W mass at Les Houches

A lot of people …

Theory uncertainties for W mass measurement

- Goal: discuss the relevant theory uncertainties for W mass measurement,
- Try to come up with some operational definitions, along the lines of the CMS+ATLAS+TH workshops organized recently
  - Florence, Oct 2014
    https://indico.cern.ch/event/340393/other-view?view=standard#all
  - CERN, Oct 2014
    https://indico.cern.ch/event/367442/other-view?view=standard#all

- Starting point: theory uncertainties as defined in Tevatron analyses likely to be very aggressive

A challenging (long term) motivation

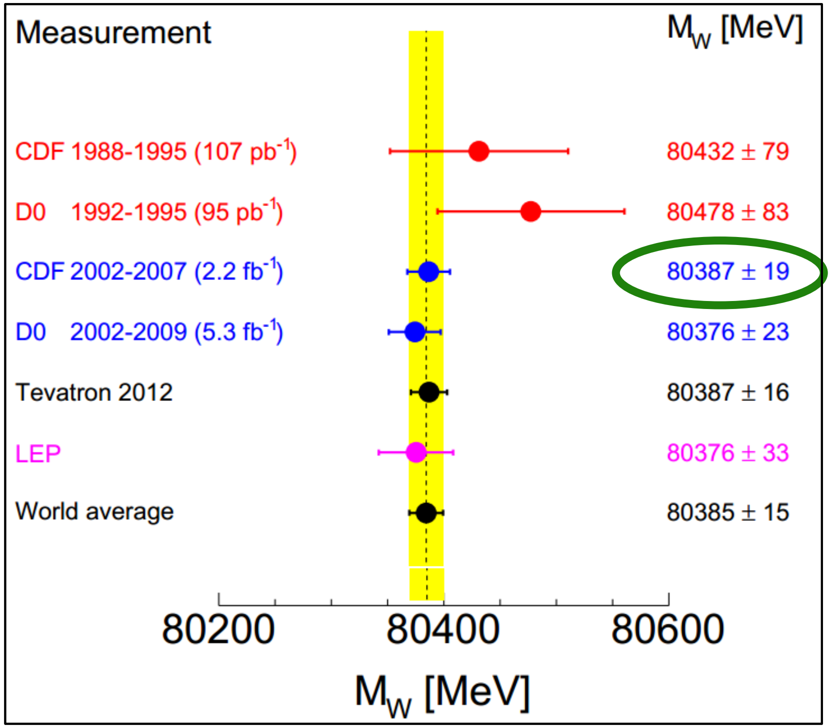
In the SM, the W mass is presently derived from the top and Higgs masses with 8 MeV uncertainty with important CMS contributions in measuring precisely the top and Higgs masses

Direct measurements have significantly worse precision;
CDF quotes 19 MeV (likely to have aggressive TH uncertainties)
The world average is 80385 ± 15 MeV

Phys. Rev. D 89, 072003 (2014)
arXiv:1311.0894

→ A high-accuracy W mass measurement provides a crucial test of the SM

The LHC data is on the table…
a competitive measurement is within reach



The CMS experimental observables and strategy

We will measure the W mass in $W \to \mu\,\nu$ decays using three transverse observables, complementary and not fully correlated:

Muon p_T $\to$ most affected by $p_T(W)$ uncertainties

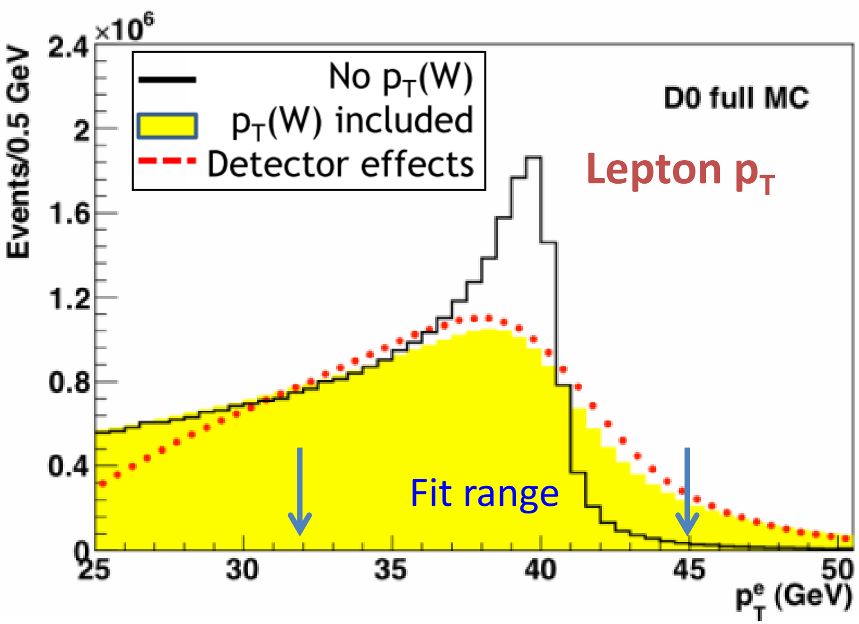
Missing E_T $\to$ most affected by detector resolution effects

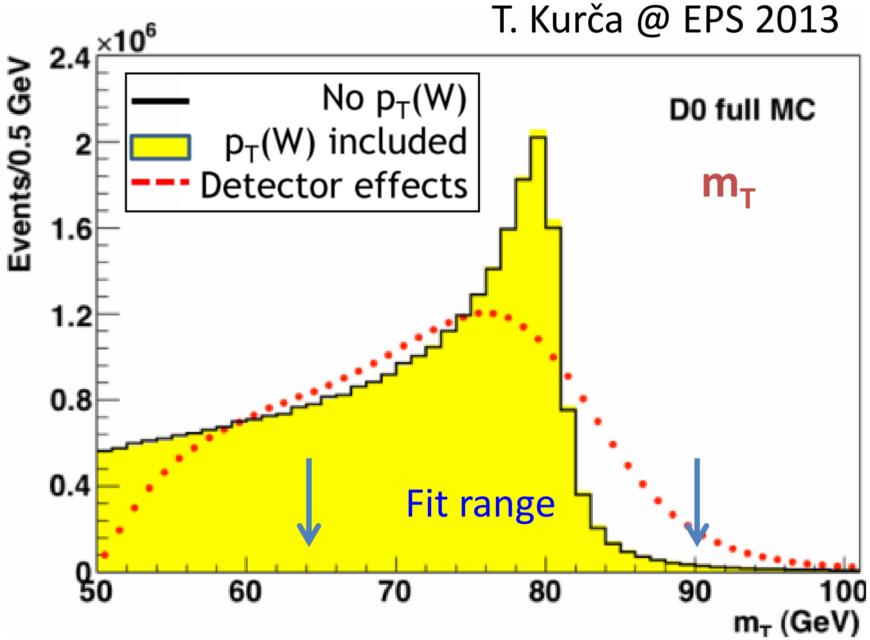
W M_T $\to$ most sensitive variable; best compromise between TH and EXP uncertainties (if MET is under control)

At low boson pT : $m_T \sim 2p_T^{\mu} + p_T^{W}$

10^{-4} precision on p_T^{μ} (40 GeV) and 10^{-3} precision on p_T^{W} (5 GeV) to get 10 MeV on m_W

T. Kurča @ EPS 2013





see also de Rujula: arXiv:1106.0396

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Strategy:

- Generate MC templates (with full simulation) for different M_W values
- Correct templates with data/MC scale factors from control samples
- Measure M_W from the template that best fits the data, with a likelihood ratio fit

Remarks:

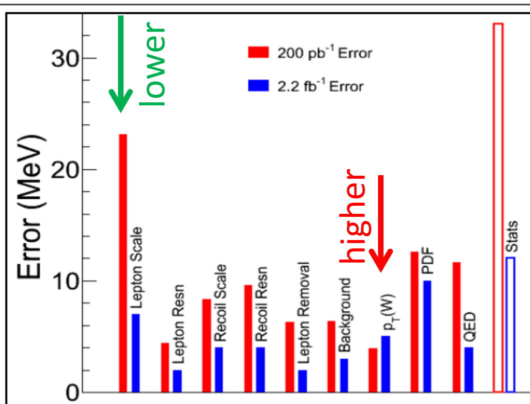
- The measurement only depends on the shapes of the distributions
- Huge effort required to understand and control detector and theory systematics

General considerations about W mass uncertainties

- When looking at Tevatron tables for W mass uncertainties, is clear that they can be divided into 2 distinct parts
  - Experimental systematics
  - Theory systematics

CDF

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19



D0

Source	Public. 2009 (1.0 fb^{-1})	Public. 2012 (4.3 fb^{-1})
Statistical	23	13
Experimental syst.		
Electron energy scale	34	16
Electron energy resolution	2	2
EM shower model	4	4
Electron energy loss	4	4
Hadronic recoil	6	5
Electron ID efficiency	5	1
Backgrounds	2	2
Subtotal experimental syst.	35	18
***W* production and decay model**		
PDF	9	11
QED	7	7
boson p_T	2	2
Subtotal W model	12	13
Total systematic uncert.	37	22
Total	**44**	**26**

lower

higher

combination: 23

Poster child example 1: EWK corrections

1. ΔM_W shifts from (improved) **fits to $\mathbf{M}_T$, $\mathbf{p}_T^\ell$, $\mathbf{E}_T$ miss.** $W \to \mu\nu + X$ (bare muons). 100M events (part. level), 200M (detec. level), using POWHEG V1 and HORACE
2. Event Selection: $|\eta^\mu| < 2.5$, $p_T^{\mu,\nu} > 20$ GeV, $50 < M_T < 100$ GeV. **No $\mathbf{p}_T^W$ / hadronic recoil cut**. **No optimal fit windows for $\mathbf{p}_T^\ell$, $\mathbf{E}_T$ miss.**: [20 – 100] GeV fit windows.

#	templates	pseudodata	Mass shift (MeV)					
			Particle level			Detector level		
			M_T	p_T	$\not{E}_T$	M_T	p_T	$\not{E}_T$
1	Powheg(QCD)+Pythia(QCD)	Powheg(QCD)+Pythia(QCD,QED)	-97.0 $\pm$ 1.0	-555.0 $\pm$ 5.0	-2.0 $\pm$ 5.0	-128.7 $\pm$ 2.0	**-239.0** $\pm$ **4.0**	-23.0 $\pm$ 5.0
2	Powheg(QCD)+Pythia(QCD)	Powheg(QCD)+Pythia(QCD)+Photos	-88.3 $\pm$ 1.0	-506.0 $\pm$ 5.0	0.0 $\pm$ 5.0	-119.7 $\pm$ 3.0	**-221.0** $\pm$ **4.0**	-20.0 $\pm$ 5.0
3	Powheg(QCD)+Herwig(QCD)	Powheg(QCD)+Herwig(QCD,QED)	-88.7 $\pm$ 1.0	-497.0 $\pm$ 4.0	2.0 $\pm$ 4.0	-129.0 $\pm$ 3.0	**-218.0** $\pm$ **4.0**	-25.0 $\pm$ 6.0
4	Powheg(QCD)+Pythia(QCD)	Powheg(QCD+EW)+Pythia(QCD)+Photos	–	–	–	–	–	–
5	Horace LO	Horace QED FSR	-91.8 $\pm$ 1.0	-106.8 $\pm$ 1.0	-7.0 $\pm$ 1.0	–	–	–
6	Horace QED FSR	Horace QED FSR + lepton pairs	-4.0 $\pm$ 2.0	-5.0 $\pm$ 1.0	-2.0 $\pm$ 1.0	–	–	–

- "Large" ΔM_W shifts due to the inclusion of QED radiation in POWHEG$_{\rm QCD}$ for lepton p_T, significantly reduced after detector smearing
- For p_T^ℓ and $\not{E}_T$ crucial impact of QCD PS on M_W shift induced by QED correction
- **QED model differences** $\sim 20 \pm 6$ **MeV for lepton p_T (detector level)**, negligible for $\not{E}_T$
- Few MeV shift due to pairs for all distributions (particle level)

New results (preliminary): p_T^W cut & NLO EWK in POWHEG V2

1. ΔM_W shifts from **fits to $\mathbf{M}_T$, $\mathbf{p}_T^\ell$, $\mathbf{E}_T$ miss.** $W \to \mu\nu + X$ (bare muons). 100M events (part. level), 20M (detec. level), **using** POWHEG V2 **with NLO EWK**
2. Event Selection: as before + $\mathbf{p}_T^W < \mathbf{30\ GeV}$. **"Optimal" $\mathbf{p}_T^\ell$, $\mathbf{E}_T$ missing fit windows**: [27.5 – 47.5] GeV (CDF/D0-like)

#	templates	pseudodata	Mass shift (MeV)					
			Particle level			Detector level		
			M_T	p_T	$\not{E}_T$	M_T	p_T	$\not{E}_T$
1	Powheg(QCD)+Pythia(QCD)	Powheg(**QCD**)+Pythia(QCD,QED)	**-97.0 $\pm$ 1.0**	**-408.0 $\pm$ 6.0**	-7.0 $\pm$ 5.0	–	–	–
2	Powheg(QCD)+Pythia(QCD)	Powheg(**QCD+EWK**)+Pythia(QCD,QED)	**-102.0 $\pm$ 1.0**	**-440.0 $\pm$ 5.0**	-30.0 $\pm$ 5.0	–	–	–

- For p_T^ℓ, mass shifts reduced by p_T^W cut
- Differences due to NLO EWK corrections in POWHEG V2 $[\mathcal{O}(\alpha)_{\rm Powheg} \otimes \rm PS]$ w.r.t. NLO_{QCD} POWHEG + $\rm PS_{QCD+QED}$
  - **Particle level: $\Delta M_W \sim 5$ MeV for M_T / $\Delta M_W \sim 30 \pm 8$ MeV for p_T^ℓ**
  - Detector level: similar differences, but still limited by statistics!
- We are going to produce numbers also with $\text{PYTHIA}_{\text{QCD}}$ + PHOTOS in POWHEG V2
- Important to study also p_T^W / hadronic recoil cut $<$ 15 GeV

Poster child example 2: PDF

Dependence of the MW PDF uncertainty on different etal_l cuts

normalized distributions			
cut on $p_\perp^W$	cut on $\|\eta_l\|$	CT10	NNPDF3.0
inclusive	$\|\eta_l\| < 2.5$	$80.400 + 0.032 - 0.027$	80.398 ± 0.014
$p_\perp^W < 20$ GeV	$\|\eta_l\| < 2.5$	$80.396 + 0.027 - 0.020$	80.394 ± 0.012
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 10$ GeV	$\|\eta_l\| < 2.5$	$80.392 + 0.015 - 0.012$	80.394 ± 0.007
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 1.0$	$80.400 + 0.032 - 0.021$	80.406 ± 0.017
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 15$ GeV	$\|\eta_l\| < 4.9$	$80.400 + 0.009 - 0.004$	80.401 ± 0.003
$p_\perp^W < 15$ GeV	$1.0 < \|\eta_l\| < 2.5$	$80.392 + 0.025 - 0.018$	80.388 ± 0.012

- the dependence on the PDFs decreases when enlarging the eta_l acceptance (effectively integrating over the whole partonic-x range, MW is extracted from normalized ptl distributions)
- the regions |eta_l|<1.0 and 1.0 < |eta_l| < 2.5 suffer of larger uncertainties compared to |eta_l|<2.5
- constrained behavior (PDF sum rules) of each replica in the two eta_l regions: if the distribution is smaller than average in one interval, it is then larger than average in the other, the sum of the contributions of the two intervals is more stable (w.r.t. replica variations)

Poster child example 2: PDF

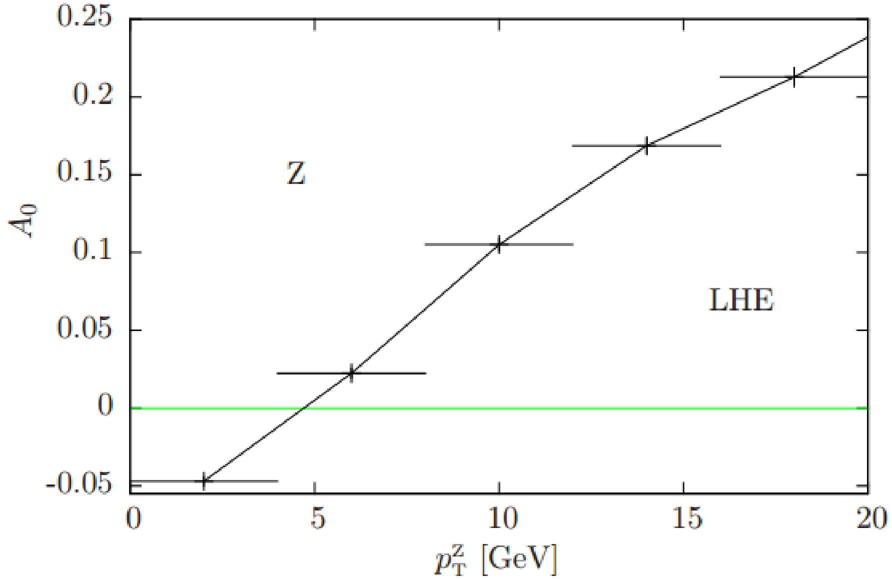
Numerical results, with and without a PTW cut

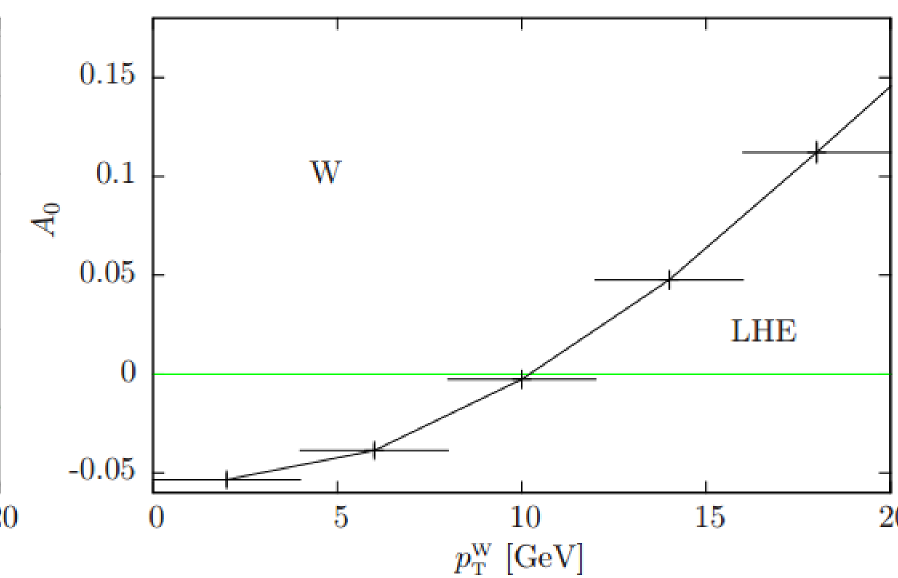
absolute distributions					
collider/channel	CT10	MSTW2008CPdeut	NNPDF2.3	NNPDF3.0	MMHT2014
Tevatron, W^+	80.406 + 0.043 − 0.046	80.428 + 0.025 − 0.017	80.400 ± 0.030	80.427 ± 0.018	80.430 + 0.022 − 0.022
LHC 8 TeV, W^+	80.394 + 0.040 − 0.029	80.422 + 0.025 − 0.016	80.398 ± 0.020	80.406 ± 0.019	80.428 + 0.027 − 0.022
W^-	80.444 + 0.055 − 0.062	80.390 + 0.038 − 0.036	80.398 ± 0.030	80.441 ± 0.027	80.404 + 0.041 − 0.048
LHC 13 TeV,W^+	80.396 + 0.045 − 0.034	80.416 + 0.020 − 0.020	80.398 ± 0.022	80.414 ± 0.022	80.422 + 0.030 − 0.024
W^-	80.416 + 0.088 − 0.065	80.374 + 0.044 − 0.033	80.398 ± 0.031	80.426 ± 0.037	80.384 + 0.037 − 0.049
normalized distributions					
collider/channel	CT10	MSTW2008CPdeut	NNPDF2.3	NNPDF3.0	MMHT2014
Tevatron, W^+	80.400 + 0.022 − 0.025	80.414 + 0.016 − 0.016	80.398 ± 0.012	80.408 ± 0.013	80.412 + 0.014 − 0.010
LHC 8 TeV, W^+	80.398 + 0.032 − 0.026	80.424 + 0.014 − 0.019	80.398 ± 0.016	80.395 ± 0.014	80.428 + 0.016 − 0.024
W^-	80.416 + 0.026 − 0.025	80.398 + 0.011 − 0.014	80.398 ± 0.014	80.396 ± 0.012	80.402 + 0.019 − 0.024
LHC 13 TeV,W^+	80.406 + 0.039 − 0.029	80.420 + 0.017 − 0.014	80.398 ± 0.018	80.404 ± 0.016	80.428 + 0.020 − 0.026
W^-	80.422 + 0.030 − 0.023	80.398 + 0.008 − 0.015	80.398 ± 0.015	80.386 ± 0.011	80.402 + 0.019 − 0.024
absolute distributions, additional cut $p_\perp^W < 15$ GeV					
collider/channel	CT10	MSTW2008CPdeut	NNPDF2.3	NNPDF3.0	MMHT2014
Tevatron, W^+	80.412 + 0.024 − 0.024	80.424 + 0.018 − 0.017	80.399 ± 0.014	80.420 ± 0.014	80.426 + 0.009 − 0.021
LHC 8 TeV, W^+	80.392 + 0.026 − 0.021	80.414 + 0.020 − 0.011	80.398 ± 0.015	80.403 ± 0.014	80.418 + 0.019 − 0.017
W^-	80.422 + 0.039 − 0.034	80.394 + 0.019 − 0.023	80.399 ± 0.018	80.423 ± 0.017	80.400 + 0.023 − 0.028
LHC 13 TeV,W^+	80.392 + 0.028 − 0.022	80.410 + 0.012 − 0.016	80.398 ± 0.016	80.408 ± 0.014	80.414 + 0.016 − 0.019
W^-	80.408 + 0.042 − 0.037	80.386 + 0.019 − 0.021	80.398 ± 0.016	80.410 ± 0.018	80.388 + 0.021 − 0.025
normalized distributions, additional cut $p_\perp^W < 15$ GeV					
collider/channel	CT10	MSTW2008CPdeut	NNPDF2.3	NNPDF3.0	MMHT2014
Tevatron, W^+	80.400 + 0.018 − 0.016	80.414 + 0.013 − 0.015	80.399 ± 0.010	80.403 ± 0.011	80.412 + 0.006 − 0.012
LHC 8 TeV, W^+	80.396 + 0.017 − 0.018	80.414 + 0.012 − 0.011	80.398 ± 0.011	80.395 ± 0.009	80.416 + 0.011 − 0.014
W^-	80.406 + 0.016 − 0.011	80.398 + 0.005 − 0.012	80.398 ± 0.010	80.398 ± 0.007	80.398 + 0.008 − 0.016
LHC 13 TeV,W^+	80.400 + 0.020 − 0.017	80.412 + 0.010 − 0.011	80.398 ± 0.012	80.400 ± 0.010	80.416 + 0.010 − 0.015
W^-	80.408 + 0.017 − 0.009	80.396 + 0.010 − 0.006	80.399 ± 0.010	80.391 ± 0.006	80.396 + 0.009 − 0.013

Polarization

- Drell Yan polarization has been measred both at Tevatron and LHC, see for instance the recent CMS paper at 8 TeV http://arxiv.org/abs/1504.03512 On one side one can “tune” some POWHEG parameters to match data on the Z case. On the other side is not clear how universal these parameters are from Z to W and which uncertainty should be assigned for this extrapolation.

Z and W production at LHE





Unphysical feature at small p_T: negative A_0.

This cannot be in an exact theory expansion, but it can happen when partial higher-order contributions are present

Boson pT

- QCD non perturbative scale choice at Tevatron driven by fit on Z data.
- QCD perturbative scale variation not taken into account at Tevatron. Fully uncorrelated scale variation would lead to several tens of MeV uncertainty. Is it possible to use Z data to (at least partially) constraint the W pT?
- Apart from NLO+PS combinations like POWHEG+Pythia, how to take into account higher order corrections from codes like the NNLO+NNLL DYRES? Reweighting? Tuning?
- Do we need to consider the propagation of UE ucnertainties?

Correlations

- PDF, Underlying event, QCD soft scale resummation and perturbative scales, polarization uncertainties are correlated.
- How to handle them properly?
- Would it be possible to remove datasets from PDF “on demand”? (for instance, no W charge asymmetry)