Search for the Higgs Boson Produced in Association with a Vector Boson Using Like-Sign Dilepton Events at CDF

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Outline

1. *Introduction*
2. *Backgrounds*
3. *Multivariate Analysis (Boosted Decision Trees)*
4. *Results & Summary*

Introduction

★ Higgs Boson **was only undiscovered elementary particle** in the Standard Model (SM).

★ 5 sigma discovery is announced in July 2012 at LHC (consistent to SM Higgs).

★ Need to investigate various channels.

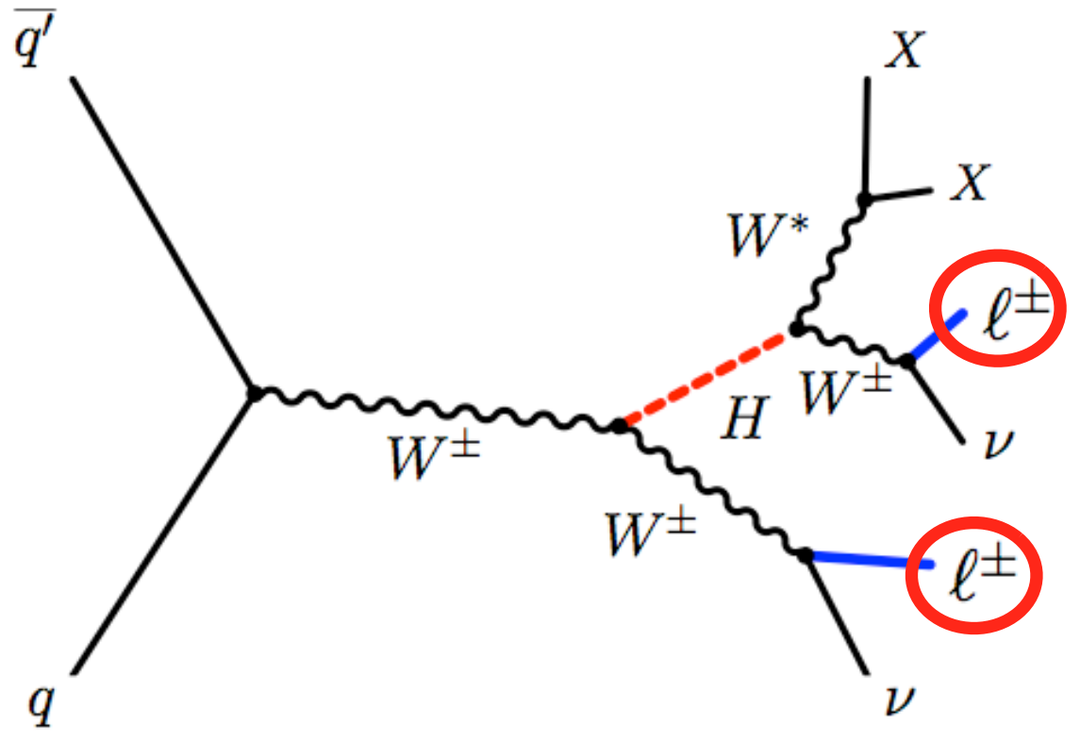
★ VH production is a strong channel at the Tevatron (relatively large cross section).

★ Final state with like-sign charge combination

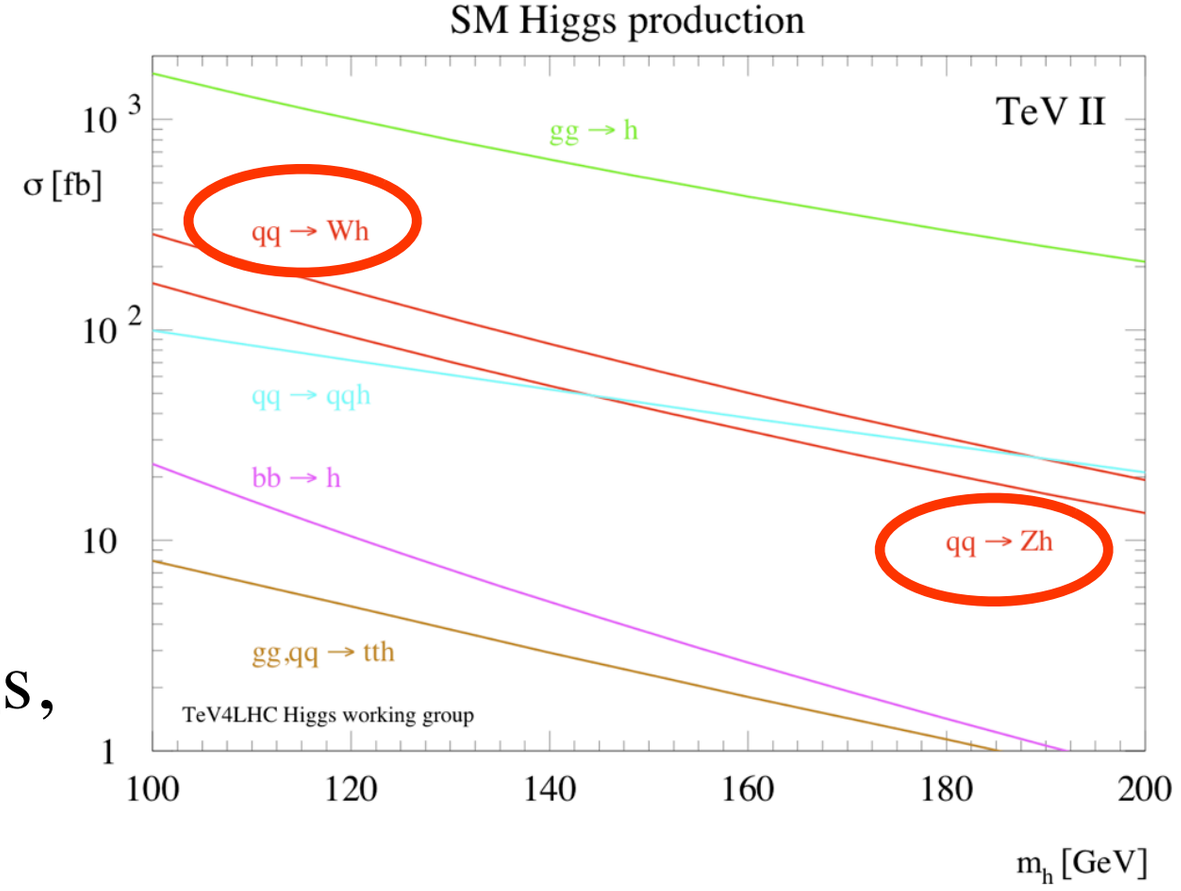
$$VH \rightarrow VWW \rightarrow \ell^{\pm}\ell^{\pm} + X$$

is very clean channel!

★ Also, this channel can be investigated Beyond SM (e.g. Fermiophobic (FP) Higgs, which cannot couple to fermions.)



SM Higgs production



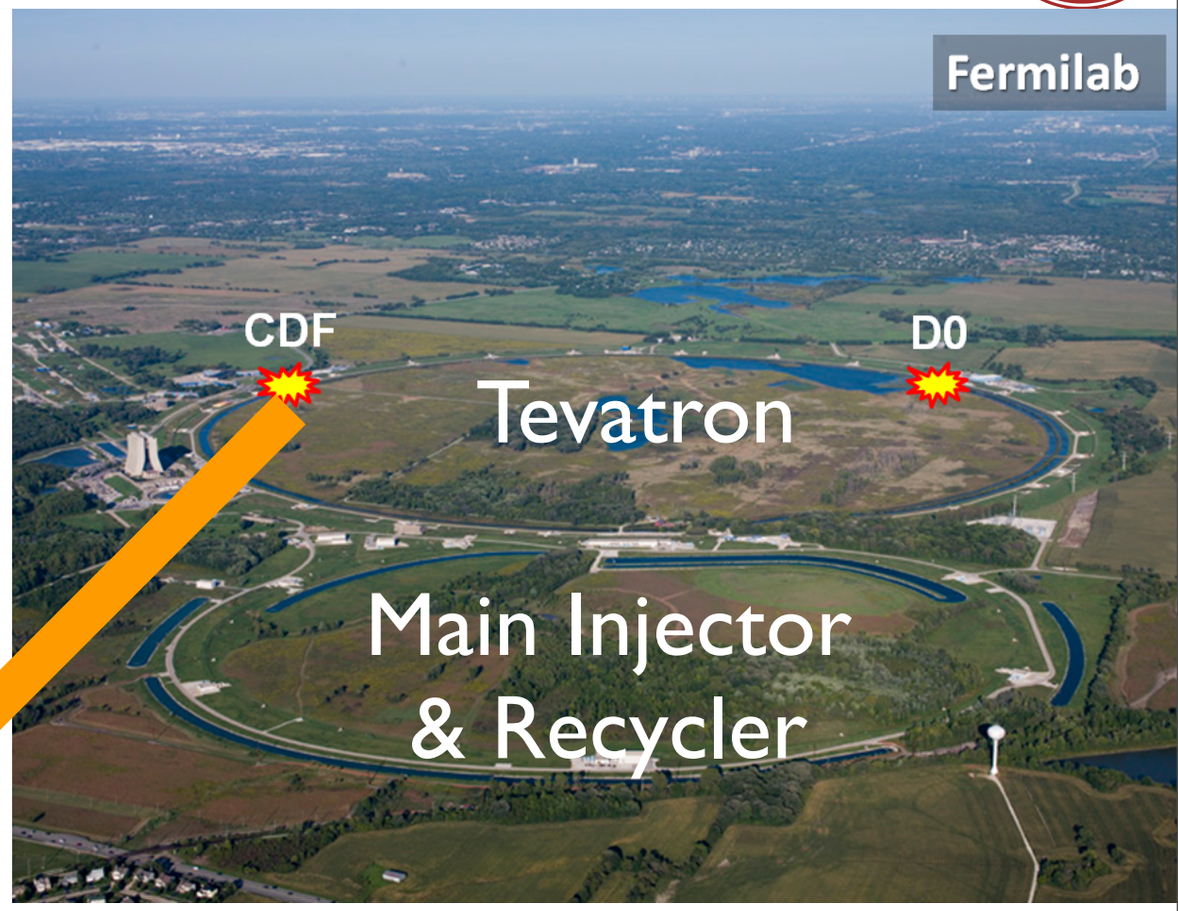
Tevatron & CDF Detector

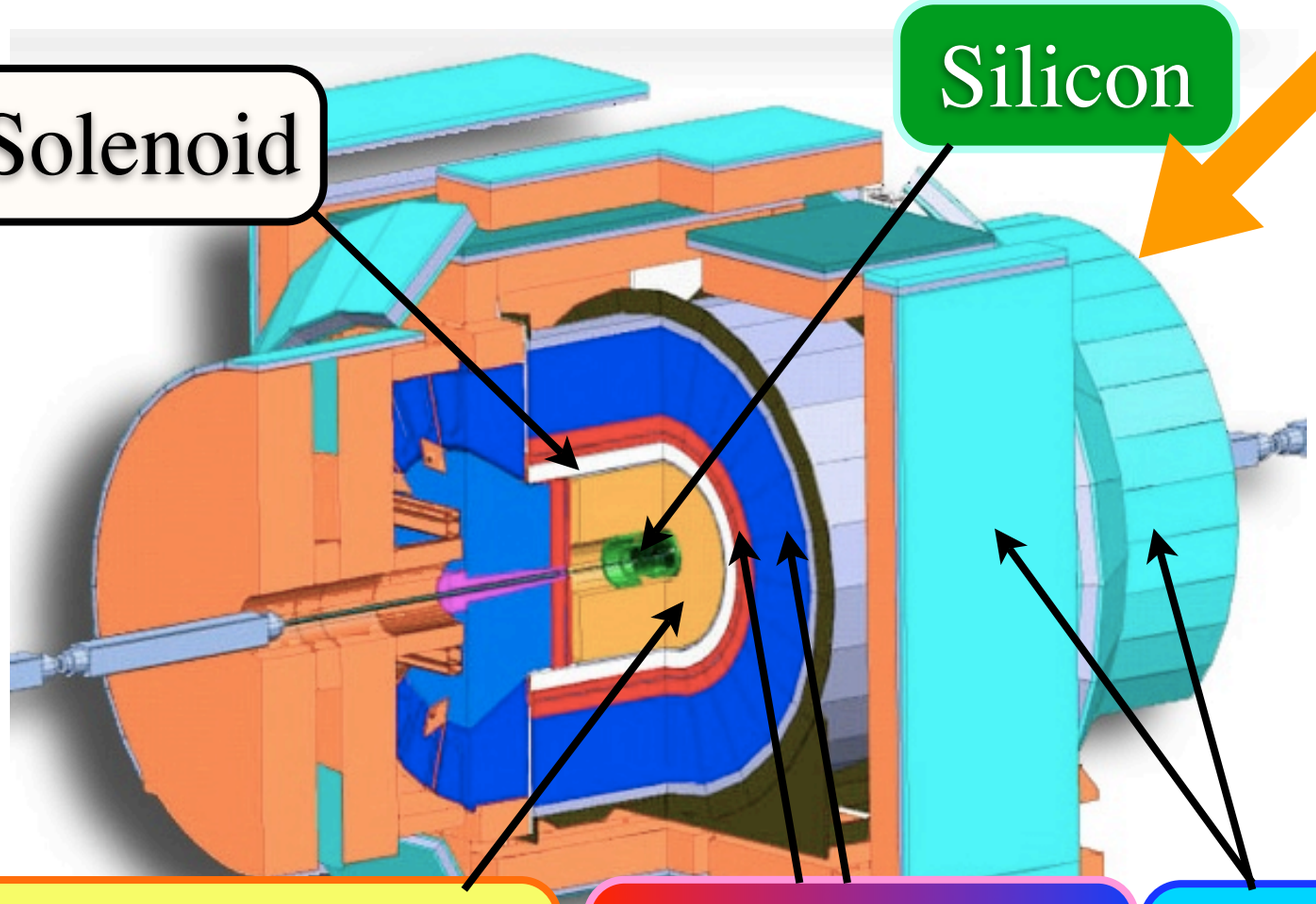
★$\sqrt{s}$ = 1.96 TeV $p\bar{p}$ collisions at CDF and D0

★ Data taking was finished in last September

★ Delivered: ~ 12 fb^{-1}

★ CDF Data taped: ~10 fb^{-1}





✻CDF Detector:
general purpose detector

Event Selection

- Data: 9.4 fb^{-1} collected by CDF (Full Dataset)
- Central leptons (Electron & Muon) + Forward Muons
- Minimum kinematical requirement for the 1st and 2nd leptons

(maximizing signal acceptance)

✓ 1st electron: $E_T > 20$ GeV & $p_T > 10$ GeV

- 1st muon: $p_T > 20$ GeV

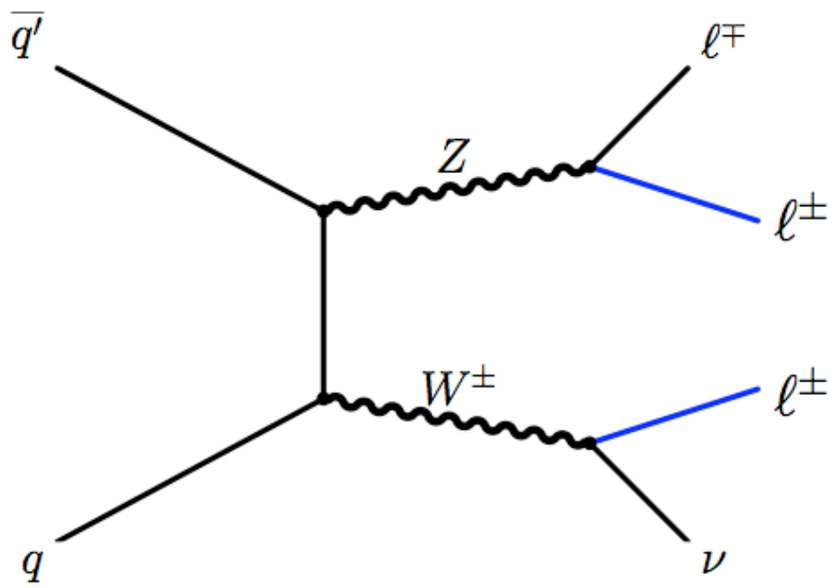
✓ 2nd lepton:

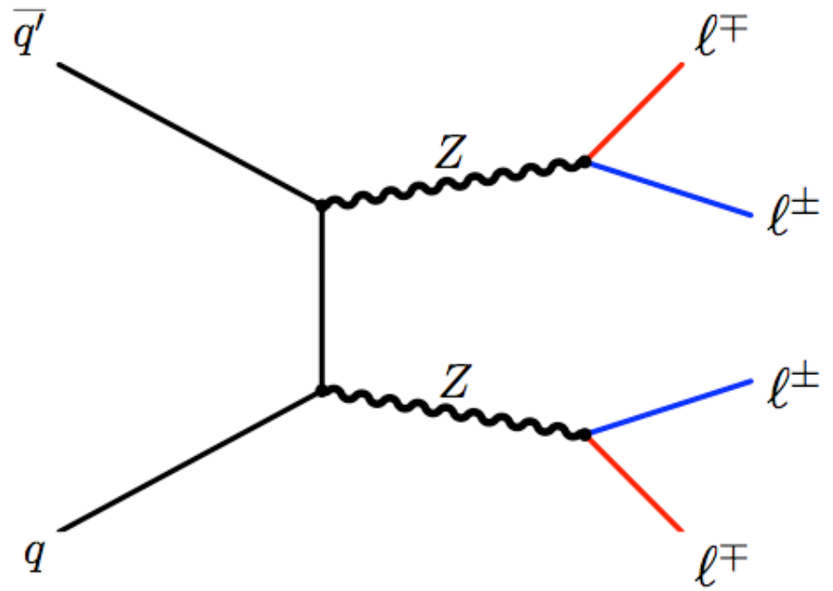
$$E_T^{\ell 2} > 6 \text{ GeV} \quad \& \quad p_T > 6 \text{ GeV}/c$$

- Isolation cuts
- Track quality cuts (including silicon hits)
- Lepton identification cuts based on likelihood method
- Z veto, dilepton mass cut, Like-sign charge combination

Backgrounds

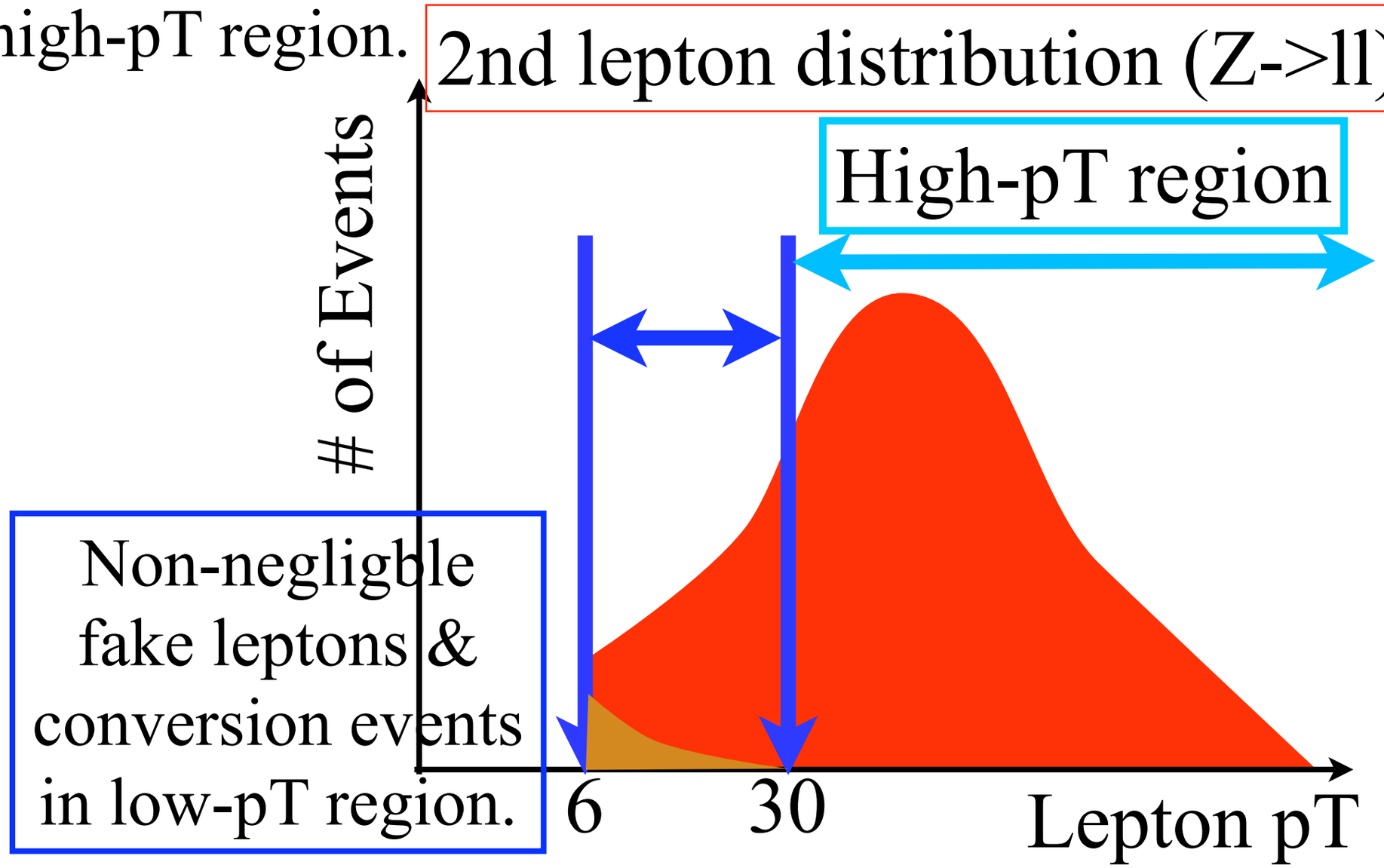
- Fake leptons (data-driven) (Details are shown in later)
  - ✓Punch-through hadrons
  - ✓Non-prompt leptons
  - ➡Fake $= R_{\mathrm{fake}} \times$(# of isolated tracks)
- Residual Conversions (data-driven) (Details are shown in later)
  - ➡RC $= R_{\mathrm{RC}} \times$ (# of conversions)
- SM backgrounds (MC) (Details are shown in later)
  - ✓WZ, ZZ
  - ✓Data/MC scale factors are estimated using Z->ll control samples.





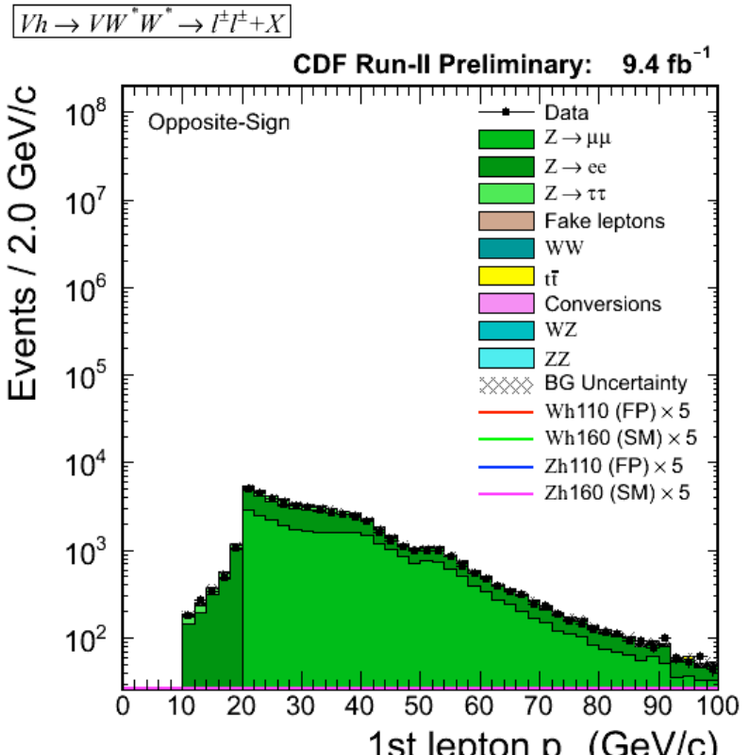
Data/MC Scale Factor

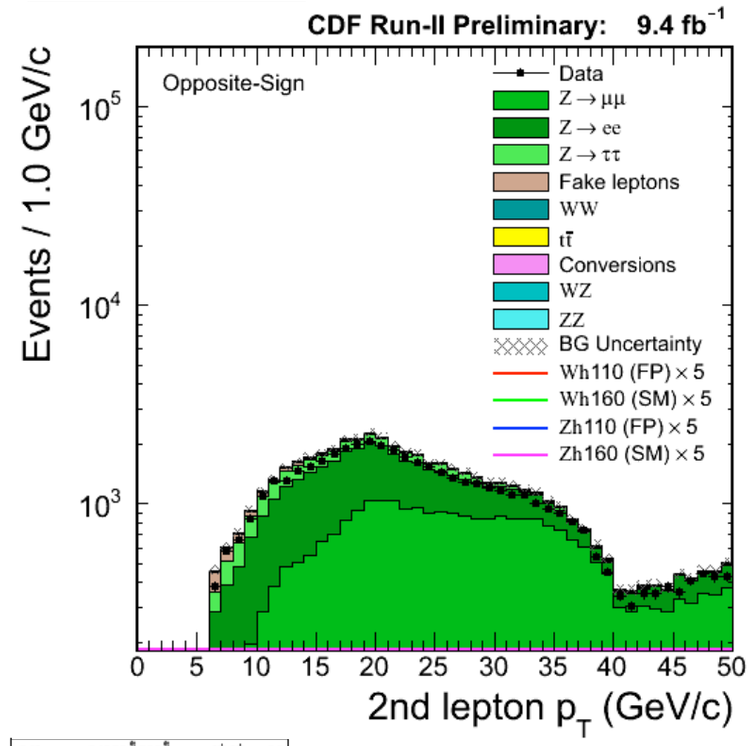
- MC simulations are not perfect. --> Need Data/MC scale factors.
- Sample: $Z \to \ell^{\pm}\ell^{\mp}$ (Data, MC), $81 < M_{\ell\ell} < 101$ GeV
- Scale factors depend on lepton pT.
- Scale factors for the forward & stubless muons are optimized in high-pT region.

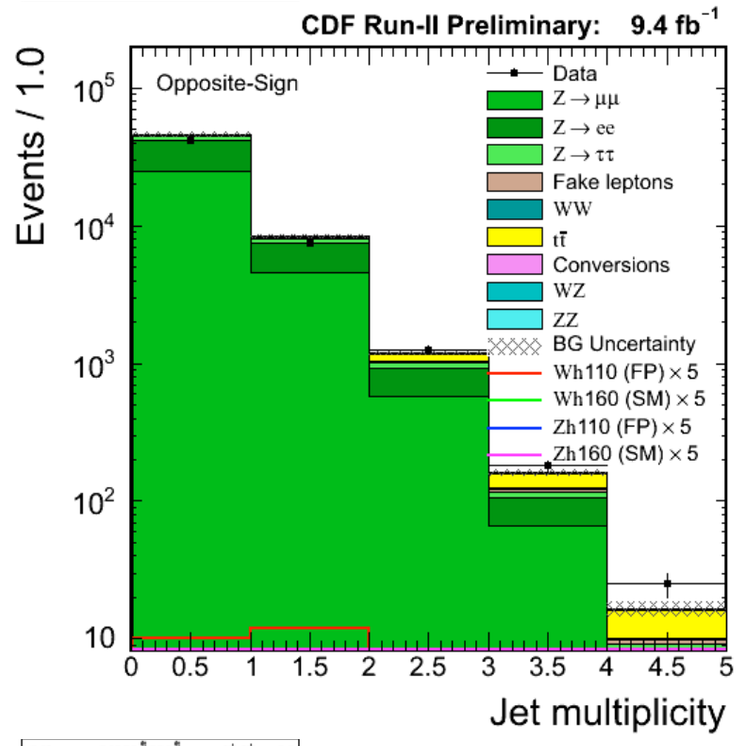


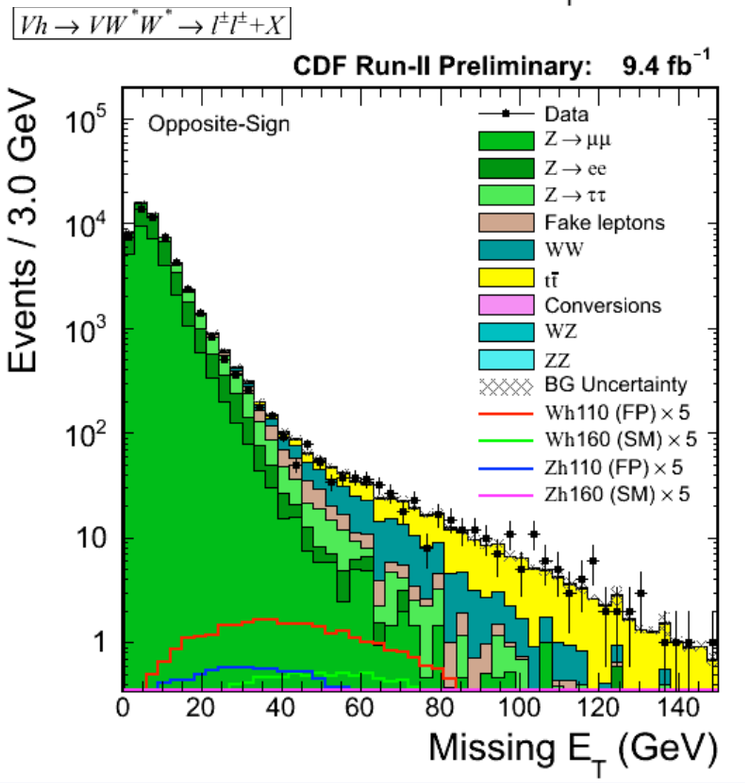
OS Dilepton Region

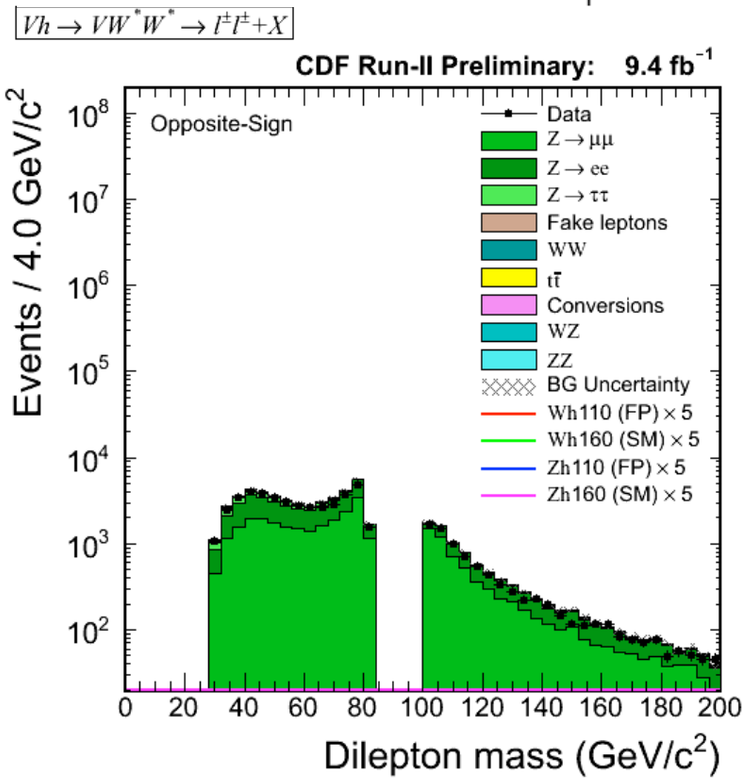
OS Dilepton Region ($M_{\ell\ell} < 81, M_{\ell\ell} > 101$)

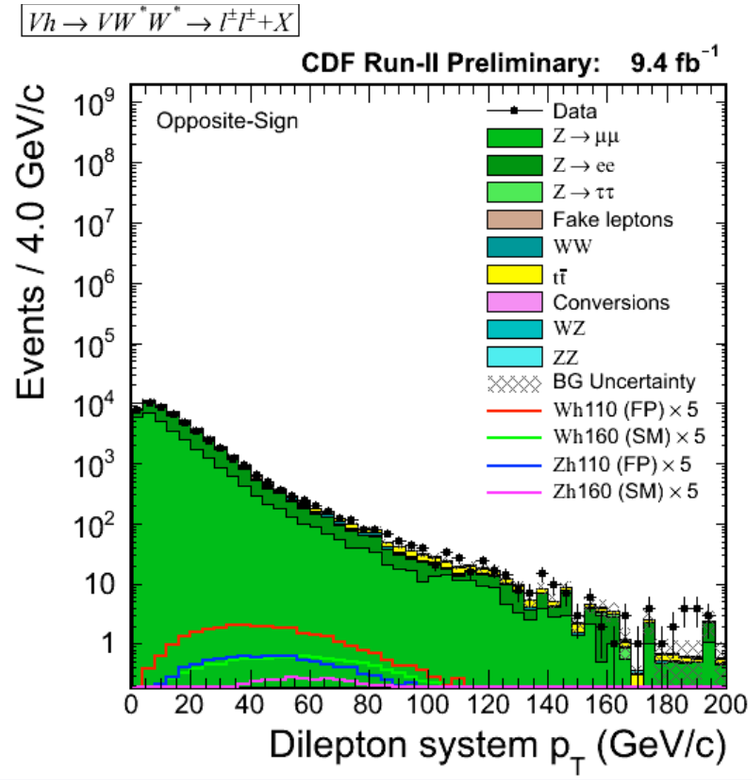












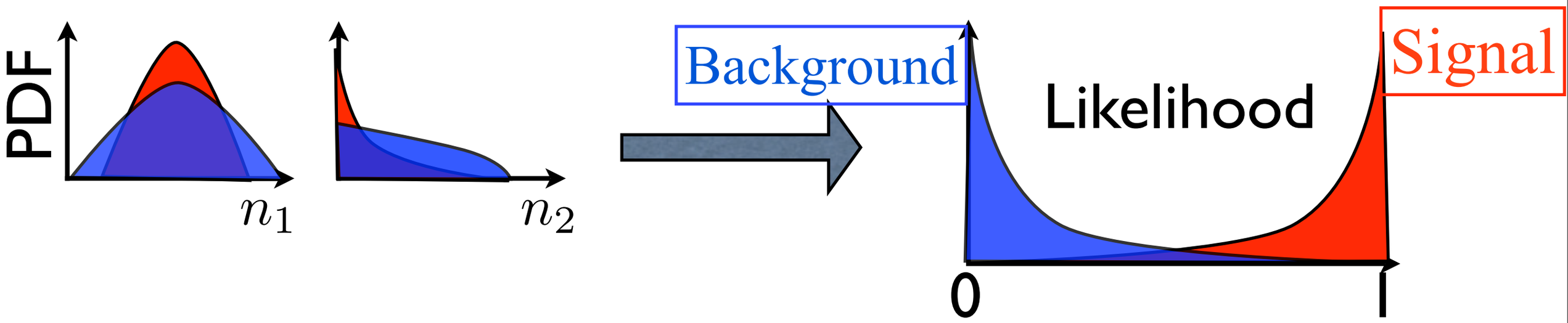
Likelihood-based Lepton ID

- S: Z-> ll candidates in high-pT lepton data
- B: lepton passing our preselections (in jet samples)
- Construct Likelihood as

$$\mathcal{L} = \mathcal{S}/(\mathcal{S}+\mathcal{B})$$

$$\mathcal{S} = \prod_{n_i} S_{\mathrm{PDF}}(n_i) \qquad \mathcal{B} = \prod_{n_i} B_{\mathrm{PDF}}(n_i)$$

- $S(B)_{\mathrm{PDF}}(n_i)$: Probability density function for variable
- variables: calorimeter energy, track-quality information, ...
- Commonly used method, especially CDF B-physics Group

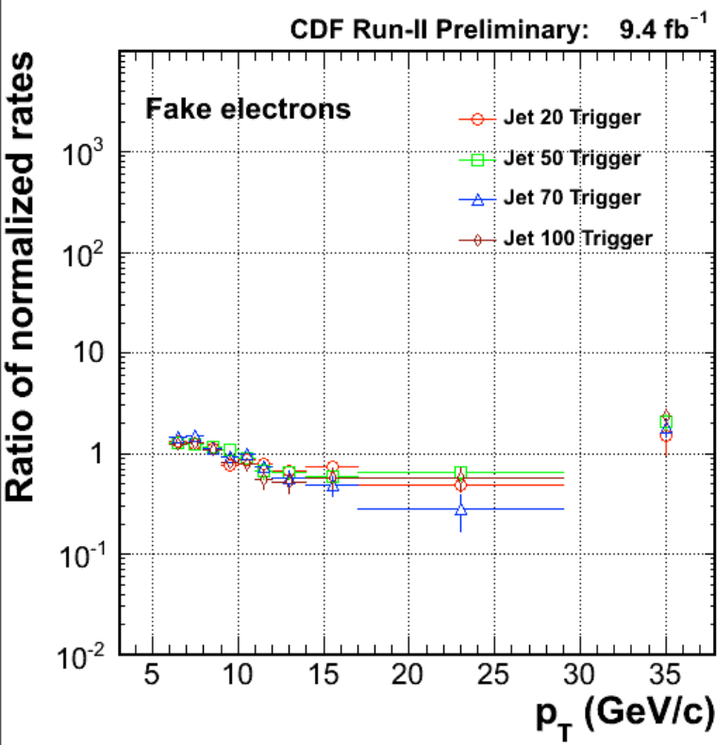


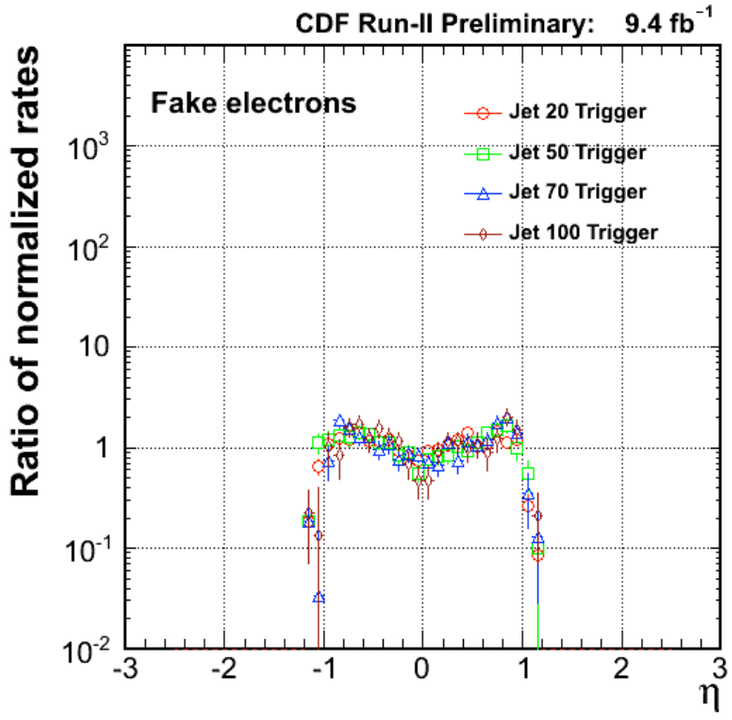
Fake Leptons

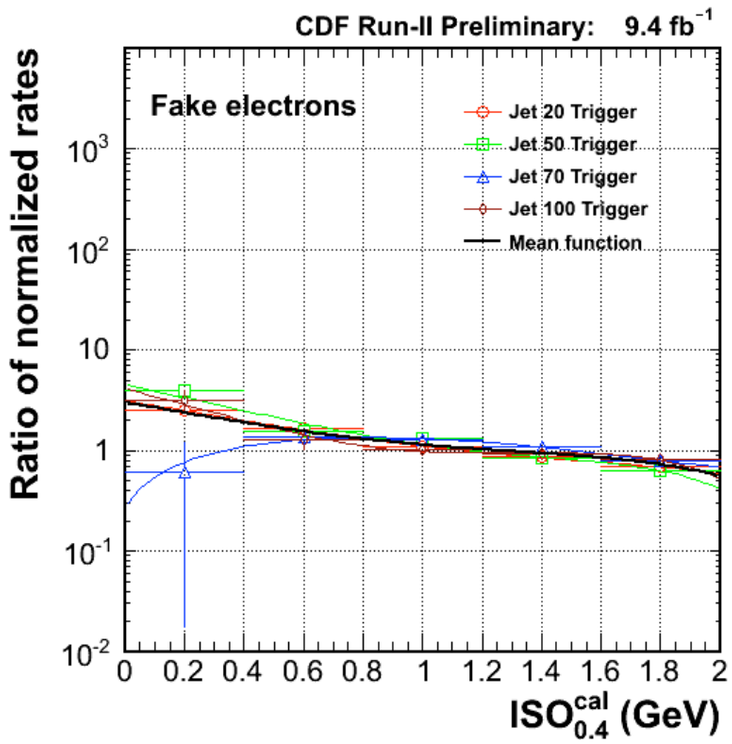
- Fake lepton components:
  - ★Interactive$\pi^{\pm}$,π^{0}+ track, punch-through hadrons
  - ★Semileptonic decay of heavy-flavor hadrons, decay-in-flight $\pi^{\pm}$, $K^{\pm}$
- 6-dim parametrization
  - ★lepton pT, pseudorapidity,$\Delta\phi(\not\!\!E_T, \ell)$, ...
- Data (jet samples) & MC (for electroweak-process subtraction) used
- Estimation:

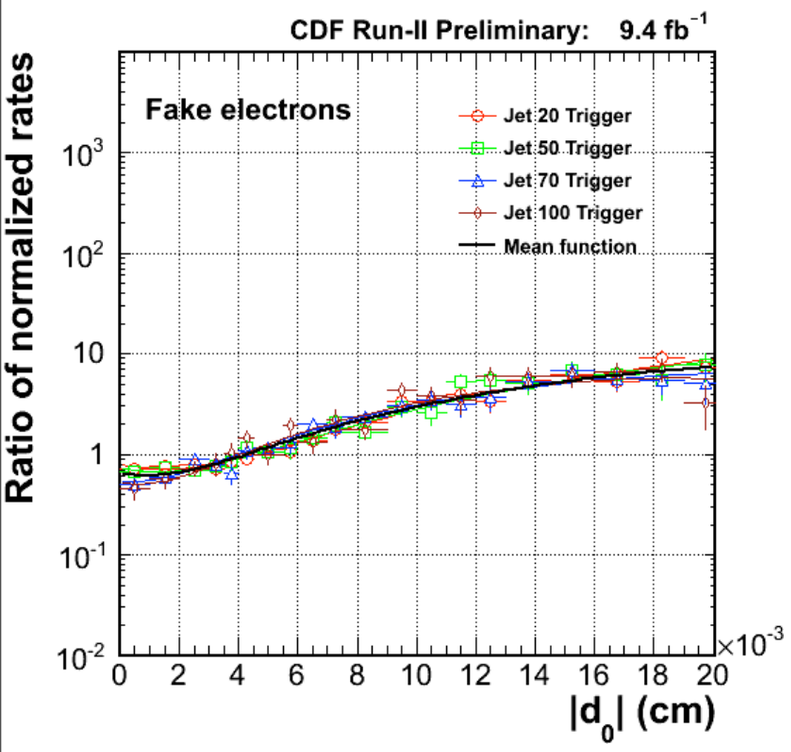
$$N_{\rm fake} = R_{\rm fake} \times N_{\rm track}, \qquad R_{\rm fake} = R_{\rm abs} \times f_{\rm norm}(p_T, \Delta\phi, ...)$$

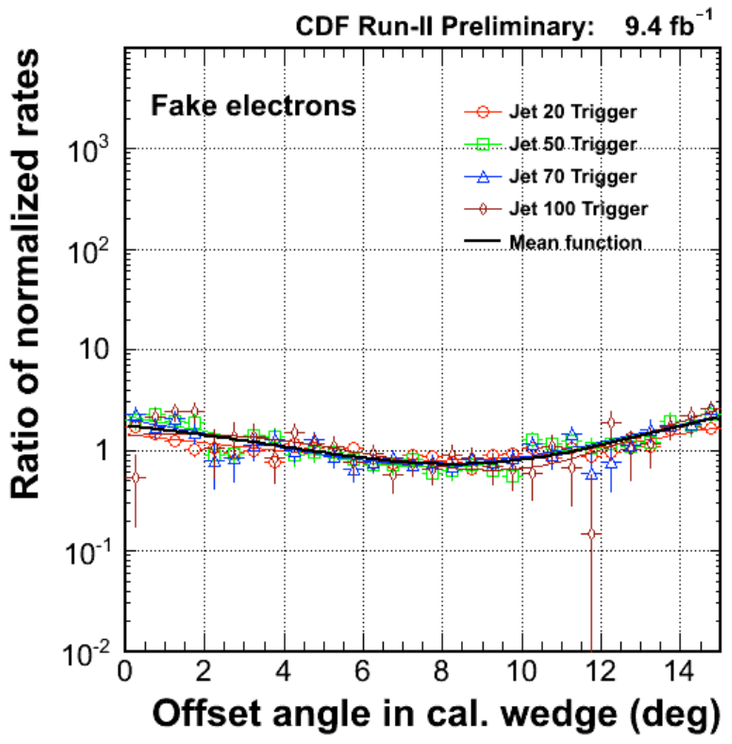
Fake Rates for Electrons

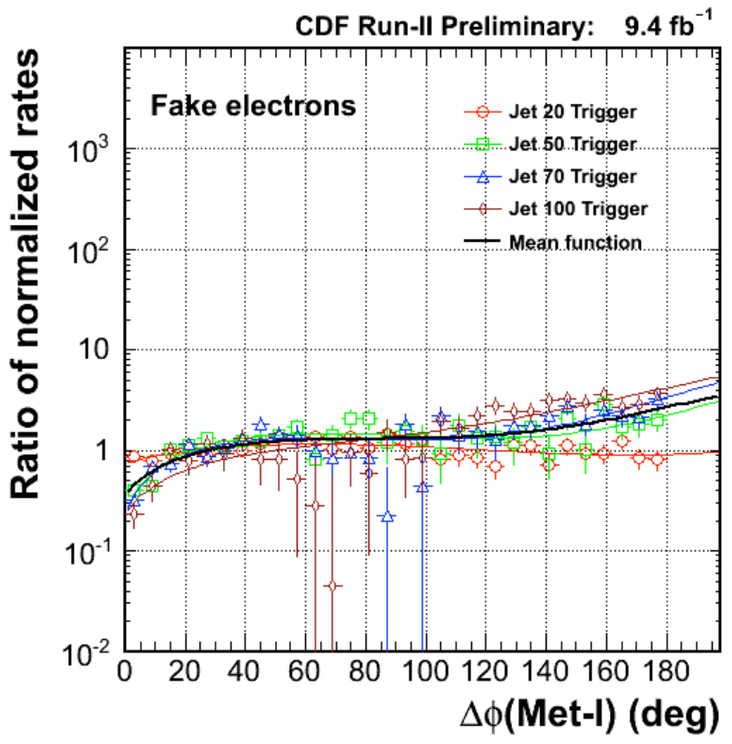






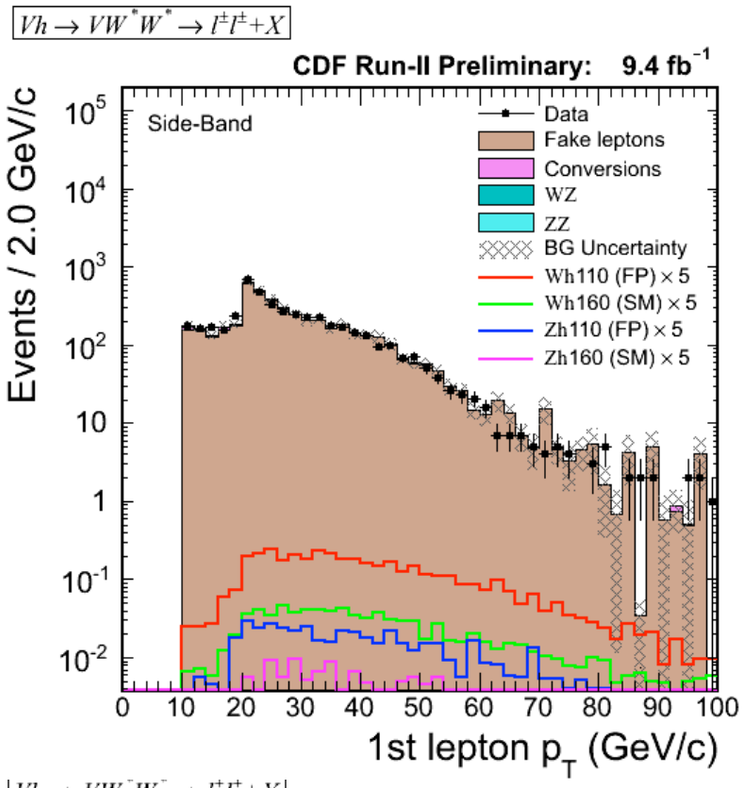


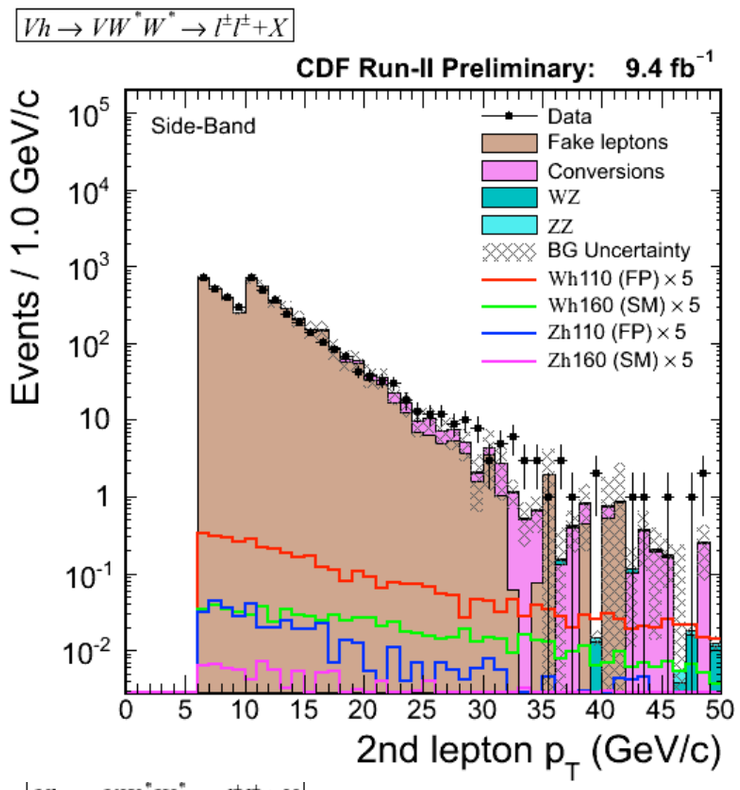


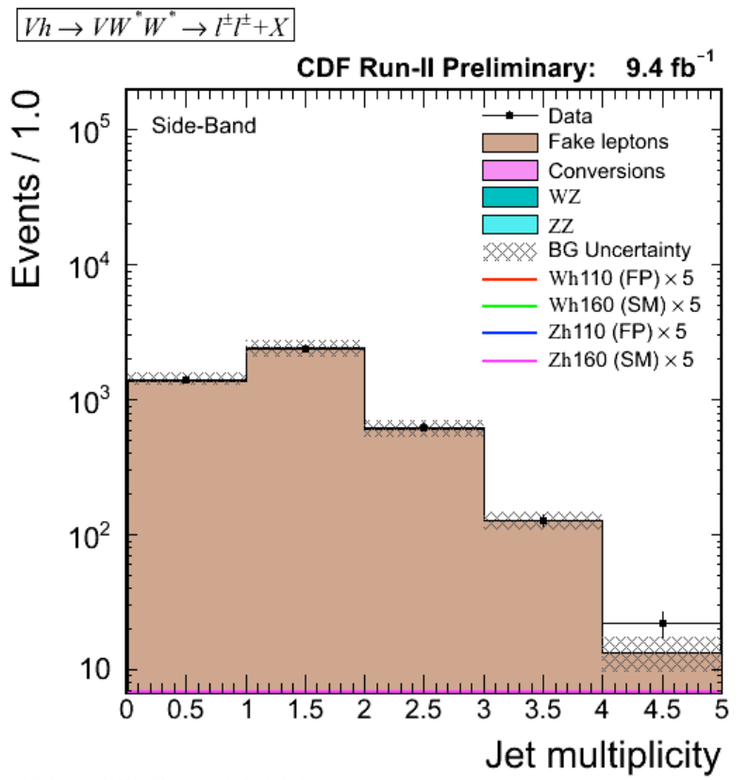


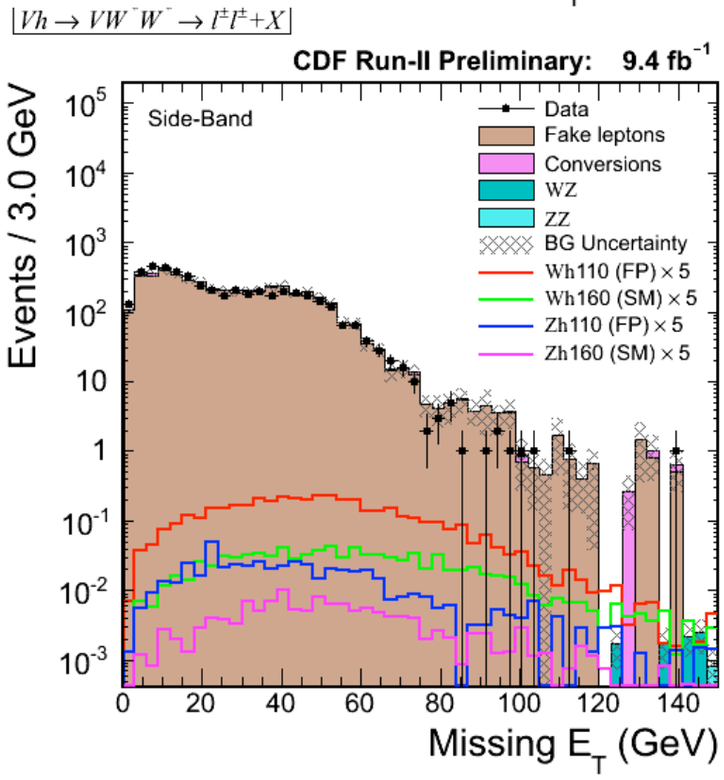
Validation for Fake Lepton

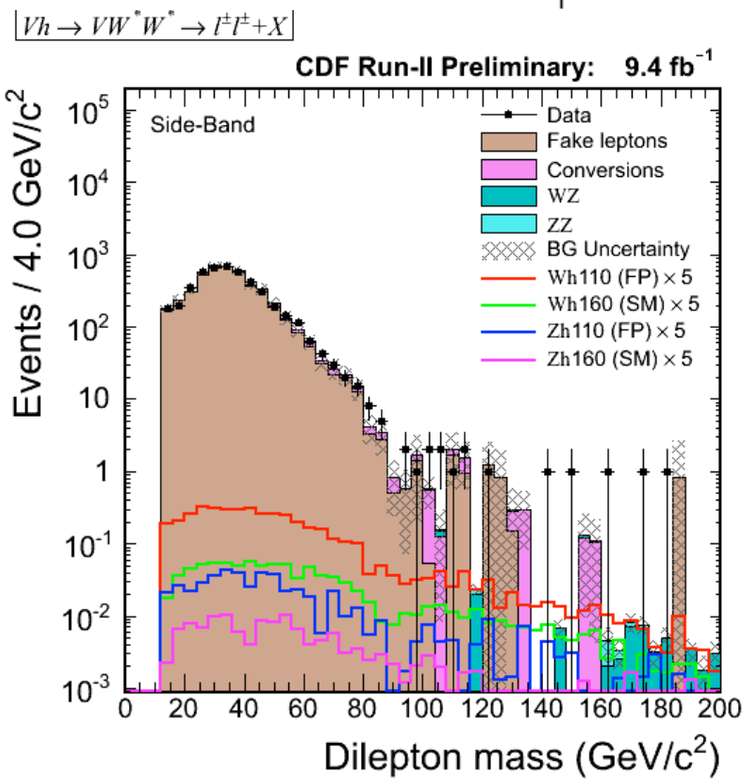
2nd lepton ID failed region: fake-lepton validation

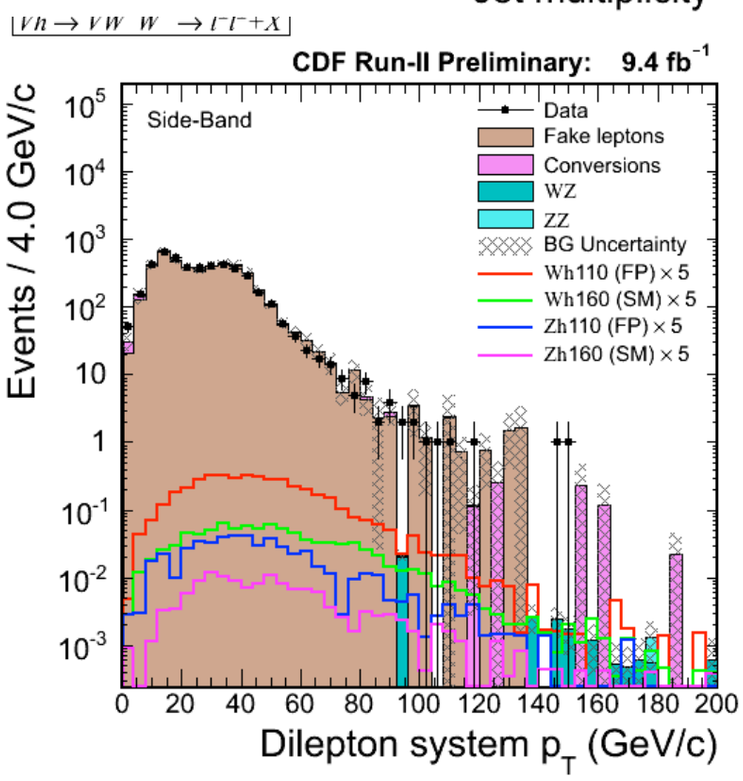






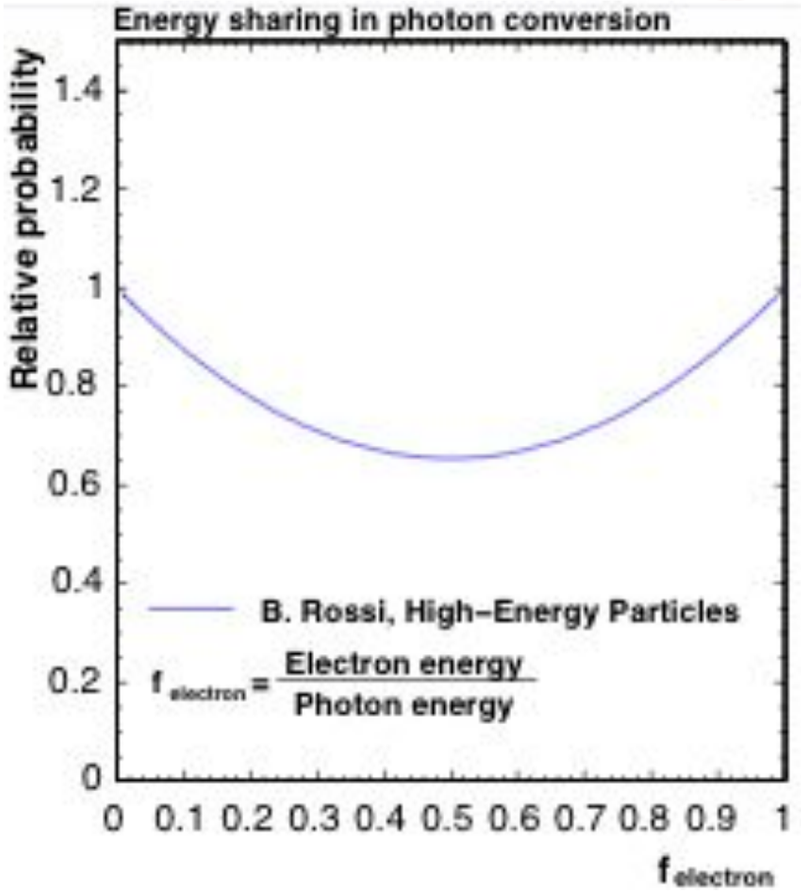






Residual Photon Conversion

- Photon-conversion events favor asymmetrical energy sharing.
  - ➡Partner-track tend to have low-pT.
  - ➡Enhance residual photon conversion backgrounds.

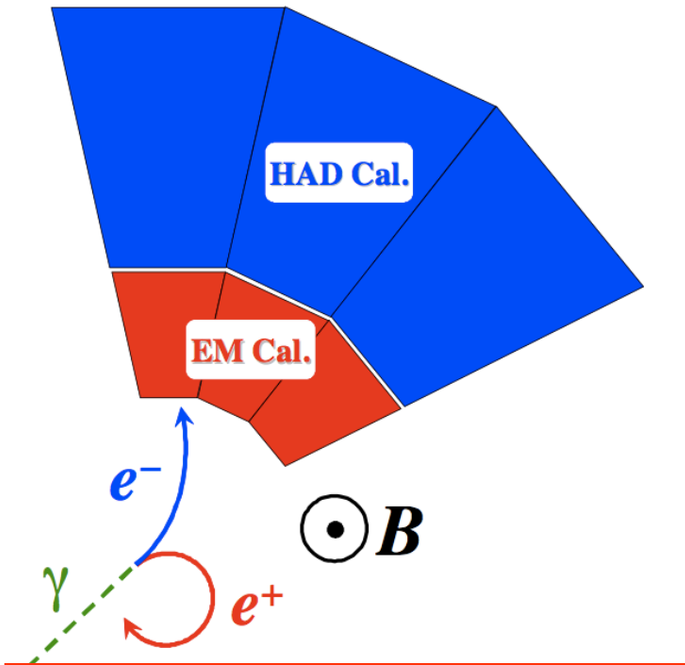


- Estimation:

$$N_{\mathrm{res}} = R_{\mathrm{res}} \times N_{\mathrm{conv}}$$

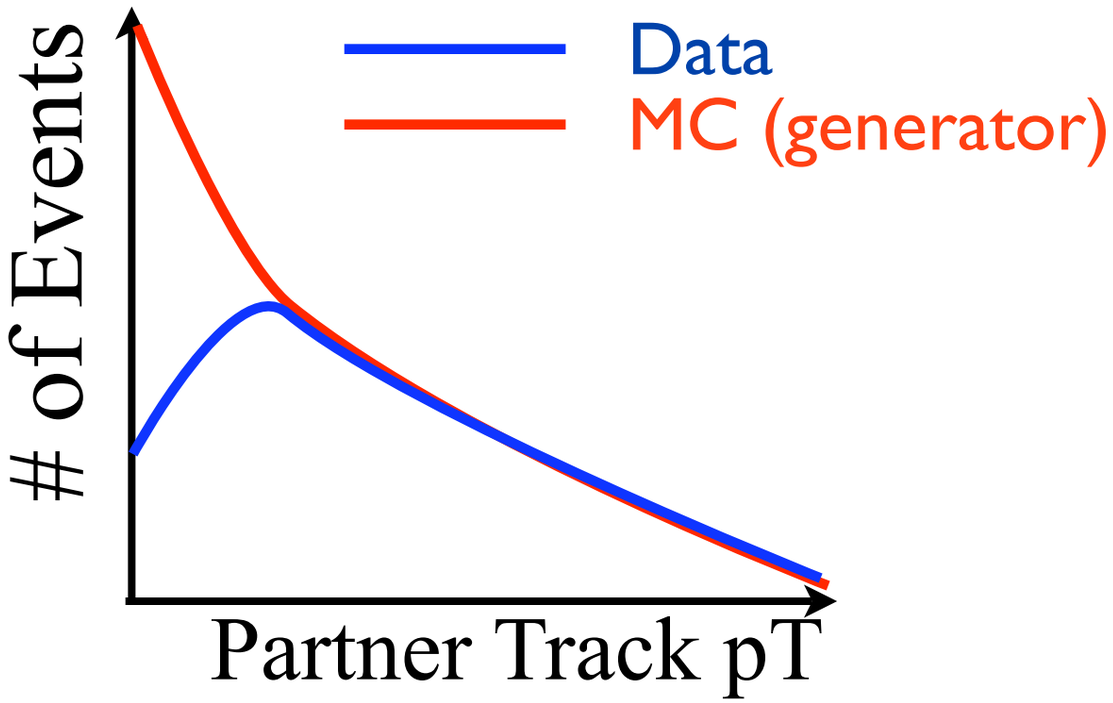
$$R_{\mathrm{res}} = \frac{N_{\mathrm{res}}}{N_{\mathrm{conv}}} = \frac{1-\varepsilon_{\mathrm{conv}}}{\varepsilon_{\mathrm{conv}}}$$

$$\varepsilon_{\mathrm{conv}} = \varepsilon_{\mathrm{rel}}(p_T) \times \varepsilon_{\mathrm{abs}}$$



Residual Photon Conversion

Relative Part



- Compare Data with MC
- Difference in low-pT region
- Reach plateau above 1 GeV/c

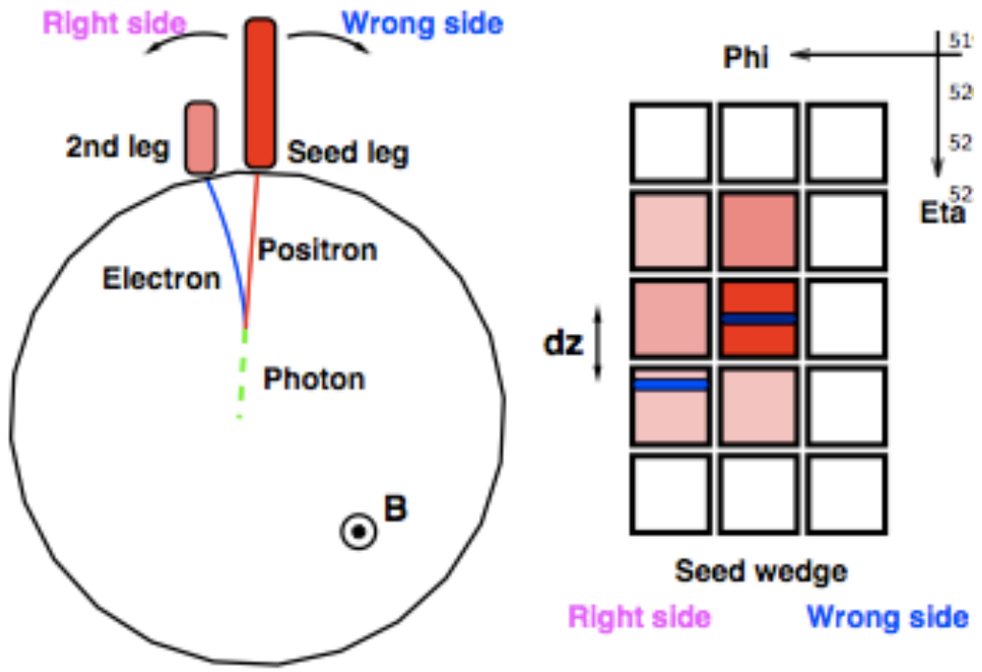
Absolute Part

- Nominal Conversion Tagging

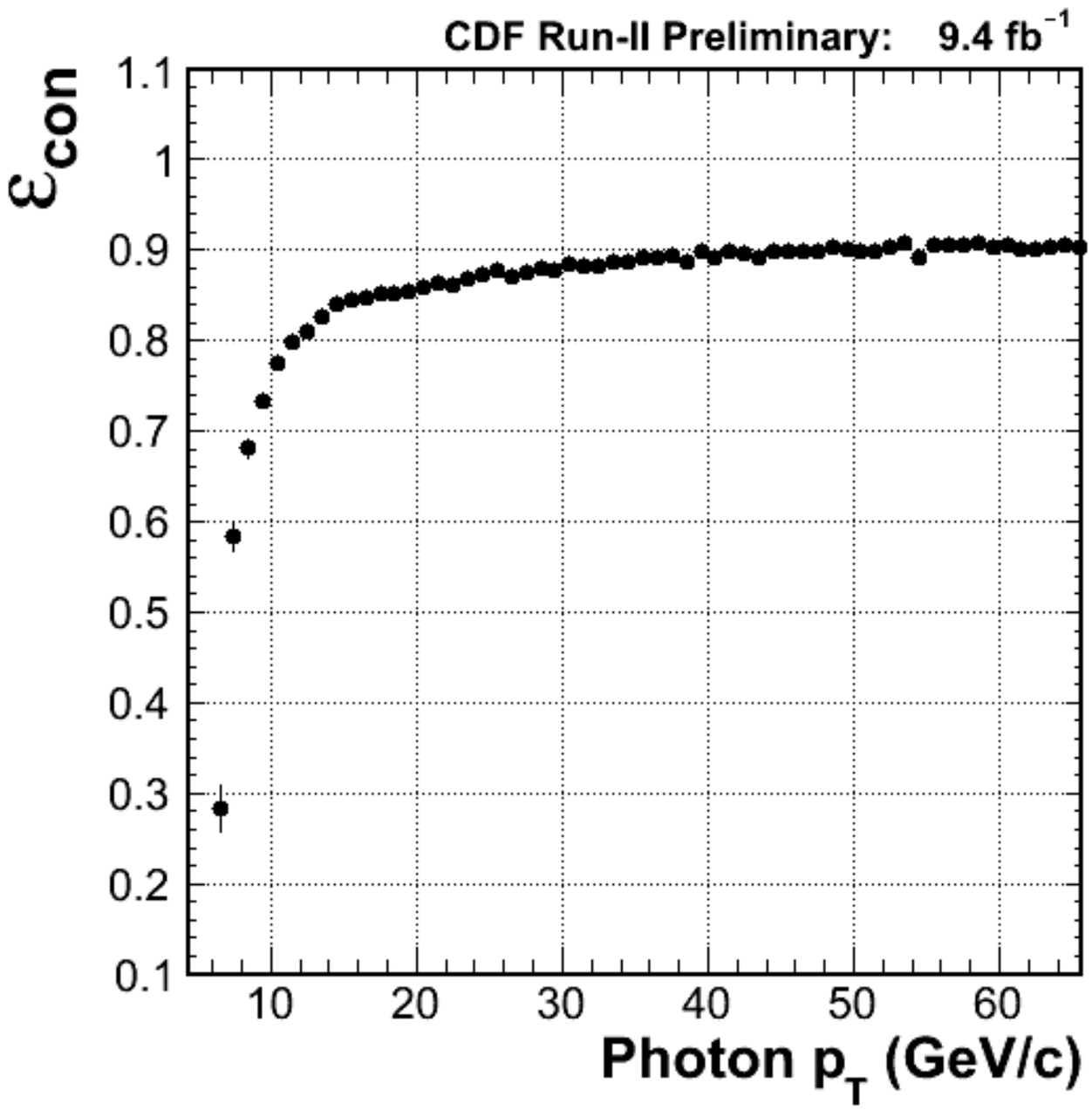
$$|\delta_{xy}| < 0.2 \text{ cm}$$
$$|\Delta(\cot\theta)| < 0.04$$

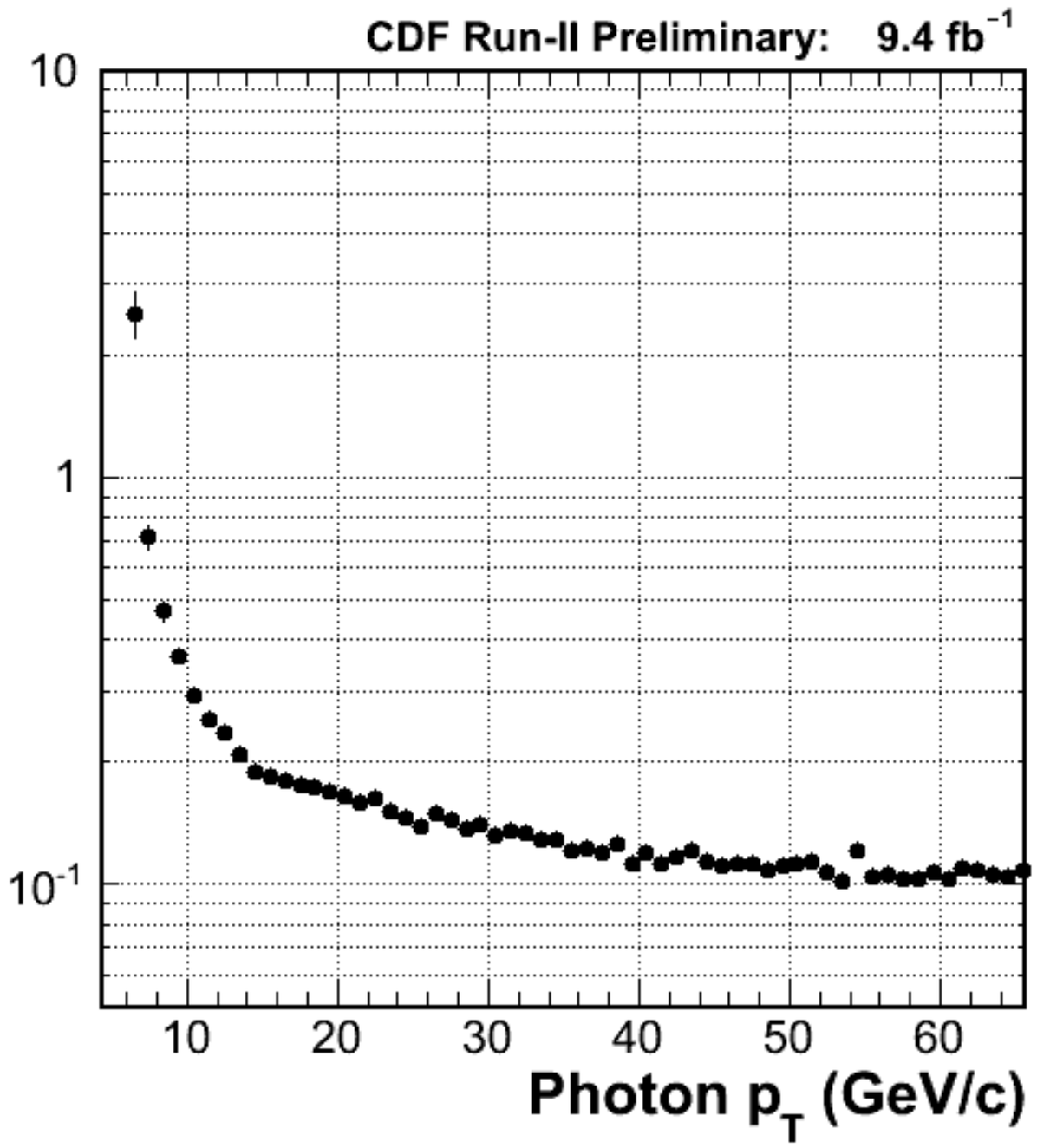
- Alternative Tagging Method (CES Method)

★Central Electromagnetic Strips (CES) hit information



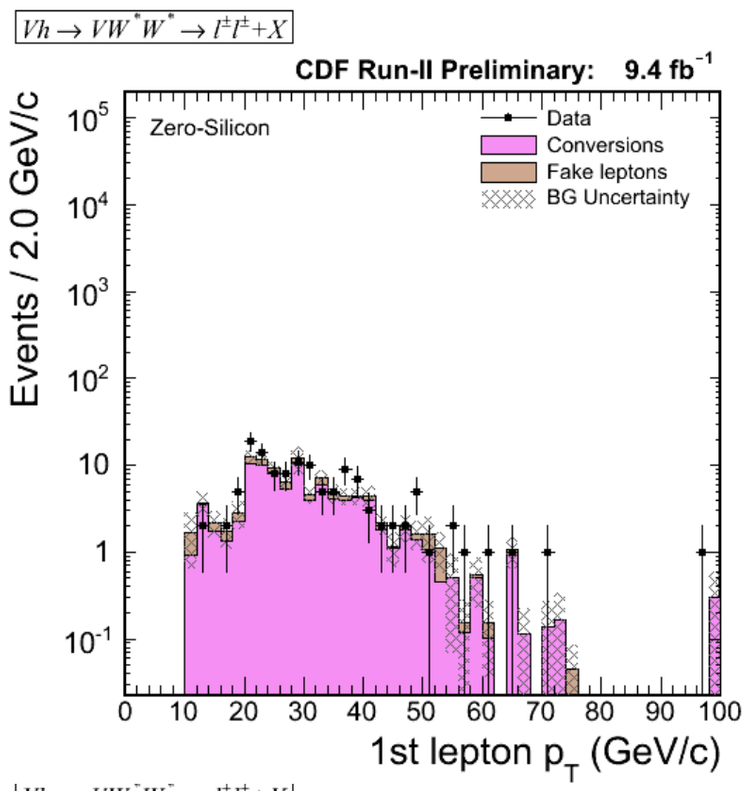
Conversion Efficiency & RC Rate

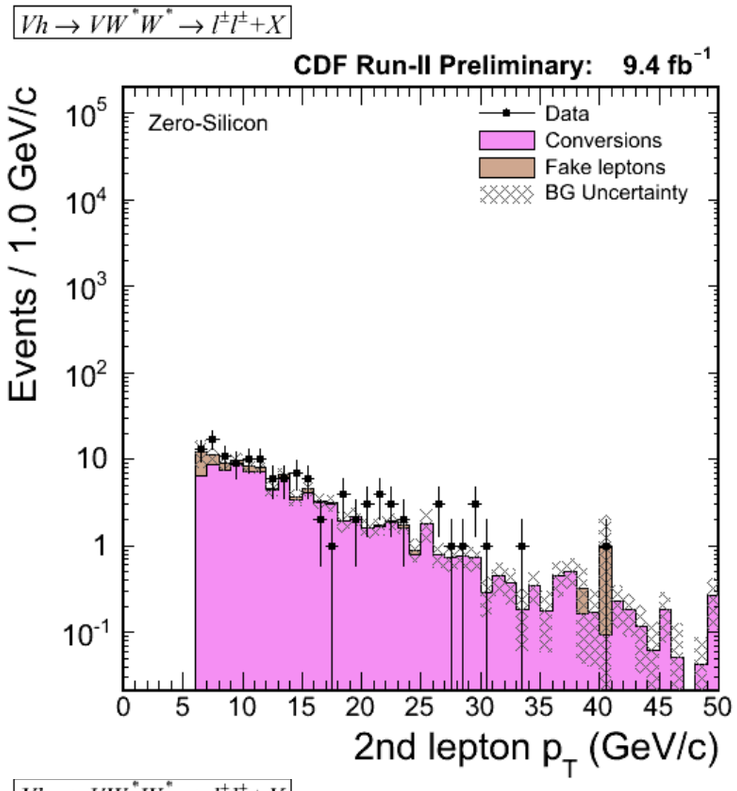


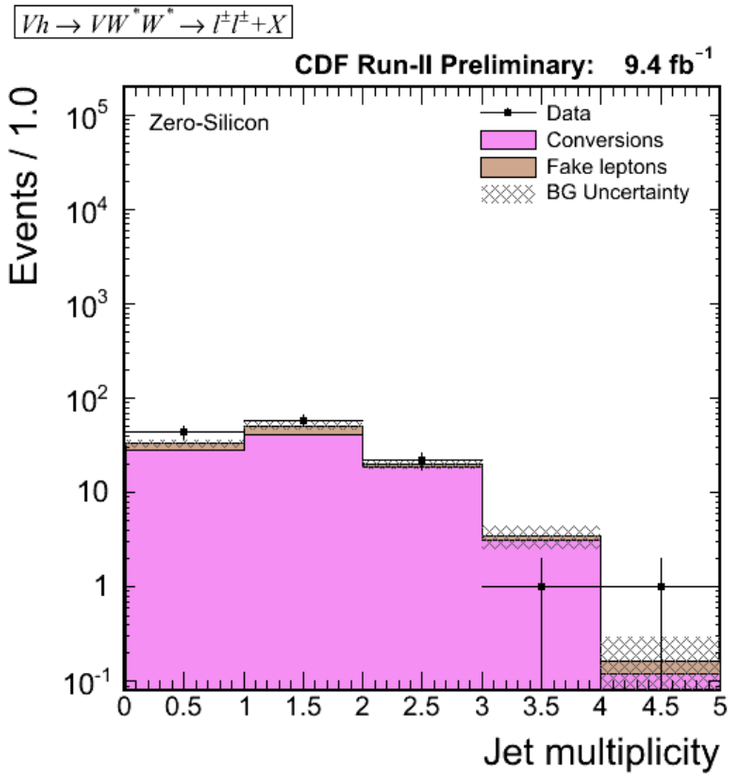


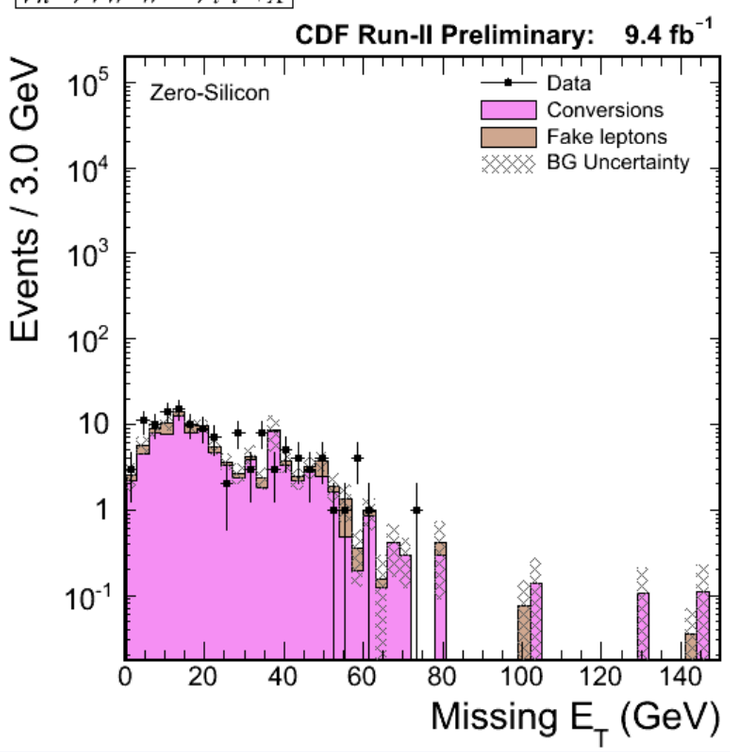
Validation for Conversion

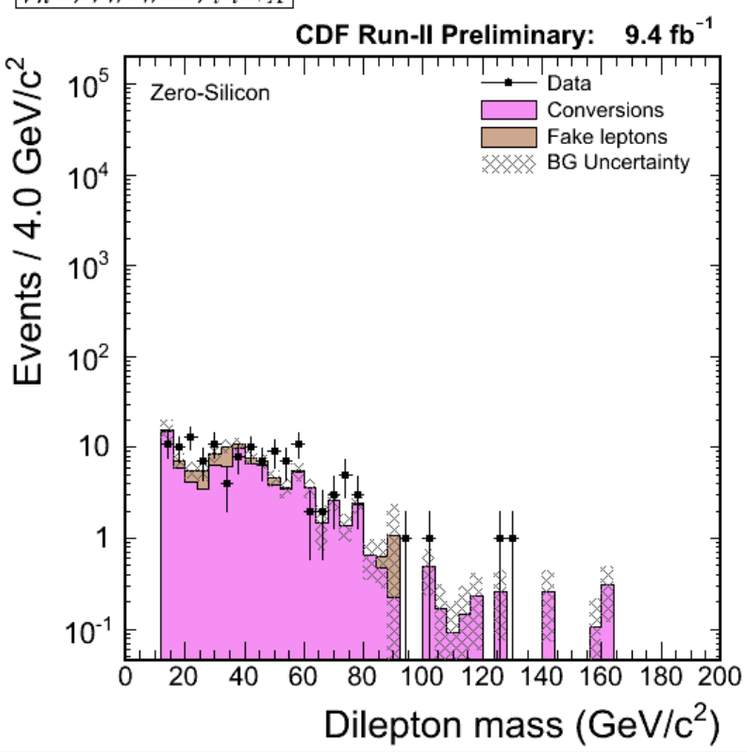
2nd lepton Zero Silicon Hit Region: Conversion rich

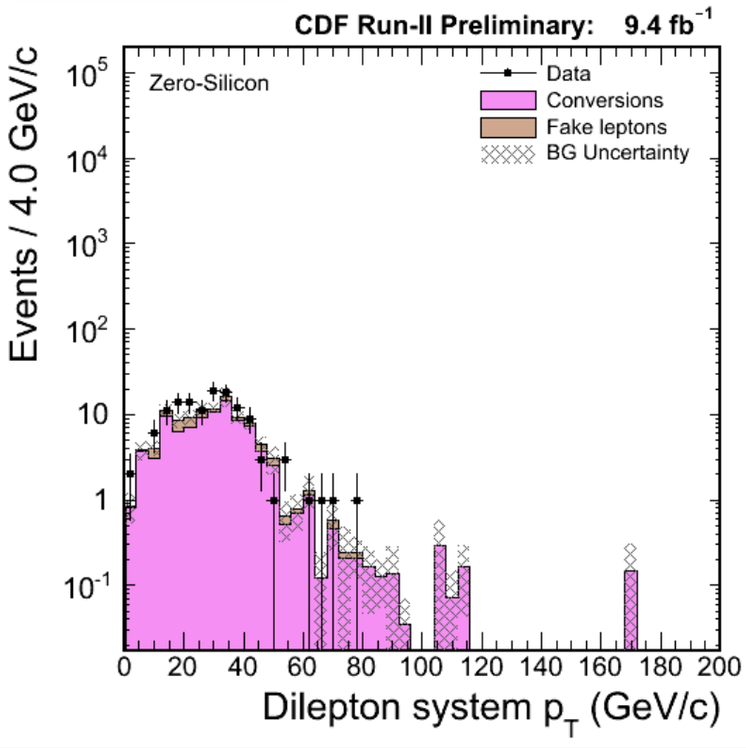










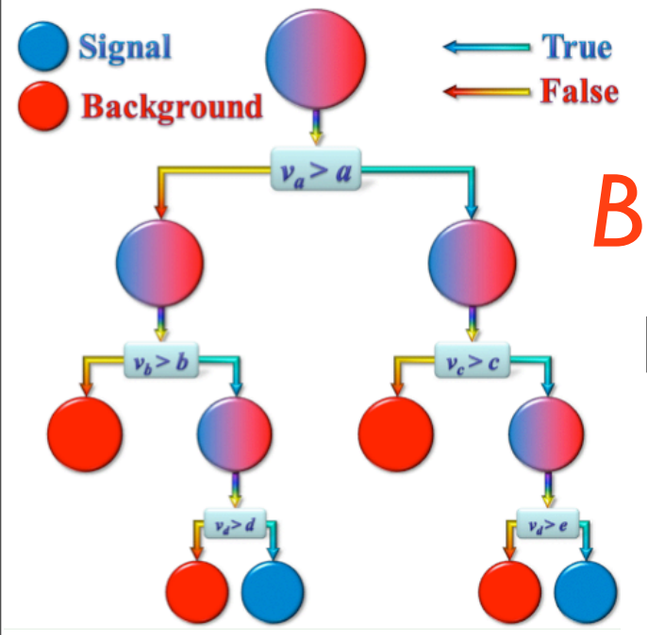


Multivariate Analysis

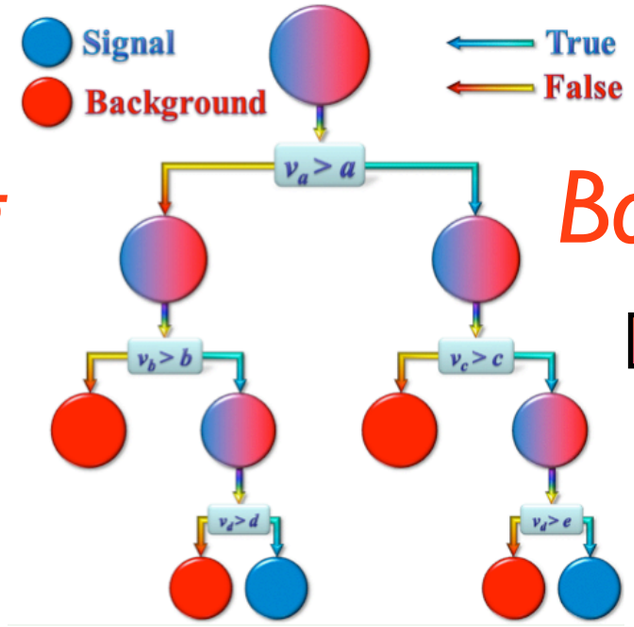
★To get more sensitivity, we employ multivariate technique.

★Boosted Decision Trees (BDT)

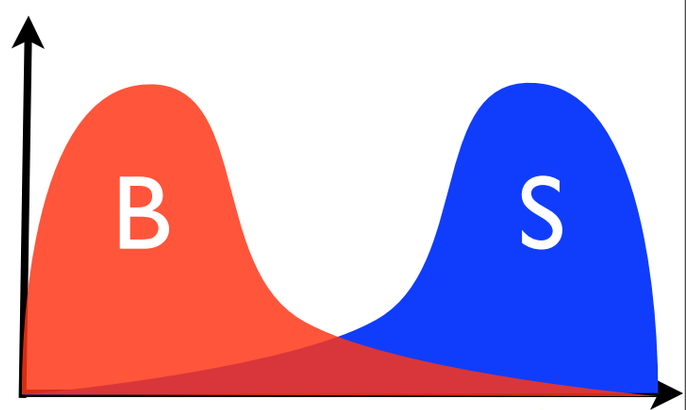
- True/False decision in each splitting (Decision Tree)
- Boosting can pick up misclassified events w/ weighting each event
- Output from many trees, combine w/ error rates



Boosting



Boosting



...(many trees)

Error Rate α_1

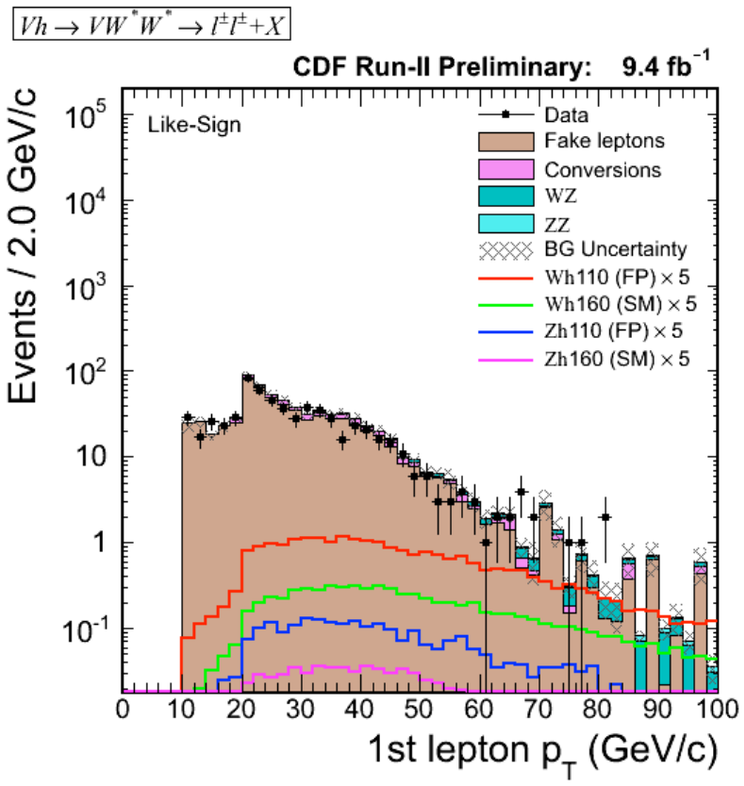
First Tree T_1

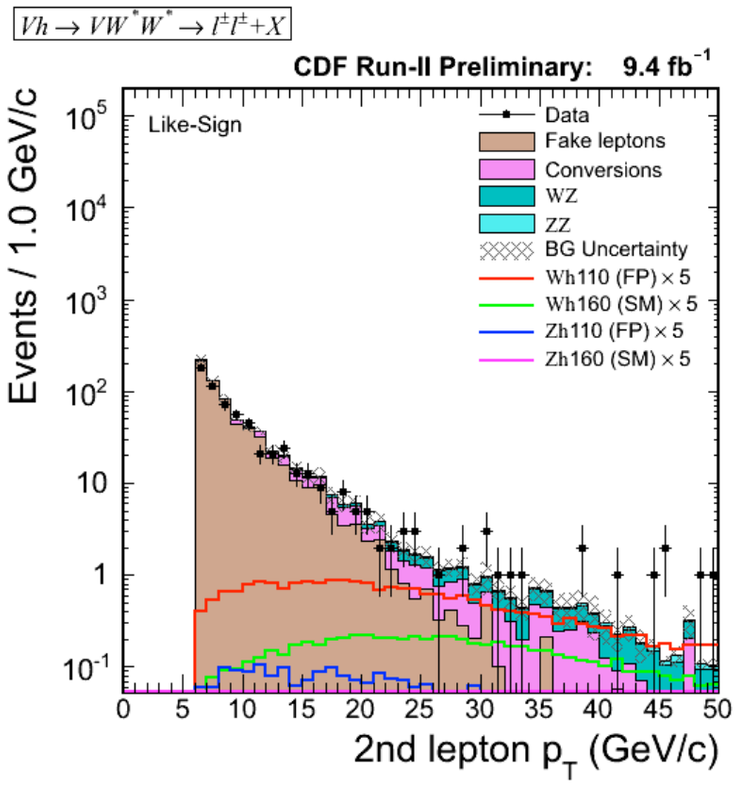
Error Rate α_2

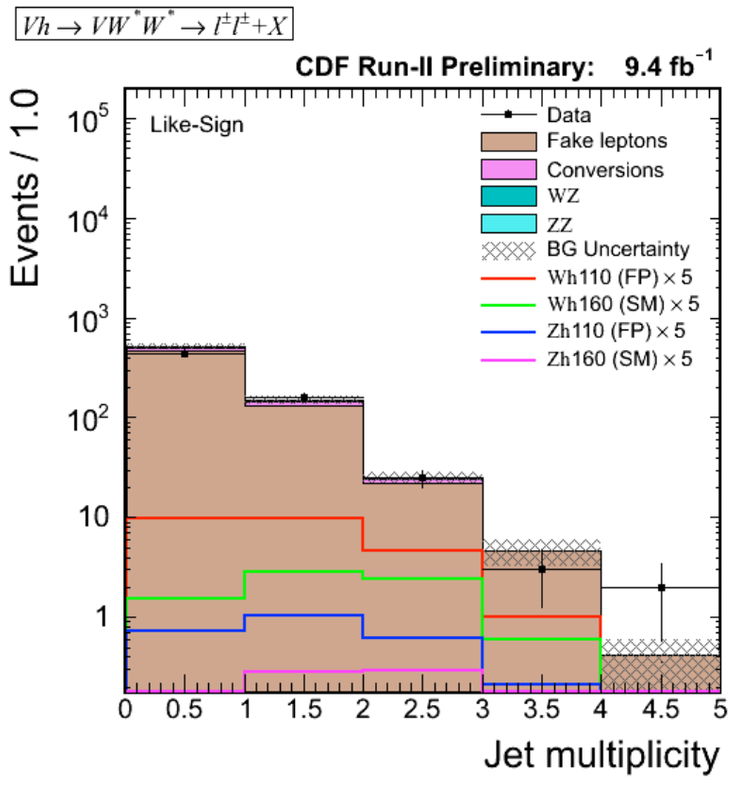
Second Tree T_2

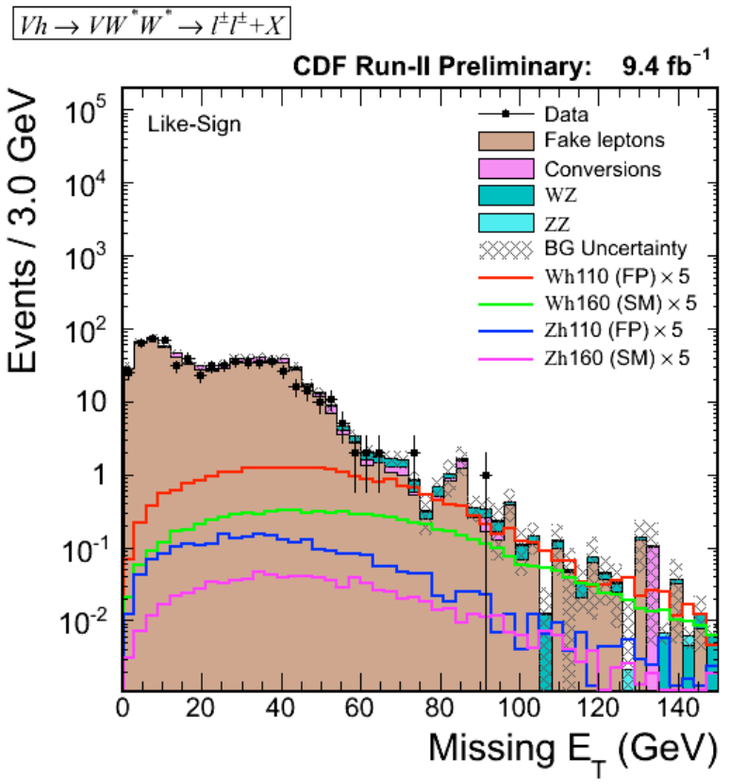
$$\text{Output} = \sum_n \alpha_n T_n$$

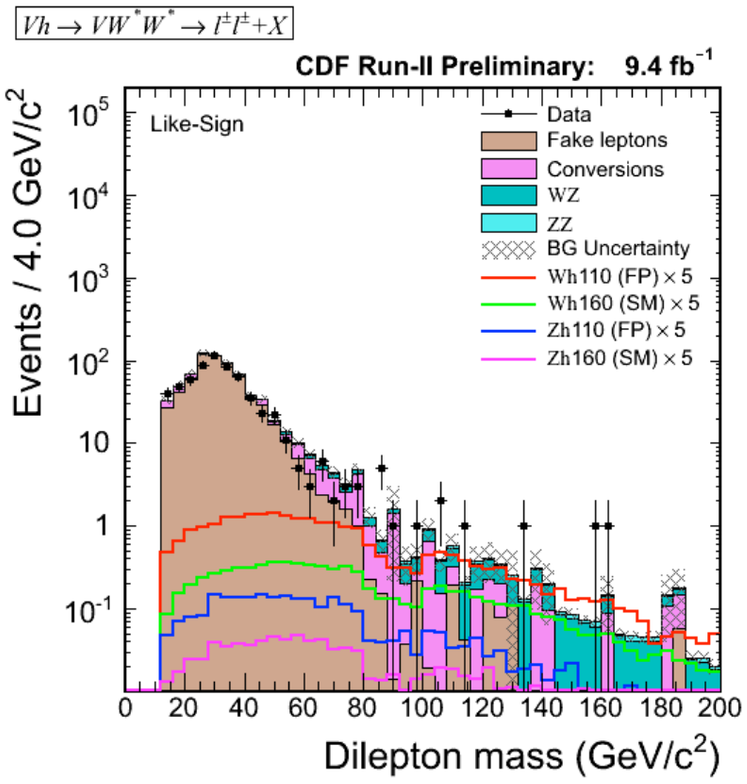
Input Variables (Selected)

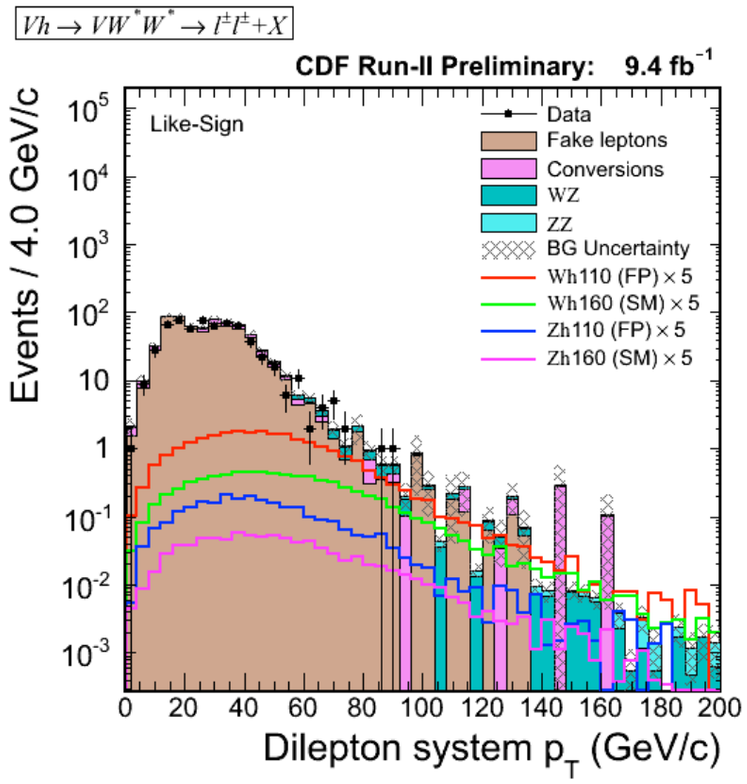












Expected & Data

$Vh \rightarrow VW^*W^* \rightarrow l^{\pm}l^{\pm} + X$

CDF Run-II Preliminary: 9.4 fb^{-1}

	Lepton ID Side-Band	Zero Silicon	OS	Signal
Fakes	4493.9±594.6	15.7±2.53	674.8±107.6	631.9±51.4
Photon-conversions	123.1±34.1	91.7±13.0	192.5±39.6	49.5±12.1
Total	4616.9±595.6	107.4±13.2	867.3±114.7	681.4±52.8
$Z/\gamma^* \rightarrow ee$	-	-	19841.4±1503.9	-
$Z/\gamma^* \rightarrow \mu\mu$	-	-	30327.3±2296.2	-
$Z/\gamma^* \rightarrow \tau\tau$	-	-	4071.3±310.2	-
$t\bar{t}$	-	-	269.2±20.4	-
WW	-	-	399.2±30.2	-
WZ	2.1±0.3	-	27.3±3.4	13.1±1.6
ZZ	0.4±0.1	-	23.7±3.0	1.7±0.2
Total MC	2.5±0.3	-	54959.4±4159.2	14.8±1.7
Fermiophobic higgs (Wh110)	0.88±0.10	-	6.31±0.71	5.09±0.59
Fermiophobic higgs (Zh110)	0.10±0.01	-	2.33±0.27	0.53±0.06
Fermiophobic Total (110)	0.98±0.10	-	8.64±0.76	5.62±0.59
SM higgs (Wh160)	0.19 ±0.02	-	2.46±0.28	1.51±0.17
SM higgs (Zh160)	0.028±0.003	-	1.15±0.13	0.18±0.02
SM Total (160)	0.21±0.02	-	3.61±0.31	1.69±0.17
Total expected	4619.4±595.6	107.4±13.2	55826.7±4214.6	696.1±52.8
Data	4598	127	51243	624

WH Systematic Uncertainties

$Wh \to WW^*W^* \to l^\pm l^\pm + X$ CDF Run-II Preliminary: 9.4 fb^{-1}

Higgs Mass (GeV/c^2)	110	120	130	140	150	160	170	180	190	200
Statistics	0.8%	0.8%	0.8%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%
PDF	2.2%	1.9%	1.6%	1.6%	1.4%	1.2%	1.4%	1.1%	0.8%	0.7%
ISR	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
FSR	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%
Z/γ^*	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%
Cross Section	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Luminosity	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Total	11.5%	11.4%	11.4%	11.4%	11.3%	11.3%	11.3%	11.3%	11.3%	11.3%

- PDF: Estimated by reweighting method
- Z/γ^*: Data/MC difference when SF estimations
- Cross Section: Theoretical uncertainty (5%)

Backgrounds Systematic

$Vh \rightarrow VW^*W^* \rightarrow l^{\pm}l^{\pm} + X$ CDF Run-II Preliminary: 9.4 fb^{-1}

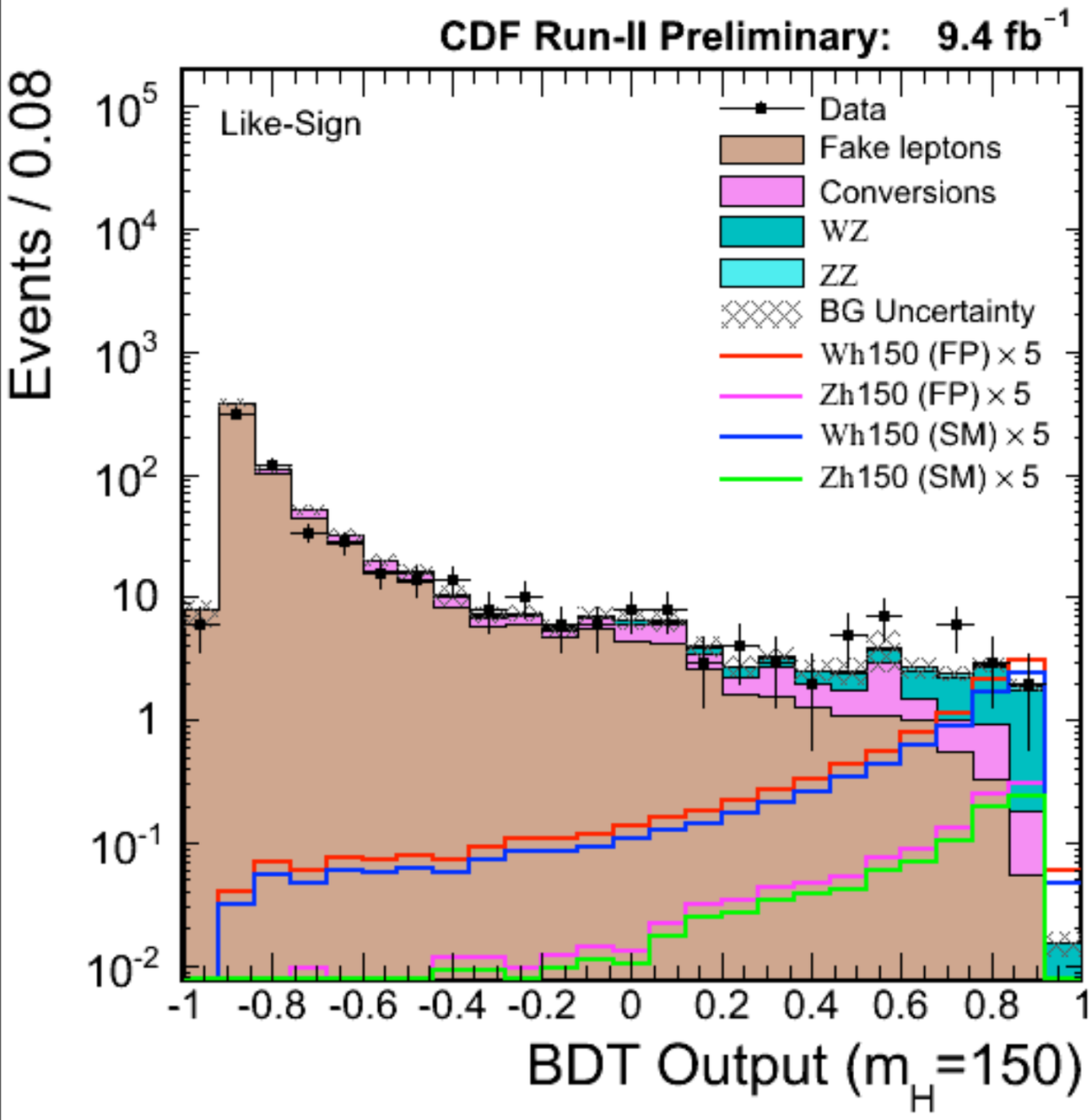
	Fake leptons	Residual photon-conversion	WZ	ZZ
Statistics	2.1%	11.1%	0.7%	2.1%
Fake rate	7.9%	-	-	-
Residual conversion rate	-	22.0%	-	-
Z/γ^*	-	-	4.6%	4.6%
Cross Section	-	-	10.0%	10.0%
Luminosity	-	-	6.0%	6.0%
Total	8.2%	24.7%	12.6%	12.7%

- Fake Rate: including the differences between jet samples
- Cross Section: Theoretical, ISR/FSR, PDF uncertainties

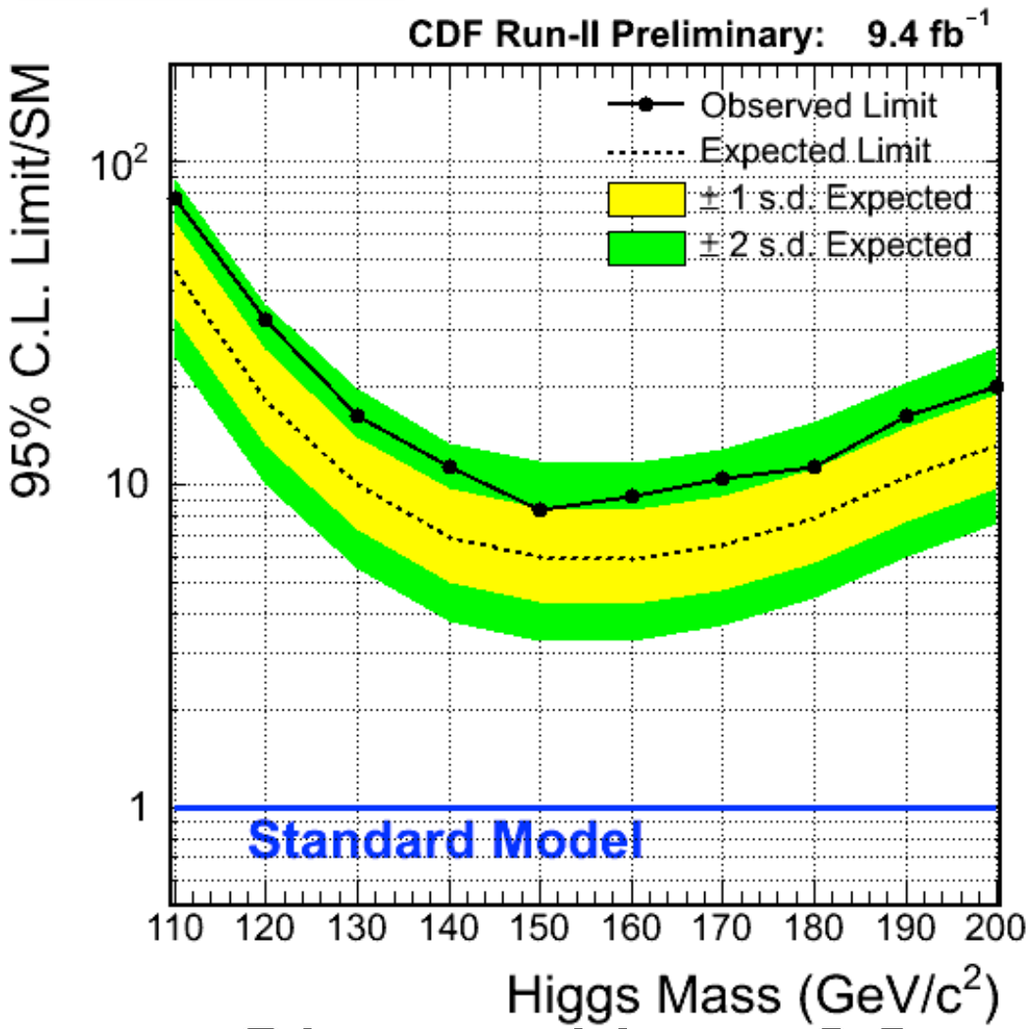
Results (SM)

- No significant differences between data & expected backgrounds
- We set 95% Confidence Level limit on the SM Higgs

$Vh \to VW^*W^* \to l^\pm l^\pm + X$



$Vh \to VW^*W^* \to l^\pm l^\pm + X$



Observed limit: 8.3

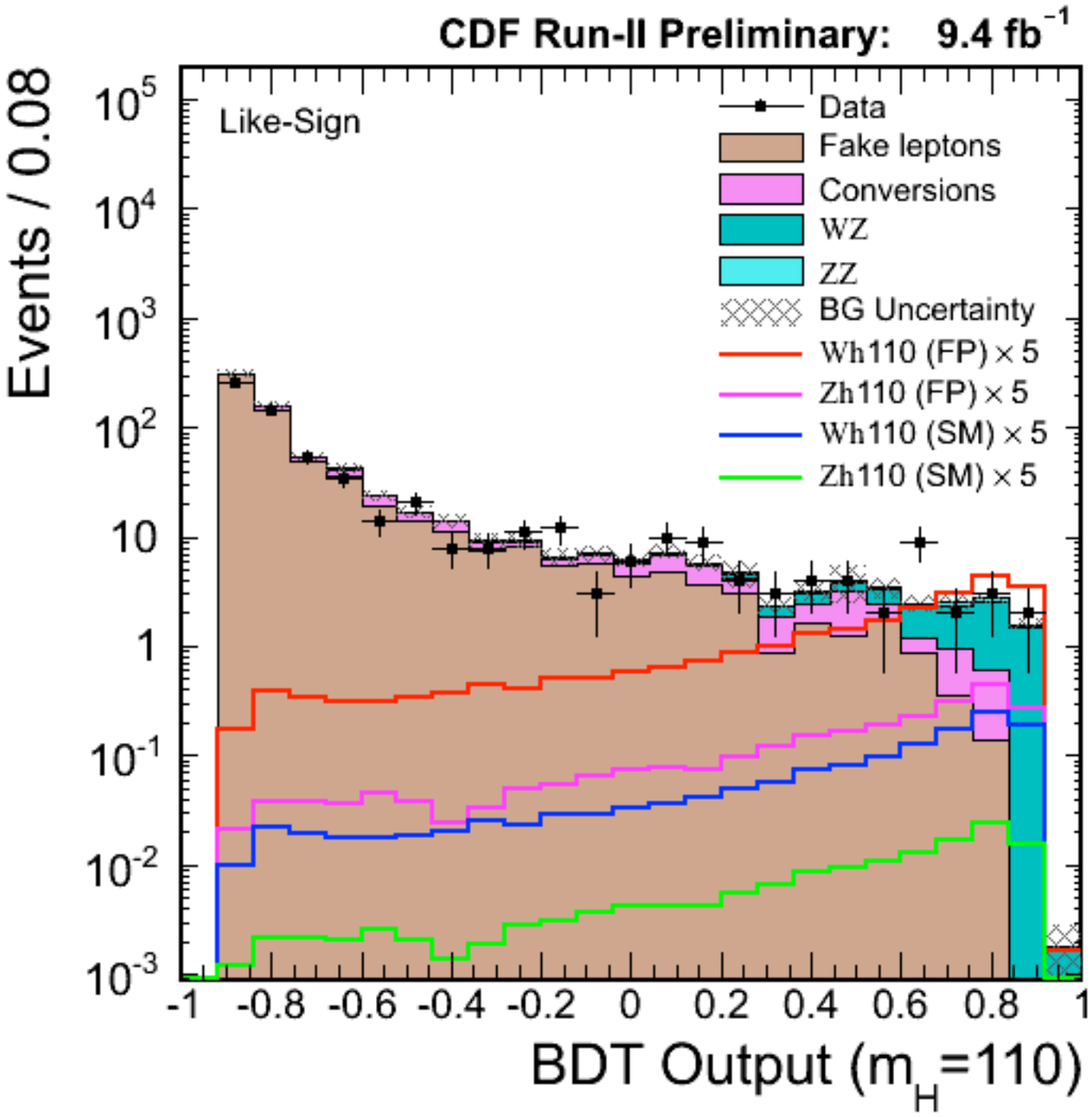
Expected limit: 6.0

$$m_H = 150\ \mathrm{GeV}/c^2$$

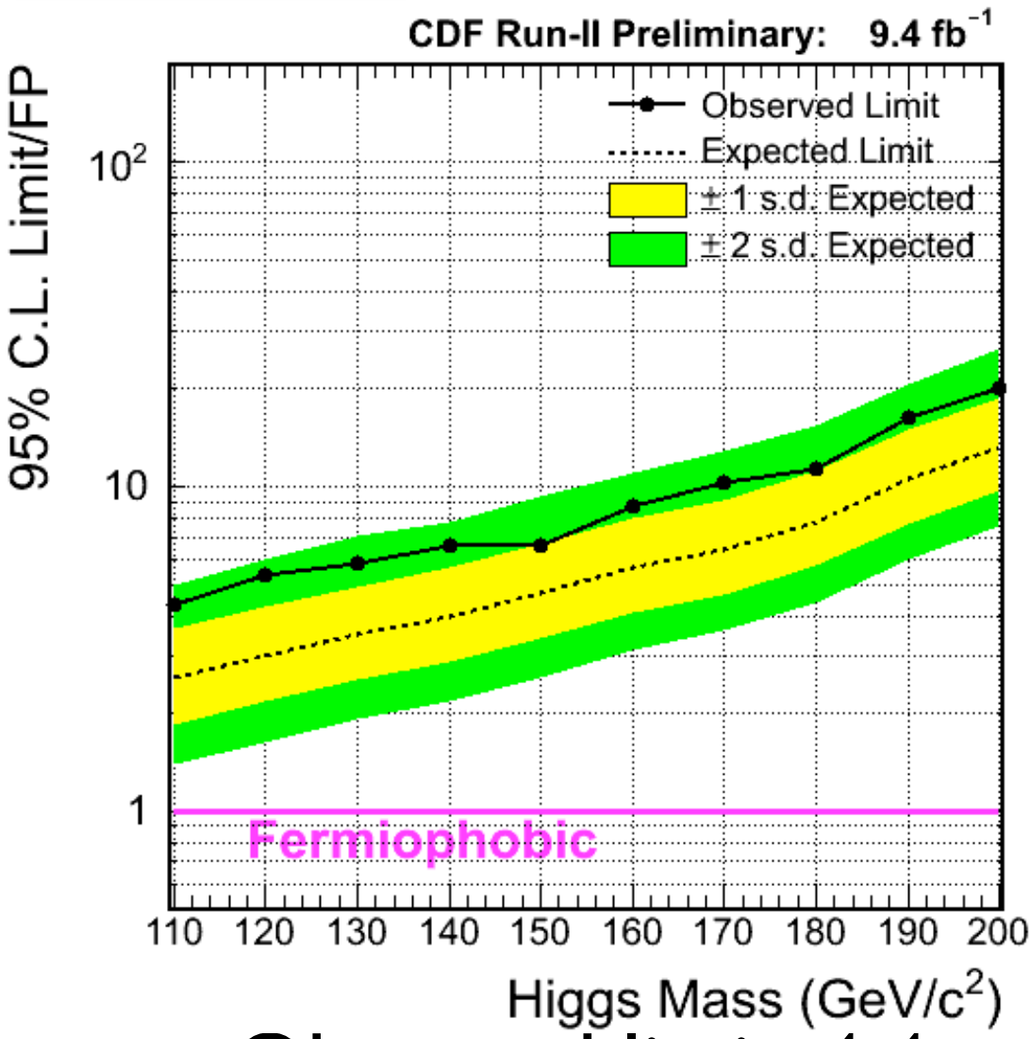
Results (Fermiophobic)

- No significant differences between data & expected backgrounds
- We set 95% Confidence Level limit on Fermiophobic Higgs

$Vh \to VW^*W^* \to l^\pm l^\pm + X$



$Vh \to VW^*W^* \to l^\pm l^\pm + X$



Observed limit: 4.4

Expected limit: 2.6

$m_{h_{FP}} = 110\ \mathrm{GeV}/c^2$

Summary & Plan

- Data 9.4 fb^{-1} used for Higgs search (Full dataset)
- No significant discrepancies between data & expected
- BDT method applied to get more sensitivity, and we get the 95% C.L. Limit:
  - ➡**8.3** × (SM Higgs 160) (Expected limit: **6.0**)
  - ➡**4.4** × (FP Higgs 110) (Expected limit: **2.6**)

✓Plan

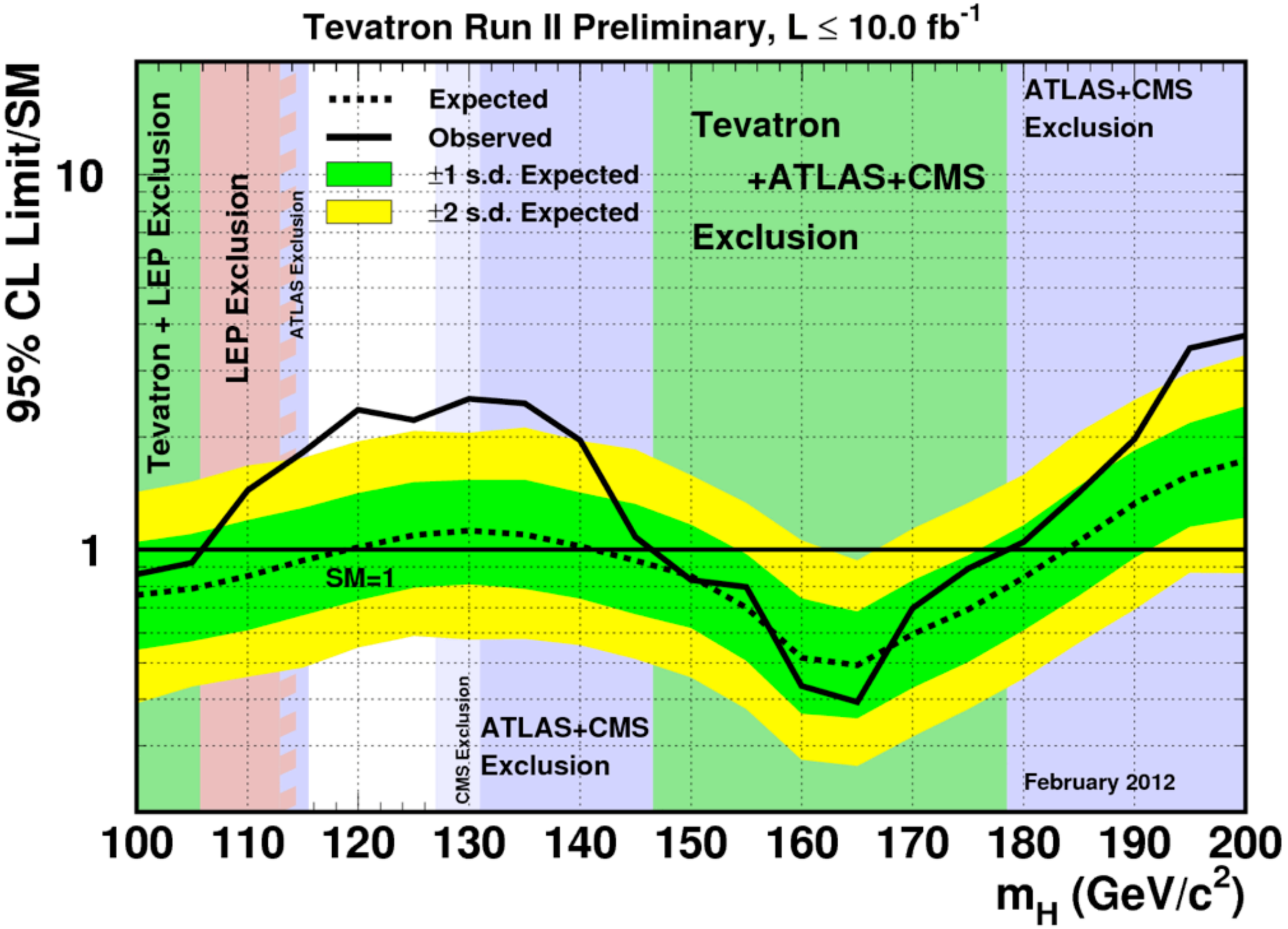
✓WZ/ZZ Measurements

✓Like-Sign Dilepton Characteristic Search

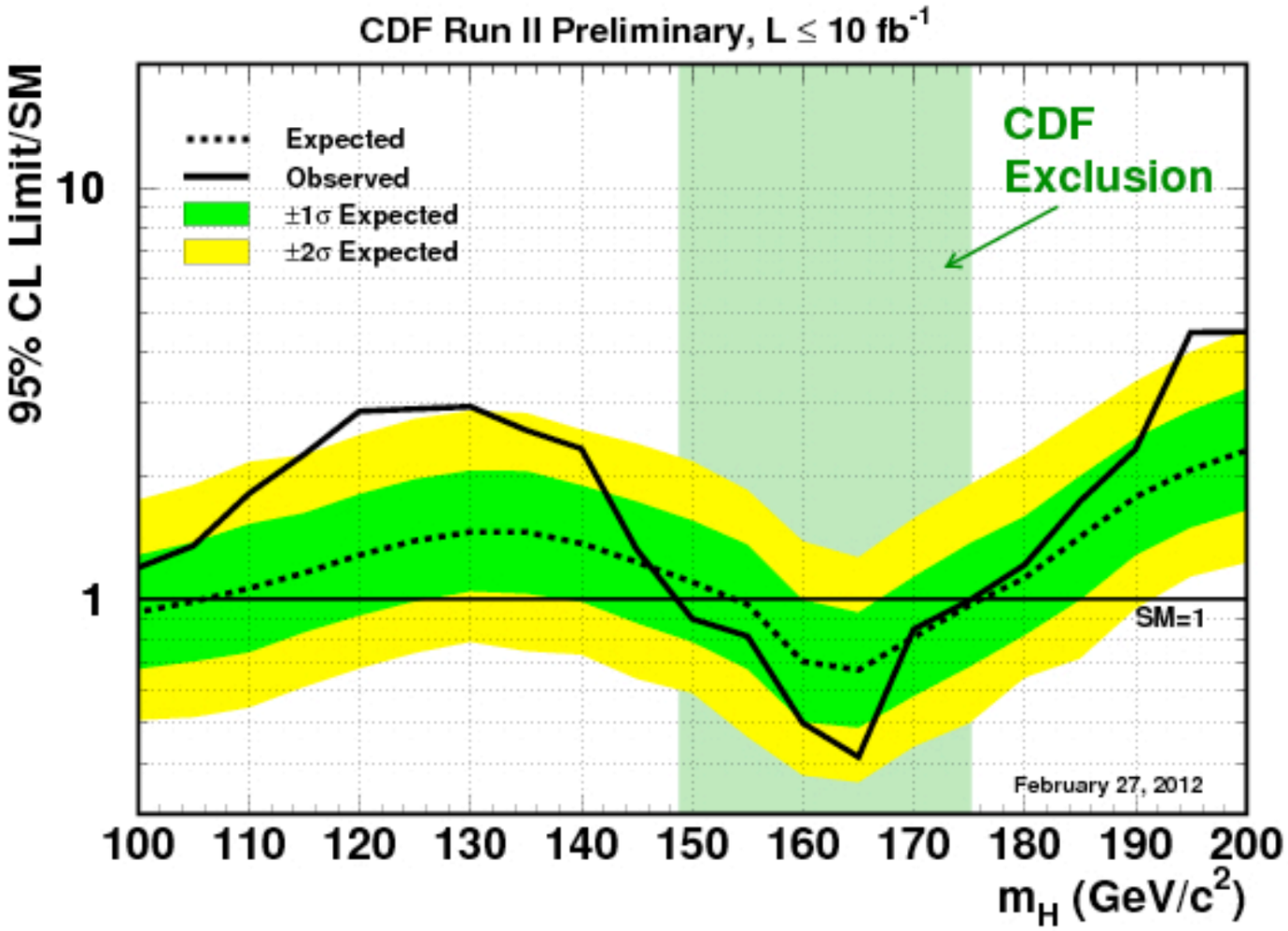
✳Heavy Majorana Neutrino

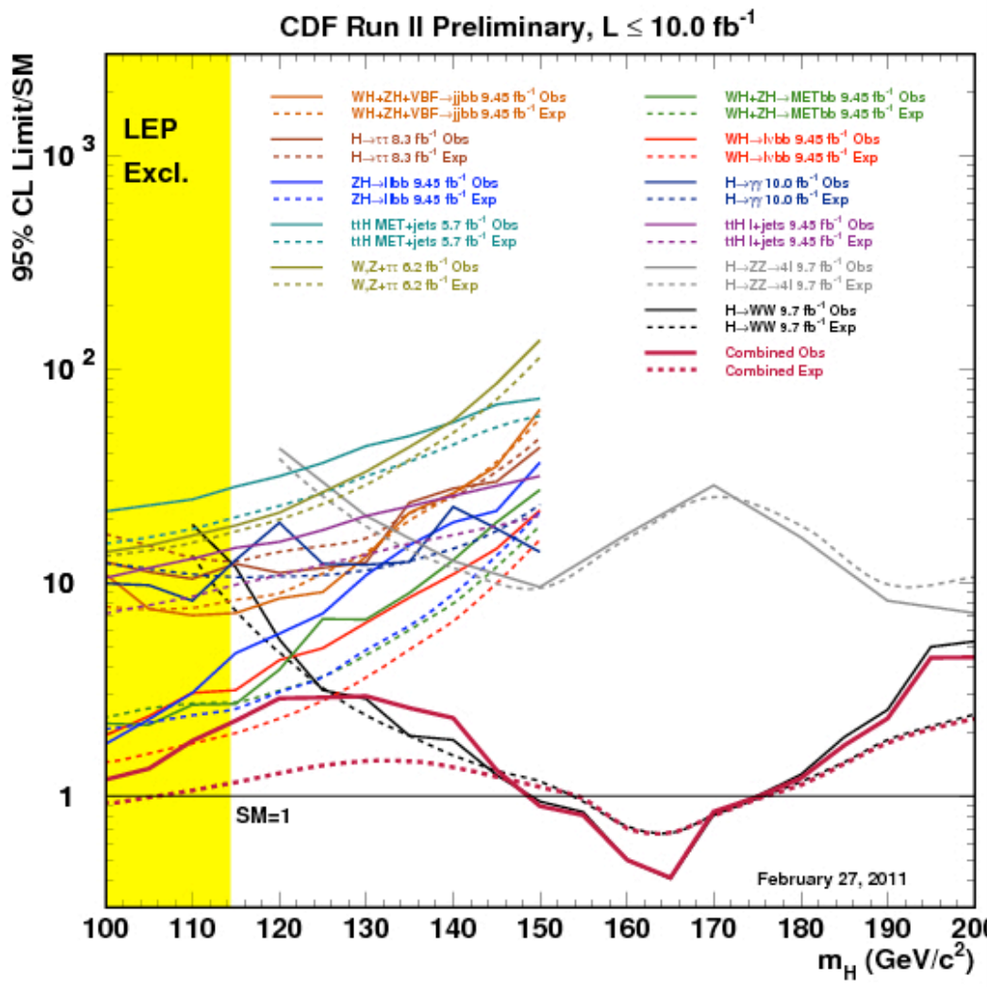
Back Up

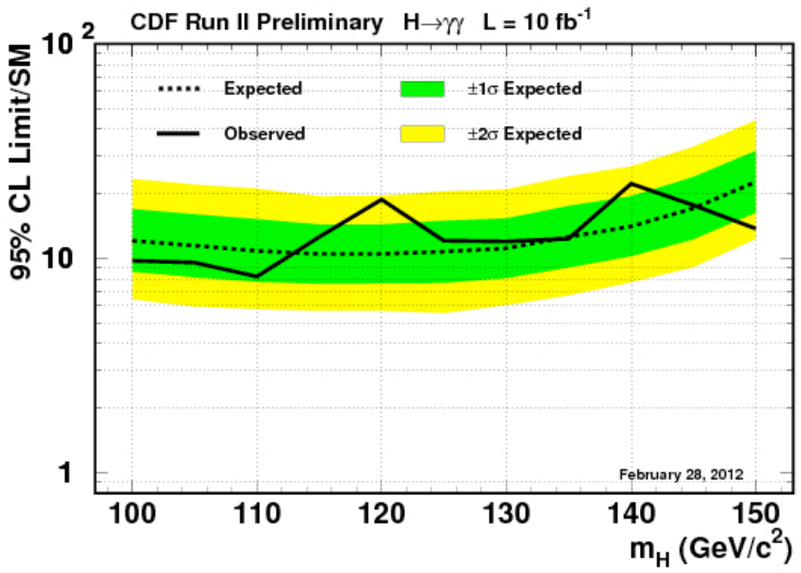
Tevatron 2012 Winter Result

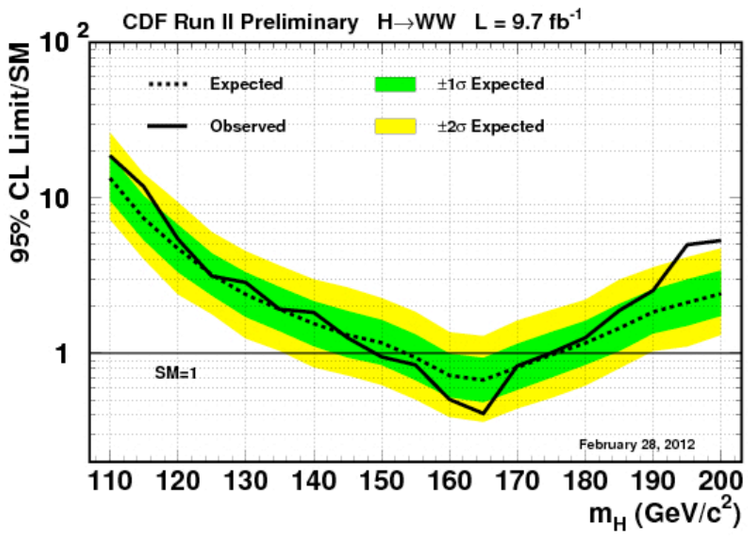


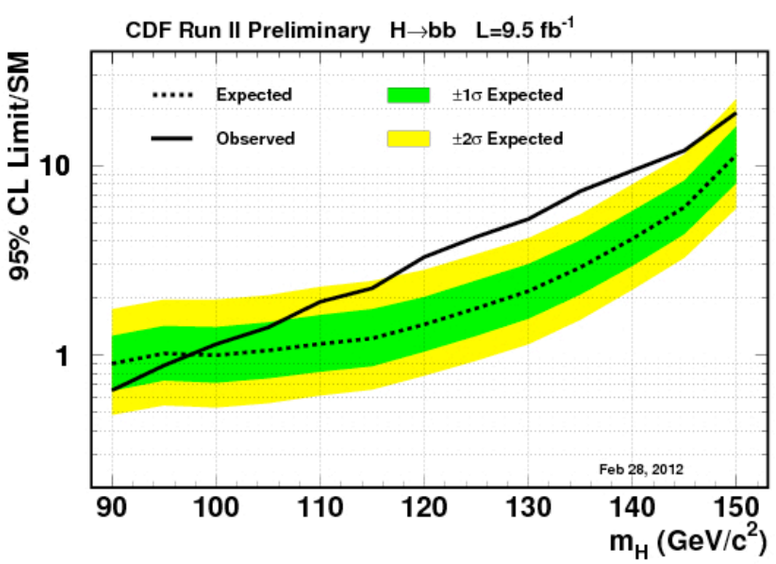
CDF Results 2012



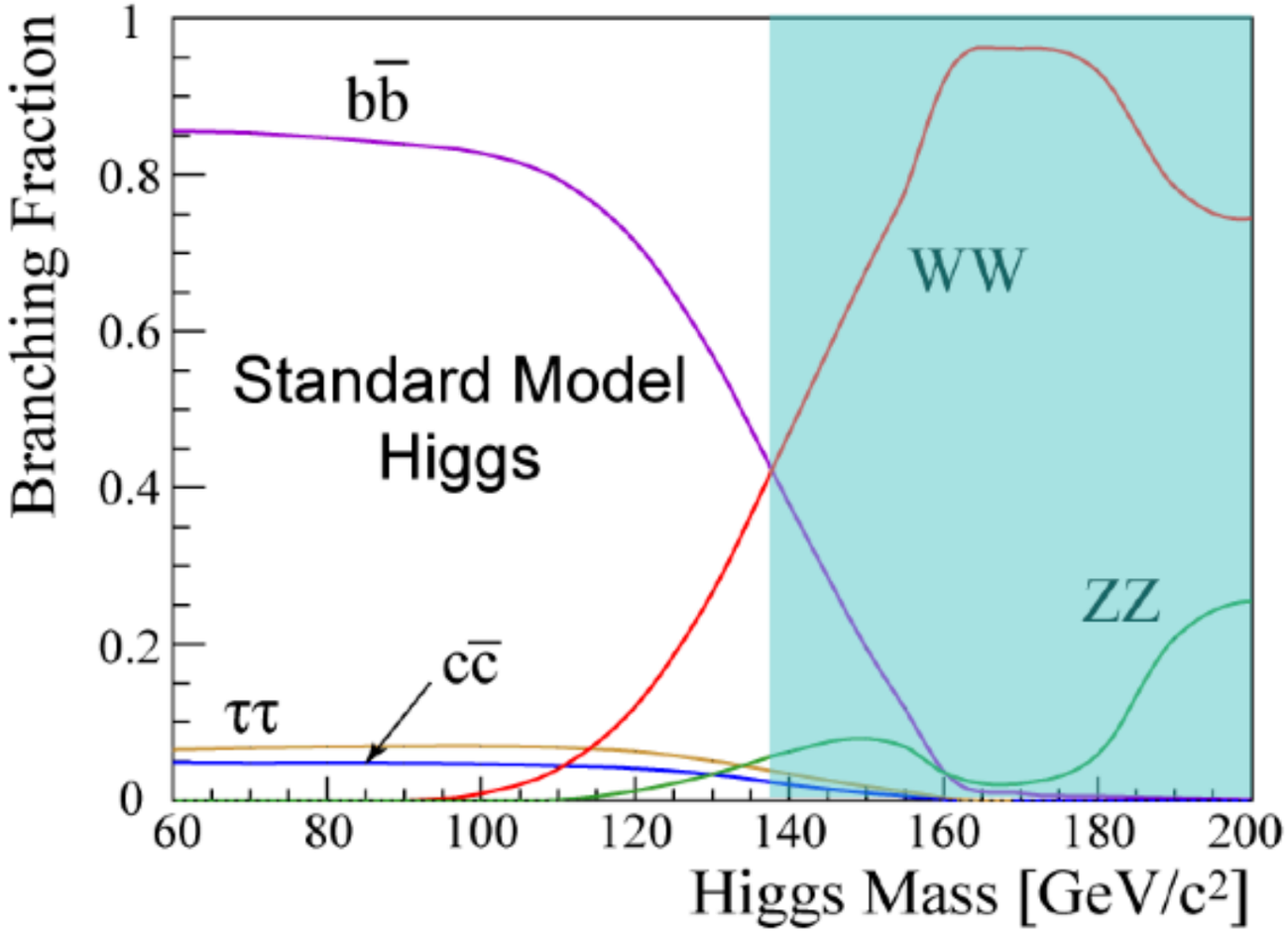


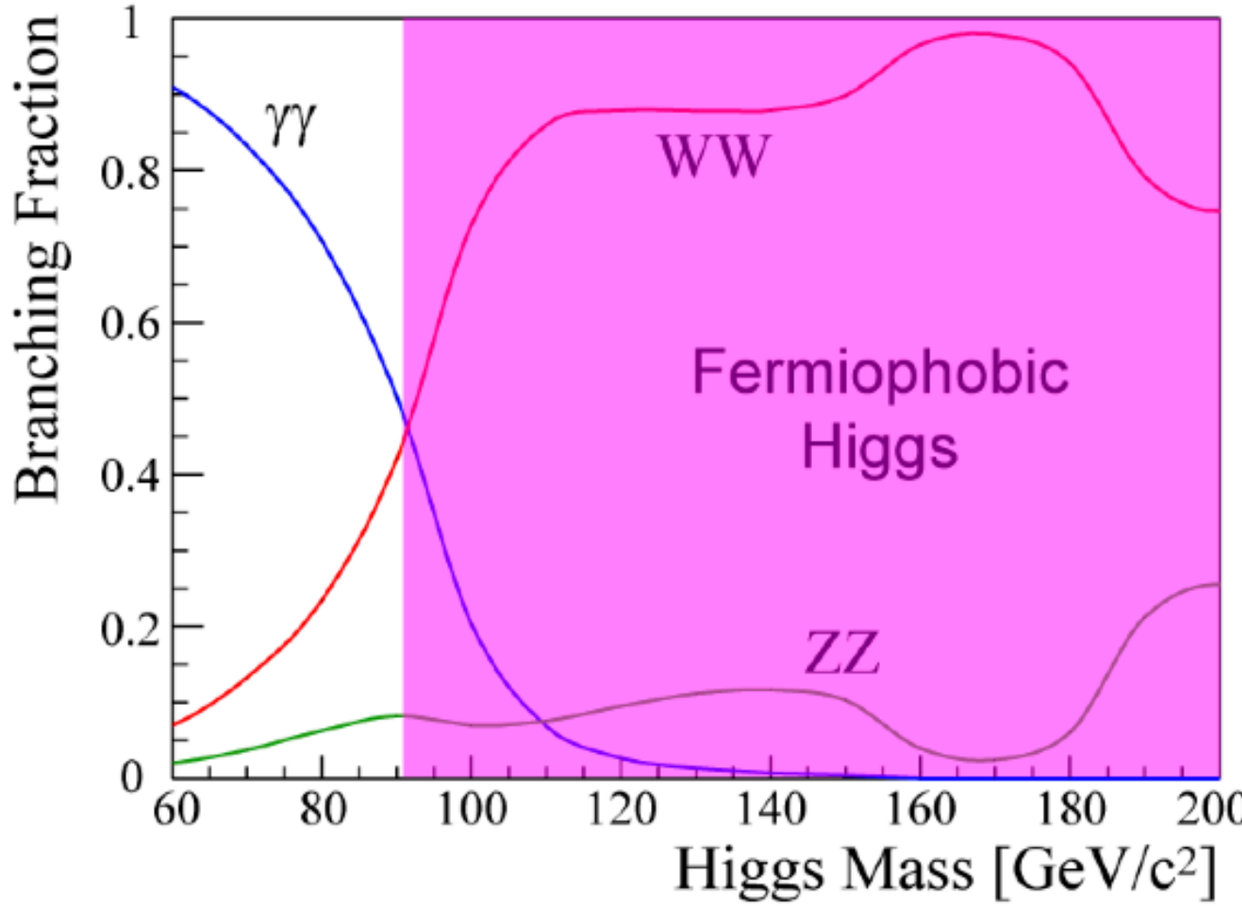




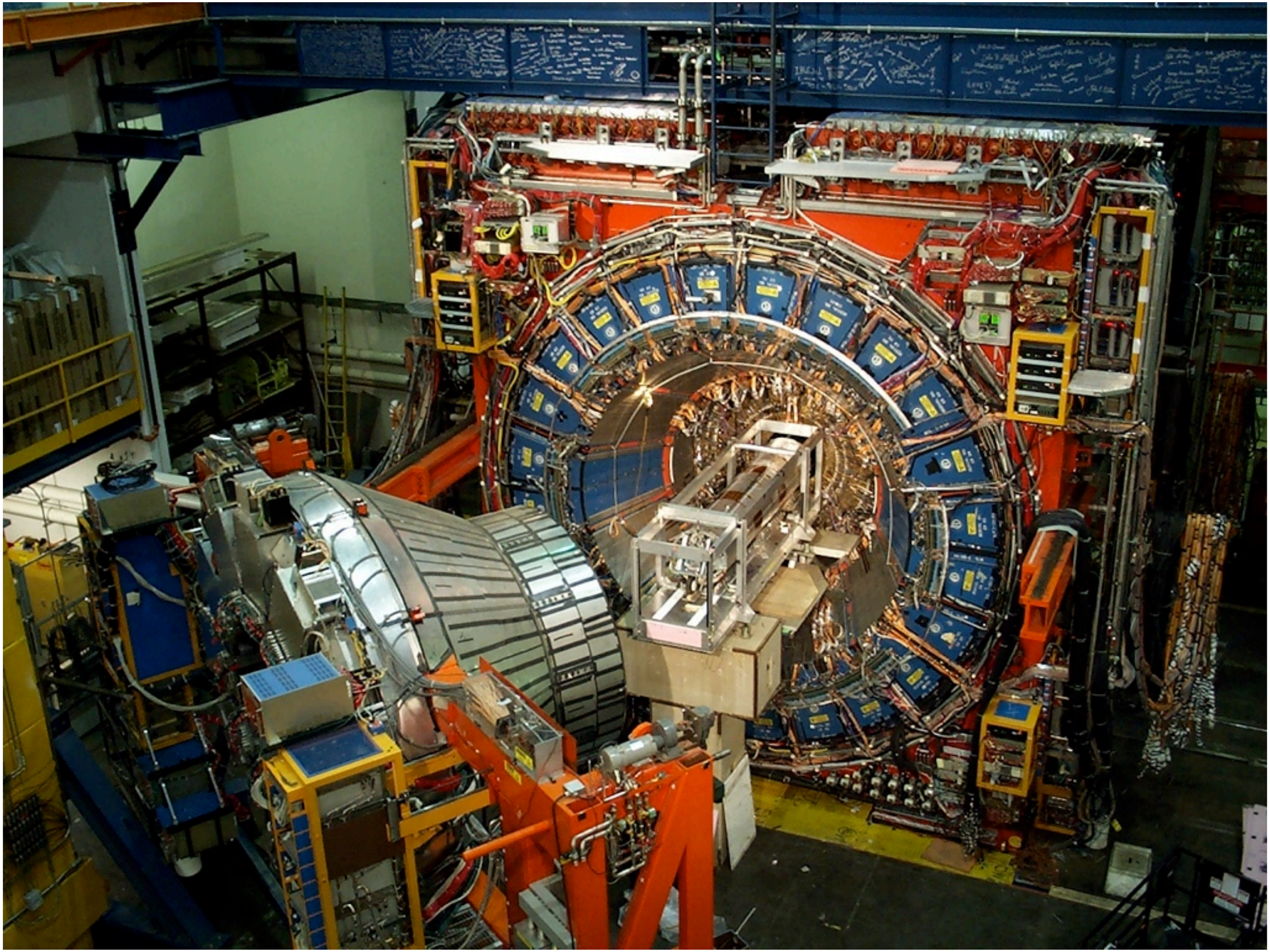


Branching Fraction

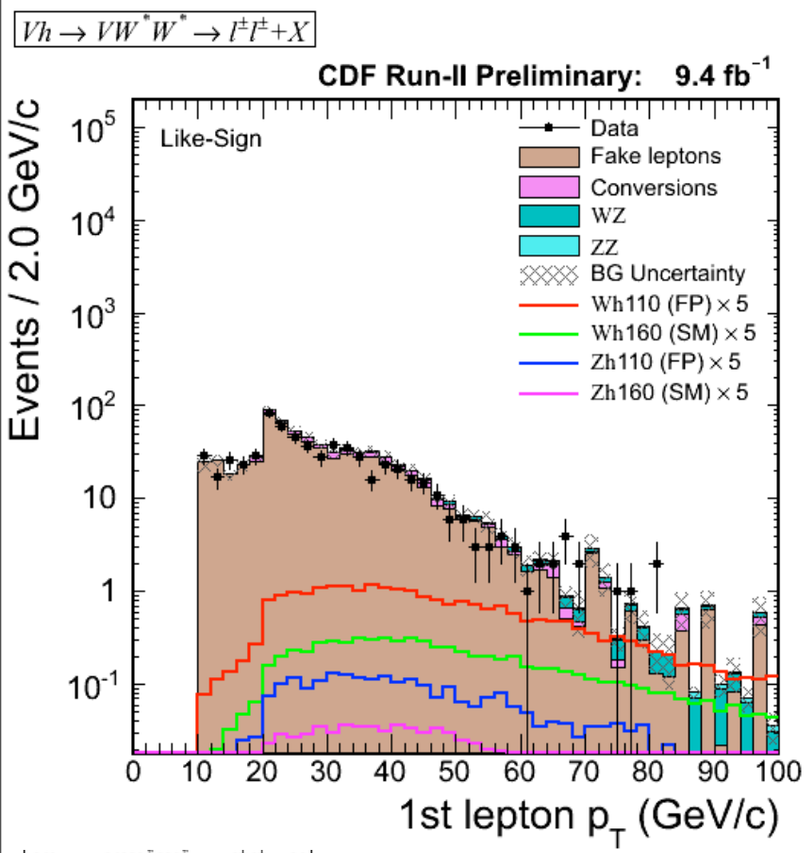


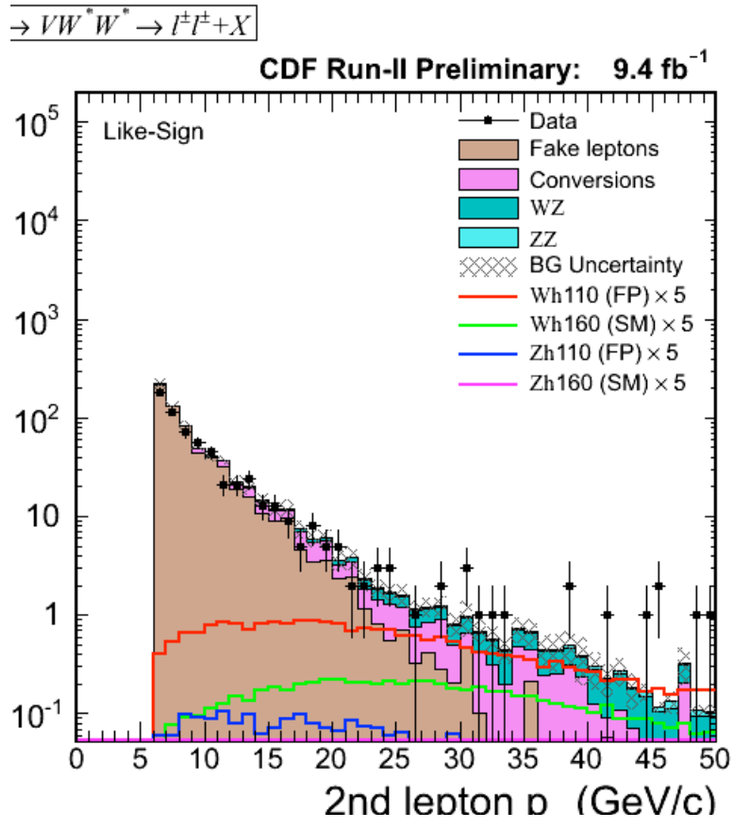


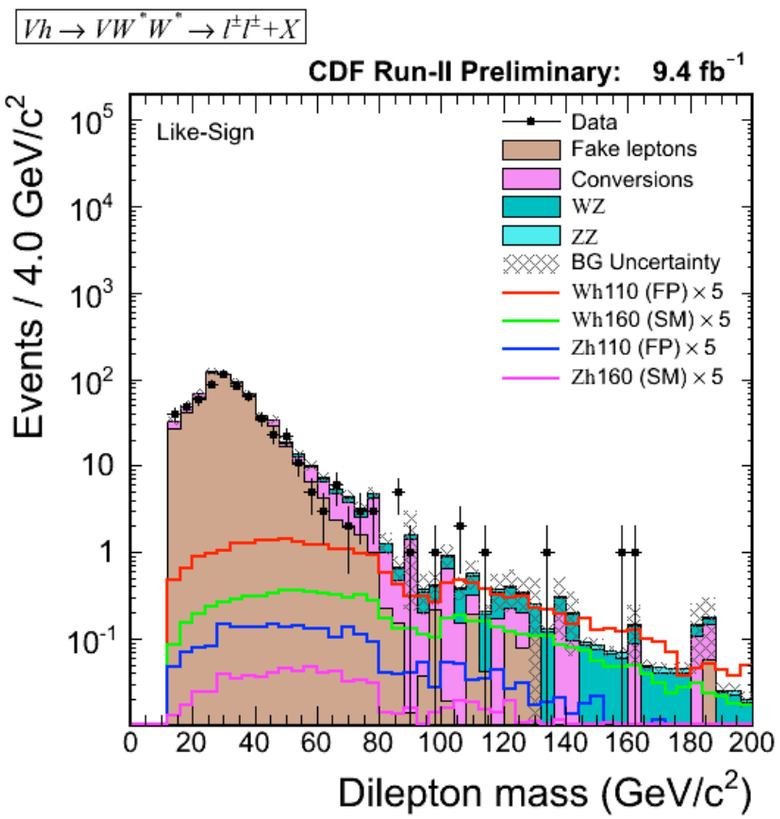
CDF Detector

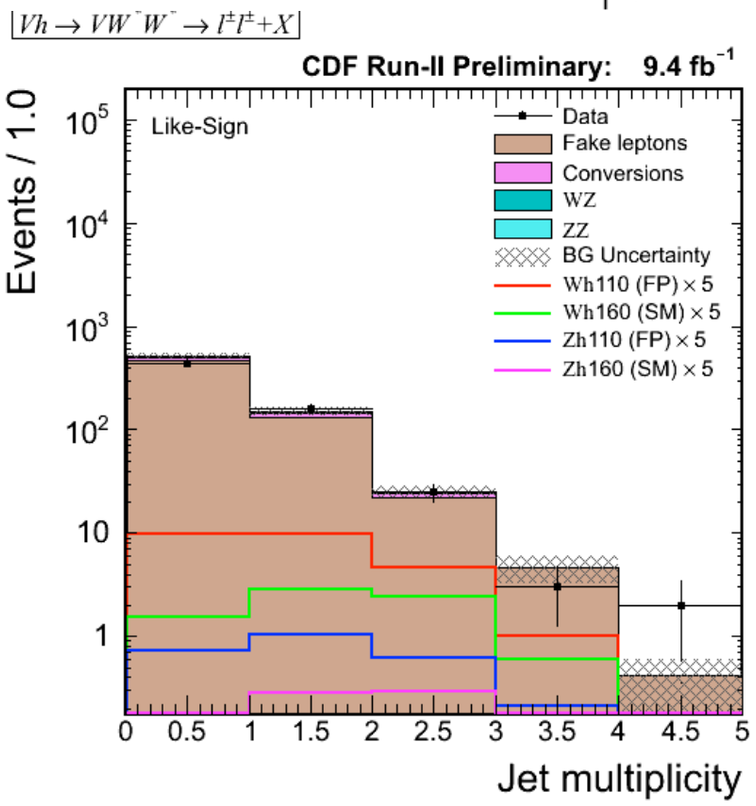


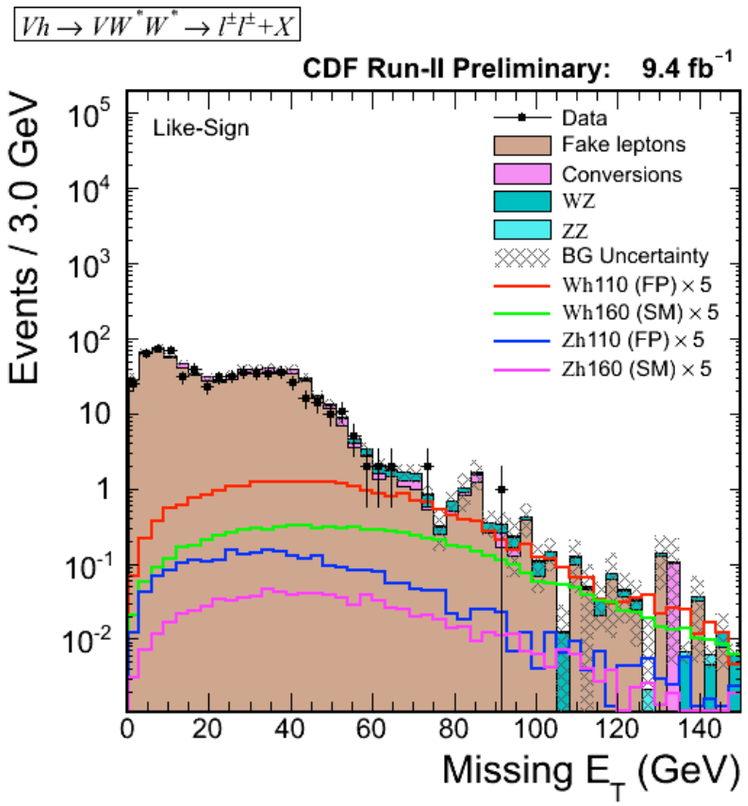
Input Variables (Selected, Log)











Residual Conversion

- Estimated by using data & MC
- Residual conversion rate:

$$R_{\mathrm{resco}} = \frac{1-\varepsilon_{\mathrm{conv}}}{\varepsilon_{\mathrm{conv}}}$$

$\varepsilon_{\mathrm{conv}}$: conversion tagging eff.

- Split to

$$\varepsilon_{\mathrm{conv}} = \varepsilon_{\mathrm{rel}}(p_T) \times \varepsilon_{\mathrm{abs}}$$

- Relative part: high-pT region fitting -> low-pT compared to obsp level with data (pT relative eff. part).
- Absolute part is derived by using CES method.

Variables

- MetSpec:
  - ➡Missing E_T if delta phi(MET, lepton or jet) > pi/2
  - ➡Missing E_T times sin(delta phi(MET, lepton or jet)) if delta phi(MET, lepton or jet) < pi/2

- Sphericity:
  - ➡To look at event shapes.
  - ➡Sphericity tensor:

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\mathbf{p}_i|^2}$$

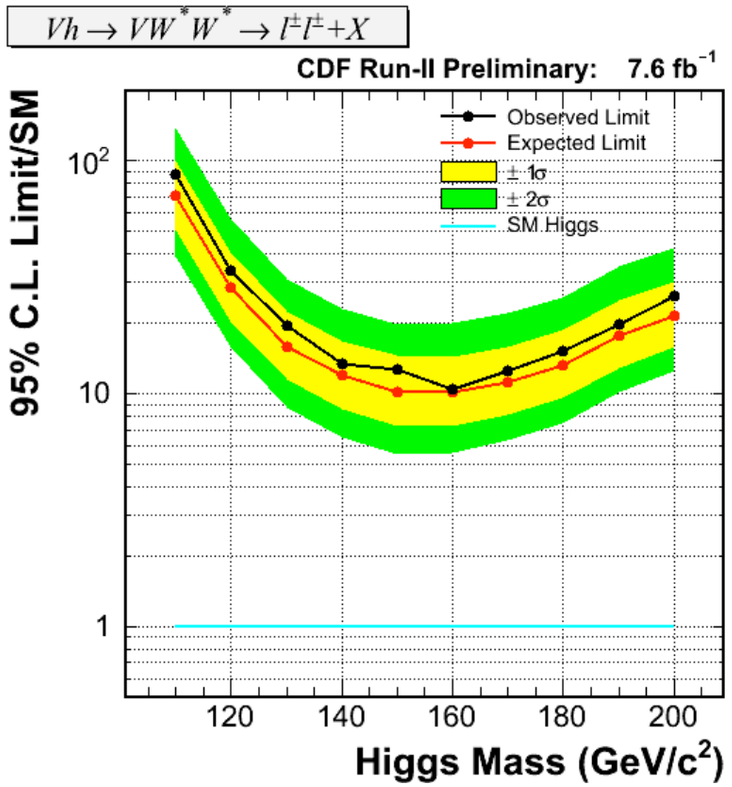
  - ➡Eigenvalues $\lambda_1, \lambda_2, \lambda_3 \quad \lambda_1 \geq \lambda_2 \geq \lambda_3, \lambda_1 + \lambda_2 + \lambda_3 = 1$
  - ➡Sphericity:

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

SM Higgs Limit

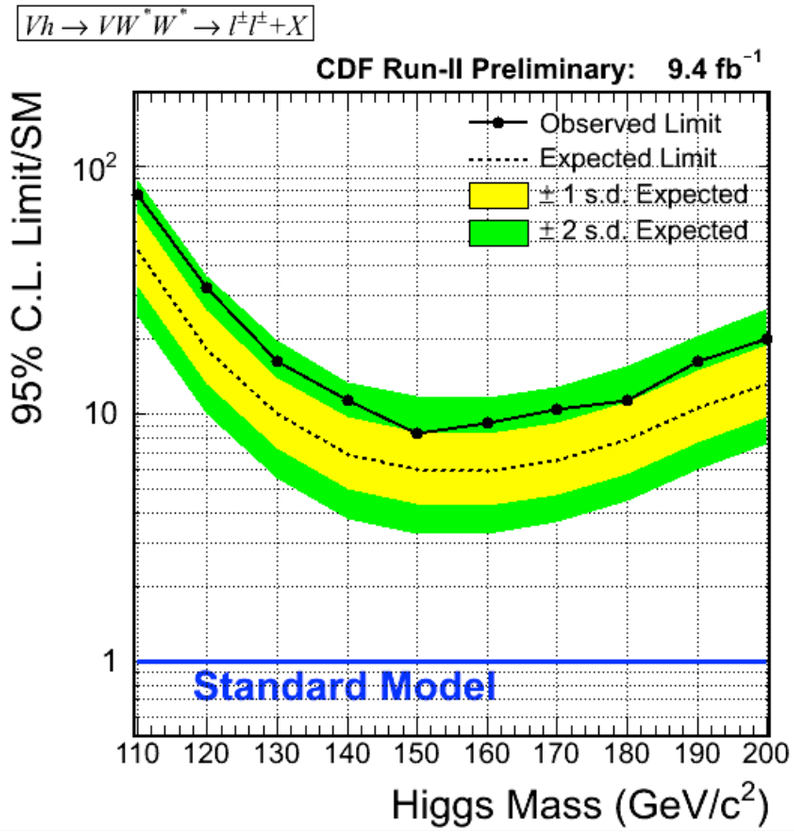
$Vh \to VW^*W^* \to l^\pm l^\pm + X$ CDF Run-II Preliminary: 7.6 fb^{-1}

Mass (GeV/c^2)	(Expected limit)/SM					(Observed limit)/SM
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
110	38.7	50.3	70.4	99.6	138.5	87.0
120	15.8	20.5	28.5	40.4	56.3	33.8
130	8.8	11.4	15.8	22.4	30.9	19.4
140	6.5	8.5	12.0	16.9	23.3	13.5
150	5.5	7.3	10.1	14.5	19.9	12.7
160	5.6	7.3	10.2	14.5	20.0	10.5
170	6.3	8.2	11.3	16.0	22.2	12.6
180	7.5	9.6	13.3	18.8	25.8	15.1
190	10.1	12.9	17.8	25.3	35.3	19.9
200	12.5	15.8	21.6	30.4	42.5	26.4



$Vh \to VW^*W^* \to l^\pm l^\pm + X$ CDF Run-II Preliminary: 9.4 fb^{-1}

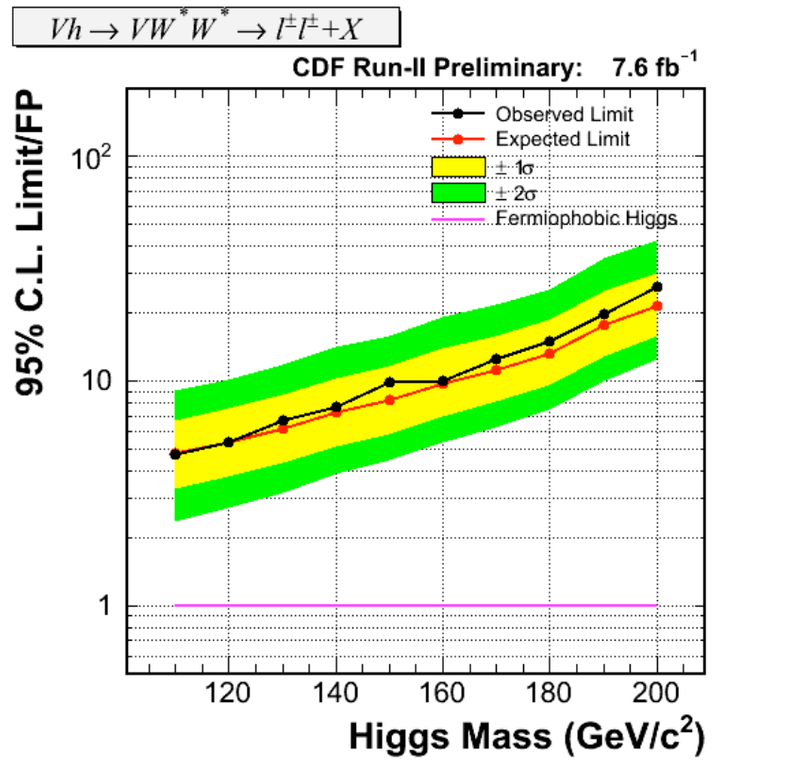
Mass (GeV/c^2)	(Expected limit)/SM					(Observed limit)/SM
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
110	24.9	32.8	45.8	65.1	89.0	77.2
120	10.0	13.2	18.3	26.1	36.2	32.5
130	5.5	7.2	10.0	14.1	19.9	16.4
140	3.8	5.0	6.9	9.7	13.4	11.4
150	3.3	4.3	6.0	8.5	11.8	8.3
160	3.3	4.3	5.9	8.4	11.6	9.2
170	3.7	4.7	6.5	9.2	12.9	10.4
180	4.5	5.7	7.9	11.2	15.6	11.4
190	6.0	7.7	10.6	15.0	20.8	16.4
200	7.6	9.7	13.3	18.9	26.5	20.2



Fermiophobic Higgs Limit

$Vh \to VW^*W^* \to l^\pm l^\pm + X$ CDF Run-II Preliminary: 7.6 fb^{-1}

Mass (GeV/c^2)	(Expected limit)/FP					(Observed limit)/FP
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
110	2.4	3.3	4.8	6.7	9.1	4.7
120	2.8	3.8	5.4	7.6	10.2	5.3
130	3.2	4.3	6.2	8.7	11.8	6.6
140	3.9	5.1	7.3	10.2	14.1	7.7
150	4.5	5.8	8.2	11.7	15.8	9.9
160	5.3	7.0	9.8	13.9	19.3	10.0
170	6.2	8.1	11.2	15.8	21.8	12.4
180	7.4	9.5	13.2	18.7	25.6	15.0
190	10.1	12.9	17.8	25.3	35.2	19.9
200	12.4	15.8	21.6	30.4	42.4	26.4



$Vh \to VW^*W^* \to l^\pm l^\pm + X$ CDF Run-II Preliminary: 9.4 fb^{-1}

Mass (GeV/c^2)	(Expected limit)/FP					(Observed limit)/FP
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
110	1.4	1.9	2.6	3.7	5.0	4.4
120	1.6	2.2	3.0	4.3	6.0	5.3
130	1.9	2.5	3.5	4.9	7.0	5.8
140	2.2	2.9	4.0	5.6	7.8	6.6
150	2.6	3.4	4.7	6.7	9.3	6.6
160	3.1	4.1	5.6	8.0	11.1	8.8
170	3.6	4.7	6.4	9.1	12.8	10.3
180	4.4	5.7	7.8	11.1	15.5	11.3
190	6.0	7.7	10.6	15.0	20.7	16.3
200	7.5	9.7	13.3	18.9	26.5	20.1