EWK at the LHC: what's next

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OUTLINE

Some experimental views/ideas on LHC EWK analyses in the short-medium term:

- W mass
- Vector boson + jets studies
- Di-boson production
- Tri-boson production
- Vector boson scattering

W mass

W mass measurement

- Difficult subject to address. What is in the LHC TDRs is probably too old to be used as starting point.
- Measuring the W mass with ≈100 MeV is relatively easy. The goal is to measure it with ≈10-20 MeV precision. Some people think it is hopeless:

$\Delta M_W = 10$ MeV/c^2 at the LHC: a forlorn hope? †

Krasny et al, arXiv:1004.2597

Abstract

At the LHC, the measurement of the W mass with a precision of $\mathcal{O}(10)$ MeV/c^2 is both mandatory and difficult. In the analysis strategies proposed so far, shortcuts have been made that are justified for proton–antiproton collisions at the Tevatron, but not for proton–proton collisions at the LHC. The root of the problem lies in the inadequate knowledge of parton density functions of the proton. It is argued that in order to reach a 10 MeV/c^2 precision for the W mass, more precise parton density functions of the proton are needed, and an LHC-specific analysis strategy ought to be pursued. Proposals are made on both issues.

W mass measurement

- Others are very optimistic (precision ≈ 7 MeV):

Re-evaluation of the LHC potential for the measurement of m_W

SN-ATLAS-2008-070

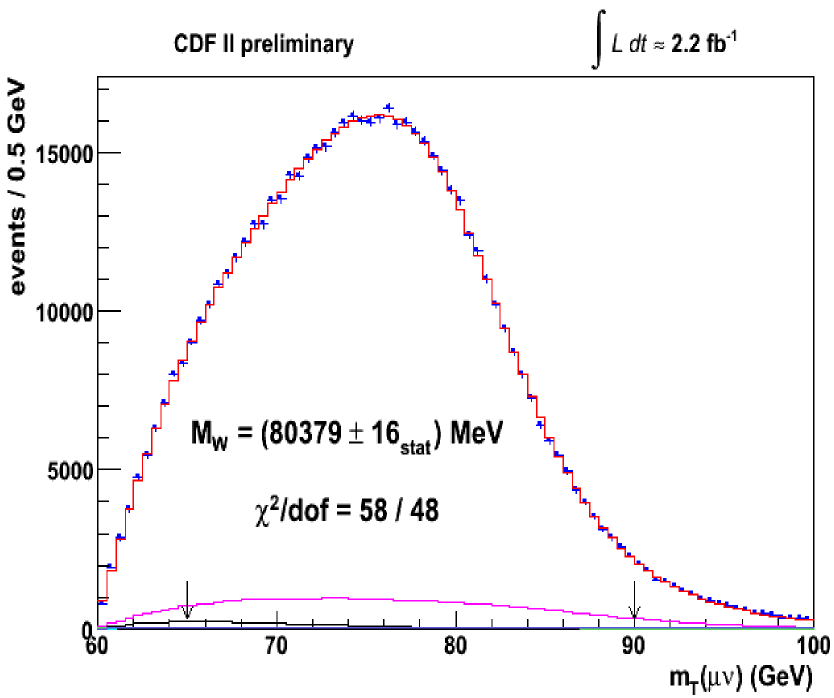
Abstract

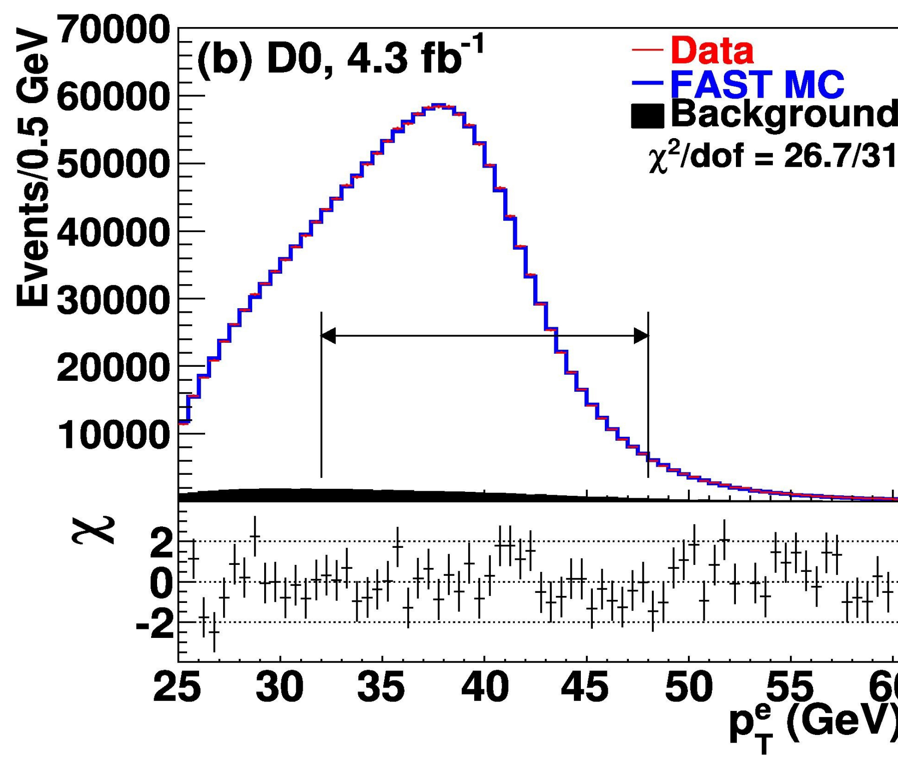
We present a study of the LHC sensitivity to the W boson mass based on simulation studies. We find that both experimental and phenomenological sources of systematic uncertainties can be strongly constrained with Z measurements: the lineshape, $d\sigma_Z/dm$, is robustly predicted, and its analysis provides an accurate measurement of the detector resolution and absolute scale, while the differential cross-section analysis, $d^2\sigma_Z/dy\,dp_T$, absorbs the strong interaction uncertainties. A sensitivity $\delta m_W \sim 7$ MeV for each decay channel ($W \to e\nu$, $W \to \mu\nu$), and for an integrated luminosity of 10 fb^{-1}, appears as a reasonable goal.

W mass: the basic strategy

a) Use the Z to calibrate/morph the lepton and/or missing E_T (MET) detector response

b) Find the W mass that better fits the observed M_T and/or p_T(lepton) shapes

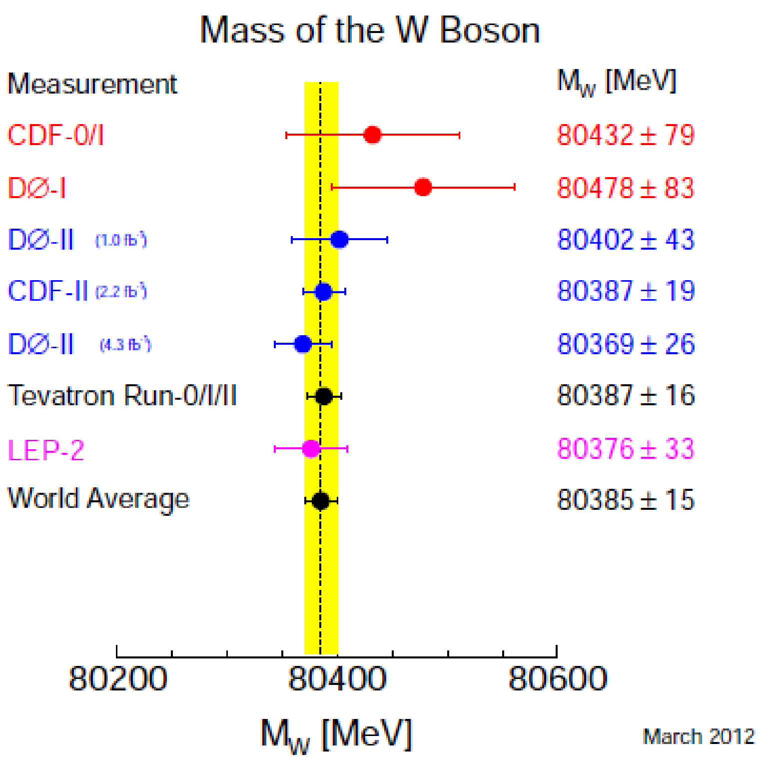


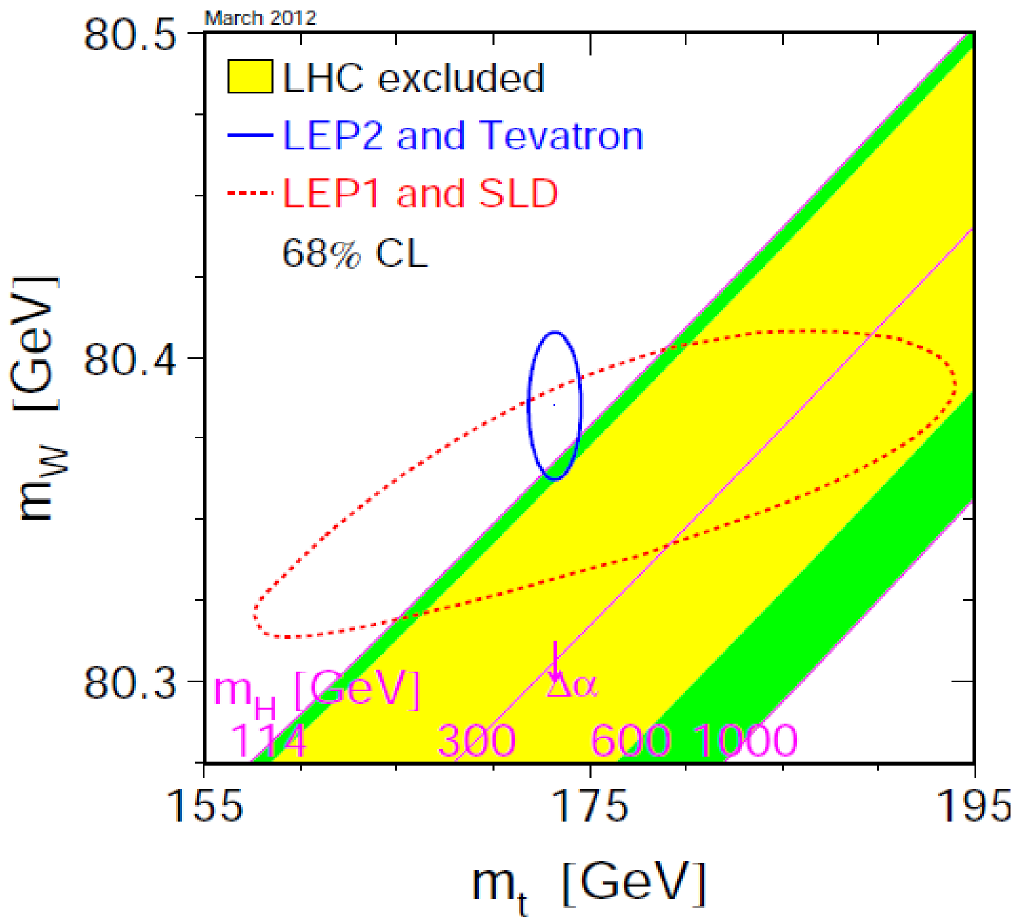


- The latest measurements from Tevatron are impressive, with uncertainties on $M_W \lesssim 20$ MeV

W mass: precise Tevatron measurements

- Tevatron data are consistent with a low mass (115-127 GeV) Higgs

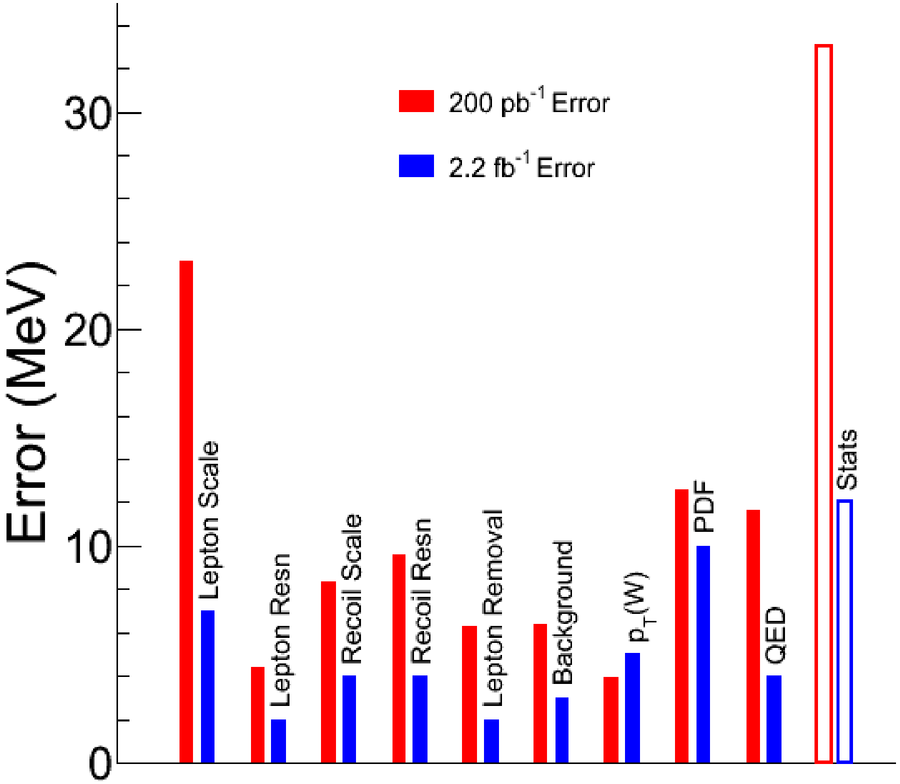




W mass: precise Tevatron measurements

- CDF measurement dominated by PDF uncertainties, D0 measurement dominated by electron energy calibration

CDF



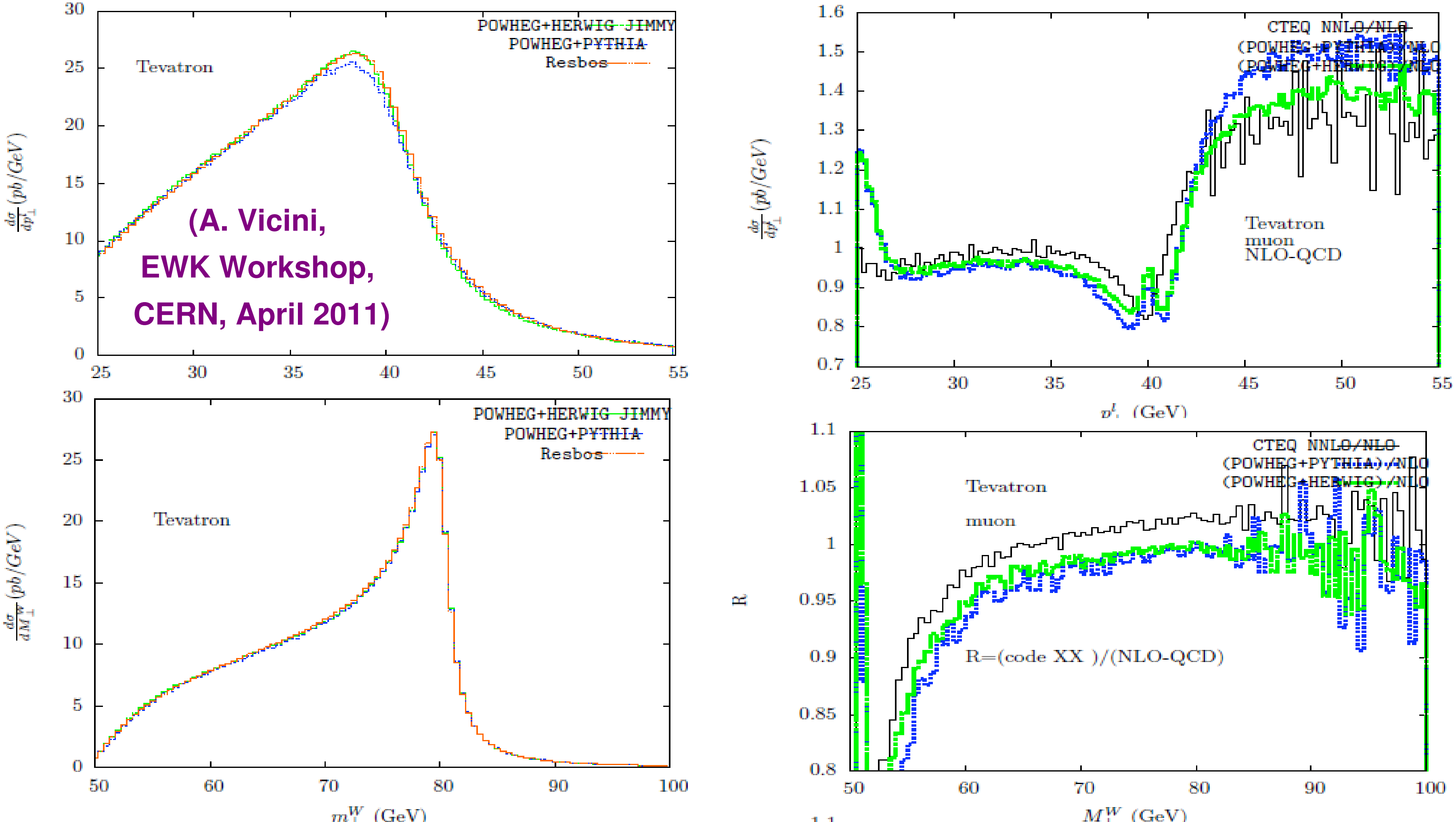
D0

TABLE II: Systematic uncertainties of the M_W measurement.

Source	ΔM_W (MeV) m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

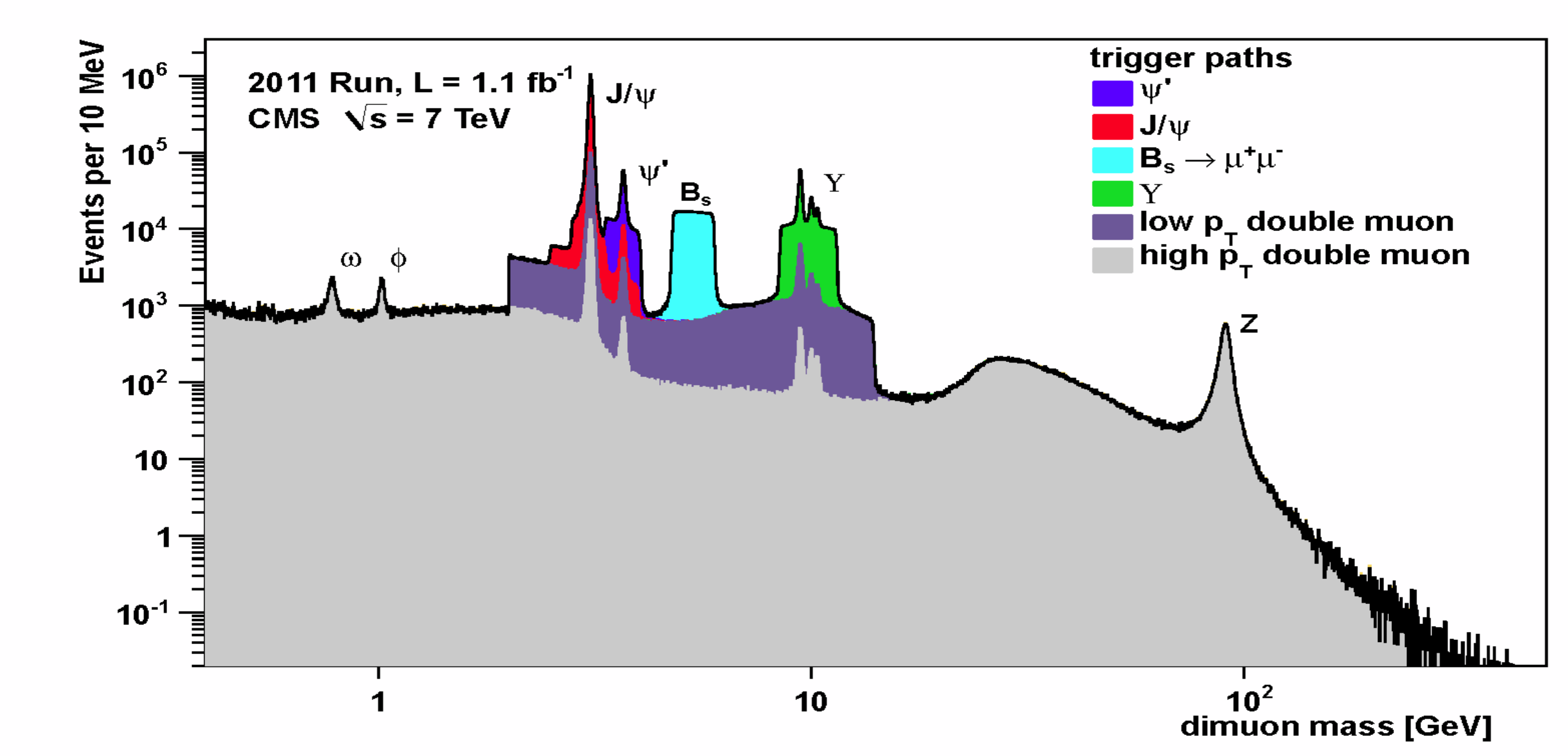
M_T or p_T

- PT is experimentally simpler (no MET involved, no pileup concerns, less Z->W extrapolation concerns)
- But theoretically MT is more stable (both at Tevatron and LHC)



Experimental challenges at LHC

- Tracking resolution (assuming a muon p_T measurement) -> adequate Z morphing:
  - This is not straightforward when we aim for a $\Delta(1/pT) \approx 0.005\ TeV^{-1}$ uncertainty ($\approx$10 MeV for a 40 GeV p_T):
    - Calibration with Z and W mass analysis must be use the same references



Experimental challenges at LHC

- Similarly for efficiencies (isolation, trigger, reconstruction, ...):
  - The optimal approach would be to implement them as corrections to the MC -> this way the level of agreement with data is directly quantifiable, and systematics easier to propagate
- Other uncertainties: backgrounds, missing E_T, EWK/FSR, ...
  - Pileup is a serious concern, particularly if M_T is used as sensitive variable
  - FSR effects are always a concern, typically more from the practical point of view than from the theoretical one ...
- Trigger
  - We need efficient single lepton triggers with low thresholds (pT>25 GeV or so). Isolation cuts are probably OK, but no energy or kinematics cuts should be present
- Options if luminosity is too high (i.e. the case at present):
  - Dedicated runs with lower luminosity (tried already in 2012)
  - Data parking (keep some events with looser triggers to be processed later in 2013)
  - Introduce looser triggers at end of fills, when instantaneous luminosity gets lower

W mass: the a priori concerns at LHC

1) At Tevatron W and Z production is fully dominated by $u\bar{u}$, $d\bar{d}$ (Z) and $u\bar{d}$, $d\bar{u}$ (W) initial valence parton collisions and there is an obvious symmetry. At the LHC:
   - Sea antiquark (and even sea quark) contributions are important
   - W+ and W- behave differently at LHC: different rapidity and decay properties
   - W production via $c\bar{s}$, $s\bar{c}$ is larger at the LHC, Z production has $c\bar{c}$ and $b\bar{b}$: precision of the Z -> W behavior extrapolation is not so straight-forward.

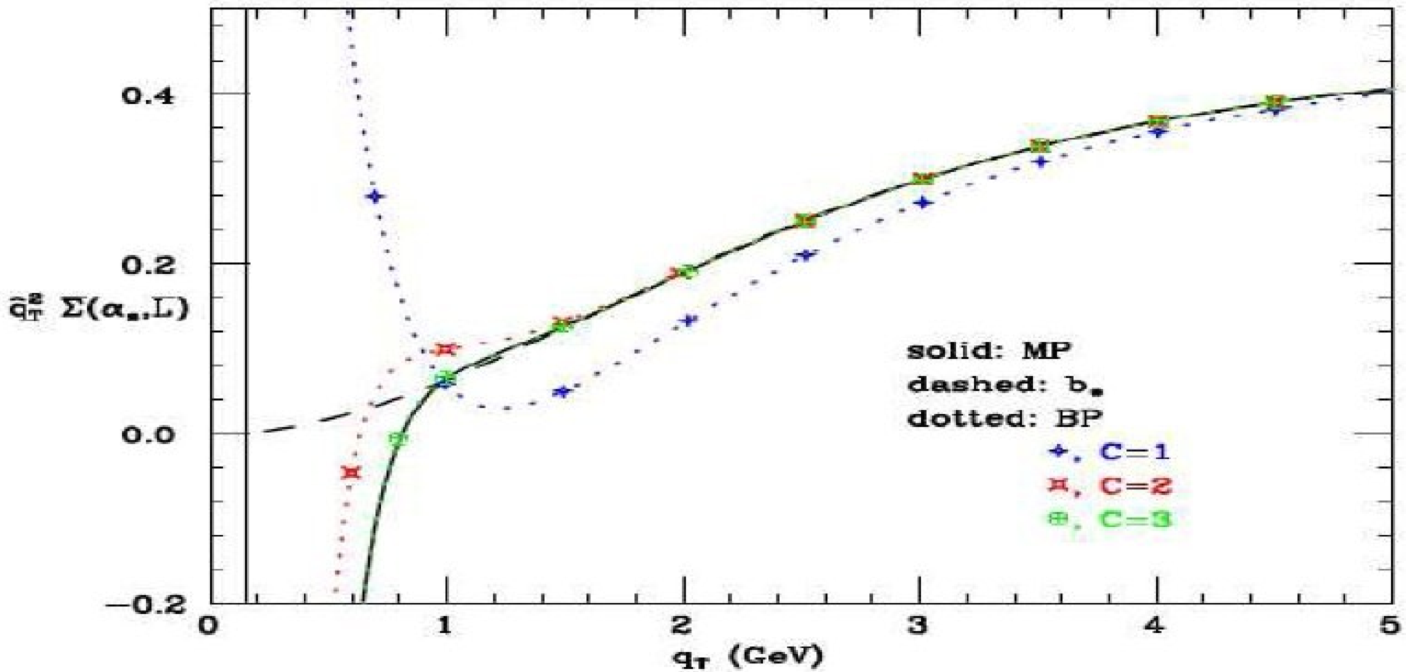
- Way to go:
   - We have to use the Z control samples in a clever way
   - Different asymmetries, W+c, ... are already constraining – and will constrain more – PDFs. The rest is V-A coupling. We should just trust the new generation of PDF uncertainties when available.

W mass: the a priori concerns at LHC

2) General feeling that the boson p_T distribution at low values has to be measured in data, and independently for W^+, W^- and Z:
    - This is a misconception. It assumes that "MC tuning" is equivalent to "non-perturbative" effects than can not be predicted by theory.
    - W and Z p_T distributions should be well known for boson $p_T \lesssim 3$ GeV

- Way to go:
    - There exist NNLO resummed pseudo-generators (RESBOS,...) that can be used as reference. We should do all efforts to tune our MCs (POWHEG, ...) to agree with those predictions -> not fully done yet
    - It requires a dedicated effort. It is not about doing many comparisons and blinding correcting parameters, but about FULL understanding

Low-PT spectrum is not a 'non-perturbative' issue

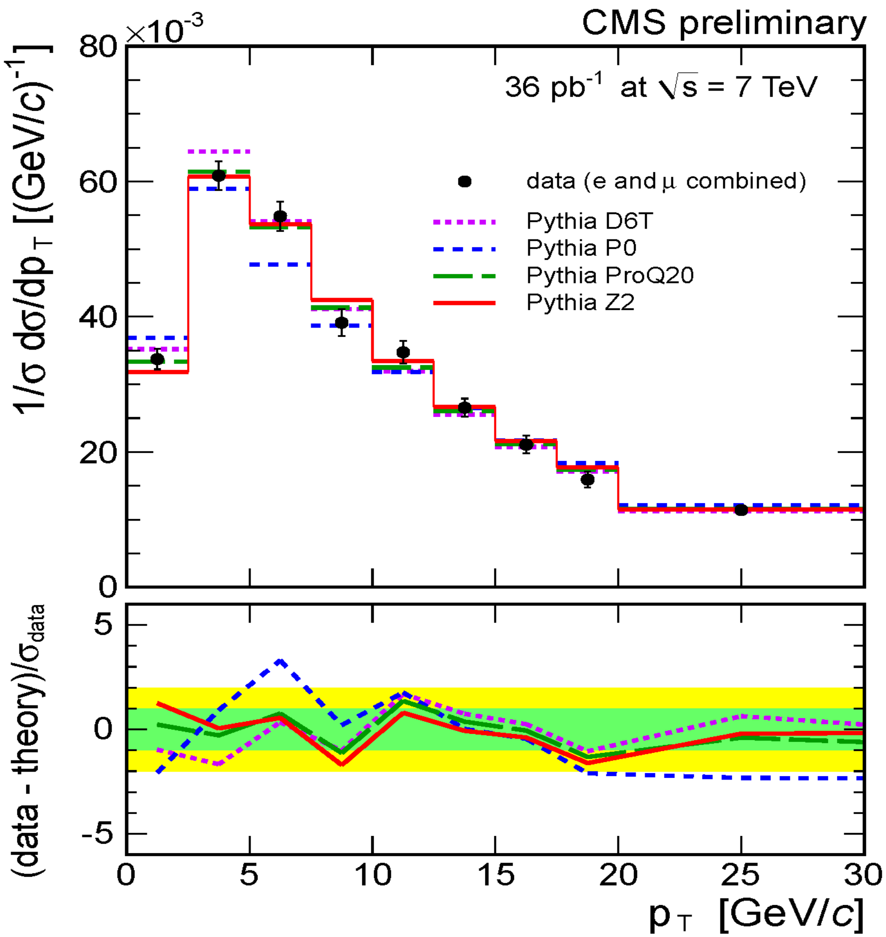


Plotted: $\frac{1}{\sigma}\frac{\mathbf{d}\sigma}{\mathbf{d}\log \mathbf{p}_T^2}$ **vs** $\mathbf{p_T}$, arXiv:0807.3830

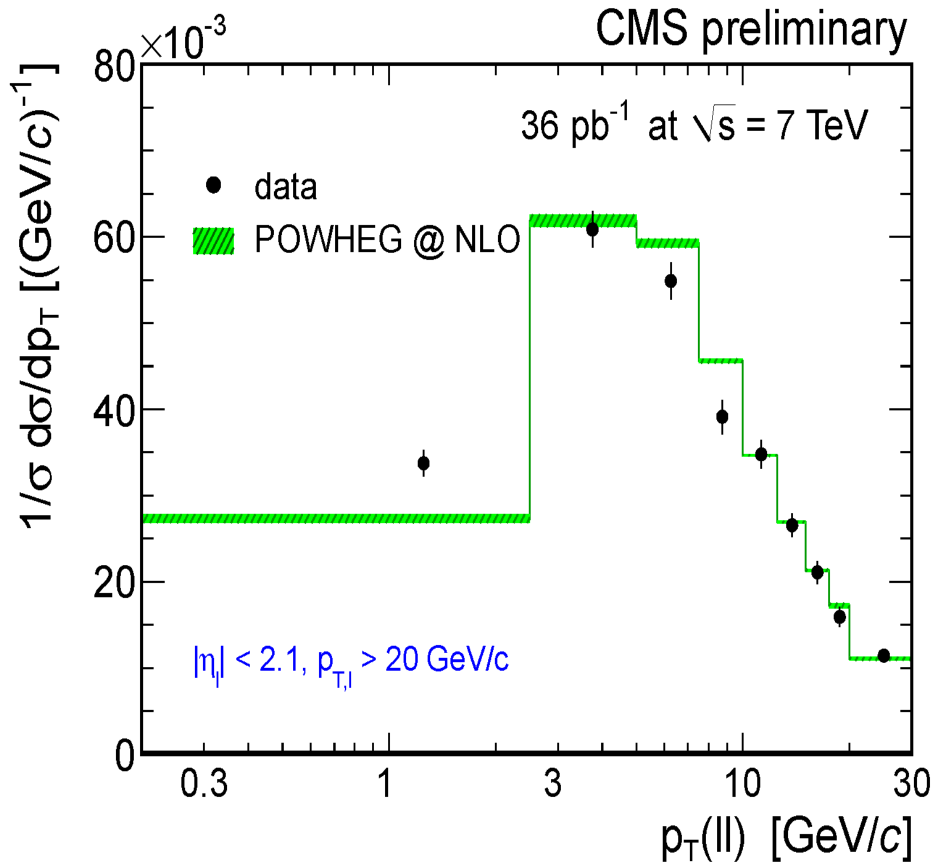
- $\mathbf{b}_*$: impact parameter prescription (Collins-Soper-Sterman, RESBOS non-perturbative default parameters)
- **MP**: Minimal prescription (to avoid singularities, Laenen et al.)
- **BP**: Possible Borel resummation prescriptions (Bonvini-Forte-Ridolfi)

Experimental tuning of boson PT distributions

- For usual MCs (with hadronic jets, not RESBOS), the PT is generated via ISR -> tuning



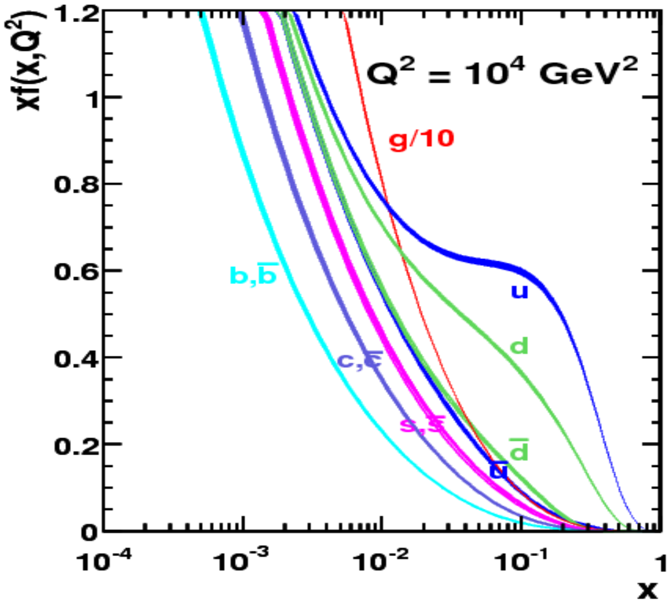
Z p_T spectrum in agreement with latest PYTHIA tunes



Z p_T spectrum in slight disagreement with current POWHEG simulation (but note that POWHEG uses PYTHIA tune Z2)

V + jets

V+jets: brief compilation



- In associated jet production, gluons play a major role:

$$u+g \rightarrow W^{+}/Z + q\text{-}jet$$
$$d+g \rightarrow W^{-}/Z + q\text{-}jet$$

- When associated to specific jet flavors, there is sensitivity to other PDFs too:

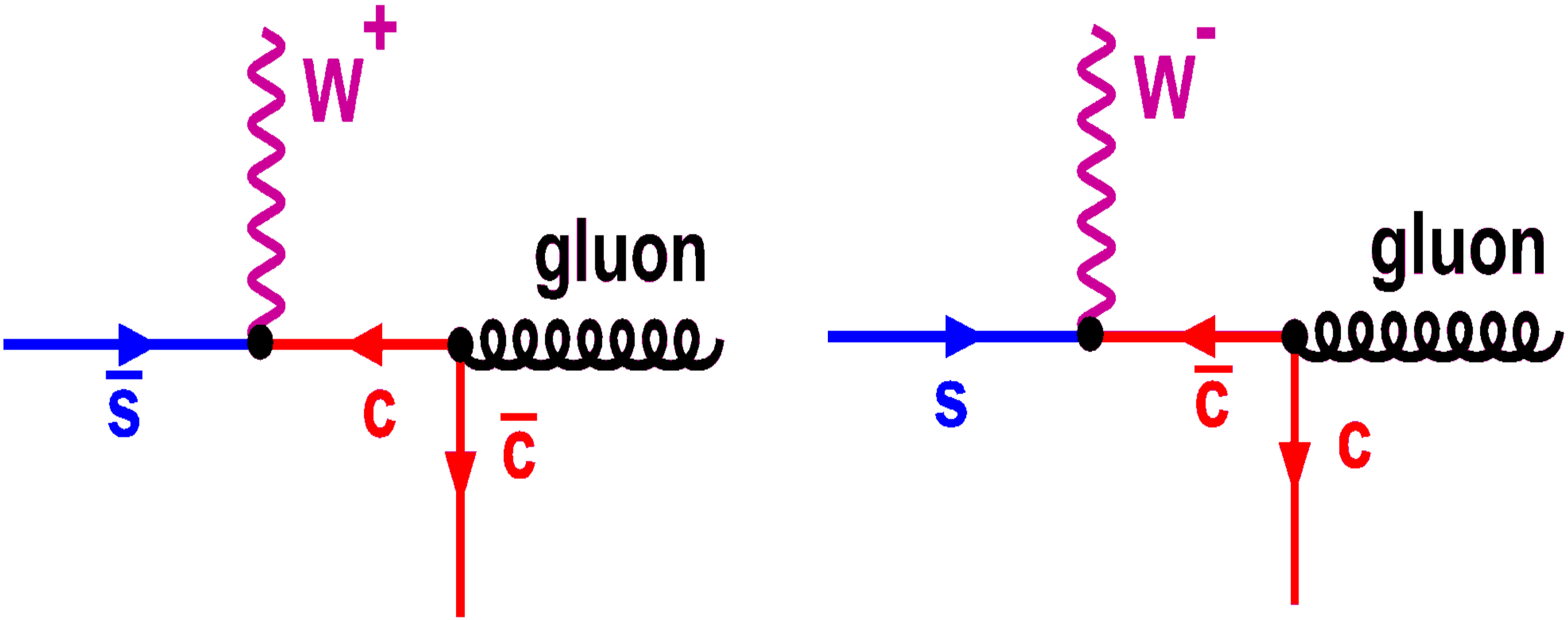
$$s+g \rightarrow W^{-}+ c$$
$$b+g \rightarrow Z+ b$$
$$c+g \rightarrow Z + c$$

- With two additional jets we test higher order diagrams, but also gluon splitting into heavy quarks. Experimentally they frequently look like one jet at low di-jet masses:

$$u+\bar{d} \rightarrow W^{+}+c\bar{c}; \qquad d+\bar{u} \rightarrow W^{-}+c\bar{c}$$
$$u+\bar{d} \rightarrow W^{+}+b\bar{b}; \qquad d+\bar{u} \rightarrow W^{-}+b\bar{b}$$
$$u+\bar{u} \rightarrow Z+b\bar{b}; \qquad u+\bar{u} \rightarrow Z+c\bar{c}$$

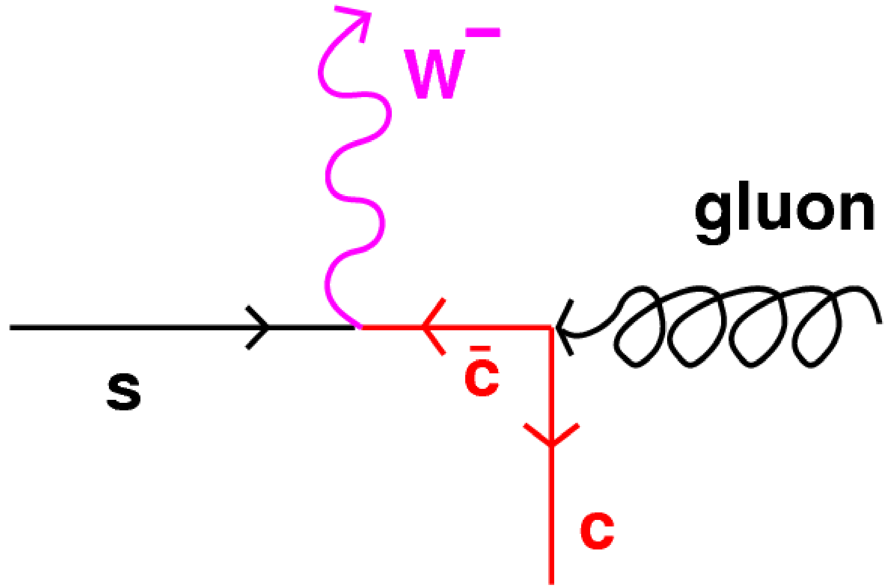
Why is W+c interesting

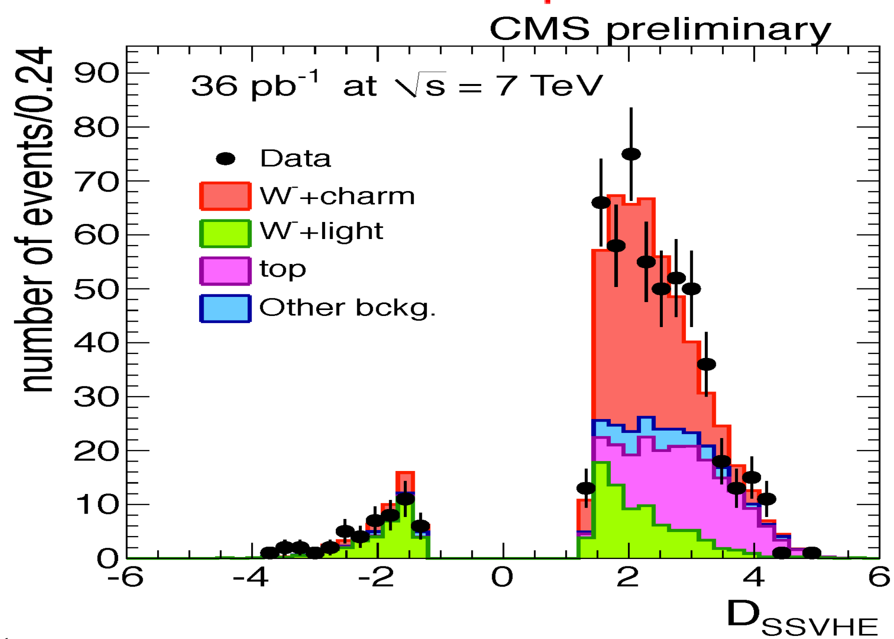
- In "W+c", the W production proceeds predominantly via "gluon + s-quark": g + s -> cc + s -> c + W$^-$". This means that this channel gives direct access to the s-quark PDFs:



V+jets with flavor tagging (W+c)

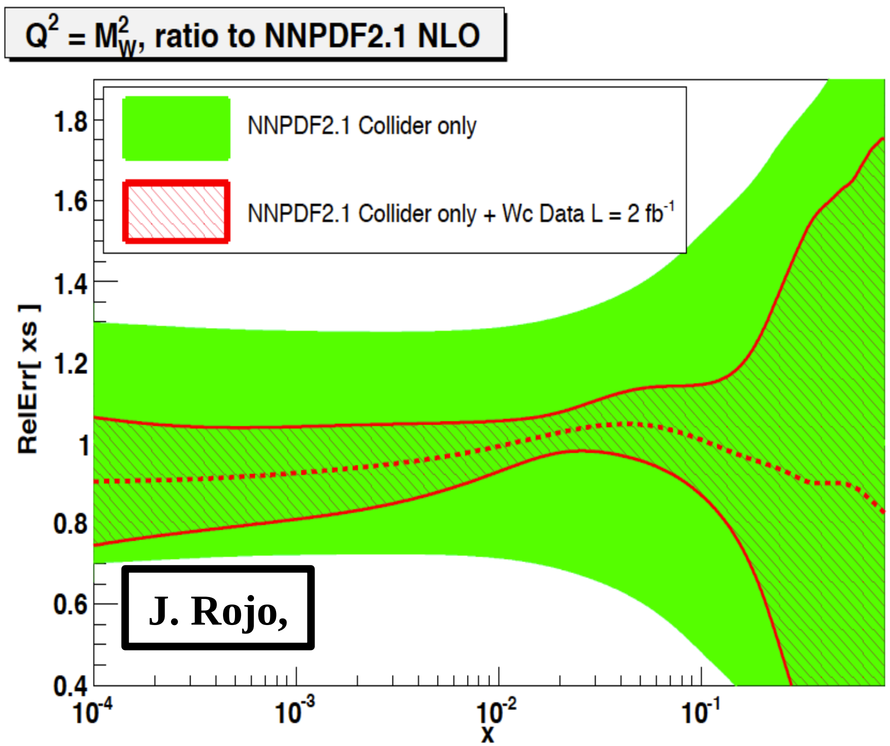
- Analyses of 2011 of data going on to obtain precise W+c measurements:
  - Preliminary CMS results with 2010 data existing already
  - We can measure W+/W-, (W+c)/(W+jets) as a function of differential variables
  - We may use double tagging to reduce systematics (c->l, vertex tagging, D-meson identification, ...)
  - Possible by-product: measurement of charm efficiency

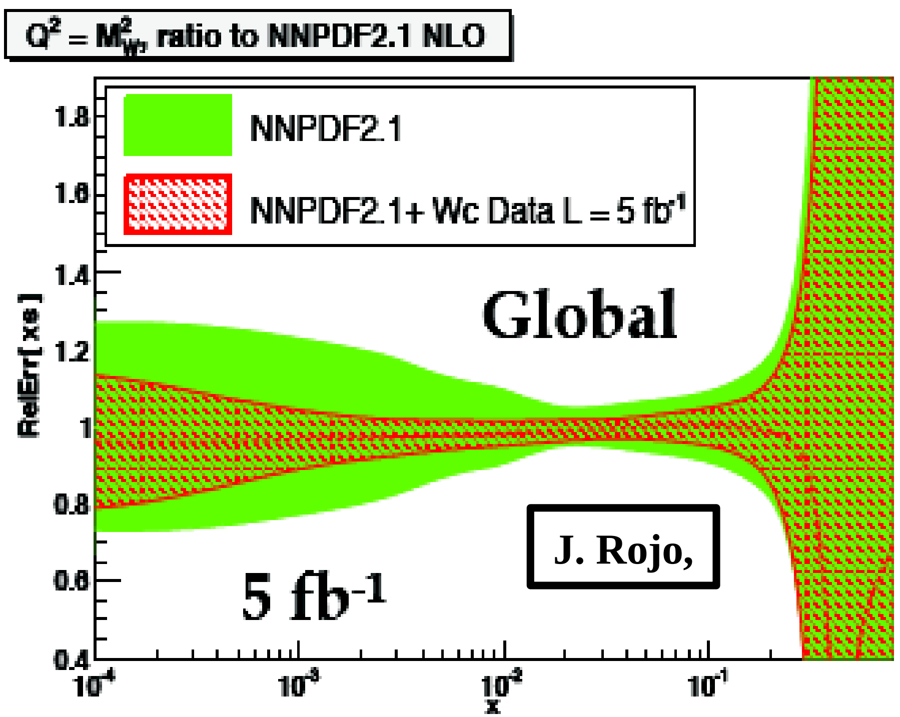




Why is W+c interesting

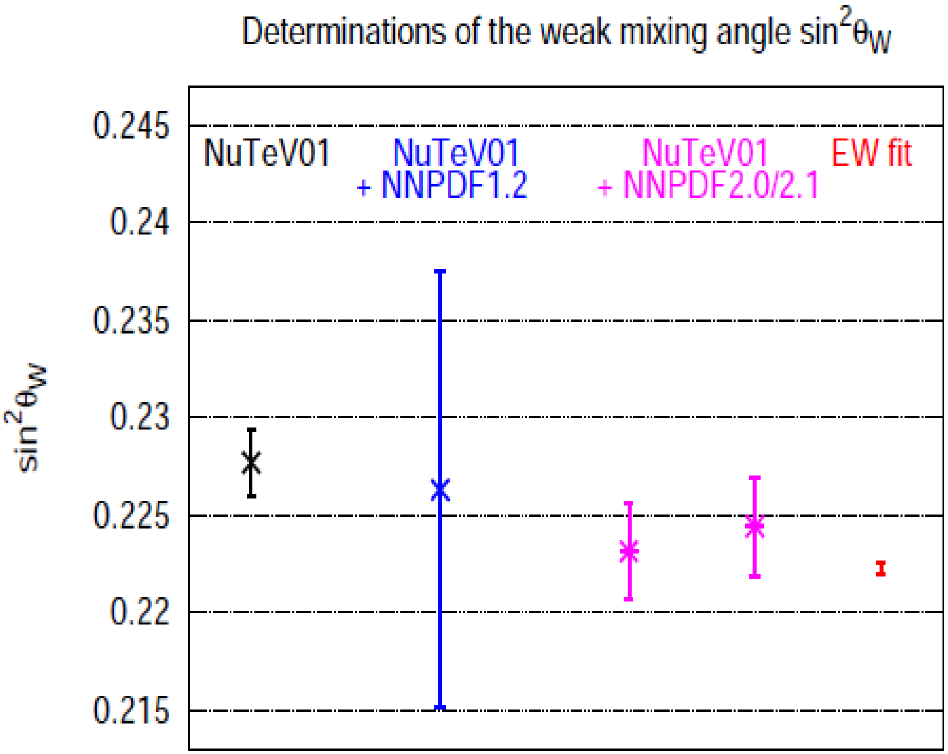
- Significant improvement over collider-only PDFs (i.e. old νN scattering measurements excluded)
  - Expected precision equivalent/better than present PDFs (that include νN measurements) but with less theor. caveats

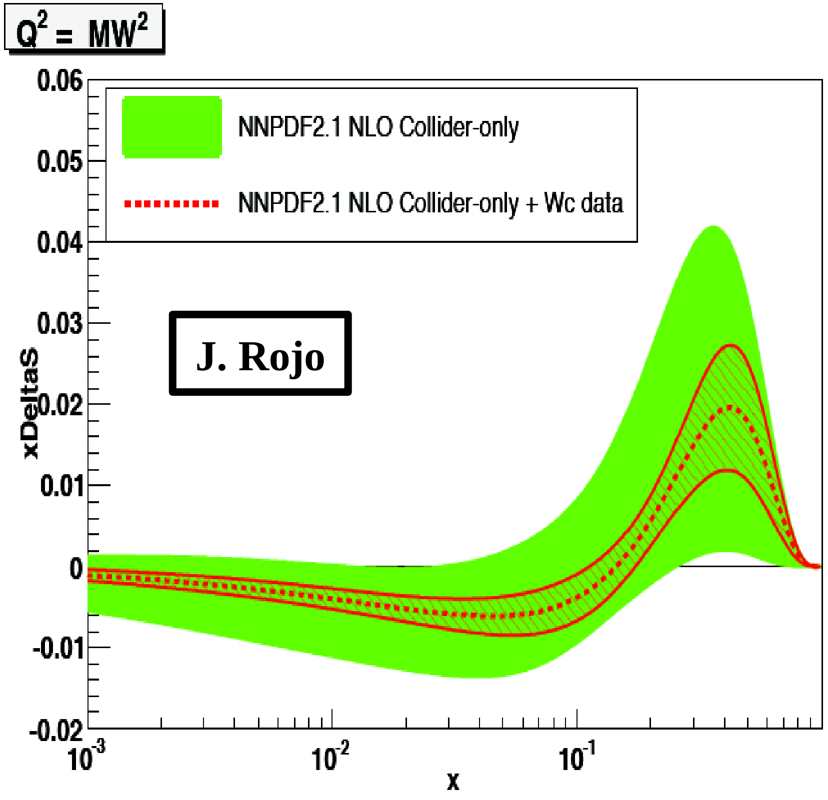




Why is W+c interesting

- The ratio (W^++charm)/(W^-+charm) is related with the so called 'NuTeV anomaly', with the measurement of $\sin^2\theta_{eff}$, ...

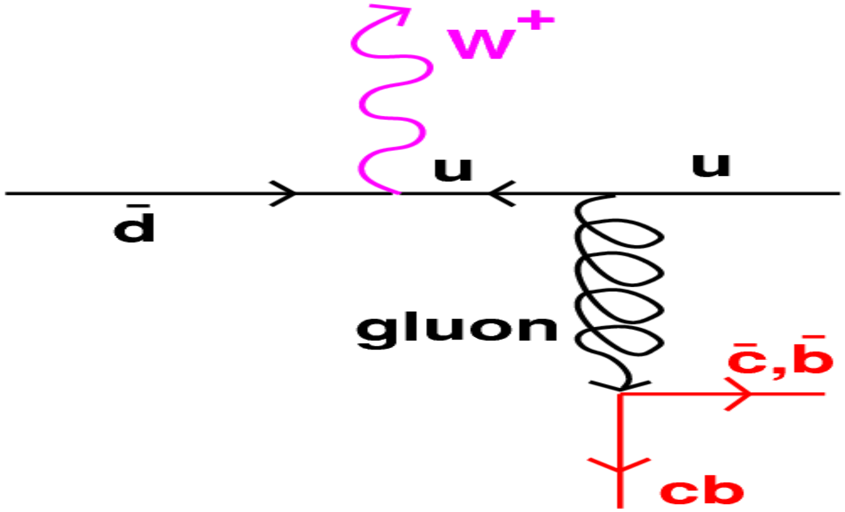


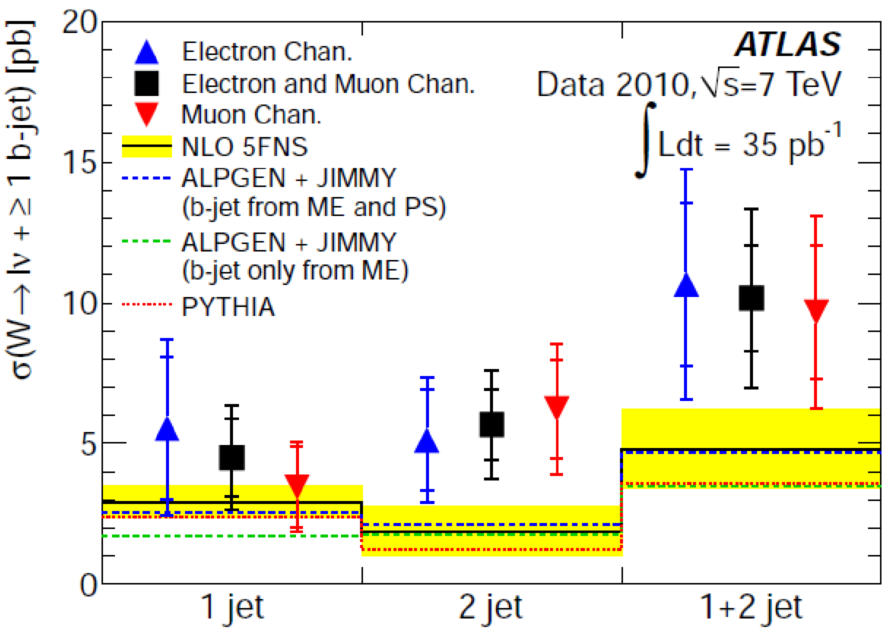


(NNPDF2.1 parton density functions, R.D. Ball et al., arXiv:1101.1300)

V+jets: with flavor tagging (W+b)

- Relevant background for important analyses (Higgs, top). Huge excess claimed by CDF
- First ATLAS measurements of W+b with 35 pb^{-1}
  - They measure a little bit more than expected, but with large uncertainties.
- Again this will be better addressed with much more statistics (> 10 fb^{-1}):
  - Measuring W+c is a convenient step
  - Can we measure the W+ 1 b jet component too (charge dependence and double lepton tagging to disentangle) ??





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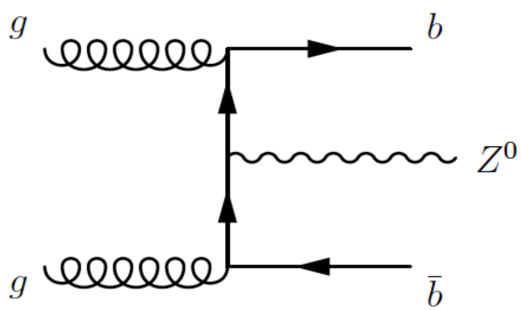
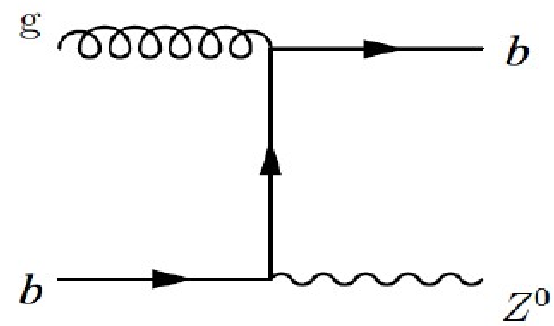
Associated Z+b jet production

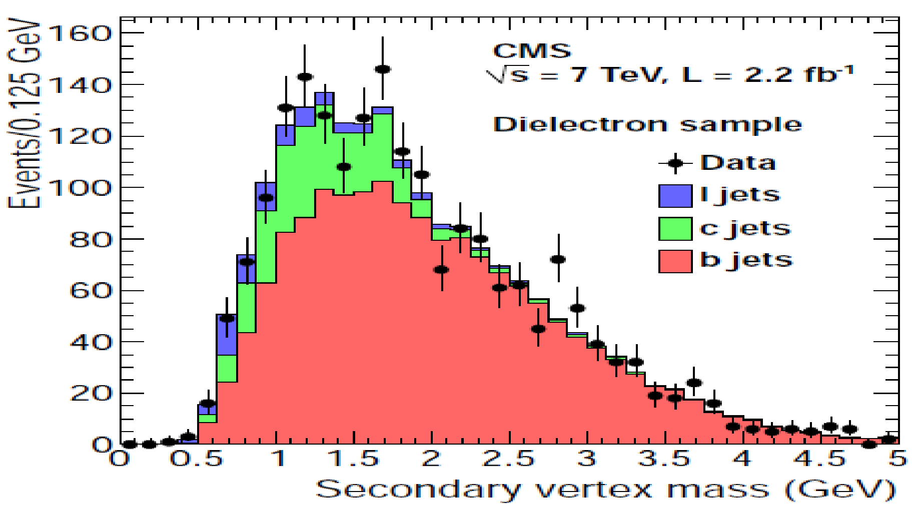
- This channel may give some information on b-quark PDF => gluon evolution, but probably it will give more insight on gluon-splitting and mass-related effects

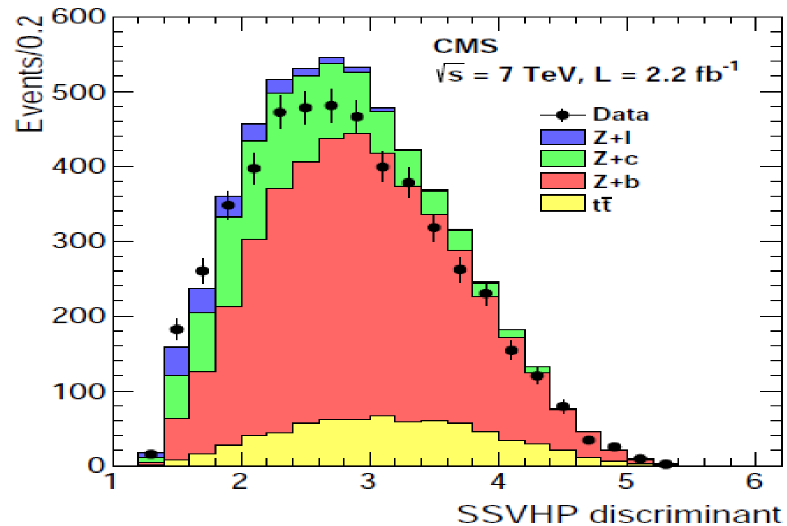


Fixed-flavor scheme (no b-quark at parton level)
Caclulations with massive b quark



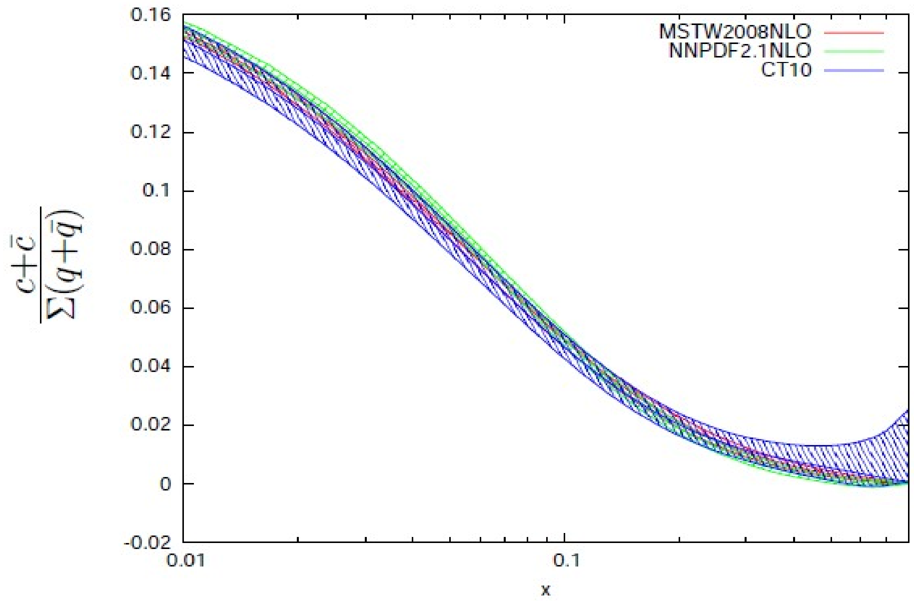
Variable-flavor scheme (b-quark at parton level)

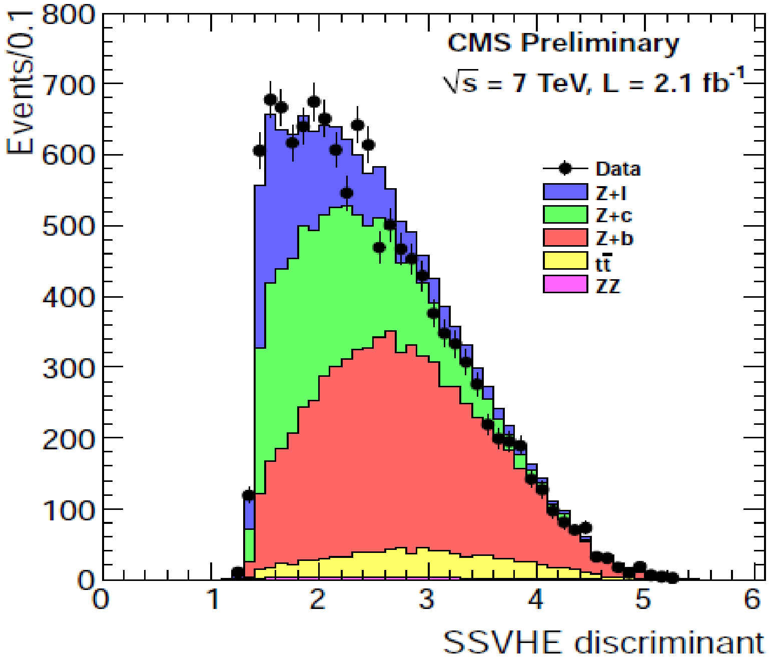




Associated Z+charm production

- It has been claimed in Stirling, Vryonidou, arXiv:1203.6781, that R^z_c provides direct access to the charm content of the proton, but also $(R^z_c)^{\pm}$ provides some access to the "intrinsic" charm/anticharm content (if any)

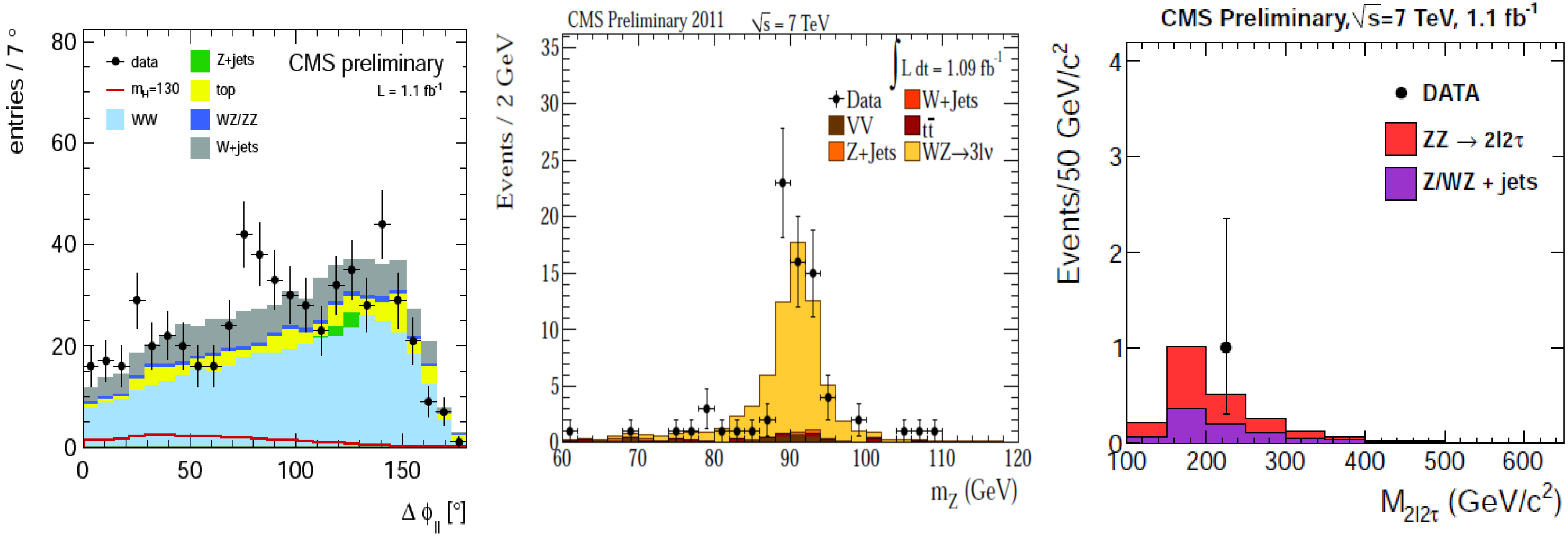




- LHC has the sensitivity to measure Z+c, but also the capability (at least with very high statistics) to disentangle Z+c from Z+anticharm using "dilepton" events.

Diboson production, triple gauge couplings

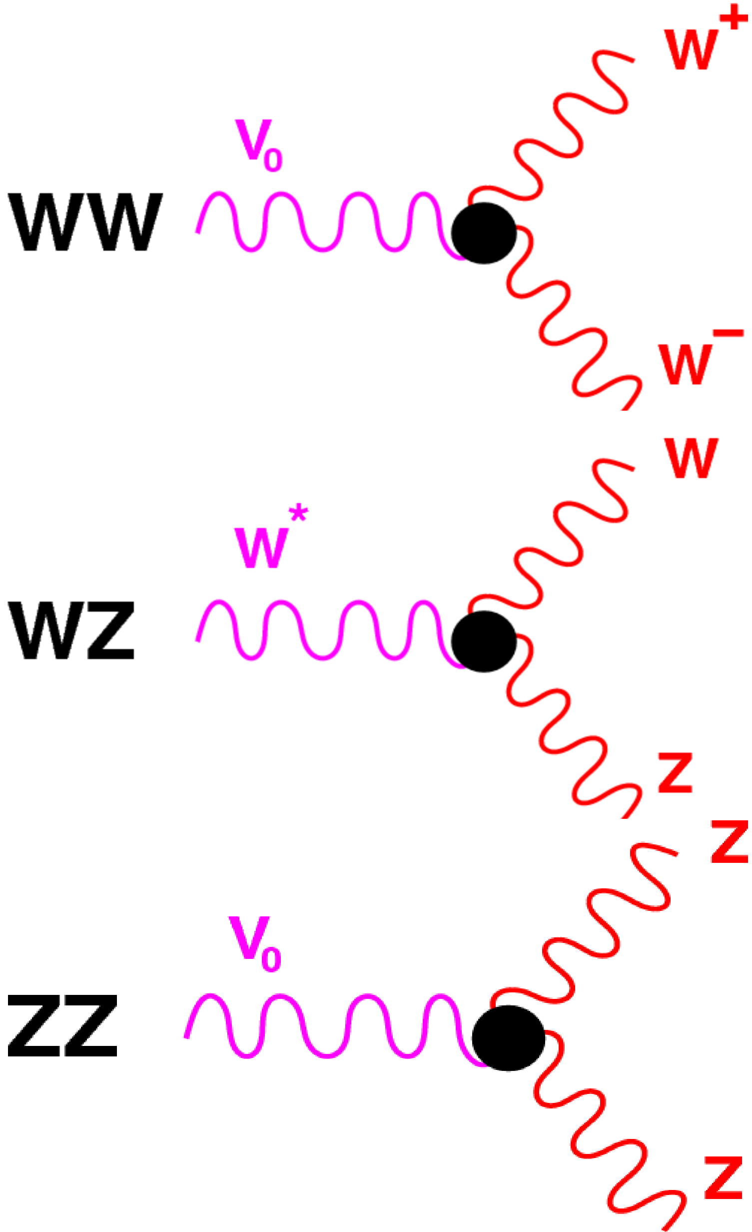
Diboson production



- With higher luminosities (>10 fb^{-1}) we are performing precision measurements of WW, WZ, ZZ production.
- What do we learn from them, beside being control samples for Higgs searches?
  - Higher order QCD effects
  - Possible deviations in a snapshot (mostly at high VV masses):
    - Anomalous triple gauge couplings, quartic couplings
    - QCD-like resonances, new deviations via effective Lagrangians

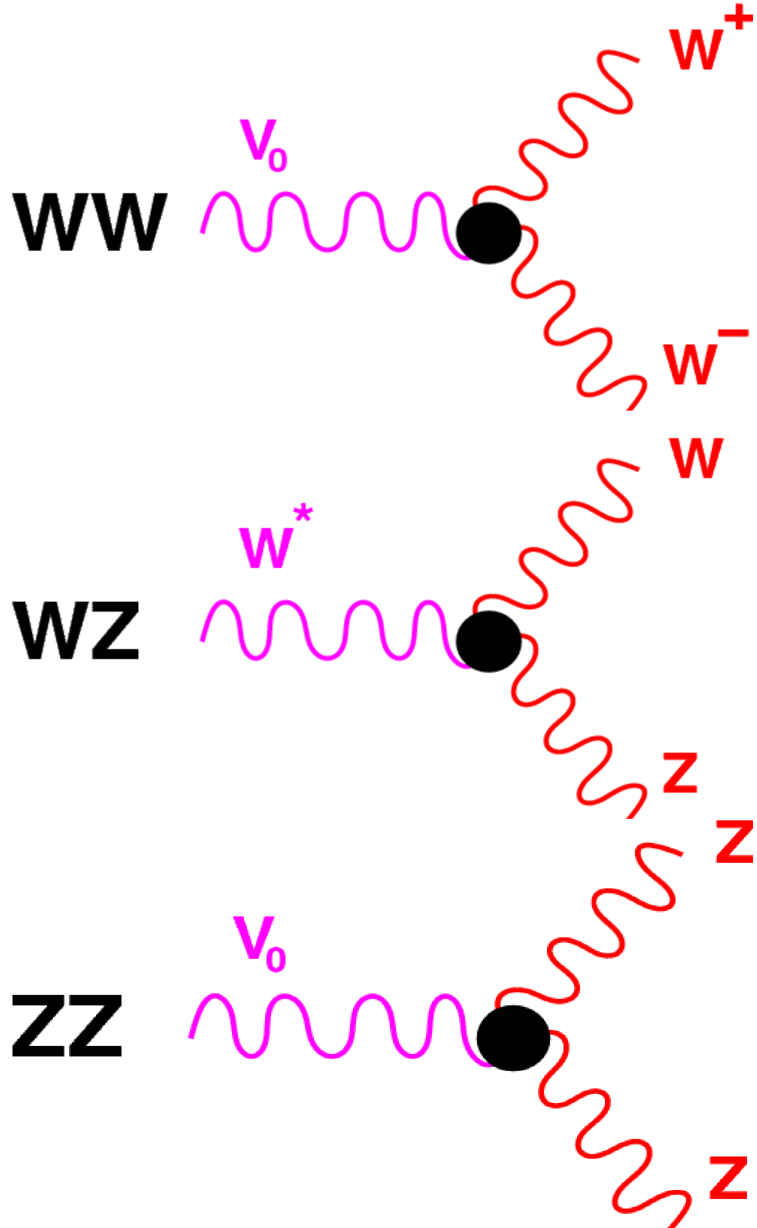
TGCs

- Our sensitivity to anomalous TGCs is already above Tevatron
- Reminder: anomalous effects lead to an increase in diboson cross sections, particularly at high p_T of the VV system:
  - Triggers or experimental conditions are not an issue, since large lepton or photon transverse energies are the key
  - Here the gain with center-of-mass energy of the accelerator is more important than an increase in luminosity. But if excesses are suspected, an increase in luminosity is important.
  - At the end of the day, 20-30 fb^{-1} means stringent tests of SM predictions for diboson production at high masses of the diboson system



TGCs and dibosons

- Going exotic...
  - Should not we consider more general deviations of the type qqbar -> VV or gg -> VV instead of just TGCs ?
    - Experimental effects are going to be similar to those of TGCs, so it is just a matter of theory interpretation
  - Consider Higgs anomalous interactions if the Higgs is found
    - Again this is probably a theory issue. It only becomes experimental if kinematics must be studied in addition
    - This does not necessarily enter in the Higgs list of tasks, since it imvolves 'indirect effects' on SM cross sections



Tri-boson production and quartic gauge couplings (QGCs)

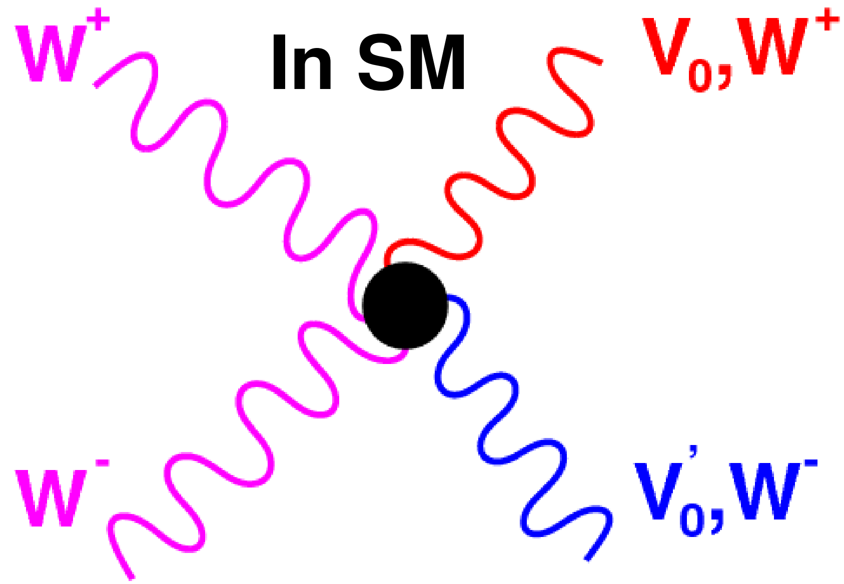
Triboson production and QGCs

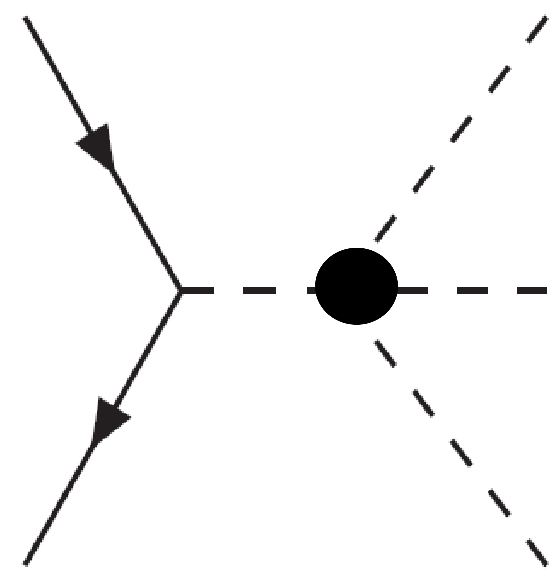
- This is `terra incognita'. Almost no studies available. A few studies at $\sqrt{s}$=14 TeV (D. Green, hep/ph-0310004, T. Binoth et al., arXiv:0804.0350, ...)

- Observation of three boson production in some channels (WWZ, WZZ) could imply a first observation of the four-boson couplings predicted in the SM (but not necessarily).. ZZW into leptonic channels (5 leptons, 2 Zs constraints + MET) is the cleanest.

- WZγ and WWγ final states can be explored at lower luminosities, but those are dominated by initial or final state QED radiation. Observation of ZZZ would almost mean automatically new physics.

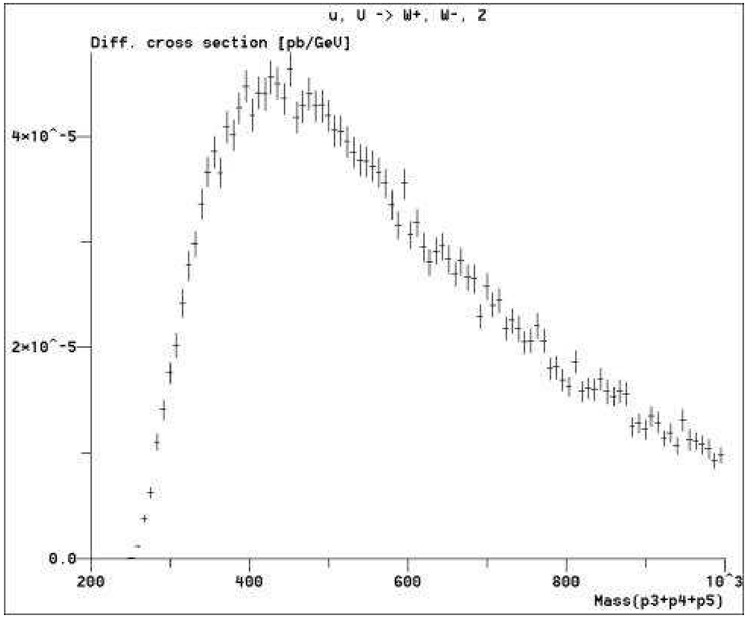
- But what are the expected rates with 30 fb^{-1}?

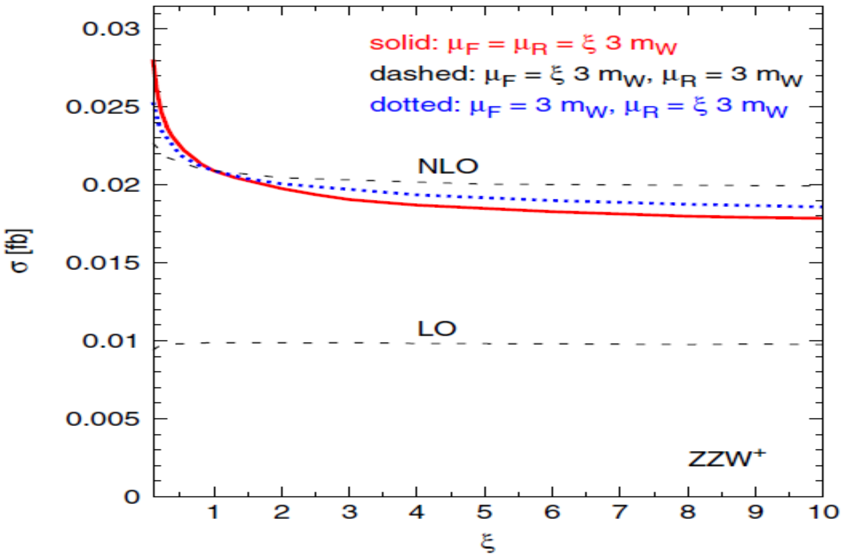




Triboson production: expectations

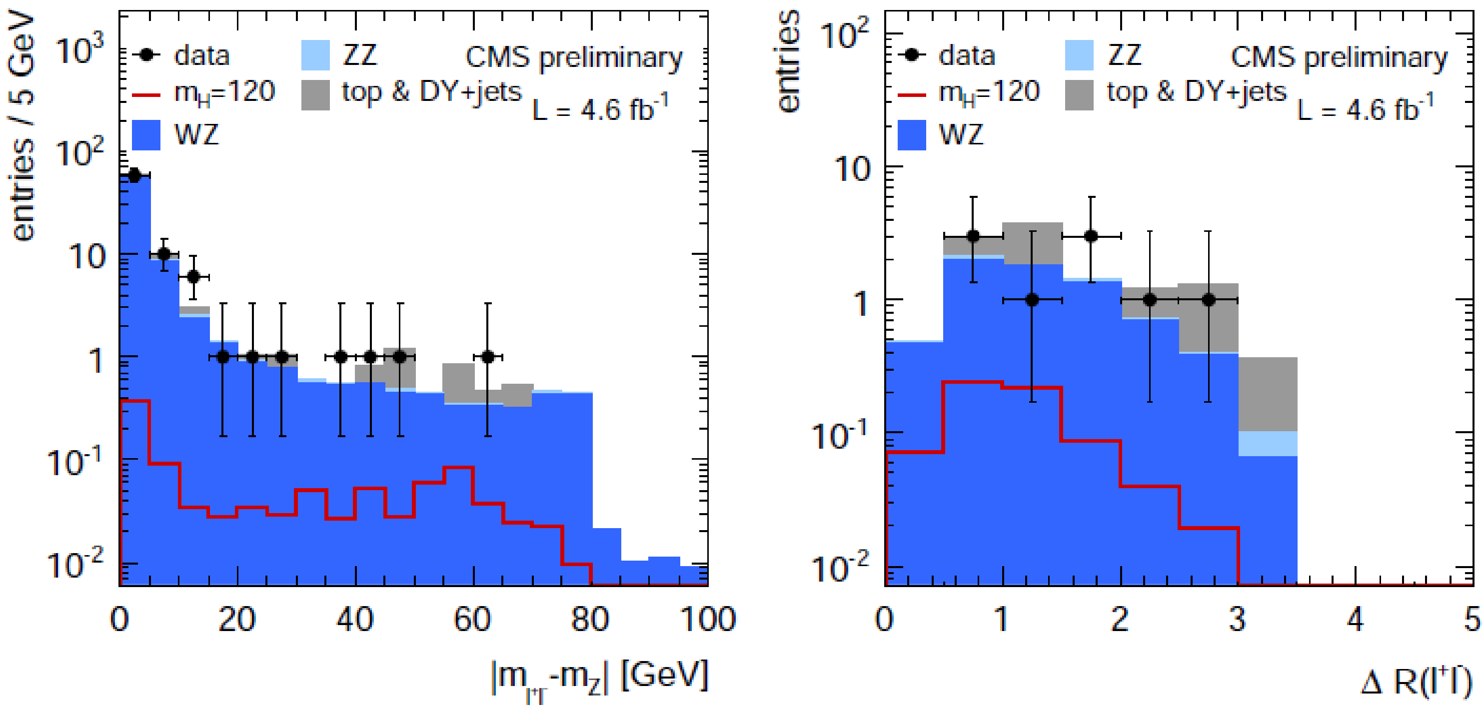
- Rules of thumb:
  - Cross section at √s=7 TeV ≈ 1/3 cross section √s=14 TeV
  - NLO/LO k factor ≈ 2
  - So old LO rates at 14 TeV must be reduced by 50% approx.
- hep/ph-0310004: study of VVZ with Z into leptons and V into jets, ~16% efficiency, ~2.5 fb cross section at 7 TeV (NLO) -> 12 events seen with 30 fb^{-1}. Caveats:
  - Efficiency is just an educated guess
  - No bkgd studies (important because W goes into jets)
  - 3 events if fully leptonic and eff~30%
- Study in Phys.Rev. D78, 094012 for WWW into leptons, with pT>10 GeV, |h|<2.5:
  - Cross section ~ 2.4 fb => 72 events for 30 fb^{-1} (efficiency of cuts missing)





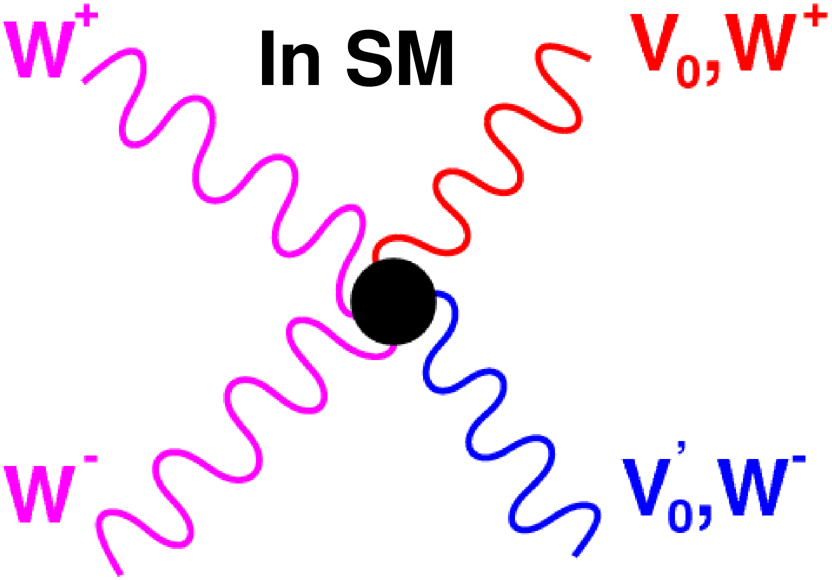
Triboson production: expectations

- We have actually looked for WWW final states in a different context (WH associated production):
  - Dominated by $WZ^{(*)}$ background for current cuts, so probably ZWW and ZZW are more promising candidates (>3 leptons in final state)

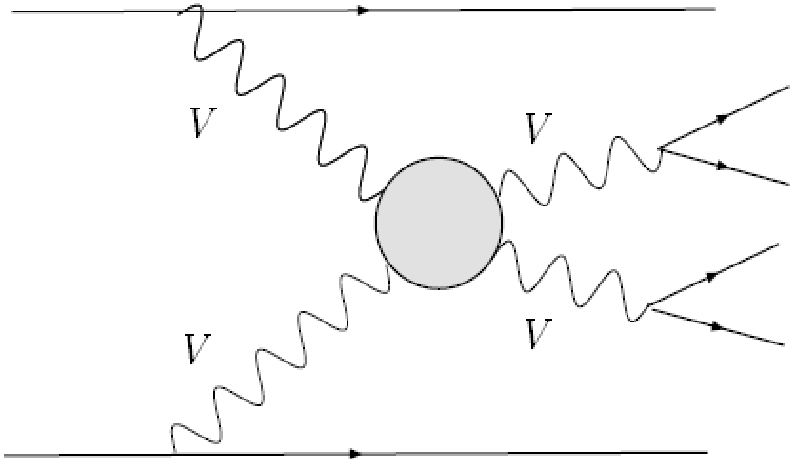


Vector boson scattering and quartic gauge couplings (QGCs)

Vector boson scattering and QGCs

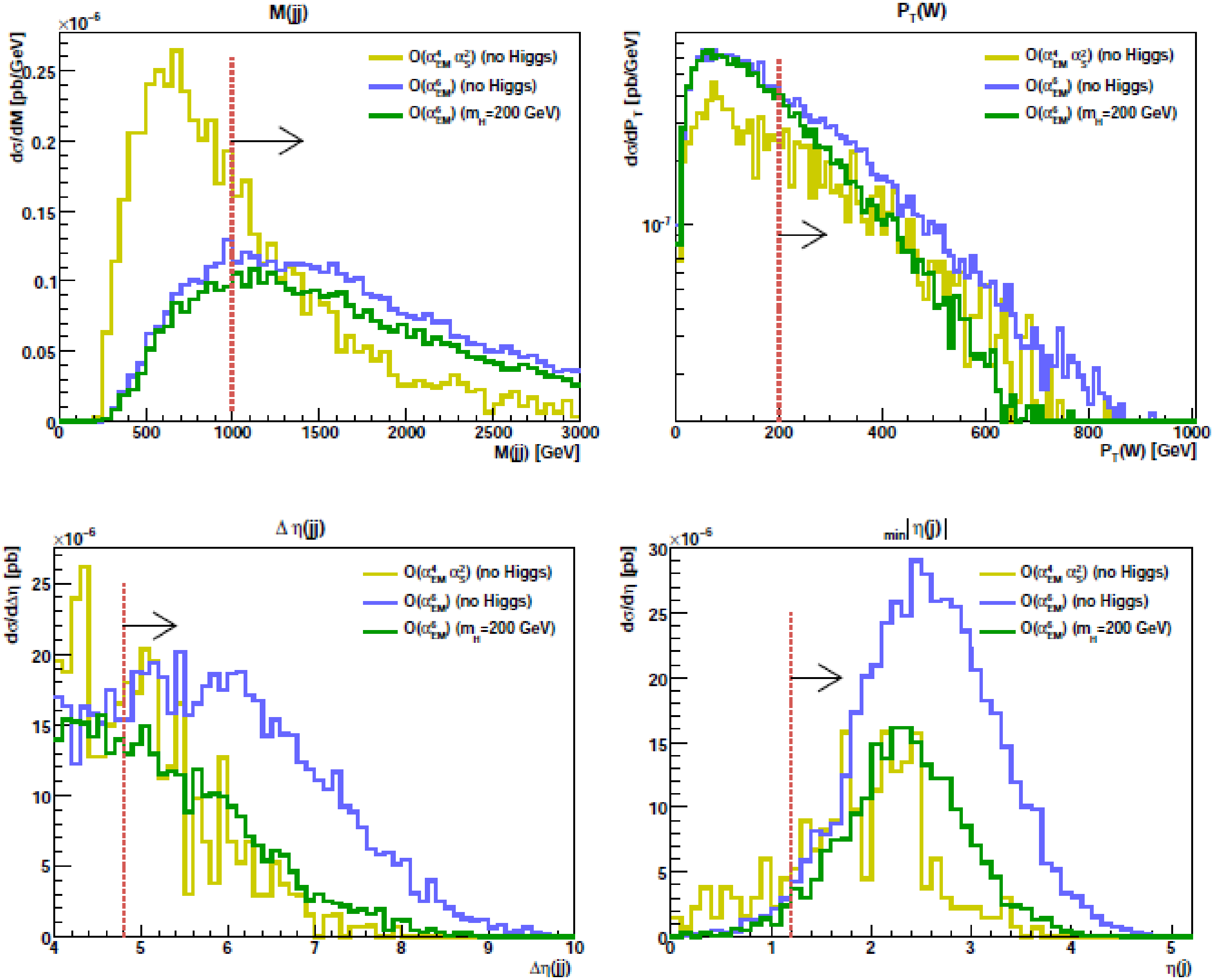


- Compared with tri-boson production, similar comments apply here. A few more phenomenological studies are available in this case, probably because this is one of the benchmark production mechanisms for the Higgs and for $W_L W_L$ scattering if no Higgs is present



- Rules of thumb:
  - Factor of 3 lost going to 7 TeV
  - NLO/LO k-factor is essentially 1
- What are the expected rates with 30 fb^{-1}?

Boson fusion studies: pp->lllν+2 jets



Selection cuts
$M(j_f j_b) > 1000$ GeV
$p_T(\ell^+\ell^-) > 200$ GeV $p_T(\ell\nu) > 200$ GeV
$\lvert\Delta\eta(j_f j_b)\rvert > 4.8$
$\lvert\eta(j_f, j_b)\rvert > 1.2$
$\lvert\Delta\eta(V j)\rvert > 1.5$
$\lvert\eta(\ell^\pm)\rvert < 2.0$
$M(V j) > 300$ GeV

Additional cuts for the $3\ell\nu + 2j$

A. Ballestrero et al., JHEP 0911:126,2009 (Phantom)

Vector boson scattering and QGCs

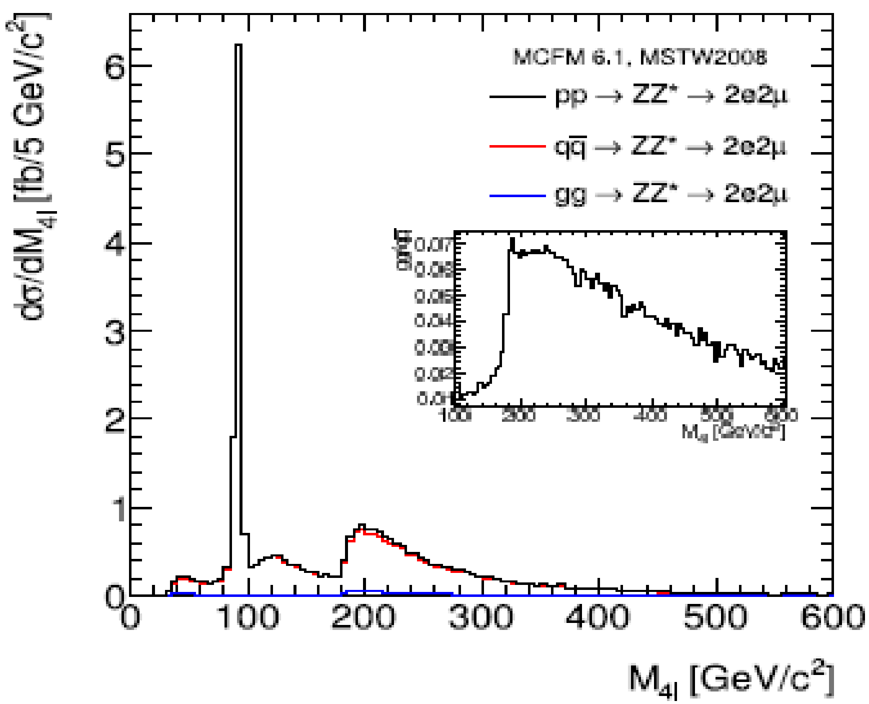
- Studies show that:
  - The cleanest channels are the leptonic channels with at least one Z->ll in the final state, but they lack statistics. For L=100 fb^{-1} at √s=14 TeV:
    - We expect at most ~50 events after selection (M>600 GeV)
    - Differences between a no-Higgs and a light Higgs scenario correspond to ~5 events or so
    - Yield to be divided by a factor of 3 at √s=7 TeV
- So life is diffficult in the absence of anomalous excesses/resonances !!

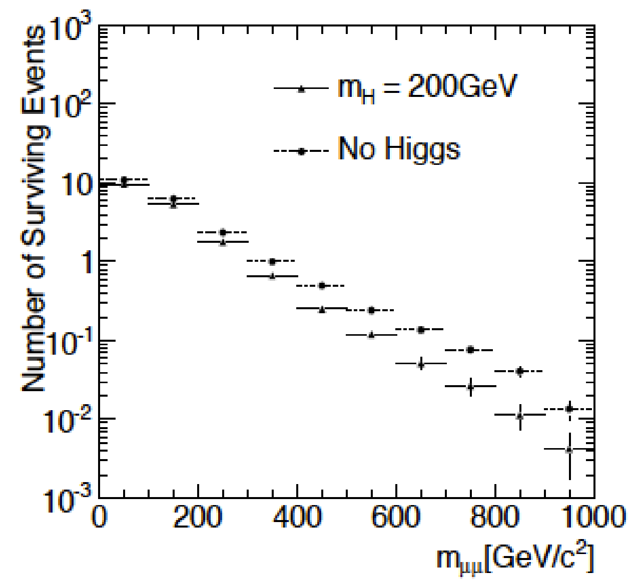
M_{cut} (GeV)	no Higgs σ(fb)	SILH σ(fb)	$M_H = 200$ GeV σ(fb)
600	0.499(0.242)	0.462(0.213)	0.452(0.204)
800	0.252(0.134)	0.227(0.114)	0.219(0.106)
1000	0.139(0.078)	0.122(0.0635)	0.117(0.0585)
1200	0.0815(0.0476)	0.071(0.0374)	0.0675(0.0339)

Table 5: Total cross section for the $3\mu\nu + 2j$ and $2\mu e\nu + 2j$ channels after acceptance cuts, Tab. 1. In parentheses the results for the $\mathcal{O}(\alpha^6_{EM})$ sample.

Vector boson scattering and QGCs

- It is a bit better for golden channels like WW->ZZ (for instance: hep-ph/0306160), although 30 fb^{-1} is probably still not enough at 8 TeV in the absence of anomalous excesses
- However there are many unexplored possibilities yet:
  - What about Z->neutrino decays (gain of a factor of 6 over ZZ->4l channels) ?
  - Dijet reconstruction not optimized at all in these studies
  - What about W+W+ / W-W- final states?





B. Zhu et el, Eur.Phys.J.C71:1514,2011

Outlook

- There are still many interesting studies to perform in the EWK sector beyond 2011. For instance:
  - W mass, even if it is difficult to improve over Tevatron
  - V+heavy flavor studies, profiting from huge statistics
  - Precision physics already moving from single-boson to double-boson production (+precise TGC constraints)
  - We will also enter at some point a new domain:
    - Triboson production and vector boson fusion process
    - Quartic gauge couplings
    - Start searching for any anomalous deviations in multiple boson production with or without the presence of a Higgs