Electroweak radiative corrections for collider physics

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thanks to discussions with C.M. Carloni Calame, M. Chiesa and G. Montagna

- previous talks already discussed several aspects/results related to EW corrections at colliders

Nadolsky, Ubiali, Campbell, Maltoni, Höche, Freitas, Hollik

- in the following I will discuss some additional issues trying to minimize overlap

Why electroweak corrections?

- LHC run2 has entered the precision phase (i.e. $\frac{\delta O}{O} \sim \%$) for several observables $\Longrightarrow$ NLO EW corrections become relevant ($\alpha_{e.m.} \sim \alpha_s^2$)
    - even more true for observables (partially) insensitive to QCD corrections, e.g.
        - Higgs decays to four leptons
        - transverse mass in the charged DY process
- from Les Houches wish/precision lists $\Longrightarrow$ a large number of processes should be known at QCD NNLO & NLO EW J. Huston
- indeed on the NLO side, EW radiative corrections to $2 \to 2$, $2 \to 3$ and few $2 \to 4$ processes are already known J.M. Campbell
- LHC run2 is exploring (with enough statistics) regions of phase space with scales $Q^2 >> M_W^2 \Longrightarrow$ dominance of Sudakov logarithms $\alpha \log^2\left(\frac{|Q^2|}{M^2}\right)$
- Which are the ingredients of any EW higher order calculation? $\Longrightarrow$

input parameters (in the gauge sector)

- we need to give a consistent set of three input parameters
- the more precise parameters would be $\alpha(0)$, G_μ and M_Z, as done for instance for LEP calculations
- but in this scheme M_W is a derived quantity
- if we need to measure M_W independently at the collider, it is better to have it as an input parameter
- the original on shell scheme could be ideal: $\alpha(0)$, M_W, M_Z
- but...
  - it maximizes the corrections because it contains terms proportional to $\Delta\alpha \sim 6\%$ (the running of the electromagnetic coupling from zero to the M_Z scale) and $\Delta\rho$ ($\sim G_\mu m_t^2 \sim 1\%$)
  - the scheme that minimizes the RC (i.e. the bulk of them is absorbed in the LO prediction) is the G_μ scheme:

$$\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_W^2 (1 - M_W^2/M_Z^2)}{\pi} \simeq \alpha(0)(1 + \Delta r)$$

  - the coupling of the real photon should however be kept $\alpha(0)$, rescaling accordingly the virtual cross section to ensure IR cancellation

Unstable particle mass treatment

- massive gauge bosons, top quarks and Higgs boson have finite widths, which are included in the tree level contributions
- a scheme is needed to account consistently at NLO unstable particles in the loops
- The most satisfactory scheme is the Complex Mass Scheme
  - LO calculations — Denner et al., hep-ph/0206070
  - NLO calculations — Denner et al., hep-ph/0505042
- the CMS scheme allows to keep under control the cancellation of IR singularities betwen virtual and real contributions
- the CMS can be easily implemented in automated NLO calculations
- in this scheme the input masses are the positions of the complex poles (not the on-shell values, with running widths, measured at LEP, Tevatron)

$$M_V^{OS} \to \frac{M_V}{\sqrt{1+(\frac{\Gamma_V}{M_V})^2}} \qquad \Gamma_V^{OS} \to \frac{M_V}{\sqrt{1+(\frac{\Gamma_V}{M_V})^2}}$$

$$\Delta M_Z \sim 34 \text{ MeV} \qquad \Delta\Gamma_Z \sim 1 \text{ MeV}$$

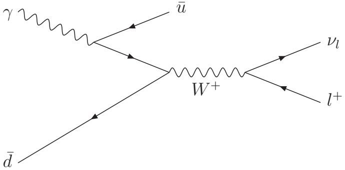
$$\Delta M_W \sim 27 \text{ MeV} \qquad \Delta\Gamma_W \sim 1 \text{ MeV}$$

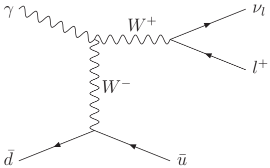
IR singularities

- being the photon massless, QED IR soft singularities as for QCD
- several calculations existing in the literature adopt the mass scheme for the regularization IR soft and collinear singularities: photon mass and fermionic masses
  - for IS collinear singularities this entails a redefinition of the PDF's to subtract collinear $\log(\frac{Q^2}{m_q^2})$
  - final state collinear $\log(\frac{Q^2}{m_l^2})$ are "physical" for exclusive observables; different effects for muons or electrons:
    - muons are detected through a magnetic field $\Longrightarrow$ they are well separated from the emitted photons (enhanced QED RC)
    - electrons are detected through a calorimetric measurement, which is sensitive to the sum of momenta of electron and collinear photons ($\log(\frac{Q^2}{m_l^2})$ partially screened, the detector sees an electromagnetic jet)
    - this is at the idea behind the schemes that use dimensional regularization for IR soft divergences and IR collinear div. from quarks but keep finite lepton masses
    - when experimental observables are defined in terms of "dressed" leptons also lepton masses can be set to 0 (this is the simplest choice for the recent automatic tools)

Photon induced processes

- at the same perturbative order of real NLO corrections contribute diagrams with γ in the initial state



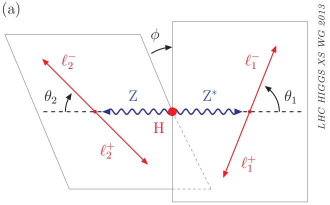


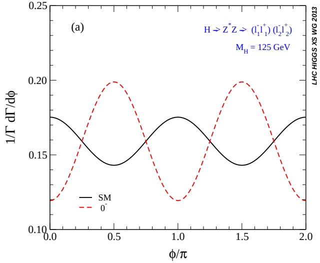
- for neutral systems of charged F.S. particles also contributions at tree level (e.g. $\gamma\gamma \to \mu^+\mu^-$ or $\gamma\gamma \to W^+W^-$)
- typically they become relavant for large invariant mass of the system and forward kinematics

Disentangling QED from weak corrections

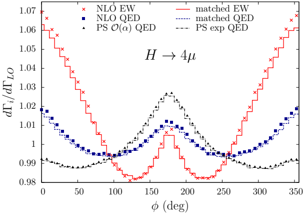
- when the tree-level is mediated by neutral currents we can separate in a gauge invariant way weak corrections from QED
- Leading Logs $\sim \alpha \log\left(\frac{Q^2}{m^2}\right)$ related to QED emissions from external fermions are in any case separated from weak corrections
- in presence of resonances, e.g. $W/Z/H$, QED corrections by far dominant and higher orders becomes necessary
- different methods to treat higher order photonic corrections
  - QED parton shower
  - QED structure functions in collinear approximation
  - YFS formalism
- aiming at precision, QED LL higher order corrections have to be matched to NLO EW corrections
  - for hadronic collisions QED NLOPS accuracy available for DY processes and Higgs decay

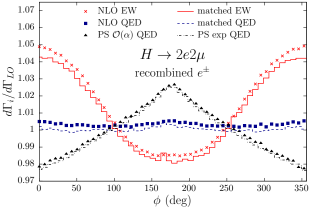
But not always dominance of QED. Example: $H \to 4l$





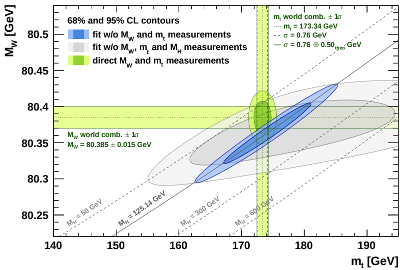
LHC Higgs Cross Section WG, arXiv:1307.1347



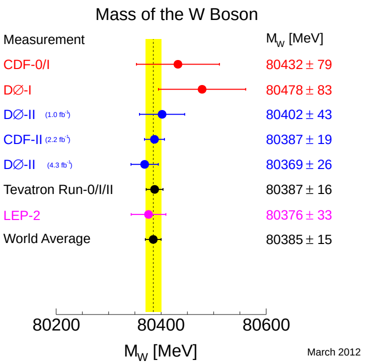


S. Boselli et al, arXiv:1503.07394

M_W direct measurement: crucial for a SM stress-test



Gfitter, EPJC 74 (2014) 3046



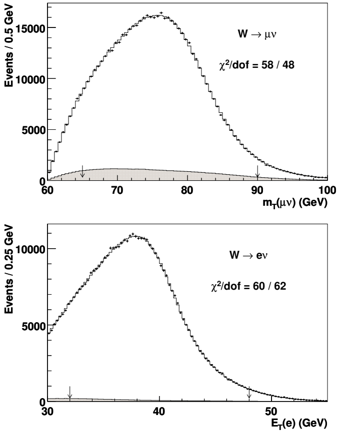
TeVatron EWWG, arXiv:1204.0042

- A precise ($\delta M_W < 10$ MeV) M_W measurement at LHC Run2 and beyond will be an important goal of the LHC precision physics pogramme [1]
- DY processes have the smallest experimental errors at hadron colliders

[1] CMS delivered recently the first W-like M_Z mass measurement @$\sqrt{s}$ =7 TeV (CMS-PAS-SMP-14-007)

M_W measurement: relevant observables

- M_W from the $p_\perp^\ell$ distribution, showing a (Jacobian) peak at $M_W/2$
- more reliable is $M_T^W = \sqrt{2p_\perp^\ell p_\perp^\nu (1 - \cos\phi_{\ell\nu})}$ (**mildly sensitive to QCD RC**)



2.2/fb, CDF, PRL 108 (2012) 151803

- M_W is extracted with a template fit technique to M_T and/or $p_\perp^\ell$ distributions

⋆ EW corrections (mainly QED FSR) can distort the shape → the extracted M_W is affected

⋆ with high lumi the lepton $p_\perp^\ell$ can be experimentally convenient (smaller uncertainties in E_{miss}^T from pile up)

EW RC calculations and MC tools for DY

- Calculations
  1. Baur, Wackeroth, et al., PRD 65 (2002) 033007, PRD 70 (2004) 073015
  2. Dittmaier, Krämer, PRD 65 (2002) 073007
  3. Jadach, Płaczek, EPJC 29 325 (2003), D. Bardin et al., Acta Phys. Polon. B40 (2009) 75
  4. Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0612 (2006) 016, JHEP 0710 (2007) 109
  5. Arbuzov et al., EPJC 46, 407 (2006), EPJC 54 (2008) 451
  6. Dittmaier, Huber, JHEP 1001 (2010) 060

- Tools
  1. **Z/WGRAD**, NLO EW to CC and NC DY
  2. **DK**, NLO EW to CC DY
  3. **WINHAC**, NLO EW + multiple photon to CC DY
  4. **HORACE**, NLO EW + matched multiple photon emission to CC and NC DY
  5. **SANC**, NLO EW to CC and NC DY
  6. **RADY**, NLO EW + MSSM to NC DY

Work in progress

PRELIMINARY

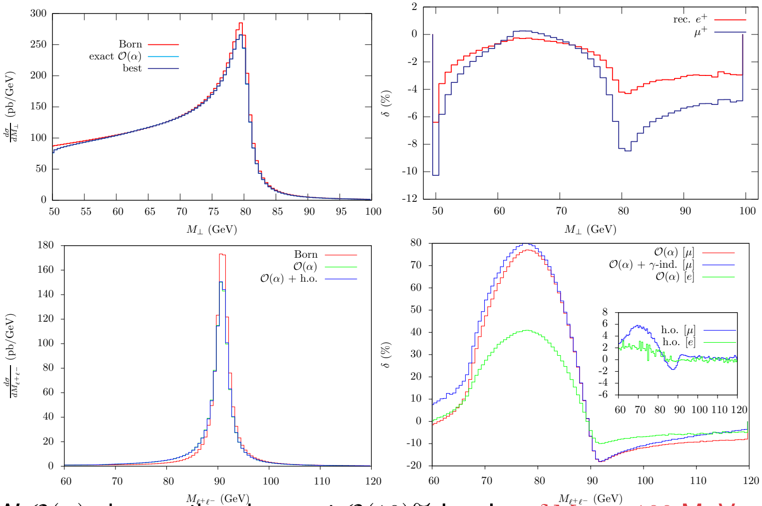
Precisions Studies of Observables in $pp \to W \to l\nu_l$ and $pp \to \gamma, Z \to l^+l^-$ processes at the LHC

coordinated by A.Vicini, D. Wackeroth

Within the LPCC EW WG activities, a report is being finalized aiming at

- ⋆ providing a benchmark framework for precise studies of DY observables, with tuned setup, reproducible results from several MC tools/calculations and comparisons among them
- ⋆ mantainining a repository of codes "blessed" by the authors to calculate QCD NNLO, QCD NLO, EW NLO, mixed EW⊗QCD, multi-photon corrections

Effects of EW corrections: W and Z production



- EW $\mathcal{O}(\alpha)$ change the shape at $\mathcal{O}(10)\%$ level $\rightarrow \delta M_W \simeq 100$ MeV
- also multi-photon emission is important $\rightarrow \delta M_W \simeq -10$ MeV

Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0710 (2007) 109

mixed QCD - EW corrections

- Perturbatively the QCD - EW interference is a two-loop effect

$$
\begin{aligned}
d\sigma &= d\sigma_0 \\
&+ d\sigma_{\alpha_s} + d\sigma_{\alpha} \\
&+ d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \ldots
\end{aligned}
$$

- the $\mathcal{O}(\alpha\alpha_s)$ calculation involves as building blocks
  - NNLO virtual corrections at $\mathcal{O}(\alpha\alpha_s)$ (not yet available)
    - necessary two-loop master integrals (with $m = 0$ external particles and $M_W = M_Z$) just appeared

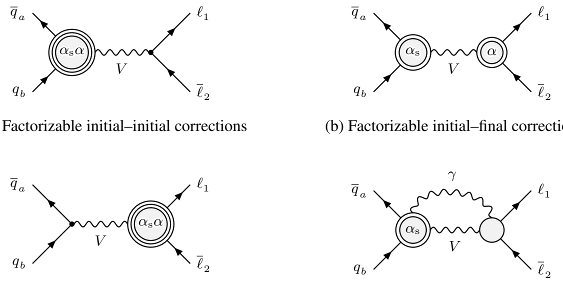
      R. Bonciani et al., arXiv:1604.08581
  - NLO EW corrections to $l\bar{l}^{(\prime)}$+ jet
  - NLO QCD corrections to $l\bar{l}^{(\prime)} + \gamma$
  - double real contributions $l\bar{l}^{(\prime)} + \gamma$+ jet
  - PDF's with NNLO accuracy at $\mathcal{O}(\alpha\alpha_s)$ (not yet available)
- what is available:
  - dominant $\mathcal{O}(\alpha_s\alpha)$ corrections to DY in pole approximation

    Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216
  - Monte Carlo estimates through NLO QCD $\otimes$ NLO EW (with higher orders)

    L. Barzè et al., JHEP 1204 (2012) 037, Eur. Phys. J. C73 (2013) 2474

$\mathcal{O}(\alpha_s\alpha)$ in pole approximation

- two main classes of contributions:
  - factorizable
  - non-factorizable



(a) Factorizable initial–initial corrections

(b) Factorizable initial–final corrections

(c) Factorizable final–final corrections

(d) Non-factorizable corrections

S. Dittmaier, A. Huss and C. Schwinn, arXiv:1601.02027

a) not known but expected to be very small

($\mathcal{O}(\alpha)$ corrections in PA $\Longrightarrow$ $M_\perp$ and $M(l^+l^-)$ insensitive to QED ISR
in addition $M_\perp$ and $M(l^+l^-)$ mildly affected by NLO QCD corrections)

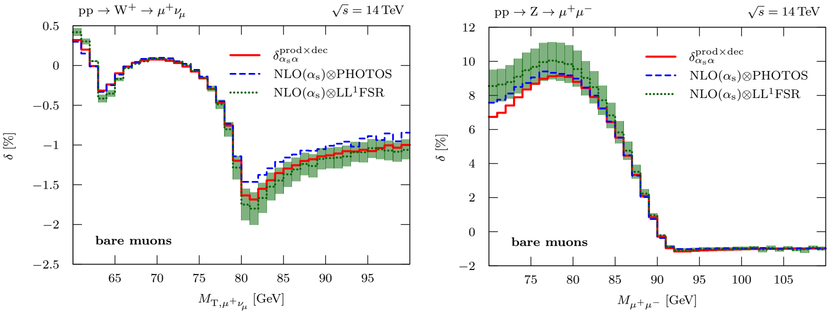
b) this gives the bulk of the contribution

c) no real contributions $\Longrightarrow$ no impact on the shape of $M_\perp$ and $M(l^+l^-)$

d) numerical impact below 0.1%

$\mathcal{O}(\alpha\alpha_s)$ with other factorized approaches

- since the bulk of the $\mathcal{O}(\alpha_s\alpha)$ corrections come from initial-final factorized contributions, it is interesting to compare the PA prediction for $\mathcal{O}(\alpha\alpha_s)$ corrections with the factorized approximation NLO QCD $\otimes$ FSR QED
- FSR QED treated with collinear structure functions or with PHOTOS



Dittmaier, Huss, Schwinn, NPB 904 (2016) 216

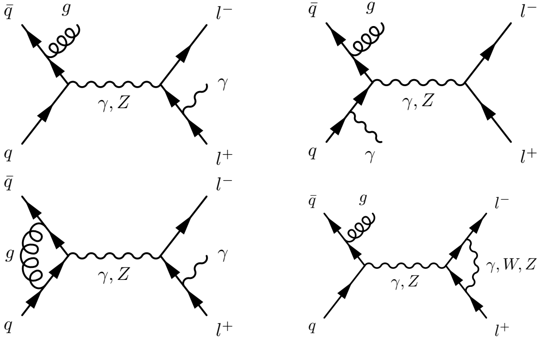
- Actually we already have this level of accuracy in the Monte Carlo $\Longrightarrow$

$\mathcal{O}(\alpha_s \alpha)$ corrections through Monte Carlo

- The POWHEG-BOX includes NLO QCD & EW corrections interfaced to QCD/QED shower, i.e. NLOPS EW $\oplus$ QCD accuracy

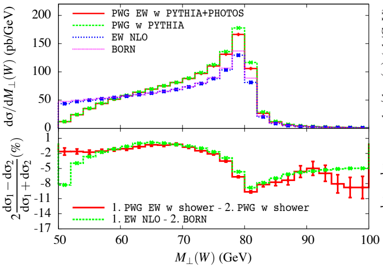
  1. **POWHEG_W_ew_BMNNP**, CC DY — Barzè et al, JHEP 1204 (2012) 037
  2. **POWHEG_W_ew_BW**, CC DY — Bernaciak and Wackeroth, PRD 85 (2012) 093003
  3. **POWHEG_Z_ew_BMNNPV**, NC DY — Barzè et al, EPJC 73 (2013) 6, 2474

- correctly taken into account the NLO contribution with one additional radiation in the soft/collinear limit



Combined EW & QCD corrections for W with POWHEG

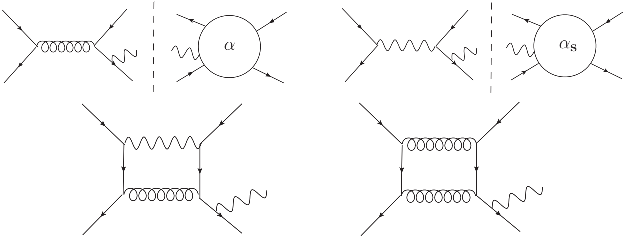
Barzè et al, JHEP 1204 (2012) 037



- EW effect not changed by QCD for M_T at peak, flattened for $p_{\perp}^{\ell}$
- validation of the MC predictions in progress within the CERN LPCC EWWG activities
  - M_W topical meeting at CERN, 8-9 June https://indico.cern.ch/event/533804/timetable/ with updates on POWHEG, OPENLOOPS+SHERPA and GENEVA

Two additional issues in more complicated processes

- Moving from leptonic to generic final states containing partons, two additional features emerge:
  - in processes with at least two quark pairs, the bookkeeping of all contributions becomes more involved. Disentangling QCD from EW corrections becomes difficult. Example: $V + 2$ jets

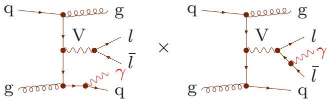


M. Chiesa, N. Greiner, F. Tramontano, arXiv:1507.08579

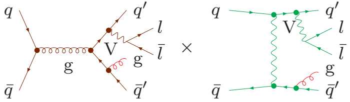
  - real radiation of photons from external final state quarks

Real corrections:

Photon emission from QCD×QCD

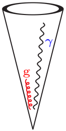


Gluon emission from QCD×EW



- Parton-photon recombination to have QED IR safe results
- Hard-photon jets (containing soft gluon) are QCD IR unsafe

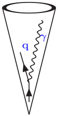
  ⇝ Cut hard-photon jets



- Hard-photons collinear to quarks also cutted → QED IR unsafe
  - Rigorous approach: fragmentation functions

    [Denner, Hofer, Scharf, U. '14]
  - Approximate approach: treate $q\gamma$ with tiny $\Delta R_{q\gamma}$ as quarks

    [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14]



Latest developments in EW NLO Tools:

- Computations of LHC processes at EW NLO:

FEYNARTS/FORMCALC + LOOPTOOLS	$pp \to VV + \mathrm{jet}$ $pp \to VVV$
RECOLA + COLLIER	$pp \to l\bar{l} + 2\ \mathrm{jets}$ $pp \to l\bar{l}\, l'\bar{l}' + X$
OPENLOOPS + COLLIER + MUNICH,SHERPA	$pp \to W + \leq 3\ \mathrm{jets}$ $pp \to l\bar{l}, \nu\bar{\nu}, l\bar{\nu} + \leq 2\ \mathrm{jets}$
MADGRAPH5_AMC@NLO + MADLOOP + CUTTOOLS	$pp \to t\bar{t}\, H$ $pp \to t\bar{t}\, V$
GOSAM	$pp \to W + 2\ \mathrm{jets}$

- COLLIER is now public on https://collier.hepforge.org
- RECOLA (+COLLIER) is now public on https://recola.hepforge.org

A quick look at the Sudakov zone

- NLO EW corrections contain terms of the form

$$DL(s) \sim \frac{\alpha}{4\pi s_W^2} \log^2 \frac{s}{M_W^2}$$
$$SL(s) \sim \frac{\alpha}{4\pi s_W^2} \log \frac{s}{M_W^2}$$

  which become large at high energies
- the structure and universality of LL and NLL corrections at one (and two) loop have been investigated since two decades

P. Ciafaloni and D. Comelli, PLB 446 (1999) 278 and following papers

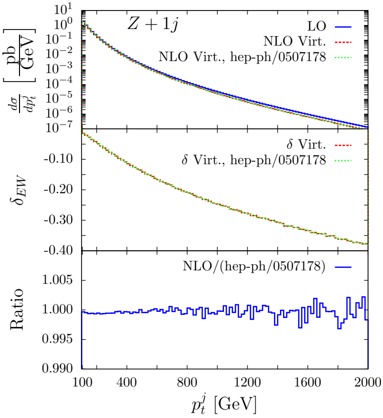
- Denner and Pozzorini algorithm, reliable when all $p_i \cdot p_j >> M_W^2$, able to express the virtual amplitude as a sum over all $SU(2)$ transformed tree-level matrix elements, each multiplied by a universal coefficient, dependent only on the flavour structure and kinematics of the tree-level process

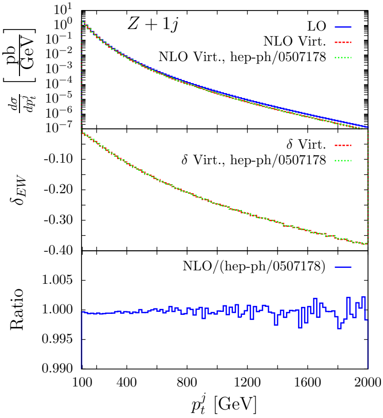
A. Denner and S. Pozzorini, EPJ C18 (2001) 461; C21 (2001) 63

- the algorithm has been implemented in ALPGEN for several processes, e.g. $V+$ multijets, multi-boson $+$ jets, multijets, $Q\bar{Q}+$ jets

M. Chiesa et al., Phys. Rev. Lett. 111 (2013) 121801

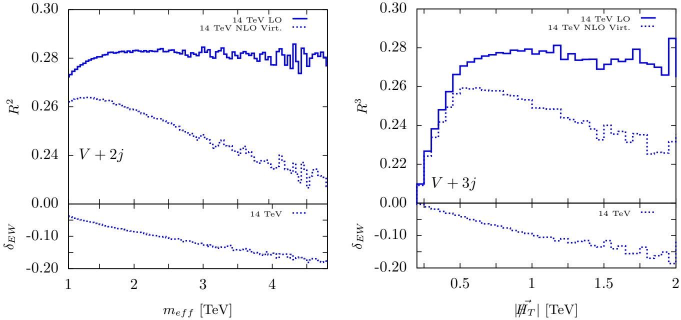
code validation for LHC at 14 TeV





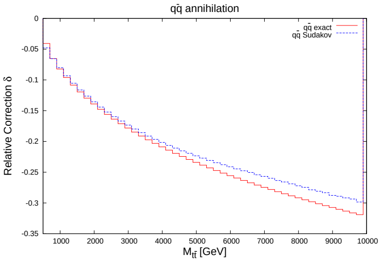
The ratio $d\sigma(Z(\to \nu\bar{\nu}) + n$ jets) / $d\sigma(\gamma + n$ jets)

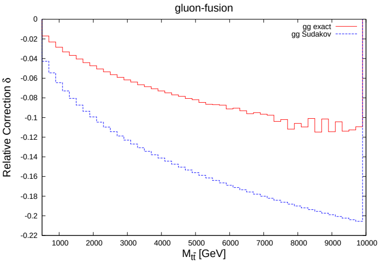
- important calibration quantity for NP searches in E_T^{miss} plus multijets
- PDFs, scale choices, higher order pQCD and hadronization effects largely cancel in the ratio



Warning: high energy not always equivalent to Sudakov zone

- consider the $t\bar{t}$ invariant mass in $t\bar{t}$ production





J.M. Campbell, D. Wackeroth, J. Zhou, arXiv:1508.06247

- while for the $q\bar{q}$ channel the large invariant mass region satisfies the Sudakov zone condition, this is not true for the gg channel. The latter is dominated by the $t-$channel which remains small also for large invariant masses (Regge regime)
- The discrepancy will be reduced with a strong cut on the top-quark $p_\perp$

Apologize for not having discussed because of lack of time

- recent SCET approaches to Sudakov log resummation
- real radiation in the Sudakov regime and log resummation
- recent EW parton shower developments

These issues become even more pressing when pushing the collider energies at the highest conceivable values $\Longrightarrow 100$ TeV