Precision EW measurements with the WBPB at the LHC

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Electroweak Standard Model

$$\alpha,\ M_Z,\ G_F$$

$$\downarrow$$

$$M_{W},\ \sin^2(\theta_W),\ \Gamma_{W},\ldots$$

…in particular M_W with much better precision…

Can we improve the measurement precision of the EW parameters at the LHC?

… the core of the problem:

Understanding and control of the Wide Band Partonic Beams (WBPBs) at the LHC

WBPB

- Flavour composition
- Valence/sea composition (drive the W and Z boson polarization effects)
- Longitudinal momentum distributions of partons - PDFs (bunch length)
- Flavour-dependent transverse emittance of the partonic beams (beam divergence and beam transverse spot size)

At the LHC we must control the WBPB with much better precision than at the Tevatron…

why?…

…at the LHC we collide pp

not $p\bar{p}$ like at the Tevatron

…at the LHC

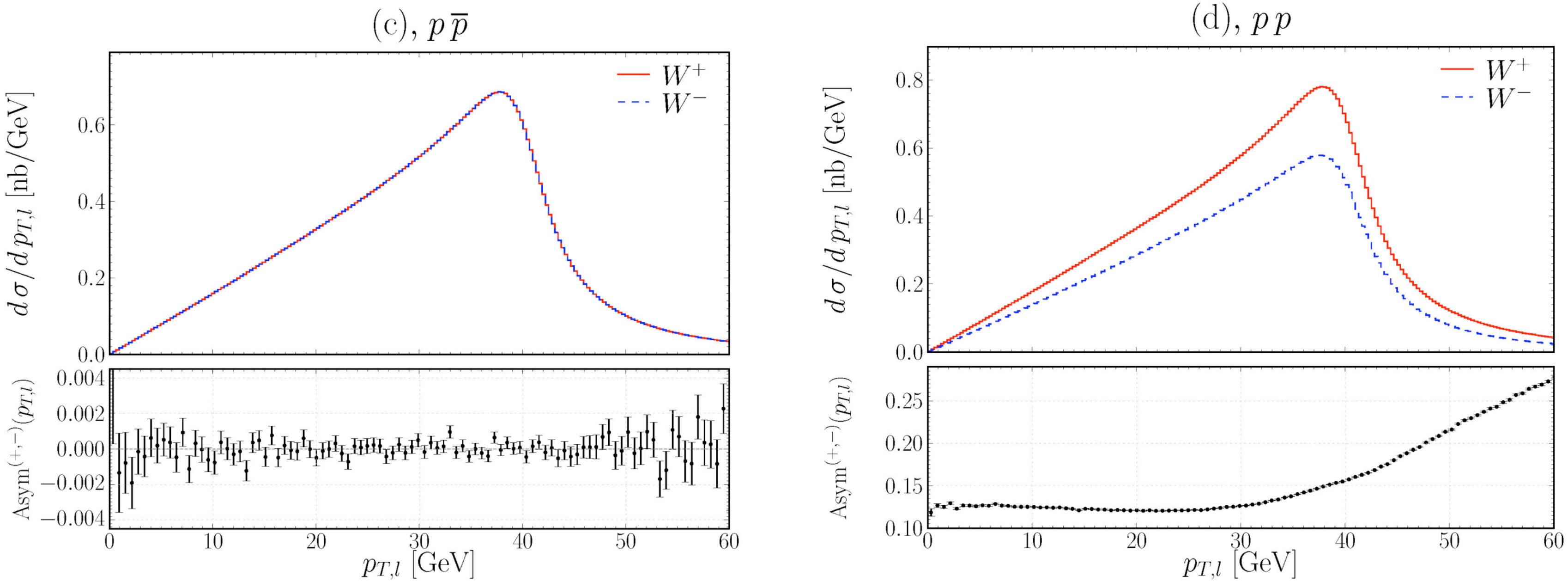
- Symmetry relations not at work (need to understand W^+,W^- and Z boson polarization effects)
- Collisions at higher energy (need to understand heavy flavours with much better precision)

How important are these effects?

(…only the LHC-specific problems discussed below common to both CMS and ATLAS)

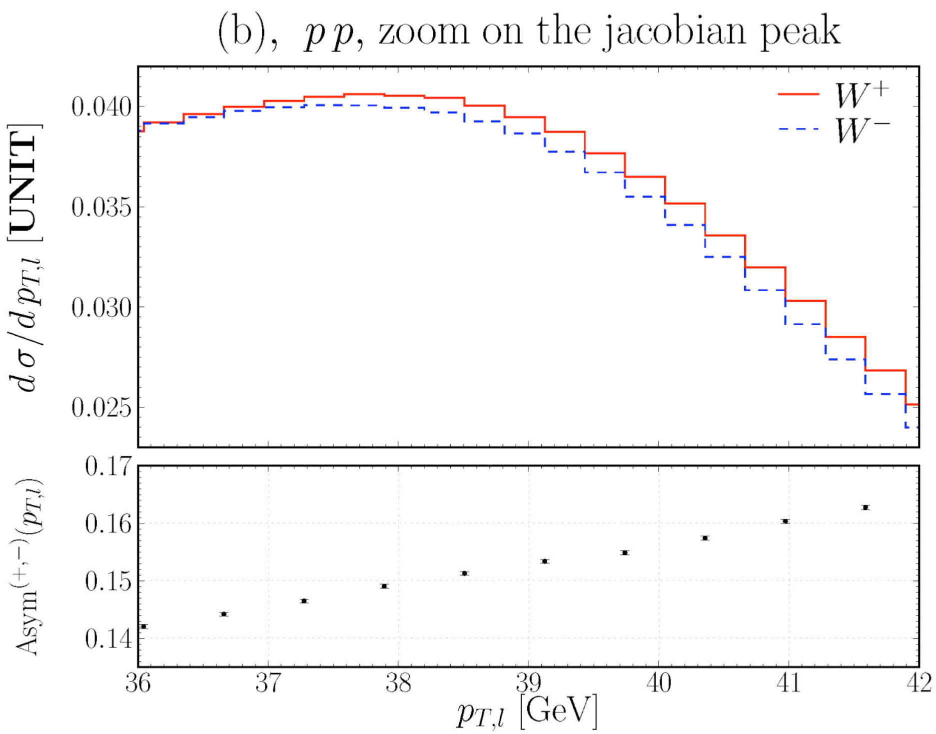
Lepton momentum scale

(note: charge-average scale from the position of the Z-peak)



At the LHC leptons coming from W decays cannot constrain the relative momentum (energy) calibration in a “PDF-independent” way

Lepton momentum scale



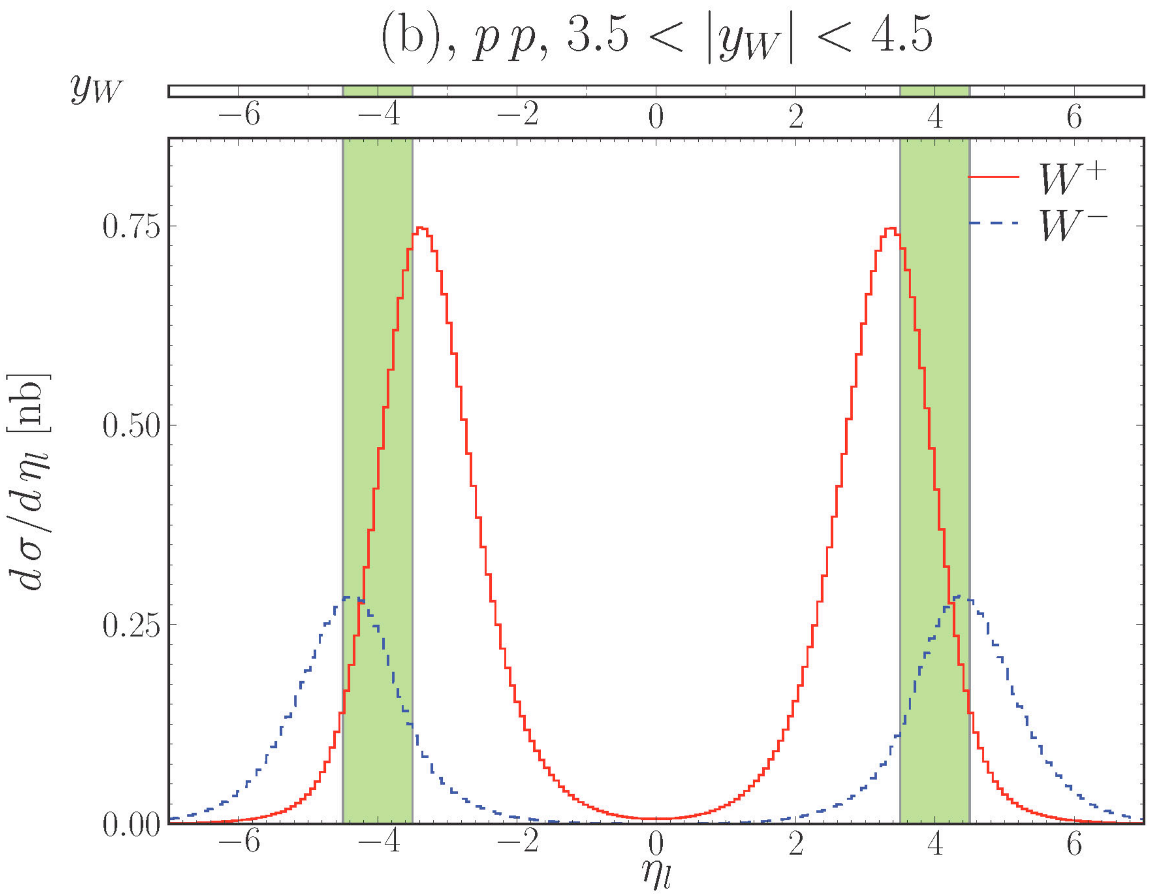
relative shifts of jacobian peak position estimated using a parabola fit in the range:

37 GeV < $p_{T,l}$ < 40 GeV

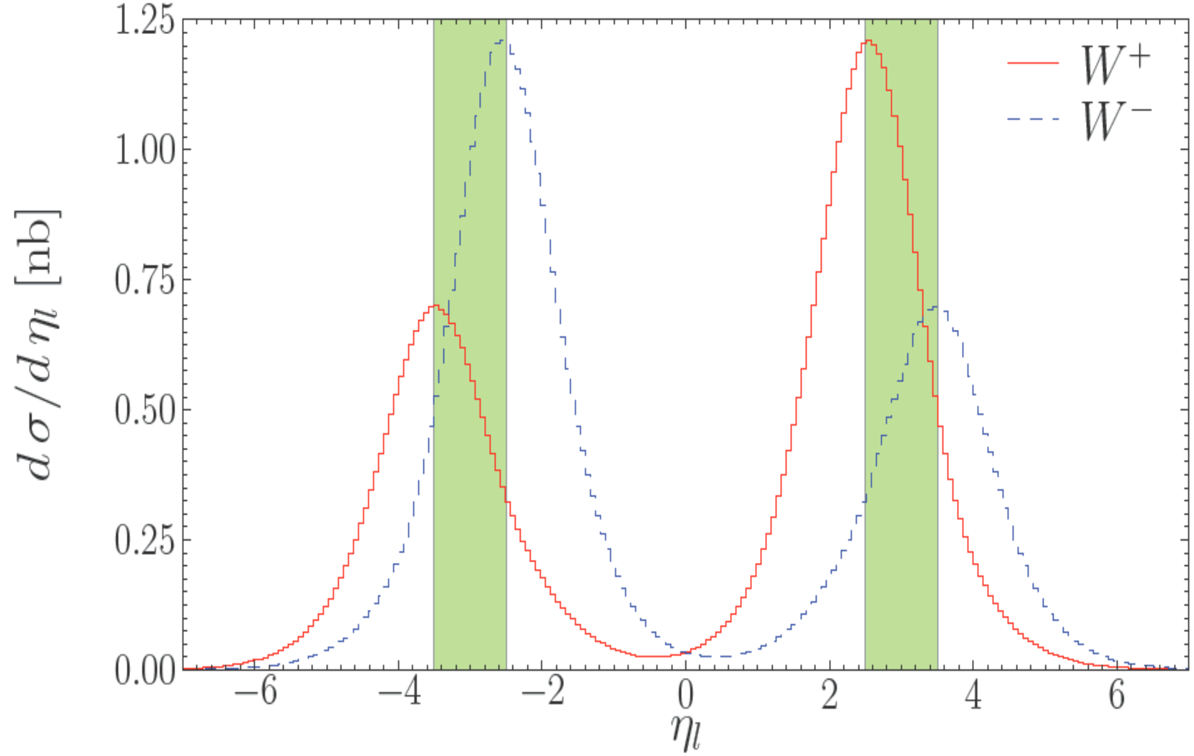
phase space domain	$\varpi_+ - \varpi_-$ [MeV]
Inclusive	170
$\lvert y_W \rvert < 0.3$	-100
$\lvert \eta_l \rvert < 0.3$	-240
$3.5 < \lvert y_W \rvert < 4.5$	300
$3.5 < \lvert \eta_l \rvert < 4.5$	2000

(M_{W+} - M_{W-} biases at the level of ~(200 - 4000) MeV …at the Tevatron 0 MeV)

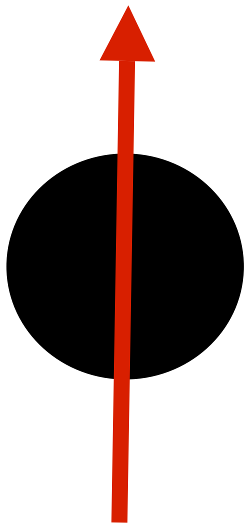
W polarization effects
pp collisions



W polarization effects
$p\bar{p}$ collisions

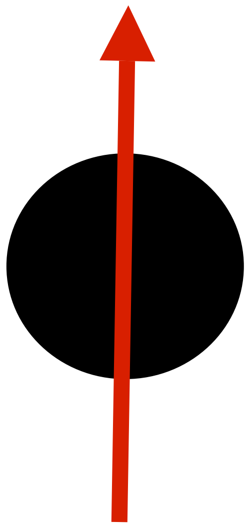


$W^+ \rightarrow l^+ \nu$



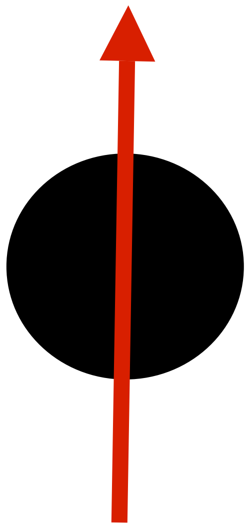
- θ = lepton emission angle w.r.t. spin vector
- $W(\theta) = 1 + \cos(\theta)$
- reflects V-A coupling

$W^- \longrightarrow l^- \nu$



- $W(\theta) = 1 - \cos(\theta)$

$Z \rightarrow l^+l^-$

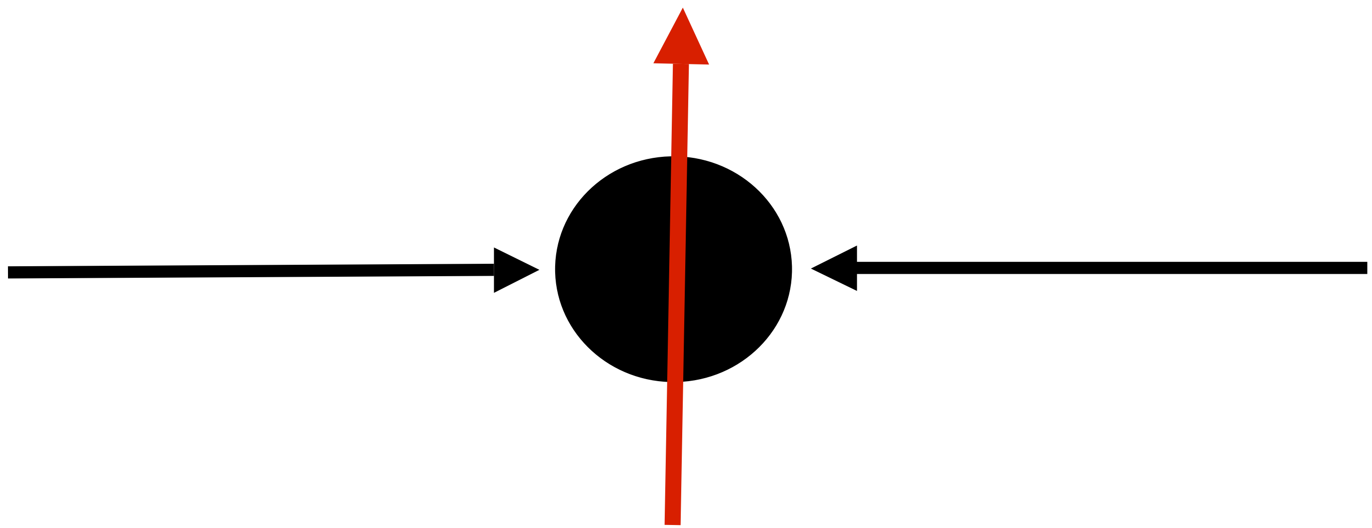


- $W(\theta) = \alpha + \beta \cos(\theta)$

- reflects mixture of V-A and V+A coupling

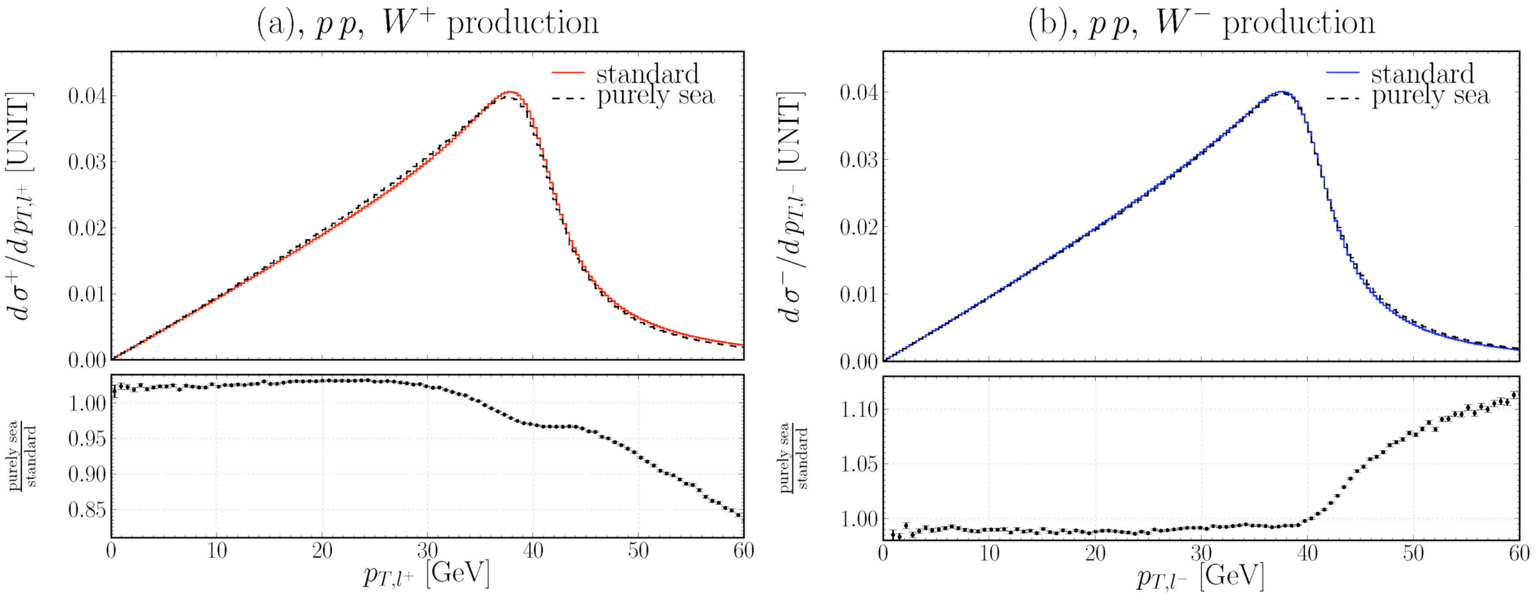
…watch out, in particular, for the asymmetries in the relative polarization of W+, W- and Z bosons in the direction perpendicular to the collision axis…

…generated by the non-zero k_t of the annihilating partons



(longitudinal W polarization and the corresponding interference terms)

Valence quarks as W polarizers



estimated shifts of the peak position due to polarisation effects

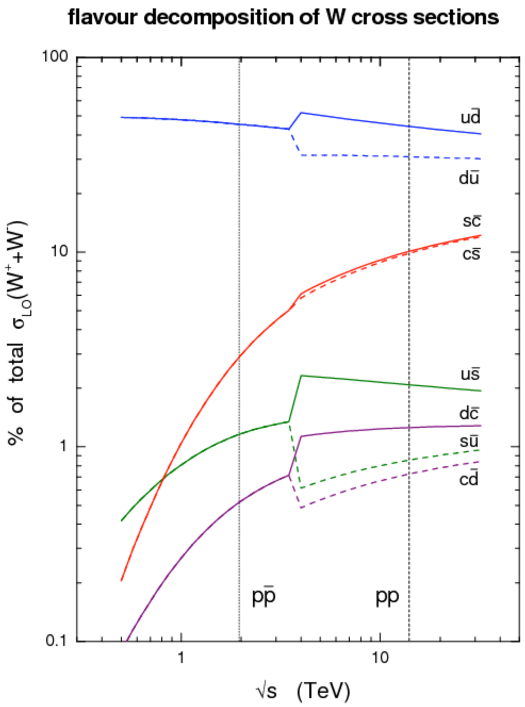
Fit range	Channel	$\varpi_{\text{standard}} - \varpi_{\text{sea}}$ [MeV]
$37\,\text{GeV} < p_{T,l} < 52\,\text{GeV}$	W^+	178.0
	W^-	-23.8

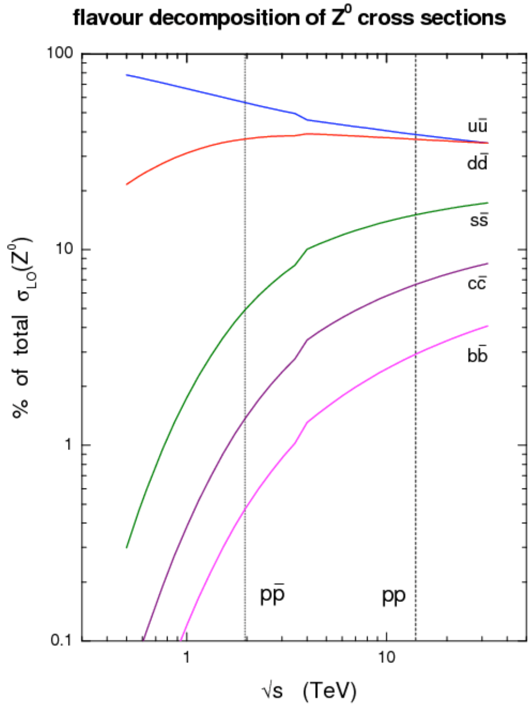
(M_W biases at the level of ~400 MeV …at the Tevatron 0 MeV)

The essence of the LHC specific problem
(a PDFs perspective):

Unfolding of the PDFs using the W-boson observables, in the presence of polarization effects and limited η_l acceptance, is not constrained at the LHC - need external constraints resolving valence/sea ambiguity to higher precision than available today… and/or dedicated measurement tricks…

Flavour asymmetries





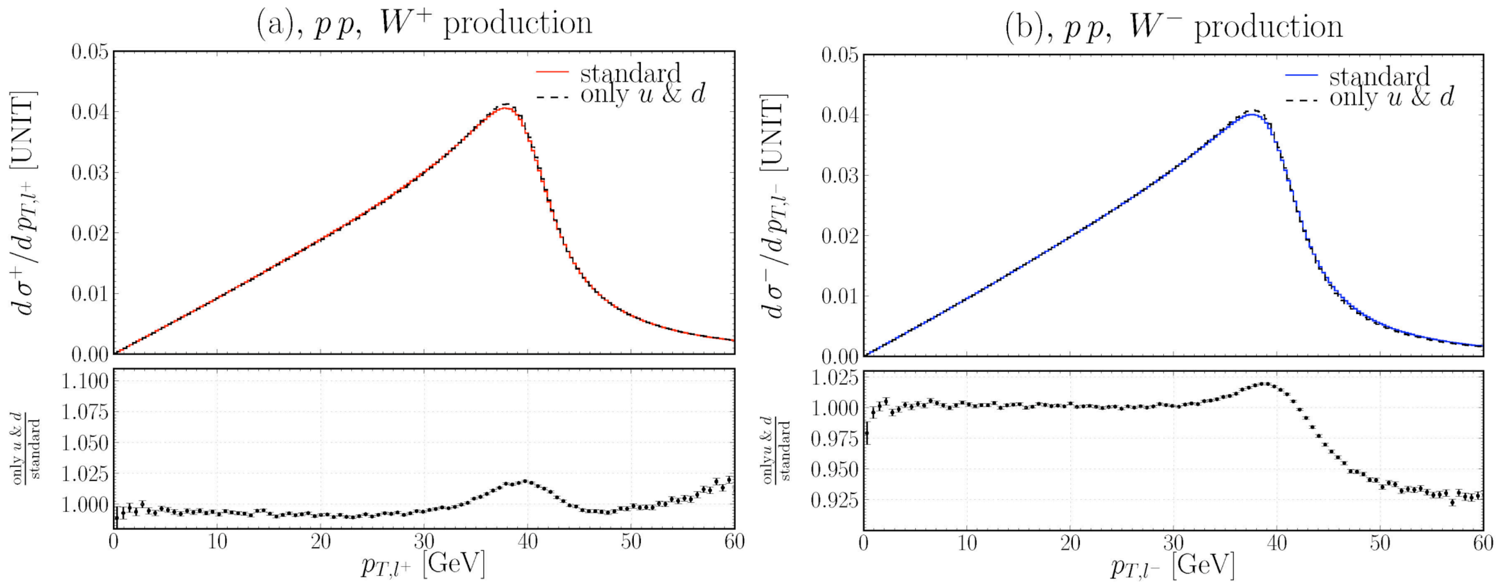
BERGE, NADOLSKY, AND OLNESS PHYSICAL REVIEW D **73,** 013002 (2006)

TABLE I. Partial contributions $\sigma_{q\bar{q}'}/\sigma_{\text{tot}}$ of quark-antiquark annihilation subprocesses to the total Born cross sections in W^+ and Z^0 boson production at the Tevatron and LHC (in percent).

	W^+					W^-					Z^0				
Subprocesses	$u\bar{d}$	$u\bar{s}$	$c\bar{d}$	$c\bar{s}$	$c\bar{b}$	$d\bar{u}$	$s\bar{u}$	$d\bar{c}$	$s\bar{c}$	$b\bar{c}$	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$
Tevatron Run-2	90	2	1	7	0	90	2	1	7	0	57	35	5	2	1
LHC	74	4	1	21	0	67	2	3	28	0	36	34	15	9	6

Flavour asymmetries

partonic mass and longitudinal momentum



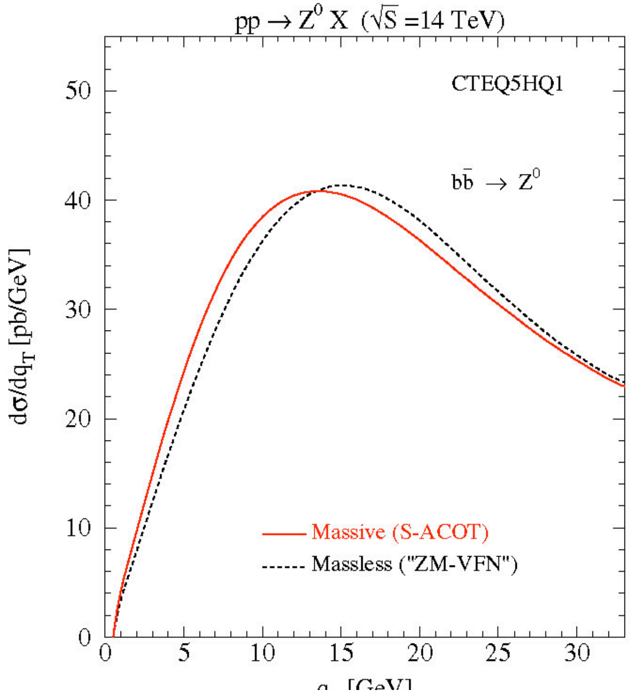
estimated shifts of the peak position due to the presence of heavy quarks in the Wide Band Partonic Beam (WBPB)

Fit range	Channel	$\varpi_{\text{standard}} - \varpi_{\text{only }u,d}$ [MeV]
$37\,\text{GeV} < p_{T,l} < 52\,\text{GeV}$	W^+	-69.9
	W^-	-59.2

(M_W biases at the level of ~150 MeV …at the Tevatron ~30 MeV)

Flavour asymmetries

mass effects



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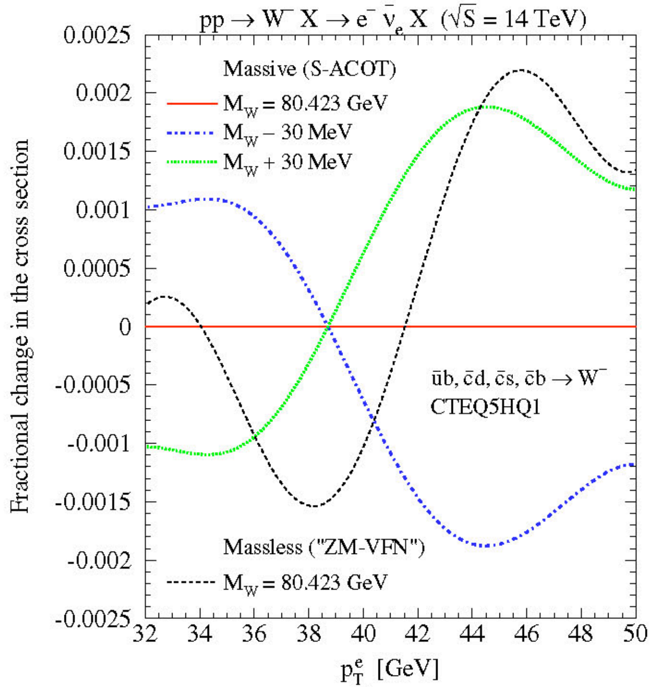

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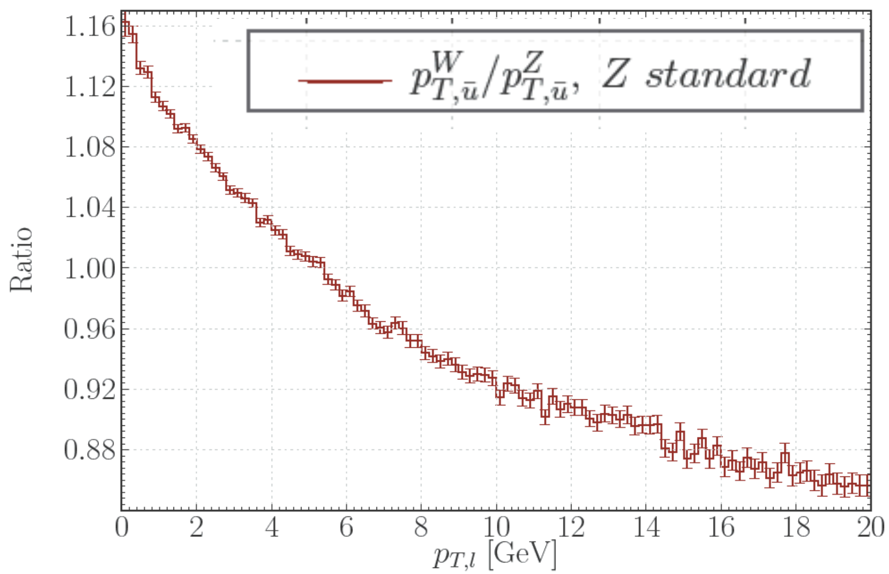
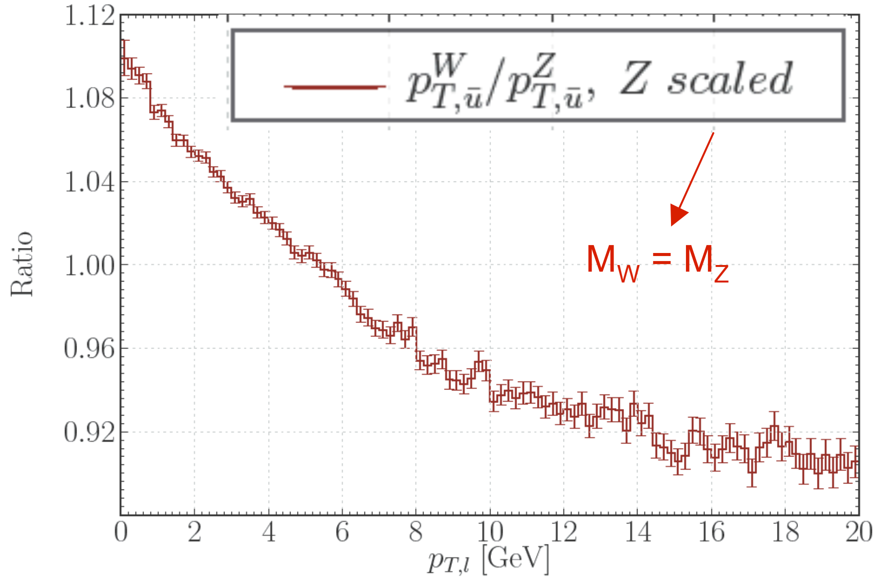
Flavour asymmetries

longitudinal momentum





- The momentum distribution of the "matching parton" (the one needed to create W- and Z-bosons) is the dominant source of the biases in the relative transverse momentum distribution of the W and Z bosons!!! Nontrivial (η_l, $p_{t,l}$) correlations involving the mixing of (1)evolution-scheme dependent effects, (2) polarization effects, and (3) quark-mass dependent effects
- Note: $u^{(v)} \neq d^{(v)}$ for the proton beam !

Lessons:
The Tevatron and the LHC

All the discussed above effects are either negligible or small at the Tevatron* - they become dominant at the LHC

Example: Precision of $M_{W.}$

Technical Remark:

1. At the LHC the W+ and the W- bosons must be treated as distinct particles. Their measurement biases will contribute with a model- dependent and fiducial-volume-dependent weights to the final measurement
2. Two equivalent measurement schemes can be employed: (M_{W+} and M_{W-}) or ($M_W = (M_{W+} + M_{W-})/2$ and $M_{W+} - M_{W-}$) - the later will be discussed in the following…

*This is, perhaps, the reason why these effects have never been considered as the precision limiting factors

The measurement and the tools for its simulation

- Apparatus: The ATLAS detector
- Luminosity: 10 fb^{-1}
- Trigger and Acceptance cuts: $p_{T,l} > 20$ GeV/c, $|\eta_l| < 2.5$
- Event Generators: WINHAC/ZINHAC (spin amplitudes) and Pythia
- Simulation: parameterized response of the ATLAS detector
- Challenge: study based on $O(10^{10})$ simulated events
- The team: F. Fayette (PhD- 2009), W. Placzek, K. Rejzner (master-2009), A. Siodmok (PhD-2009), M.W. Krasny - France-Pologne (COPIN) cooperation program

Polarisation

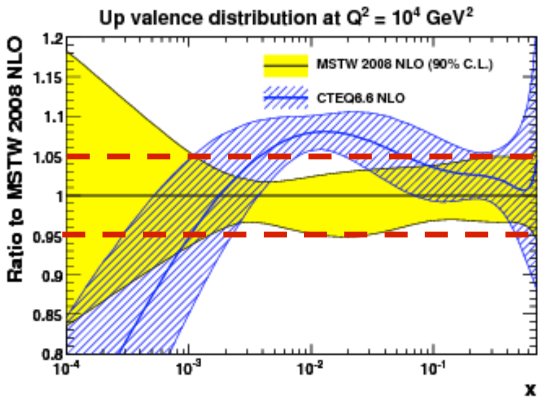
expected precision

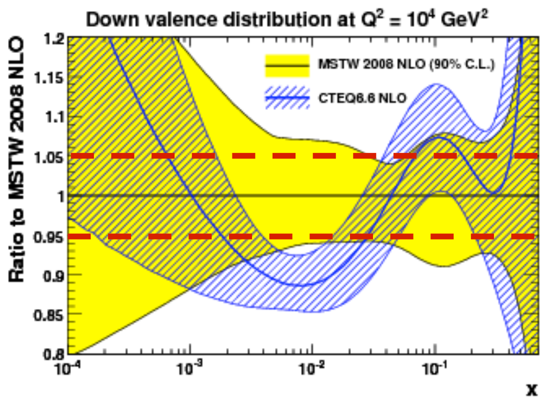
Expected biases in the measured values of M_{W+}-M_{W-}

$u^{(v)},\ d^{(v)(*)}$	$u^{(v)}_{max} = 1.05\,u^{(v)}$ $d^{(v)}_{min} = d^{(v)} - .05\,u^{(v)}$	114.5
	$u^{(v)}_{min} = 0.95\,u^{(v)}$ $d^{(v)}_{max} = d^{(v)} + .05\,u^{(v)}$	-138.5
	$u^{(v)}_{max} = 1.02\,u^{(v)}$ $d^{(v)}_{min} = 0.92\,d^{(v)}$	85.2
	$u^{(v)}_{min} = 0.98\,u^{(v)}$ $d^{(v)}_{max} = 1.08\,d^{(v)}$	-85.9

Expected biases in the measured values of M_W

$u^{(v)},\ d^{(v)}$	$u^{(v)}_{max} = 1.05\,u^{(v)}$ $d^{(v)}_{min} = d^{(v)} - .05\,u^{(v)}$	79
	$u^{(v)}_{min} = 0.95\,u^{(v)}$ $d^{(v)}_{max} = d^{(v)} + .05\,u^{(v)}$	-64
	$u^{(v)}_{min} = 1.02\,u^{(v)}$ $d^{(v)}_{max} = d^{(v)} - .02\,u^{(v)}$	32
	$u^{(v)}_{min} = 0.98\,u^{(v)}$ $d^{(v)}_{max} = d^{(v)} + .02\,u^{(v)}$	-18
	$u^{(v)}_{max} = 1.02\,u^{(v)}$ $d^{(v)}_{min} = 0.92\,d^{(v)}$	48
	$u^{(v)}_{min} = 0.98\,u^{(v)}$ $d^{(v)}_{max} = 1.08\,d^{(v)}$	-32





Note: Only mutually compensating shifts leave the Z-boson rapidity distributions invariant

The flavour asymmetries

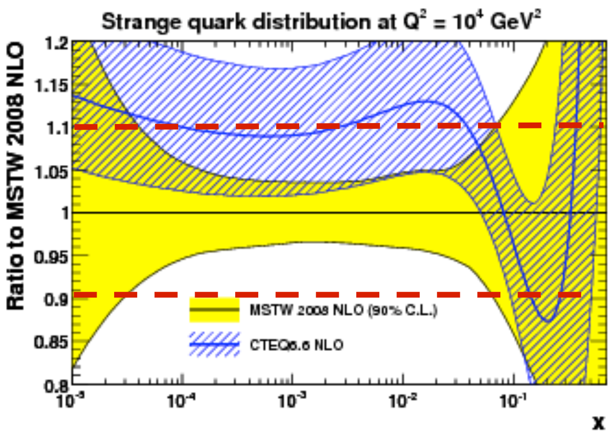
expected precision

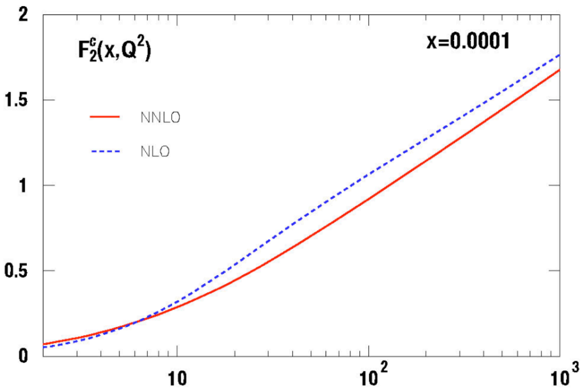
Expected biases in the measured values of M_{W+}-M_{W-}

$s,\ c^{(*)}$	$c_{\text{min}} = 0.9\,c$, $s_{\text{max}} = s + 0.1\,c$	17.1
	$c_{\text{max}} = 1.1\,c$, $s_{\text{min}} = s - 0.1\,c$	-10.8
	$c_{\text{min}} = 0.8\,c$, $s_{\text{max}} = s + 0.2\,c$	38.8
	$c_{\text{max}} = 1.2\,c$, $s_{\text{min}} = s - 0.2\,c$	-29.0

Expected biases in the measured values of M_W

$s,\ c$	$c_{\text{min}} = 0.8\,c$, $s_{\text{max}} = s + 0.2\,c$	257
	$c_{\text{max}} = 1.2\,c$, $s_{\text{min}} = s - 0.2\,c$	-237
	$c_{\text{min}} = 0.9\,c$, $s_{\text{max}} = s + 0.1\,c$	148
	$c_{\text{max}} = 1.1\,c$, $s_{\text{min}} = s - 0.1\,c$	-111
	$c_{\text{min}} = 0.95\,c$, $s_{\text{max}} = s + 0.05\,c$	78
	$c_{\text{max}} = 1.05\,c$, $s_{\text{min}} = s - 0.05\,c$	-58





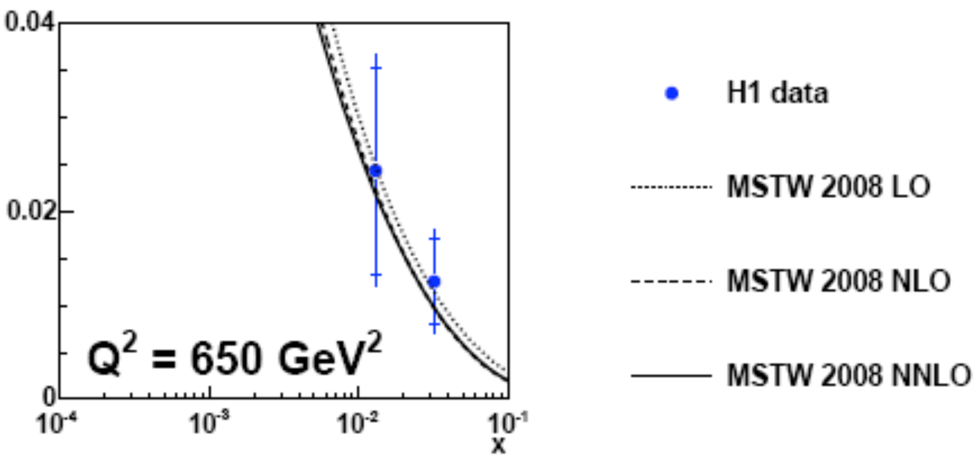
Note: Only mutually compensating shifts leave the Z-boson rapidity distributions invariant

The flavour asymmetries

expected precision

Expected biases in the measured values of M_W

b	$b_{\mathrm{max}} = 1.4\, b$	77
	$b_{\mathrm{min}} = 0.6\, b$	-56
	$b_{\mathrm{max}} = 1.2\, b$	42
	$b_{\mathrm{min}} = 0.8\, b$	-39
	$b_{\mathrm{max}} = 1.1\, b$	13
	$b_{\mathrm{min}} = 0.9\, b$	-12



Note: b-quarks influence the biases while relating the spectra for W-bosons to the corresponding ones for Z-bosons

…The precision of M_W $\sin^2(\theta_W)$ and Γ_W cannot be improved at the LHC …

…neither now nor at the completion of the standard LHC programme…

Why three PDF degrees of freedom?

- 5 sea-quark flavours and 2 valence quark flavours
- 4 constraints coming from the $(p_{T,l}, \eta_l)$ spectra for W^{+}, W^{-}, "Z^{+}" and "Z^{-}" decays
- 3 degrees of freedom in the flavour-dependent pdf's remain unconstrained

<u>Important note:</u>

At the Tevatron only the first family is of relevant and $u = \bar{u}$ and $d = \bar{d}$ (CP-symmetry).

This leaves only 2 (out of 7) flavour dependent pdf's. They can be constrained unambiguously using the $(p_{T,l}, \eta_l)$ spectra for $W = W^{+} + W^{-}$, and $Z=$ "Z^{+}"+"Z^{-}" combinations (these combinations were chosen at the Tevatron to minimise the systematic error on M_W...)

Why choosing $u^{(v)}$-$d^{(v)}$,s-c and b

1. $u^{(v)}$ - $d^{(v)}$ drive the relative W/Z polarization effects
2. s-c drive the dominant flavour asymmetry effects
3. b has a special role as it influences only the Z-boson spectra

In addition:

The relative movement of $u^{(v)}$ w.r.t $d^{(v)}$ and s w.r.t c leave explicitly the rapidity distribution for Z-bosons unchanged* (do not expect a significant improvement of these combinations at the LHC)

The non-singlet partonic distributions have only residual scale dependence (they are robust with respect to the choice: (1) of QCD evolution scheme and (2) of order of perturbative expansion (LO, NLO, etc.))

The way forward

- Novel ("beyond Tevatron") calibration and measurement methods for the LHC precision programme

<u>and</u>

- A dedicated "precision-support" programme auxiliary to the standard LHC programme

The way forward:

LHC-dedicated calibration and measurement methods

- Reduction of the relative measurement errors for the W and Z samples collected over a long period of time (trigger, event selection scheme, event reconstruction scheme, event storage scheme, detector noise treatment, experimental control of the relative EW radiative corrections, dedicated "QCD-noise-robust" observables, control event samples (B-field, cm-energy)…)

- Making Z boson "QCD-identical" to the W bosons (getting rid of all the relative, flavour singlet, QCD effects in the W and Z boson production up to all orders of the perturbation theory using data only)

- Dedicated calibration method of the positive and the negative lepton momentum (energy) scales

The standard and QCD-robust observables for the LHC

Standard observables (at fixed η_l):

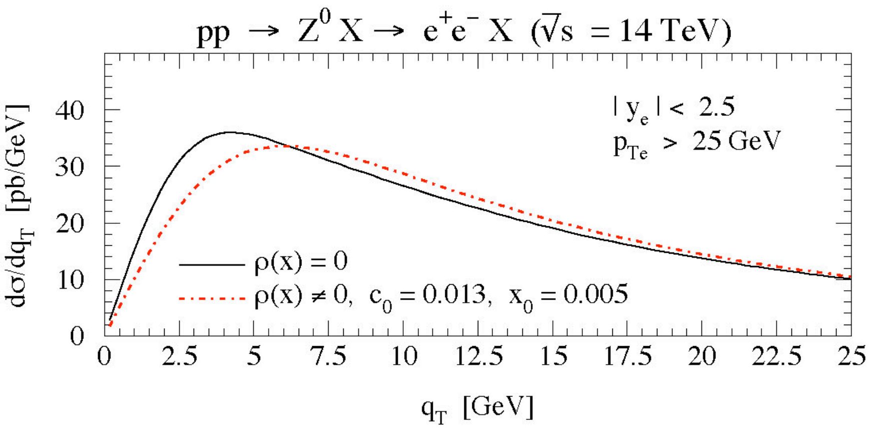
$$w_+ = d\sigma_W/dp_{T,l+},\ w_- = d\sigma_W/dp_{T,l-},\ z_+ = d\sigma_Z/dp_{T,l+}\ ,\ z_- = d\sigma_Z/dp_{T,l-}$$

QCD-robust observables:

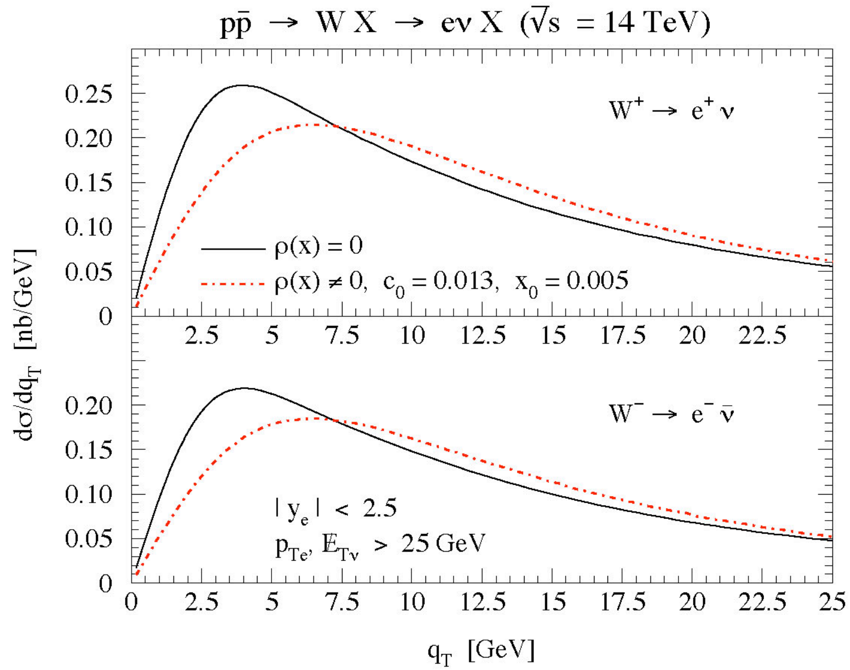
$$Asym_W{}^{(+,-)}\,(p_{T,l}, M_{W+}, M_{W-}) = (w_+ - w_-)/\,(w_+ + w_-)$$
$$Asym_Z{}^{(+,-)}\,(p_{T,l}, M_Z) = = (z_+ - z_-)/\,(z_+ + z_-)$$
$$R^{QCD}{}_{WZ}\,(p_{T,l}\,, M_{W+}, M_{W-}) = C_{QCD} \times (w_+ + w_-)/\,(z^c{}_+ + z^c{}_-)$$

"Z^c" - distributions for Z-bosons corrected for the effects due to $M_Z \neq M_W$ (except for the scale difference, C_{QCD} corrects, up to all orders of the perturbative expansion the scale effects in the evolution)

The role of the QCD-robust observables



S. Berge, et al., hep-ph/0410375.



- The relationship between the transverse momentum distributions of the Z-bosons and the W-bosons cannot be predicted and must be modelled. It involves a choice of: (1) the evolution scheme (DGLAP, BFKL, CCFM,…), (2) the parameters of the nonperturabative Sudakov form factors, (3) primordial k_T modelling
- Our QCD-robust allows to get rid of all the flavour singlet aspects of modelling these distributions

Simplified proof:
Making Z boson "QCD-identical" to W boson

Biases in the measured value of M_W [MeV]

		R_{WZ}	R_{WZ}^{QCD}
σ_{k_T} [GeV]	0	180	8
	3	68	3
	5	−100	0
	6	−206	−4

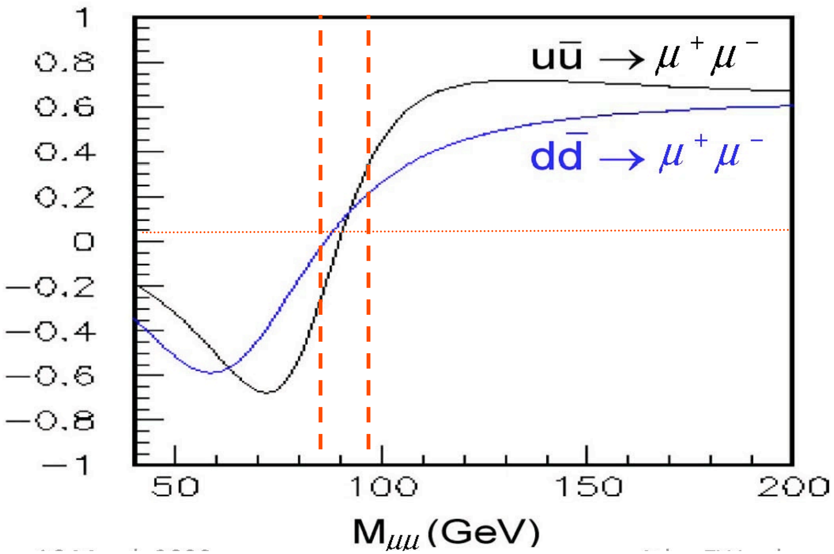
σ_{kT} - stands for a Gaussian, flavour independent smearing of the transverse momentum of partons biases with respect to the central value of: σ_{kT} = 4 GeV

…details in M.W. Krasny et al., EPJC 51, 607 (2007)

Dedicated, PDF-independent, relative calibration of the positive and negative lepton momentum (energy) scale

$$A_{FB} = \frac{3}{4}\frac{-2q_q a_q a_\ell \operatorname{Re}(\chi) + 2v_q a_q 2v_\ell a_\ell |\chi|^2}{q_q^2 - 2q_q v_q v_\ell \operatorname{Re}(\chi) + (v_q^2 + a_q^2)(v_\ell^2 + a_\ell^2)|\chi|^2}; \qquad \chi(\hat{s}) = \frac{\sqrt{2}G_F}{16\pi\alpha}\frac{\hat{s}M_Z^2}{\hat{s} - M_Z^2 + i\hat{s}\Gamma_Z/M_Z}$$

$$a_f = 2I_3^f; \qquad v_f = 2I_3^f - 4q_f \sin^2\theta_W; \qquad f = q, \ell$$



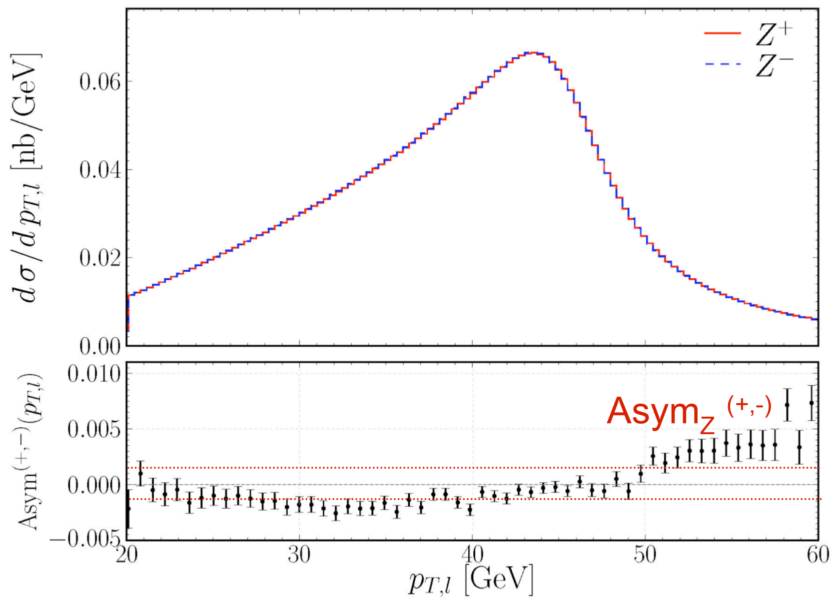
- Exploit the lucky coincidence that the $\sin^2(\theta_W)$ value chosen by nature happens to:

  (1) “equalize” the forward-backward asymmetry in the Z-resonance region (statistics)

  (2) gives rise to a very small F/B asymmetry in the chosen region

- Use the lepton-pair events in the mass region where the FB asymmetries for u and d quark cross each other - in order to be independent of the u/d structure of protons.

Dedicated relative calibration of the positive and negative lepton momentum (energy) scale



- 0.1% precision in the calibration of the relative scale can be achieved using Asym$_Z$ $^{(+,-)}$ in the selected mass region

- To achieve the precision of 0.01% the valence quark distribution must be controlled to the precision of 10% (OK) - statistics is the only limitation

The way forward

- Novel (“beyond Tevatron”) calibration and measurement methods for the LHC precision programme

<u>and</u>

- Dedicated “precision-support” programme(s) for the LHC measurements

Programme 1: Isoscalar beams at the LHC (elegant .. but unrealistic)

- Isoscalar beams $u^{(v)} = d^{(v)}$ (up to a small ~0.2 % QED corrections) - cancellation of relative polarization effects for W and Z

Expected biases in the measured values of M_{W+} - M_{W-} [MeV]

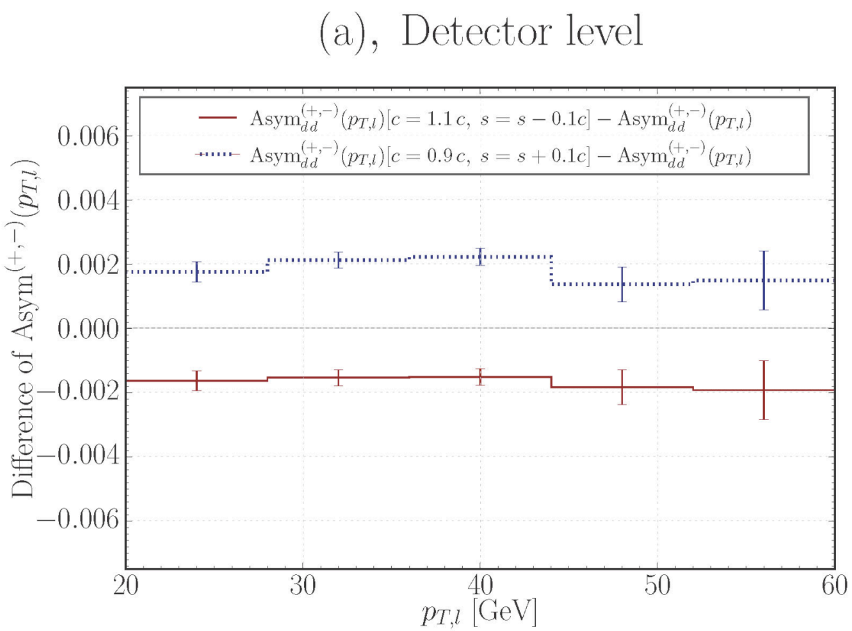
	Systematic ξ	pp - $\lvert\eta_l\rvert < 2.5$	pp - $\lvert\eta_l\rvert < 0.3$	pp - $\lvert y_W\rvert < 0.3$	dd - $\lvert\eta_l\rvert < 2.5$
$u^{(v)}, d^{(v)(*)}$	$u^{(v)}_{max} = 1.05\,u^{(v)}$, $d^{(v)}_{min} = d^{(v)} - .05\,u^{(v)}$	114.5	74.4	-38.1	2.4
	$u^{(v)}_{min} = 0.95\,u^{(v)}$, $d^{(v)}_{max} = d^{(v)} + .05\,u^{(v)}$	-138.5	-83.8	59.8	2.9
	$u^{(v)}_{max} = 1.02\,u^{(v)}$, $d^{(v)}_{min} = 0.92\,d^{(v)}$	85.2	51.2	-34.7	4.1
	$u^{(v)}_{min} = 0.98\,u^{(v)}$, $d^{(v)}_{max} = 1.08\,d^{(v)}$	-85.9	-53.2	47.2	-0.1

PDF context: the measurement of the W-bosons charge asymmetry constrain directly the s-c distribution…

$$(\sigma^+ - \sigma^-)_{dd} = \int dx_1 dx_2 \left\{ u_1^{(v)} \left(|V_{us}|^2 \bar{s}_2 - |V_{cd}|^2 \bar{c}_2 + |V_{ub}|^2 \bar{b}_2 \right) \right\} \hat{\sigma}'_{q\bar{q}'}$$

~(s-c) sin(θ_C) Cabbibo suppressed contribution

Expected unfolding precision for L= 10 fb $^{-1}$



Note: valence quark distribution measured using the $\mathrm{Asym}_Z^{(+,-)}(p_{T,l}, M_Z)$

Programme 2: involving a dedicated muon DIS experiment

- Goal: Unfolding of the following unknown functions (parameters):

  $u^{(v)}, d^{(v)}, u^{(s)}, d^{(s)}, s, c, b; \varepsilon+ - \varepsilon-, M_{W+}, M_{W-}, \sin^2(\theta_W)$

  where: $q_f = q_f\,(x, k_t, m)$

- Procedure: Measure the following 4 independent observables at the LHC:

  $Asym_W^{(+,-)}\,(p_{T,l}, \eta_l)$, $Asym_Z^{(+,-)}\,(p_{T,l}, \eta_l)$,

  $R^c_{WZ}\,(p_{T,l}, \eta_l)$, $d\sigma_Z^c/dp_{T,l+}d\eta_l + d\sigma_Z^c/dp_{T,l-})$

- Assume:
  1. $M_{W+} = M_{W-}$ (muon life-time, CPT)
  2. $\sin^2(\theta_W) = \sin^2(\theta_W)$ [Particle Data Book]
  3. for fixed $\sin^2(\theta_W)$ new method of the relative (+/-) scale calibration using "Z+" and "Z-" samples (independent of q_f distributions at the requiste precision level of 0.1%)
  4. b-quark distribution uncertainties avoided in restricted measurement region: $2.0 < |\eta_l| < 2.5$
  5. $s = s\,(u^{(v)}, d^{(v)}, u^{(s)}, d^{(s)} \,|\, \kappa_s)$ (sufficient for k_t-dependence, … not for x dependence)

- Result: 5 unknown distributions constrained by 4 observables - one high precision constraint (preferentially in the light quark sector) needed…

- Measure: the radiative-corrected asymmetry $Asym_{DIS}^{(p,n)}(Q^2,x)$ in a dedicated precision O(0.1%) deep inelastic scattering of muons on deuterium and proton targets:

$$Asym_{DIS}^{(p,n)}(Q^2,x) = (d\sigma^p /dQ^2dx - d\sigma^n /dQ^2dx)/(d\sigma^p /dQ^2dx + d\sigma^n /dQ^2dx)$$

…where $d\sigma^n /dQ^2dx = d\sigma^d /dQ^2dx - d\sigma^p /dQ^2dx$

- Analyze the LHC measurements of: $Asym_W^{(+,-)}(p_{T,l}, \eta_l)$, $Asym_Z^{(+,-)}(p_{T,l}, \eta_l)$, $R^c_{WZ}(p_{T,l}, \eta_l)$, $d\sigma_Z^c/dp_{T,l+}d\eta_l + d\sigma_Z^c/dp_{T,l-})$ in terms $q_f = q_f(x, k_t, m)$ keeping as an unconstrained d.o.f a suitable combination $F[u^{(v)}, d^{(v)}, u^{(s)}, d^{(s)}]$ which is the least sensitive to the effects of (1) the Fermi motion, (2) shadowing, (3) higher twists and (4) $R(x,Q^2)$.

- Constrain fully $u^{(v)}, d^{(v)}, u^{(s)}, d^{(s)}$ using the values of $Asym_{DIS}^{(p,n)}(Q^2,x,E)$ measured at the three energy settings (tools for such an "inverse" extrapolation are being prepared…S. Jadach et al.)

(details in a LOI for such an experiment … to be submitted to SPSC by F. Dydak and M.W. Krasny)

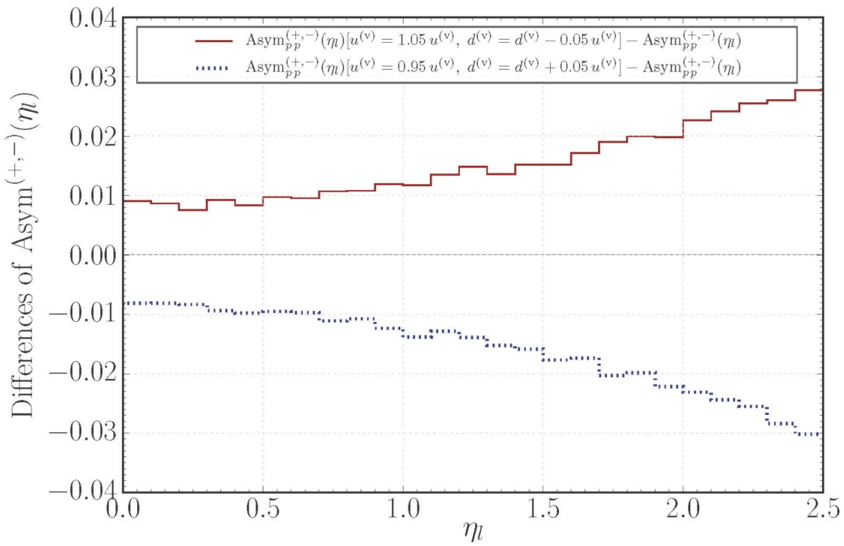
- Complementarities:

$$\mathrm{Asym}_{DIS}^{(p,n)} \sim 1/3\,(u^{(v)} - d^{(v)}) + 2/3\,(u^{(s)} - d^{(s)})$$

$$\mathrm{Asym}_{W}^{(+,-)} \sim u^{(v)}d^{(s)} - u^{(s)}d^{(v)}$$

… in the presence $u^{(s)}/d^{(s)}$ asymmetry $\mathrm{Asym}_{DIS}^{(p,n)}$ provides a precious, independent constraint for the valence/sea decomposition - obligatory to control the W polarisation at the LHC

Example: Expected statistical precision of unfolding the $u^{(v)}$ vs. $d^{(v)}$ for L = 10 fb $^{-1}$ for a fixed $\mathrm{Asym}_{DIS}^{(p,n)}$ constraint



Conclusions

- Contrary to present paradigms, the EM precision measurements at the LHC require dedicated measurement programmes in order to be competitive with the LEP and the Tevatron ones.

- Precise experimental control of those of the aspects of the WBPB which cannot be circumvented using the LHC-dedicated tricks (notably: flavour non-singlet distributions, valence/sea separation, …) is at heart of these programmes.

- As a by product the precision EW measurements will provide the most precise constraints on $q_i(x,k_t,m_i)$ and thus on the PDFs at the weak boson mass scale

Conclusions

- Two examples of such programmes have been presented in this talk and evaluated. Both could contribute to better understanding of the PDFs.
- Complementing the proton beams by the isoscalar beams at the LHC (e.g. D-beams) could allow for a full unfolding of PDFs at the ~$M_{W.}$ Such runs are technically feasible but, certainly, will always be of low priority.
- Measurement of the proton/neutron $\mu-$DIS cross section asymmetry appears to be the simplest way of complementing the LHC EW precision measurement program.
- In particular, if organized from the point of view of delivering the missing input to the LHC data (rather than as a next round of the PDF measurements) it will put the LHC back in the competition in the EW-sector precision quest.