Electroweak and QCD corrections to Higgs-boson production in vector-boson fusion at the LHC

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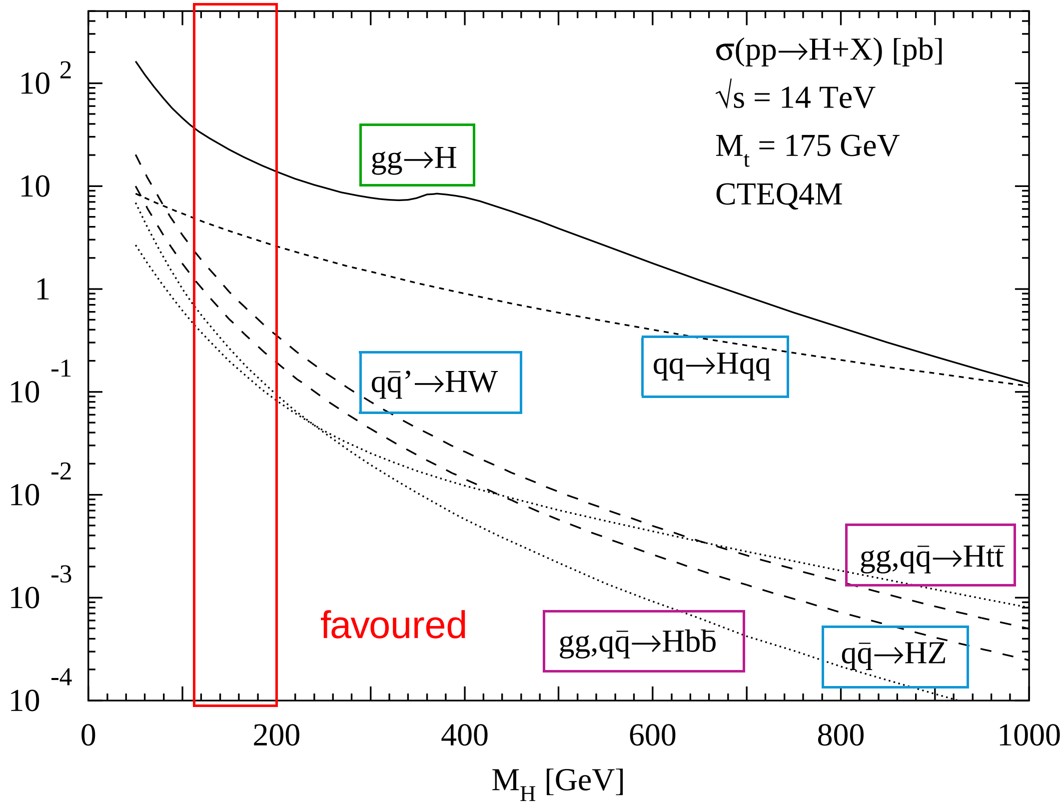
based on PRL 99 (2007) 161803 [arXiv:0707.0381, hep-ph] and PRD 77 (2008) 013002 [arXiv:0710.4749, hep-ph]

Contents

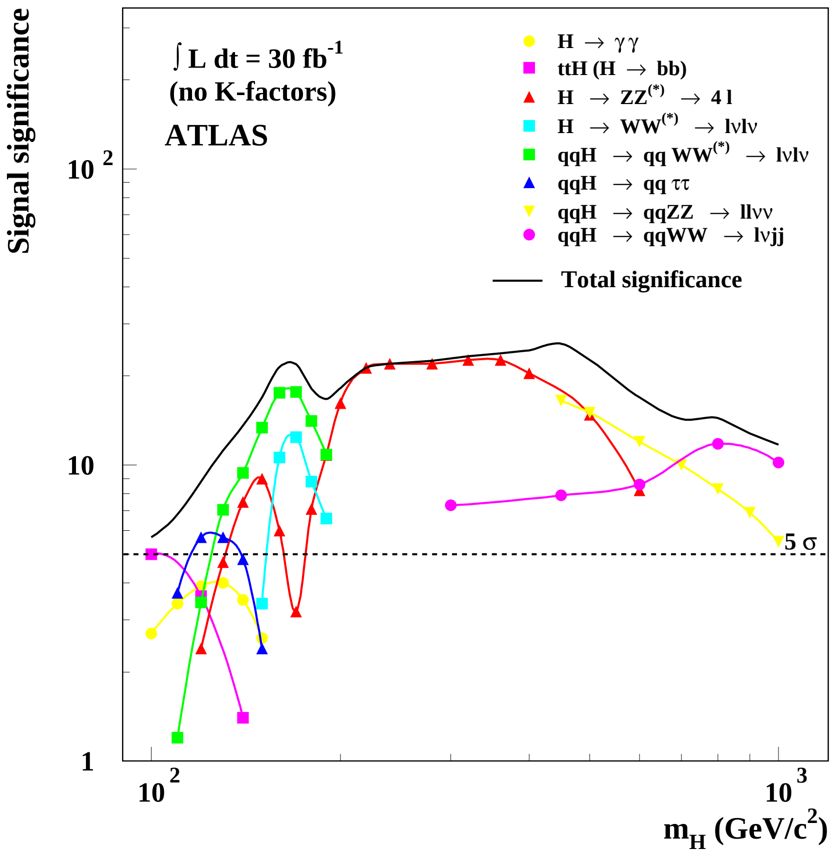
1 Introduction

Cross sections and significance of the Higgs signal at the LHC

Spira et al. '98



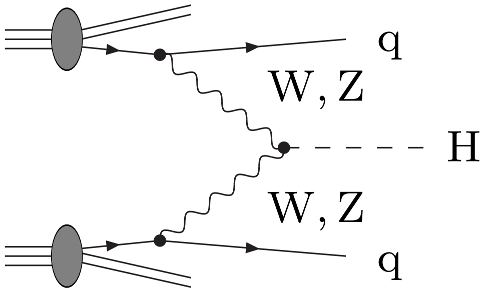
ATLAS '04



Higgs production via VBF ("qqH") is cornerstone in Higgs search in entire M_{H} range

$\hookrightarrow$ calculate / control higher orders to reduce theoretical uncertainty down to the level of PDF ($\sim 3–4\%$) and experimental uncertainties ($\sim 5–10\%$)

Process topology of Higgs production via VBF



colour exchange between quark lines suppressed

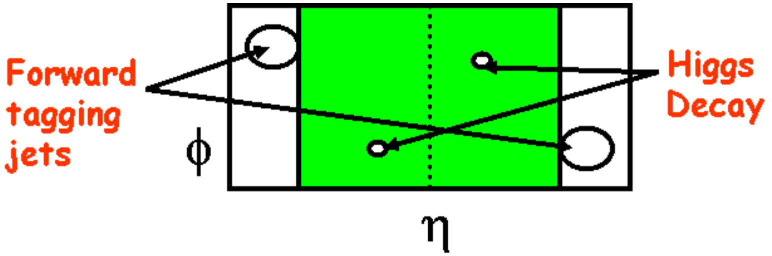
$\Rightarrow$ small QCD corrections

Han, Valencia, Willenbrock '92; Spira '98;
Djouadi, Spira '00; Figy, Oleari, Zeppenfeld '03

$\hookrightarrow$ "t-channel approximation" (vertex corrections)

VBF cuts and background suppression:

signature = Higgs + 2jets



- 2 hard "tagging" jets demanded:
  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$
- tagging jets forward–backward directed:
  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0$

$\hookrightarrow$ Suppression of background

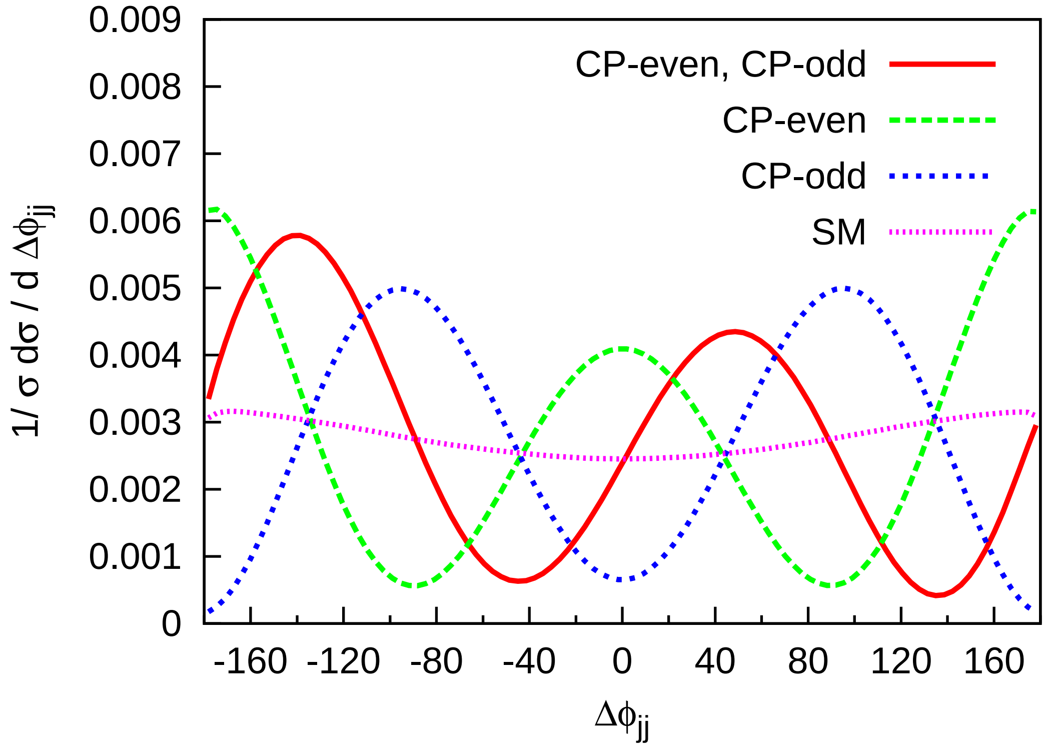
- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or WW production Zeppenfeld et al. '94-'99
- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

WWH and ZZH coupling analyses

- Higgs via VBF plays important role in global Higgs couplings analysis

  Dührssen et al. '04

- azimuthal angle difference $\Delta\phi_{\rm jj}$ of tagging jets is sensitive to BSM effects:



Hankele, Klämke, Zeppenfeld, Figy '06

(Individual contributions without SM)

CP-even: $\mathcal{L} \propto HW^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto g_{\mu\nu}(k_+k_-) - k_{+,\nu}k_{-,\mu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto \epsilon_{\mu\nu\rho\sigma}k^\rho_+k^\sigma_-$

Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in "t-channel approximation" (vertex corrections)
  - ◇ total cross section — Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00
  - ◇ distributions — Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04

  $\hookrightarrow$ impact $\sim 5\text{–}10\%$

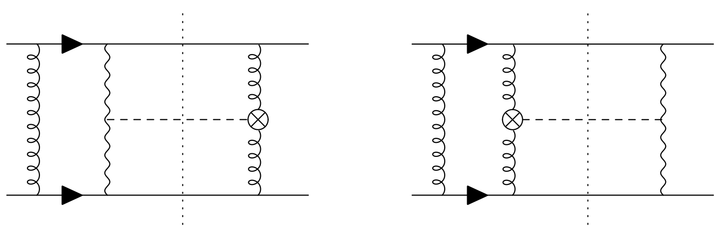
- NLO QCD corrections to gluon-initiated channels — Campbell, R.K.Ellis, Zanderighi '06
  (effective $\mathrm{H}gg$ coupling)

  $\hookrightarrow$ contribution to VBF $\sim 5\%$ — Nikitenko, Vazquez '07 (NLO scale uncertainty $\sim 35\%$)

- (full) NLO QCD+EW corrections to VBF — Ciccolini, Denner, S.D. '07

  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim 5\text{–}10\%$ $\rightarrow$ discussed in this talk !

- QCD loop-induced interferences between VBF and gluon-initiated channels

  Andersen, Binoth, Heinrich, Smillie '07
  Bredenstein, Hagiwara, Jäger '08

  $\rightarrow$ impact $\lesssim 10^{-3}\,\%$ (negligible!)

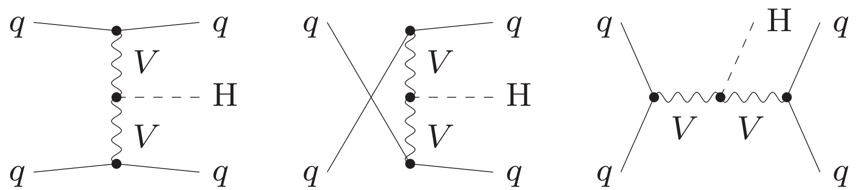
- SUSY QCD+EW corrections — Hollik, Plehn, Rauch, Rzehak '08

  $\hookrightarrow$ $|\mathrm{MSSM} - \mathrm{SM}| \lesssim 1\%$ for SPS points ($2\text{–}4\%$ for low SUSY scales)

2 Details of the NLO calculation

EW production of Higgs+2jets in LO:

- many subcontributions from qq, $q\bar{q}$, and $\bar{q}\bar{q}$ channels
- each channel receives contributions from one or two topologies ("t, u, s"):



$\hookrightarrow$ all contributions and interferences taken into account in LO and NLO

EW production of Higgs+2jets in NLO:

- partonic channels for
  - ◇ one-loop diagrams: qq, $q\bar{q}$, $\bar{q}\bar{q}$
  - ◇ real QCD corrections qq, $q\bar{q}$, $\bar{q}\bar{q}$ (gluon emission), qg, $\bar{q}g$ (gluon induced)
  - ◇ real QED corrections qq, $q\bar{q}$, $\bar{q}\bar{q}$ (photon emission), $q\gamma$, $\bar{q}\gamma$ (photon induced)
- collinear initial-state singularities from QCD and QED splittings

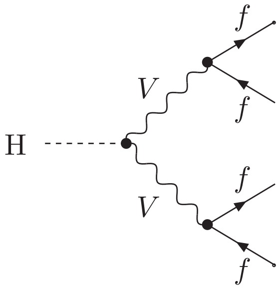
$\hookrightarrow$ factorization and PDF redefinition for QCD and QED singularities

Recycling strategy:

obtain all LO and NLO amplitudes via crossing
from NLO EW and QCD corrections to $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$ Bredenstein, Denner, S.D., Weber '06

Survey of Feynman diagrams for NLO EW and QCD corrections

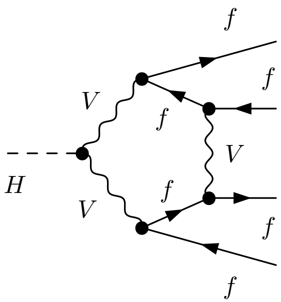
Lowest order:



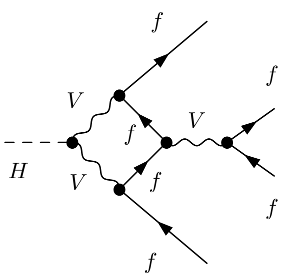
(one or two diagrams per flavour channel)

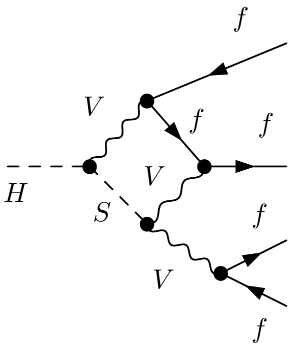
Typical one-loop diagrams: # diagrams = $\mathcal{O}(200-400)$

pentagons

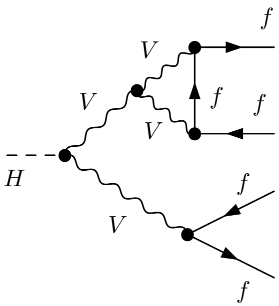


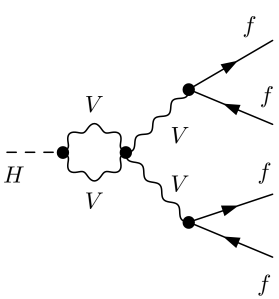
boxes



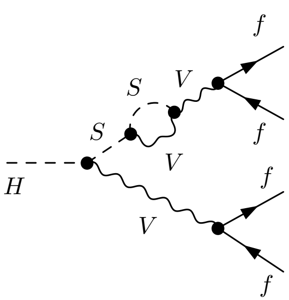


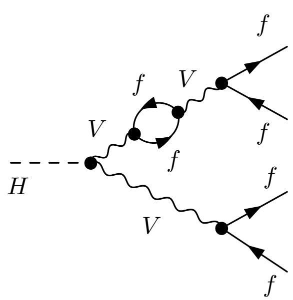
vertices





self-energies



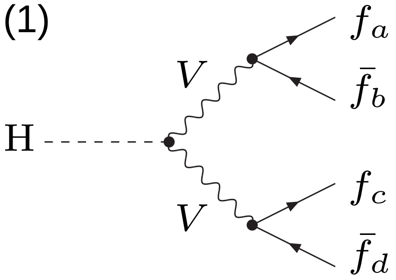


$+$ tree graphs with real photons or gluons

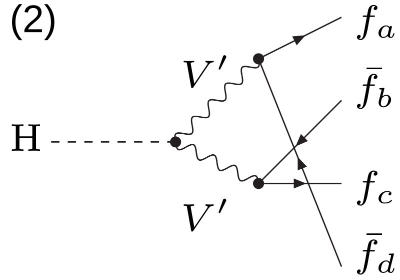
Classification of QCD corrections

Possible Born diagrams:

(1)



(2)



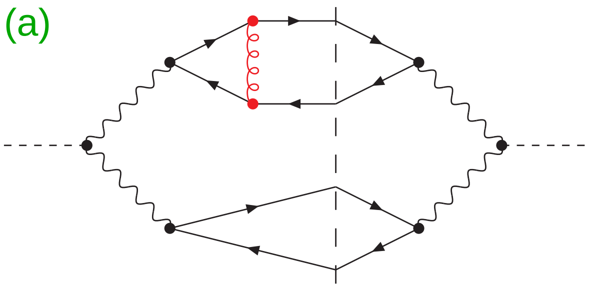
diagrams (2) only for

$q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels

(q' = weak-isospin partner of q)

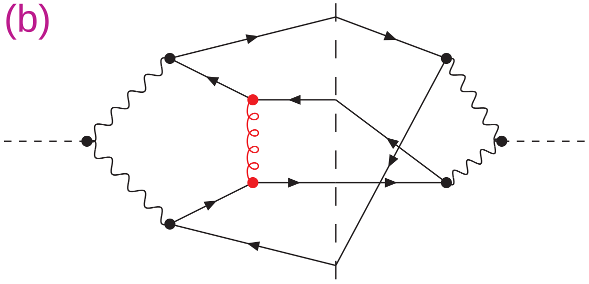
Classification of QCD corrections into four categories: (typical diagrams shown)

(a)

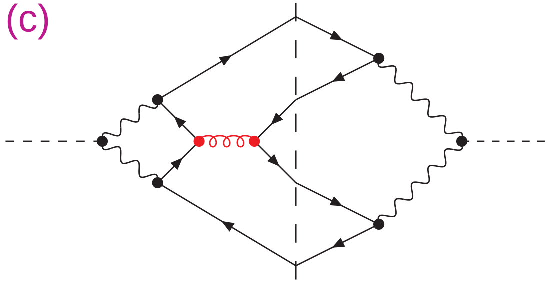


(a) contains previously known "t-channel approximation"

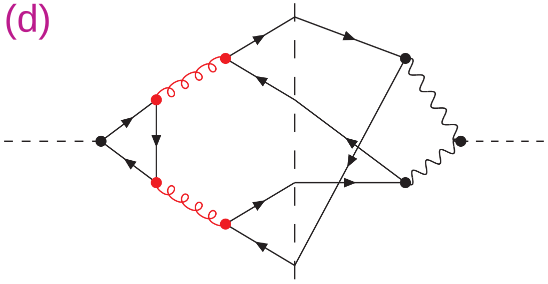
(b)



(c)



(d)



(b,c,d) = corrections to interferences (only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels)

Technical details of the calculation:

$\hookrightarrow$ two independent calculations of each ingredient !

Virtual corrections:

- algebraic part:
  - ◇ version 1:
    - diagram generation with FeynArts 1 Böhm, Denner, Eck, Küblbeck '90,'92
    - algebraic reduction by in-house Mathematica routines
  - ◇ version 2:
    - diagram generation with FeynArts 3 Hahn '01
    - algebraic reduction based on FormCalc Hahn, Perez-Victoria '99; Hahn '00
- tensor and scalar loop integrals:
  two independent in-house libraries supporting complex masses in loops
- leading 2-loop heavy-Higgs effects $\propto G_\mu^2 M_{\mathrm{H}}^4$ Ghinculov '95
  Frink, Kniehl, Kreimer, Riesselmann '96

Real corrections:

- compact matrix elements via helicity spinor formalism
- multi-channel Monte Carlo integration Berends, Kleiss, Pittau '94; Kleiss, Pittau '94
- singularities isolated via two-cutoff slicing or dipole subtraction
  Catani, Seymour '96; S.D. '00; S.D., Kabelschacht, Kasprzik '08

Main complications in the loop calculation:

- numerical instabilities in Passarino–Veltman reduction of tensor integrals
  $\hookrightarrow$ new reduction methods developed Denner, S.D. '02,'05
- gauge-invariant treatment of W and Z resonances (appearing in s-channels)
  $\hookrightarrow$ "complex-mass scheme" Denner, S.D., Roth, Wieders '05

New concepts already used in NLO EW correction to $\mathrm{e}^+\mathrm{e}^- \to 4f$ Denner, S.D., Roth, Wieders '05
and NLO QCD+EW corrections to $\mathrm{H} \to 4f$ Bredenstein, Denner, S.D., Weber '06

Numerical evaluation of one-loop integrals

Passarino–Veltman reduction of tensor to scalar integrals

$\hookrightarrow$ inverse Gram determinants of external momenta

$\hookrightarrow$ serious numerical instabilities where $\det(\mathrm{Gram}) \to 0$
(at phase-space boundary but not only !)

Our solutions: Denner, S.D., Nucl.Phys. B734 (2006) 62 [hep-ph/0509141]

- 1- and 2-point integrals $\rightarrow$ stable direct calculation
- 3- and 4-point integrals $\rightarrow$ two hybrid methods

  (i) Passarino–Veltman $\oplus$ seminumerical method $\oplus$ analytical special cases
  related to Ferroglia et al. ’02

  (ii) Passarino–Veltman $\oplus$ expansions in small Gram and other kin. determinants
  related to R.K.Ellis, Giele, Zanderighi ’04,’05

- 5- and 6-point integrals

  $\hookrightarrow$ stable reduction to lower-point integrals without Gram determinants
  related to Binoth et al. ’05

$\Rightarrow$ Techniques ready for further applications
(dim. regularization for IR singularities possible; complex masses supported)

The complex-mass scheme at NLO

Denner, S.D., Roth, Wieders '05

Basic idea: mass^2 = location of propagator pole in complex p^2 plane

$\hookrightarrow$ consistent use of complex masses everywhere !

Application to gauge-boson resonances:

- replace $M_{\mathrm{W}}^2 \to \mu_{\mathrm{W}}^2 = M_{\mathrm{W}}^2 - \mathrm{i} M_{\mathrm{W}} \Gamma_{\mathrm{W}}$, $M_{\mathrm{Z}}^2 \to \mu_{\mathrm{Z}}^2 = M_{\mathrm{Z}}^2 - \mathrm{i} M_{\mathrm{Z}} \Gamma_{\mathrm{Z}}$

  and define (complex) weak mixing angle via $c_{\mathrm{W}}^2 = 1 - s_{\mathrm{W}}^2 = \frac{\mu_{\mathrm{W}}^2}{\mu_{\mathrm{Z}}^2}$

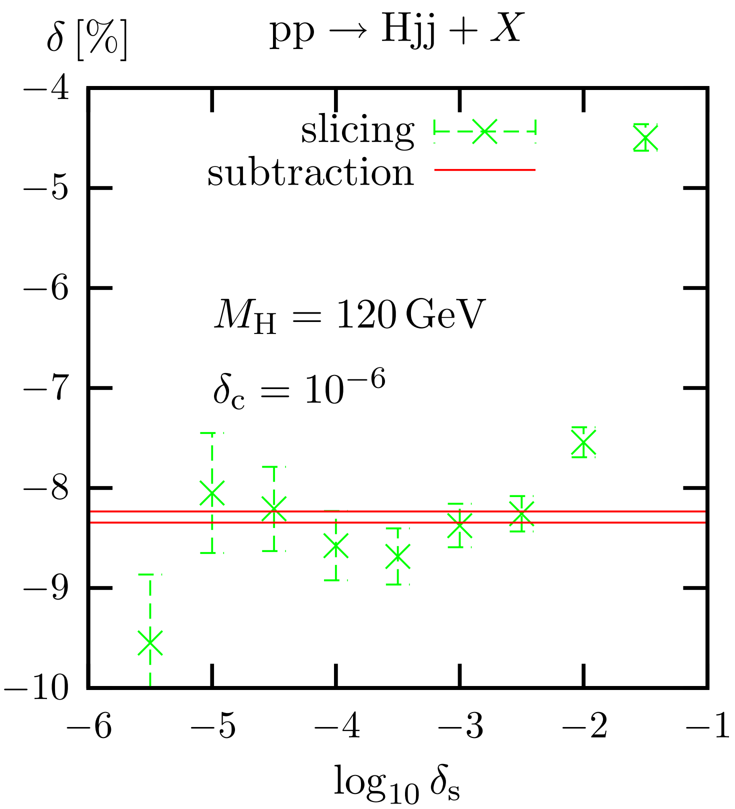
- virtues:
  - ◇ gauge-invariant result (Slavnov–Taylor identities, gauge-parameter independence)
    $\hookrightarrow$ unitarity cancellations respected !
  - ◇ perturbative calculations as usual (loops and counterterms)
  - ◇ no double counting of contributions (bare Lagrangian unchanged !)

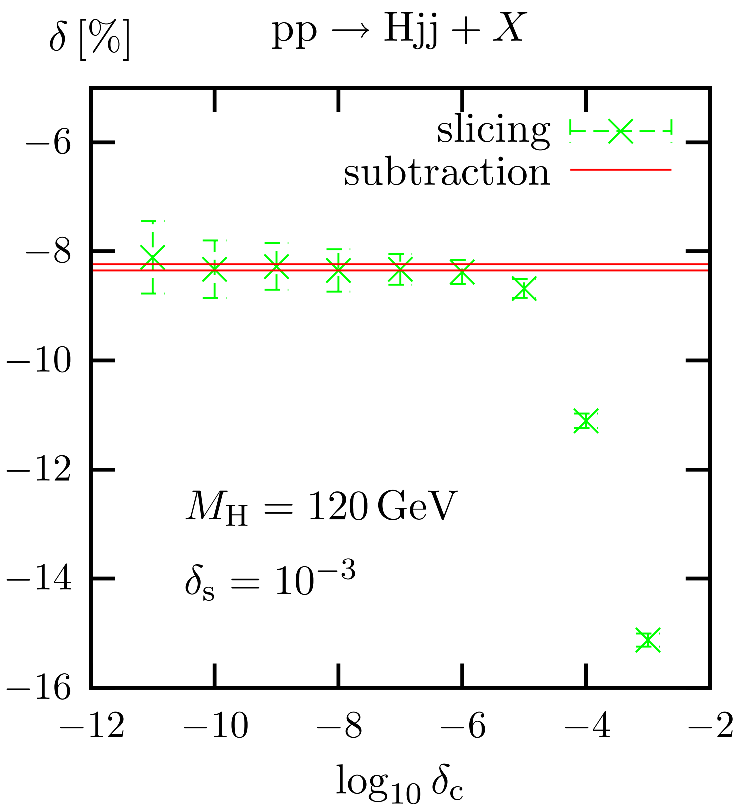
- drawbacks:
  - ◇ unitarity-violating spurious terms of $\mathcal{O}(\alpha^2)$ $\to$ but beyond NLO accuracy !
    (from t-channel/off-shell propagators and complex mixing angle)
  - ◇ complex gauge-boson masses also in loop integrals

Checks:

- UV structure of virtual corrections
  $\hookrightarrow$ independence of reference mass μ of dimensional regularization
- IR structure of virtual + soft-photonic corrections
  $\hookrightarrow$ independence of $\ln m_\gamma$ (m_γ = formally infinitesimal photon mass)
- mass singularities of virtual + related collinear photonic corrections
  $\hookrightarrow$ independence of $\ln m_{f_i}$ (m_{f_i} = small masses of external fermions)
- gauge invariance of amplitudes with $\Gamma_\mathrm{W}, \Gamma_\mathrm{Z} \neq 0$
  $\hookrightarrow$ identical results in 't Hooft–Feynman and background-field gauge
  Denner, S.D., Weiglein '94
- real corrections
  $\hookrightarrow$ squared amplitudes compared with MADGRAPH Stelzer, Long '94
- combination of virtual and real corrections
  $\hookrightarrow$ identical results with two-cutoff slicing and dipole subtraction
  Catani, Seymour '96; S.D. '00; S.D., Kabelschacht, Kasprzik '08
- two completely independent calculations of all ingredients !

Comparison of subtraction and slicing results:





Ciccolini, Denner, S.D. '07

$(\mu_{ren} = \mu_{fact} = M_H)$

- slicing cuts in partonic CM frame:
  soft region: $E_\gamma < \delta_s \frac{\sqrt{\hat{s}}}{2}$, collinear cone: $1 - \cos(\theta_{\{\gamma,g\}q}) < \delta_c$
- slicing: 10^9 events, subtraction: 10^8 events
  $\hookrightarrow$ subtraction is much more efficient!

3 Numerical results

Definition of observables

- Jet definition: k_T algorithm as used at Tevatron run II — Blazey et al. '00

  $\hookrightarrow$ clusters partons with $|\eta| < 5$ into jets with $D = 0.8$ (photons included!)

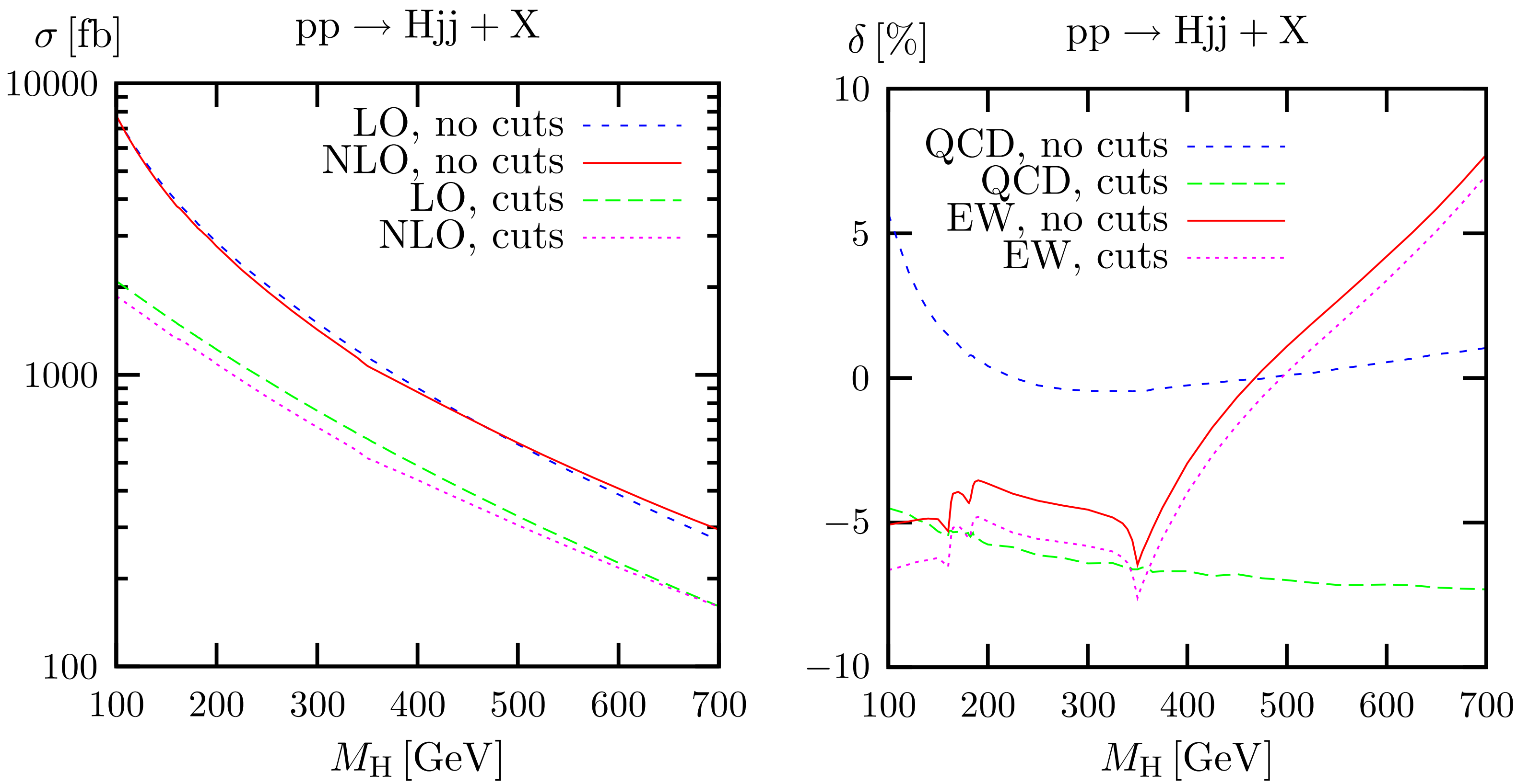
- VBF cuts:
  - ◇ 2 hard "tagging" jets demanded: $p_{\mathrm{Tj}_1} > p_{\mathrm{Tj}_2} > 20\,\mathrm{GeV}$, $|y_{\mathrm{j}_{1,2}}| < 4.5$
  - ◇ tagging jets forward–backward directed: $\Delta y_{\mathrm{jj}} > 4$, $y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0$
  - ◇ no cuts on Higgs momentum (should be adjusted to specific decays)

NLO settings:

- central scales: $\mu_\mathrm{ren} = \mu_\mathrm{fact} = M_\mathrm{W}$
- PDFs: MRST2004QED which includes QED corrections and γ PDF
- $\alpha_\mathrm{s}(\mu_\mathrm{ren})$ with 5 active flavours (top-quark decoupled)
- α defined in G_μ scheme: $\alpha_{G_\mu} = \sqrt{2} G_\mu M_\mathrm{W}^2 (1 - M_\mathrm{W}^2/M_\mathrm{Z}^2)/\pi$

  $\hookrightarrow$ absorbs running of α from $Q = 0$ to EW scale and $\Delta\rho$ in $Wq\bar{q}'$ coupling

3.1 Results on integrated cross sections



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- QCD and EW corrections are of same generic size
- scale uncertainty $\sim 3\%$ within $M_{\rm W}/2 < \mu_{\rm ren/fact} < 2M_{\rm W}$ in NLO ($\sim 10\%$ in LO)
- sensitivity to cuts: large for QCD, small for EW corrections
- heavy-Higgs corrections at $M_{\rm H} \sim 700\,{\rm GeV}$: $\underbrace{G_\mu M_{\rm H}^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_{\rm H}^2)^2}_{\text{2-loop}} \sim 4\%$
  $\hookrightarrow$ breakdown of perturbation theory

Size of specific corrections and subcontributions to cross sections:

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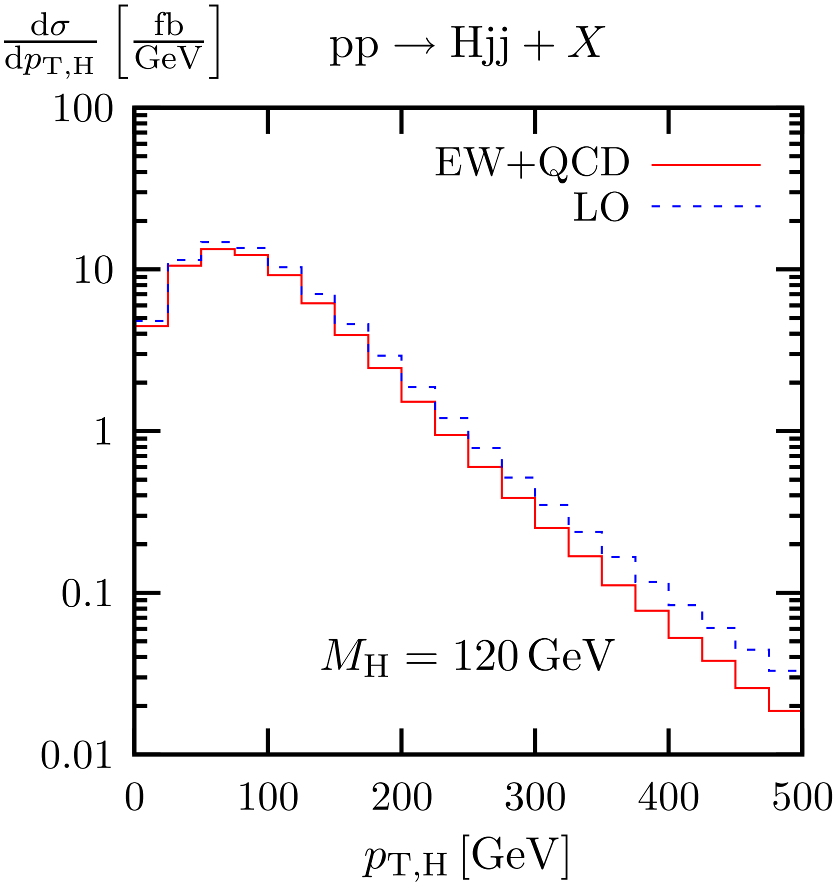
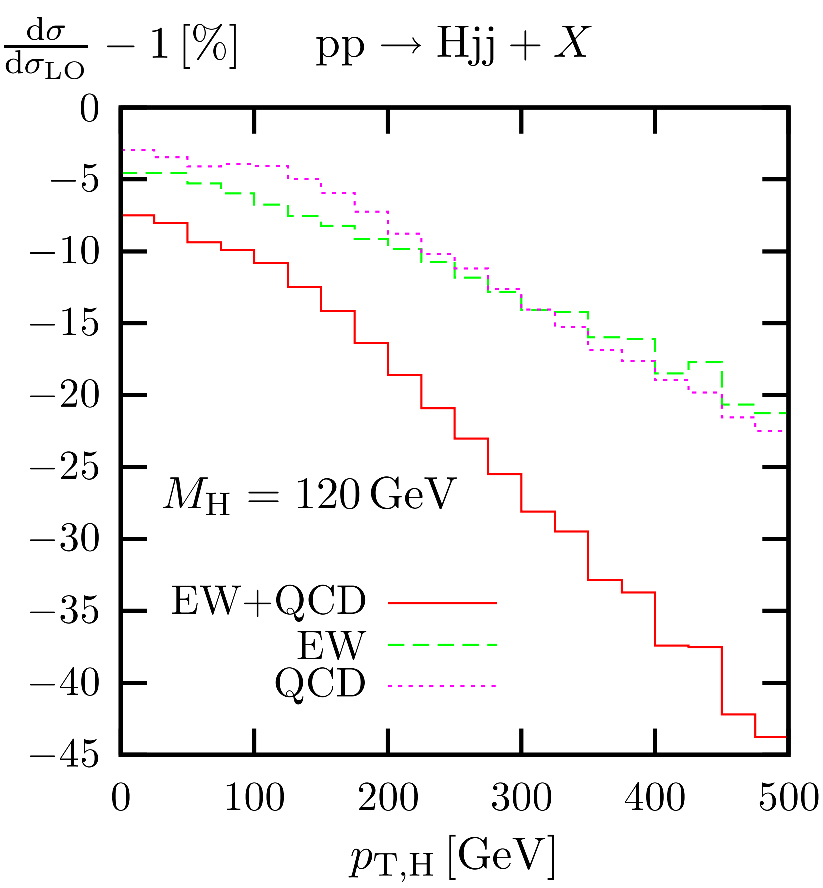
	no cuts		VBF cuts		
$M_\mathrm{H}\,[\,\mathrm{GeV}]$	$120{-}200$	700	$120{-}200$	700	
various corrections:					
$\delta_{\mathrm{QCD(a)}}\,[\%]$	$4{-}0.5$	$+1$	≈ -5	-7	$\mathcal{O}(5{-}10\%)$
$\delta_{\mathrm{QCD(b+c+d)}}\,[\%]$	$\lesssim 0.2$	-0.1	< 0.1	< 0.1	negligible
$\delta_{\mathrm{EW},qq}\,[\%]$	≈ -6	$+6$	≈ -7	$+5$	$\mathcal{O}(5{-}10\%)$
$\delta_{\mathrm{EW},q\gamma}\,[\%]$	$\approx +1$	$+2$	$\approx +1$	$+2$	
$\delta_{G_\mu^2 M_\mathrm{H}^4}\,[\%]$	< 0.1	$+4$	< 0.1	$+4$	negligible for $M_\mathrm{H} < 400\,\mathrm{GeV}$
specific contributions:					
$\Delta_{s-\mathrm{channel}}\,[\%]$	$30{-}10$	1	< 0.6	< 0.1	negligible with VBF cuts
$\Delta_{t/u-\mathrm{interference}}\,[\%]$	< 0.5	< 0.1	< 0.1	< 0.1	negligible
$\Delta_{\mathrm{b-quarks}}\,[\%]$	≈ 4	1	≈ 2	1	

3.2 Selected results on differential cross sections

Distribution in the Higgs transverse momentum $p_{\mathrm{T,H}}$

Ciccolini, Denner, S.D. '07



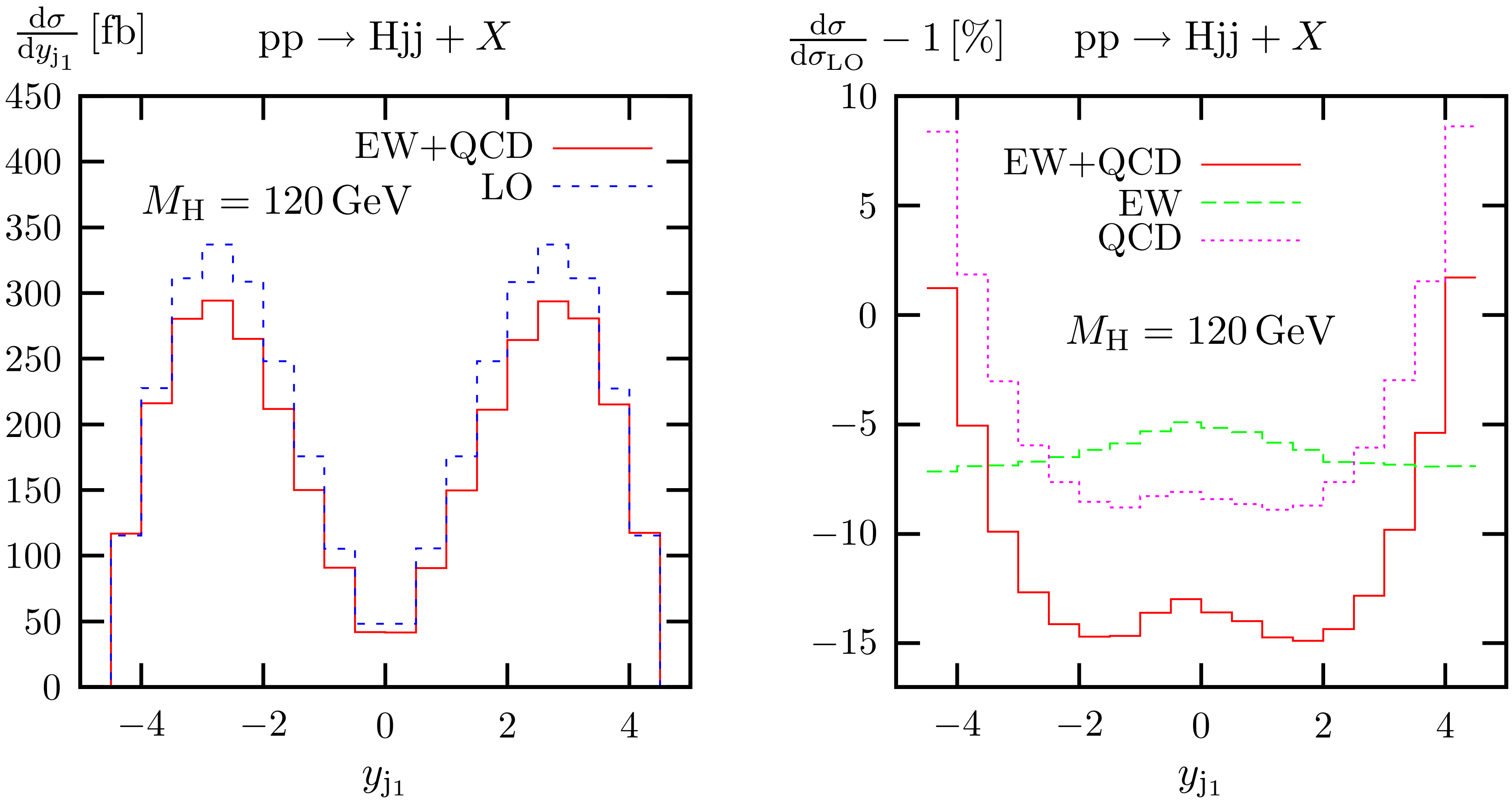


$\hookrightarrow$ QCD and EW corrections distort shapes

QCD+EW $\sim$ $20\%(40\%)$ at $p_{\mathrm{T,H}} = 200\,\mathrm{GeV}(500\,\mathrm{GeV})$

Distribution in the rapidity y_{j_1} of the leading tagging jet

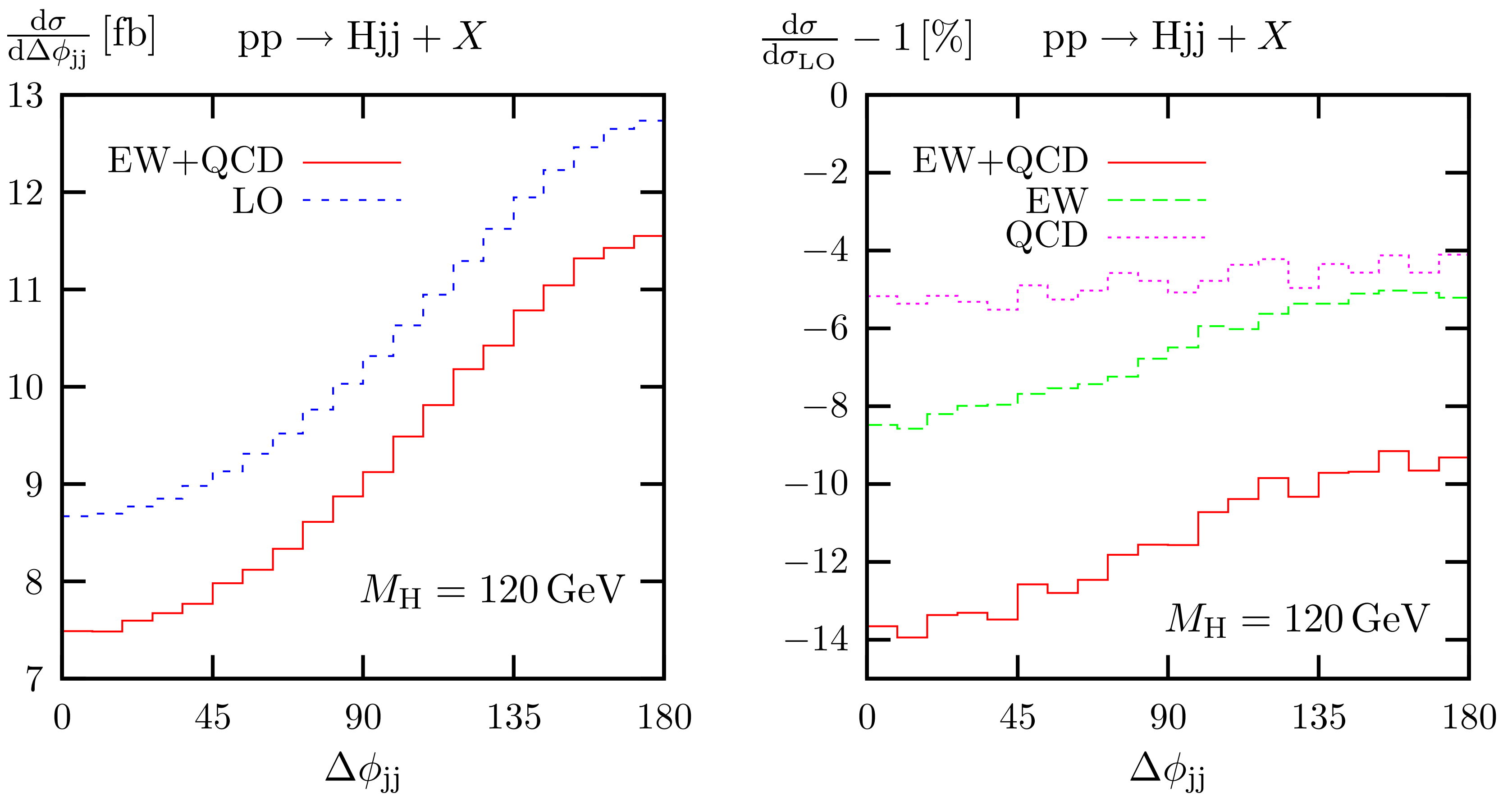
Ciccolini, Denner, S.D. '07



$\hookrightarrow$ Significant shape distortions by QCD effects, but EW effects almost uniform

Distribution in the azimuthal angle difference $\Delta\phi_{jj}$ of the tagging jets

Ciccolini, Denner, S.D. '07



↪ QCD+EW corrections induce small distortions similar to BSM effects

4 Conclusions

Higgs production via VBF is important at the LHC

- for Higgs discovery
- for Higgs coupling analyses

Recent progress in predictions:

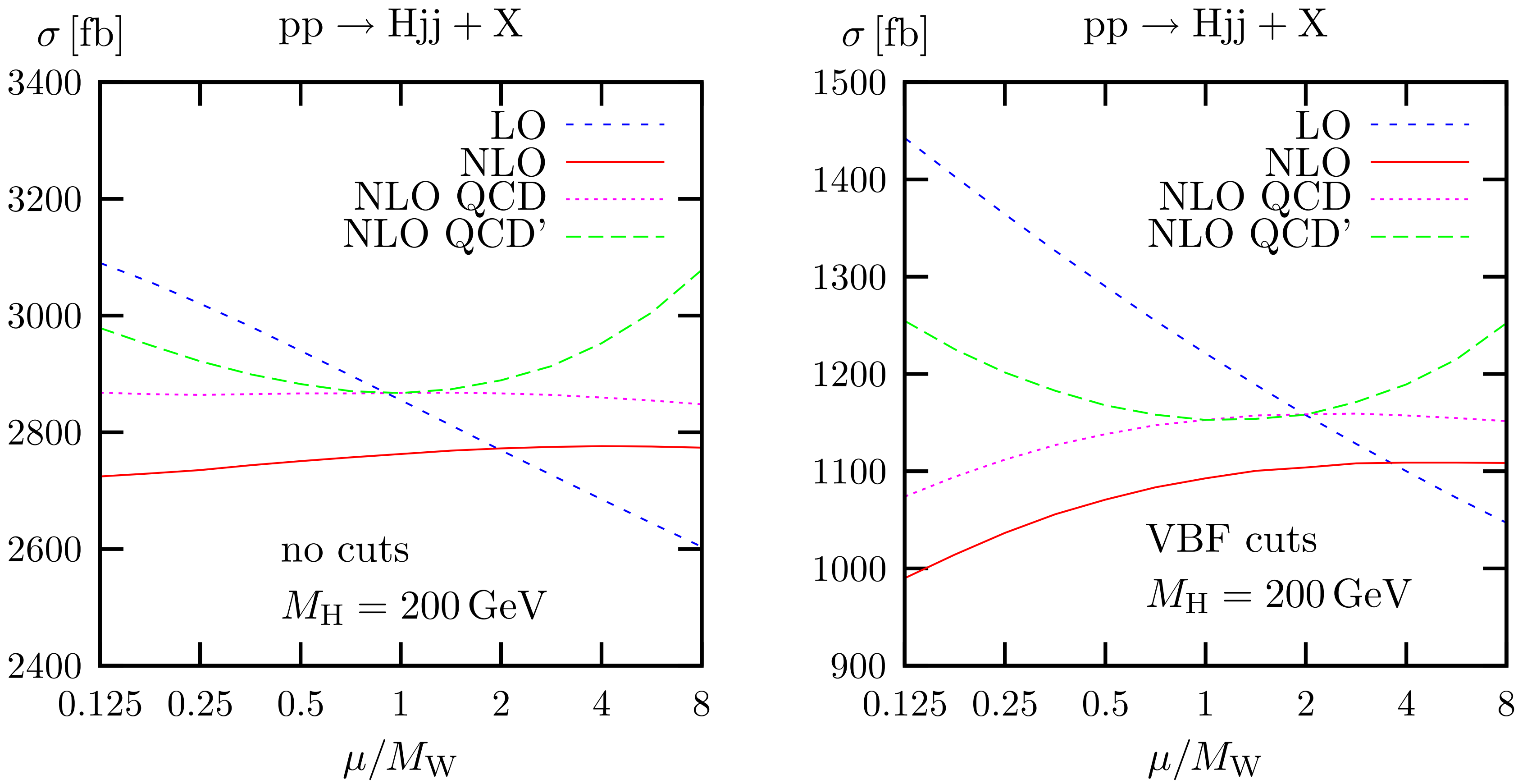
- Full NLO QCD confirms validity of old "t-channel approximation" for VBF setup
- NLO EW corrections are as important as NLO QCD effects:
  - ◇ each $= \mathcal{O}(5{-}10\%)$ for cross sections
  - ◇ larger corrections to distributions which get distorted
  - ◇ heavy-Higgs effects negligible for $M_{\mathrm{H}} < 400\,\mathrm{GeV}$, but 1-loop $\sim$ 2-loop at $M_{\mathrm{H}} \sim 700\,\mathrm{GeV}$ (breakdown of perturbation theory)
- Suppressed effects ($\lesssim 1{-}2\%$ at least in VBF setup): b-quarks in initial/final states, photon-induced processes, s-channel contributions, interferences among $s/t/u$ channels, gluon-induced strong/weak interferences

$\hookrightarrow$ Theoretical accuracy (for intermediate Higgs masses) matches uncertainties from PDFs and expected experimental errors

Extra slides

Scale dependence of LO and NLO cross sections

Ciccolini, Denner, S.D. '07

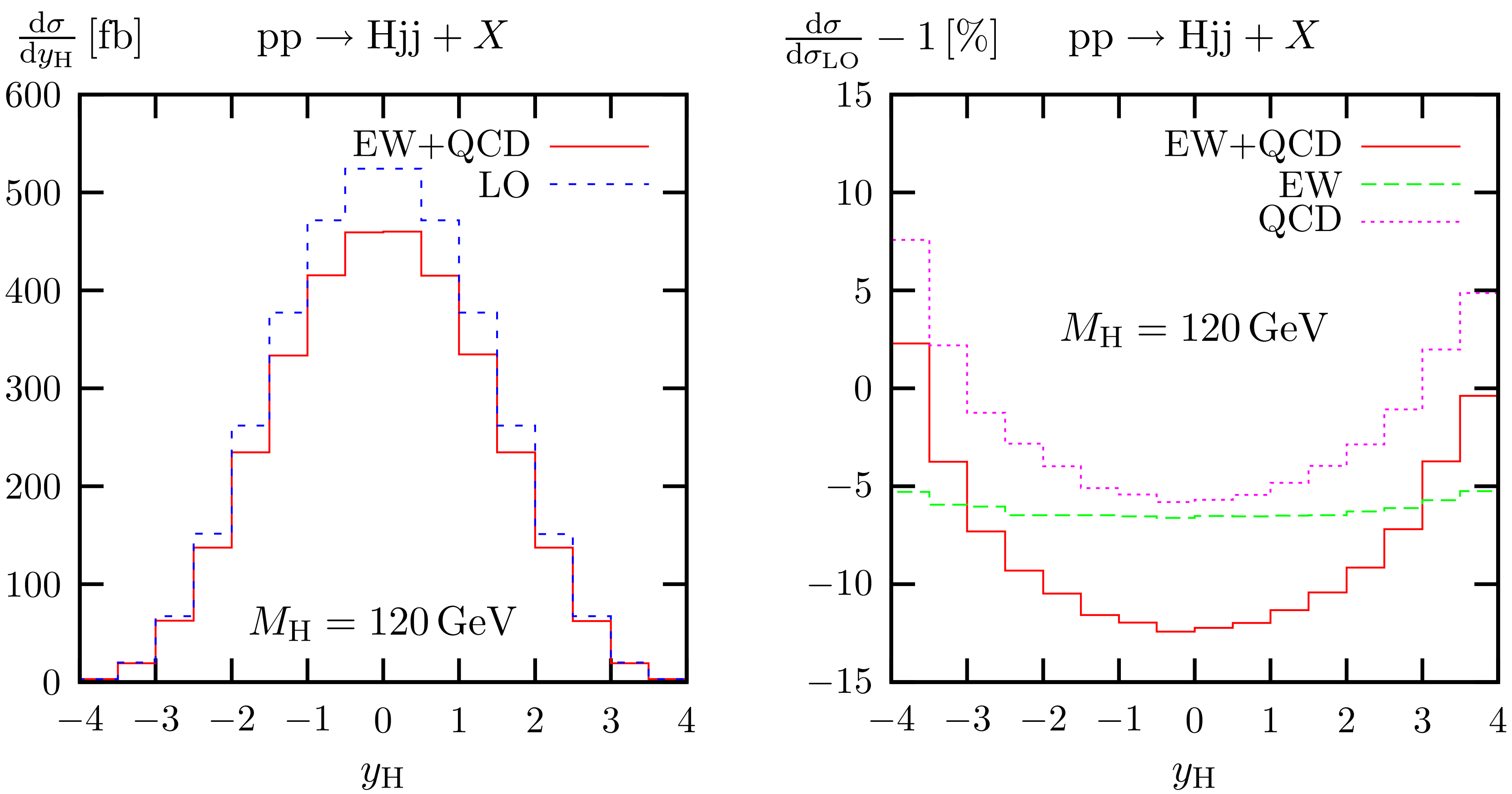


QCD: $\mu = \mu_{\rm fact} = \mu_{\rm ren}$

QCD': $\mu = \mu_{\rm fact} = M_W^2/\mu_{\rm ren}$

Higgs rapidity distribution

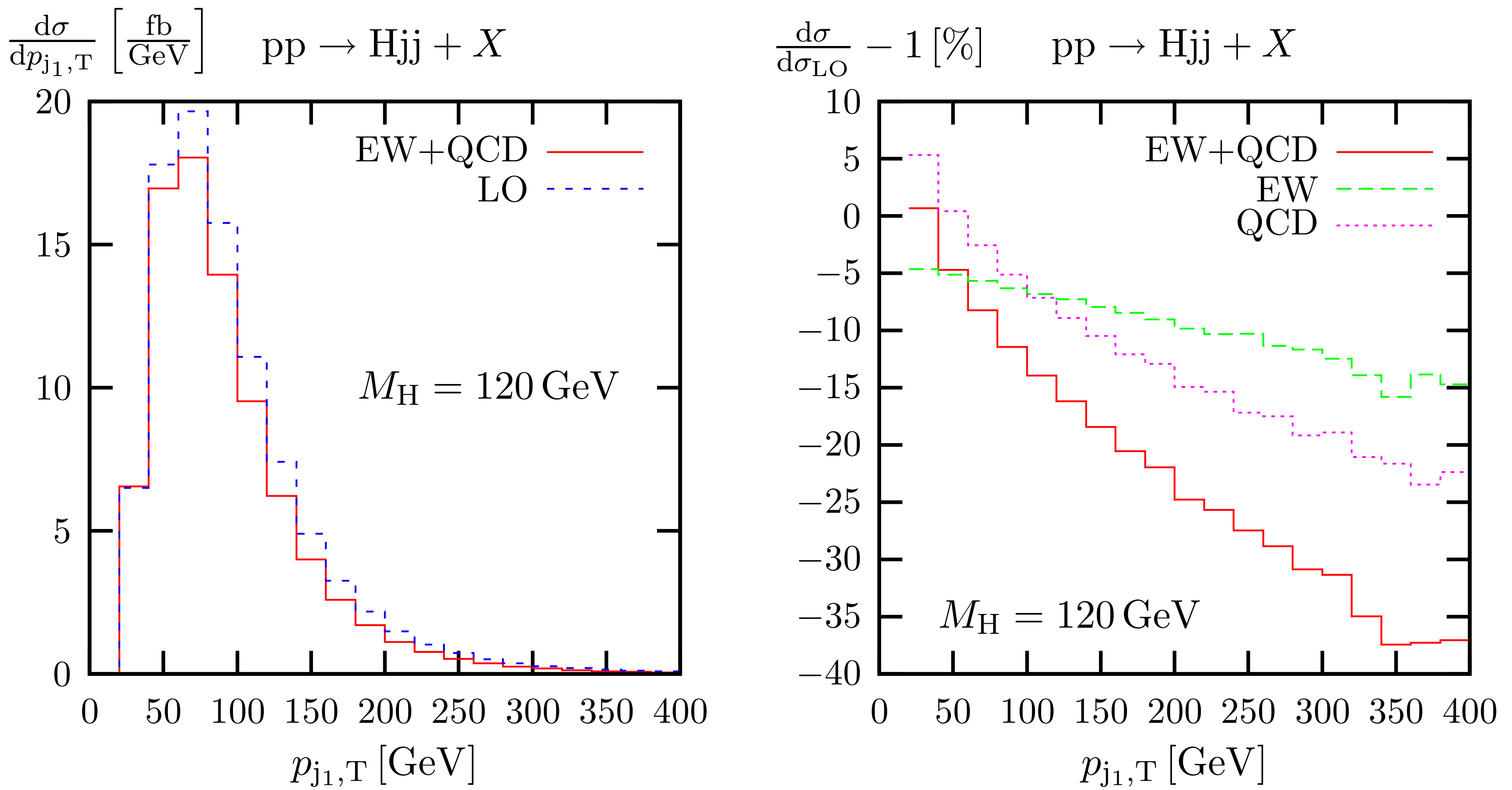
Ciccolini, Denner, S.D. ’07



$\hookrightarrow$ Significant shape distortions by QCD effects, but EW effects almost uniform

Distribution in the transverse momentum $p_{\mathrm{T}j_1}$ of the leading tagging jet

Ciccolini, Denner, S.D. ’07

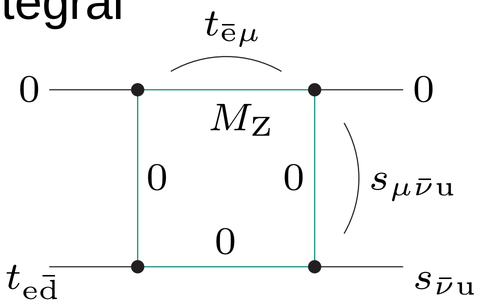


$\hookrightarrow$ QCD and EW corrections distort shapes

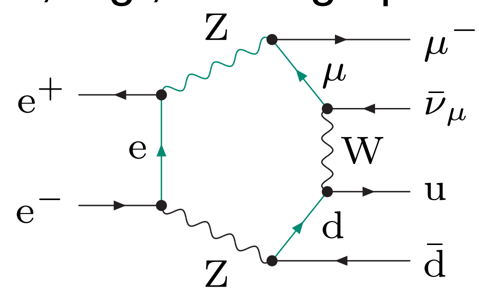
QCD+EW $\sim 25\%(40\%)$ at $p_{\mathrm{T,H}} = 200\,\mathrm{GeV}(500\,\mathrm{GeV})$

A typical example with small Gram determinant:

Box integral



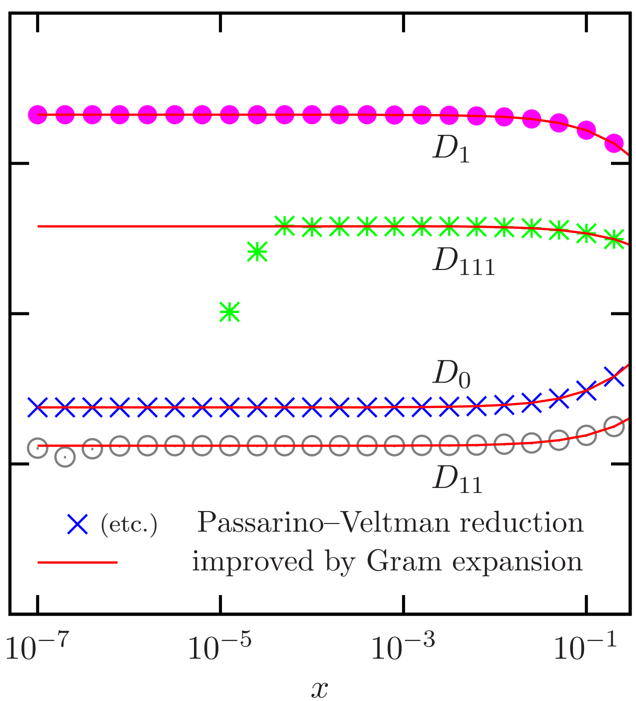
appears, e.g., in subgraph of diagram



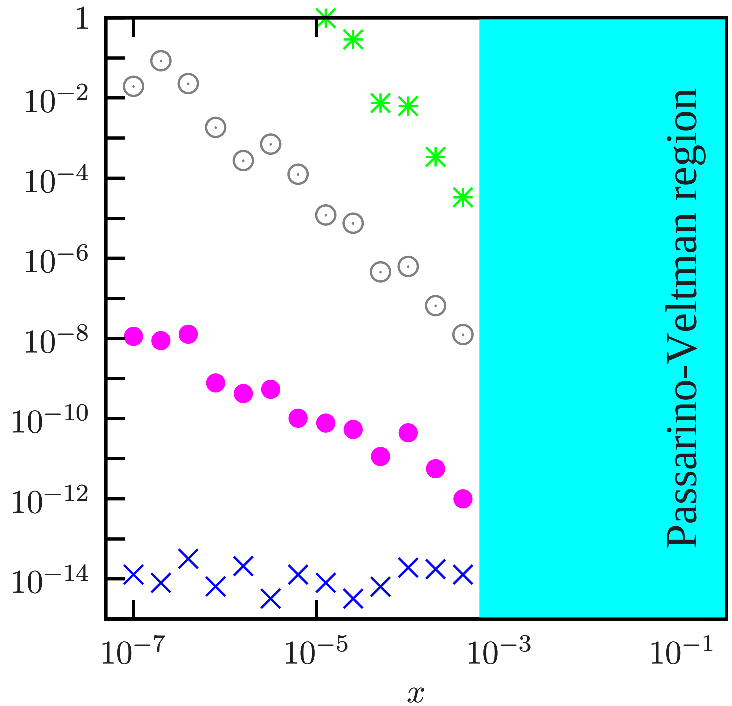
Gram det.: $\det(\text{Gram}) \to 0$ if $t_{e\bar{d}} \to t_{\text{crit}} \equiv \dfrac{s_{\mu\bar{\nu}u}(s_{\mu\bar{\nu}u} - s_{\bar{\nu}u} + t_{\bar{e}\mu})}{s_{\mu\bar{\nu}u} - s_{\bar{\nu}u}}$

Numerical comparison: maximal tensor rank $= 6$ (similar to $ee \to 4f$ application)

Absolute predictions



Relative deviations from "best"



$$x \equiv \frac{t_{e\bar{d}}}{t_{\text{crit}}} - 1$$

$$\begin{aligned} s_{\mu\bar{\nu}u} &= +2\times10^4\ \text{GeV}^2 \\ s_{\bar{\nu}u} &= +1\times10^4\ \text{GeV}^2 \\ t_{\bar{e}\mu} &= -4\times10^4\ \text{GeV}^2 \\ t_{\text{crit}} &= -6\times10^4\ \text{GeV}^2 \end{aligned}$$

PV reduction breaks down,
but Gram exp. stable
for $\det(\text{Gram}) \to 0$!

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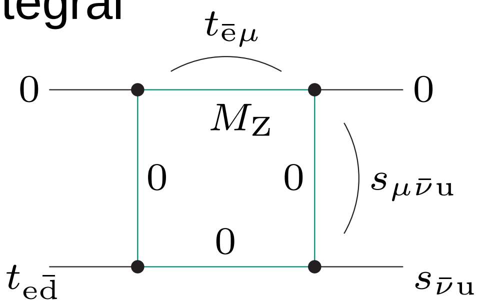

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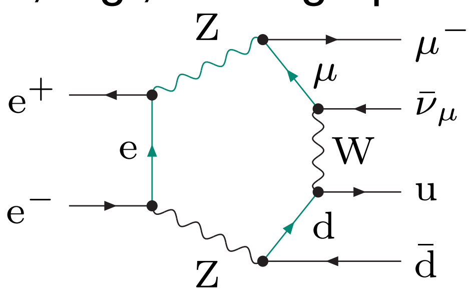

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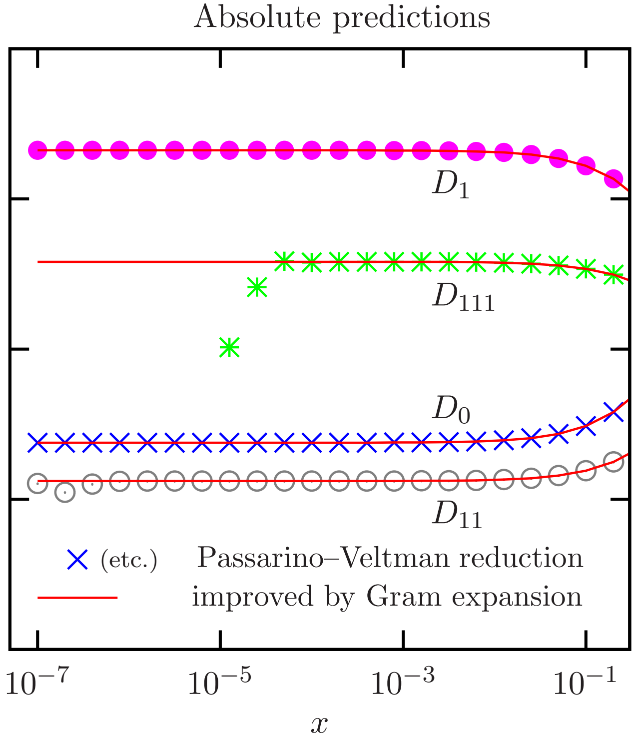
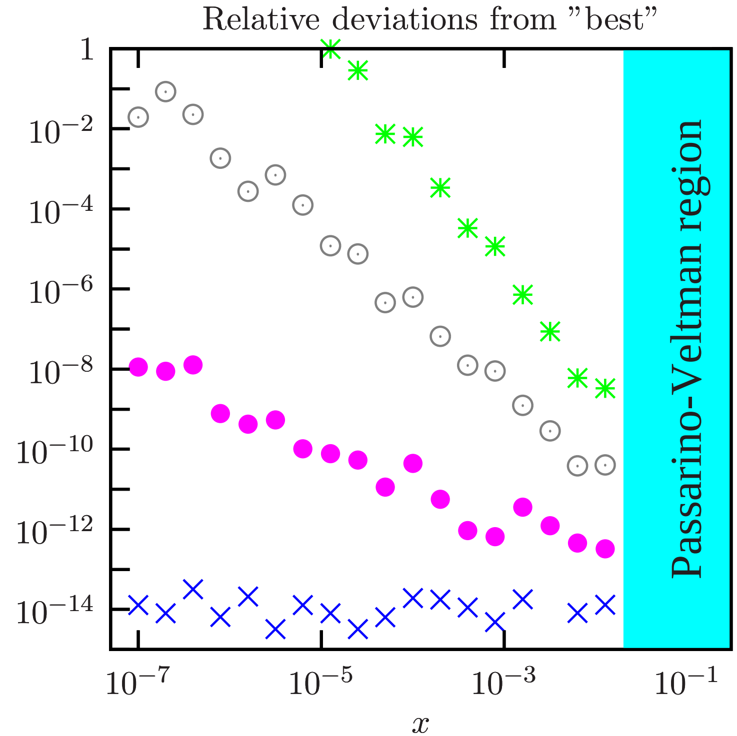
Numerical comparison: maximal tensor rank $= 12$





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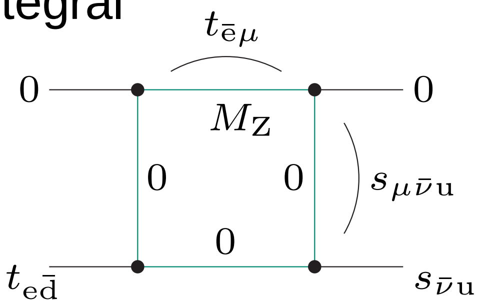

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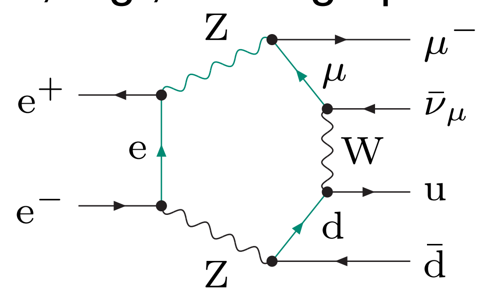

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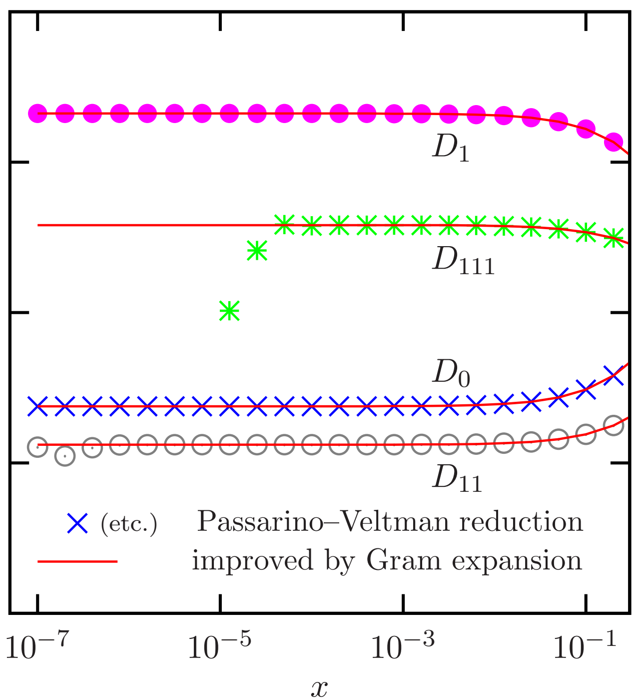
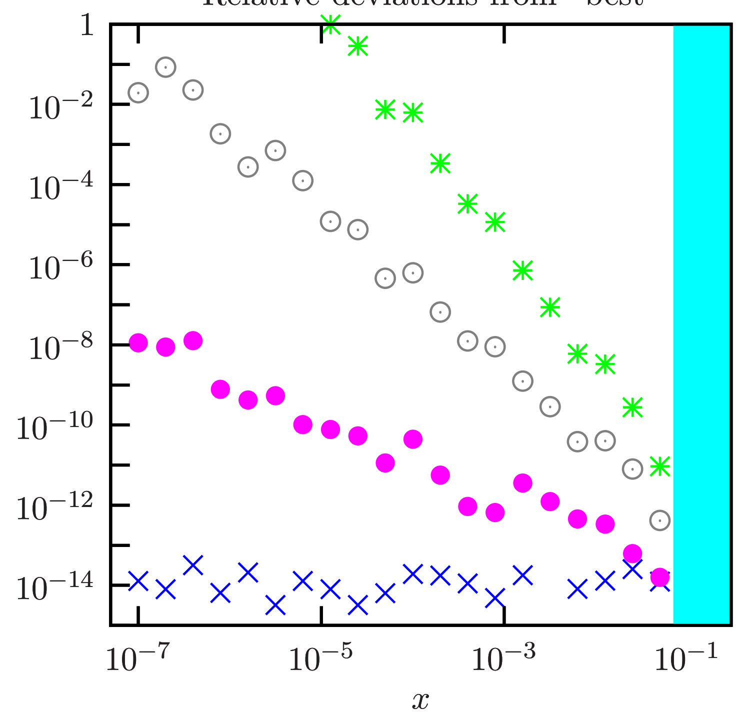
Numerical comparison: maximal tensor rank $= 25$

Absolute predictions



Relative deviations from "best"



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