Searches for new exotic scalars at the ILC

Analysis of the scalar particle S decay channel into invisible final states

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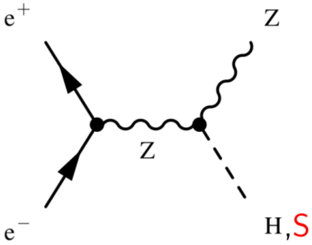
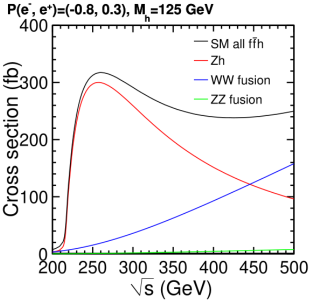
Outline

1. Introduction
2. Event generation
3. Event pre-selection
4. Variables reconstruction
5. Event classification with boosted decision trees
6. Limits on the scalar production cross section

Introduction

Exotic scalar production in scalar-strahlung process is considered.





arXiv:1306.6352

Previously studied for $S \to \tau\tau$ (presented on 19th June 2024).

$Z \to q\bar{q}$ and $S \to inv$ (possibly from DM sector) is assumed.

ILC H-20 running scenario at 250 GeV.

Event and detector simulation

Signal and background samples generated with WHIZARD 3.1.2 using built-in SM_CKM model.

Signal samples generated by varying H mass in the model and forcing its decay to 4 ν.

All relevant 2 and 4-fermion final states for e^+e^-, as well as constributions from processes with beamstrahlung or EPA photons in initial state included in the background samples.
SM-like Higgs boson contribution included in the background simulation.

ISR and luminosity spectra for ILC running at 250 GeV taken into account

H-20 running scenario for ILC assumed with $\pm 80\% / \pm 30\%$ polarisation for e^-/e^+beams.

"pure" initial states ($\pm$100% polarisation) generated and mixed
$\Rightarrow$ only two combinations (LR and RL) relevant for most processes

Fast detector simulation with Delphes ILCgen model.

Generated luminosities and event weights - e^+e^- processes

	L_{gen} for generator polarisation [fb^{-1}]			
background process	LR	RL	LL	RR
$e^+e^- \to qqqq$	69.9	103	-	-
$e^+e^- \to qq\tau\tau$	338	633	-	-
$e^+e^- \to qqll$	97.3	156	384	384
$e^+e^- \to qq\nu\nu$	93.9	254	-	-
$e^+e^- \to qql\nu$	103	576	850	849
$e^+e^- \to qq\tau\nu$	107	1150	-	-
$e^+e^- \to \tau\tau ll$	487	556	689	688
$e^+e^- \to \tau\tau\tau\tau$	836	13500	-	-
$e^+e^- \to qq$	15.7	14.4	-	-
$e^+e^- \to qqll\nu\nu$	1110	1880	-	-

$$w = \frac{N_{exp}}{N_{gen}} = \frac{\sigma_{exp} N_{exp}}{L_{gen}} = \frac{L_{exp}}{L_{gen}}$$

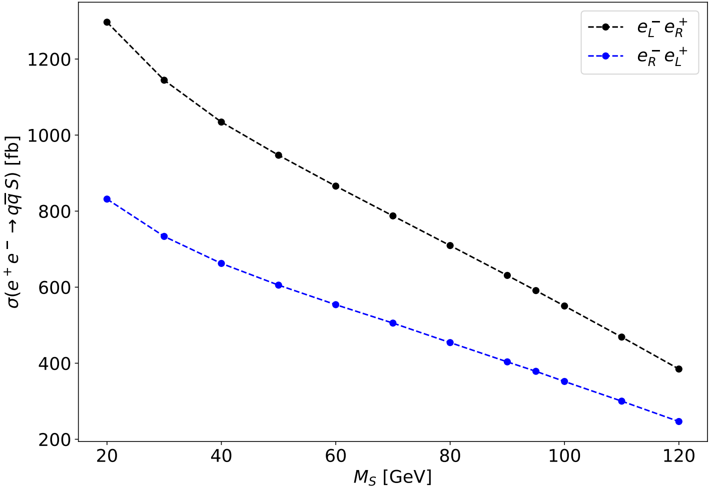
Generated luminosities and event weights - $e^{\pm}\gamma$ and $\gamma\gamma$ processes

	L_{gen} for generator polarisation [fb^{-1}]			
background process	LR	RL	LL	RR
$e^{\pm}\gamma^{BS} \rightarrow qq\nu$	4590	-	4510	-
$\gamma^{BS}e^{\pm} \rightarrow qq\nu$	4370	-	-	4720
$e^{\pm}\gamma^{EPA} \rightarrow qq\nu$	122	-	122	-
$\gamma^{EPA}e^{\pm} \rightarrow qq\nu$	121	-	-	121
$\gamma^{BS}\gamma^{BS} \rightarrow qq$	36.4	36	35.9	36.1
$\gamma^{BS}\gamma^{EPA} \rightarrow qq$	17.0	16.9	17.0	17.1
$\gamma^{EPA}\gamma^{BS} \rightarrow qq$	16.8	17.0	16.9	16.9
$\gamma^{EPA}\gamma^{EPA} \rightarrow qq$	10.2	10.2	10.2	10.2

$e^{\pm}\gamma$ and $\gamma\gamma$ luminosities include scaling factors for γ in the beam.

$$w = \frac{N_{exp}}{N_{gen}} = \frac{\sigma_{exp} N_{exp}}{L_{gen}} = \frac{L_{exp}}{L_{gen}}$$

Signal cross section



Cross section for $e^+e^- \to q\overline{q}\,S$ $(q\overline{q} \sim Z)$ process at Whizard level as a function of scalar mass

Events pre-selection

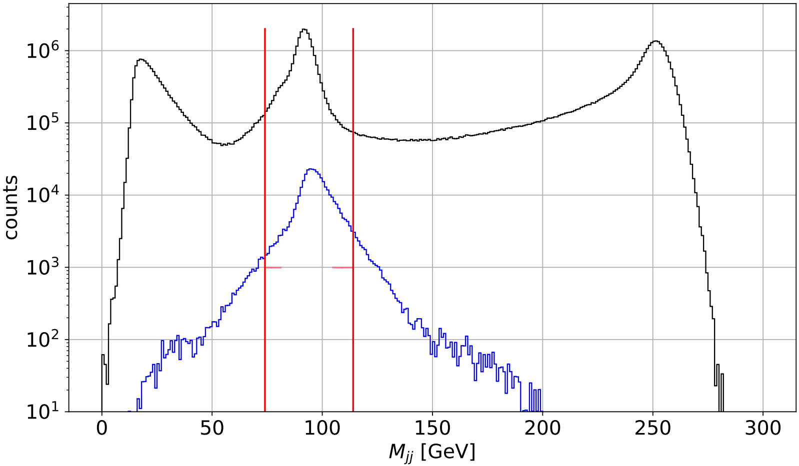
Pre-selection cuts on number of objects:

1. no isolated electrons and muons
2. no isolated photons
3. no isolated photons in BeamCal
4. only two jets

Pre-selection cuts on reconstructed variables:

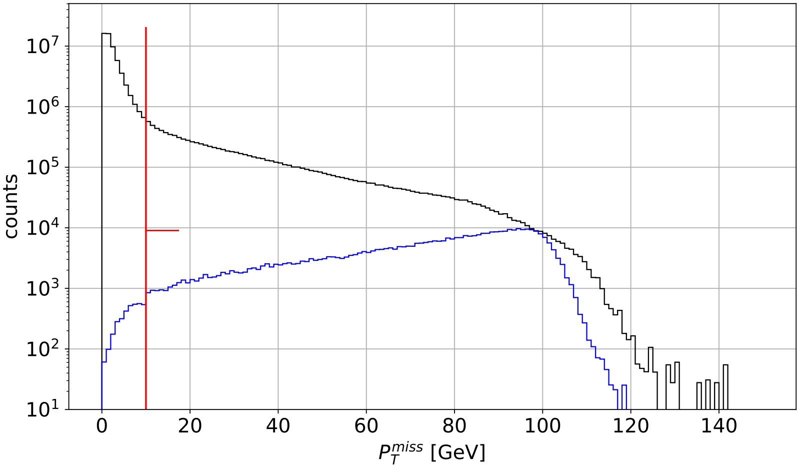
1. Reconstructed di-jet invariant mass in the range [74 GeV, 114 GeV]
2. Missing transverse momentum greater than 10 GeV

Events pre-selection



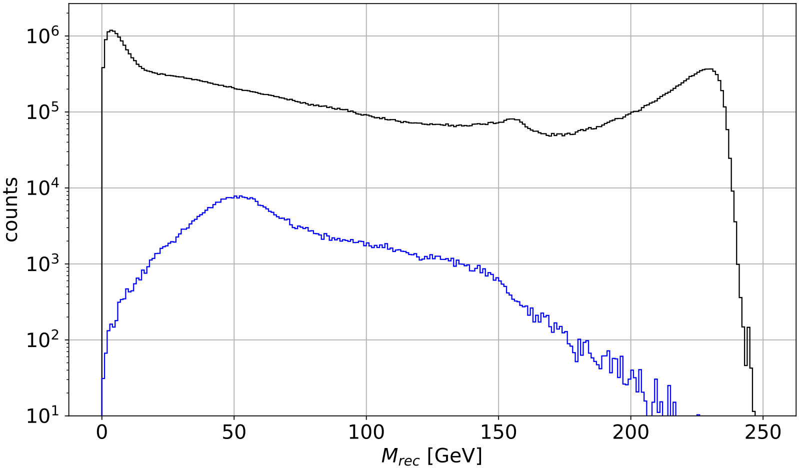
Reconstructed **Z invariant mass**
for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

Events pre-selection



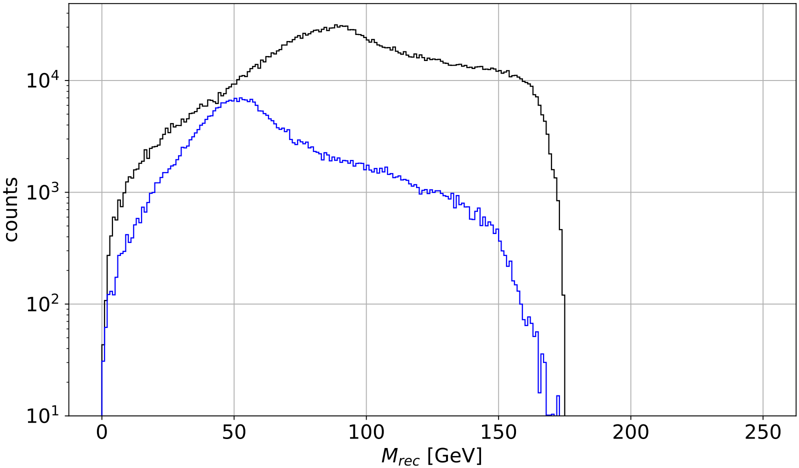
Reconstructed **missing transverse momentum** for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

Event reconstruction



Reconstructed **recoil mass - without cuts**
for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

Event reconstruction



Reconstructed **recoil mass** - **with cuts**
for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

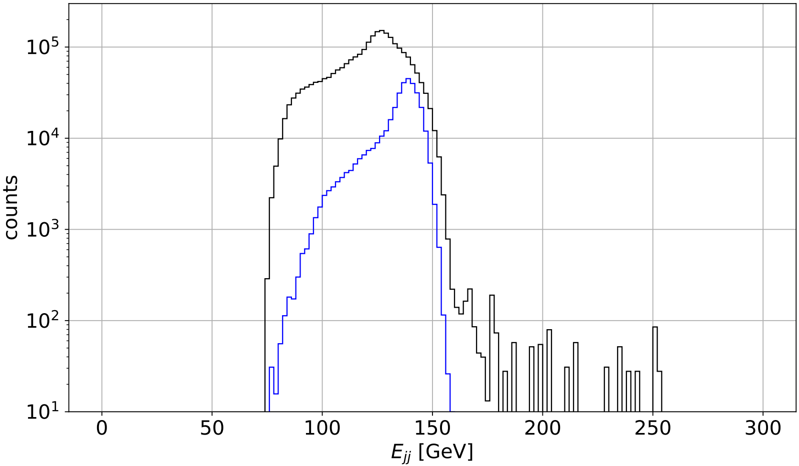
Variables used for training

Two jets taken as Z candidate

Variables used in classification:

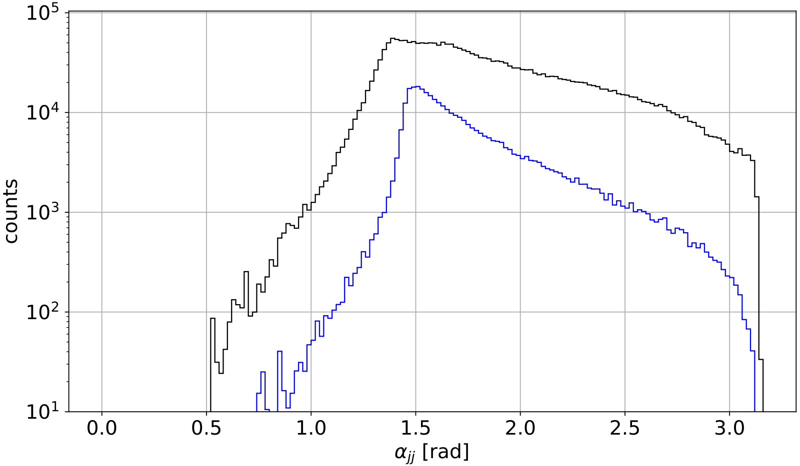
- Z candidate invariant mass
- Z candidate energy
- missing transverse momentum
- cosine of the Z candidate polar angle
- angle between two jets
- invariant mass recoiling against Z candidate
- y_{23} and y_{34} variables from clustering algorithm

Variables used for training



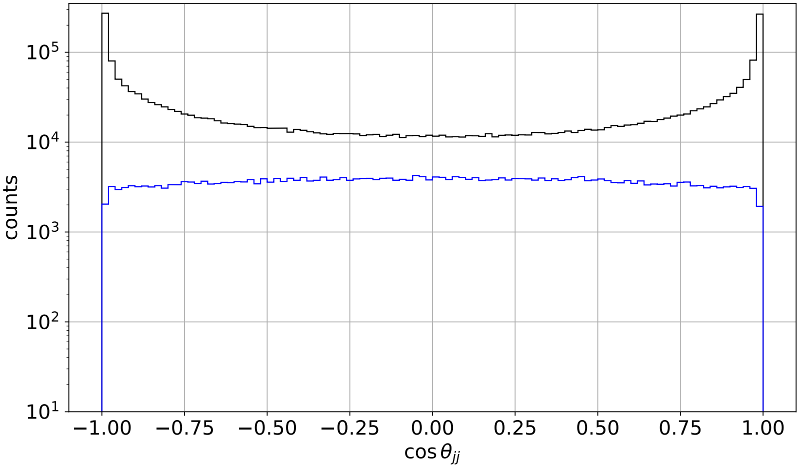
Reconstructed **Z energy** - **with cuts**
for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

Variables used for training



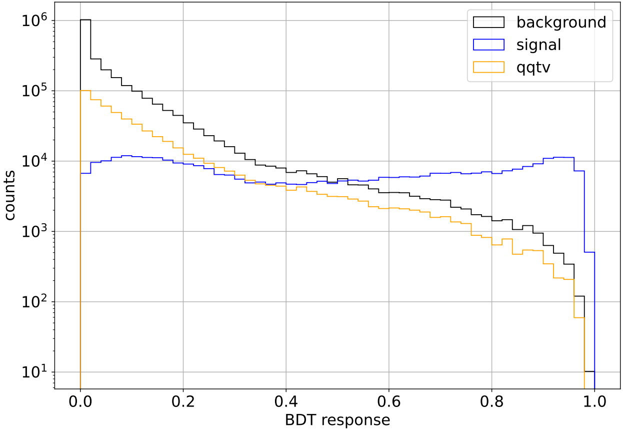
Reconstructed **angle between jets - with cuts** for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

Variables used for training



Reconstructed **cosine of Z polar angle - with cuts** for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

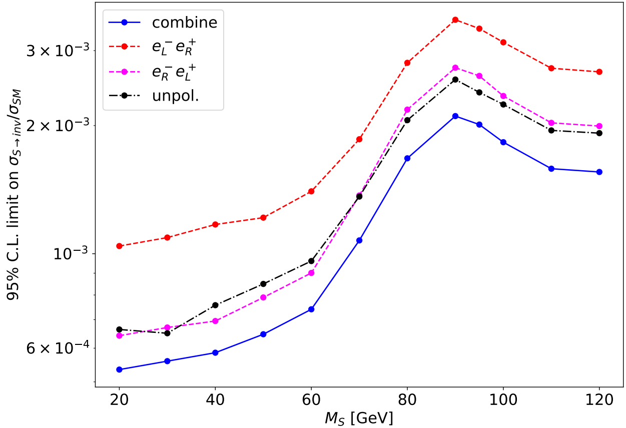
Classification results



BDT response distribution for sgn and bkg events with most significant background process $qq\tau\nu$,
for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and scalar mass of **50 GeV**.

95% C.L. limits on the production cross section

in units of the SM cross section for Higgs-strahlung process
(with given scalar mass)

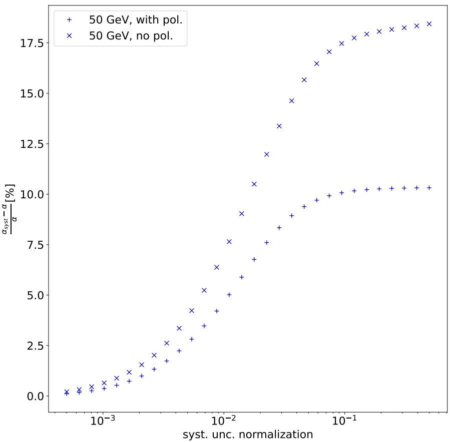


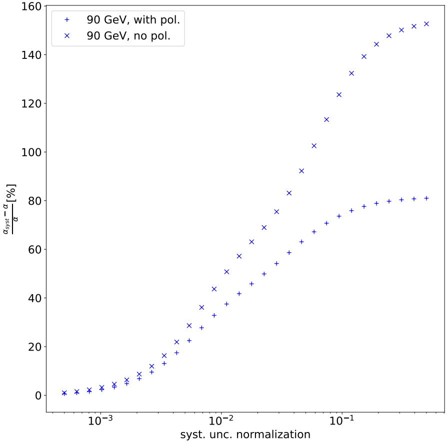
$e_L^- e_R^+$ and $e_R^- e_L^+$ luminosities from ILC H-20 running scenario at 250 GeV

Systematic uncertainties

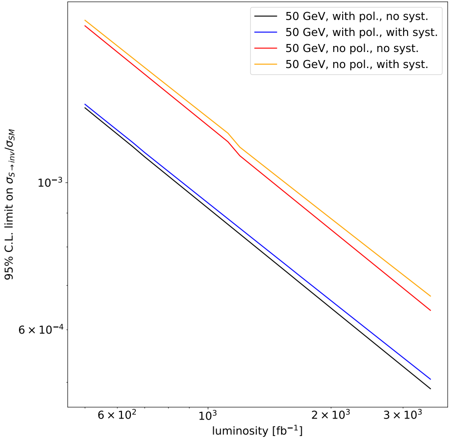
Seven normalization variations (4 lumi and 5 theory) considered.

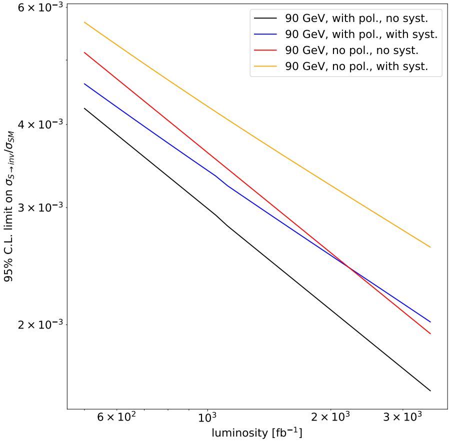
Significant impact of systematic uncertainties





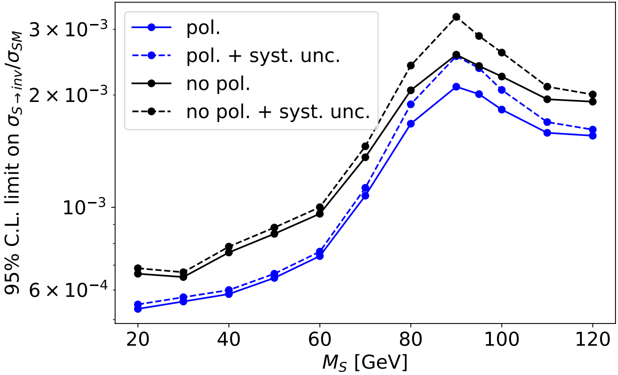
Limits dependence on luminosity





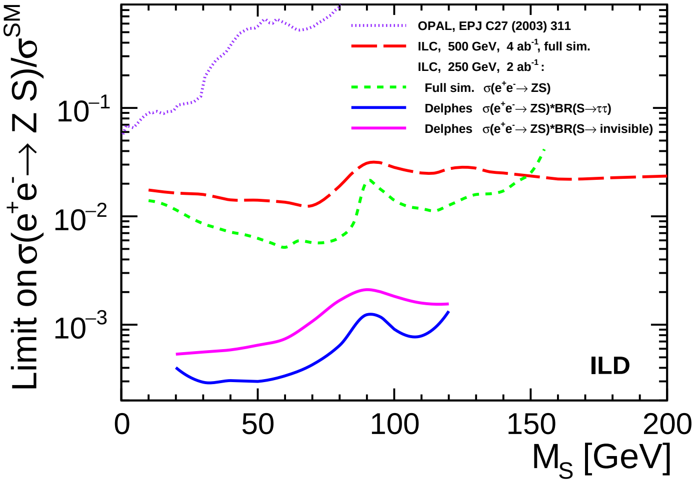
95% C.L. limits on the production cross section

in units of the SM cross section for Higgs-strahlung process (with given scalar mass), **with systematic effects**



$e^-_L e^+_R$ and $e^-_R e^+_L$ luminosities from ILC H-20 running scenario at 250 GeV

Previous results



Limits for $S \to inv$ are worse than $S \to \tau\tau$ - worse background rejection due to less kinematic constraints

Conclusions

1. Follow-up of the previously presented $S \to \tau\tau$ analysis
2. Event selection and reconstruction was modified for invisible decay channel
3. Additional background channels with initial state photons were included
4. Boosted decision trees were used for classification
5. **Limits for scalar production cross section were calculated**
6. Impact of beam polarisation and normalization uncertainties were considered

Backup - sample mixing and expected luminosities

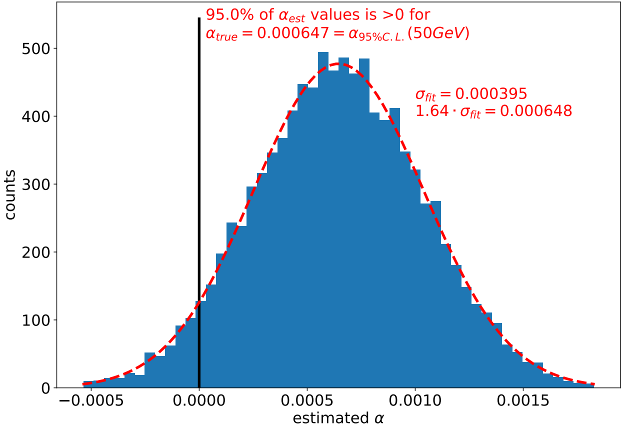
	Generated sample			
	eLpR ($e^-_L e^+_R$)	eRpL ($e^-_R e^+_L$)	eLpL ($e^-_L e^+_L$)	eRpR ($e^-_R e^+_R$)
Beam polarisation setting	Weight factor			
	$\frac{(1-P_{e^-})(1+P_{e^+})}{4}$	$\frac{(1+P_{e^-})(1-P_{e^+})}{4}$	$\frac{(1-P_{e^-})(1-P_{e^+})}{4}$	$\frac{(1+P_{e^-})(1+P_{e^+})}{4}$
$(-,+)$	0.585	0.035	0.315	0.065
$(+,-)$	0.035	0.585	0.065	0.315
$(-,-)$	0.315	0.065	0.585	0.035
$(+,+)$	0.065	0.315	0.035	0.585
unpol.	0.25	0.25	0.25	0.25
	Expected H-20 sample luminosities [fb^{-1}]			
$(-,+)$	526.5	31.5	283.5	58.5
$(+,-)$	31.5	526.5	58.5	283.5
$(-,-)$	31.5	6.5	58.5	3.5
$(+,+)$	6.5	31.5	3.5	58.5
unpol.	500	500	500	500

Backup - validation

Expected number of events in $i th$ bin: $\mu_i = b_i + \alpha s_i$

Pseudo-experiments generated for $\alpha = \alpha_{95\% C.L.}(50 GeV)$

Distribution of estimated α values



Backup - formulas

Expected number of events in ith bin:

$$\mu_i = \sum_{i=1}^{N_{bin}} b_i + \alpha s_i$$

Log-likelihood function:

$$l(\alpha) = \sum_{i=1}^{N_{bin}} (n_i \log \mu_i - \mu_i) - \sum_{i=1}^{N_{bin}} n_i!$$

Log-likelihood 1^{st} derivative:

$$\frac{dl}{d\alpha}(\alpha) = \sum_{i=1}^{N_{bin}} \left(\frac{n_i}{\mu_i} - 1 \right) \frac{d\mu_i}{d\alpha} \; (= 0)$$

Log-likelihood 2^{nd} derivative:

$$-\frac{d^2 l}{d\alpha^2}(\alpha) = \sum_{i=1}^{N_{bin}} \frac{n_i}{\mu_i^2} \left(\frac{d\mu_i}{d\alpha} \right)^2 = \sum_{i=1}^{N_{bin}} \frac{s_i^2}{b_i} = \frac{1}{\delta_\alpha^2}, \quad \alpha_{95\% C.L.} = 1.64 \cdot \delta_\alpha$$