Precise electroweak calculation of the charged current Drell-Yan process

Carlo M. Carloni Calame

INFN, Sezione di Pavia

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thanks to Stefano and the SHEP group for the invitation!

Outline

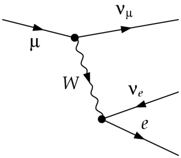
- Motivations for precise predictions of Drell-Yan processes
  - ⋆ precise measurement of M_W (and Γ_W)
  - ⋆ luminosity monitor
  - ⋆ PDFs constraint
  - ⋆ background to New Physics searches
- Overview of the literature
  - ⋆ QCD calculations
  - ⋆ EW calculations
- The event generator `HORACE`
  - first version (with a QED Parton Shower)
  - inclusion of exact $\mathcal{O}(\alpha)$ electro-weak corrections
  - technicalities
  - results
- Conclusions & outlook

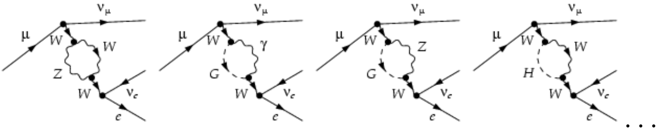
M_W in the Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}(\alpha, M_W, M_Z; M_H; m_f; ckm)$$

$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2}(1+\Delta r) \qquad \Delta r = \Delta r(m_{top}, M_W, M_Z, M_H, ...)$$

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu(1-\Delta r)}$$



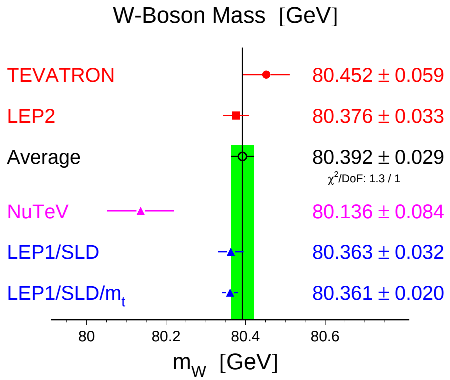


- the W mass can be predicted

$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha(1+\Delta r)}{G_\mu\sqrt{2}M_Z^2}}\right) \rightarrow M_W = 80.363 \pm 0.032 \text{ GeV}$$

Direct measurement of M_W

- at LEP2, from $e^+e^- \to WW$ (at threshold and higher energies)
- at hadron colliders, from the M_T distribution



Future goals for ΔM_W

- ⋆ Tevatron Run II ⇒ 27 MeV
- ⋆ LHC ⇒ 15 MeV

Future goals for $\Delta\Gamma_W$

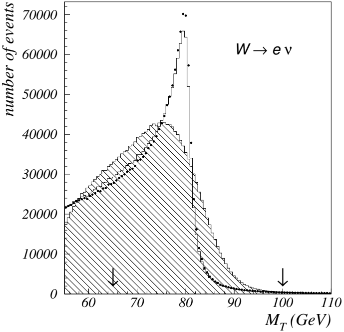
- ⋆ Tevatron Run II ⇒ 30 MeV
- ⋆ LHC ⇒ $\leq$ 30 MeV

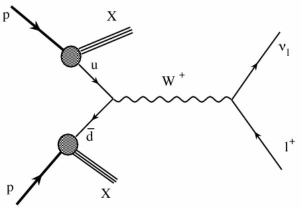
- A small ΔM_W (and Δm_{top}) will constraint the indirect limit on M_H

$\Delta M_W = 27\ [15]$ MeV and $\Delta m_{top} = 2.7\ [1]$ GeV $\to \Delta M_H/M_H \simeq 35\ [18]\%$

M_W at Hadron Colliders

- M_W is extracted from the $p_\perp^\ell$ distribution, showing a (Jacobian) peak at $M_W/2$
- more reliable is $M_T^W = \sqrt{2 p_\perp^\ell p_\perp^\nu (1 - \cos\phi_{\ell\nu})}$
  - ⋆ less sensitive to QCD corrections (e.g. $p_\perp^W$)





- The th. description of M_T spectrum has to match the aimed exp. accuracy

- the ratio $\frac{d\sigma/dM_T^W}{d\sigma/dM_T^Z}$ can be also used to extract M_W. Competitive at high luminosities

Other motivations

- it is possible to monitor the collider luminosity, the parton luminosities or to measure the PDFs

Frixione & Mangano ’04 and refs. therein

  - ⋆ relevant observables: total cross section, W (and Z) rapidity distribution, lepton rapidity distribution

$$\sigma^{\text{exp}} \equiv \frac{1}{\text{BR}(W \to \ell\nu)} \frac{1}{\int \mathcal{L}dt} \frac{N^{obs}}{A} = \sigma^{\text{theory}} \equiv \sum_{ab} \mathcal{P}_{ab} \otimes \hat{\sigma}_{ab}$$

  - ⋆ an accuracy of $\mathcal{O}(1\%)$ is required/achievable
- DY processes are background to New Physics searches
  - ⋆ invariant mass (transverse mass) distribution tails have to be precisely simulated

Theoretical cross section at hadron colliders

$$\sigma^{\text{theory}} = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i,A}(x_1,\mu^2) f_{j,B}(x_2,\mu^2) \int d\sigma^H_{i,j}(x_1 x_2 s, \mu^2)$$

- it relies on *factorization theorems*
- $f_{k,C}$ $(k = u, \bar{u}, d, \cdots, g, \cdots)$ are the PDFs of hadron C
- $d\sigma^H_{k,l}$ describes the hard parton-parton process, as accurately as possible, including
  - QCD Parton Shower evolution
  - QCD fixed order corrections
  - EW corrections
  - $\cdots$
- μ^2 is the factorization scale. Evolution up to μ^2 is driven by DGLAP equations

Status of QCD calculations (& tools)

- NLO/NNLO corrections to W/Z total production rate

G. Altarelli, R.K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246** (1984) 12

R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. **B359** (1991) 343

R.V. Harlander and W.B. Kilgore, Phys. Rev. Lett. **88** (2002) 201801

- resummation of LL/NLL p_T^W/M_W logs (RESBOS)

C. Balazs and C.P. Yuan, Phys. Rev. **D56** (1997) 5558

- NLO ME merged with `HERWIG` Parton Shower [PS] (`MC@NLO`)

S. Frixione and B.R. Webber, JHEP **0206** (2002) 029

- Matrix elements Monte Carlos (`ALPGEN`, `SHERPA`,...) matched with PS

M.L. Mangano et al., JHEP **0307**, 001 (2003)

F. Krauss et al., JHEP **0507**, 018 (2005)

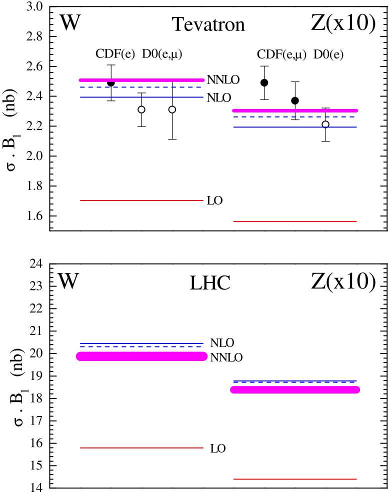
- NNLO corrections to W/Z rapidity distribution (VRAP)

C. Anastasiou et al., Phys. Rev. **D69** (2004) 094008

K. Melnikov and F. Petriello, `hep-ph/0603182`

QCD predictions for W/Z total rates

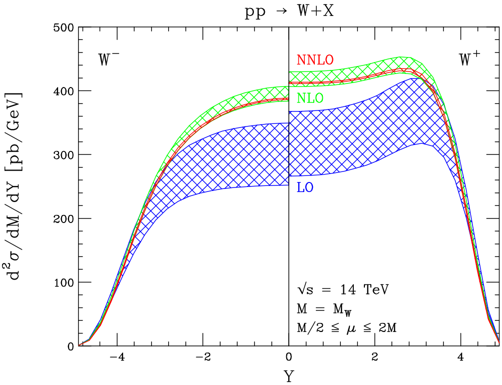
A.D. Martin *et al.*, Eur. Phys. J. **C18** (2000) 117



- Good convergence of α_s expansion. NLO-NNLO difference $\sim$ 2% at the LHC

High-precision QCD: W/Z rapidity @ NNLO

C. Anastasiou et al., Phys. Rev. **D69** (2004) 094008



- First calculation of a differential distribution at NNLO in α_s. NNLO corrections at ~ 2% at the LHC and residual scale dependence below 1%.
- $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \rightarrow$ need to worry about electroweak corrections!

EW calculations for W & tools

- Electroweak corrections to W production
  - ⋆ Pole approximation ($\sqrt{\hat{s}} = M_W$)
    - → D. Wackeroth and W. Hollik, PRD **55** (1997) 6788
    - → U. Baur et al., PRD **59** (1999) 013002
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections
    - → V.A. Zykunov et al., EPJC **3** 9 (2001)
    - → S. Dittmaier and M. Krämer, PRD **65** (2002) 073007 DK
    - → U. Baur and D. Wackeroth, PRD **70** (2004) 073015 WGRAD2
    - → A. Arbuzov, et al., EPJC **46**, 407 (2006) SANC
    - → C.M.C.C. et al., `hep-ph/0609170` HORACE
- Multi-photon radiation
  - → C.M.C.C. et al., PRD **69**, 037301 (2004), JHEP 0505:019 (2005), `hep-ph/0609170` HORACE
  - → S. Jadach, W. Płaczek, EPJC **29** 325 (2003) WINHAC

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    - → A. Arbuzov, et al., EPJC **46**, 407 (2006) `SANC`
    - → C.M.C.C. et al., `hep-ph/0609170` `HORACE`
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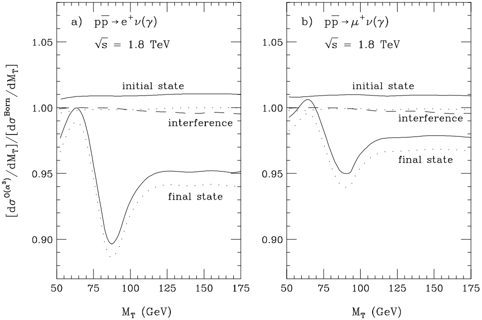
  - → S. Jadach, W. Płaczek, EPJC **29** 325 (2003) `WINHAC`

$\mathcal{O}(\alpha)$ EW correction effects

U. Baur, S. Keller, D. Wackeroth, Phys. Rev. **D59** (1999) 013002



- around the W peak, EW RC dominated by final-state [FS] (photonic) corrections
- FS radiation modifies the shape of the M_T distribution
- at TeVatron, $\mathcal{O}(\alpha)$ EW RC shift M_W by $\mathcal{O}(100)$ MeV

CDF coll., PRD 64 052001 (2001)

⋆ are QED higher orders (h.o.) important? Quoted as systematic uncertainty of $\mathcal{O}(10\text{-}20)$ MeV by TeVatron colls.

HORACE: first version

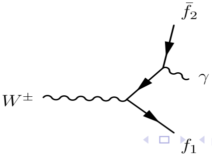
- The Monte Carlo event generator HORACE was originally developed to simulate QED multi-photon radiation in DY (W and Z) processes in LL accuracy, by means of a QED Parton Shower [PS]. Only final state radiation was accounted for

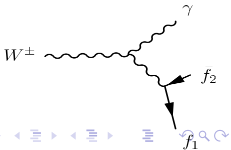
C.M.C.C. et al., PRD **69** 037301 (2004)

C.M.C.C et al., JHEP 0505:019 (2005)

- as in QCD, the QED PS solves the QED DGLAP equation, allowing for
  - ⋆ inclusion of QED LL corrections up to all orders (resummation)
  - ⋆ fully exclusive event generation (up to ∞ photons)
- by comparing the resummed PS and its $\mathcal{O}(\alpha)$ truncation, the effects purely due to h.o. can be disentangled
- photons' angular generation in W decay

$$\cos\vartheta_\gamma \propto E_\gamma^2 \left(\frac{p_\ell}{p_\ell \cdot k_\gamma} - \frac{p_W}{p_W \cdot k_\gamma}\right)^2$$





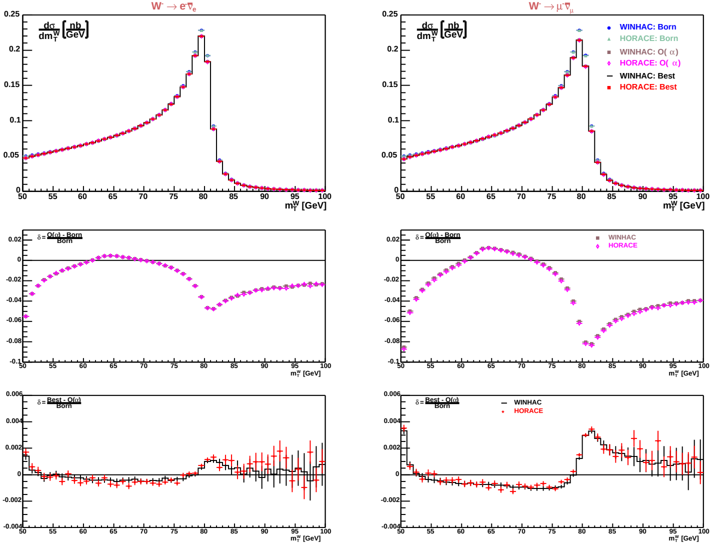
First HORACE vs WINHAC

C.M.C.C et al., Acta Phys. Pol. B35 1643 (2004), `hep-ph/0402235`

- during the 2003 MC4LHC CERN workshop, HORACE and WINHAC (Jadach & Płaczek) where compared
- WINHAC exploits the YFS approach to exponentiate exact $\mathcal{O}(\alpha)$ EW corrections to W decay
- e.g., cross sections for W^- production (in nb) at parton (p) and hadron (h) level, with (c) and without (nc) cuts at LHC:

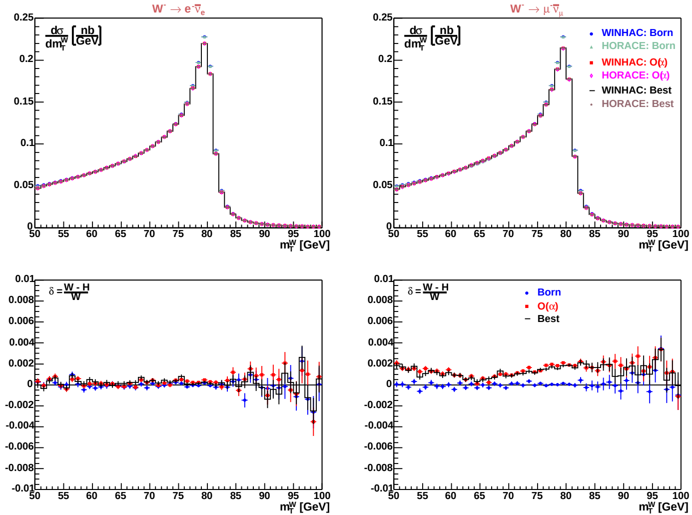
	Born		$\mathcal{O}(\alpha)$		with h.o.	
	HORACE	WINHAC	HORACE	WINHAC	HORACE	WINHAC
p e^- (nc)	8.8872	8.8871(2)	8.8872	8.8855(1)	8.8872	8.8840
p μ^- (nc)	8.8872	8.8871(1)	8.8869	8.8853(1)	8.8869	8.8844
h e^- (nc)	7.7331(4)	7.7331	7.7331(4)	7.7317(1)	7.7325(4)	7.7304
h μ^- (nc)	7.7332(4)	7.7332(1)	7.7332(4)	7.7316	7.7328(4)	7.7307
h e^- (c)	3.2363(1)	3.2363(1)	3.1871(1)	3.1878(1)	3.1869(1)	3.1876(1)
h μ^- (c)	3.2363(1)	3.2363(1)	3.1599(1)	3.1642(1)	3.1601(1)	3.1641(1)

First HORACE vs WINHAC: M_T distribution



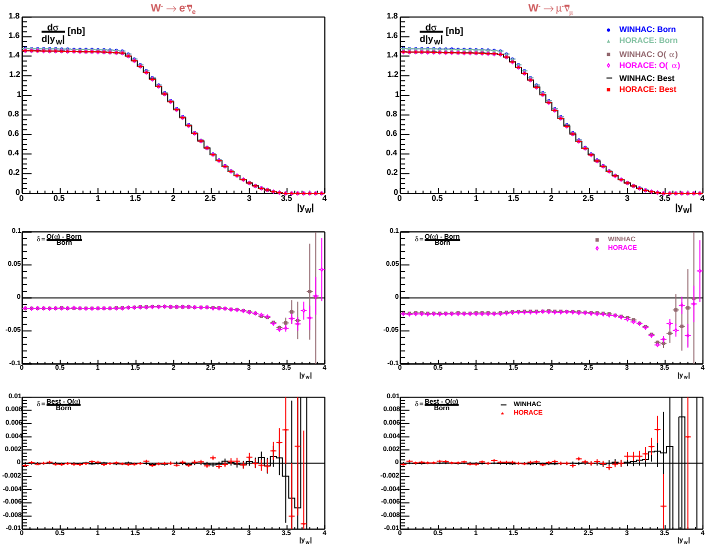
- for e^-, a calorimetric event selection [ES] criterium is used

First HORACE vs WINHAC: M_T distribution differences

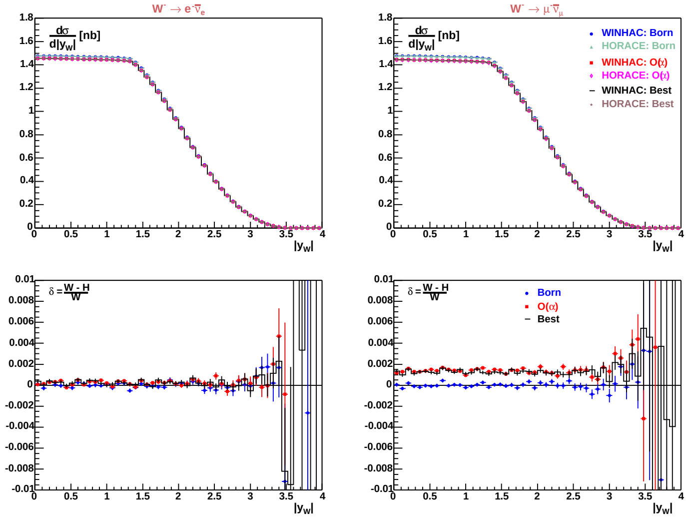


- expected (0.2%) differences at $\mathcal{O}(\alpha)$. The relative effect of exponentiation is the same

First HORACE vs WINHAC: y_W distribution



First HORACE vs WINHAC: y_W distribution differences



- expected (0.2%) differences at $\mathcal{O}(\alpha)$. The relative effect of exponentiation is the same

M_W shift induced by h.o. QED RC

- by means of the first HORACE, we estimated the impact of multi-photon radiation on the extraction of M_W from M_T distr.
- a "pseudo-experiment" was performed (χ^2 analysis):

① generate a sample of pseudo-data at Born level for M_W^{ref}

② consider the M_T spectrum and bin it into 100 bins within the fit region 65 - 100 GeV

③ consider N different M_W around M_W^{ref} and generate N radiatively corrected M_T spectra

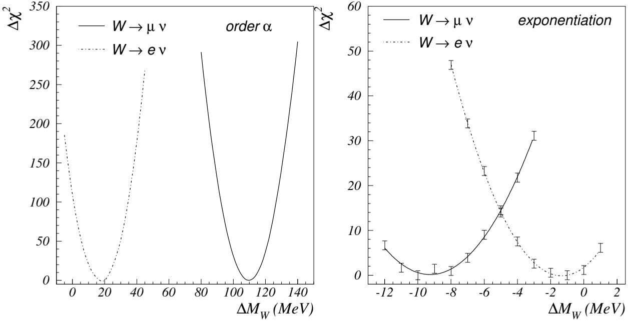
④ for each mass, calculate the χ^2 between corrected and Born spectra

$$\chi^2(M_W) = \sum_{i=bins} \left(\frac{d\sigma_{i,QED}}{\sigma_{QED}} - \frac{d\sigma_{i,Born}}{\sigma_{Born}} \right)^2 / \left[\left(\Delta \frac{d\sigma_{i,QED}}{\sigma_{QED}} \right)^2 + \left(\Delta \frac{d\sigma_{i,Born}}{\sigma_{Born}} \right)^2 \right]$$

⑤ at the minimum of the χ^2 distribution, read the M_W shift

M_W shift induced by h.o. QED RC

- the execise was performed by including (naive) detector effects, which are important



$\Delta M_W^{\alpha,e} \sim 20$ MeV
$\Delta M_W^{\alpha,\mu} \sim 110$ MeV

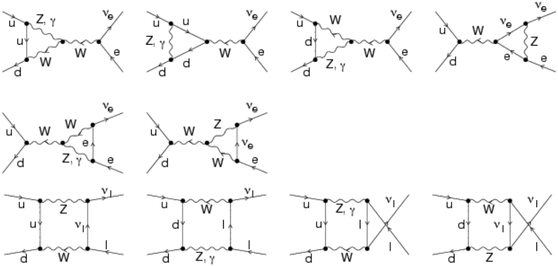
$\Delta M_W^{\infty,e} \sim 2$ MeV
$\Delta M_W^{\infty,\mu} \sim 10$ MeV

- for the electron, a recombination criterium was adopted → smaller effect
- W-mass shift due to multiphoton radiation is about 10% of that caused by one photon emission → non negligible for precise W mass!

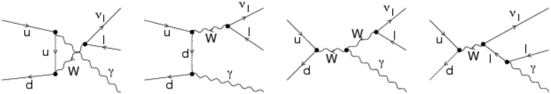
HORACE: new version

C.M.C.C., G. Montagna, O. Nicrosini, A. Vicini, hep-ph/0609170

- http://www.pv.infn.it/hepcomplex/horace.html
- HORACE now includes exact $\mathcal{O}(\alpha)$ EW corrections, in order to go beyond the LL QED accuracy and include weak corrections (e.g. important at high M_T)
  - ⋆ virtual RC



  - ⋆ real RC



NLO EW calculation

As usual, the (partonic) NLO EW calculation is split into two parts

- $u\bar{d} \to \ell^+ \nu_\ell$

$$\mathcal{M}_{2\to 2} = \mathcal{M}_0 + \mathcal{M}_\alpha^{virt}(\lambda)$$

- $u\bar{d} \to \ell^+ \nu_\ell \gamma$

$$\mathcal{M}_{2\to 3} = \mathcal{M}_\alpha^{soft}(\lambda, \Delta E) + \mathcal{M}_\alpha^{hard}(\Delta E)$$

$$|\mathcal{M}_\alpha^{soft}(\lambda, \Delta E)|^2 = \delta^{soft}(\lambda, \Delta E)|\mathcal{M}_0|^2$$

⋆ $2 \to 2$ cross section

$$d\sigma_{2\to 2} = d\sigma_{SV} \propto |\mathcal{M}_0|^2 + 2\Re[\mathcal{M}_0^* \mathcal{M}_\alpha^{virt}(\lambda)] + \delta^{soft}(\lambda, \Delta E)|\mathcal{M}_0|^2$$

⋆ $2 \to 3$ cross section

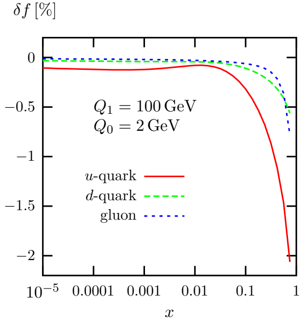
$$d\sigma_{2\to 3} = d\sigma_H \propto |\mathcal{M}_\alpha^{hard}(\Delta E)|^2$$

- the phase space integration is performed with MC techniques
- infrared singularities are regularized with a small photon mass λ; collinear ones with a finite (unphysical) quark mass

⋆ IS collinear singularities must be subtracted

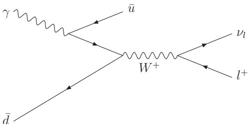
Subtraction of initial state collinear singularities

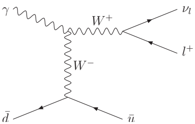
- IS quark masses regularize the collinear QED divergencies
- the QED IS singularities have to be subtracted from the hard cross section [in analogy with NLO QCD], since they are already accounted in the (QED) evolution of PDFs
- the set `MRSTQED` (2004) includes the QED evolution



e.g. M. Roth, S. Weinzierl, PLB 590 190 (2004)

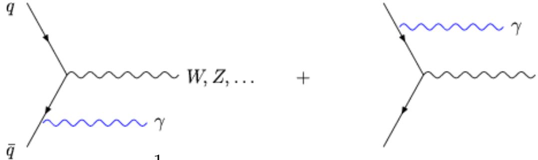
- ⋆ QED evolution modifies PDFs at 0.1% level for $x < 0.1$
- ⋆ dynamic generation of photon distr. function. Need to include photon induced processes in DY





Subtraction of IS collinear singularities

- QED initial-state collinear singularities are universal → are absorbed into PDFs, as in QCD
- the singular partonic cross section is convoluted with a modified PDF, subtracting IS singularities



$$
\begin{aligned}
f(x) \quad \rightarrow \quad & f(x,\mu_F^2) - \int_x^1 \frac{dz}{z}\, f\left(\frac{x}{z},\mu_F^2\right) \frac{\alpha}{2\pi}\, Q_q^2 \times \\
& \times \left\{ \ln\left(\frac{\mu_F^2}{m_q^2}\right) \left[P_{ff}(z)\right]_+ - \left[P_{ff}(z)\left(2\ln(1-z)+1\right)\right]_+ + C(z) \right\}
\end{aligned}
$$

$$
C(z) = \begin{cases} 0 & \overline{\text{MS}} \\ \left[P_{ff}(z)\left(\ln\left(\frac{1-z}{z}\right) - \frac{3}{4}\right) + \frac{9+5z}{4}\right]_+ & \text{DIS} \end{cases}
$$

Les Houches 2005 comparison

C. Buttar et al., `hep-ph/0604120`

- during the Les Houches 2005 workshop, a tuned comparison among EW $\mathcal{O}(\alpha)$ calculations was done
  - ⋆ DK (Dittmaier & Krämer), `HORACE`, `SANC`, `WGRAD2`
- Setup for comparison (cuts & lepton ID)
  - ⋆ LHC, W^+ production

    $p_\perp^\ell > 25$ GeV $\quad p_\perp^{\text{miss}} \equiv p_\perp^\nu > 25$ GeV $\quad |\eta_\ell| < 2.5$

    $\ell =$ bare μ^+, bare e^+, recombined e^+
  - ⋆ recombination criteria (kill FS collinear $\alpha \log \frac{s}{m_e^2}$, due to KLN theorem):

    if $|\eta_\gamma| > 2.5$ and $R_{e^+\gamma} = \sqrt{(\eta_{e^+} - \eta_\gamma)^2 + \phi_{e^+\gamma}^2} \leq 0.1$ photon and electron momenta are summed (i.e. $p_e = p_e + p_\gamma$)
- similar comparison for the TeV4LHC workshop still going on. Naive-detector effects are also investigated here.

Les Houches comparisons, varying $p_\perp^\ell$ cut

C. Buttar et al., `hep-ph/0604120`

$\mathrm{pp} \to \nu_l l^+(+\gamma)$ @ $\sqrt{s} = 14\,\mathrm{TeV}$ (with MRSTQED04)

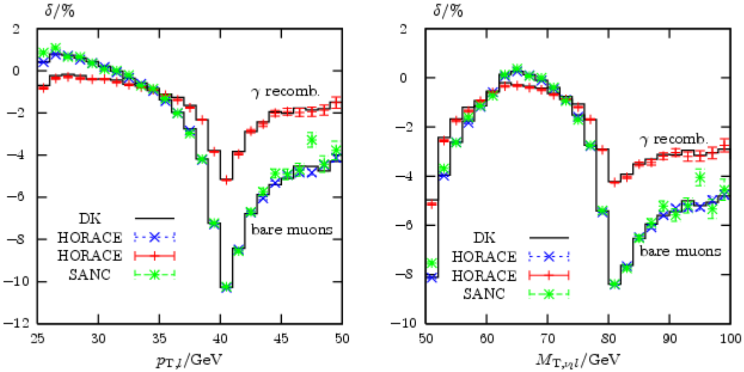
$p_{\mathrm{T},l}/\mathrm{GeV}$	25–∞	50–∞	100–∞	200–∞	500–∞	1000–∞
σ_0/pb						
DK	2112.2(1)	13.152(2)	0.9452(1)	0.11511(2)	0.0054816(3)	0.00026212(1)
HORACE	2112.21(4)	13.151(6)	0.9451(1)	0.11511(1)	0.0054812(4)	0.00026211(2)
SANC	2112.22(2)	13.1507(2)	0.94506(1)	0.115106(1)	0.00548132(6)	0.000262108(3)
WGRAD	2112.3(1)	13.149(1)	0.94510(5)	0.115097(5)	0.0054818(2)	0.00026209(2)
$\delta_{\mathrm{e}+\nu_\mathrm{e}}/\%$						
DK	−5.19(1)	−8.92(3)	−11.47(2)	−16.01(2)	−26.35(1)	−37.92(1)
HORACE	−5.23(1)	−8.98(1)	−11.49(1)	−16.03(1)	−26.36(1)	−37.92(2)
WGRAD	−5.10(1)	−8.55(5)	−11.32(1)	−15.91(2)	−26.1(1)	−38.2(2)
$\delta_{\mu+\nu_\mu}/\%$						
DK	−2.75(1)	−4.78(3)	−8.19(2)	−12.71(2)	−22.64(1)	−33.54(2)
HORACE	−2.79(1)	−4.84(1)	−8.21(1)	−12.73(1)	−22.65(1)	−33.57(1)
SANC	−2.80(1)	−4.82(2)	−8.17(2)	−12.67(2)	−22.63(2)	−33.50(2)
WGRAD	−2.69(1)	−4.53(1)	−8.12(1)	−12.68(1)	−22.62(2)	−33.6(2)
$\delta_{\mathrm{recomb}}/\%$						
DK	−1.73(1)	−2.45(3)	−5.91(2)	−9.99(2)	−18.95(1)	−28.60(1)
HORACE	−1.77(1)	−2.51(1)	−5.94(1)	−10.02(1)	−18.96(1)	−28.65(1)
SANC	−1.89(1)	−2.56(1)	−5.97(1)	−10.02(1)	−18.96(1)	−28.61(1)
WGRAD	−1.71(1)	−2.32(1)	−5.94(1)	−10.11(2)	−19.08(3)	−28.73(6)
$\delta_{\gamma q}/\%$						
DK	+0.071(1)	+5.24(1)	+13.10(1)	+16.44(2)	+14.30(1)	+11.89(1)

Les Houches comparisons: distributions

- EW corrections varying M_T cut

$M_{\mathrm{T}}/\mathrm{GeV}$	50–∞	100–∞	200–∞	500–∞	1000–∞
$\delta_{\mathrm{rec}}/\%$	$-1.73(1)$	$-3.43(2)$	$-6.52(2)$	$-12.55(1)$	$-19.51(1)$
$\delta_{\gamma q}/\%$	$+0.0567(3)$	$+0.1347(1)$	$+0.2546(1)$	$+0.3333(1)$	$+0.3267(1)$

- perfect agreement between independent calculations on $p_\perp^\ell$, M_T distributions (δ due to EW $\mathcal{O}(\alpha)$)



The new `HORACE`: version `2.0`

C.M.C.C., Montagna, Nicrosini, Vicini, `hep-ph/0609170`, submitted to JHEP

- we would like to combine (merge, match) the old QED PS based formulation with the exact EW $\mathcal{O}(\alpha)$ calculation, in order to
  - ⋆ preserve PS advantages (multi-photon effects, exclusive event generation)
  - ⋆ go beyond its approximation (LL accuracy, missing contributions already at $\mathcal{O}(\alpha)$)
- the matching has to avoid the double counting of $\mathcal{O}(\alpha)$ LL, already accounted for by the PS, and to “produce” a formula well suited for Monte Carlo generation
- a solution to the problem has been found…

- the issue has a long story also in QCD (e.g. `MC@NLO`, `POWHEG`)

PS and exact $\mathcal{O}(\alpha)$ matrix elements (at parton level)

Consider the LL [$LL \equiv PS$] resummed, $LL\ \mathcal{O}(\alpha)$ and exact $\mathcal{O}(\alpha)$ cross sections

- $d\sigma^{\infty}_{LL} = \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ |\mathcal{M}_{n,LL}|^2\ d\Phi_n$
- $d\sigma^{\alpha}_{LL} = [1 + C_{\alpha,LL}]\,|\mathcal{M}_0|^2 d\Phi_0 + |\mathcal{M}_{1,LL}|^2 d\Phi_1 \equiv d\sigma_{SV}(\varepsilon) + d\sigma_H(\varepsilon)$
- $d\sigma^{\alpha}_{exact} = [1 + C_{\alpha}]\,|\mathcal{M}_0|^2 d\Phi_0 + |\mathcal{M}_1|^2 d\Phi_1$
- $F_{SV} = 1 + (C_\alpha - C_{\alpha,LL}) \qquad F_H = 1 + \frac{|\mathcal{M}_1|^2 - |\mathcal{M}_{1,LL}|^2}{|\mathcal{M}_{1,LL}|^2}$
- $d\sigma^{\alpha}_{exact} \overset{\text{at } \mathcal{O}(\alpha)}{=} F_{SV}(1 + C_{\alpha,LL})|\mathcal{M}_0|^2 d\Phi_0 + F_H|\mathcal{M}_{1,LL}|^2 d\Phi_1$

$$\boxed{d\sigma^{\infty}_{matched} = F_{SV}\ \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ \left(\prod_{i=0}^{n} F_{H,i}\right)\ |\mathcal{M}_{n,LL}|^2\ d\Phi_n}$$

Contents of the *matched* formula

- F_{SV} and $F_{H,i}$ are infrared safe and account for missing EW $\mathcal{O}(\alpha)$, avoiding double counting of QED LL
- $\left[\sigma^{\infty}_{matched}\right]_{\mathcal{O}(\alpha)} = \sigma^{\alpha}_{exact}$
- $\sigma^{\infty}_{matched}$ is “made of” exact $\mathcal{O}(\alpha)$ one-loop building blocks
- resummation of higher-order LL contributions preserved
- the cross section is still fully differential in the momenta of the final state particles (including the photons)

- Problem:
  the $\mathcal{O}(\alpha)$ calculation presents IS collinear singularities
  ($\propto \alpha \log \frac{M_W^2}{m_q^2}$), which are exponentiated in the matched formula.
  A subtraction procedure up to all orders needs to be devised!

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IS subtraction to all orders

- the idea is to start with a subtracted $\mathcal{O}(\alpha)$ cross section

$$d\sigma^{\alpha}_{exact} = d\sigma^{\alpha}_{exact} - d\sigma^{\alpha}_{sub} + d\sigma^{\alpha}_{sub} \equiv d\tilde{\sigma}^{\alpha}_{exact} + d\sigma^{\alpha}_{sub}$$

  where $d\sigma^{\alpha}_{sub}$ contains the LL initial state collinear singularities, both for the S+V part and the real part

  (see `hep-ph/0609170` for explicit formulae)

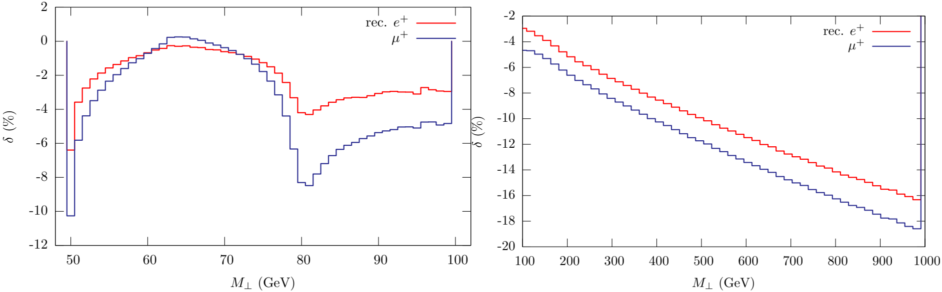
- then the resummation and matching are performed by using the subtracted $\mathcal{O}(\alpha)$ building blocks of $d\tilde{\sigma}^{\alpha}_{exact}$, which is free of IS collinear singularities
- proof of the independence from quark masses

  e.g., W^+ cross section (nb) at LHC (within typical cuts)

	$\mathcal{O}(\alpha)$	matched
m_q	4410.98 ± 0.20	4412.14 ± 0.26
$m_q/10$	4410.92 ± 0.26	4411.89 ± 0.33
$m_q/100$	4410.99 ± 0.29	4411.92 ± 0.50

$\mathcal{O}(\alpha)$ EW results with HORACE

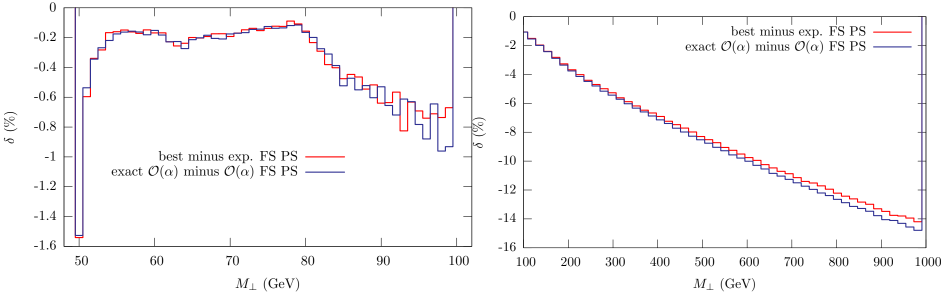
- LHC, $pp \to W^+ \to \ell^+ \nu_\ell$, $p_{\perp,\ell}$ and $p_{\perp,\nu} > 25$ GeV, $|\eta_\ell| < 2.5$
- $\mathcal{O}(\alpha)$ EW corrections to the M_T distribution



- $\mathcal{O}(\alpha)$ corrections at 5% - 10% level around the peak and increasingly large in the M_T tail due to the presence of the EW Sudakov (logs)^2, $\alpha_W \log^2 \frac{s}{M_Z^2}$

Weak $\mathcal{O}(\alpha)$ and QED non-log corrections on M_T

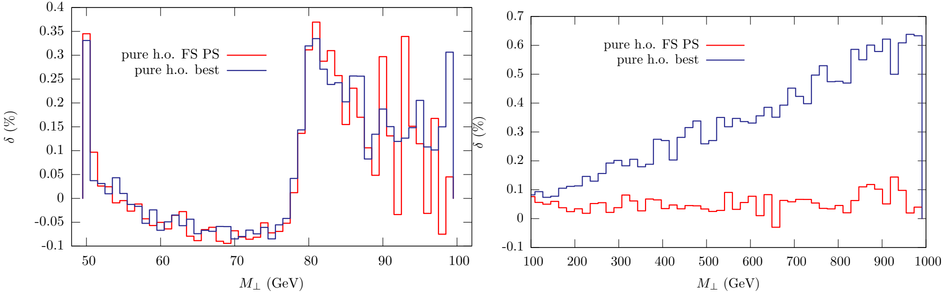
- differences between matched result and final-state [FS] QED PS



- blue $= (d\sigma^{\alpha}_{exact} - d\sigma^{\alpha}_{PS})/d\sigma_0$ red $= (d\sigma^{\infty}_{matched} - d\sigma^{\infty}_{PS})/d\sigma_0$
- Sum of weak $\mathcal{O}(\alpha)$, QED FS non-logs and QED IS remnant flat around the peak, increasingly large in the tail
- the FS QED PS calculation is improved consistently by missing $\mathcal{O}(\alpha)$ with the matching procedure

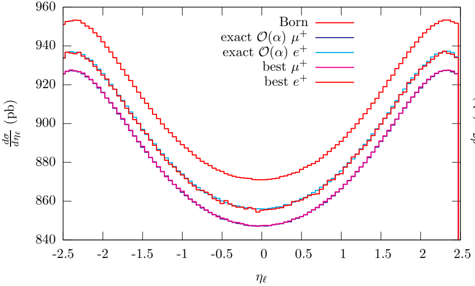
Effects of multi-photon radiation on M_T

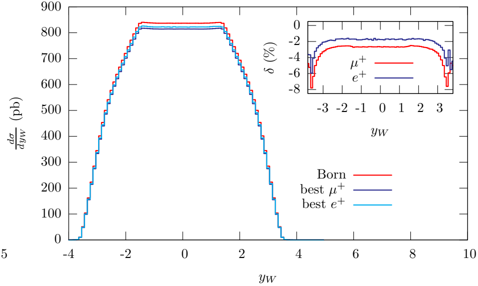
- higher-order EW corrections to the M_T distribution



- blue $= (d\sigma^{\infty}_{matched} - d\sigma^{\alpha}_{exact})/d\sigma_0$ red $= (d\sigma^{\infty}_{PS} - d\sigma^{\alpha}_{PS})/d\sigma_0$
- QED h.o. around the peak distort the shape. In the tail, induced effects by EW Sudakov $\otimes$ $\mathcal{O}(\alpha)$ QED LL
- the $\mathcal{O}(\alpha)$ calculation is improved consistently by h.o. with the matching procedure

Effects on lepton and W rapidities

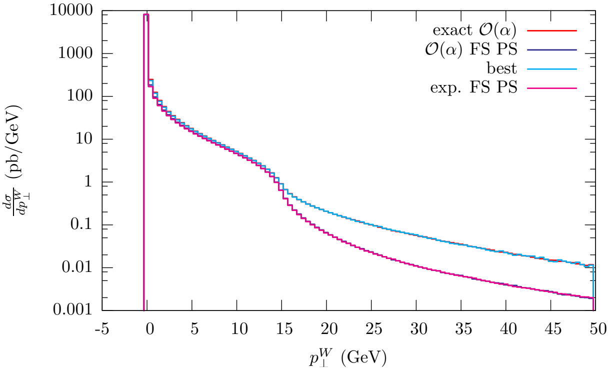




- $\mathcal{O}(\alpha)$ effects al the level of 2%, resummation negligible
- important for acceptances determination, luminosity and PDFs constraints

Effects on $p_\perp^W$

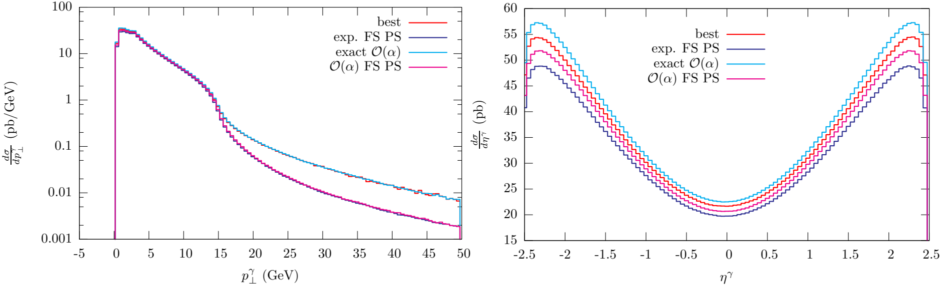
- no QCD effects
- $p_\perp^W$ is defined as the $p_\perp$ of the $\ell^+\nu$ pair, different from zero because of photon radiation



- at high $p_\perp^W$ using the exact photon emission ME is crucial, both for $\mathcal{O}(\alpha)$ and resummed distribution

Photonic observables (radiative events)

- besides leptonic cuts, we require $|\eta_\gamma| < 2.5$ and $E_\gamma > 3$ GeV for the hardest photon
- this signature can be used e.g. to study the $WW\gamma$ trilinear vertex



- as expected, the exact real emission ME gives large corrections w.r.t. the LL approximation
- here radiative events (one more α) are selected

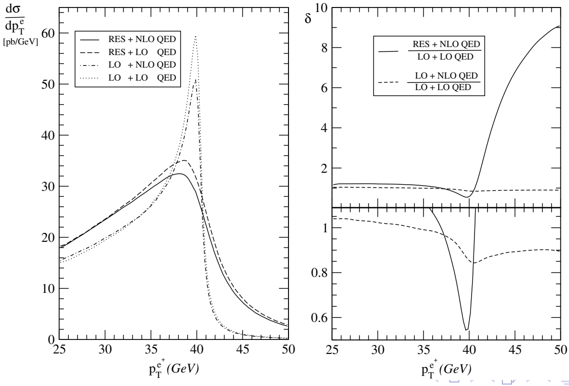
Combining EW & QCD corrections

A unified tool simulating “at best” EW and QCD corrections would be highly desiderable for data analysis

- e.g., RESBOS combined with factorizable FS EW corrections of `WGRAD2` → `RESBOS-A`

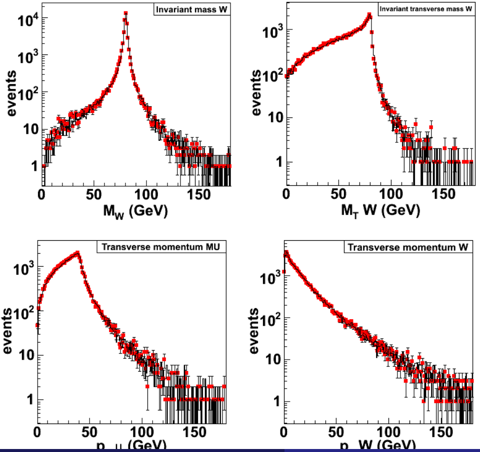
Q. Cao, C.P. Yuan, PRL 93 042001 (2004)

Q. Cao, C.P. Yuan, `hep-ph/0401171`



HORACE & QCD showering MCs

- HORACE is “Les Houches Accord” compliant. Its events can be passed through QCD Parton Shower & hadronization MCs (`HERWIG` or `PYTHIA`) to include at least LL QCD effects.
- e.g. `HORACE` (with QED PS)+`PYTHIA` vs. `PYTHIA+PHOTOS`

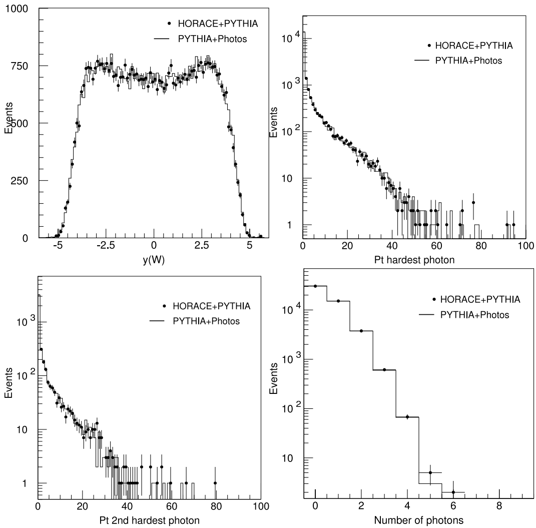


courtesy of G. Polesello and M. Bellomo (ATLAS)

● `HORACE+PYTHIA`

– `PYTHIA+PHOTOS`

HORACE & QCD showering MCs (II)



- ⋆ interface to more refined QCD tools (`MC@NLO`, `ALPGEN`) is in progress. . .

Conclusions & outlook

- DY processes are a fertile ground for (challenging) precision physics at hadron colliders
  - ⋆ precise M_W measurement ($\Delta M_W = 15$ MeV at LHC)
  - ⋆ PDF constraints
  - ⋆ collider luminosity (with accuracy $\mathcal{O}(5\%)$)
  - ⋆ it is a background to New Physics searches
- Theoretical calculations are essential ingredients for the success of the physics program. Higher order QCD and EW corrections must be taken into account
- The Monte Carlo “EW event generator” `HORACE` has been developed, including
  - ⋆ exact $\mathcal{O}(\alpha)$ EW corrections matched with a
  - ⋆ QED Parton Shower to simulate multi-photon radiation
- Combining QCD and EW generators is needed for data analysis
- Work in progress to
  - ⋆ interface “at best” `HORACE` with more refined QCD tools
  - ⋆ extend the EW matching to $\gamma/Z \to \ell^+\ell^-$ channel

thank you!