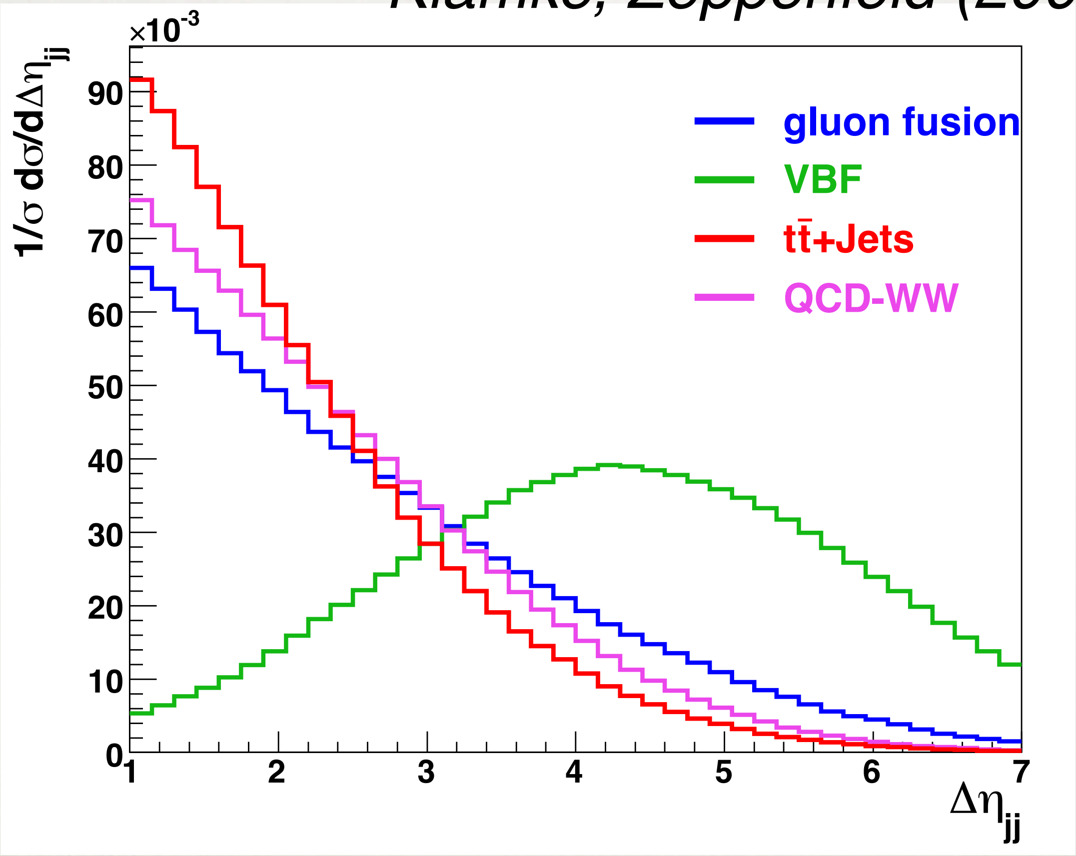
example: backgrounds to $pp \to Hjj$ via VBF in the $H \to W^+W^- \to e^\pm\mu^\mp \not{p}_T$ decay mode include

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

TAGGING JETS: PROPERTIES

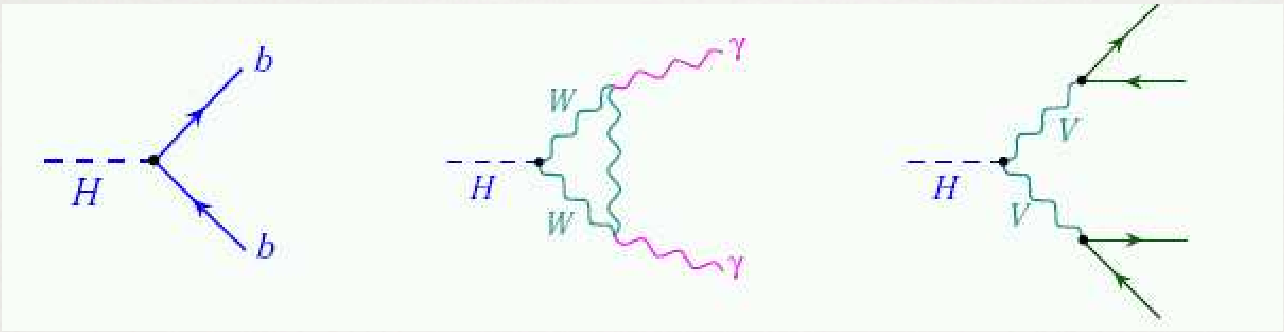
rapidity separation of the tagging jets

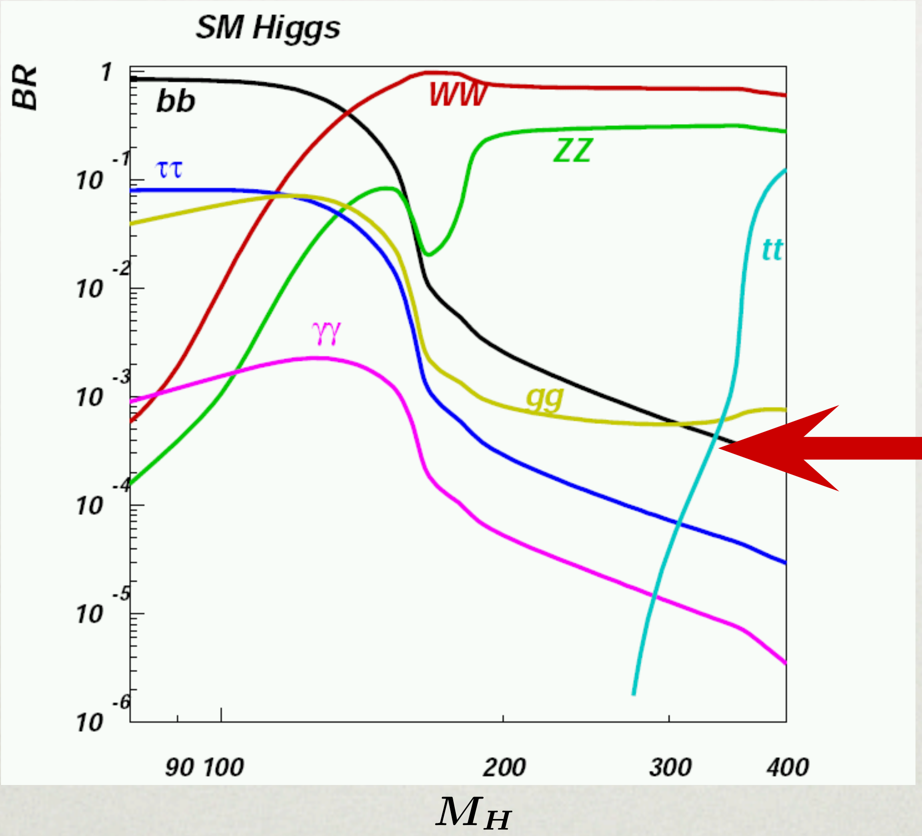
Klämke, Zeppenfeld (2007)



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

Higgs decay





branching fractions

DETERMINATION OF THE $Hb\bar{b}$ COUPLING

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

- $Ht\bar{t}$ production with $H \to b\bar{b}$ decay: large backgrounds;
  new approach: accessible by jet-deconstruction techniques?

  [Plehn, Salam, Spannowsky (2009)]

- WBF Hjj production with $H \to b\bar{b}$ decay: large backgrounds:

  QCD production of $b\bar{b}jj$, $jjjj$, $t\bar{t}$, $t\bar{t}j$; $(Z^\star/\gamma^\star \to b\bar{b})jj$;
  $b\bar{b}jj$ and $jjjj$ production via overlapping events

  [Mangano et al. (2002)]

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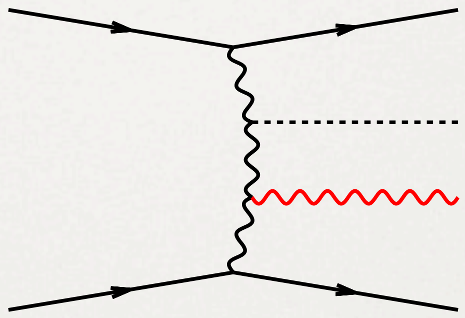
EXTRA PHOTON RADIATION IN VBF: $pp \to H\gamma jj$



Gabrielli et al. (2007):

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

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

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

EXTRA PHOTON RADIATION IN VBF: $pp \to H\gamma jj$

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?

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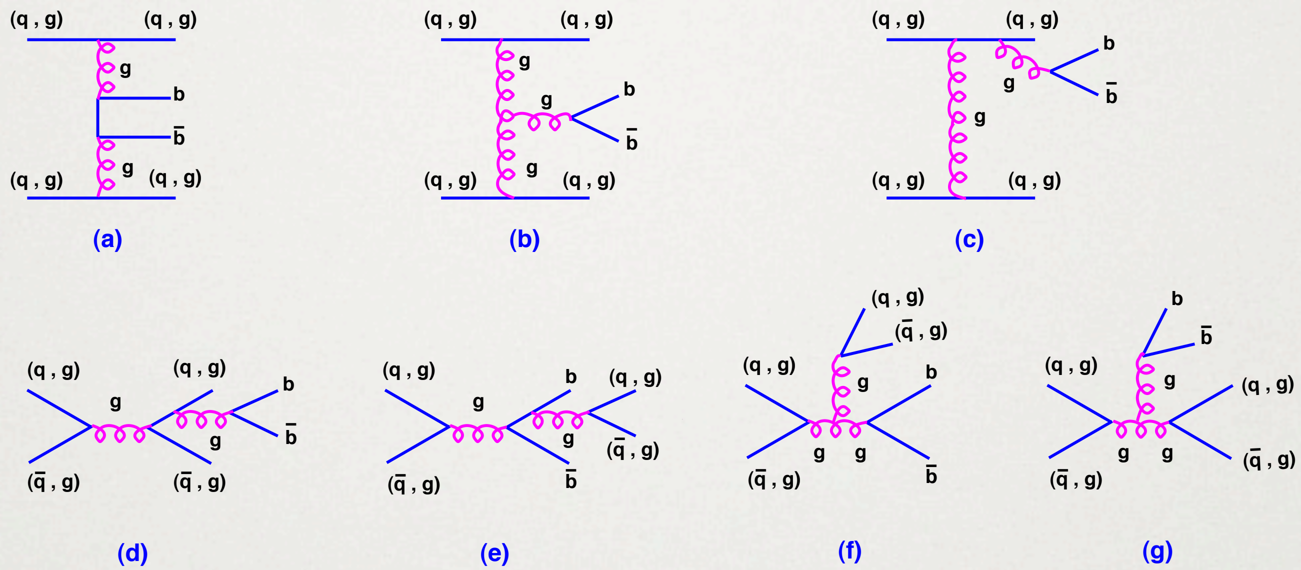
- S/B not much affected
- signal significance decreases

☞ no advantage?

✔ decrease in rate for QCD multi-jet final states

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

EXTRA PHOTON RADIATION IN VBF: $pp \to H\gamma jj$



✔ 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

EXTRA PHOTON RADIATION IN VBF: $pp \to H\gamma jj$

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: $pp \to H\gamma jj$

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

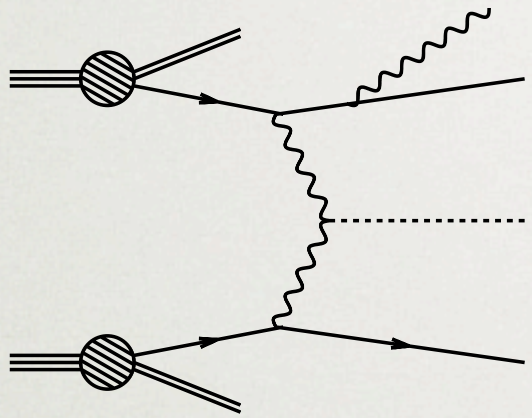
backgrounds: $\sigma_\gamma/\sigma \sim 1/3000$

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

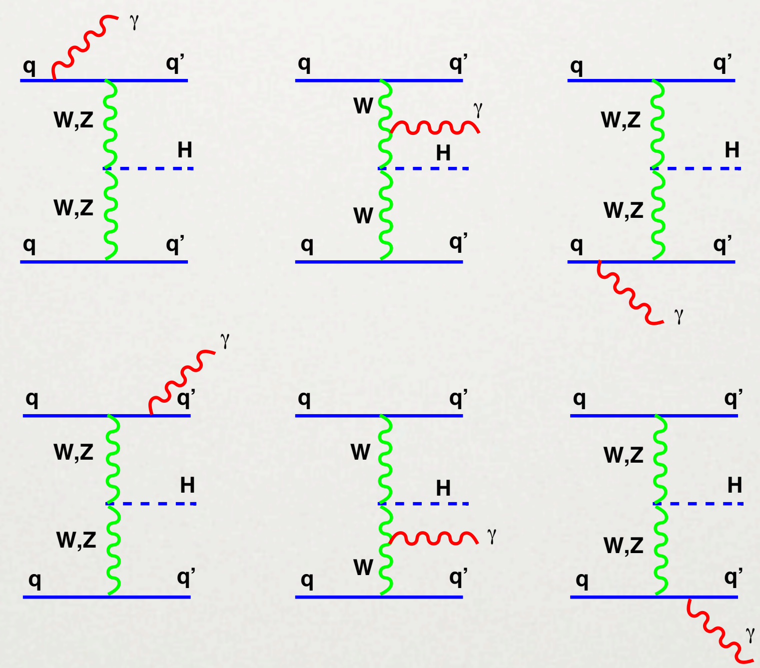
note: QCD structure of the process
identical to γjj production via WBF

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

Elements of the calculation: LO

need to compute numerical value for

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



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

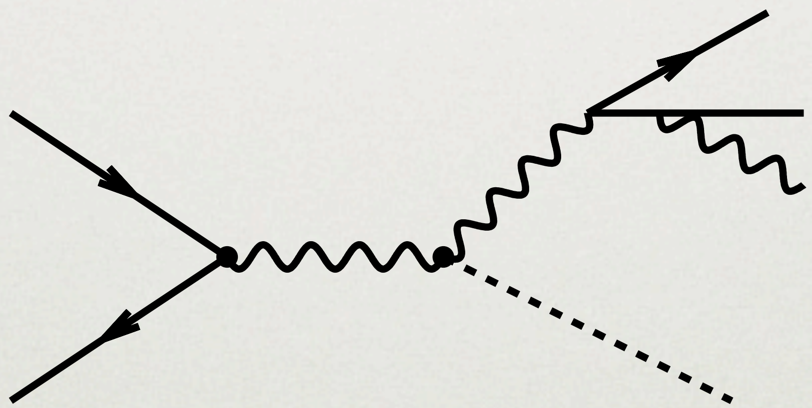
strategy: develop modular structure with fermionic currents
and bosonic tensors (to be recycled at NLO)

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

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- interference contributions of t- and u-channel diagrams in processes with identical quarks

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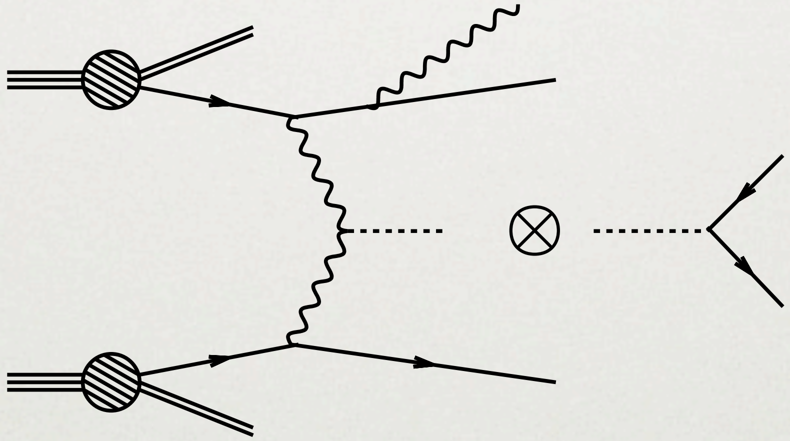
neglected terms strongly suppressed in PS region where VBF can be observed experimentally
(require two widely separated quark jets of large invariant mass)

Elements of the calculation: Higgs decay

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

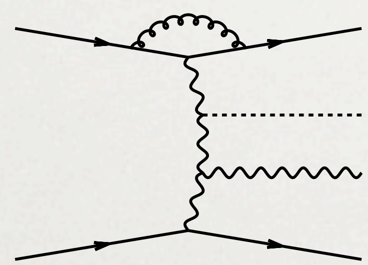
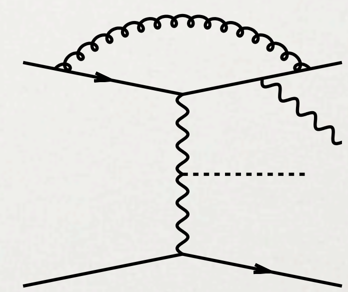
$$pp \to H\gamma jj \;\otimes\; H \to dd$$



- 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

$\mathcal{M}_V =$  $+$  $+ \cdots$

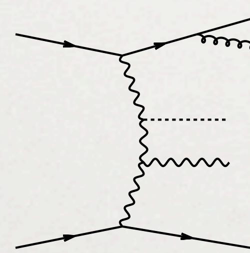
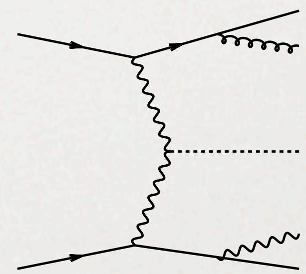
$$= \mathcal{M}_B \, F(Q) \left[-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} \right] + \tilde{\mathcal{M}}_V^{finite}$$

$\tilde{\mathcal{M}}_V^{finite}$ … 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

$|\mathcal{M}_R|^2 = \Big|$  $+$  $+ \cdots \Big|^2$

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

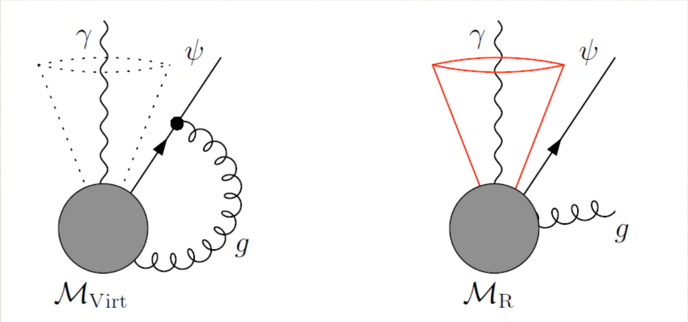
PHOTON ISOLATION

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: $d\sigma^R \to d\sigma^A$
- ✔ 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

Selection cuts

apply k_T jet algorithm and use CTEQ6 parton distributions

inclusive cuts

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

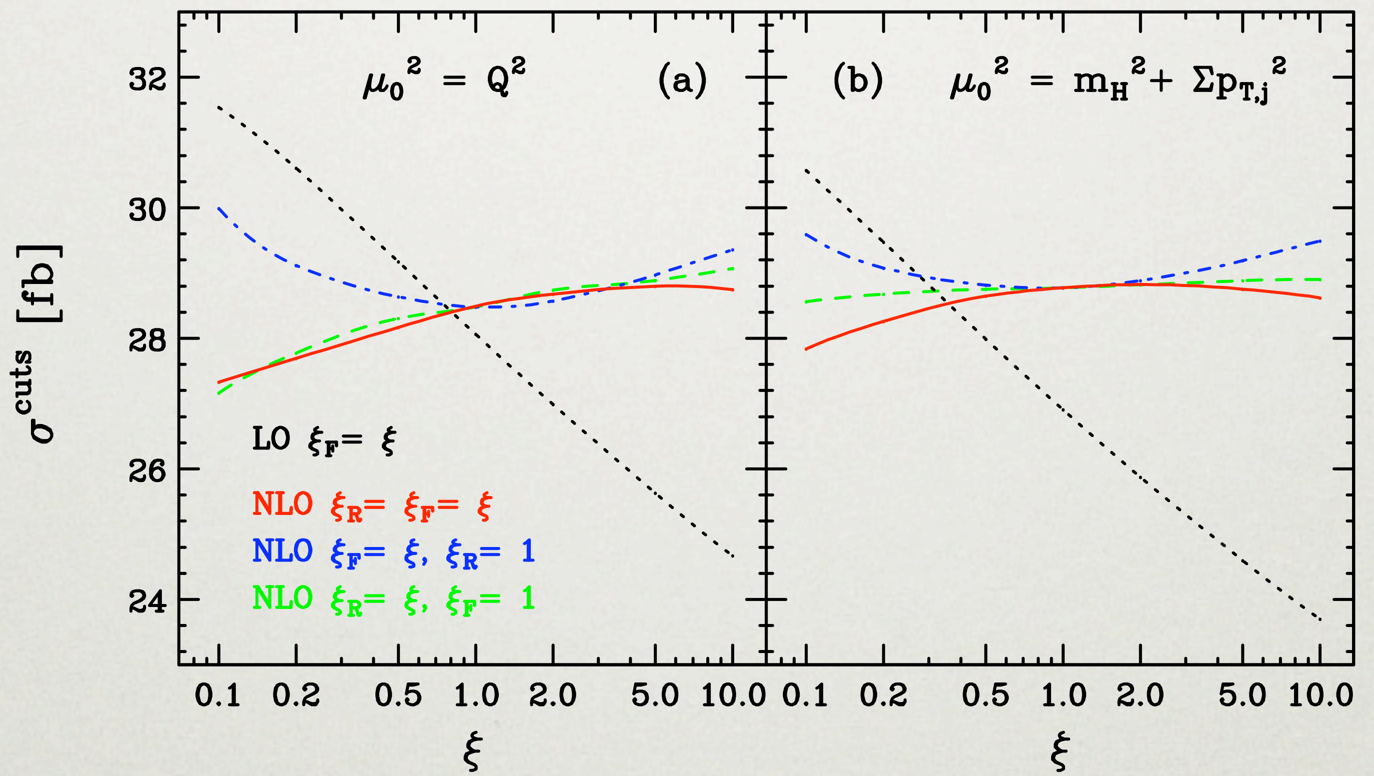
WBF cuts

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

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 $\boldsymbol{\sigma^{\mathrm{WBF}}}$ for $\boldsymbol{Q^2/2 \leq \mu^2 \leq 2Q^2}$:

CTEQ6

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

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

MSTW

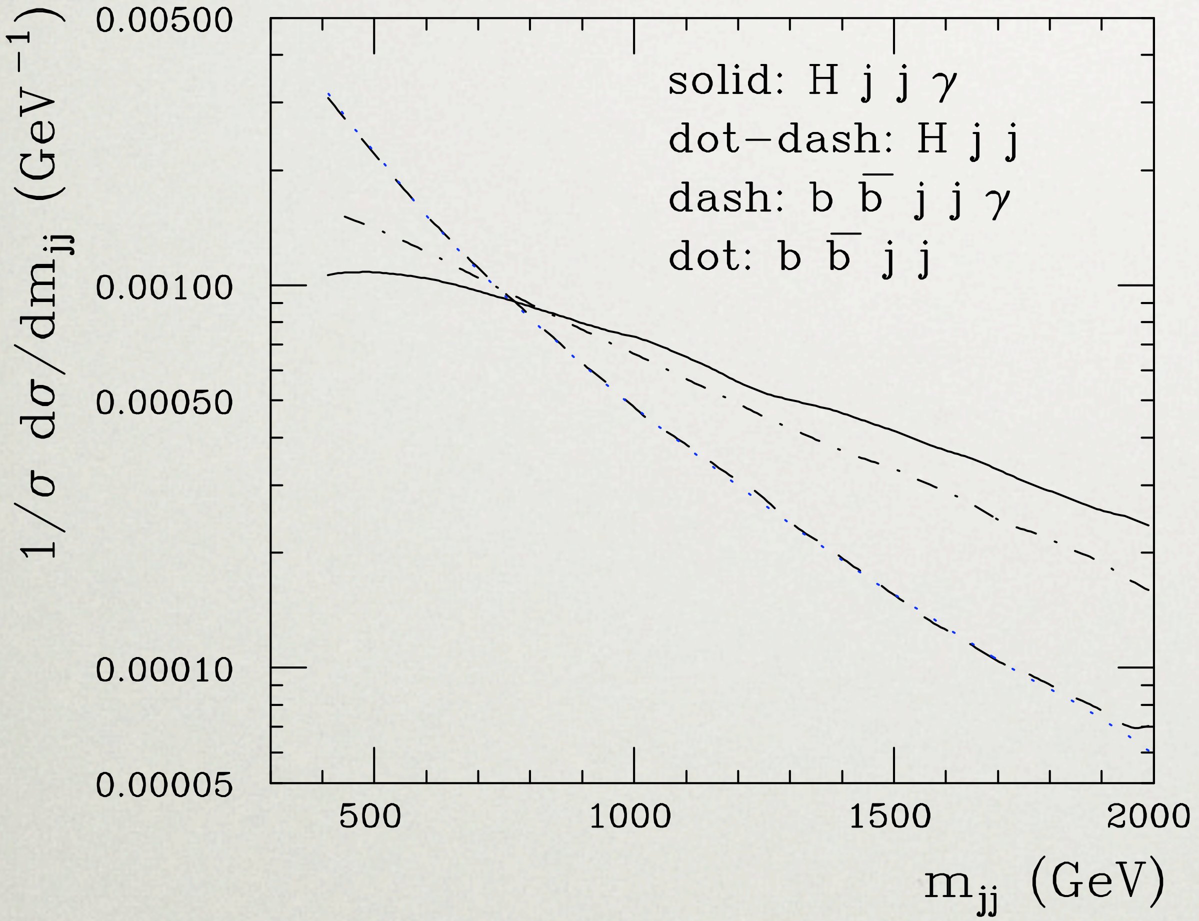
LO: $\mathbf{14.40^{+1.13}_{-1.0}}$ fb

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

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

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

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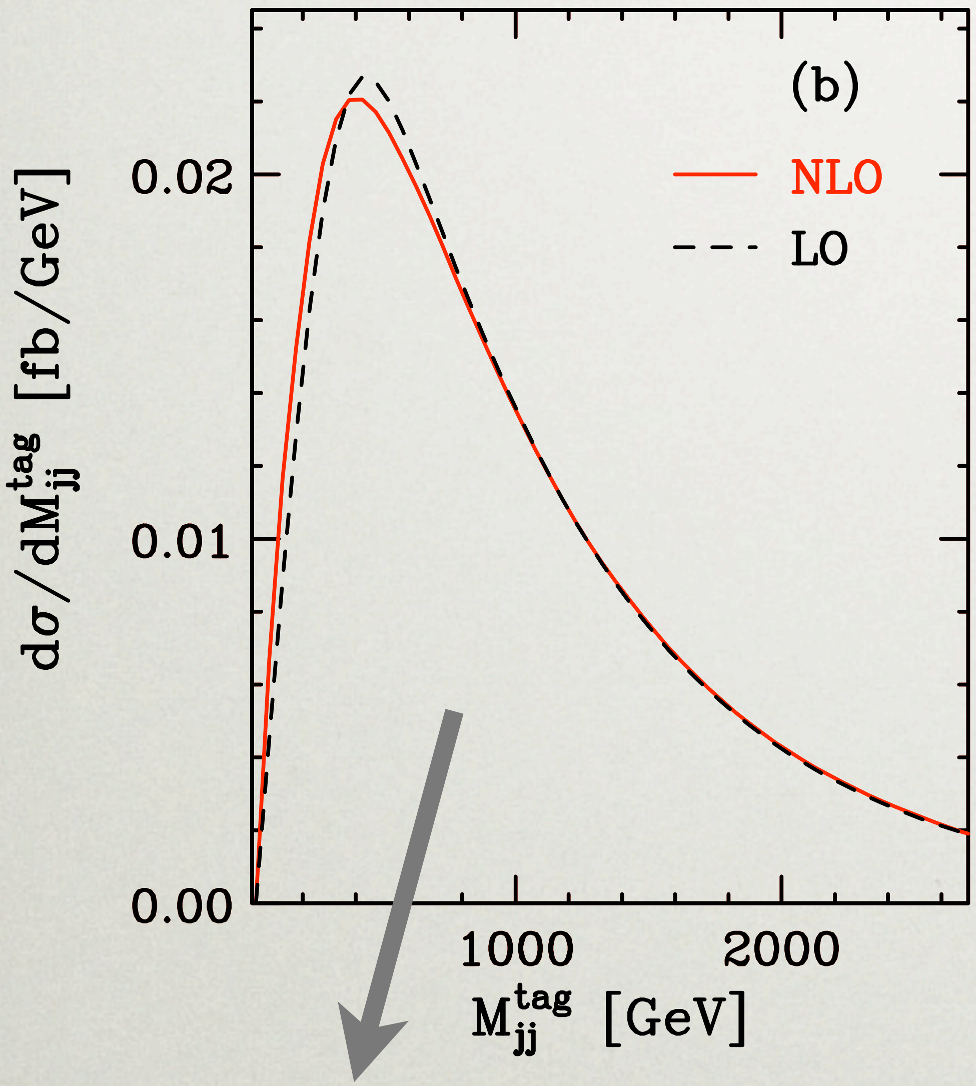

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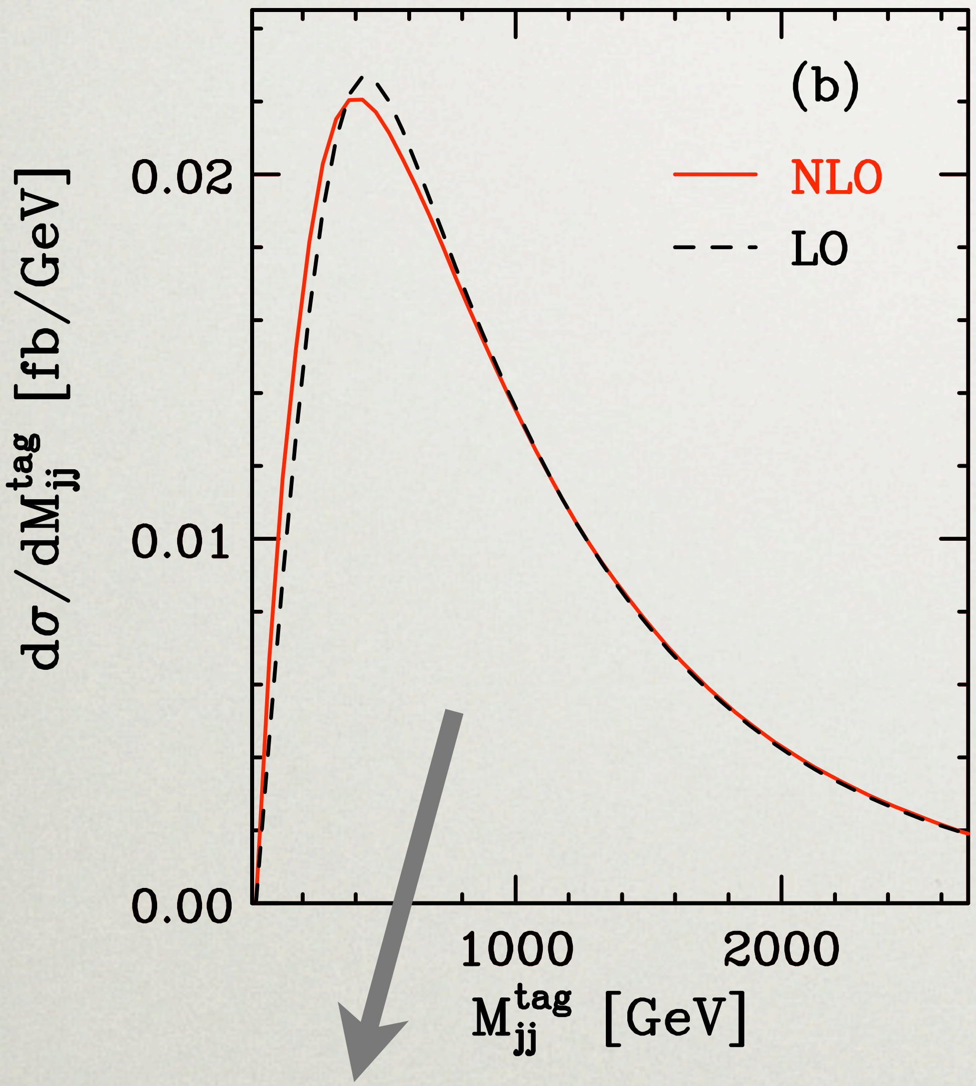

effect of NLO-QCD corrections small

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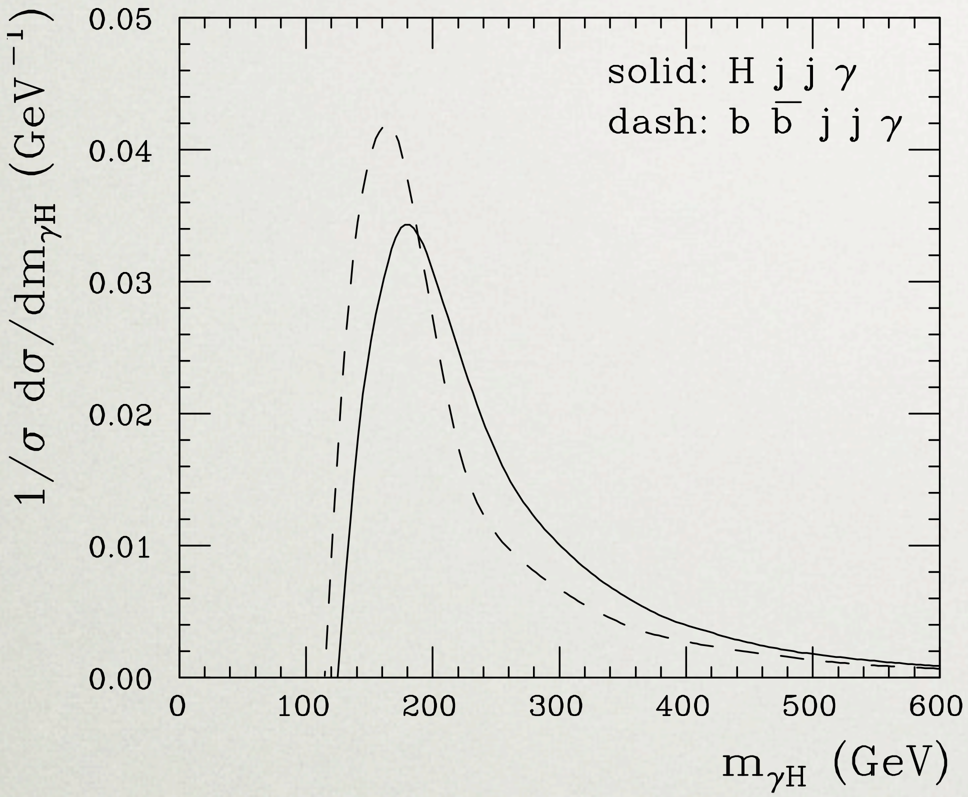
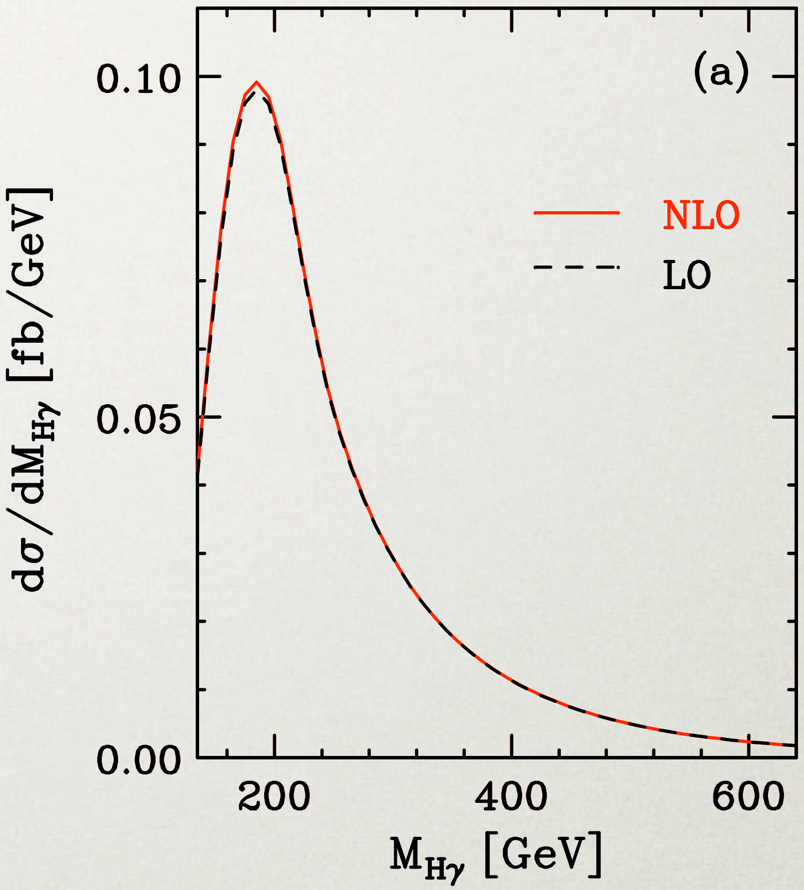
invariant mass of the photon-Higgs system

Gabrielli et al. (2007)



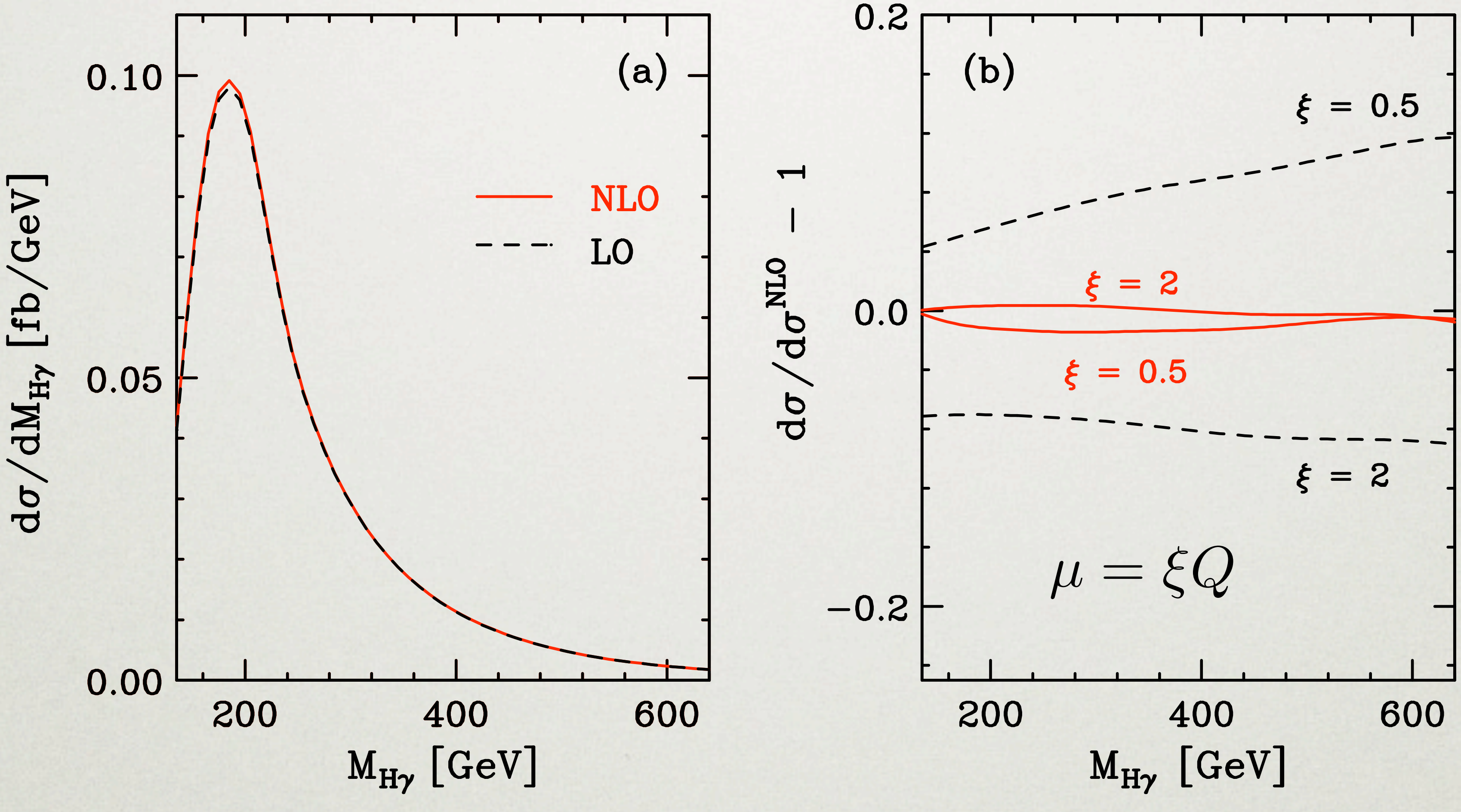
Arnold, TF, Jager, Zeppenfeld



$$m_H = 120\ \text{GeV}$$

INVARIANT MASS OF THE PHOTON-HIGGS SYSTEM

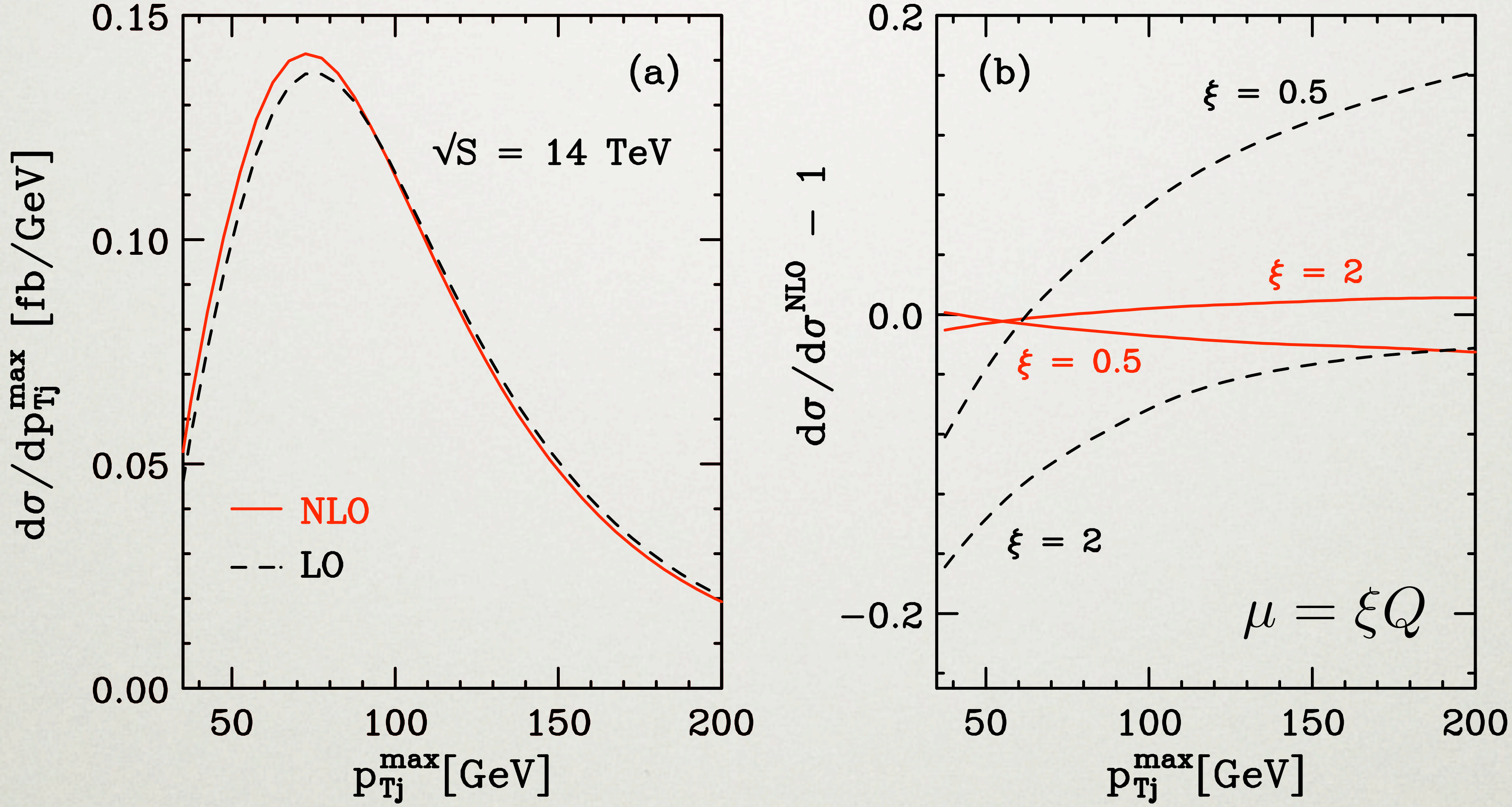
Arnold, TF, Jager, Zeppenfeld



$$m_H = 120 \text{ GeV}$$

TRANSVERSE MOMENTUM OF THE HARDEST JET

Arnold, TF, Jager, Zeppenfeld



$$\sqrt{S} = 14 \text{ TeV}$$

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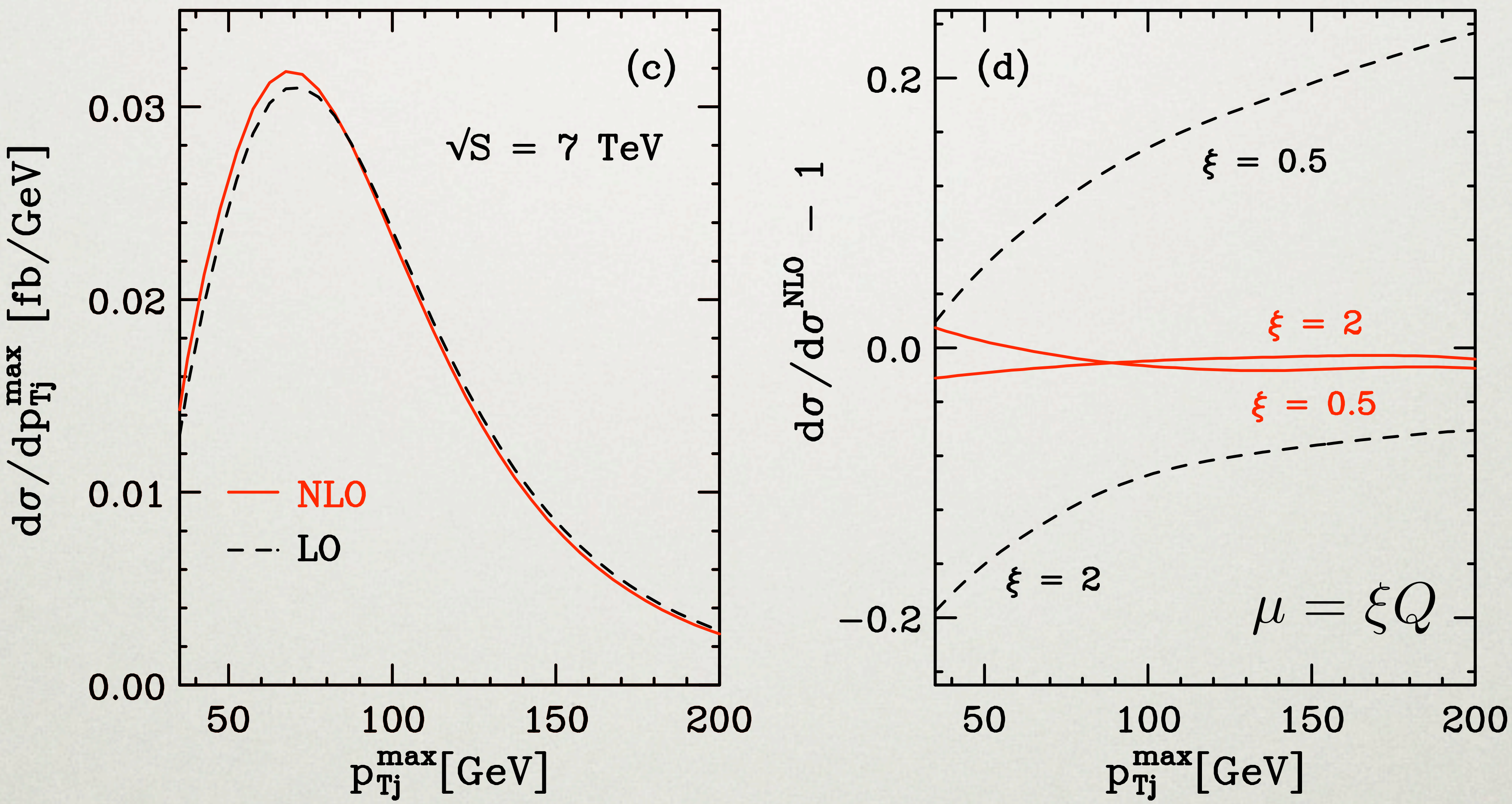
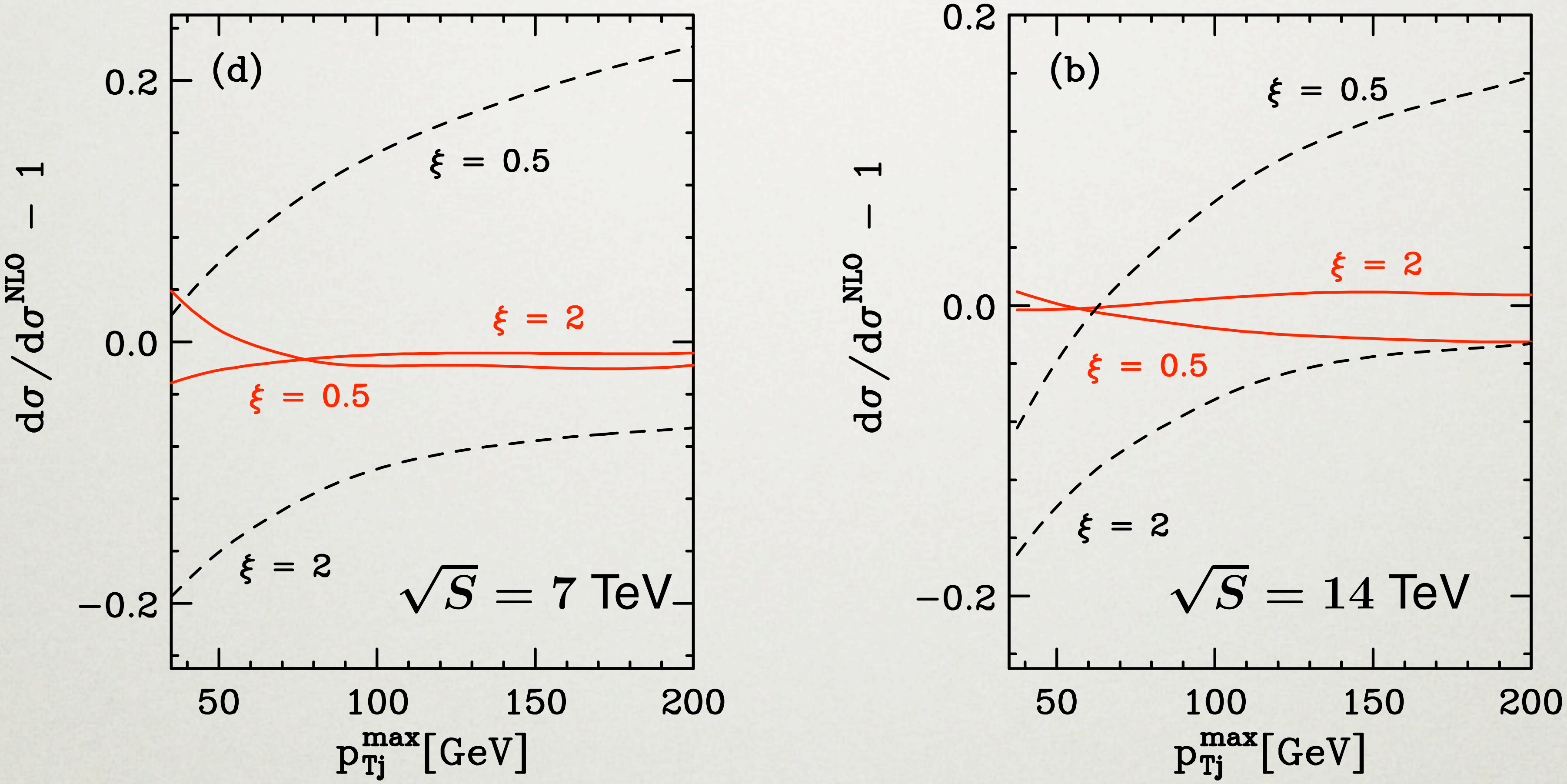


$$\sqrt{S} = 7 \text{ TeV}$$

TRANSVERSE MOMENTUM OF THE HARDEST JET

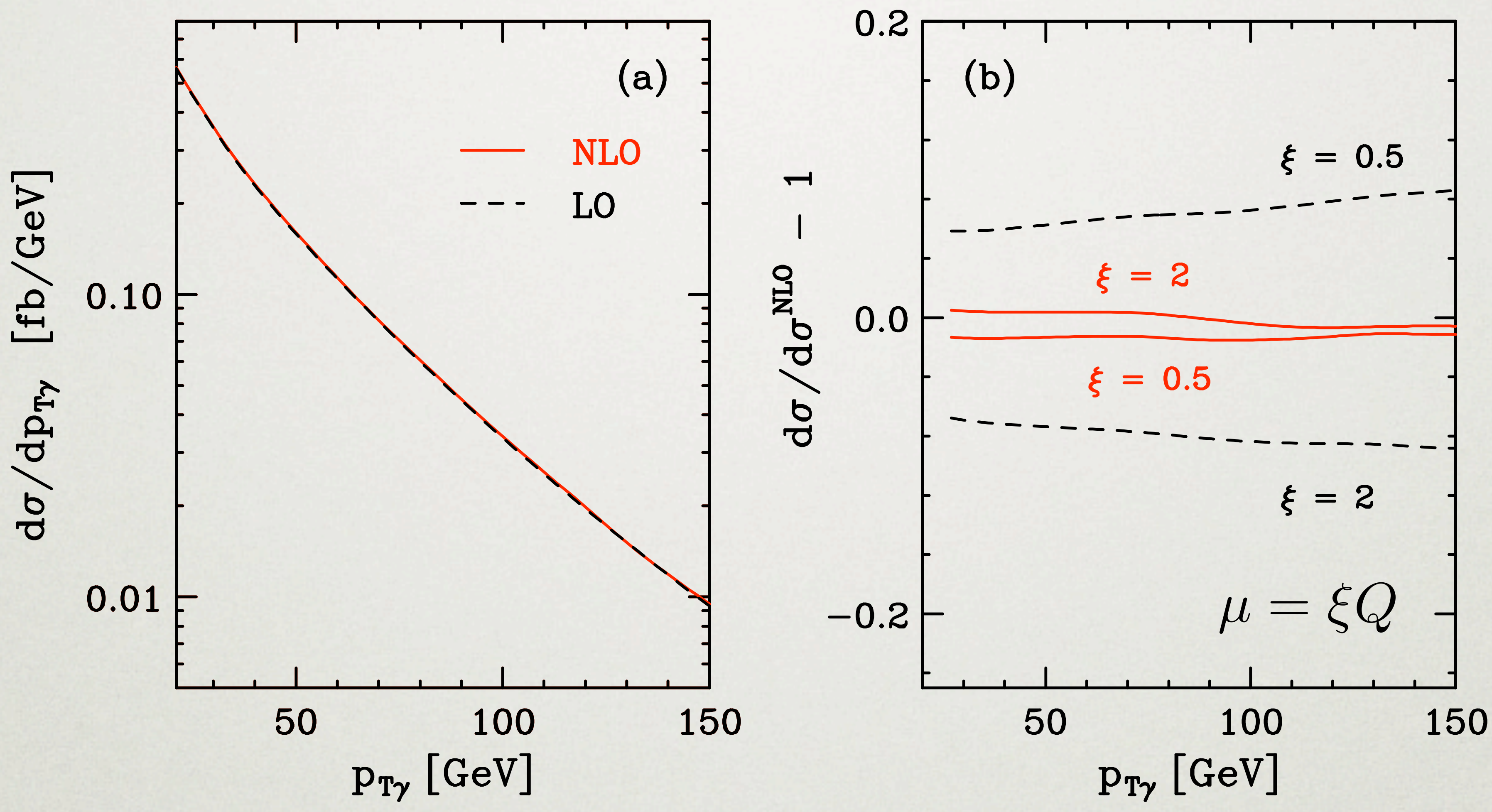
Arnold, TF, Jager, Zeppenfeld



$$\mu = \xi Q$$

TRANSVERSE MOMENTUM OF THE PHOTON

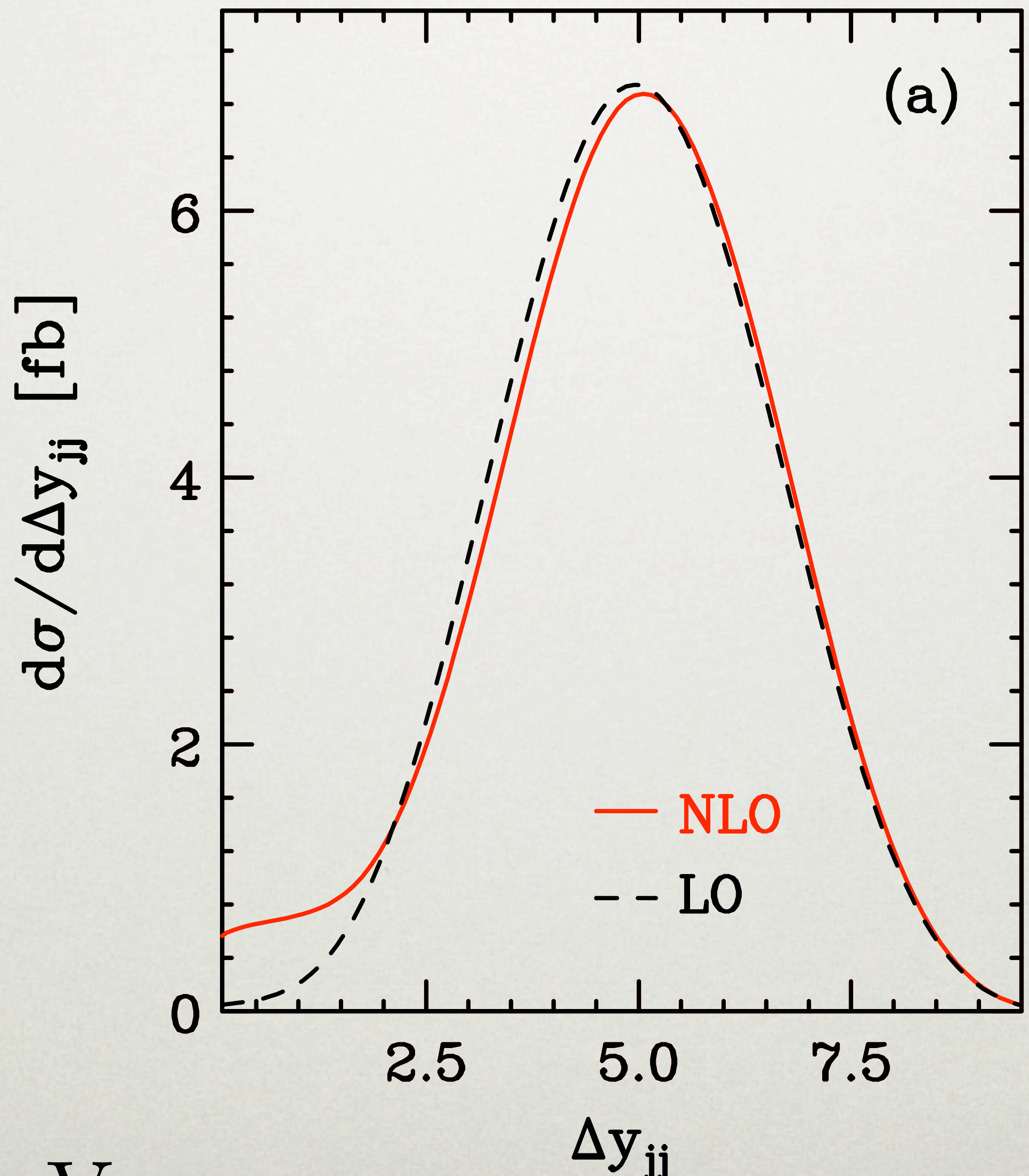
Arnold, TF, Jager, Zeppenfeld



$$\sqrt{S} = 14 \text{ TeV}$$

Rapidity separation of Tagging Jets

Arnold, TF, Jager, Zeppenfeld



$m_H = 120$ GeV

$\sqrt{S} = 14$ TeV

Summary & conclusions

- ★ WBF offers prospects for Higgs boson search
- ★ $H \to b\bar{b}$ mode profits from the requirement of hard, central photon:
  - ★ trigger efficiencies improved
  - ★ QCD backgrounds suppressed significantly
  - ★ signal significance: $S/\sqrt{B} \sim 3$ for 100 fb^{-1}
- ★ perturbative QCD corrections well under control (modest scale uncertainties & K-factors)
- ★ some kinematic distributions are sensitive to radiative corrections