Higgs Recoil Mass and Cross Section Analysis at ILD

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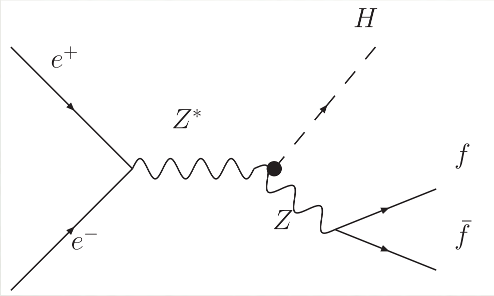
OUTLINE

- Introductory Remarks
- Lepton ID and Track Selection
- Background Suppression
  - Rejection by Cuts
    - MI Analysis: Independent of Higgs Decay modes
    - MD Analysis: Assumptions made on Higgs decay mode
  - Further Rejection by Likelihood
- Fits
- Bremsstrahlung Recovery
- Results
- Summary

Introductory Remarks

- Higgs-Strahlung Process:



- Higgs Recoil Mass:

$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$

- Cross Section and Coupling Strength Measurement:

$$g^2 \propto \sigma = N/\mathcal{L}\epsilon$$

- M_H = 120 GeV
- Ecm = 250 GeV
- Beam Energy Spread: e^-:0.28%, e^+:0.18%
- Beamstrahlung: included
- Luminosity: 250 fb^{-1}
- Polarization:
  - $e^-_R e^+_L$: (e^-: +80%, e^+: -30%)
  - $e^-_L e^+_R$: (e^-: -80%, e^+: +80%)
- Detector Model: ILD_00
- Event Generation:
  WIZARD v1.40 (by SLAC)
- Simulation & Reconstruction:
  ILCSoft v01-06 (by DESY & KEK)

Introductory Remarks

Cross-Sections

$e^-_R e^+_L$

μμX

Process	Cross-Section
$\mu\mu X$	**7.87 fb**
$\mu\mu$	8.12 pb (58.26 fb)
$\tau\tau$	4850.05 fb
$\mu\mu\nu\nu$	52.37 fb
$\mu\mu f f$	1130.01 fb

eeX

Process	Cross-Section
eeX	**8.43 fb**
ee	17.30 nb (335.47 fb)
$\tau\tau$	4814.46 fb
$ee\nu\nu$	107.88 fb
$eeff$	4135.97 rb

$e^-_L e^+_R$

μμX

Process	Cross-Section
$\mu\mu X$	**11.67 fb**
$\mu\mu$	10.44 pb (84.86 fb)
$\tau\tau$	6213.22 fb
$\mu\mu\nu\nu$	481.68 fb
$\mu\mu f f$	1196.79 fb

eeX

Process	Cross-Section
eeX	**12.55 fb**
ee	17.30 nb (357.14 fb)
$\tau\tau$	6213.22 fb
$ee\nu\nu$	648.51 fb
$eeff$	4250.58 fb

(1) eeX also includes ~7% ZZ fusion

(2) *μμνν* and *eeνν* have major contribution from WW, but also from ZZ.

(2) *μμff* refers to *μμee* + *μμμμ* + *μμττ* + *μμqq*,

eeff refers to *eeμμ* + *eeee* + *eeττ* + *eeqq*

Pre-cuts for ee and μμ:
(cross-sections after pre-cuts are in brackets)

ee process	$\mu\mu$ process
$\lvert cos\theta_{e^+/e^-}\rvert < 0.95$	
$M_{dl} \in (71.18, 111.18)$ GeV	$M_{dl} \in (71.18, 111.18)$ GeV
$P_{Tdl} > 10$ GeV	$P_{Tdl} > 10$ GeV
$M_{recoil} \in (105, 165)$ GeV	$M_{recoil} \in (105, 165)$ GeV

Production Statistics:

1) Signal: 10 ab^{-1} each
2) Background: mostly larger than 250 fb^{-1}, re-weighted to correct luminosity spectrum with a dedicated algorithm (thanks to M. Berggren).

Preparations

1) Cuts for lepton ID:

	μ-Identification	e-Identification
E_{ecal}/E_{total}	< 0.5	> 0.6
E_{total}/P_{track}	< 0.3	> 0.9

Efficiency of lepton pair ID:
(pair selection according to Z Mass)

μμX (muon ID) : 95.4%
eeX (electron ID) : 98.8%

2) ΔP/P² criterion on tracks in the selection of lepton candidates

- Parameterize ΔP/P² for central region

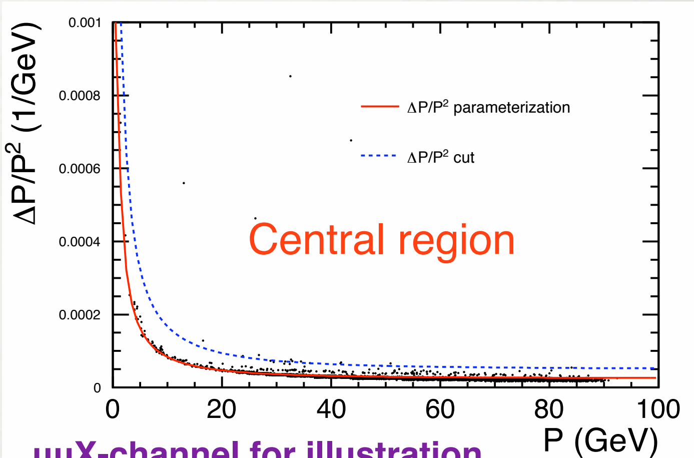
$$\Delta P/P^2 = a \oplus b/P;$$
$$where\ a = 2.5 \times 10^{-5};\ b = 8 \times 10^{-4}$$

- The criterion ΔP/P² applied

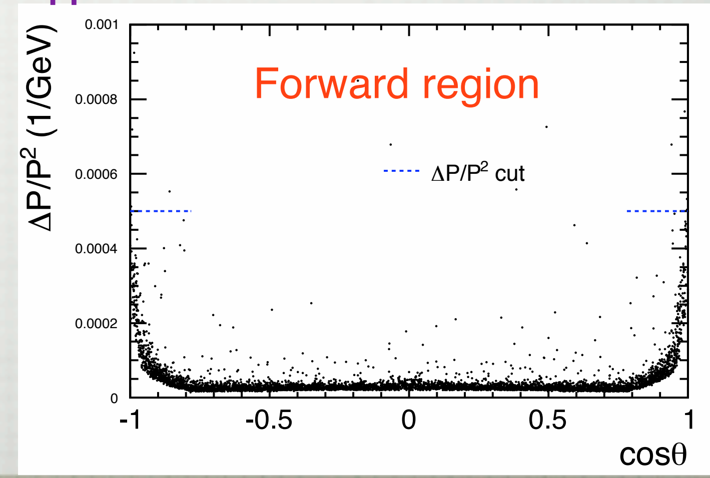
$$|cos\theta| < 0.78: \quad \Delta P/P^2 < 2 \times (2.5 \times 10^{-5} \oplus 8 \times 10^{-4}/P)$$
$$|cos\theta| > 0.78: \quad \Delta P/P^2 < 5 \times 10^{-4}$$

ΔP is propagated from tracking error matrix

Same cuts applied on both μμX and eeX channels



μμX-channel for illustration



Analysis Procedures

<table>
<tr><th>Analysis Models</th><th>Model Independent (MI)</th><th>Model Dependent (MD)</th></tr>
<tr><td rowspan="2">Background Rejection</td><td>MI Cut-chain</td><td>MD Cut-chain</td></tr>
<tr><td colspan="2">Likelihood Further Rejection</td></tr>
<tr><td colspan="3">Fits and Results</td></tr>
</table>

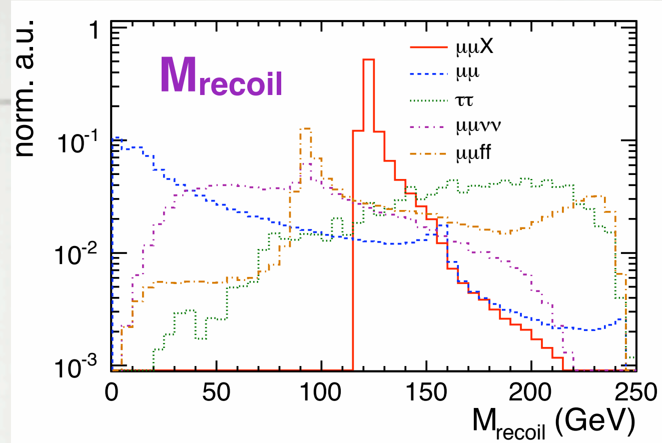
- Background Rejection
  - Rejection by Cuts
    - MI Cut-Chain: Independent of Higgs Decay Modes
    - MD Cut-Chain: Assumes more than two charged tracks from Higgs decay
  - Further Rejection by Likelihood with Model Independent variables
- Fit and Results

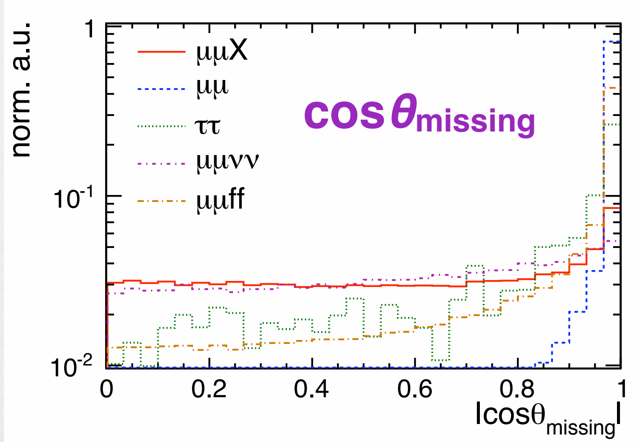
Background Rejection by Cuts: MI Cut-Chain

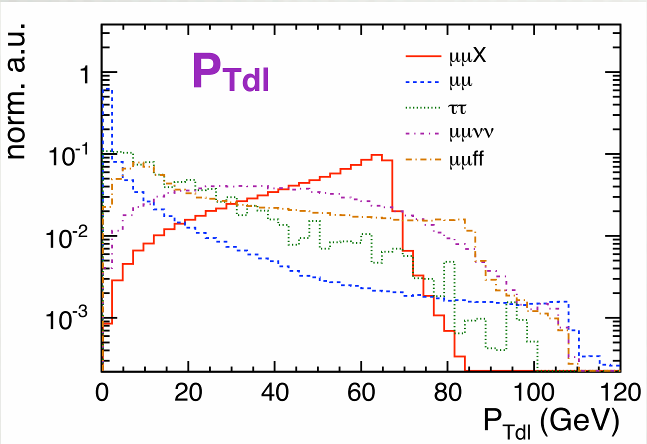
MI Cut-Chain & Nevts after each cuts:

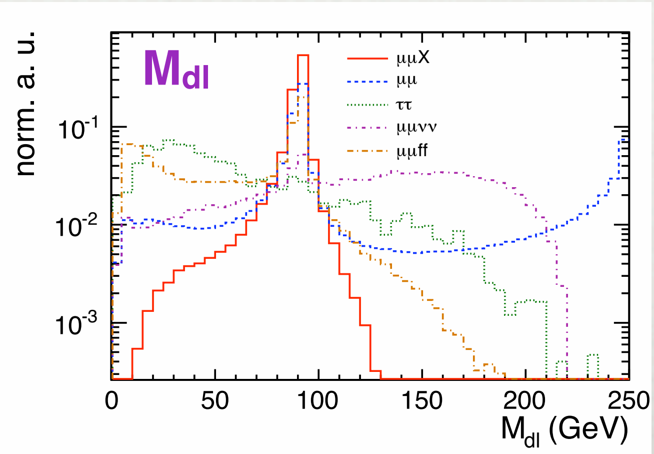
Pol. $e^-_L e^+_R$, μμX-channel for illustration

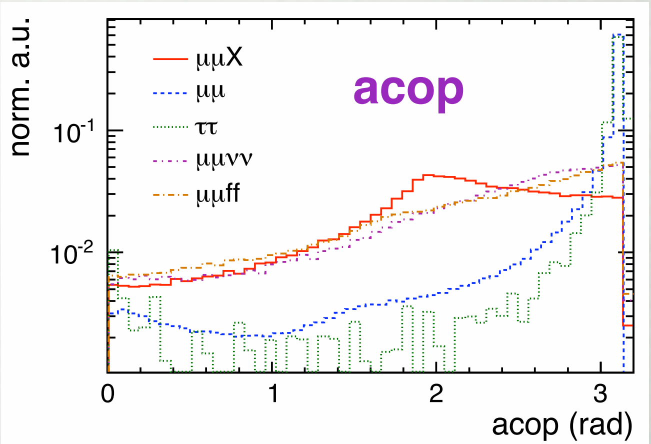
N_{evts} Remained	$\mu\mu X$	$\mu^+\mu^-$	$\tau^+\tau^-$	$\mu^+\mu^-\nu\nu$	$\mu^+\mu^- ff$
Before any restriction	2918 (100.0%)	2.6M	1.6M	111k	317k
+ Lepton ID + Tightened Pre-Cuts	2472 (84.72%)	9742	4582	9268	8175
+ $P_{Tdl} > 20$GeV	2408 (82.50%)	7862	3986	8462	7222
+ $M_{dl} \in (80, 100)$GeV	2292 (78.54%)	6299	2679	5493	5658
+ $acop \in (0.2, 3.0)$	2148 (73.61%)	5182	112	5179	5083
+ $\Delta P_{Tbal.} > 10$GeV	2107 (72.20%)	335	80	4705	4706
+ $\lvert\Delta\theta_{2tk}\rvert > 0.01$	2104 (72.11%)	149	80	4647	4676
+ $\lvert\cos\theta_{missing}\rvert < 0.99$	2046 (70.09%)	82	80	4647	3614
+ $M_{recoil} \in (115, 150)$GeV	2028 (69.48%)	75	80	3642	2640











Background Rejection by Cuts: MI Analysis

ISR P_T balance for μμ and ee rejection

Idea: (Thanks to F. Richard)

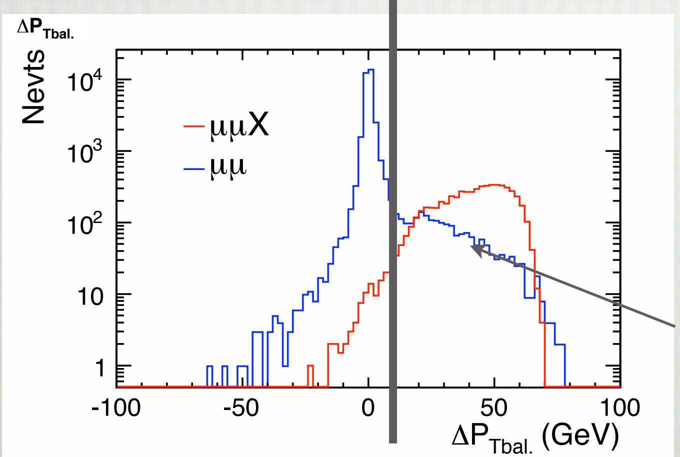
- **For μμ and ee: P_T of ISR photon should balance the P_T of di-lepton system;**
- **For signal: Impossible to have ISR to balance Z P_T, independent of Higgs decay model.**

Requirements:

- **$M_{dl} \in (80, 100)$ GeV: large FSR events are removed**
- **$P_{Tdl} > 20$ GeV: Large P_T ISR photon**

Define $\Delta P_{Tbal.} = P_{Tdl} - P_{T\gamma}$

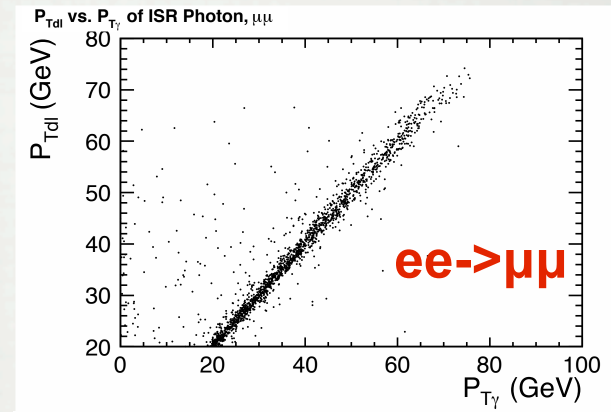
$\Delta P_{Tbal.} > 10$ GeV

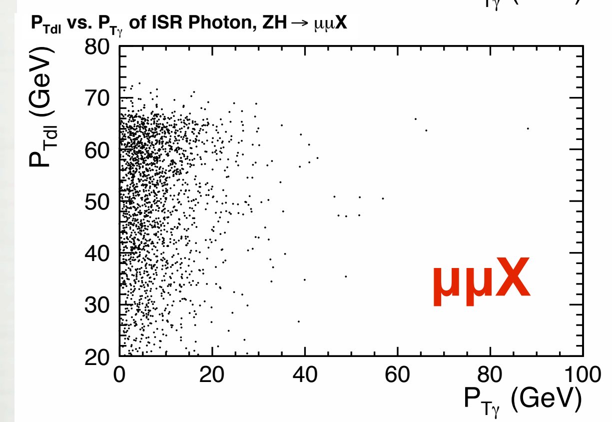


ISR photon conversions

Reduces μμ and ee further by 1 to 2 orders of magnitude

Signal lost: ~1%





To reject the ISR Photon conversions:

- **Cut $|\Delta\theta_{2tk}|>0.01$: Only apply on events with 2 additional tracks**
- **Reject μμ and ee Further by a factor of 2.**

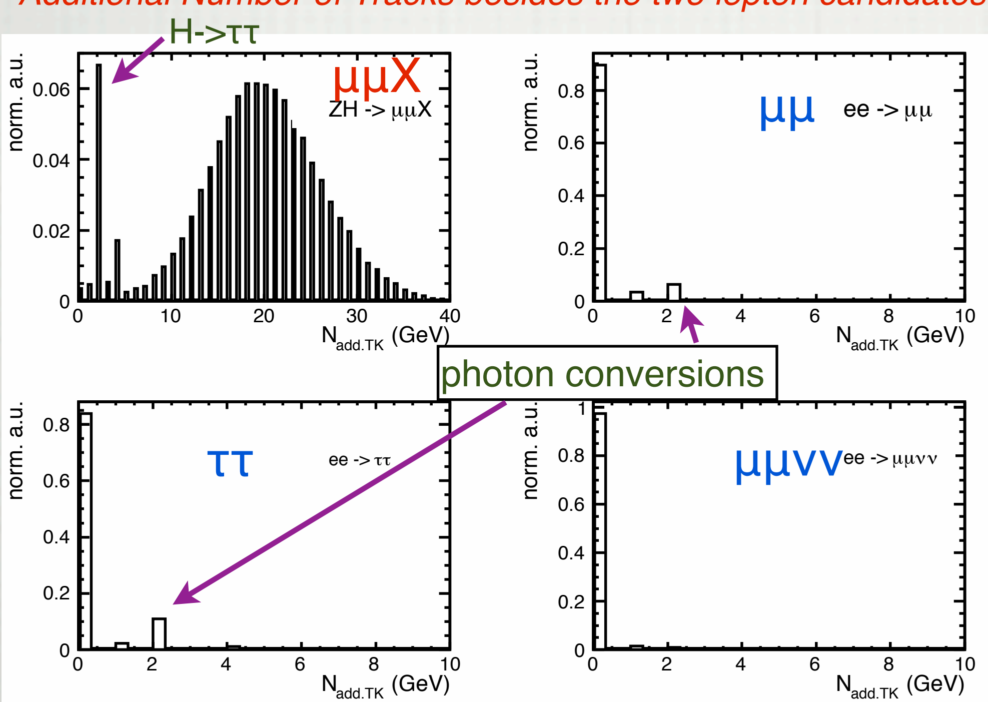
Background Rejection by Cuts: MD Cut-Chain

MD Cut-Chain & Nevts after each cuts:

Pol. $e^-_L e^+_R$, μμX-channel for illustration

N_{evts} Remained	$\mu\mu X$	$\mu^+\mu^-$	$\tau^+\tau^-$	$\mu^+\mu^-\nu\nu$	$\mu^+\mu^- f f$
Before any restriction	2918 (100.0%)	2.6M	1.6M	111k	317k
+ Lepton ID + Tightened Pre-Cuts	2472 (84.72%)	9742	4582	9268	8175
+ $N_{add.TK} > 1$	2453 (84.05%)	604	842	145	6321
+ $\|\Delta\theta_{2tk}\| > 0.01$	2449 (83.91%)	63	816	14	6254
+ $\|\Delta\theta_{min}\| > 0.01$	2417 (82.81%)	38	261	1	5711
+ $acop \in (0.2, 3.0)$	2256 (77.29%)	32	0	1	5051
+ $\|\cos\theta_{missing}\| < 0.99$	2189 (75.00%)	16	0	1	3843
+ $M_{recoil} \in (115, 150)$GeV	2154 (73.81%)	15	0	1	2830

Additional Number of Tracks besides the two lepton candidates



For SM Higgs decay, multiplicity in the final states is the most efficient criterion to reject the 2f and WW

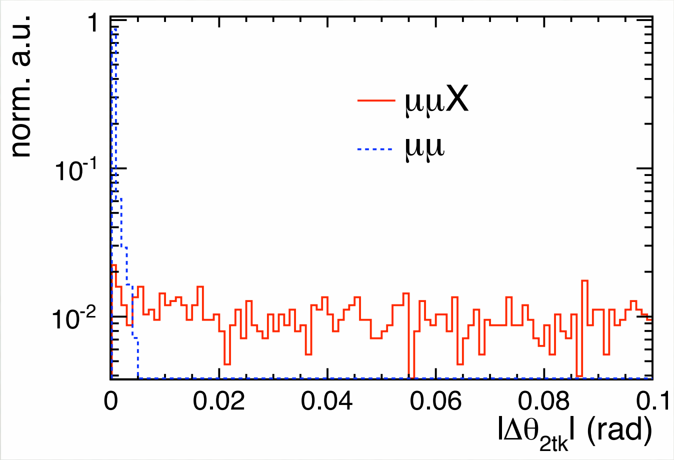
- In order to keep the H->ττ in the signals :
  - At most: $N_{add.tks}>1$
  - How to reject evts with $N_{add.tks}=2$ in μμ and ττ?
  - Photon conversions

Background Rejection by Cuts: MD Cut-Chain

To reject evts with $N_{add.tks}$=2 in μμ and ττ

1)

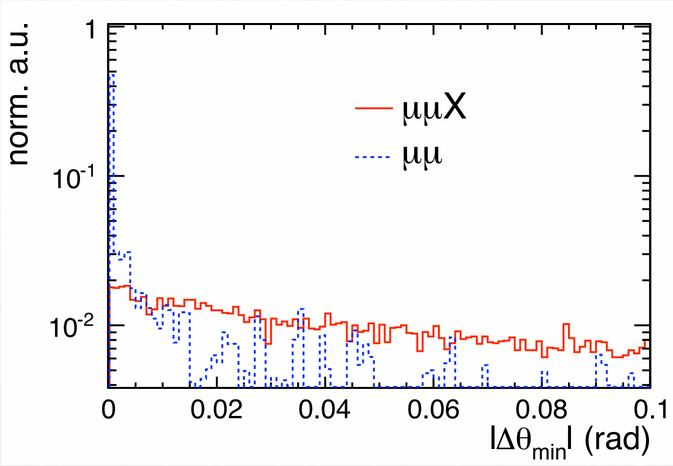
- Define $\Delta\theta_{2tk}$: Δθ between these two additional tracks for events with $N_{add.tks}$=2.
- Apply $|\Delta\theta_{2tk}|>0.01$ to reject photon conversions



- Reduced the μμ/ee further by ~ 1 order of magnitude, with a signal lost of only ~ 0.2%

2)

- Define $\Delta\theta_{min}$: the smallest Δθ between the additional tracks and the lepton candidates
- Because mis-identification of photon conversions to be lepton candidates
- Apply $|\Delta\theta_{min}|>0.01$



Further Rejection by Likelihood: For both MI and MD analyses

After cuts rejection, further rejection using Likelihood Method is applied

Likelihood:

$$L = \prod_i P_i$$

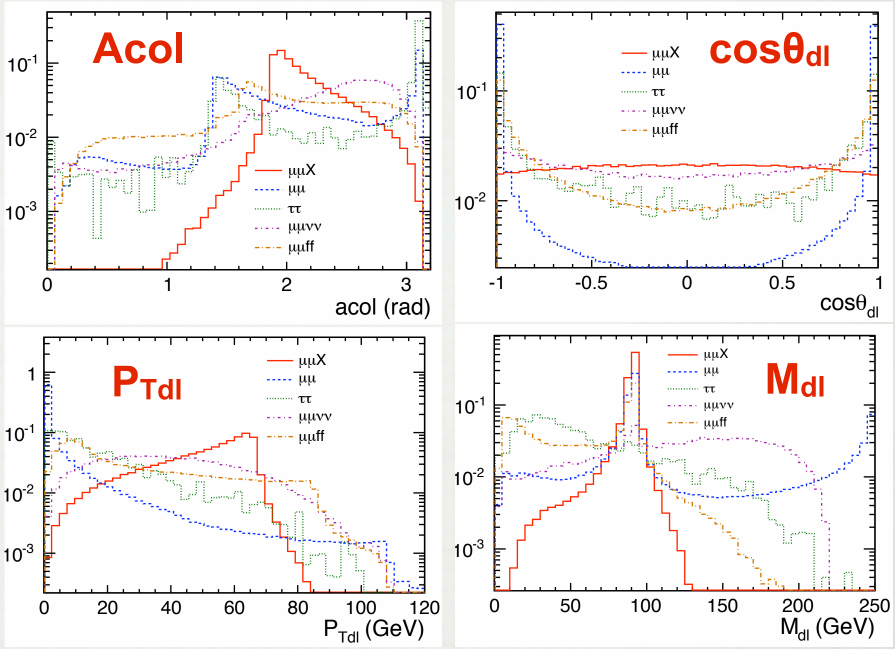
Probability (P_i); *i* th Variable (i)

Likelihood Fraction:

$$f_L = L_S/(L_S + L_B)$$

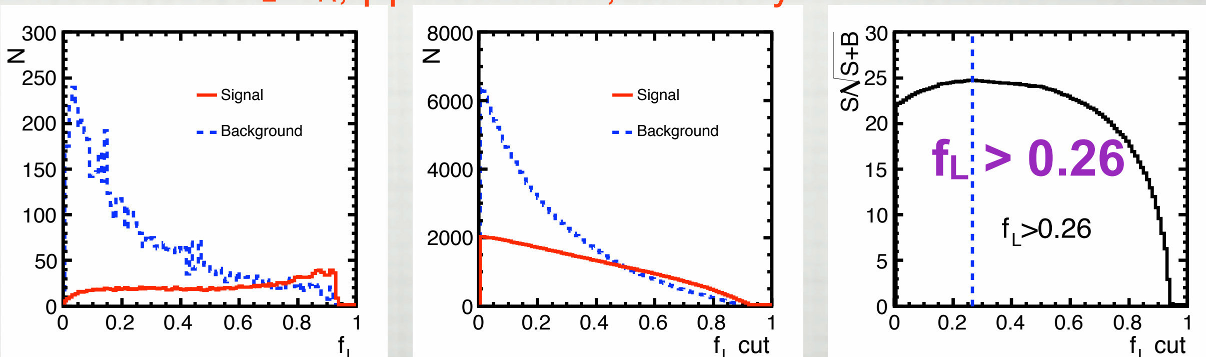
within (0, 1)

PDFs



Decide the f_L cut by the maximum significance for each particular analysis channel

Pol. $e^-_L e^+_R$, μμX-channel, MI Analysis for illustration



f_L Distribution | Nevt vs. f_L | Significance

On average, Likelihood further rejection suppresses background by a factor of 2, with a loss of signal about 10%.

Background Rejection Summary Table

Efficiency: μμX around 60%, eeX around 40%,
S/B: on average around 1

Ana.	Pol.	Ch.	S (%)	B
MI	$e^-_R e^+_L$	$\mu\mu X$	1165 (59.20%)	1023
		eeX	909 (43.14%)	1991
	$e^-_L e^+_R$	$\mu\mu X$	1596 (54.68%)	2563
		eeX	1153 (36.74%)	3508
MD	$e^-_R e^+_L$	$\mu\mu X$	1289 (65.53%)	883
		eeX	889 (42.20%)	1139
	$e^-_L e^+_R$	$\mu\mu X$	1911 (65.49%)	1397
		eeX	1378 (43.90%)	1679

Fit Methods

Signal Functions: (three functions are studied, with identical results)

GPET Function: Gaussian core for the Peak with an Exponential complementing the tail, updated from previous contributions.

Kernel Estimation: An universal method for all kinds of distributions, Intensively used at LEP for Higgs searches,

Physics Motivated Function: New!

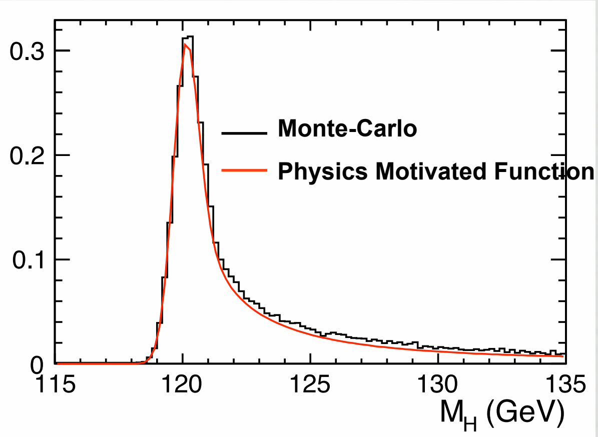
Yokoya-Chen ⊗ ISR ⊗ Gaussian ⟹ Higgs Recoil Mass

Analytical — Numerical — Propagate to

- Novel Developed in my thesis (LAL 09-118),
- Based on Yokoya-Chen's Beamstrahlung Approximation and ISR Approximation,

With beam parameters given in advance, Can predict the MC distribution

Not a fit, but a prediction of the MC distribution!!!



Background: Polynomial Function

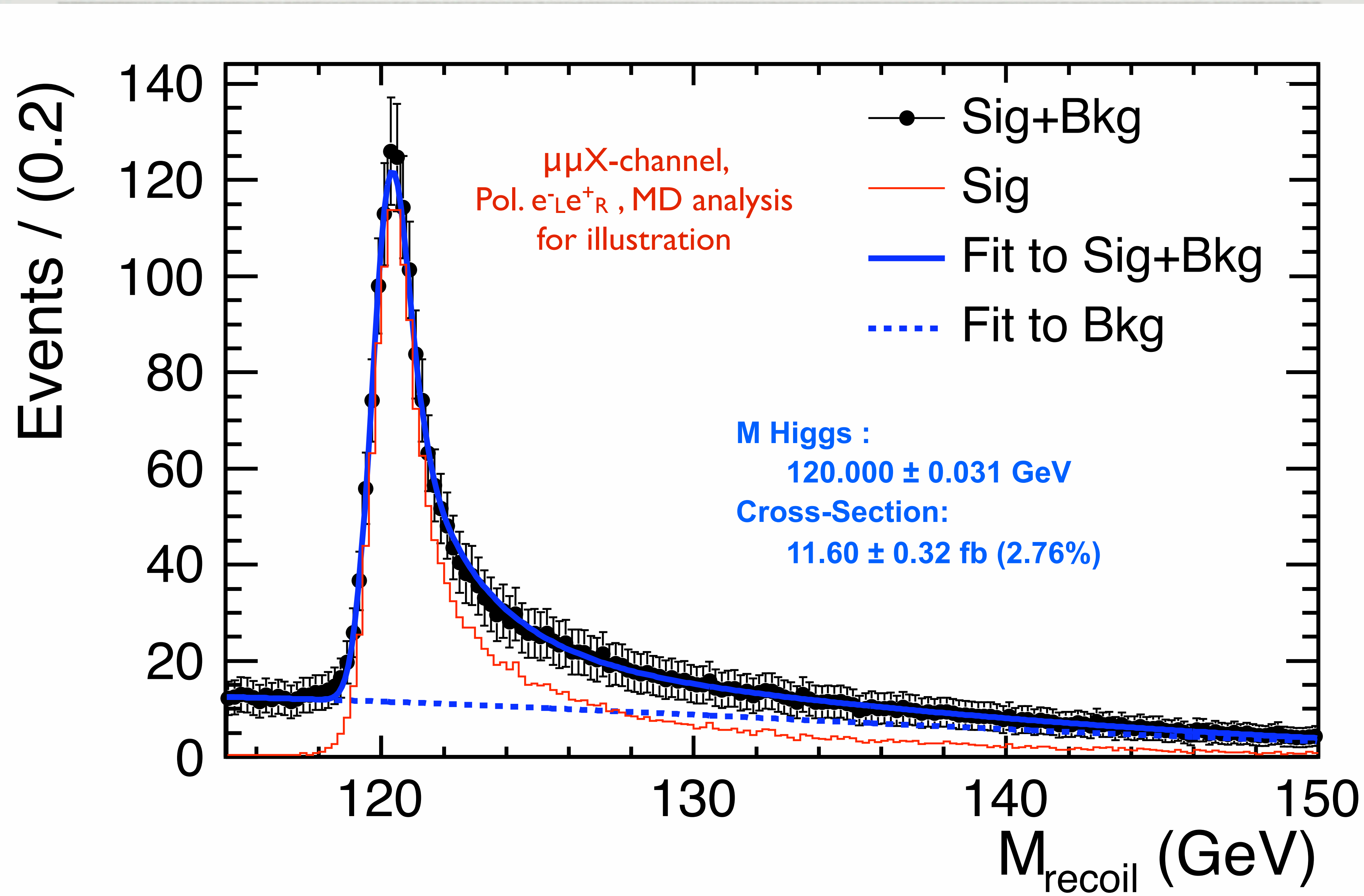
Build Composite Model: $F(x) = N_S f_S(x) + N_B f_B(x)$

Fitting:
1) Determine fitting parameters from MC (a separate data set)
2) Fix all the parameters except the Ns and M_H
3) Fit to the "Sig+Bkg" to get the results

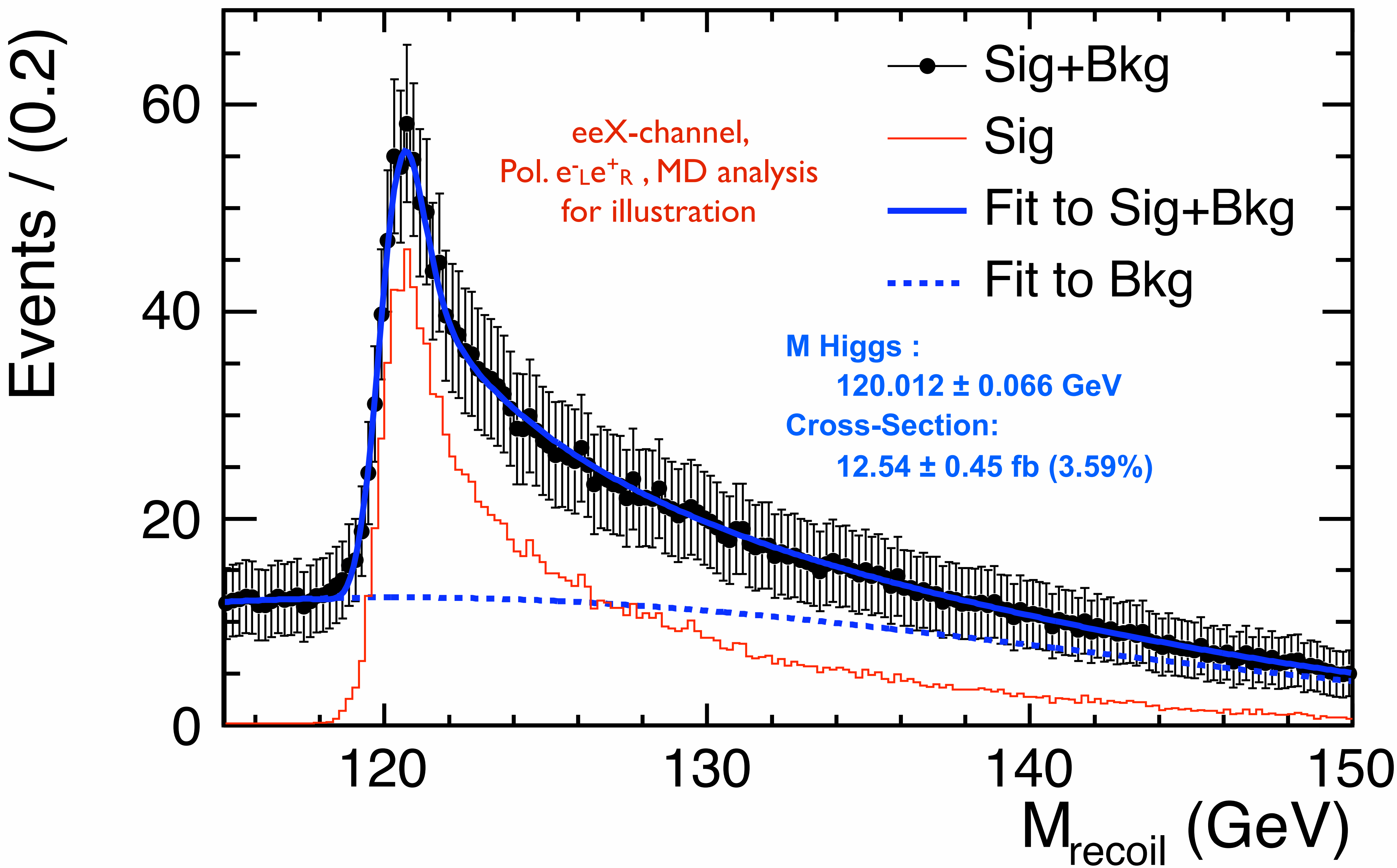
To minimize the error on the error of the result:

1) Signal is scaled down from $10ab^{-1}$ to 250 fb^{-1}
2) Background is regenerated 100 times based on the fitting parameters from MC and scaled down to 250 fb^{-1}

Fit: (Physics Motivated Function)



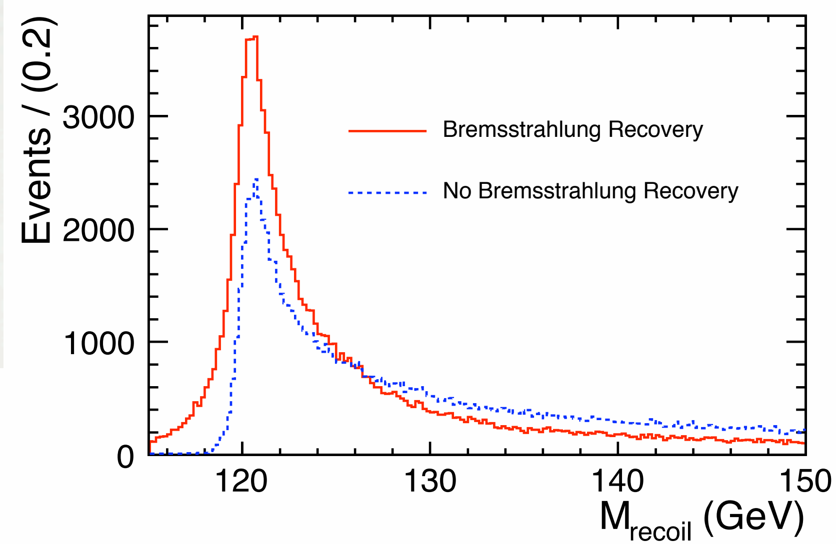
Fit: (Physics Motivated Function)

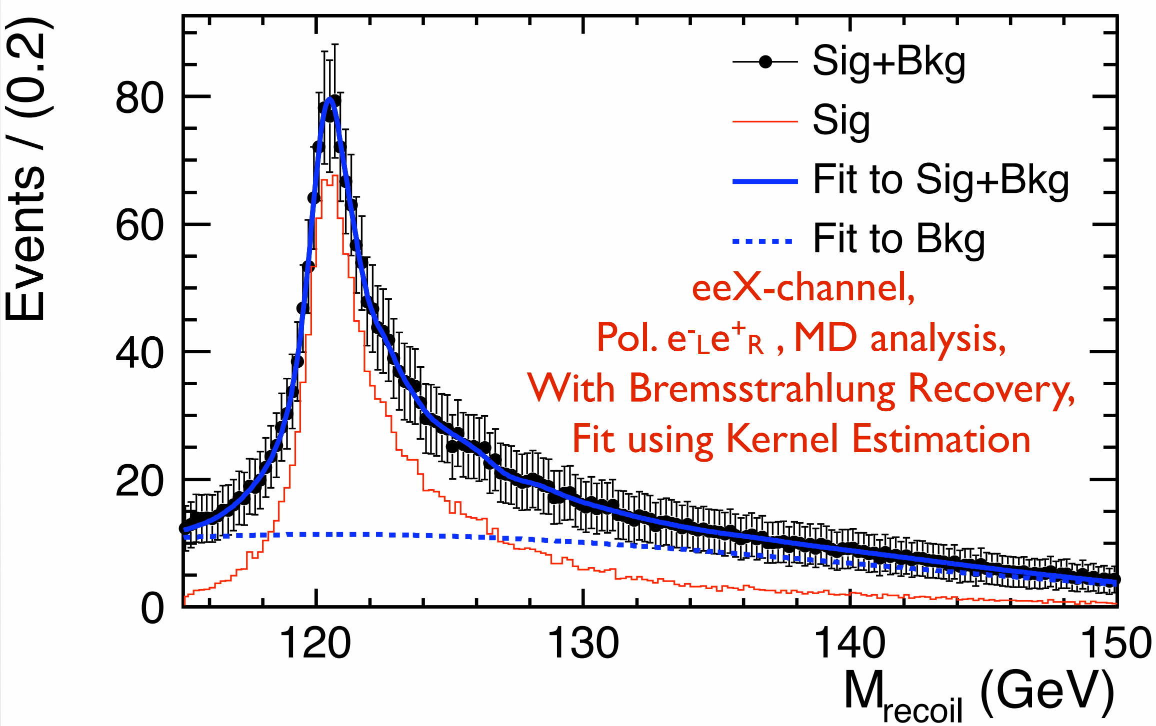


Bremsstrahlung Recovery

A dedicated algorithm for inclusion of Bremsstrahlung photons. (Thanks to M. Thomson)

- Significantly increases the statistics
- Degrades the mass resolution.
  (worse ECAL resolution for low energy photon reconstruction)





- Same background suppression methods applied.
- Number of Signal and Background Remaining:

Ana.	Pol.	Ch.	S (%)	B
MI	$e^-_R e^+_L$	eeX	1029 (48.84%)	1408
	$e^-_L e^+_R$	eeX	1491 (41.51%)	3394
MD	$e^-_R e^+_L$	eeX	1152 (54.66%)	1114
	$e^-_L e^+_R$	eeX	1724 (54.94%)	1513

M Higgs : 119.999 ± 0.060 GeV (~10% improv.)

Cross-Section: 12.51 ± 0.38 fb (3.04%) (~20% improv.)

Results [a]

[a] Results are identical from all three fit methods.
[b] ee(nγ)X: refers to eeX results with Bremsstrahlung Recovery
[c] Merged: Results with merged statistics of μμX and ee(nγ)X.

Ana.	Pol.	Ch.	δM_H (MeV)	$\delta\sigma/\sigma$ (%)
MI	$e^-_R e^+_L$	μμX	40	3.58
		eeX	93	5.09
		ee(nγ)X[b]	81	4.28
		merged [c]	36	2.75
	$e^-_L e^+_R$	μμX	37	3.35
		eeX	87	4.92
		ee(nγ)X	73	3.91
		merged	33	2.54

Ana.	Pol.	Ch.	δM_H (MeV)	$\delta\sigma/\sigma$ (%)
MD	$e^-_R e^+_L$	μμX	38	3.32
		eeX	82	4.51
		ee(nγ)X	74	3.69
		merged	34	2.47
	$e^-_L e^+_R$	μμX	31	2.76
		eeX	66	3.59
		ee(nγ)X	60	3.04
		merged	28	2.04

1. Best results obtained : δM = 28 MeV, δσ/σ=2.0% combining μμX and eeX two channels
2. Precisions from eeX-channel are worse by a factor of 2 for M_H measurement, while 1.5 for cross-section measurement, on average, than that of the μμX-channel, due to
   Bremsstrahlung of electron final states and larger background related
3. MD analysis are more precise by about 10% than MI analysis on average.
4. Polarization $e^-_L e^+_R$ gives better results than $e^-_R e^+_L$ by about 10% in MI analysis and 20% in MD analysis, because:
   (1) $e^-_R e^+_L$ suppresses the WW background, but also suppresses the signal by about 20%
   (2) WW background can be efficiently rejected by analysis methods independent of the beam polarization.
5. Bremsstrahlung recovery improves the eeX-channel results by about 10% on the M_H measurement, and about 20% on the cross-section measurement, on average.

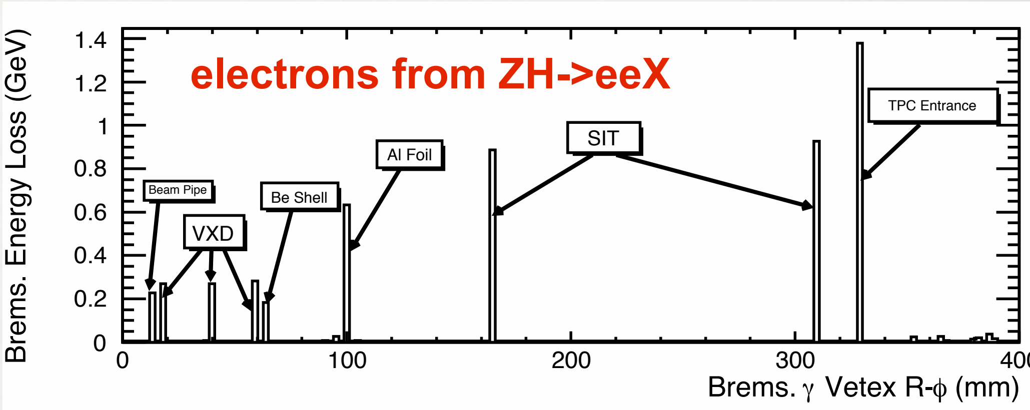
Summary

- Realistic Methods and Techniques are developed for the Higgs Recoil Mass and Higgs-strahlung cross-section measurement

- eeX-channel suffers from Bremsstrahlung, material budget has potential to be revised.

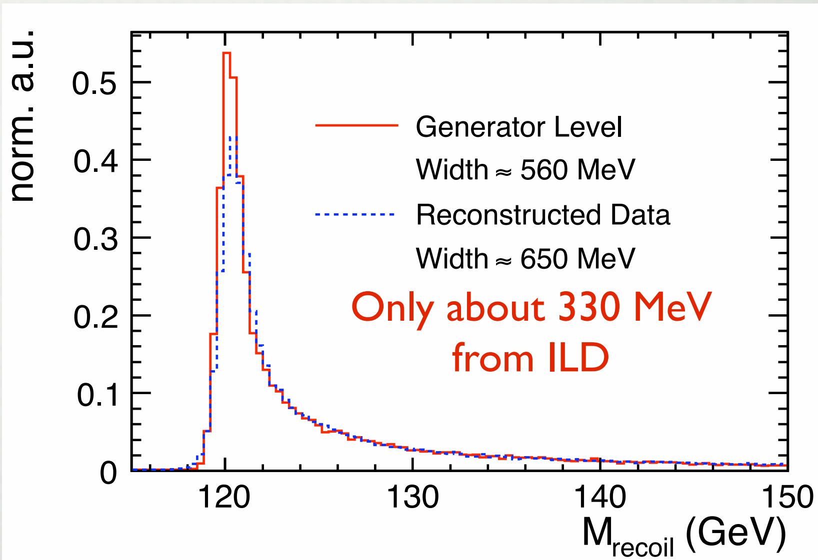
- Bremsstrahlung photons are included in the eeX-channel analysis, better results obtained:
  - ~ 10% in MH;
  - ~ 20% in cross-section

Brems. mean energy loss V.S. vertex position



- Measurements precision achieved (L=250fb^{-1}):
  - Higgs Mass: merged result: 28 MeV
  - Cross-Section: merged result: 2.0%

- The Higgs Recoil Mass measurement is very sensitive to accelerator effects:
  - Beam Energy Spread: Increases the width of recoil mass peak, thus reduce the accuracy of the measurement.
  - Beamstrahlung: Largely reduces the effective statistics on the recoil mass peak

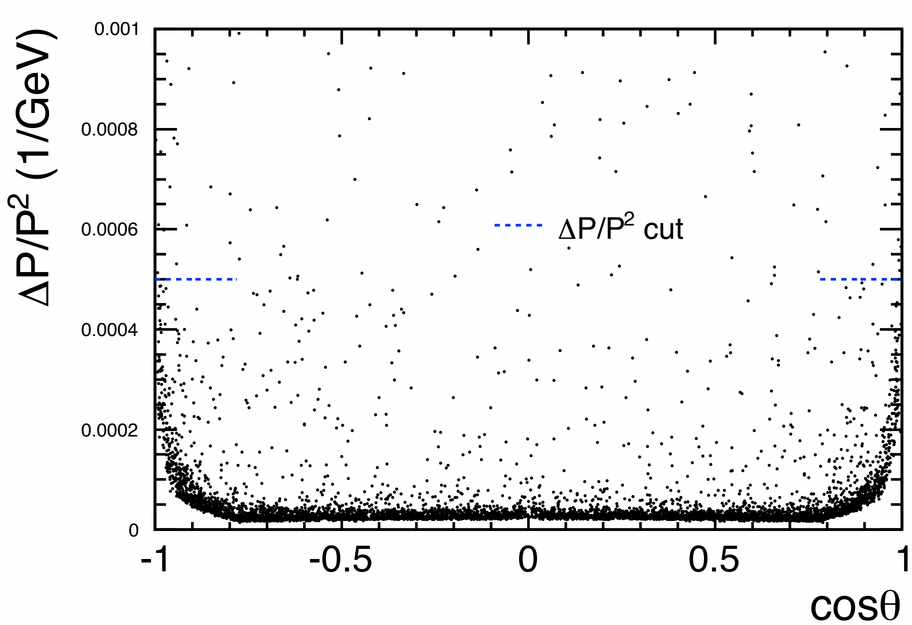


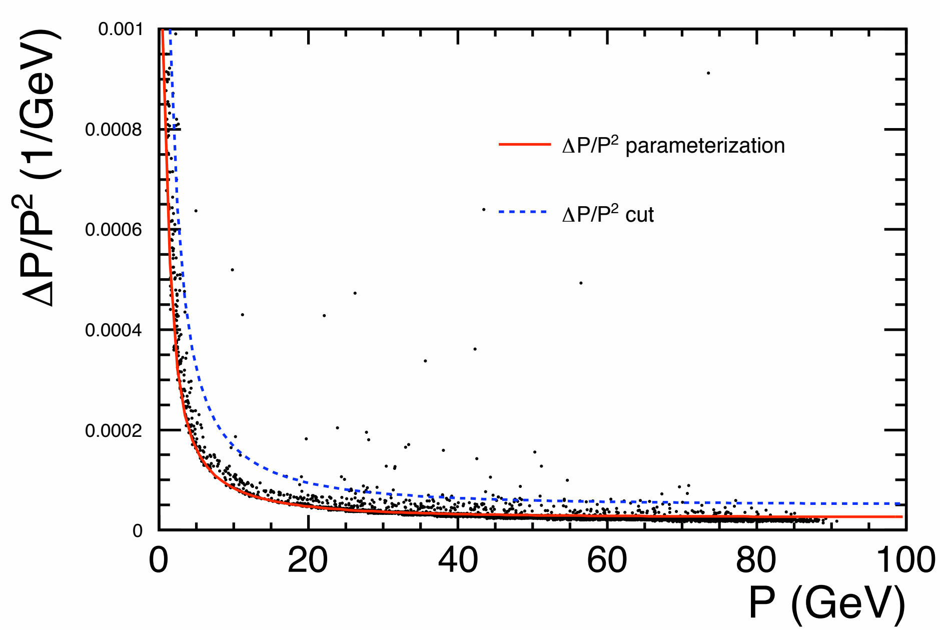
Comparisons of recoil mass spectra in generator level and after full simulation, with 0.28%/0.18% beam energy spread for each beam, (of μμX)

Thanks!

Backup Slides

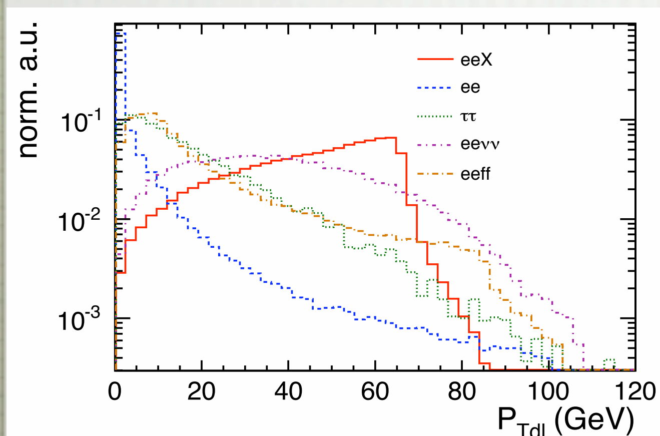
Track Selection, eeX-channel

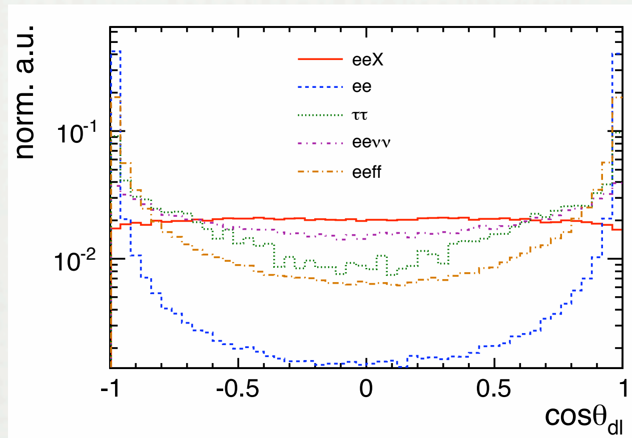


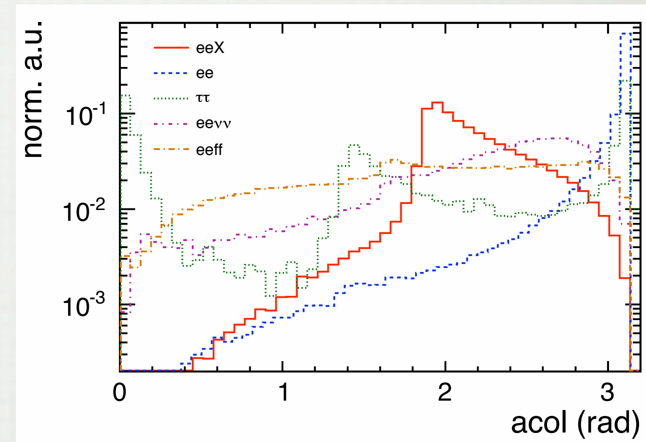


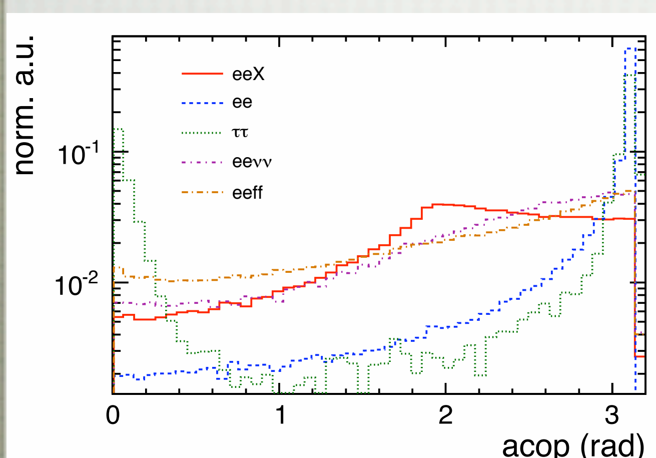
- Same track selection cuts applied on eeX-channel, as show in figures above
- However, due to Bremsstrahlung:
  - larger number of bad reconstructed tracks than that of the μμX-channel
  - larger number of low energetic tracks than that of the μμX-channel

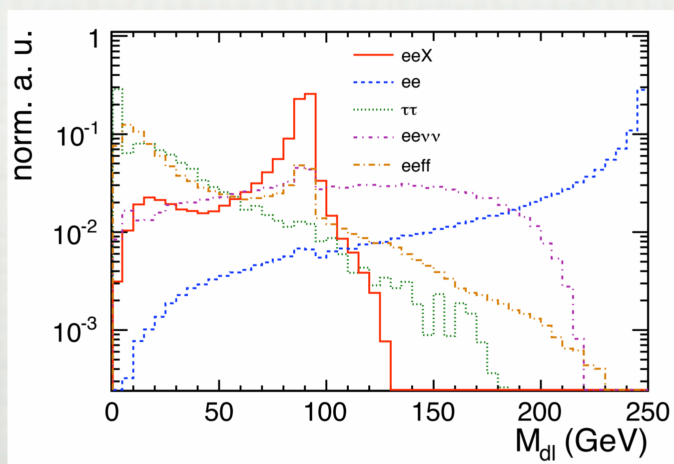
Distributions of Background Rejection Variables in eeX-channel

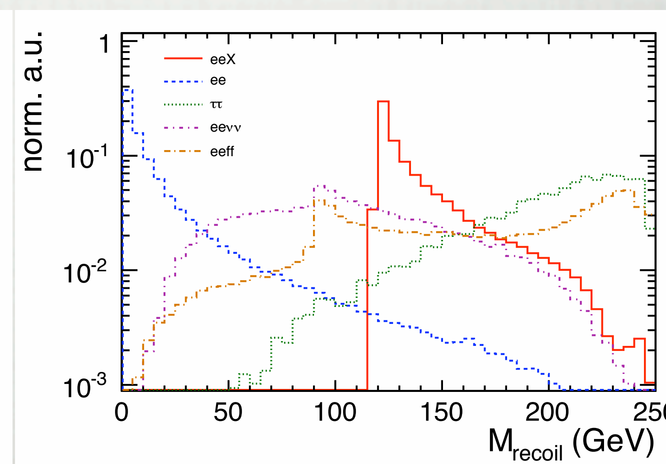




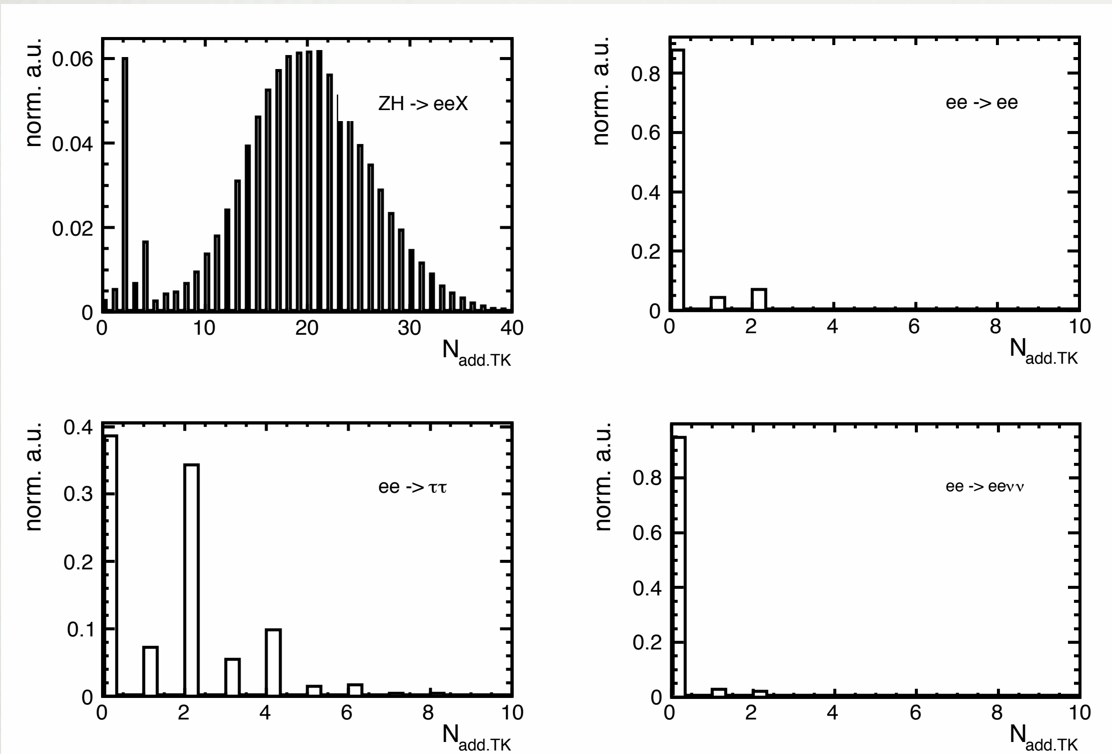


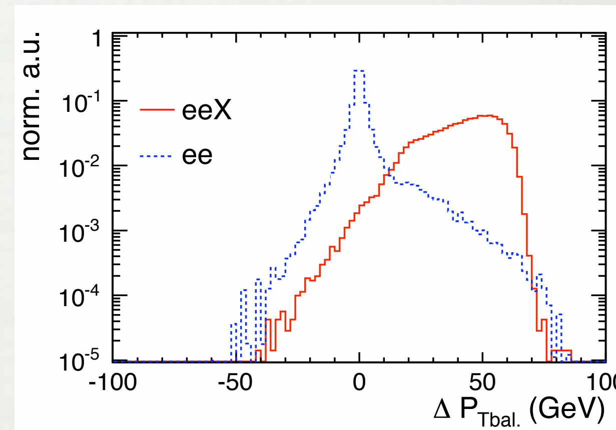


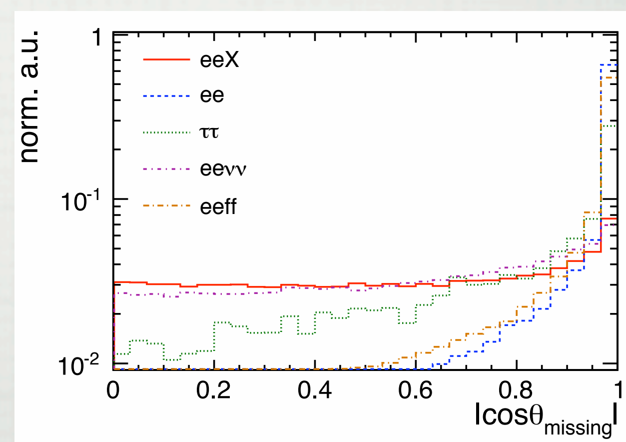


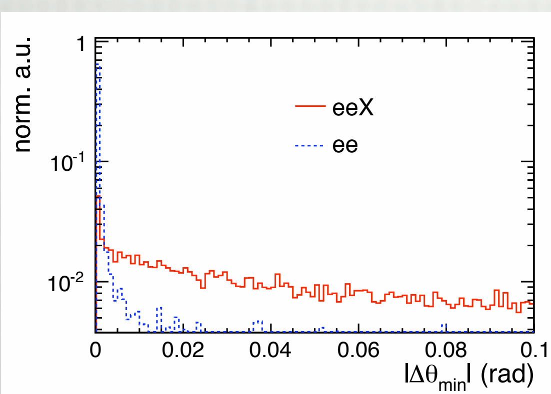


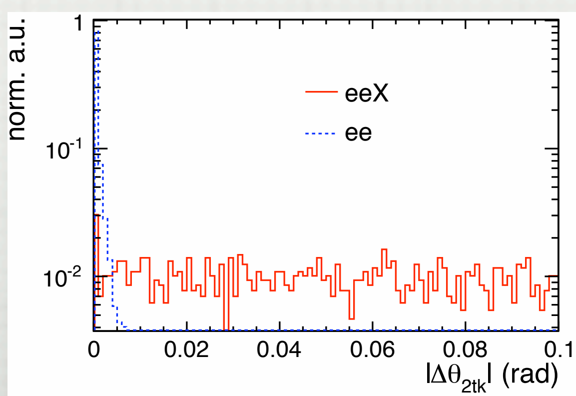
Distributions of Background Rejection Variables in eeX-channel



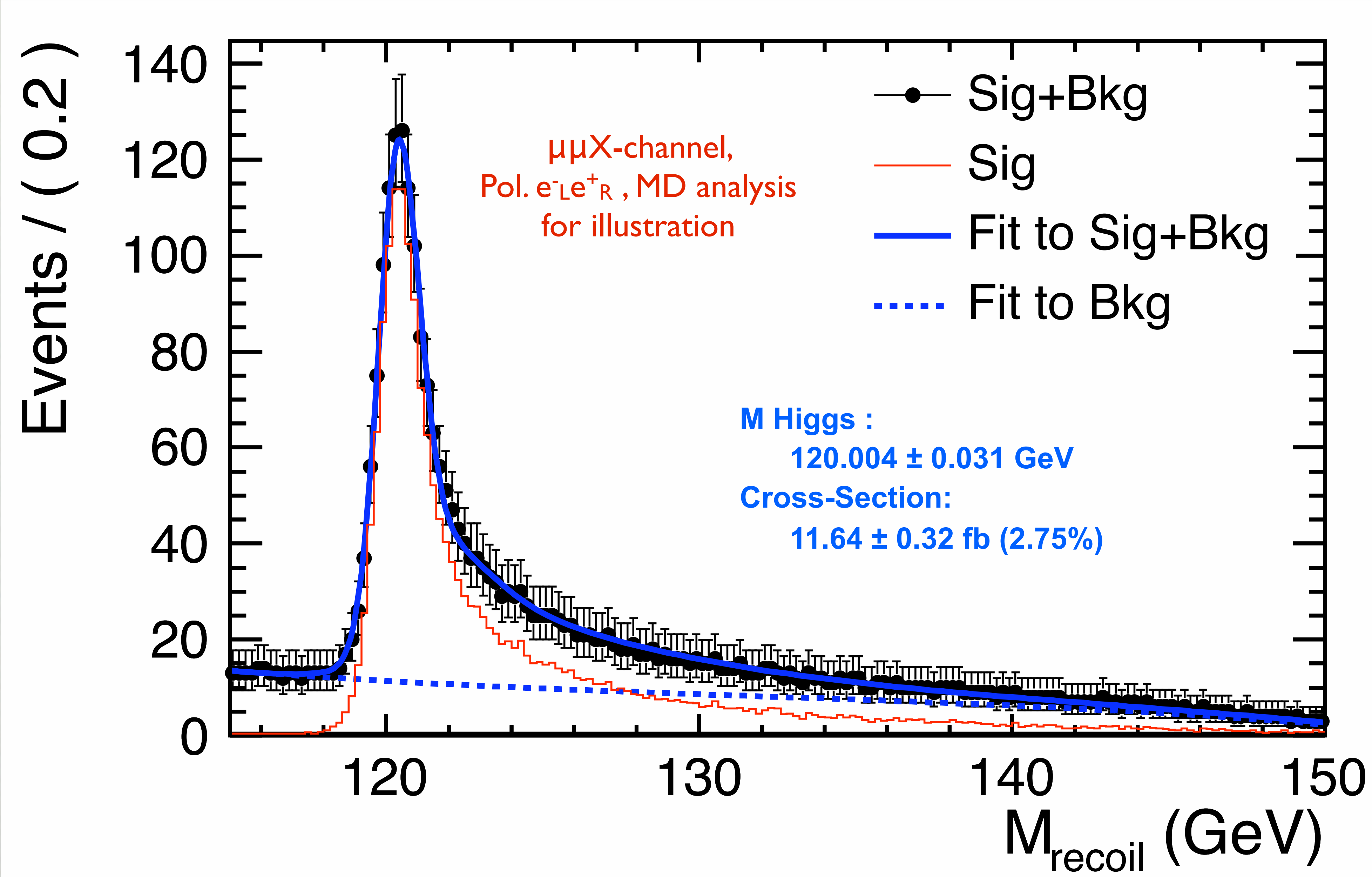




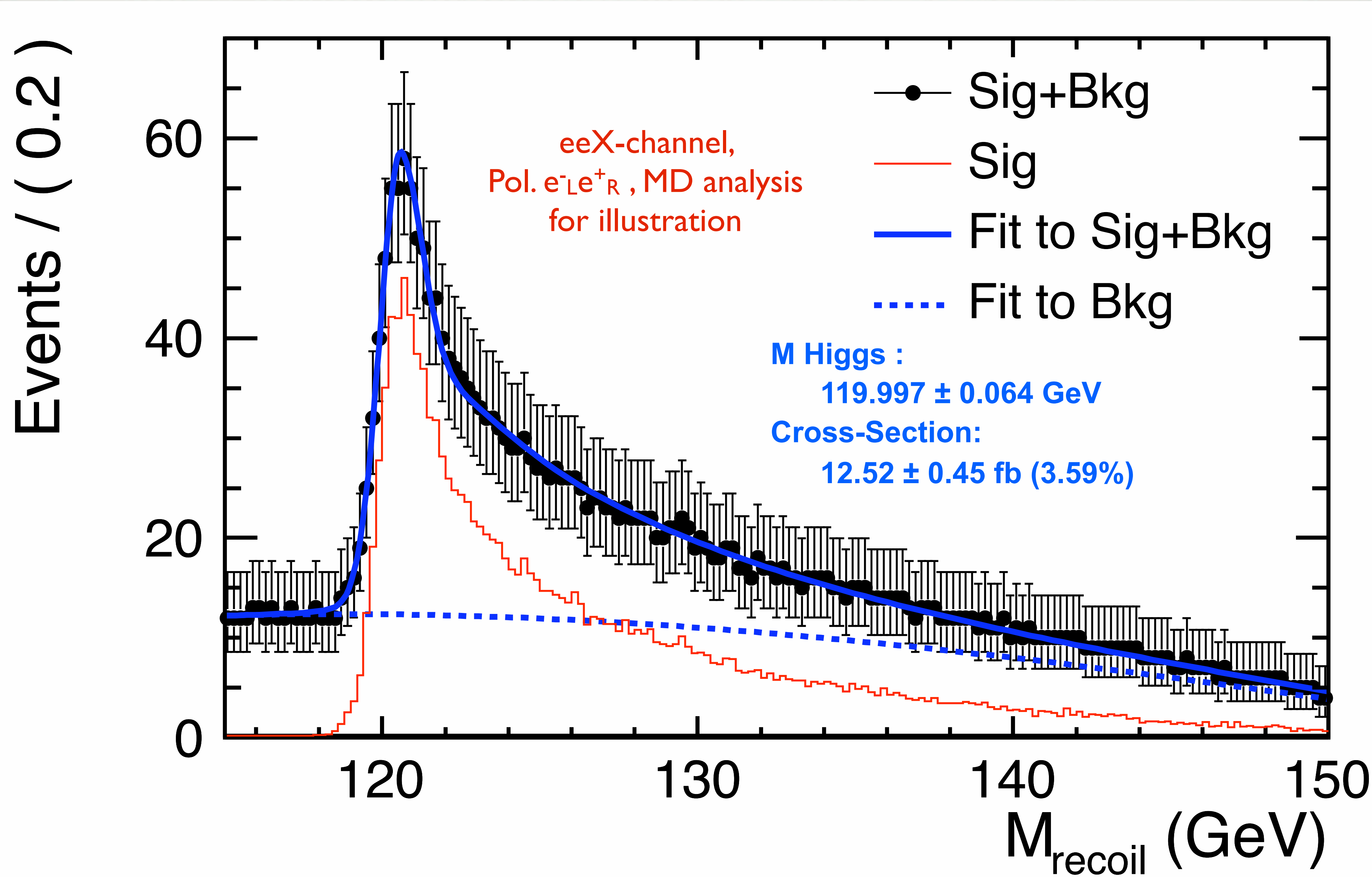




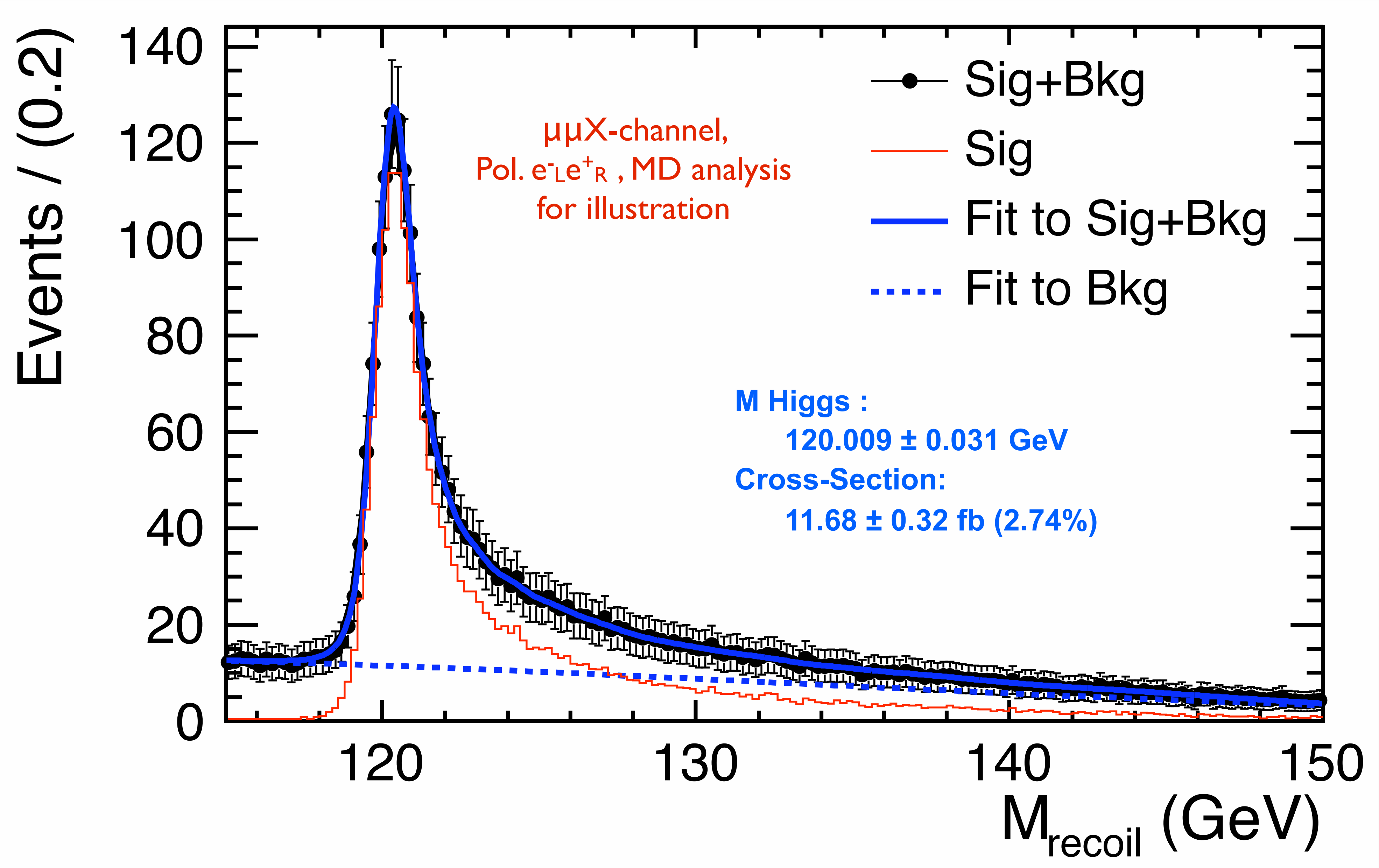
Fit: (GPET Function)



Fit: (GPET Function)



Fit: (Kernel Estimation)



Fit: (Kernel Estimation)