Single Top at LHeC

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Content

Introduction

- Measure the anomalous W tb couplings in the single anti-top quark production through e–p collisions.
- Test the generic lowest order CP conserving Lagrangian for the W tb interaction, which allows a right-handed vector, as well as left- or right-handed tensor couplings.
- Examine the one dimensional distributions of the various kinematic observables corresponding to all anomalous couplings in both hadronic and leptonic decay modes of W−.
- Providing the constrain on the anomalous couplings on LHeC

Single top production

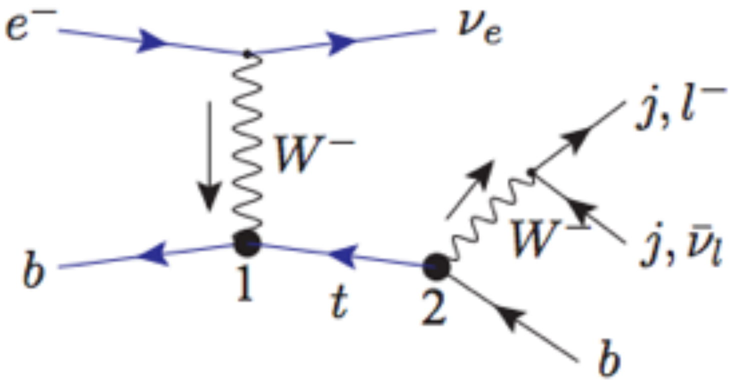
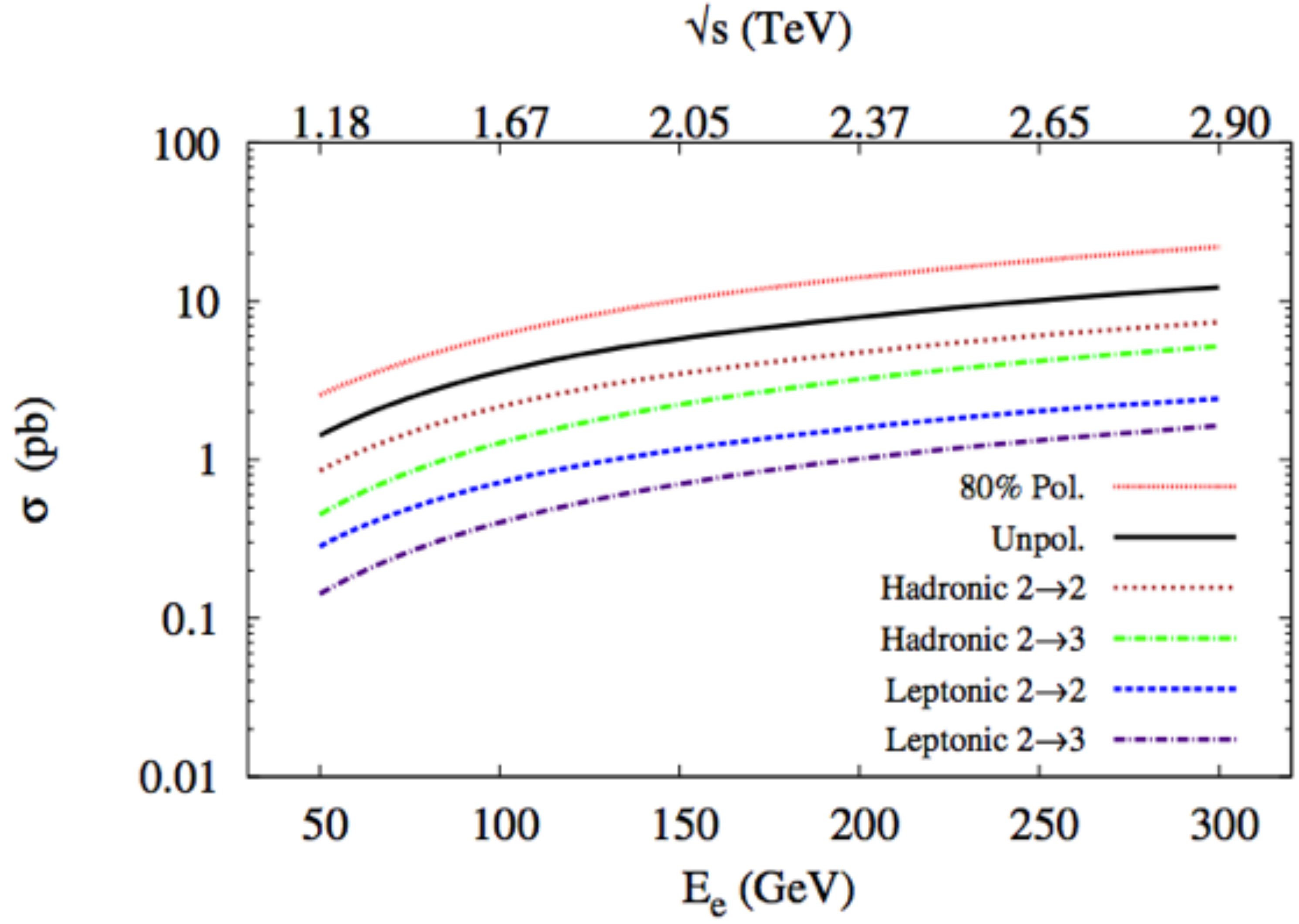
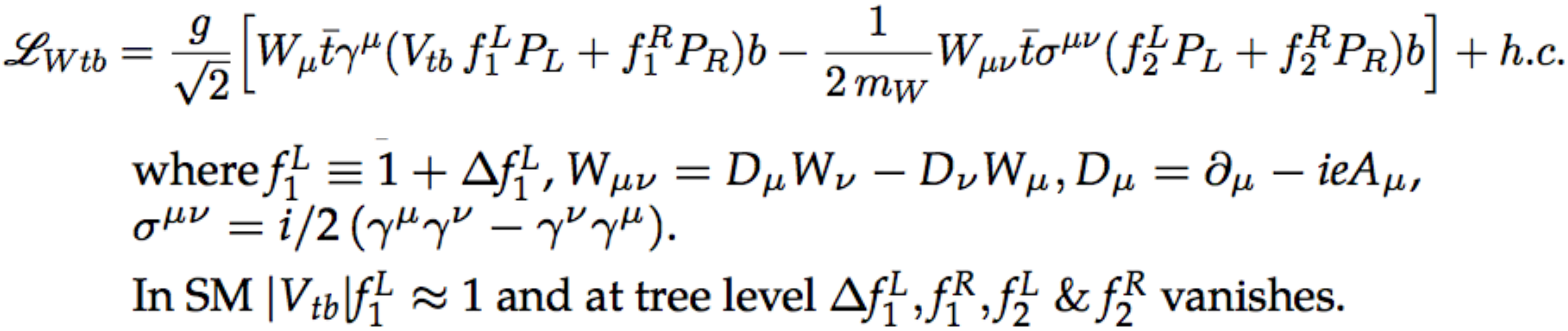


Figure 1. *Single anti-top quark production through charge current at the e-p collider. The blobs at vertices 1 and 2 show the effective $W^-\bar{t}\bar{b}$ couplings, which includes the SM contribution. Further W^- decays into hadronic mode via light quarks ($j \equiv \bar{u}, d, \bar{c}, s$) or leptonic mode ($l^- \equiv e^-, \mu^-$) with missing energy.*



- Single top production as a function of Ee, Ep=7TeV

Theoretical modelling



$$\mathscr{L}_{Wtb} = \frac{g}{\sqrt{2}}\left[W_\mu \bar{t}\gamma^\mu (V_{tb}\, f_1^L P_L + f_1^R P_R) b - \frac{1}{2\, m_W} W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f_2^L P_L + f_2^R P_R) b\right] + h.c.$$

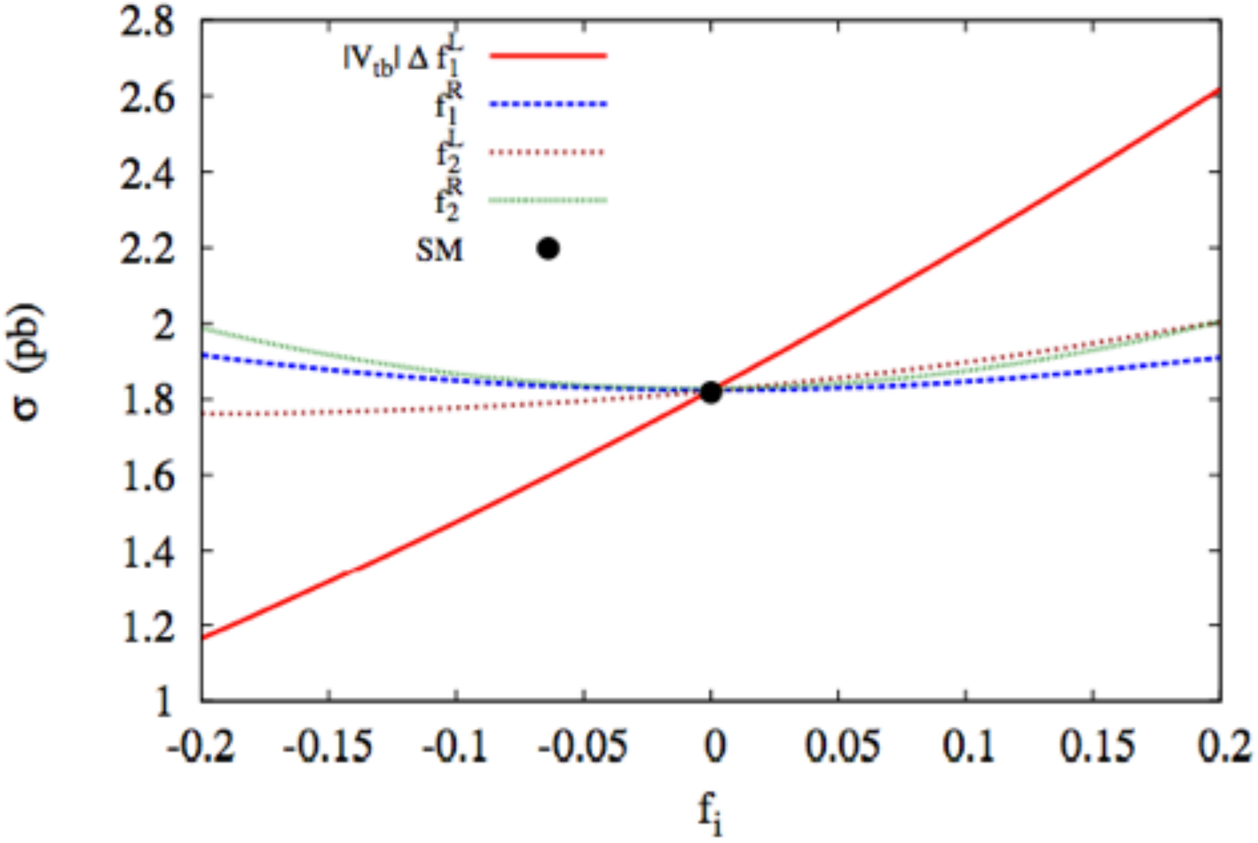
where $f_1^L \equiv 1 + \Delta f_1^L$, $W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu$, $D_\mu = \partial_\mu - ieA_\mu$,
$\sigma^{\mu\nu} = i/2\,(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.

In SM $|V_{tb}| f_1^L \approx 1$ and at tree level $\Delta f_1^L, f_1^R, f_2^L$ & f_2^R vanishes.

- CP conserving, f is real,
- CP violating, f is complex[hep-ph/0605190]
- Measure the influence of fs on xsection and kinematic shapes

Upper limits from other experiment

- Assuming only one anomalous coupling to be non-zero at a time $-0.13 \le |V_{tb}|f_1^L \le 0.03$, $-0.0007 \le f_1^R \le 0.0025$, $-0.0015 \le f_2^L \le 0.0004$, $-0.15 \le f_2^R \le 0.57$ from B decays [Phys. Rev. D **78**, 077501 (2008)]
- Single top production at DØ assuming $|V_{tb}|f_1^L = 1$, $|f_1^R| \le 0.548$, $|f_2^L| \le 0.224$, $|f_2^R| \le 0.347$ [Phys. Lett. B **713**, 165 (2012)]
- Associated tW production at LHC through γp collision $|f_1^R| \le 0.55$, $|f_2^L| \le 0.22$, $|f_2^R| \le 0.35$ [Phys. Rev. D **86**, 074026 (2012)]
- ATLAS: asymmetries associated through angular distribution $\mathrm{Re}(f_1^R) \in$ [-0.44,0.48], $\mathrm{Re}(f_2^L) \in$ [-0.24,0.21], $\mathrm{Re}(f_2^R) \in$ [-0.49,0.15]. [ATLAS-CONF-2011-037]



MC production and detector setup

- Use Ep=7TeV, Ee=60GeV, the electron beam is 80% polarised
- Using FeynRules, MadGraph to generate signal and backgrounds.
- The PDFset is CTEQ6L1, factorization and renormalization scale μF = μR = mt = 172.5GeV, mb = 4.7 GeV, mW = 80.399 GeV, |Vtb| f_1^{L}= 1
- Using Delphes for detector simulation, jet |pseudorapidity| <5, lepton and b jet |pseudorapidity|<2.5, jet energy resolution =0.6/sqrt(E)
- Jet algorithm, Antikt4, Btagging, efficiency@60%, truth match@0.4, c-jet and light jet are weighted with b tagging fake rate @10% and 1%, respectively
- W decay to jets or leptons (Hadronic or Leptonic channel)

Largest background for hadronic, cc-jjj

```
Hadronic Channel:
sig: p e- > ve t~, W > j j :    1.034 pb
ccjjb: p e- > ve j j b :        0.073 pb
ccjjj: p e- > ve j j j :        27.40 pb
ncjjb: p e- > e- j j b :        2.84  pb
ncjjj: p e- > e- j j j :        311.6 pb
chad : p e- > ve c~, W > j j:   0.0194 pb
f1l=0.5:  2.32 pb
f1r=0.5:  1.38 pb
f2l=-0.5: 1.07 pb
f2l=0.5:  1.48 pb
f2r=0.5:  1.68 pb

Leptonic Channel:
sig: p e- > ve t~, W > l vl :   0.346 pb
cclvb: p e- > ve l vl b :       0.0059 pb
cclvj: p e- > ve l vl j :       0.2096 pb
nclvj: p e- > e- l vl j :       0.434 pb
clep : p e- > ve c~, W > l vl:  0.0063 pb
f1l=0.5:  0.776 pb
f1r=0.5:  0.447 pb
f2l=-0.5: 0.322 pb
f2l=0.5:  0.472 pb
f2r=0.5:  0.566 pb
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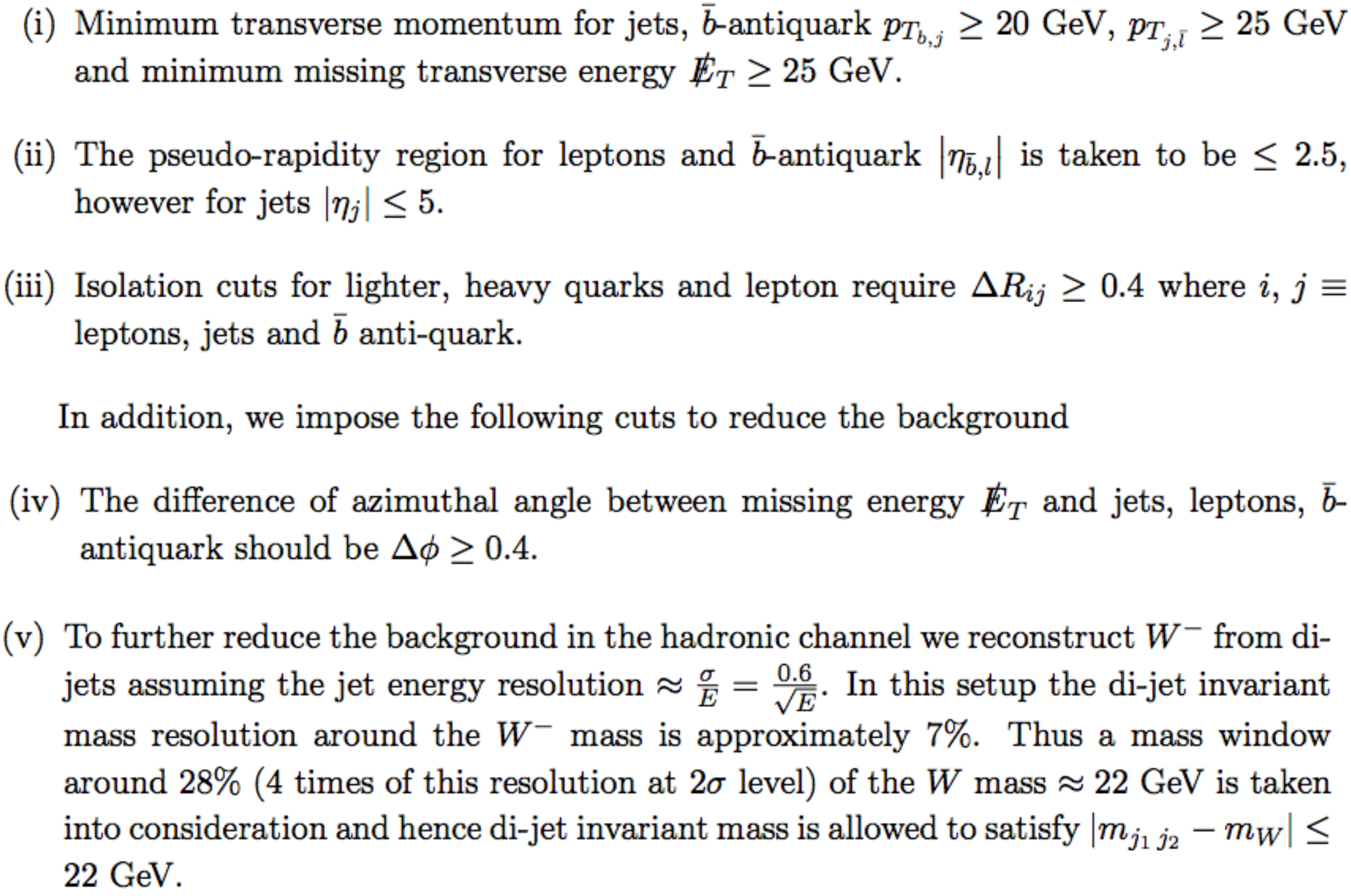
Event selection (hadronic)



(i) Minimum transverse momentum for jets, $\bar{b}$-antiquark $p_{T_{\bar{b},j}} \geq 20$ GeV, $p_{T_{j,\bar{l}}} \geq 25$ GeV and minimum missing transverse energy $\not{E}_T \geq 25$ GeV.

(ii) The pseudo-rapidity region for leptons and $\bar{b}$-antiquark $|\eta_{\bar{b},l}|$ is taken to be ≤ 2.5, however for jets $|\eta_j| \leq 5$.

(iii) Isolation cuts for lighter, heavy quarks and lepton require $\Delta R_{ij} \geq 0.4$ where $i, j \equiv$ leptons, jets and $\bar{b}$ anti-quark.

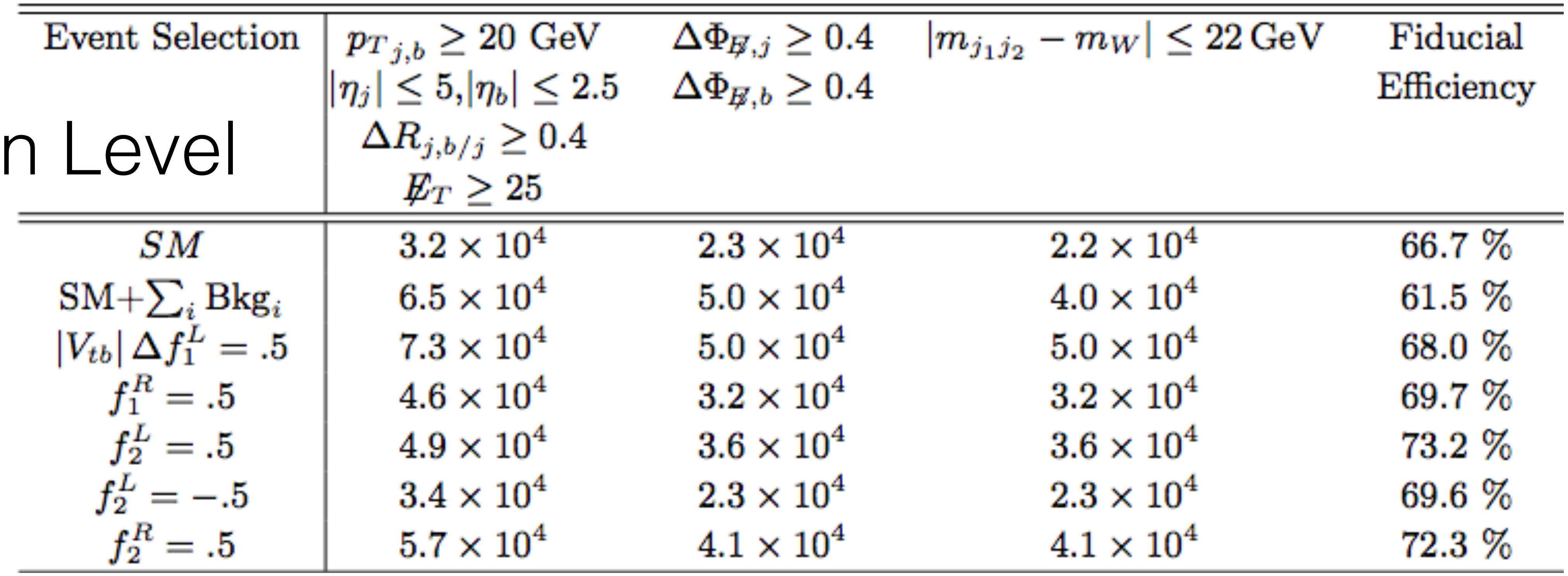
In addition, we impose the following cuts to reduce the background

(iv) The difference of azimuthal angle between missing energy $\not{E}_T$ and jets, leptons, $\bar{b}$-antiquark should be $\Delta\phi \geq 0.4$.

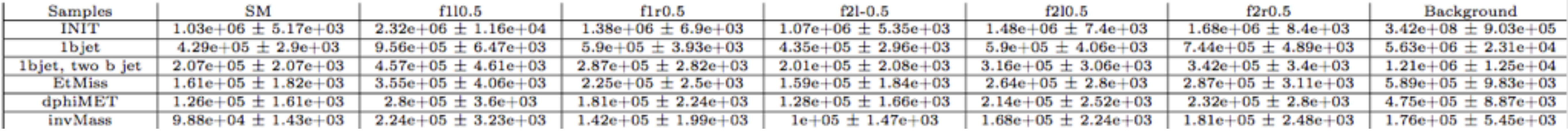
(v) To further reduce the background in the hadronic channel we reconstruct W^- from di-jets assuming the jet energy resolution $\approx \frac{\sigma}{E} = \frac{0.6}{\sqrt{E}}$. In this setup the di-jet invariant mass resolution around the W^- mass is approximately 7%. Thus a mass window around 28% (4 times of this resolution at 2σ level) of the W mass ≈ 22 GeV is taken into consideration and hence di-jet invariant mass is allowed to satisfy $|m_{j_1 j_2} - m_W| \leq$ 22 GeV.

Event selection (hadronic@100fb-1)

Parton Level



Event Selection	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$	$\lvert m_{j_1 j_2} - m_W\rvert \leq 22$ GeV	Fiducial Efficiency
SM	3.2×10^4	2.3×10^4	2.2×10^4	66.7 %
SM+$\sum_i$ Bkg$_i$	6.5×10^4	5.0×10^4	4.0×10^4	61.5 %
$\lvert V_{tb}\rvert\,\Delta f_1^L = .5$	7.3×10^4	5.0×10^4	5.0×10^4	68.0 %
$f_1^R = .5$	4.6×10^4	3.2×10^4	3.2×10^4	69.7 %
$f_2^L = .5$	4.9×10^4	3.6×10^4	3.6×10^4	73.2 %
$f_2^L = -.5$	3.4×10^4	2.3×10^4	2.3×10^4	69.6 %
$f_2^R = .5$	5.7×10^4	4.1×10^4	4.1×10^4	72.3 %



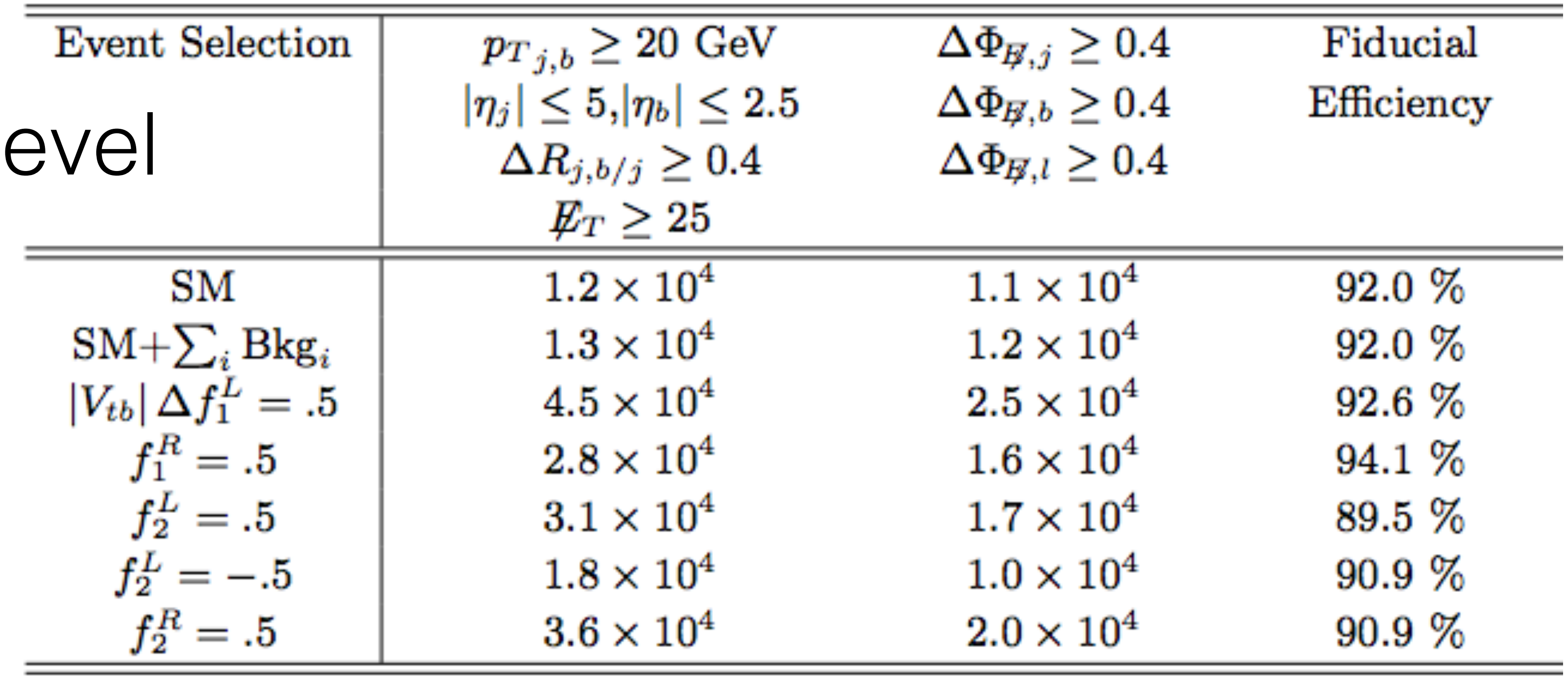
Samples	SM	f1l0.5	f1r0.5	f2l-0.5	f2l0.5	f2r0.5	Background
INIT	1.03e+06 ± 5.17e+03	2.32e+06 ± 1.16e+04	1.38e+06 ± 6.9e+03	1.07e+06 ± 5.35e+03	1.48e+06 ± 7.4e+03	1.68e+06 ± 8.4e+03	3.42e+08 ± 9.03e+05
1bjet	4.29e+05 ± 2.9e+03	9.56e+05 ± 6.47e+03	5.9e+05 ± 3.93e+03	4.35e+05 ± 2.96e+03	5.9e+05 ± 4.06e+03	7.44e+05 ± 4.89e+03	5.63e+06 ± 2.31e+04
1bjet, two b jet	2.07e+05 ± 2.07e+03	4.57e+05 ± 4.61e+03	2.87e+05 ± 2.82e+03	2.01e+05 ± 2.08e+03	3.16e+05 ± 3.06e+03	3.42e+05 ± 3.4e+03	1.21e+06 ± 1.25e+04
EtMiss	1.61e+05 ± 1.82e+03	3.55e+05 ± 4.06e+03	2.25e+05 ± 2.5e+03	1.59e+05 ± 1.84e+03	2.64e+05 ± 2.8e+03	2.87e+05 ± 3.11e+03	5.89e+05 ± 9.83e+03
dphiMET	1.26e+05 ± 1.61e+03	2.8e+05 ± 3.6e+03	1.81e+05 ± 2.24e+03	1.28e+05 ± 1.66e+03	2.14e+05 ± 2.52e+03	2.32e+05 ± 2.8e+03	4.75e+05 ± 8.87e+03
invMass	9.88e+04 ± 1.43e+03	2.24e+05 ± 3.23e+03	1.42e+05 ± 1.99e+03	1e+05 ± 1.47e+03	1.68e+05 ± 2.24e+03	1.81e+05 ± 2.48e+03	1.76e+05 ± 5.45e+03

Preliminary result at detector level @1000fb-1 (on going)

In the detector level, the signal efficiency is down to half due to requiring two additional jets.
The background efficiency remains. need to re-optimizing the selection

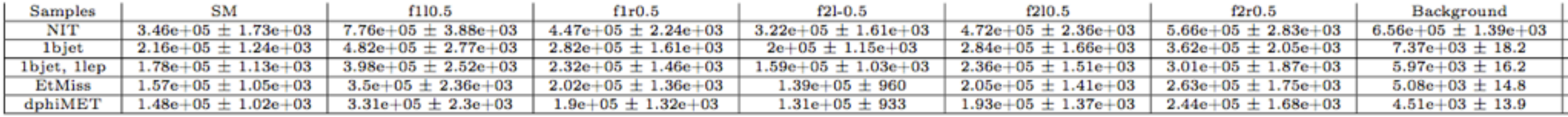
Event selection(leptonic)

Parton Level



Event Selection	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$ $\Delta\Phi_{\not{E},l} \geq 0.4$	Fiducial Efficiency
SM	1.2×10^4	1.1×10^4	92.0 %
SM+$\sum_i$ Bkg$_i$	1.3×10^4	1.2×10^4	92.0 %
$\lvert V_{tb}\rvert\, \Delta f_1^L = .5$	4.5×10^4	2.5×10^4	92.6 %
$f_1^R = .5$	2.8×10^4	1.6×10^4	94.1 %
$f_2^L = .5$	3.1×10^4	1.7×10^4	89.5 %
$f_2^L = -.5$	1.8×10^4	1.0×10^4	90.9 %
$f_2^R = .5$	3.6×10^4	2.0×10^4	90.9 %

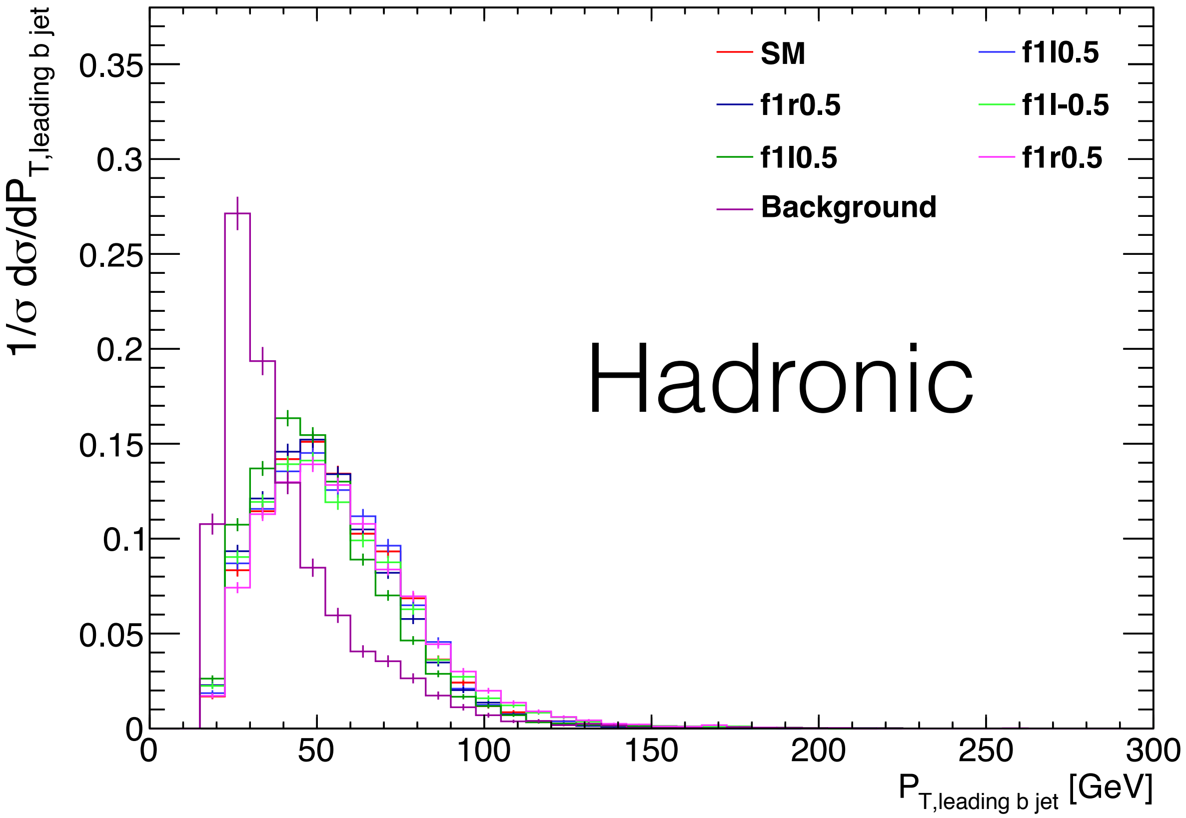
Preliminary result at detector Level @1000 fb-1 (on going)

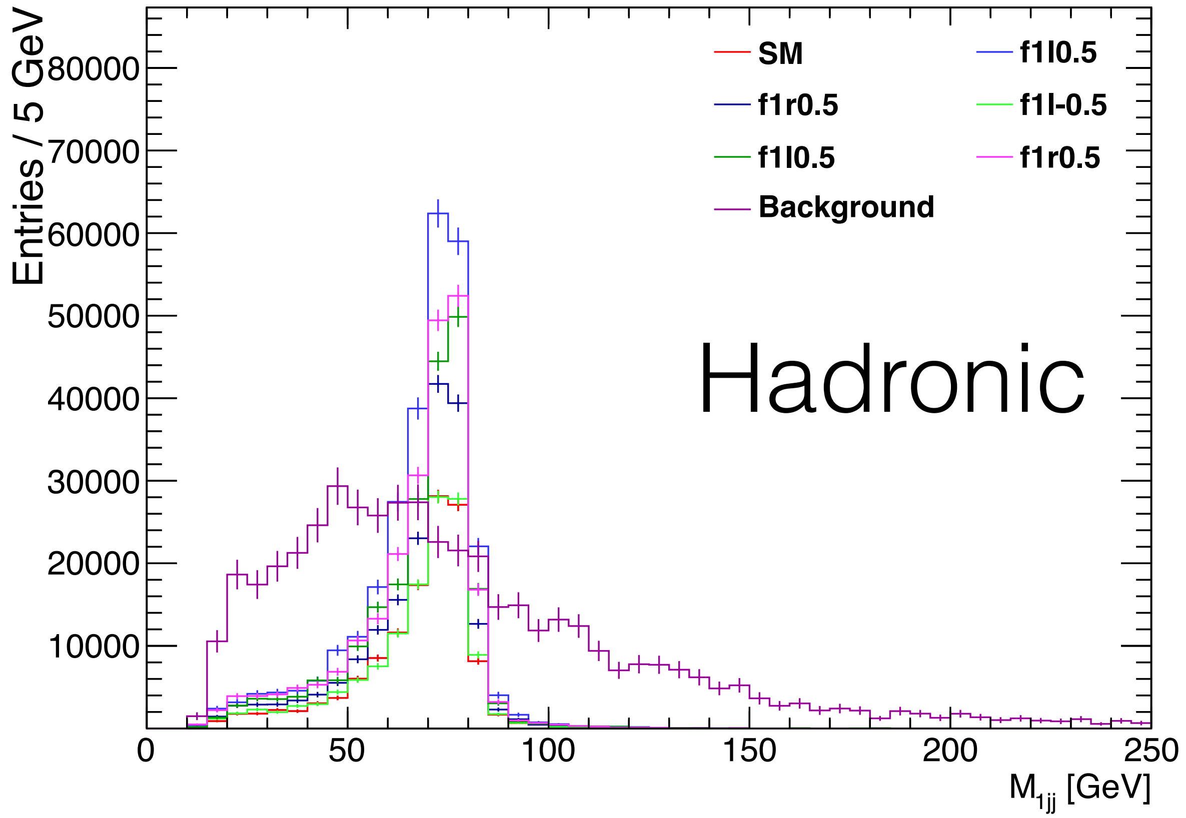


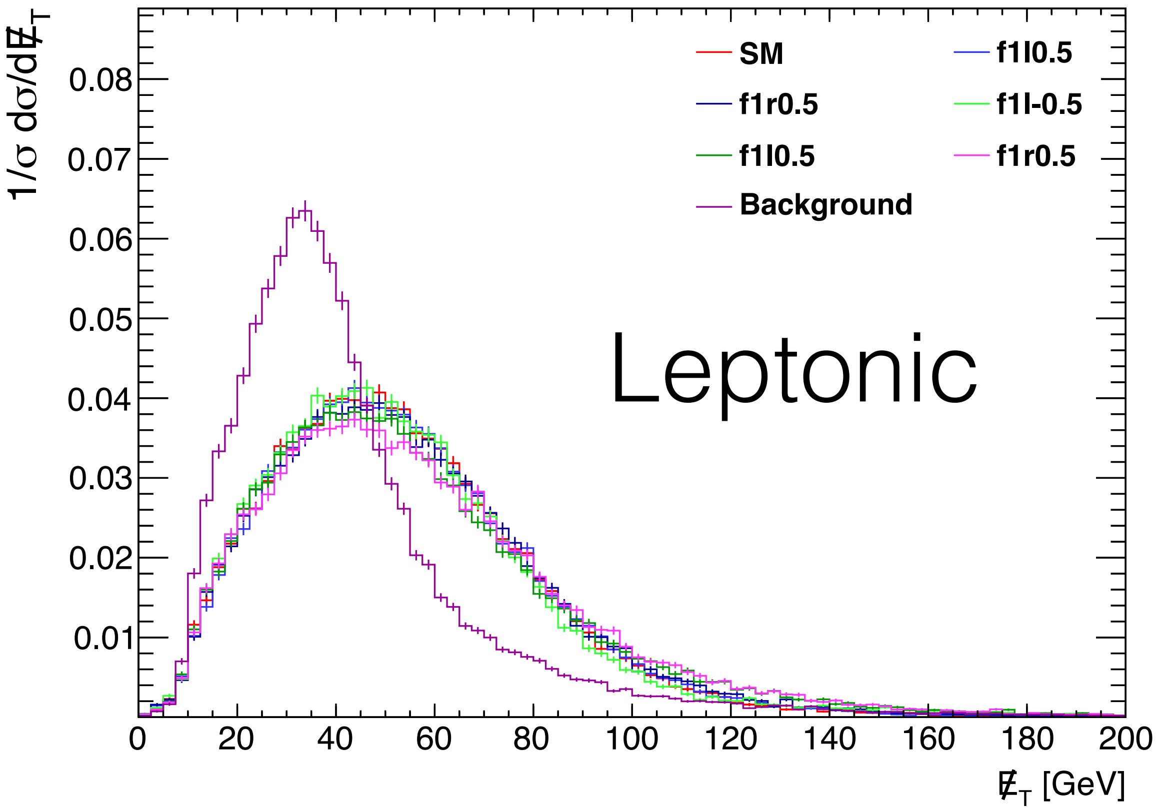
Samples	SM	f1l0.5	f1r0.5	f2l-0.5	f2l0.5	f2r0.5	Background
NIT	3.46e+05 ± 1.73e+03	7.76e+05 ± 3.88e+03	4.47e+05 ± 2.24e+03	3.22e+05 ± 1.61e+03	4.72e+05 ± 2.36e+03	5.66e+05 ± 2.83e+03	6.56e+05 ± 1.39e+03
1bjet	2.16e+05 ± 1.24e+03	4.82e+05 ± 2.77e+03	2.82e+05 ± 1.61e+03	2e+05 ± 1.15e+03	2.84e+05 ± 1.66e+03	3.62e+05 ± 2.05e+03	7.37e+03 ± 18.2
1bjet, 1lep	1.78e+05 ± 1.13e+03	3.98e+05 ± 2.52e+03	2.32e+05 ± 1.46e+03	1.59e+05 ± 1.03e+03	2.36e+05 ± 1.51e+03	3.01e+05 ± 1.87e+03	5.97e+03 ± 16.2
EtMiss	1.57e+05 ± 1.05e+03	3.5e+05 ± 2.36e+03	2.02e+05 ± 1.36e+03	1.39e+05 ± 960	2.05e+05 ± 1.41e+03	2.63e+05 ± 1.75e+03	5.08e+03 ± 14.8
dphiMET	1.48e+05 ± 1.02e+03	3.31e+05 ± 2.3e+03	1.9e+05 ± 1.32e+03	1.31e+05 ± 933	1.93e+05 ± 1.37e+03	2.44e+05 ± 1.68e+03	4.51e+03 ± 13.9

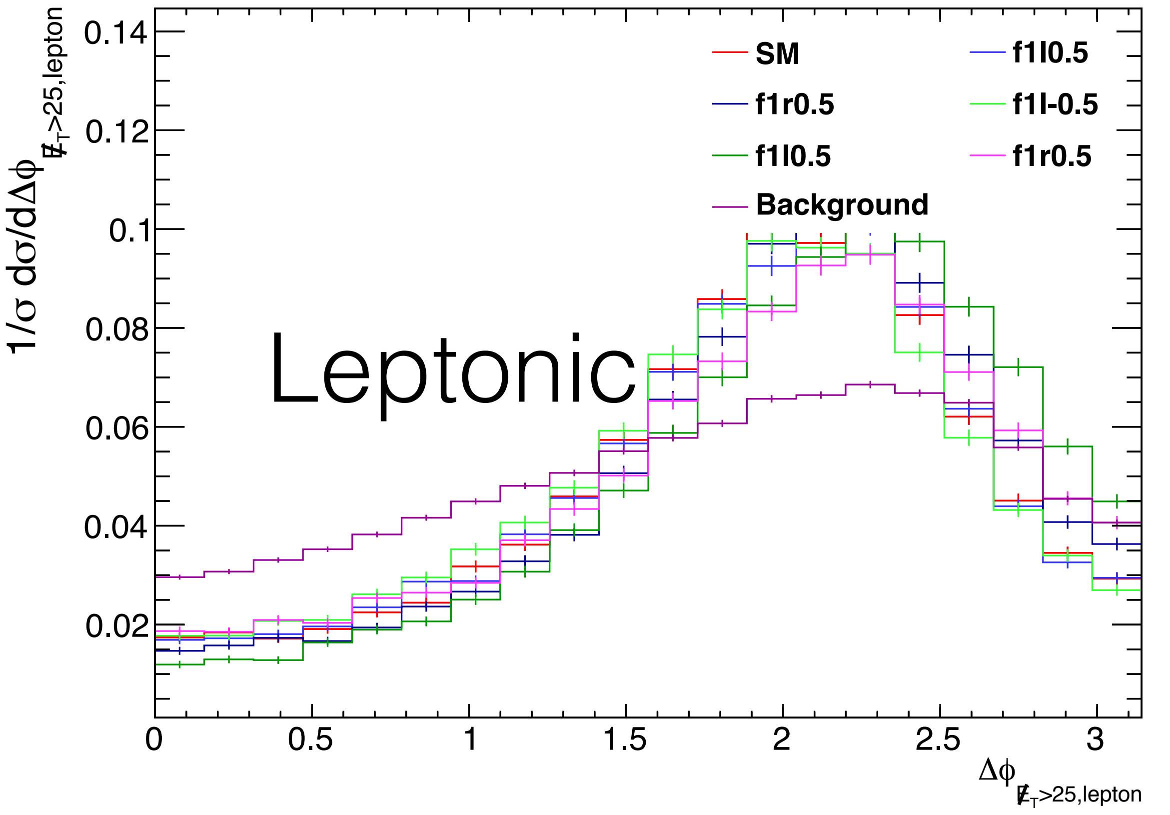
In the detector level, the signal efficiency is almost same, background is suppressed further more. Though background here is a small fraction.

Detector level figures

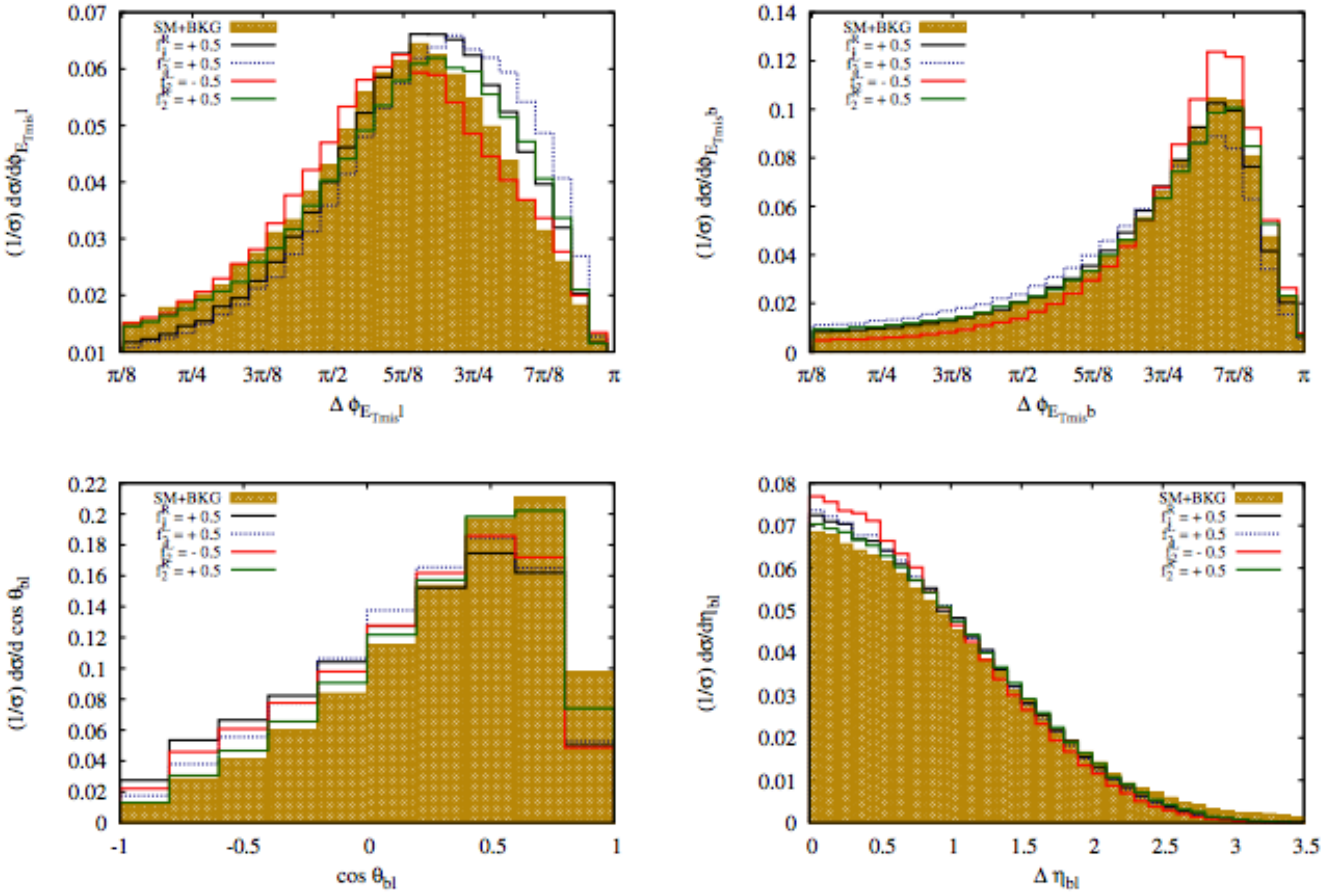








Angular asymmetry analysis (leptonic)



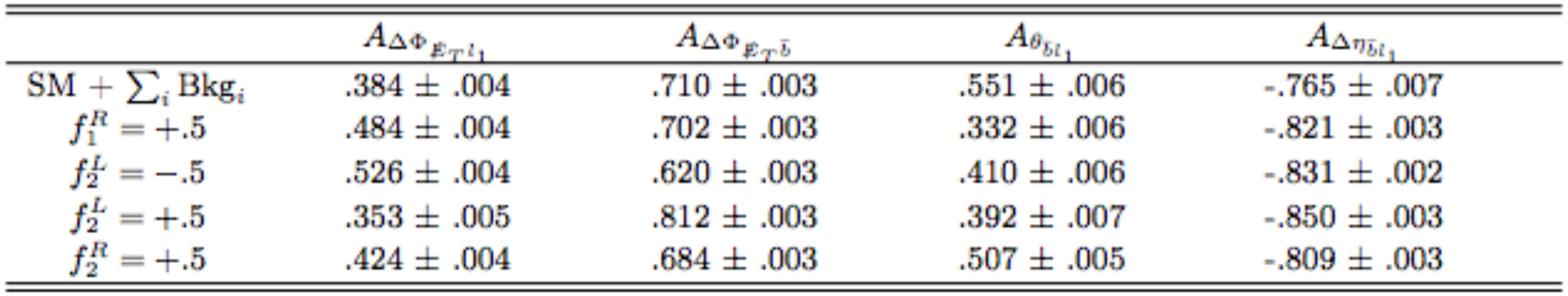
Parton level

- i, j means leptons, jets, b jets and EtMiss

$$A_{\theta_{ij}} = \frac{N_+^A(\cos\theta_{ij} > 0) - N_-^A(\cos\theta_{ij} < 0)}{N_+^A(\cos\theta_{ij} > 0) + N_-^A(\cos\theta_{ij} < 0)}$$

$$A_{\Delta\eta_{ij}} = \frac{N_+^A(\Delta\eta_{ij} > 0) - N_-^A(\Delta\eta_{ij} < 0)}{N_+^A(\Delta\eta_{ij} > 0) + N_-^A(\Delta\eta_{ij} < 0)}$$

$$A_{\Delta\Phi_{ij}} = \frac{N_+^A\left(\Delta\phi_{ij} > \frac{\pi}{2}\right) - N_-^A\left(\Delta\phi_{ij} < \frac{\pi}{2}\right)}{N_+^A\left(\Delta\phi_{ij} > \frac{\pi}{2}\right) + N_-^A\left(\Delta\phi_{ij} < \frac{\pi}{2}\right)}$$



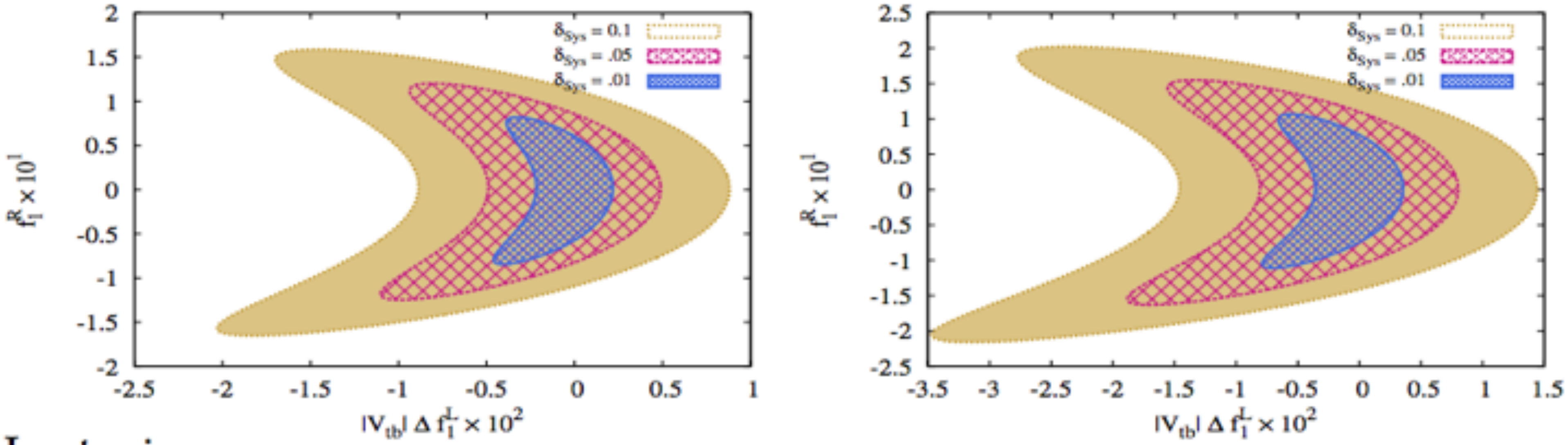
	$A_{\Delta\Phi_{\not E_T l_1}}$	$A_{\Delta\Phi_{\not E_T \bar b}}$	$A_{\theta_{\bar b l_1}}$	$A_{\Delta\eta_{\bar b l_1}}$
SM + $\sum_i$ Bkg$_i$	.384 ± .004	.710 ± .003	.551 ± .006	-.765 ± .007
$f_1^R = +.5$	.484 ± .004	.702 ± .003	.332 ± .006	-.821 ± .003
$f_2^L = -.5$	.526 ± .004	.620 ± .003	.410 ± .006	-.831 ± .002
$f_2^L = +.5$	.353 ± .005	.812 ± .003	.392 ± .007	-.850 ± .003
$f_2^R = +.5$	.424 ± .004	.684 ± .003	.507 ± .005	-.809 ± .003

Chi2 analysis using bin information

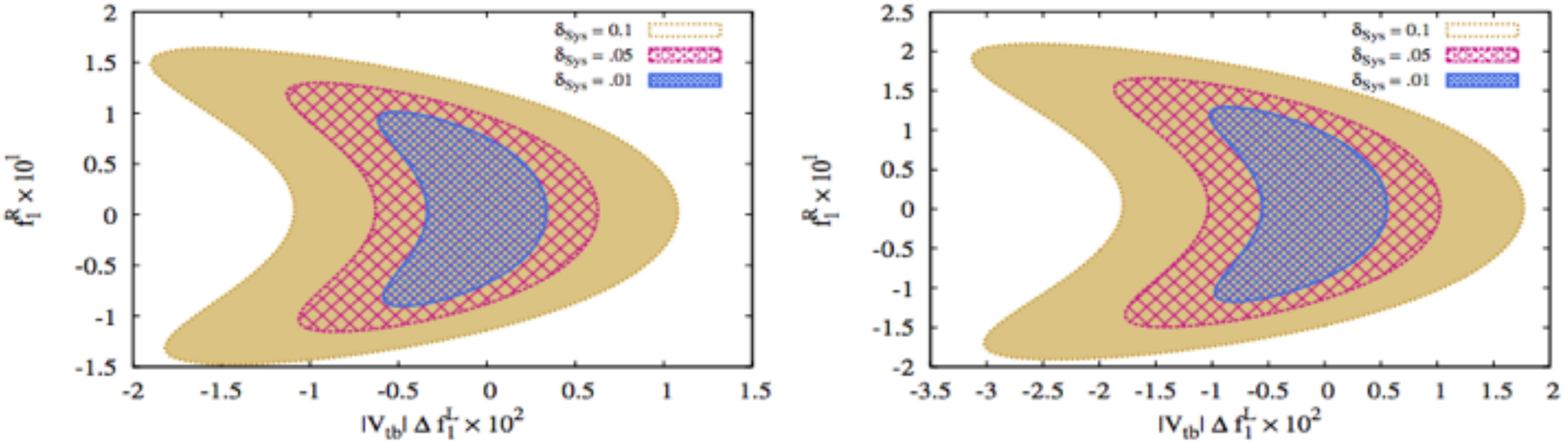
$$\chi^2(f_i,f_j)=\sum_{k=1}^{N}\left(\frac{\mathcal{N}_k^{\rm exp}-\mathcal{N}_k^{\rm th}(f_i,f_j)}{\delta\mathcal{N}_k^{\rm exp}}\right)^2$$

where $\delta\mathcal{N}_k^{\rm SM+\sum_i Bkg_i}=\sqrt{\mathcal{N}_k^{\rm SM+\sum_i Bkg_i}\left(1+\delta_{sys}^2\mathcal{N}_k^{\rm SM+\sum_i Bkg_i}\right)}.$

Hadronic



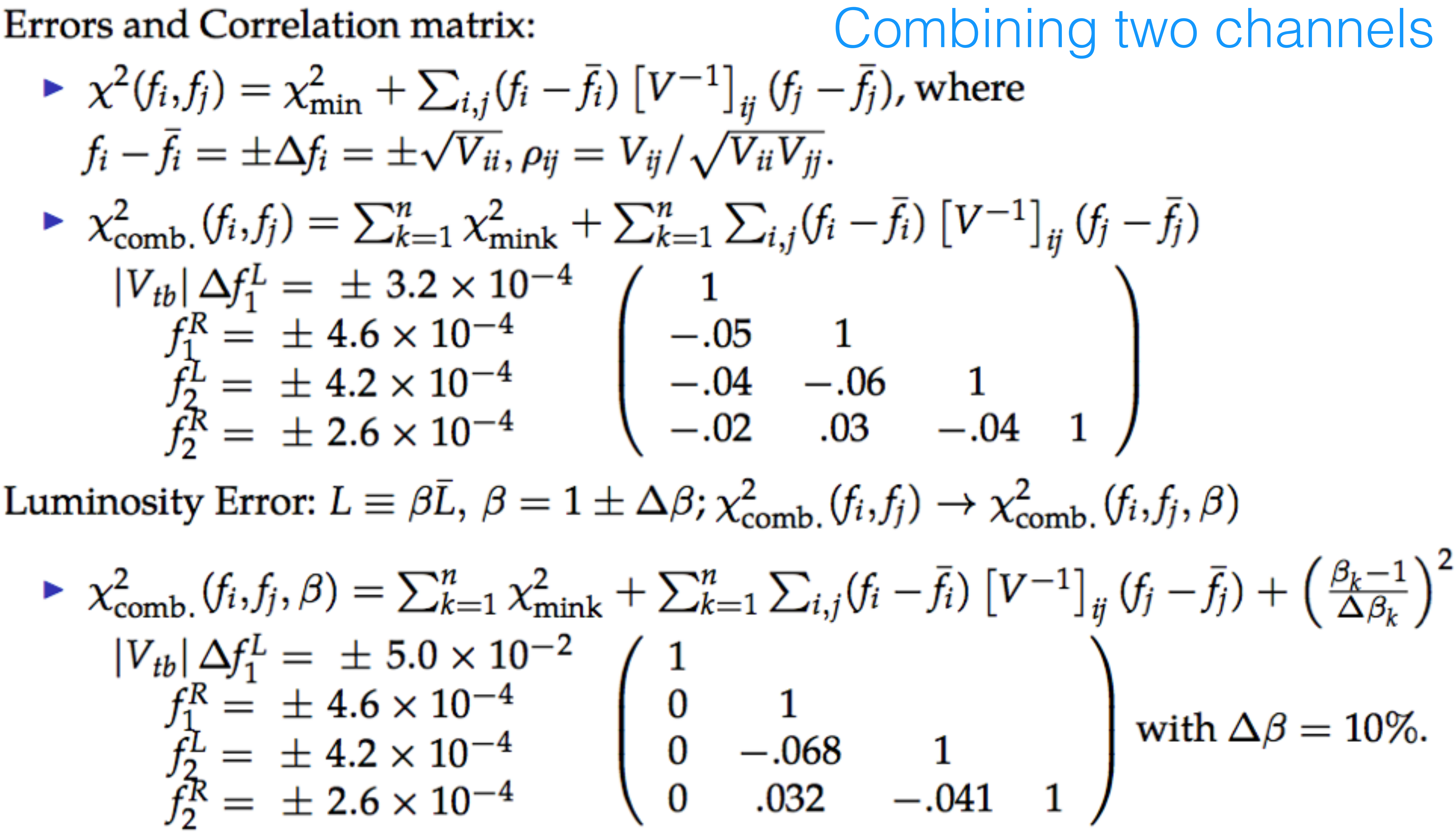
Leptonic



- 68% contour

Correlation and error

Combining two channels



Errors and Correlation matrix:

- $\chi^2(f_i,f_j) = \chi^2_{\text{min}} + \sum_{i,j}(f_i - \bar{f}_i)\,\left[V^{-1}\right]_{ij}\,(f_j - \bar{f}_j)$, where
  $f_i - \bar{f}_i = \pm\Delta f_i = \pm\sqrt{V_{ii}},\ \rho_{ij} = V_{ij}/\sqrt{V_{ii}V_{jj}}$.
- $\chi^2_{\text{comb.}}(f_i,f_j) = \sum_{k=1}^{n}\chi^2_{\text{mink}} + \sum_{k=1}^{n}\sum_{i,j}(f_i - \bar{f}_i)\,\left[V^{-1}\right]_{ij}\,(f_j - \bar{f}_j)$

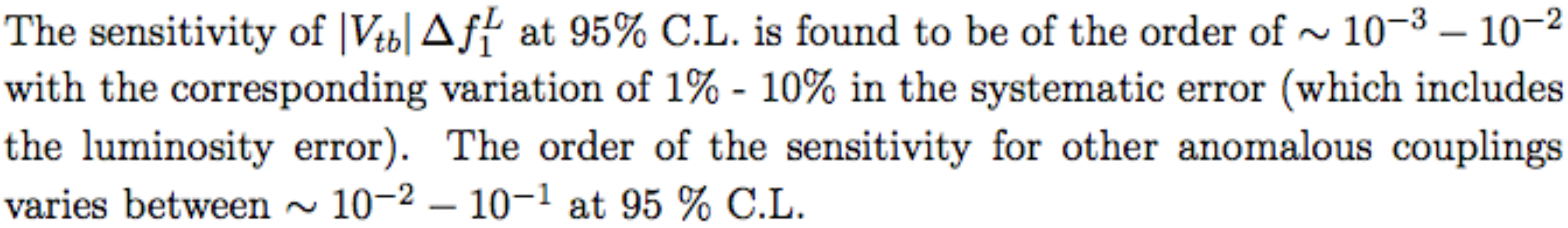
$$\begin{array}{rcl} |V_{tb}|\,\Delta f_1^L &=& \pm\,3.2\times10^{-4} \\ f_1^R &=& \pm\,4.6\times10^{-4} \\ f_2^L &=& \pm\,4.2\times10^{-4} \\ f_2^R &=& \pm\,2.6\times10^{-4} \end{array} \qquad \begin{pmatrix} 1 & & & \\ -.05 & 1 & & \\ -.04 & -.06 & 1 & \\ -.02 & .03 & -.04 & 1 \end{pmatrix}$$

Luminosity Error: $L \equiv \beta\bar{L},\ \beta = 1 \pm \Delta\beta;\ \chi^2_{\text{comb.}}(f_i,f_j) \to \chi^2_{\text{comb.}}(f_i,f_j,\beta)$

- $\chi^2_{\text{comb.}}(f_i,f_j,\beta) = \sum_{k=1}^{n}\chi^2_{\text{mink}} + \sum_{k=1}^{n}\sum_{i,j}(f_i - \bar{f}_i)\,\left[V^{-1}\right]_{ij}\,(f_j - \bar{f}_j) + \left(\frac{\beta_k - 1}{\Delta\beta_k}\right)^2$

$$\begin{array}{rcl} |V_{tb}|\,\Delta f_1^L &=& \pm\,5.0\times10^{-2} \\ f_1^R &=& \pm\,4.6\times10^{-4} \\ f_2^L &=& \pm\,4.2\times10^{-4} \\ f_2^R &=& \pm\,2.6\times10^{-4} \end{array} \qquad \begin{pmatrix} 1 & & & \\ 0 & 1 & & \\ 0 & -.068 & 1 & \\ 0 & .032 & -.041 & 1 \end{pmatrix} \quad \text{with } \Delta\beta = 10\%.$$

Prospects



The sensitivity of $|V_{tb}|\,\Delta f_1^L$ at 95% C.L. is found to be of the order of $\sim 10^{-3} - 10^{-2}$ with the corresponding variation of 1% - 10% in the systematic error (which includes the luminosity error). The order of the sensitivity for other anomalous couplings varies between $\sim 10^{-2} - 10^{-1}$ at 95 % C.L.

- Rough estimation, with higher luminosity, eg 1ab-1, the limit on |Vtb| f_1^L will be reduced to 1/3 (sqrt(10)) of its current limit (stat only). In that case the systematics is critical.

- LHeC can provide stronger constraint on the anomalous couplings, when statistics increasing.

- Both hadronic and leptonic channel providing sensitivity to measure the anomalous couplings, the leptonic channel has higher signal purity

- Detector level study is ongoing, the hadronic channel suffers stronger background but the leptonic channel has good performance.

Conclusion

- We observe high yields of single anti-top quark production with fiducial efficiency of ~ 70% and ~ 90% in the hadronic and leptonic decay of W–, respectively after imposing selection cuts.

- Asymmetries of different kinematic variable, bin analysis help to improve the sensitivity of anomalous couplings to the order of 10^{-3}-10^{-2} for $|V_{tb}|\ \Delta f^L_1$ with the variation of 1%-10% systematic error and others are of order 10^{-2}-10^{-1} at 95%.

- Luminosity error affect $|V_{tb}|\ \Delta f^L_1$.

- Overall comparison with different data shows that Wtb anomalous couplings can be probed at LHeC with very high accuracy.