Electroweak production of Z bosons with forward-backward jets

arXiv:1305.7389, *sub. to JHEP*

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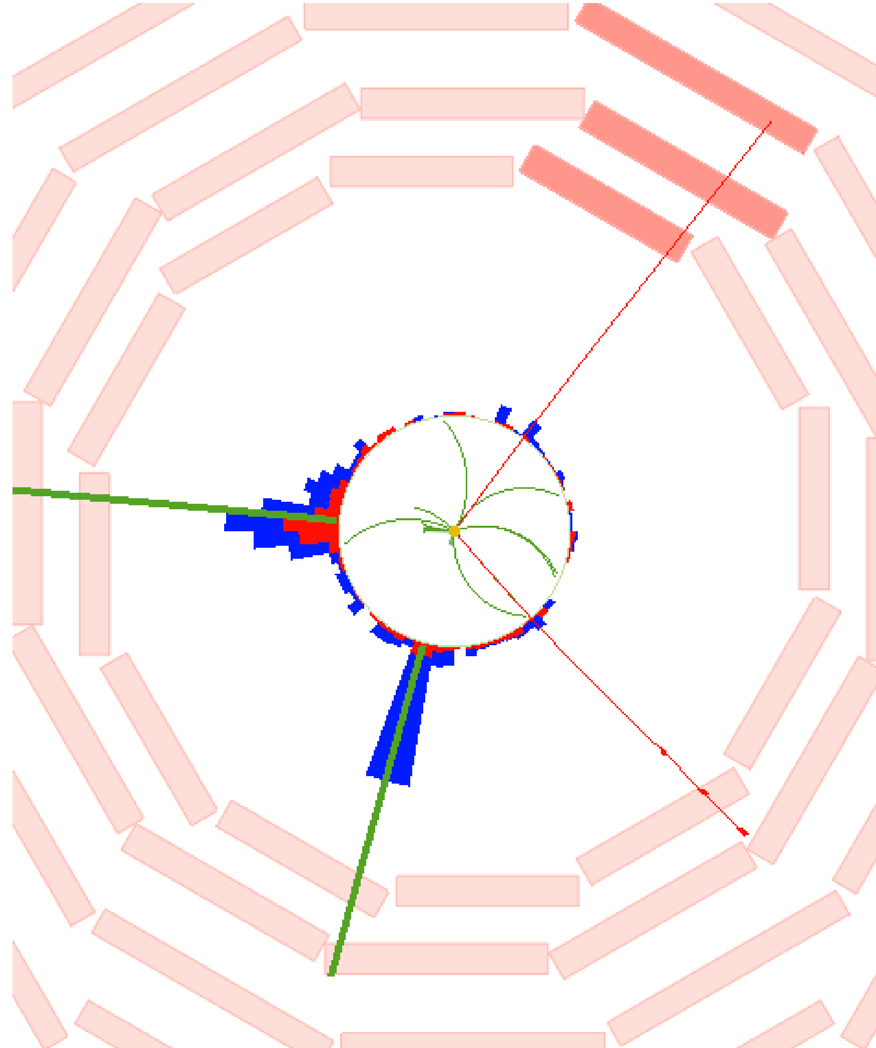
on behalf of the CMS collaboration



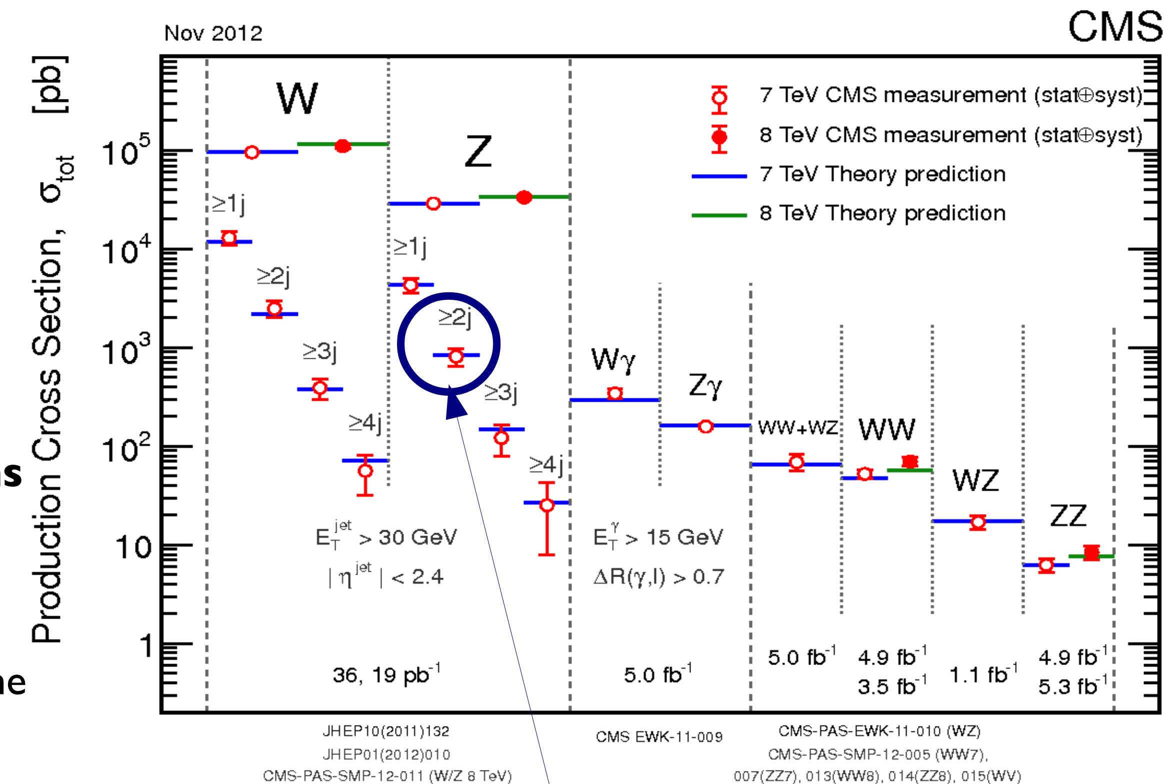
HEP 2013
Stockholm
18-24 July 2013

Studying W/Z+jets production

W/Z production in association with jets at the LHC

- Crucial for:
  - testing **pQCD**
  - tuning **MC generators**
  - probing the content of the proton (strangeness, heavy flavours)
  - constraining **parton density functions**
  - **probing triple/quartic EWK gauge-couplings**
  - establishing accurately the properties of the **backgrounds for new physics** searches

see talk by S. Lee



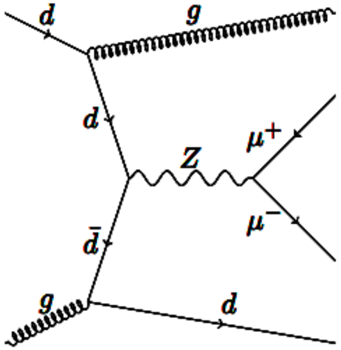
Will focus on this phase space region

Studying EWK V+2 jets production

W/Z production in association with two jets at O(α^4_{EW}) at the LHC

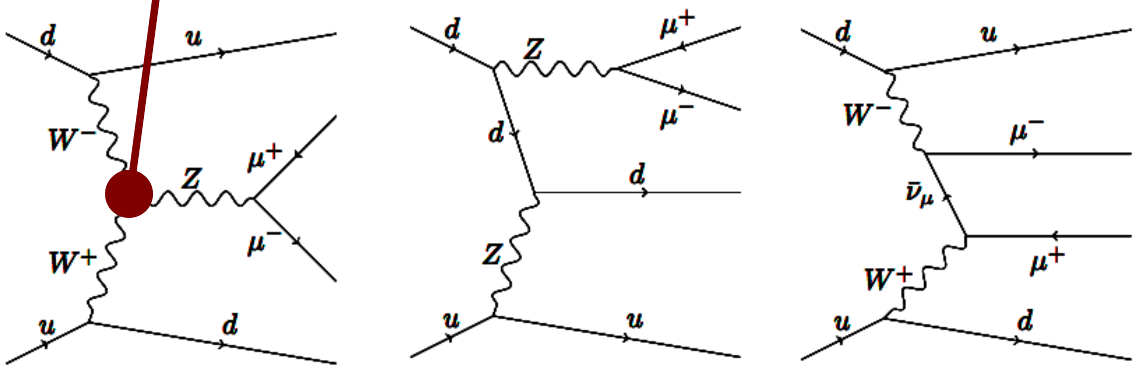
- **Jets have distinct properties (wrt to the main background) ▼**
  - two extra jets are produced color singlet exchanges
  - W, Z or γ exchange via t-channel

    $$Q^2 = E_q^2 \cdot (1-x) \cdot \theta \sim M_W^2 \rightarrow \theta \sim 0$$
  - Production of additional minijets is suppressed



- Production includes **triple gauge coupling vertex** amongst the diagrams ▼
  - Negative interference terms suppress σ(VBF Z) by a factor of ≈2.5
  - σ(EWK Z_{ll}+2j)/σ(VBF H126)=0.14

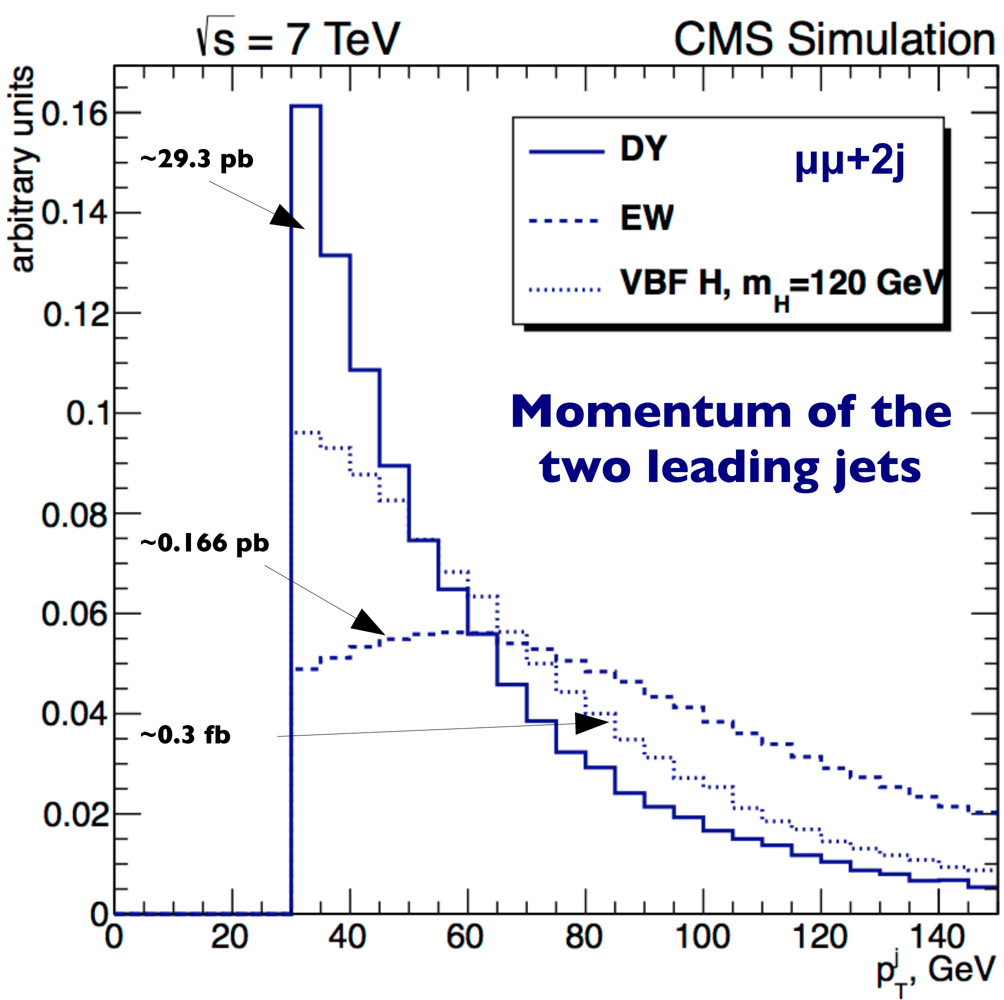
a high statistics sample to probe the properties of color singlet exchange at the LHC

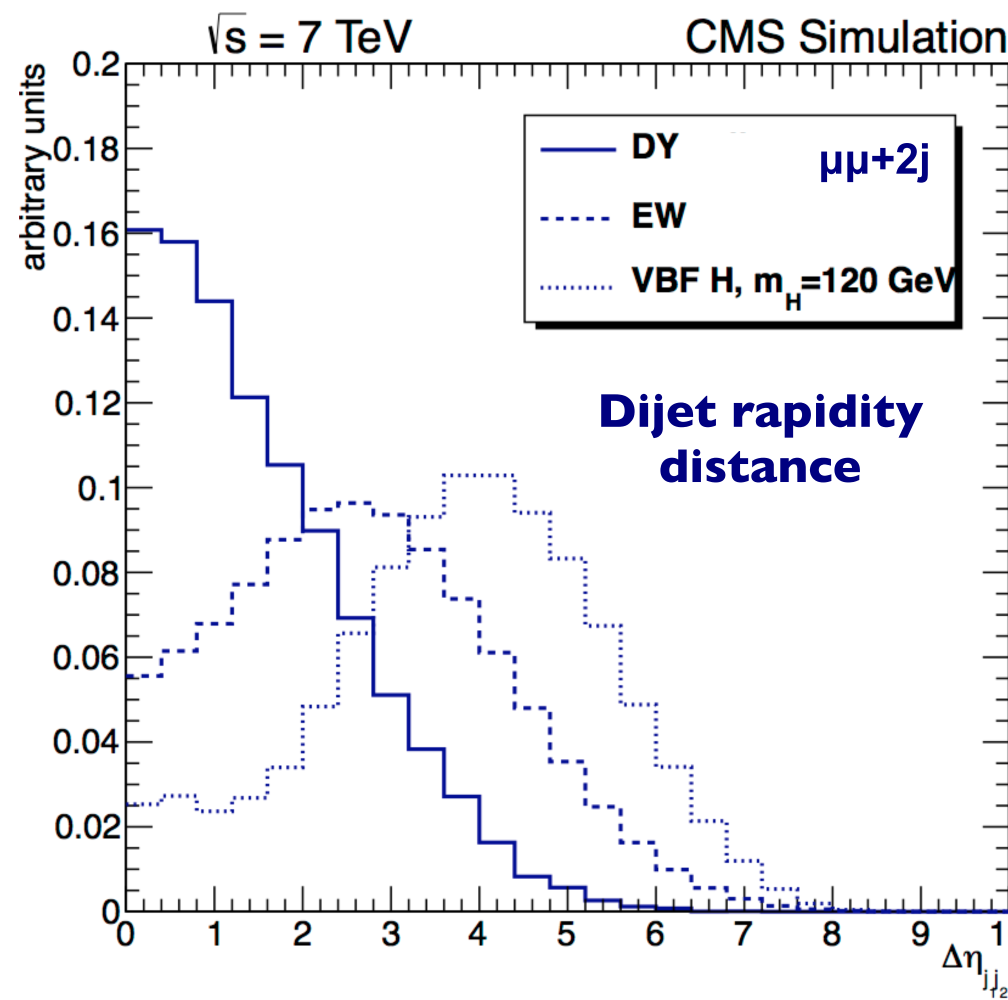


e.g. PRD54 (1996) 6680-6689, EPJC26 (2003) 429-440, PRD69 (2004) 093004

Z+2 jets and vector boson fusion

- **High p_T** jets (harder than VBF H) and **large rapidity distance** dijet system (smaller than VBF H)
  - bremmstrahlung and multiperipheral diagrams + interference → different kinematics
  - EWK Z+2 jets (VBF H) involves tranverse (longitudinal) W polarizations
  - **σ(EWK lljj)=166 fb** for M_{jj}>120 GeV, M_{ll}>50 GeV, p_T^j>25 GeV, $|\eta^j|$<4, CT10 PDF $\mu_R=\mu_F$=90 GeV

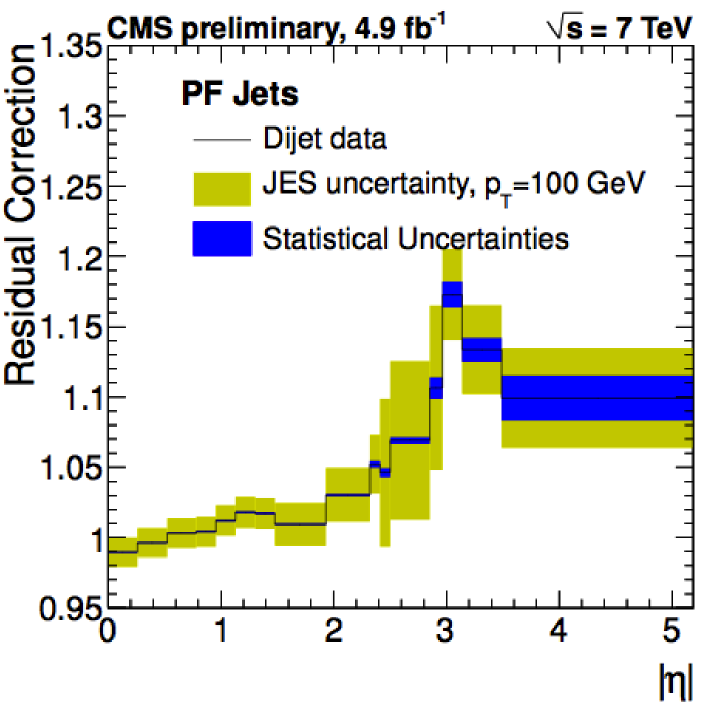


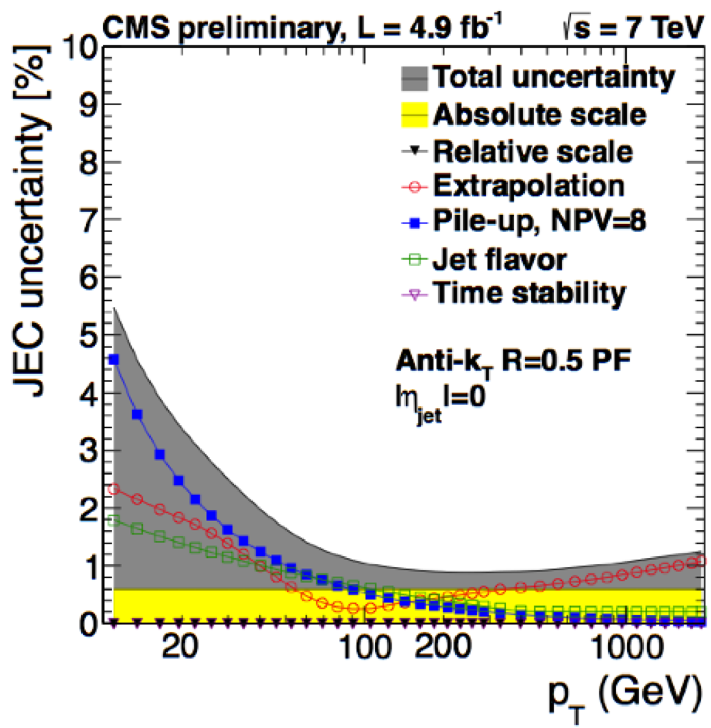


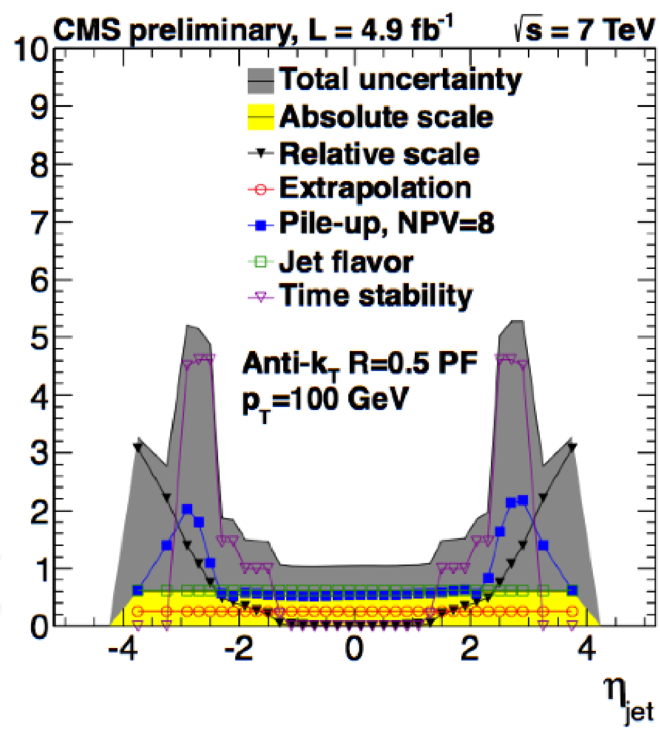
Main experimental challenges - I

CMS DP-2012/006, 2011 JINST 6 P11002

- **AK5 jet energy scale**
  - Two approaches: particle flow (tracker driven) versus jet-plus-tracks (calo-driven with tracker corrections)
  - Pileup mitigated by jet-by-jet subtraction of FastJet computed median energy density and in-time-pileup tracks
  - Final residual correction is p_T independent and has significant importance in forward region
  - time stability, pileup, relative scale unc. are relevant in regions with coarser granularity + no tracker acceptance



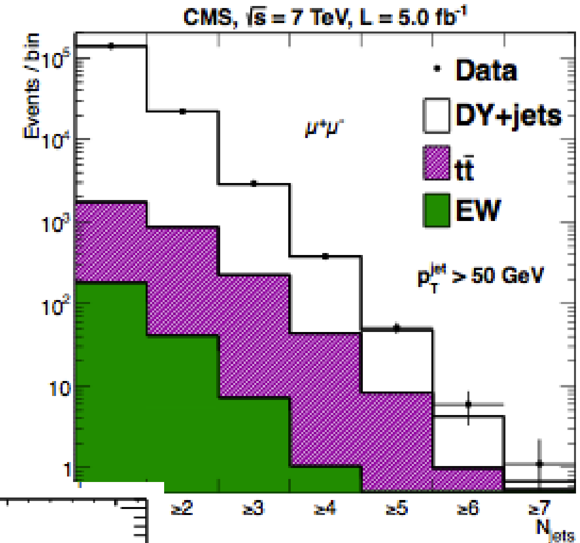


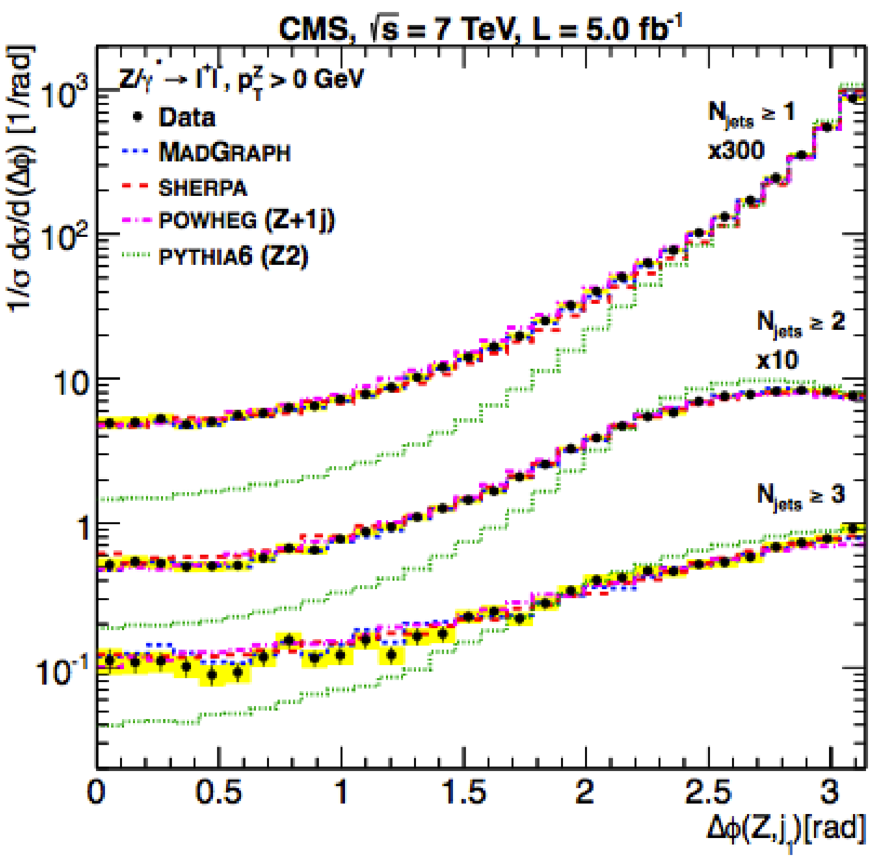


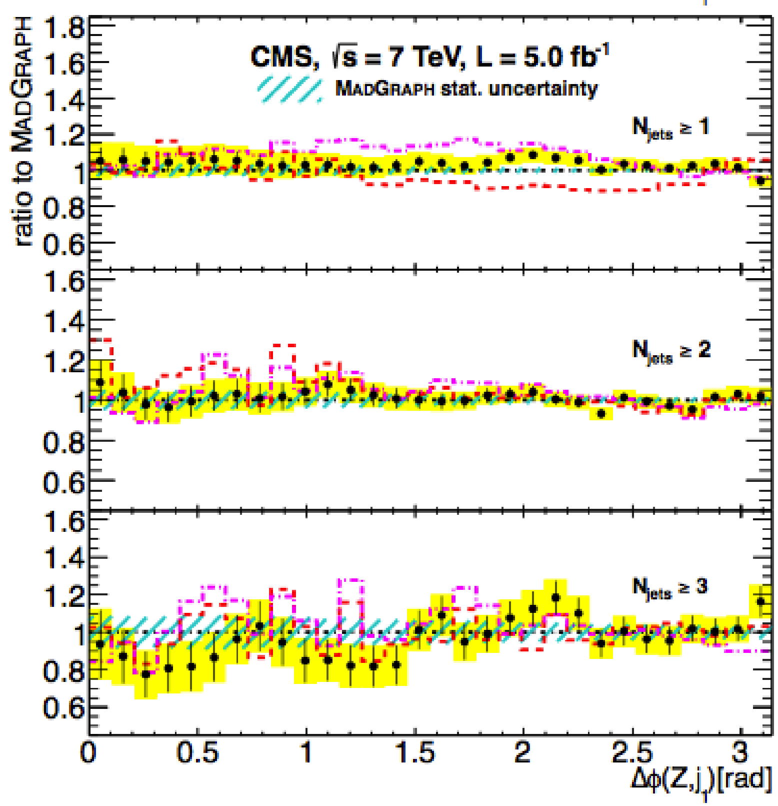
see talks by H. Kirschenmann, I. Fernandez

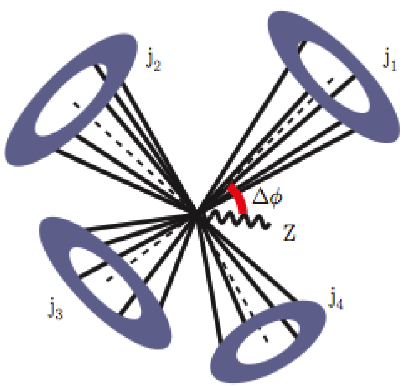
- **Controlling QCD Z+2 jets production**
  - Simple Z selection: 2 charged leptons p_T>20 GeV, |η|<2.4 and $|M-M_Z|$<20 GeV
  - Counting jets with p_T>50 GeV and |η|<2.5
  - Comparison after unfolding to generator level jets

  Madgraph in fair agreement with data (Powheg/Sherpa ~10% off for 1st bin)







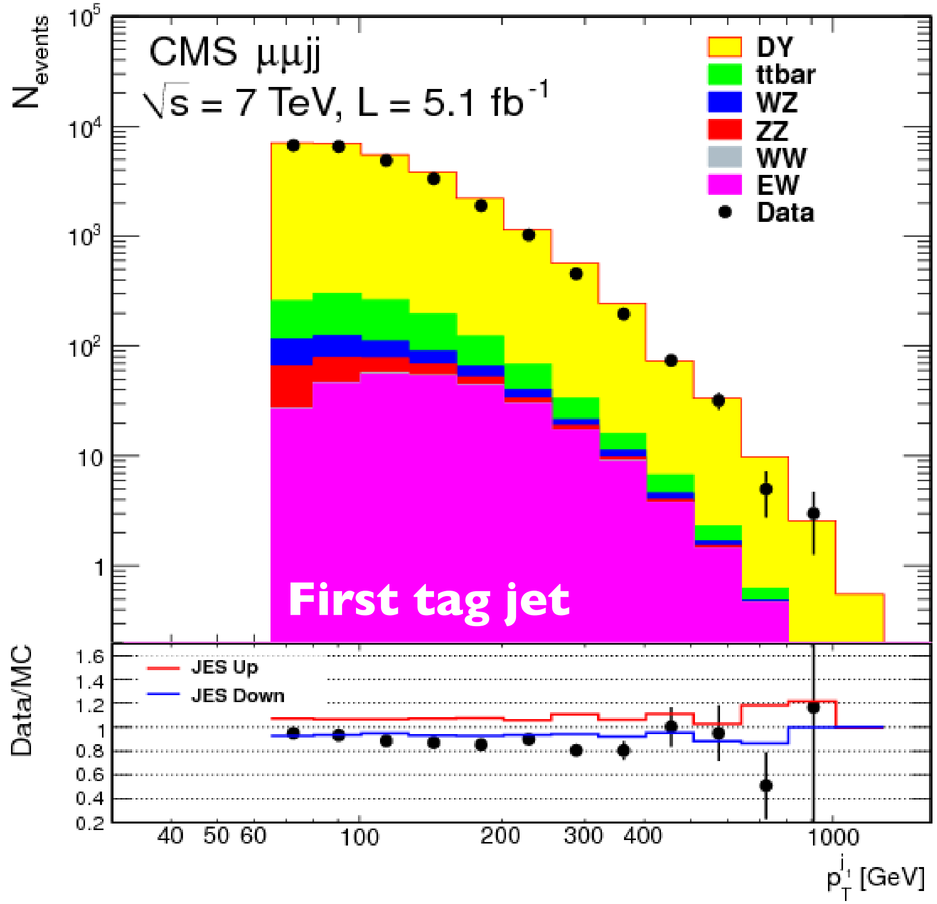


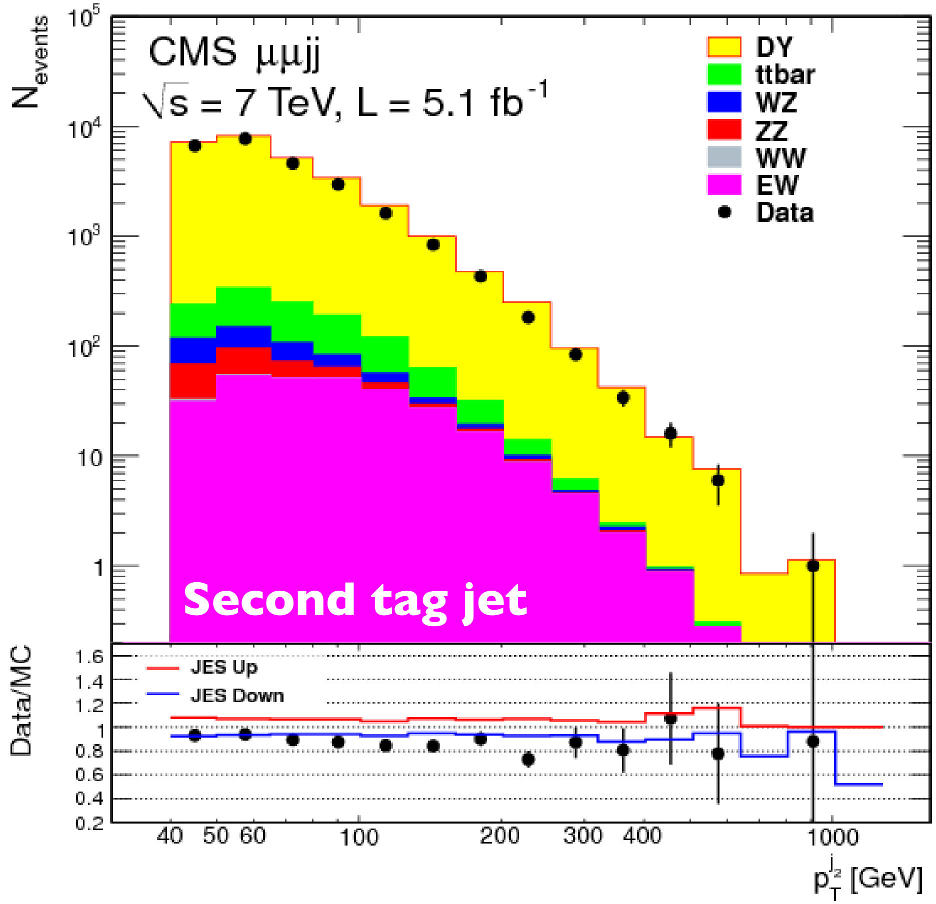
see talk by M.Weber

Event selection for EWK Z+2 jets

arXiv:1305.7389, *sub. to JHEP*

- Simple Z selection as before (tighter Z-mass window for μμ, ±15 GeV)
- Choose tagging jets amongst the two leading p_T jets within $|\eta|<3.6$
  - $p_T(1)>65$ GeV $p_T(2)>40$ GeV   (TJ1)





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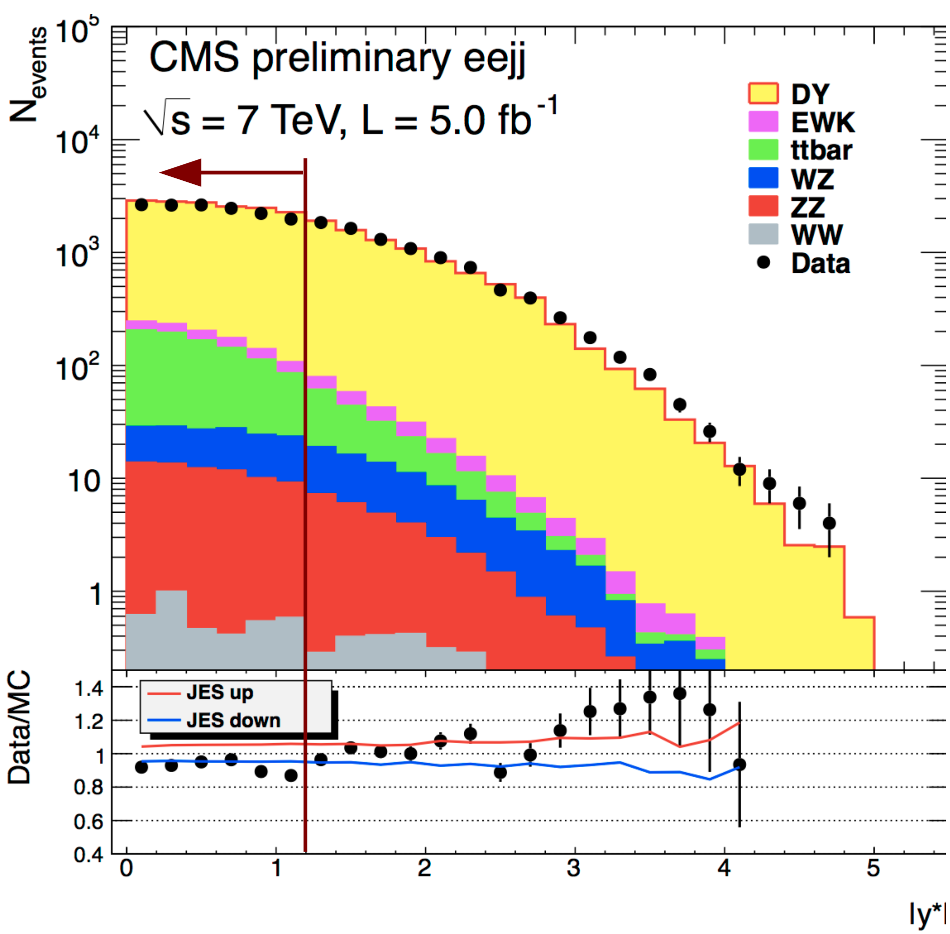
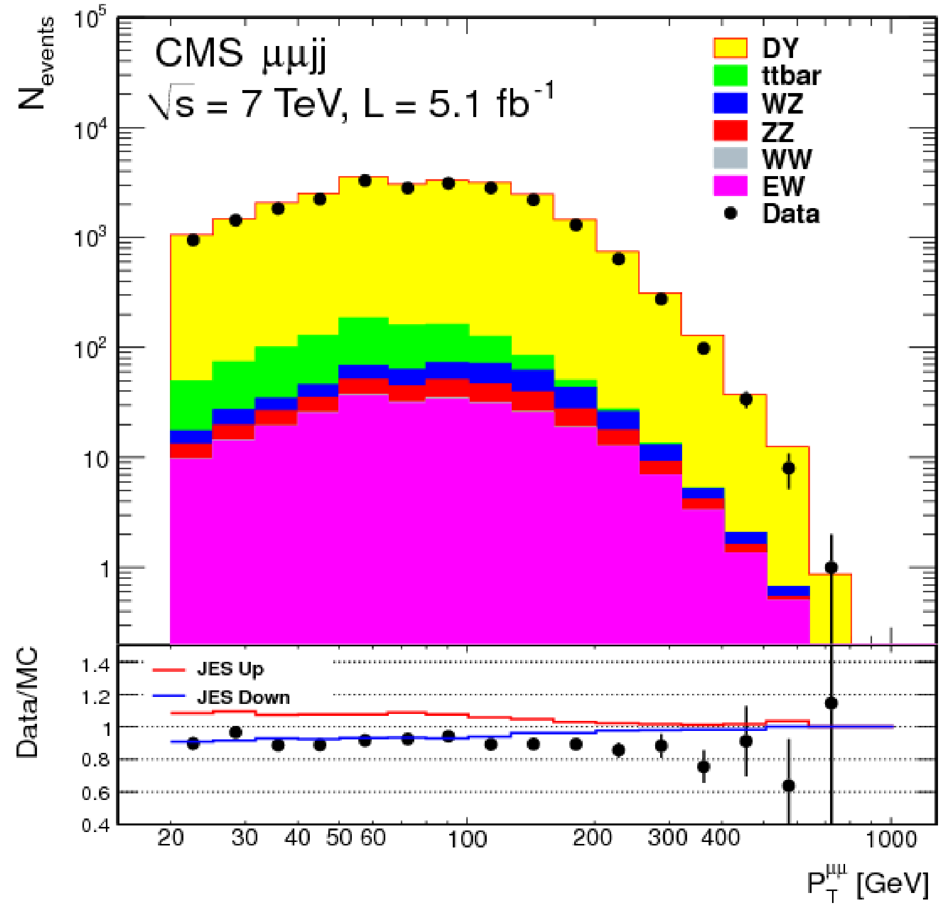
    - $p_T(1)>65$ GeV $p_T(2)>40$ GeV (TJ1)
    - Z is central in the dijet rest frame: $\mathbf{y^*} = y_Z - \frac{1}{2}(y_{j1} + y_{j2}) < \mathbf{1.2}$ (YZ)





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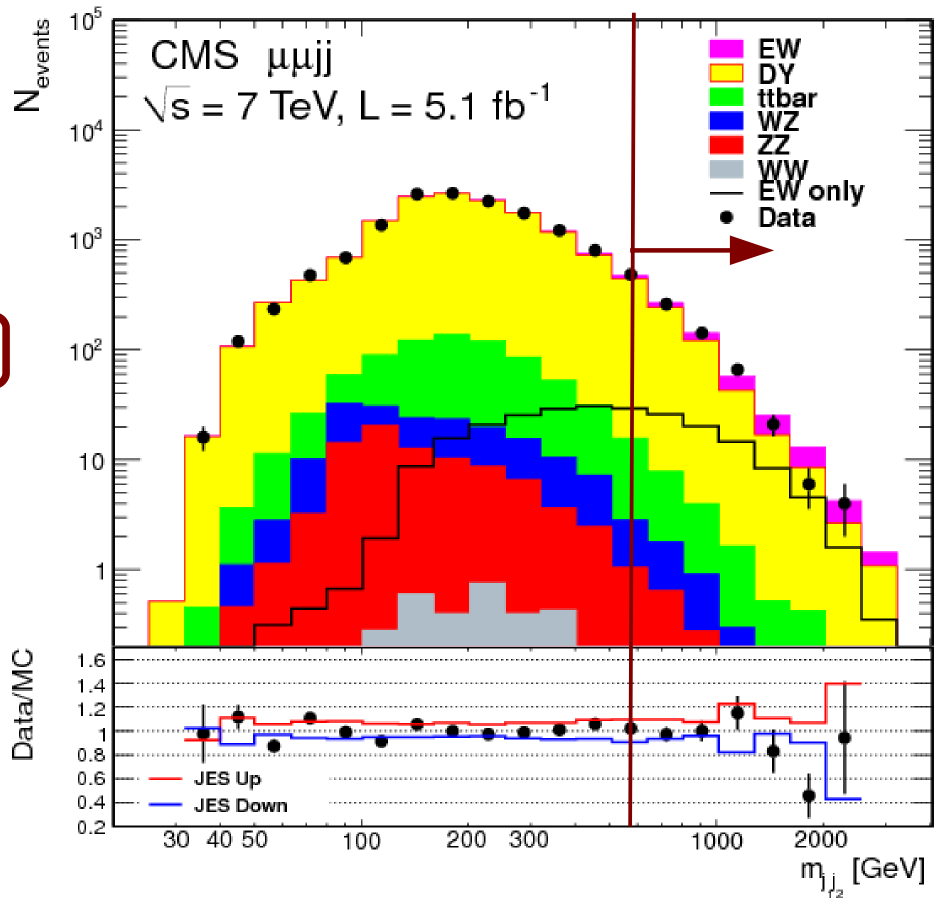
  - Z is central in the dijet rest frame: $\mathbf{y^*} = y_Z - \frac{1}{2}(y_{j1} + y_{j2}) < \mathbf{1.2}$ (YZ)
  - Large dijet invariant mass $M_{jj}>600$ GeV (TJ2)

Selection	Jet type	Data	EW $\ell\ell$jj	DY $\ell\ell$jj	$t\bar{t}$	WW	WZ	ZZ
$Z_{\mu\mu}$		1.7×10^6	460	1.7×10^6	1400	300	1300	850
requirement TJ1	JPT	25000	290	26000	690	5.2	180	120
	PF	26000	280	26000	680	5.3	170	110
requirement YZ	JPT	15000	210	16000	590	3.4	98	83
	PF	16000	200	16000	580	3.4	93	76
requirement TJ2	JPT	600	74	600	14	0	2.2	1.3
	PF	640	72	610	14	0	2.4	1.2



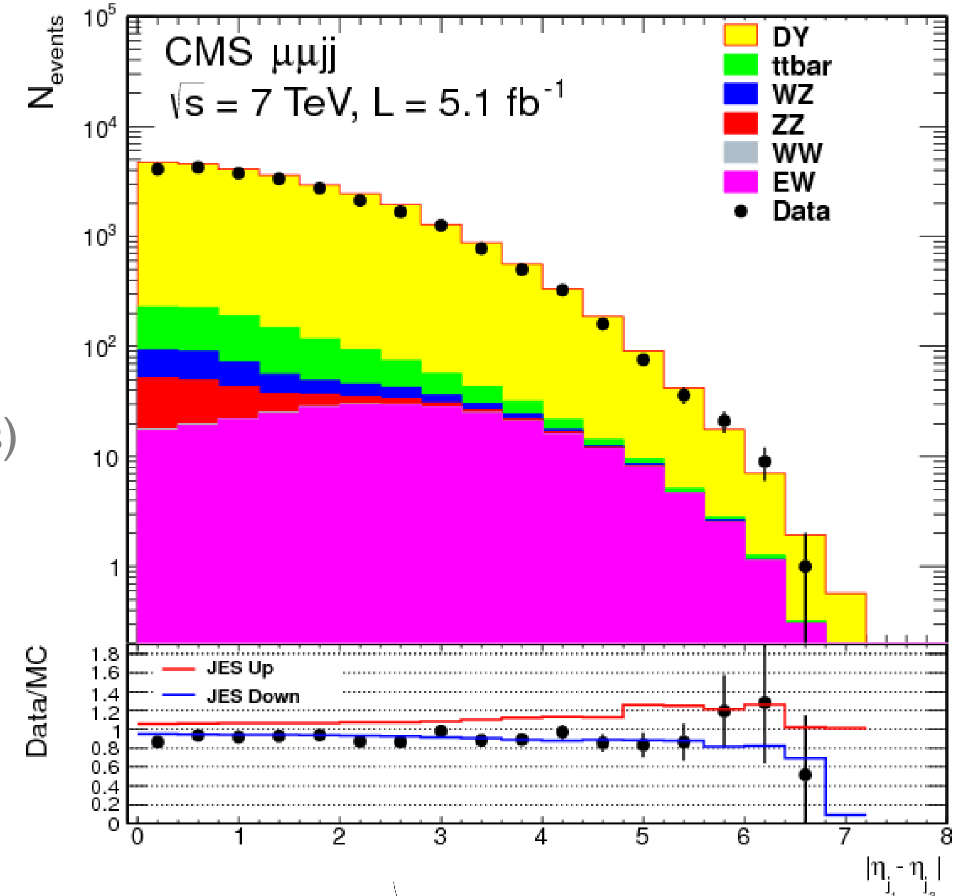
- **After full selection**
  - the efficiency for signal is ~6% for ee and μμ
    (36% efficiency after Z selection)
  - **expect S/B~11%**

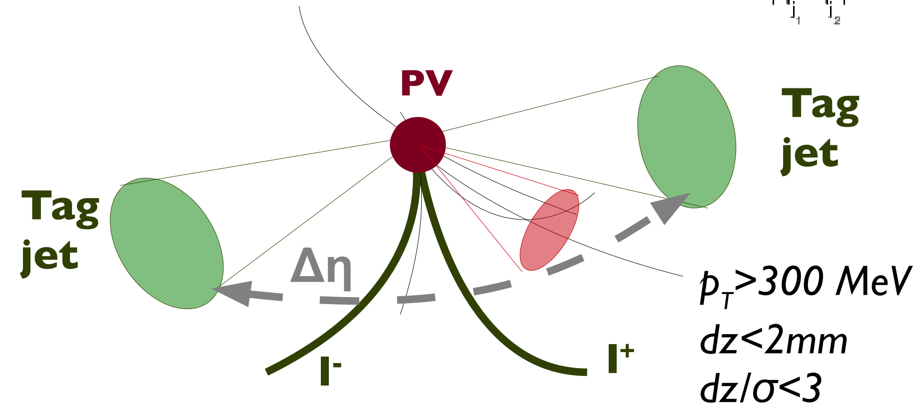
Study of the hadronic activity

arXiv:1305.7389, *sub. to JHEP*

- Rapidity span of the dijet system can test pQCD
  - Δη can be viewed as an evolution variable for the emission of extra jets
  - Compare BFKL-based prediction with data as in e.g. arXiv:1003.1241
- **Color octet exchanges** expect process-independent correlation (modulo PDF differences)
  - ability of the process to radiate
  - flat probability for the extra emission
  - opening of phase space for radiation
- **Color singlet exchange** expect suppression of extra hadronic activity
- **Pileup-resilient strategies are followed**
  - consider extra-hard emissions p_T>40 GeV
  - consider track-jets associated to the PV ►

$$\eta_{\min}^{\text{tag jet}} + 0.5 < \eta < \eta_{\max}^{\text{tag jet}} - 0.5$$

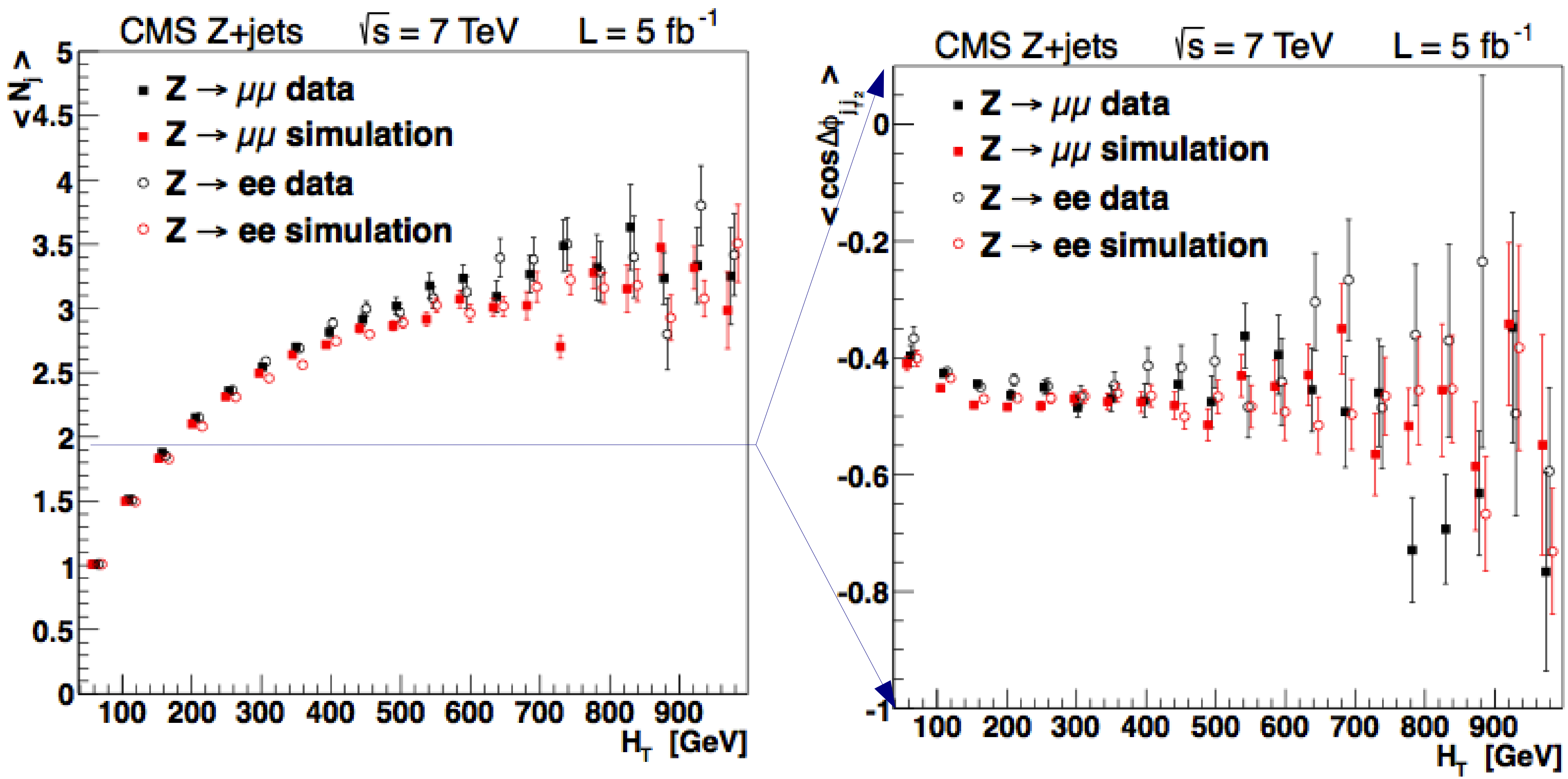




Jet activity profiles - I

arXiv:1305.7389, *sub. to JHEP*

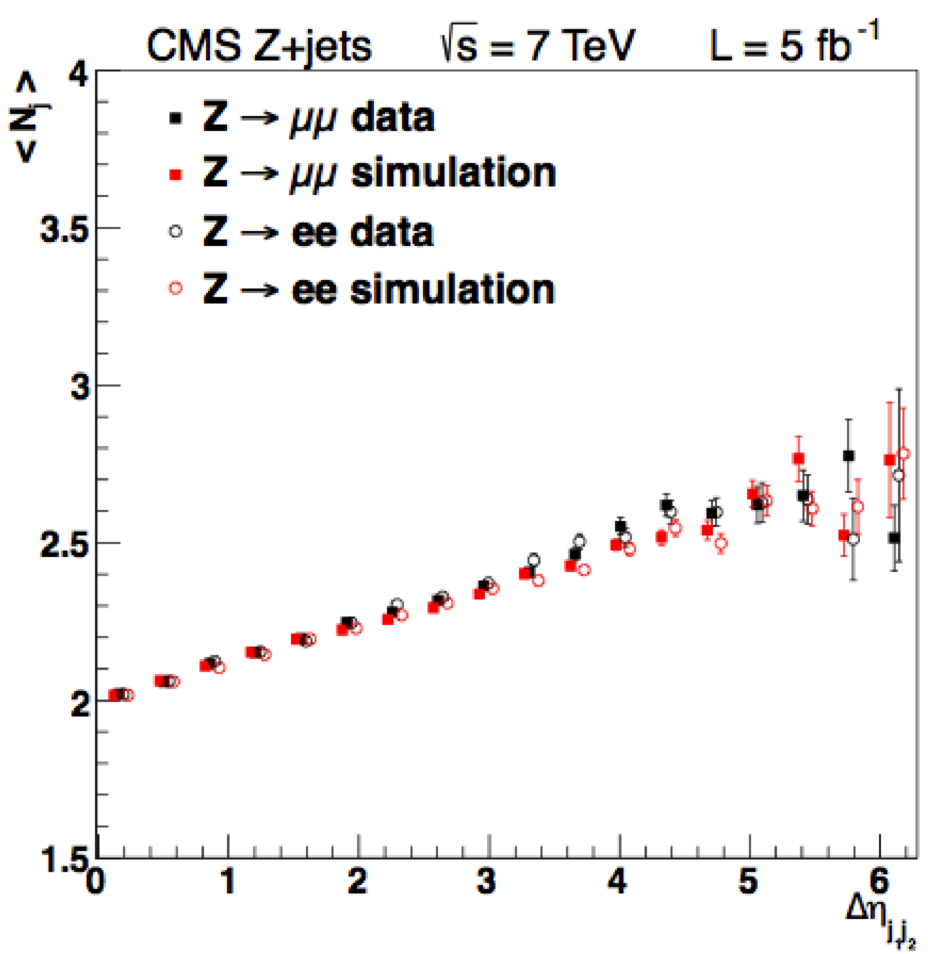
- Profile radiation pattern for jets with p_T>40 GeV produced in association with the Z boson
- Measure activity as function of H_T= scalar sum of the jet's p_T
- Data and Madgraph-based predictions in agreement (reconstruction level, backgrounds included)
- Forward-backward jets produced with a 120° opening in average in the transverse plane

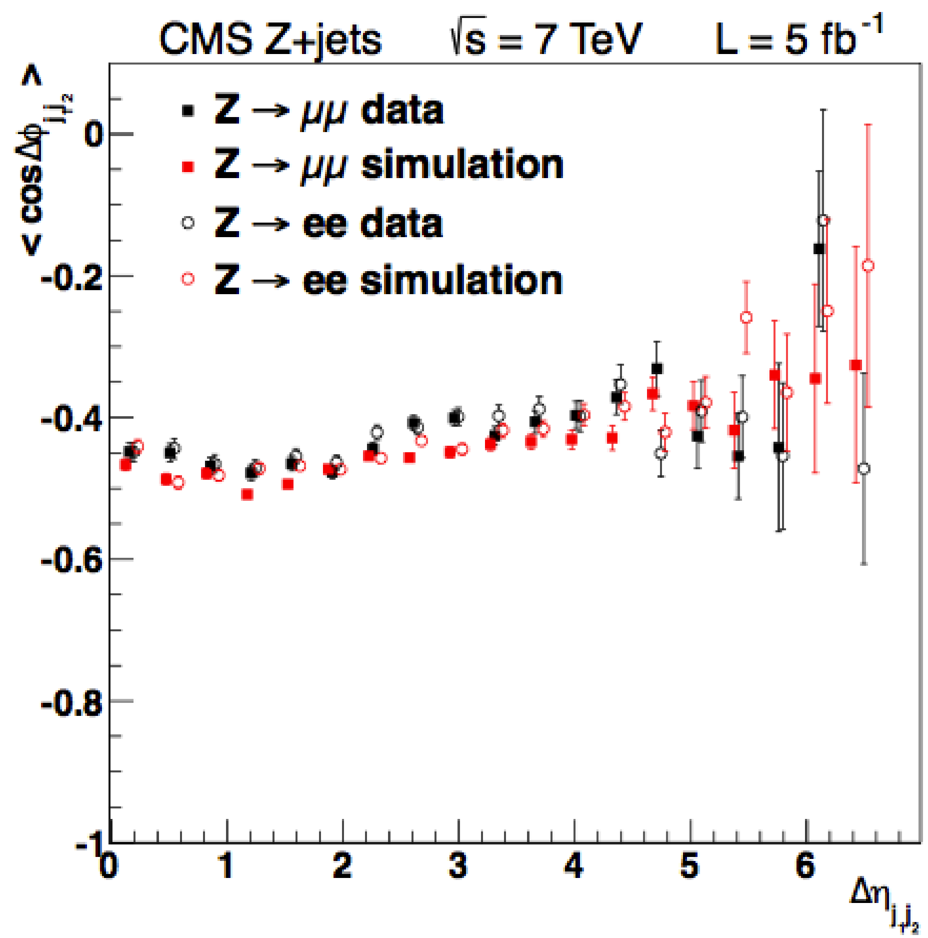


Jet activity profiles - II

arXiv:1305.7389, *sub. to JHEP*

- For events with two jets we profile radiation pattern as function of the rapidity span
  - Clear correlation between hadronic activity and rapidity span
- Good match between data and Madgraph-based predictions (again at reconstruction level)

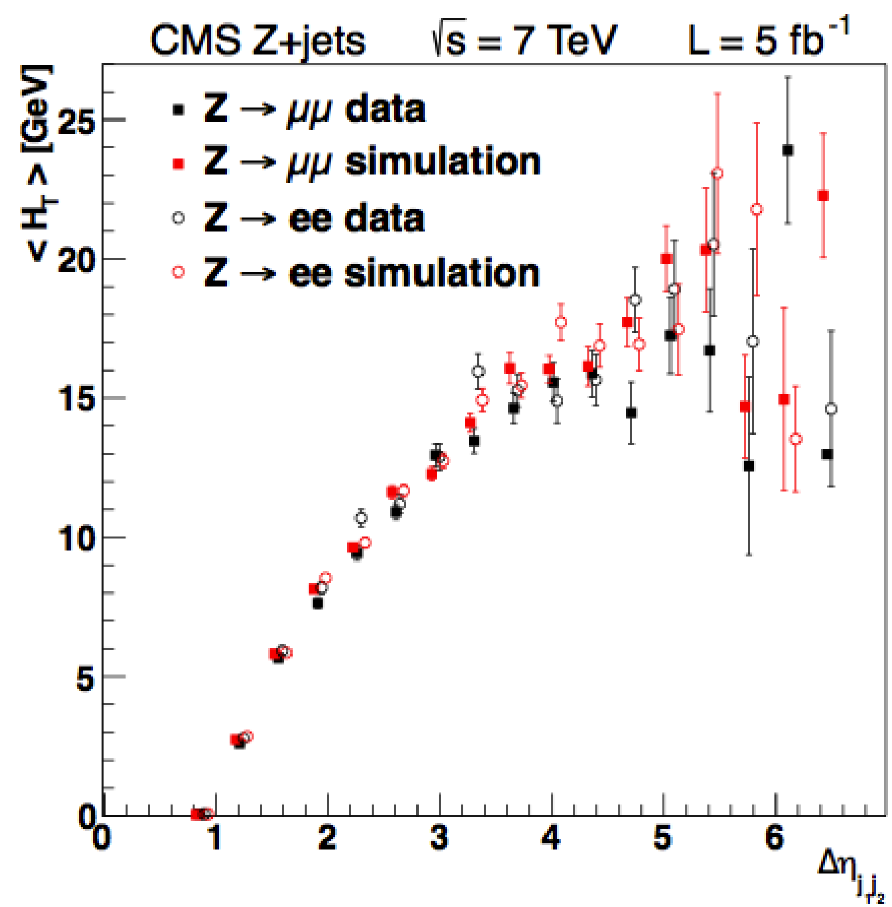


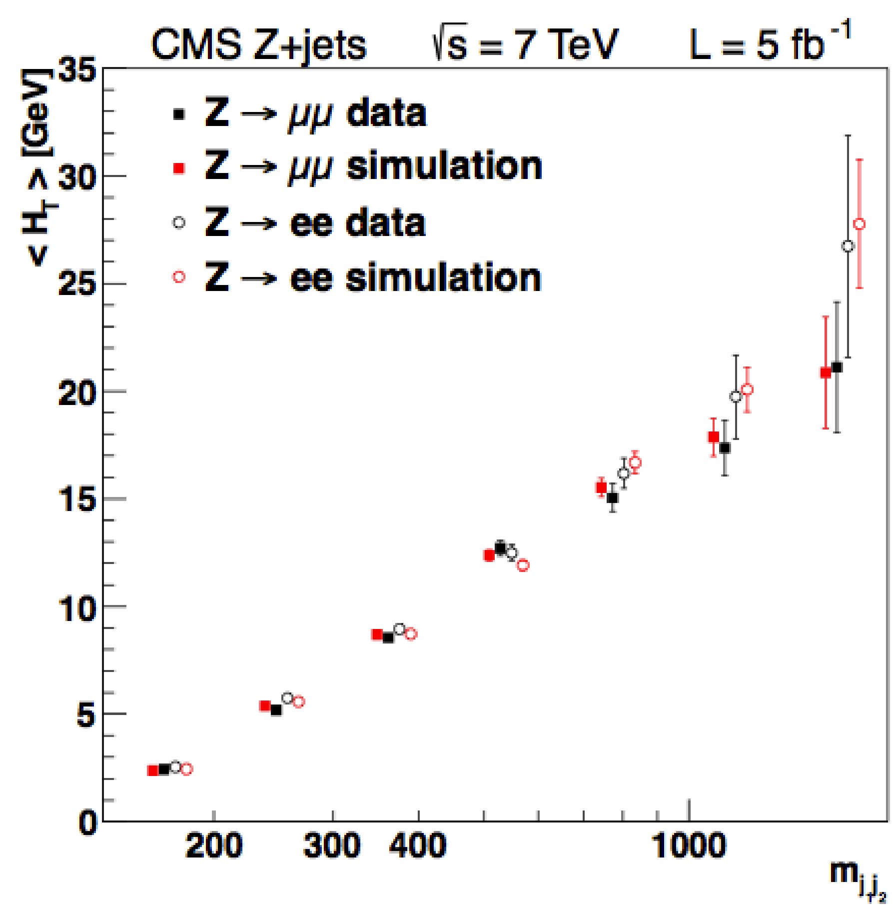


Soft track activity profile

arXiv:1305.7389, *sub. to JHEP*

- Correlation between rapidity span and soft hadronic activity is well simulated by Madgraph
  - No background subtraction or unfolding (comparison at reconstructed level)
  - Similar correlation as function of the dijet invariant mass
  - Due to universal properties expect to gain insight on "hadronic-based vetoes" in the future





Strategy for signal extraction

arXiv:1305.7389, *sub. to JHEP*

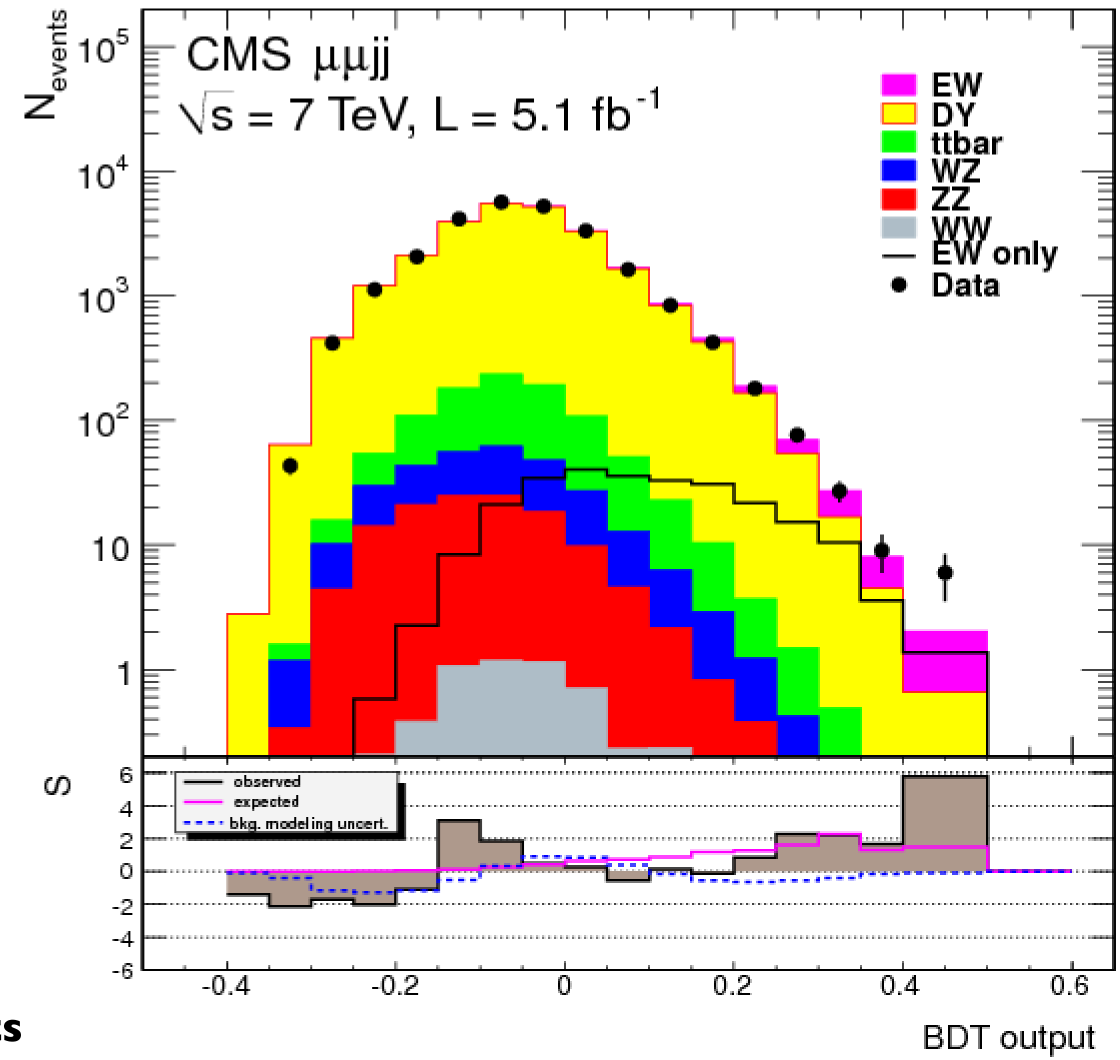
- Established level of agreement between data and simulation with respect to hadronic activity
- Can proceed to signal extraction
  - no single variable has sufficient discrimination power or robustness against systematic uncertainties
  - Sequential cuts tend to shape main background to resemble like the signal
  - Use a multivariate approach
- **Combine several variables:**

tag jet kinematics: $p_T(1)$, $p_T(2)$

q/g discriminator (ee channel only)

dijet kinematics: M_{jj}, $\Delta\varphi$, $\Delta\eta$, $\eta_1+\eta_2$

Z kinematics: p_T^Z, y^*, $\Delta\varphi(Z,j_1)$, $\Delta\varphi(Z,j_2)$



- Boosted decision tree is **trained using signal and simulated DY+top events**
- Extract **$\mu=\sigma/\sigma_{th}$ after maximizing likelihood** with signal and background shapes (fraction fit to data)

Systematic uncertainties

arXiv:1305.7389, *sub. to JHEP*

- Jet energy scale is the main uncertainty
- Background modeling is the second uncertainty (theory and statistics in the signal region)
  - Correct the Madgraph prediction using the NLO MCFM prediction
  - Take full difference in fit with alternative shape as uncertainty: impact on M_{jj} and y^*

Source of uncertainty	Uncertainty	
	$\mu^+\mu^-$ channel	e^+e^- channel
Theoretical uncertainties		
Background modeling	0.15	0.16
Signal modeling	0.05	0.05
$t\bar{t}$ cross section	0.03	0.03
Diboson cross sections	0.02	0.02
Total	0.16	0.17
Experimental uncertainties		
JES+JER	0.22	0.29
Pileup modeling	0.03	0.03
MC statistics	0.13	0.19
Gluon-quark discriminator	not used	0.02
Dilepton selection	0.02	0.02
Total	0.26	0.35
Luminosity	0.02	0.03

Results

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- Result of the signal strength fit indicates background over-estimation (consistent with systs)

Channel	Jets	Signal	Background
$\mu\mu$	JPT	0.90 ± 0.19	0.905 ± 0.006
	PF	0.85 ± 0.18	0.937 ± 0.007
ee	PF	1.17 ± 0.27	0.957 ± 0.010

- **The signal strength is applied to the generator-phase space cross section**
  - re-scale the LO Madgraph prediction used to model the signal acceptance
  - cross-check independently the results with two jet algorithms in the di-muon channel
  - combine particle-flow based results between electrons and muons for the final result

$$\sigma^{EW}_{\mu\mu}\,(\mathrm{JPT}) = 146 \pm 31\,(\mathrm{stat.}) \pm 42\,(\mathrm{exp.\ syst.}) \pm 26\,(\mathrm{th.\ syst.}) \pm 3\,(\mathrm{lum.})\,\mathrm{fb}$$

$$\sigma^{EW}_{\mu\mu}\,(\mathrm{PF}) = 138 \pm 29\,(\mathrm{stat.}) \pm 40\,(\mathrm{exp.\ syst.}) \pm 25\,(\mathrm{th.\ syst.}) \pm 3\,(\mathrm{lum.})\,\mathrm{fb}$$

$$\sigma^{EW}_{ee}\,(\mathrm{PF}) = 190 \pm 44\,(\mathrm{stat.}) \pm 57\,(\mathrm{exp.\ syst.}) \pm 27\,(\mathrm{th.\ syst.}) \pm 4\,(\mathrm{lum.})\,\mathrm{fb}$$

  - all results are consistent with each other and with the VBFNLO NLO-based expectations

- **We measure:** $\sigma^{EW}_{\ell\ell\,(\ell=e,\mu)} = 154 \pm 24\,(\mathrm{stat.}) \pm 46\,(\mathrm{exp.\ syst.}) \pm 27\,(\mathrm{th.\ syst.}) \pm 3\,(\mathrm{lum.})\,\mathrm{fb}$

$m_{\ell\ell} > 50\,\mathrm{GeV},\ p_T^j > 25\,\mathrm{GeV},\ |\eta^j| < 4.0,\ m_{jj} > 120\,\mathrm{GeV}$

Conclusions

- **Presented the first attempt to measure EWK Z+2 jets production** at the LHC
  - Vector boson fusion production of a Z included but interference effects are non-negligible
  - A unique sample to probe the properties of colour-singlet exchange at the LHC
- Studies of **hadronic profiles in Z+jets events**
  - universality of the hadronic activity evolution being probed
  - fair agreement with Madgraph predictions
- **Cross section extracted** with a multivariate approach
  - Gain in significance and robustness versus systematic uncertainties
  - Result is compatible with NLO prediction but significance is still low (~2.6σ)

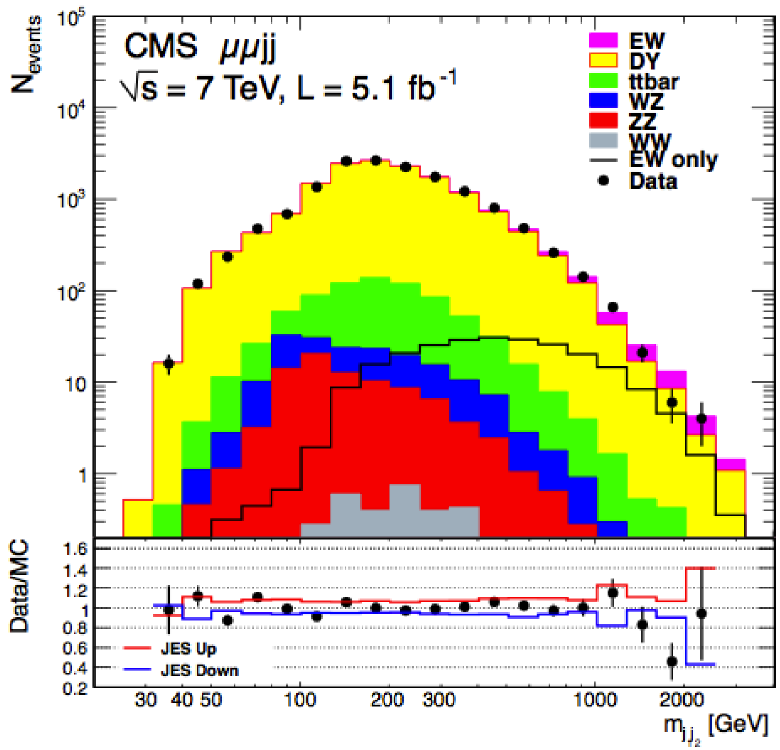
$$\sigma^{\mathrm{EW}}_{\ell\ell\,(\ell=\mathrm{e},\mu)} = 154 \pm 24\,(\mathrm{stat.}) \pm 46\,(\mathrm{exp.\ syst.}) \pm 27\,(\mathrm{th.\ syst.}) \pm 3\,(\mathrm{lum.})\ \mathrm{fb}$$

- Outlook for the near future
  - Analyze the 8 TeV data (4x integrated luminosity)
  - Include EWK W+2 jets (10x gain in cross section)

Backup

Signal extraction with M_{jj}

- Main discrimination variable: affected by jet energy scale uncertainty
- Result used as a cross-check of the main analysis



Channel	Jets	Signal	Background
$\mu\mu$	JPT	1.14 ± 0.28	0.869 ± 0.008
	PF	1.14 ± 0.30	0.897 ± 0.008

Source of uncertainty	Uncertainty
Theoretical uncertainties	
Background modeling	0.20
Signal modeling	0.05
$t\bar{t}$ cross section	0.02
Diboson cross sections	0.01
Total	0.21
Experimental uncertainties	
JES+JER	0.44
Pileup modeling	0.05
MC statistics	0.14
Dimuon selection	0.02
Total	0.47
Luminosity	0.02

Quark/gluon discrimination

- Approximately half of the jets in DY events are gluon originated
- Combine several variables in a likelihood ratio method to discriminate gluon-like jets

- **Central region ($|\eta|<2$)**

  Major and minor axis (η-φ RMS)

  Pull (asymmetry)

  Charged multiplicity

  R_{ch}= leading p_T^{ch} / Σp_T

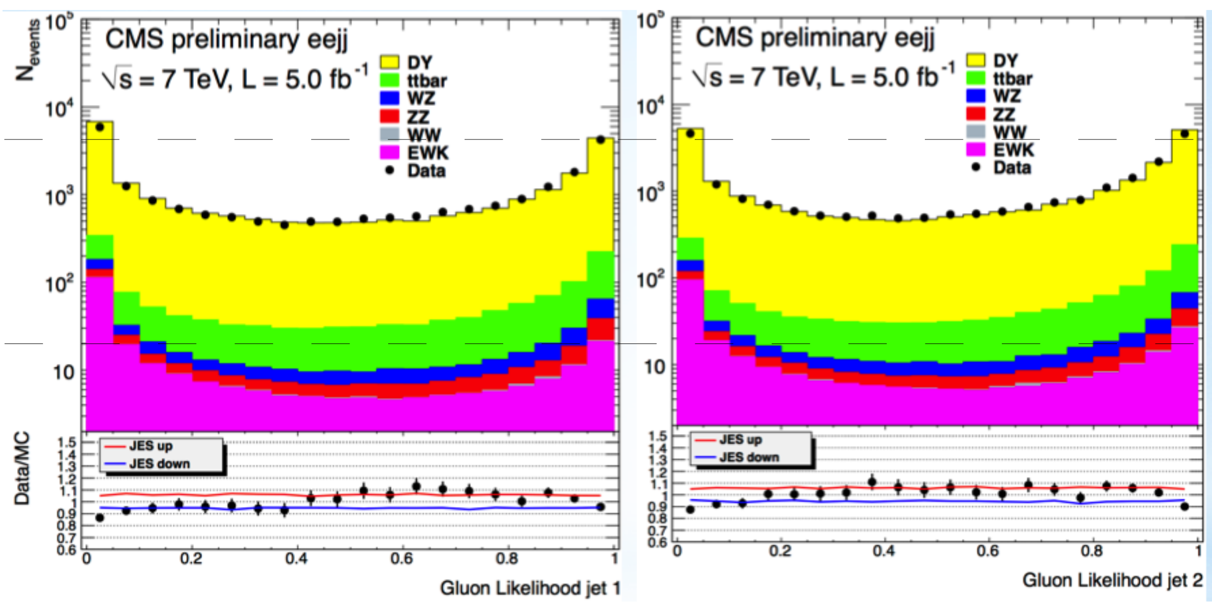
- **Transition/forward region ($|\eta|>2$)**

  Major and minor axis (η-φ RMS)

  Pull (asymmetry)

  Charged multiplicity+neutral multiplicity

  R_{ch}= leading p_T^{ch} / Σp_T



background is equally "gluon/quark-like"

signal is less "gluon-like"

Chosen variables inspired by PRL 107 (2011) 172001

Central jet veto

- We **vary the tag jets selection criteria**
  - $\Delta\eta_{jj}$>3.5, p_T^{j3}>20 GeV, $|\eta^{j3}|$<2
  - Harder p_T tag jets tend to have more jets in between

$p_T^{j_1(j_2)}$	>25 GeV	>35 GeV	>45 GeV
data	0.78 ± 0.01	0.68 ± 0.01	0.63 ± 0.02
simulation	0.80	0.71	0.66

- We **vary also the dijet rapidity span and invariant mass**
  - Observe soft jet multiplicity increase with larger dijet rapidity span
  - Saturation observed for large M_{jj} values: tag jets are harder at low $\Delta\eta_{jj}$

$\Delta\eta_{j_1j_2}$	>2.5	>3.5	>4.5
data	0.71 ± 0.01	0.68 ± 0.01	0.66 ± 0.02
simulation	0.73	0.71	0.67
with $m_{j_1j_2} > 700$ GeV selection			
data	0.56 ± 0.03	0.58 ± 0.03	0.62 ± 0.04
simulation	0.56	0.57	0.58

Soft hadronic activity (track jets)

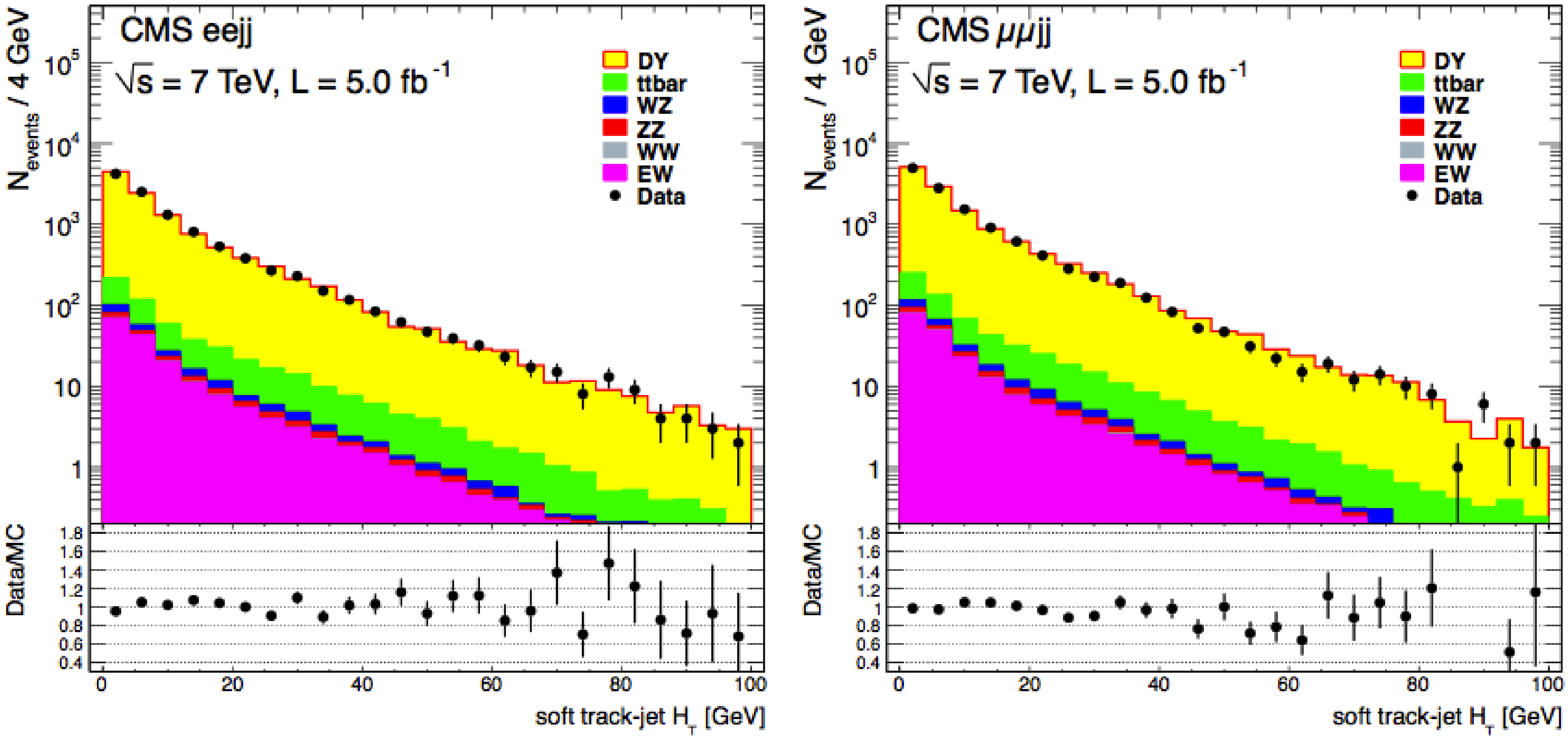


Figure 6: The H_T distribution of the three leading soft track jets in the pseudorapidity interval between the tagging jets with $p_T^{j_1,j_2} > 65, 40\,\mathrm{GeV}$ in DY Zjj events for dielectron (left) and dimuon (right) channels. The bottom panels show the corresponding data/MC ratios. The data points are shown with the statistical uncertainties.