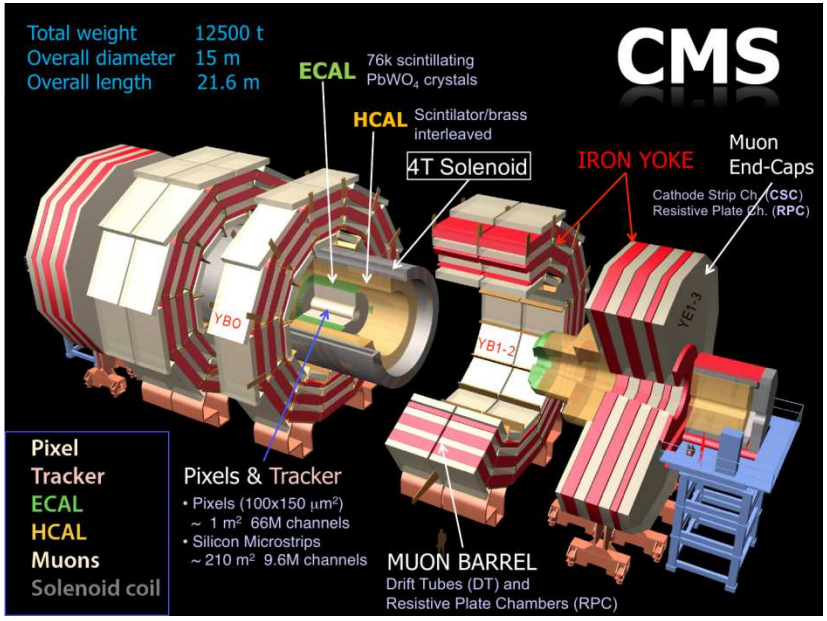
# W/Z + Jets Results from CMS

*Osipenkov, Ilya (Texas A&M University)*

*On behalf of the CMS Collaboration*

*Standard Model at the LHC*



# Outline

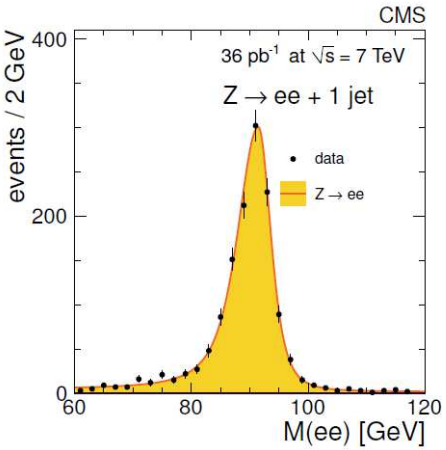
- **V+Jets Spectrum**
  - Standard candle process
  - Can be used to validate detector performance as well as develop/test theory simulation
  - Background to subsequent measurements
- **W/Z + heavy flavor analyses**
  - Rely on long lived hadrons in the final state
  - Useful tools in probing heavy quark content of the proton
  - Comparisons to theoretical models (e.g. pQCD)
  - Backgrounds to New Physics searches (e.g. Higgs)
- **$M_{jj}$ Spectrum in W+jets**
  - Search for an excess of events near $M_{jj}$=150GeV
  - Observed at CDF, but not D0 or ATLAS
  - Compare to potential New Physics models
- **Summary**

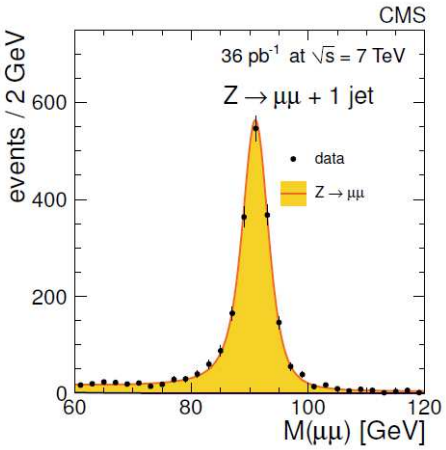
# V+jets Production Rates

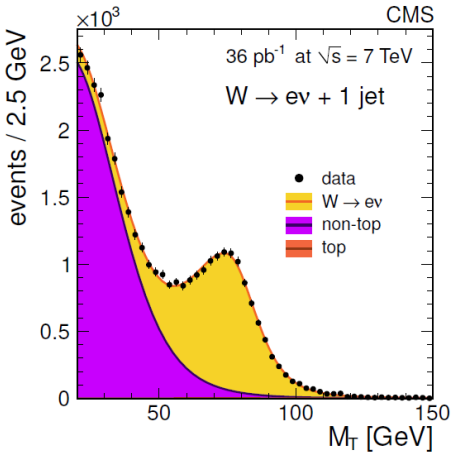
- JHEP01(2012)010 : **$36pb^{-1}$**
- **Cuts:**
  - **$\mu_1$ [$\mu_2$] - $p_T$>20GeV [10GeV], $|\eta|$<2.1 [<2.4], Iso<0.15, $|d_{xy}|$<2*mm*.**
  - ***$e_1$* [*$e_2$*] - $p_T$>20GeV [10GeV], $|\eta|$<2.5 (excluding 1.44< $|\eta|$<1.57), isolation confined to $\Delta R$<0.3 cone, veto $\mu$ events with $p_T$>15GeV & $|\eta|$<2.4.**
  - **60GeV<$M_{ll}$<120GeV → Z+jets, otherwise W+jets event ($W_{mT}$>20GeV).**
  - **PF Jets (anti-$k_T$, R=0.5) with $E_T$>30 GeV, $|\eta|$<2.4 , $\Delta R_e$>0.3**
- **Backgrounds:**
  - **Top events - shape derived from simulation**
  - **Other: mostly QCD multijet – shape derived from data samples with inverted id/iso**
  - **Normalizations determined from a fit to the data**
- **Systematics:**
  - **Jet Energy Corrections**
  - **Jet Flavor dependence**
  - **PileUp Subtraction**

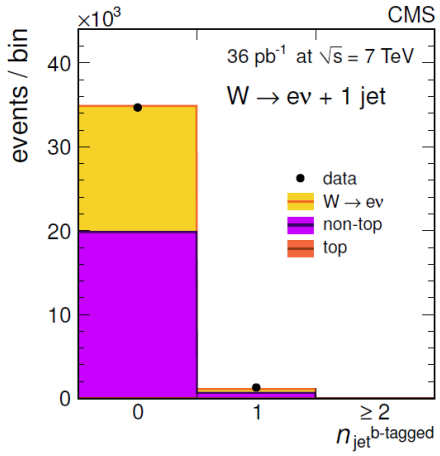
# V+jets - Fit

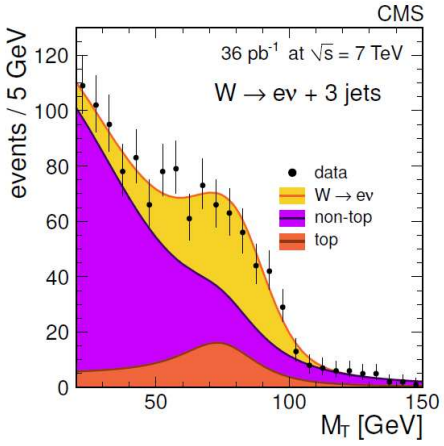
- **Extended Maximum Likelihood Fit:**
  - **Asymmetric Gaussian probability distribution functions**
  - **Z+jets - fit $M_{ll}$, combine all backgrounds**
  - **W+jets - fit $W_{mT}$ & $n_j^{b\text{-tagged}}$**

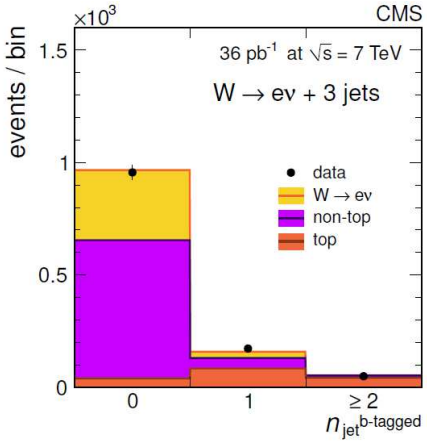


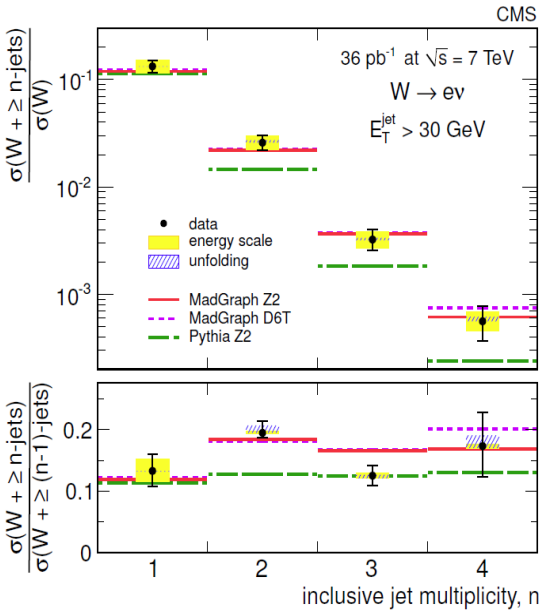



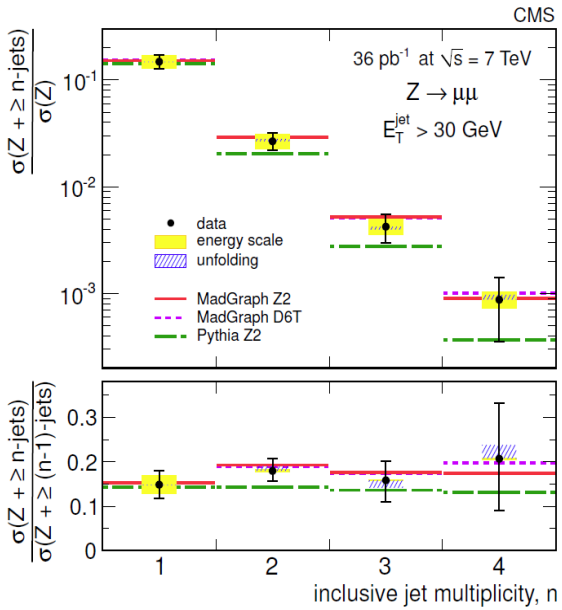



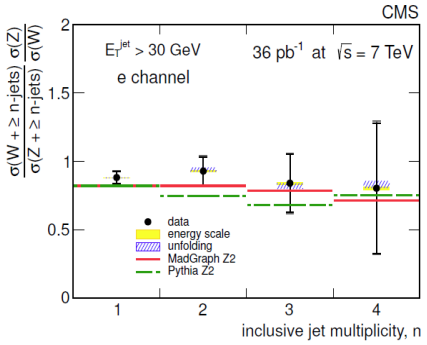



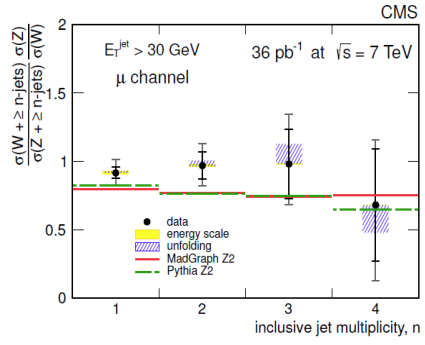
# V+jets - Results

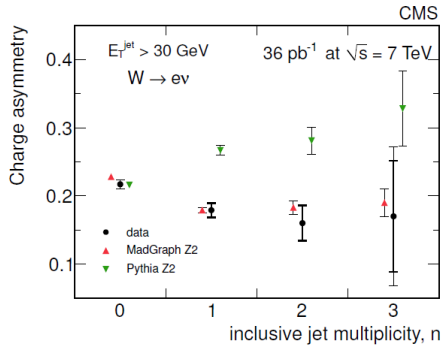


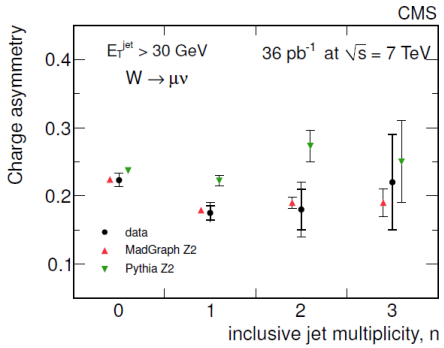




- **Examine Jet Multiplicity $\sigma(V + \geq n_j)/\sigma(V)$ vs n-jets**
- **Remove theoretical and systematic uncertainties by taking ratios $\sigma(V+\geq n_j)/\sigma(V+\geq n_{j-1})$**



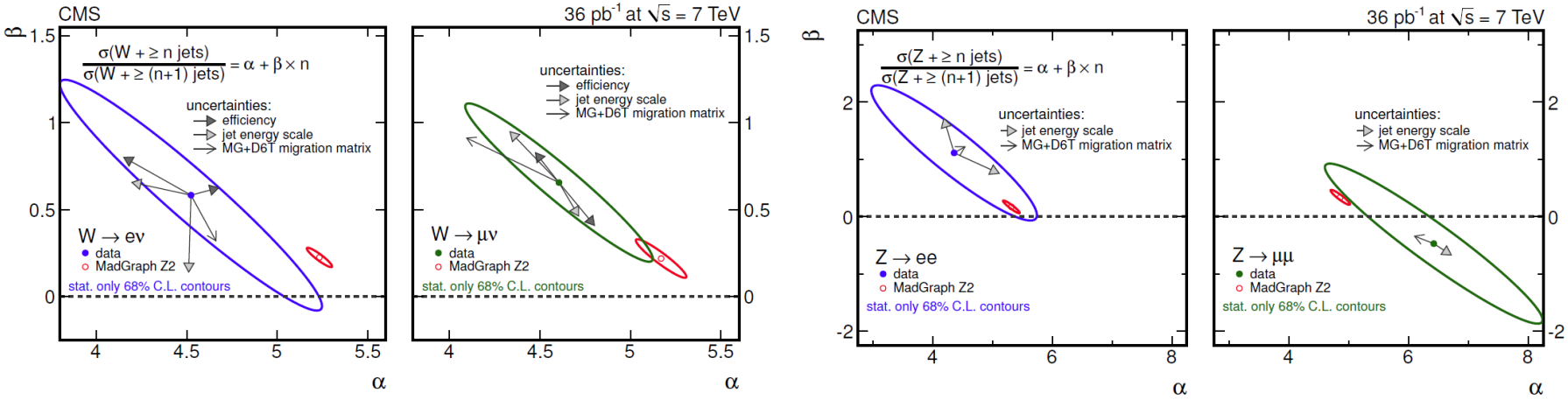




- **$\sigma(W+jets)/\sigma(Z+jets)$**
- **Charge Asymmetry: $(\sigma(W^+)-\sigma(W^-))/(\sigma(W^+)+\sigma(W^-))$**

## ❖ Parameterize $\sigma(V+\geq n_j)/\sigma(V+\geq n_{j+1})$ as $\alpha+\beta n$, $\beta\sim 0$ at CDF and D0

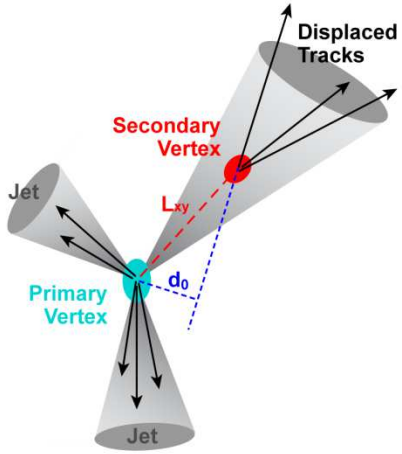



## ❖ Summary

- **"Standard Model Candle" processes, which can be used to test pQCD calculations.**
- **MADGRAPH generator, which relies on matrix-element calculations and PYTHIA parton shower matching, gives results consistent with the Data.**
- **PYTHIA simulations by themselves fail at higher jet multiplicity.**
- **Complimentary results in W+Jets and Z+Jets channels with different backgrounds & parton interactions.**

# V+heavy flavor

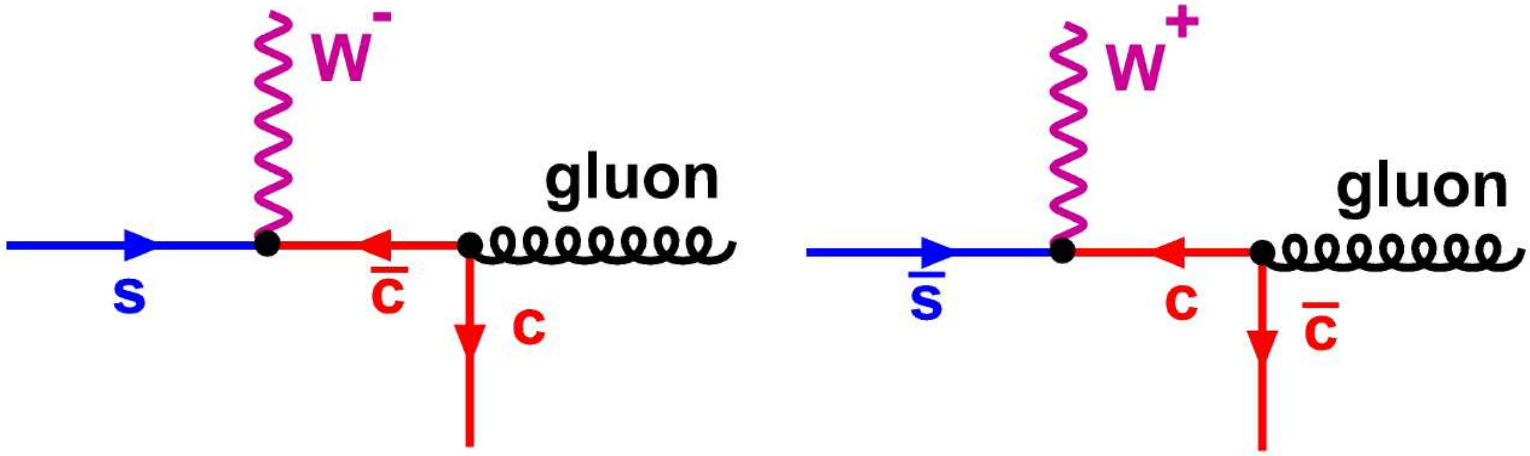
- **Rely on SSVHE (Simple Secondary Vertex High-Efficiency) to identify secondary vertices**
  - **Takes advantage of the long hadron lifetime**
  - **A function of the three-dimensional flight distance from the reference PV (with highest $\sum_{tracks} p_T$)**
  - **HE variant - all secondary vertices built from two tracks or more are considered**




- **Probe (proton) quark content /PDF**
- **Test & guide for corresponding theory predictions**
- **Backgrounds for new physics searches**

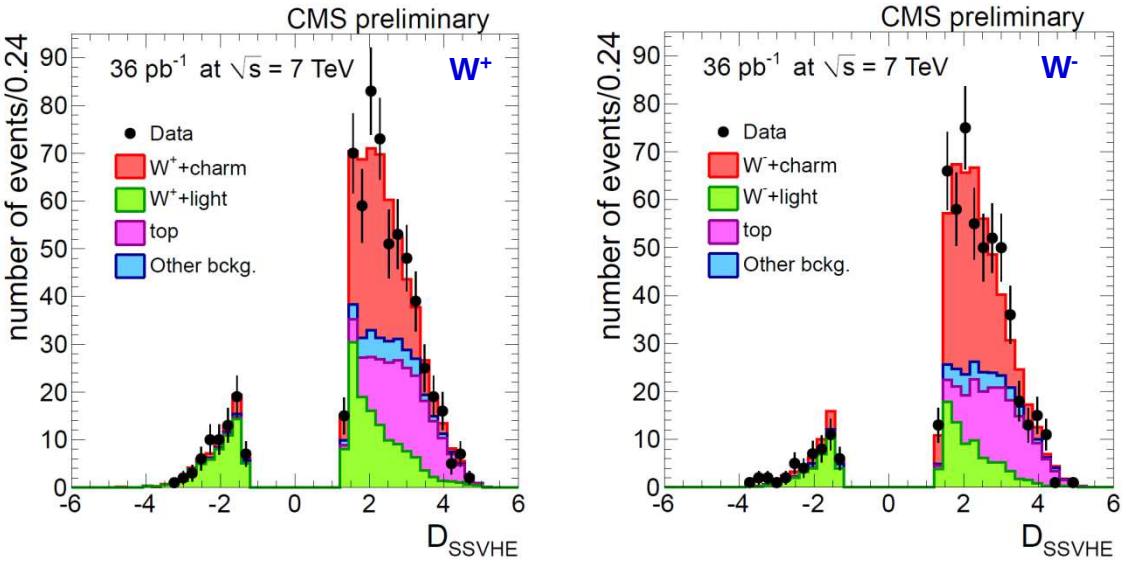
# W + c + X

- CMS PAS EWK-11-013 : **36pb$^{-1}$**




- **Selection:**
  - **$\mu_1$ - $p_T$>25GeV, |η|<2.1, Iso<0.1, $W_{mT}$>50GeV.**
  - **PF Jets (anti-$k_T$, R=0.5) with $p_T$>20 GeV, |η|<2.1 , $\Delta R_\mu$>0.3**
- **Backgrounds: top, light-jet, 'other' (including W+b)**
- **We fit the shape of the SSVHE Discriminator, with each contribution taken from the simulation**

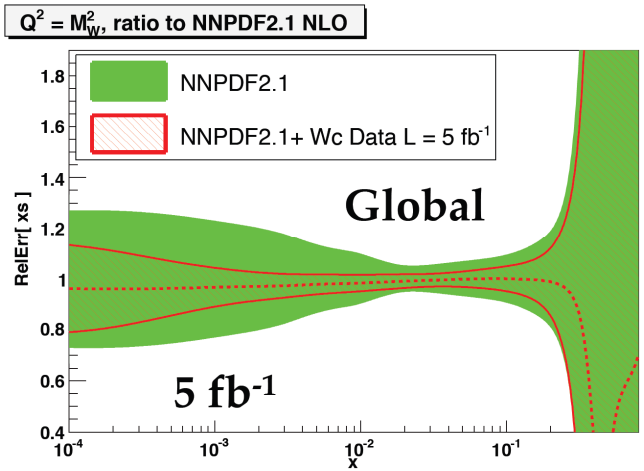
# W + c + X Results




- **Maximum Likelihood Fit : Extract $N(W^+c)$, $N(W^-c)$**
- **Study $R^{\pm}_c = N(W^+c)/N(W^-c)$, $R_c = (N(W^+c)+N(W^-c))/N(W+\text{jets})$**
- **$R^{\pm}_c = 0.92 \pm 0.19(\text{stat.}) \pm 0.04\ (\text{syst.})$**
- **$R_c = 0.143 \pm 0.015(\text{stat.}) \pm 0.024(\text{syst.})$**

**Analytical MCFM Calculations**

| Ratio | MCFM (CT10) | MCFM (MSTW08) | MCFM (NNPDF21) |
|---|---|---|---|
| $R_c^{\pm}$ | $0.915^{+0.006}_{-0.006}$ | $0.881^{+0.022}_{-0.032}$ | $0.902 \pm 0.008$ |
| $R_c$ | $0.125^{+0.013}_{-0.007}$ | $0.118^{+0.002}_{-0.002}$ | $0.103 \pm 0.005$ |

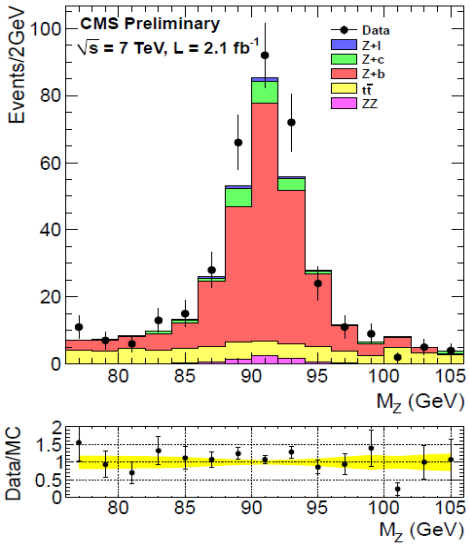


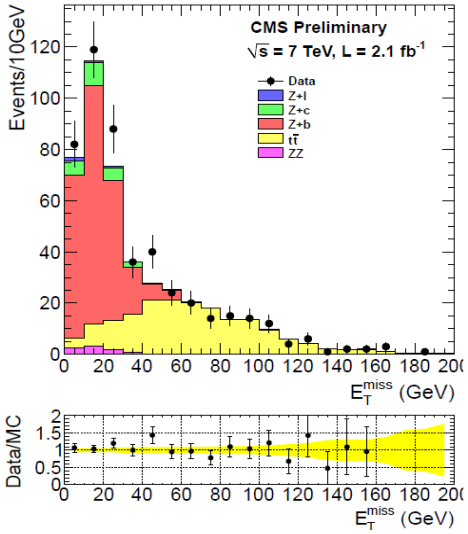

Juan Rojo, LPCC Elecroweak Working Group workshop 2011

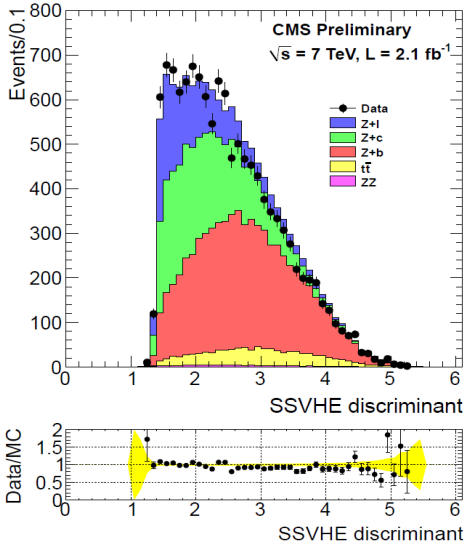
- **The measured values are in agreement with the NLO theoretical predictions computed with MCFM and CT10 PDFs**
- **Potential improvements in modeling the s-quark PDF**

# $Z/\gamma^*$+bb ($Z/\gamma^*$+b) Cross Section

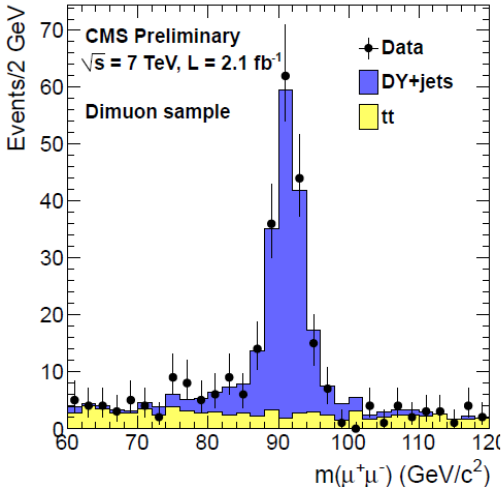
- CMS PAS SMP-12-003 (EWK-11-012) : **2.1fb$^{-1}$**
- **Selection:**
  - **$\mu$ - $p_T$>20GeV, $|\eta|$<2.1, Iso<0.15**
  - ***e*** **- $p_T$>25GeV, $|\eta|$<2.5 (excluding 1.44< $|\eta|$<1.57), confined to $\Delta R$<0.3 cone**
  - **PF Jets (anti-$k_T$, R=0.5) with $p_T$>25GeV, $|\eta|$<2.1, $\Delta R_l$>0.5**
  - **76<$M_{ll}$<106GeV (60<$M_{ll}$<120GeV for $Z/\gamma^*$+b measurement)**
  - **MET > 50GeV**
  - **SSVHE discriminant cut: mistag probability for a light quark (as a b-quark) < 1% (SSVHP variant with a mistag probability <0.1%)**

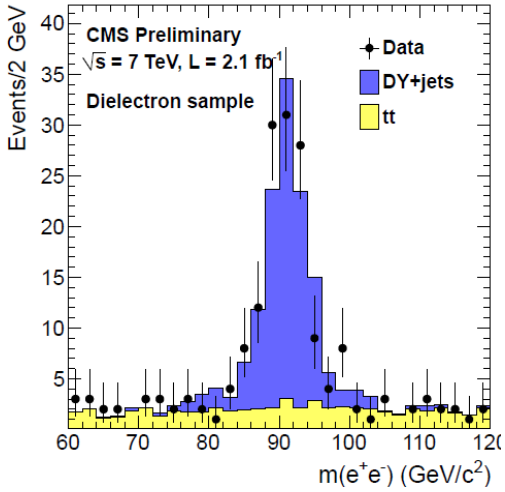


# $Z/\gamma^*$+bb Signal Extraction

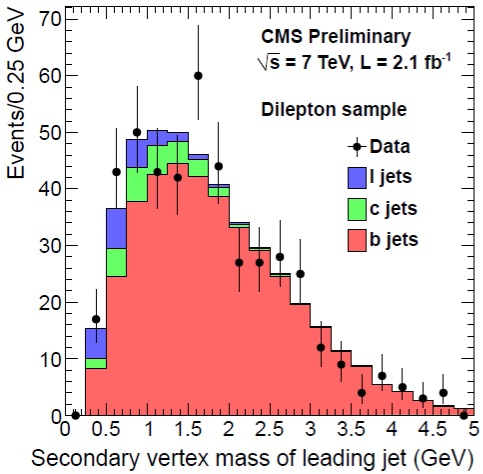


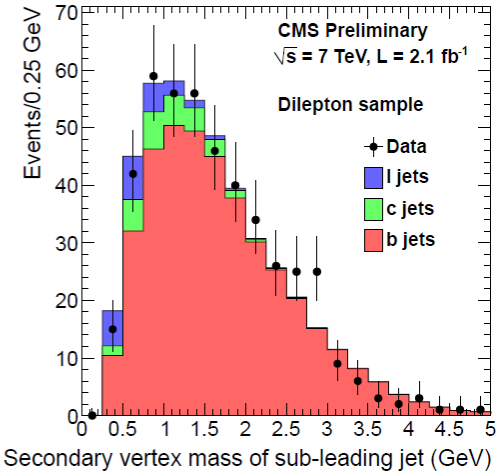




- Fit $M_{ll}$ to extract the tt fraction
- Fit the secondary vertex mass for both jets to determine $f_{bb}=1-f_{cc}-f_{bl}-f_{lb}$, i.e. distinguish Z+bb from Z+cc & Z+bl

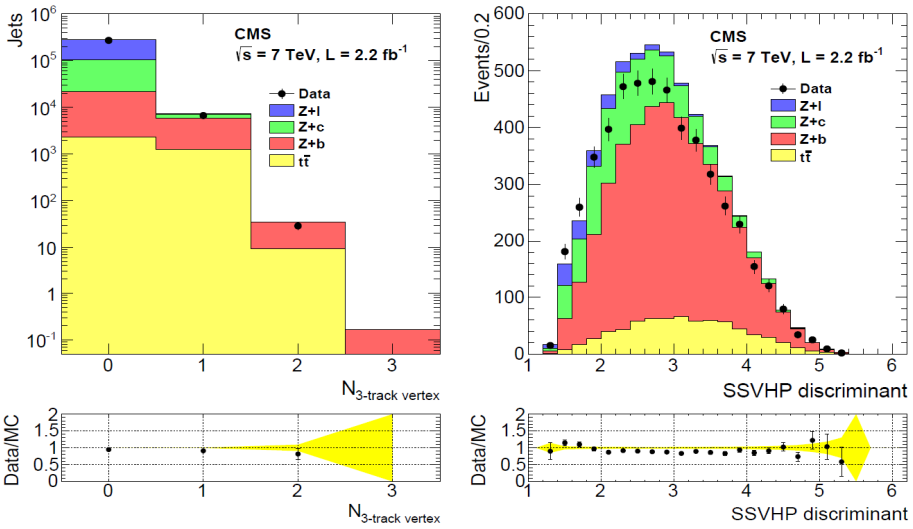
- The Z+bc, cl and ll contributions are minor and are assigned (a 4.5%) systematic
- The fraction of ZZ events is estimated from MC and is explicitly subtracted from the fit:

$$N^{sig}_{Z(ll)+bb} = N_{Z(ll)+bb} \times (f_{bb} - f_{t\bar{t}}) - N_{ZZ}$$



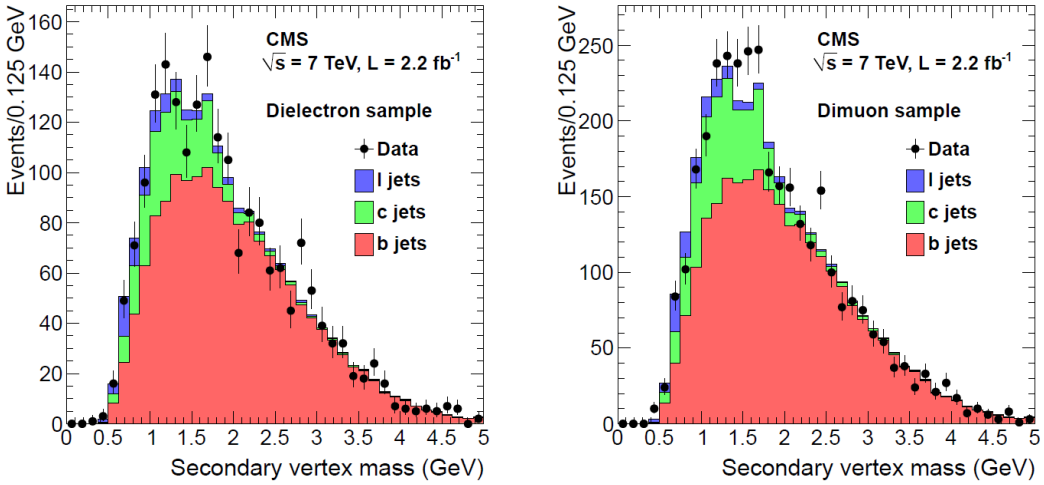
# Z/γ*+b Results




- Obtain the tt fraction from the upper sideband ($M_{ll}$>120GeV)
- Fit the secondary vertex mass of the leading jet to determine the purity $f_{bb}$
- Use the (reweighted MADGRAPH) inclusive jet samples to obtain the results and the Z/γ*+jets sample to estimate the systematic on $f_{bb}$

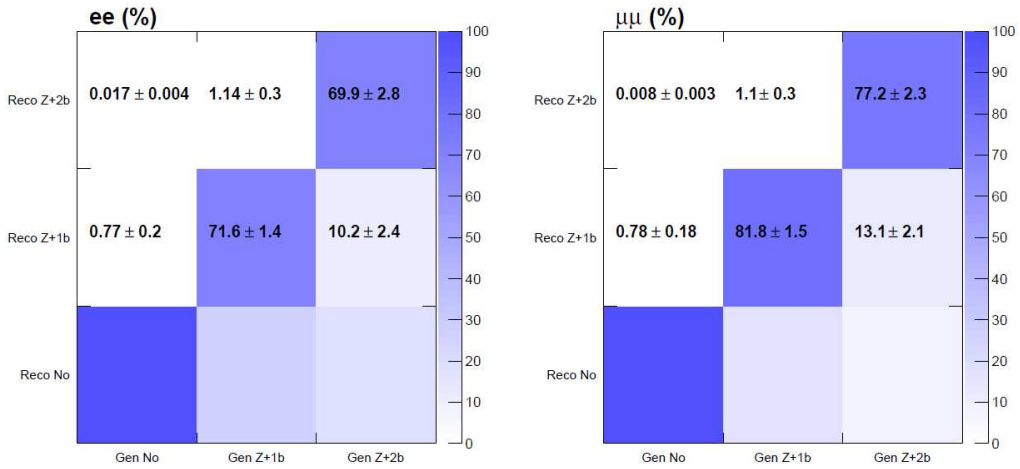
- b-tagging, tt (Data/MC scale factor uncertainty), JES, JER, PileUp and mistagging rate systematics are taken into account

- $\sigma(Z+b)=5.84\pm0.08(stat.)\pm0.72(syst.)^{+0.25}_{-0.55}(theory)$ pb
- NLO MCFM (CTEQ6M) hadron-level-corrected prediction: 3.97±0.47pb



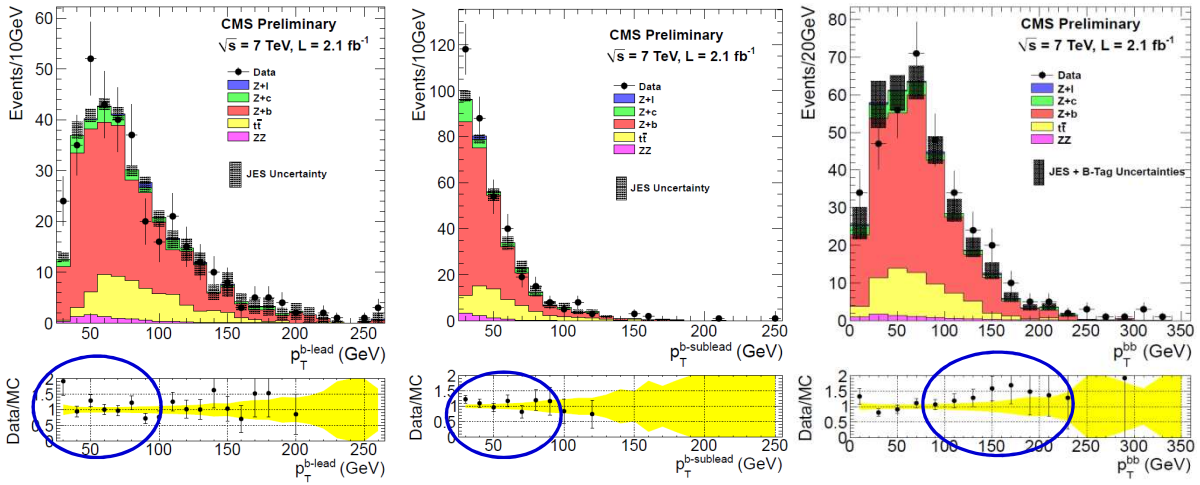
# Z/γ*+bb Results

**Migration matrix used in the unfolding from reconstructed to hadron levels**




- Fit: $N_{ee}(Z+bb)=95\pm15$, $N_{\mu\mu}(Z+bb)=133\pm21$
- Perform unfolding to parton level
- Systematics: JES, JER, PileUp, b-tagging efficiency, b-jet purity, MC statistics, selection cuts, Luminosity, Theory (PDF and scale uncertainties).

- $\sigma(Z+bb)=0.37\pm0.02(stat.)\pm0.07(syst.)\pm0.02(theory)$ pb
- Some differences in Data vs MC comparison of kinematic distributions
- Additional studies involving NLO MC predictions may resolve the discrepancies

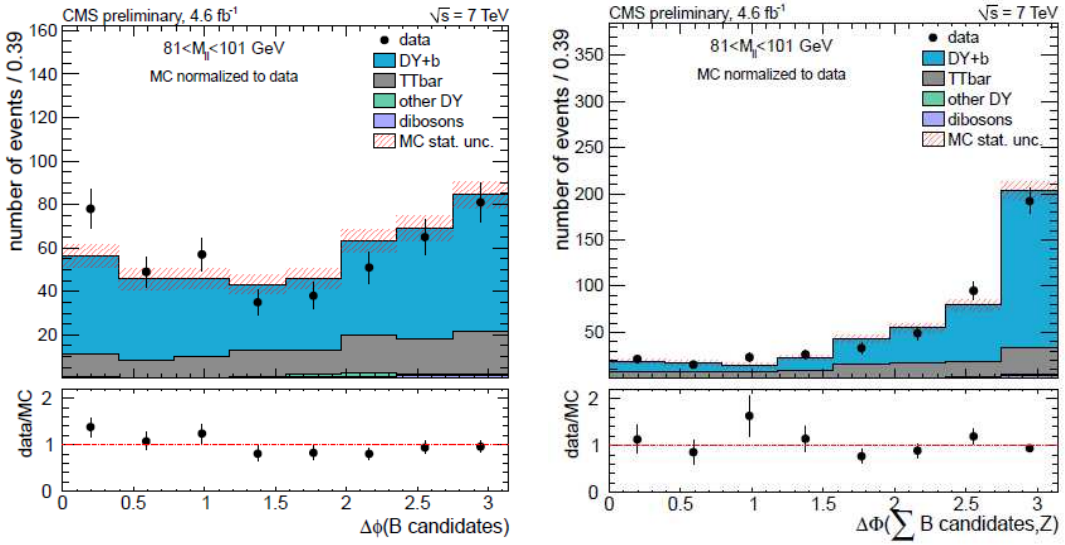


# BB Angular Correlation in Z+bb

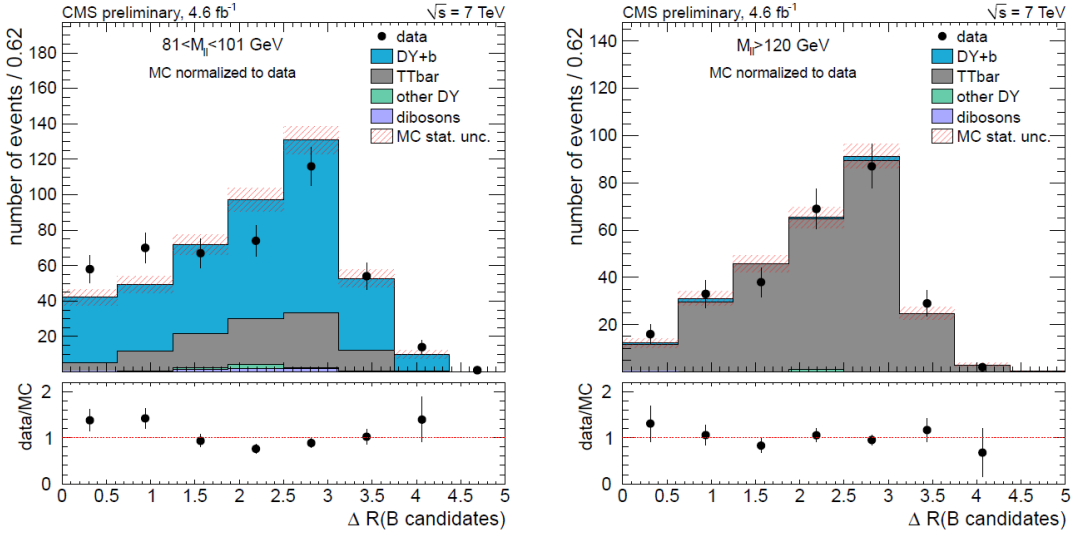
- CMS PAS EWK-11-015 : **4.6fb$^{-1}$**
- **Selection:**
  - **$\mu_1$ - $p_T$>20GeV, |η|<2.1, Iso<0.15**
  - **$e_1$ - $p_T$>25GeV [10GeV], |η|<2.5 (excluding 1.44< |η|<1.57), confined to ΔR<0.3 cone**
  - **60GeV<$M_{ll}$<120GeV**
  - **B candidates - $p_T$>8GeV, |η|<2, $m_{SV}$>1.4GeV**

- **Inclusive Secondary Vertex Finder (IVF):**
  - **Relies on tracking information (no use of jets)**
  - **Identifies charged products from B decays and combines tracks, while relying on the pion mass hypothesis**
  - **Allows us to study B-pair production even with small angular separation**

**Angular Separation Validation Plots**



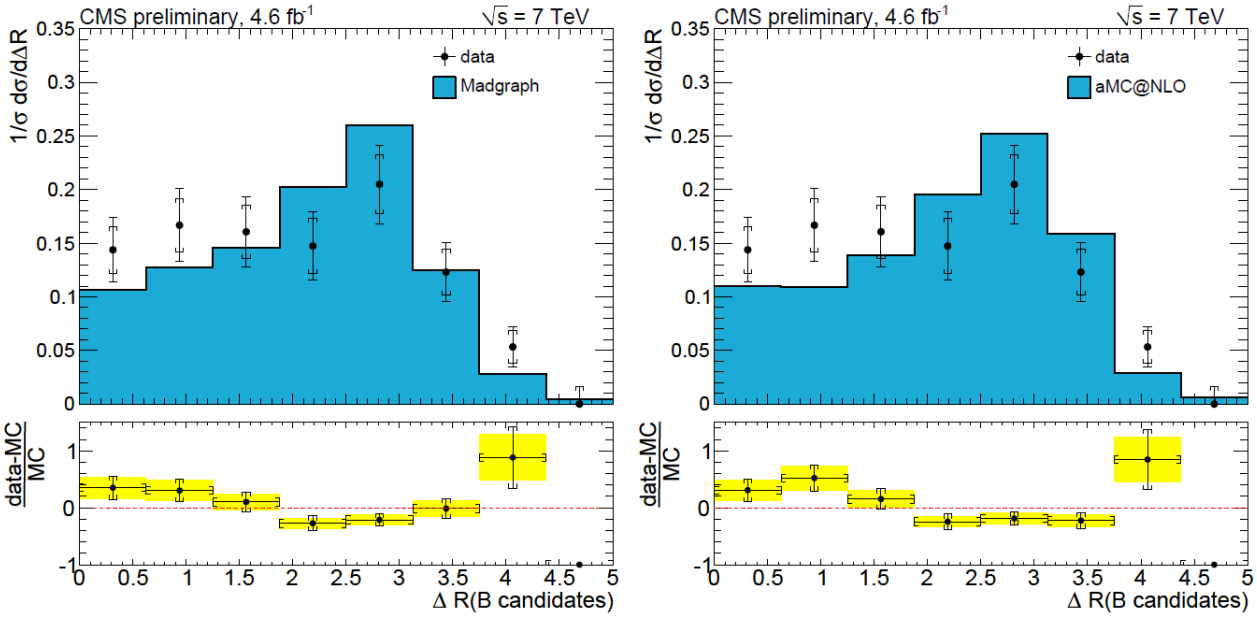
# Z+BB : ΔR Dependence




- **Agreement in the sideband region supports the robustness of the IVF technique.**
- **Distributions in the signal region need to be corrected for detector acceptance and efficiency effects.**

- **Extended Unbinned Maximum Likelihood Fit to $M_{ll}$ in each ΔR bin.**
  - **Signal - Breit-Wigner convoluted with a Gaussian resolution function. The shape parameters are taken from the fit**
  - **Background - Second-order Chebychev Polynomial, parameters are taken from the simulation**
- **Systematics: Lepton and B kinematics, IVF purity and phase space corrections, Fit uncertainty, MC statistics.**

# Z+BB Angular Dependence

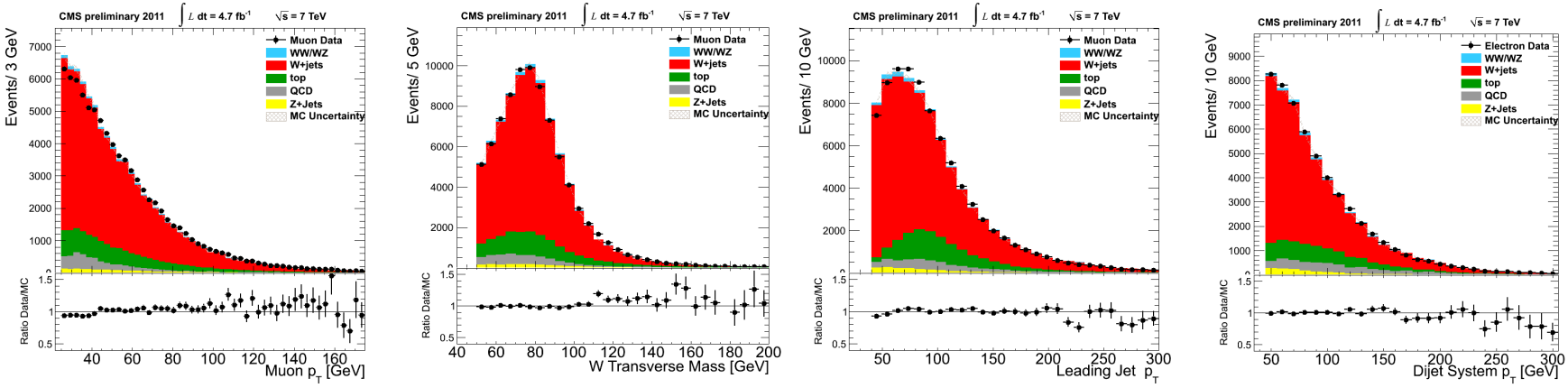



- **Perform the ($M_{ll}$) fit using either MADGRAPH (left) or aMC@NLO (right) simulation**
- **aMC@NLO does not include events with b's originating from MPI (multiple parton interactions) and light radiation coming from (only) hard scattering**

- **Reasonable agreement for most ΔR values**
- **Measured distributions suggest a globally flatter shape**
- **Need to understand the role of MPI and hard scattering process modeling - IVF absolute efficiency is required**

# Dijet Invariant Mass in W+Jets

- CMS PAS EWK-11-017 : **4.7fb$^{-1}$**
- **Selection:**
  - **$\mu$ - $p_T$>25GeV, $|\eta|$<2.1**
  - ***e*** **- $p_T$>35GeV, $|\eta|$<2.5 (excluding 1.44< $|\eta|$<1.57)**
  - **High quality lepton ID & Isolation and second lepton veto**
  - **MET>25(30)GeV for muon(electron) samples, $W_{mT}$>50GeV**
  - **PF Jets (anti-$k_T$, R=0.5) with $p_T$>30 GeV, $|\eta|$<2.4 , $\Delta R_l$>0.3**
- **Additional quality Cuts:**
  - **Leading Jet $p_T$>40GeV, $p_T^{jj}$>45GeV, $|\Delta\eta_{jj}|$<1.2, 0.3<Jet2$p_T/m_{jj}$<0.7**
  - **Designed to avoid removing potential New Physics**



# $M_{jj}$ in W+jets Fit Procedure

- Unbinned maximum likelihood for $40 < M_{jj} < 400$ GeV
- Exclude the potential signal region: $123 < M_{jj} < 186$ GeV
- Four Distinct Fits: $\mu_{2J}$, $\mu_{3J}$, $e_{2J}$ and $e_{3J}$ Bins (combine the results when setting exclusion limits)

- The (non W+jets) background contributions are free to float subject to Gaussian constraints.

**Backgrounds**

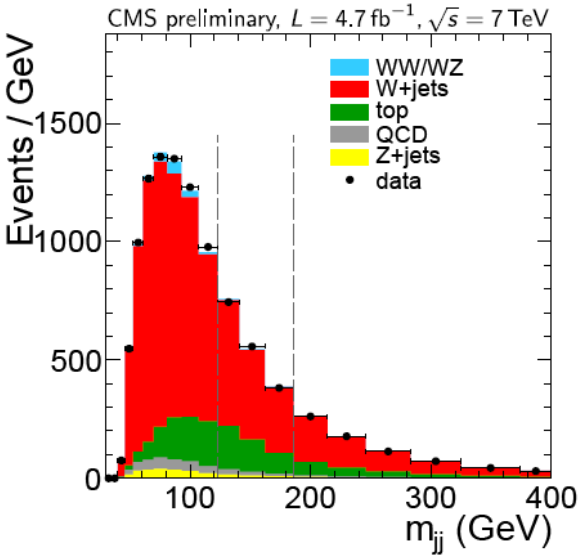
| Process | Shape | External constraint on normalization |
|---|---|---|
| W plus jets | MC/data | Unconstrained |
| Diboson | MC | Constrained: (NLO) 61.2 pb ± 10% |
| $t\bar{t}$ | MC | Constrained: (NLO) 163 pb ± 7% |
| Single top | MC | Constrained: (NNLO) [25–27] ± 5% |
| Drell-Yan plus jets | MC | Constrained: (NLO, $m_{ll} > 50$ GeV) 3048 pb ± 4.3% |
| Multijet | data | Constrained: $\not{E}_T$ fit in data ± 50% (100%) for electron (muon) |

- W+jets shape is a combination of:
  - Default (MADGRAPH) MC
  - Either Matrix Element - Parton Shower Matching Up ($\mu=2\mu_0$) or Matching Down ($\mu=0.5\mu_0$) MC
  - Either Factorization Scale Up ($q'=2q_0$) or Scale Down ($q'=0.5q_0$) MC
- The choice of Up or Down Sample is based on the best fit to the Data
- The relative fractions ($\alpha$,$\beta$) and the overall normalization are free to vary in the fit (empirical model):

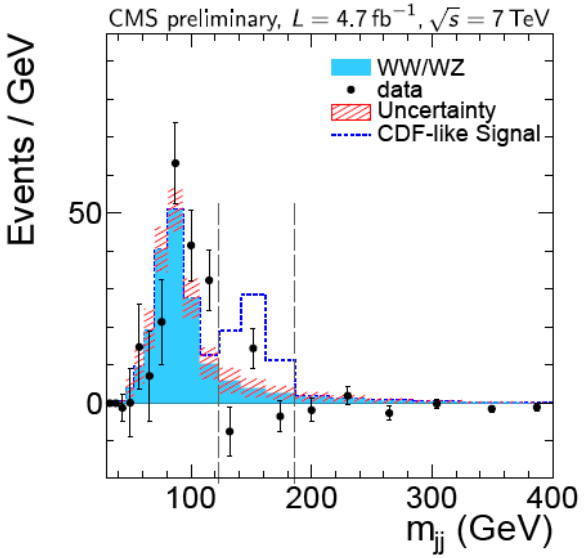
$$\mathcal{F}_{\text{W+jets}} = \alpha \cdot \mathcal{F}_{\text{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\text{W+jets}}(\mu'^2, q_0^2) + (1-\alpha-\beta) \cdot \mathcal{F}_{\text{W+jets}}(\mu_0^2, q_0^2)$$

# $M_{jj}$ in W+jets Fit Result

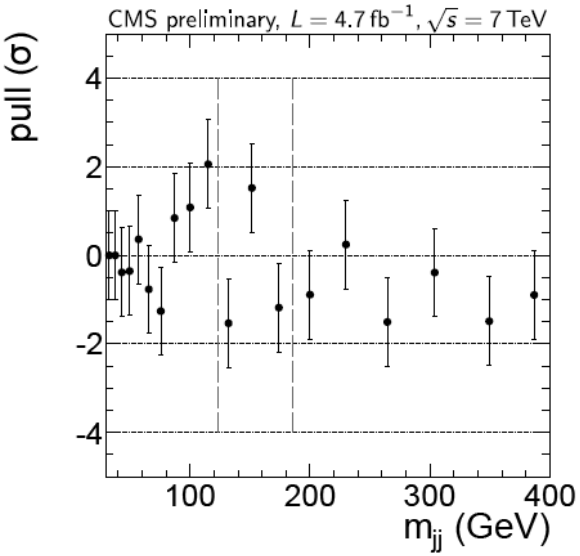
**Mjj Fit Result**




**All SM backgrounds, except WW+WZ subtracted**



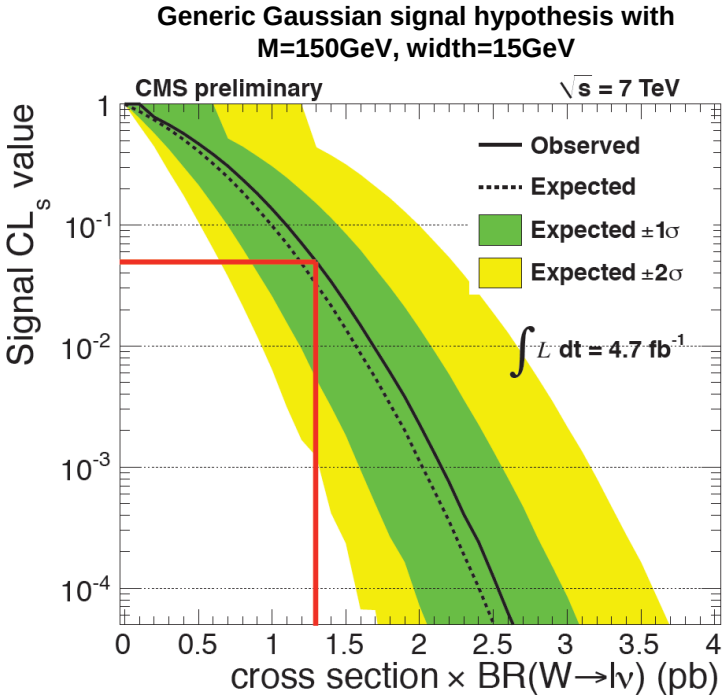

**Normalized Residual: [Data - Fit]/FitUncertainty**



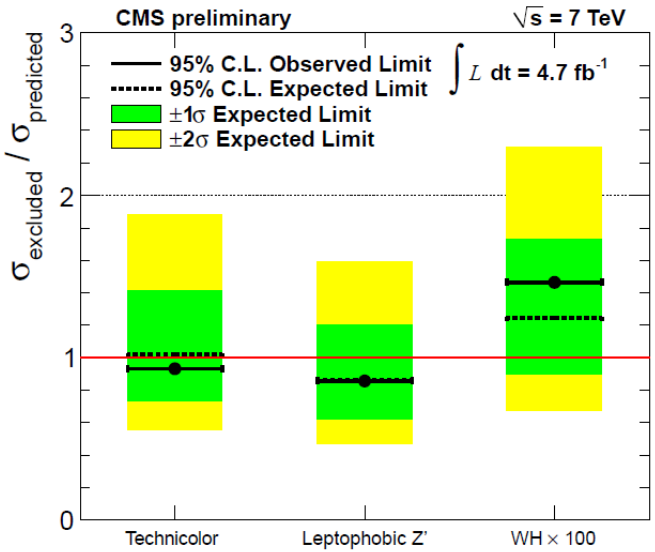

## ❖ Systematics

- **Mjj distribution shape uncertainty for W+jets is covered by the empirical modeling**
- **We validate the fitter by performing pseudo-experiments (with correlations taken into account) and correct the yields (errors) based on the resulting (pull) distributions. The procedure also covers the uncertainty due to limited MC.**
- **Uncertainties due to JES, JER, MET resolution, trigger efficiency, lepton reconstruction & selection efficiency and luminosity are included.**

# $M_{jj}$ in W+jets Exclusion Limits




- Upper limit on $\sigma x BR_{l\nu}$ of 1.3pb at 95% CL
- Compare to 3.4pb - equivalent of 4pb at the Tevatron, assuming the process is dominated by quark-antiquark annihilation (a conservative assumption).
- 95% CL upper limits for potential New Physics models




- No evidence for a resonant enhancement near a dijet mass of 150 GeV
- Several theoretical models are excluded

# Summary

- **V+Jets**
  - The Data is accurately described by MADGRAPH + PYTHIA Showering simulation, while PYTHIA alone fails for higher jet multiplicities
  - Results in W+Jets and Z+Jets Channels
- **W/Z + heavy flavor**
  - Rely on Secondary Vertex algorithms
  - Comparison between data and theory predictions
  - Quark PDF information (leading to improved EW precision & W-mass measurements)
  - Backgrounds to New Physics searches
- **$M_{jj}$ Spectrum in W+jets**
  - Search for an excess of events near $M_{jj}$=150GeV
  - Requires empirical background parameterization and fits in four separate channels
  - No significant excess is observed and several theoretical models are excluded

# References


- JHEP01(2012)010
- CMS PAS EWK-11-013
- CMS PAS SMP-12-003
- CMS-EWK-11-012, arXiv:1204.1643v1 [hep-ex]
- CMS PAS EWK-11-015
- CMS PAS EWK-11-017
- https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=145744
- CDF Collaboration, "Invariant Mass Distribution of Jet Pairs Produced in Association with a W boson in ppbar Collisions at sqrt(s) = 1.96 TeV", Phys. Rev. Lett. 106 (2011) 171801
- DØ Collaboration, "Bounds on an anomalous dijet resonance in W+jets production in ppbar collisions at sqrt(s) =1.96 TeV", Phys. Rev. Lett. 107 (2011) 011804
- Single Top [25-27]:
  - N. Kidonakis, "NNLL resummation for s-channel single top quark production", Phys.Rev. D81 (2010) 054028
  - N. Kidonakis, "Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production", Phys.Rev. D83 (2011) 091503
  - N. Kidonakis, "Two-loop soft anomalous dimensions for single top quark associated production with a W- or H-", Phys.Rev. D82 (2010) 054018