New Developments in SM Predictions

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Outline

The exploration of the Higgs sector and the search for new physics at the LHC requires accurate, stable and flexible higher-order QCD+EW predictions involving jets, heavy quarks, W, Z, γ and the Higgs boson.

Recent advances in Higgs predictions: please see R.Boughezal's talk

Please note that this is a personal selection of results illustrating recent activities in:

- Fixed order(+resummed): NNLO QCD+NNLL resummation, NLO EW and weak Sudakov logs (recent advances in resummation not covered here, please see Radja's talk for examples)
- Automation: aMC@NLO (MadLoop+MadFKS+Madgraph), Sherpa (GOSAM +MC@NLO)
- NLO and PS merging: NLO QCD×PS (Sherpa+MC@NLO), NLO(QCD+EW)×PS

For a more exhaustive overview see, e.g.,:

The LoopFest XII (2013): http://indico.cern.ch/conferenceDisplay.py?confId=223649

Les Houches 2013: http://phystev.in2p3.fr/wiki/2013:programme

NNLO for more hadron collider processes!

- For a long time, only color singlet final states available at full NNLO, mostly 2 → 1 at Born level: H, W, Z, $\gamma\gamma$
- 2013 will be remembered as the year of 2 → 2 at NNLO

From:
LoopFest 2013 summary talk by Lance Dixon

pp→jj @ NNLO QCD

- Provides information of the gluon content of the proton, needed for NNLO PDFs
- Determination of α_s
- Precision test of QCD

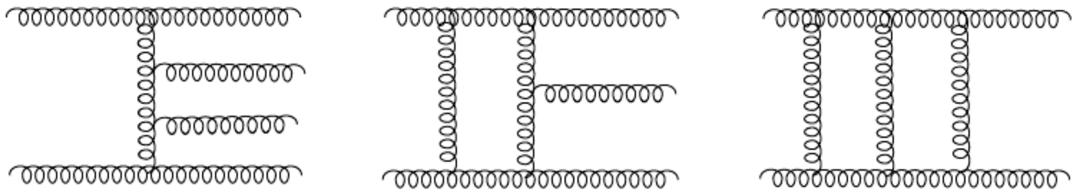
A.Gehrmann-de Ritter, T. Gehrmann, E.W.N Glover. J. Pires, arXiv:1301.7310:

- Fully differential di-jet and inclusive jet cross sections at NNLO accuracy
- implemented in parton level generator NNLOJET
- based on gluonic channels and leading color (quark channels are work in progress)

Challenge: complex structure of IR singularities

Jao Pires @ LoopFest 2013:

$pp \to 2j$ AT NNLO: GLUONIC CONTRIBUTIONS



$A_6^{(0)}(gg \to gggg)$ $A_5^{(1)}(gg \to ggg)$ $A_4^{(2)}(gg \to gg)$

[Berends, Giele '87], [Mangano, Parke, Xu '87], [Britto, Cachazo, Feng '06]
[Bern, Dixon, Kosower '93]
[Anastasiou, Glover, Oleari, Tejeda-Yeomans '01],[Bern, De Freitas, Dixon '02]

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\Phi_4} \mathrm{d}\hat{\sigma}^{RR}_{NNLO} + \int_{\mathrm{d}\Phi_3} \mathrm{d}\hat{\sigma}^{RV}_{NNLO} + \int_{\mathrm{d}\Phi_2} \mathrm{d}\hat{\sigma}^{VV}_{NNLO}$$

- explicit infrared poles from loop integrations
- implicit poles in phase space regions for single and double unresolved gluon emission
- procedure to extract the infrared singularities and assemble all the parts in a parton-level generator

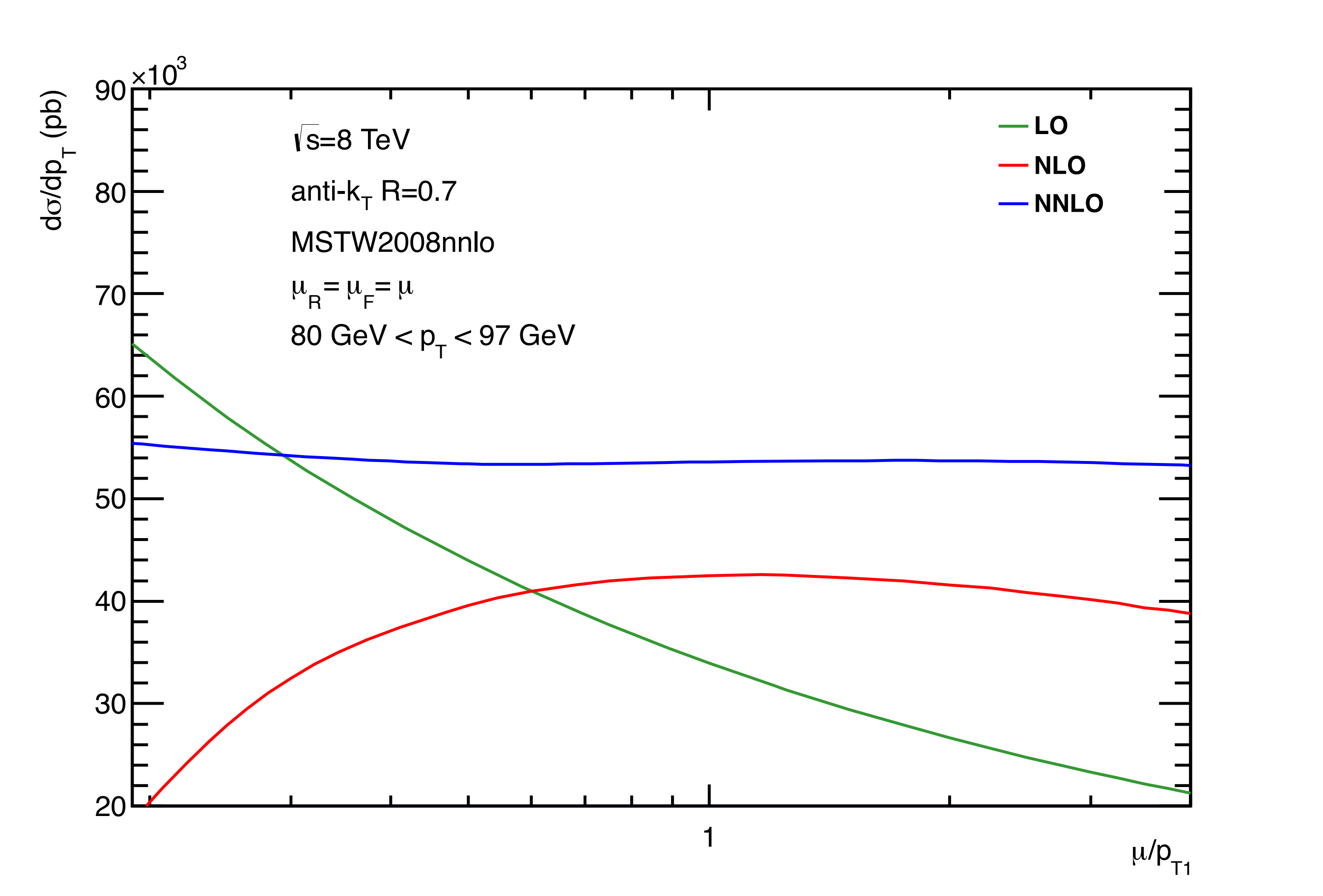
Antenna subtraction now also for IS partons

Jao Pires @ LoopFest 2013:

$$\begin{aligned} d\hat{\sigma}_{NNLO} &= \int_{d\Phi_4} \left(d\hat{\sigma}^{RR}_{NNLO} - d\hat{\sigma}^{S}_{NNLO} \right) \\ &+ \int_{d\Phi_3} \left(d\hat{\sigma}^{RV}_{NNLO} - d\hat{\sigma}^{T}_{NNLO} \right) \\ &+ \int_{d\Phi_2} \left(d\hat{\sigma}^{VV}_{NNLO} - d\hat{\sigma}^{U}_{NNLO} \right) \end{aligned}$$

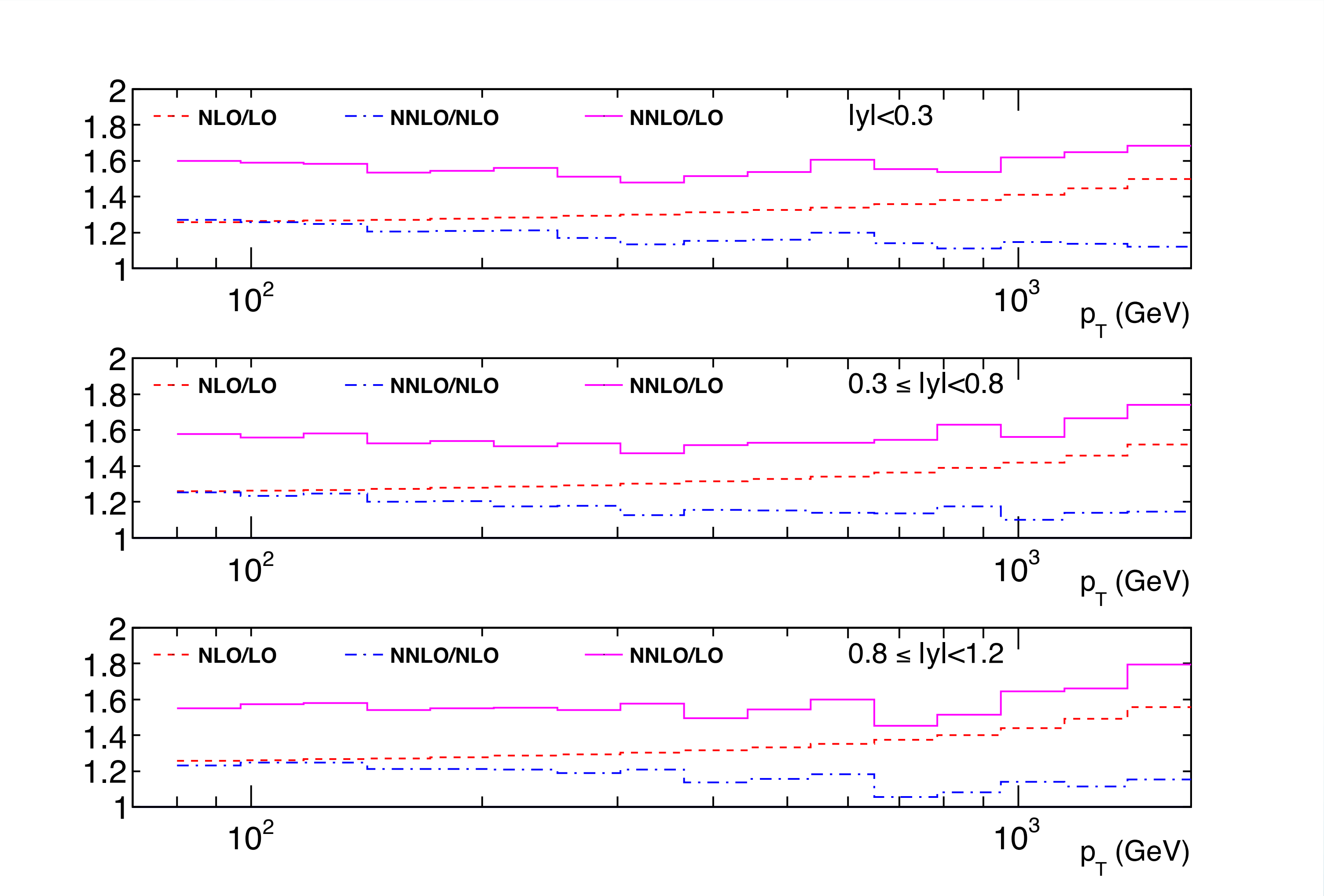
- $d\hat{\sigma}^{S}_{NNLO}$: real radiation subtraction term for $d\hat{\sigma}^{RR}_{NNLO}$
- $d\hat{\sigma}^{T}_{NNLO}$: one-loop virtual subtraction term for $d\hat{\sigma}^{RV}_{NNLO}$
- $d\hat{\sigma}^{U}_{NNLO}$: two-loop virtual subtraction term for $d\hat{\sigma}^{VV}_{NNLO}$
- subtraction terms constructed using the antenna subtraction method at NNLO for hadron colliders $\rightarrow$ presence of initial state partons to take into account
- contribution in each of the round brackets is finite, well behaved in the infrared singular regions and can be evaluated numerically

Scale dependence of inclusive jet P_T cross section at the 8 TeV LHC



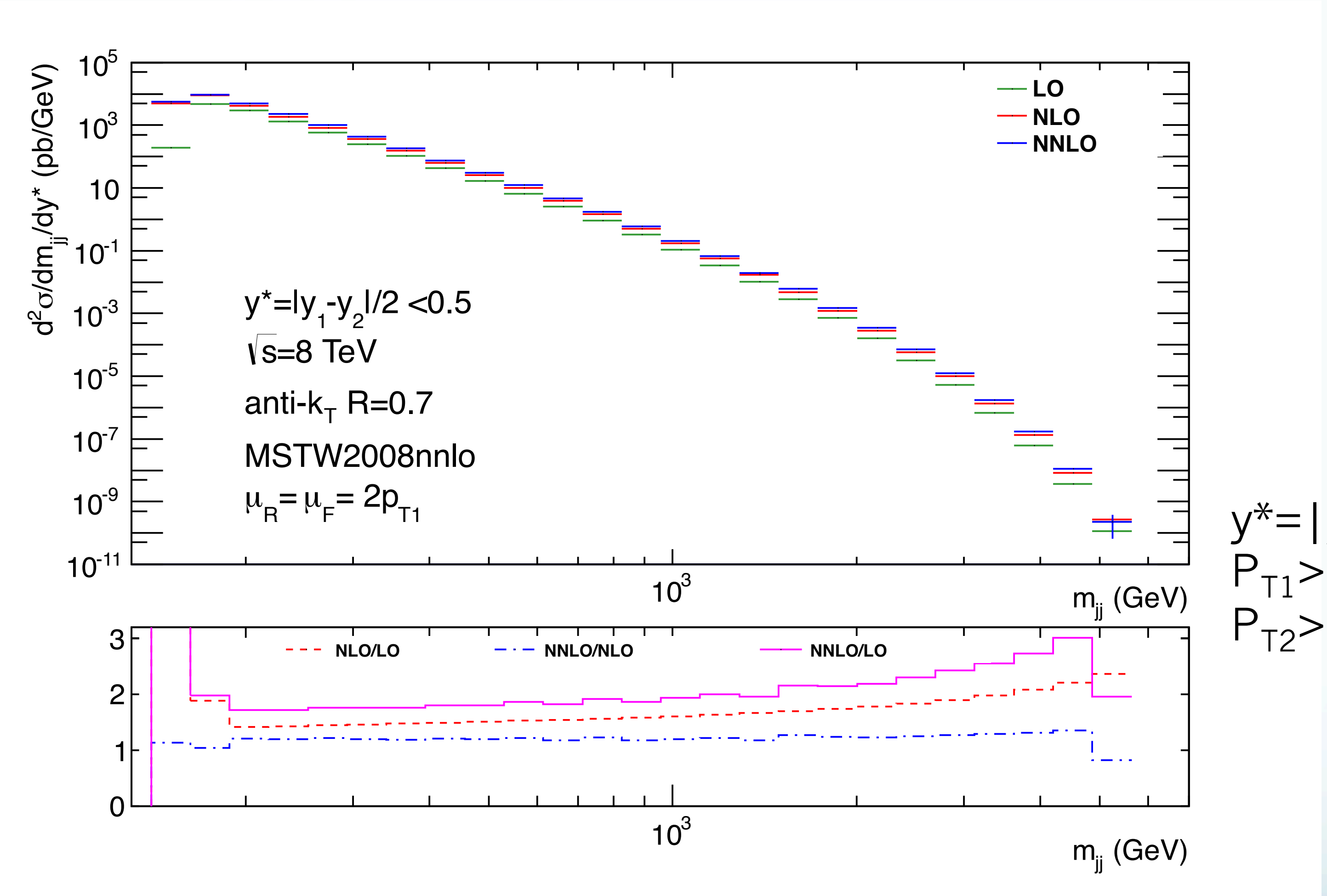
A.Gehrmann-de Ritter, T. Gehrmann, E.W.N Glover. J. Pires, arXiv:1301.7310

K factors for inclusive jet for different |y| slices



A.Gehrmann-de Ritter, T. Gehrmann, E.W.N Glover. J. Pires, arXiv:1301.7310

Exclusive di-jet d$^2\sigma$/dmjj dy* distribution

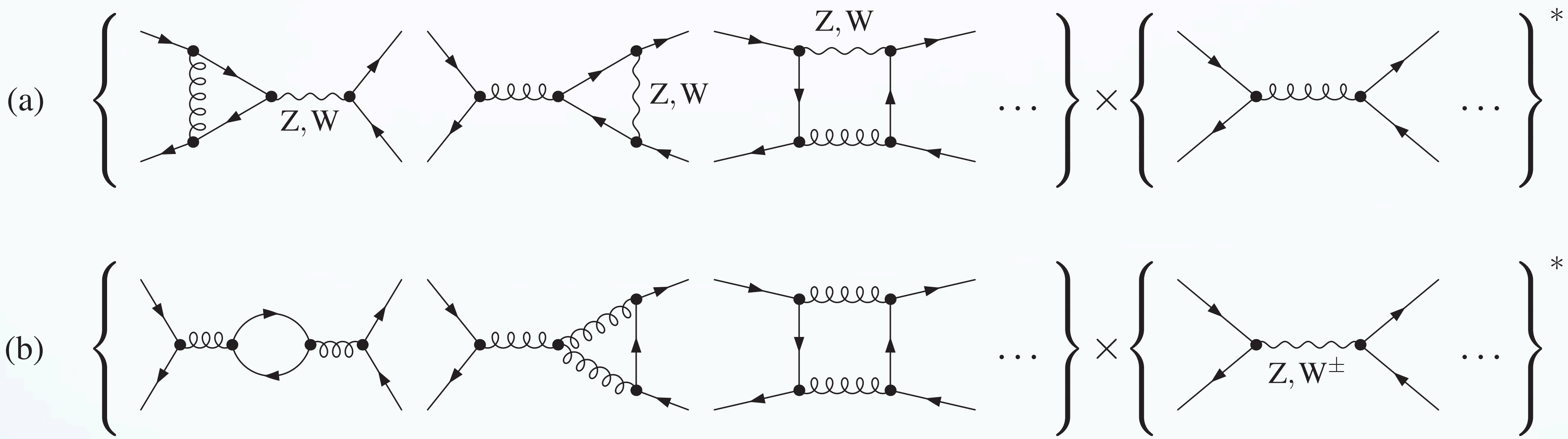


y*=|y1-y2|<0.5
P_{T1}>80 GeV,
P_{T2}>60 GeV

A.Gehrmann-de Ritter, T. Gehrmann, E.W.N Glover. J. Pires, arXiv:1301.7310

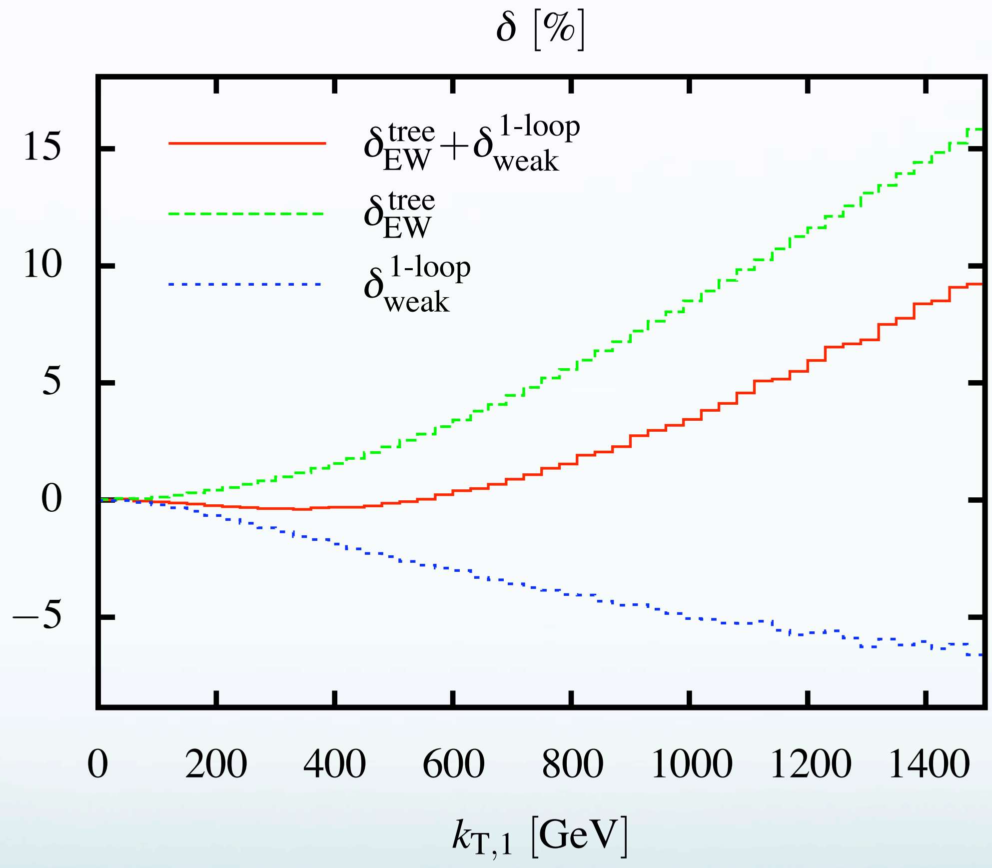
Weak 1-loop corrections to di-jet production

Examples of 1-loop weak corrections:



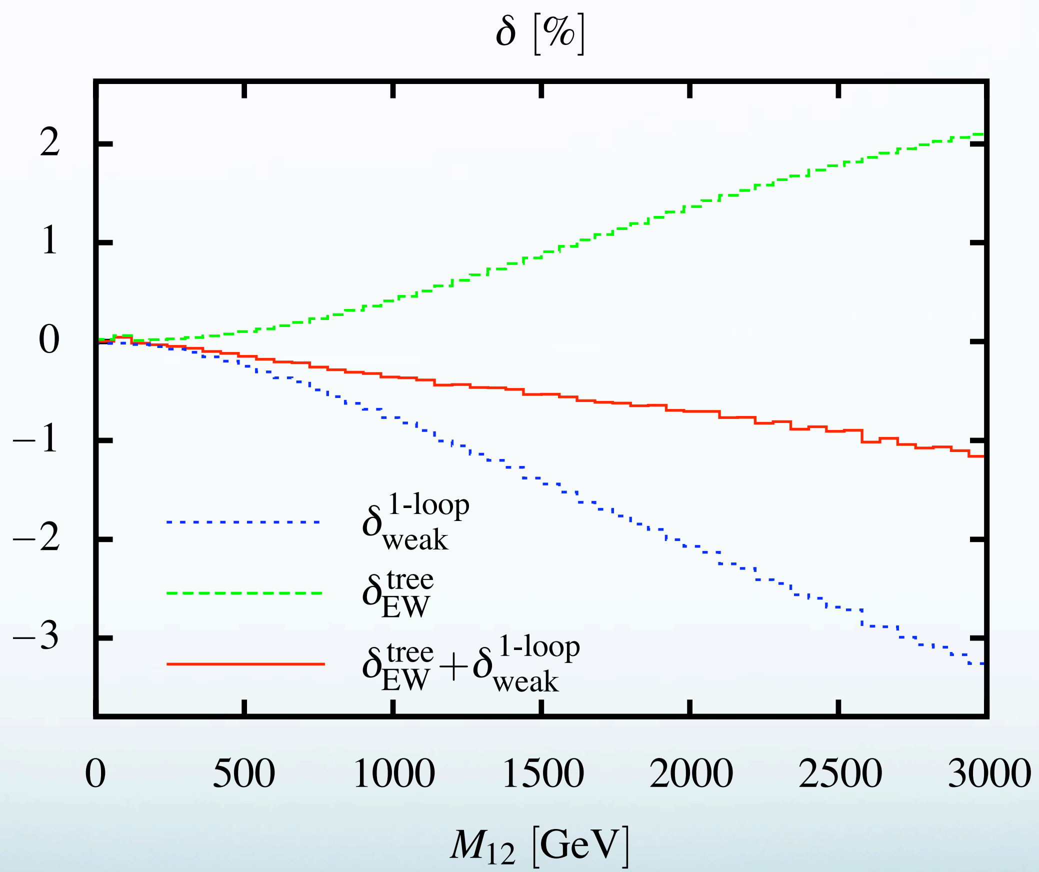
S.Dittmaier, A.Huss, C.Speckner, arXiv:1306.6298

Relative weak corrections to leading kT distribution to pp->jj+X at the 8 TeV LHC



S.Dittmaier, A.Huss, C.Speckner, arXiv:1306.6298

Relative weak corrections to di-jet invariant mass distribution to pp➔jj+X at the 8 TeV LHC



S.Dittmaier, A.Huss, C.Speckner, arXiv:1306.6298

Top-pair production at NNLO QCD

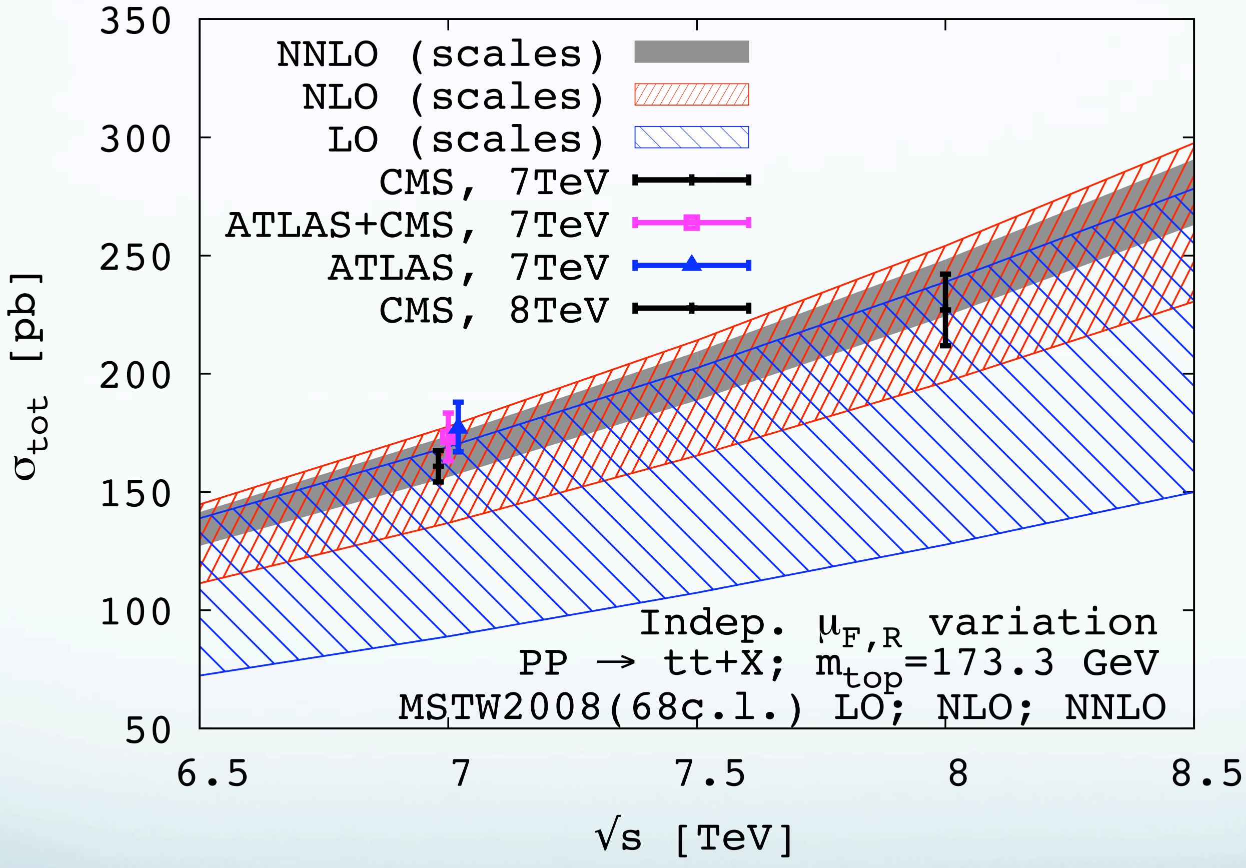
$$\sigma_{\rm tot} = \sum_{i,j} \int_0^{\beta_{\rm max}} d\beta \, \Phi_{ij}(\beta, \mu_F^2) \, \hat{\sigma}_{ij}(\beta, m^2, \mu_F^2, \mu_R^2) \, .$$

$$\Phi_{ij}(\beta, \mu_F^2) = \frac{2\beta}{1-\beta^2} \, \mathcal{L}_{ij}\left(\frac{1-\beta_{\rm max}^2}{1-\beta^2}, \mu_F^2\right) \qquad \mathcal{L}_{ij}(x, \mu_F^2) = x \, (f_i \otimes f_j) \, (x, \mu_F^2)$$

$$\hat{\sigma}_{ij}\,(\beta) = \frac{\alpha_S^2}{m^2}\left(\sigma_{ij}^{(0)} + \alpha_S \sigma_{ij}^{(1)} + \alpha_S^2 \sigma_{ij}^{(2)} + \mathcal{O}(\alpha_S^3)\right)$$

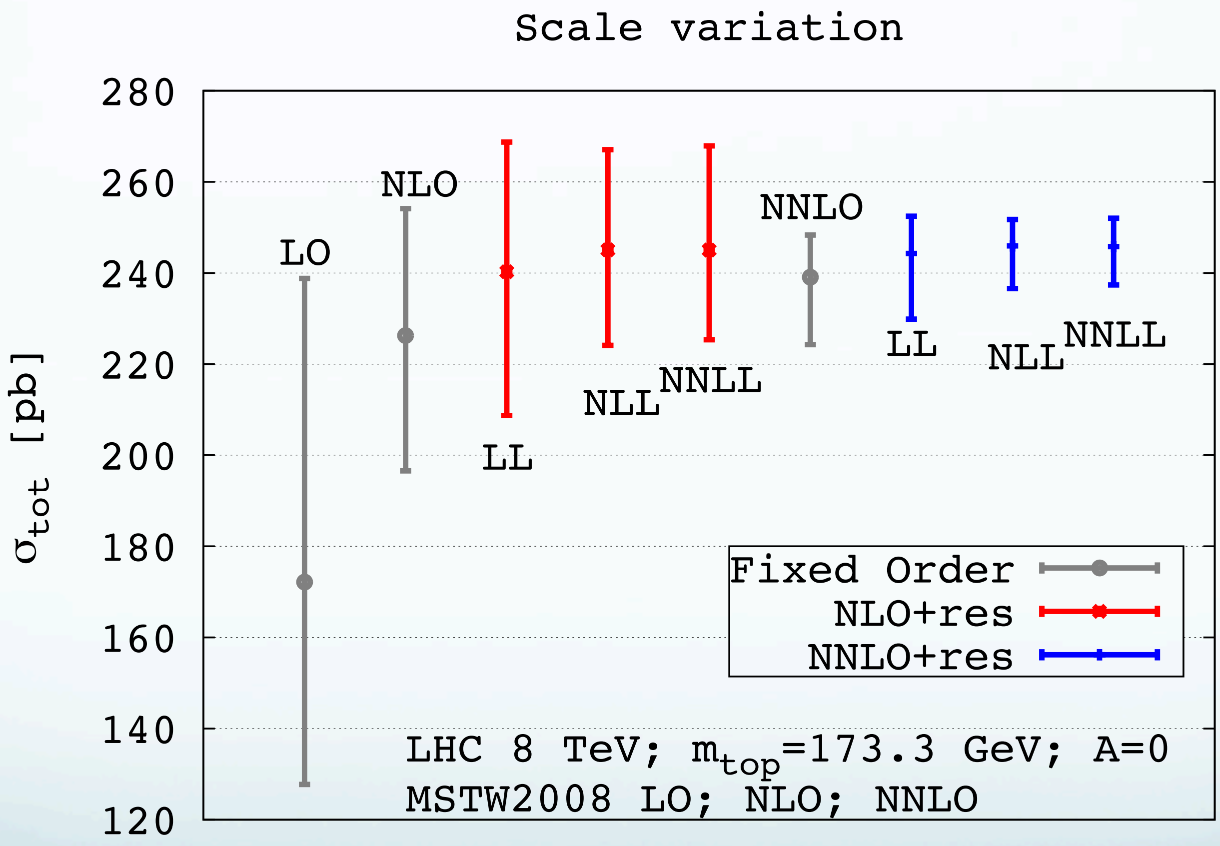
M.Czakon, P. Fiedler, A. Mitov, arXiv:1303.6254
Implemented in publicly available code Top++:
http://www.alexandermitov.com/software/

Independent μ_R and μ_F variation at LO, NLO, NNLO of σ_{tot} at the LHC



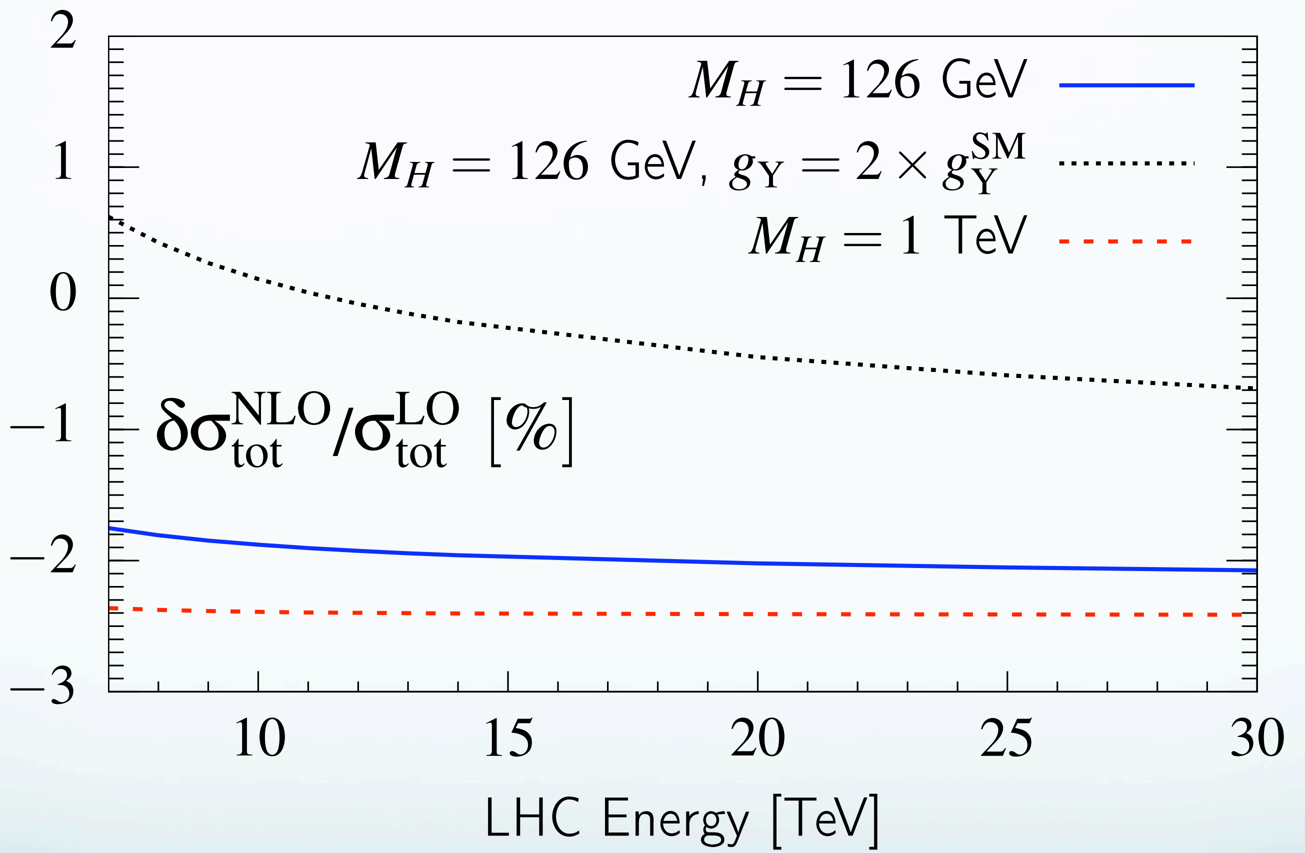
M.Czakon, P. Fiedler, A. Mitov, J. Rojo, arXiv:1305.3892

Scale variation at LO, NLO, NNLO and when including LL, NLL, NNLL resummation



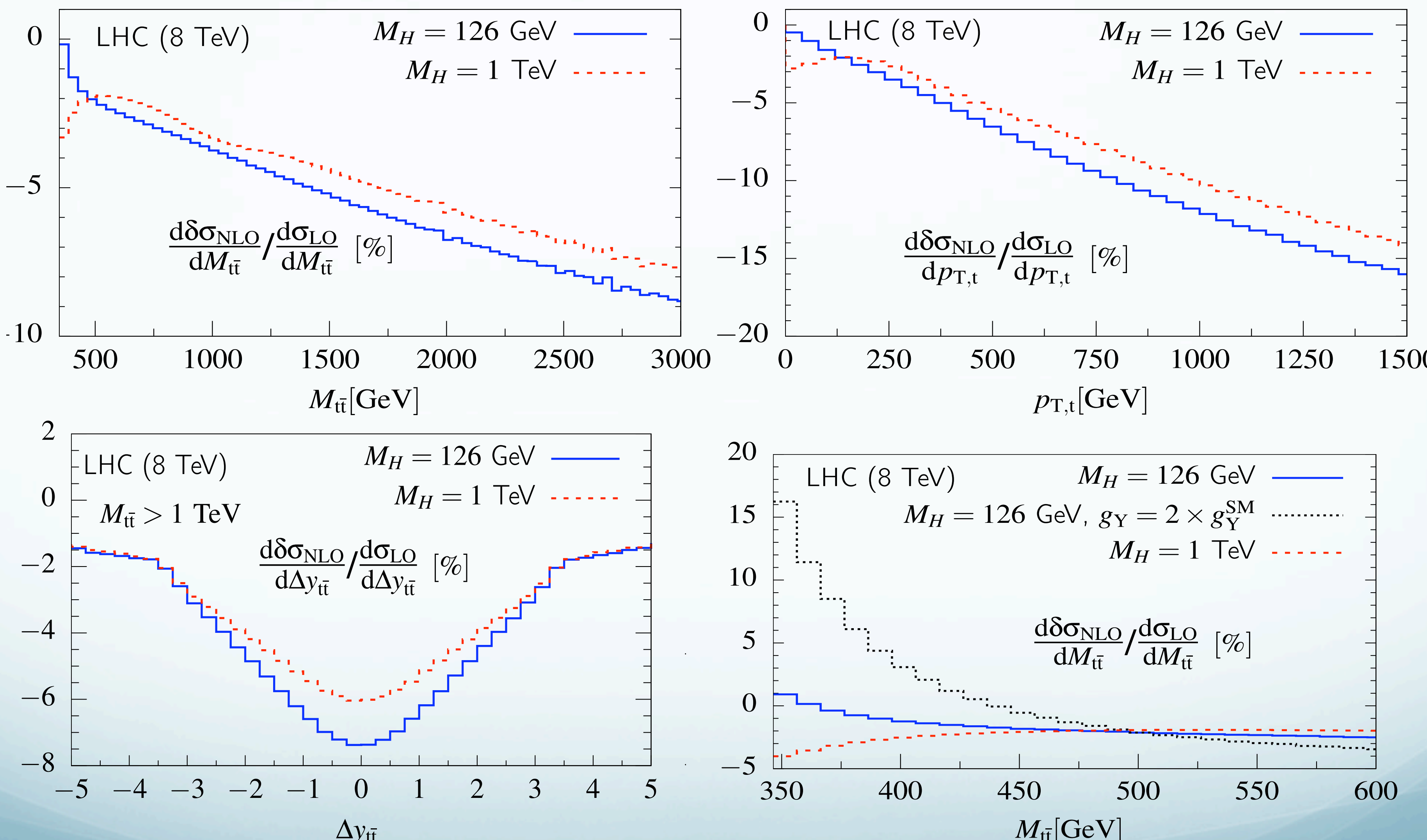
M.Czakon, P. Fiedler, A. Mitov, J. Rojo, arXiv:1305.3892

Impact of weak 1-loop corrections in top-pair production at the 8 TeV LHC



H.Kühn, A. Scharf and P. Uwer, arXiv:1305.5773

Impact of weak 1-loop corrections in top-pair production at the 8 TeV LHC



H.Kühn, A. Scharf and P. Uwer, arXiv:1305.5773

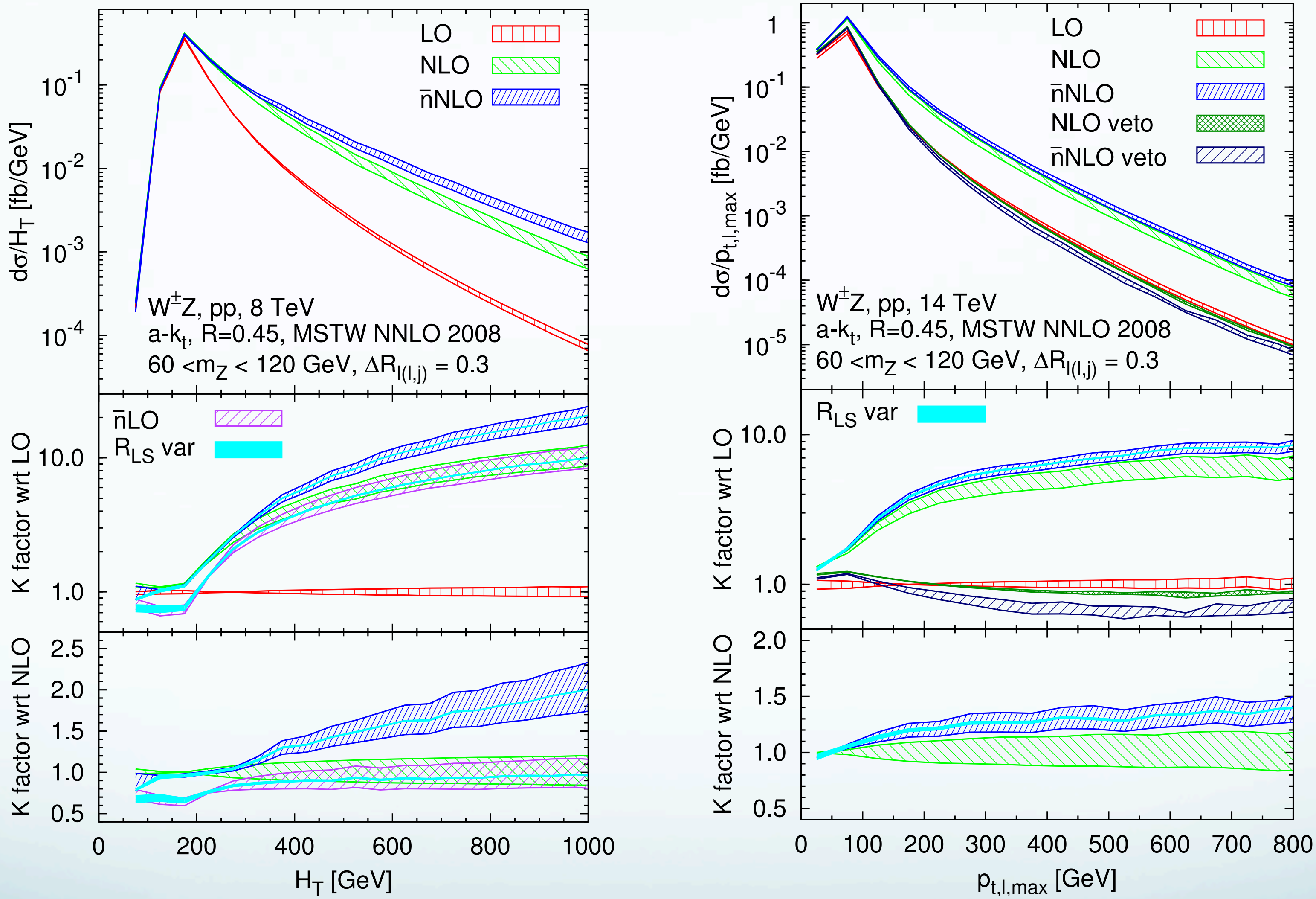
VV and VVV (w/o jets) processes

- NLO QCD prediction available for VV, VVV, WWj, WZj, Wγj, ZZj, WWjj, W$\gamma\gamma$j, WZjj (new in VBFNLO)
- Electroweak corrections at NLO to Zγ,WW, WZ, ZZ

Large K-factors: how about di-boson@NNLO QCD ?

- di-photon@NNLO QCD: Catani et al (2012)
- VBFNLO+LOOPSIM: approximate NNLO for WZ production (LO:qq➔WZ) Campanario *et al*, 1307.2261; LOOPSIM: M.Rubin et al (2010): 2-loop master integrals for qq->VV: T.Gehrman et al (1306.6344), WZj@NLO from MCFM or VBFNLO
- LOOPSIM produces approximate 2-loop virtual corrections needed to cancel IR uncertainties.

WZ@nNLO (approximate NNLO) at the 14 TeV LHC

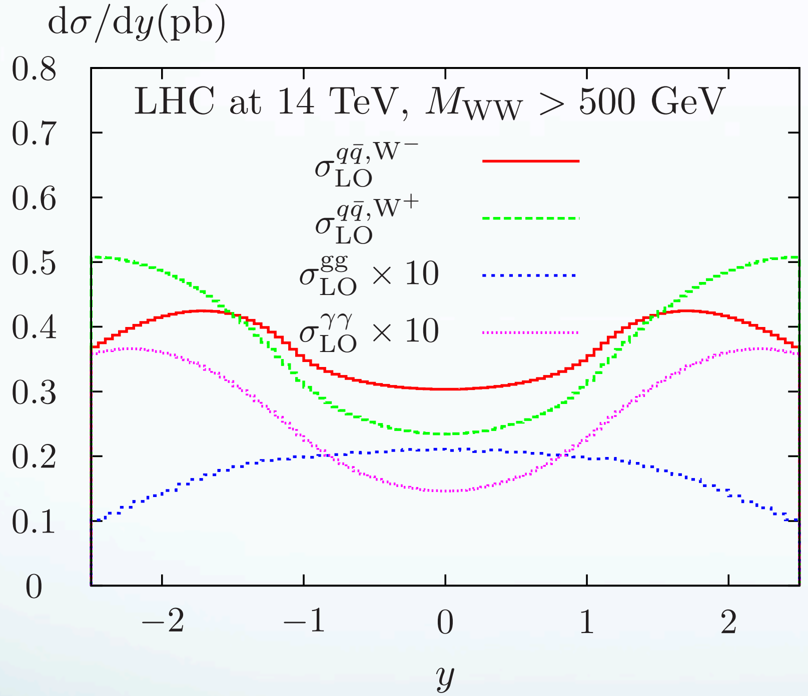


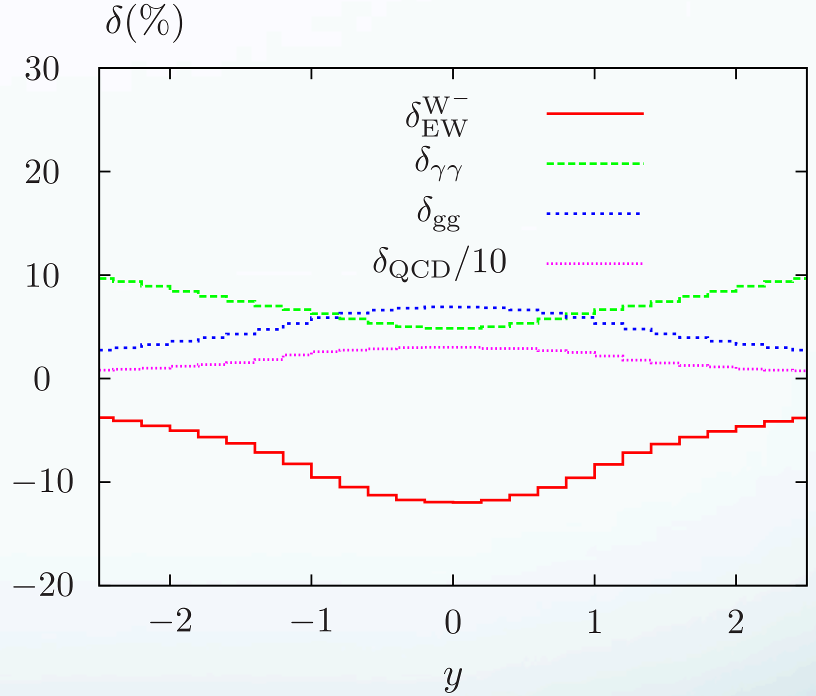
$$p_{T,\ell} \geq 15(20), \quad |y_l| \leq 2.5, \quad E_{T,\text{miss}} > 30\,\text{GeV}, \quad 60 < m_{l^+l^-} < 120\,\text{GeV}$$

Campanario *et al*,1307.2261

pp➔W⁺W⁻ at NLO EW at the LHC

W rapidity LO distributions and relative NLO EW corrections for different initial states:





Bierweiler *et al*, 1208.3147; WZ,ZZ: 1305.5402

NLO predictions for processes with high multiplicity

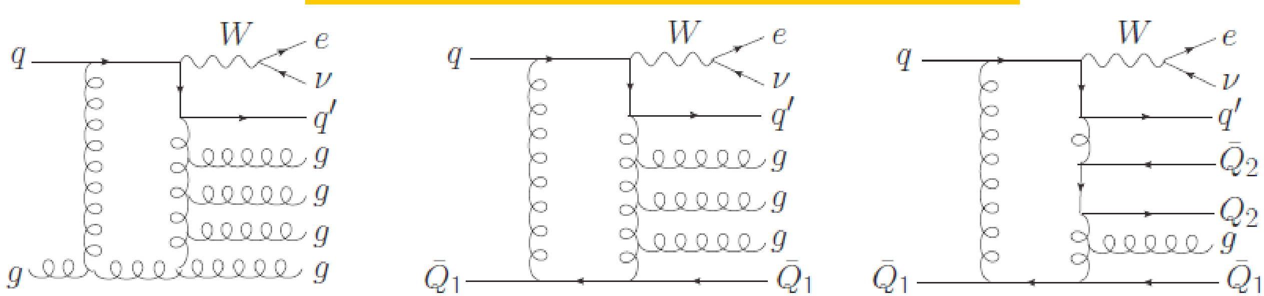
NLO QCD with Blackhat+Sherpa

From talk by F. Febres Cordero at LoopFest 2013:

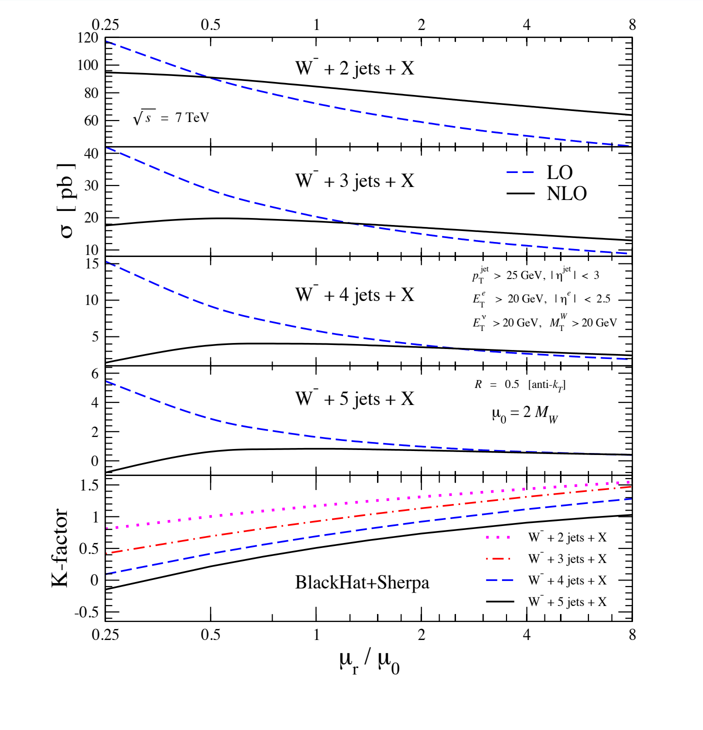
W+5 Jets Calculation Setup

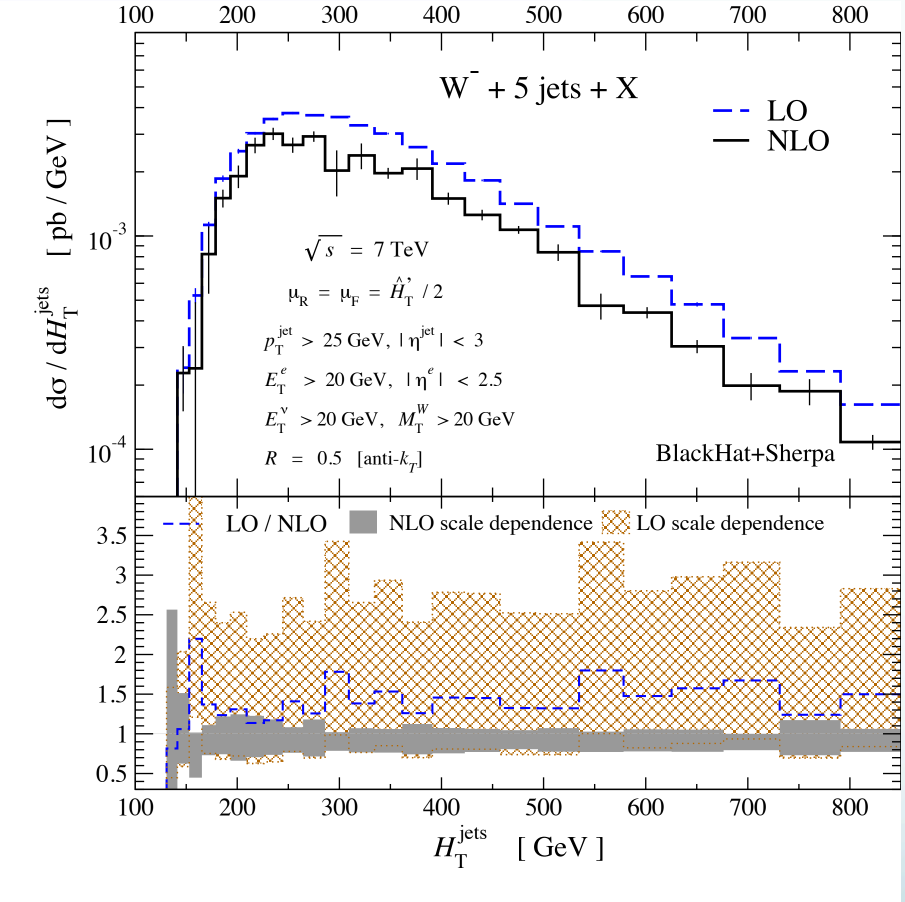
$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

Sample of Loop Parent Diagrams



W+5 jets@NLO QCD





Z.Bern *et al.*, arXiv:1304.1253

Electroweak 1-loop corrections to Z/W+n jets

- Exact 1-loop EW corrections are known for W/Z+1 jet Kuhn et al, hep-ph/057178, 0708.0476; Denner et al, 1211.507,0906.1656
- and for Z+2 jet (only gluonic contributions, 4-quark contributions in progress) , Actis et al, arXiv:1211.6316
- At energy scales above the electroweak scale EW corrections are dominated by weak Sudakov logarithms

for a review see, e.g., H.Kuhn, Acta Physica Polonia B39(2008); talk by S.Dittmaier at Les Houches 2013

- Weak 1-loop Sudakov corrections to Z+1,2,3 jets production are now implemented in Alpgen 1.4.1.2, Chiesa *et al*. arXiv:1305.6837

Weak Sudakov logs: $(\alpha_w/\pi)^l \, Log^n(Q^2/M^2), n \leq 2l$

- Origin: remnants of UV singularities after renormalization and soft/collinear emission of real and virtual W and Z bosons.

- In contrast to QED and QCD, these corrections do not cancel in inclusive observables Ciafaloni, Ciafaloni, Comelli (2000)

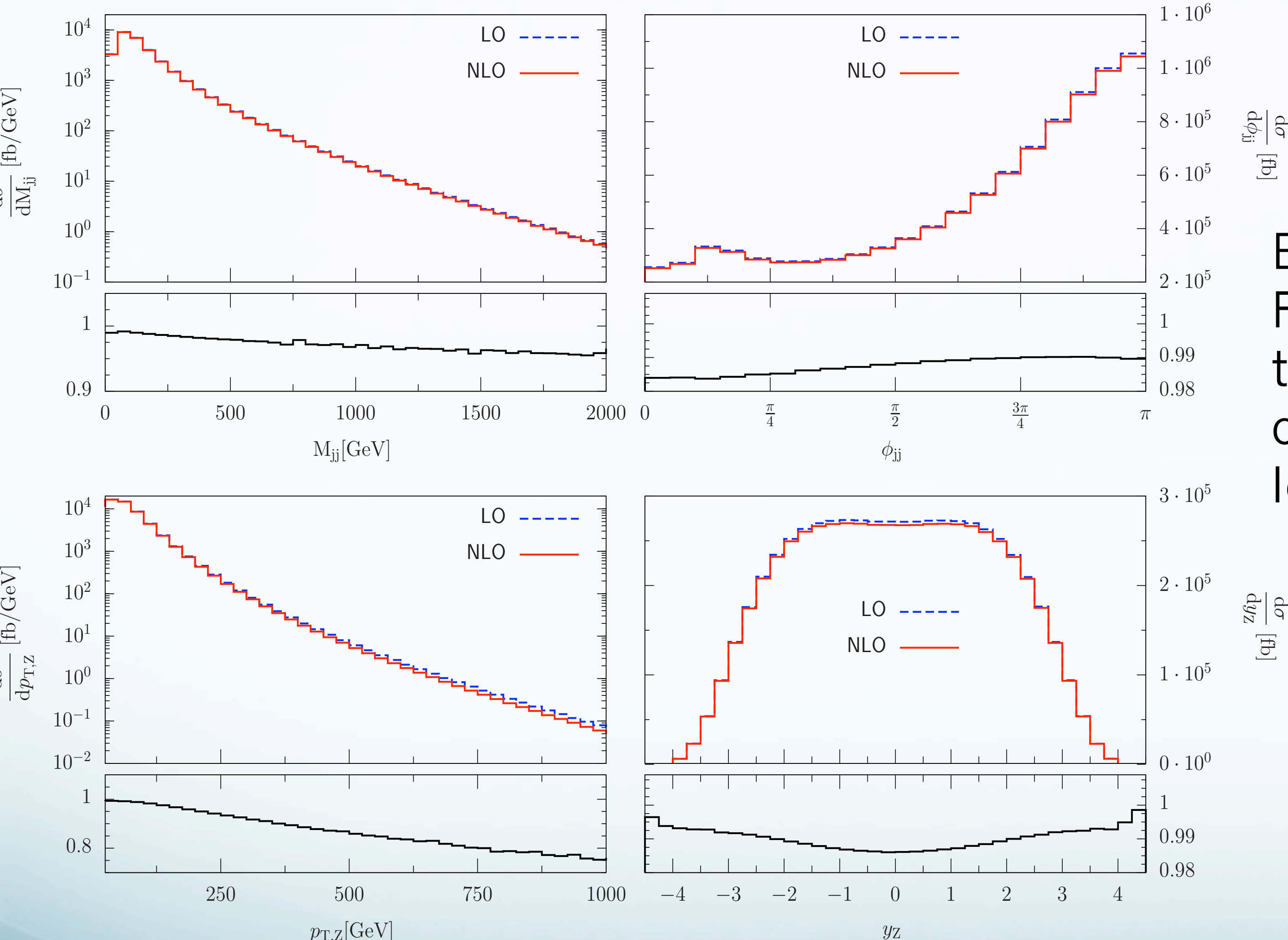
In the high-energy limit, $\frac{Q}{M_{W,Z}} \to \infty$, EW Sudakov logarithms have been studied in analogy to soft/collinear logarithms in QED,QCD.

- 1-loop: LL and NLL are universal and factorize Denner, Pozzorini (2001)
- Beyond 1-loop: Resummation techniques based on IR evolution equations (IREE) or SCET yield results up to NNLL ($ln^n(\frac{s}{M_W^2}), n = 2, 3, 4$).
  - IREE: EW theory splits into symmetric $SU(2) \times U(1)$ ($M_W = M_Z = M_\gamma = M$ for $\mu > M$) and QED regime and effect of EW symmetry breaking neglected. Fadin, Lipatov, Martin, Melles (2000)
  - SCET: At $\mu = Q$ match full theory to SCET($M = 0$), evolve to $\mu = M$ SCET($M \neq 0$), match to SCET with no gauge bosons.
  - SCET and IREE Sudakov form factors are equivalent. Chiu, Golf, Kelley, Manohar (2008); Chiu, Fuhrer, Hoang, Kelley, Manohar (2009); Chiu, Fuhrer, Kelley, Manohar (2010), Fuhrer et al (2011)

Resummation results at LL and NLL confirmed by explicit diagramatic one-loop and two-loop calculations.

Melles (2000), Hori et al (2000), Beenakker, Werthenbach (2000,2002), Pozzorini (2004); Feucht et al (2003,2004); Jantzen et al (2005,2006); Denner et al (2003,2008)

Z+2j @ NLO EW at the 8 TeV LHC

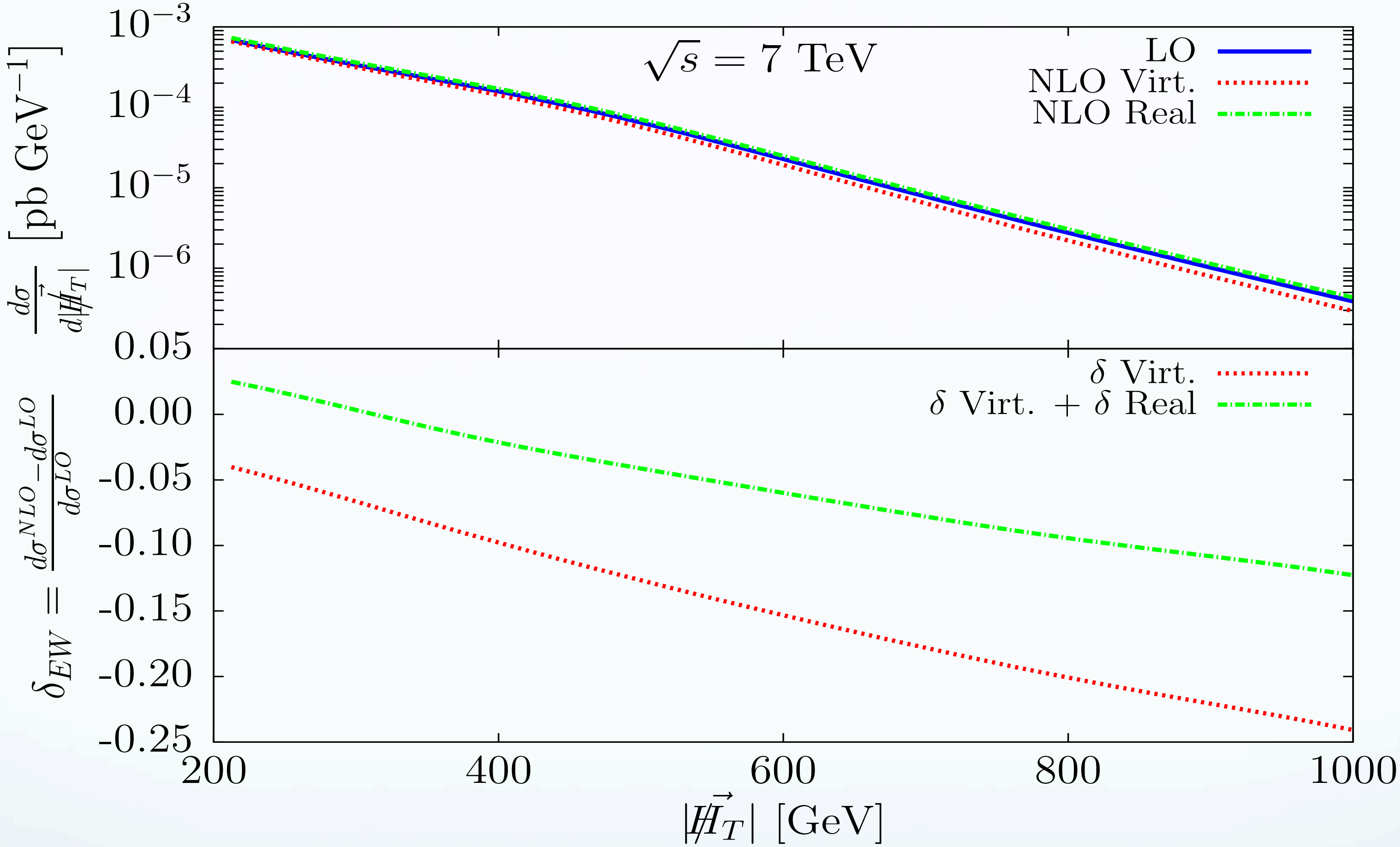


Based on REcola: Fortran90 code for the recursive calculation of one-loop amplitudes

Actis et al, arXiv:1211.6316

$$p_{T,\text{jet}} > 25\,\text{GeV}, \qquad |y_{\text{jet}}| < 4.5$$

Z+3j: Weak 1-loop Sudakov corrections in Alpgen



$H_T > 500$ GeV $\quad |\vec{H\!\!\!/}_T| > 200$ GeV $\quad \vec{H\!\!\!/}_T = -\sum_i \vec{p}_{t\,i},$

$p_T^j > 50$ GeV $\quad |\eta_j| < 2.5 \quad \Delta R_{(j_i, j_k)} > 0.5$

$\Delta\phi(\vec{p}_T^{\,j_1,j_2}, \vec{H\!\!\!/}_T) > 0.5 \quad \Delta\phi(\vec{p}_T^{\,j_3}, \vec{H\!\!\!/}_T) > 0.3$

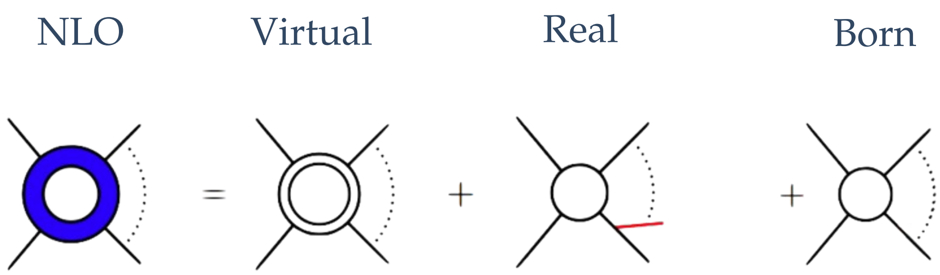
Chiesa *et al*. arXiv:1305.6837

Automation of NLO predictions: “Madgraph for loops”

aMC@NLO

Talk by O.Mattelaer at LoopFest 2013:

NLO Basics



$$\sigma^{NLO} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

Need to deal with singularities

$$\sigma^{NLO} = \int_m d^{(d)}\left(\sigma^V + \int_1 d\phi_1 C\right) + \int_{m+1} d^{(d)}\left(\sigma^R - C\right) + \int_m d^{(4)}\sigma^B$$

MadLoop **MadFKS** **MadGraph**

MadLoop based on CutTools (OPP reduction method)

Ossala, Papadopoulos, Pittau (2006)

aMC@NLO

http://amcatnlo.web.cern.ch/amcatnlo/

Talk by O.Mattelaer at LoopFest 2013:

results

- Errors are the MC integration uncertainty only
- Cuts on jets, γ*/Z decay products and photons, but no cuts on b quarks (their mass regulates the IR singularities)
- Efficient handling of exceptional phase-space points: their uncertainty always at least two orders of magnitude smaller than the integration uncertainty
- Running time: two weeks on ~150 node cluster leading to rather small integration uncertainties

	Process	μ	n_{lf}	Cross section (pb)	
				LO	NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+\, j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ\, j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

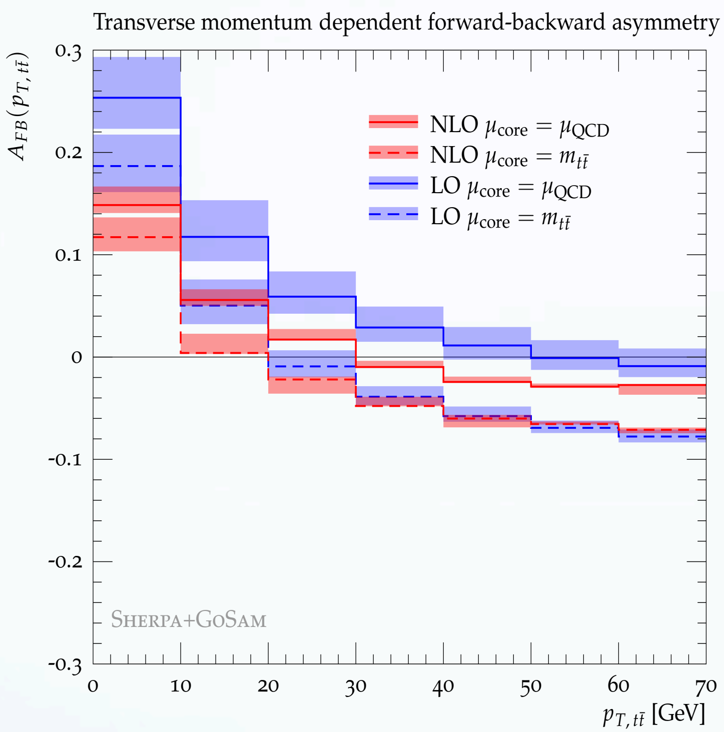
NLO and PS merging

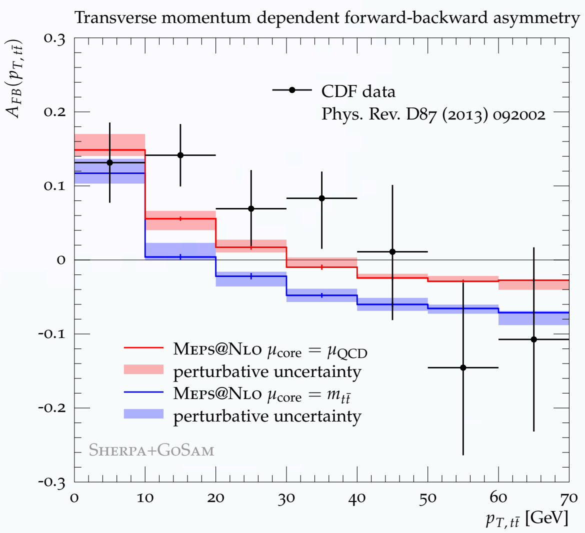
Merging of multiple NLO QCD calculations with different jet multiplicity with PS in Sherpa

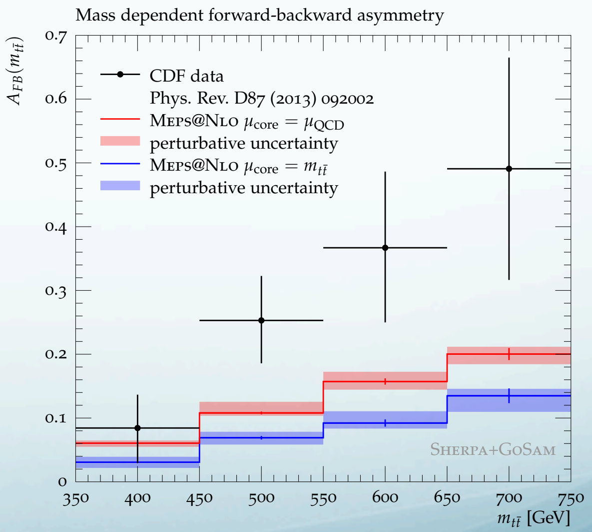
- Recent application: 0+1jet combined NLO analysis of A_{FB} in top-pair production
- MEPS@NLO: combines multiple NLO with PS => merged simulation of **t t** and **t t** +jet production which preserves both the NLO accuracy of the fixed-order prediction and the logarithmic accuracy of the parton shower
- GOSAM (Samurai+Golem): virtual NLO QCD corrections (interface to Sherpa with BLHA) G.Cullen et al. 1111.2034
- MC@NLO automated in Sherpa: modified subtraction to avoid overlap between NLO and PS

S.Hoche et al, 1306.2703

$A_{FB}(P_T)$ and $A_{FB}(M_{tt})$: Comparison with CDF data







S.Höche et al, 1306.2703

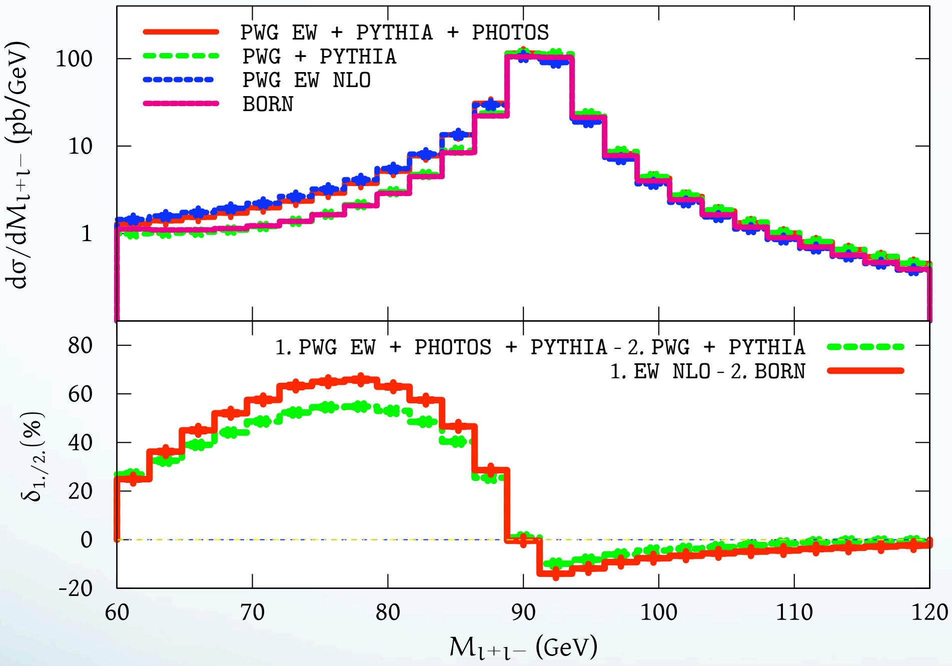
Combining QCD and EW NLO predictions

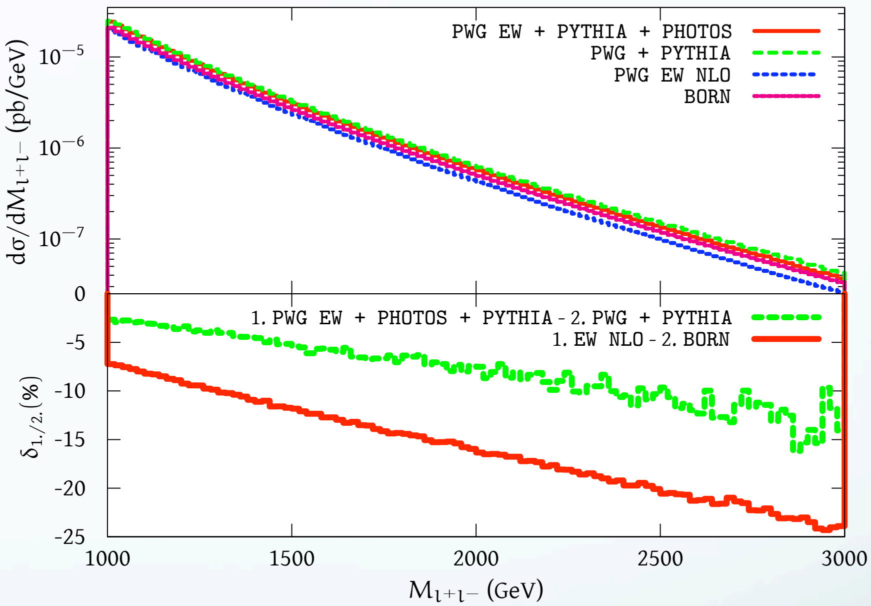
NLO EW×QCD to W and Z production in POWHEG

$$d\sigma = \sum_{\text{flavors}} \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\text{min}}) + \sum_{\alpha_r} \frac{\left[d\Phi_{\text{rad}} \Delta(\Phi_n, k_T > p_T^{\text{min}}) R(\Phi_{n+1}) \right]}{B(\Phi_n)} \right\}$$

- Implementation in POWHEG-W by Bernaciak et al 1201.4804 and Barze et al. 1202.0465
- New: Implementation in POWHEG-Z by Barze et al, 1302.4606

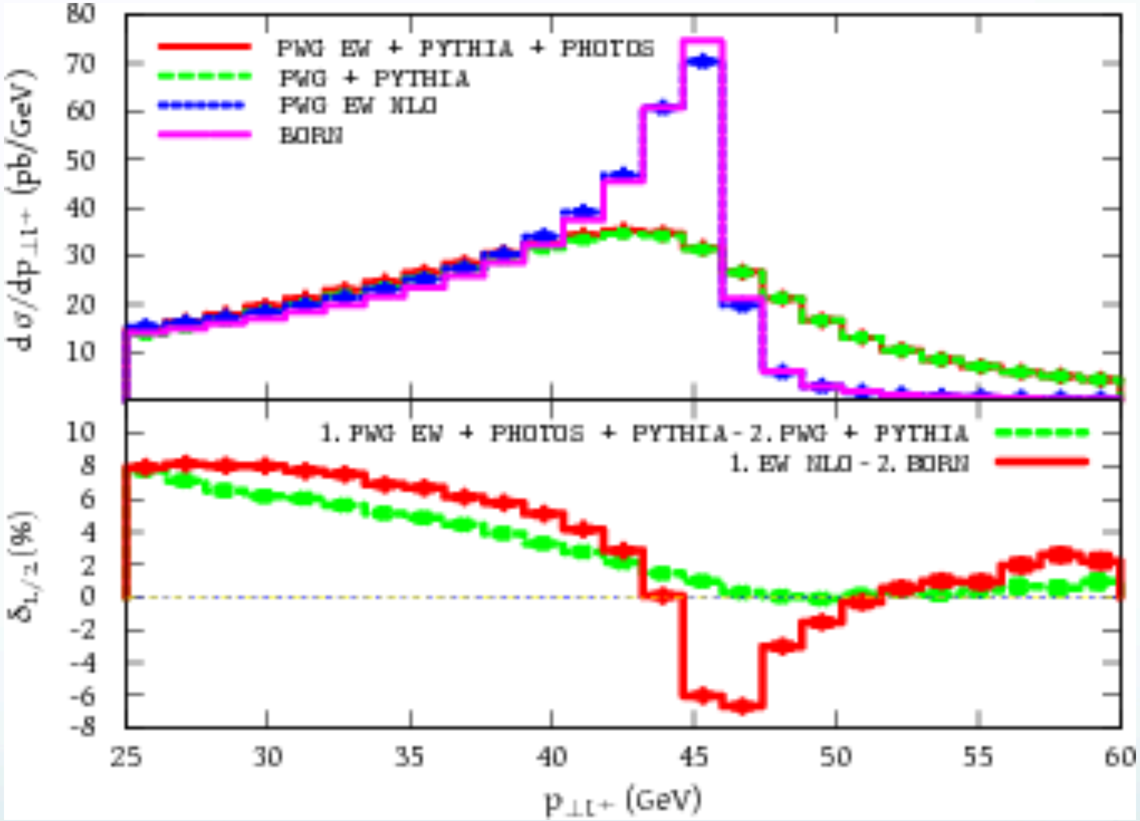
Impact of NLO EW in presence of QCD corrections on M(ll) in pp->γ,Z->l^+l^- at the LHC





Barze *et al*, 1302.4606

Impact of NLO EW in presence of QCD corrections on P_T(lepton) in pp-> γ Z->l^+l^-



Barze *et al*, 1302.4606

Instead of conclusions an invitation (see also J.Rosners' talk)

- **Snowmass Study group: Quantum Chromodynamics and the Strong Force**
- Conveners: John Campbell,Kenichi Hatakeyama, Joey Huston, Frank Petriello
- Selection of questions (see Snowmass webpage): What are the prospects for future higher order calculations at NLO and matched with parton showers? What subtleties remain to be understood for precision measurements? What is the best way to distribute the results of complex NLO, and emerging NNLO, calculations to the experimental community? Survey of the importance of electroweak corrections (both those already calculated and possible impact of as-yet uncalculated contributions).

Instead of conclusions an invitation

- **Snowmass study group: Precision Study of Electroweak Interactions**
- Conveners: Ashutosh Kotwal, Michael Schmitt, D. W.
- Charge (see webpage for more details): Identify the most important precision observables that can reveal deviations from the standard model. Identify the thresholds of precision that needs to be achieved for each of these observables in order to be definitively sensitive to new physics. Study the precision that can be achieved at each proposed facility on these observables, and ask what machine and detector parameters are required to reach the discovery threshold. Identify the calculational tools needed to predict standard model rates and distributions in order to perform these measurements at the required precision.