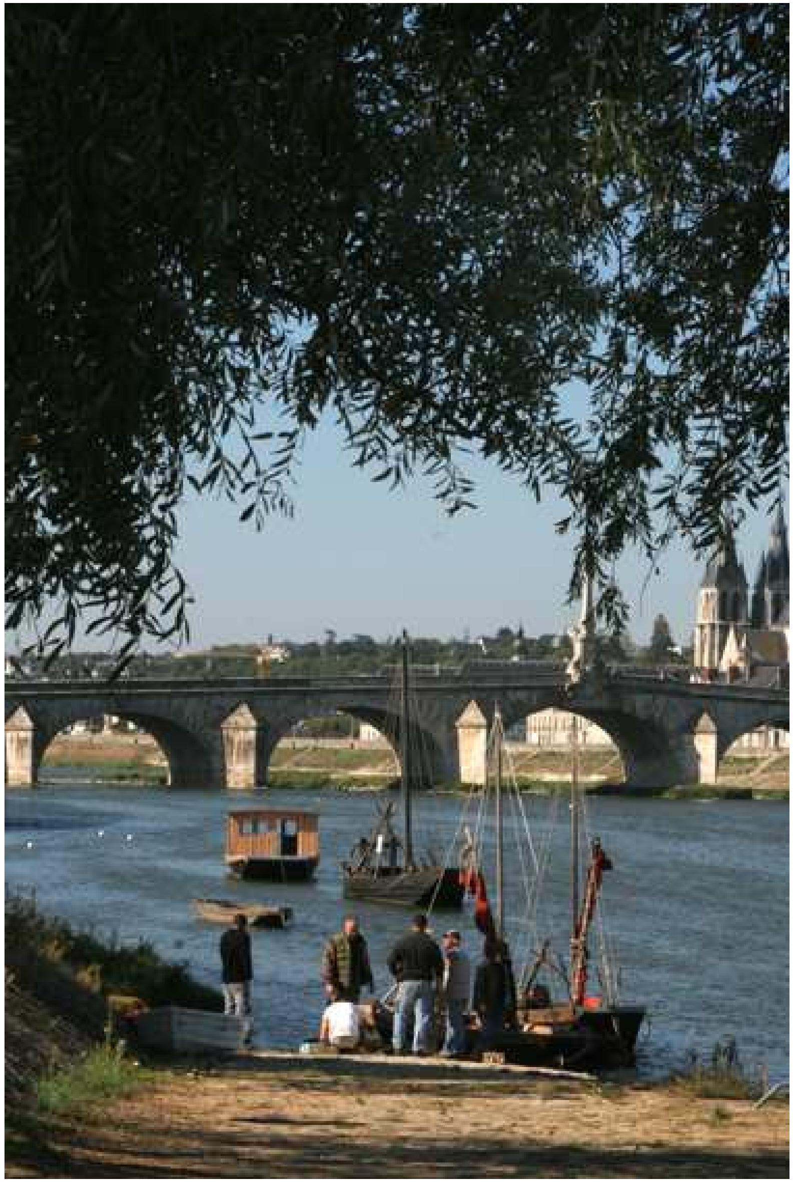


Rencontres de Blois

May 2016

# Progress in Precision Calculations


Barbara Jäger

University of Tübingen

**“precision” – definition:**

1 the quality or state of being precise : EXACTNESS

2 a: the degree of refinement with which an operation is performed or a measurement stated

b: the accuracy (as in binary or decimal places) with which a number can be represented usually expressed in terms of the number of computer words available for representation <double precision arithmetic permits the representation of an expression by two computer words>

3 RELEVANCE

[Merriam-Webster’s dictionary]

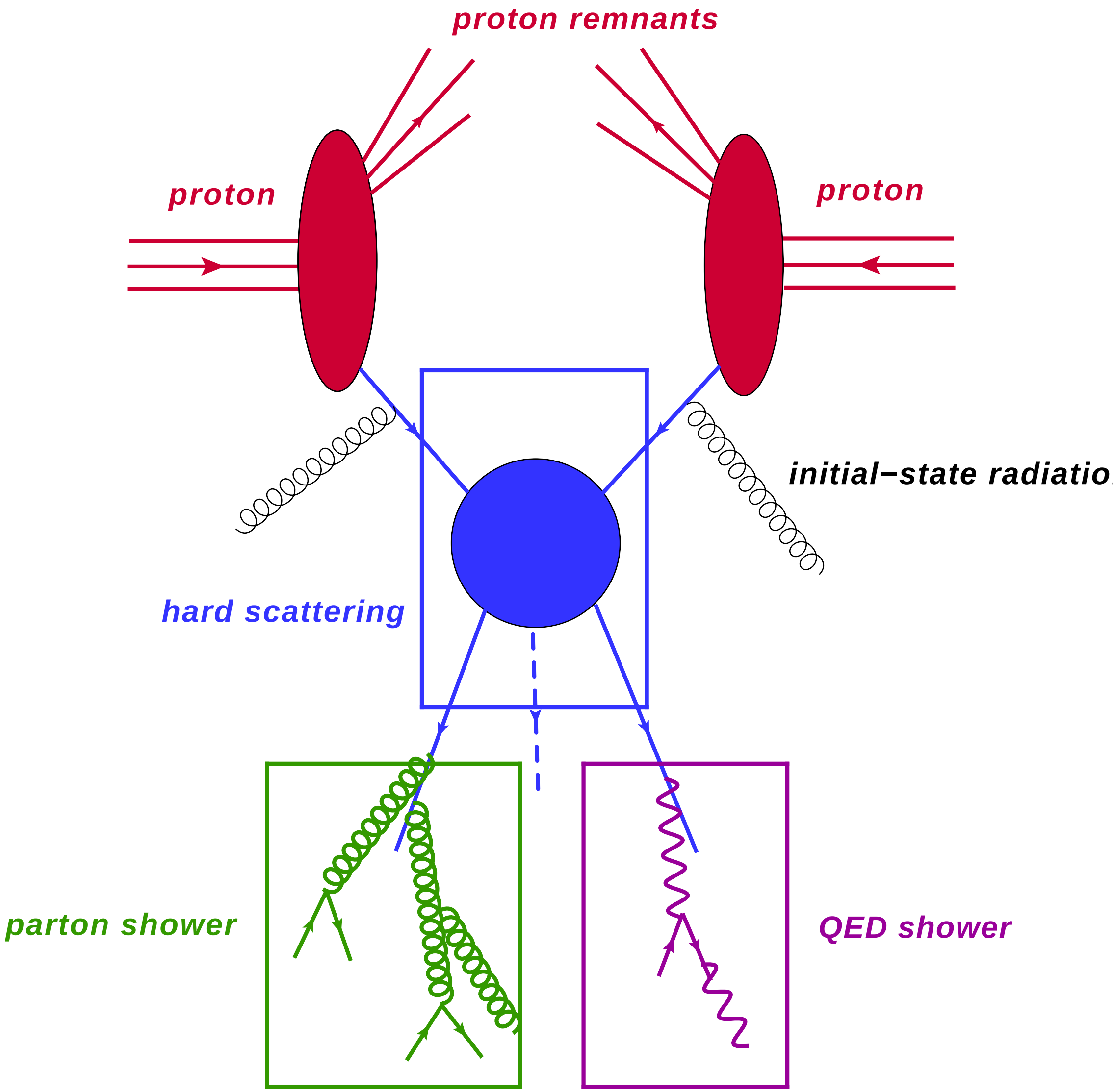
# progress in precision calculations . . . for the LHC


this talk:

focus on recent precision calculations which I consider representative for on-going progress on the theory side and relevant for the LHC physics program

☞ apologies for incompleteness

# anatomy of an LHC event




<u>today:</u>

focus on high-energy perturbative scattering process

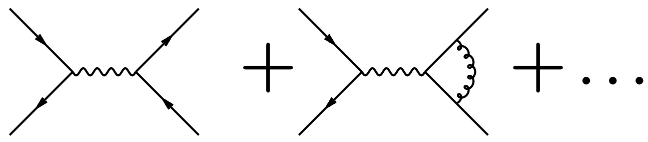
<u>not covered:</u>

- underlying event
- PDFs
- hadronization

# hard scattering: the perturbative approach

high energies: (ideally) series expansion in $\alpha_s$ (or $\alpha$)

$$\sigma = \sum_{n=n_0}^{N} \alpha_s^n \sigma^{(n)} + \mathcal{O}(\alpha_s^{N+1})$$



truncation at fixed order $\alpha_s^N$ ($\rightarrow$ LO, NLO, ...)

order $N$ provided by theoretician *("# of loops")* depends on:

- complexity of the problem
  - kinematic properties of the reaction
  - multiplicity of the final state *("# of legs")*
  - mass scales of involved particles
  - ...
- accuracy which can be achieved in experiment
- computational skills of the perturbationist

# perturbative corrections: types

- fixed order QCD corrections: LO, NLO, NNLO, ...
- QCD resummations:
  - with (conventional) analytical methods (LL, NLL, NNLL, ...)
  - with (non-conventional) analytical methods (SCET, ...)
  - via parton shower Monte Carlo tools
- NLO EW corrections:

  generically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$, but systematic enhancements by
  - Sudakov logarithms $\sim \ln^n(M_W/Q)$ at high scales $Q$
  - kinematic effects from photon radiation off leptons
- consistent combination of various types of corrections

# the leading order

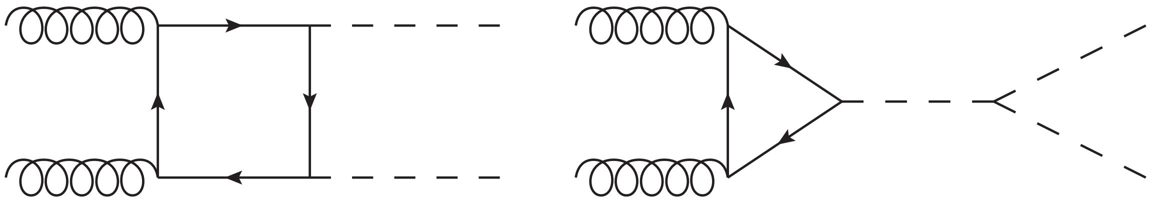
several public programs on the market for
automated generation of hard scattering matrix elements at
tree level in the Standard Model:

`Alpgen, CompHep, Helac, MadGraph, Sherpa, ...`

extra features:

- physics beyond the Standard Model
- facilities for phase-space integration
- analysis tools
- interfaces to parton-shower generators
- ...

# leading order at one loop



loop-induced processes: e.g. $gg \to HH$, $gg \to VV$, ...

loop calculators for amplitudes: `MadLoop, OpenLoops`

more details: talks by
Olivier Mattelaer and Benoit Hespel

# QCD: the next-to-leading order

development of new techniques over last 15 years:

OPP algorithm, generalized unitarity, loops from trees, recursion relations, . . .

☞ starting point of automated approaches to loop calculations

multi-purpose tools for (more or less) automated computation of NLO QCD amplitudes

`MadGraph5_aMC@NLO, OpenLoops, GoSam, ...`

dedicated tools for efficient calculation of specific processes

`HAWK, MCFM, VBFNLO, ...`

# public loop integral libraries

*Carazza, Ellis, Zanderighi (2007, 2016)*

QCDLoop

Object-oriented one-loop scalar Feynman integrals framework

DOWNLOAD LIVE DEMO

*Denner, Dittmaier, Hofer (2016)*

COLLIER

**A Complex One-Loop LIbrary with Extended Regularizations**

# frontiers of NLO QCD

exact NLO calculation of multi-leg processes possible

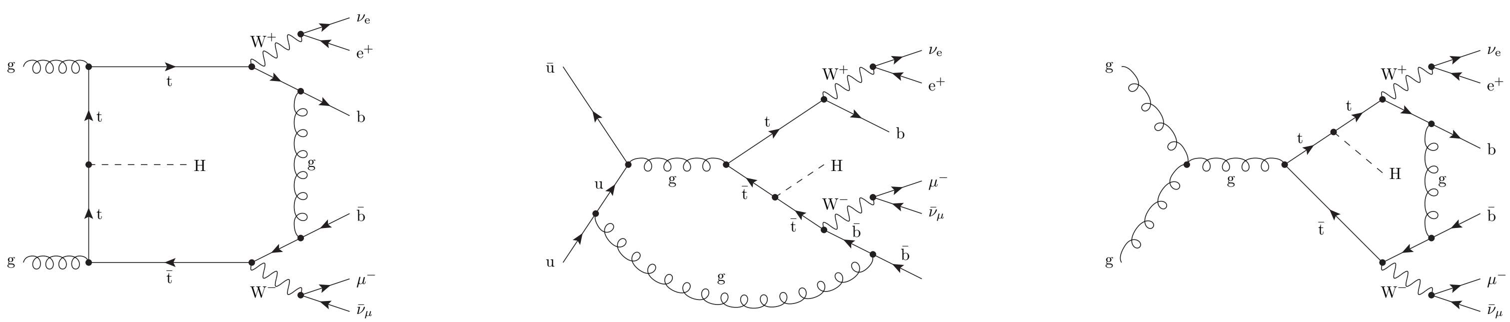
☞ accurate treatment of off-shell configurations (narrow-width approximation no longer necessary)

example: $t\bar{t}H$ (with $t \to Wb \to \ell\nu b$)

*[Beenakker et al.; Dawson et al. (2001-03)]*

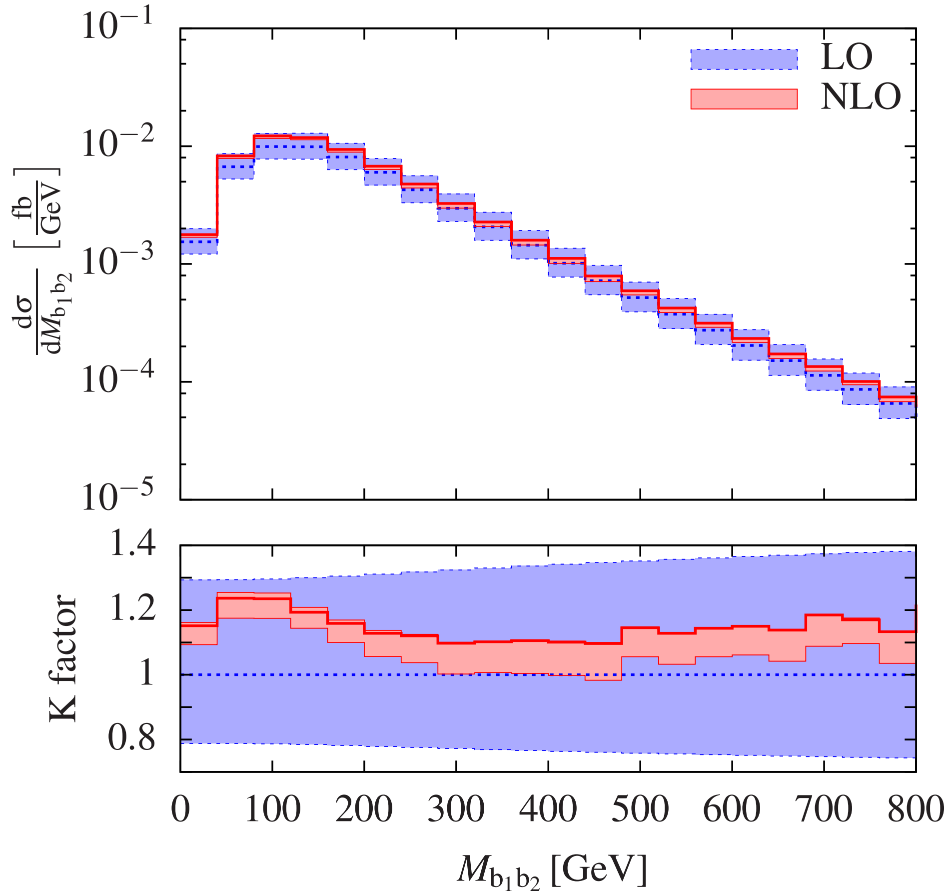
↓

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$ *[Denner, Feger (2015)]*



# $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$ at NLO QCD

*Denner, Feger (2015)*




tremendous complexity:

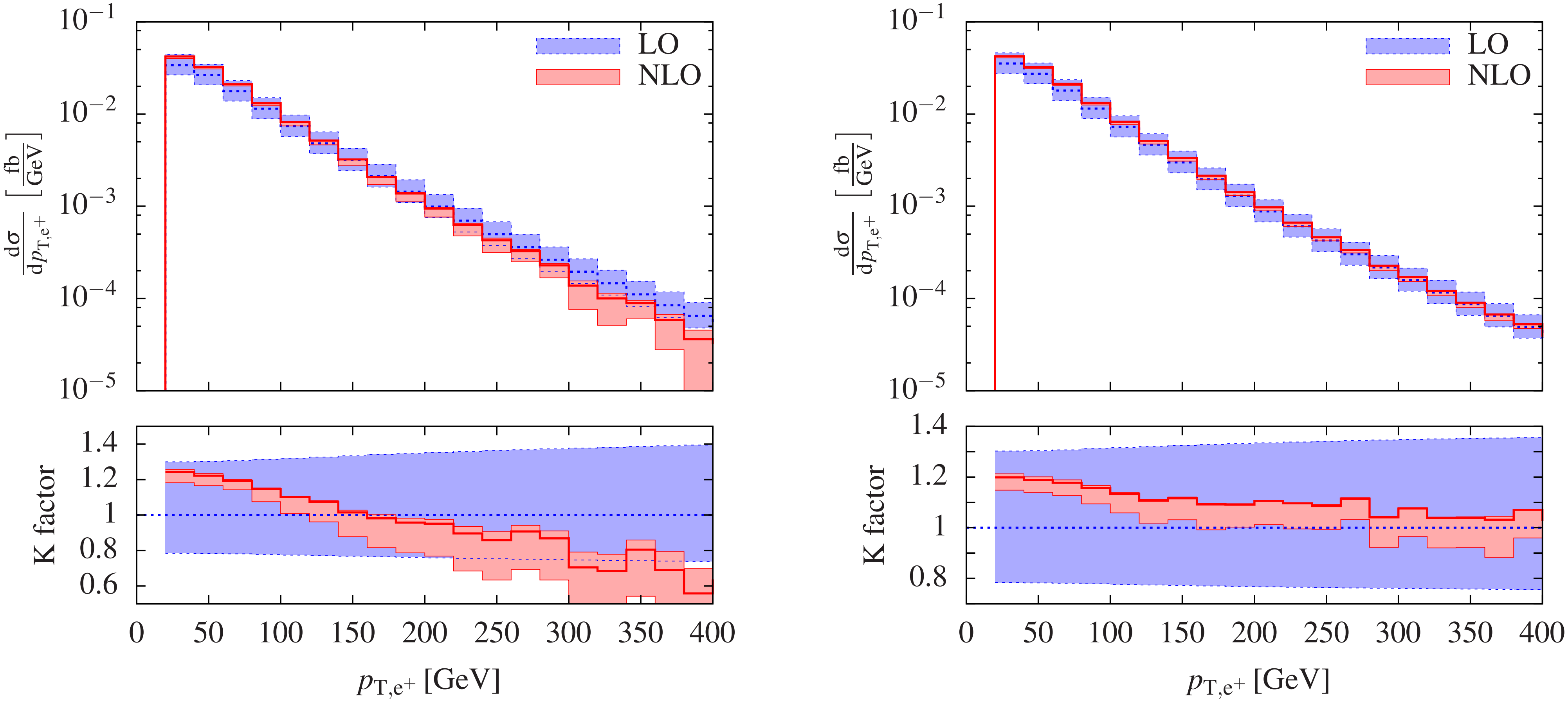
- amplitudes generated with the help of automated tool `RECOLA`
- loop integrals are evaluated with the `COLLIER` library
- bottle neck: efficient phase-space integration

gain: full control on final-state particles

(realistic cuts on leptons and $b$-jets, access to decay correlations, . . . )

# $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$ at NLO QCD

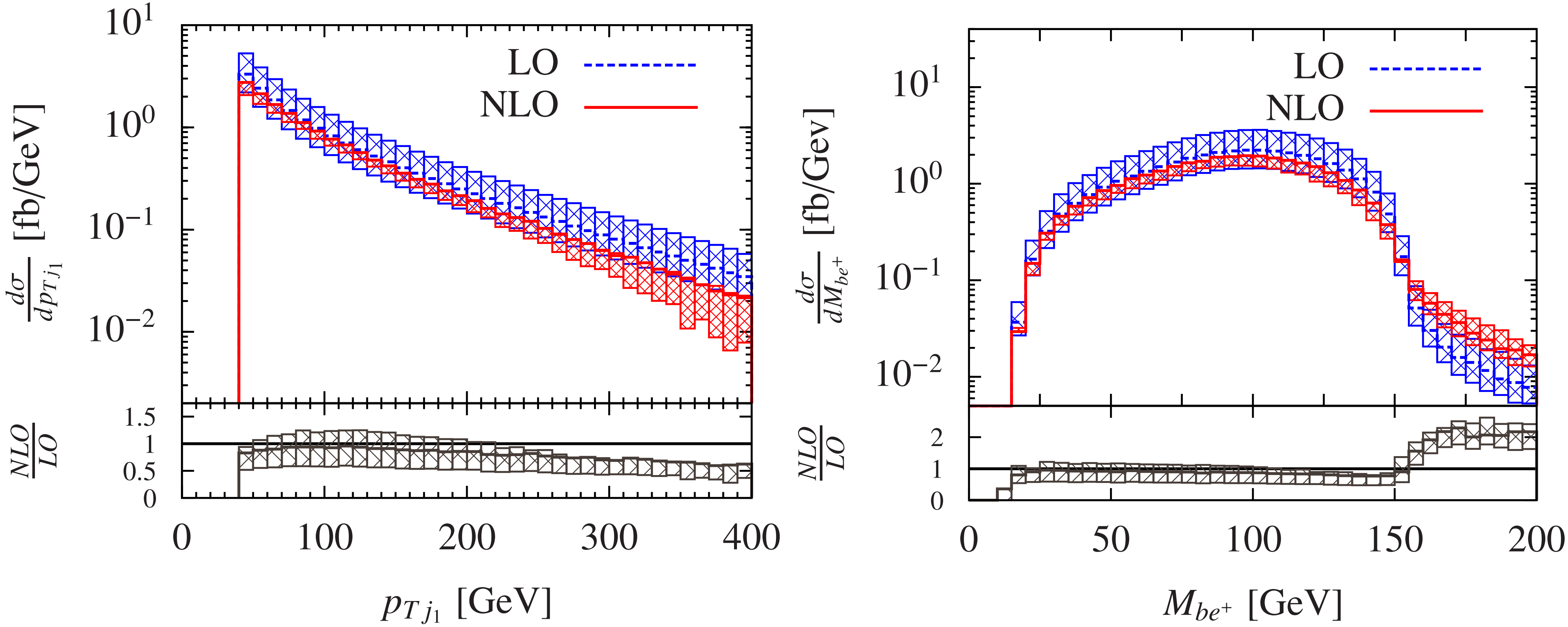
*Denner, Feger (2015)*




dynamical scale improves perturbative stability

# from $pp \to t\bar{t}j$ to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j$

*Bevilaqua et al. (2015)*




full off-shell effects for $pp \to t\bar{t}j$ using the programs `Helac-1Loop`, `OneLoop`, `CutTools`

# QCD: the next-to-next-to leading order

amazing progress in computation of total cross sections and differential distributions for benchmark processes at NNLO QCD

requiring: two-loop amplitudes for a process $X$, one-loop amplitudes for the processes $X + 1$ parton, tree-level amplitudes for the processes $X + 2$ partons

prerequisites:

- ✔ availability of 2-loop master integrals
- ✔ efficient subtraction techniques for infrared divergences

  ($q_T$ subtraction, N-jettiness, antenna subtraction, sector decomposition, projection to Born)

- ✔ powerful Monte-Carlo programs of high numerical stability

# $pp \to X$ beyond one loop

| process | motivation |
|---|---|
| dijets | PDFs, strong coupling, BSM |
| $H$ | Higgs couplings |
| $H$+jet | Higgs couplings |
| $t\bar{t}$ | top properties, PDFs, BSM |
| single top | top properties, PDFs |
| VBF | Higgs couplings |
| V+jet | PDFs |
| VH | Higgs couplings |
| VV | gauge couplings, BSM |
| HH | Higgs potential |

# NNLO QCD: new public Monte Carlo programs

brand-new: implementation of several NNLO QCD processes with color-singlet final states in the public Monte Carlo program `MCFM`

$pp \to H, Z, W, HZ, HW, \gamma\gamma$ (including decays)

performance: very CPU efficient
(1% statistical accuracy within a few hours on 8 cores)

*Boughezal et al. (05/2016)*

in preparation: fully differential NNLO process library `MATRIX`

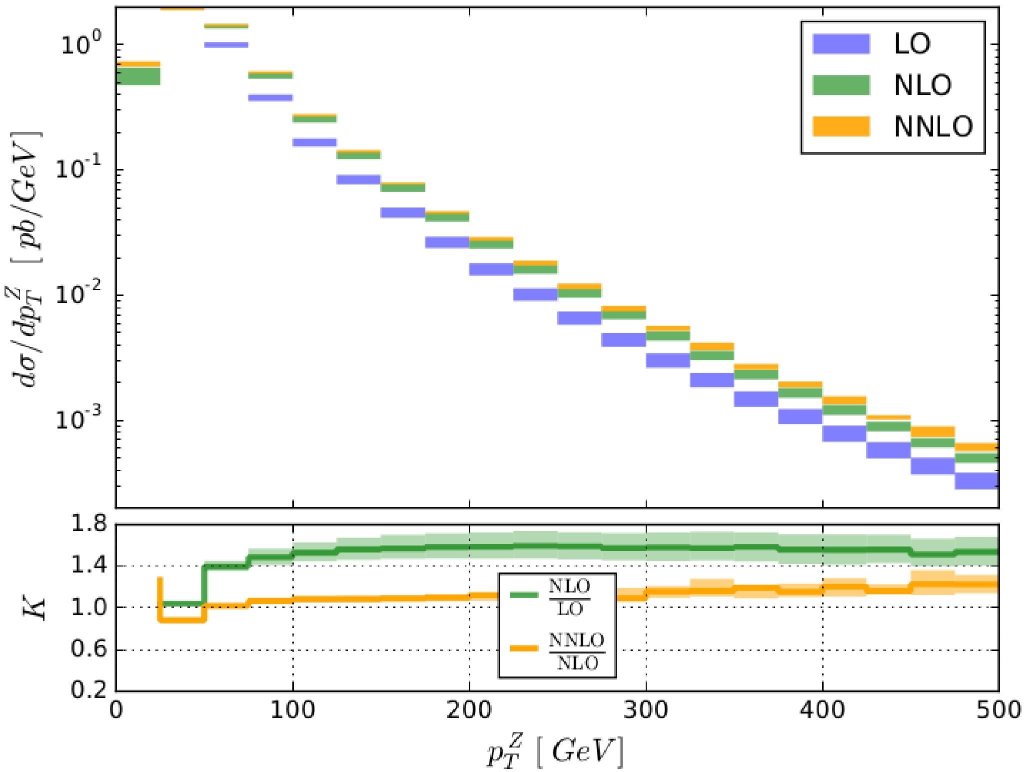
$pp \to Z, W, H, \gamma\gamma, ZZ, WW, WZ$ (partly including decays)

*Grazzini et al. (release planned for this year)*

☞ talk by Marius Wiesemann

# $pp \to Zj$ at NNLO QCD

*Boughezal et al. (2015)*




2015: two completely independent calculations

*[Gehrmann-De Ridder et al. & Boughezal et al.]*

using different techniques

(antenna vs. N-jettiness subtraction)

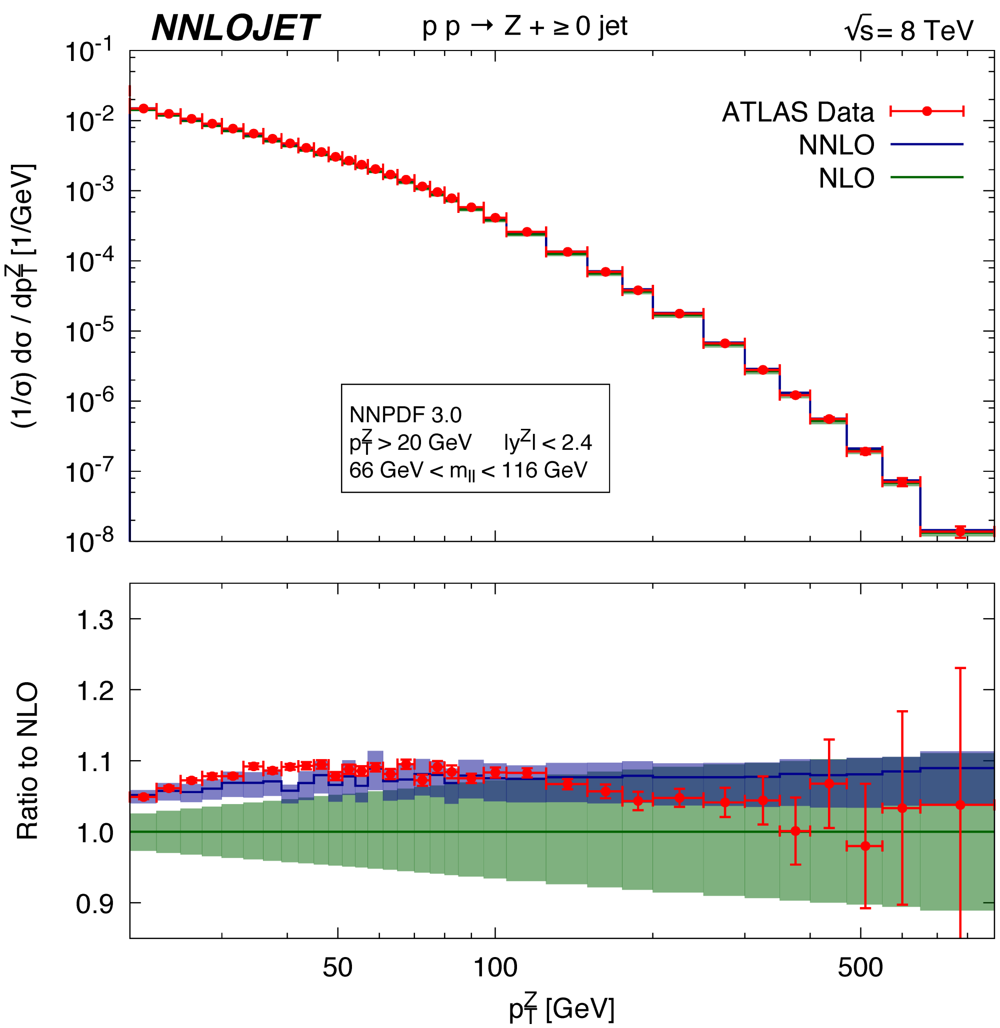
✔ scale uncertainties reduced
✔ perturbative expansion stable

NNLO QCD corrections are at percent level for inclusive xsec,

up to 10% in tails of distributions

# $pp \to \ell^+\ell^- j$ at NNLO QCD

*Gehrmann-De Ridder et al. (2016)*

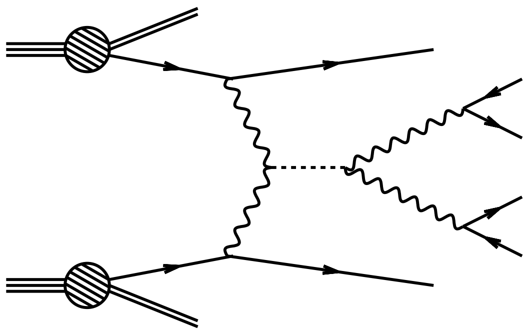



differential predictions at NNLO accuracy soften tension between theory and experiment

optimal: normalize to inclusive Drell-Yan xsec

($\to$ minimize impact of experimental uncertainties)

# Higgs production via vector boson fusion (VBF)



distinctive signature:

✔ helps for signal-to-background optimization

✔ clean environment for coupling measurements

✧ NLO corrections moderate and well known for long time

*[Han et al. (1992), Figy et al. (2003), Berger et al. (2004), Ciccolini et al. (2007)]*

✧ NNLO QCD corrections for inclusive setup:

*Bolzoni et al. (2011)*

- in full agreement with NLO results
- residual scale uncertainties are reduced from $\sim$4% to 2%
- NNLO PDF uncertainties are at the 2% level

# VBF @ NNLO: exclusive results

*Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)*

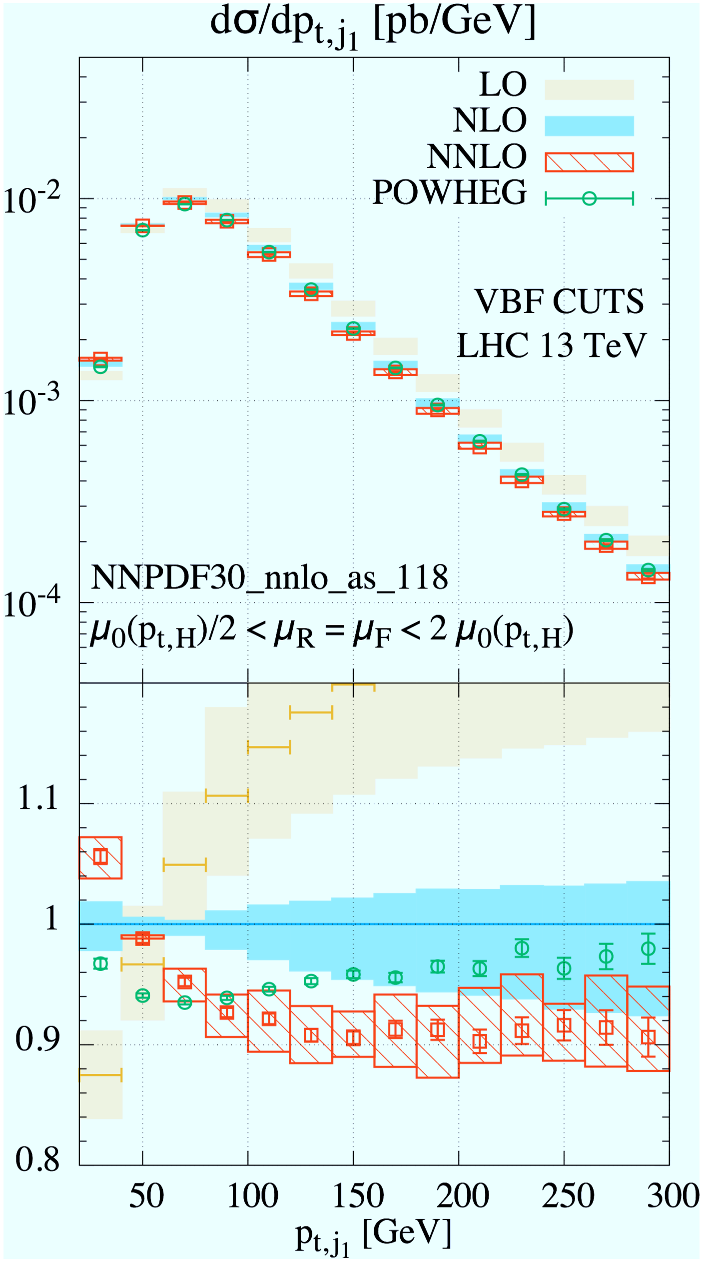
| | $\sigma^{(\text{no cuts})}$ [pb] | $\sigma^{(\text{VBF cuts})}$ [pb] |
|---|---|---|
| LO | $4.032\,^{+0.057}_{-0.069}$ | $0.957\,^{+0.066}_{-0.059}$ |
| NLO | $3.929\,^{+0.024}_{-0.023}$ | $0.876\,^{+0.008}_{-0.018}$ |
| NNLO | $3.888\,^{+0.016}_{-0.012}$ | $0.826\,^{+0.013}_{-0.014}$ |

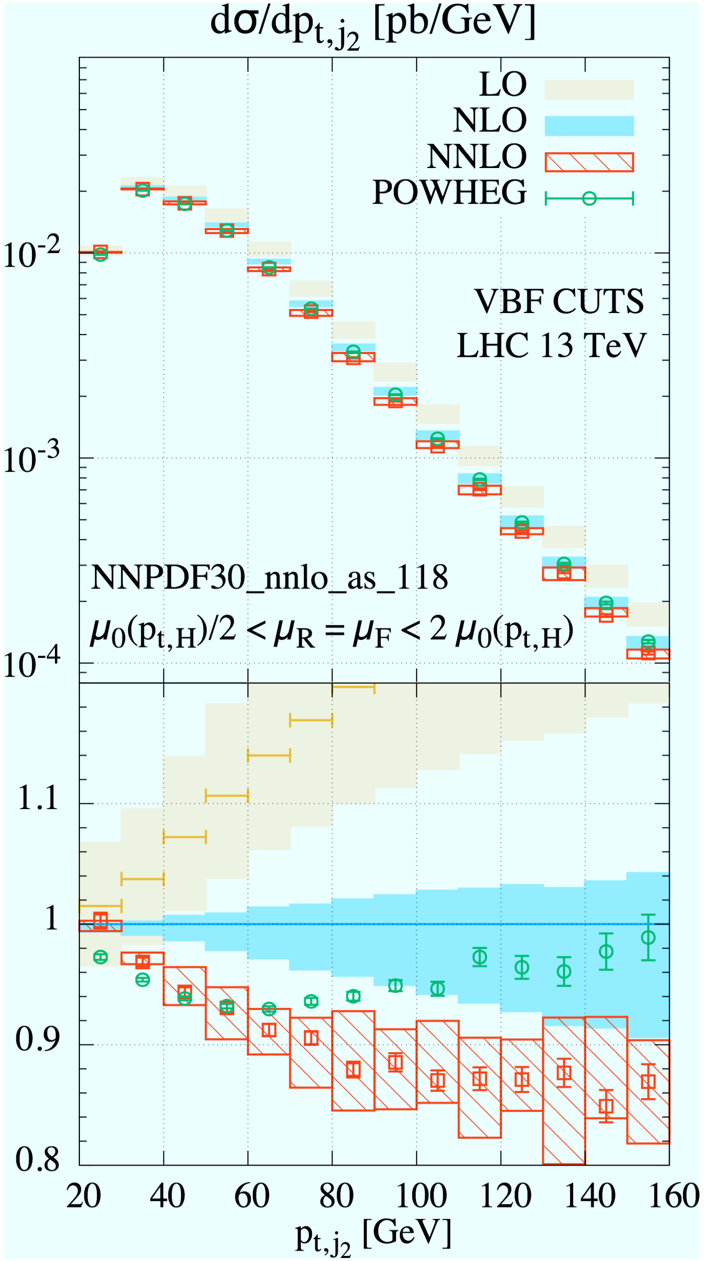
relative NNLO corrections $\sim 1\%$

relative NNLO corrections $\sim 6\%$

NNLO QCD corrections are much larger in VBF setup than for inclusive cuts

# VBF @ NNLO: exclusive results



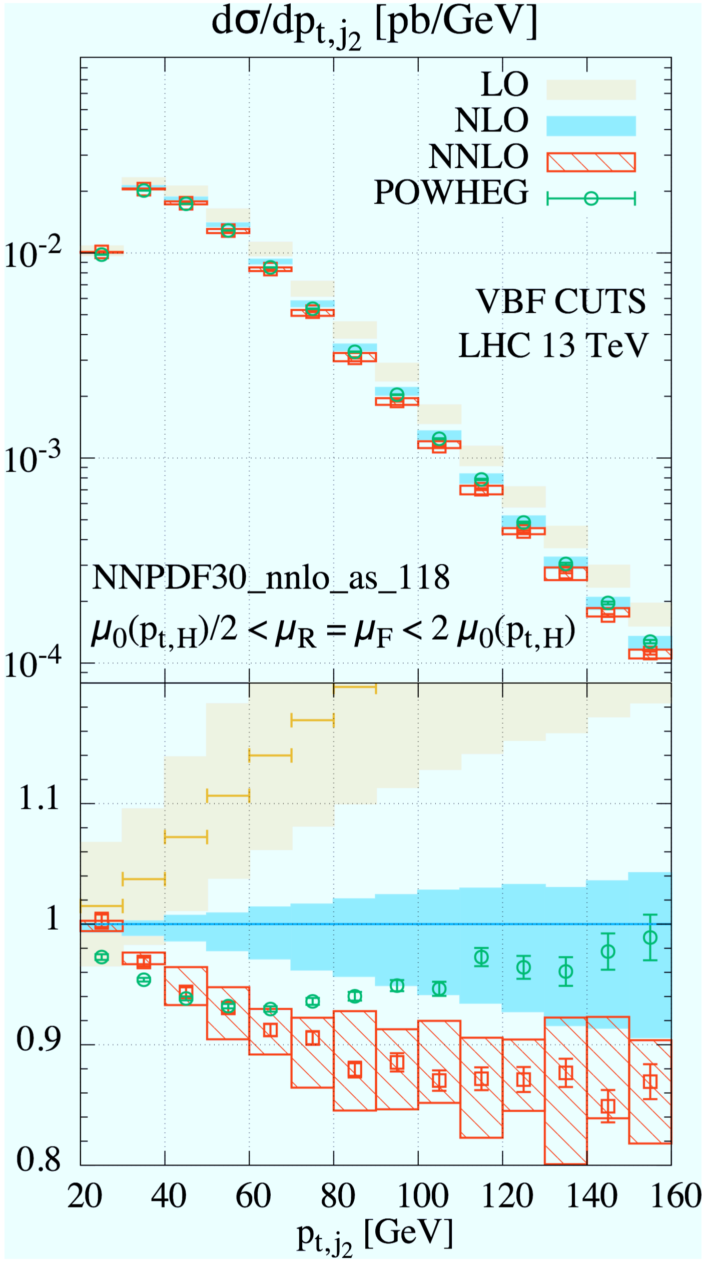




*Cacciari et al. (2015)*

# VBF @ NNLO: exclusive results

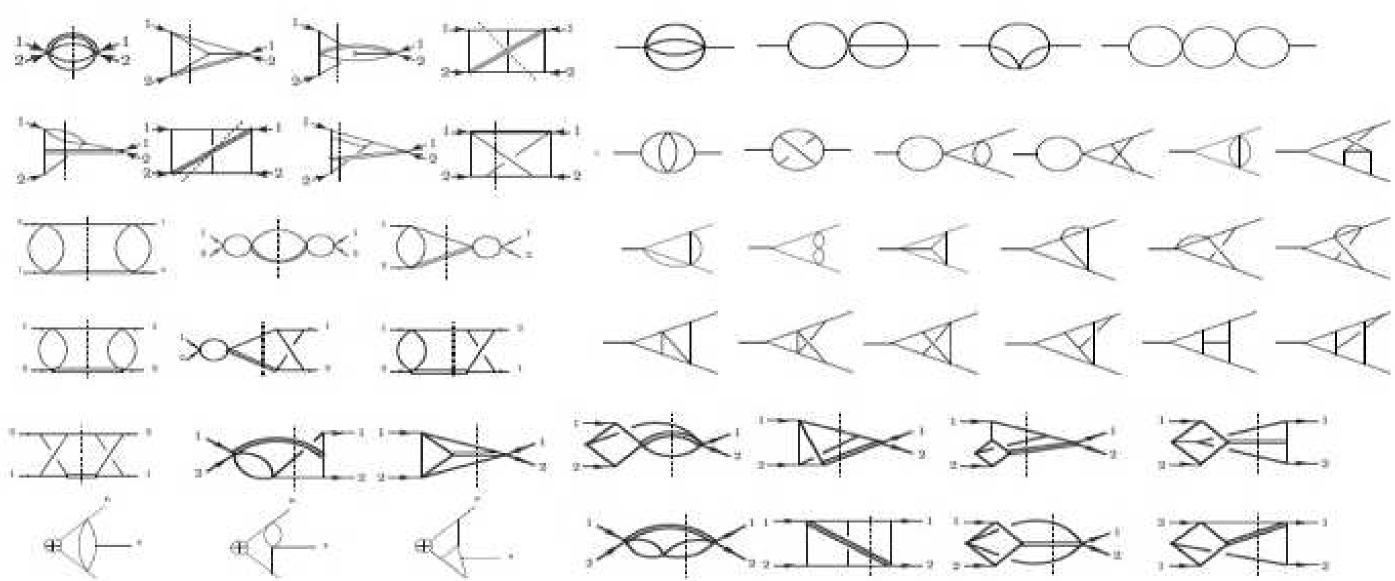
NNLO corrections
make jets softer

$\rightarrow$ fewer events pass VBF cuts




*Cacciari et al. (2015)*

# $gg \to H$ at N$^3$LO QCD



- only collider process known to such high orders in QCD
- outstanding complexity:

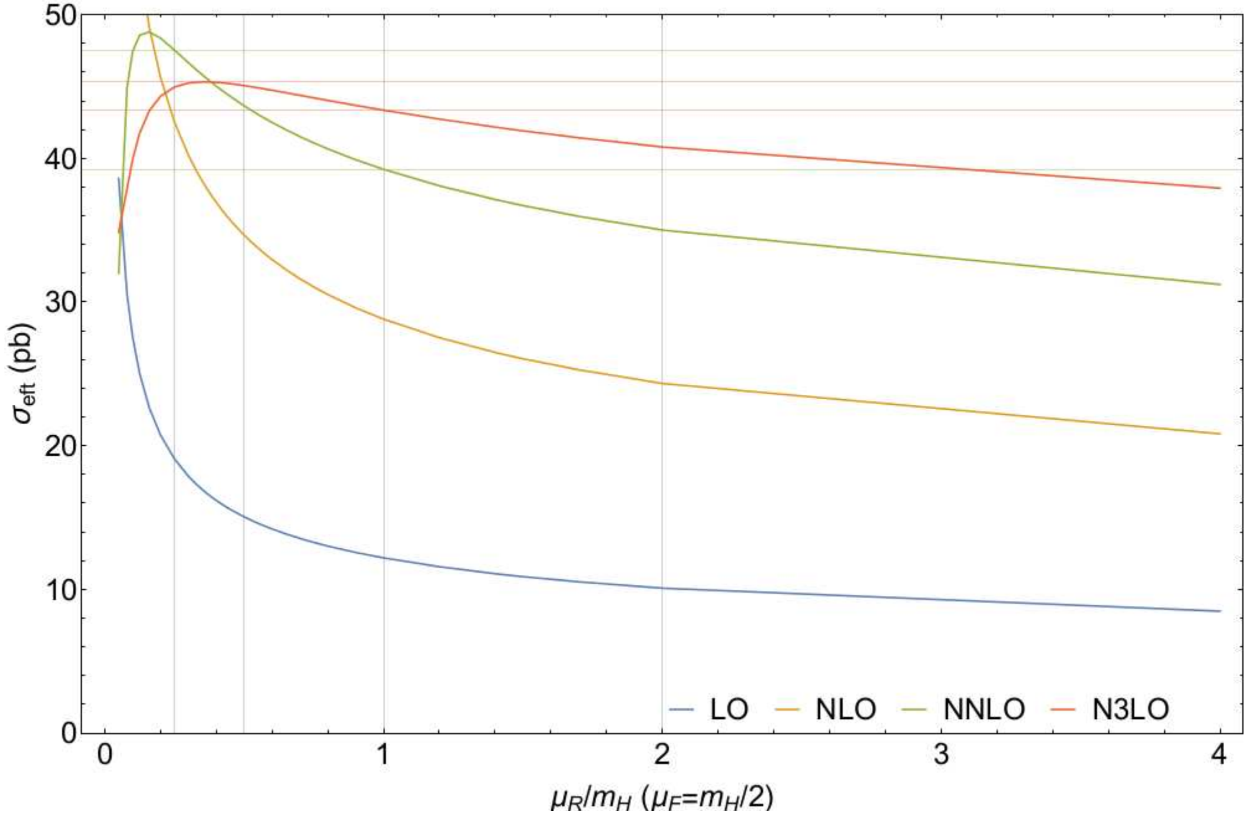
  $\mathcal{O}(10^3)$ three-loop master integrals,

  $\mathcal{O}(10^5)$ interference diagrams,

  $\mathcal{O}(10^7)$ phase-space integrals
- immediate implications on physics at the LHC

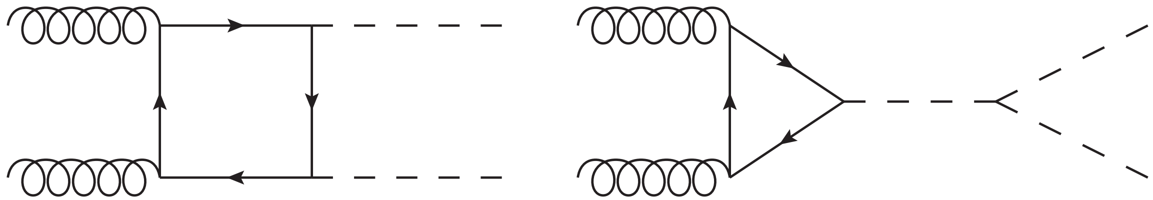
# $gg \to H$ at N$^3$LO QCD

*Anastasiou et al. (2016)*




- perturbative result stabilized
- scale dependence reduced

# Higgs boson pair production



✔ access to self-coupling of the Higgs boson

✘ loop-induced process

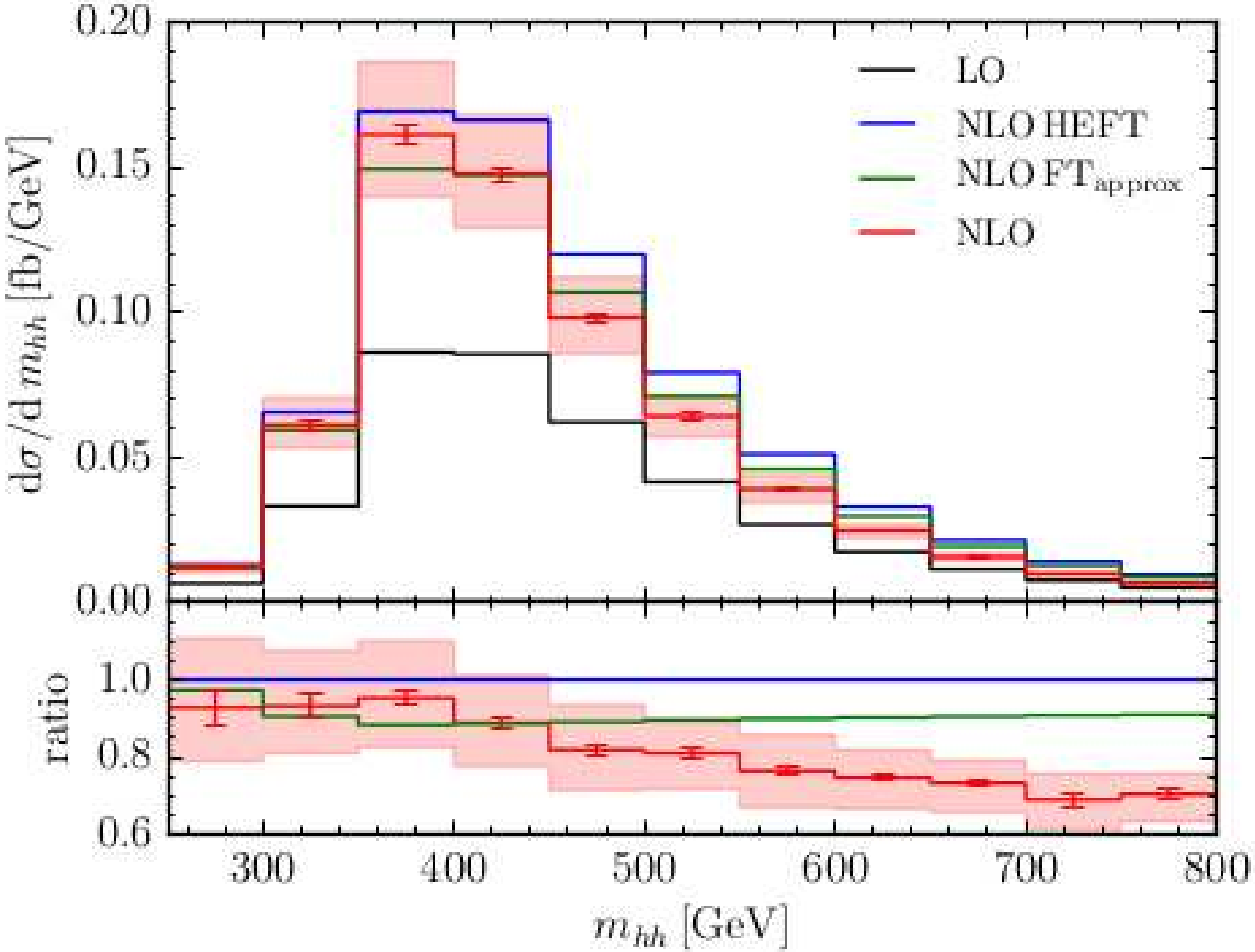
$\longrightarrow$ two-loop corrections required at NLO QCD

✘ technically challenging: previous calculations relied on approximations (no full top-mass dependence)

*De Florian, Mazzitelli (2013); Grigo et al. (2013-15); Maltoni et al. (2014)*

# Higgs boson pair production at two loops

*S. Borowka et al. (04/2016)*

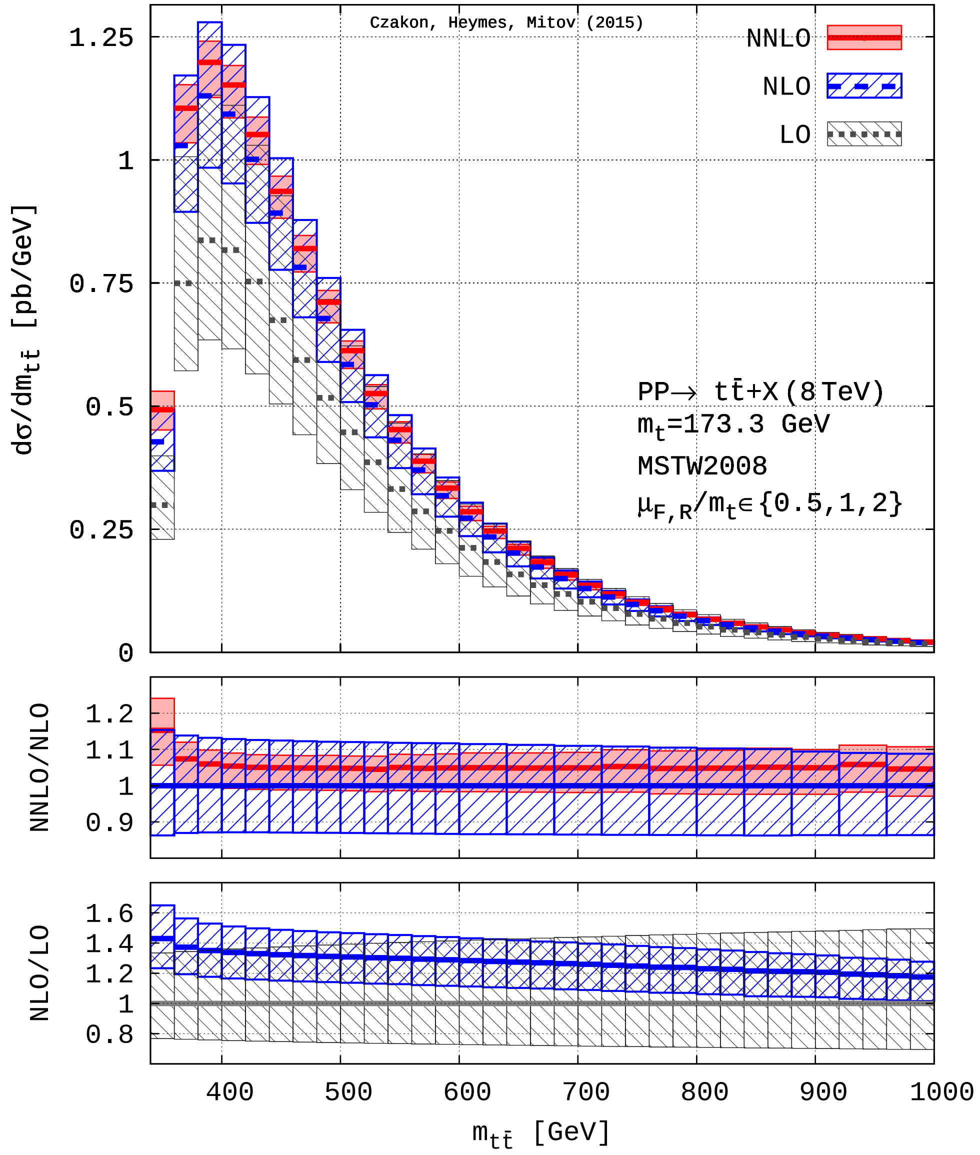



results of new NLO calculation cannot fully be accounted for by approximative calculations

☞ more details: Sophia Borowka's talk

# $pp \to t\bar{t}$: going differential at NNLO QCD

*Czakon, Heymes, Mitov (2015)*

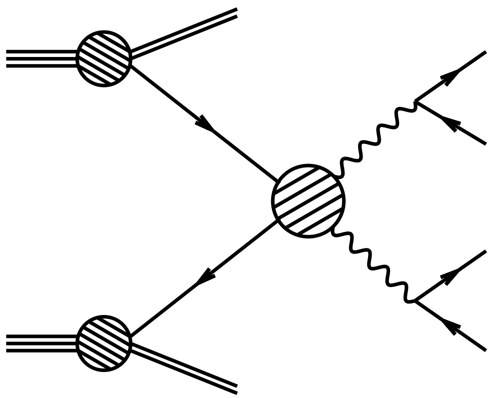



- perturbative result stabilized
- scale dependence reduced
- improved agreement with data from Tevatron and LHC

future applications:

PDF fits, precision measurements of the top mass, $\alpha_s$ extraction

# gauge-boson pair production



probe for the non-Abelian structure of the SM at high energies:

- (anomalous) triple gauge-boson couplings
- dynamics of longitudinal massive gauge bosons

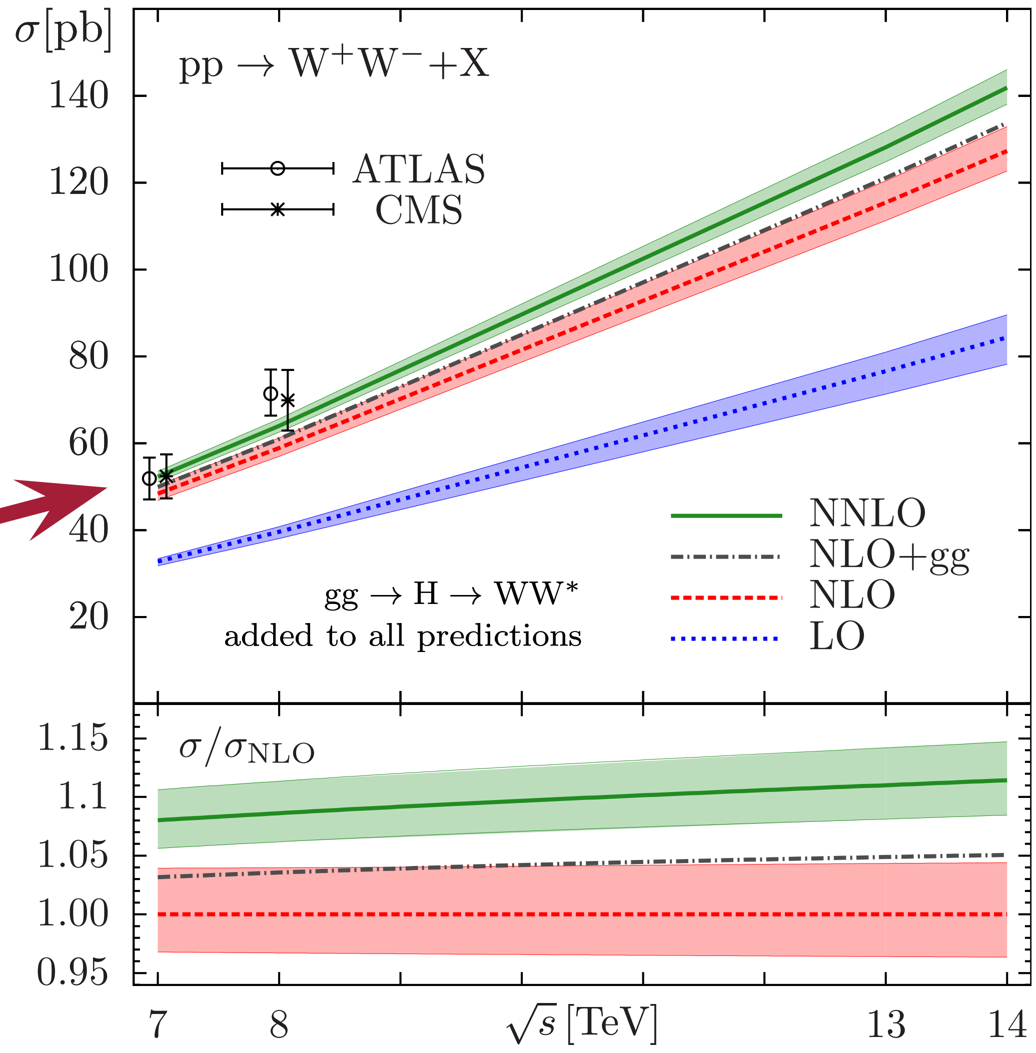
constitutes important class of background processes to:

- the Higgs search in the mode $pp \to H \to VV$
- new physics searches with leptons+$\not{E}_T$ signatures (e.g. SUSY-particle pair production)

# $pp \to WW$ @ NNLO QCD!

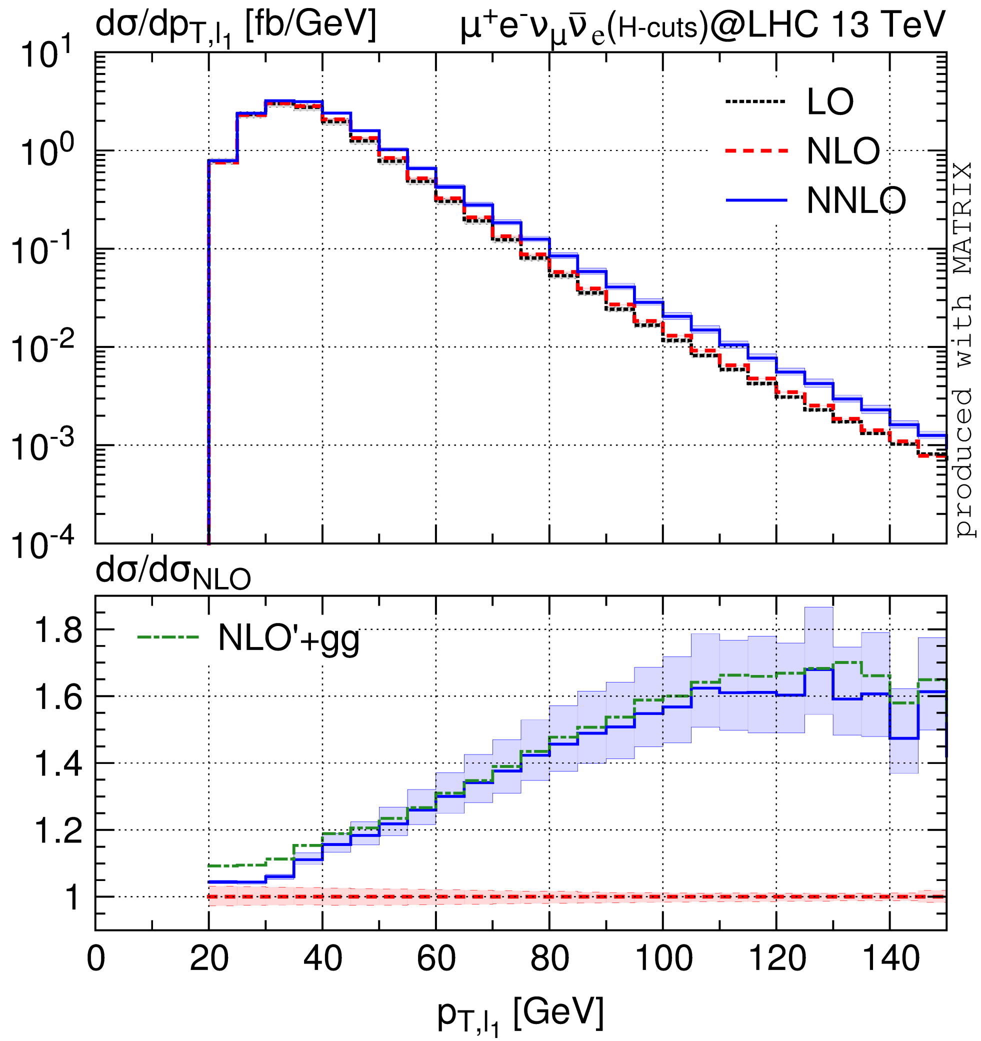
*Gehrmann et al. (08/2014)*

note:
improved agreement with LHC data



# $pp \to WW$ @ NNLO QCD: going differential

*Grazzini et al. (05/2016)*




fully differential Monte Carlo:

allows for arbitrary cuts
and distributions/correlations of
leptonic decay products

✔ realistic predictions possible

☞ talk by Marius Wiesemann

# progress in NLO EW calculations

- NLO EW often more demanding than NLO QCD calculations

  (richer resonance structure, more mass scales, . . . )

- most NLO EW results available based on dedicated calculations

  ($pp \to V$, $Vj$, $HV$, $VV$, 4 leptons, dijets, VBF, . . . )

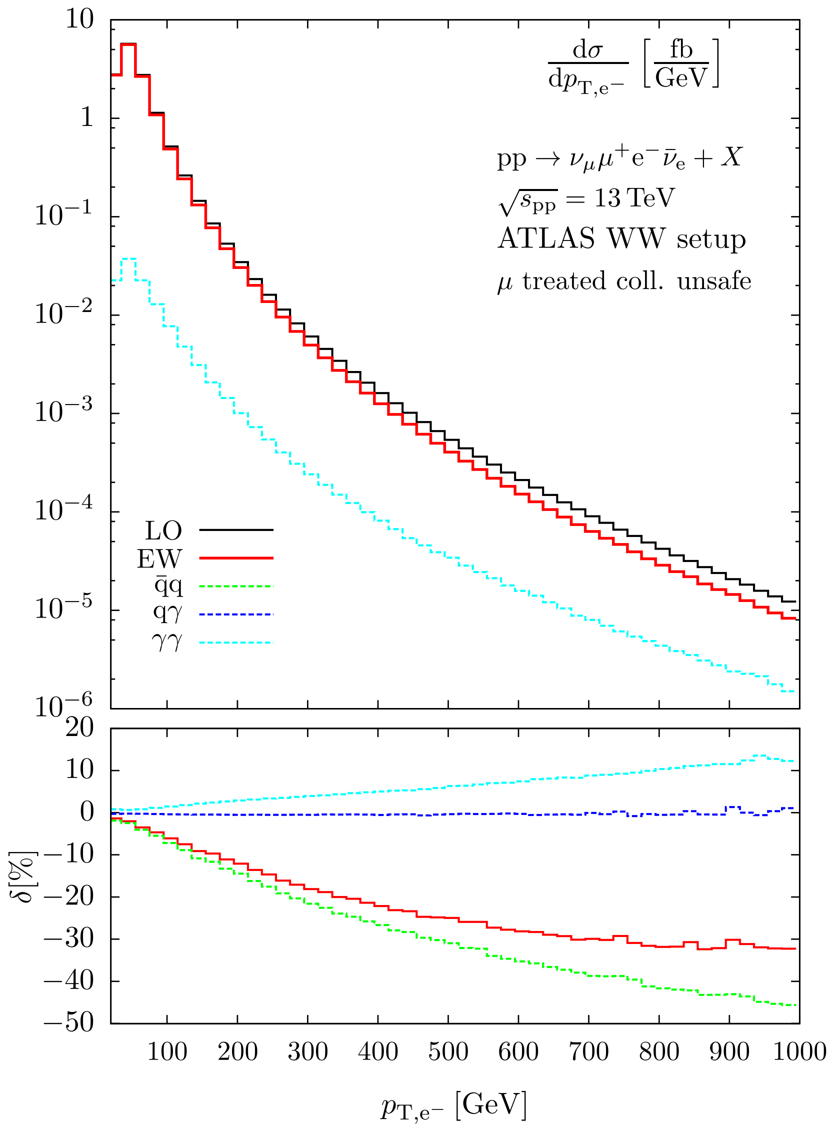
- automated tools start to play a more important role:

  `Recola, OpenLoops, MadGraph5_aMC@NLO`

  ($pp \to Vjj$, 4 leptons, $t\bar{t}V$, . . . )

# $pp \to WW \to 4f$: full NLO EW calculation

*Biedermann et al. (05/2016)*



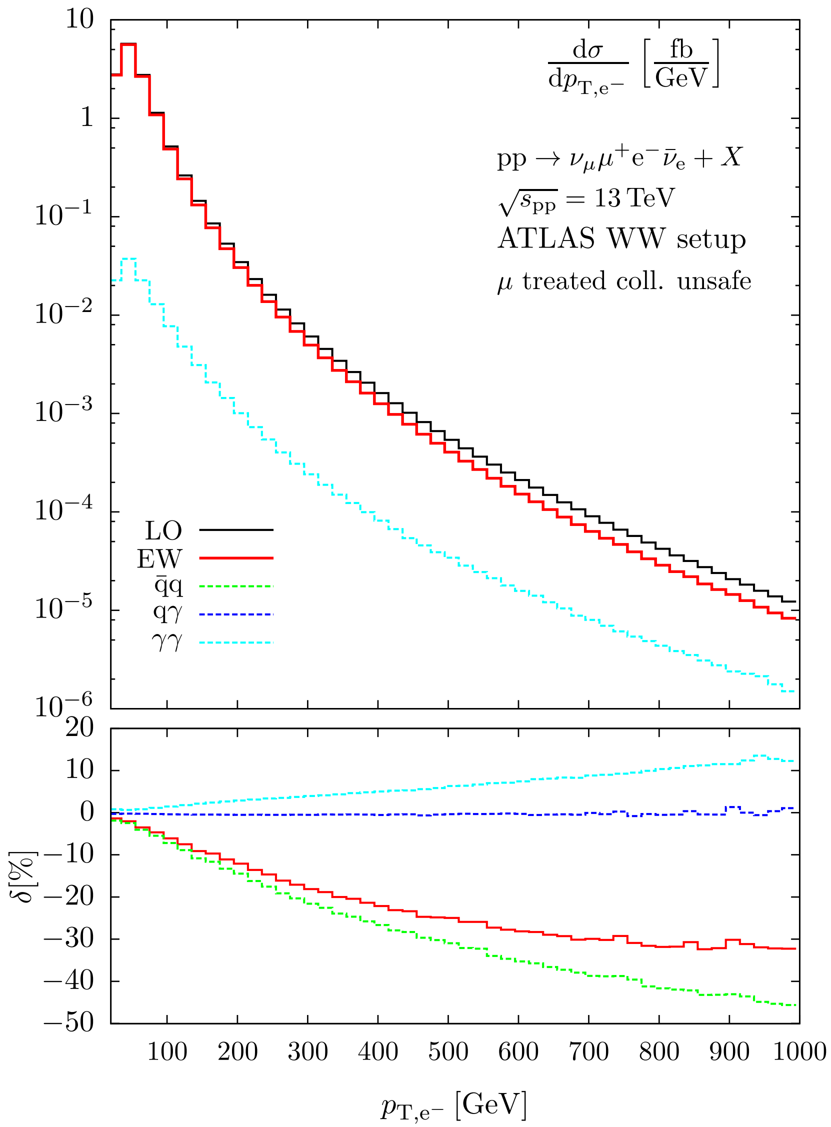

flexible Monte-Carlo approach gives full control on lepton distributions and correlations with realistic selection cuts:

EW corrections small for total XS, but large and negative at high scales

note: based on two independent calculations (`Recola` vs. dedicated standalone calculation)

# $pp \to WW \to 4f$: full NLO EW calculation

*Biedermann et al. (05/2016)*




flexible Monte-Carlo approach gives full control on lepton distributions and correlations with realistic selection cuts:

EW corrections small for total XS, but large and negative at high scales

☞ c.f. Jochen Meyer's talk for impact on experiment

# combination of QCD and EW corrections

current experimental precision requires combination of NLO EW corrections with best QCD prediction

how to combine?
factorized or additive approach?

$$\left(1+\delta^{\mathrm{QCD}}\right) \times \left(1+\delta^{\mathrm{EW}}\right)$$

versus

$$\left(1+\delta^{\mathrm{QCD}}+\delta^{\mathrm{EW}}\right)$$

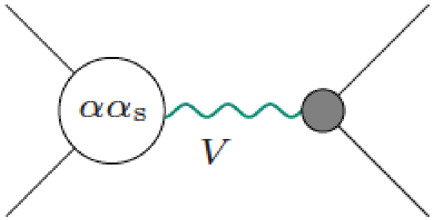
can only be resolved by computing

mixed QCD-EW corrections $\mathcal{O}(\delta^{\mathrm{QCD}}\delta^{\mathrm{EW}})$

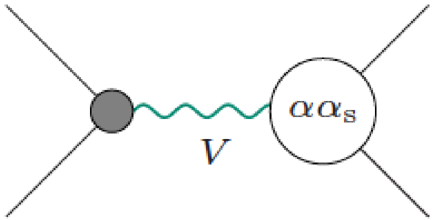
# Drell-Yan: mixed QCD$\times$EW corrections

*Dittmaier, Huss, Schwinn (2014-16):*

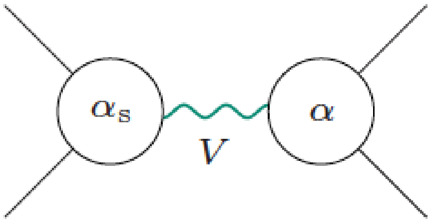
Factorizable contributions: (only virtual contributions indicated)




- no significant resonance distortion expected
- no PDFs with $\mathcal{O}(\alpha\alpha_s)$ corrections

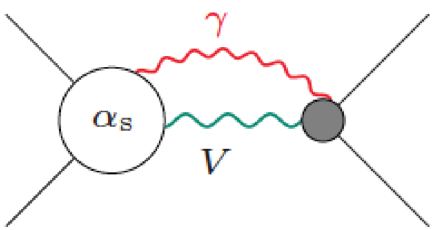



- only $Vl\bar{l}'$ counterterm contributions
  $\hookrightarrow$ uniform rescaling, no distortions




- significant resonance distortions from FSR
- calculated, preliminary results

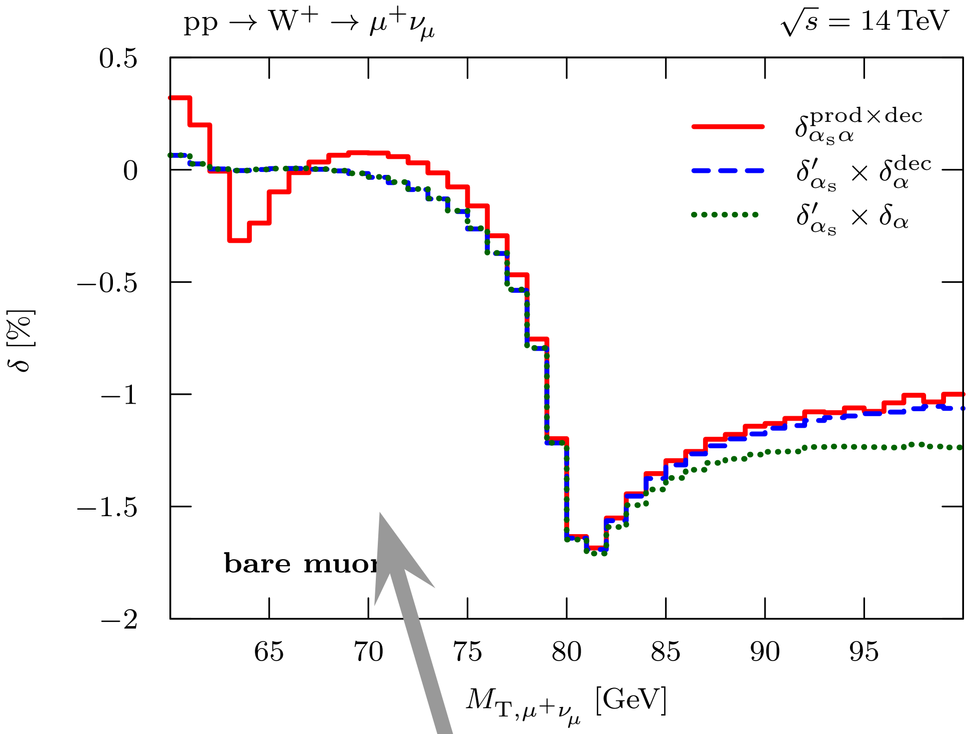
Non-factorizable contributions: (only virtual contributions indicated)

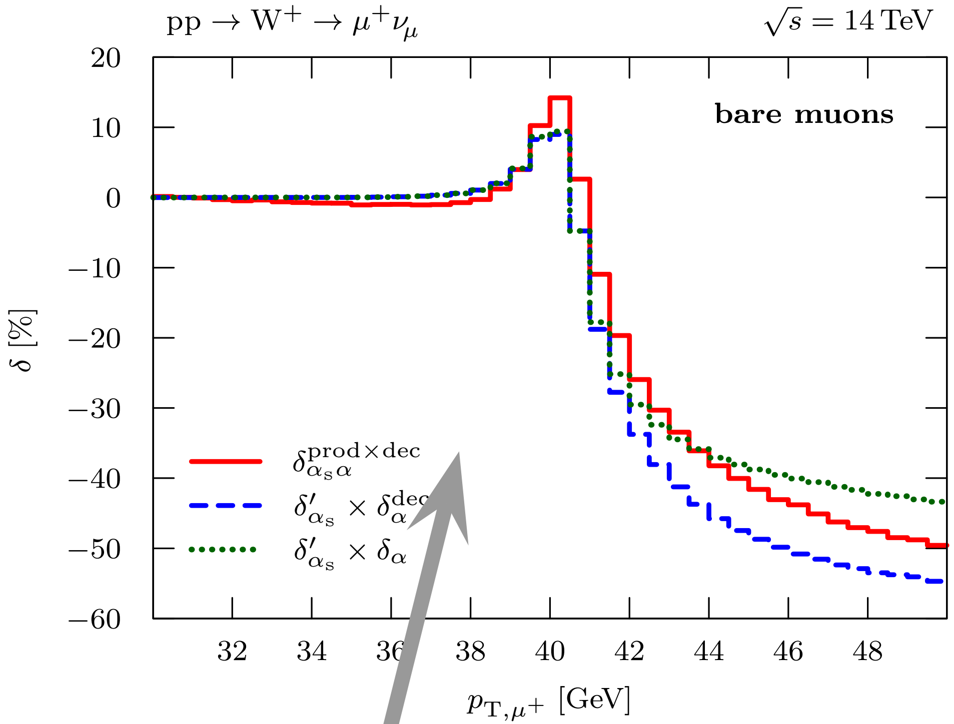



- could induce shape distortions
- calculated, turn out to be small

# Drell-Yan: mixed QCD×EW corrections

*Dittmaier, Huss, Schwinn (2014-16):*




naive factorization

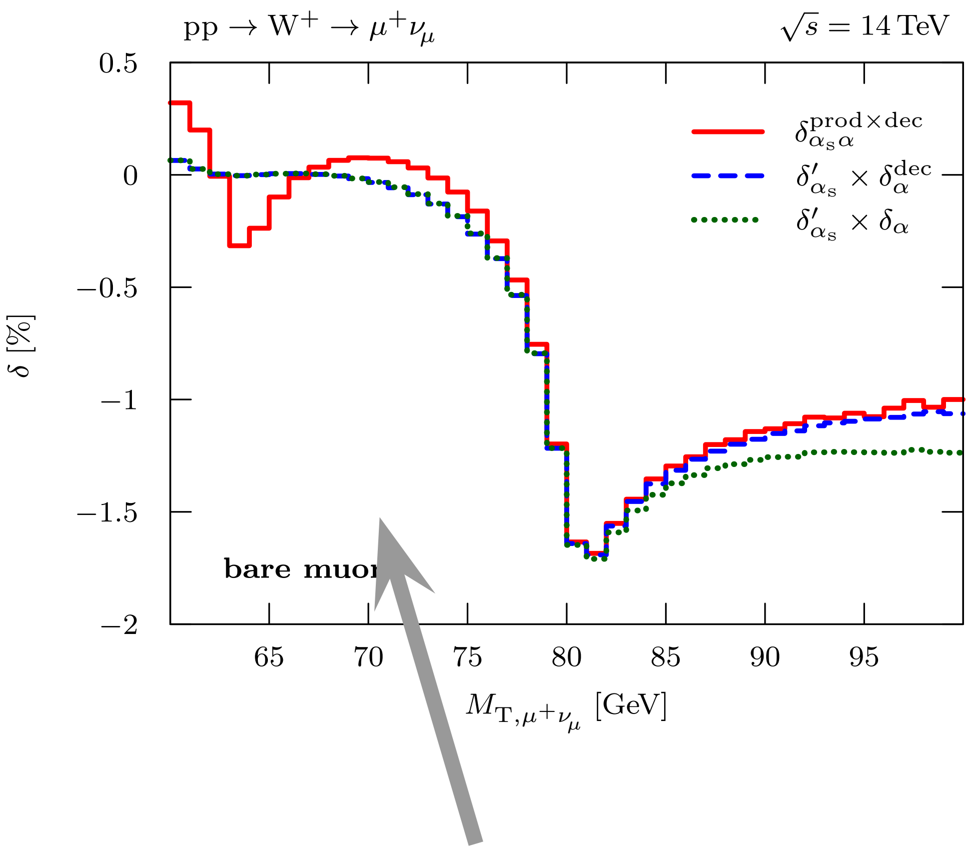
QCD×EW works

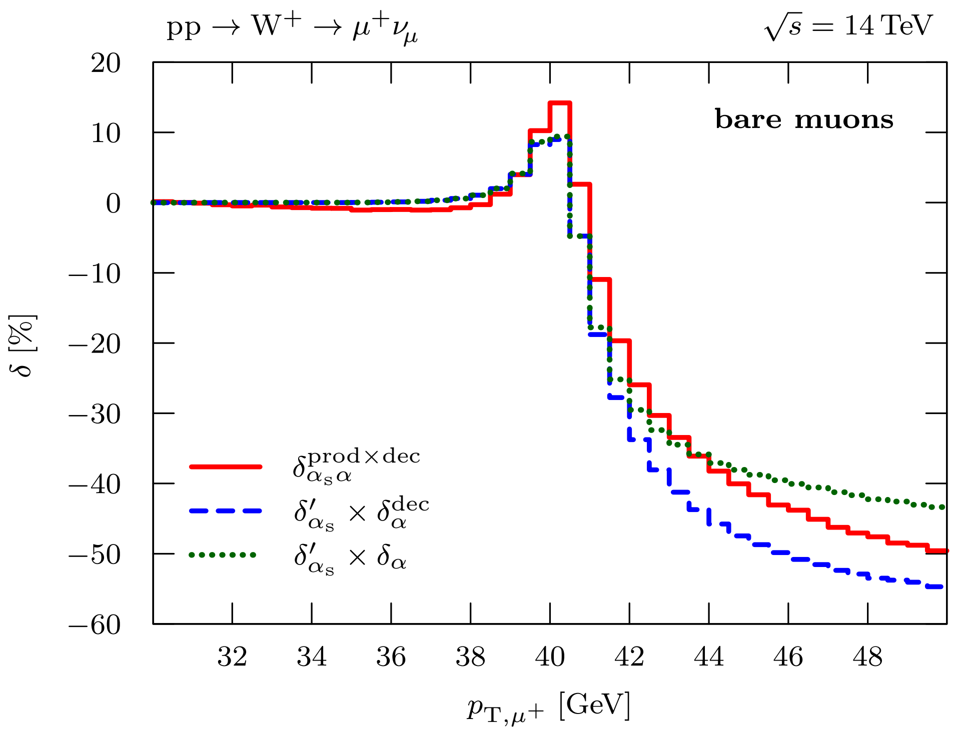
naive factorization poor for

$p_{T,\mu} > M_W/2$

# Drell-Yan: mixed QCD×EW corrections

*Dittmaier, Huss, Schwinn (2014-16):*



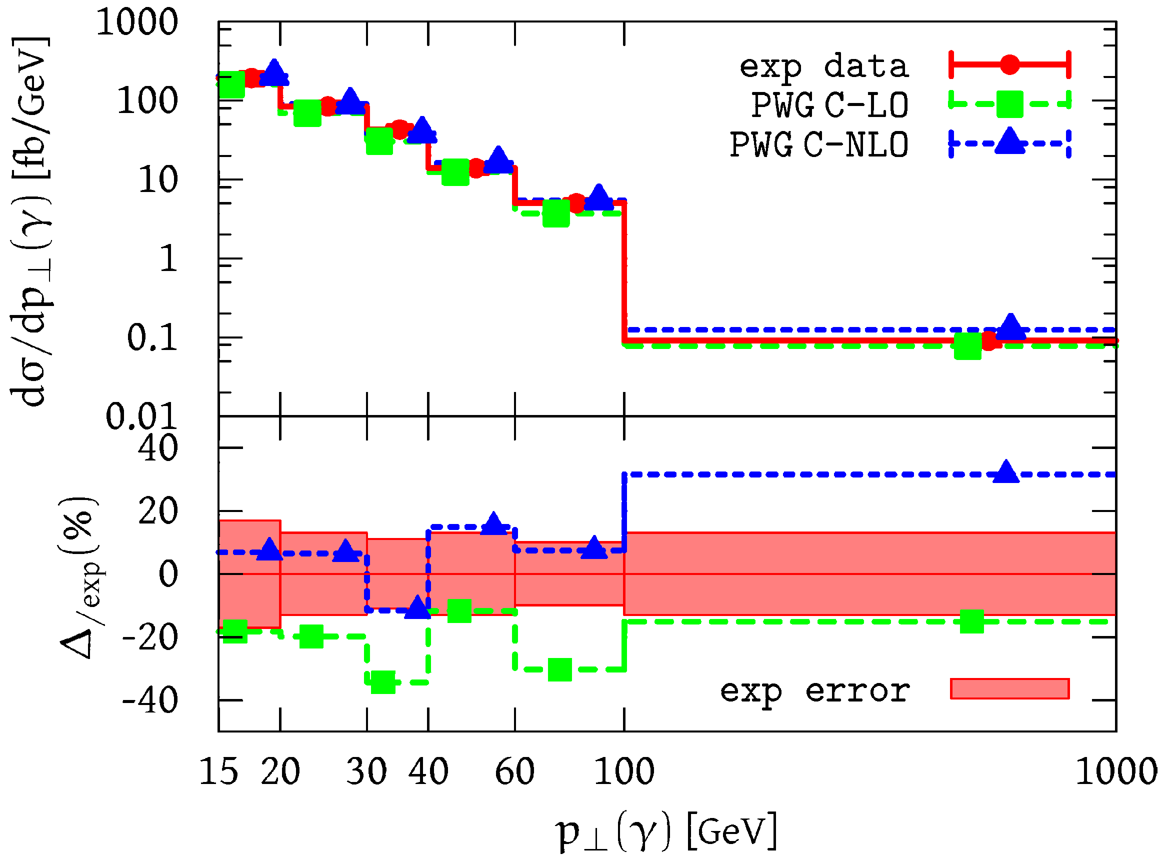

naive factorization

QCD×EW works

☞ talk by Alexander Huss

# NLO QED and NLO QCD with parton showers

*[Barzè et al. (2014)]*

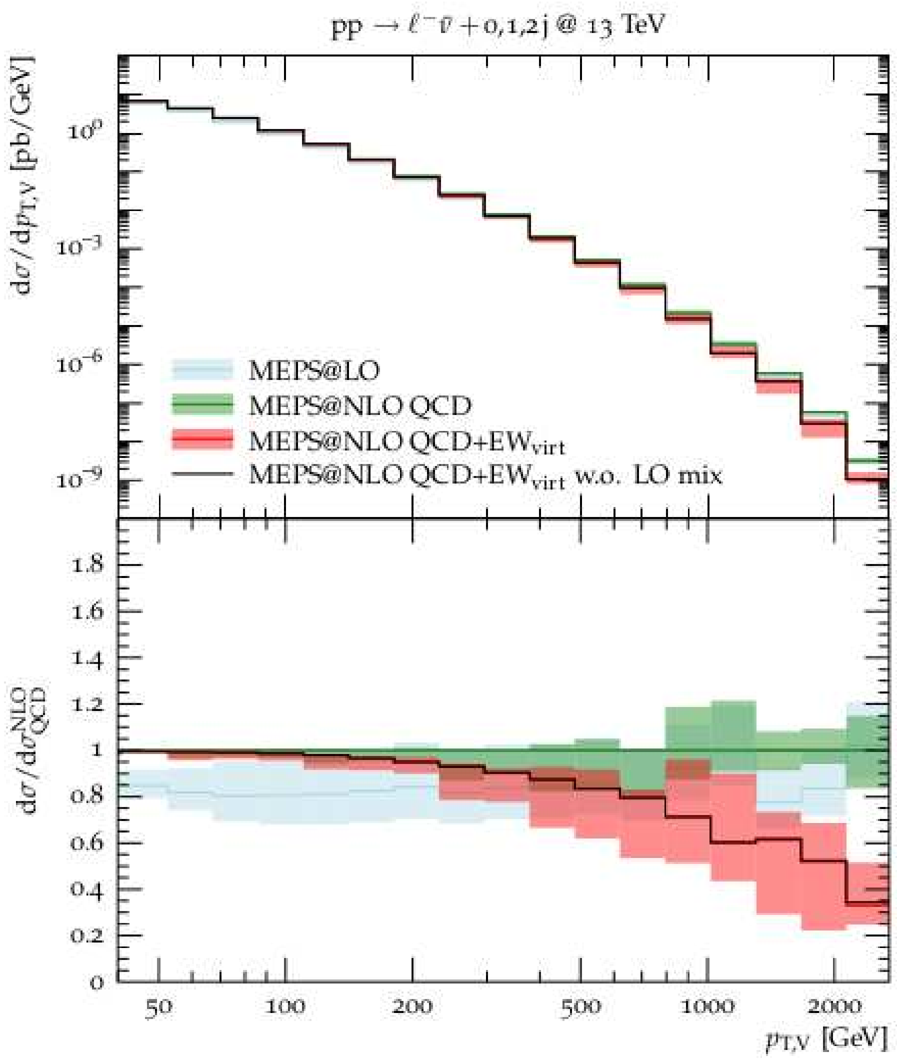



QED and QCD corrections can be combined and matched consistently with parton shower using the POWHEG framework

first implementation: $pp \to W\gamma$

# NLO QCD+EW and multi-jet merging

*Kallweit et al. (2015)*




merged samples for

$pp \to V + 0, 1, 2, 3$ jets

at NLO QCD accuracy

✔ including virtual EW corrections

✘ neglecting real photon emission

making use of tools

`OpenLoops & Munich/Sherpa`

# NNLO QCD and parton showers

first steps toward matching of NNLO QCD calculations with parton shower programs:

- ✔ realistic exclusive description of specific final state
- ✔ multi-parton interactions, hadronization, underlying event
- ✔ best possible perturbative accuracy of hard interaction
- ✔ proper modeling of jets (e.g. sub-structure)

☞ immediate impact on LHC physics program

(Higgs, EW precision measurements, . . . )

# NNLO QCD and parton showers

first steps toward matching of NNLO QCD calculations with parton shower programs:

- POWHEG+MINLO

  $pp \to H$, $HW$, Drell-Yan *[Zanderighi et al. (2013-16)]*

- UNNLOPS

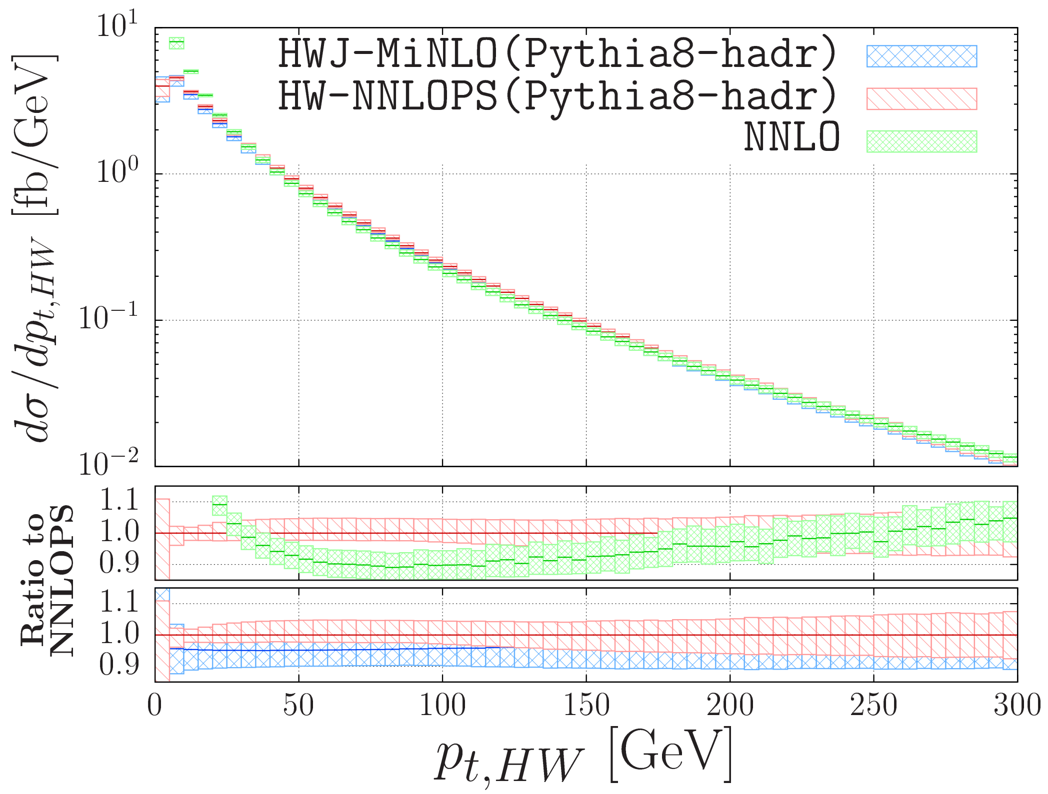
  $pp \to H$, Drell-Yan *[Höche, Li, Prestel (2014)]*

- GENEVA

  Drell-Yan *[Alioli et al. (2014)]*

# NNLO QCD and parton showers

*Astill et al. (2016)*




- scale uncertainties reduced from about 10% to 2%
- agreement with NNLO results for inclusive lepton observables
- jet distributions sensitive to parton-shower effects
- NNLO+PS tool more flexible than pure NNLO calculation

NNLO+PS accurate description of $pp \to HW$ using the `POWHEG+MINLO` approach

# recent BSM developments: NLO+PS tools

**MadGraph5_aMC@NLO**:

- Higgs effective field theory *[Artoisenet et al. (2013)]*
- top-quark flavor changing neutral processes *[Degrande et al. (2015)]*
- colored scalar pair production *[Degrande et al. (2015)]*
- two Higgs doublet model *[Degrande et al. (2015)]*
- dark matter production *[Backovic, Mattelaer, Neubert et al. (2015)]*

. . .

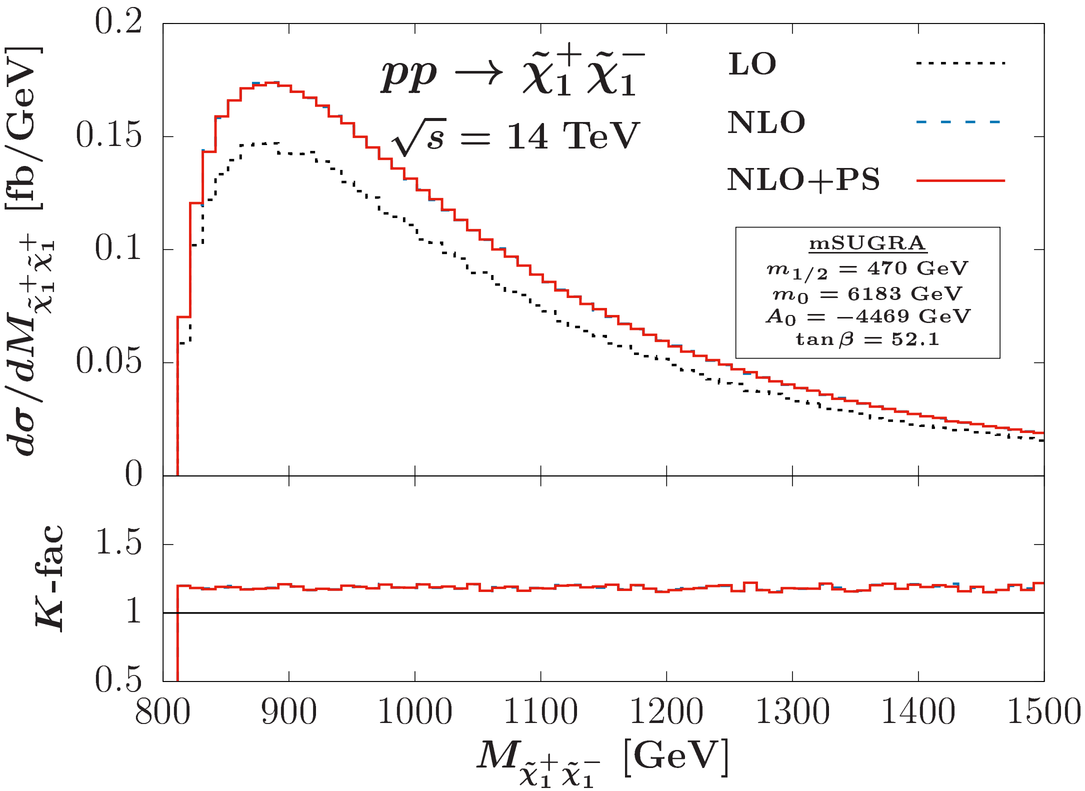
**POWHEG-BOX**:

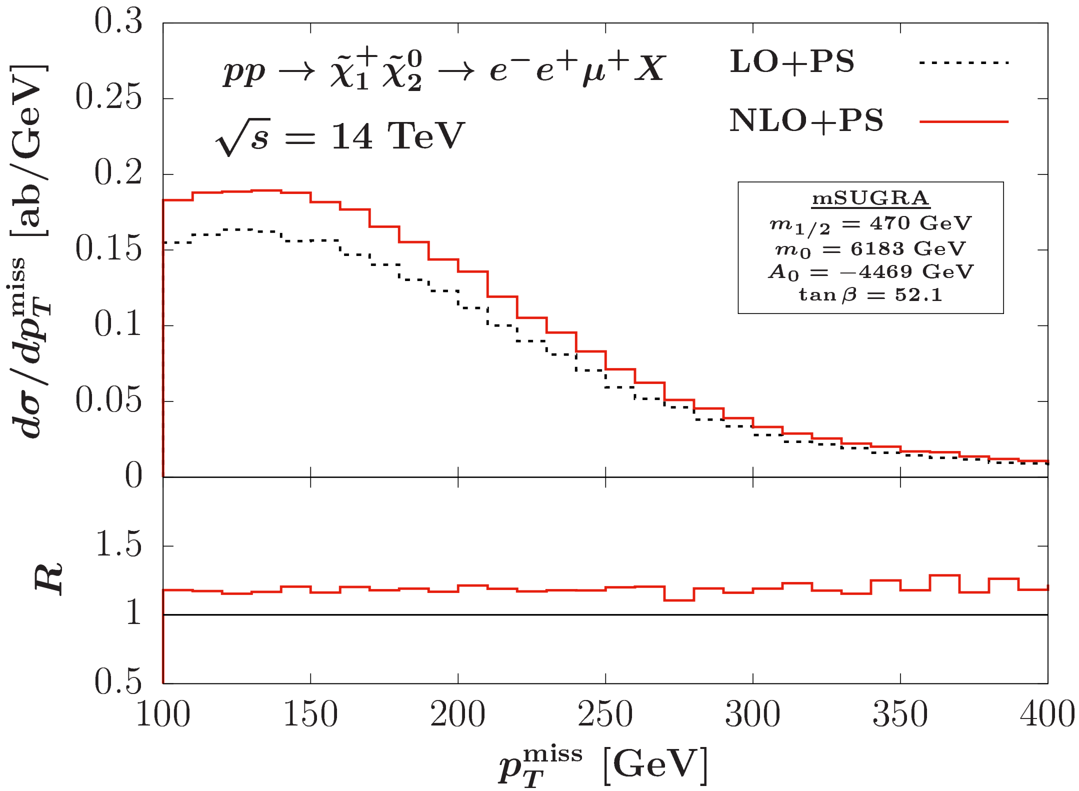
- dark matter + mono-jet production *[Haisch et al. (2013-15)]*
- slepton-pair production *[Thier et al. (2012-14)]*
- squark production and decay *[Gavin et al. (2013-14)]*
- weakino pair production *[Baglio et al. (2016)]*

. . .

# weakino pair production at NLO+PS accuracy

*[Baglio et al. (2016)]*




fully differential predictions for production+decay

☞ NLO corrections sizable

# summary

- presented personal selection of recent results to illustrate ongoing progress in precision calculations

  (apologies for what I could not show here)

- to achieve precision required by experiment:
  - consider (N)NLO QCD and NLO EW corrections
  - disregard approximations (infinite top mass, narrow width, . . . )
  - match precision calculations to parton-shower programs
  - merge samples of different jet multiplicities

- open issue: systematic quantification of Monte-Carlo uncertainties

  (dependence on matching scheme, merging scale, parton shower algorithm, . . . )

- status of theory predictions advanced, several public tools available

Thank

You.