Recoil Mass Study using $Z \rightarrow l^+l^-$ at 250 GeV at ILC

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Target

One of the advantages of the ILC is model independent(MI) analysis of Higgs properties by recoil method.

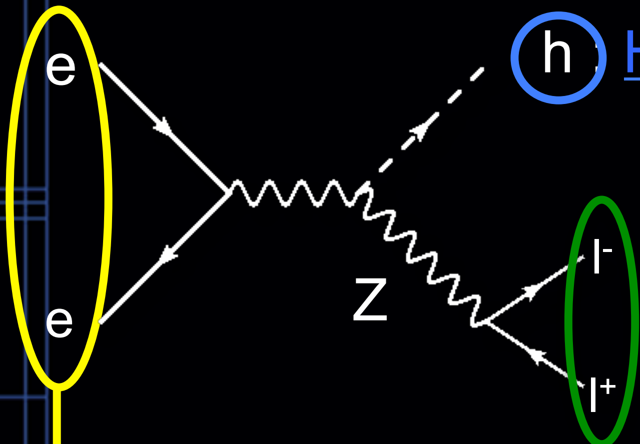
- How precise can we measure Higgs mass and cross section by this method? The considered situation is …

Higgs mass	Center of Mass Energy	Integrated Luminosity	Spin Polarization	Detector Simulation
125 [GeV]	250 [GeV]	250 fb^{-1}	$P(e^-, e^+)$ =(-0.8, +0.3)	ILD_01_v05 (DBD ver.)

- Using only Zh -> llh (l=μ, or e) signal event.

What's the Recoil Method?

- ILC is a **lepton collider**
  = We already know initial state 4 momentum



Higgs (any decay mode is allowed)

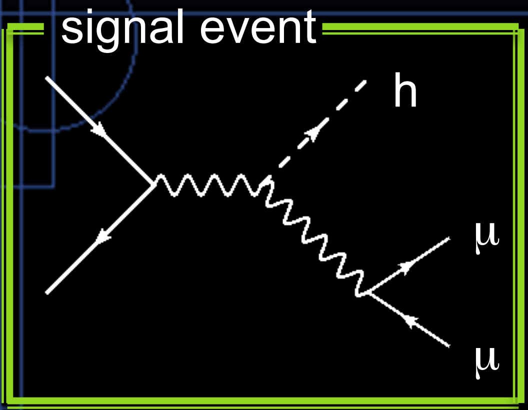
$p_h = p_{e-} + p_{e+} - p_Z$

✧ We can calculate the 4momentum of Higgs.

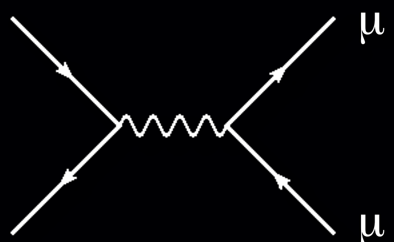
Aim for Higgs mass distribution

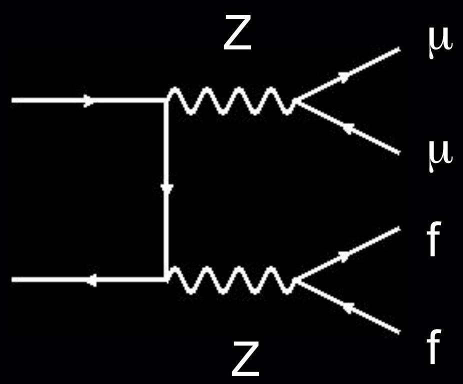
✗ Directly	It depends on the model of Higgs decay
Recoil method	We can measure Higgs model independently

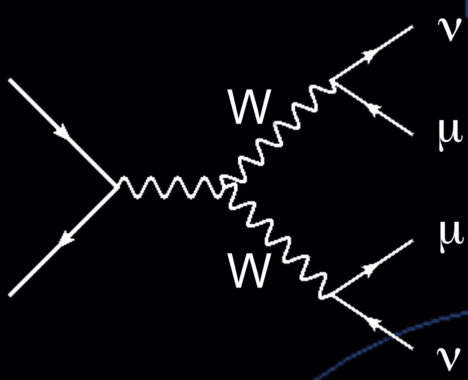
Signal and Background Events



- These are μμh channel signal & BGs.
- For eeh channel study, character of “μ” is altered to “e”.



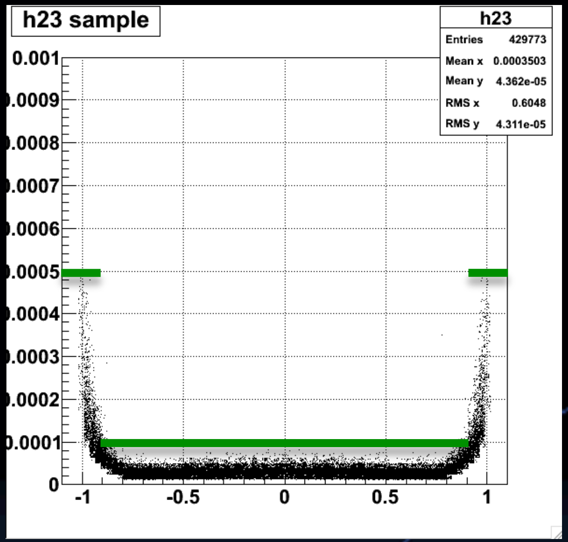




- Dominant Background is “μμ”, “μμνν”, “μμff” events, and other BG is rejected significantly.
- “ f ” means fermion except neutrino.

Lepton Selection

- Muon (and electron) selection
  - Momentum p > 15 [GeV]
  - Small (Large) energy deposited in caloriemeters
    - $E_{ecal} / E_{total} < 0.5$ (> 0.6)
    - $E_{total} / p_{track} < 0.3$ (> 0.9)
- Good track selection
  - Track with small error (different selections between polar angle of tracks, barrel or end cap)
    $dp / p^2 < 2.5 \times 10^{-5} \oplus 8 \times 10^{-4} / p$ (for $\cos\theta < 0.78$)
    $dp / p^2 < 5 \times 10^{-4}$ (for $\cos\theta > 0.78$)

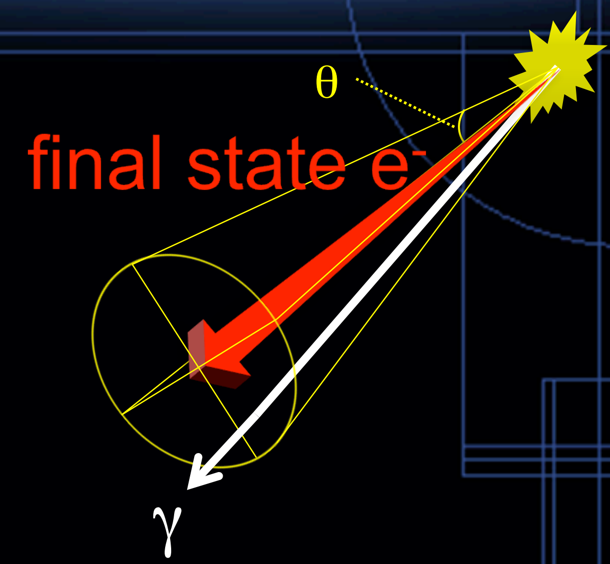


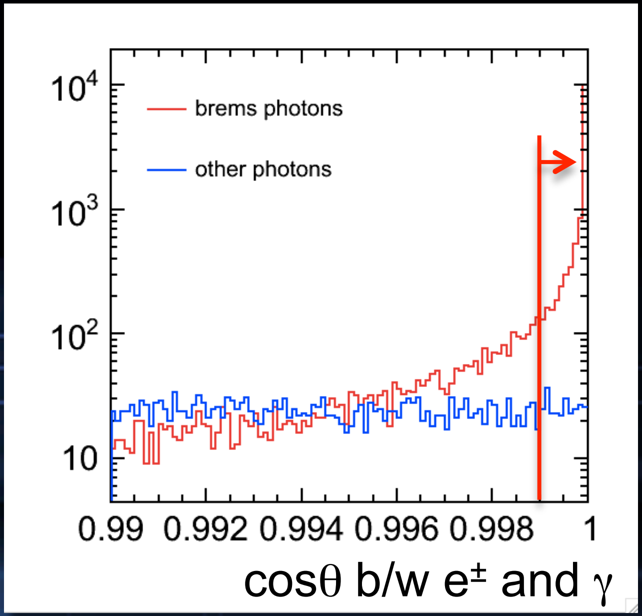
dp / p^2

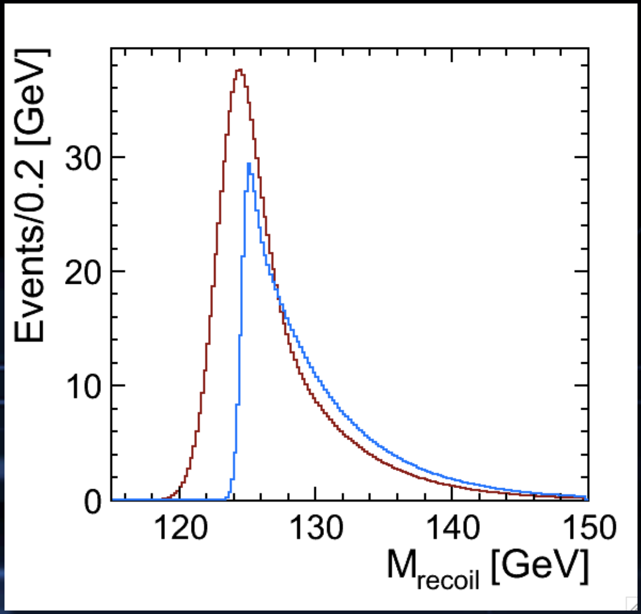
- Impact parameter (only for muon)
  - To suppress muons from tau decays which tend to have large impact parameters.
    $D_0 / dD_0 < 5$

Bremsstrahlung Recovery

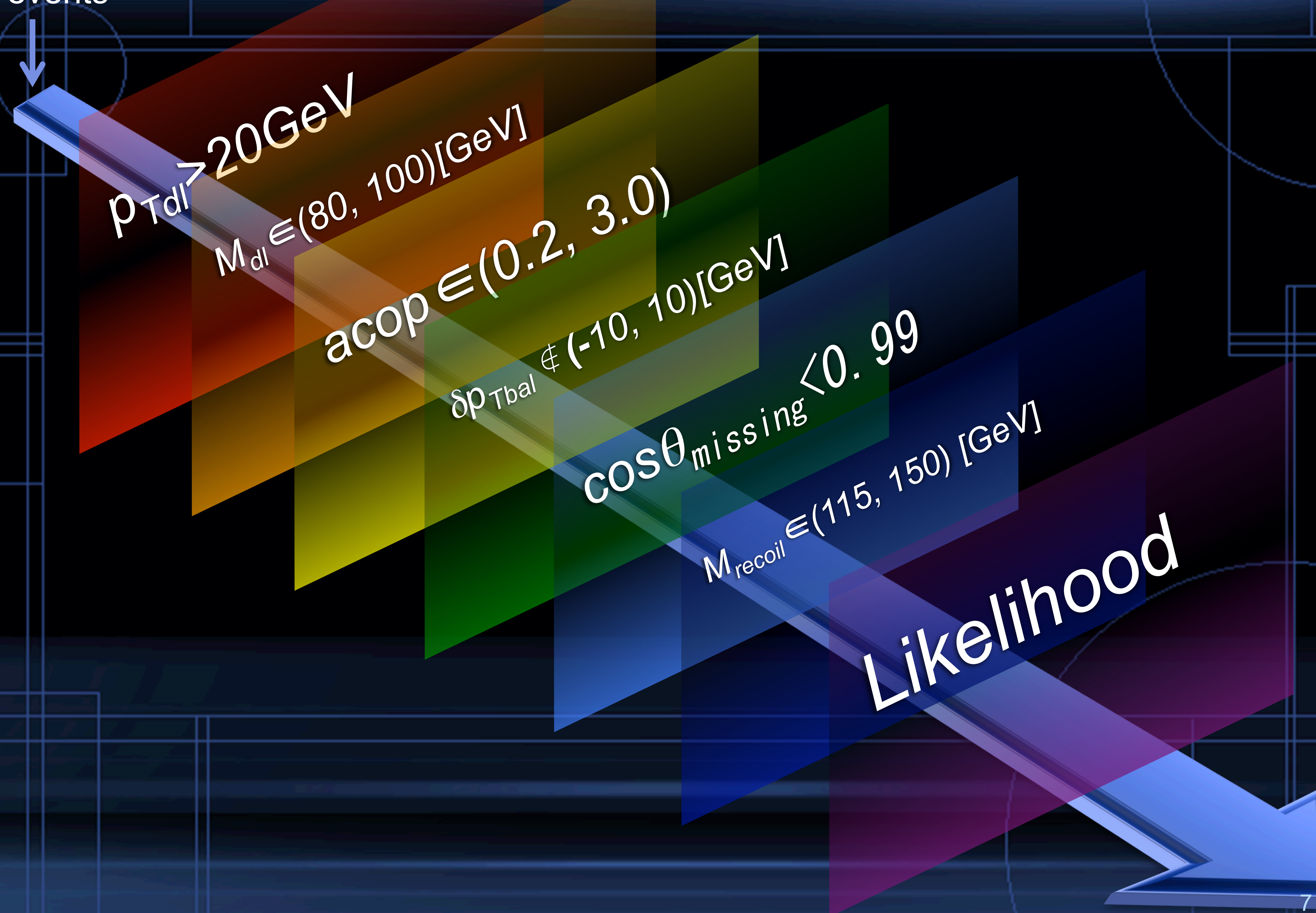
- Only for eeh channel cross section measurements, the photon's momentum around final state electron ($\cos\theta > 0.999$) is added to the electron.
- This process contributes to the distribution of recoil mass significantly.
- For mass analysis, it is effective not to perform the recovery.







Background Rejection



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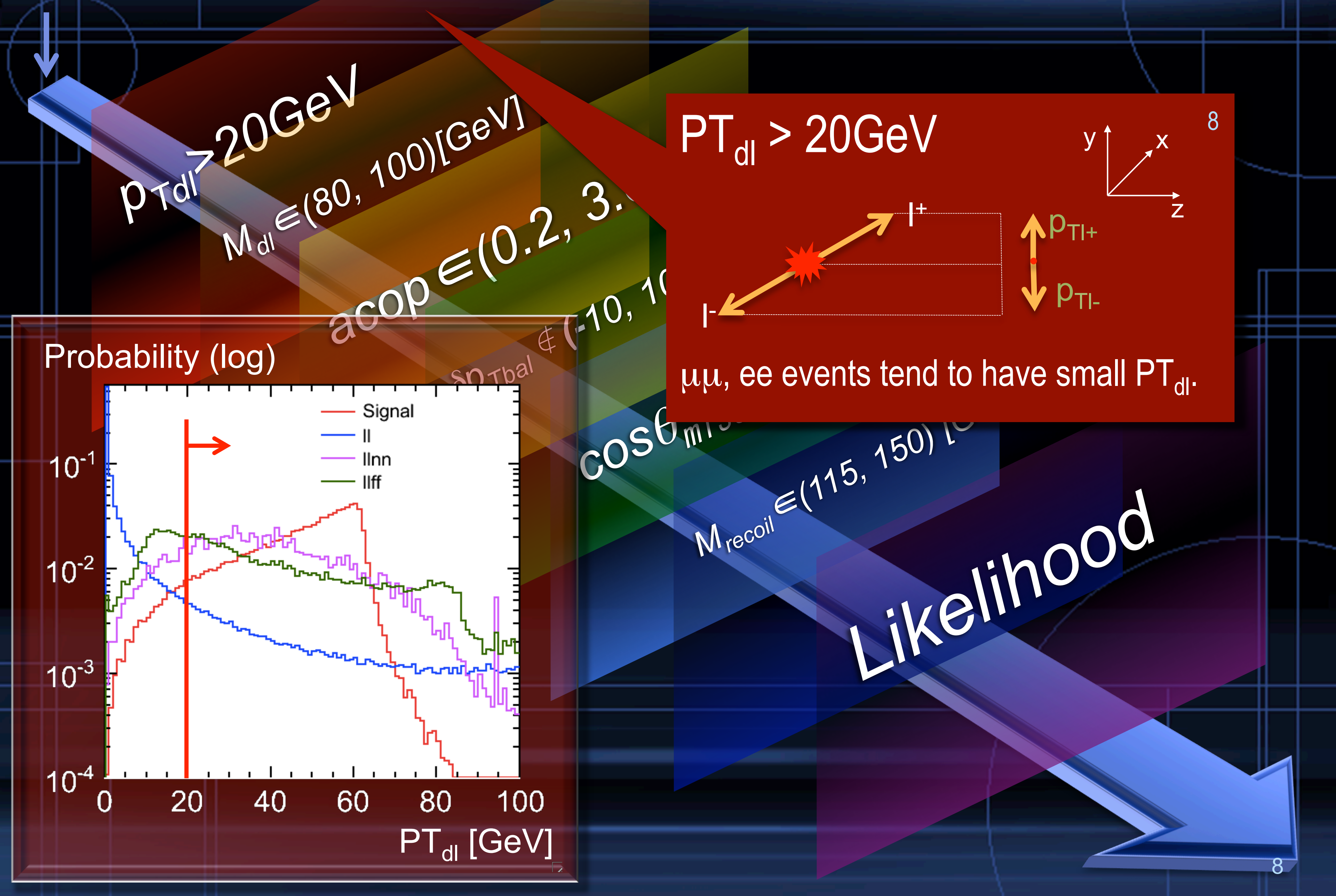

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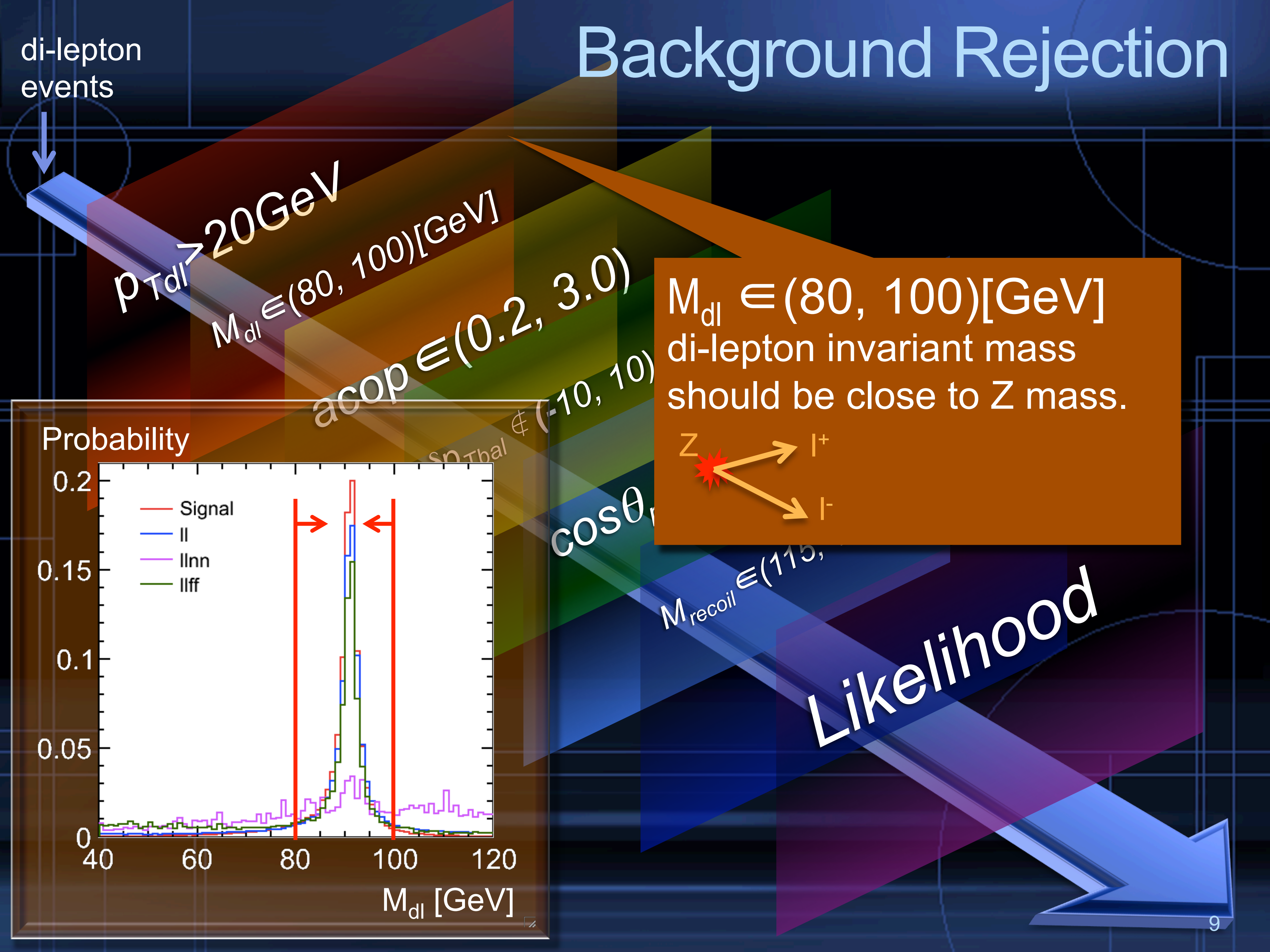

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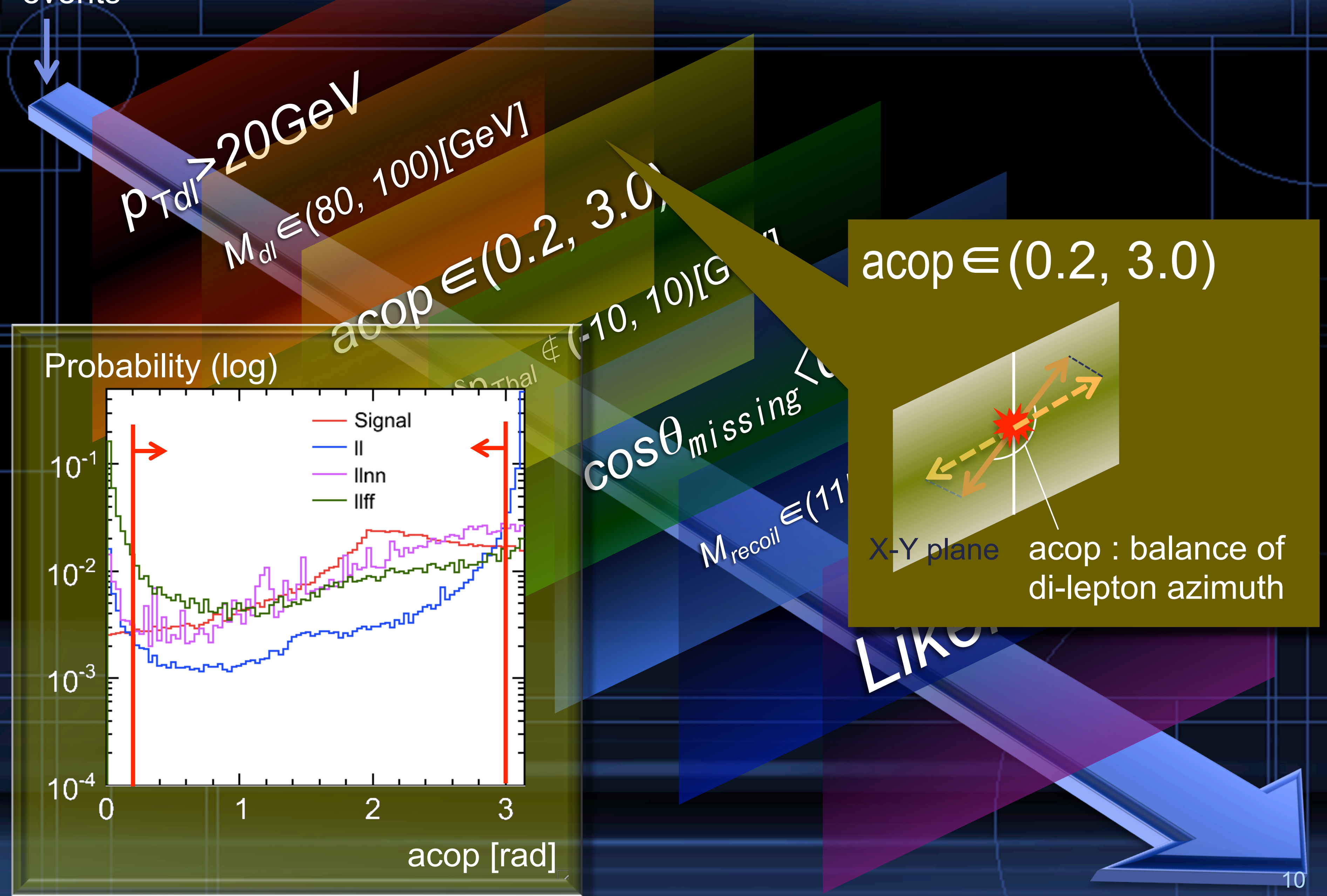
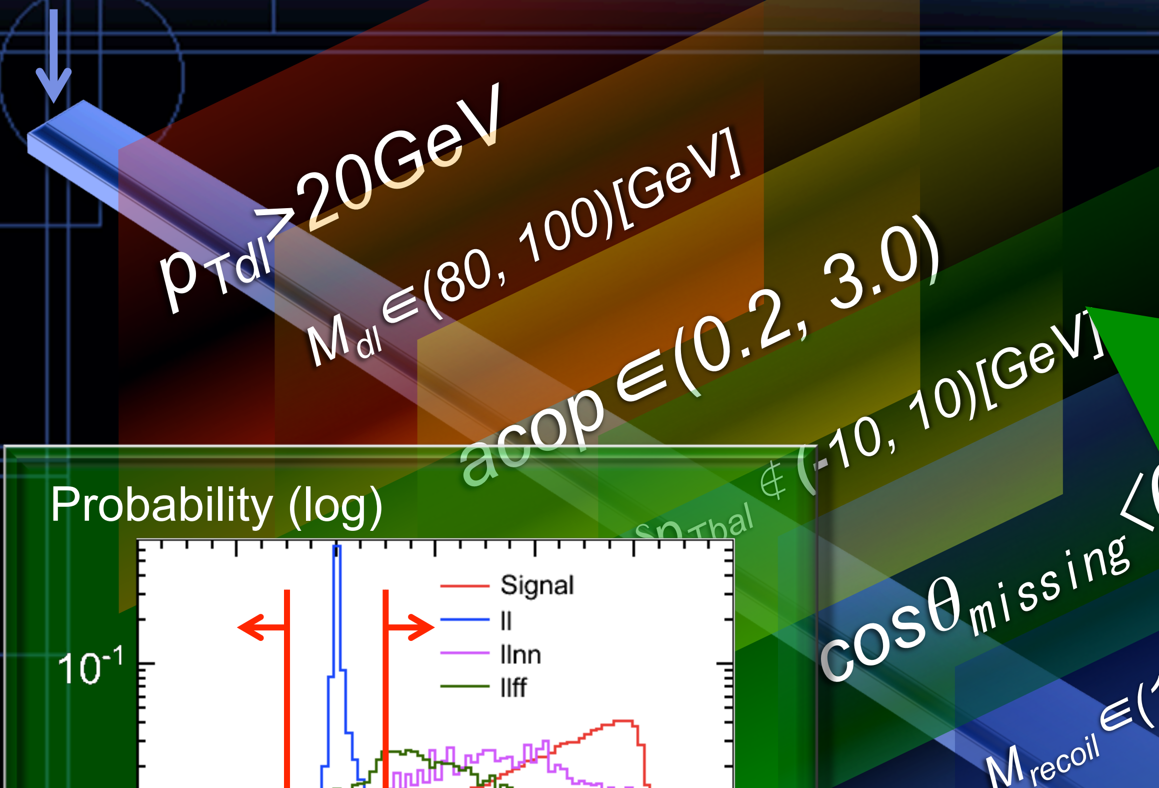
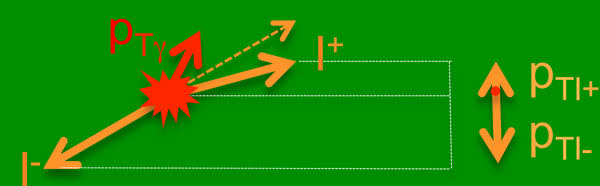


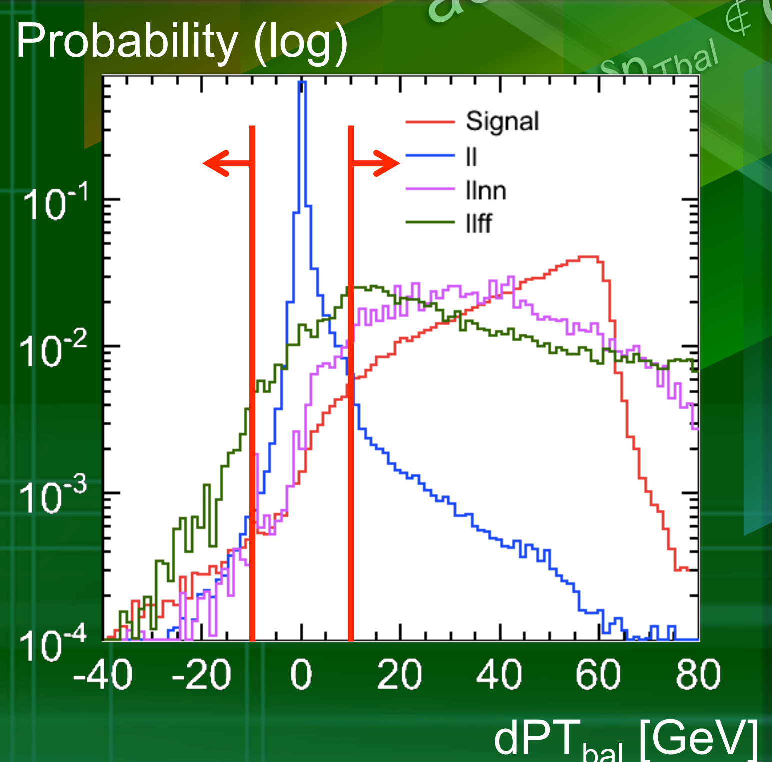
Background Rejection



$\delta PT_{bal} \notin (-10, 10)$[GeV]

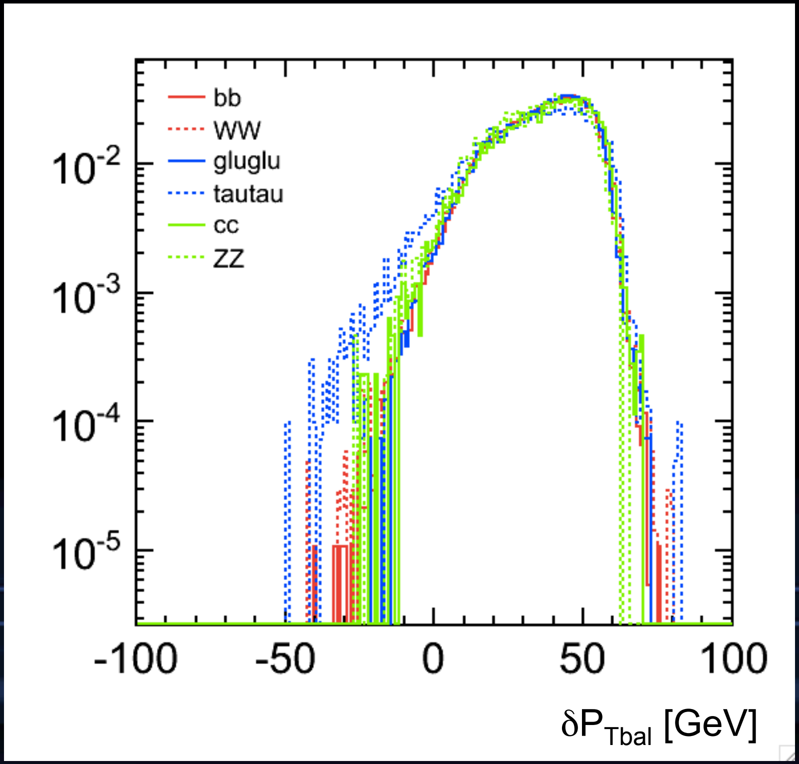


δP_{Tbal} : balance between PT_{dl} and PT of high energy photon (ISR).



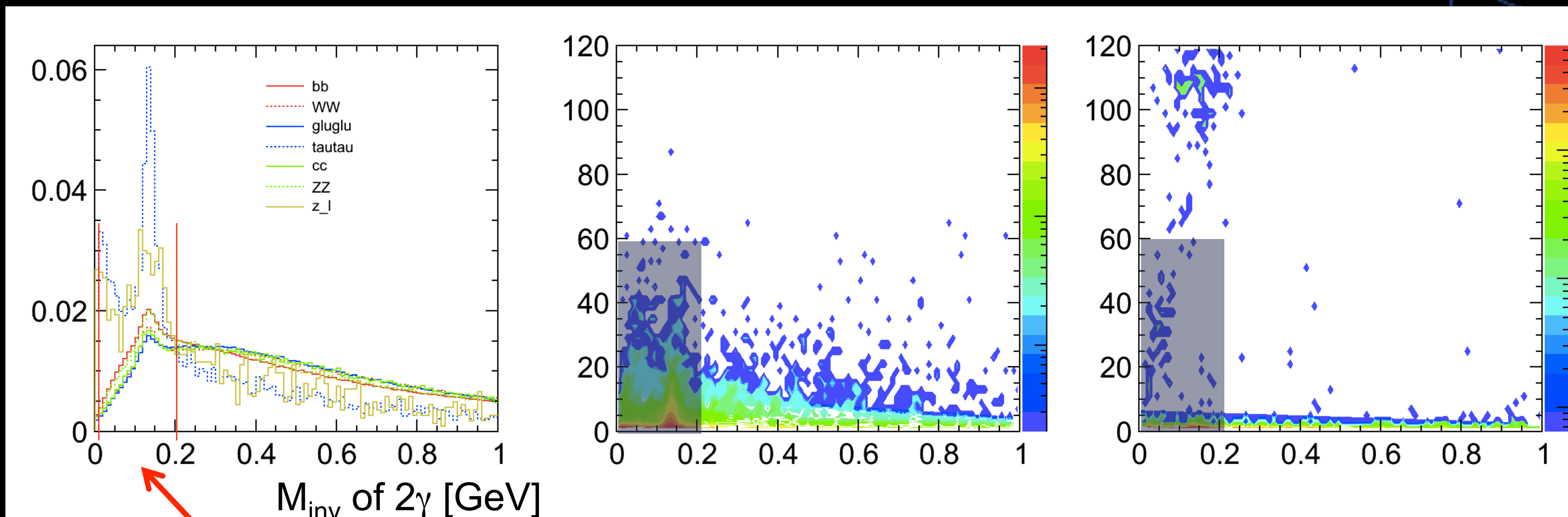
Bias Suppression (for δP_{Tbal})

- In δP_{Tbal} selection, we look at other particles (photon) besides di-lepton :
  $\delta P_{Tbal} \equiv PT_{dl} - PT_{\gamma}$
- So there is bias for some Higgs decay mode ($h \rightarrow \tau\tau$ mode).



Bias Suppression (for δP_{Tbal})

- We can suppress this bias using Energy of photon and invariant mass of each photon pair.

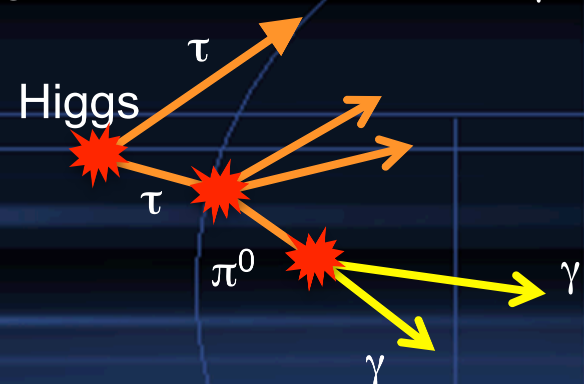


In h→ττ, there is a peak at $m_{2\gamma} \sim m_\pi$

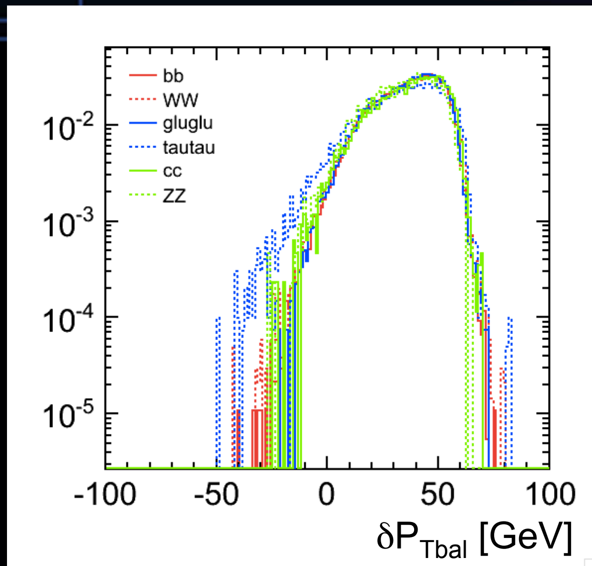
h->ττ signal

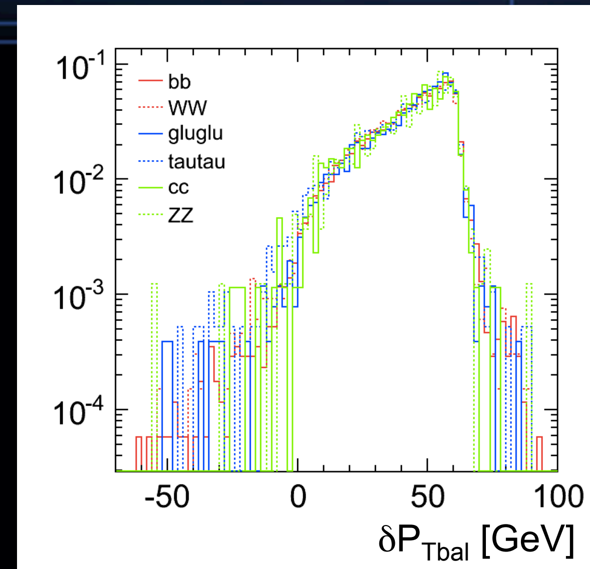
llγ BG

condition of used γ
$m_{2\gamma}$ > 0.2 [GeV]
or E_γ > 60 [GeV]



Bias Suppression (for δP_{Tbal})





	efficiency of δPT_{bal} cut			
	bb	ττ	cc	z_l (BG)
Simple calc.	99.4%	95.3%	99.0%	14.5%
My calc.	99.8%	97.8%	99.6%	22.2%

- In new calculation of δP_{Tbal}, bias will decrease.

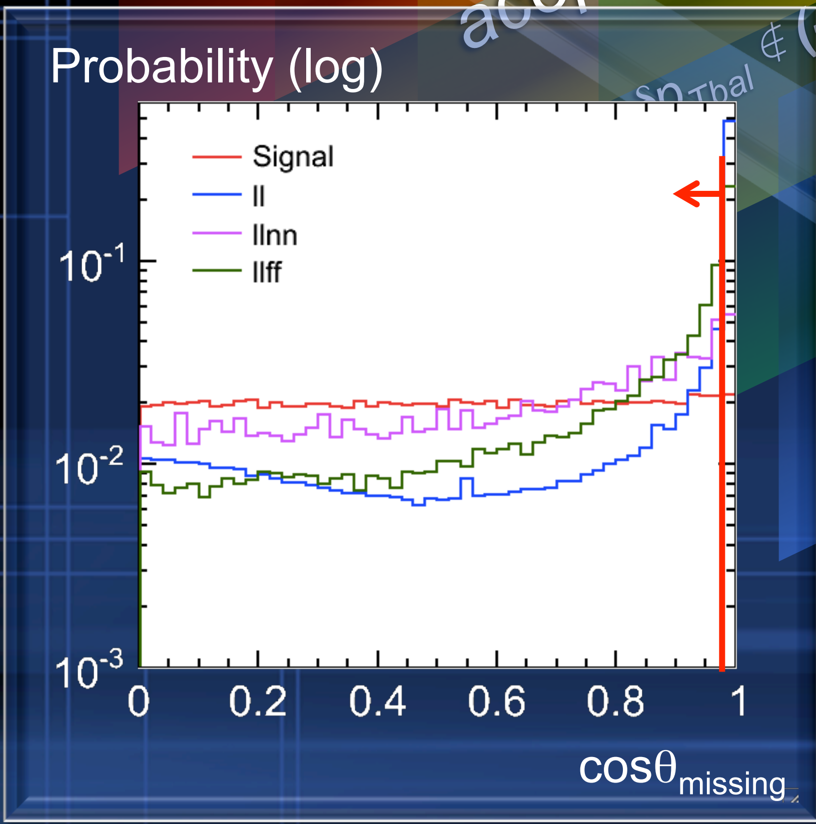
Background Rejection

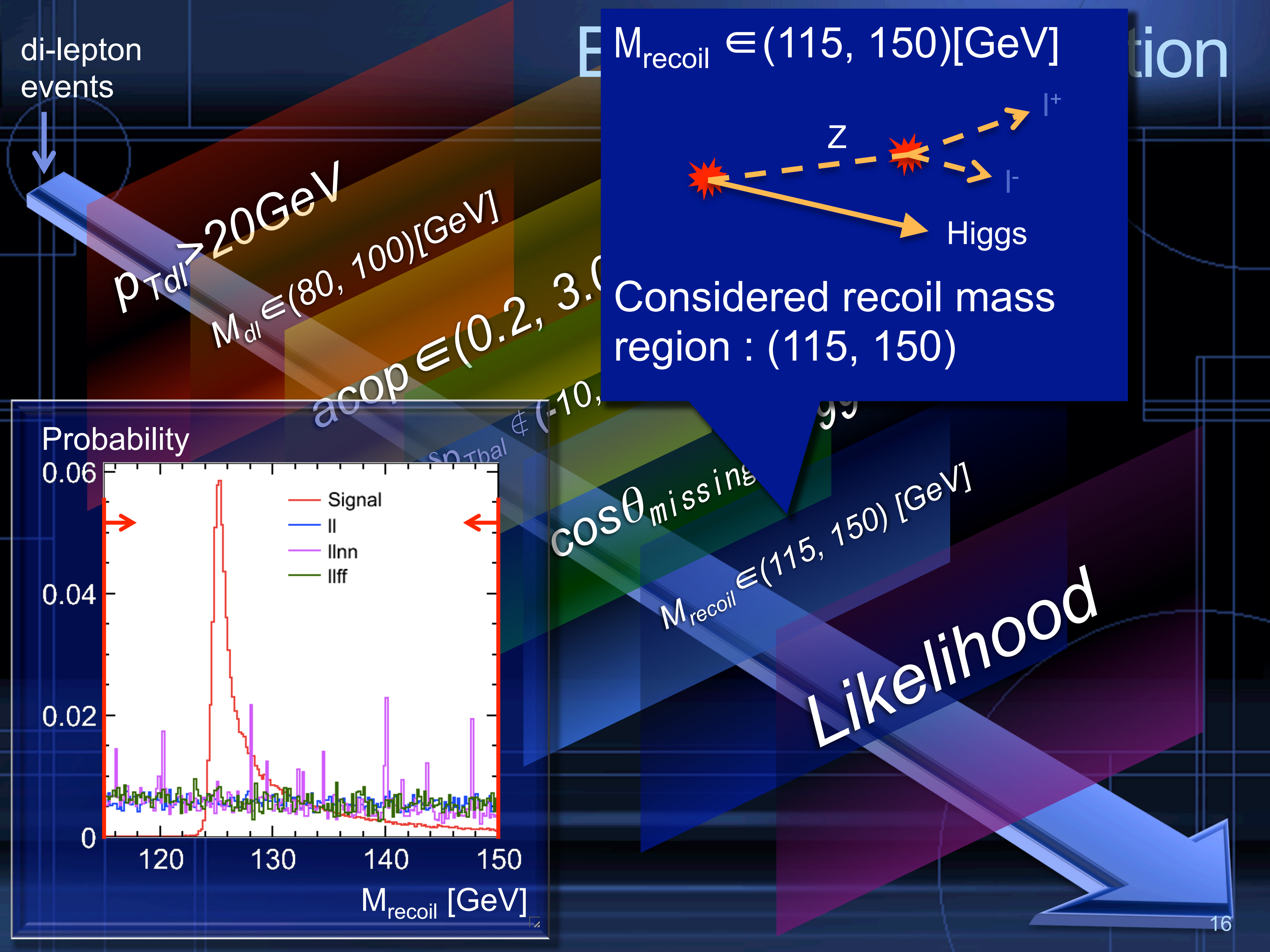
di-lepton events

- p_{Tdl}>20GeV
- $M_{dl}\in(80, 100)$[GeV]
- acop$\in(0.2, 3.0)$
- $p_{Tbal} \notin (-10, 10)$[GeV]
- $\cos\theta_{missing}$<0.99
- $M_{recoil}\in(115, 150)$ [GeV]
- Likelihood

$|\cos\theta_{missing}|<0.99$

Angle of undetected particles.
$\mu\mu$ or ee events tend to have ~1 value.





di-lepton
events
p_{Tdl}>20GeV
$M_{dl}\in(80, 100)$[GeV]
$M_{recoil}\in(115, 150)$ [GeV]
Likelihood
$M_{recoil}\in(115, 150)$[GeV]
Z
l^+
l^-
Higgs
Considered recoil mass
region : (115, 150)
Probability
0.06
0.04
0.02
0
Signal
ll
llnn
llff
120
130
140
150
M_{recoil} [GeV]

Background Rejection

di-lepton events

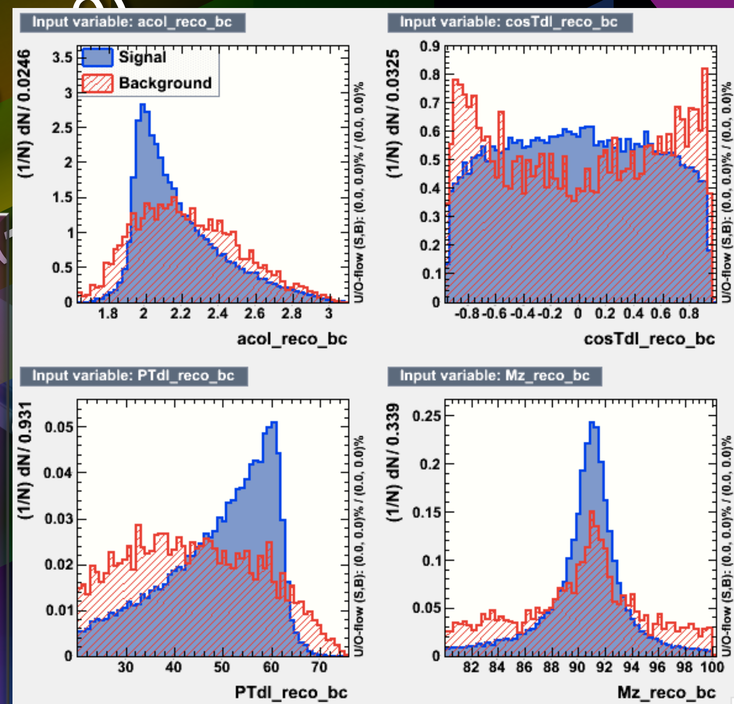
$p_{Tdl} > 20\text{GeV}$

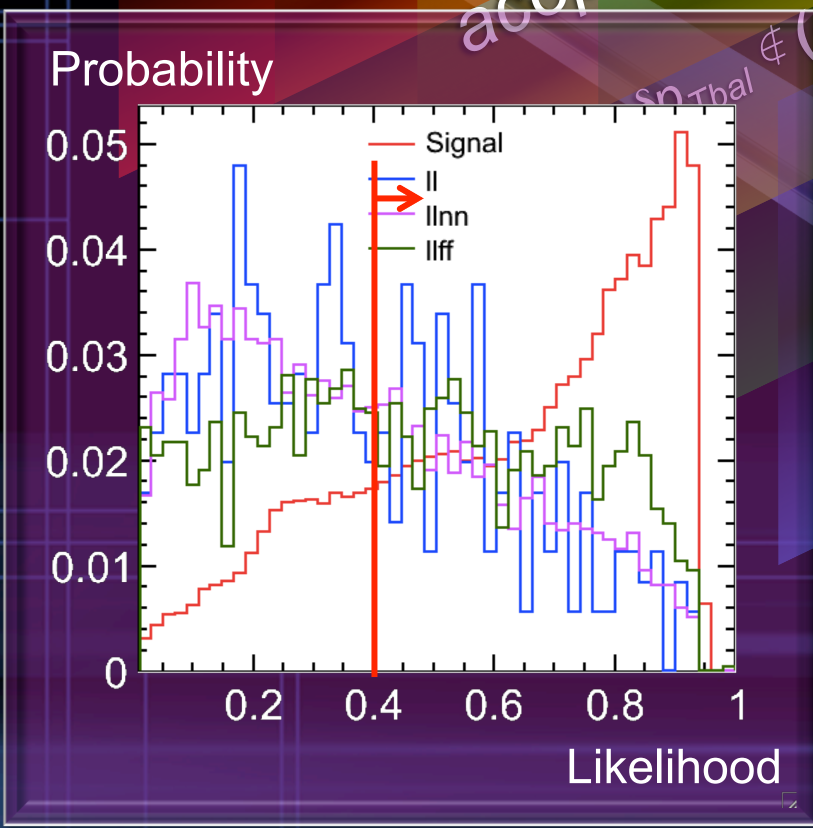
$M_{dl} \in (80, 100)[\text{GeV}]$

acop ∈(0.2,

Likelihood

Input parameters : “M_{dl}”, “$\cos\theta_{dl}$”, “PT_{dl}”, “acol”





Efficiency

- μμh channel   250 fb^{-1}

l = μ, τ	μμh	ll	llνν	llff
No Cut	2603	~5.5M	539514	788002
After	1436 (55.2%)	707 (0.01%)	2418 (0.45%)	2091 (0.27%)

- eeh channel

l = e, τ	eeh	ll	llνν	llff
No cut	2729	~11M	661637	854375
After	1062 (38.9%)	1774 (0.07%)	3039 (1.59%)	1483 (0.50%)

※ Other events will be rejected and will not affect results significantly.

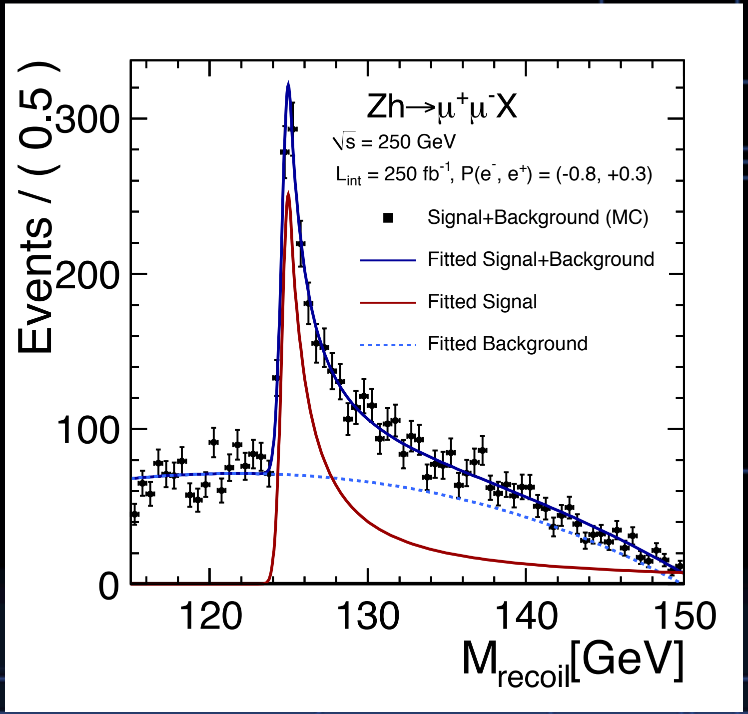
Fitting Method

- Signal yields and Higgs mass are extracted by fitting to recoil mass distributions.
- Fitting function
  - signal → Gaussian Peak with Exponential Tail :

$$
\begin{cases}
N e^{-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2} & \left(\frac{x-\bar{x}}{\sigma} < k\right) \\
N\left\{ b e^{-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2} + (1-b) e^{-k\frac{x-\bar{x}}{\sigma}} e^{\frac{b^2}{2}} \right\} & \left(\frac{x-\bar{x}}{\sigma} \geq k\right)
\end{cases}
$$

  - BG → 3rd order polynomial :

$$1 + C_1 x + C_2 x^2 + C_3 x^3$$



Fitting Method

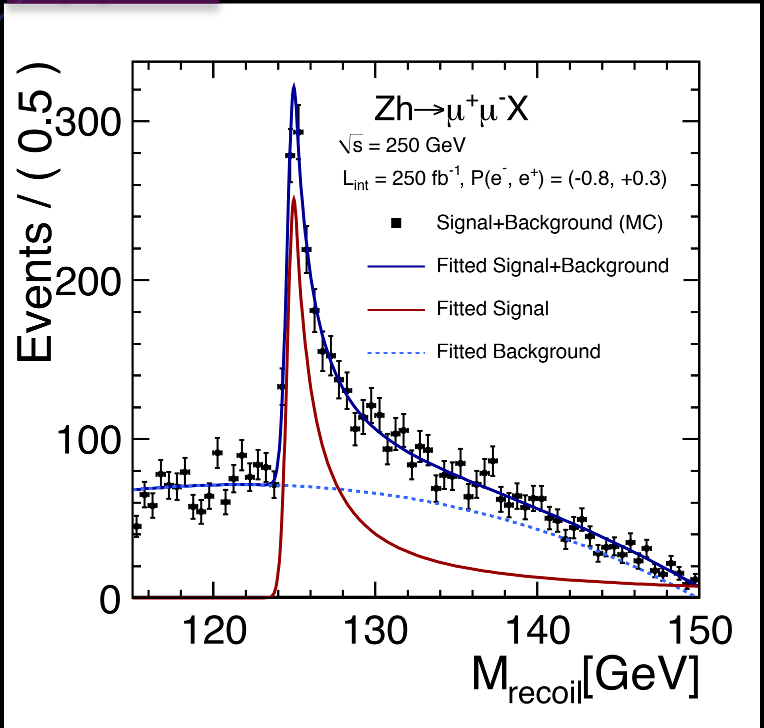
- Procedure
  - Fit recoil mass distribution using GPET + 3rd order polynomial PDF.
  - Make Poisson random events around this PDF (toy-MC), and fit this toy-MC using same function fixing some parameters (namely, fix function shape).
  - Estimate statistical error of cross section and mass from signal yields and mean parameters.

	GPET (signal)				3rd order poly. (BG)			Yields	
	mean	width	k	b	p1	p2	p3	Y_{sig}	Y_{BG}
First Fit	float	float	float	float	float	float	float	float	float
toy-MC	float	fix	fix	fix	fix	fix	fix	float	float

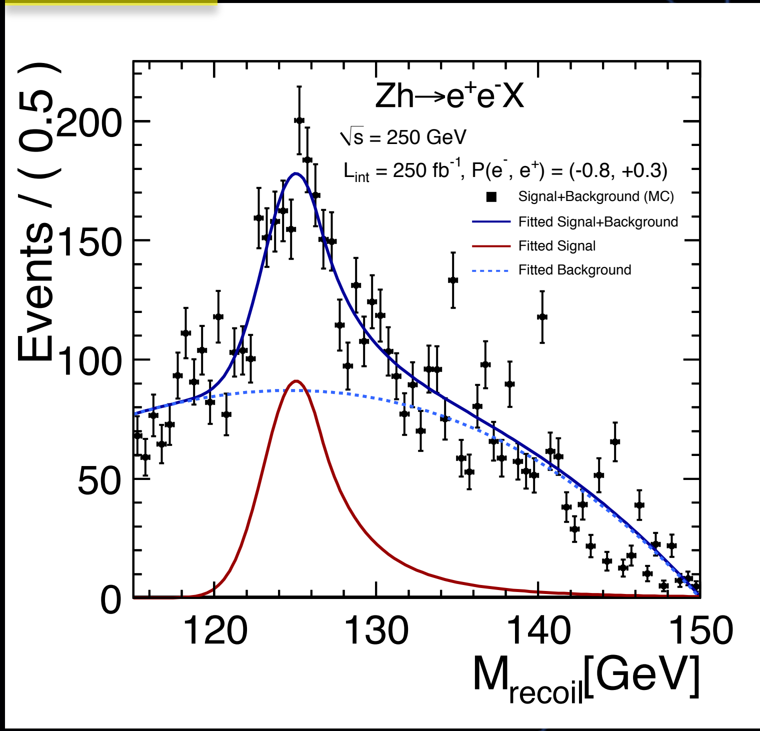
※ k : boundary, b : junction

Fitting Results and Error Estimation

μμh



eeh



	μμh	eeh	combined
cross section	4.0%	5.9%	3.3%
mass	34 [MeV]	158 [MeV]	33 [MeV]

Bias of Signal Selection

H decay mode	$\mu\mu h$ efficiency	eeh efficiency
bb	55.48 ± 0.16	39.14 ± 0.63
WW	55.57 ± 0.21	38.67 ± 0.99
gluglu	55.25 ± 0.25	38.82 ± 1.63
$\tau\tau$	54.66 ± 0.26	37.85 ± 1.91
cc	55.77 ± 0.28	39.43 ± 2.74
ZZ	55.65 ± 0.28	39.39 ± 3.13

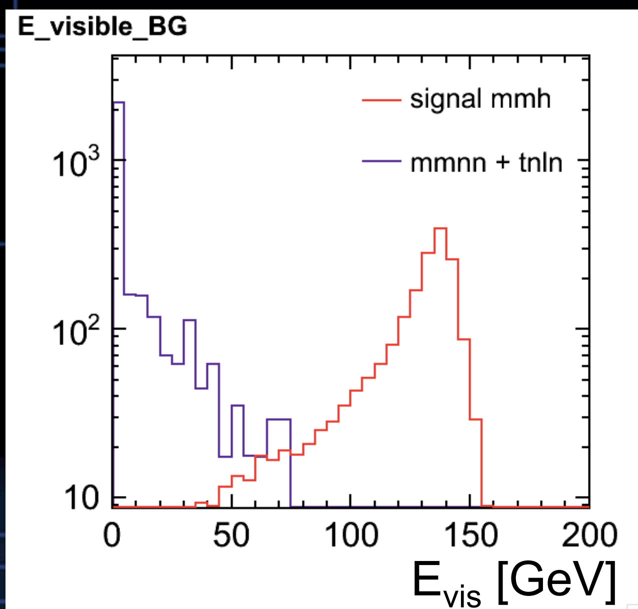
- $h \to \tau\tau$ mode will be rejected more because of δPT_{bal} cut.
- However, difference from other major modes such as bb or WW is ~1%, which is smaller than statistical error (3.3%) of measurement of cross section.

Additional Analysis

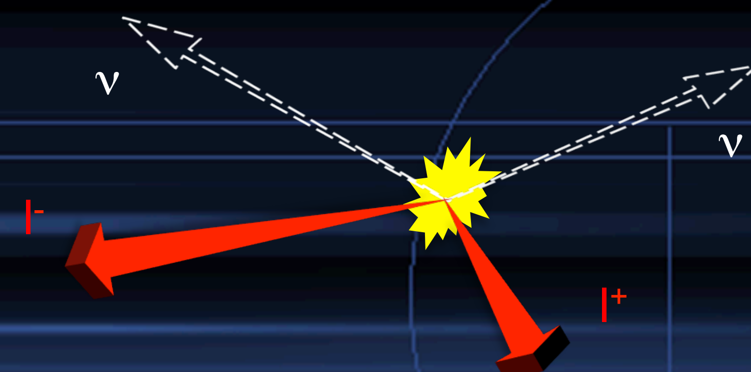
Semi Model-Independent Analysis

l = μ, τ	μμh	[illegible]	[illegible]	[illegible]	llνν		llff	
After	1436	[illegible]	[illegible]	[illegible]	2418	0.45%	2091	0.27%
l = e, τ	eeh	[illegible]	[illegible]		llνν		llff	
After	1062	38.92%	1774	0.07%	3039	1.59%	1483	0.50%

There seems to be large number of remaining llνν BG.



- Since contribution from Higgs invisible decays can be calibrated with data, visible energy selection is effective for reducing these BG.
- $E_{vis} := E_{PFOs} - E_{di\text{-}lepton} > 5$ [GeV]
- Loose selection is applied to avoid bias in signal selection.



Results of Loose $E_{visible}$ Selection

- μμh channel

l = μ, τ	μμh	ll	llνν	llff
~ M_{recoil}	1853	1638	5687	3965
$E_{visible}$	1852	1638	1823	3965
f_L	1451	715	779	2139

- eeh channel

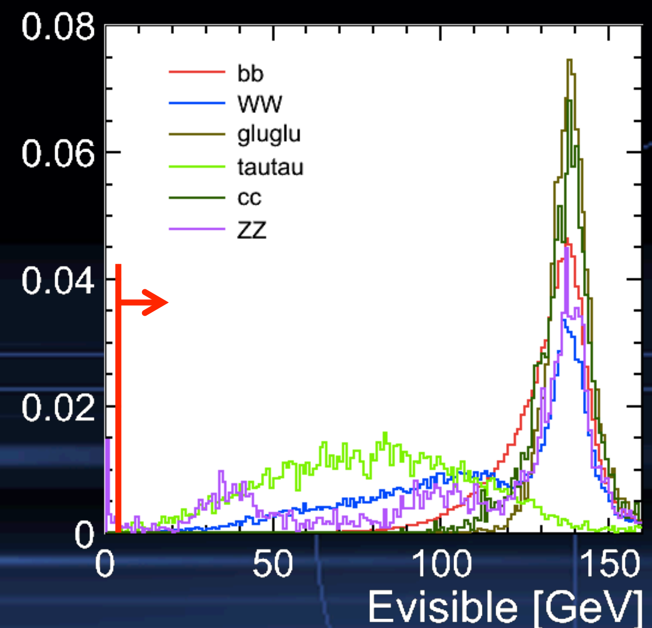
l = e, τ	eeh	ll	llνν	llff
~ M_{recoil}	1565	7298	10543	4232
$E_{visible}$	1564	7298	3712	4232
f_L	1061	1774	1000	1483

	μμh	eeh	combined
cross section	3.8%	5.6%	3.1%
mass	32 [MeV]	130 [MeV]	31 [MeV]

Efficiency of $E_{visible}$

H decay mode	$\mu\mu h$ (E_{vis} eff.)	After all cut	eeh (E_{vis} eff.)	After all cut
bb	100%	66.31%	98.68%	39.14%
WW	100%	66.00%	98.31%	38.67%
gluglu	100%	65.40%	98.67%	38.82%
$\tau\tau$	99.94%	65.66%	98.43%	37.82%
cc	100%	66.32%	98.25%	39.43%
ZZ	96.64%	63.98%	94.84%	37.90%

- Bias as expected from SM.



Summary

- The recoil mass technique is important feature at the ILC to measure Higgs mass and cross section of Zh event.
- The measurement errors are …

		Float BG yields of toy-MC fitting		
		μμh	eeh	combined
MI	cross section	4.0%	5.9%	3.3%
	mass [MeV]	34 [MeV]	158[MeV]	33 [MeV]
semi MI	cross section	3.8%	5.6%	3.1%
	mass [MeV]	32 [MeV]	130[MeV]	31 [MeV]

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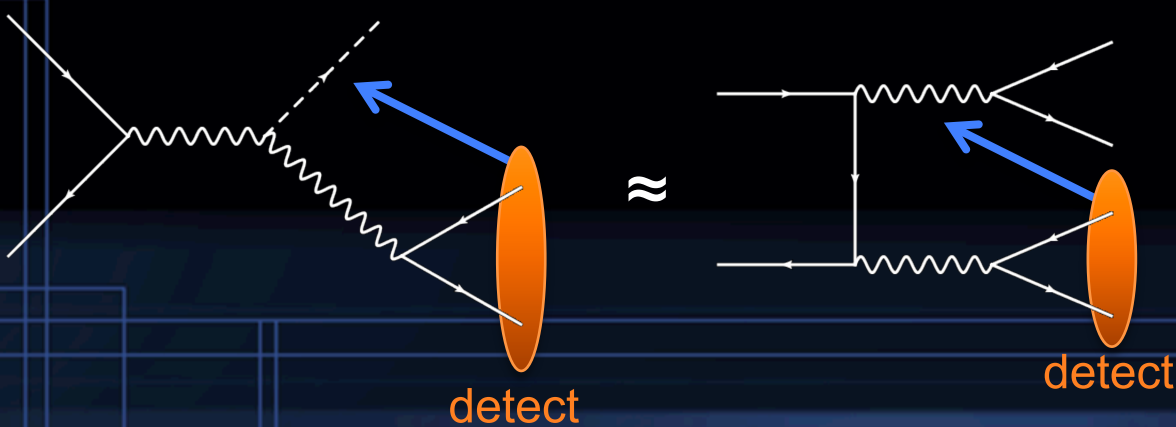
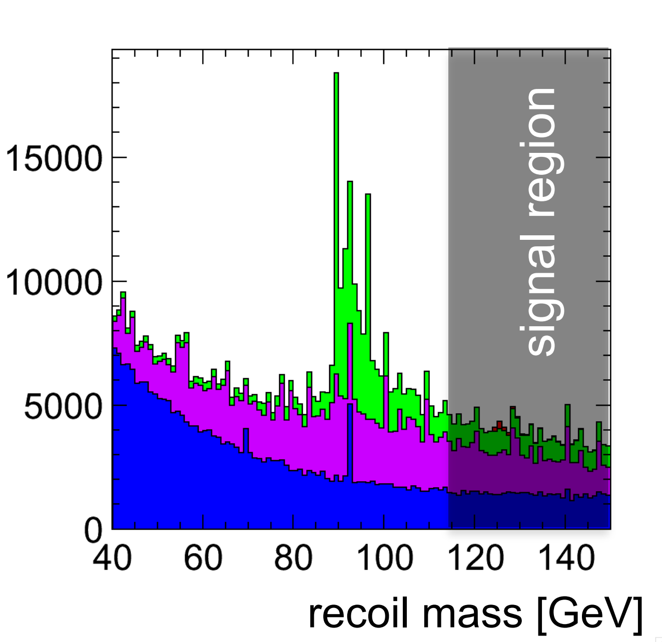
semi MI	cross section	3.8%	5.6%	3.1%
	mass [MeV]	32 [MeV]	130[MeV]	31 [MeV]

Preliminary

Next Plan

- If possible, we can estimate signal or BG shape :
  - BG estimation
    From sideband of some selection, such as M_{dl}.
    - This may be difficult because BG distribution will be changed by some selections.
  - signal estimation
    From Z-pole of ZZ BG distribution





… And fix some fitting parameters.