Study of combined QCD and EW corrections to the charged Drell-Yan process

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Workshop sui Monte Carlo, la Fisica e le Simulazioni a LHC

in collaboration with G. Montagna, M. Moretti, O. Nicrosini, F. Piccinini, M. Treccani, A. Vicini

Outline (& introduction)

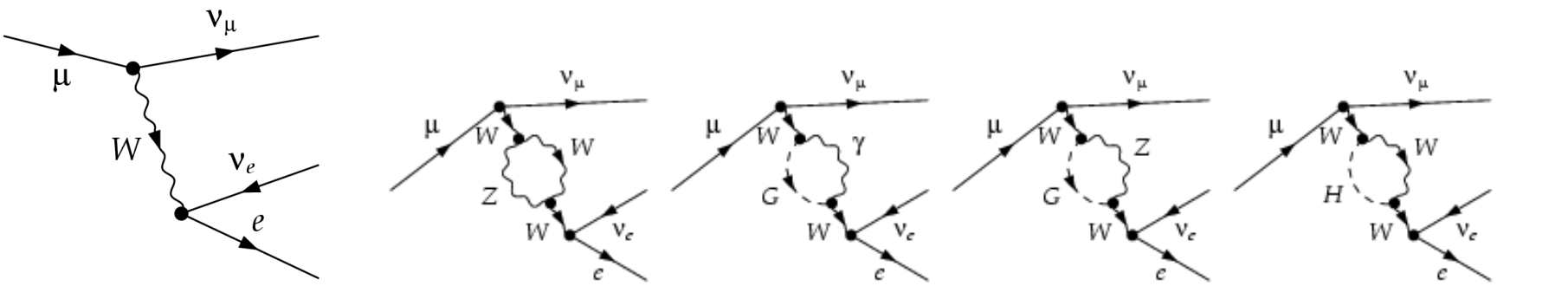
- Motivations for precise predictions of charged Drell-Yan
  - ⋆ precise measurement of M_W
  - ⋆ luminosity monitor
  - ⋆ PDFs constraint
- The event generator HORACE
  - http://www.pv.infn.it/hepcomplex/horace.html
  - electro-weak corrections to charged DY
  - technicalities & results
- Combining QCD & EW corrections
- Conclusions

Indirect prediction of M_W in the SM

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

$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2}(1 + \Delta r)$$

$$\Delta r = \Delta r(m_{top}, M_H, ...)$$

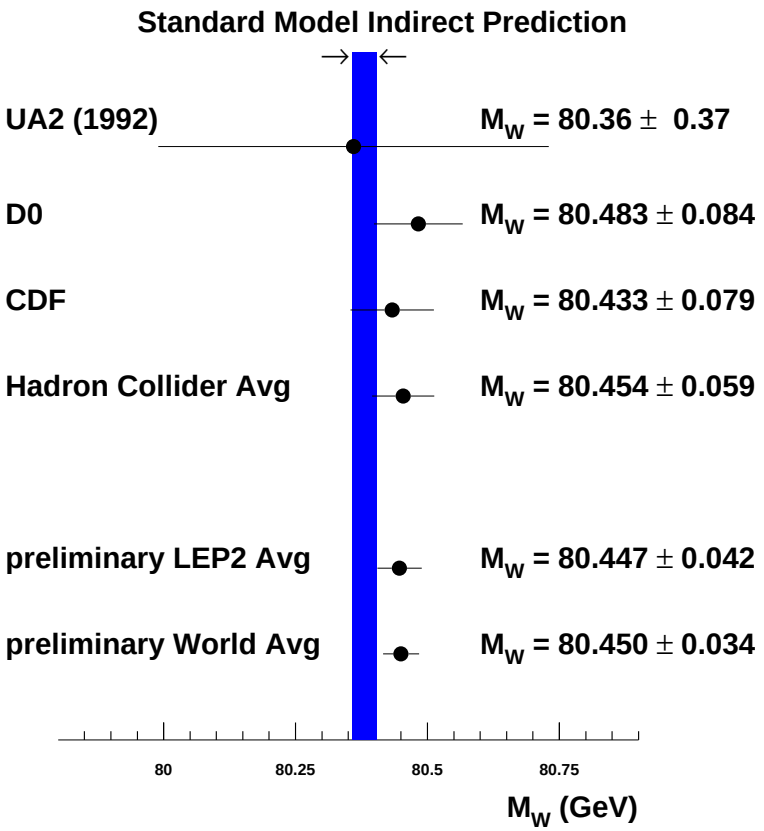


- the W mass can be calculated

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

Direct measurement of M_W

- at LEP2, from $e^+e^- \to WW$
- at hadron colliders, from the M_T distribution



Future goals for ΔM_W

- ⋆ Tevatron Run II $\Rightarrow$ 27 MeV
- ⋆ LHC $\Rightarrow$ 15 MeV

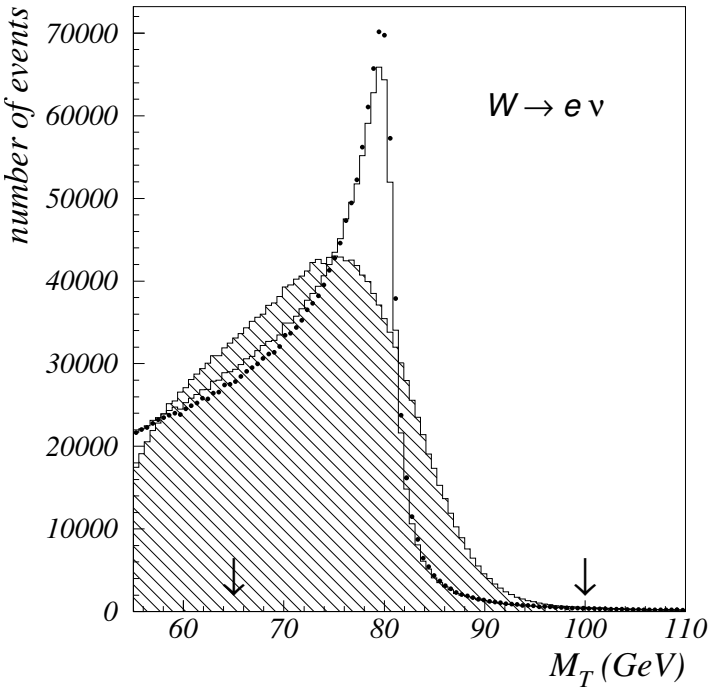
Future goals for $\Delta \Gamma_W$

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

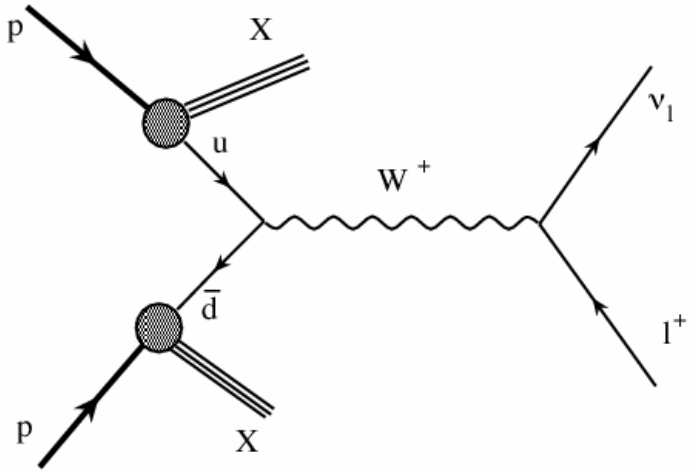
A small ΔM_W (and Δm_{top}) will constraint the indirect limit on M_H

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 $M_T^W = \sqrt{2p_\perp^\ell p_\perp^\nu (1-\cos\phi_{\ell\nu})}$



- 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



The theoretical description of the M_T spectrum has to be very precise

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 PS (MC@NLO)

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

- 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

- 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)

EW calculations & tools

- $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \rightarrow$ need to worry about electroweak corrections!
- 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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HORACE: first version

- The Monte Carlo event generator HORACE was originally developed to simulate QED multi-photon radiation in DY (W and Z) processes

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

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

- Photon emission was simulated (in LL accuracy) by means of a QED Parton Shower. Only final state radiation was accounted for
- HORACE has been successfully compared to WINHAC

C.M.C.C. et al., Acta Phys.Pol. B35 1643 (2004)

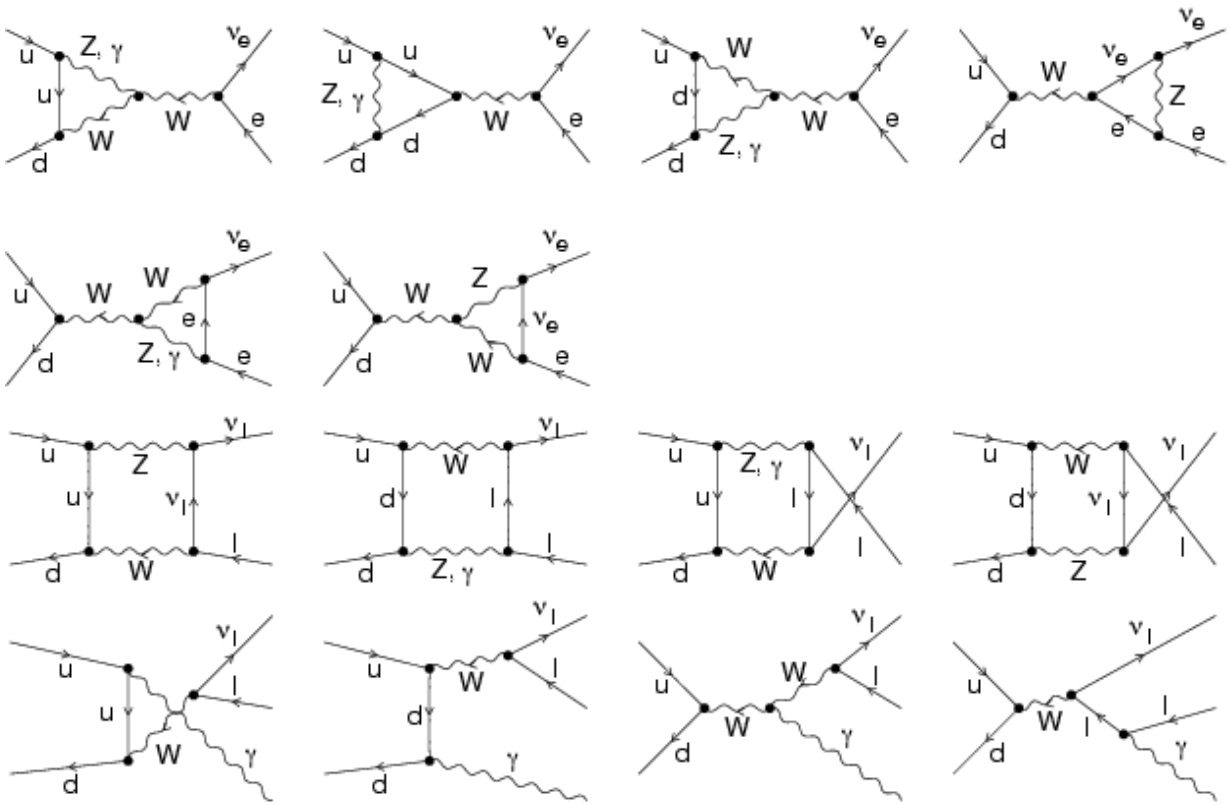
- final state (FS) QED radiation distorts the M_T spectrum, higher orders QED radiation can affect the measurement of M_W at the level of the aimed experimental accuracy

$$[\Delta M_W]_\alpha \sim 100 \text{ MeV} \qquad [\Delta M_W]_\infty \sim 10 \text{ MeV}$$

HORACE: new version

C.C., Montagna, Nicrosini, 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)



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

QED PS and exact $\mathcal{O}(\alpha)$ matrix elements must be combined and matched. How?

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

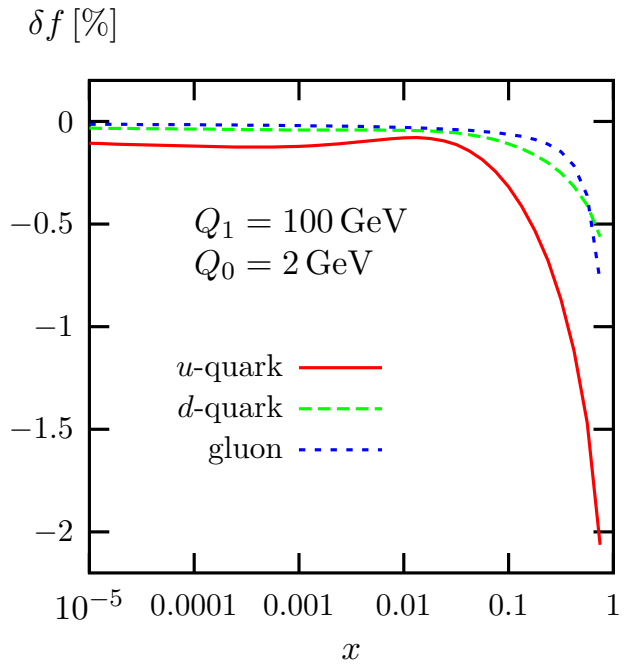
$$d\sigma^{\infty}_{matched} = F_{SV}\ \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ \left(\prod_{i=0}^{n} F_{H,i}\right)\ |\mathcal{M}_{n,LL}|^2\ d\Phi_n$$

Contents of the *matched* formula

- F_{SV} and $F_{H,i}$ are infrared safe and account for missing EW $\mathcal{O}(\alpha)$ non-logs, avoiding double counting of QED LL
- $\left[\sigma^{\infty}_{matched}\right]_{\mathcal{O}(\alpha)} = \sigma^{\alpha}_{exact}$
- 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)

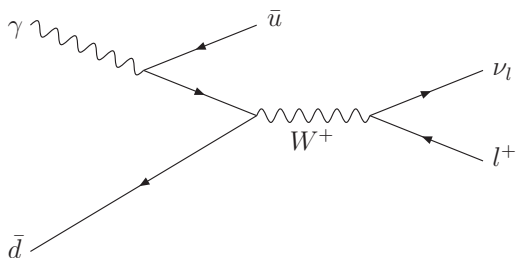
Subtraction of initial state collinear singularities

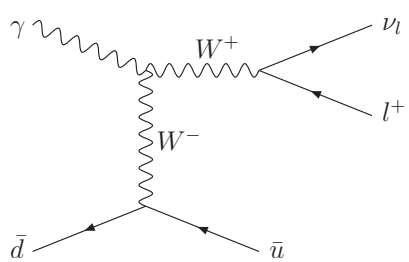
- IS quark masses regularize the collinear QED divergencies
- the QED IS singularities have to be subtracted from the hard cross section [in analogy with NLO QCD], since they are already accounted in the (QED) evolution of PDFs
- the set MRSTQED (2004) includes the QED evolution



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 singularities

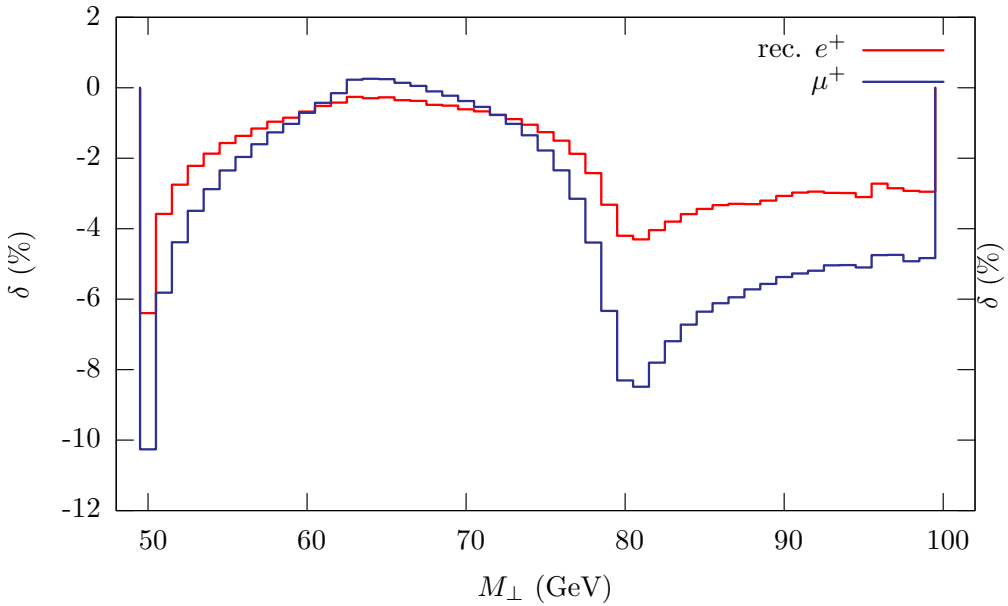
- at $\mathcal{O}(\alpha)$ the subtraction is performed by modifying PDFs (DIS or $\overline{MS}$ scheme)
  - $q_i(x,\mu^2) \to q_i(x,\mu^2) - \int_x^1 \frac{dz}{z} q_i\left(\frac{x}{z},\mu^2\right) \frac{Q_q^2\alpha}{2\pi}\left(\log\frac{\mu^2}{m_q^2} - 1\right) P_+(z)$
  - the leading singularities $\propto \log s/m_q^2$ are removed in the integrated cross section
- it has been generalized to the QED resummed & matched cross section (see `hep-ph/0609170`)
  e.g., W^+ cross section (nb) at LHC within some cuts

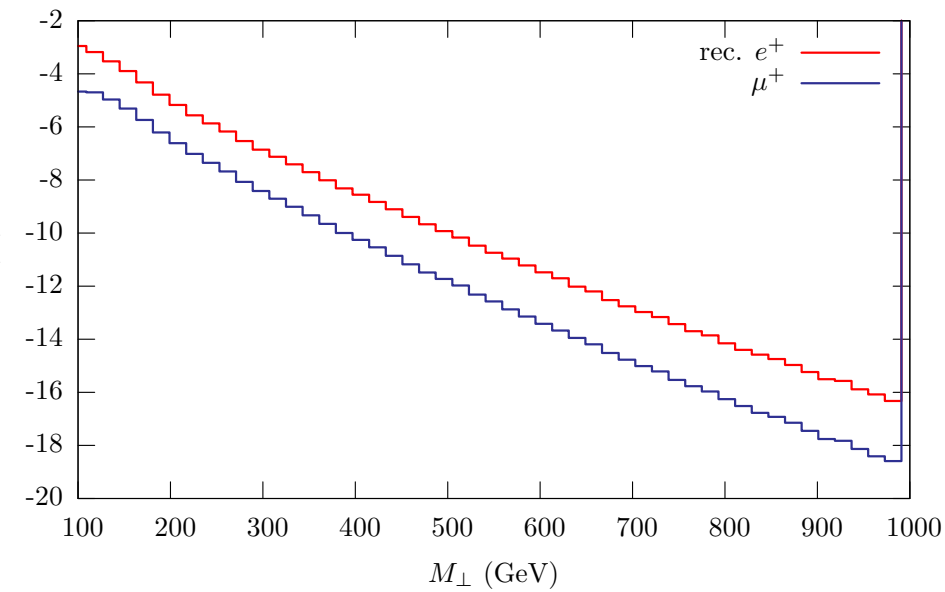
	$\mathcal{O}(\alpha)$	matched
m_q	4410.98 ± 0.20	4412.14 ± 0.26
$m_q/10$	4410.92 ± 0.26	4411.89 ± 0.33
$m_q/100$	4410.99 ± 0.29	4411.92 ± 0.50

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

C.C., Montagna, Nicrosini, Vicini, `hep-ph/0609170`

- 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

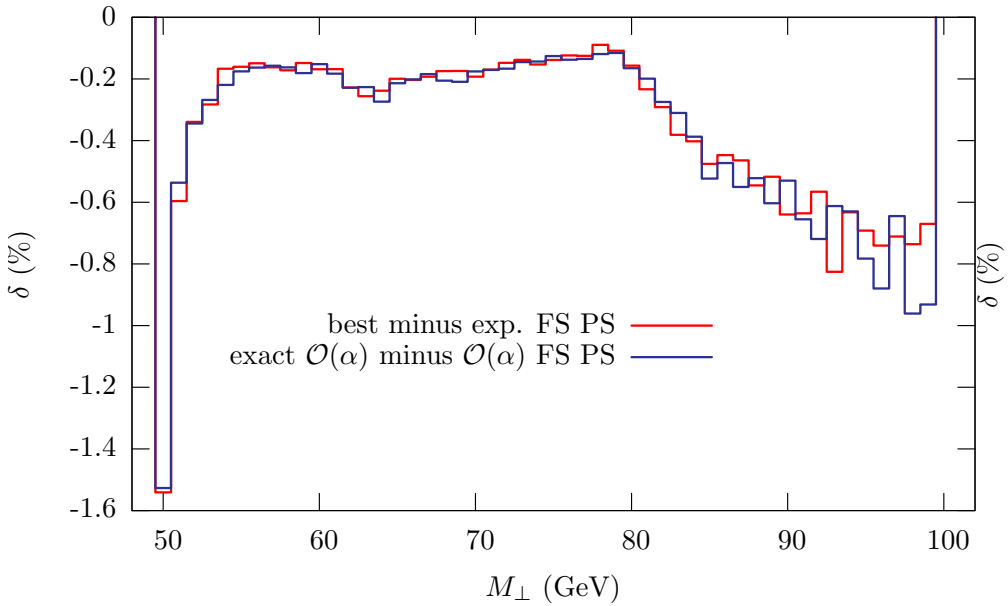


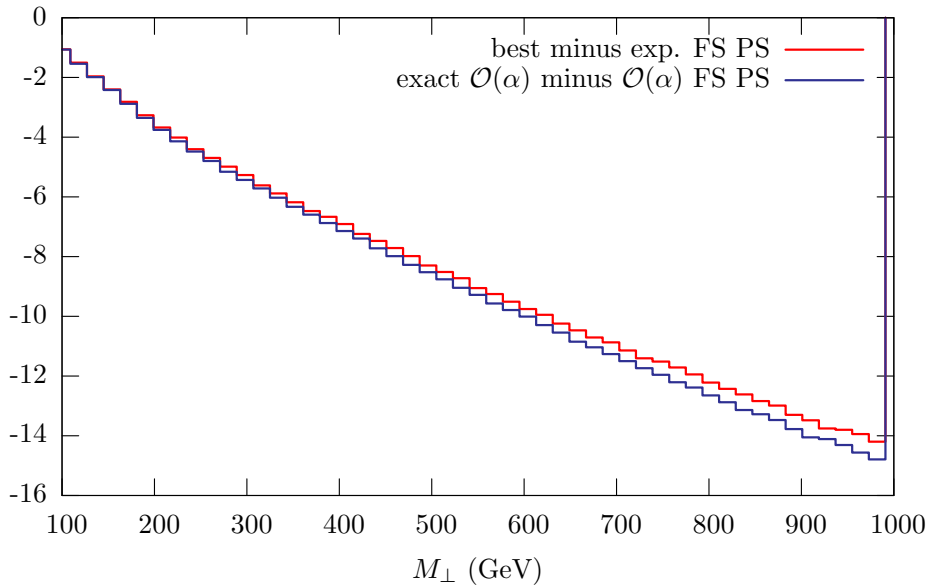


- $\mathcal{O}(\alpha)$ corrections at 5% - 10% level around the peak and increasingly large in the M_T tail due to the presence of the EW Sudakov (logs)^2, $\alpha_W \log^2 \frac{s}{M_Z^2}$

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

- differences between best and FS QED PS

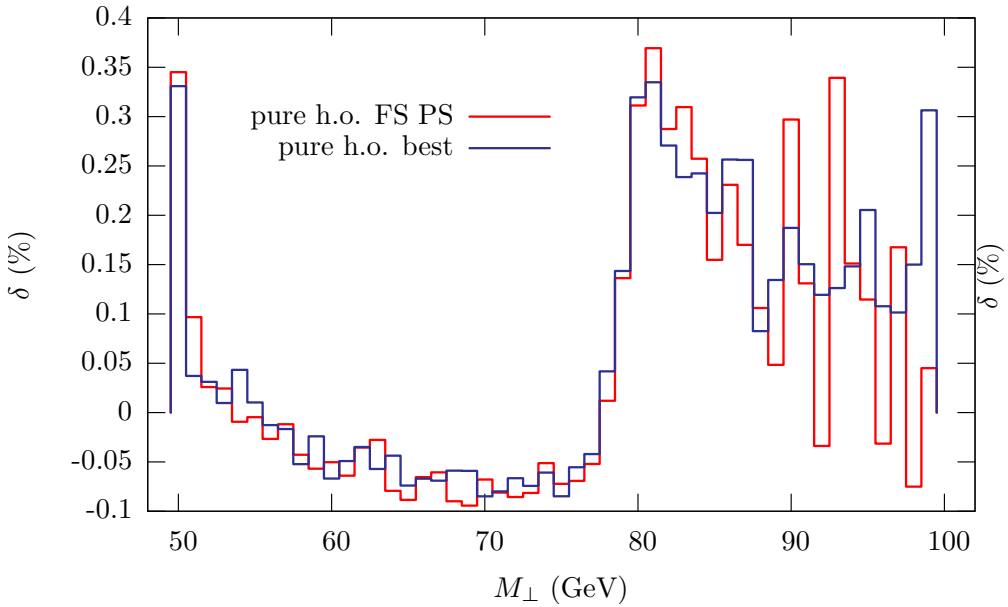


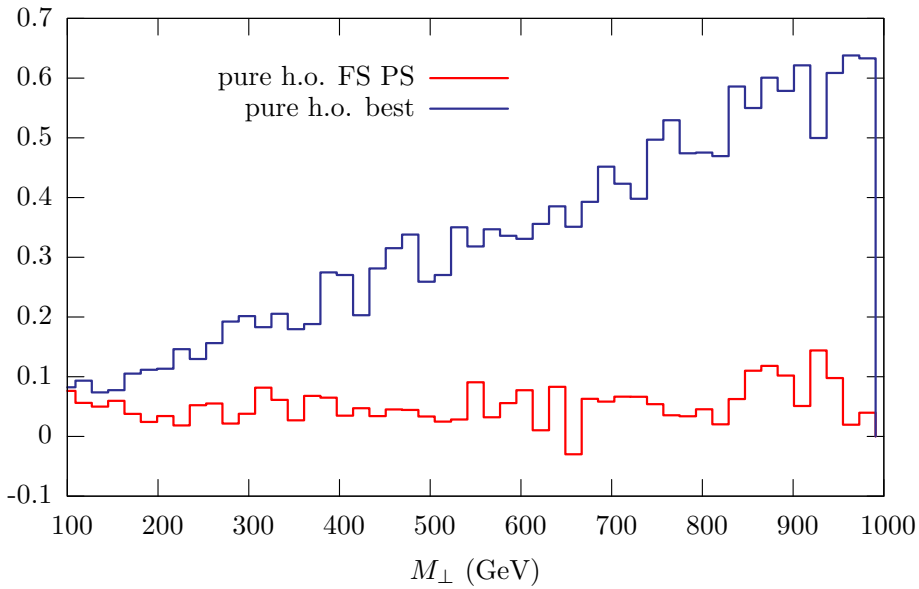


- Sum of weak $\mathcal{O}(\alpha)$, QED FS non-logs and QED IS remnant flat around the peak, increasingly large in the tail
- the FS QED PS calculation is improved consistently by missing $\mathcal{O}(\alpha)$ with the matching procedure

Effects of multi-photon radiation

- higher-order EW corrections to the M_T distribution





- QED h.o. around the peak distort the shape. In the tail, induced effects by EW Sudakov $\otimes$ QED LL
- the $\mathcal{O}(\alpha)$ calculation is improved consistently by h.o. with the matching procedure

Combining EW and QCD corrections

- it would be useful to combine EW and QCD corrections, for a better theoretical prediction of DY observables
- first attempt by Cao & Yuan, combining RESBOS with FS $\mathcal{O}(\alpha)$ corrections of WGRAD2

Cao and Yuan PRL 93 042001 (2004) and hep-ph/0401171

- our attempt (preliminary exercise) is based on the following formula

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\oplus\text{EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\text{best QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{best EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{Born}}\right\}_{\text{HERWIG PS}}$$

- best QCD $\Rightarrow$ ALPGEN (with CKKW PS matching according to MLM prescription, 0+1 jet), MC@NLO
- EW part (HORACE) is interfaced to HERWIG PS (EW $\otimes$ QCD LL)

$\star$ not suited for true event generation. . .

Warning!

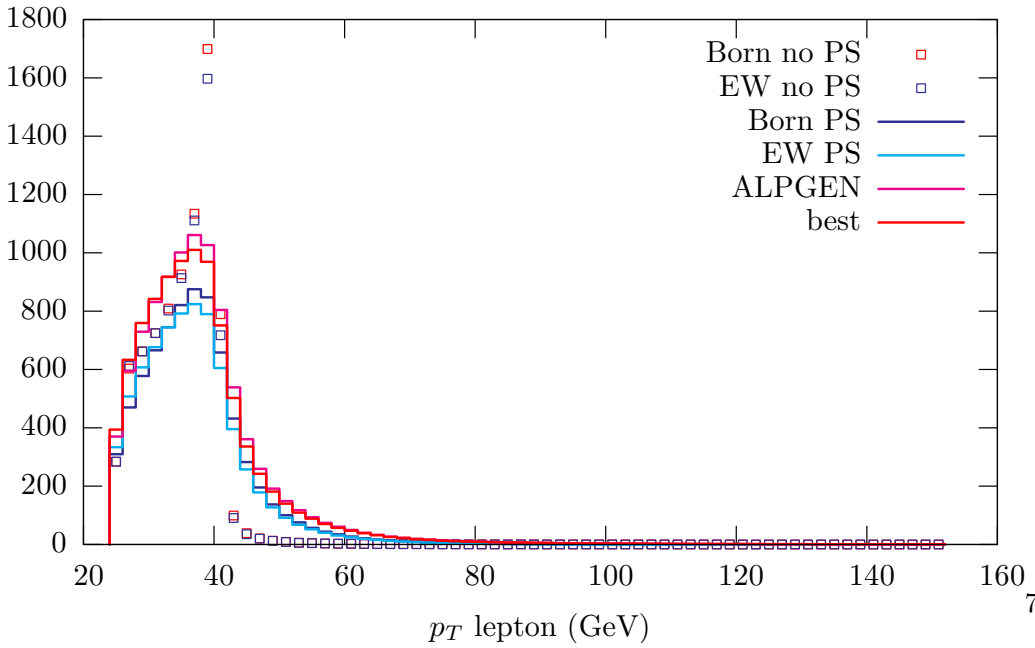
the following plots are preliminary...

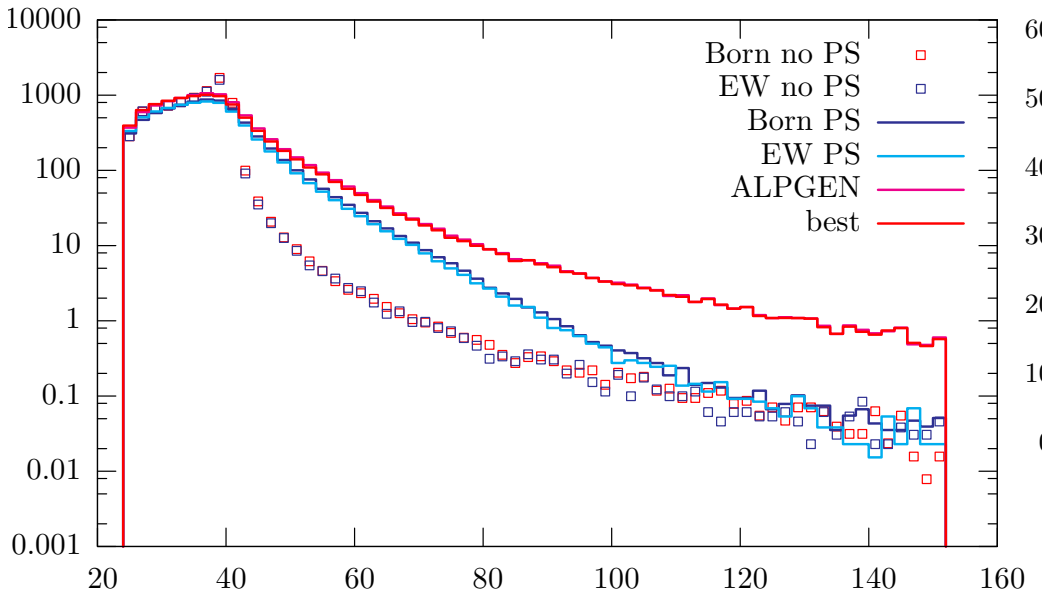
- Setup:

  LHC
  $pp \to W^{\pm} \to \mu\nu$
  $p_{\perp,\mu}$ and $p_{\perp,\nu} > 25$ GeV
  $|\eta_\mu| < 2.5$

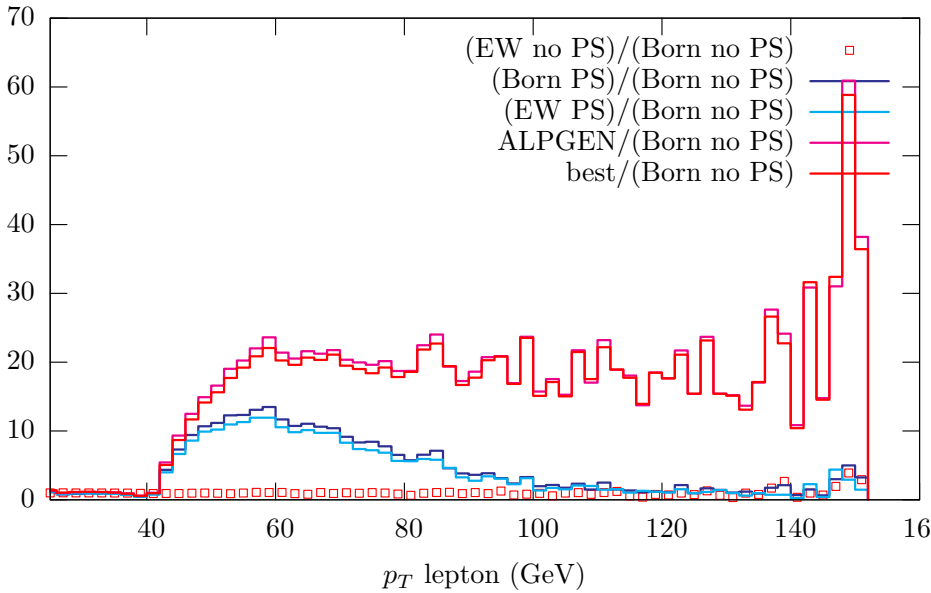
  generation cuts for additional QCD partons
  $p_T > 20$ GeV, $|\eta_j| < 5$, $\Delta R > 0.7$
  matching parameters
  $E_{T,clus.} = 25$ GeV, $|\eta_j| = 5$, $R_j = 1.05$

Lepton $p_\perp$ around the peak

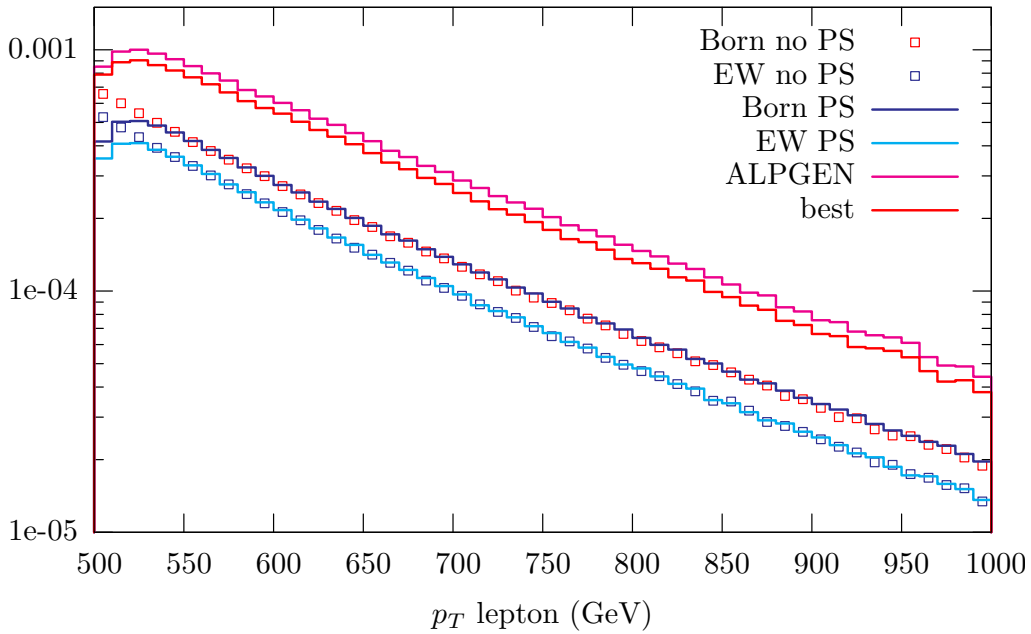


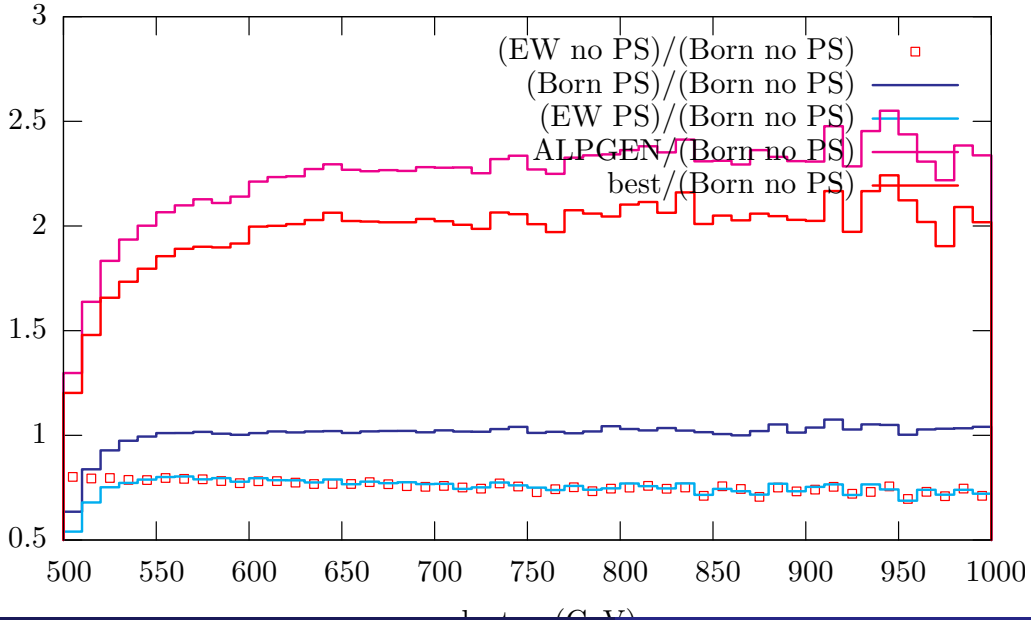


- lepton $p_\perp$ very sensitive to QCD PS ($p_{\perp,W}$)
- CKKW-MLM matching $\sim$ 20% around the peak
- large QCD (PS & ME) corrections due to $p_{\perp,W}$



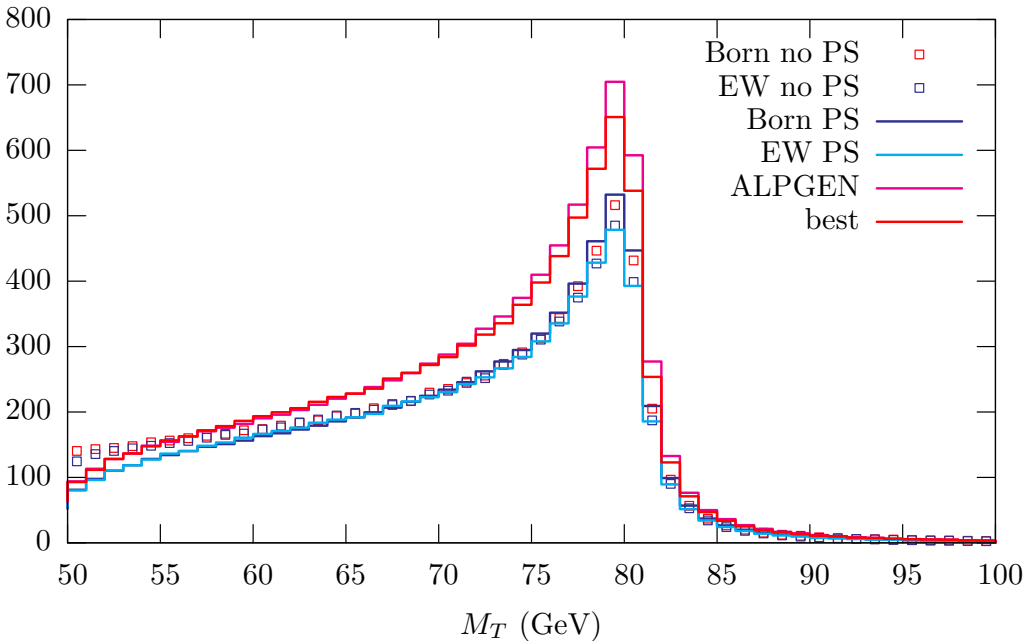
Lepton $p_\perp$ in the tail

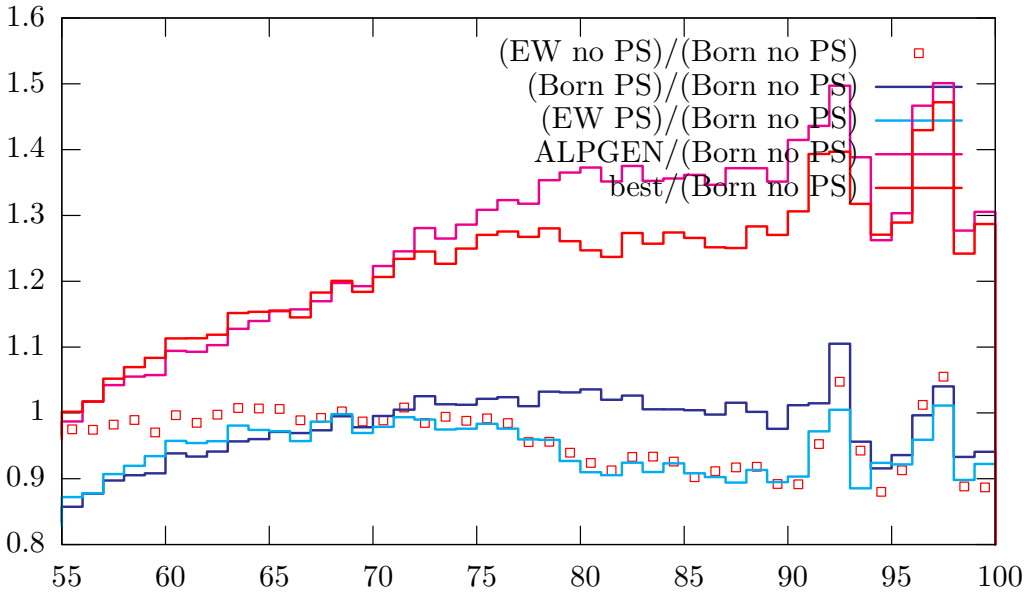




- an explicit cut $M_T > 1$ TeV is imposed
- small QCD PS corrections
- large ME corrections to $q\bar{q}'$ and gluon-induced processes

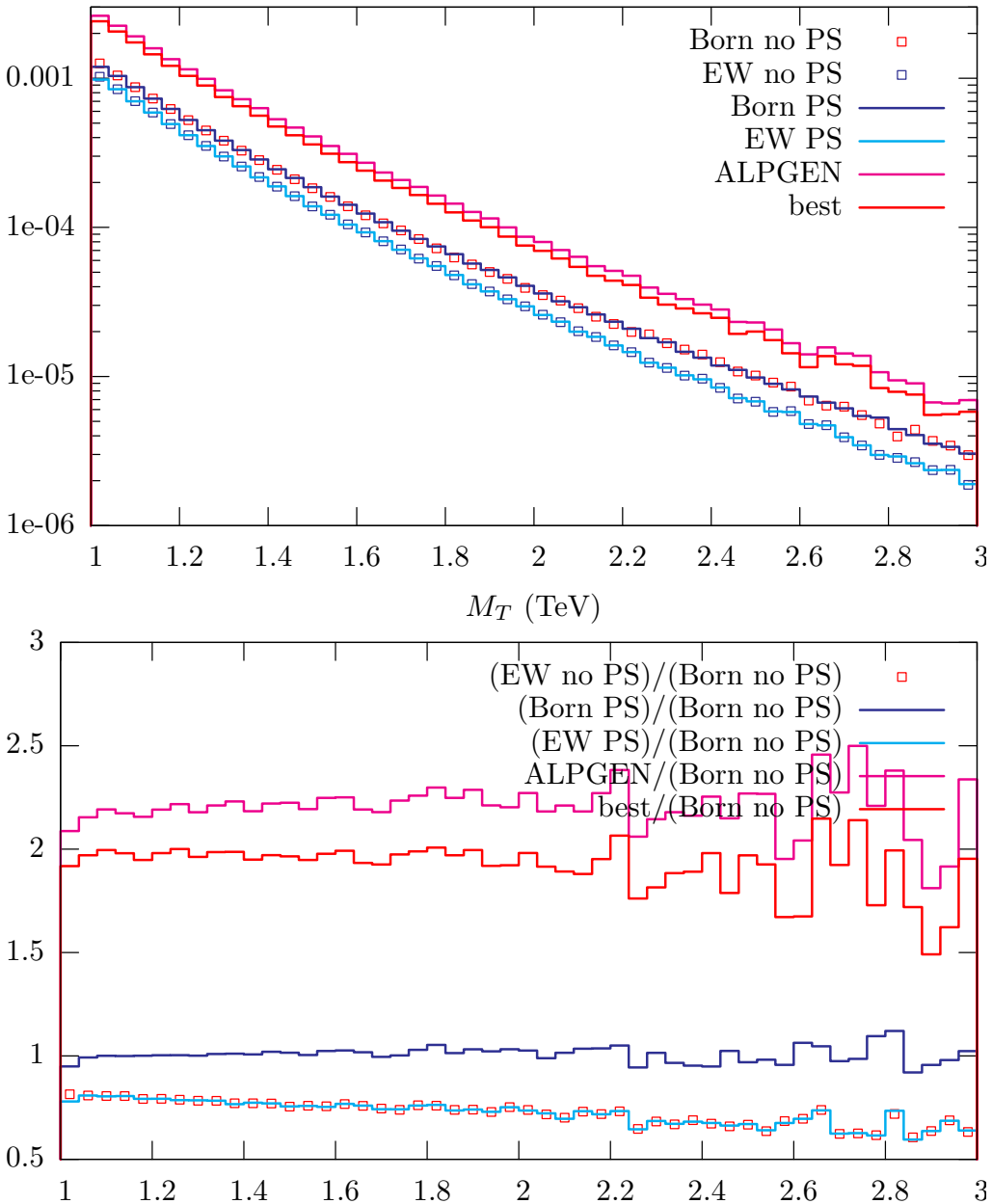
Transverse mass around the peak





- much less sensitive to $p_{\perp,W}$
- “small” QCD PS corrections
- large corrections due to exact QCD ME

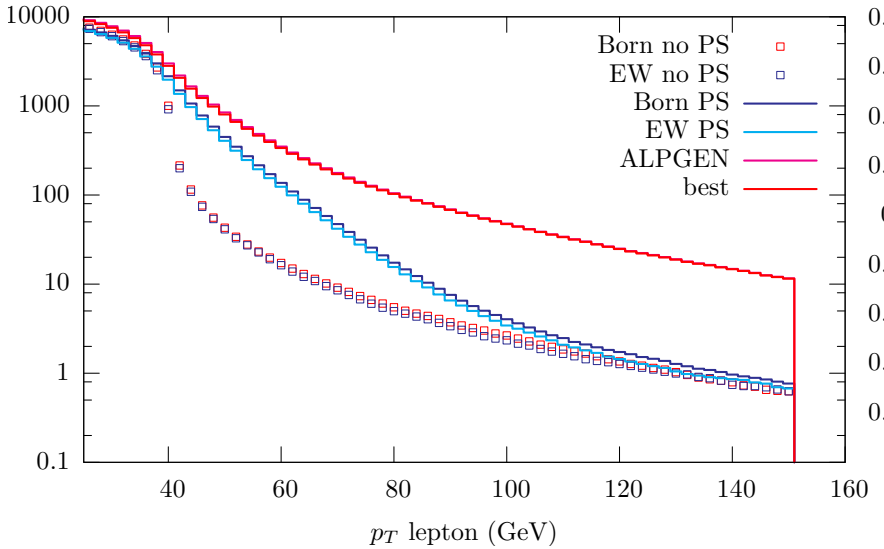
Transverse mass in the tail

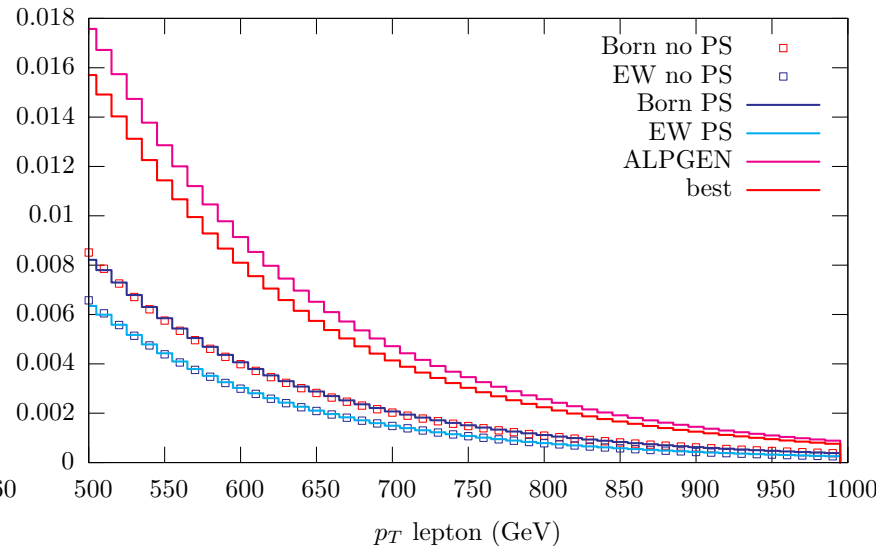


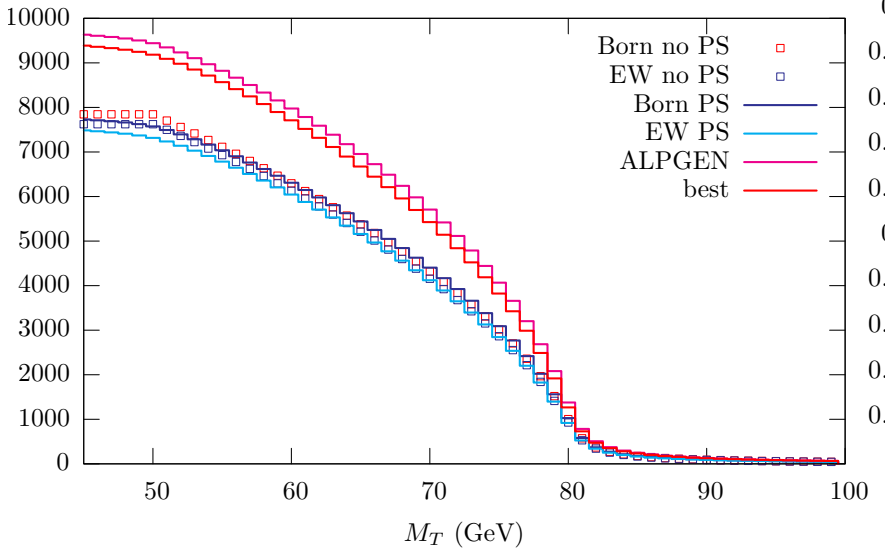
- a cut $M_T > 1$ TeV is explicitly imposed
- small QCD PS corrections
- large QCD exact ME corrections

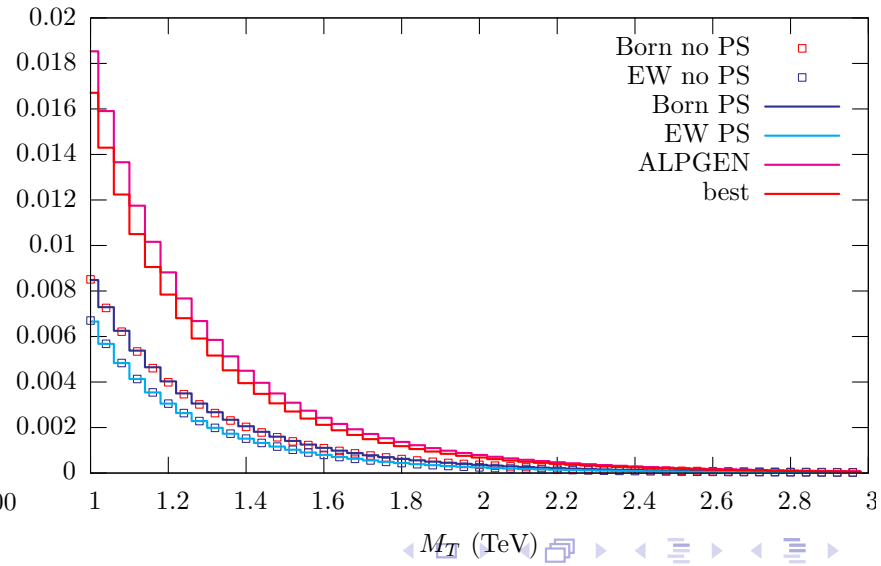
Integrated cross sections

- $\sigma(\mathcal{O}) \equiv \int_{\mathcal{O}}^{\infty} d\sigma$ is plotted









Conclusions

- DY processes are a fertile ground for precision physics at hadron colliders
  - ⋆ precise M_W measurement ($\Delta M_W = 15$ MeV at LHC)
  - ⋆ PDF constraints
  - ⋆ collider luminosity (with accuracy $\mathcal{O}(5\%)$)
  - ⋆ New Physics searches
- Higher-order QCD and EW corrections must be taken into account
- The HORACE EG has been developed, including
  - ⋆ exact $\mathcal{O}(\alpha)$ EW corrections matched with a
  - ⋆ QED Parton Shower to simulate multi-photon radiation
  - ⋆ a “Les Houches Accord” interface is provided
  - ⋆ `http://www.pv.infn.it/hepcomplex/horace.html`
- We started to combine QCD and EW results, to have a more realistic and complete answer. Work is in progress...