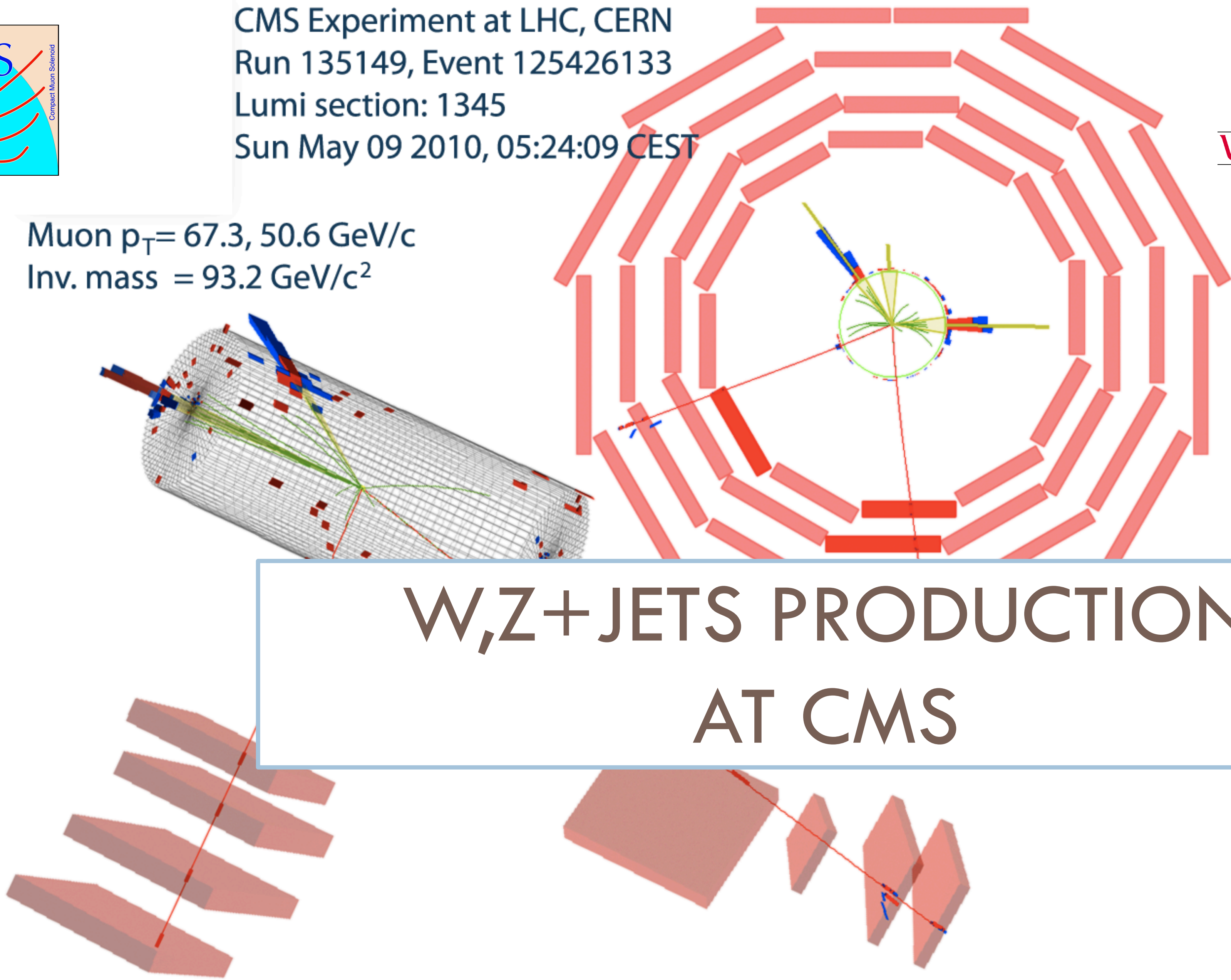


W,Z+JETS PRODUCTION AT CMS

Monika Grothe (U Wisconsin)

Introduction

- W & Z produced in abundance at LHC
  - Important SM candles for detector commissioning
  - Important test of and handle on QCD
  - Major background to many NP searches
- Very clean final state that contain all the typical elements of final states at the LHC: leptons, jets, missing ET (MET)
- V+jets complementary to inclusive V production:
  - At LO inclusive W and Z production proceeds via collisions of a valence quark and a sea antiquark
  - In associated jet production, gluons play a major role:

$$u + g \rightarrow W^{+} + q; \quad d + g \rightarrow W^{-} + q$$

  - When associated to specific jet flavors, additional pdfs are accessible

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

- Ideal for PDF measurements

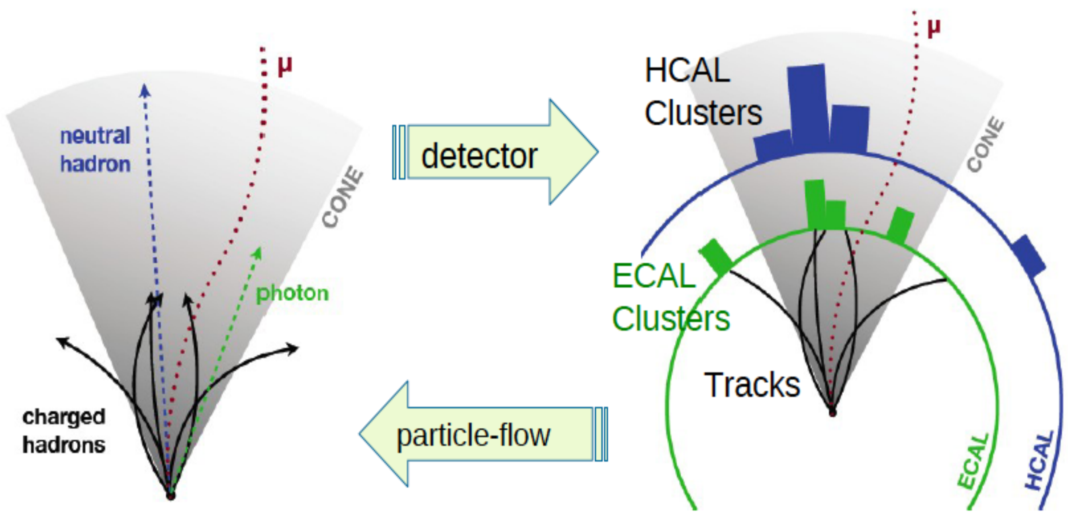
Contents

- This Talk: Present 4 analyses of 2010 CMS data (36pb^{-1})
  - W & Z + jet cross-section and scaling properties
    - CMS-PAS-EWK-10-012
  - Measurement of polarization in boosted W decays
    - CMS-EWK-10-014; CERN-PH-EP-2011-043; arXiv:1104.3829
  - Z production in association with b jets
    - CMS-PAS-EWK-10-015
  - W production in association with c jets
    - CMS-PAS-EWK-11-013

Experimental techniques

- **Muons** in CMS reconstructed with the help of the Si tracker and the muon chambers
- Typical p_T resol. for EWK studies: 1-2%
- Identification based on compatibility of tracking, calorimeter and muon chamber info with muon hypothesis

- **Electrons** in CMS reconstructed with the help of the Si tracker and the $PbWO_4$ crystal calorimeter
- Typical E_T resol. for EWK studies: 1%
- Identification based on shower shapes, track matching and Had./El. ratio

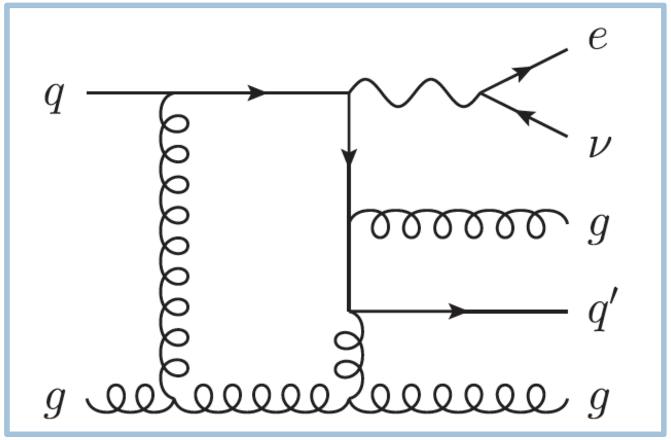


- Reconstruction of jets and MET uses **particle-flow techniques** that aim at reconstructing all constituents in the event or jet
- For **jets,** use infrared-safe anti-k_T algorithm with cone radius of 0.5
- Typical jet energy scale uncertainty for EWK measurements < 3%, typical jet energy resolution 10-15%

V+Jets at the LHC

- Key background in many new physics searches
- Diagram is ordinary EWK+QCD
  - Extra jets make NLO predictions very challenging
  - Current state of the art:

    W(Z)+4(3)Jets calculations available
    - Phys.Rev.Lett.106:092001,2011 Phys.Rev.D82:074002,2010



- Standard strategy :
  - a) LO matrix element calculations for each jet multiplicity,
  - b) interfaced with parton shower MCs using specific matching recipes
  - Implemented in ME+PS Monte Carlo generators like ALPGEN, MadGraph, SHERPA
- Madgraph used as main reference in this analysis
- Results are presented in terms of ratios, in order to cancel systematic effects (energy scale, luminosity, selection)
- W and Z selection kept as similar as possible
- Use data-driven techniques (tag-and-probe, shapes used in fits) as much as possible
- To ease comparison with theoretical predictions, all results are quoted within acceptance

Event Selection

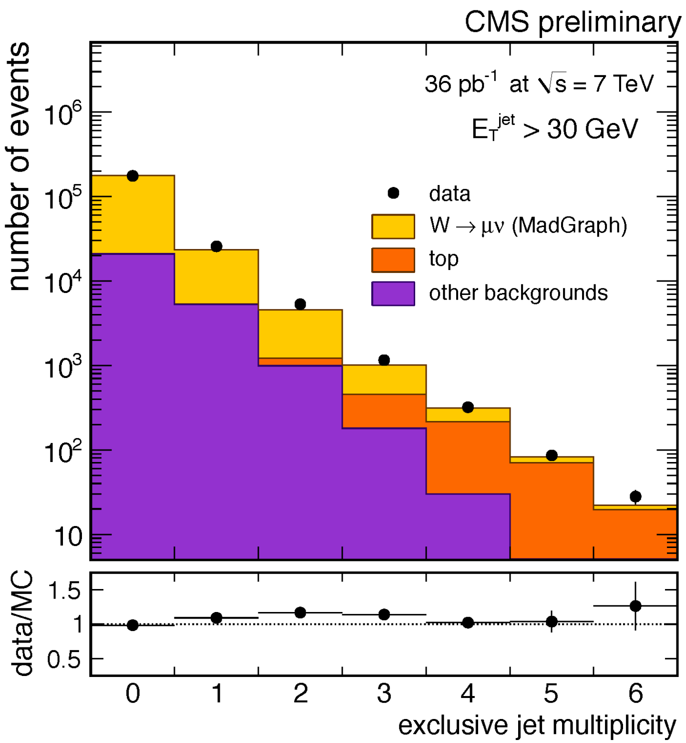
CMS-PAS-EWK-10-012

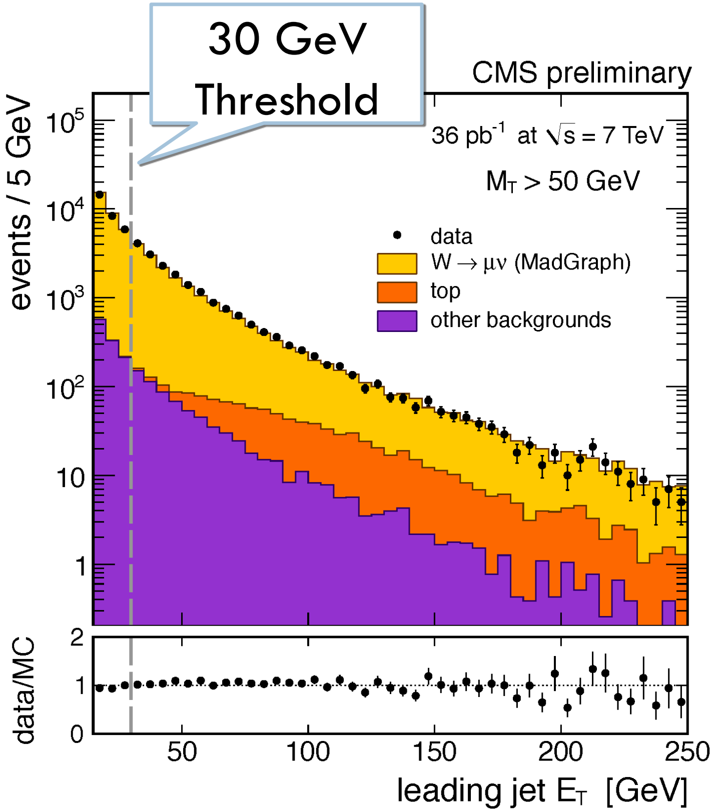
	Muons	Electrons
	Leading: $P_T > 20$ GeV; $\vert\eta\vert < 2.1$; Tight isolation, matched to triggered object; Tight muon ID	**Leading:** $P_T > 20$ GeV; $\vert\eta\vert < 2.5$; Tight isolation, matched to triggered object; $1.44 < \vert\eta\vert < 1.57$ excluded; Electron ID, conversion rejection
W	**Transverse Mass:** $M_T > 20$ GeV using Particle-flow MET **Z Veto**	**Transverse Mass:** $M_T > 20$ GeV using Particle-flow MET **Z Veto**
Z	**Second:** $P_T > 10$ GeV; $\vert\eta\vert < 2.4$; Loose muon ID, no isolation **Mass:** 60 GeV $< M_{\mu\mu} <$ 120 GeV	**Second:** $P_T > 10$ GeV; $\vert\eta\vert < 2.5$; Loose isolation **Both:** $1.44 < \vert\eta\vert < 1.57$ excluded; Electron ID, conversion rejection **Mass:** 60 GeV $< M_{ee} <$ 120 GeV

Jet Distributions: Example $W \rightarrow \mu\nu$

CMS-PAS-EWK-10-012

- Anti-K_T Particle-flow jets with cone radius 0.5
- E_T > 30 GeV; $|\eta|$ < 2.4; Pile-up subtracted (Phys.Lett.**B659**:119-126,2008)
- **Muons:** Removed before jet clustering; **Electrons:** Use ΔR veto of 0.3
- Madgraph MC scaled to NNLO X-section, others to NLO

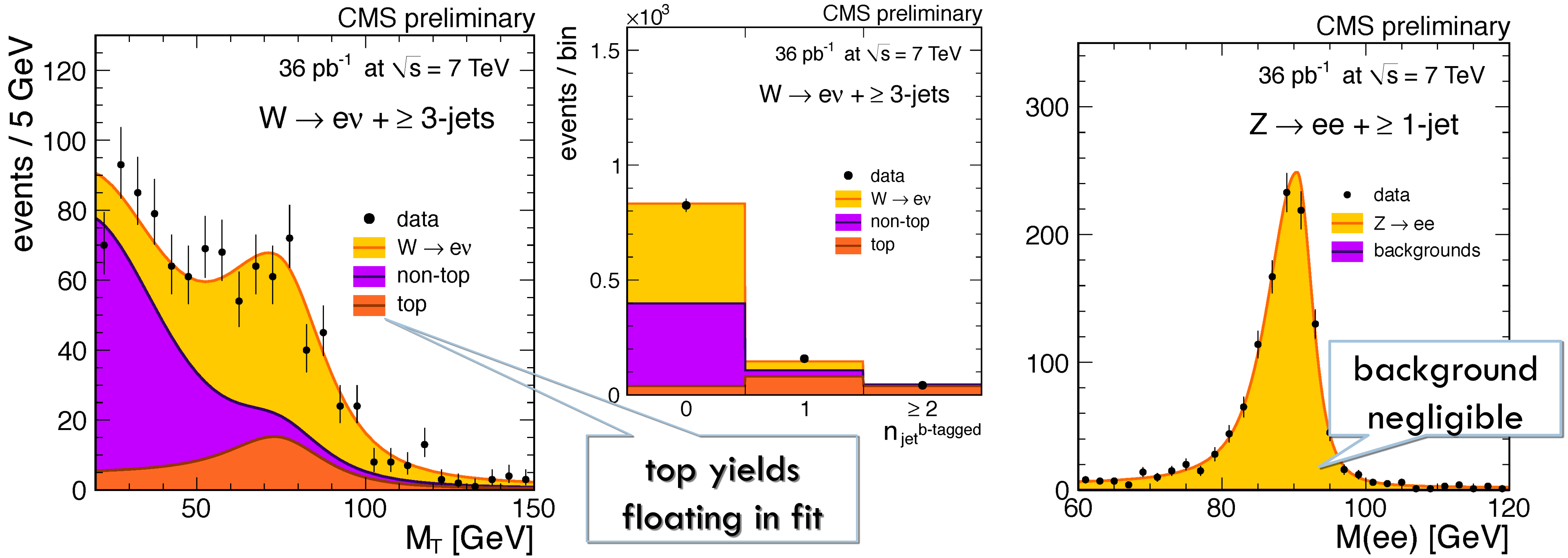




Observed, uncorrected jet distributions

Signal Extraction

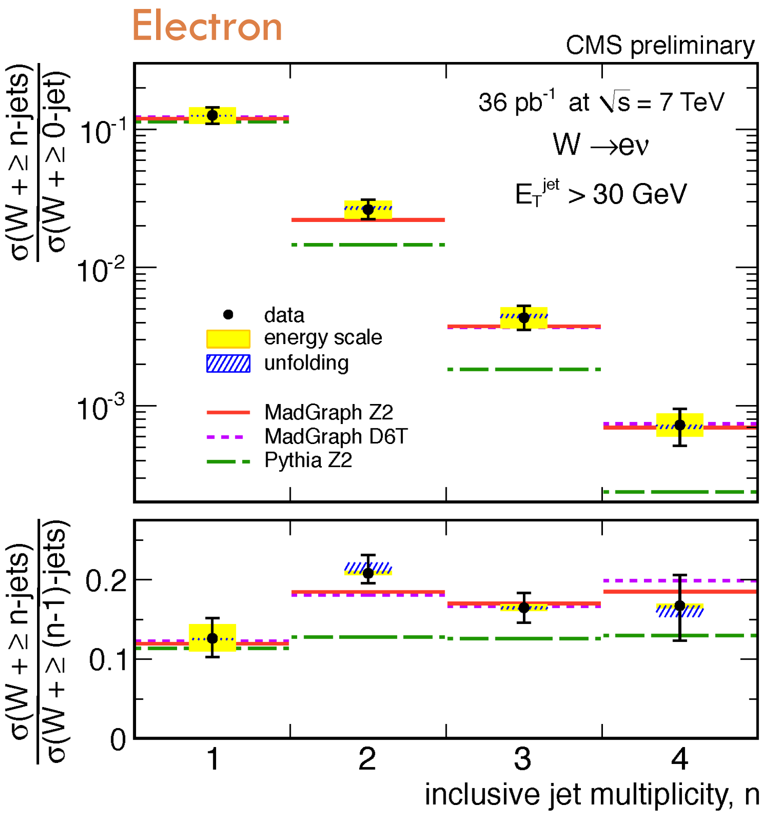
CMS-PAS-EWK-10-012

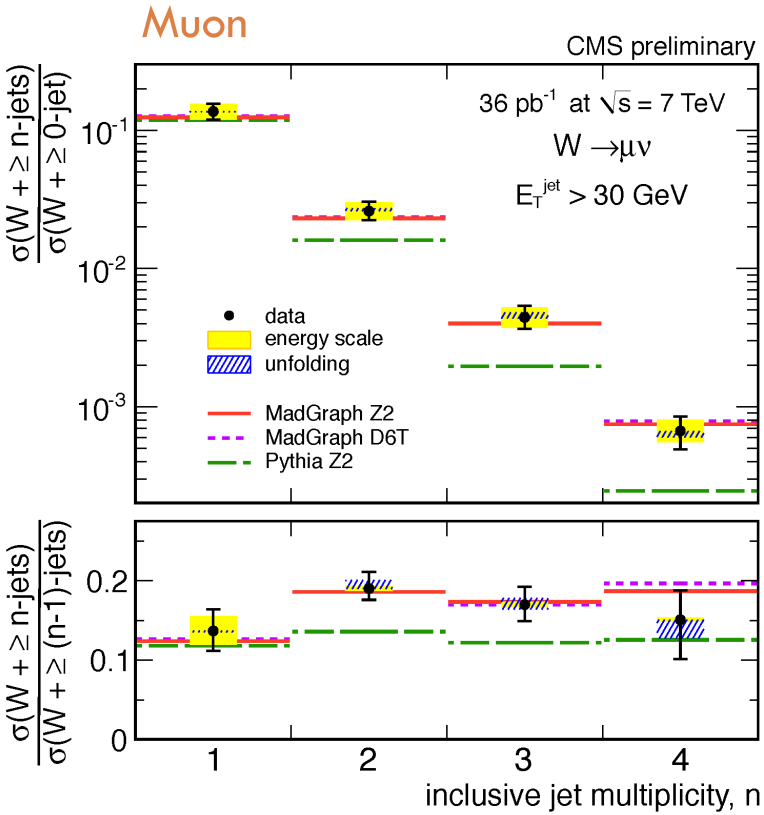


- Done for each jet multiplicity:
  - Z+jet: fit to the di-lepton invariant mass distribution
  - W+jet: fit to the MT distribution and to the number of b-tagged jets (to extract the top contribution in a data-driven way)

Results for E_T^{jet} > 30GeV: W

CMS-PAS-EWK-10-012



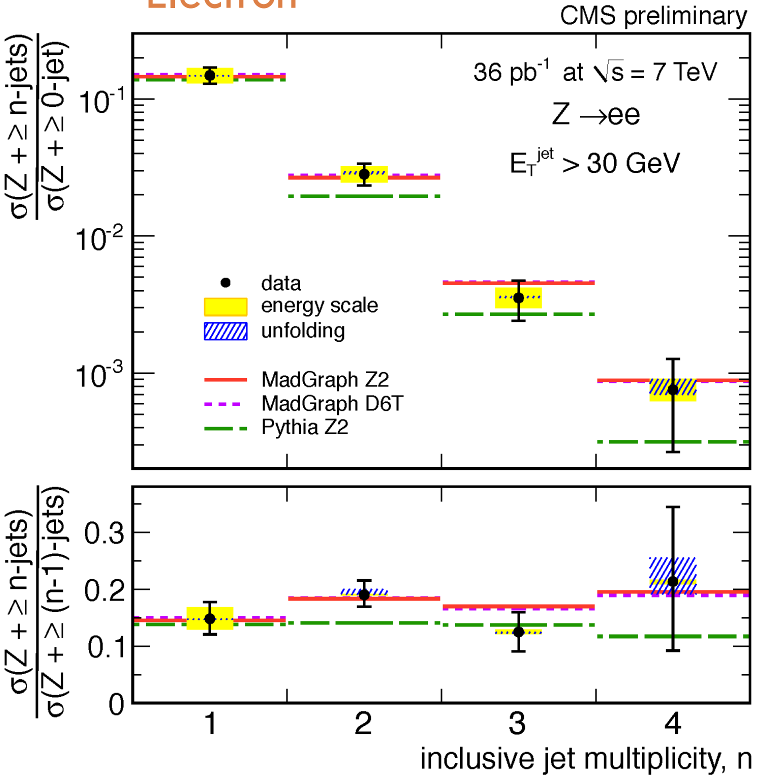


- Use single value decomposition unfolding to correct migrations due to jet resolution
- Efficiencies of trigger, reconstruction and selection determined with tag-and-probe method on Z→ ll events and corrected for
- Leading systematics: Jet energy scale uncertainty and unfolding at high multiplicities

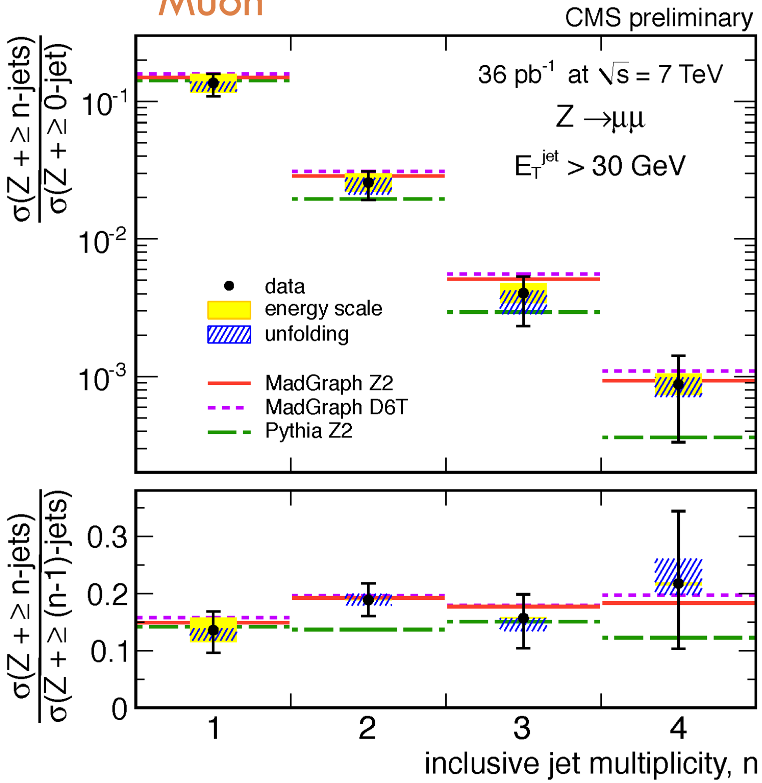
Results for $E_T^{jet} > 30$GeV: Z

CMS-PAS-EWK-10-012

Electron



Muon



For W+jets and Z+jets:

➜ Results agree well with the expectations from ME+PS MC MADGRAPH

➜ PYTHIA does not agree with the data (only expected to describe up to 1 hard jet + soft/collinear radiation (LO+ME reweighting))

Berends-Giele Scaling in V+Jets

CMS-PAS-EWK-10-012

- Test scaling behaviour:

$$C_n = \frac{\sigma(V+\text{ n jets})}{\sigma(V+(n+1)\text{jets})}$$

- Naïve LO expectation:

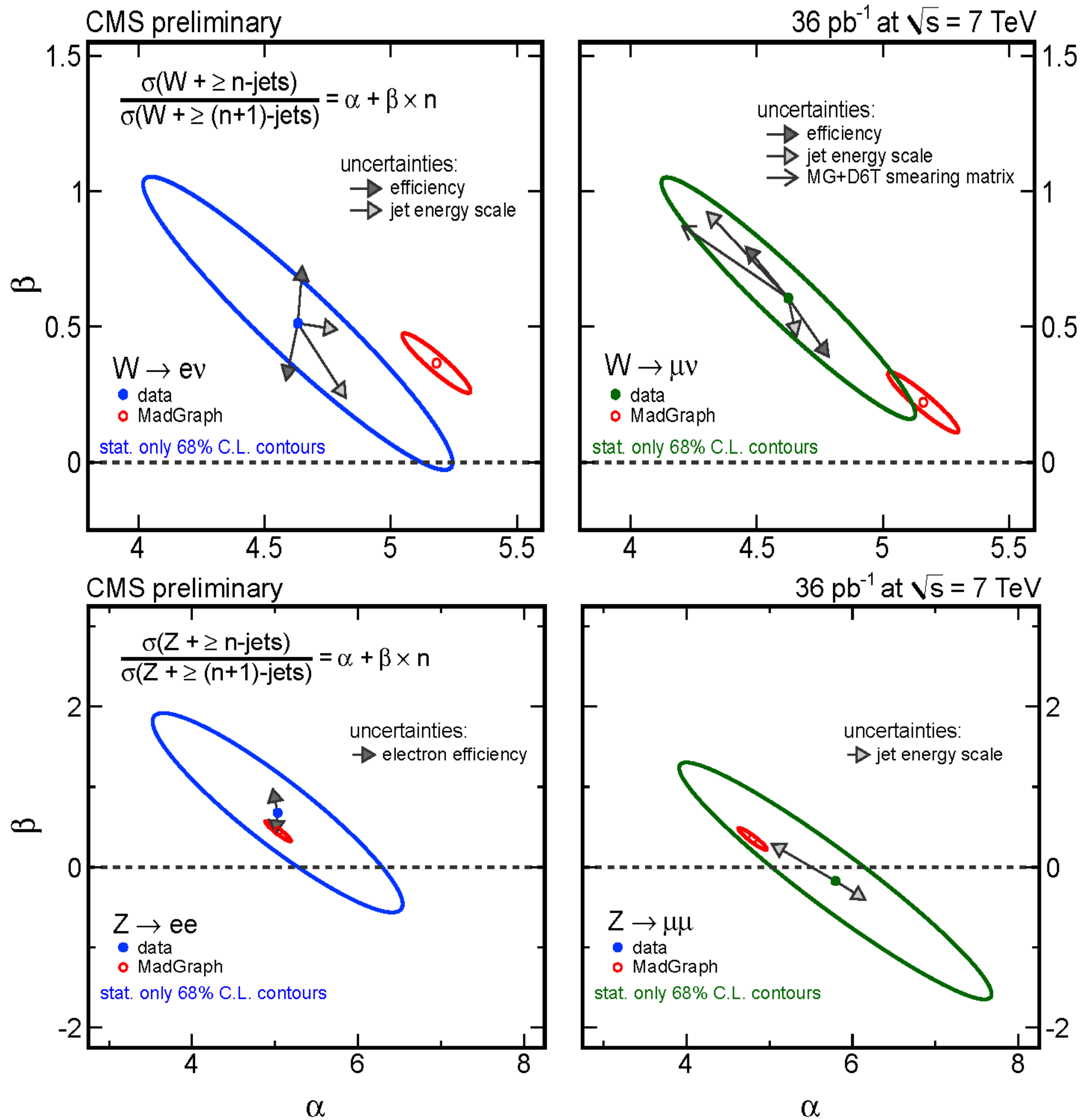
  $C_n = \text{const} = \alpha$

  Constant proportional to α_s^{-1}

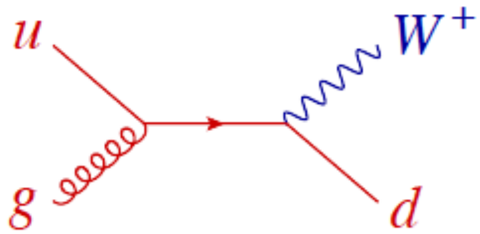
- Allow deviation from naïve scaling in fit:

$$C_n = \alpha + \beta n$$

➜ Results in reasonable agreement with MADGRAPH expectations

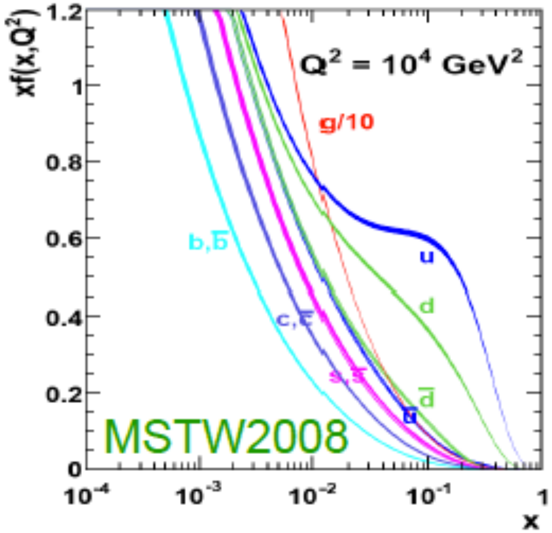


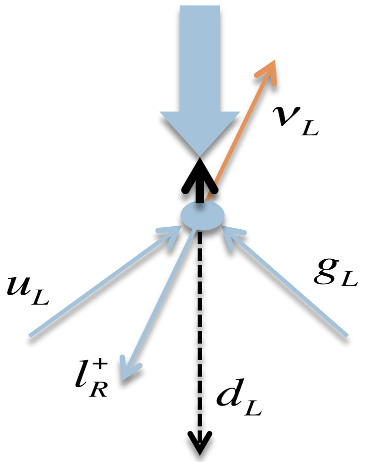
Boosted W Polarization



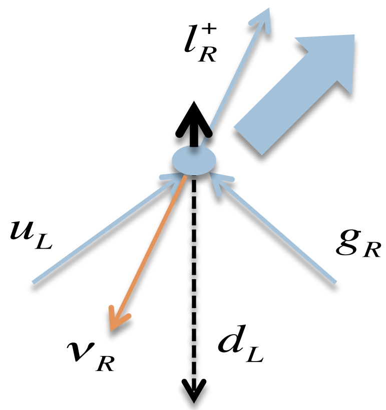
CMS-EWK-10-014

- For production of high p_T W bosons at the LHC:
  - Dominated at LO by production from valence quark and gluon because of pdfs
  - Hence SM expectation:
    - Charge: N(+)>N(-) ➔ net charge asymmetry
    - Helicity: $N(q_L)>N(q_R)$ ➔ net polarization asymmetry
    - Helicity argument same for ug and dg initial state
- In NP scenarios W polarization may differ significantly from SM prediction





a) u, gluon left-handed:
W spin in d quark direction
W_L 100%



b) u, gluon right-handed:
W spin opposite to u quark
W_R preferred: 100% at infinite $P_T(W)$

(amplitude a)^2/(amplitude b)^2 = 4/1 at infinite $P_T(W)$

Illustrations in W restframe


W Spin

➔ W flight direction

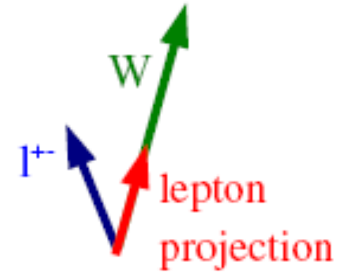
$u_L g$: incoming particles

$\upsilon_R d_L l_R^+$: outgoing particles

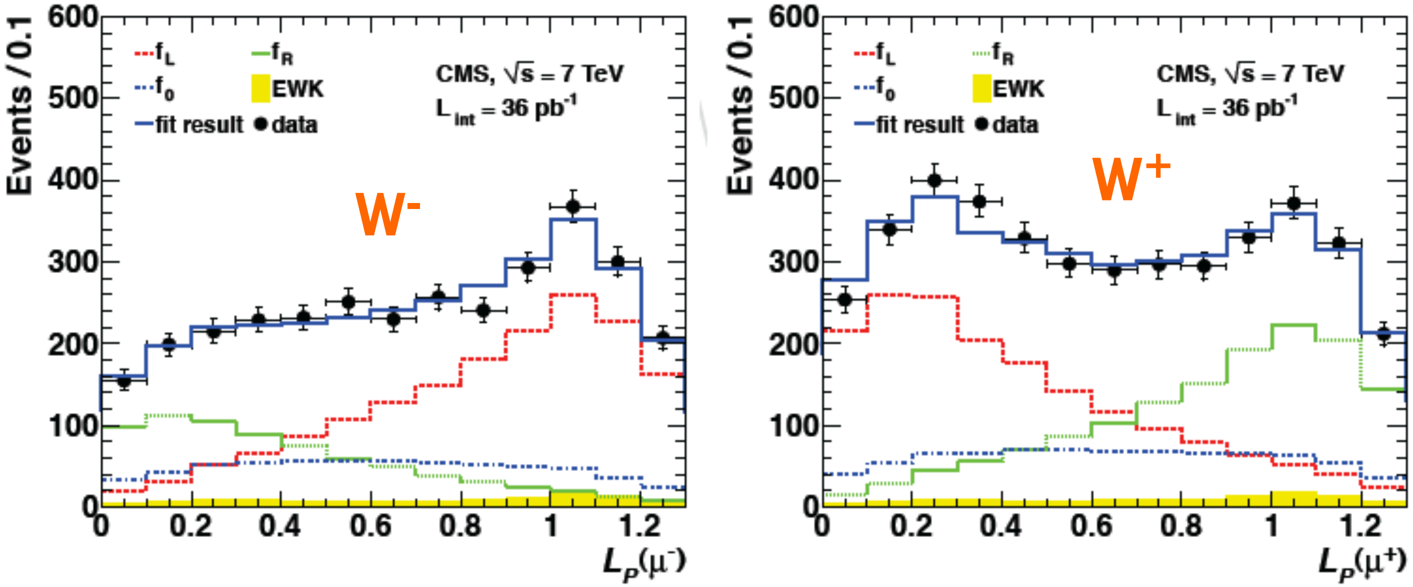
Boosted W Polarization: Exp. technique

CMS-EWK-10-014

- Selection:
  - M_T > 50 (30) GeV for electron (muon) channel to reject QCD background
  - No more than 3 jets with E_T > 30 GeV to reject top background
  - $P_T(W)$>50GeV to enhance qg component that leads to polarized Ws
- Since $P_z(W)$ undetermined, cannot fully determine the angular distribution as function of cos θ^* of the lepton in the helicity center-of-mass frame of the W
- Instead, use lepton projection in the transverse plane in the lab frame



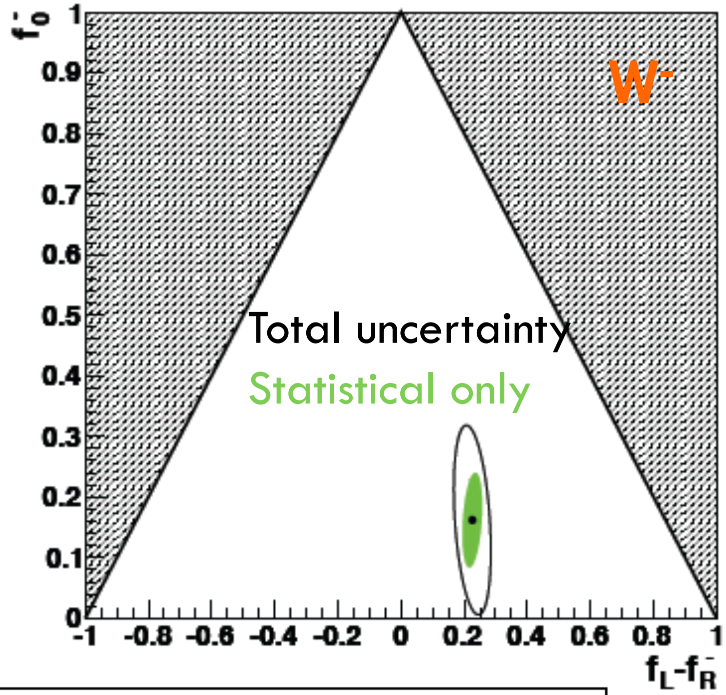
$$L_p = \frac{\vec{p}_T(l)\cdot\vec{p}_T(W)}{|\,\vec{p}_T(W)\,|^2}; \qquad \lim_{p_T(W)\gg M_W,\,p_Z(W)} 1+\frac{\cos\theta^*}{2}$$

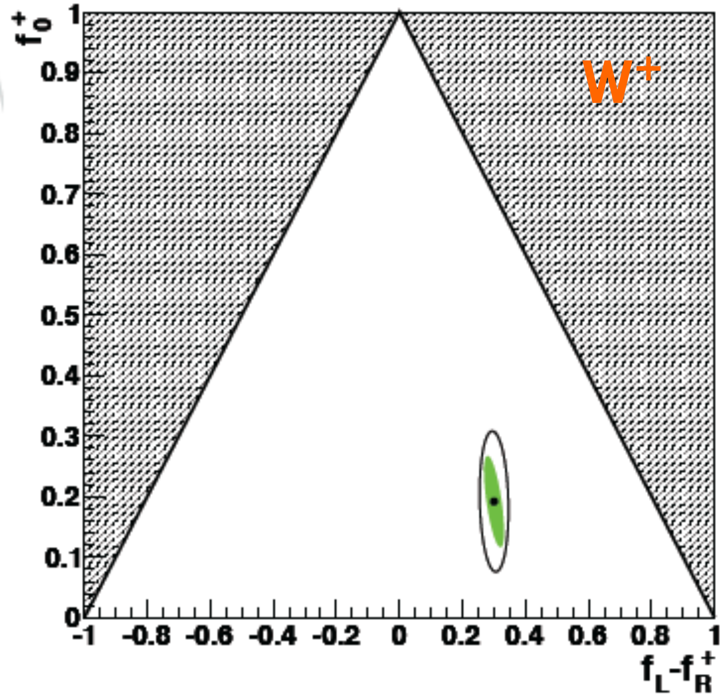


Boosted W Polarization: Results

CMS-EWK-10-014

Systematic error dominated by recoil (MET) systematics





	Combined Results
$(f_L - f_R)^-$	0.226 ± 0.031 (stat) ± 0.050 (syst)
f_0^-	0.162 ± 0.078 (stat) ± 0.136 (syst)
$(f_L - f_R)^+$	0.300 ± 0.031 (stat) ± 0.034 (syst)
f_0^+	0.192 ± 0.075 (stat) ± 0.089 (syst)

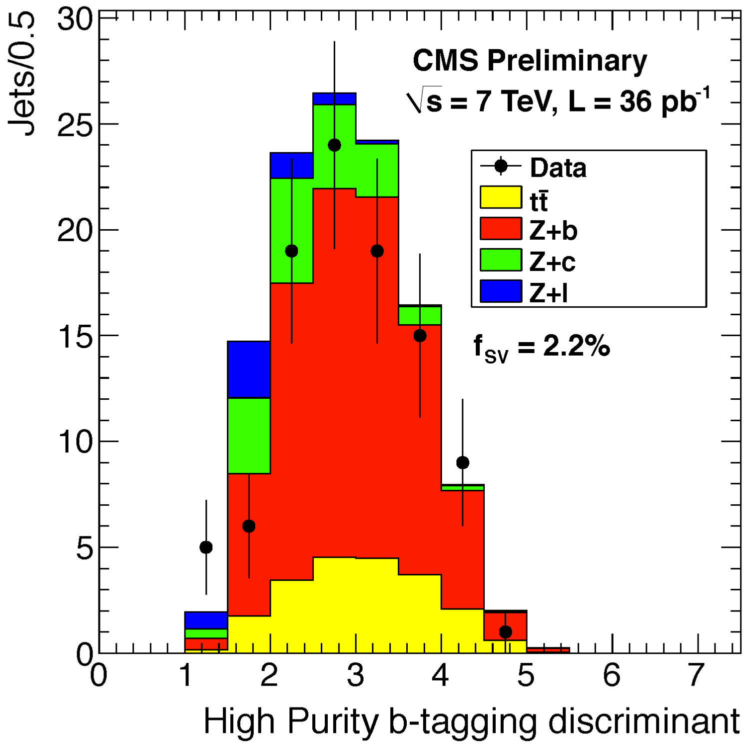
$f_L - f_R > 0$
with 6σ (W^+) and 4.5σ (W^-)

→ Clear observation of W polarization at the LHC

Observation of Z+b with Z→ll

CMS-PAS-EWK-10-015

- Z+b benchmark for high tan β MSSM Higgs searches
- H+b NLO prediction has large uncertainties
  - 30% scheme dependence (variable vs fixed flavor schemes)
  - Z+b data should help to clarify
- Select Z+≥1 jet events
  - Jet ET > 25 GeV; separated from lepton by ΔR >0.5
  - Require secondary vertex
  - M_T < 40 GeV to reject top
  - 29 dieletron and 36 dimuon events after sele
- B-tagging descriminant variable built from flight distance between PV and SV
  - SSVHE: high efficiency selection with ≥2 tracks attached to SV
  - SSVHP: high purity selection with ≥3 tracks attached to SV

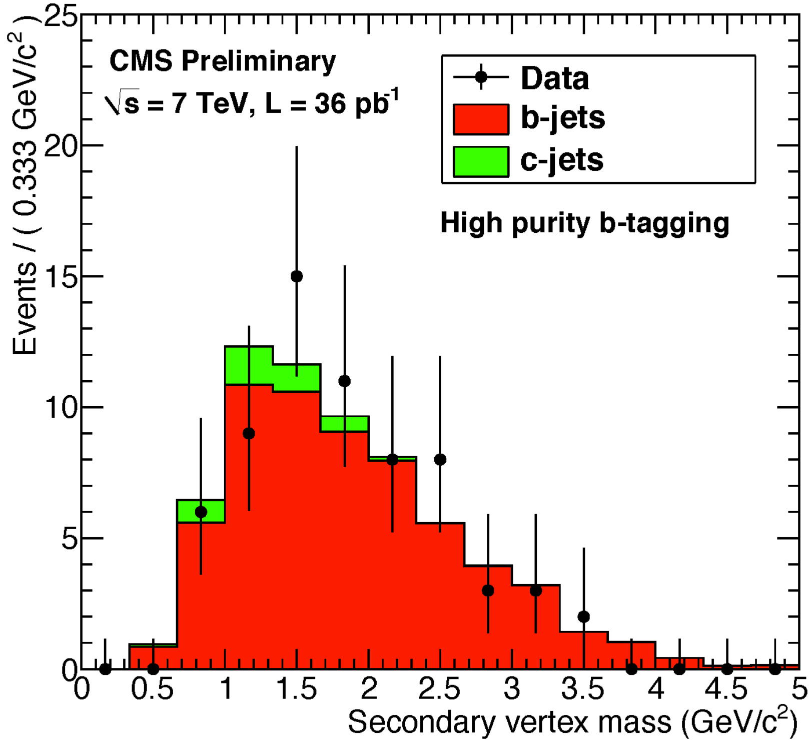


Z+b/Z+jets Ratio

CMS-PAS-EWK-10-015

- Determine Z+b purity in selected sample from binned ML fit:
  - of SV mass or B-tag discriminant shape
  - MC templates for b, c, ligh-jet components

Purity (%)	SSVHE	SSVHP
data	55±9	88±11
MC	57±3	82±4



➜ Results compatible with Madgraph (scaled to NLO) & MCFM

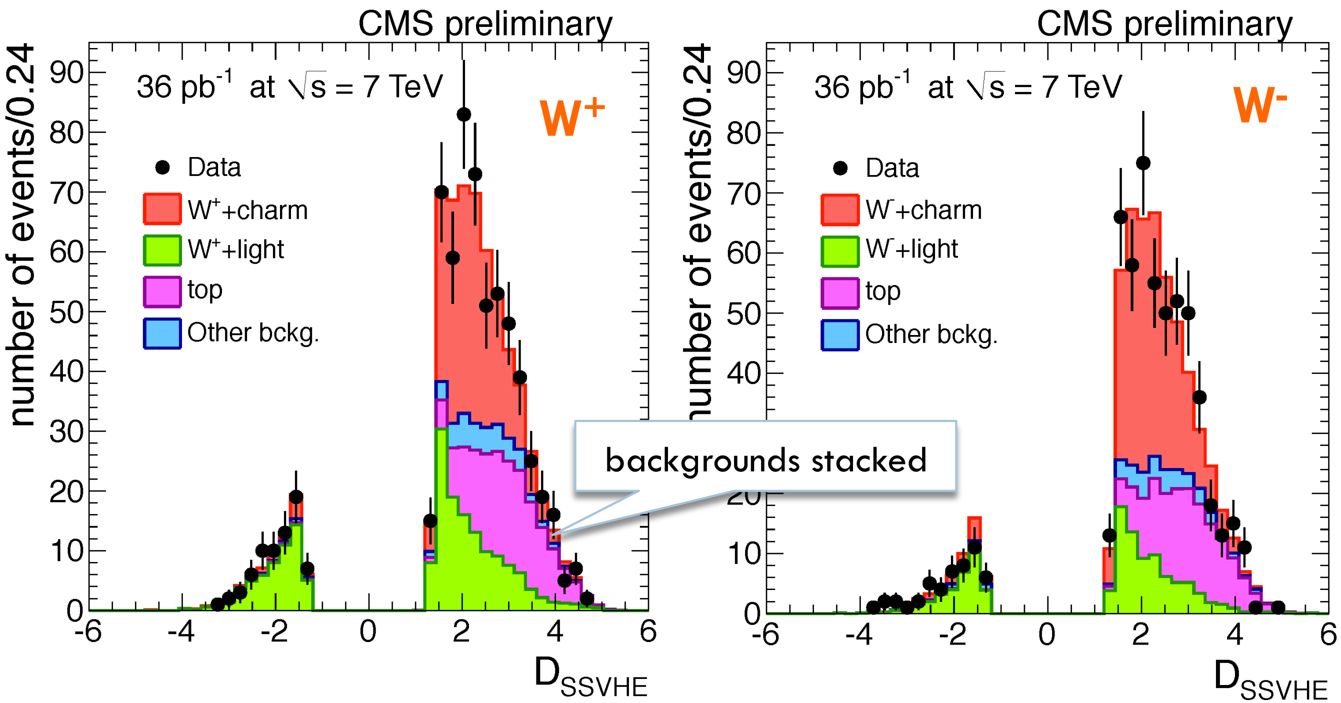
➜ Limited statistics: scheme dependence cannot be resolved yet

Sample	$\frac{pp\to ee+b+X}{pp\to ee+j+X}$ (%) $p_T^e > 25$ GeV, $\|\eta^e\| < 2.5$	$\frac{pp\to \mu\mu+b+X}{pp\to \mu\mu+j+X}$ (%) $p_T^\mu > 20$ GeV, $\|\eta^\mu\| < 2.1$
Data SSVHE	$4.3 \pm 0.6(stat) \pm 1.1(syst)$	$5.1 \pm 0.6(stat) \pm 1.3(syst)$
Data SSVHP	$5.4 \pm 1.0(stat) \pm 1.2(syst)$	$4.6 \pm 0.8(stat) \pm 1.1(syst)$
MADGRAPH	$5.1 \pm 0.2(stat) \pm 0.2(syst) \pm 0.6(theory)$	$5.3 \pm 0.1(stat) \pm 0.2(syst) \pm 0.6(theory)$
MCFM	$4.3 \pm 0.5(theory)$	$4.7 \pm 0.5(theory)$

Study of W+c with W→ μ υ

 CMS-PAS-EWK-11-013

- Process dominated by sbar g → W^+ cbar and sg→ W^- c
- Probes s and sbar content of proton
- Select W+≥1 jet events in muon channel
  - M_T > 50 GeV to reject QCD background
  - Jet E_T > 20 GeV
  - Require SV with ≥2 associated tracks and significantly displaced from PV
- B-tagging descriminant variable D_{SSVHE} built from flight distance between PV and SV



ML fit of signal, top, W+light quarks, DY components to observed D_{SSVHE}

Negative values of D_{SSVHE} due to detector resolution effects and well suited to constrain light quark component

$(W^+ + c)/(W^- + c)$ and $(W+c)/(W+jets)$ ratios

CMS-PAS-EWK-11-013

- For leading jet with $E_T > 20$GeV and $|\eta| < 2.1$:

$$R_c^{\pm} \equiv \sigma(W^+\bar{c})/\sigma(W^- c)$$

$$R_c^{\pm} = 0.92 \pm 0.19\,(stat.) \pm 0.04\,(syst.)$$

  - Leading source of sys error: PDF uncertainties, pile-up effect and background templates

$$R_c \equiv \sigma(W+c)/\sigma(W+\ jets)$$

$$R_c = 0.143 \pm 0.015\,(stat.) \pm 0.024\,(syst.)$$

  - Leading source of sys error: Tracking resolution

→ Results in agreement with NLO predictions

Summary and Outlook

- Presented 4 CMS analysis with 2010 data set; 36pb^{-1} integrated luminosity
- Presented V+Jets results from CMS
  - Jet p_T distributions and rates in good agreement with ME+PS MC simulation
  - First direct measurement of Berends-Giele scaling
  - Under preparation: Ratio of cross sections separately for W^+ , W^-
- Clear observation of boosted W polarization
- Observation of Z+b and W+c events
- All results so far show good agreement with MC+PS Monte Carlo generators and NLO calculations
- Outlook for results from 2011 data:
  - So far in 2011 CMS recorded 1.25 fb^{-1} 2011
  - Characterize V+jets in more detail with differential distributions: $d\sigma/dET$ for each jet, $d\sigma/dRjj$, $d\sigma/dMjj$, $d\sigma/d\Delta yjj$ etc
  - Use V+jets to constrain PDFs at the LHC

Backup Slides

V+Jets at the LHC

CMS-PAS-EWK-10-012

Table 3: Relative systematic and statistical uncertainties on the measured jet multiplicity in W events.

Uncertainties on jet rate in $W \to e\nu$ events [%]					
Jet multiplicity	0	1	2	3	≥ 4
Jet counting	∓ 5	± 8	$^{+11}_{-10}$	$^{+14}_{-12}$	$^{+16}_{-15}$
Lepton efficiency	± 3	$^{+6}_{-5}$	$^{+7}_{-6}$	± 10	$^{+24}_{-12}$
Signal extraction		± 0.1	± 0.4	± 2.9	± 8.5
Total systematics	± 6	± 10	$^{+13}_{-12}$	$^{+18}_{-16}$	$^{+30}_{-21}$
Statistical uncertainty	± 0.3	± 1.0	± 2.4	± 7.5	± 22
Uncertainties on jet rate in $W \to \mu\nu$ events [%]					
Jet multiplicity	0	1	2	3	≥ 4
Jet counting	∓ 5	± 8	$^{+11}_{-10}$	$^{+14}_{-12}$	$^{+16}_{-15}$
Lepton efficiency	± 3	± 6	± 4	± 10	± 17
Signal extraction		± 0.1	± 0.4	± 2.9	± 8.5
Total systematics	± 6	± 10	$^{+13}_{-12}$	$^{+19}_{-17}$	± 26
Statistical uncertainty	± 0.2	± 0.8	± 2.3	± 6.5	± 27

V+Jets at the LHC

CMS-PAS-EWK-10-012

Table 4: Relative systematic and statistical uncertainties on the measured jet multiplicity in Z events.

Uncertainties on jet rate in $Z \rightarrow e^+e^-$ events [%]					
Jet multiplicity	0	1	2	3	≥ 4
Jet counting	∓ 5	± 8	$^{+11}_{-10}$	$^{+14}_{-12}$	$^{+16}_{-15}$
Efficiency	± 3	$^{+6}_{-5}$	$^{+7}_{-6}$	± 10	$^{+24}_{-12}$
Total systematics	± 6	± 10	$^{+13}_{-12}$	$^{+18}_{-16}$	$^{+30}_{-21}$
Statistical uncertainty	± 1.0	± 3.0	± 8.0	± 20	± 47
Uncertainties on jet rate in $Z \rightarrow \mu^+\mu^-$ events [%]					
Jet multiplicity	0	1	2	3	≥ 4
Jet counting	∓ 5	± 8	$^{+11}_{-10}$	$^{+14}_{-12}$	$^{+16}_{-15}$
Efficiency	± 3	$^{+6}_{-5}$	$^{+7}_{-6}$	± 10	$^{+24}_{-12}$
Total systematics	± 6	± 10	$^{+13}_{-12}$	$^{+18}_{-16}$	$^{+30}_{-21}$
Statistical uncertainty	± 1.1	± 2.7	± 5.2	± 18	± 35

V+Jets at the LHC

CMS-PAS-EWK-10-012

Table 5: $\sigma(W+\geq n \text{ jets})/\sigma(W)$, the jet multiplicities normalized to the inclusive cross section.

num jets	σ ratio	stat	stat + fit and efficiency	JES	unfolding
electron channel					
$\geq 1 / \geq 0$ jets	0.126	0.001	0.004	$^{+0.018}_{-0.016}$	$^{+0.000}_{-0.002}$
$\geq 2 / \geq 0$ jets	0.026	0.000	0.002	$^{+0.004}_{-0.004}$	$^{+0.001}_{-0.000}$
$\geq 3 / \geq 0$ jets	0.0043	0.0002	0.0005	$^{+0.0008}_{-0.0007}$	$^{+0.0003}_{-0.0000}$
$\geq 4 / \geq 0$ jets	0.0007	0.0000	0.0002	$^{+0.0002}_{-0.0001}$	$^{+0.0000}_{-0.0000}$
muon channel					
$\geq 1 / \geq 0$ jets	0.137	0.001	0.007	$^{+0.019}_{-0.017}$	$^{+0.000}_{-0.002}$
$\geq 2 / \geq 0$ jets	0.026	0.000	0.001	$^{+0.004}_{-0.004}$	$^{+0.001}_{-0.000}$
$\geq 3 / \geq 0$ jets	0.0044	0.0001	0.0005	$^{+0.0008}_{-0.0007}$	$^{+0.0004}_{-0.0001}$
$\geq 4 / \geq 0$ jets	0.0007	0.0000	0.0002	$^{+0.0001}_{-0.0001}$	$^{+0.0000}_{-0.0001}$

Table 6: $\sigma(Z+\geq n \text{ jets})/\sigma(Z)$, the jet multiplicities normalized to the inclusive cross section.

num jets	σ ratio	stat	stat + fit and efficiency	JES	unfolding
electron channel					
$\geq 1 / \geq 0$ jets	0.148	0.003	0.007	$^{+0.020}_{-0.019}$	$^{+0.000}_{-0.002}$
$\geq 2 / \geq 0$ jets	0.028	0.001	0.003	$^{+0.004}_{-0.004}$	$^{+0.001}_{-0.000}$
$\geq 3 / \geq 0$ jets	0.0035	0.0005	0.0010	$^{+0.0007}_{-0.0005}$	$^{+0.0001}_{-0.0000}$
$\geq 4 / \geq 0$ jets	0.0008	0.0000	0.0005	$^{+0.0002}_{-0.0001}$	$^{+0.0002}_{-0.0001}$
muon channel					
$\geq 1 / \geq 0$ jets	0.136	0.003	0.009	$^{+0.022}_{-0.020}$	$^{+0.003}_{-0.018}$
$\geq 2 / \geq 0$ jets	0.026	0.001	0.003	$^{+0.004}_{-0.004}$	$^{+0.002}_{-0.005}$
$\geq 3 / \geq 0$ jets	0.0040	0.0005	0.0011	$^{+0.0007}_{-0.0006}$	$^{+0.0002}_{-0.0012}$
$\geq 4 / \geq 0$ jets	0.0009	0.0000	0.0005	$^{+0.0002}_{-0.0001}$	$^{+0.0001}_{-0.0002}$

V+Jets at the LHC

CMS-PAS-EWK-10-012

Table 7: $\sigma(W+\geq n\text{ jets})/\sigma(W+\geq(n-1)\text{ jets})$, the ratio of jet multiplicities.

num jets	σ ratio	stat	stat + fit and efficiency	JES	unfolding
electron channel					
$\geq 1 / \geq 0$ jets	0.126	0.002	0.004	$^{+0.018}_{-0.016}$	$^{+0.002}_{-0.000}$
$\geq 2 / \geq 1$ jets	0.208	0.009	0.012	$^{+0.003}_{-0.002}$	$^{+0.000}_{-0.013}$
$\geq 3 / \geq 2$ jets	0.165	0.015	0.018	$^{+0.004}_{-0.004}$	$^{+0.002}_{-0.002}$
$\geq 4 / \geq 3$ jets	0.167	0.035	0.039	$^{+0.002}_{-0.003}$	$^{+0.014}_{-0.000}$
muon channel					
$\geq 1 / \geq 0$ jets	0.137	0.001	0.007	$^{+0.019}_{-0.017}$	$^{+0.002}_{-0.000}$
$\geq 2 / \geq 1$ jets	0.190	0.005	0.013	$^{+0.004}_{-0.003}$	$^{+0.000}_{-0.011}$
$\geq 3 / \geq 2$ jets	0.170	0.011	0.018	$^{+0.004}_{-0.003}$	$^{+0.006}_{-0.008}$
$\geq 4 / \geq 3$ jets	0.151	0.025	0.037	$^{+0.003}_{-0.002}$	$^{+0.023}_{-0.000}$

Table 8: $\sigma(Z+\geq n\text{ jets})/\sigma(Z+\geq(n-1)\text{ jets})$, the ratio of jet multiplicities.

num jets	σ ratio	stat	stat + fit and efficiency	JES	unfolding
electron channel					
$\geq 1 / \geq 0$ jets	0.148	0.006	0.007	$^{+0.020}_{-0.019}$	$^{+0.002}_{-0.000}$
$\geq 2 / \geq 1$ jets	0.190	0.020	0.020	$^{+0.002}_{-0.001}$	$^{+0.000}_{-0.010}$
$\geq 3 / \geq 2$ jets	0.125	0.034	0.034	$^{+0.004}_{-0.004}$	$^{+0.003}_{-0.000}$
$\geq 4 / \geq 3$ jets	0.214	0.117	0.117	$^{+0.003}_{-0.004}$	$^{+0.022}_{-0.042}$
muon channel					
$\geq 1 / \geq 0$ jets	0.136	0.005	0.009	$^{+0.022}_{-0.020}$	$^{+0.018}_{-0.003}$
$\geq 2 / \geq 1$ jets	0.189	0.017	0.025	$^{+0.001}_{--0.001}$	$^{+0.009}_{-0.011}$
$\geq 3 / \geq 2$ jets	0.157	0.038	0.041	$^{+0.002}_{-0.001}$	$^{+0.023}_{-0.000}$
$\geq 4 / \geq 3$ jets	0.218	0.109	0.110	$^{+0.002}_{-0.004}$	$^{+0.020}_{-0.043}$

V+Jets at the LHC

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Table 9: Results for the Berends-Giele parameters in the electron channel compared with expectations from MadGraph Z2 at particle level.

		data	stat	JES	$\epsilon(\ell)$	Theory
Z	α	5.0	±1.0	$^{+0.1}_{-0.0}$	$^{+0.00}_{-0.06}$	5.04 ± 0.10
	β	0.7	±0.8	$^{+0.08}_{-0.04}$	$^{+0.3}_{-0.6}$	0.45 ± 0.08
W	α	4.6	±0.4	$^{+0.2}_{-0.0}$	$^{-0.05}_{+0.02}$	5.18 ± 0.09
	β	0.5	±0.4	$^{+0.0}_{-0.3}$	±0.2	0.36 ± 0.07

Table 10: Results for the Berends-Giele parameters in the muon channel compared with expectations from MadGraph Z2 at particle level.

		data	stat	JES MC	$\epsilon(\ell)$	D6T tune	Theory
Z	α	5.8	$\pm$ 1.2	±0.6	±0.1	+0.3	4.8 ± 0.1
	β	-0.2	$\pm$ 1.0	±0.3	±0.1	-0.0	0.35 ± 0.09
W	α	4.3	±0.3	±0.2	±0.2	-0.4	5.16 ± 0.09
	β	0.7	±0.3	±0.2	±0.3	+0.3	0.22 ± 0.06