Search for Higgs decaying to exotic scalers

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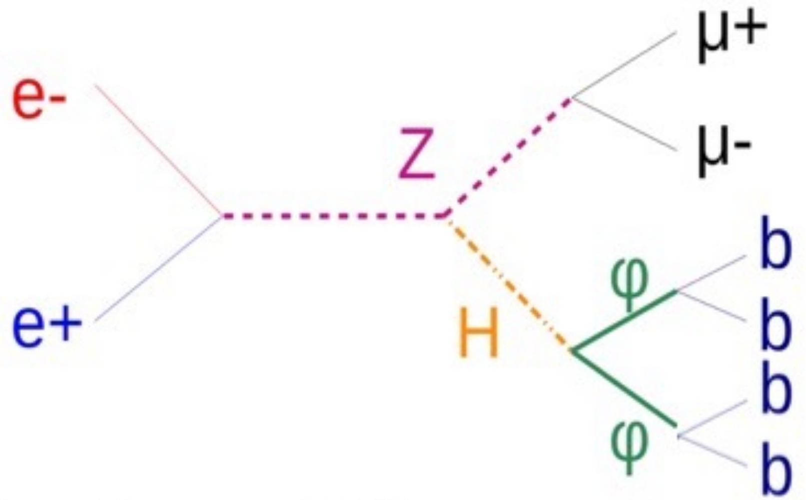
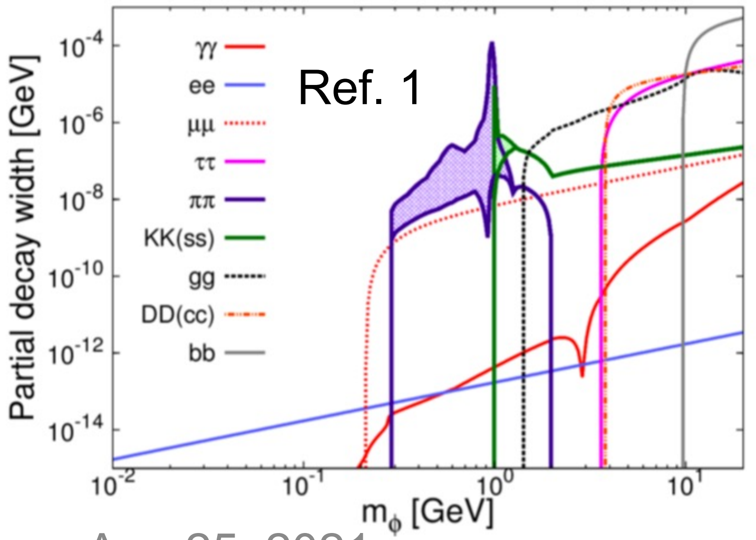
Search for Higgs → scalar mediator



- Model: SM + singlet
  - Higgs can couple to WIMP DM through the scalar mediator(φ).
  - The mediator appears as the Higgs exotic decay.
  - Model parameters: mediator mass(mφ), mixing angle(θ)
- Target channel:
  e+e- → ZH, Z → ee/μμ, H → φφ → 4b
  - with ILD full detector simulation
  - Mediator mass range: 15 - 60 GeV
  - 95% C.L. upper limit of BR(H→4b) ~ 0.1%

$$\Gamma(\phi \to \mathrm{SMs}) = \sin^2\theta \times \Gamma(h_{\mathrm{SM}} \to \mathrm{SMs})|_{m^2_{h_{\mathrm{SM}}} \to m^2_\phi}$$
$$\Gamma(h \to \mathrm{SMs}) = \cos^2\theta \times \Gamma(h_{\mathrm{SM}} \to \mathrm{SMs}),$$



Ref. 2

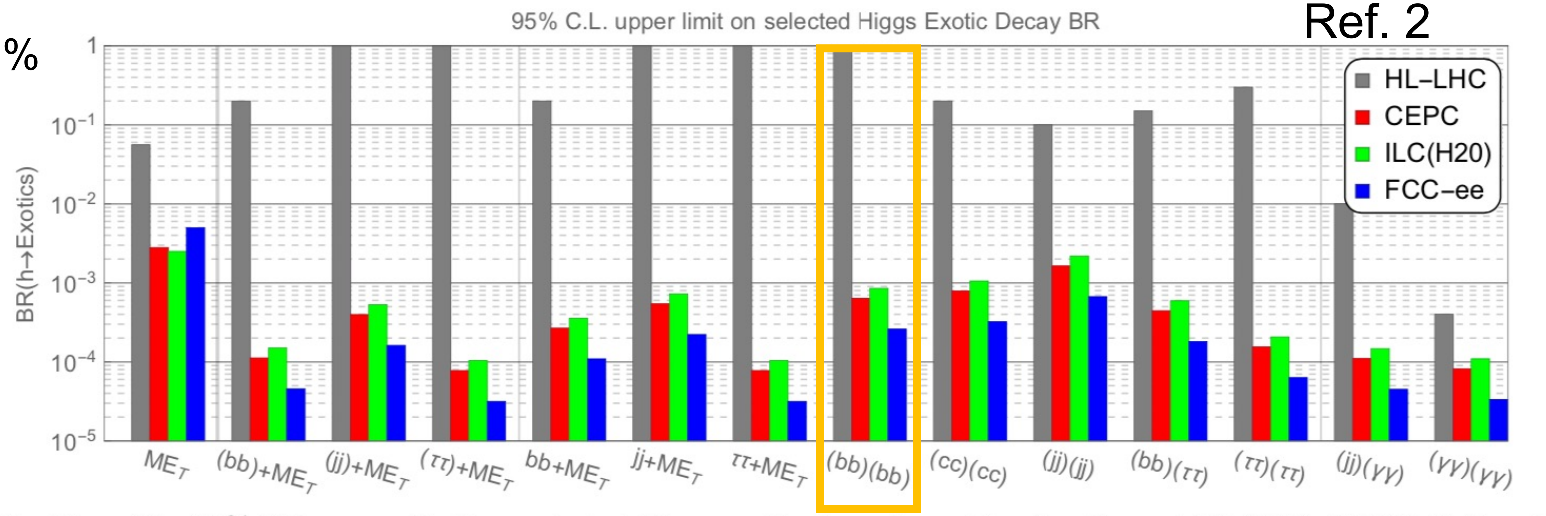
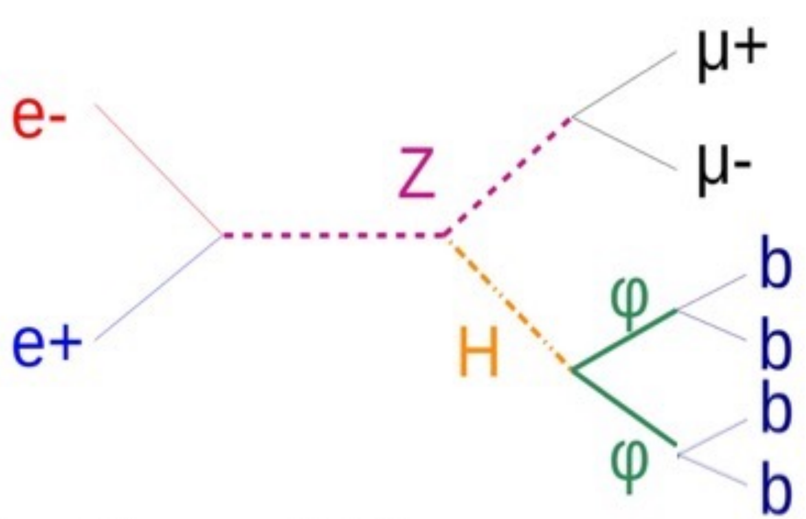


Fig. 12. The 95% C.L. upper limit on selected Higgs exotic decay branching fractions at HL-LHC, CEPC, ILC and FCC-*ee*. The benchmark parameter choices are the same as in Table 3. We put several vertical lines in this figure to divide different types of Higgs exotic decays.

Search for Higgs → scalar mediator



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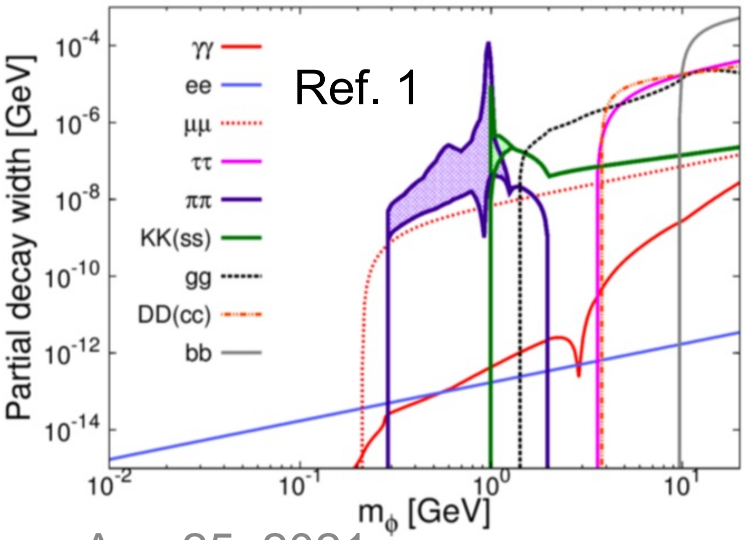

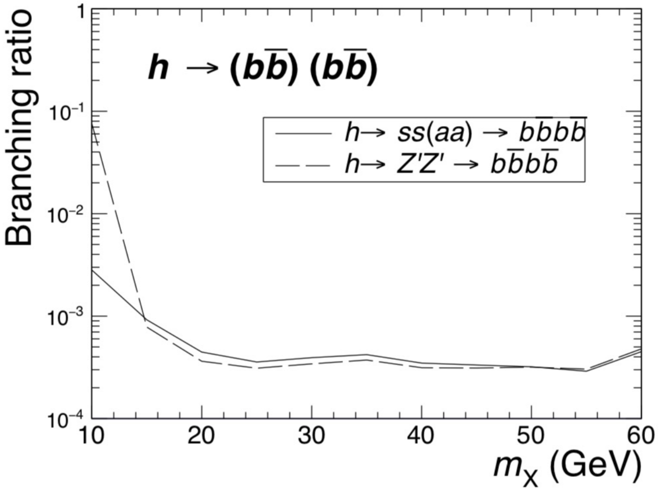

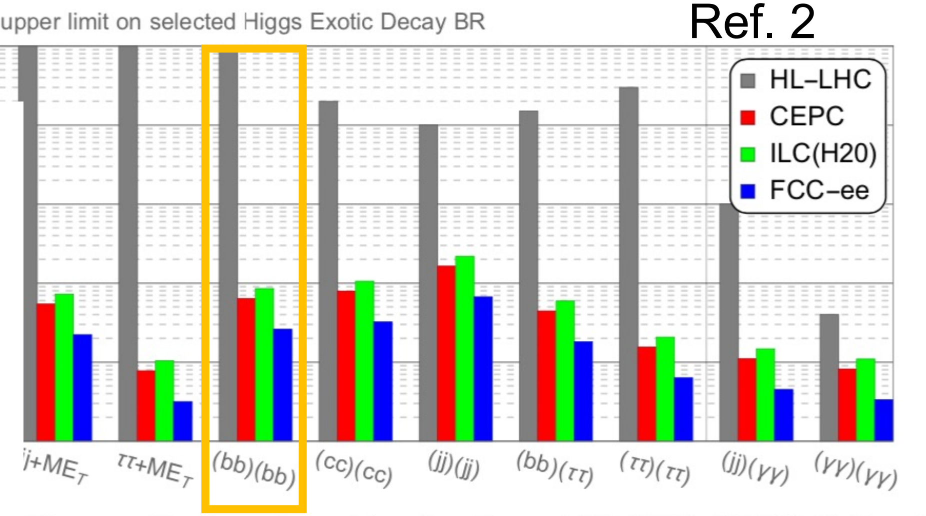

Higgs exotic decay branching fractions at HL-LHC, CEPC, ILC and
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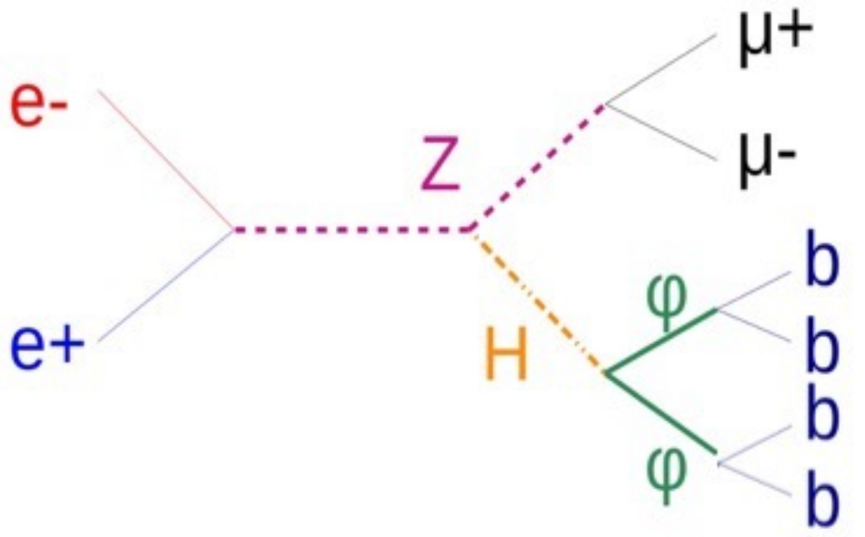
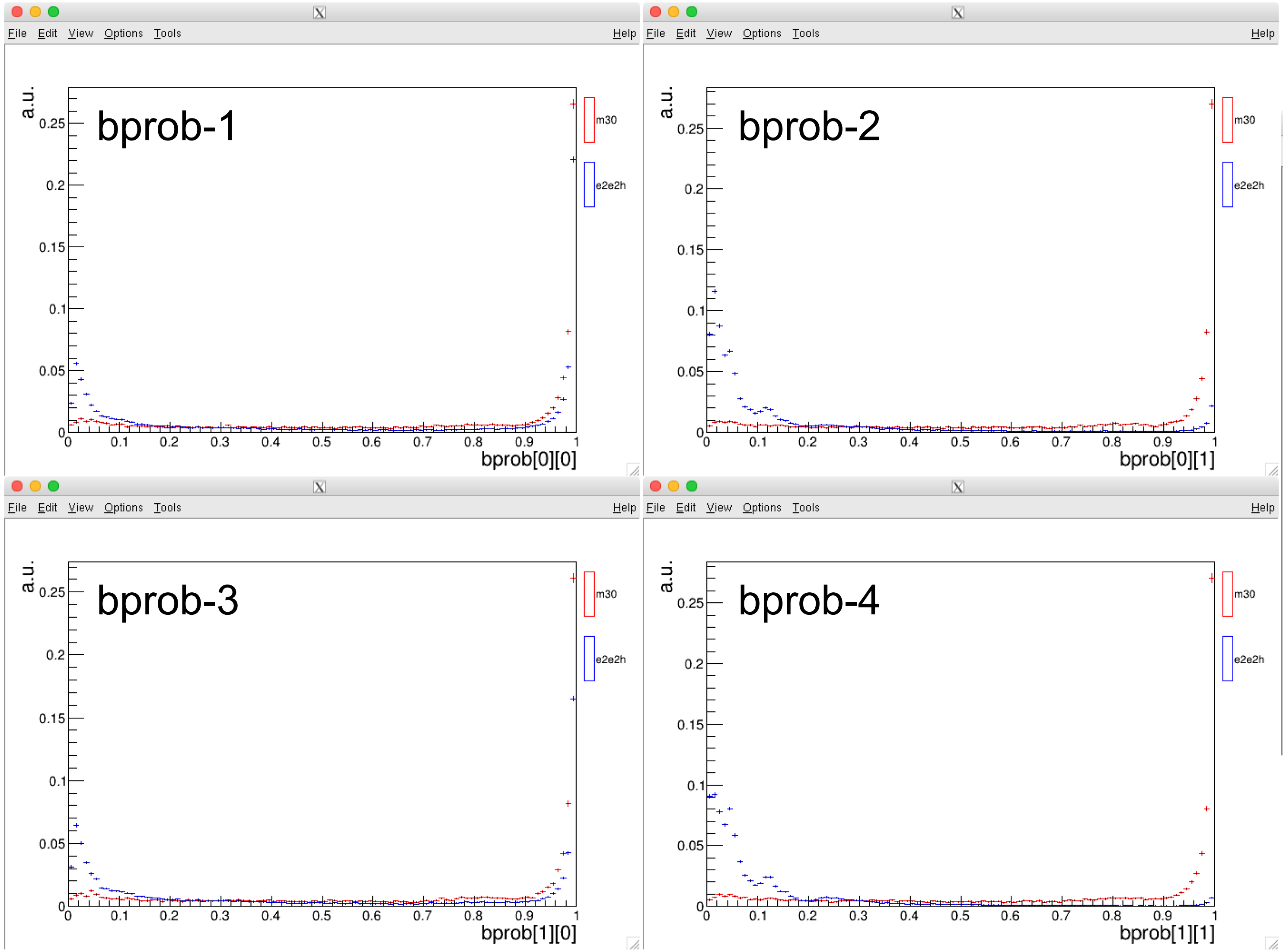
Search for Higgs → scalar mediator



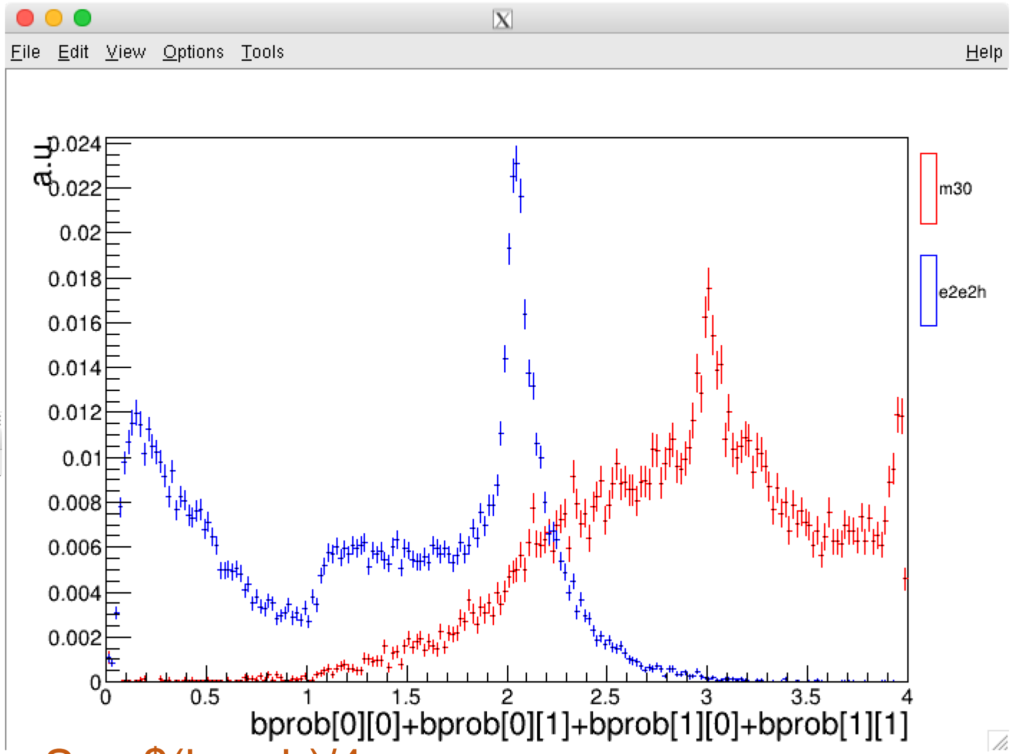
- Target channel:
  - e+e- → ZH, Z → ee/μμ, H → φφ → 4b
- Simulation setup:
  - Generator: WHIZARD 2.8.5
    - Model: MSSM_CKM
    - Assumption of φ mass: 15, 30, 45, 60 [GeV]
  - ILC parameters:
    - √s = 250 GeV, polarization { (-0.8,+0.3), (+0.8,-0.3) }
  - Detector: ILD latest setting (same as mc-2020)
- Analysis flow:
  1. IsolatedLeptonTagging
     - require nIsoLep = 2
  2. LCFIPlus
     - Jet clustering: forced to 4 jets
     - Flavor tagging
  3. Jet pairing
     - require m12 = m34
- Samples:
  - Signal 20,000 events / mφ / pol.
  - Background
    - ffh 500,000 events / process / pol.
    - 4f_zz_sl
      - _lr 4,200,000 events
      - _rl 2,400,000 events
    - Other 2f, 4f, 6f 10,000 events / process / pol.
- Main variables
  - b-probability
  - recoil mass
  - mean of mφ

Fast Analysis of hφφ: b-probability



Signal(mφ=30GeV) vs μμH

- LCFIPlus flavor tagging are used after the jet clustering with Durham forced to 4 jets.



Sum$(bprob)/4

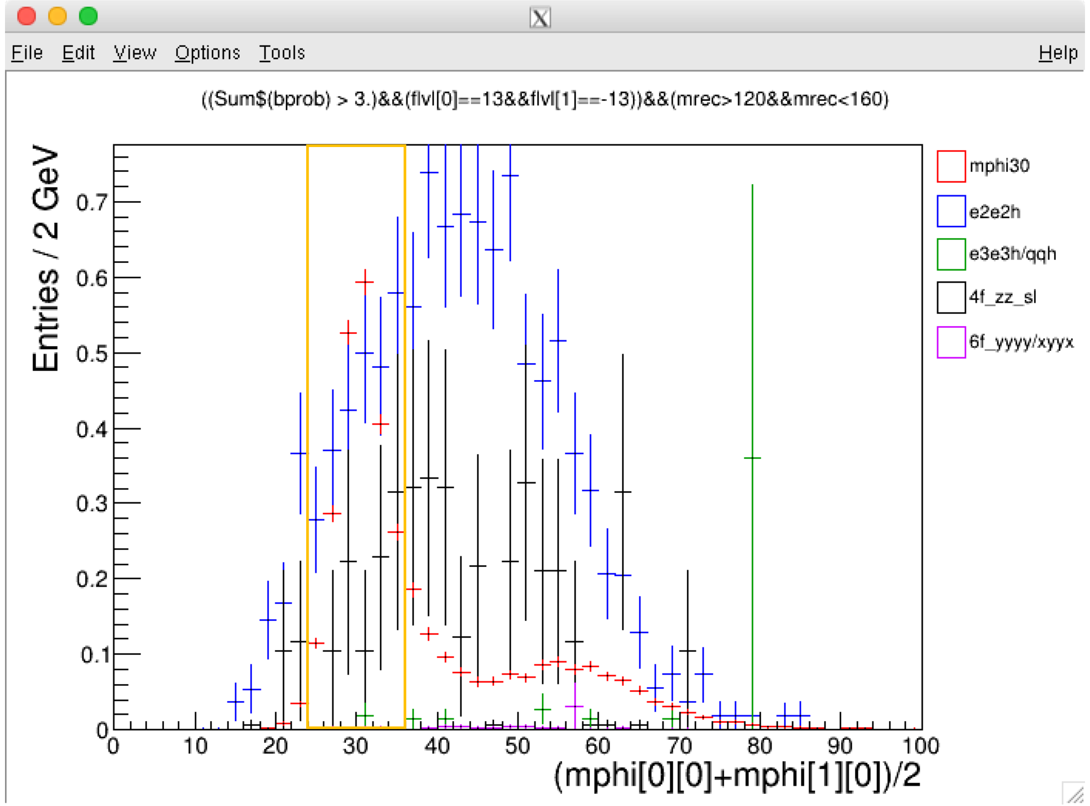
Max Significance = 0.010

when Sum$(bprob)/4 = 0.764

-> Sum$(bprob) = 3.056

(eff=0.38, pur=0.29)

Result of fast analysis: μμ + 4b

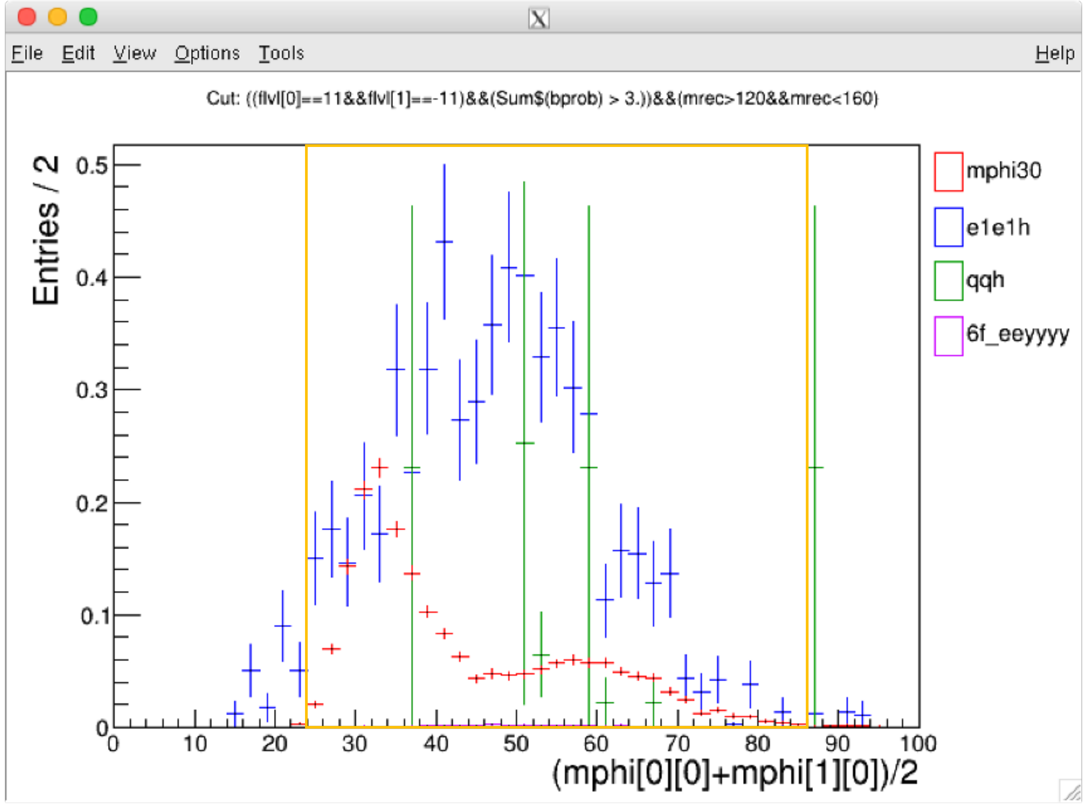


$L = 900\ fb^{-1}$
Pol = (-0.8,+0.3)
mφ = 30 GeV
BR(H->φφ->4b) = 0.1%

← $(m\varphi_1+m\varphi_2)/2$, [24 - 36] GeV
optimized to maximize significance
Ns = 2.12
Nb = 3.63
significance = 0.908
UL_{95} = 0.182%

- Cut
  - The number of isolated muons = 2
  - The sum of 4 jet b-probabilities > 3
  - The recoil mass is included in (120 GeV, 160 GeV).
- The remaining backgrounds are mainly μμH , 4f_zz_ sl.

Result of fast analysis: ee + 4b



$L = 900\ fb^{-1}$

Pol = (+0.8,-0.3)

mφ = 30 GeV

BR(H->φφ->4b) = 0.1%

← $(m\varphi_1+m\varphi_2)/2$, [24 - 86] GeV

optimized to maximize significance

Ns = 1.96

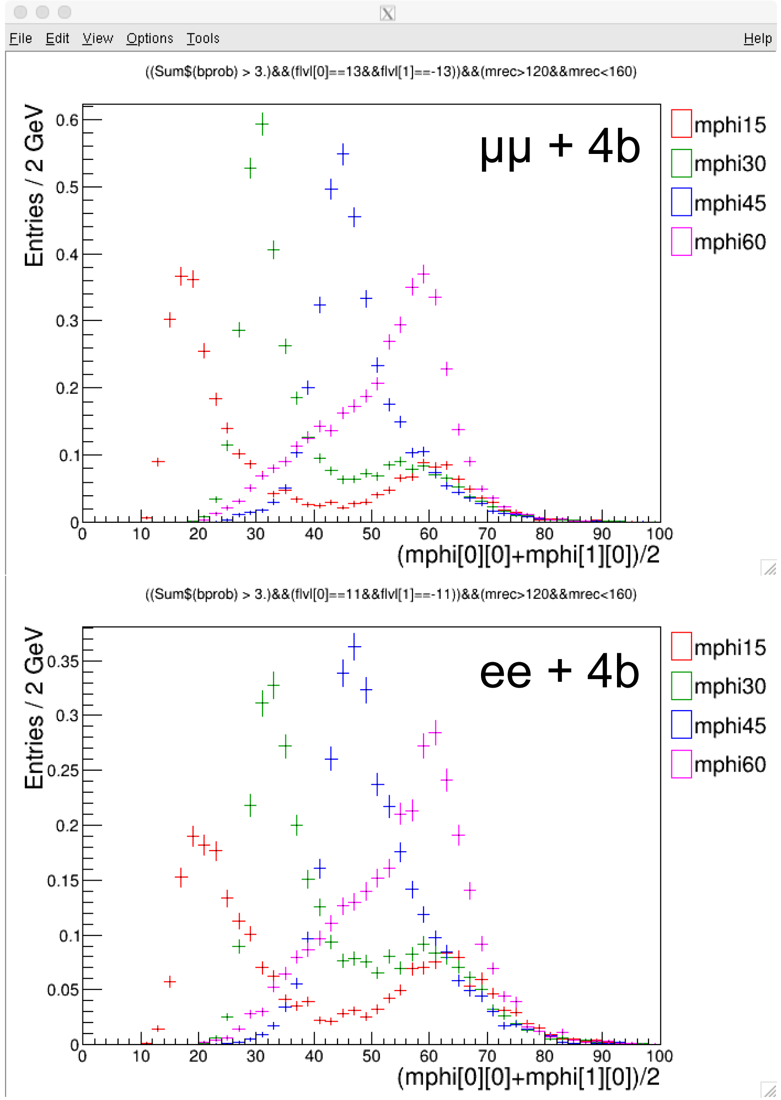
Nb = 6.85

significance = 0.662

UL_{95} = 0.249%

- Cut
  - The number of isolated electrons = 2
  - The sum of 4 jet b-probabilities > 3
  - The recoil mass is included in (120 GeV, 160 GeV).
- The remaining backgrounds are mainly eeH , qqH.

Comparison of φ mass & Combined results



μμ + 4b

mφ	UL-left	UL-right	combined
15	0.165%	0.198%	0.127%
30	0.182%	0.222%	0.141%
45	0.175%	0.227%	0.139%
60	0.175%	0.228%	0.139%

ee + 4b

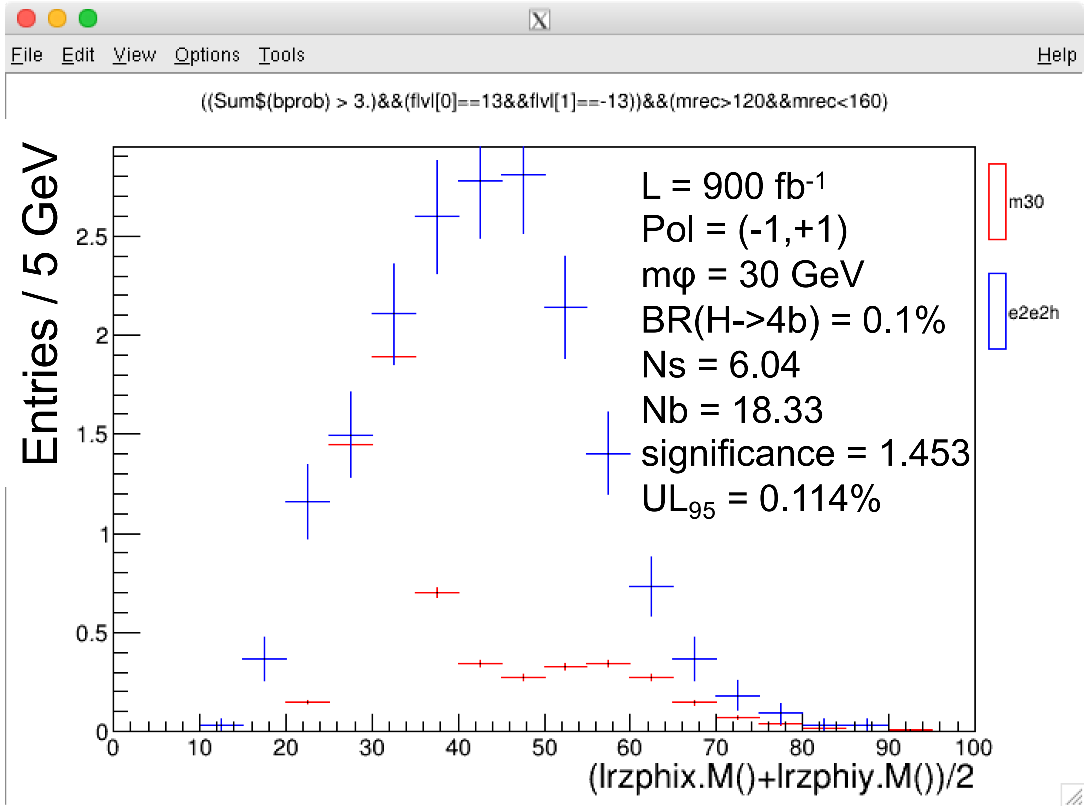
mφ	UL-left	UL-right	combined
15	0.207%	0.264%	0.163%
30	0.215%	0.249%	0.163%
45	0.200%	0.225%	0.149%
60	0.199%	0.229%	0.150%

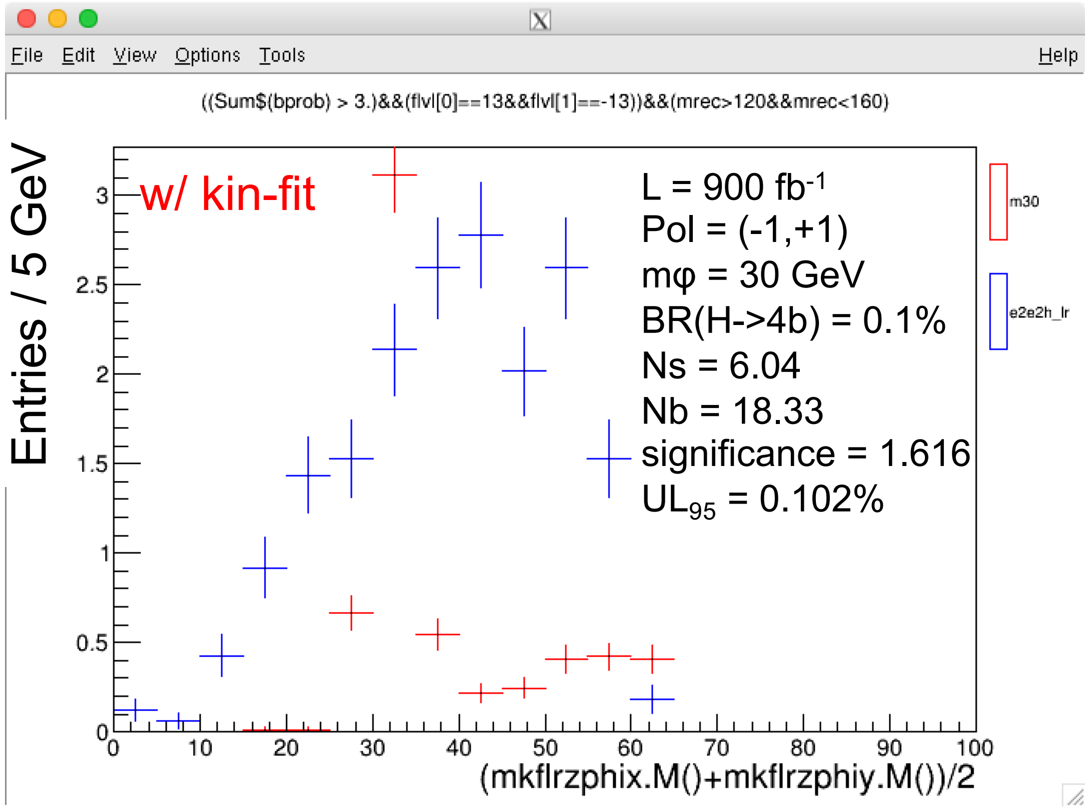
mφ	ee + μμ
15	0.100%
30	0.107%
45	0.102%
60	0.102%

- After breif analysis, we obtained UL_{95} ~ 0.1% for all mφ.
- The smaller peaks would be due to mis-pairing.

Ideas for update: Kinematic fitting

- The kinematic fitting are tested using a part of events, and got some improvement.
  - Fit Object
    - 2 muons
    - 4 jets with b-jet resolution
    - 1 ISR photon
  - Constraint
    - Total Energy/Px/Py/Pz for all FOs
    - Higgs mass = 125 GeV
    - Same mass of φs





Summary and Plan

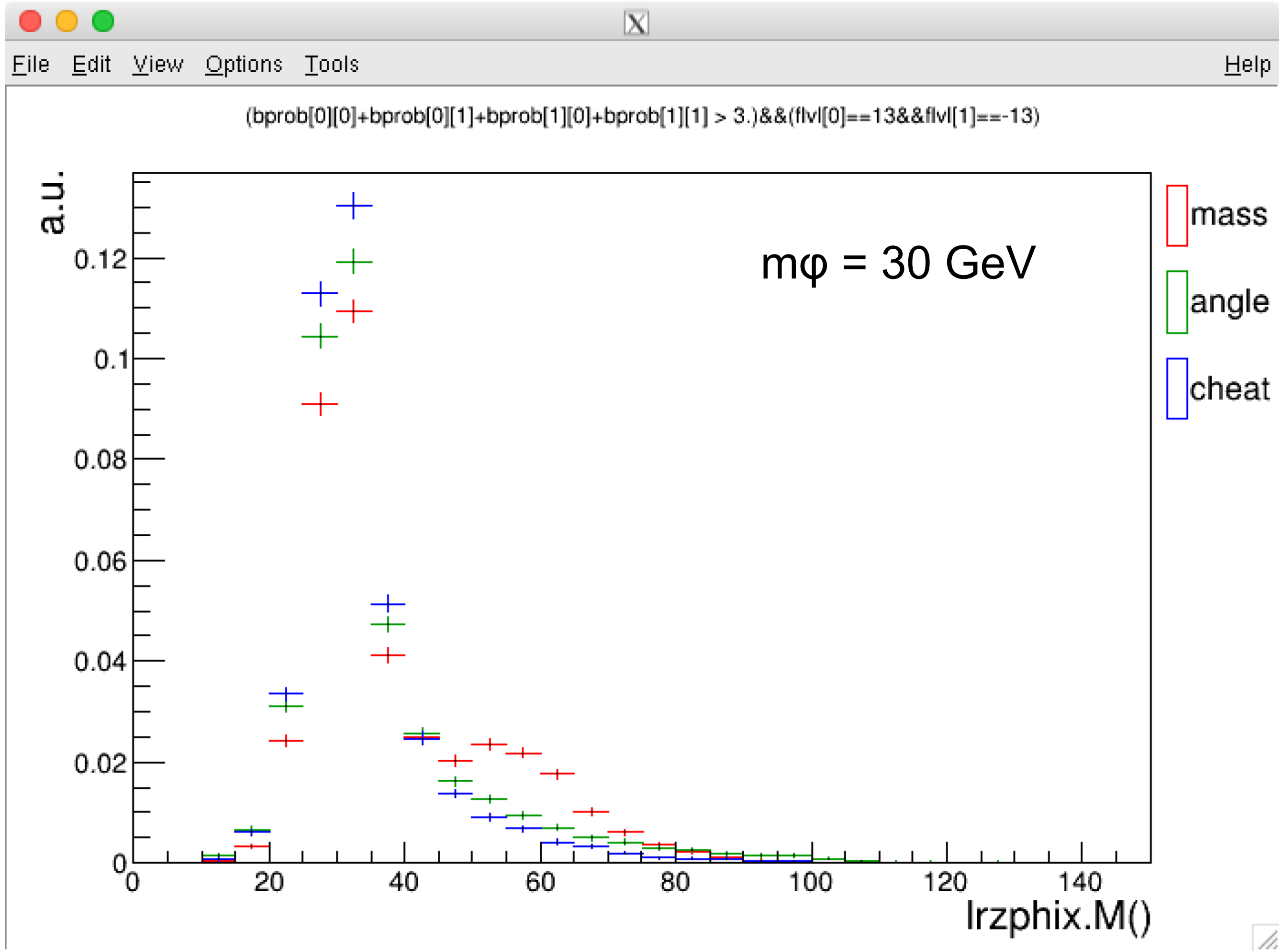
- Higgs can couple to WIMP DM through the scalar mediator.
- The ILC has the possibility to search for Higgs exotic decays to the scalar mediators.
- We performed a full simulation study at the 250 GeV ILC using ILD concept.
- The target channels are $e^+e^- \to ZH$, $Z \to ee/\mu\mu$, $H \to \varphi\varphi \to 4b$.
- We obtained UL_{95} of $BR(H\to\varphi\varphi\to 4b) \sim 0.1\%$ in the range of 15 – 60 GeV for m_φ.
- Next plans:
  - Optimize the parameters of high-level reconstruction and the cut conditions
  - Apply the kinematic fitting after several tunings
  - Add the hadronic channel $Z \to qq$

backup

To Do

- 6f
- eeH
- Add higgs_excl

Fast Analysis of hφφ: Jet pairing

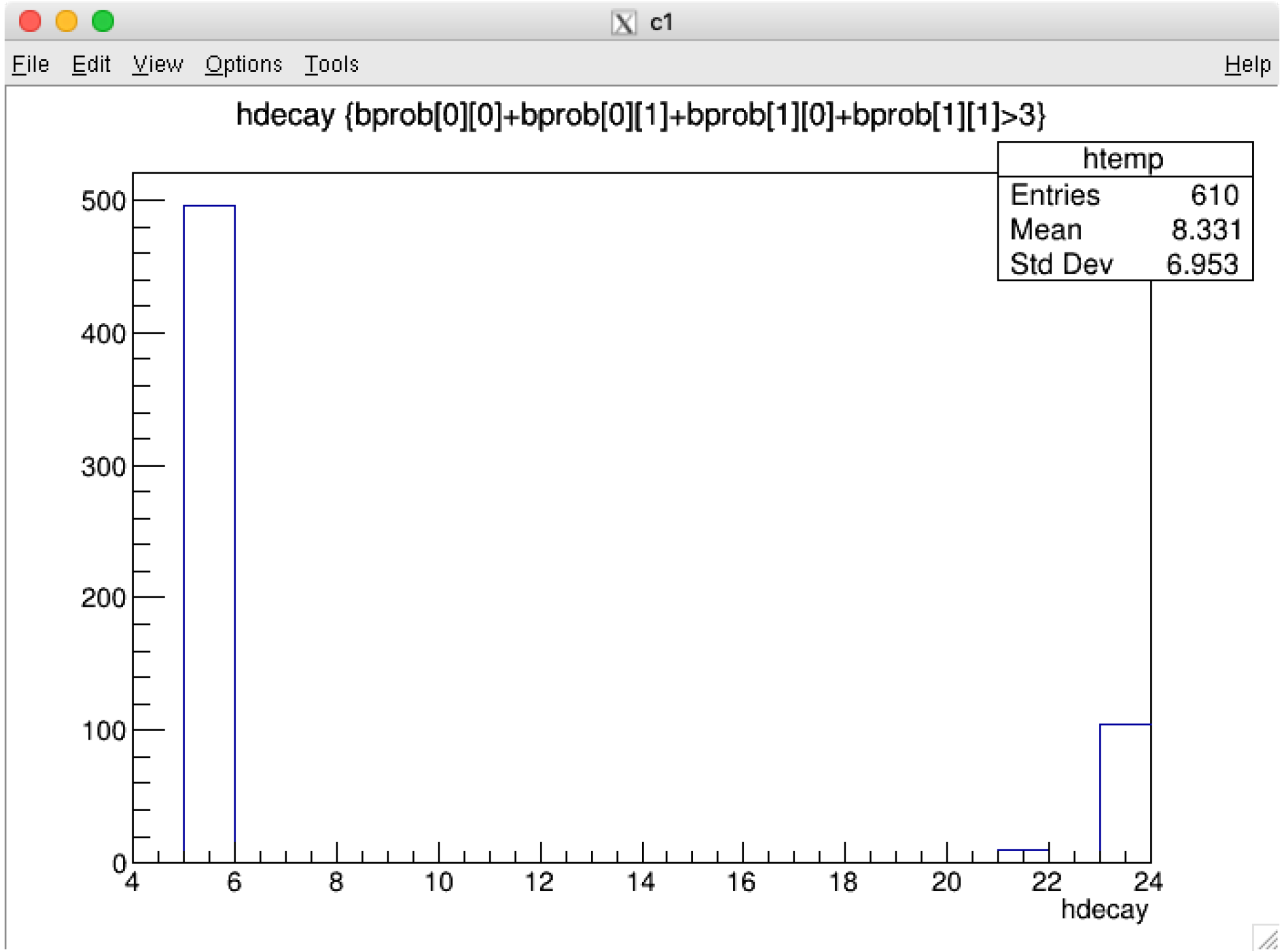


- $m_{12} = m_{34}$ (equal mass)
- back-to-back φ pair in H rest frame
- Jet direction matching b/w Rec/MC

Pairing accuracy

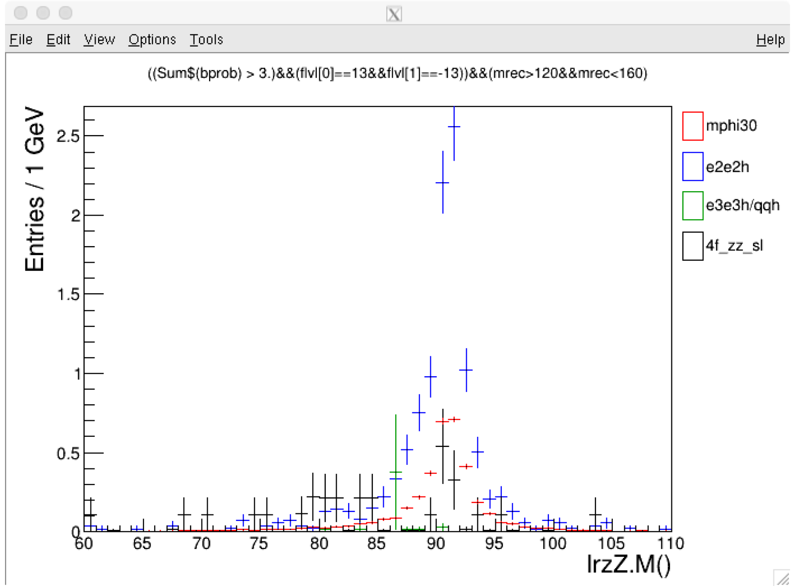
mphi	equal mass	back-to-back
15	79.1%	93.6%
30	75.1%	85.0%
45	62.8%	52.4%
60	37.1%	5.8%

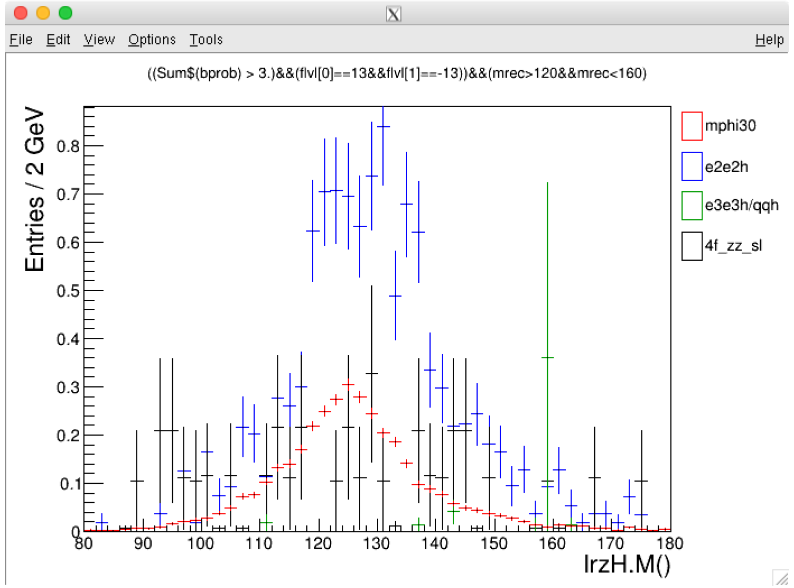
Higgs decay mode in remaining μμH process

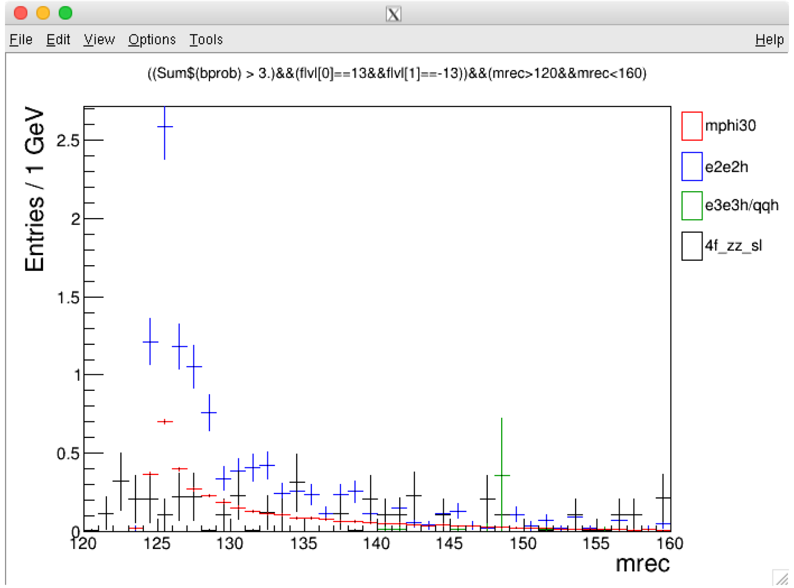


- Pol. = (-1,+1)
- Cut: Sum$(bprob)/4 > 3
- Efficiency = 0.122%
- Remaining decay mode
  - H->bb: ~82%
  - H->ZZ: ~16%
  - H->gg: ~2%

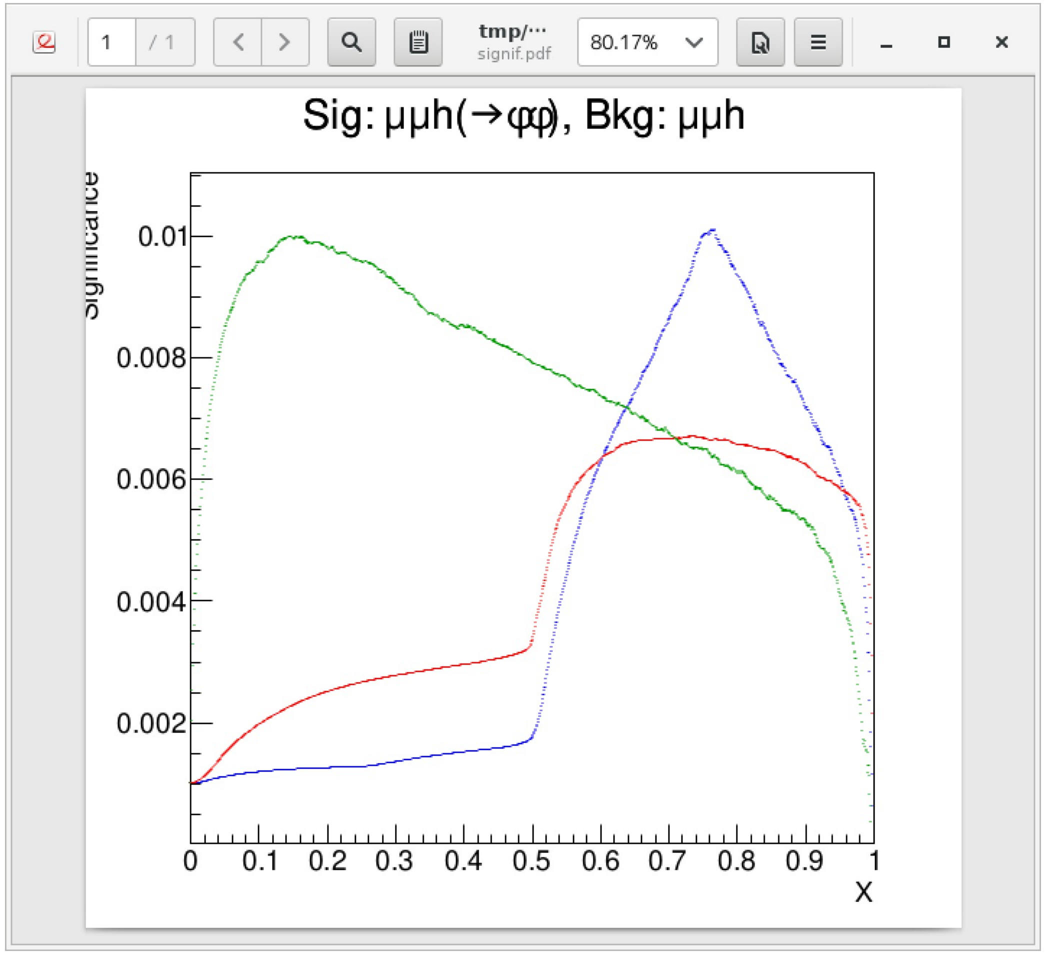
mZ, mH, mrecoil

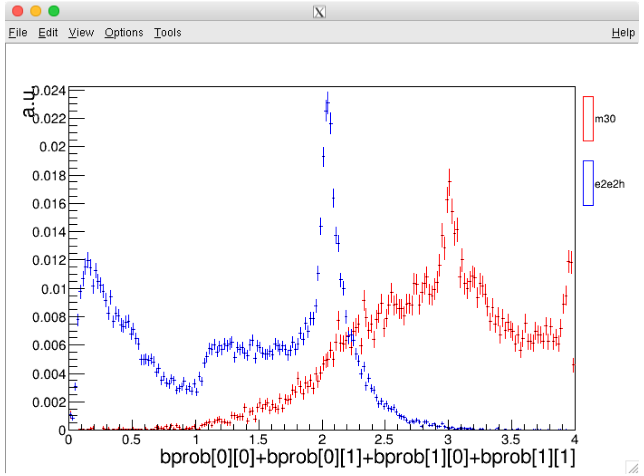






b-tag cut



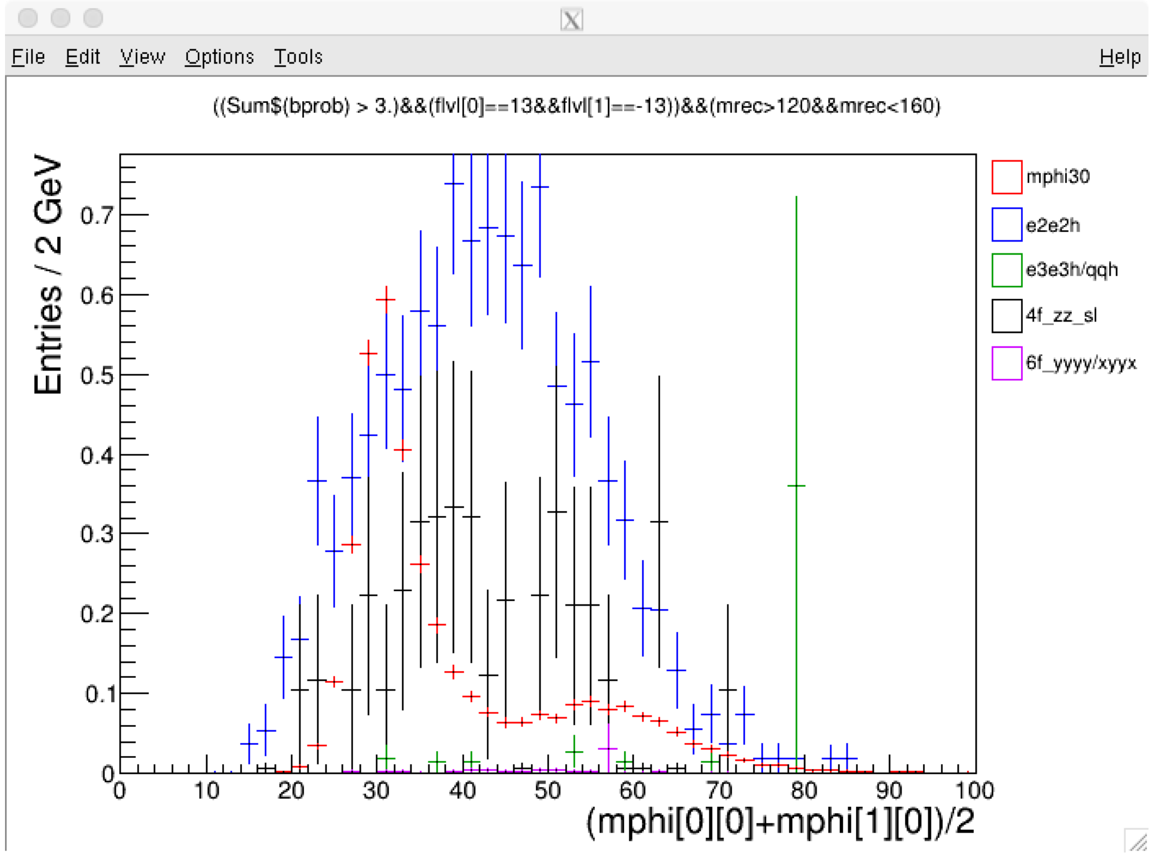


Sum$(bprob)/4 ← BEST
Max Significance = 0.0101048
when Sum$(bprob)/4 = 0.764 -> Sum$(bprob) = 3.056
eff=0.37548, pur=0.290283

(bprob[0][1]+bprob[1][1])/2
Max Significance = 0.00671638
when (bprob[0][1]+bprob[1][1])/2 = 0.734
eff=0.484895, pur=0.0993059

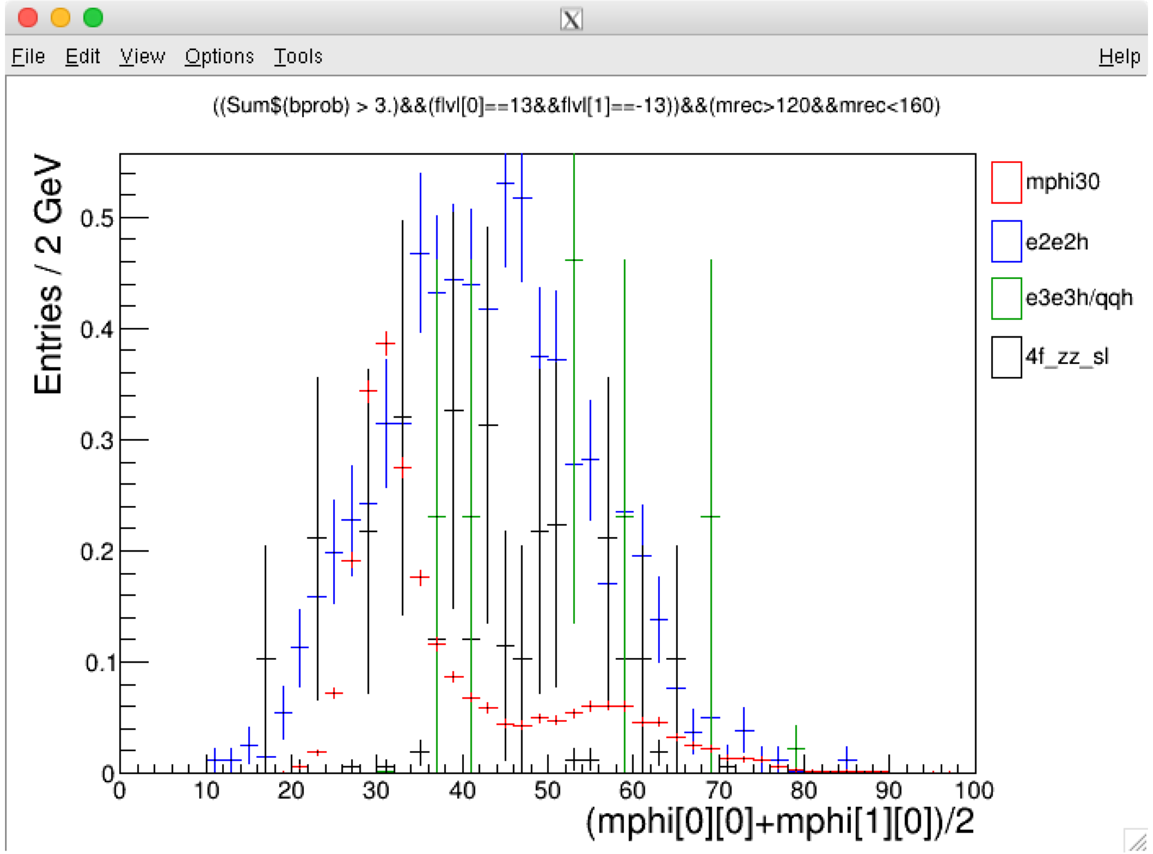
bprob[0][0]*bprob[0][1]*bprob[1][0]*bprob[1][1]
Max Significance = 0.0100021
when bprob[0][0]*bprob[0][1]*bprob[1][0]*bprob[1][1] = 0.147
eff=0.411827, pur=0.259309

μμH, H→φφ→4b, mφ = 30 GeV, (-0.8,+0.3)



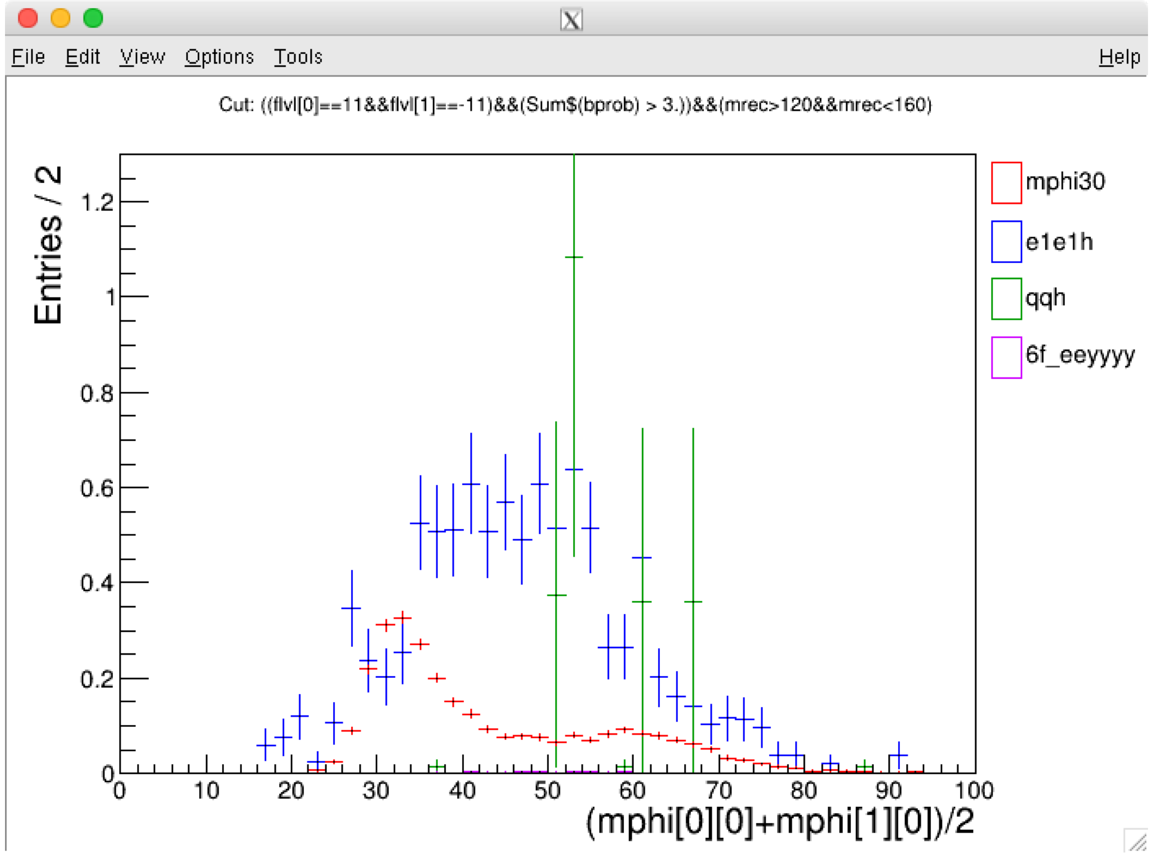
Draw (mphi[0][0]+mphi[1][0])/2
Cut: ((Sum$(bprob) > 3.)&&(flvl[0]==13&&flvl[1]==-13))&&(mrec>120&&mrec<160)
output_all/eqmass/hphiphi_m30_lr.root: nGen = 20000, xsec = 16.9786, eff = 0.3954
output_all/eqmass/hphiphi_m30_rl.root: nGen = 20000, xsec = 10.8586, eff = 0.39175
output_all/eqmass/e2e2h_lr.root: nGen = 500000, xsec = 16.9707, eff = 0.0012
output_all/eqmass/e2e2h_rl.root: nGen = 500000, xsec = 10.8691, eff = 0.001152
output_all/eqmass/skimmed/4f_zz_sl_lr_skimmed.root: nGen = 4199600, xsec = 838.079, eff = 8.81036e-06
output_all/eqmass/skimmed/4f_zz_sl_rl_skimmed.root: nGen = 2400000, xsec = 466.816, eff = 1.125e-05
output_all/eqmass/skimmed/e3e3h_lr_skimmed.root: nGen = 500000, xsec = 16.9407, eff = 2e-06
output_all/eqmass/skimmed/e3e3h_rl_skimmed.root: nGen = 500000, xsec = 10.8434, eff = 0
output_all/eqmass/skimmed/qqh_lr_skimmed.root: nGen = 500000, xsec = 343.03, eff = 2e-06
output_all/eqmass/skimmed/qqh_rl_skimmed.root: nGen = 500000, xsec = 219.486, eff = 1.2e-05
[Entries] hS: 15743 hB: 1248
[Integral] hS: 3.66813 hB: 15.6315
nbin = 50, bw = 2
xl = 24, xu = 36, nS = 2.18892, nB = 3.6282, sig = 0.907561
Significance = 0.907561, UL = 0.00181806

μμH, H→φφ→4b, mφ = 30 GeV, (+0.8,-0.3)




```
root [10] drawHist("(mphi[0][0]+mphi[1][0])/2",0,100,50,1)
Draw (mphi[0][0]+mphi[1][0])/2
Cut: ((Sum$(bprob) > 3.)&&(flvl[0]==13&&flvl[1]==-13))&&(mrec>120&&mrec<160)
Warning in <TCanvas::Constructor>: Deleting canvas with same name: c1
output_all/eqmass/hphiphi_m30_lr.root: nGen = 20000, xsec = 16.9786, eff = 0.3954
output_all/eqmass/hphiphi_m30_rl.root: nGen = 20000, xsec = 10.8586, eff = 0.39175
output_all/eqmass/e2e2h_lr.root: nGen = 500000, xsec = 16.9707, eff = 0.0012
output_all/eqmass/e2e2h_rl.root: nGen = 500000, xsec = 10.8691, eff = 0.001152
output_all/eqmass/skimmed/4f_zz_sl_lr_skimmed.root: nGen = 4199600, xsec = 838.079, eff = 8.81036e-06
output_all/eqmass/skimmed/4f_zz_sl_rl_skimmed.root: nGen = 2400000, xsec = 466.816, eff = 1.125e-05
output_all/eqmass/skimmed/e3e3h_lr_skimmed.root: nGen = 500000, xsec = 16.9407, eff = 2e-06
output_all/eqmass/skimmed/e3e3h_rl_skimmed.root: nGen = 500000, xsec = 10.8434, eff = 0
output_all/eqmass/skimmed/qqh_lr_skimmed.root: nGen = 500000, xsec = 343.03, eff = 2e-06
output_all/eqmass/skimmed/qqh_rl_skimmed.root: nGen = 500000, xsec = 219.486, eff = 1.2e-05
[Entries] hS: 15743 hB: 1248
[Integral] hS: 2.4511 hB: 11.6409
nbin = 50, bw = 2
 xl = 24, xu = 36, nS = 1.44346, nB = 2.33527, sig = 0.742559
Significance = 0.742559, UL = 0.00222204
```

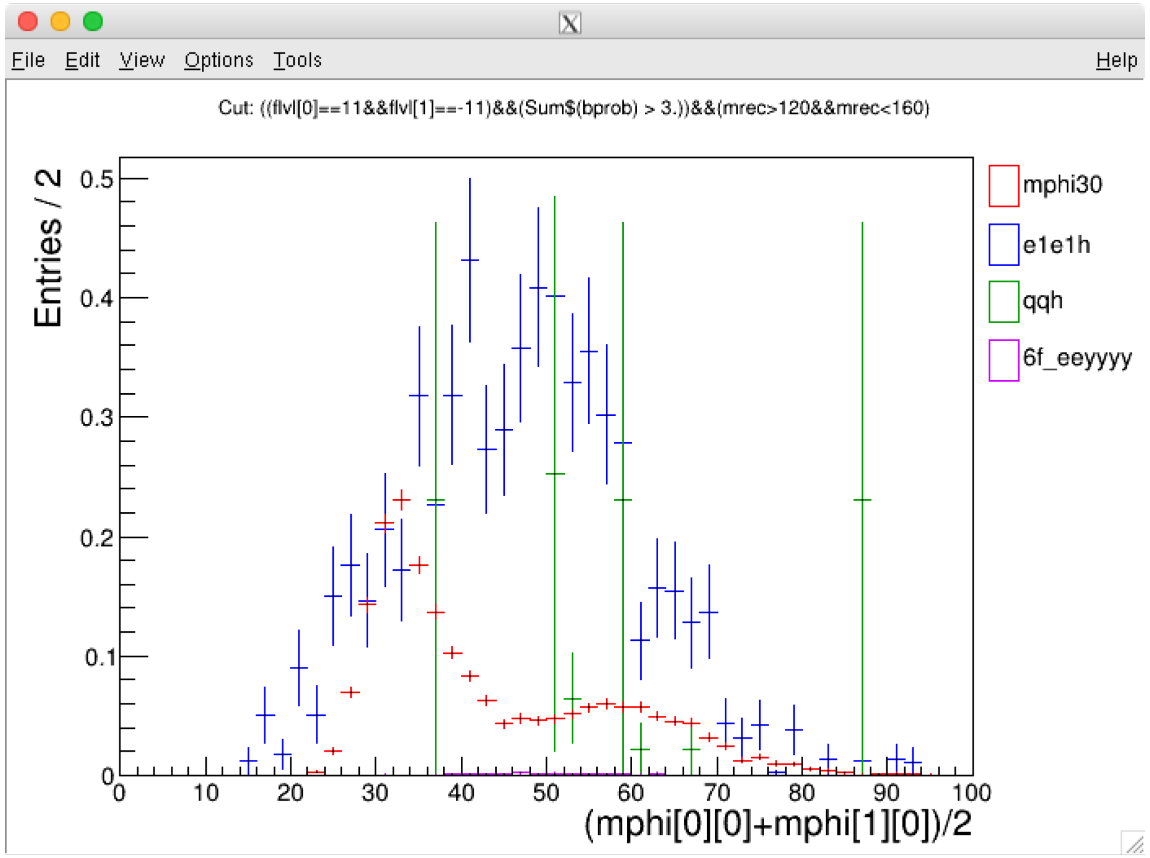
μμH, H→φφ→4b, mφ = 30 GeV, (-0.8,+0.3)



Draw (mphi[0][0]+mphi[1][0])/2
Cut: ((flvl[0]==11&&flvl[1]==-11)&&(Sum$(bprob) > 3.))&&(mrec>120&&mrec<160)
mphi30_lr: nExp = 8.95261, nGen = 20000, xsec = 17.004, eff = 0.31395
mphi30_rl: nExp = 0.342176, nGen = 20000, xsec = 10.8627, eff = 0.31565
e1e1h_lr: nExp = 9304.04, nGen = 500000, xsec = 17.6715, eff = 0.000964
e1e1h_rl: nExp = 350.875, nGen = 500000, xsec = 11.1389, eff = 0.000946
e1e1h_ll: nExp = 176.758, nGen = 500000, xsec = 0.623485, eff = 0.000886
e1e1h_rr: nExp = 36.4739, nGen = 498800, xsec = 0.623485, eff = 0.000813953
qqh_lr: nExp = 180605, nGen = 500000, xsec = 343.03, eff = 1.2e-05
qqh_rl: nExp = 6913.81, nGen = 500000, xsec = 219.486, eff = 8e-06
6f_eeyyyy_lr: nExp = 8.27105, nGen = 20000, xsec = 0.0157095, eff = 0.00365
6f_eeyyyy_rl: nExp = 0.243157, nGen = 20000, xsec = 0.00771928, eff = 0.00435
6f_eeyyyy_ll: nExp = 0.219506, nGen = 20000, xsec = 0.000774273, eff = 0.0077
6f_eeyyyy_rr: nExp = 0.0461558, nGen = 20000, xsec = 0.000788988, eff = 0.008
[Entries] hS: 12592 hB: 2288
[Integral] hS: 2.91687 hB: 11.7428
nbin = 50, bw = 2

xl = 22, xu = 40, nS = 1.60073, nB = 2.7385, sig = 0.768443
Significance = 0.768443, UL = 0.0021472

μμH, H→φφ→4b, mφ = 30 GeV, (+0.8,-0.3)



Draw (mphi[0][0]+mphi[1][0])/2
Cut: ((flvl[0]==11&&flvl[1]==-11)&&(Sum$(bprob) > 3.))&&(mrec>120&&mrec<160)
Warning in <TCanvas::Constructor>: Deleting canvas with same name: c1
mphi30_lr: nExp = 0.535626, nGen = 20000, xsec = 17.004, eff = 0.31395
mphi30_rl: nExp = 5.71923, nGen = 20000, xsec = 10.8627, eff = 0.31565
e1e1h_lr: nExp = 556.652, nGen = 500000, xsec = 17.6715, eff = 0.000964
e1e1h_rl: nExp = 5864.62, nGen = 500000, xsec = 11.1389, eff = 0.000946
e1e1h_ll: nExp = 36.4739, nGen = 500000, xsec = 0.623485, eff = 0.000886
e1e1h_rr: nExp = 176.758, nGen = 498800, xsec = 0.623485, eff = 0.000813953
qqh_lr: nExp = 10805.5, nGen = 500000, xsec = 343.03, eff = 1.2e-05
qqh_rl: nExp = 115559, nGen = 500000, xsec = 219.486, eff = 8e-06
6f_eeyyyy_lr: nExp = 0.494849, nGen = 20000, xsec = 0.0157095, eff = 0.00365
6f_eeyyyy_rl: nExp = 4.0642, nGen = 20000, xsec = 0.00771928, eff = 0.00435
6f_eeyyyy_ll: nExp = 0.045295, nGen = 20000, xsec = 0.000774273, eff = 0.0077
6f_eeyyyy_rr: nExp = 0.223678, nGen = 20000, xsec = 0.000788988, eff = 0.008
[Entries] hS: 12592 hB: 2288
[Integral] hS: 1.97304 hB: 7.33642
nbin = 50, bw = 2

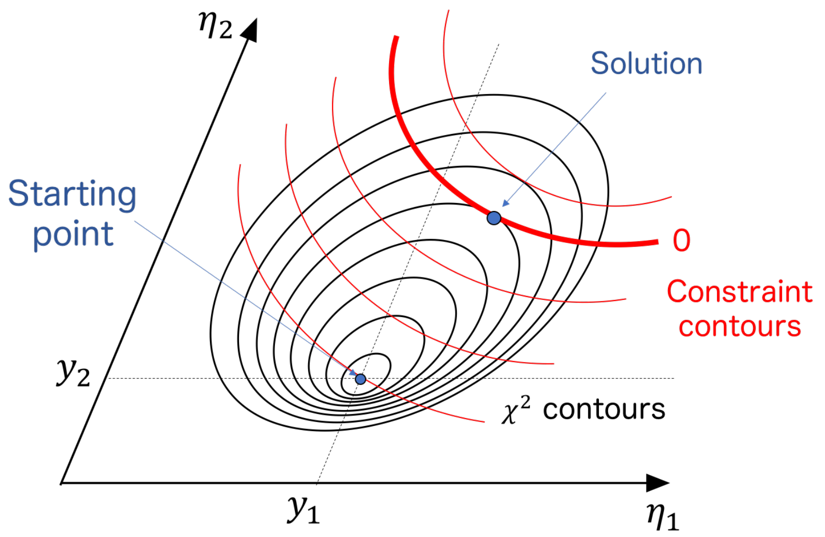
xl = 24, xu = 86, nS = 1.96365, nB = 6.84502, sig = 0.661621
Significance = 0.661621, UL = 0.00249388

Introduction: Kinematic fit

- Kinematic fit:
  - one of the constrained optimization method
  - adjustment of measured kinematic parameters under certain constraints
    - distributions of parameters e.g. energy resolution
    - kinematic relations among the parameters e.g. energy conservation
- Purposes:
  - improve accuracy of measurements (reconstruction)
  - estimate how well a given event matches a signal model (event selection)
- Standard procedure: minimize χ^2

$$\chi^2(\boldsymbol{\eta},\boldsymbol{\xi},\boldsymbol{\lambda}) = (\boldsymbol{y}-\boldsymbol{\eta})^T \boldsymbol{V}^{-1}(\boldsymbol{y}-\boldsymbol{\eta}) - 2\boldsymbol{\lambda}^T \boldsymbol{h}(\boldsymbol{\eta},\boldsymbol{\xi})$$

$\boldsymbol{y}$: measured variables
$\boldsymbol{\eta}$: fit parameters
$\boldsymbol{V}$: covariance matrix
$\boldsymbol{\xi}$: unmeasured parameters
$\boldsymbol{\lambda}$: Lagrange multipliers
$\boldsymbol{h}$: constraint functions



Our approach for non-Gaussian distributions

- The basic method assumes that the measured parameters would have Gaussian error against the true value.
- In order to treat arbitrary error distributions, the chi-square term is re-defined as the log-likelihood function;

$$\chi^2(\boldsymbol{\eta}, \boldsymbol{\xi}, \boldsymbol{\lambda}) = -2\ln L_{fo}(\boldsymbol{\eta}) - 2\boldsymbol{\lambda}^T \boldsymbol{h}(\boldsymbol{\eta}, \boldsymbol{\xi}) - 2\ln L_{sc}(\boldsymbol{\eta}, \boldsymbol{\xi})$$

$$L_{fo}(\boldsymbol{\eta}) = \prod_{i=1}^{n} f_i(y_i; \eta_i) \qquad L_{sc}(\boldsymbol{\eta}, \boldsymbol{\xi}) = \prod_{i=1}^{m} s_i(\boldsymbol{\eta}, \boldsymbol{\xi})$$

f_i : error distributions　　　s_i : soft constraint distributions

Note:

- The error distributions are normalized as the peak position returns 1.
- The soft constraint term is applied optionally.

- In the case of Gaussian distributions, the basic method is reproduced.

Notes on implementation

Requirements

- Numerical differentiation
  - Although the Gaussian case can be solved analytically, the arbitrary case needs numerical calculation.
- Resolution information
  - It is necessary to prepare the error distribution functions for each measured parameters.

Fitter algorithm

- Based on Sequential Quadratic Programming (SQP) method
- Hessian matrix is approximated by damped-BFGS method. (quasi-Newton method)
- The size of the iteration step (α) is adjusted by Armijo condition.

B-jet energy resolution

- The b-jet has asymmetric energy distribution due to neutrinos from semi-leptonic decay.
- We need to know the true energy distribution when a particular measured energy is obtained.
- The definition of the true jet:

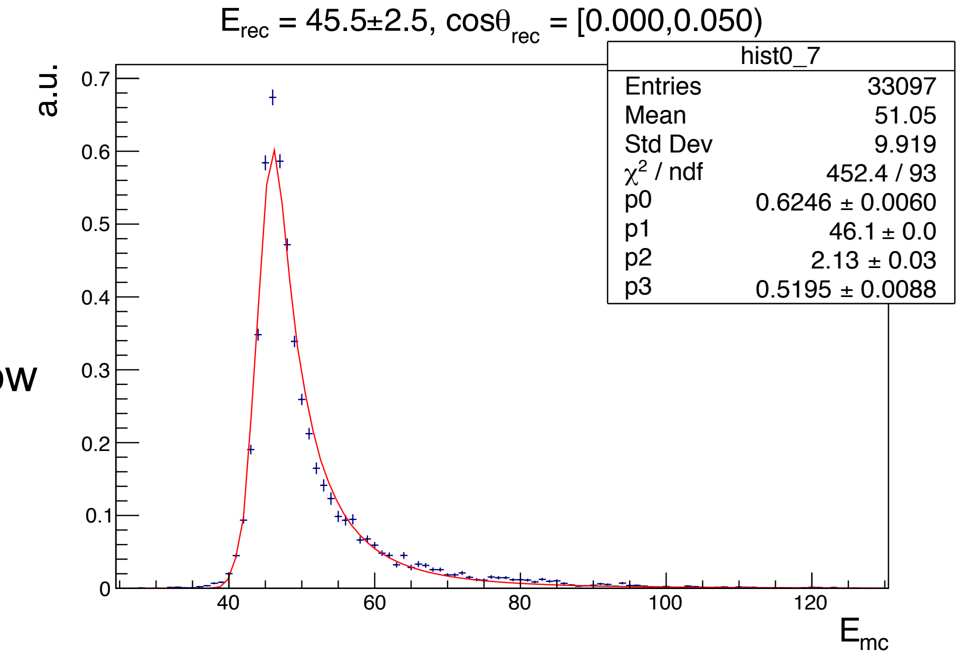
  Sum of the MCParticles which direction is close to reconstructed jet
  - Including neutrinos
- The resolutions are evaluated as the function of (E_{rec}., $\cos\theta_{rec}$) for each jet.

B-jet energy resolution: Evaluation setup

- Sample: b-jet pair
  - ILD DBD full simulation
  - E_{cm}: 20 - 240 GeV
  - PandoraPFA -> Durham jet clustering (LCFIPlus)

- Workflow:
  1. prepare data set of (E_{mc}, E_{rec}) in specific $\cos\theta_{rec}$ window
  2. generate E_{mc} histogram in specific E_{rec} window
     - normalized by all E_{rec} histogram
     - Each E_{mc} entry is shifted according as E_{rec} value.
  3. fit the spectrum

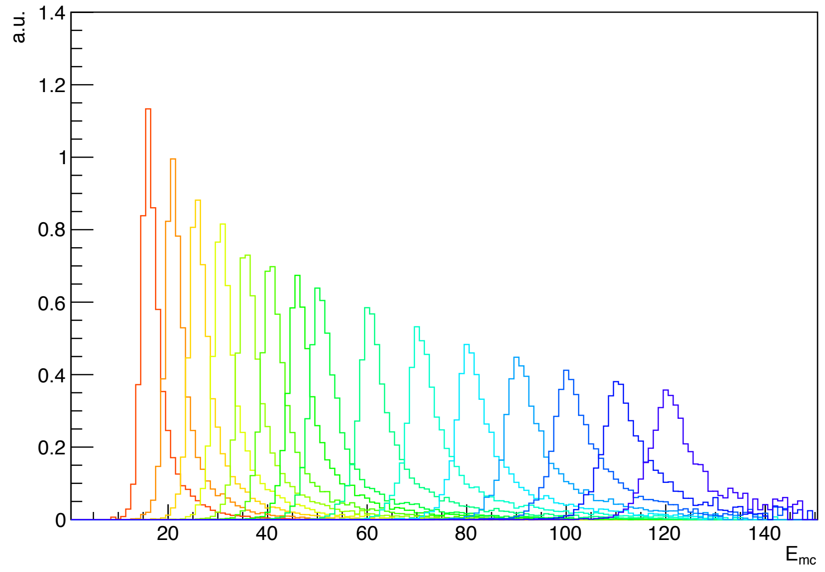
- Fit function: Crystal Ball (Gaussian & quartic polynomial)
  - p1: Gaussian mean
  - p2: Gaussian sigma
  - p3: Connection boundary in sigma unit

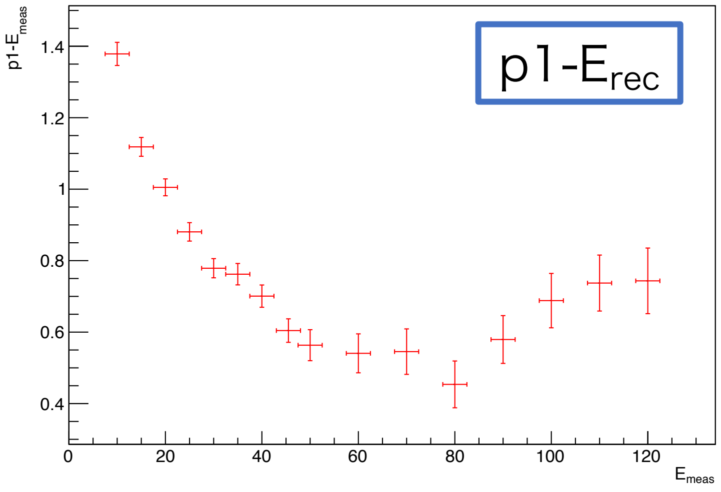


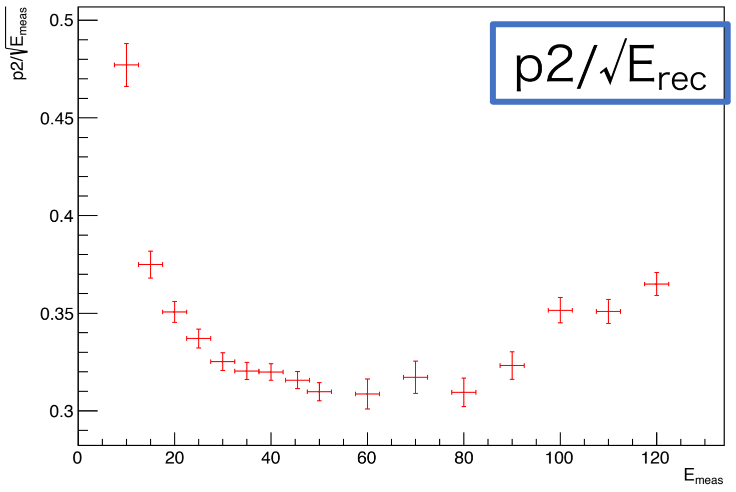
↑ True jet energy distribution for E_{rec} = 45.5 ± 2.5 GeV, $\cos\theta_{rec}$ = [0.,0.05)

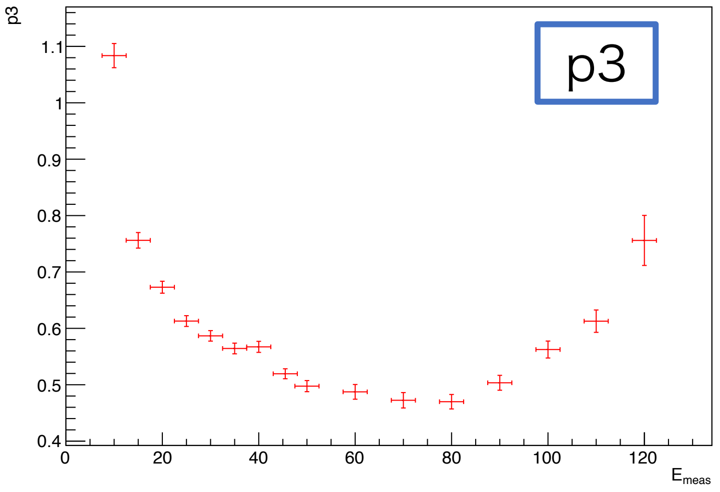
B-jet energy resolution: Energy dependence

- Energy scan in the barrel region
  - $\cos\theta_{rec}$ = [0.,0.05)
- In the higher edge the spectrum varies due to the lack of statistics.
- Parameters between points are interpolated.



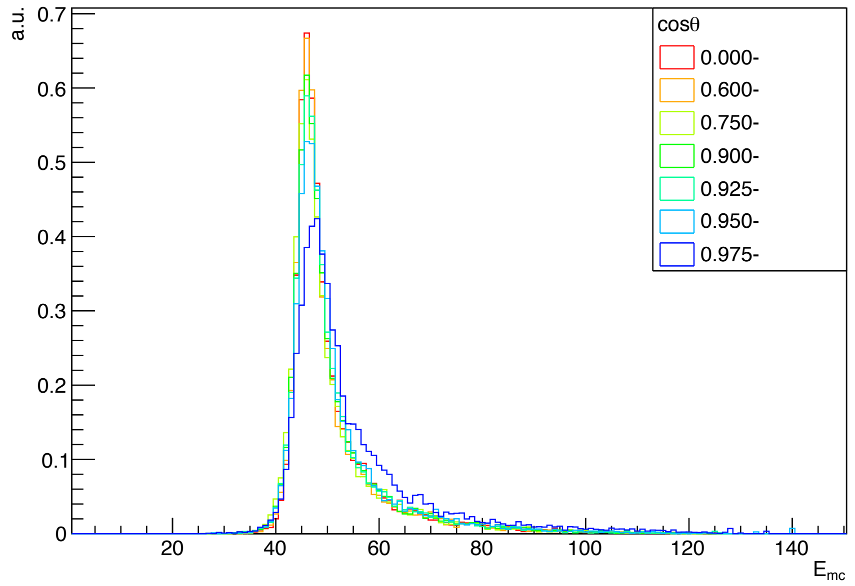


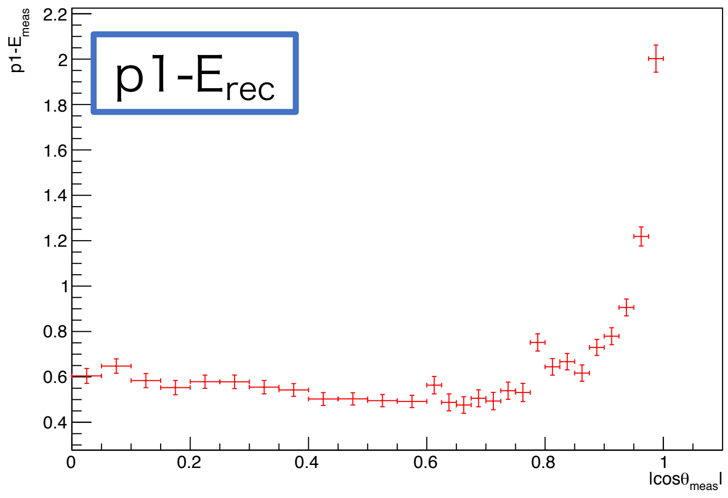


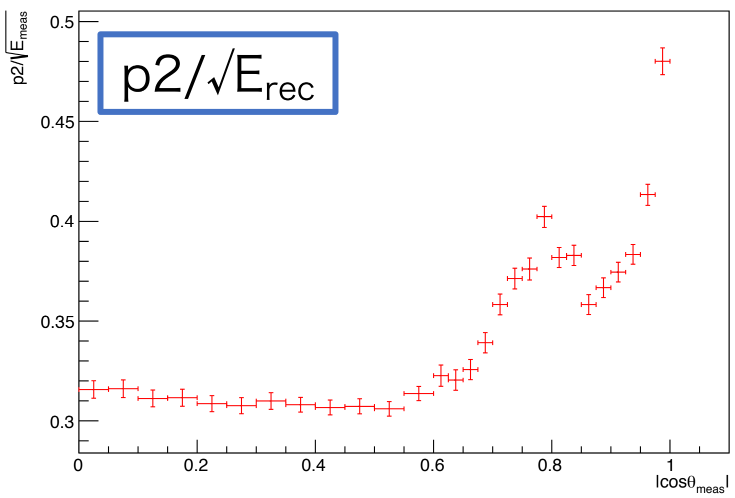


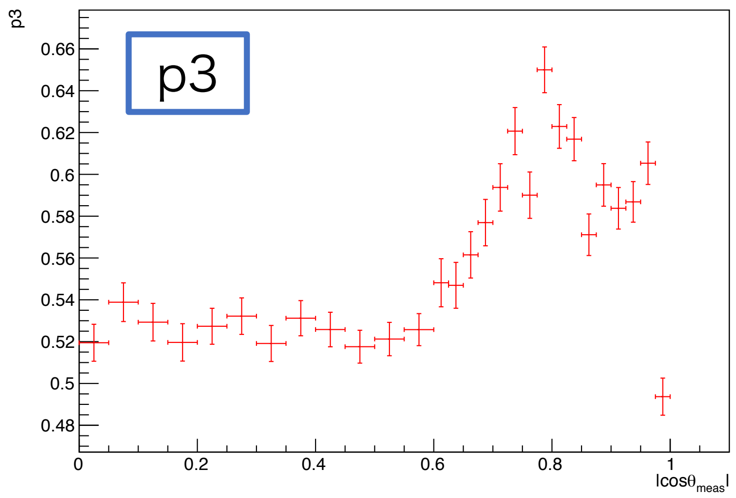
B-jet energy resolution: Angle dependence

- Angle scan at E_{rec} = 45.5 GeV
- JER is worse for forward jet as expected.



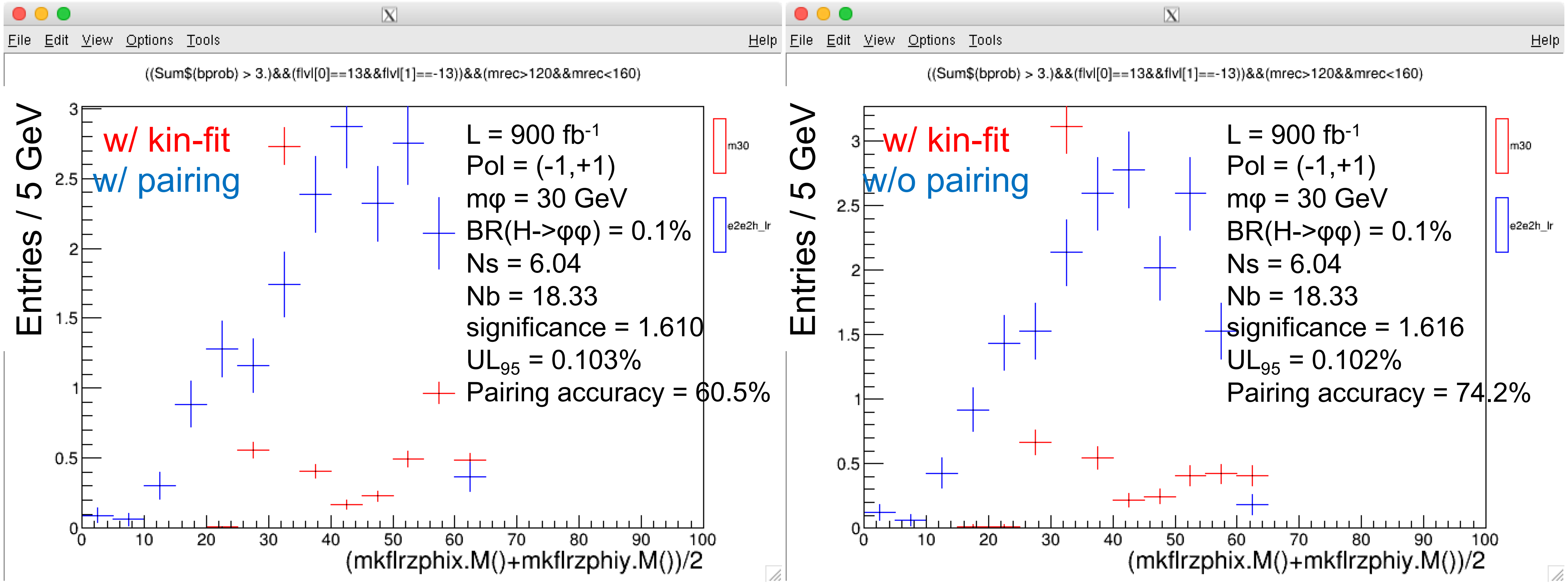






Test kinematic fitting

- Signal: 20,000 events / pol.
- e2e2h: 500,000 events / pol.

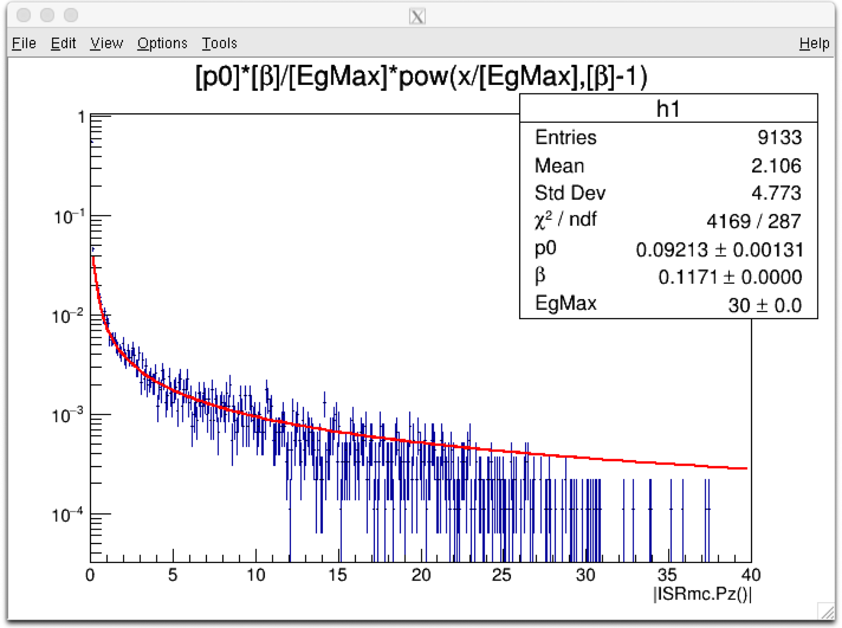


ISR spectrum

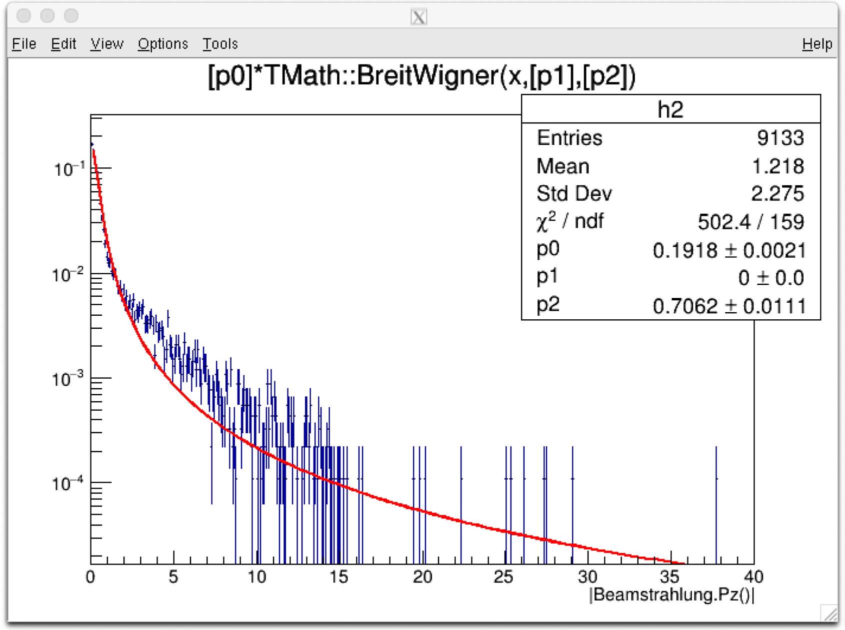
M. Beckmann, “Treatment of Photon Radiation in Kinematic Fits at Future e+e– Colliders”
F.A. Berends and R. Kleiss, Nucl. Phys. B177 (1981) 237

- ISR: $$\mathcal{P}\left(p_{z,\gamma}\right) = \frac{\beta}{2E_{\max}} \cdot \left|\frac{p_{z,\gamma}}{E_{\max}}\right|^{\beta-1} \qquad \beta = \frac{2\alpha}{\pi}\left(\ln\frac{s}{m_e^2} - 1\right)$$
- beamstrahlung: ?

ISR



beamstrahlung



Ecm - Z - H