

EW phenomena at the highest Q^2 in p–p collisions at 100 TeV

Fulvio Piccinini

INFN, Sezione di Pavia

ICHEP, Chicago, 3-10 August, 2016

based on arXiv:1607.01831

CERN-TH-2016-112

Physics at a 100 TeV pp collider: Standard Model processes

M.L. Mangano¹, G. Zanderighi¹ (conveners), J.A. Aguilar Saavedra², S. Alekhin^{3,4}, S. Badger⁵, C.W. Bauer⁶, T. Becher⁷, V. Bertone⁸, M. Bonvini⁸, S. Boselli⁹, E. Bothmann¹⁰, R. Boughezal¹¹, M. Cacciari^{12,13}, C.M. Carloni Calame¹⁴, F. Caola¹, J. M. Campbell¹⁵, S. Carrazza¹, M. Chiesa¹⁴, L. Cieri¹⁶, F. Cimiglia¹⁷, F. Febres Cordero¹⁸, P. Ferrarese¹⁰, D. D'Enterria¹⁹, G. Ferrera¹⁷, X. Garcia i Tormo⁷, M. V. Garzelli³, E. Germani²⁰, V. Hirschi²¹, T. Han²², H. Ita¹⁸, B. Jäger²³, S. Kallweit²⁴, A. Karlberg⁸, S. Kuttimalai²⁵, F. Krauss²⁵, A. J. Larkoski²⁶, J. Lindert¹⁶, G. Luisoni¹, P. Maierhöfer²⁷, O. Mattelaer²⁵, H. Martinez⁹, S. Moch³, G. Montagna⁹, M. Moretti²⁸, P. Nason²⁹, O. Nicrosini¹⁴, C. Oleari²⁹, D. Pagani³⁰, A. Papaefstathiou¹, F. Petriello³¹, F. Piccinini¹⁴, M. Pierini¹⁹, T. Pierog³², S. Pozzorini¹⁶, E. Re³³, T. Robens³⁴, J. Rojo⁸, R. Ruiz²⁵, K. Sakurai²⁵, G. P. Salam¹, L. Salfelder²³, M. Schönherr²⁸, M. Schulze¹, S. Schumann¹⁰, M. Selvaggi³⁰, A. Shivaji¹⁴, A. Siodmok^{1,35}, P. Skands²⁰, P. Torrielli³⁶, F. Tramontano³⁷, I. Tsinikos³⁰, B. Tweedie²², A. Vicini¹⁷, S. Westhoff³⁸, M. Zaro¹³, D. Zeppenfeld³²

6 Jul 2016

A study of the features and challenges of SM processes in p-p collisions at
 $\sqrt{s} = 100 \text{ TeV}$

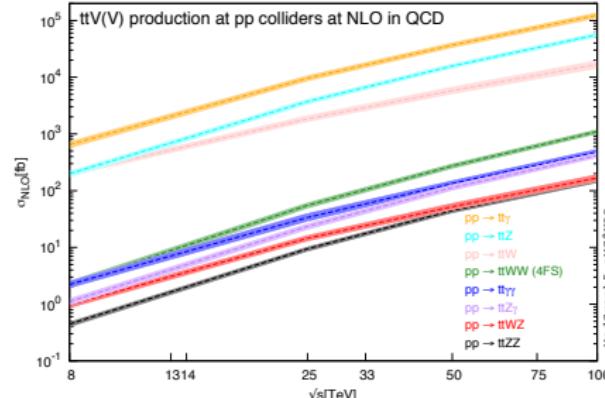
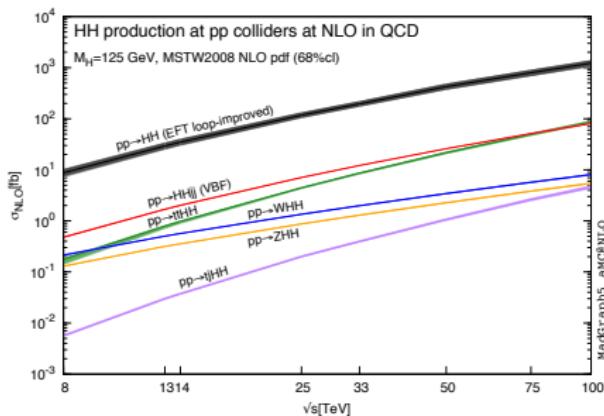
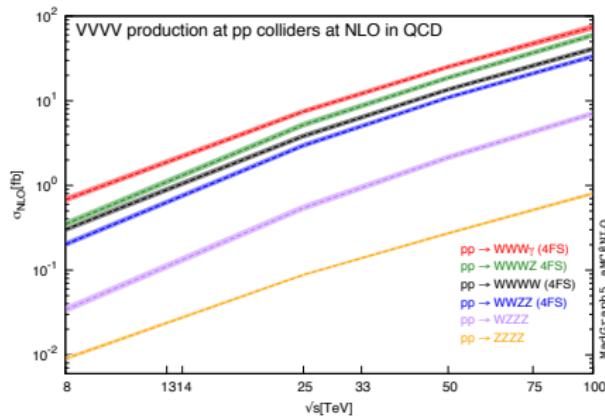
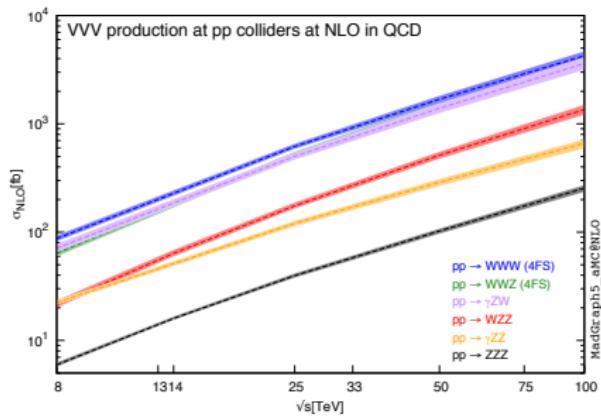
Not quoted in the following all citations to the original material contained in the report

EW phenomena at $\sqrt{s} = 100$ TeV

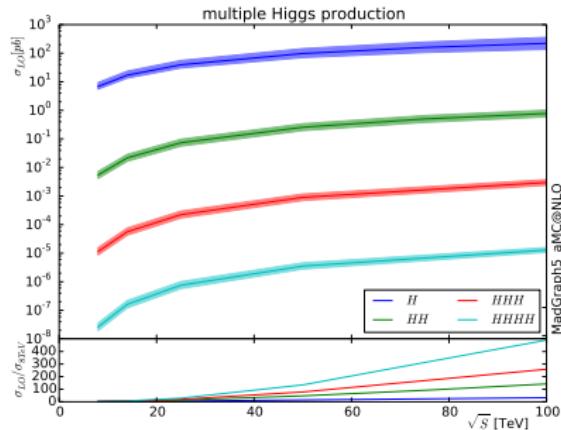
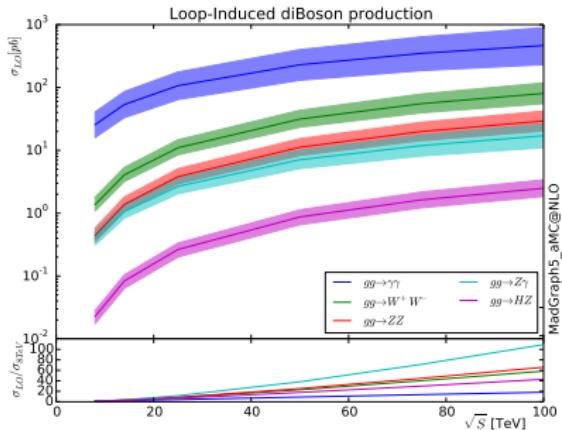
see also talks by M.L. Mangano on Higgs and top-quark physics

- At a 100 TeV p-p collider EW interactions are characterized by new, until now unexplored, features:
 - processes very poorly tested or even not seen at the LHC
 - new processes with multi heavy objects can be easily produced
 - loop-induced processes
 - higher-order electroweak interactions enter a new regime and become necessary to investigate the highest Q^2 available energy regions

multi heavy object production



Loop-induced processes



- All these processes would provide important information on the sectors of the SM not directly tested at the LHC, such as the Higgs self-interactions and quartic gauge and gauge-Higgs couplings

Higher-order EW corrections

- At $\sqrt{Q^2} \lesssim$ EW scale higher order EW corrections to scattering processes are dominated by QED corrections
- genuine EW corrections (exchange/emission of massive gauge bosons) usually $\lesssim \mathcal{O}(\%)$
- for extremely high scales ($\sqrt{Q^2} \gg$ EW scale) EW corrections enter a new regime where they can become very large
- actually virtual EW corrections contain terms of the form

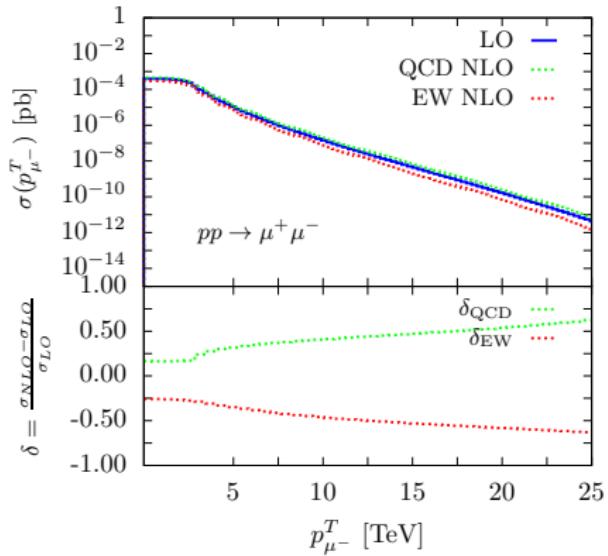
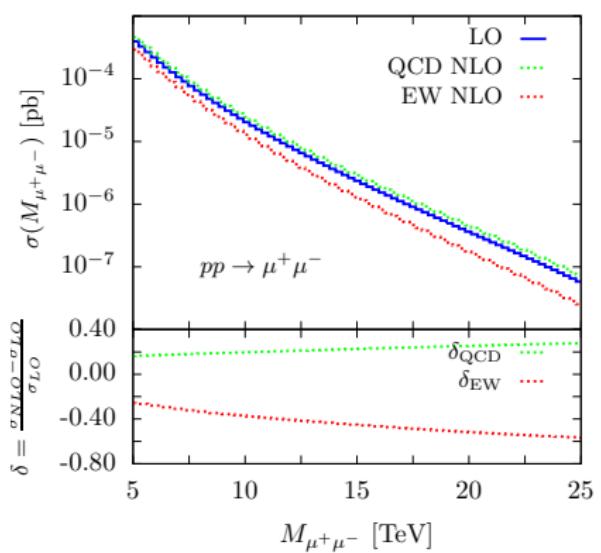
$$\frac{\alpha}{4\pi} \ln^2 \left(\frac{M_V^2}{s} \right) \quad (V = W, Z) \quad \text{Sudakov logs}$$

$\sim 0.3\% @ \sqrt{s} = 1 \text{ TeV} \quad \sim 5\% @ \sqrt{s} = 10 \text{ TeV} \quad \sim 10\% @ \sqrt{s} = 100 \text{ TeV}$

- W/Z masses act as IR cutoff: meaningful to consider only virtual corrections
- Experimentally weak boson emission usually can be separated (see later)
- contrary to IR divergences of QED and QCD, which cancel in inclusive quantities, Sudakov logs do not: final states are not $SU(2)$ singlets
- moreover PDF's give different weights to the initial states
- size of the EW corrections depend on process and observable

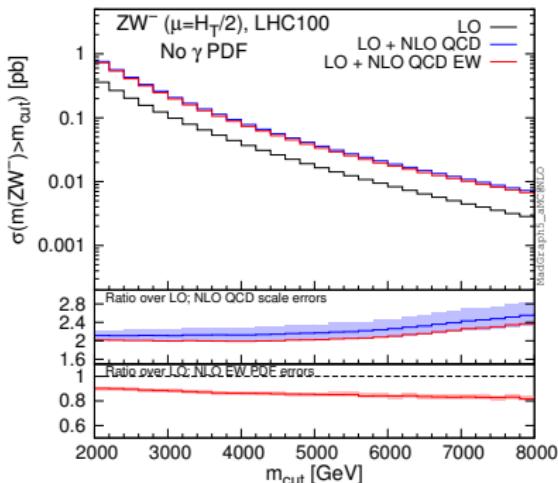
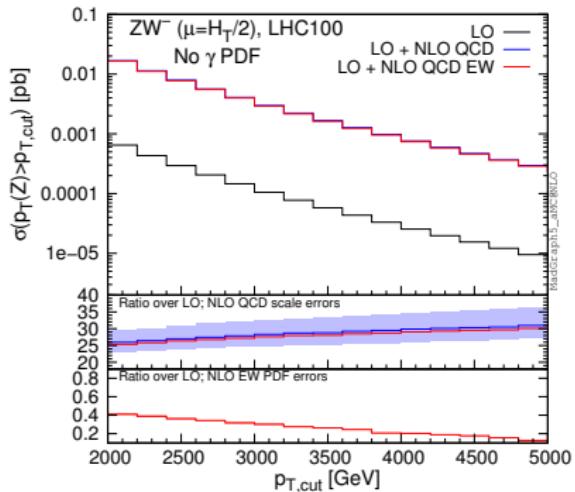
Numerical investigations at 100 TeV done using

- existing codes developed for EW corr's at Tevatron-LHC (HORACE and POWHEG)
- new automated tools able to cope with complex final states @NLO (Madgraph5_aMC@NLO, MUNICH/SHERPA+OPENLOOPS)
- improved version of ALPGEN which implements EW corrections for several processes in the logarithmic approximation (double and single logs)
- with these tools different observables for several key processes have been calculated to quantify the impact of EW corrections



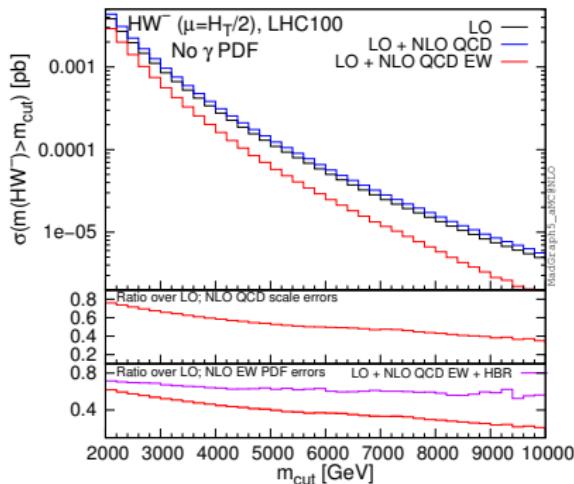
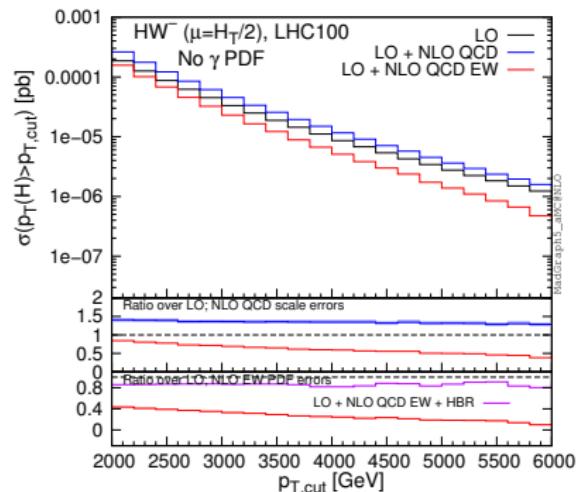
- for invariant masses in the multi-TeV region EW corrections $\sim -50\%$

Diboson production: ZW^-



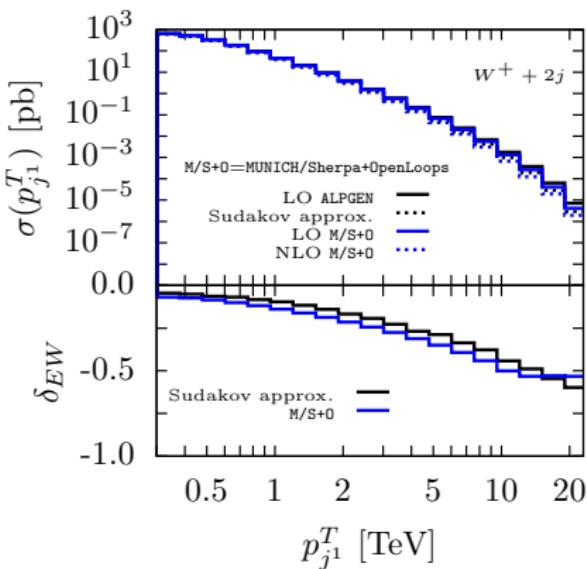
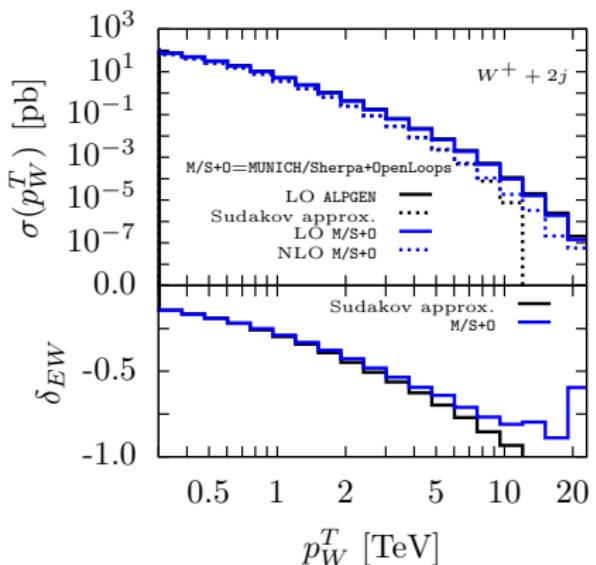
- huge QCD corrections for large p_T^Z : at NLO QCD the dominant configuration is the Z recoiling against a hard parton which emits a soft/collinear $W \implies \alpha_s \ln^2 \frac{p_T^Z}{M_W}$ enhancement
- EW corrections large for p_T^Z and moderate for diboson invariant mass, which is dominated by t -channel configurations with small p_T^Z
- similar effects for W^+W^- and ZZ final states

Higgs associate production: HW^-



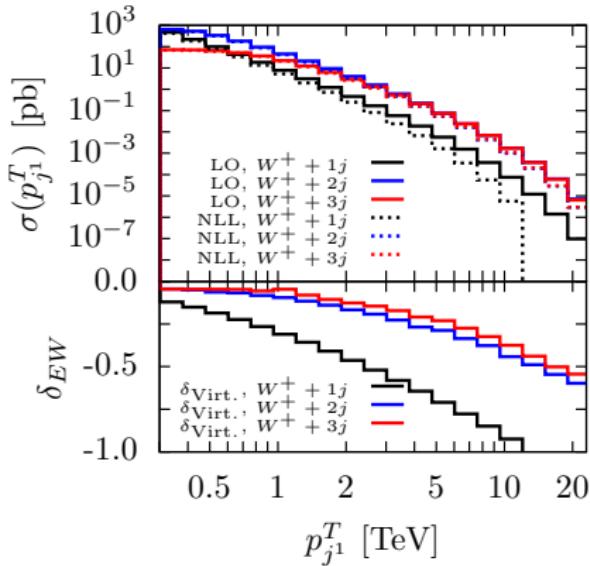
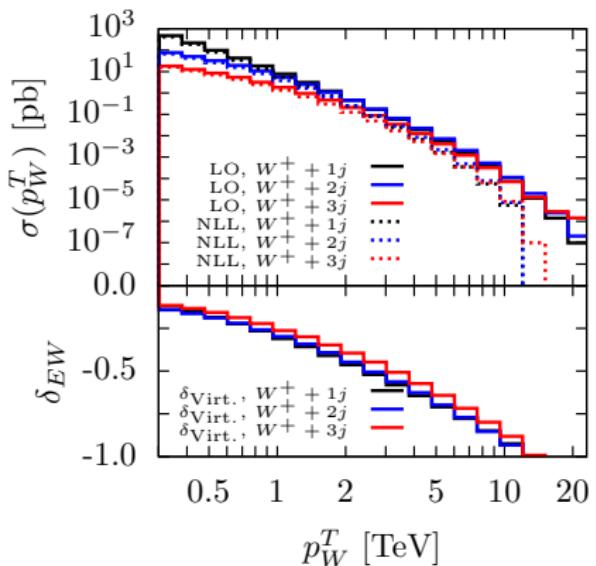
- no strong enhancements on NLO QCD corr's to p_T^H due to absence of tree-level $pp \rightarrow Hj$
- large EW corrections to p_T^H and $m(HW^-)$: no LO t -channel diagrams
⇒ large $m(HW^-) \sim$ large p_T^H
- similar consideration apply to $pp \rightarrow ZH$

$V + 2 \text{ jets}$



- nice agreement between NLO and NLL approximation
- huge corrections on p_W^T , milder on $p_{j^1}^T$
- similar results for $Z + 2$ jets

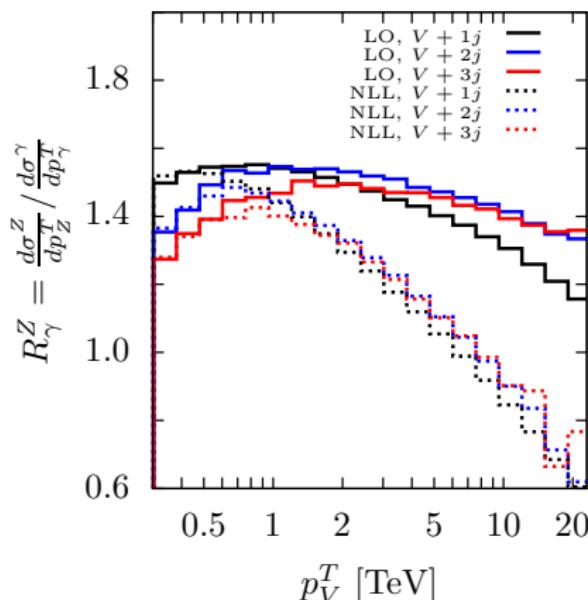
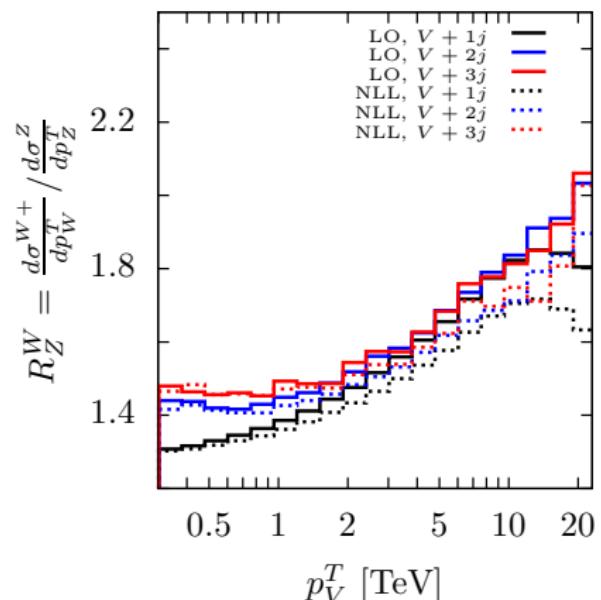
$V + n$ jets, different multiplicities



- corrections on p_W^T independent of the jet multiplicities
- same as for $p_{j^1}^T$, except for $n = 1$, where $p_{j^1}^T = p_W^T$

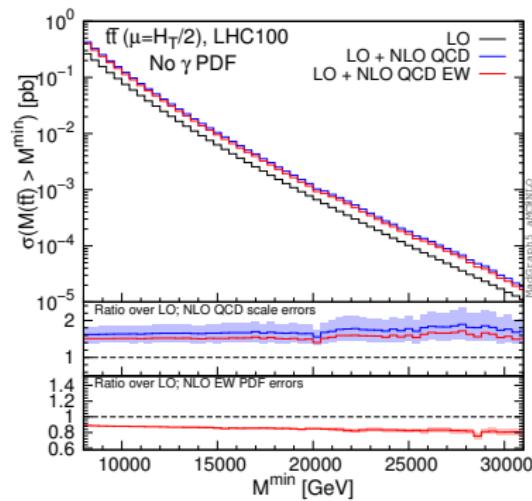
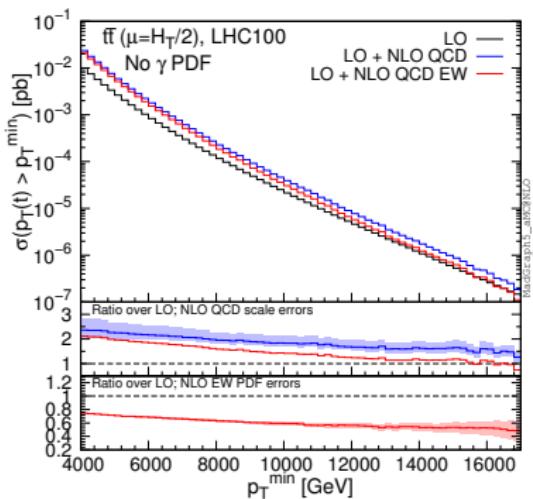
W/Z and γ/Z ratios

- important observables for PDF constraints and background normalization for NP searches in MET+ jets
- QCD effects and uncertainties partially cancel in the ratios



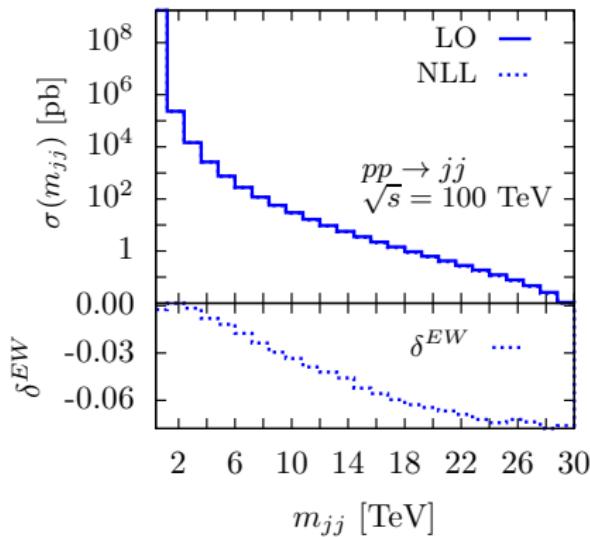
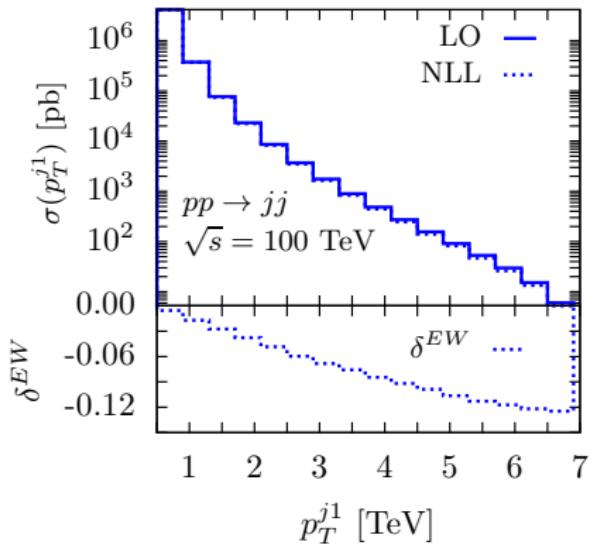
- EW corrections do not cancel and produce relevant shape distortions

$t\bar{t}$ production



- EW corrections much more moderate w.r.t. processes with external gauge/Higgs bosons

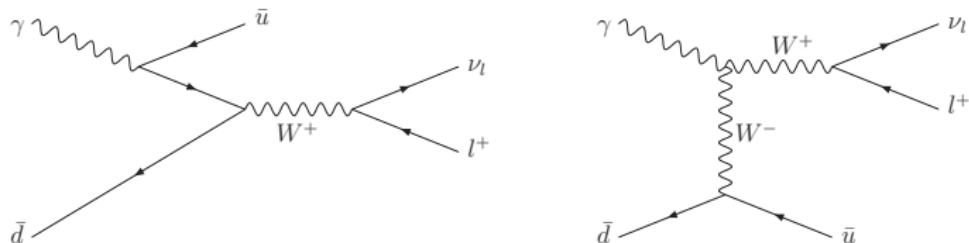
di-jet production



- EW corrections smaller than $t\bar{t}$, because of the presence of the subprocess $gg \rightarrow gg$ and because of averaging over quark flavours
- the logarithmic approximation is expected to overestimate the correction to m_{jj} due to the presence of $u-$ and $t-$ channels (but small anyway)

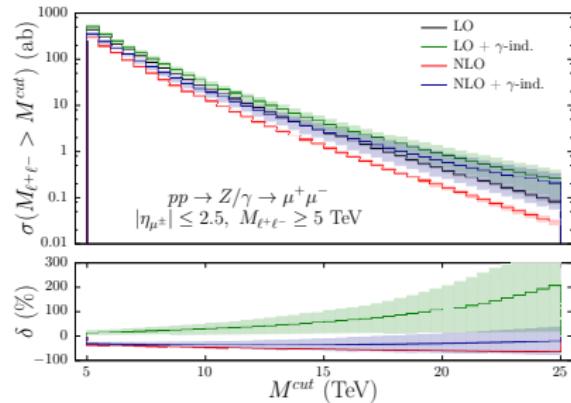
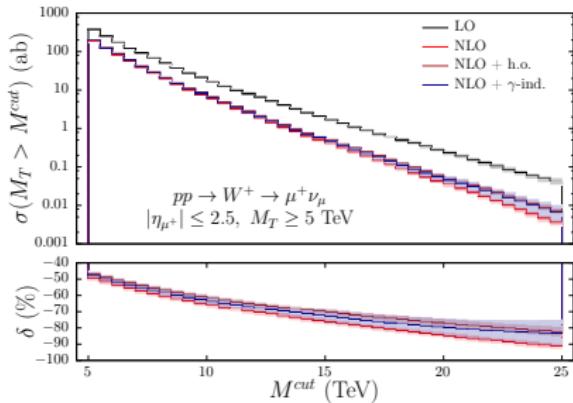
Photon induced processes

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



- for neutral systems of charged F.S. particles also contributions at tree level (e.g. $\gamma\gamma \rightarrow \mu^+\mu^-$ or $\gamma\gamma \rightarrow W^+W^-$)
- typically they become relevant for large invariant mass of the system and forward kinematics, when possible t -channel enhancements are possible
- Necessary PDF sets which provide the γ PDF
- existing sets
 - MRST2004QED
 - NNPDF2.3QED (used for the present studies), NNPDF3.0QED
 - CT14QED

DY predictions including γ -induced processes



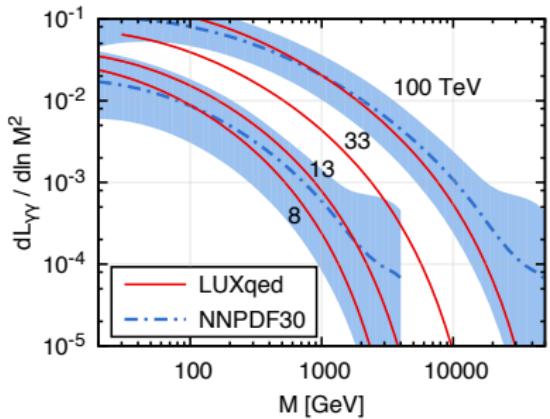
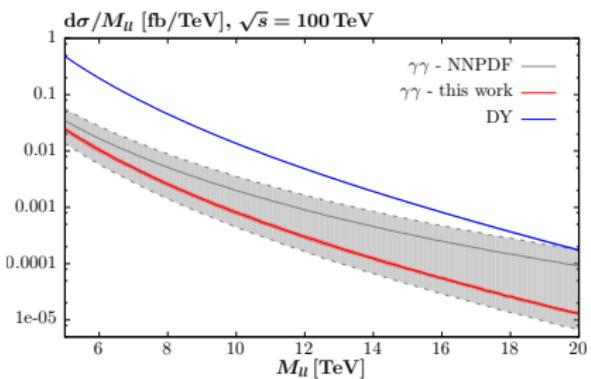
- huge uncertainties due to γ PDF. Smaller for W production because there is no LO contribution
- similar uncertainties also for the other studied processes

The problem of the γ PDF uncertainty

- Very recently it has been realized that the available parameterizations do not include the information from coherent emission $p \rightarrow p\gamma$ at low Q^2 , which is well measured experimentally through the electric and magnetic proton form factors
 - the coherent emission is crucial for the input PDF at low Q^2 scale

Manohar, Nason, Salam, Zanderighi, arXiv:1607.04266

Harland-Lang, Khoze and Ryskin, arXiv:1607.04635

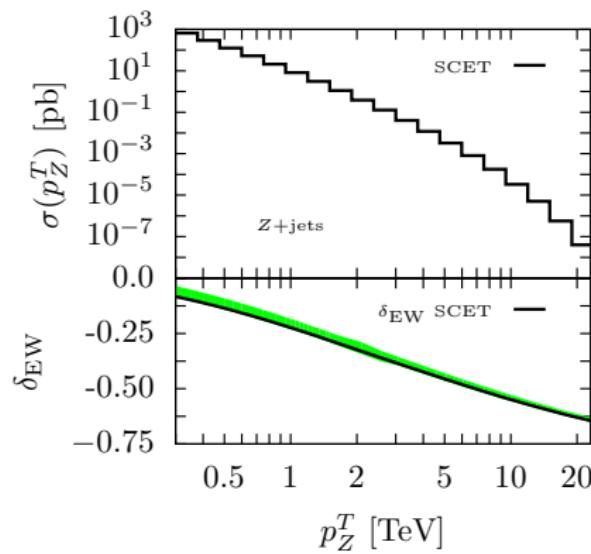
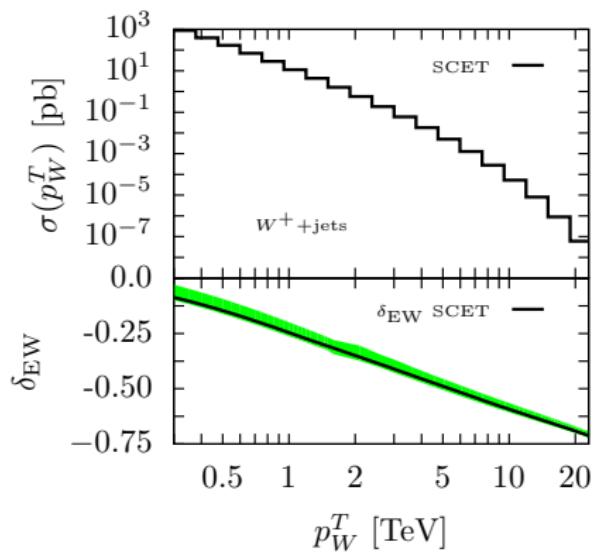


- uncertainty already well below 10% and central value close to the minimum predicted by NNPDF \Rightarrow impact at $\sqrt{s} = 100$ TeV should be reassessed

Resummation of Sudakov logs

- in several cases EW corrections become very large \Rightarrow the fixed order calculation becomes not reliable
- resummation is needed \Rightarrow SCET offers a general framework for resumming Sudakov logs

Chiu, Golf, Kelley, Manohar, 2008



Warning: also subleading logs could be relevant

- During the past studies for a future e^+e^- Linear Collider, NLC, (\sim first decade of 2000), several groups studied the issue of high energy EW logs at one, two loops and their possible resummation

e.g. Beccaria, Ciafaloni, Comelli, Fadin, Kühn, Lipatov, Melles, Denner, Penin, Smirnov, Pozzorini, . . .

- e.g., at two loops accuracy, EW corrections to the total cross section for $e^+e^- \rightarrow \mu^+\mu^-$ read

Kühn, Penin, Smirnov, hep-ph/0005301

$$\frac{\sigma}{\sigma_B} = 1 + 10.09l(s) - 1.39L(s) - 21.66l(s)L(s) + 1.41L^2(s)$$

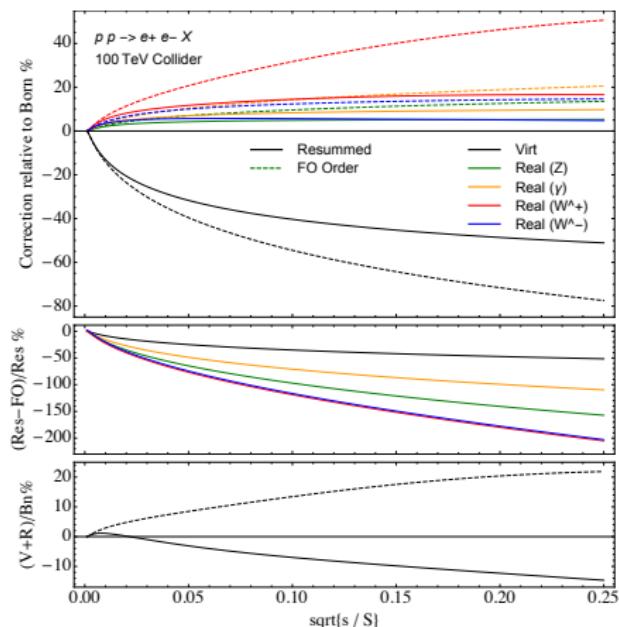
$$l(s) = \frac{g^2}{16\pi^2} \ln\left(\frac{-s}{M^2}\right)$$

$$L(s) = \frac{g^2}{16\pi^2} \ln^2\left(\frac{-s}{M^2}\right)$$

- Leading and subleading logs have opposite signs and the coefficients of the subleading ones large
- Issue of higher order subleading terms and possible resummation worth to be addressed at FCC-hh

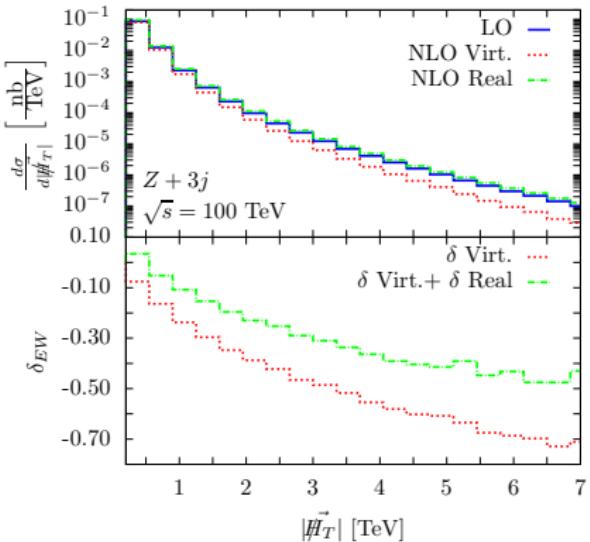
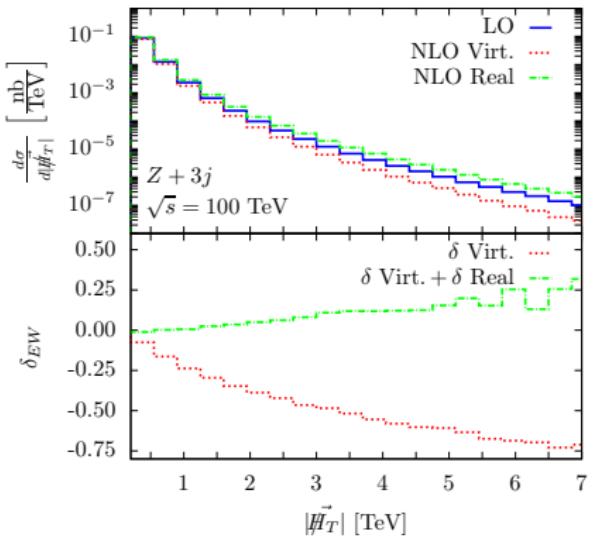
Also real EW radiation can play an important role

- Recent investigations on the resummation of Sudakov logs for real rad
- Results for NC DY



- Resummation of real radiation at FCC-hh important as for virtual corr's

Real EW radiation: inclusive vs realistic evt. selection



- Left: Real defined as $Z(\rightarrow \nu\bar{\nu}) + 3$ jets + additional W/Z , no cuts on the latter
- Right: Real defined as all possible $VV^{(t)} +$ jets producing a final state degenerate with $Z(\rightarrow \nu\bar{\nu}) + 3$ jets, as discussed in