Search for Higgs decaying to exotic scalers using kinematic fit

Yu Kato, Tomohiko Tanabe, Masakazu Kurata,

Shogo Kajiwara, Takanori Mogi, Satoru Yamashita

The University of Tokyo, Iwate Prefectural University, KEK, ICEPP

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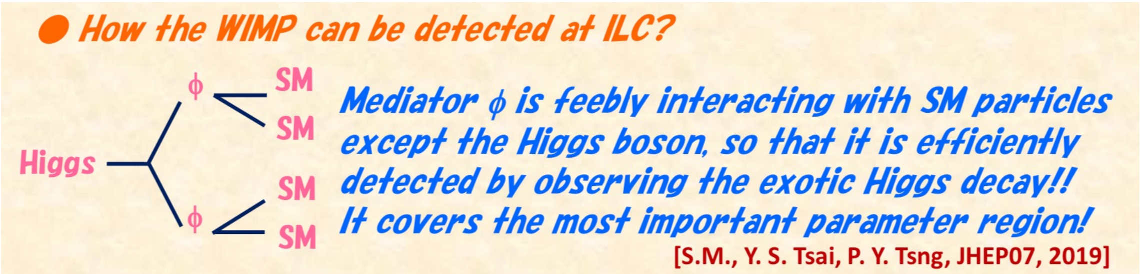
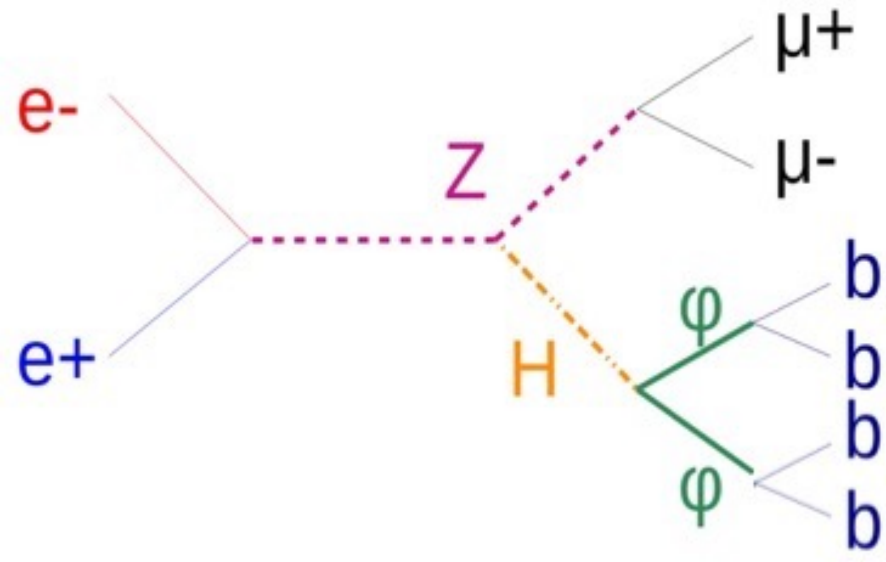
Search for Higgs → scalar mediator

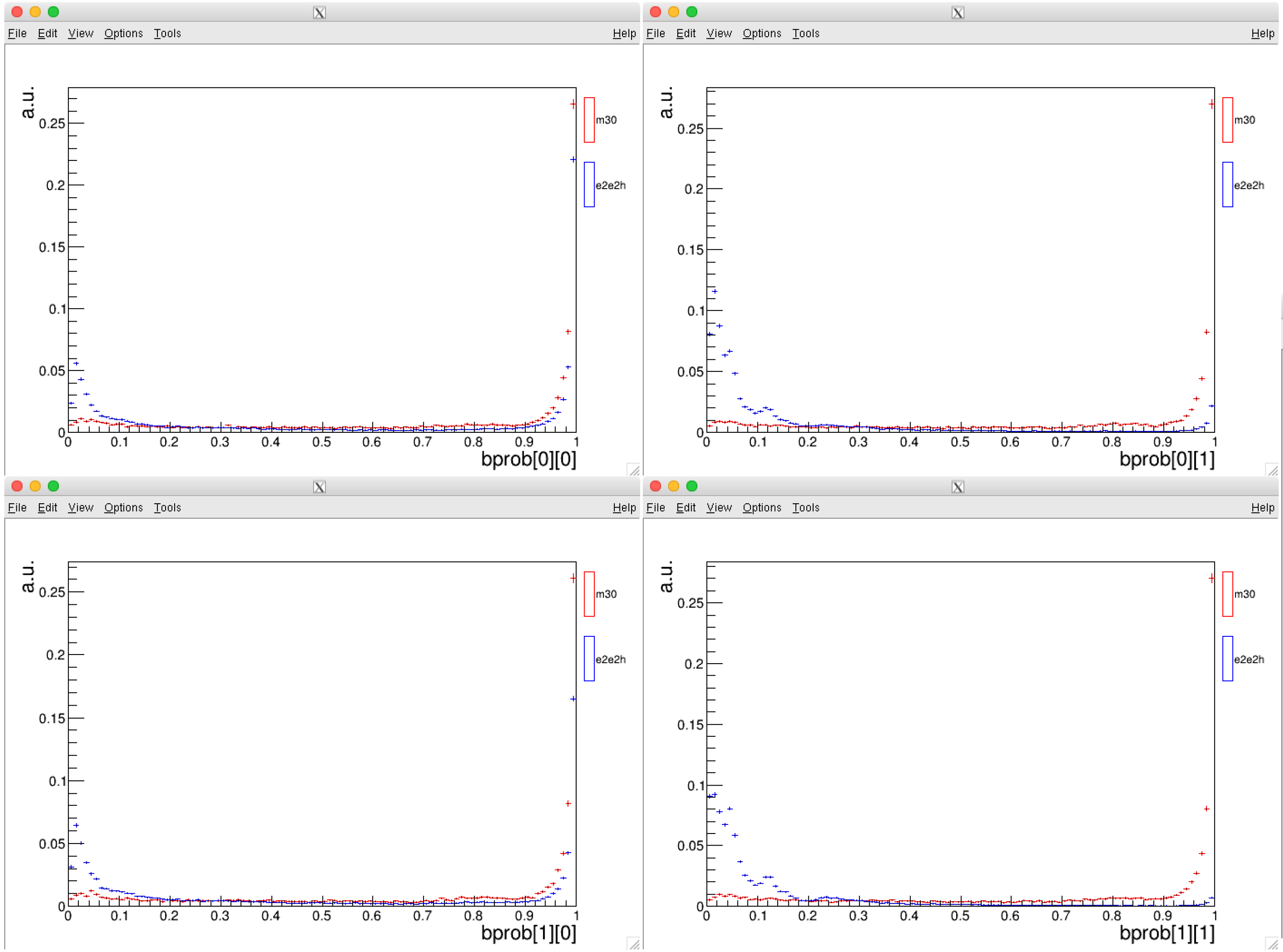
- Motivation:
  - Higgs can couple to WIMP DM through the scalar mediator φ.
  - The mediator appears as the Higgs exotic decay.
- Target channel:
  - e+e- → ZH → μμφφ → μμbbbb
- Simulation setup:
  - Generator: WHIZARD 2.8.5
    - Assumption of φ mass: 15, 30, 45, 60 [GeV]
  - ILC parameter:
    - √s = 250 GeV, polarization { (-0.8,+0.3), (+0.8,-0.3) }
  - Detector: ILD latest setting (mc-2020)
- Status:
  - ✓ Sample preparation
    - Generate sample with the MSSM_CKM model
    - Simulate with DDSim, Reconstruct with MarlinStdReco, the same as the mc-2020 setting
  - ✓ Fast analysis
    - IsolatedLeptonTagging, JetClustering (4-jet) and Flavor tagging
    - I use only the main background process of μμH.
  - ➢ Test fitting
  - ☐ Detailed analysis



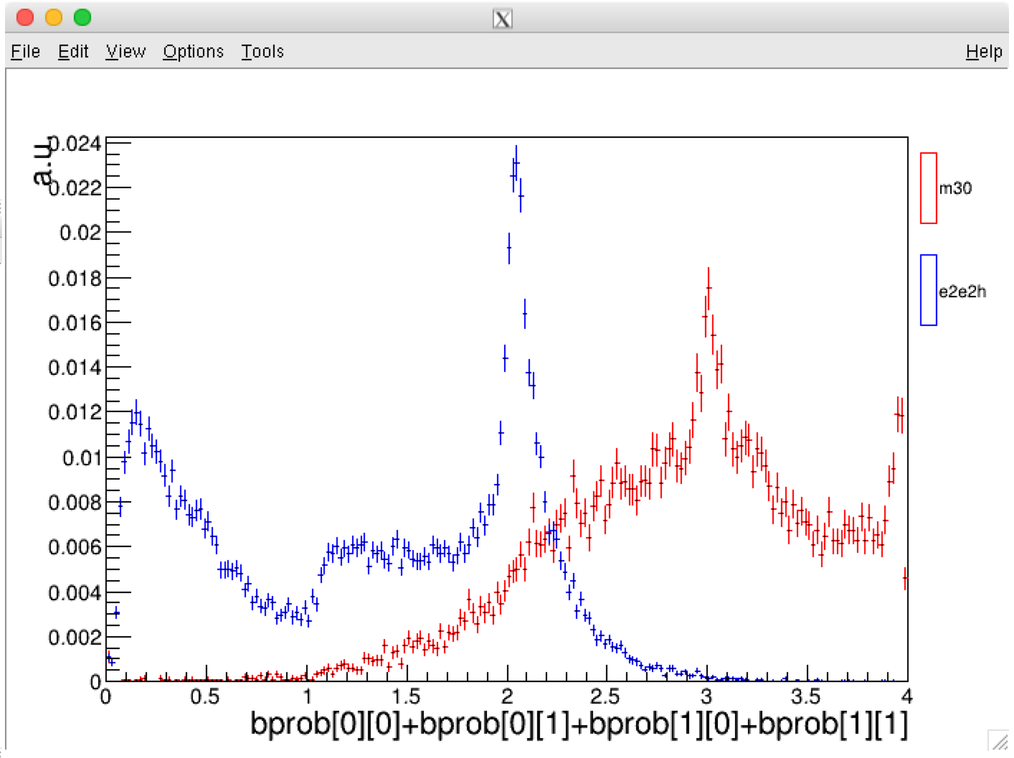
S. Matsumoto(Kavli IPMU), ILC summer camp 2020



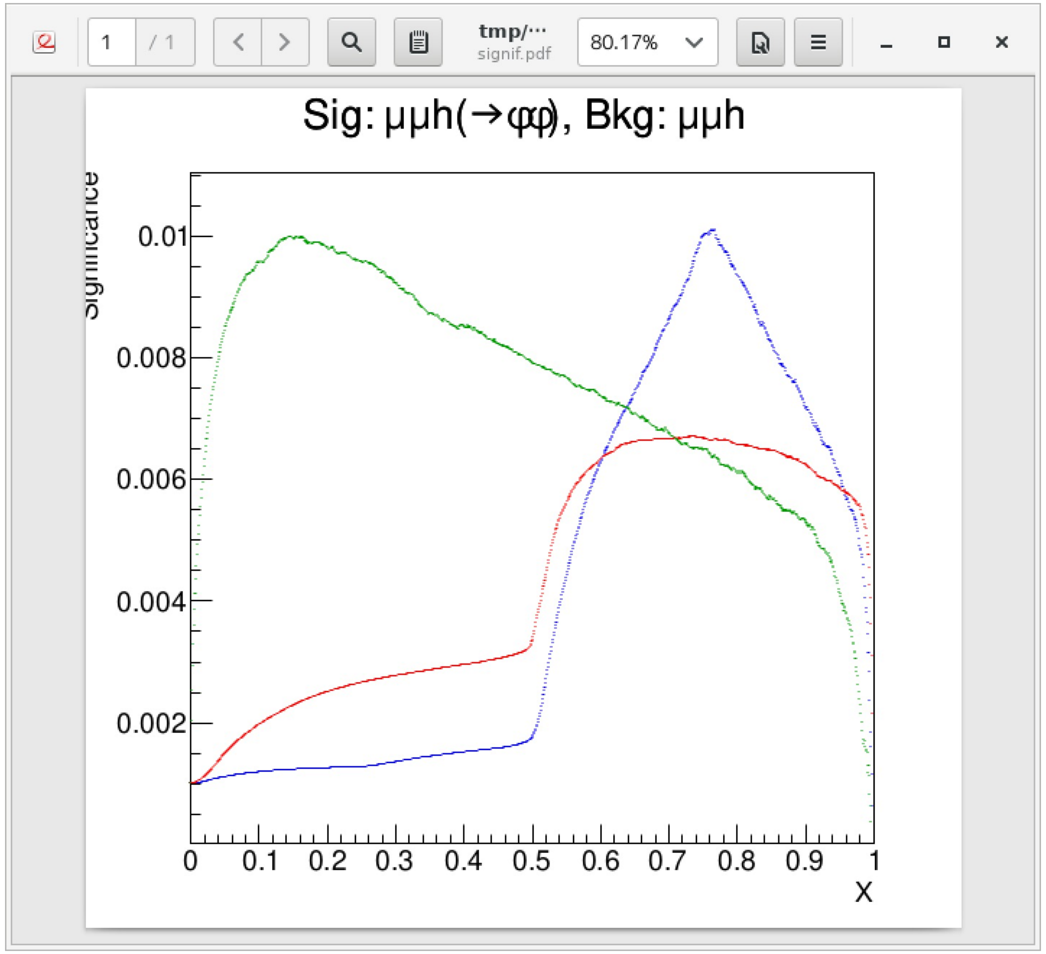
Fast Analysis of hφφ: b-probability

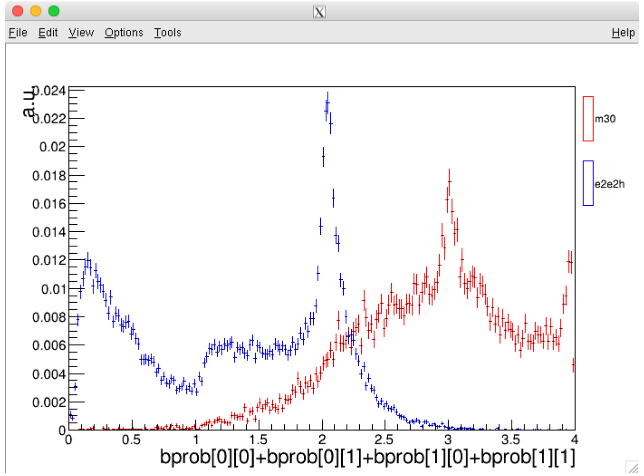


- LCFIPlus flavor tagging are used after the jet clustering with Durham forced to 4 jets.



b-tag cut



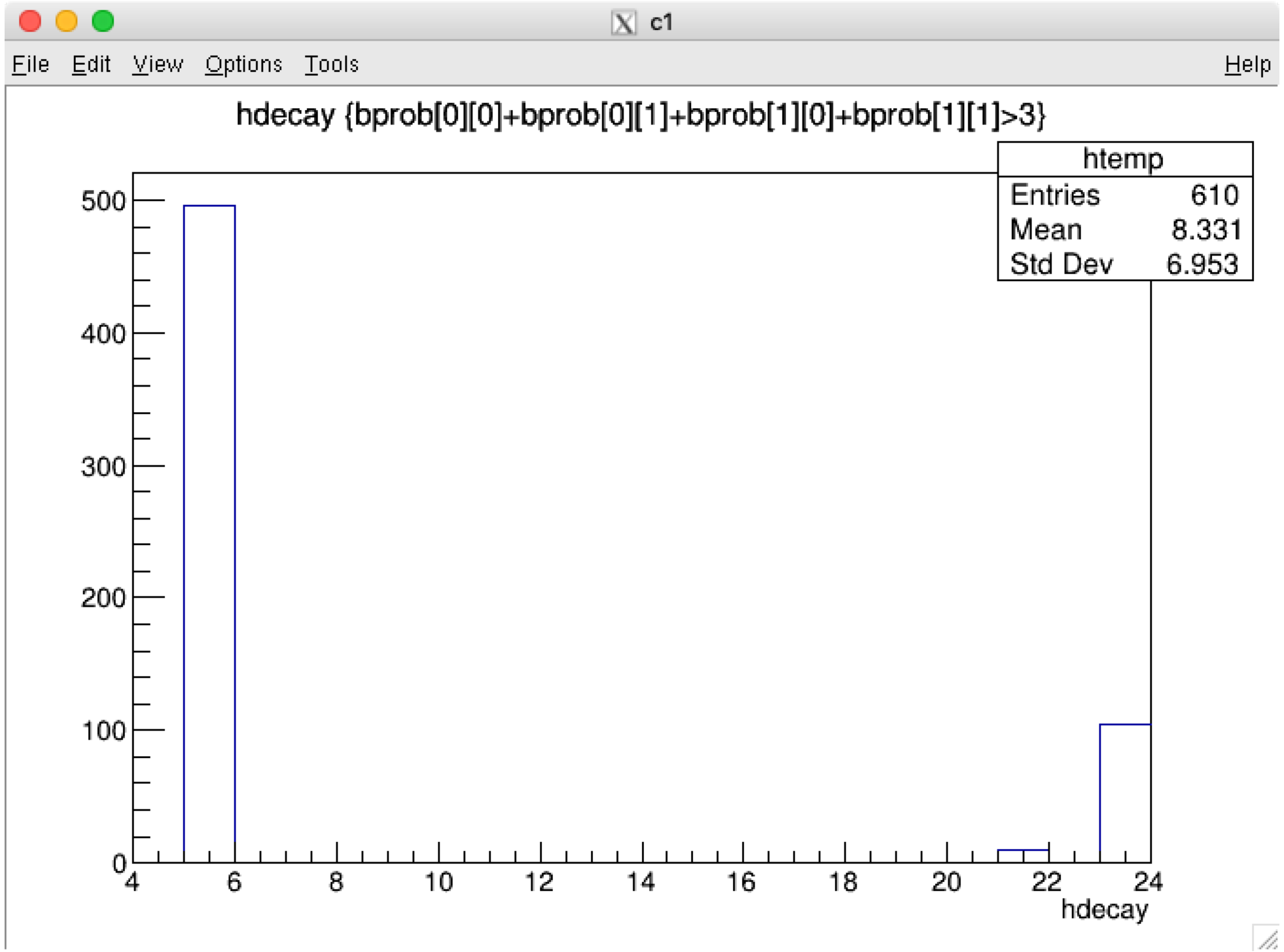


Sum$(bprob)/4 ← BEST
Max Significance = 0.0101048
when Sum$(bprob)/4 = 0.764 -> Sum$(bprob) = 3.056
eff=0.37548, pur=0.290283

(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

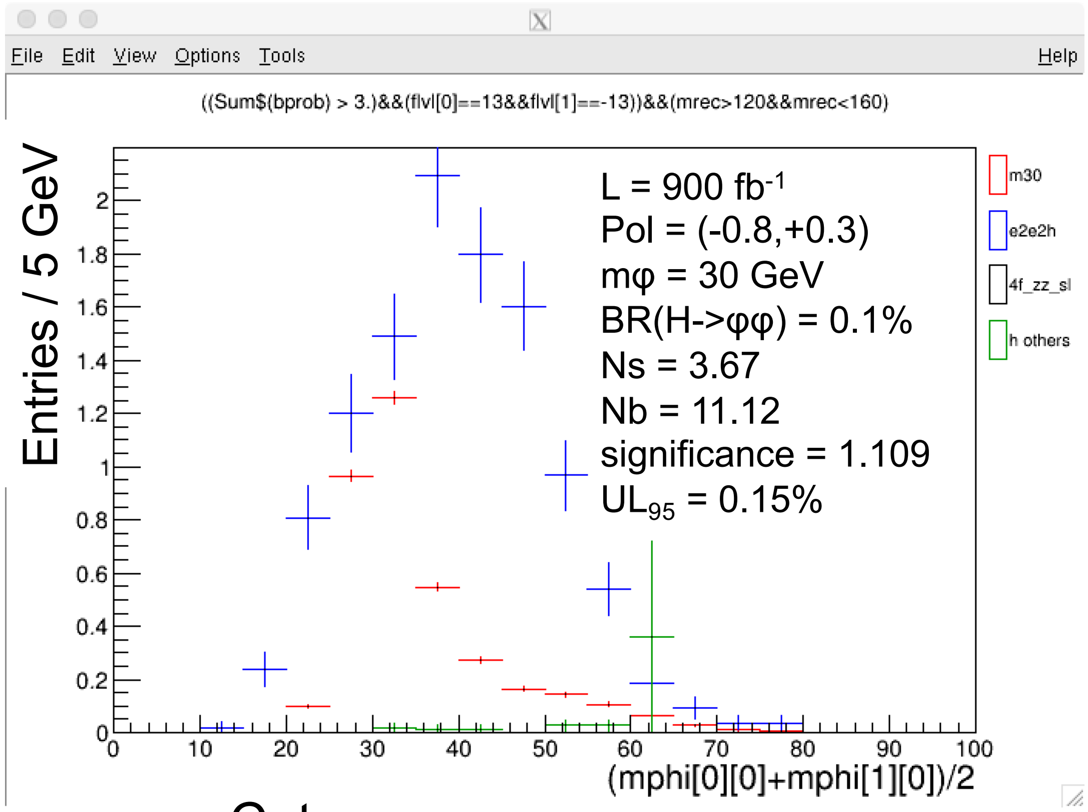
Higgs decay mode in remaining μμH process

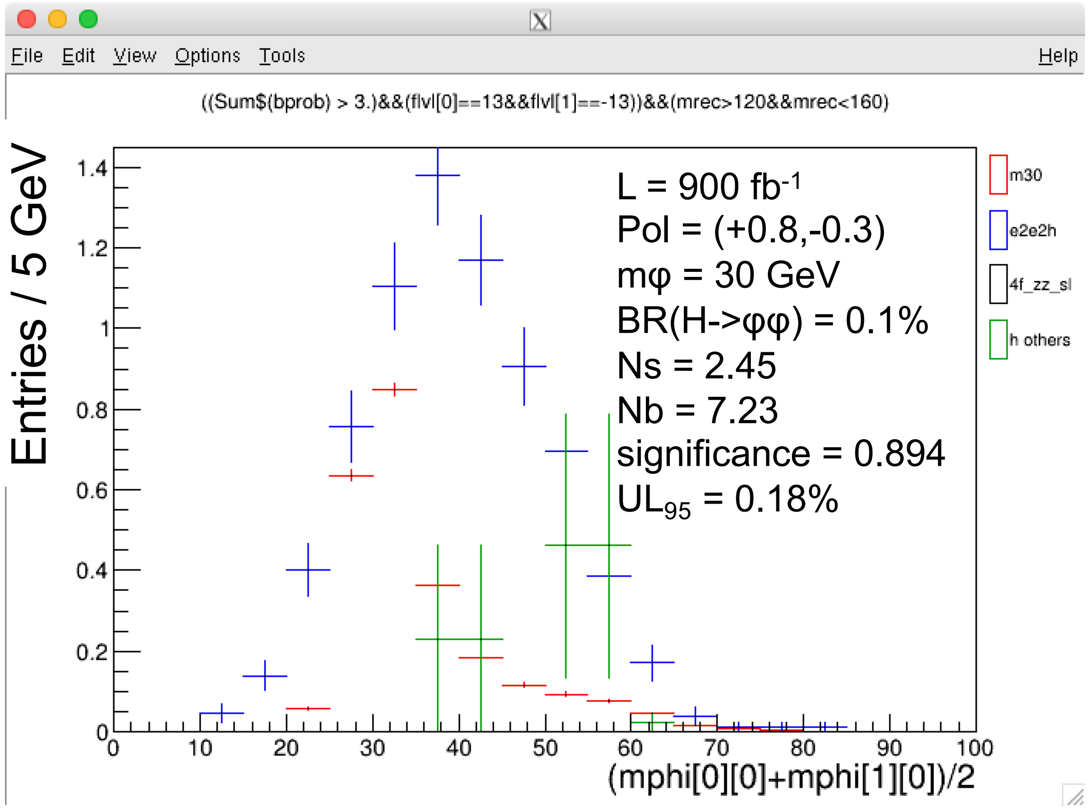


- Pol = (-1,+1)
- Cut: Sum$(bprob)/4 > 3
- Efficiency = 610/500,000 = 0.122%
- Remaining decay mode
  - H->bb: ~82%
  - H->ZZ: ~16%
  - H->gg: ~2%

Fast Analysis of hφφ

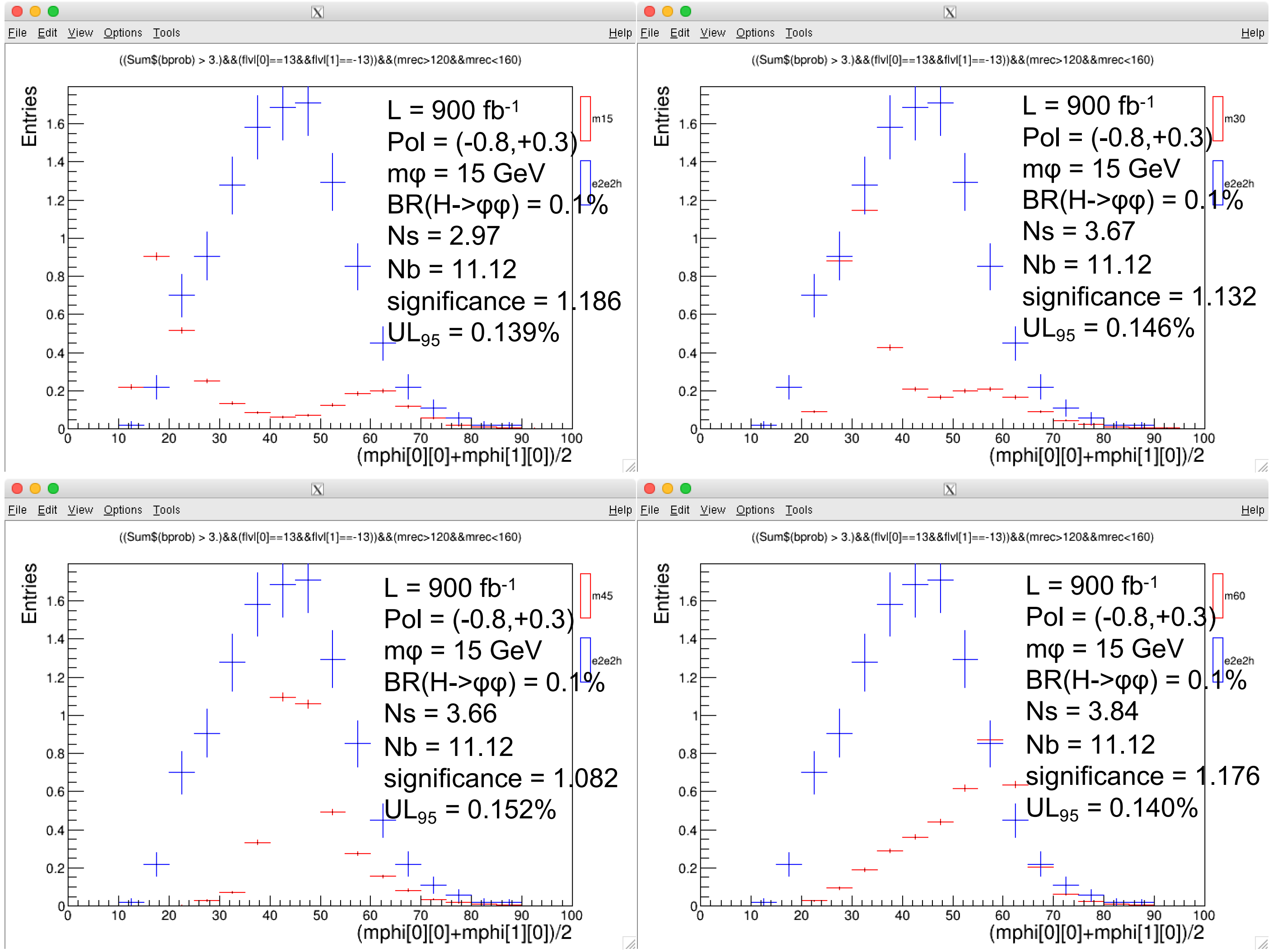
- Signal: 20,000 events / pol.
- e2e2h: 500,000 events / pol.





- Cut
  - Number of isolated lepton = 2, and tagged as muon pair
  - Sum of 4 jet b-probability > 3
  - The recoil mass is included in (120 GeV, 160 GeV).
- Including all the 2f, 4f and SM higgs backgrounds
- Remaining background is mainly μμH and a few qqH, ττH.

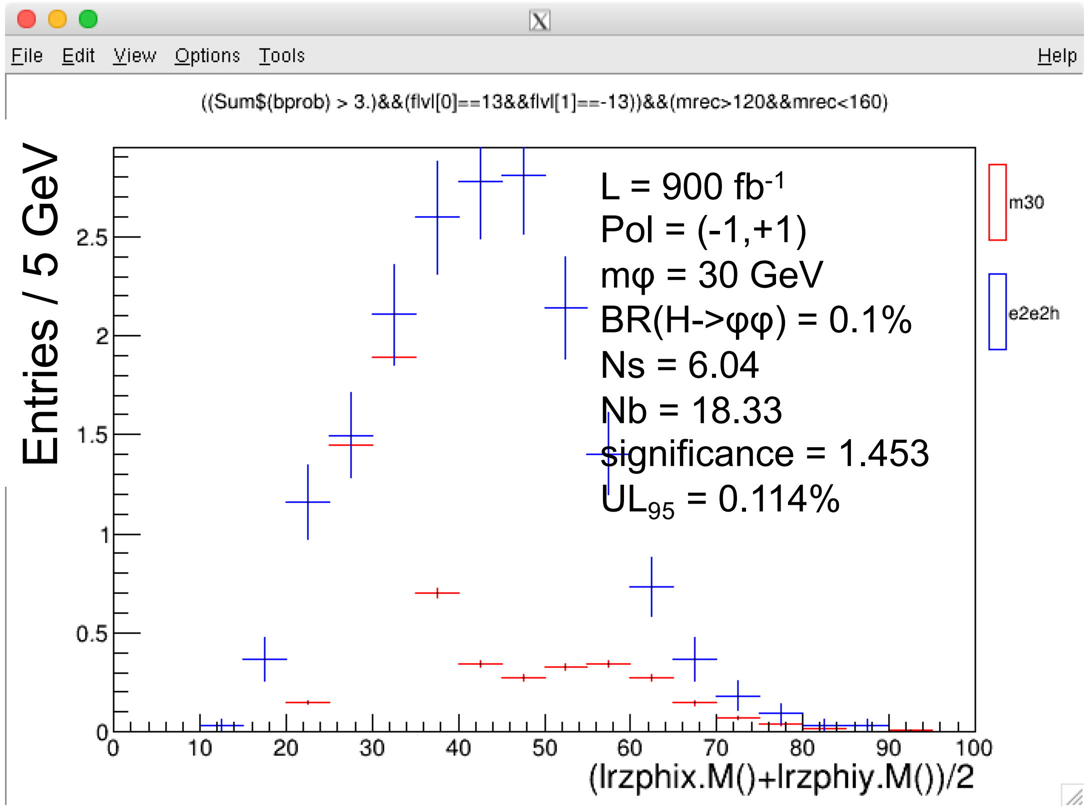
Comparison of φ mass

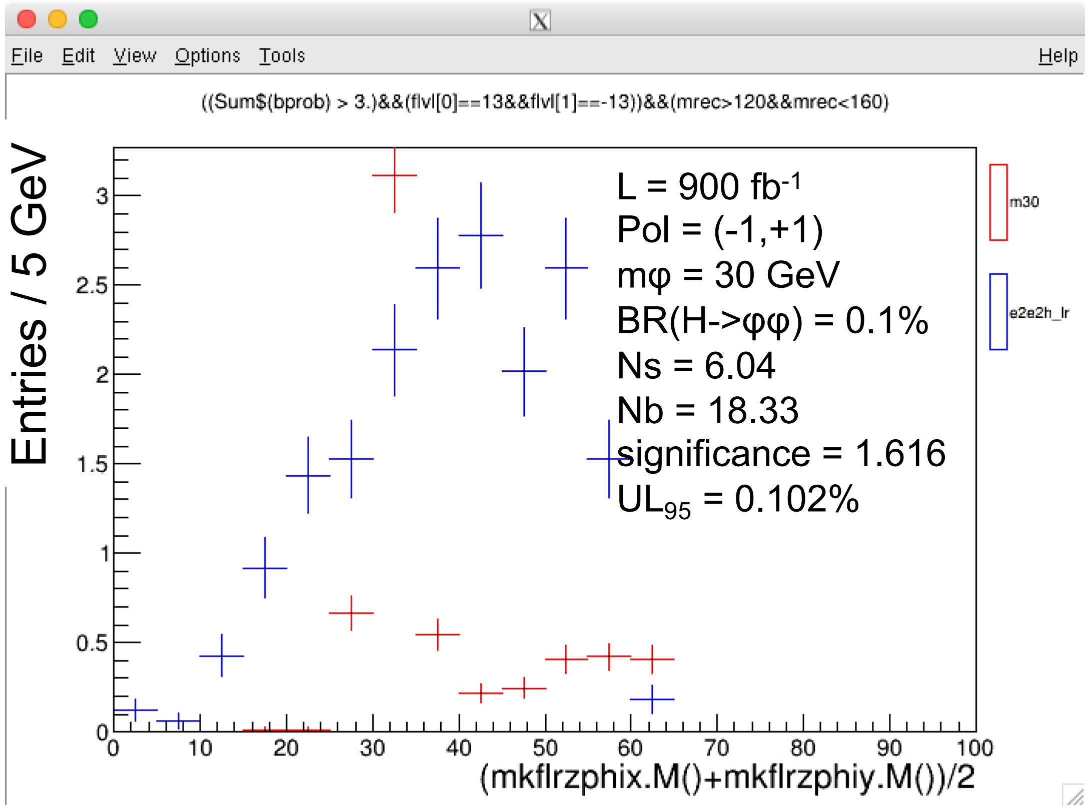


mφ	UL-left	UL-right	UL-comb
15	0.139%	0.163%	0.106%
30	0.146%	0.177%	0.113%
45	0.152%	0.183%	0.117%
60	0.140%	0.170%	0.108%

Test kinematic fitting

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

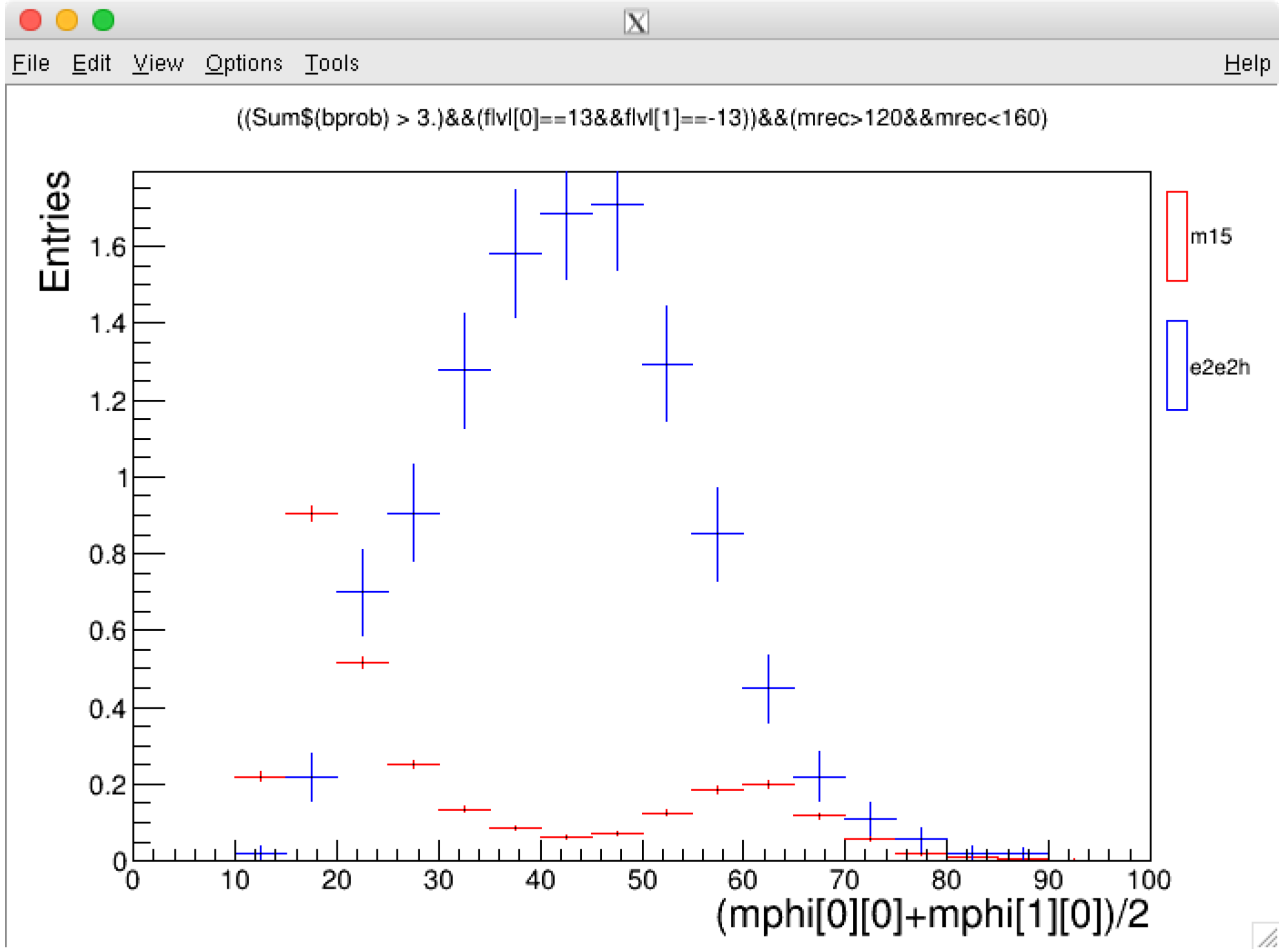




- Kinematic fitting are performed and get some improvement.
  - Fit Object
    - 2 MuonFitObject
    - 4 JetFitObject
    - 1 ISRPhotonFitObject
    - Jet resolution: b-jet pair
  - Constraint
    - Total Energy/Px/Py/Pz for all FOs
    - Higgs mass = 125 GeV for bb
    - Same mass of φs

backup

15 GeV

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Draw (mphi[0][0]+mphi[1][0])/2
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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
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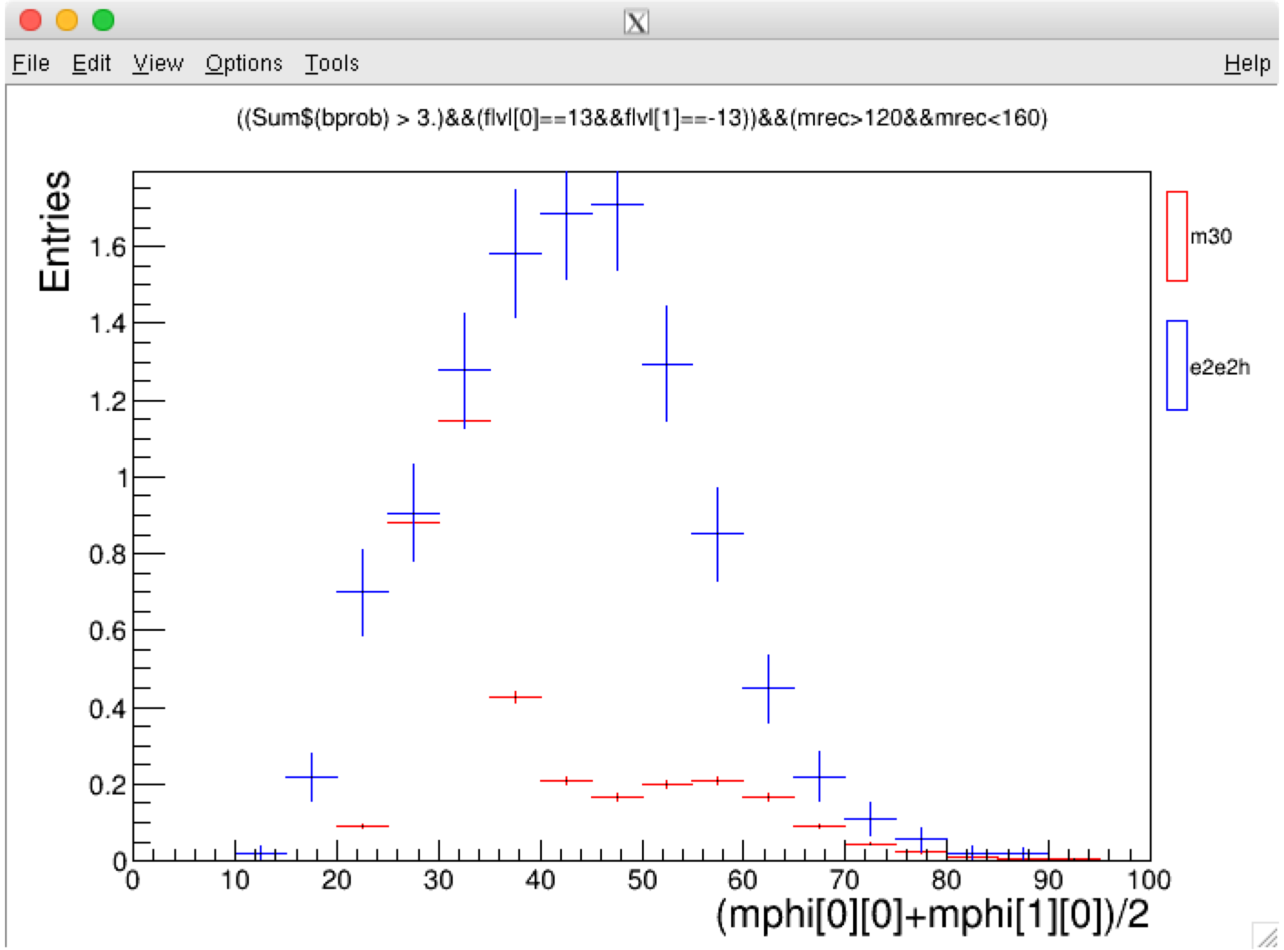
```

30 GeV



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x = 32.5, nS = 1.14801, nB = 1.27755, nS/nB = 0.898609
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x = 47.5, nS = 0.16574, nB = 1.70979, nS/nB = 0.096936
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x = 87.5, nS = 0.00288701, nB = 0.0178701, nS/nB = 0.161555
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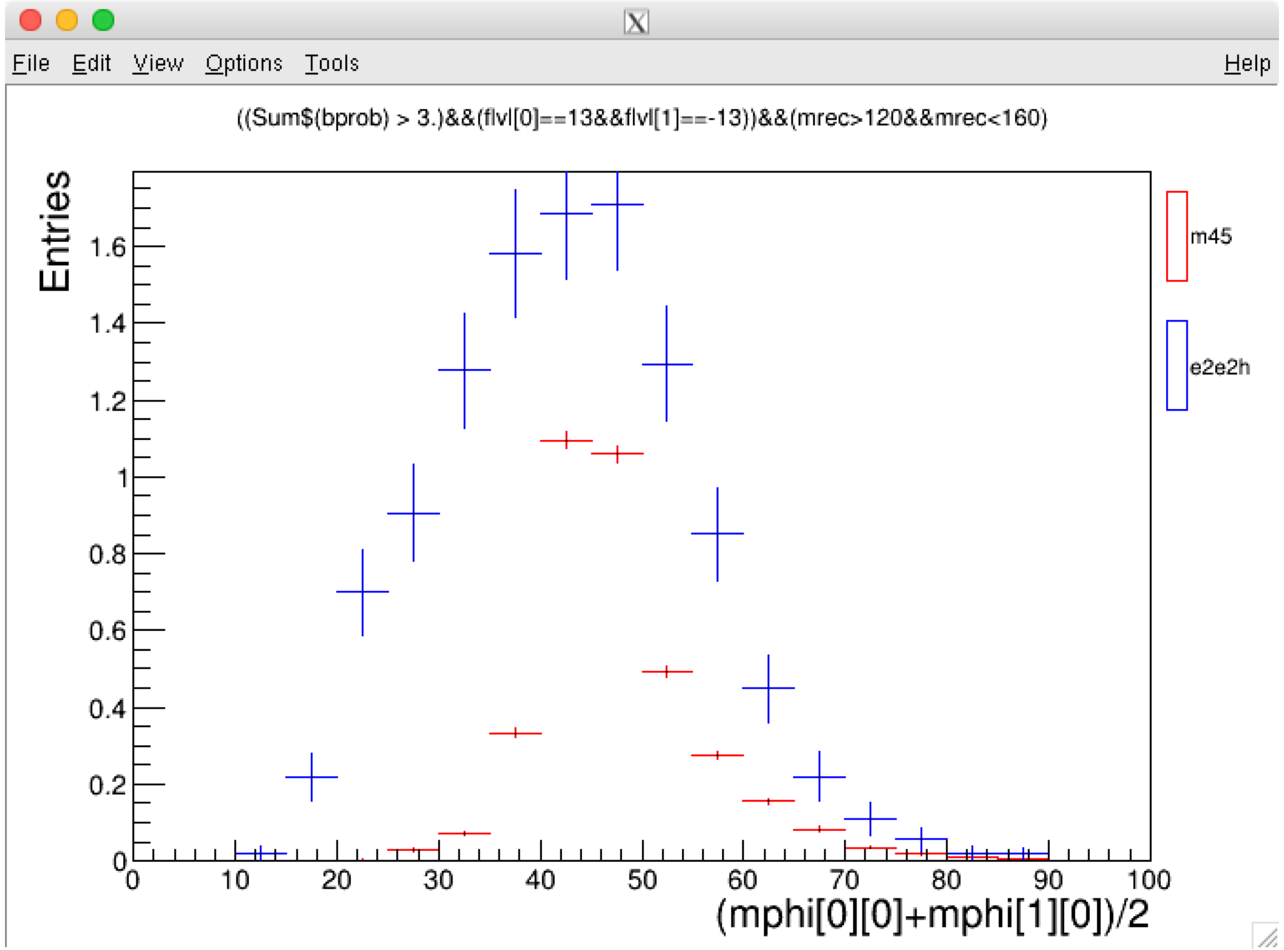
45 GeV

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```
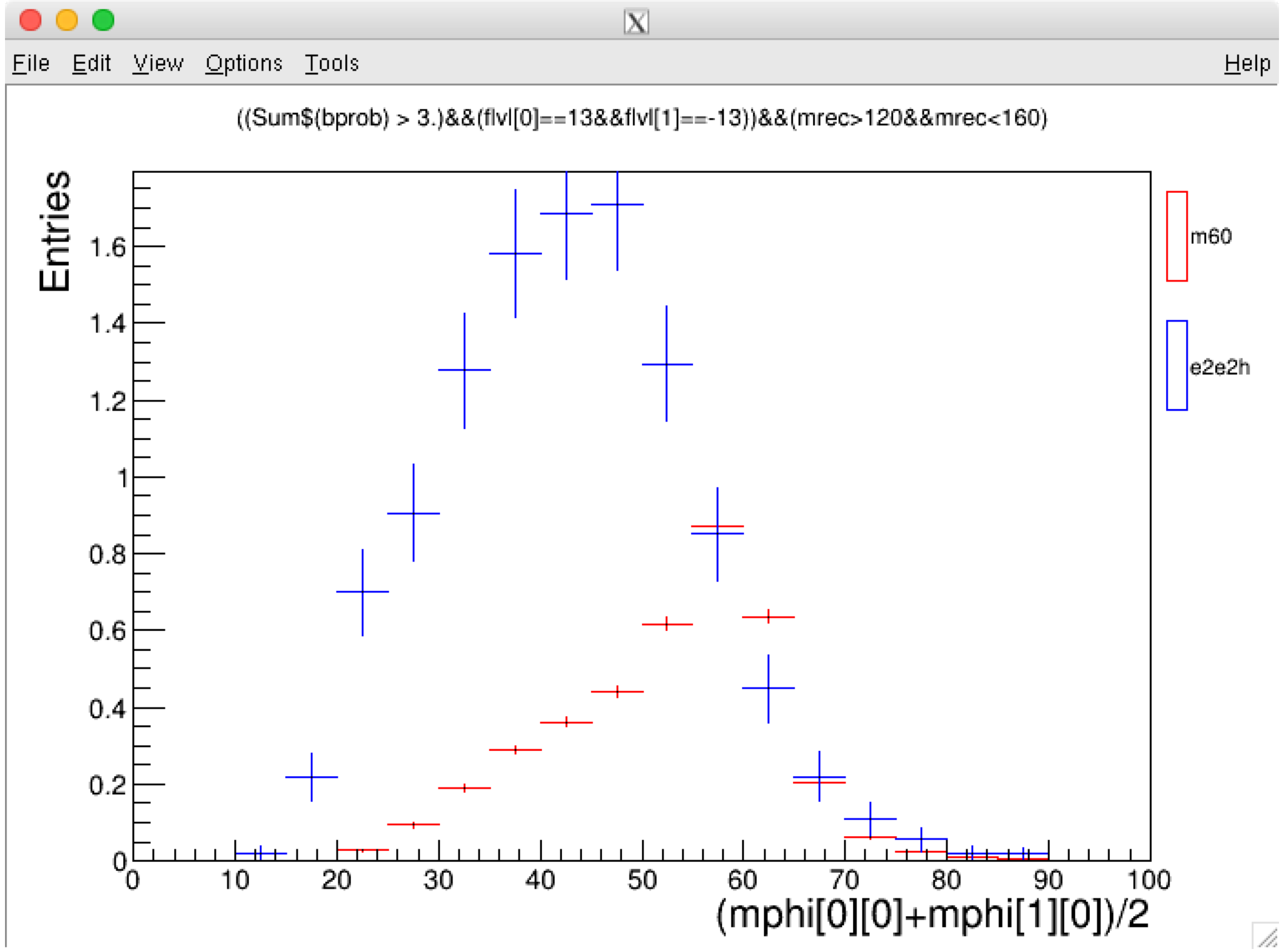

60 GeV



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Draw (mphi[0][0]+mphi[1][0])/2
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arxiv.org/1612.09284

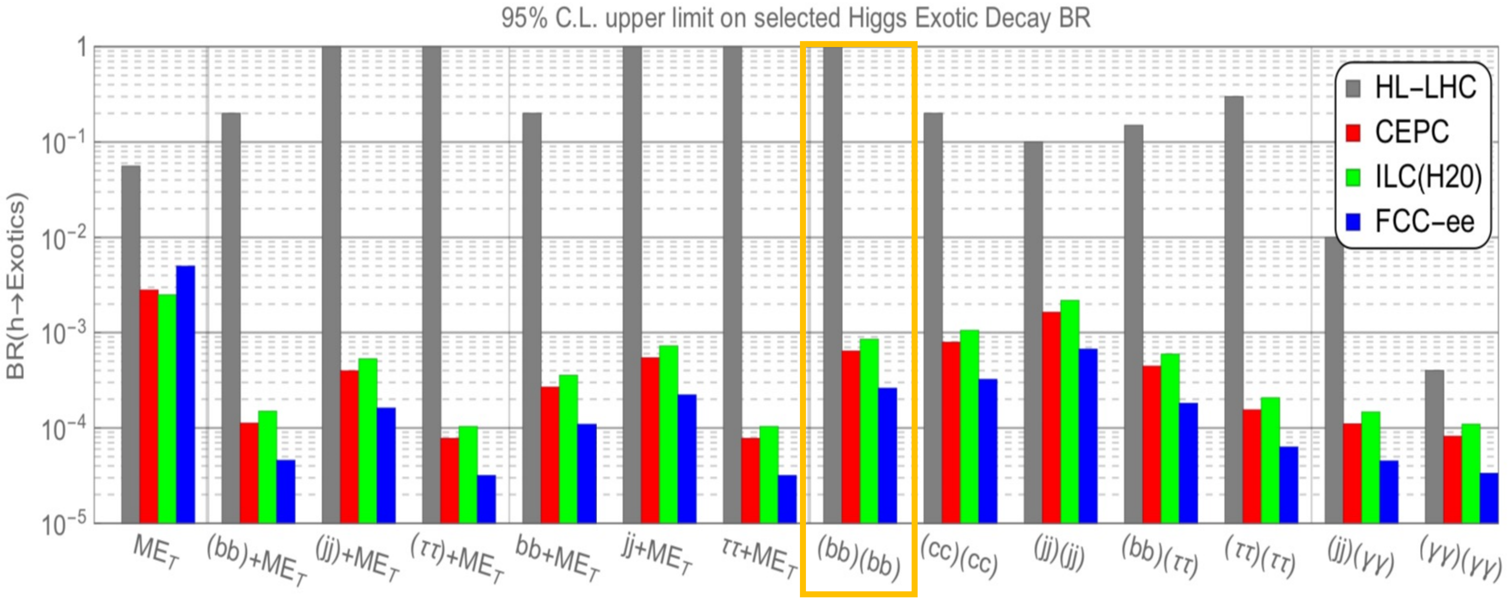


Fig. 12. The 95% C.L. upper limit on selected Higgs exotic decay branching fractions at HL-LHC, CEPC, ILC and FCC-*ee*. The benchmark parameter choices are the same as in Table 3. We put several vertical lines in this figure to divide different types of Higgs exotic decays.

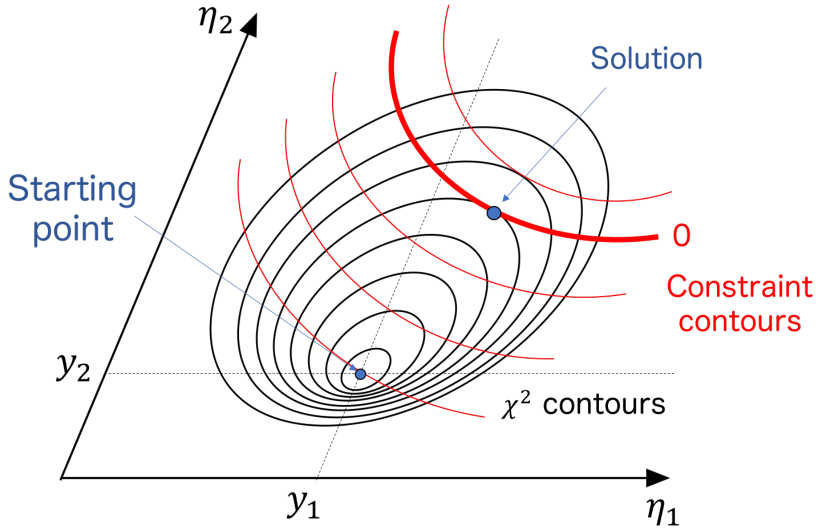
Introduction: Kinematic fit

- 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

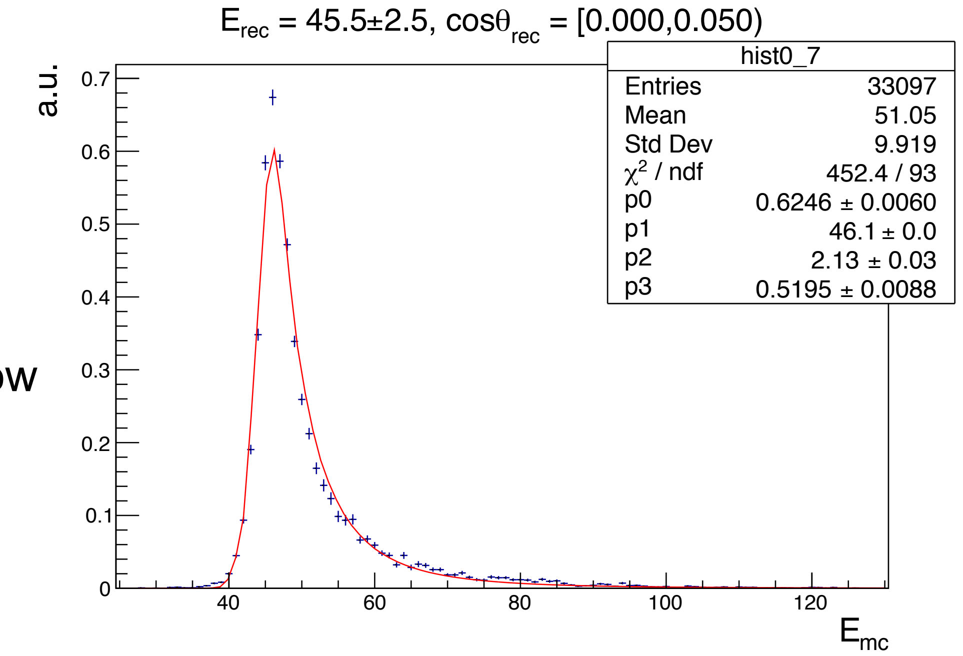
◦ The resolutions are evaluated as the function of (E_{rec}, $\cos\theta_{rec}$) for each jet.

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

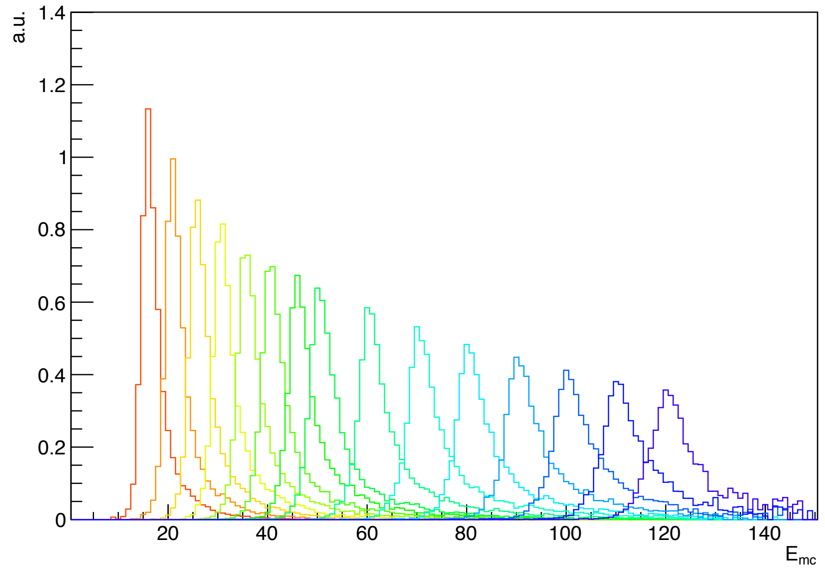
◦ Fit function: Crystal Ball (Gaussian & quartic polynomial)
  - p1: Gaussian mean
  - p2: Gaussian sigma
  - p3: Connection boundary in sigma unit

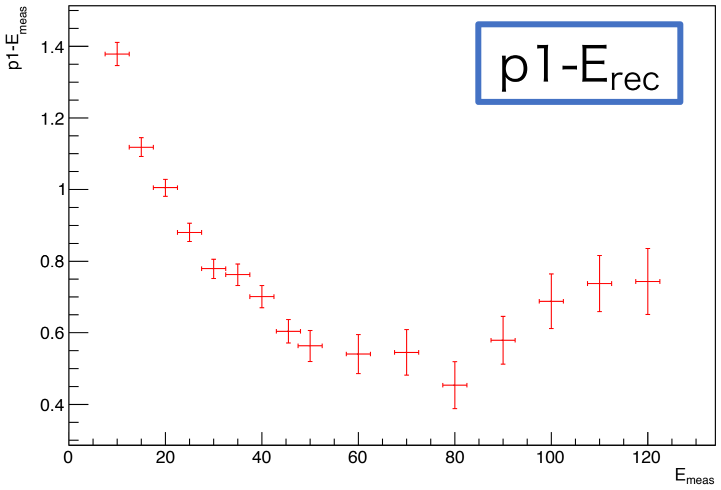


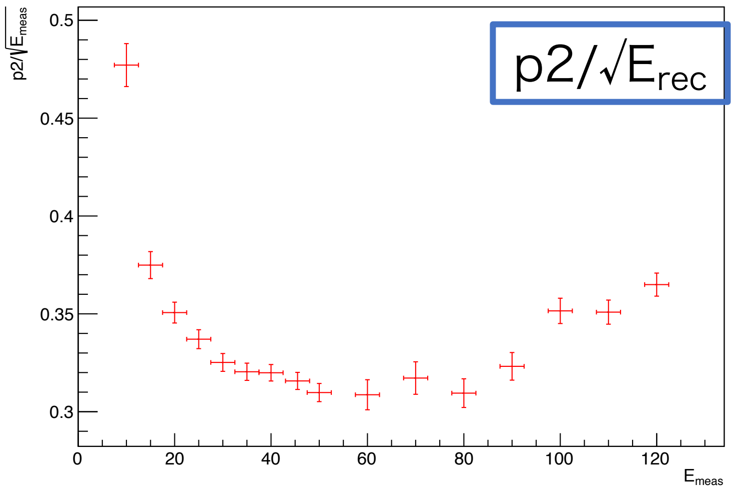
↑ True jet energy distribution for E_{rec} = 45.5 ± 2.5 GeV, $\cos\theta_{rec}$ = [0.,0.05)

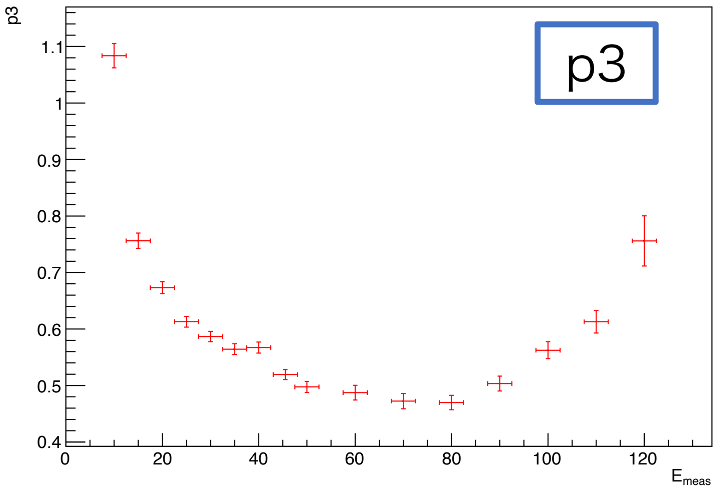
B-jet energy resolution: Energy dependence

- 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.



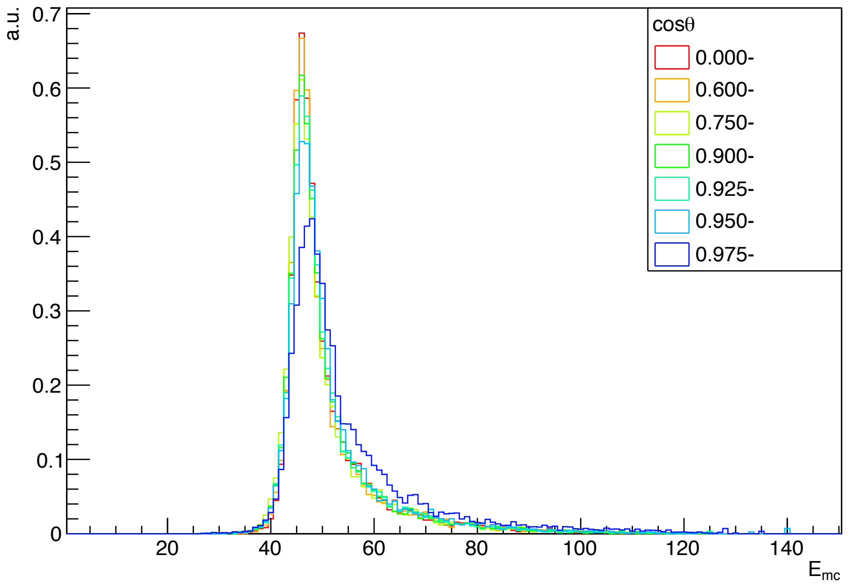


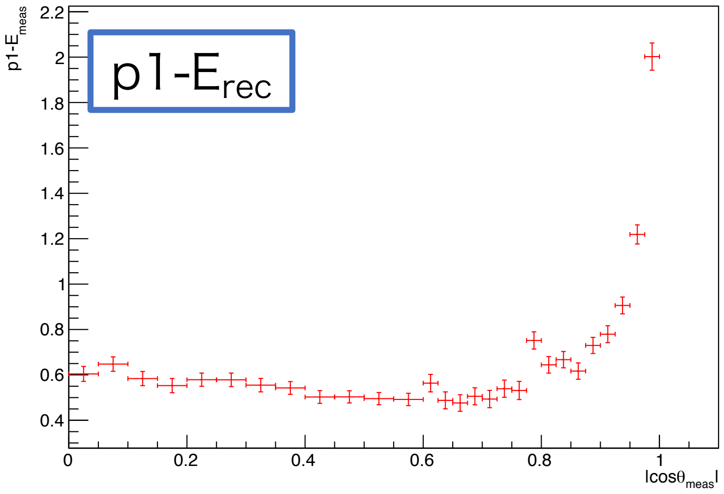


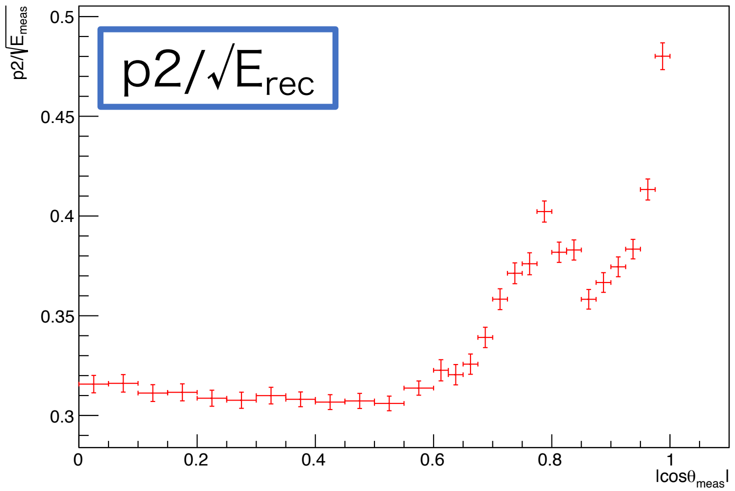


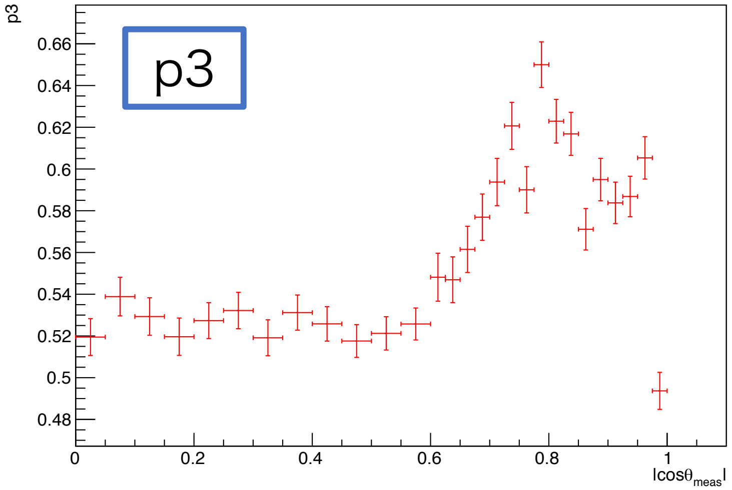
B-jet energy resolution: Angle dependence

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







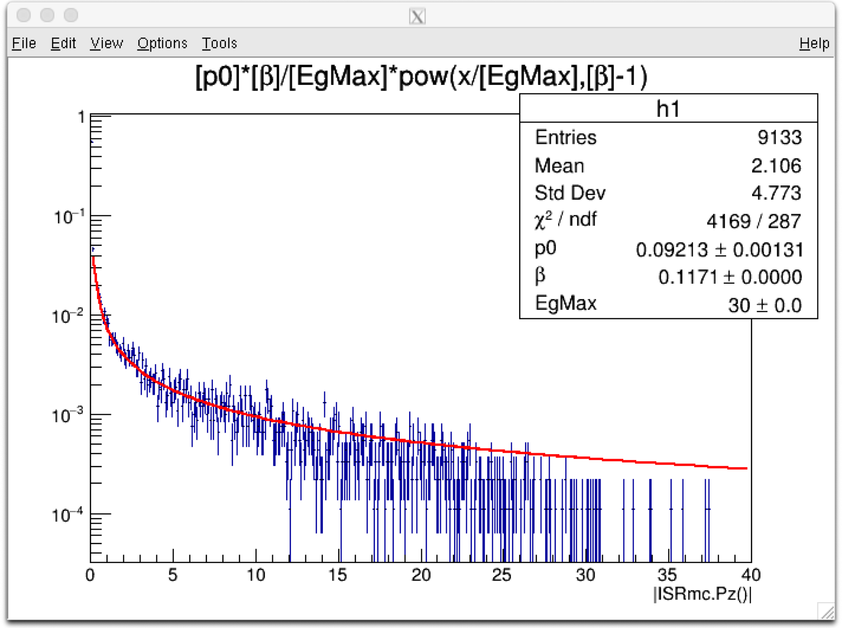


ISR spectrum

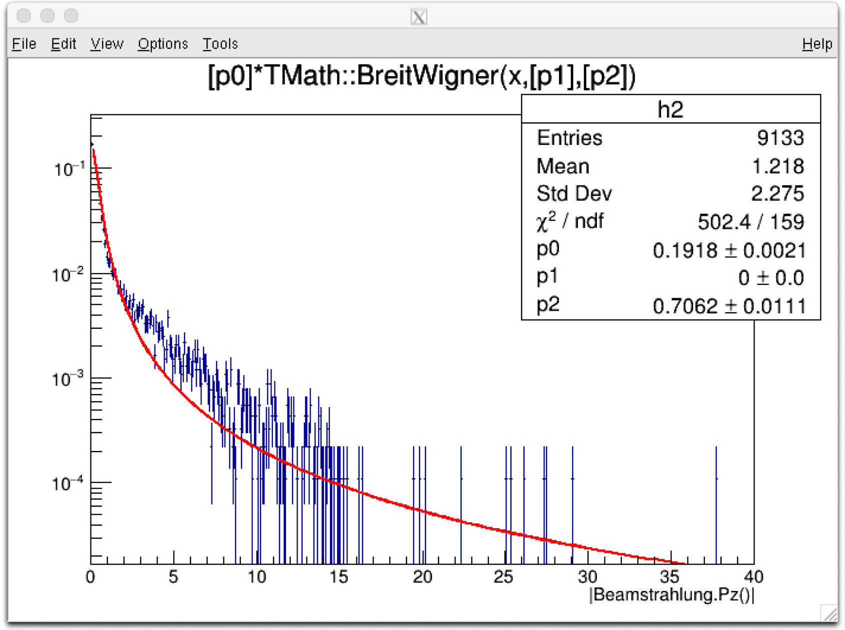
M. Beckmann, “Treatment of Photon Radiation in Kinematic Fits at Future e+e– Colliders”
F.A. Berends and R. Kleiss, Nucl. Phys. B177 (1981) 237

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

ISR



beamstrahlung



Ecm - Z - H