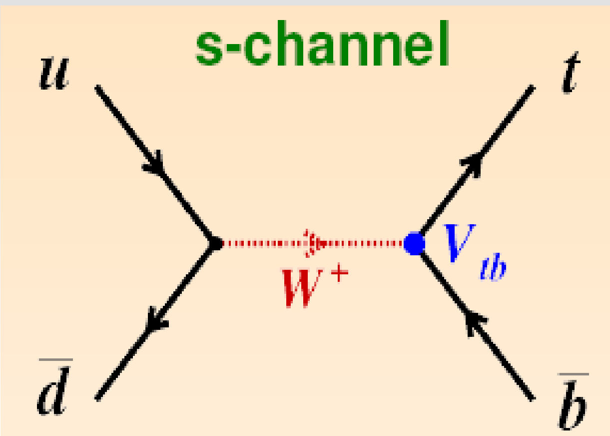
Single Top and Associate Vector Boson Production

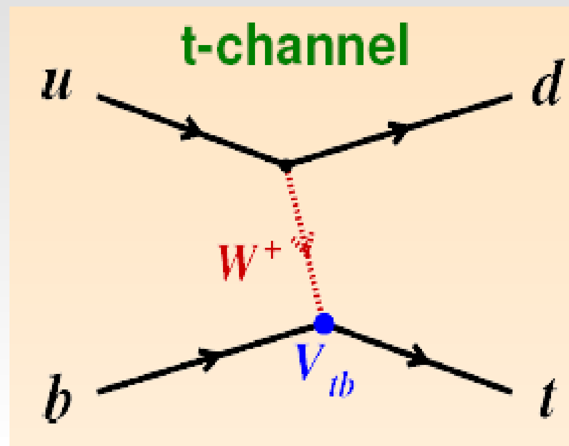
Outline :

- Single top cross section measurement
- Heavy di-boson cross section
  - WZ
  - ZZ

Single Top Cross Section: Introduction

LO diagrams





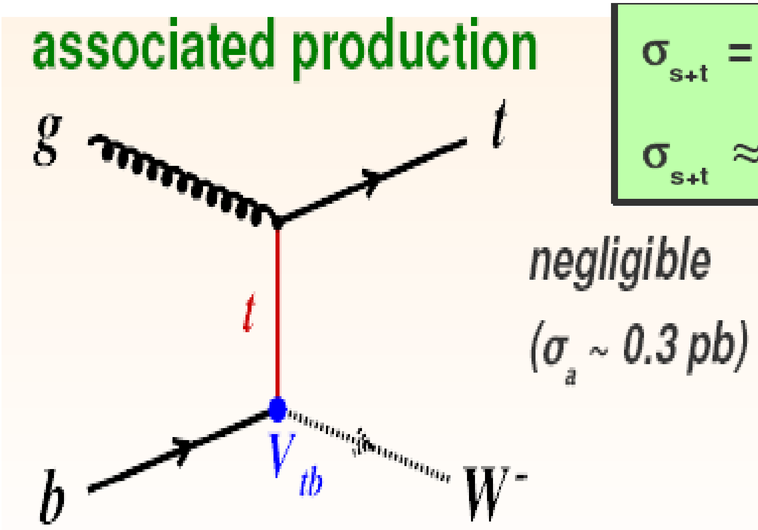
Standard Model prediction:

$\sigma_{t\text{-channel NLO}} = 2.0 \pm 0.3$ pb

$\sigma_{s\text{-channel NLO}} = 0.9 \pm 0.1$ pb

$\sigma_{\text{single top NLO}} = 2.9 \pm 0.4$ pb

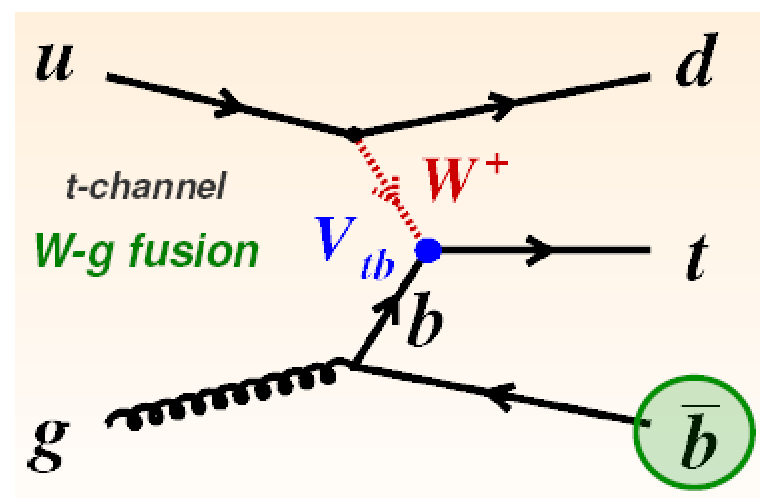
Harris et al., Phys. Rev. D 66, 054024
Sullivan, Phys. Rev. D 70, 114012



$\sigma_{s+t} = 2.9 \pm 0.4$ pb

$\sigma_{s+t} \approx 0.4\ \sigma_{\text{top pair}}$

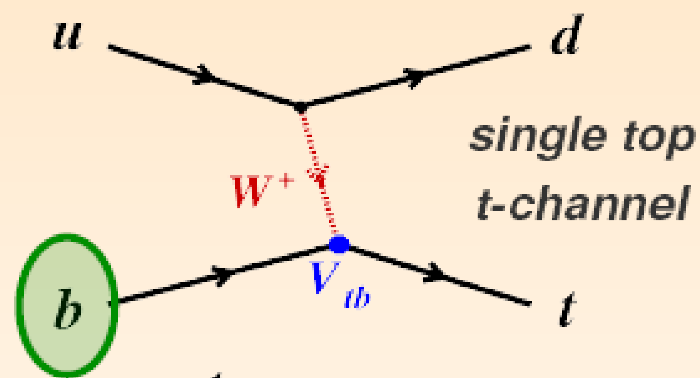
Most important NLO diagram



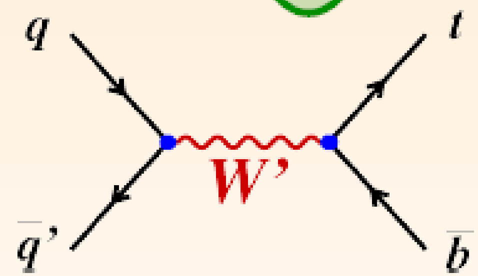
Single Top Cross Section: Why Interesting?

Production of single top quarks:

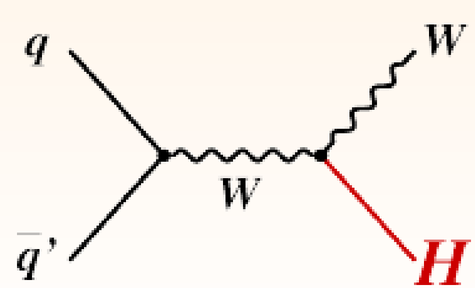
- Test of SM prediction
- $\sigma_{\text{single top}} \sim |V_{tb}|^2$ → measurement of V_{tb}



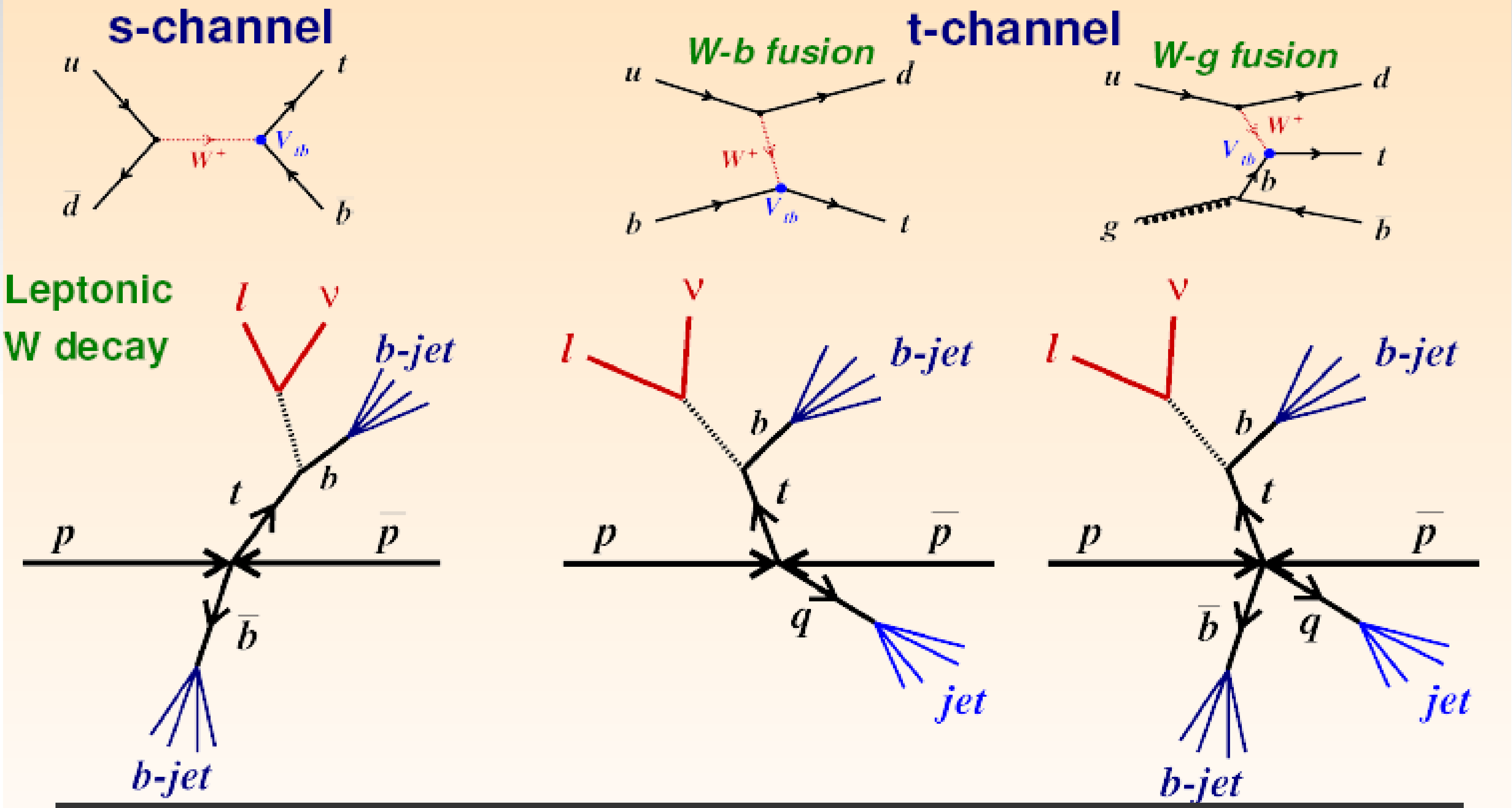
- Test of **b-quark** structure function
  (DGLAP evolution)
- Search for non-SM contributions
  (W' or H+)



- Technical motivation - WH, H → $b\bar{b}$
  (Same final state, $\sigma_{WH} \approx 0.1\ \sigma_{\text{single top}}$)



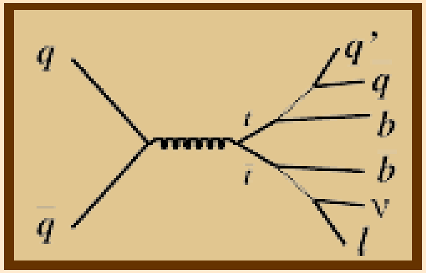
Single Top: Event Topology

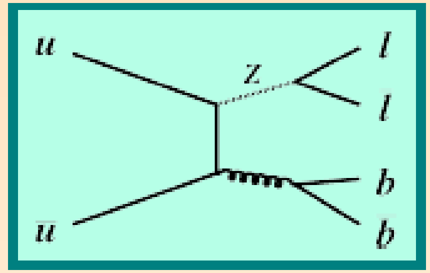


Signature: Exactly one isolated high p_T e or μ, missing E_T, ≥ 2 jets, ≥ 1b-jet

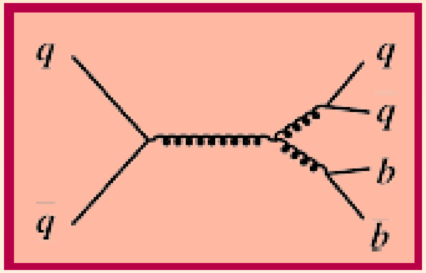
Single Top Cross background process

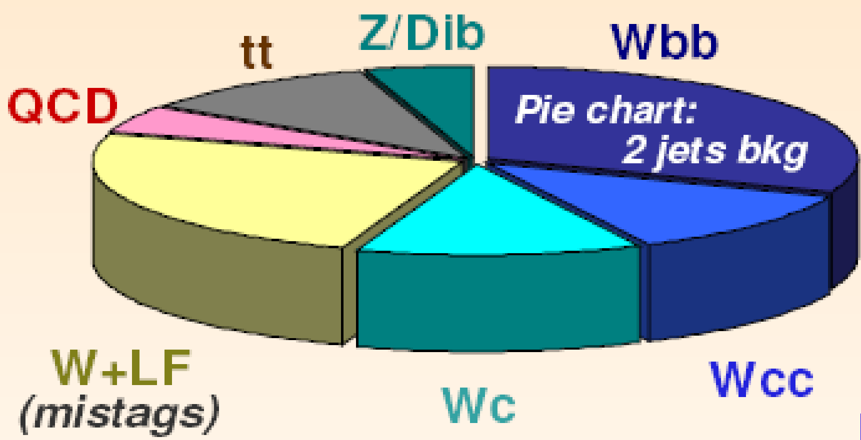
N_{jets}: 2 or 3

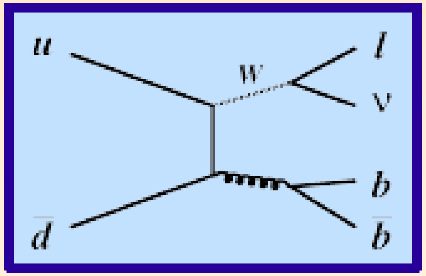




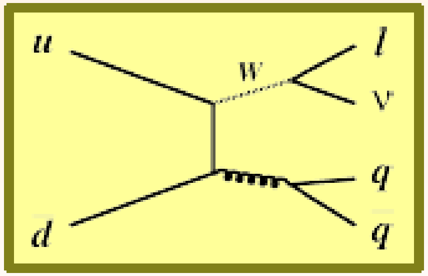
Apply a Z-veto

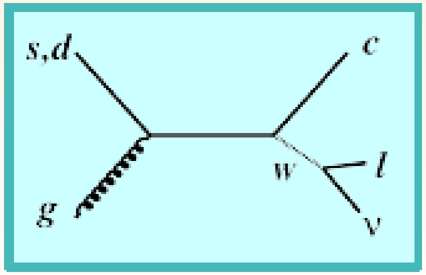


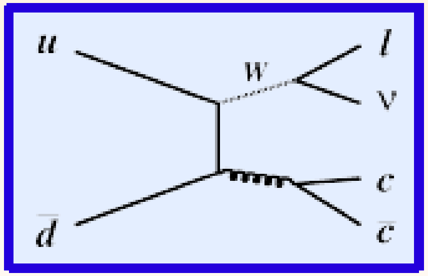




Apply a QCD-veto







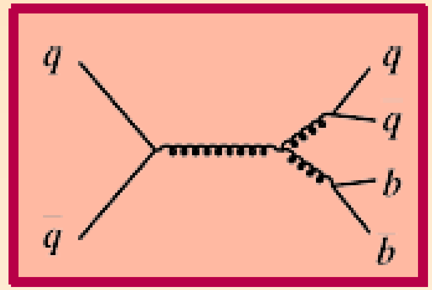
Require at least one jet with a secondary vertex

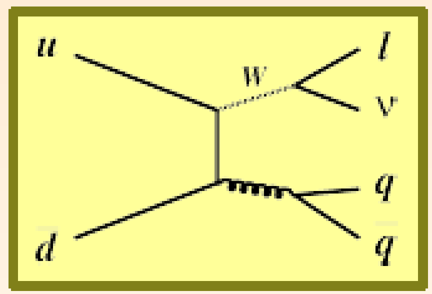
Single Top: background estimation

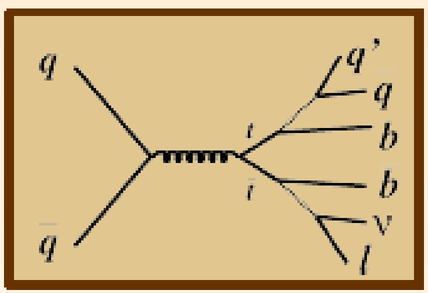
Diboson-, Z+jets- and top pair production:

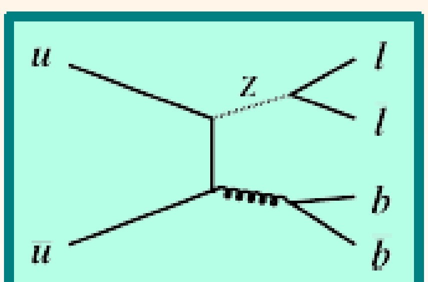
Determined with MC

$$N_{pred} = \sigma_{theo} \cdot \epsilon_{evt} \cdot \int \mathcal{L}\, dt$$









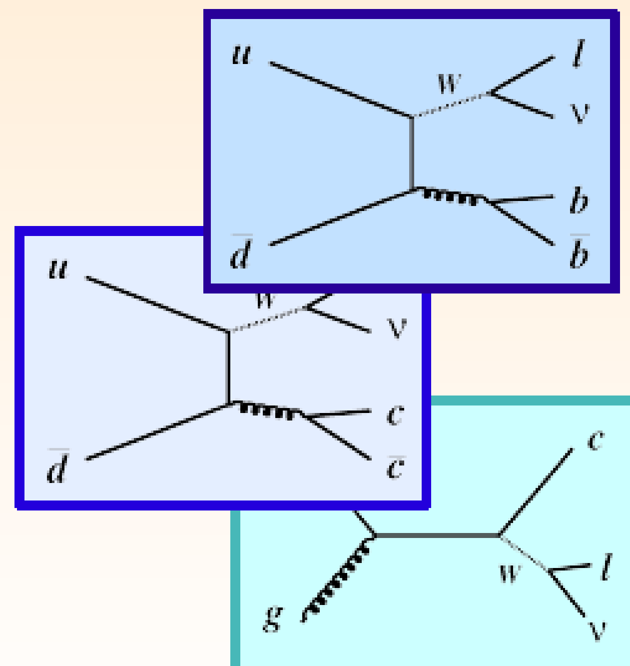
Mistags (W+LF jets) and QCD:

Determined from data

W+HF jets:

W+jets normalization from data, HF-fraction from ALPGEN MC

(calibrated in W+1jet events with b-tag)



Single Top: events selection

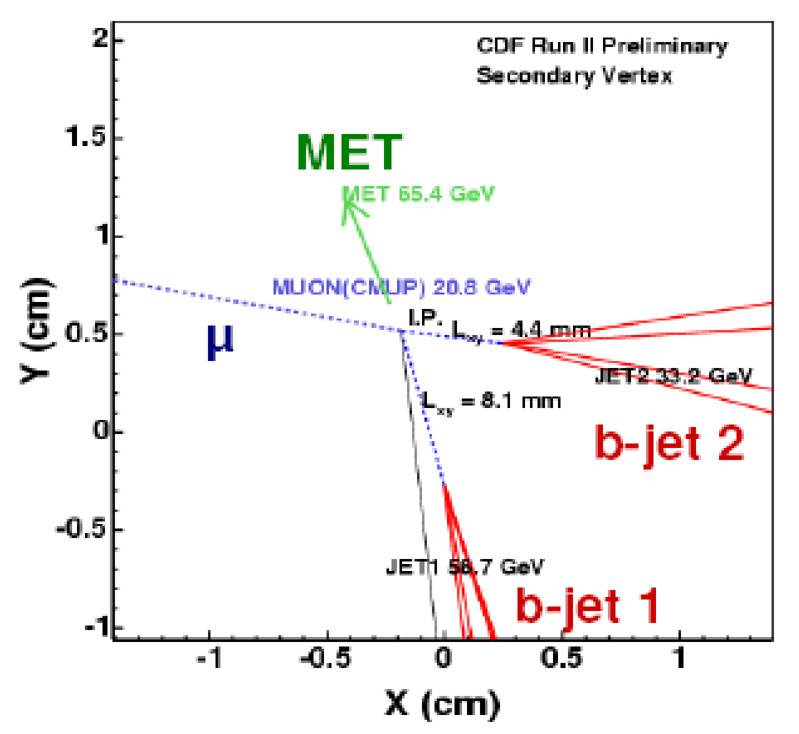
- **1 Lepton (e or μ)**
  High p_T lepton triggers,
  MET+jets trigger (ME, BDT analyses)
  $p_T > 20$ GeV/c^2, $|\eta| < 2.0$

- **Missing E_T (MET)**
  MET > 25 GeV

- **2 or 3 jets (hadron level)**
  $E_T > 20$ GeV, $|\eta| < 2.8$

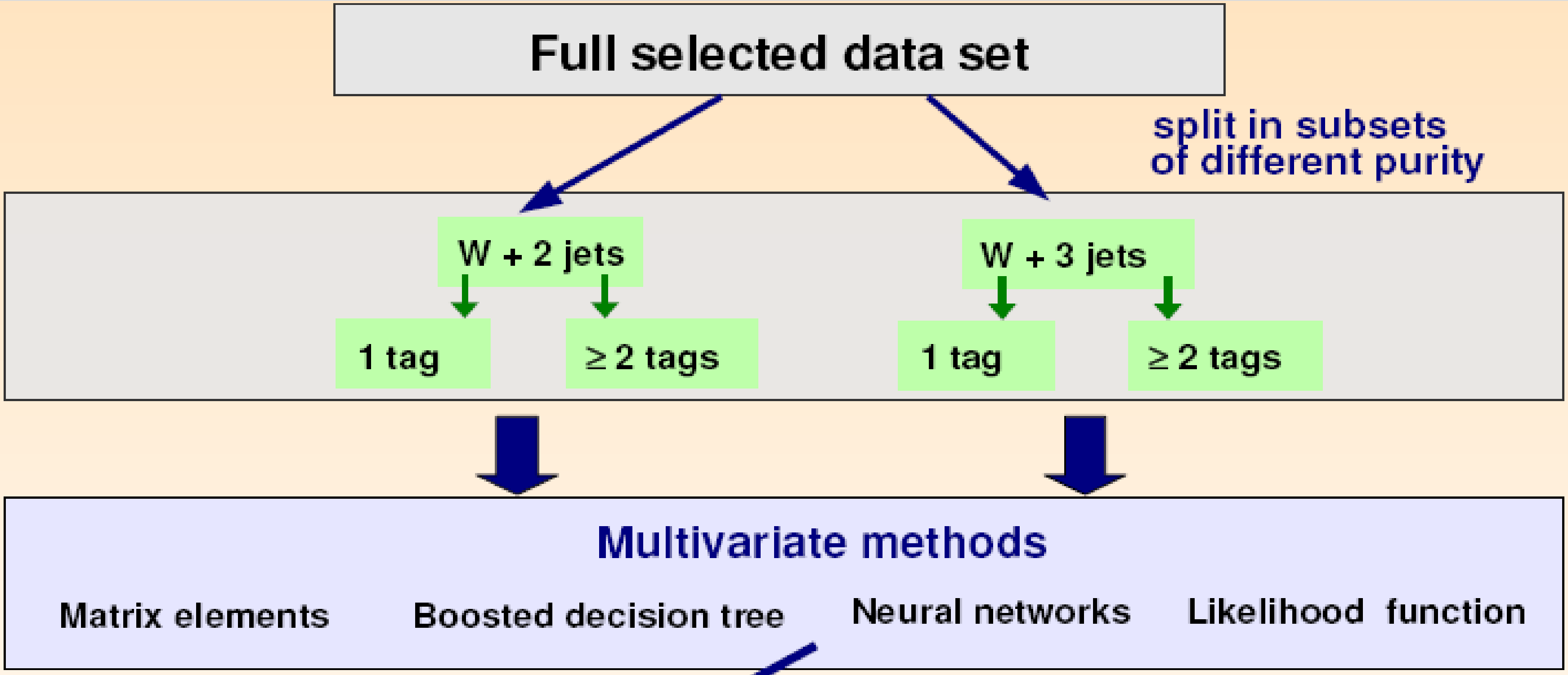
- **At least one b-tagged jet**
  secondary vertex tag

- **Z-veto and QCD-veto**



	W+2jets	W+3jets
s-channel	42 ± 6	14 ± 2
t-channel	62 ± 9	18 ± 3
Total pred.	103 ± 15	22 ± 5

Single Top: Analysis Strategy



Combined search

- t- + s-channel = one single-top signal
- σ ratio is fixed to SM value
- important for „discovery“

Separate search

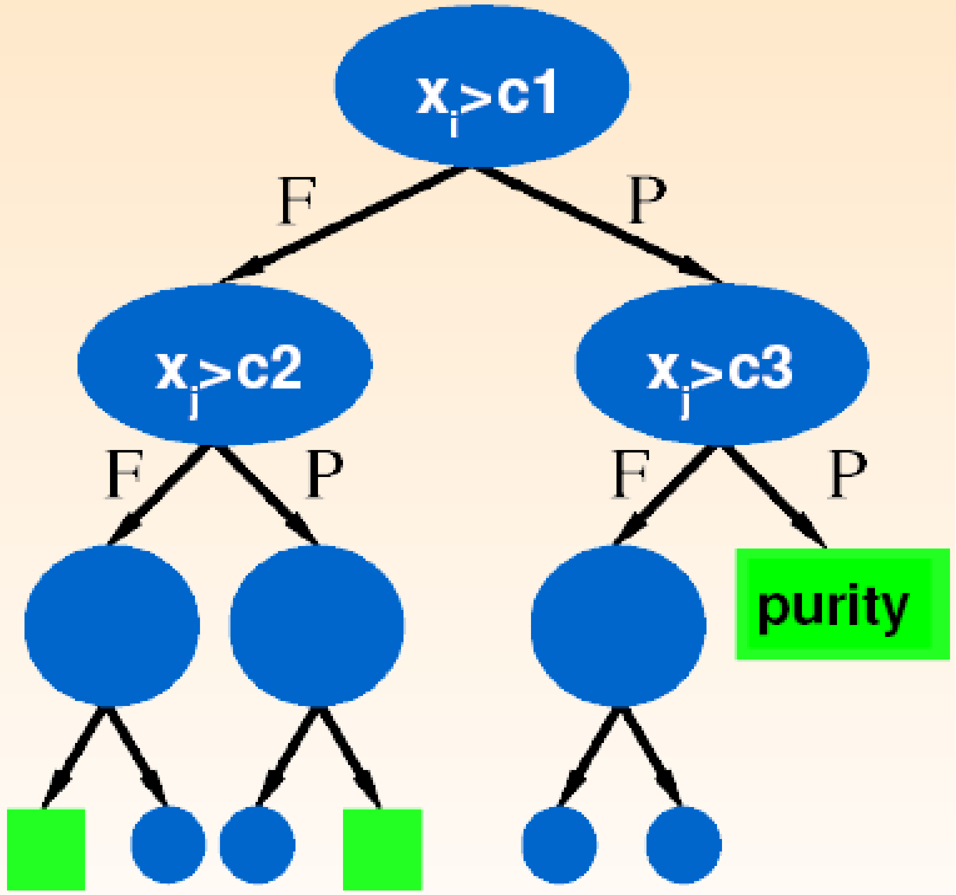
- σ ratio is not fixed to SM value
- Sensitive to new physics processes

Old LF (1.5/fb), NN (1.0/fb) results;
New s-channel meas. (optimized sel., LF)

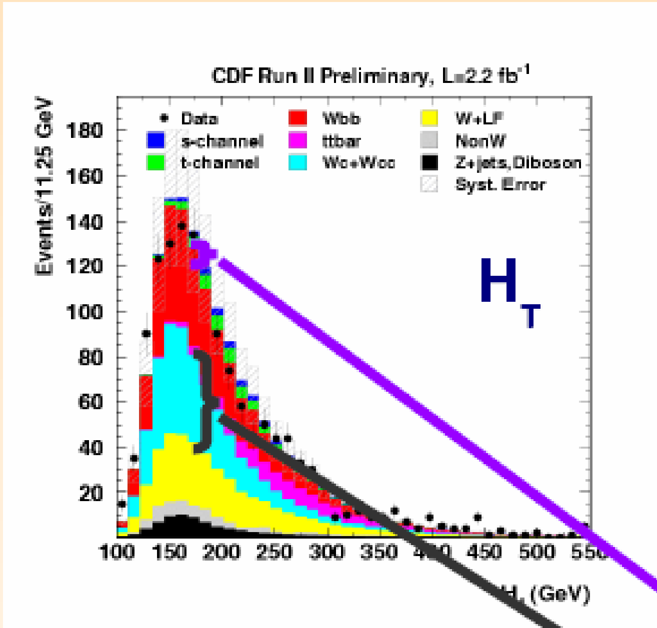
Single Top: Decision Tree example

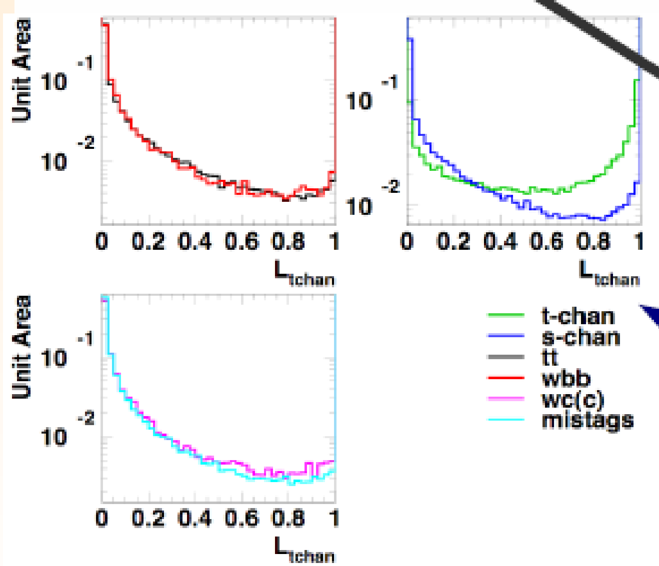
Idea: Effective extension of a cut-based analysis

- Use many input variables (20)
- Non-discriminating variables are automatically ignored, but don't degrade the performance
- Optimize series of binary cuts with training sample
- Calculate for each leaf purity $p = s/(s+b)$
- Sort events by output purity
- Create series of "boosted" trees by reweighting based on value of misclassification



Single Top: Cross Section measurement





Idea: Combine many variables into one more powerful discriminant

- Binned likelihood function *(LEP technique)*
- Correlations between variables not taken advantage of
- Use 7-10 variabes

N_i^{sig}, N_{ij}^{bkg} → $p_i^{sig} = \dfrac{N_i^{sig}}{N_i^{sig} + \sum_{j=1}^{n_{bkg}} N_{ij}^{bkg}}$

Fit output: N_i^{sig}

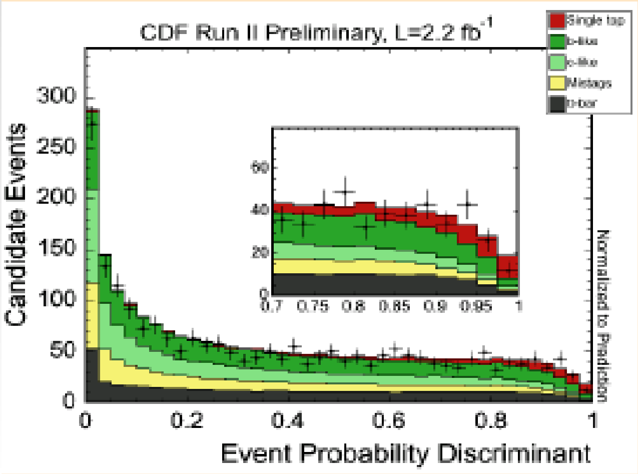
Norm. values

Bkg: Wbb,top pair, Wcc/Wc, mistags

$$L(x) = \frac{\prod_{i=1}^{n_{var}} p_i^{sig}(x_i)}{\prod_{i=1}^{n_{var}} p_i^{sig}(x_i) + \sum_j^{n_{bkg}} \prod_{i=1}^{n_{var}} p_i^{bkg}(x_i)}$$

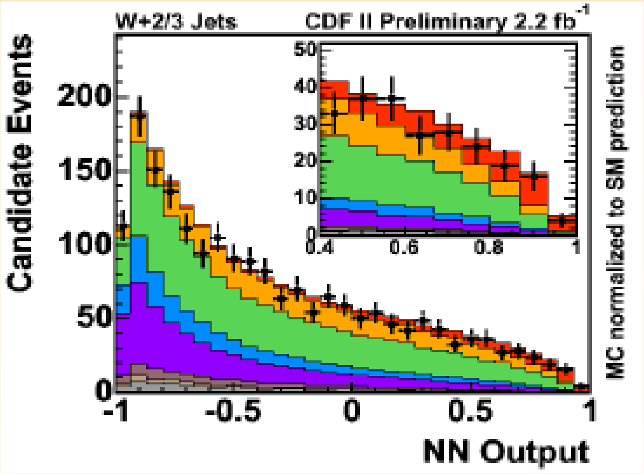
Single Top: Results

Matrix element method



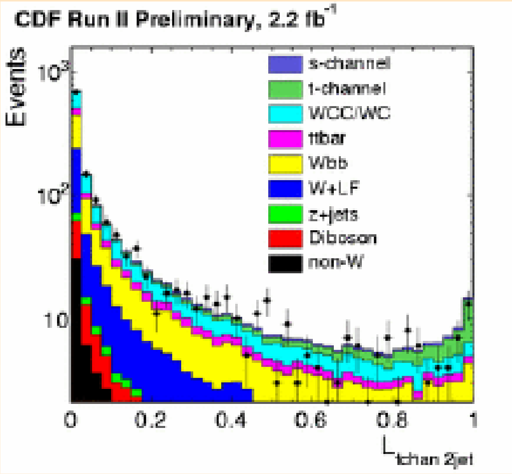
$$\sigma_{s+t}=2.2^{+0.8}_{-0.7}\ \text{pb}$$

Neural networks

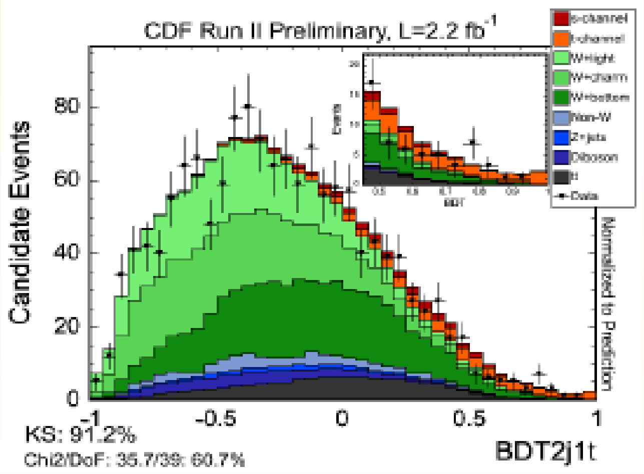


$$\sigma_{s+t}=2.0^{+0.9}_{-0.8}\ \text{pb}$$

Likelihood function



$$\sigma_{s+t}=1.8^{+0.9}_{-0.8}\ \text{pb}$$



Boosted decision tree

$$\sigma_{s+t}=1.9^{+0.8}_{-0.7}\ \text{pb}$$

SM prediction:

$\sigma_{s+t} \approx 2.9 \pm 0.4$ pb

Analyses are consistent with each other

Single Top: Significance

Cross Section:

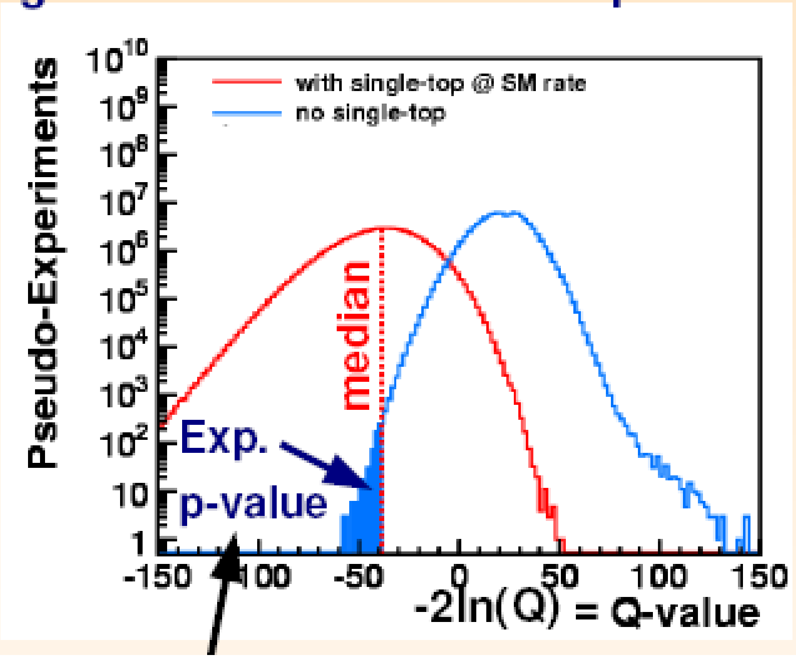
- Bayesian treatment (flat prior in σ_{s+t})
- Binned Likelihood fit including all rate and shape systematic uncertainties

Significance definition

- Perform Pseudo-experiments (PE) with and without single top
  - fluctuate systematic rate and shape in PE
  - binned likelihood fit for each PE
- $-2\ln(Q)$, $Q=L(SM\ \sigma_{s+t})/L(\sigma_{s+t}=0)$

Probability for data to come only from background

Significance: Definition of p-value

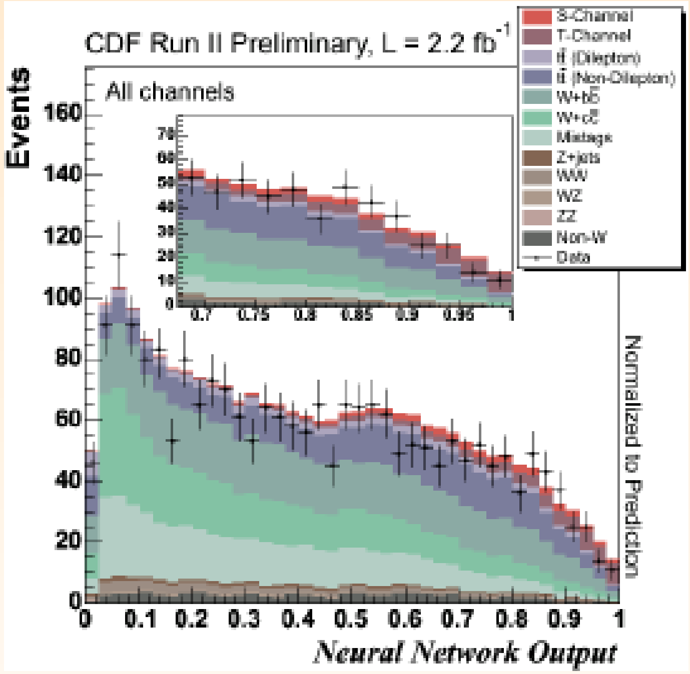


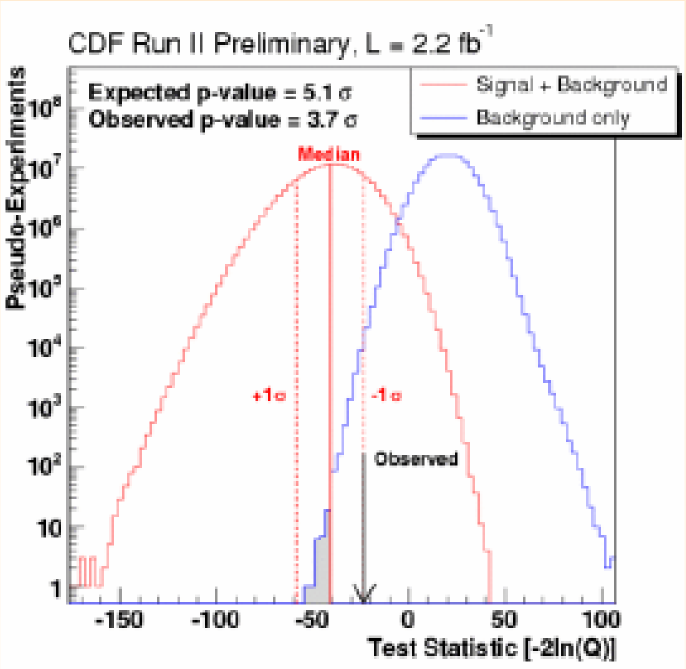
p-value defined via likelihood ratio is the most powerful criteria to distinguish among two hypothesis

Single Top Combined Cross Section

Combine ME, NN, LF discriminants as inputs to a neural net (NEAT)

Neuro-**E**volution of **A**ugmenting **T**opologies: *designed to optimize the discovery significance*





Exp. p-value:

0.00002% (5.1σ)

Obs. p-value:

0.0094% (3.7 σ)

Cross section:

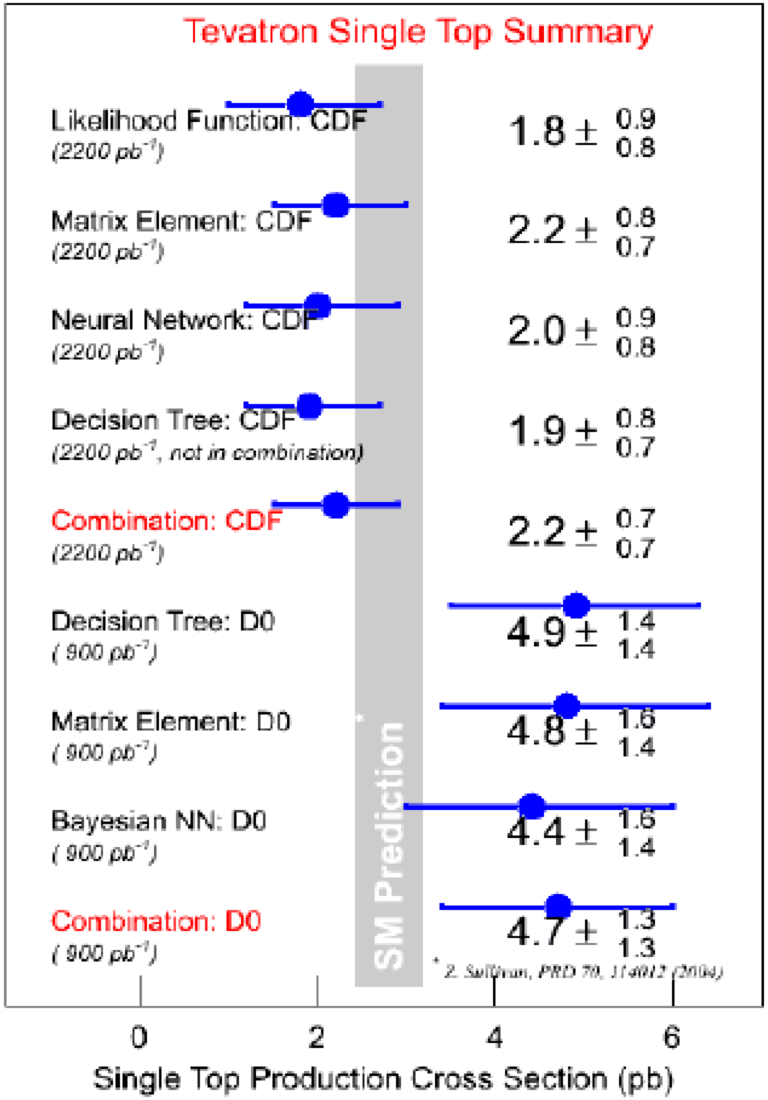
$$\sigma_{s+t} = 2.2^{+0.7}_{-0.7} \text{ pb}$$

SM prediction:

$\sigma_{s+t} \approx 2.9 \pm 0.4$ pb

σ_{s+t} lower than SM prediction but consistent with SM prediction

Single Top Cross Section Results



Combined search:

Cross section: $\sigma_{s+t} = 2.2^{+0.7}_{-0.7}$ pb

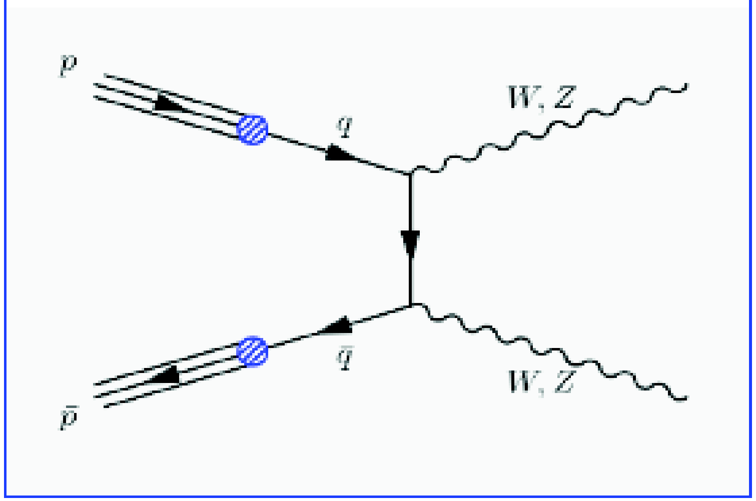
Exp. p-value: 5.1σ Obs.: 3.7 σ

Wait for more data!

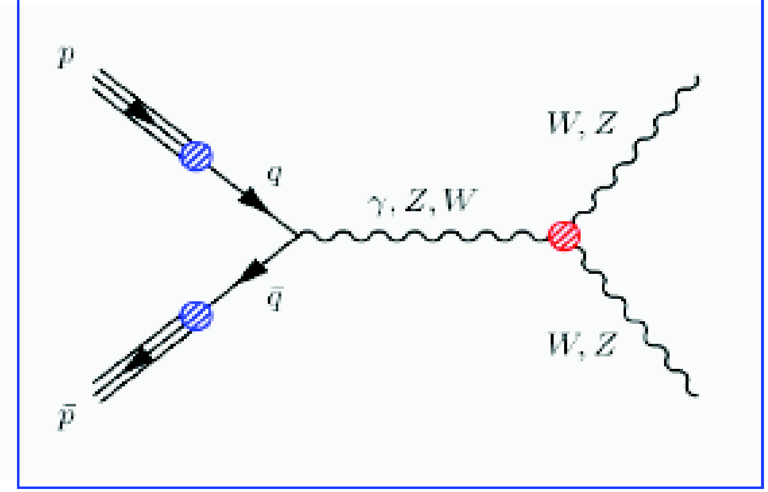
Heavy di-boson Production: Introduction

Leading order diagrams :

t-channel



s-channel

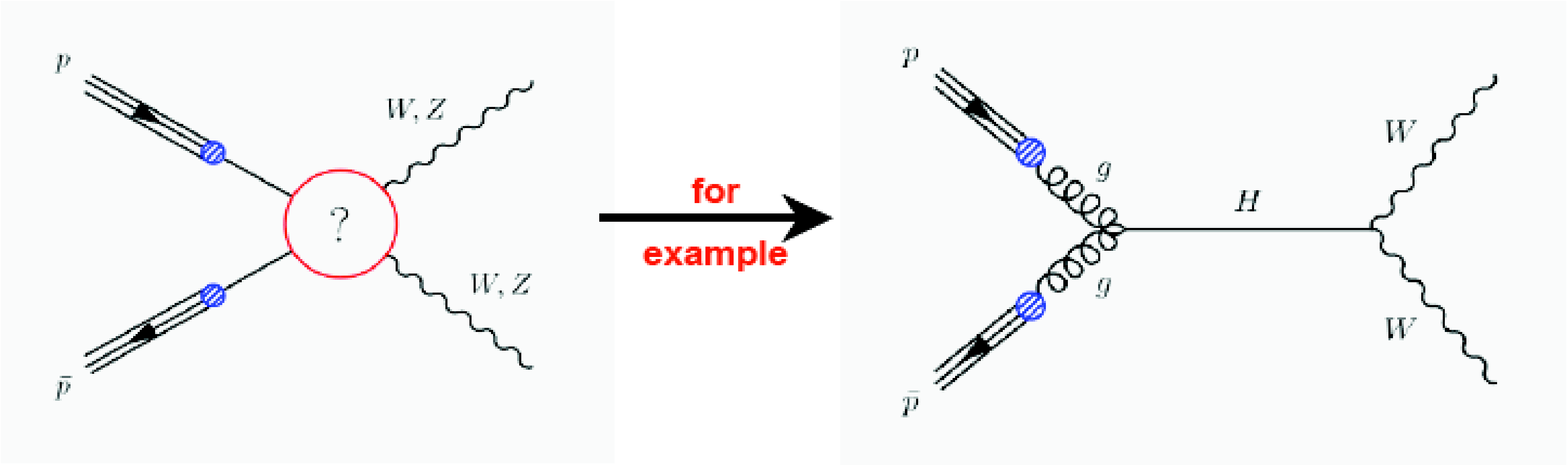


- (QCD) production : PDF's, (NLO/LO) k-factors, diboson-p_T spectrum.
- (EWK) production : Triple Gauge Couplings predicted by $SU(2)_L \otimes U(1)_Y$.

- Measuring the production cross sections and kinematics provide a verification of all these production model ingredients.

Heavy di-boson Production: Introduction

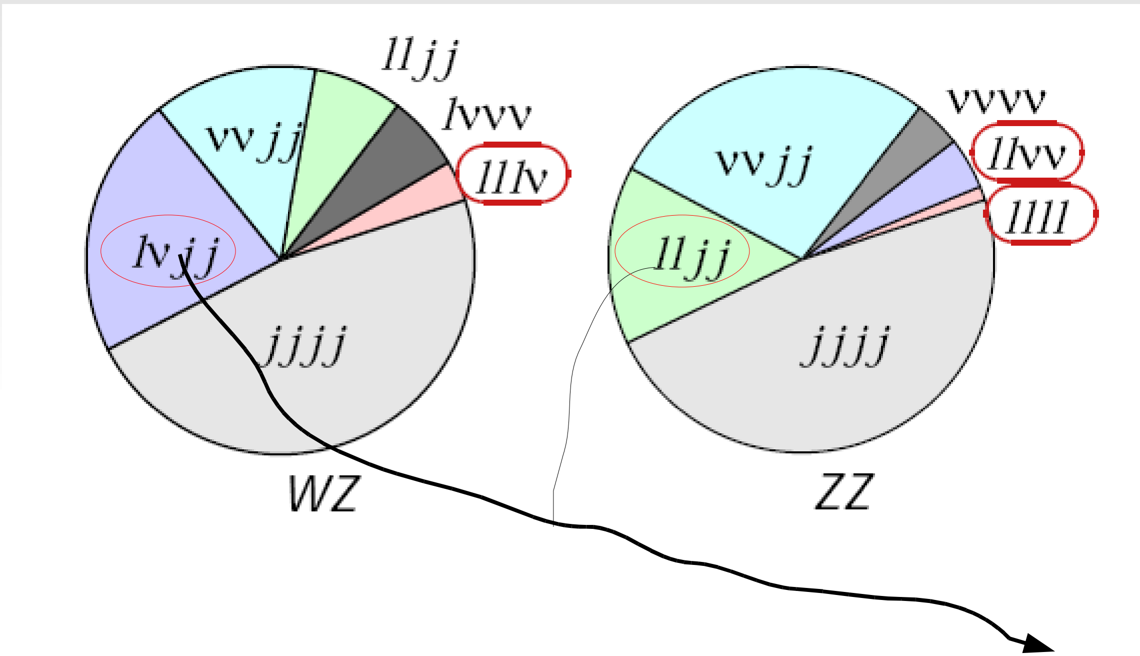
- Heavy diboson production as a signature of new physics :



- Indeed, heavy diboson production is intimately related to Higgs searches:
  - **WW** production is a (quasi-) irreducible background to **H→WW**
  - **WZ and ZZ** production are critical backgrounds to **WH** & **ZH** assoc. prod.
  - Technically many of the techniques developed for diboson measurements have applications in Higgs searches.
  - Heavy diboson measurements provide a "standard-candle" for the measurement of very small cross sections.

Heavy di-boson Production: Analysis

Decay modes used:



Fully leptonic decay modes

- small branching ratio
- low background

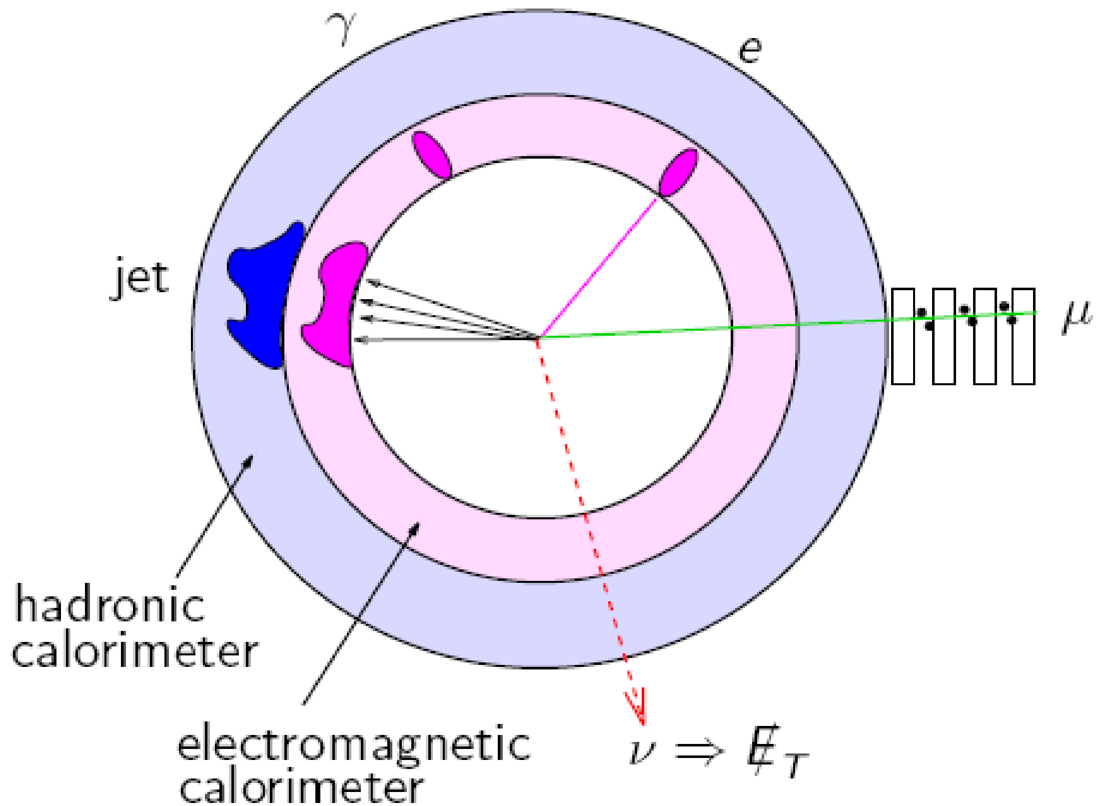
Semi-leptonic decay modes

- branching ratio ~10xleptonic
- background ~1000xleptonic

Heavy di-boson Production: Techniques

Finding electrons, muons, and neutrinos

- $\approx$ 1000 times more jets than leptons!
  - hadronic fluctuations
  - decay in flight
  - heavy flavor
  - fakes either e or μ
- $W\gamma$ and $Z\gamma$ still 100 times bigger
  - photons convert to e^+e^- in material

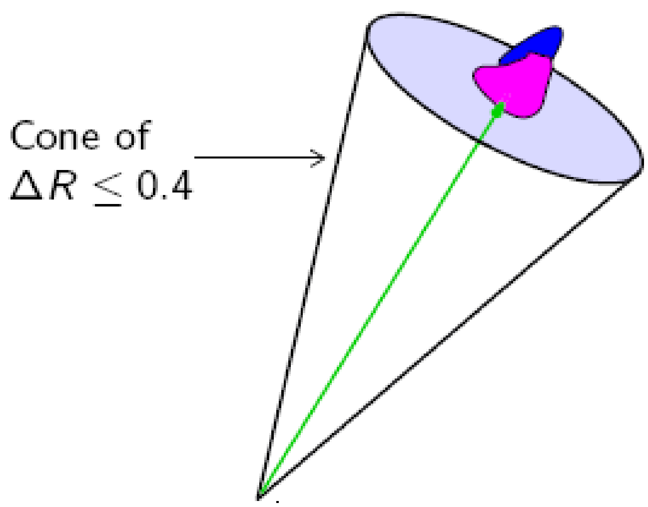


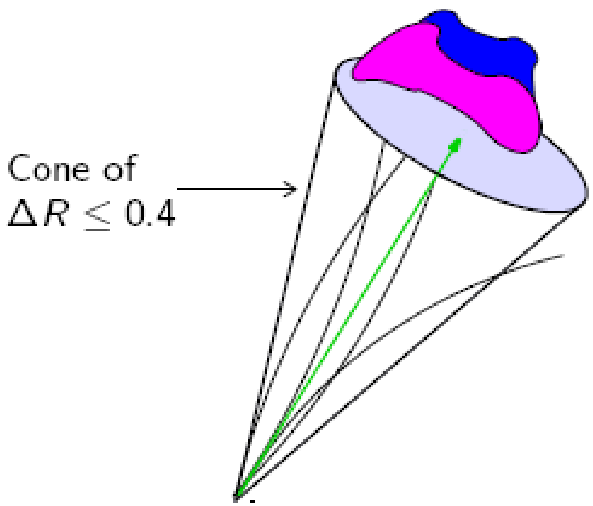
- $\not{E}_T$: Measure neutrinos with transverse momentum balance
  - "Missing Transverse Energy"
  - EM and hadronic components measured in calorimeters
  - Corrected for muons

Heavy di-boson Production: Techniques

Powerful handle to separate leptons from boson decay from the products of hadronic processes

Boosted Cone: $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$





Real Leptons from Boson Decay

- Electrons from converted photons from diboson decays also isolated

Fake or *Real* Leptons in Jet

- Real leptons in jets from flavor decay (π, K, D, B,...) and photon conversions

Cut: non-lepton related energy $<$10% of the lepton energy in the cone

Heavy di-boson Production: WZ search

WZ->$\ell\ell\ell\nu$

Events Selection:

- 3 high Pt leptons: one pair of same flavor.
  Opposite sign lepton must be consistent with Z mass
- MET

Main Backgrounds:

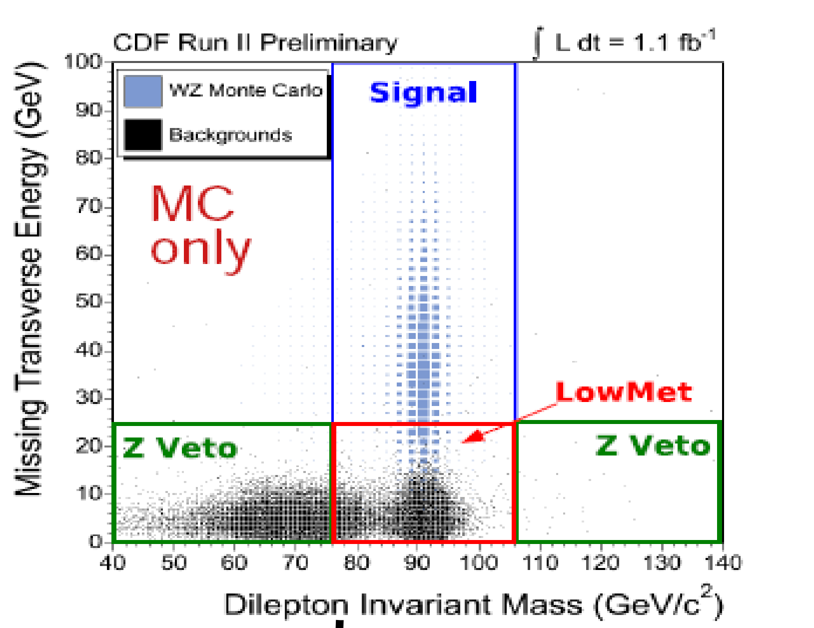
- Z+Jets, Z+γ and tt

Use Monte Carlo to simulate:

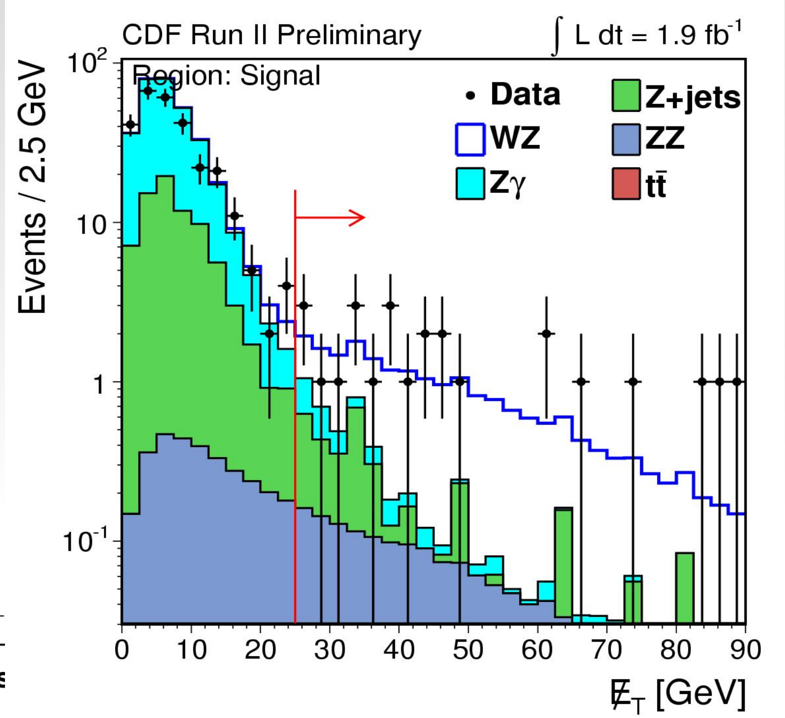
WZ, ZZ, Zγ and tt

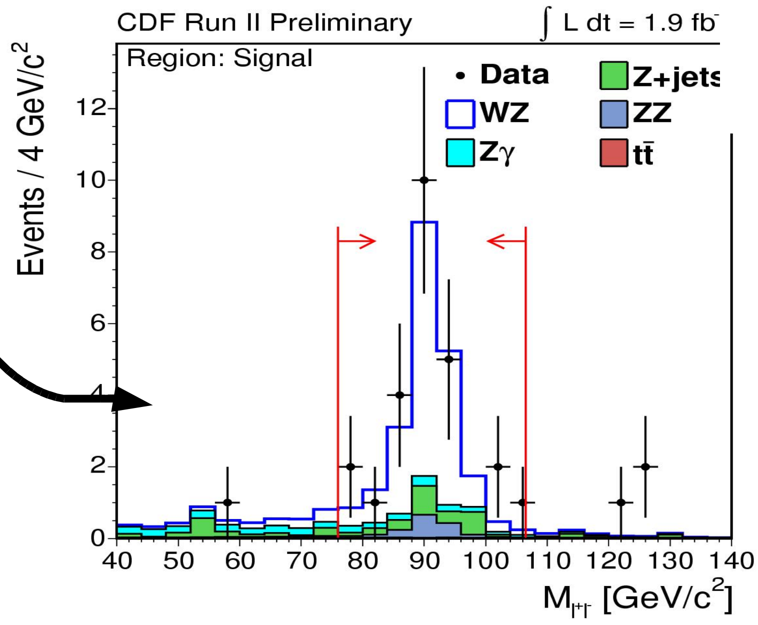
Use a combination of data and Monte Carlo to measure Z+Jets

Heavy di-boson Production: WZ search



MET





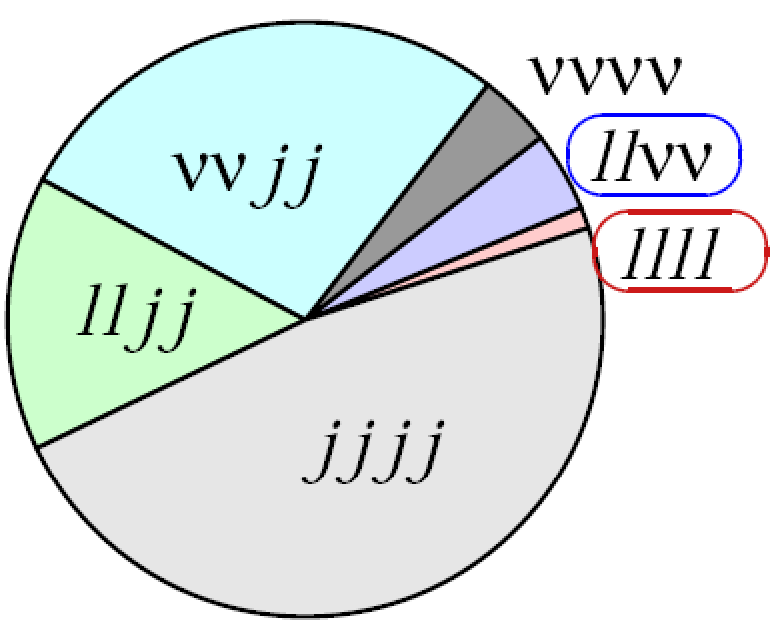
Heavy di-boson Production: WZ result

Source	Expected ± Stat ± Syst ± Lumi
Z+jets	39.35 ± 1.88 ± 7.17 ± 0.00
ZZ	0.75 ± 0.01 ± 0.09 ± 0.04
$Z\gamma$	385.31 ± 1.12 ± 126.35 ± 23.12
$t\bar{t}$	0.05 ± 0.01 ± 0.01 ± 0.00
WZ	0.75 ± 0.01 ± 0.09 ± 0.05
Total	426.21 ± 2.19 ± 126.73 ± 23.21
Observed	**375**

$$4.3^{+1.3}_{-1.0}(stat.) \pm 0.4(syst. + lumi.)pb$$

$$4.3^{+1.3}_{-1.0}(stat.) \pm 0.2(syst.) \pm 0.3(lumi.)pb$$

Heavy di-boson Production: ZZ search



- Two viable modes
- $ZZ \to$ 4 leptons
  - Very clean
  - Very small BR: $(2 \times 0.033)^2 = 0.0044$
- $ZZ \to ll\nu\nu$
  - 6 times larger BR: $2 \times 0.2 \times (2 \times 0.033) = 0.026$
  - Several significant backgrounds WW, WZ, Drell-Yan
  - Use Matrix Elements to discriminate signal and background
- The strategy is to combine this into one result

Heavy di-boson Production: ZZ search

Events Selection:

Z->ℓℓℓℓ

- 4 high Pt leptons
  - 1 lepton pair: $76<M_{\ell\ell}<106$ GeV
  - 1 lepton pair: $40<M_{\ell\ell}<140$ GeV

Z->ℓℓν

- 2 high Pt leptons
- MET significance >2.5 $GeV^{1/2}$
- Njet<2 to cut tt
- MET not along leptons

Main Backgrounds:

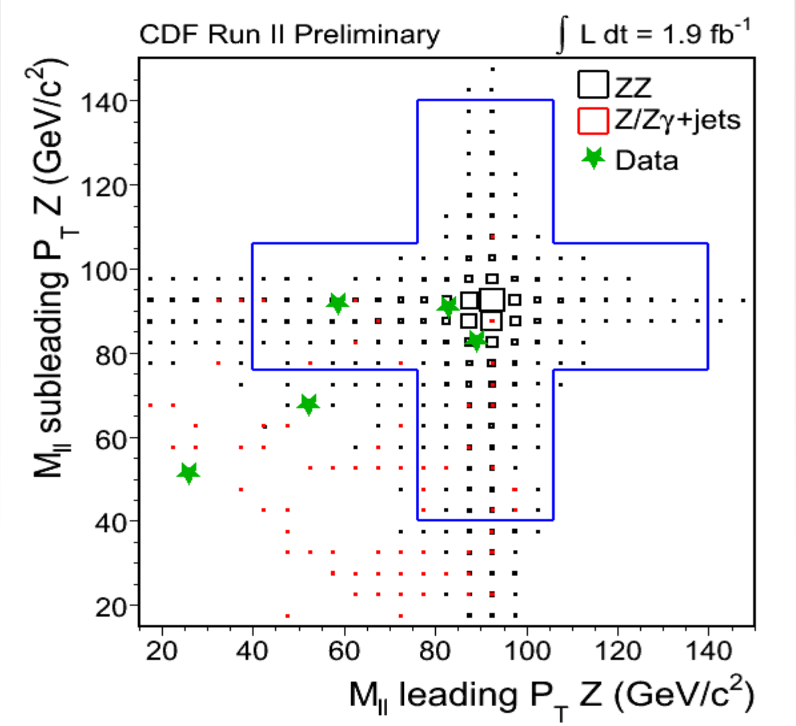
- Z+Jets:
  two jets misidentified as leptons
- Z+γ
  γ and jets misidentified as leptons
- fakes like trackless electrons

- WW
- W+jets
- WZ

Use Monte Carlo to simulate:

ZZ and Zγ Use a combination of data and MC to measure Z+Jets

Heavy di-boson Production: ZZ->ℓℓℓℓ



Three candidates out of five pass the mass cuts

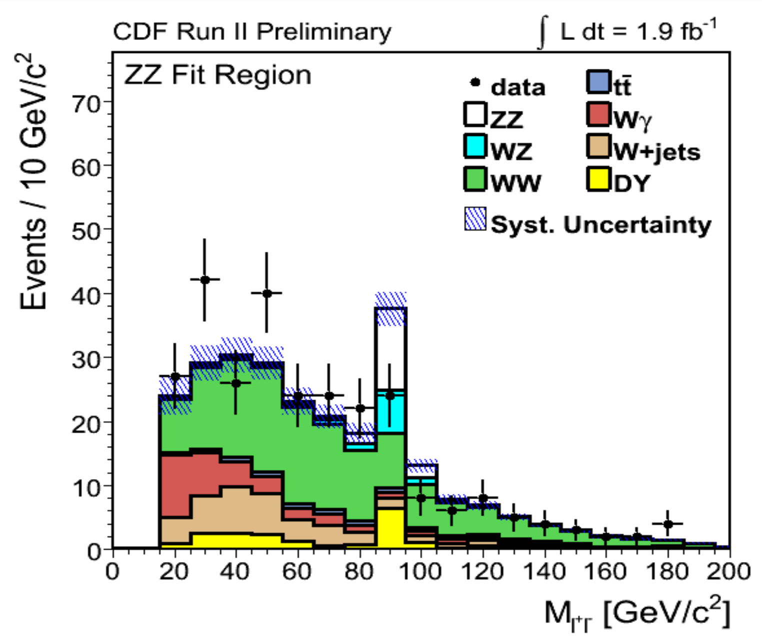
Category	Candidates without a trackless electron	Candidates with a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	**2**	**1**

Heavy di-boson Production: ZZ->ℓℓν

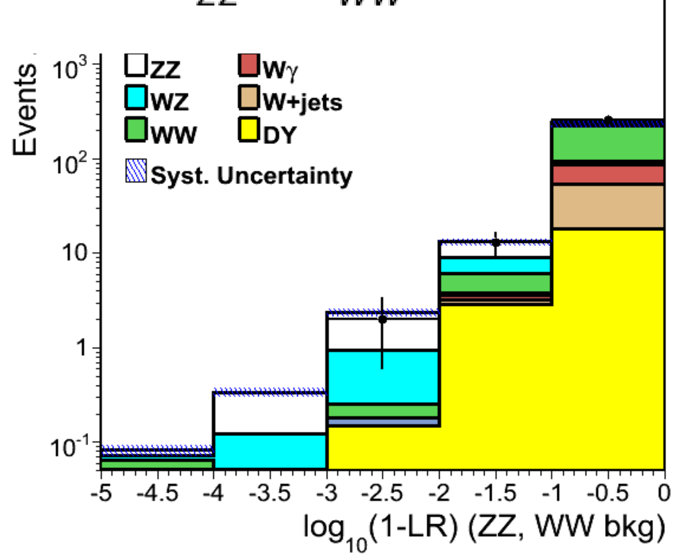
Signal and background expectations

ZZ Fit Region

Category	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Total	Data
$e\ e$	43.7	4.8	5.4	2.7	8.7	24.8	19.3	109 $\pm$10	118
$e\ \mu$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0 $\pm$ 0	0
$\mu\ \mu$	33.7	3.7	4.4	2.4	7.0	0.0	2.7	54 $\pm$ 5	45
e trk	35.3	2.3	2.2	2.4	3.8	5.9	9.9	62 $\pm$ 5	69
μ trk	19.2	1.5	1.5	1.4	1.5	1.1	5.2	31 $\pm$ 3	44
Total	131.8	12.3	13.5	9.0	21.1	31.7	37.1	256 $\pm$21	276



$$LR \equiv \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$



$$LR \equiv \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$

Fit to extract the p-value and the cross section

Heavy di-boson: ZZ->ℓℓℓℓ+ZZ->ℓℓw

Combine the two modes:

Test Statistic = Likelihood Ratio

- ZZ floating = test hypothesis (value $\rightarrow$ cross-section)
- ZZ fixed to zero = null hypothesis

$$ts = (-2\ln\mathcal{L}_{ZZ\ free}) - (-2\ln\mathcal{L}_{ZZ\ fixed})$$

10 million pseudo experiments (bin statistics & systematics varied)

$$\text{p-value} = \frac{\text{\# of background experiments with larger } ts \text{ than data}}{\text{\# pseudo-experiments generated}}$$

Heavy di-boson: ZZ->ℓℓℓℓ+ZZ->ℓℓw

Probability of Observing a Signal

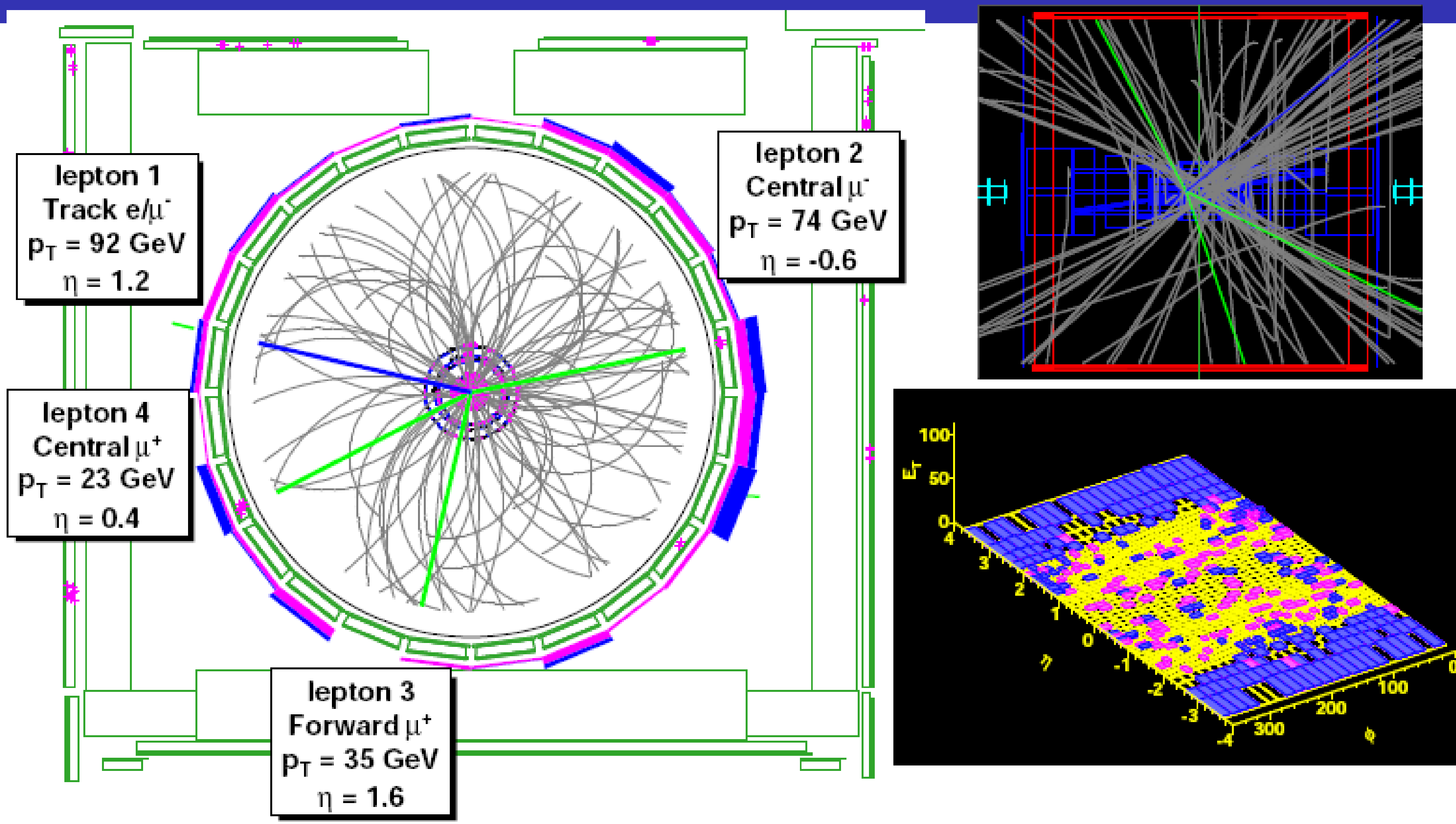
Significance	$ll\nu\nu$	4 lepton	combined
2σ	0.55	0.82	0.87
3σ	0.33	0.67	0.75
5σ	0.06	0.34	0.50

Combined Results

		$ll\nu\nu$	4 lepton	Combined
Significance	P-Value	0.12	1.1×10^{-5}	5.1×10^{-6}
	Significance	$1.2\ \sigma$	$4.2\ \sigma$	$4.4\ \sigma$

Measured Cross-Section $1.4^{+0.7}_{-0.6}(stat. + syst.)$ pb (NLO prediction is 1.4 pb)

Event Display:Z->4leptons

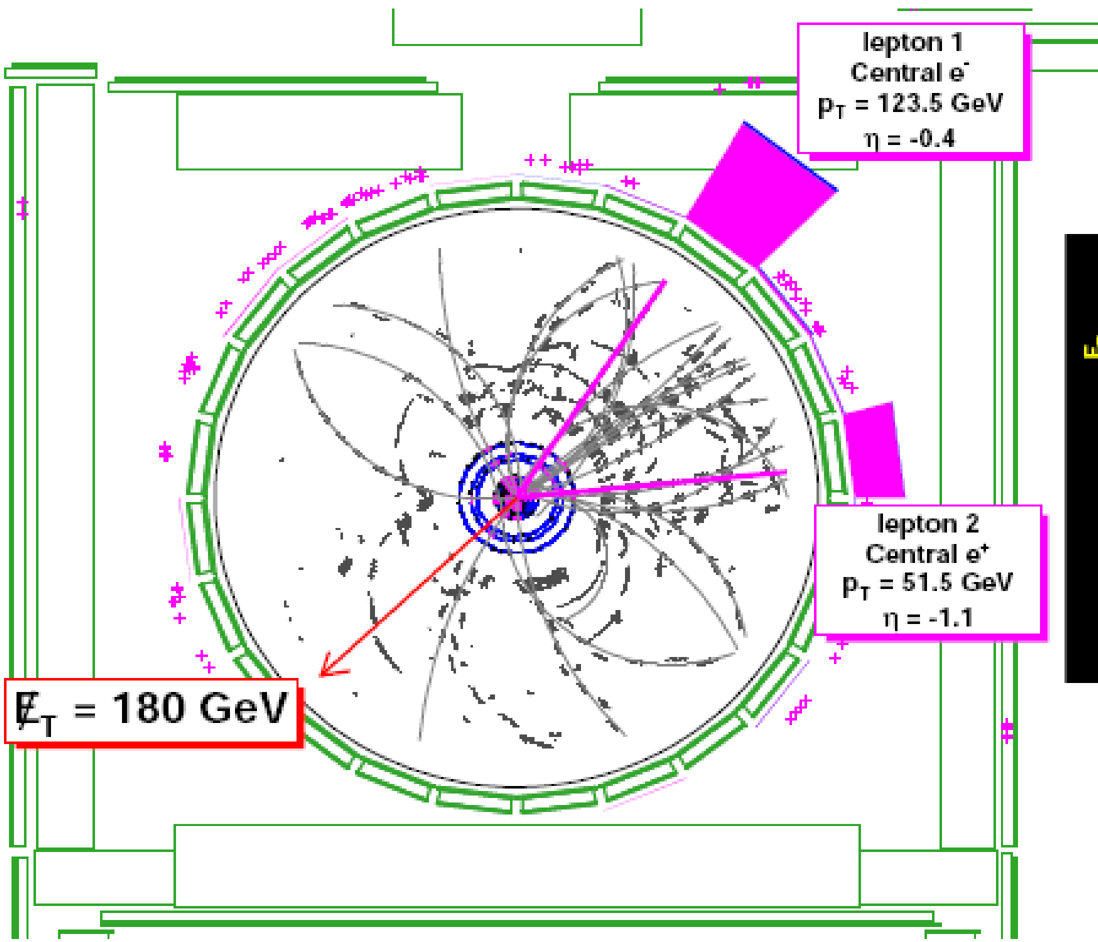


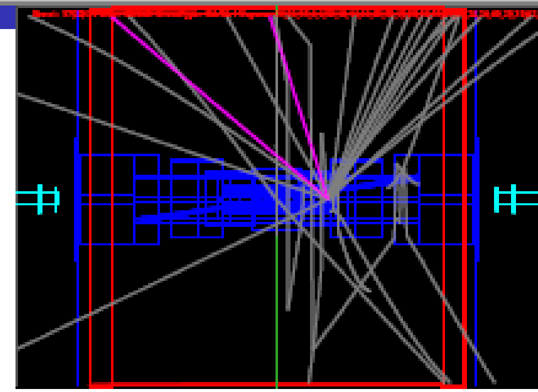
m_{ll1}=90.92 GeV $\quad$ $|\not{E}_T|$=8.7 GeV

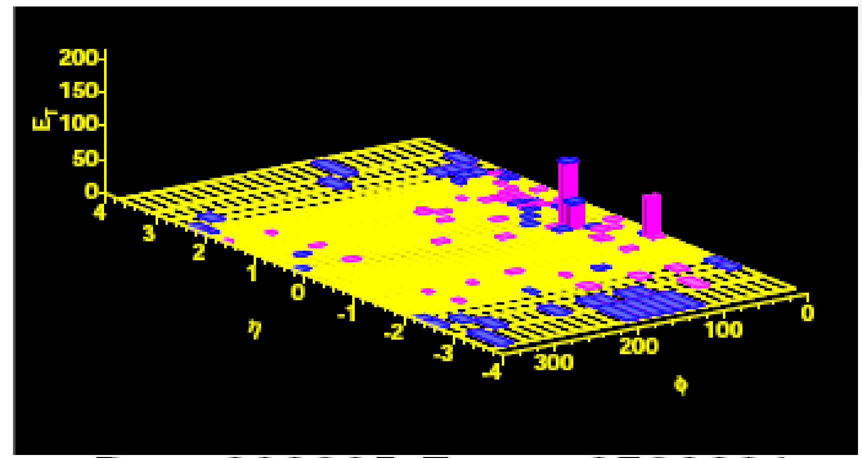
m_{ll2}=83.03 GeV $\quad$ N_{jets} = 0

M_{llll}=312.4 GeV/c^2

Event Display:Z->2lepton+w







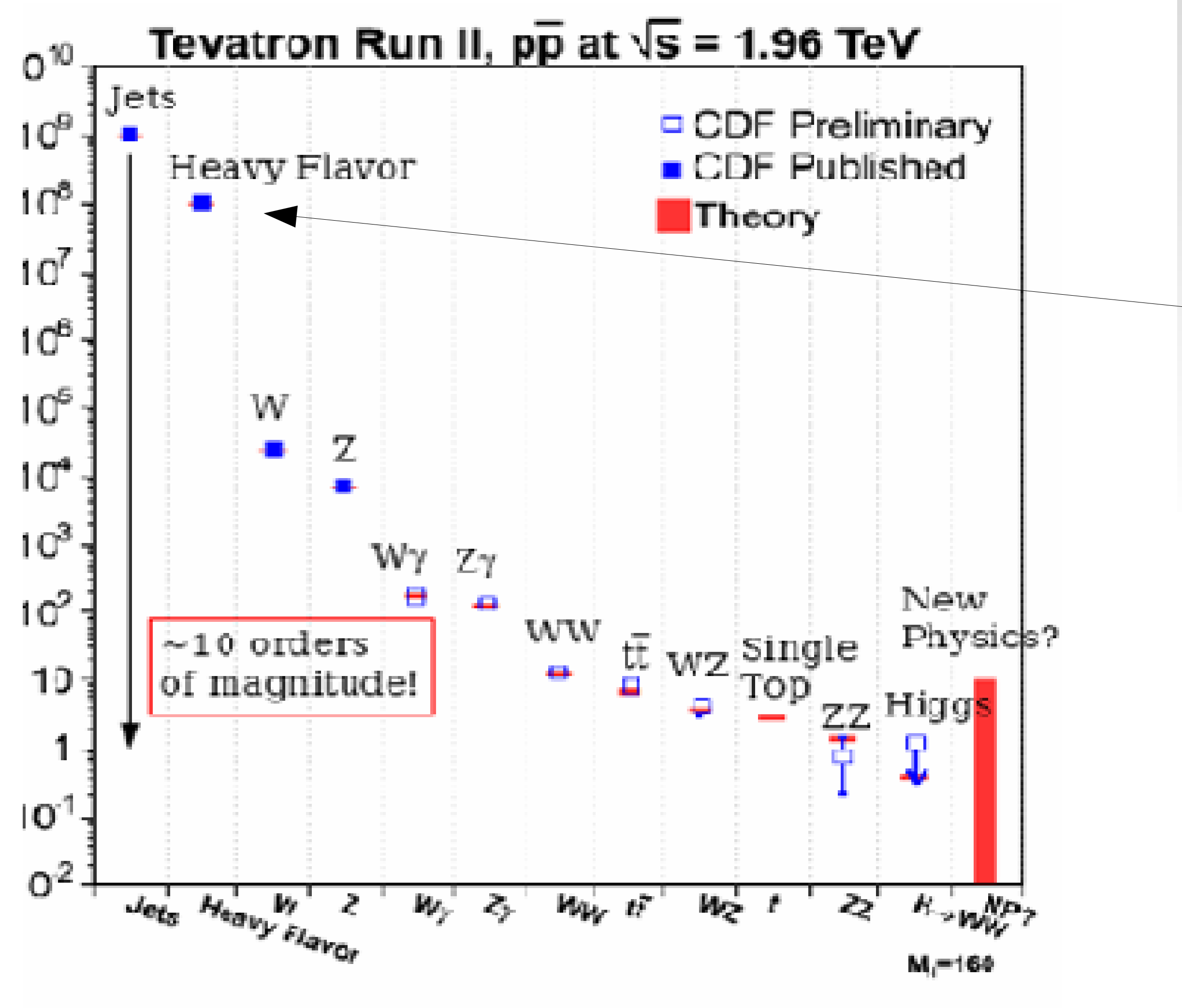
Run=203265 Event=3792931

m_{12}=91.22 GeV

$|\not\!\!E_T|$=180.5 GeV

Type	p_T	η	ϕ
Central *e*	123.5	-0.4	1.0
Central *e*	51.5	-1.1	0.1

Summary



Next two lessons will be for high statistic sample