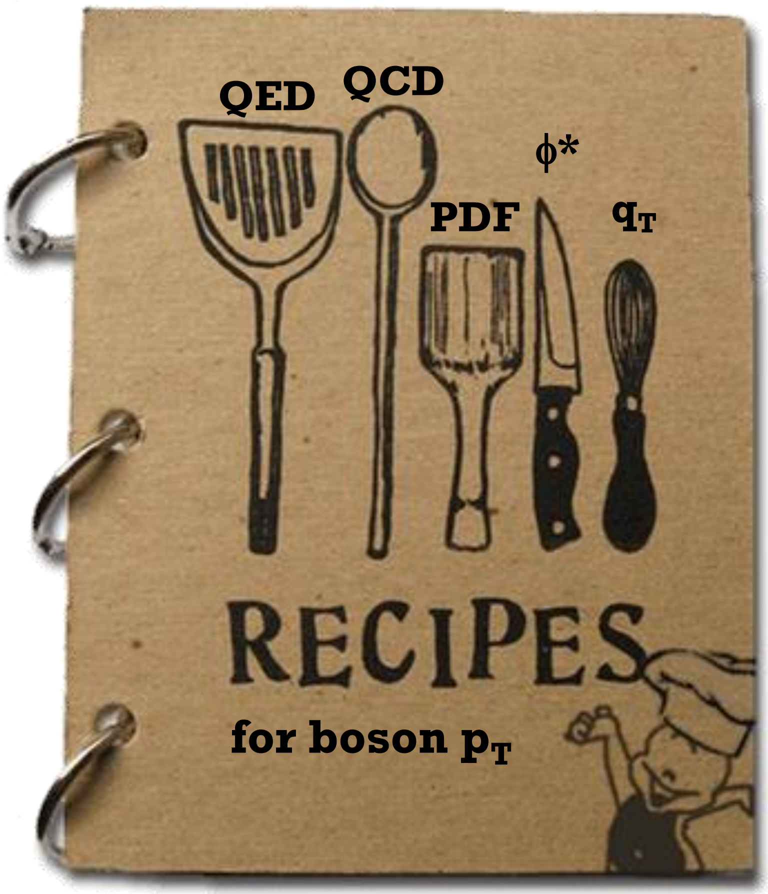
Vector boson p_T distributions and W mass
Measurements, MC tools and tuning



Nathalie Besson, Maarten Bonekamp,
Stefano Camarda, Mariarisaria D'Alfonso,
Andre David, Luca Perrozzi
for the CMS and ATLAS collaborations

W mass workshop
October 20^{th}-21^{st} 2014
GGI Institute, Florence

Disclamer

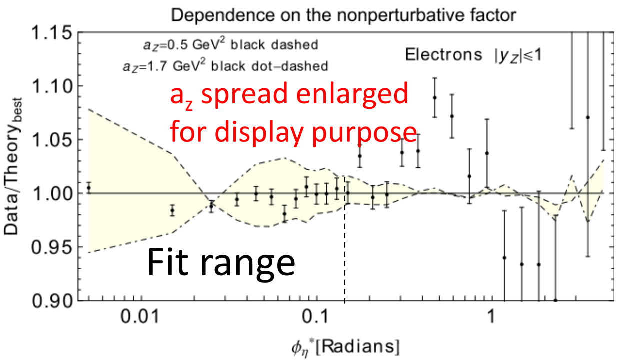
- This talk IS meant to:
  - Review the available LHC measurements of the Vector boson distributions and how they can be used as input for the W mass
  - Describe the tools and settings being tested by the CMS and ATLAS collaborations
  - Start a discussion to define a practical procedure to accurately simulate the W pT distribution and assign systematic uncertainties
- This talk IS NOT meant to deal with theoretical aspects of MC tools in a strictly rigorous way…
  - Some questions are rethorical, some could seem a bit provocative but the aim is to stimulate the discussion on this very delicate topic

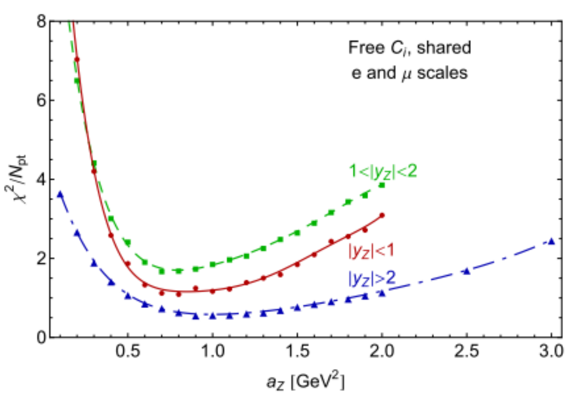
Recap of the basic recipe

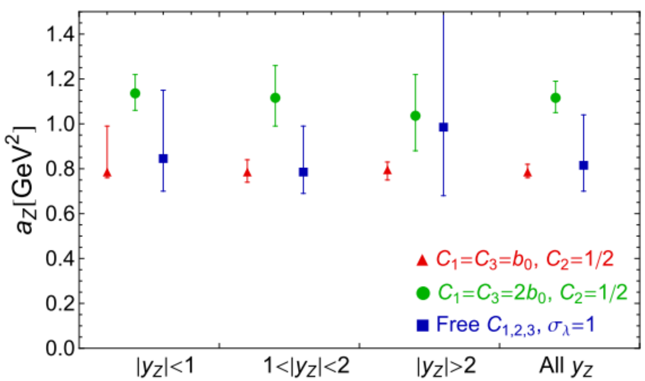
1) Take a given set of data points on transverse distribution quantities measured in Z events
   - At the center of mass energy used to perform the W mass measurement
2) Take a given theoretical prediction, featuring
   - A given degree of accuracy, e.g. (N)(N)LO combined with (N)(N)LL
   - A certain number of adjustable parameters, theoretically motivated
   - The production of both Z and W events
3) Fit the Z data points with the theoretical prediction, varying its adjustable parameters in theoretically motivated (pre-) defined ranges to obtain the best agreement with some minimization technique
   - Define parameter variations corresponding to 68% C.L. and their correlations
4) Finally, use the theoretical prediction with the parameters set to the best fit values to produce W events with tuned p_T shape to quote the central W mass value
   - Use the W p_T shapes obtained by varying the adjustable parameters to assign a systematic uncertainty on the W mass due to the boson p_T modeling

Quintessential case: Tevatron approach

- Use ϕ^* measurement in Z events (D0, arXiv:1010.0262)
  - Unfolded to bare leptons (after FSR)
- Use Resbos GNW version matched with PHOTOS (arXiv:1309.1393)
  - Resbos is accurate at (approximate) NNLO + NNLL
  - Mainly 4 parameters: 3 perturbative ($C_{1,2,3}$) and 1 non perturbative (a_z)
- Fit non-perturbative parameter a_z with χ^2 data/mc comparison
  - Use only first 12 bins up to ϕ^*~0.1
- Use fitted a_z parameter to generate W events and assign systematics
  - Two approaches are used to fit a_z with a χ^2 technique:
    - Type I: C_i fixed to theoretically motivated values
      - $a_Z = 0.79 \pm 0.03$ GeV^2 for $C_{1,2,3}$= {1.0*b0, 0.5, 1.0*b0}
      - $a_Z = 1.12 \pm 0.07$ GeV^2 for $C_{1,2,3}$ = {2.0*b0, 0.5, 2.0*b0}
    - Type II: C_i free to vary (Hessian approach a' la PDF fit)
      - $a_Z = 0.82 + 0.22 - 0.11$ for $C_{1,2,3}$ = {1.42*b0, 0.33, 1.23*b0}







Comments and questions about Tevatron approach

- Use of high order state of the art QCD generator motivated by the absence of reliable ME+PS generators in the "old days"
  - Full event characteristics mimicked with customized parametric fast-sim
- Resbos generation works as a 2 step program
  - Step 1: generate grids for given a_z and $C_{1,2,3}$ scale choice and PDF set/member with Legacy
    - Legacy code is not public, need to ask authors to produce them
  - Step 2: generate events using grids from Step 1
    - Event generation is extremely fast and accurate (consistency in physics observables)
- At Tevatron, central scales motivated theoretically $C_{1,2,3}$ = {2.0*b0, 0.5, 2.0*b0} have been used to generate events for different a_z values
  - Fitted scales are $C_{1,2,3}$ = {1.42*b0, 0.33, 1.23*b0} and no uncertainties are provided in arXiv:1309.1393
- Quoted W mass uncertainty due to W pT at Tevatron
  - Corresponds to the variation of a_z only and is very small (~9 MeV for lepton p_T, ~3 MeV for m_T)
  - No perturbative scale variation is considered
  - Theoretical approach for scale variation (usual factor $1/2 \rightarrow 2$) adds uncertainties of several tens of MeV
    - Likely to be highly over-estimated since no constraint from the Z data is used

- Can we refine the recipe for the LHC measurements?
  - How and where to improve?

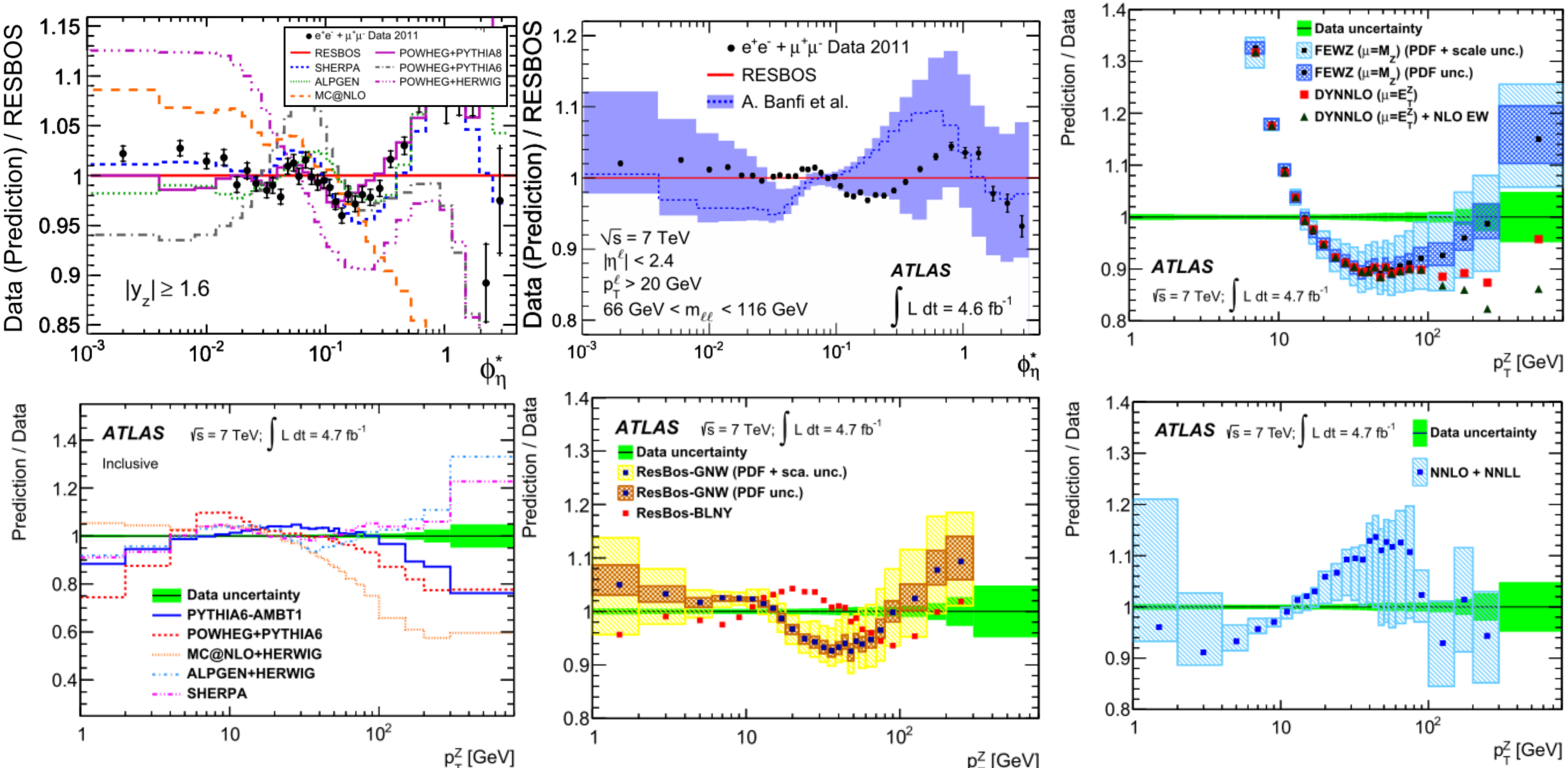
LHC measurements on transverse distribution quantities measured in Z and W events

- Z pT
  - Measurement at 7 TeV by CMS with 35 pb^{-1} [arXiv:1110.4973]
  - Measurement at 7 TeV by ATLAS with 35 pb^{-1} [arXiv:1107.2381]
  - Measurement at 7 TeV by ATLAS with 4.7 fb^{-1} [arxiv:1406.3660]
  - Measurement at 8 TeV by CMS with 20 pb^{-1} [PAS SMP-12-025]
- Z ϕ^*
  - Measurement at 7 TeV by ATLAS with 4.7 fb^{-1} [arXiv:1211.6899]
- W p_T
  - Measurement at 7 TeV by ATLAS with 35 pb^{-1} [arXiv:1108.6308]
  - Measurement at 8 TeV by CMS with 20 pb^{-1} [PAS SMP-13-006]

- Measurements also relevant in this context
  - Underlying event variables in Z events
    - Measurement at 7 TeV by CMS with 4.7 fb^{-1} [arXiv:1204.1411]
    - Measurement at 7 TeV by ATLAS with 4.7 fb^{-1} [arxiv:1409.3433]
  - Z p_T in association with b-jets
    - Measurement at 7 TeV by ATLAS [arxiv:1407.3643]
    - Measurement at 7 TeV by CMS [arXiv:1402.1521]

An ATLAS approach (I)

- ATLAS released 2 measurement in Z events at 7 TeV with full statistics: Z p_T and ϕ^*
  - Very precise (uncertainties <1%)
  - Large number of bins at low "p_T", 3 rapidity bins + inclusive
  - Distributions compared to a large number of theoretical predictions



An ATLAS approach (II)

- Use Z p_T and ϕ^* ATLAS measurement in Z events at 7 TeV with full statistics
  - Use leptons unfolded to dressed definition
    - Recombination of photons emitted in a $\Delta R=0.1$ cone
  - Use range: $Zp_T < 26$ GeV, and $\phi^* < 0.29$ inclusive in rapidity
- Use POWHEG interfaced to Pythia8
  - POWHEG is accurate at NLO and has 1 tunable parameter:
    - ptsqmin: sets the p_T cut-off below which events are generated without extra radiation. The phase space is then populated by Pythia8
  - Pythia8 resums to LL order and has hundreds of parameters.
  - QED effects handled by Pythia8
  - Initial Pythia8 parameters are set to 4C tune, then some are varied

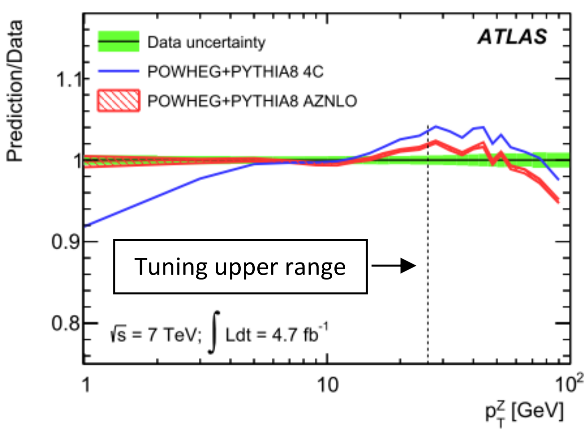
Parameter	Variation Range PYTHIA8 tune	Variation Range PYTHIA8+POWHEG tune
Primordial k_T [GeV]	1.0–2.5	0.5–2.5
ISR $\alpha_S^{ISR}(m_Z)$	0.120–0.140	0.118
ISR cut-off [GeV]	0.5–2.5	0.5–3.0
ISR α_S order	LO	NLO
PYTHIA8 base tune	tune 4C	tune 4C
POWHEG cut-off [GeV^2]	-	4.0

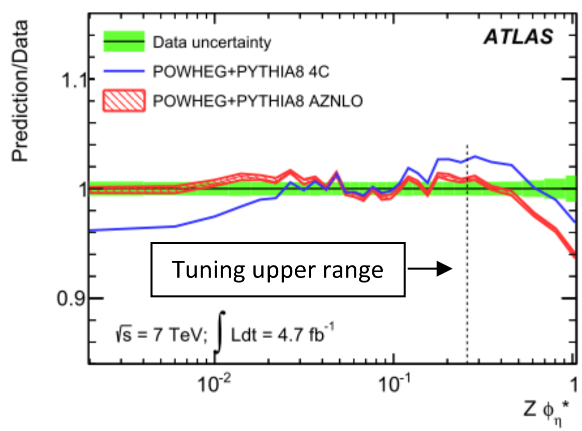
Let's focus on the POWHEG+PYTHIA8 case

An ATLAS approach (III)

- Tuning performed using Professor
  - Tune on ZpT performed first independently from ϕ* and then jointly since results are compatible

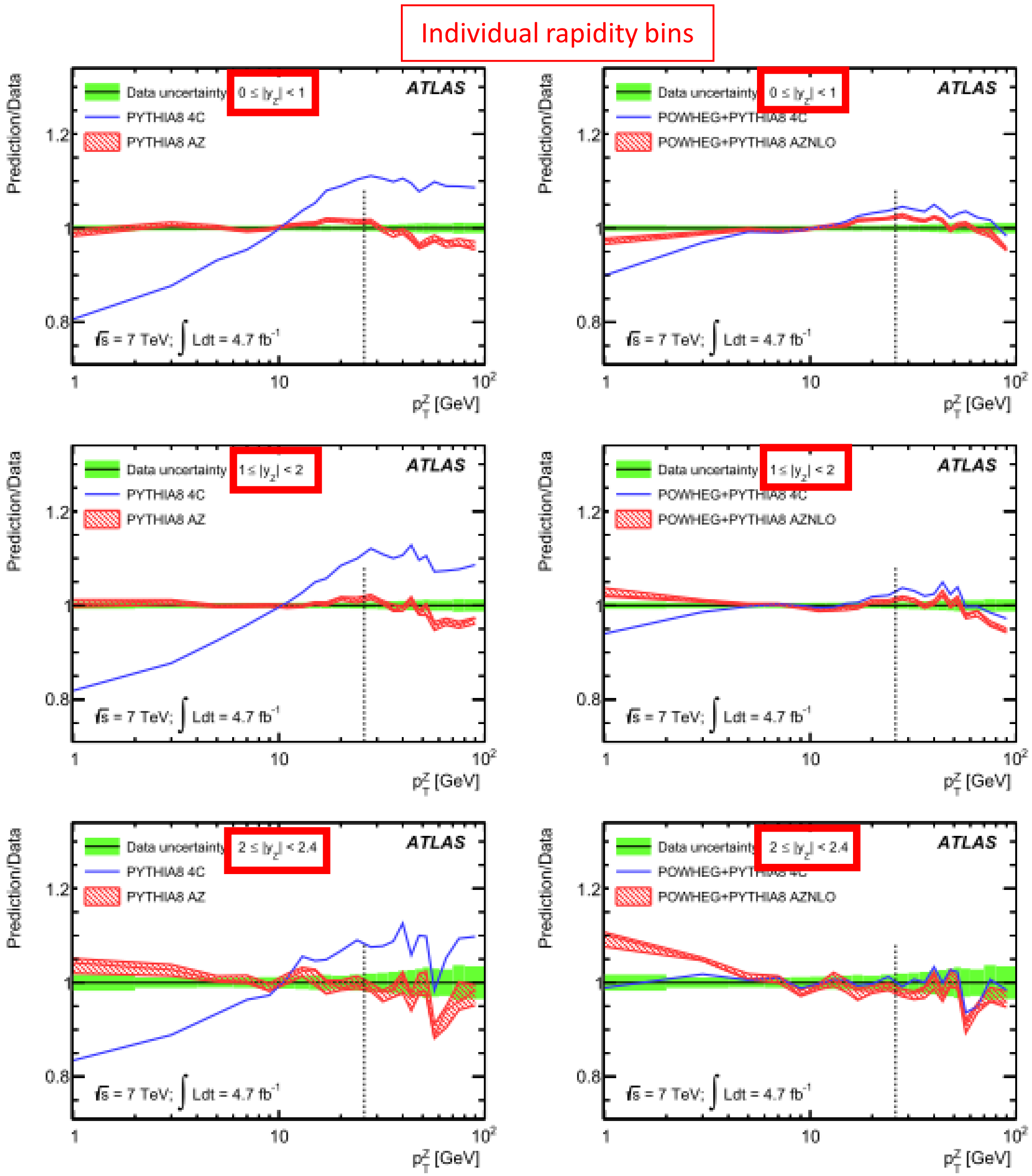
	PYTHIA8	POWHEG+PYTHIA8	Base tune
Tune Name	AZ	AZNLO	4C
Primordial k_T [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
ISR $\alpha_S^{ISR}(m_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
χ^2_{min}/dof	45.4/32	46.0/33	-





Inclusive rapidity bin

An ATLAS approach (IV)



- Reminder: the tuning is performed on the inclusive rapidity bin
- With Pythia8 standalone there is good agreement across the different rapidity bins
- With POWHEG+Pythia8 the agreement in the inclusive rapidity bin is not well preserved when splitting in bins

and W

Comments and questions about ATLAS approach

- Use of ME+PS generators motivated by dramatic improvements in the last years
  - Fast, highly automated and reliable event generation widely used by CMS and ATLAS
  - Full event characteristics simulated from "first principles" or effective theoretical model
- POWHEG parameter ptsqmin increased from default 0.8 GeV^2 to 4.0 GeV^2
  - Without this increase, data/MC agreement is much worse
  - In private communications, POWHEG authors strongly dislike this. Why?
- Some tuned Pythia8 parameters are non-perturbative
  - What is the accuracy when porting to W events these parameters, constrained on Z ?
  - No attempt to incorporate POWHEG perturbative scale variations
- Accuracy of POWHEG is NLO, of PS like Pythia is LL
  - Is the good POWHEG+Pythia8 agreement in the inclusive rapidity bin spoiled because of missing higher order corrections?
- Higher order tools on the market? Can we use them? How?

A CMS approach (in progress…)

- Use available Z p_T measurement from CMS and Z p_T, ϕ^* ones from ATLAS in Z events at 7 TeV
  - Use leptons unfolded to Born (i.e. pre-FSR) definition
  - Use range: $Zp_T < 30$ GeV, and $\phi^* < 0.26$(CHECK) inclusive in rapidity
- Use POWHEG (incl. NLO EWK effects) interfaced to Pythia8
  - POWHEG ptsqmin set to 2.5 GeV^2 as suggested by authors
  - QED effects handled by Pythia8 (dedicated emission veto to cope with NLO EWK effects in POWHEG)
  - Pythia8 parameters set to 4C tune
- Tune both Resbos and DYRES (independently)
  - 4 main parameters for both: 3 perturbative scales and 1 non-perturbative parameter
  - Pre-define parameter variations considered acceptable from theoretical considerations

- Reweight POWHEG+Pythia8 boson p_T spectrum to the tuned higher order prediction(s)
  - In Z events to calibrate lepton scale and missing energy
  - In W events to measure the W mass
  - Using the 4 parameters corresponding to the best fit
  - Systematic uncertainties on W mass assigned by varying parameters within 68% C.L. of best fit taking into account correlations

Comments and questions about CMS approach

- How to "safely" reweight POWHEG+Pythia8 with higher order calculations
  - Which effect(s) can spoil the required level of precision?
  - Assuming that the same PDF set must be used in the procedure, which order shall be used?
    - NLO for POWHEG+Pythia8 and NNLO for Resbos/DYRES
    - (N)NLO for all
  - Shall we also reweight boson rapidity, i.e. a 2D (p_T,Y) procedure?
    - Computational time to get enough statistics could diverge
- Use of parameters different from default values, suggested by authors on theoretical considerations, usually strongly disfavored
  - "Why?"
  - Does this hold also if the parameters lie within pre-defined ranges considered acceptable from theoretical considerations?
  - What would "mean" to perform a fit to find the best agreement and then stick to the central parameter values?
- Systematic uncertainties assigned by varying parameters within 68% C.L. of best fit usually strongly disfavored by authors
  - "Why?"
  - Can this be considered as the best compromise to incorporate data points and sit between:
    - no uncertainty option (especially on the perturbative side)
    - usual factor 1/2 $\rightarrow$ 2 option (which would lead to most probably artificially inflated uncertainties)
- Shall additional systematic uncertainty be considered?
- In any case, we need the most reliable "transfer function" from Z to W
  - The higher the order of the theoretical prediction, the more reliable is this transfer function
    - Right?

Pushing things further

- Include variation of fitted boson p_T parameters directly into the W mass fit as nuisance parameters
  - To get further constraint from the W data and check consistency in the post-fit pull
- Consider a common generated boson pT distribution (or even the same generators and settings) for CMS and ATLAS analyses for both Z and W events
  - De facto, at Tevatron it was the case because they used Resbos with the same grids
- Interface (N)NLO calculation to PS at (N)NLL
  - POWHEG started moving towards NNLO+PS
  - What else can be done? In which timescale?
- Are there ways to motivate better sources of theoretical uncertainty other than scale variations?
  - Common topic as in Higgs discussions
  - Usually theorists agree that scale variations are not sources of uncertainty, just ways to gauge uncertainties in an ad hoc way.
  - What are the actual sources of uncertainty which data can meaningfully constrain?
    - With these dof we would like to “cover” the theory “missing higher orders”

Open questions

- PDF: role of b-bbar in Z production and pT spectrum when porting to W
  - At LHC energies O(1%) Z events come from b-bbar
  - Measured Z p_T spectra in the presence of b jets seem to indicate larger deviations from predictions wrt inclusive ones
    - b's are massless in the 5 flavour scheme
    - Would the use of 4 flavour scheme be more reliable?
      - But large uncertainties from calculations containing the resummation of b's collinear to the beam
- QED: use measured Born or dressed level spectra
  - ATLAS study estimates this as a negligible effect
  - Missing QCDxQED interference terms: how much do they count in the boson pT shape
    - The effect should be very small compared to QCD

Summary and conclusions

- At least 3 possible approaches on the table
  - Generate events with tuned state of the art theoretical prediction
  - Generate events with tuned ME+PS theoretical prediction
  - Generate events with ME+PS theoretical prediction, reweighted to tuned state of the art theoretical prediction

- A lot of questions to be addressed

- Let’s discuss about it…

Backup

Complete references of LHC measurements

- ATLAS
  - Measurement of distributions sensitive to the underlying event in inclusive Z-boson production in *pp* collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-42/ http://arxiv.org/abs/1409.3433
  - Measurement of differential production cross-sections for a Z boson in association with b-jets in 7 TeV proton-proton collisions with the ATLAS detector https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-15/ http://arxiv.org/abs/1407.3643
  - Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} =7$~TeV with the ATLAS detector https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-23/ http://arxiv.org/abs/1406.3660 JHEP09(2014)145
  - Measurement of the phi* distribution of Drell-Yan lepton pairs to probe Z/gamma* boson transverse momentum at sqrt(s) = 7 TeV with the ATLAS detector https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-06/ Phys. Lett. B 720 (2013) 32-51
  - Measurement of the Transverse Momentum Distribution of W bosons in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-15/ Phys.Rev. D85 (2012) 012005
  - Measurement of the transverse momentum distribution of Z/gamma* bosons in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-09/ doi:10.1016/j.physletb.2011.10.018
- CMS
  - Measurement of the Underlying Event Activity in the Drell-Yan process in proton-proton collisions at $\sqrt{s}$ = 7 TeV https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsQCD11012 Eur. Phys. J. C 72 (2012) 2080
  - "Measurement of the production cross sections for a Z boson and one or more b jets in pp collisions at 7 TeV" https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13004 JHEP 06 (2014) 120
  - Measurement of the Rapidity and Transverse Momentum Distributions of Z Bosons https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK10010 10.1103/PhysRevD.85.032002
  - Measurement of the transverse momentum distribution of Z bosons decaying to dimuons in pp collisions at = 8 TeV https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12025
  - Measurement of the transverse momentum of W bosons in pp collisions at = 8 TeV https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13006
  - Measurement of the Z+b-jet cross section in pp collisions at sqrt(s) = 7 TeV https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11012 JHEP 06 (2012) 126