Measurement of WW and WZ production in the lepton plus heavy flavor jets final state at CDF

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on behalf of the CDF Collaboration

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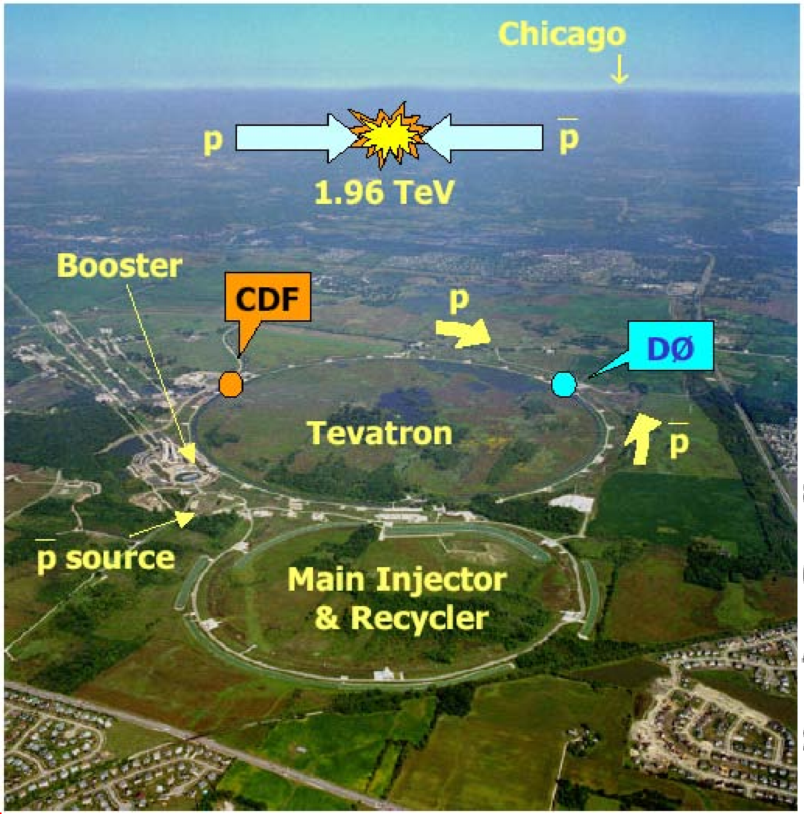
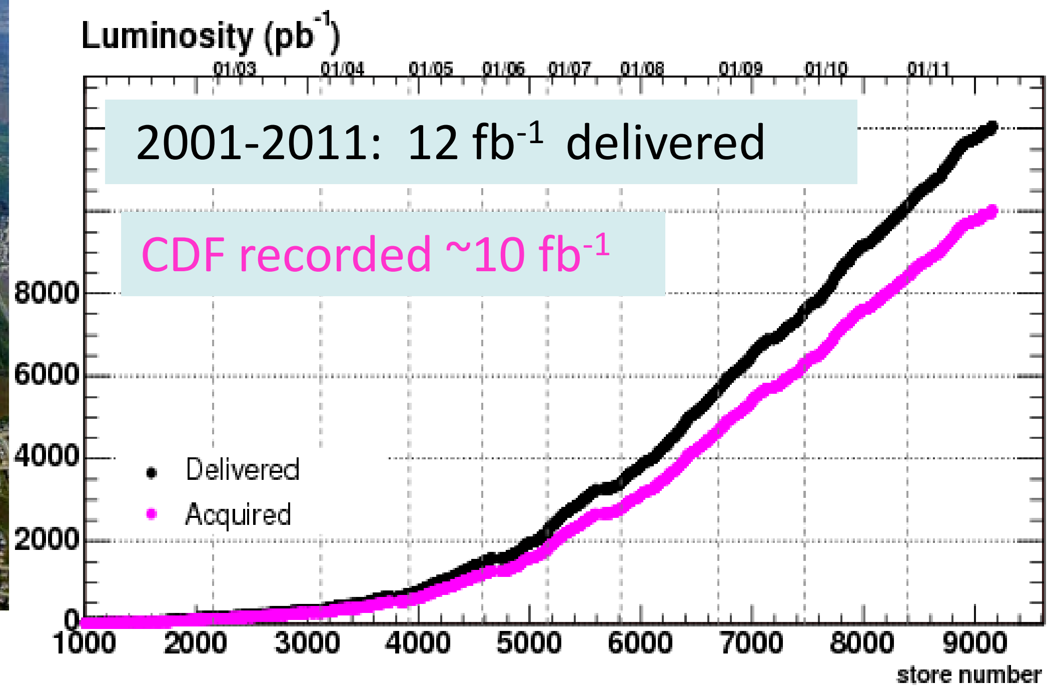
The Tevatron and CDF



Run II: √s = 1.96 TeV
Tevatron stopped providing p-pbar collisions on september 30, 2011



Among other interesting Standard Model results, Tevatron experiments took actively part to the hunt for the Higgs boson

Motivation for Diboson Search in $l\nu$ + heavy-flavor jets

- Diboson production is a theoretically well known process
- Probe of SM couplings $\Rightarrow$ a significant excess would open a window on new physics
- Often used as "benchmark" of experimental sensitivity to rare processes, in a variety of final states

$\Rightarrow$ one of the ways in which the Higgs was hunted is through its associated production with W bosons:

➢ WH $\rightarrow$ l ν + bb and WZ $\rightarrow$ l ν + bb share same final state

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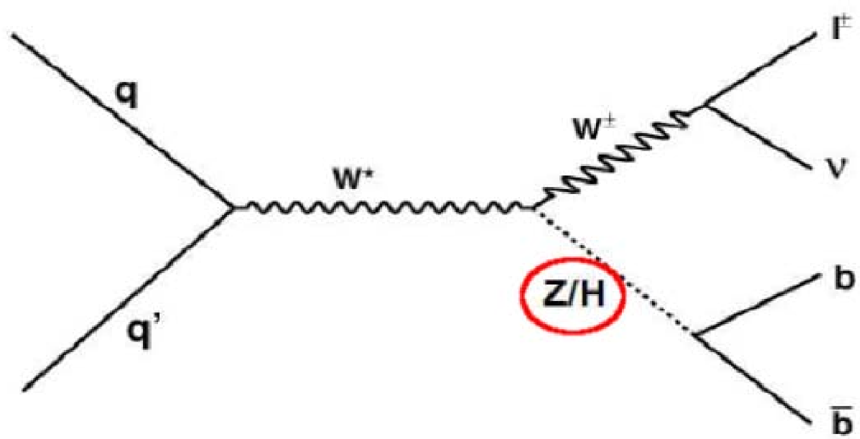
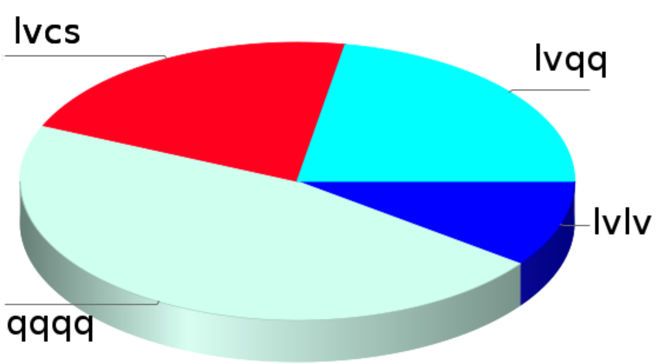
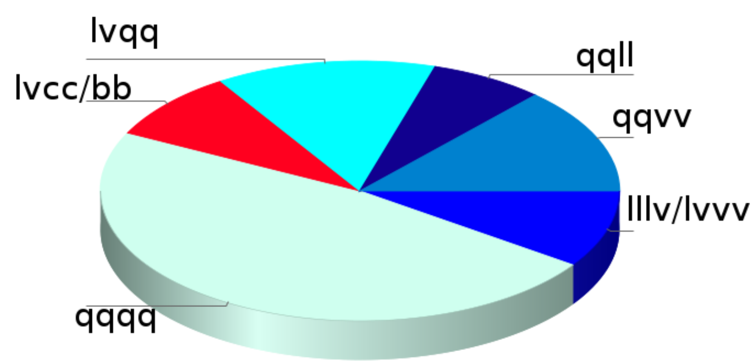


Motivation for Diboson Search in lν + heavy-flavor jets

- Leptonic final states:
  - ⇒ Clean signature, low background, small BR
  - ⇒ Measured with good precision at LHC and Tevatron
- Semi-leptonic final states:
  - ⇒ Experimentally challenging both at Tevatron and LHC
  - ⇒ Large non-resonant background: V+jets QCD production
  - ⇒ Poor di-jet mass resolution: no W-to-Z separation
- No precise measurement of WZ in semi-leptonic final state:
  - ⇒ Feasible using WW and WZ heavy-flavor (HF) decays



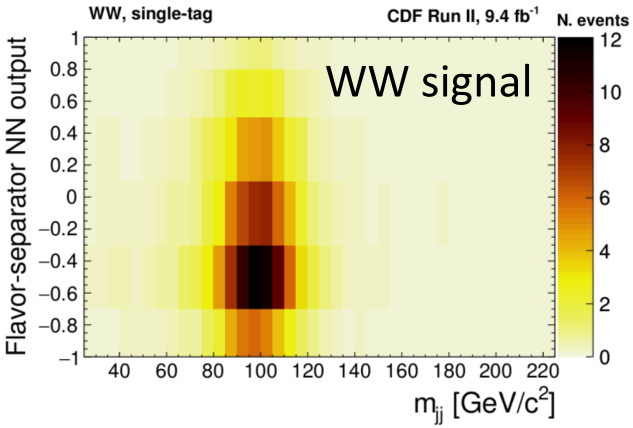
WW final state BRs

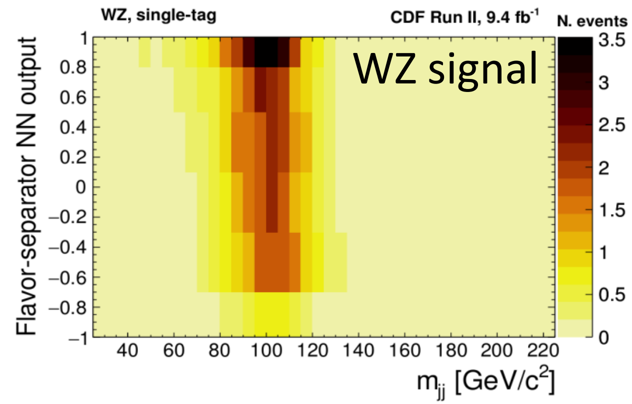


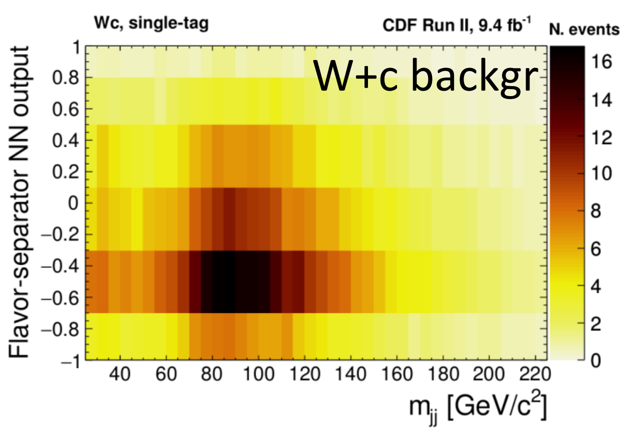
WZ final state BRs

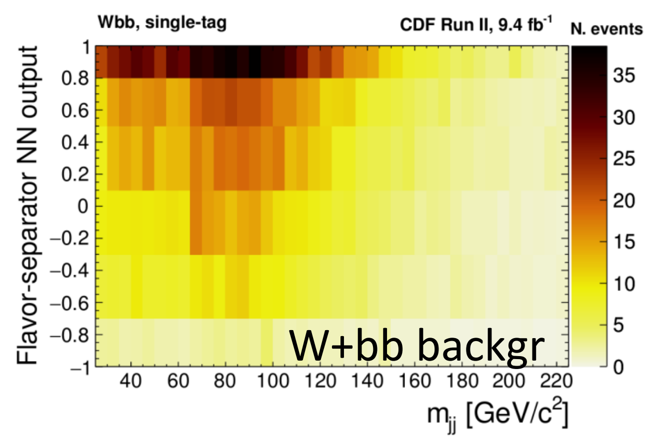
Analysis Strategy

- High-acceptance lepton-plus-two-jets selection (similar to single-top and WH):
  - $\Rightarrow$ Support Vector Machine discriminant used to suppress multi-jet (MJ) background
- Secondary-vertex jet tagging to enrich sample in HF and reduce W+jets background
- Search of a peak over large non-resonant background $\Rightarrow$ use m_{jj} as discriminant
- WW $\rightarrow l\nu$+cs versus WZ $\rightarrow l\nu$ +cc/bb $\Rightarrow$ 1-tag vs 2-tag and Flavor-separator NN









Event Selection

Full Run II data set: L =9.4 fb^{-1} with 6% uncertainty

- **Trigger: 4 event categories:**
  - ⇒ Central electrons
  - ⇒ Forward electrons
  - ⇒ Central muons
  - ⇒ Extended muons (using MET+jets)

- **Offline lepton selection:**
  - ⇒ Exactly 1 e/μ candidate: E_T (P_T) > 20 GeV
  - ⇒ Use of 10 lepton-ID classes:
    - ✓ central and forward electrons
    - ✓ 2 tight central muons
    - ✓ 5 loose muons
    - ✓ isolated tracks

- **Selection of pretag control sample:**
  - ⇒ Exactly two jets: $E_T > 20$ GeV, $|\eta| < 2{:}0.$
  - ⇒ $\not{E}_T > 15$ GeV,

- **HF-tagged signal samples:**
- One-tag:
  - ⇒ 1 jet tagged by SecVtx-tight
- Two-tags:
  - ⇒ Both jets tagged by SecVtx-tight or SecVtx-loose working points

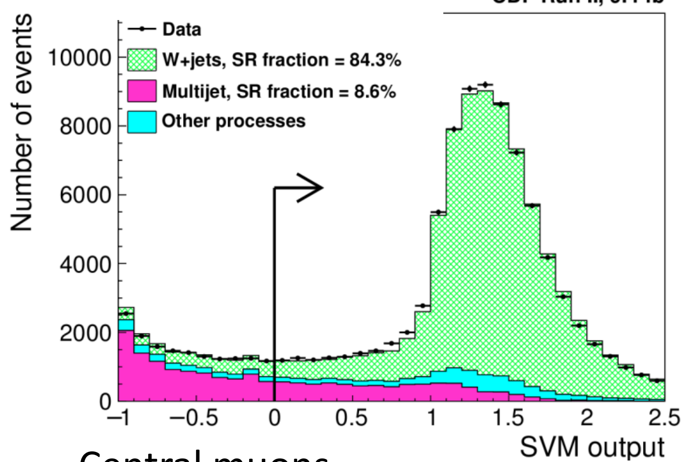
Background Estimate

- Main contributions from:
  - ⇒ W + heavy flavor, main source of irreducible background
  - ⇒ W + light flavor, mistakenly identified as a HF
  - ⇒ EWK: contributions from processes with a real lepton and HF jets
  - ⇒ Multi Jet (MJ): giving a boson-like signature and false missing ET
- Templates for EWK and W+jets backgrounds from simulation
- Normalization of the W+jets simulation determined in each lepton category using data before requiring b-tagging
- Data-driven models for MJ background:
  - ⇒ Muons: reverse Isolation cut (Iso > 0.1)
  - ⇒ Electrons: reverse at least 2 (out of 5) shower-id cuts (anti-e sample)
- MJ and W+jets template normalizations are left free in the fit

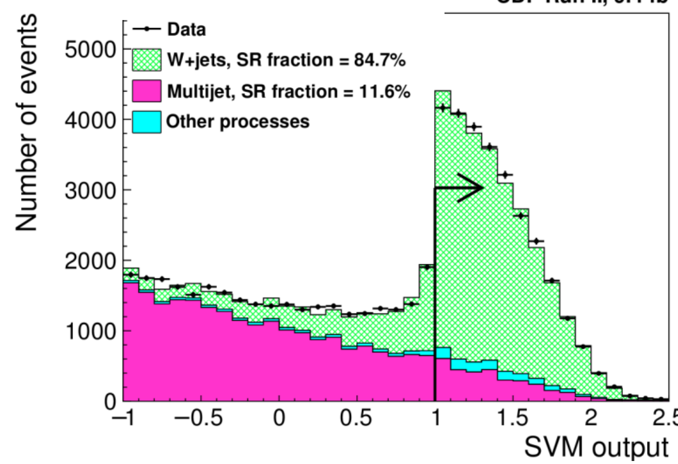
Multi-Jet Rejection and Normalization Extraction

- Data is superposition of multi-jet and W+jets contribution
- SVM multi-variate discriminant used for MJ rejection, and for templates of normalization fit

Central electrons

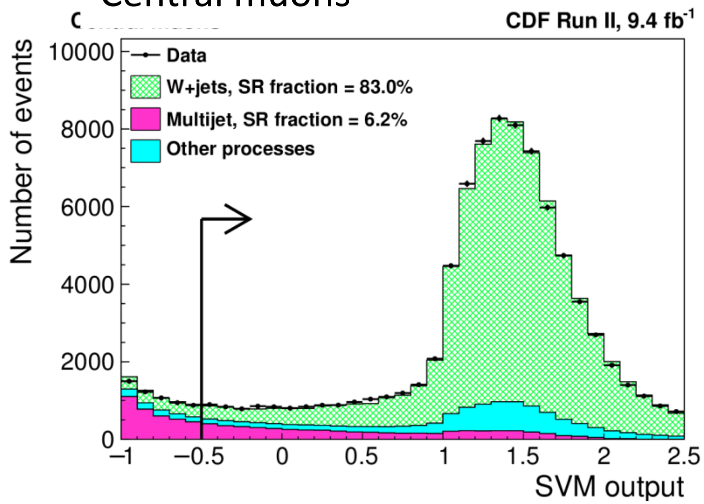


Forward electrons

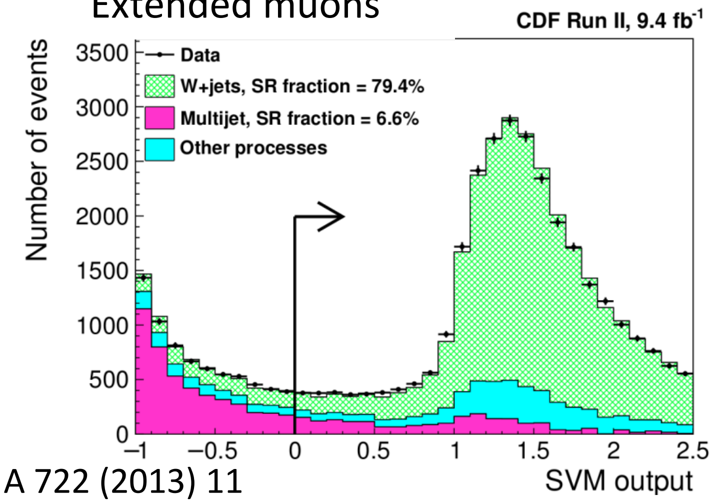


Arrows define the signal region

Central muons



Extended muons



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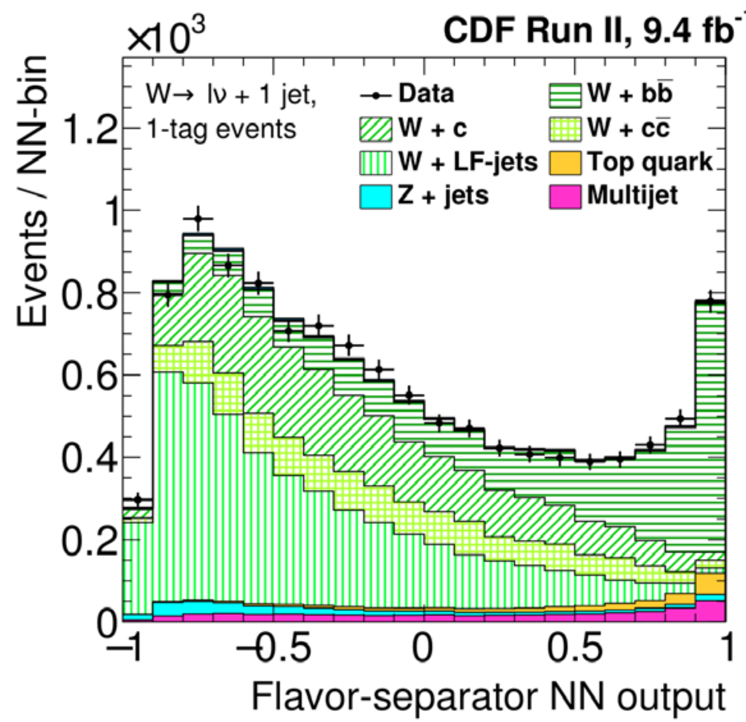
W + Heavy Flavor Estimate

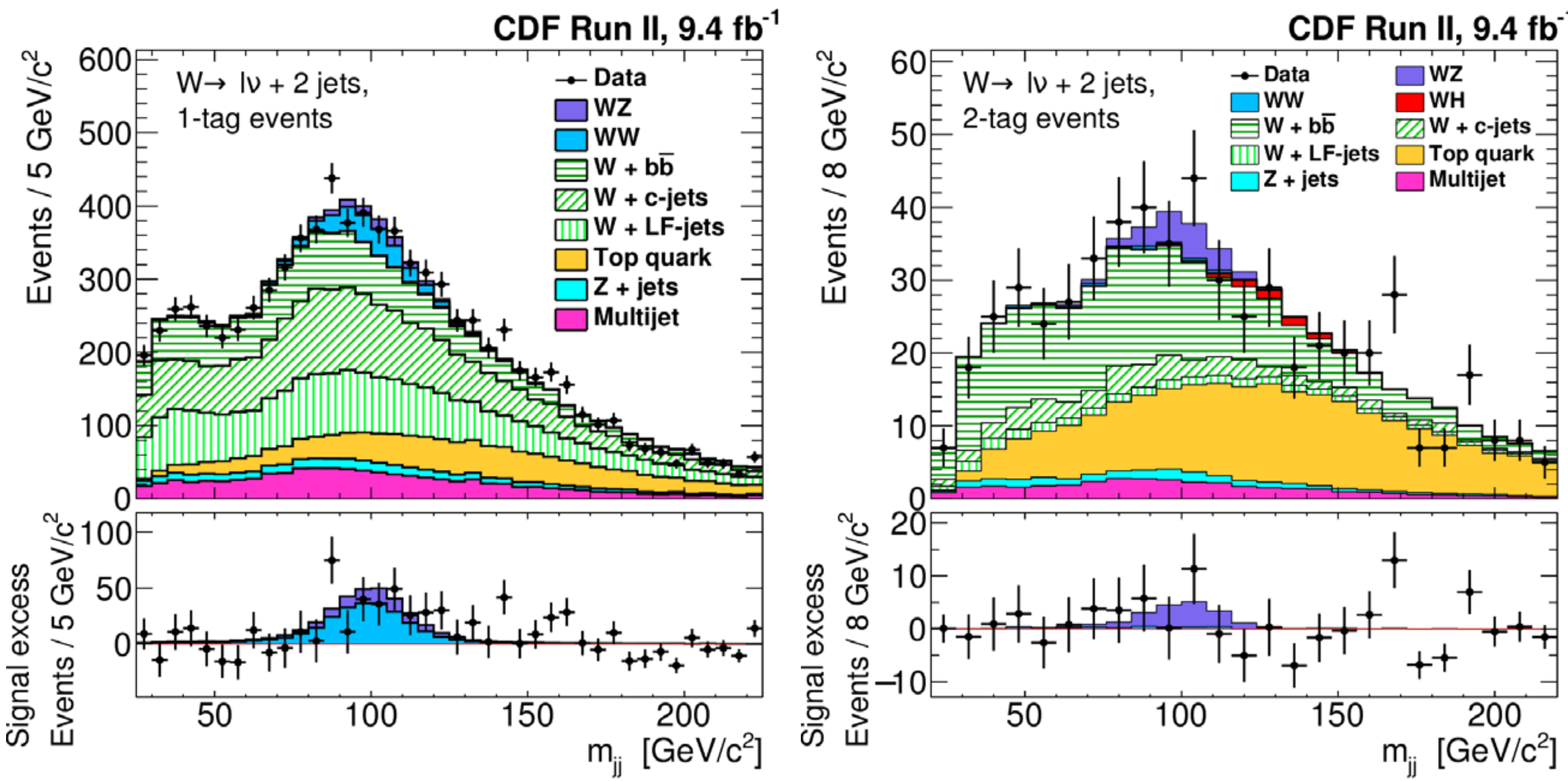
- Normalize W+jets yield to data
- Fraction of W+jets events with heavy flavor estimated from Alpgen MC
- Calibrate HF fractions using W+1 jet sample

$$N_{Wbb}^{data} = \left(\frac{N_{Wbb}}{N_{W+jets}}\right)^{MC} \cdot K_{HF} \, N_{W+jets}^{data}$$

$K_{cc} = K_{bb} = 1.24 \pm 0.25, \; K_c = 1.0 \pm 0.3$



Di-jet Invariant Mass Distributions

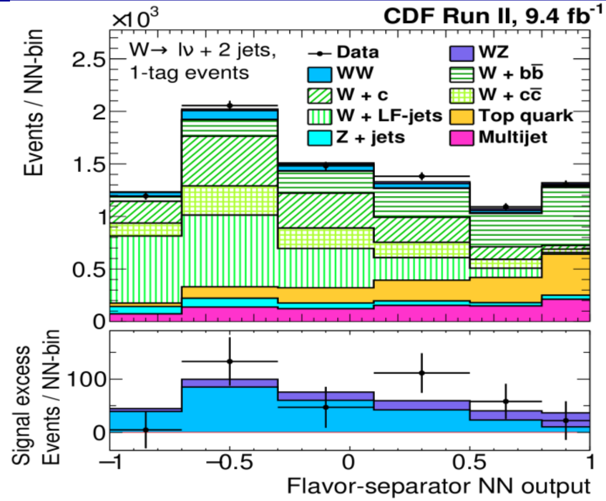


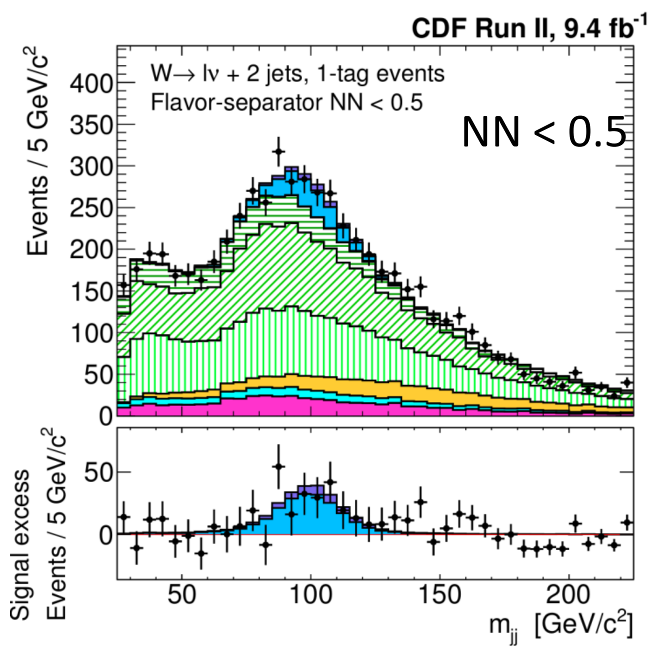
Single-tag events

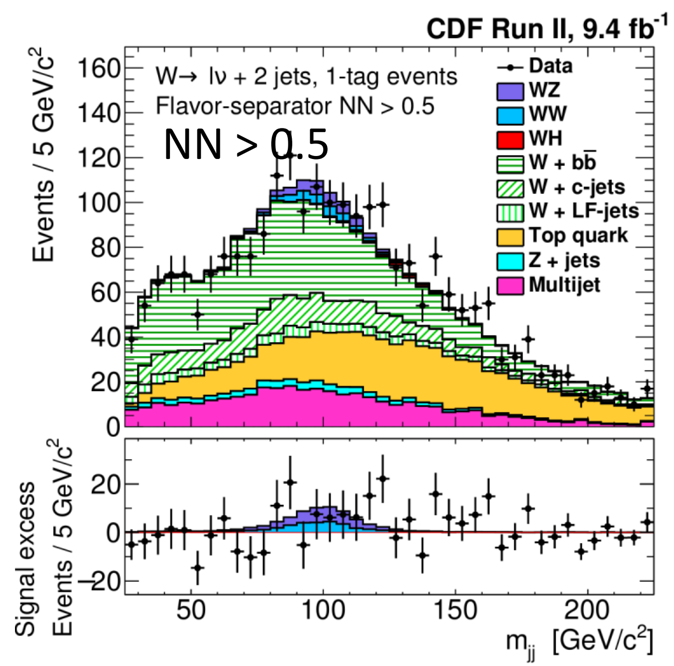
Double-tag events

Signal extraction using 2-dim variable

- Using flavour-separator NN to obtain b-quark versus c-quark separation
- 2-dimensional m_{jj} vs flavour-separator NN for single-tag events
- Different signal and background composition across NN values





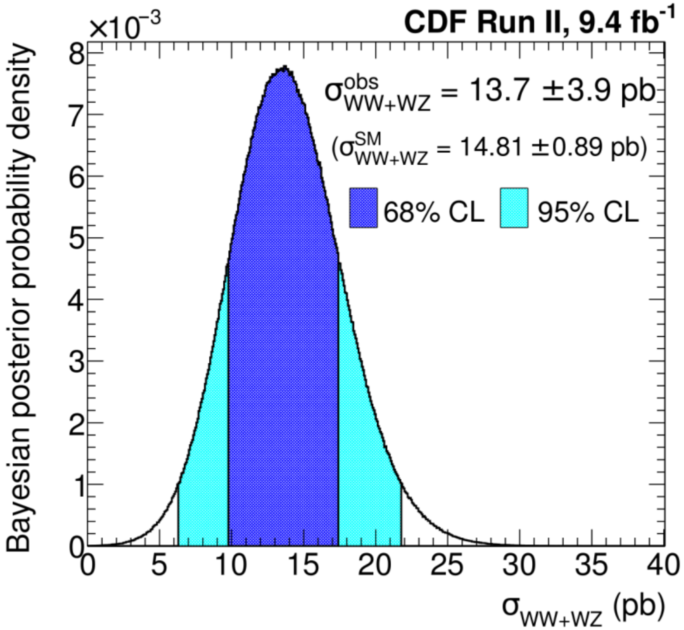


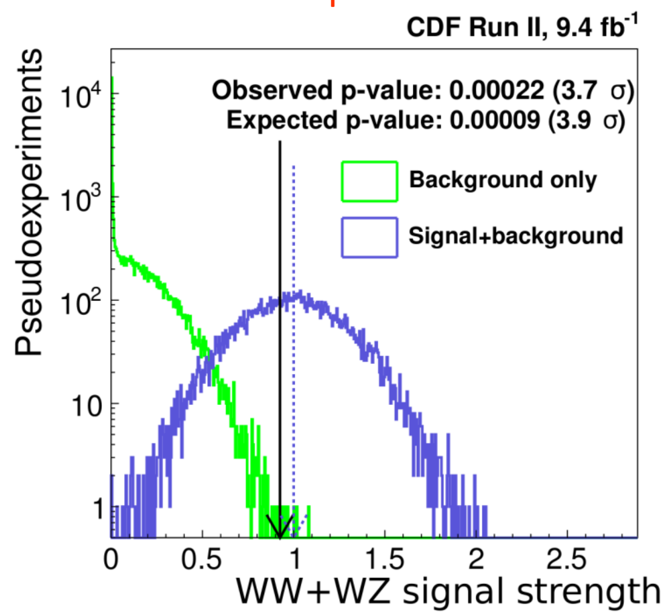
Measured WW+WZ Cross Section

- Likelihood function built with signal and background yield and shape predictions combining:
  - ⇒ Four lepton-analysis categories
  - ⇒ m_{jj} vs flavour-separator NN distributions for 1-tag
  - ⇒ m_{jj} distribution for 2-tag events

arXiv:1606.06823
Accepted by PRD

- Cross section extraction using Bayesian analysis:
  - ⇒ marginalize the posterior probability distribution over nuisance parameters





Posterior WW + WZ cross section:

$$\sigma^{obs}_{WW+WZ} = 13.7 \pm 2.4(\mathrm{stat}) \pm 2.9(\mathrm{syst}) = 13.7 \pm 3.9\ \mathrm{pb}$$

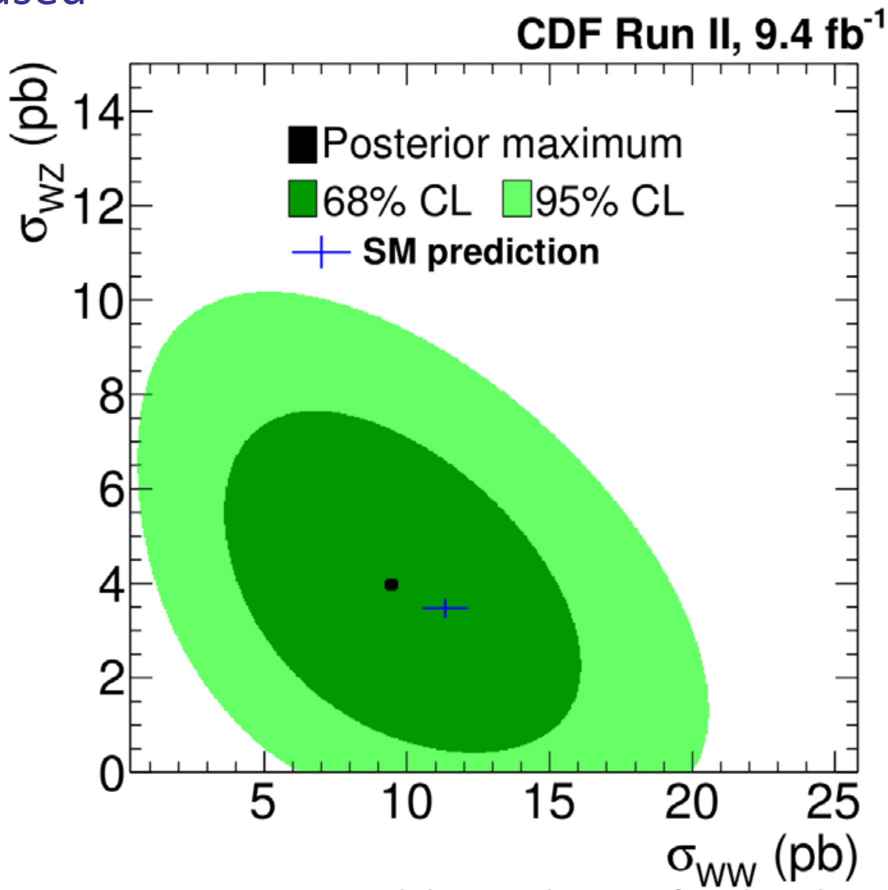
σ_{SM} = 14.8 ± 0.9 pb

Pseudoexperiments of background-only hypothesis compared to measurement:

WW + WZ signal significance: 3.7 σ
(3.9 σ expected)

Separate WW and WZ Cross Section Measurements

- WW vs WZ simultaneous signal extraction ⇒ 2-dimensional posterior distribution is used



- Measured cross sections compatible with SM for both WW and WZ signals detected in HF-enriched final state

WW and WZ Signal Results

- Measured integrating one or the other cross-section variable of 2-dim. posterior:

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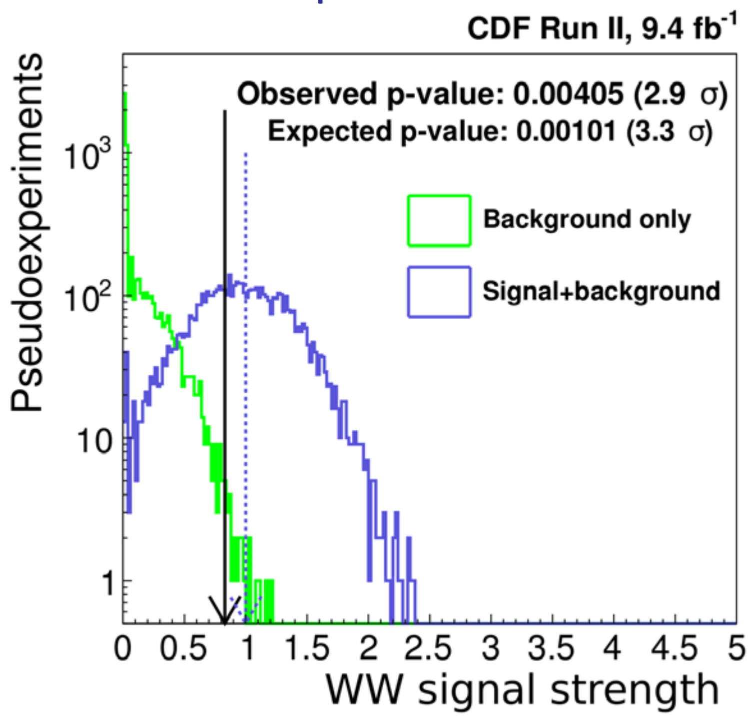
$$\sigma^{obs}_{WW} = 9.4^{+3.0}_{-3.0}(\text{stat})^{+2.9}_{-2.9}(\text{syst}) = 9.4 \pm 4.2 \text{ pb}$$

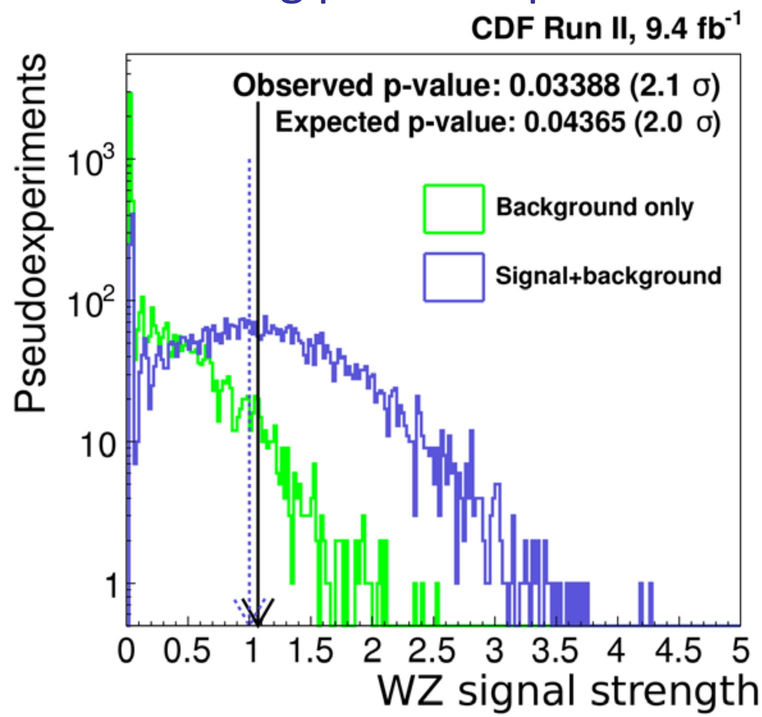
$$\sigma^{obs}_{WZ} = 3.7^{+2.0}_{-1.8}(\text{stat})^{+1.4}_{-1.2}(\text{syst}) = 3.7^{+2.5}_{-2.2} \text{ pb}$$

σ_{WW}^{SM}=11.7±0.9pb

σ_{WZ}^{SM}=3.5±0.2pb

- Evaluation of separate WW and WZ significance using pseudoexperiments:





- Significance: 2.9 σ for WW (3.3 σ expected), 2.1 σ for WZ (2.0 σ expected)

Conclusions

- WW and WZ diboson production have been measured in a semi-leptonic final state enriched in HF jets on the full Run II CDF data set
- Di-jet invariant mass and a flavour-separator NN have been used to extract the total and separate WW and WZ signal cross sections
- Total diboson cross section measured with a precision of about 30%, comparable with other experiment measurements in semi-leptonic final-states
- Separate WW and WZ cross sections measured with a precision of 45% and 60% respectively, with WZ measurement being the most precise in this final state
- Almost 5 years after the shutdown of the Tevatron, still digging out interesting results from the Tevatron data!!!

Conclusions

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Thank you!

Thanks to all the CDF collaborators and the Fermilab/Tevatron staff for many years of real fun!!

Backup

Event Selection

Full Run II data set: L =9.4 fb^{-1} with 6% uncertainty

- **Trigger strategy and 4 event categories:**
  - ⇒ Central electrons
  - ⇒ Forward electrons
  - ⇒ Central muons
  - ⇒ Extended muons (using MET+jets)
- Events selected by common trigger have homogeneous kinematic and background composition

- **Offline lepton selection:**
  - ⇒ Exactly 1 e/μ candidate: E_T (P_T) > 20 GeV
  - ⇒ Use of 10 lepton-ID classes:
    - ✓ central and forward electrons
    - ✓ 2 tight central muons
    - ✓ 5 loose muons
    - ✓ isolated tracks
- All leptons isolated in calorimeter, except iso-tracks isolated in tracking

- **Selection of pretag control sample:**
  - ⇒ Exactly two jets: E_T > 20 GeV, $|\eta|$ < 2:0.
- Jet energy corrections: JES and Quark-Gluon response in MC
- $\not{E}_T$ > 15 GeV, corrected for muon track, JES, primary-vertex

- **Definition of HF-tagged signal samples:**
- One-tag:
  - ⇒ 1 jet tagged by SecVtx-tight
- Two-tags:
  - ⇒ Both jets tagged by SecVtx-tight or SecVtx-loose working points

Background and Signal Yield Estimates

Process	Pretag	one-tag	two-tag
MJ	$18\,100 \pm 2700$	800 ± 330	30 ± 14
W+LF	$161\,700 \pm 3700$	2440 ± 350	29.5 ± 6.8
$W + c\bar{c}$	$13\,400 \pm 1700$	1190 ± 290	33 ± 16
$W + c$	$11\,600 \pm 2200$	930 ± 310	12.5 ± 5.5
$W + b\bar{b}$	6370 ± 930	2190 ± 520	313 ± 125
Z + jets	9400 ± 1900	281 ± 42	13.5 ± 2.1
$t\bar{t}$	1600 ± 230	663 ± 94	137 ± 22
Single-top ($s + t$ channels)	1109 ± 42	441 ± 23	70.8 ± 8.4
ZZ	93.4 ± 4.4	10.1 ± 0.7	2.0 ± 0.3
WH+ZH	40.0 ± 1.4	17.6 ± 0.8	5.4 ± 0.6
WW	5530 ± 400	240 ± 30	3.0 ± 0.7
WZ	904 ± 53	91.4 ± 7.6	17.2 ± 2.1
Total prediction	$229\,900 \pm 5800$	9300 ± 1200	670 ± 140
Observed data	$232\,145$	9074	604

- Rate systematics uncertainties included in the table:

  $\Rightarrow$ theory, luminosity, trigger-efficiency, lepton-ID SF, HF K-factor, SecVtx SF, MJ rate
- Additional shape and rate systematics considered:

$\Rightarrow$ JES, ALPGEN Q^2, flavour-separator response to c-jets, Light Flavor jets and Multi-Jet events

Background Estimate

- Method developed for l+jets, HF-tagged analyses. The key points are:
- W+jet pretag normalization extracted from template-fit of multi-jet (MJ) vs W+jets:

$$N^{W+Jets} = N^{Data}_{Pretag}(1 - F^{MJ}) - N^{MC}$$

- W+jets line-shape and HF component from ALPGEN LO, multi-leg simulation
- Estimate of W + HF (W + bb, W + cc, W + c) normalization:

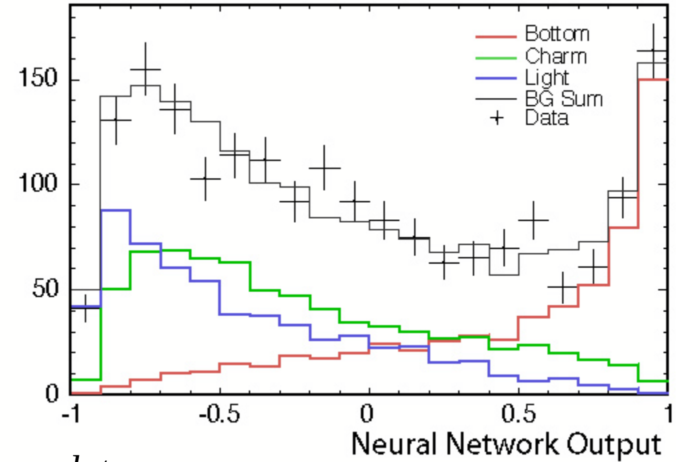
$$N^{HF} = N^{W+jets} \times f^{HF} \times \epsilon_{tag} \times K^{HF}$$

- $f^{HF} = \frac{W+HF}{W+jets}$: HF fractions derived from MC
- ϵ_{tag} : tagging efficiency derived from MC and corrected by per-jet SF_{tag}
- $K^{HF} = \frac{f^{HF}_{data}}{f^{HF}_{MC}}$: correction to HF production rate in MC:

$\Longrightarrow$ Extracted from W + 1 jet control sample

W + Heavy Flavor Estimate

- Normalize W+jets yield to data
- Fraction of W+jets events with heavy flavor estimated from Alpgen MC
- Calibrate HF fractions using W+1 jet sample



$$N_{Wbb}^{data} = \left(\frac{N_{Wbb}}{N_{W+jets}}\right)^{MC} \cdot K_{HF} \cdot N_{W+jets}^{data}$$

Correct data for non W+jets events

$$N_{W+jets}^{data} = N_{Candidates}^{data} - N_{non-W} - N_{EWK}$$

$$N_{EWK} = \sigma_{EWK} \cdot A \cdot L$$

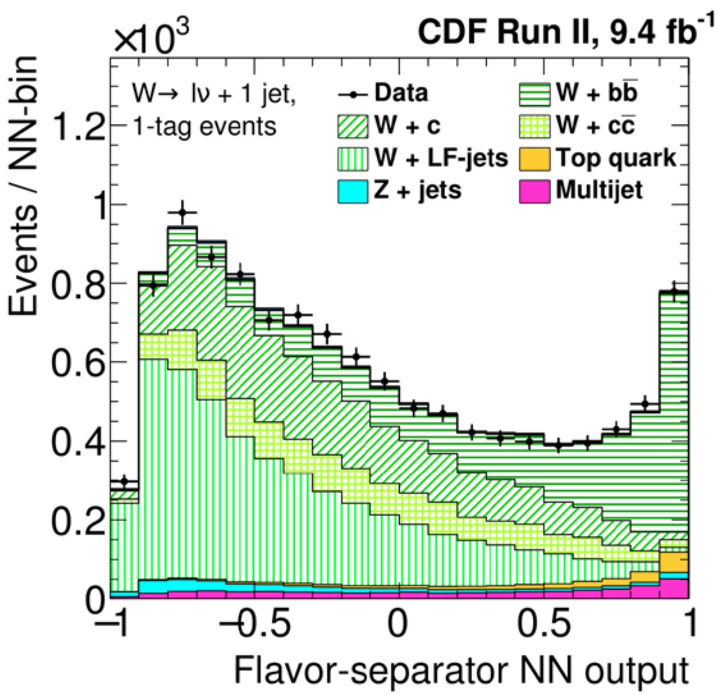
Heavy flavor fractions and b-tagging efficiencies from LO ALPGEN Monte Carlo

Calibrate ALPGEN heavy flavor Fractions by comparing W + 1jet data with ALPGEN Monte Carlo

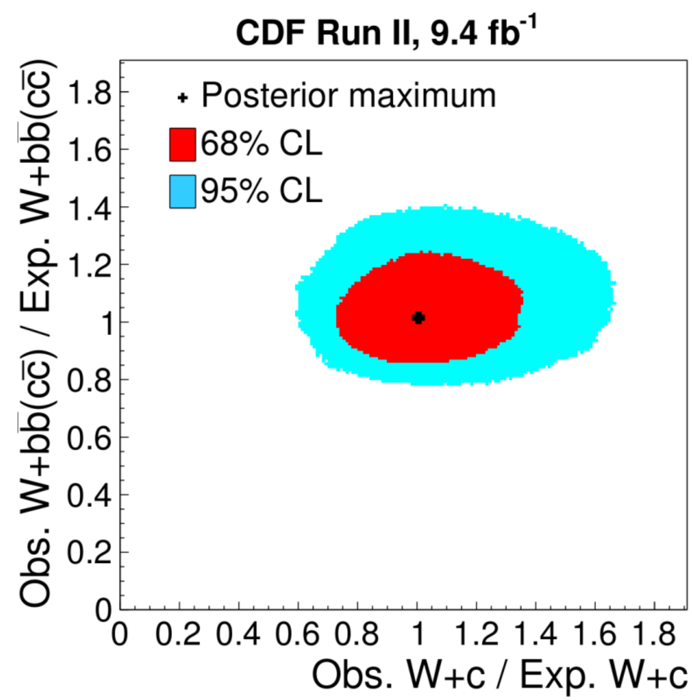
Evaluation of HF Correction Factors

- W + bb/cc and W + c K-factors extraction from W + 1 jet control sample:
- Analysis repeated for central tight leptons, 1-jet selection, pretag and 1-tag cat.
- Simultaneous extraction of Kcc = Kbb and Kc using flavour-separator NN
- Iterative measurement ⇒ Kcc = Kbb and Kc re-included in successive iterations

Flavor-separator NN for 1-jet events



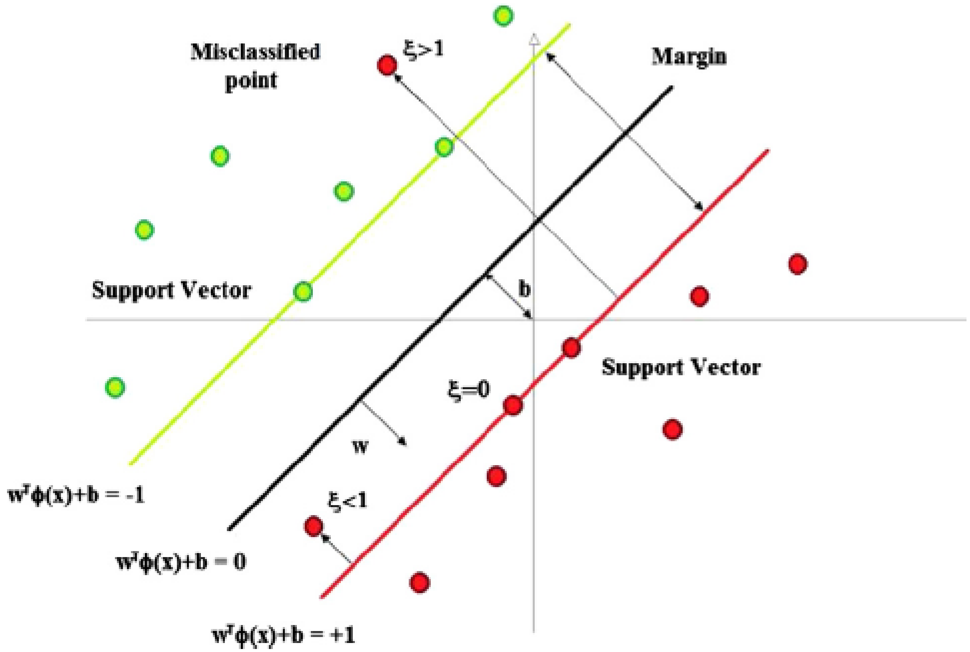
Last iteration of correction factors extraction



- **Result: Kcc = Kbb = 1.24, Kc = 1.0, 20% and 30% uncertainties respectively**

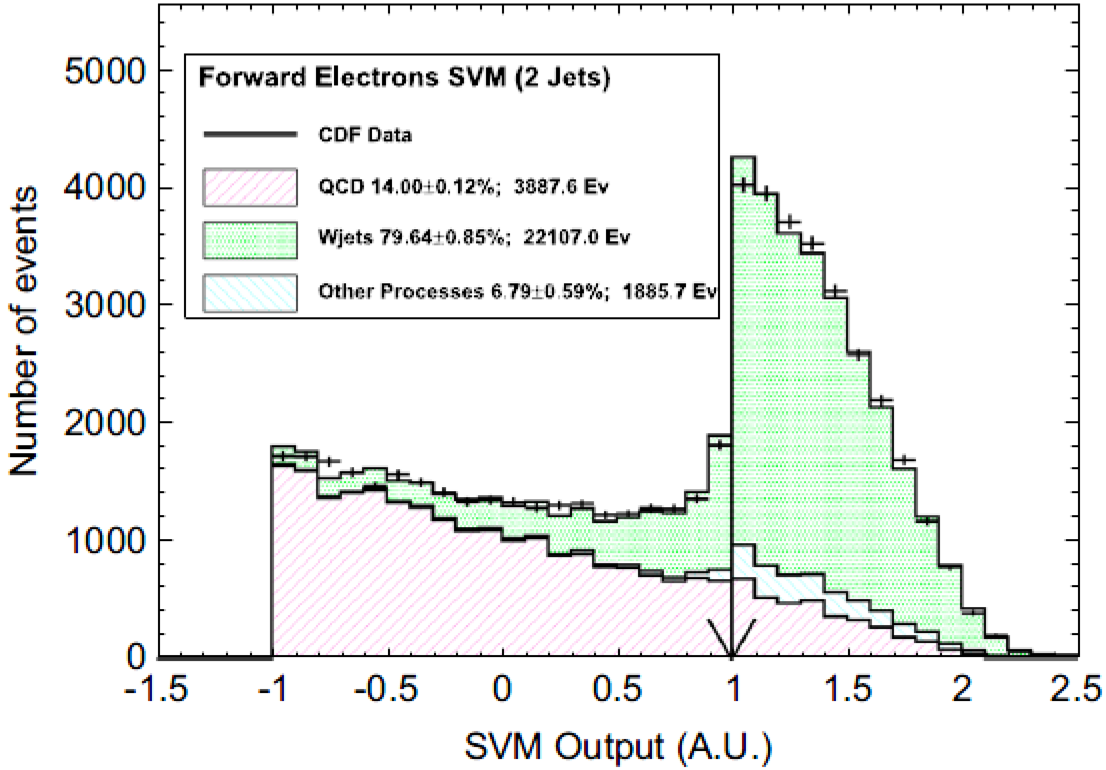
Support vector machine

How the linear classification problem can be formalized:



Two linearly separable classes of vectors are represented with red and blue dots.The plane leading to a maximum separation is defined by the weight vector w and the constant term b. NIM A 722 (2013) 11-19.

Multi jet background rejection in W+jets data sample



Contribution of the different physics processes to the shape of the SVM output distribution D used during the forward electron sample selection.The multi-jet background fraction (in magenta) is extracted from the fit together with the total W+ jets component (in green). The remaining physics processes are normalized to the expected production cross-sections. The SVM selection threshold for the final signal region identification is D=1

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SVM input variables

All the possible input variables used for the SVM training and optimization.

Possible input variables							
1	p_T^{lep}	7	$E_T^{raw,jet1}$	13	$\Delta\phi(\not{p}_T, lep)$	19	$\Delta R(lep, jet2)$
2	$\not{E}_T$	8	$E_T^{raw,jet2}$	14	$\Delta\phi(\not{p}_T, \not{E}_T)$	20	$\Delta R(\nu^{min}, jet1)$
3	$\not{E}_T^{raw}$	9	$E_T^{cor,jet1}$	15	$\Delta\phi(\not{p}_T, \not{E}_T^{raw})$	21	$\Delta R(\nu^{min}, jet2)$
4	$\not{p}_T$	10	$E_T^{cor,jet2}$	16	$\Delta\phi(lep, \not{E}_T)$	22	$\Delta R(\nu^{min}, lep)$
5	M_T^W	11	$\Delta\phi(jet1, \not{E}_T)$	17	$\Delta\phi(lep, \not{E}_T^{raw})$	23	$\Delta R(\nu^{max}, jet1)$
6	$MetSig$	12	$\Delta\phi(jet2, \not{E}_T)$	18	$\Delta R(lep, jet1)$	24	$\Delta R(\nu^{max}, jet1)$

Final input variables used for the central and forward SVM multi-jet discriminant:

Final SVM input variables			
Central SVM:	M_T^W	$\not{E}_T^{raw}$	$\not{p}_T$
	$MetSig$	$\Delta\phi(\not{p}_T, \not{E}_T)$	$\Delta\phi(lep, \not{E}_T)$
	$\Delta R(\nu^{Min}, lep)$	$\Delta\phi(jet1, \not{E}_T)$	
Forward SVM:	M_T^W	$\not{E}_T^{raw}$	$\not{p}_T$
	$MetSig$	$\Delta\phi(\not{p}_T, \not{E}_T)$	$\Delta\phi(\not{p}_T, \not{E}_T^{raw})$

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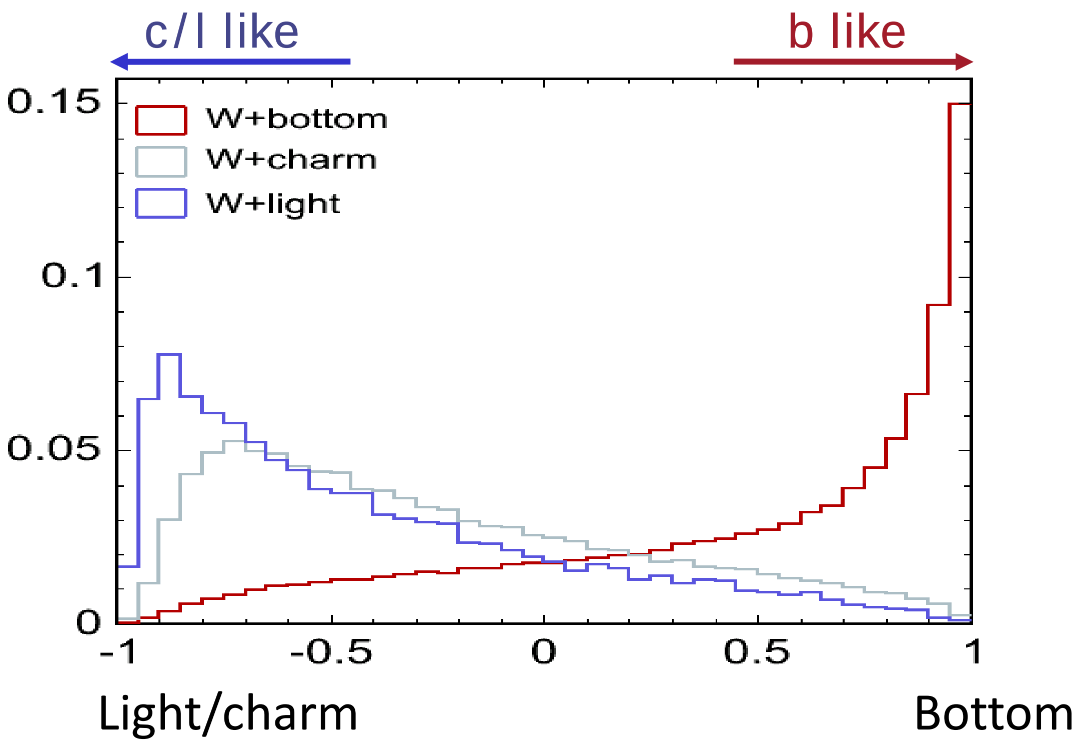
Flavor Separator NN

- Developed for single top search
- Train Neural Network with jet and secondary vertex tracking information (25 input variables) for bottom/charm/light flavor separation

  $\Rightarrow$ Lxy, vertex mass, track multiplicity, impact parameter, semi-leptonic decay information, etc...
- Replaces Yes-No tag decision by a continuous variable *(0<b<1)*



Systematic uncertainties

- Affecting the rate:
  - ⇒ luminosity (6%)
  - ⇒ lepton acceptance (including trigger efficiencies, lepton reconstruction scale factors, from 2% to 5%)
  - ⇒ b and c tagging efficiency (from 3% to 10%)
  - ⇒ PDFs and radiative corrections (approx. 4%)
  - ⇒ Theory uncertainties on EWK backgrounds (from 5% to 40% for Z+jets)
  - ⇒ Mistag estimate (15% and 23% for single and double tag)
  - ⇒ W + HF fractions corrections (from 20% to 40%)
- Affecting both rate+shape
  - ⇒ Flavor separator NN
  - ⇒ Multi-Jet model
  - ⇒ Jet energy corrections
  - ⇒ W+jets Q^2