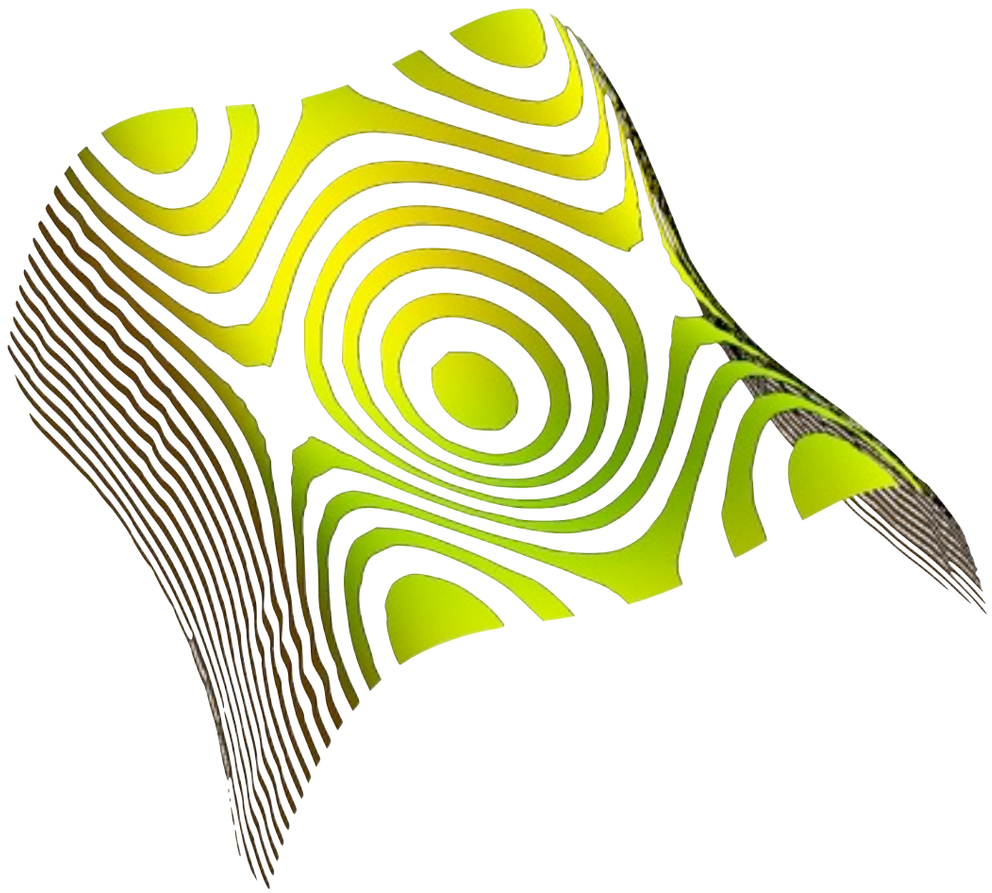
NEW YORK UNIVERSITY



$H \to ZZ^* \to 4l$ Likelihood in ATLAS

Sven Kreiss, Kyle Cranmer
on behalf of the ATLAS HSG2 group

Likelihoods for the LHC Searches
January 22, 2012

$H \to ZZ^* \to 4l$

Low count

- "statistics dominated": observed data matters the most. Systematic uncertainties are small.
- high resolution

Discovery Likelihood

- only observable: m_{4l}
- 8 categories: one category for each final state for 7 TeV and 8 TeV runs

Likelihood for Spin studies

- spin dependent variables are mapped to one discriminating variable (either a BDT output or MELA-type variable)
- not the focus of this talk

Model Likelihood - Overview

"marked Poisson model" (as used in HistFactory):

$$\mathcal{P}(\{x_1 \ldots x_n\}|\mu) = \underbrace{\mathrm{Pois}(n|\mu S + B)}_{\text{Poisson probability for observing exactly } n \text{ events}} \underbrace{\left[\prod_{e=1}^{n} \frac{\mu S f_{\mathrm{S}}(x_e) + B f_{\mathrm{B}}(x_e)}{\mu S + B}\right]}_{\text{weighted sum of signal and background PDFs evaluated at all observed events}}$$

- ➡ $f_S(x)$ and $f_B(x)$ are probability density functions (PDFs).
- ➡ In the case of HistFactory, the PDFs and data are provided in binned form.

COMPONENTS OF THE MODEL

H→ZZ*→4l Overview

Almost the Likelihood:

The Likelihood is similar to this picture but separated into the two years.

Some components of the Likelihood are grouped in these plots.

10x finer binning was used in the Likelihood: 500 MeV bins.

➡ 2000 bins per category

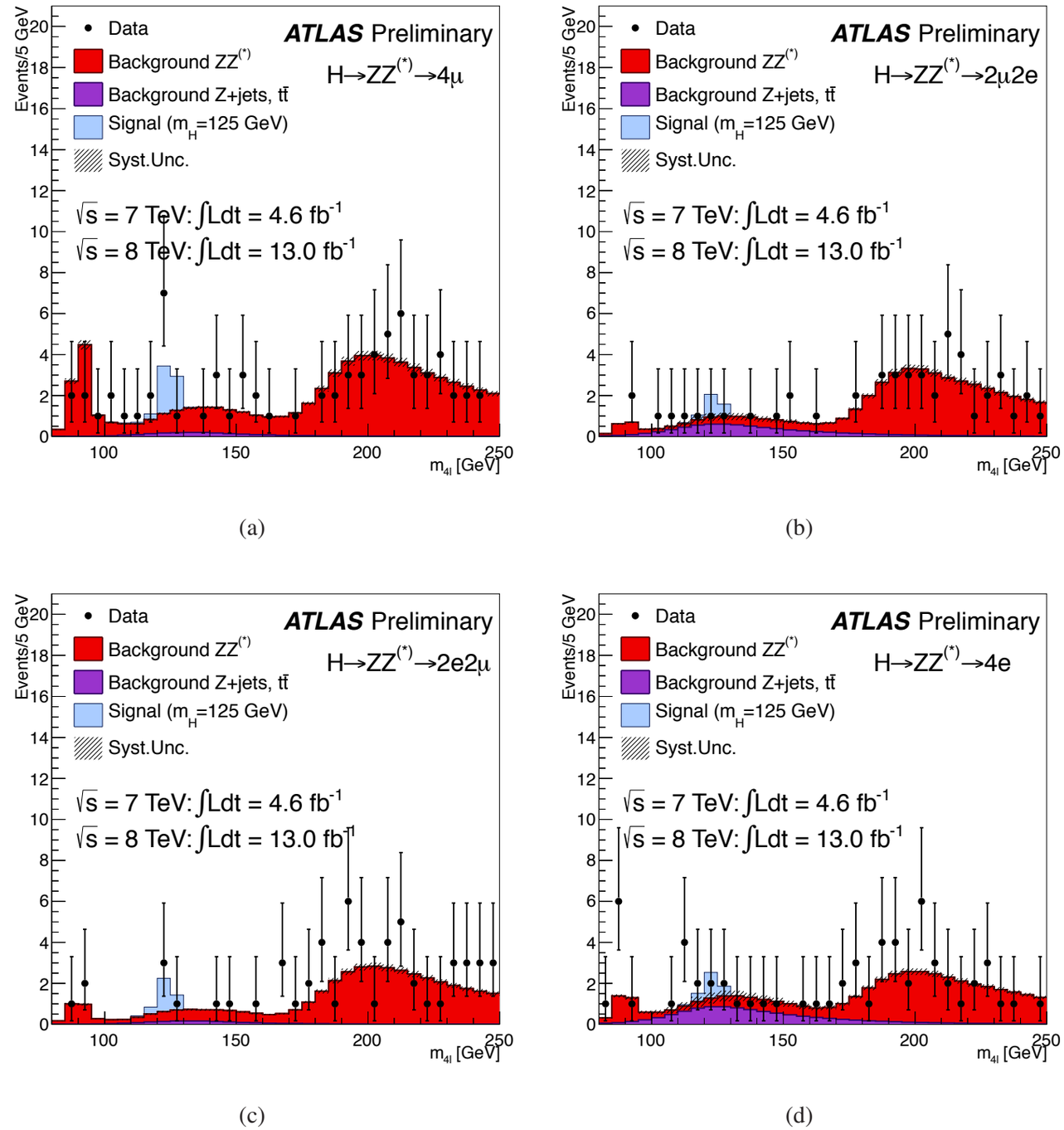


Figure 10: The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates for the combined $\sqrt{s}$ = 8 TeV and $\sqrt{s}$ = 7 TeV data sets for the various sub-channels, (a) 4μ, (b) $2\mu 2e$, (c) $2e2\mu$ and (d) $4e$, compared to the background expectation for the $80-250$ GeV mass range. Error bars represent 68.3% central confidence intervals. The signal expectation for one m_H hypothesis is also shown.

ZZ Background

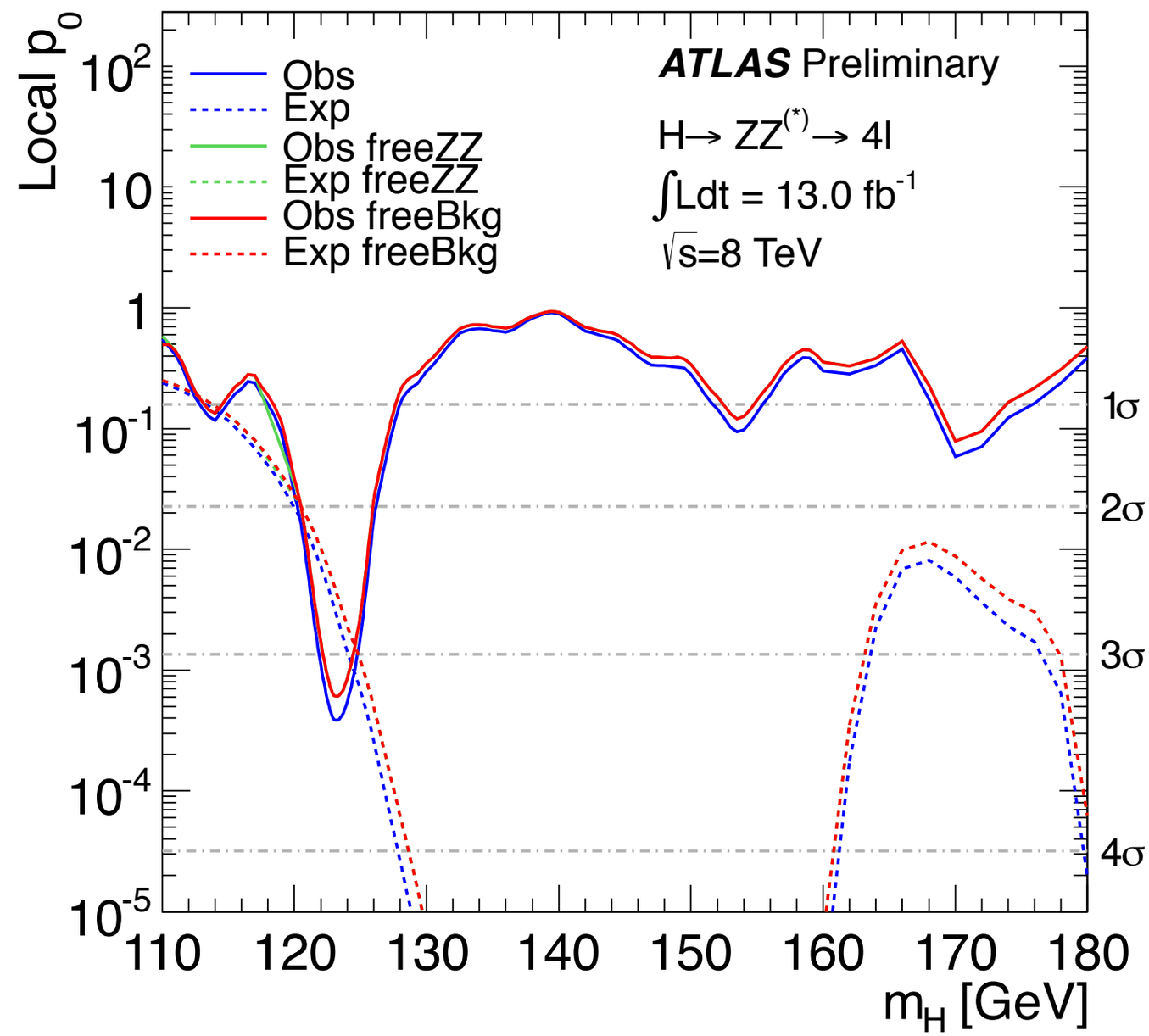
POWHEG for $q\bar{q}$ production and gg2ZZ for ggF production normalized to MCFM prediction.

QCD scale uncertainty is ±5%

PDF and α_s uncertainties are ±4% (±8%) for quark-initiated (gluon-initiated) processes

TAUOLA for tau decays

Removing any constraint on the ZZ normalization and leaving it floating in the fit ("freeZZ") or leaving all background normalizations floating ("freeBkg") has almost no effect on the p-value.



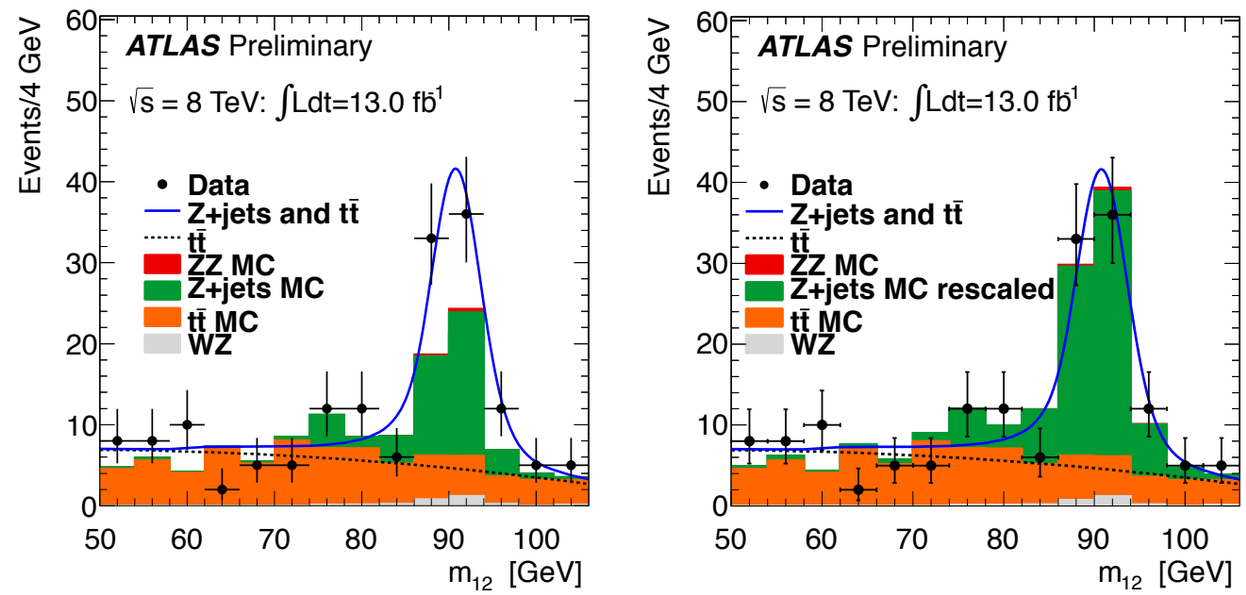
Z+jets and ttbar Background

Z+jets: ALPGEN

Z+μμ:

- ➡ light jets (including Zcc in massless c-quark approximation and Zbb from parton showers)
- ➡ Zbb using ME calculations that take into account the b-quark mass.
- ➡ for b jets:
  - ΔR > 0.4: events are taken from ME calculation
  - ΔR < 0.4: parton-shower bbbar pairs are used

For comparison: FEWZ for inclusive Z production and MCFM for Zbb production



(a) (b)

Figure 2: Distribution of m_{12}, for $\sqrt{s} = 8$ TeV, in the control region where the isolation requirements are not applied to the two sub-leading muons, and at least one of these muons is required to fail the impact parameter significance requirement. The fit used to obtain the yields for $t\bar{t}$ and Z + jets is presented in (a), with the MC expectations also shown for comparison. The same distribution with the Z + jets MC rescaled by the data fit is shown in (b).

Z+ee:

- ➡ CR: relaxed identification requirements on sub-leading electrons
- ➡ sources of electron background separated into reconstruction categories (electron-like and fake-like)
- ➡ efficiencies to extrapolate to SR from MC
- ➡ estimates sum of ttbar and Z+jets normalization

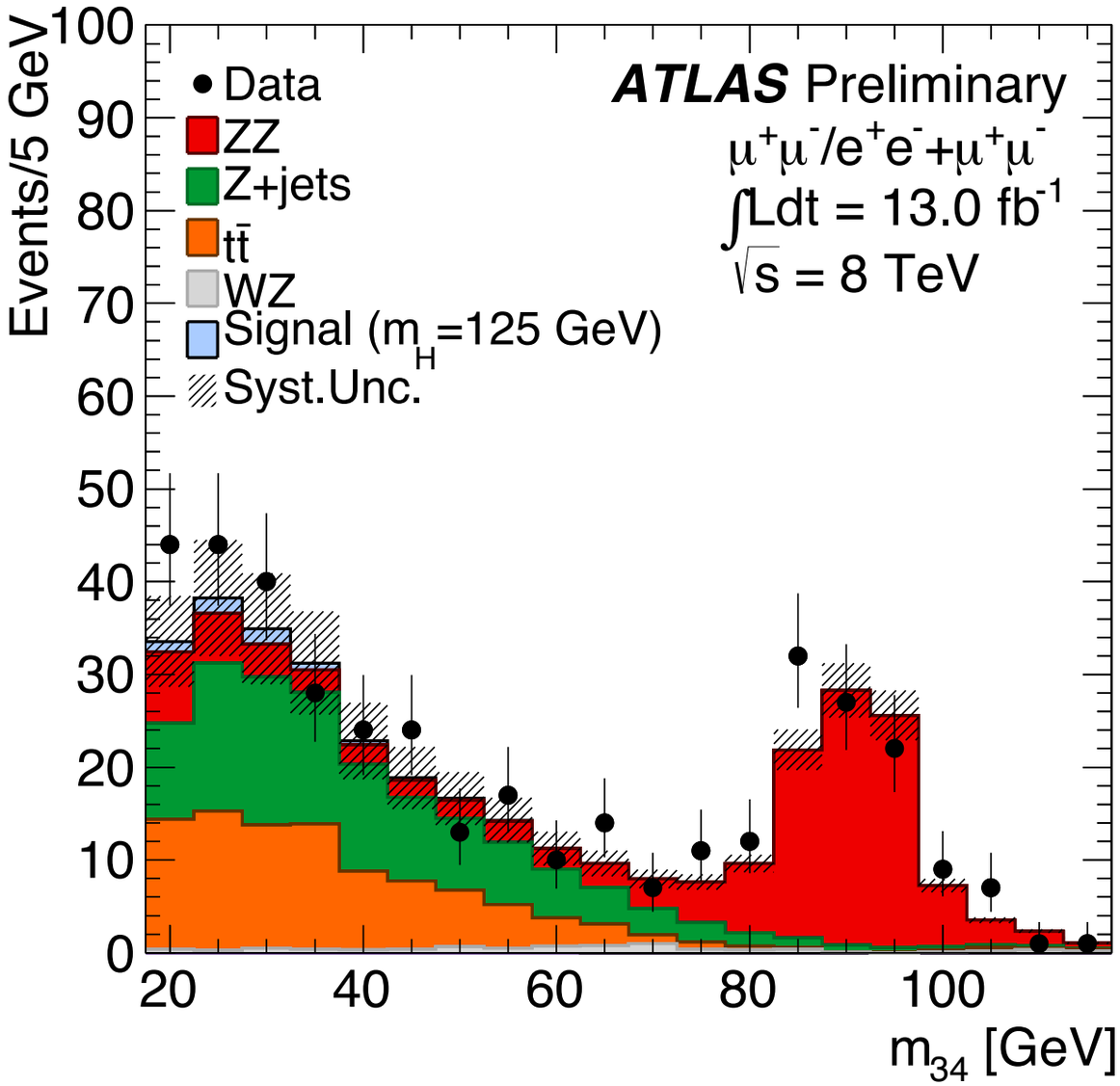
ttbar: MC@NLO, for comparison: HATHOR

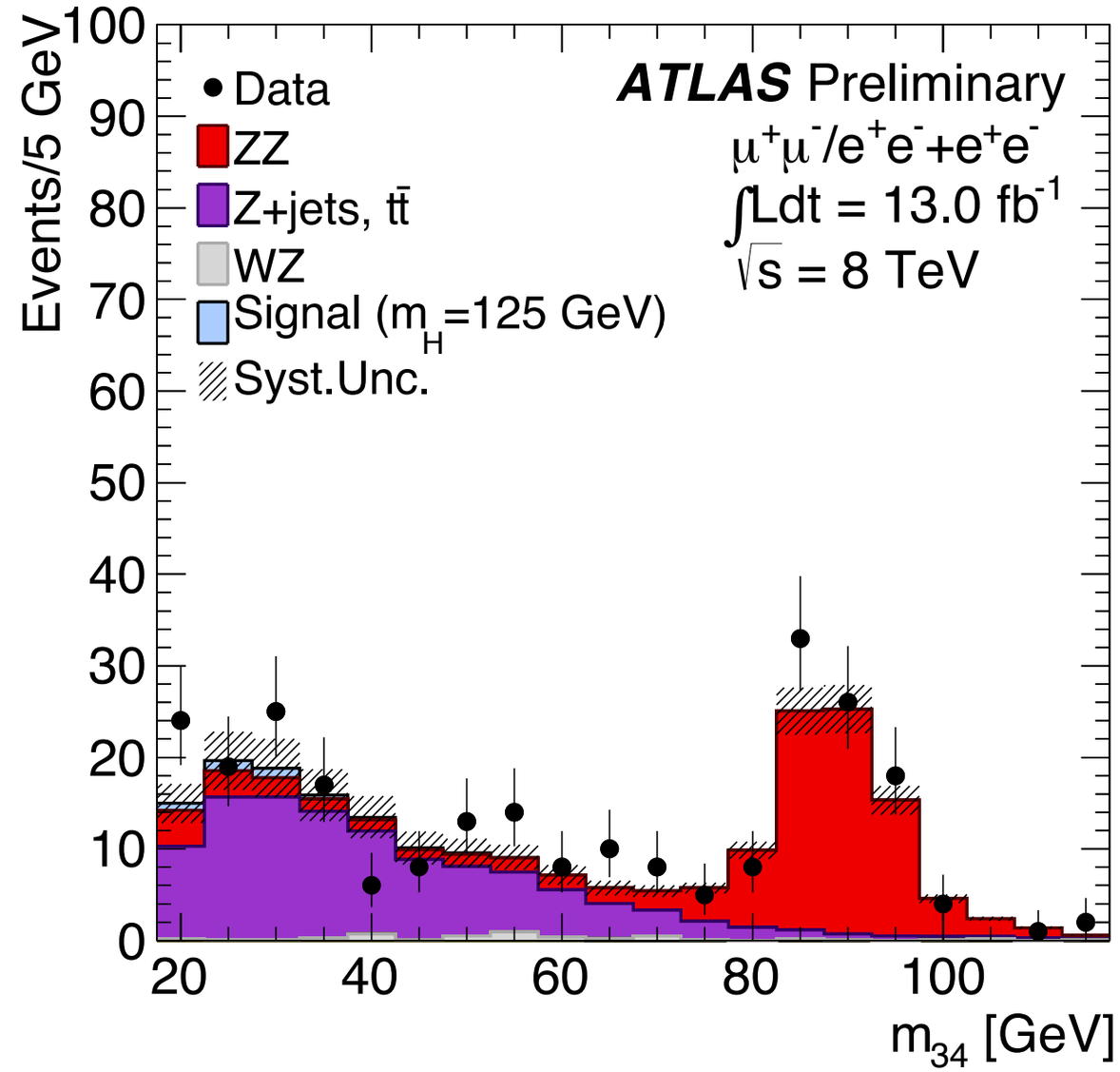
QCD scale uncertainty: +4% -9%

PDF and α_s uncertainties is ±7%

Estimates not treated using CR in Likelihood.

Different Contributions from Fakes depending on Category

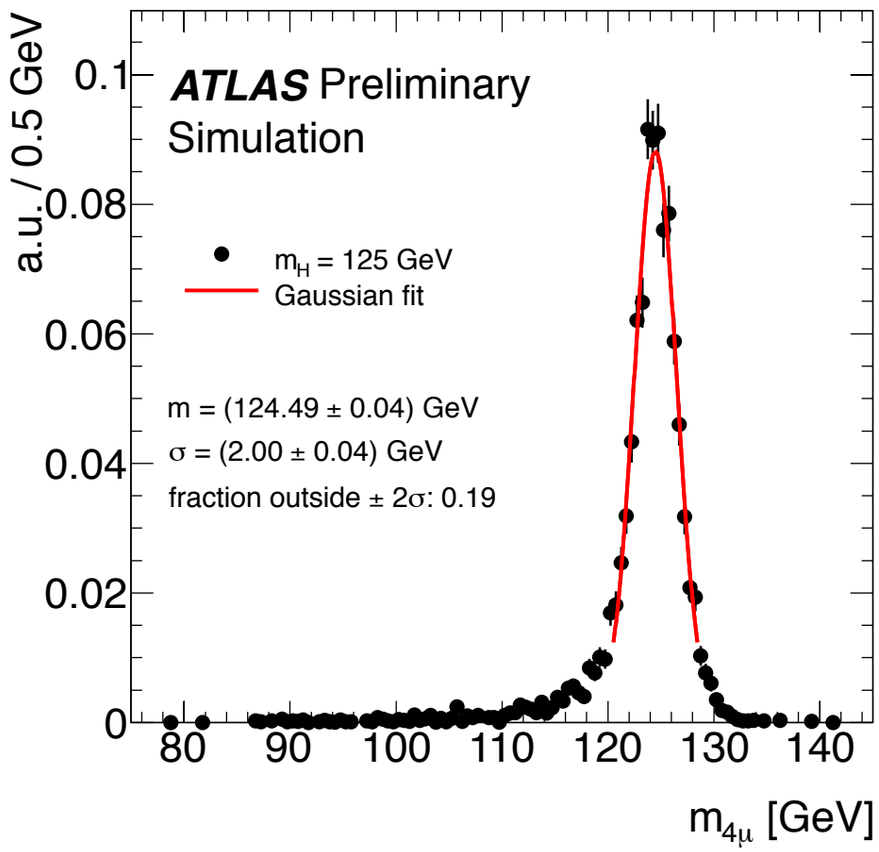


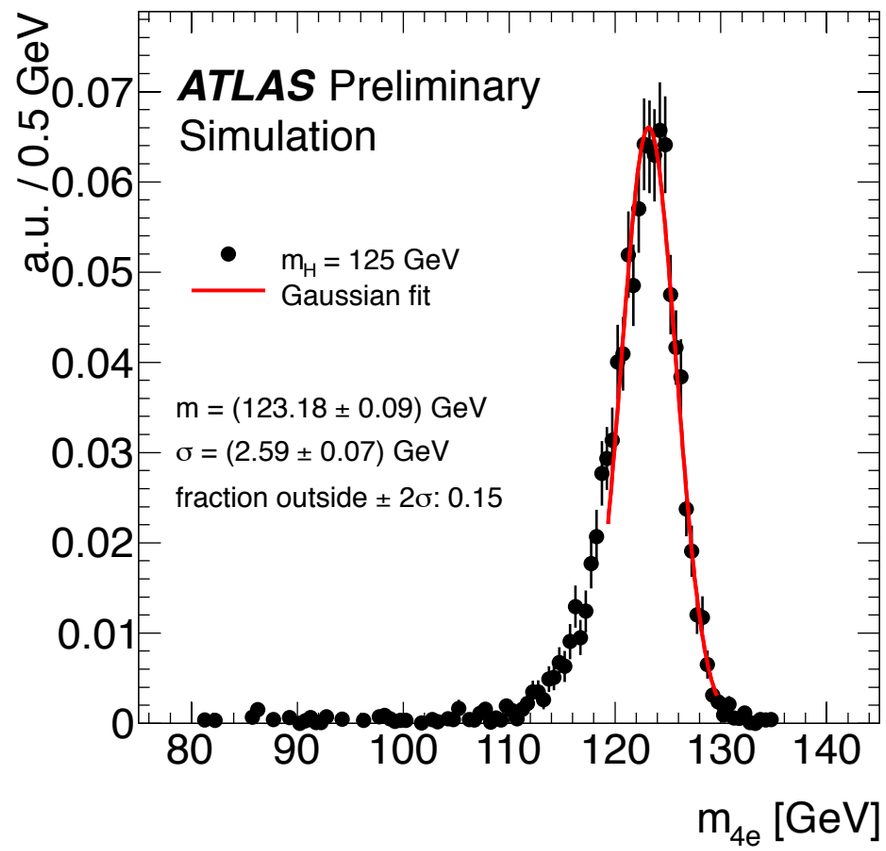


Isolation and impact parameter significance requirements only on leading lepton pair.

➡ Categorization makes model more powerful.

Signal Shapes





At low mass, signal MC produced in 5 GeV steps.
Closer to discovery, additional MC points were added in 1 GeV steps.

- ➡ Interpolation between MC samples is always necessary. Additional models with fixed m_H can be created with e.g. Moment Morph (Max Baak) and Integral Morph (Alex Read, NIM A 425 (1999) 357-369).

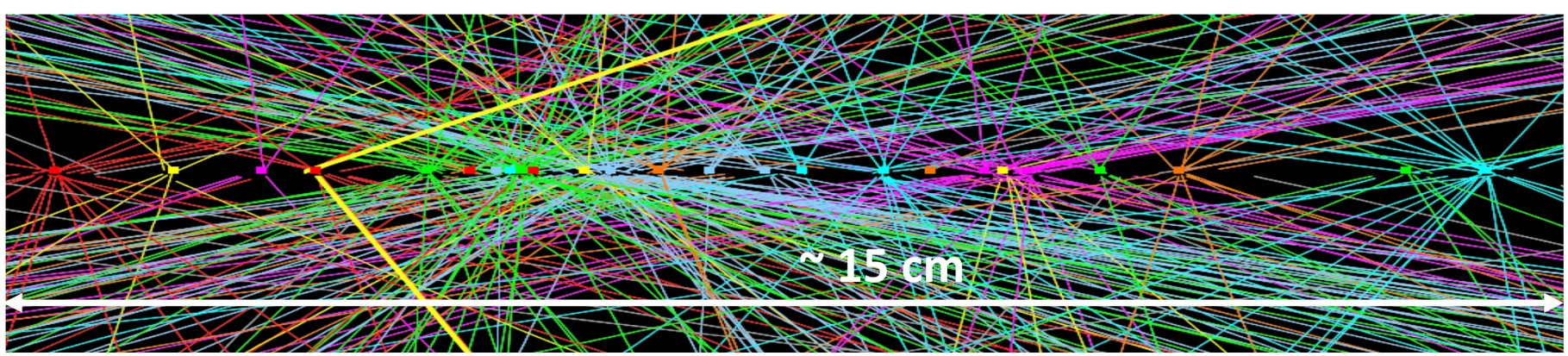
m_H dependent QCD scale and PDF and α_s uncertainties.
Additional uncertainty above m_H = 300 GeV to account for ZWA.

Events

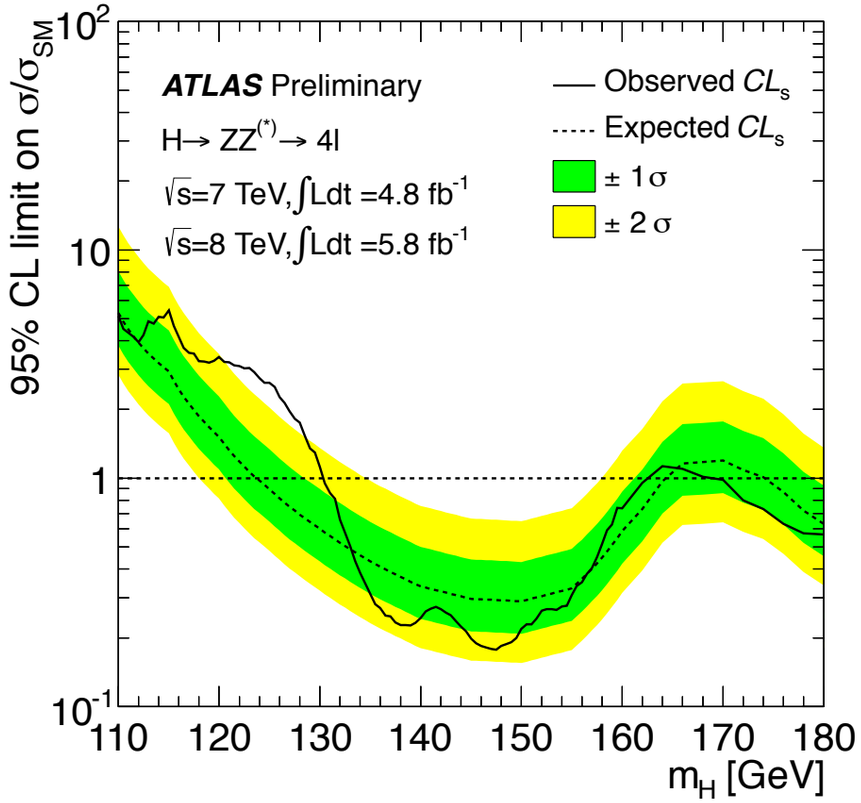
ALPGEN and MC@NLO are interfaced to HERWIG (parton shower hadronization) and JIMMY (underlying event)

GEANT4 for detector simulation

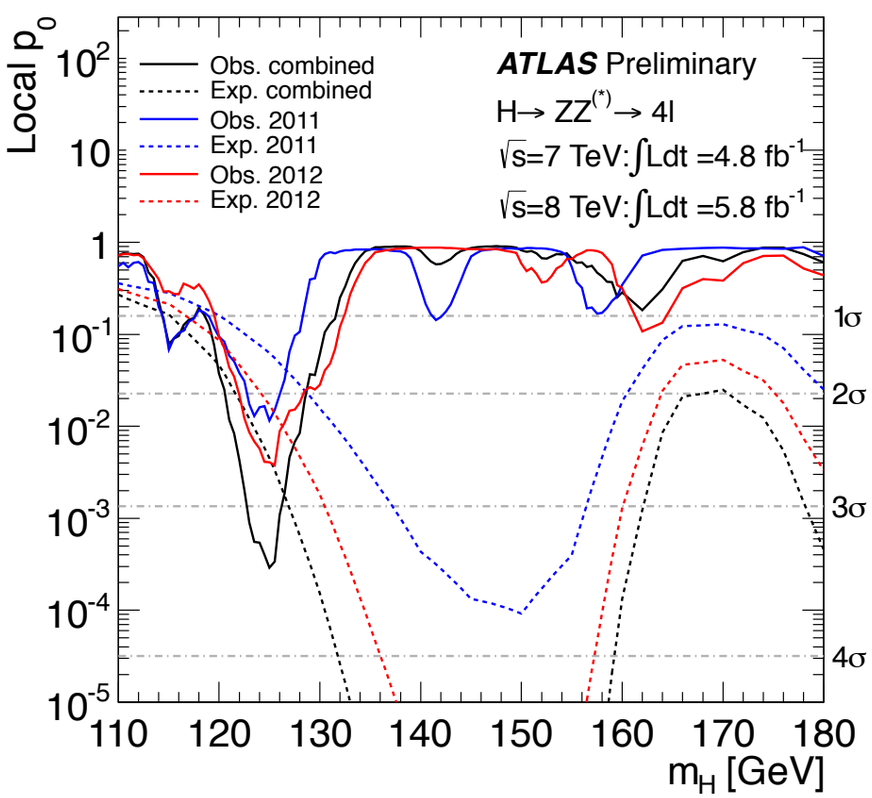
- additional pp interactions in the same and nearby bunch crossings are included
- MC samples are re-weighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data



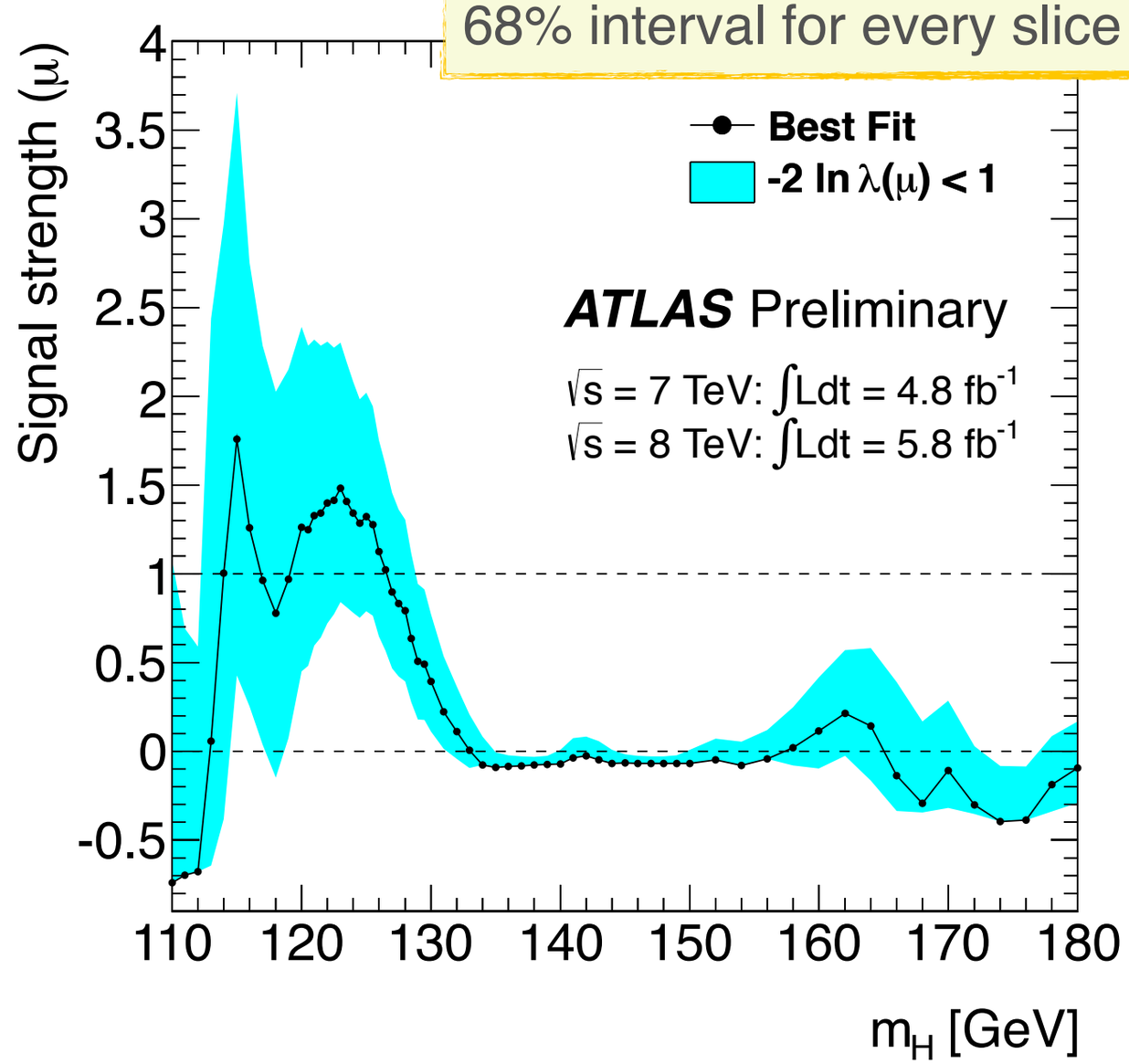
For Discovery: Fixed m_H Scans



Interpolation between MC samples is necessary. Additional models with fixed m_H can be created with e.g. Moment Morph (Max Baak) and Integral Morph (Alex Read, NIM A 425 (1999) 357-369).



68% interval for every slice in m_H

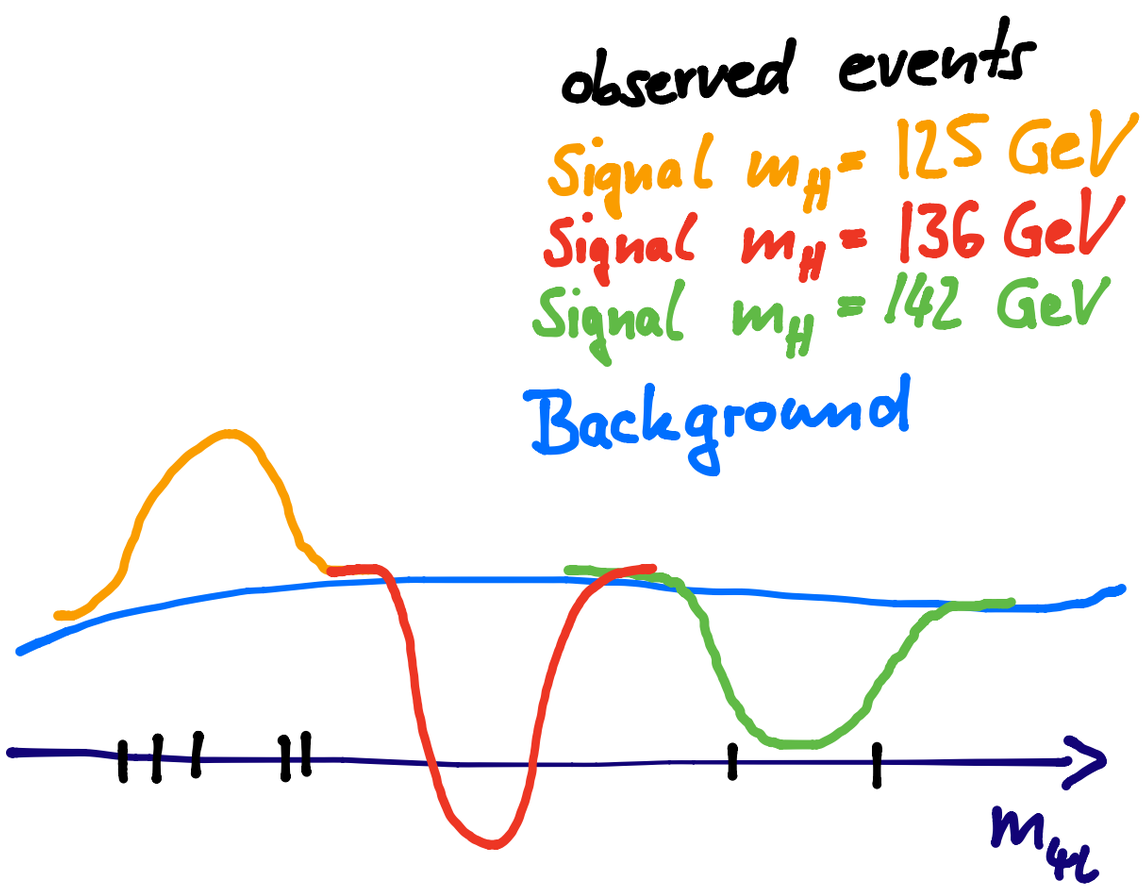


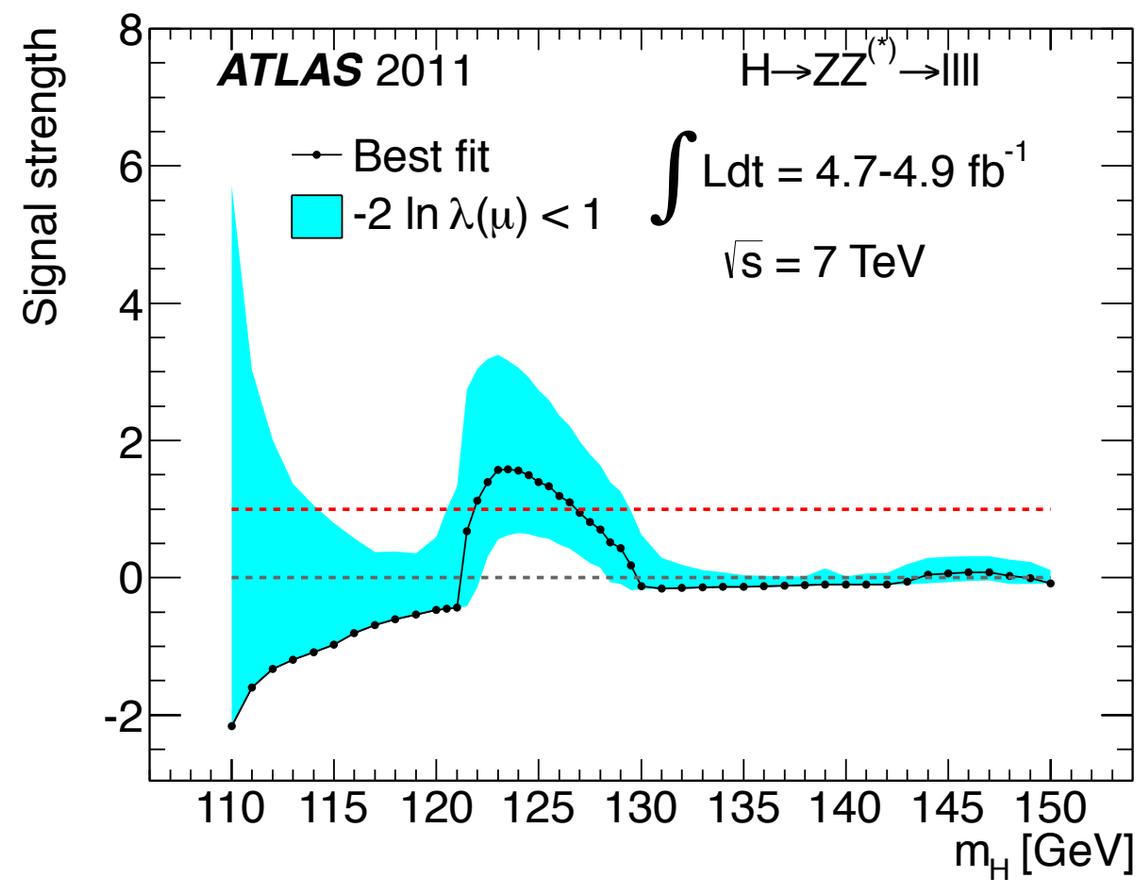
Phantom Events for Signal Strength Plots

Want to allow for negative signal strengths to see deficits, but ...

only evaluated at observed events

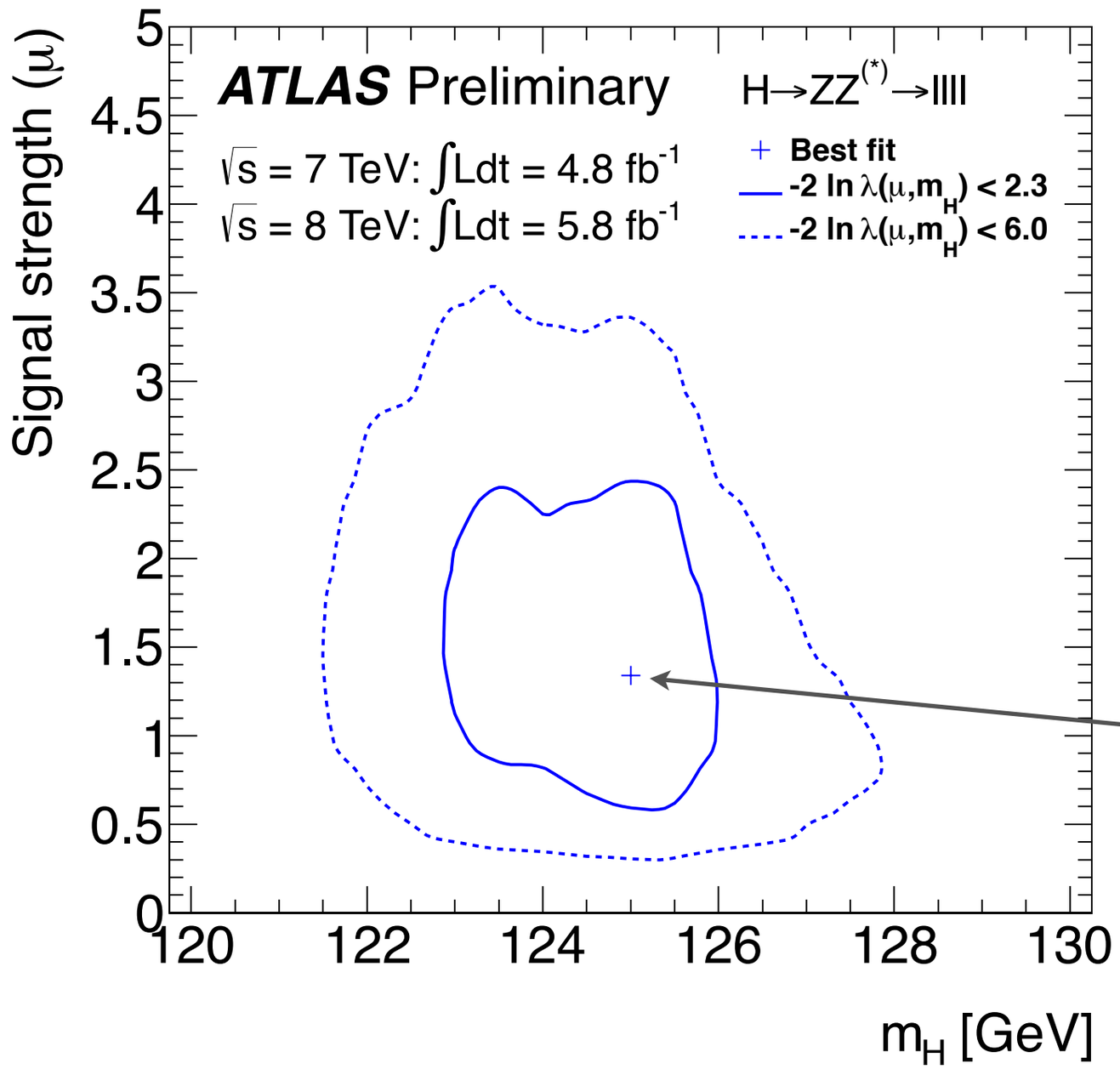
$$\mathcal{P}(\{x_1 \ldots x_n\}|\mu) = \mathrm{Pois}(n|\mu S + B) \left[\prod_{e=1}^{n} \frac{\mu S f_{\mathrm{S}}(x_e) + B f_{\mathrm{B}}(x_e)}{\mu S + B} \right]$$





For Discovery: Fixed m_H Scans

2D 68% contour:



with fixed m_H models, this cannot be obtained from a fit in (μ, m_H)

FROM DISCOVERY TO PROPERTY MEASUREMENTS

PARAMETRIZATION

- Production modes
- Unbinned Signal Parametrization in m_H
- Unbinned data

From Discovery Models to Property Models

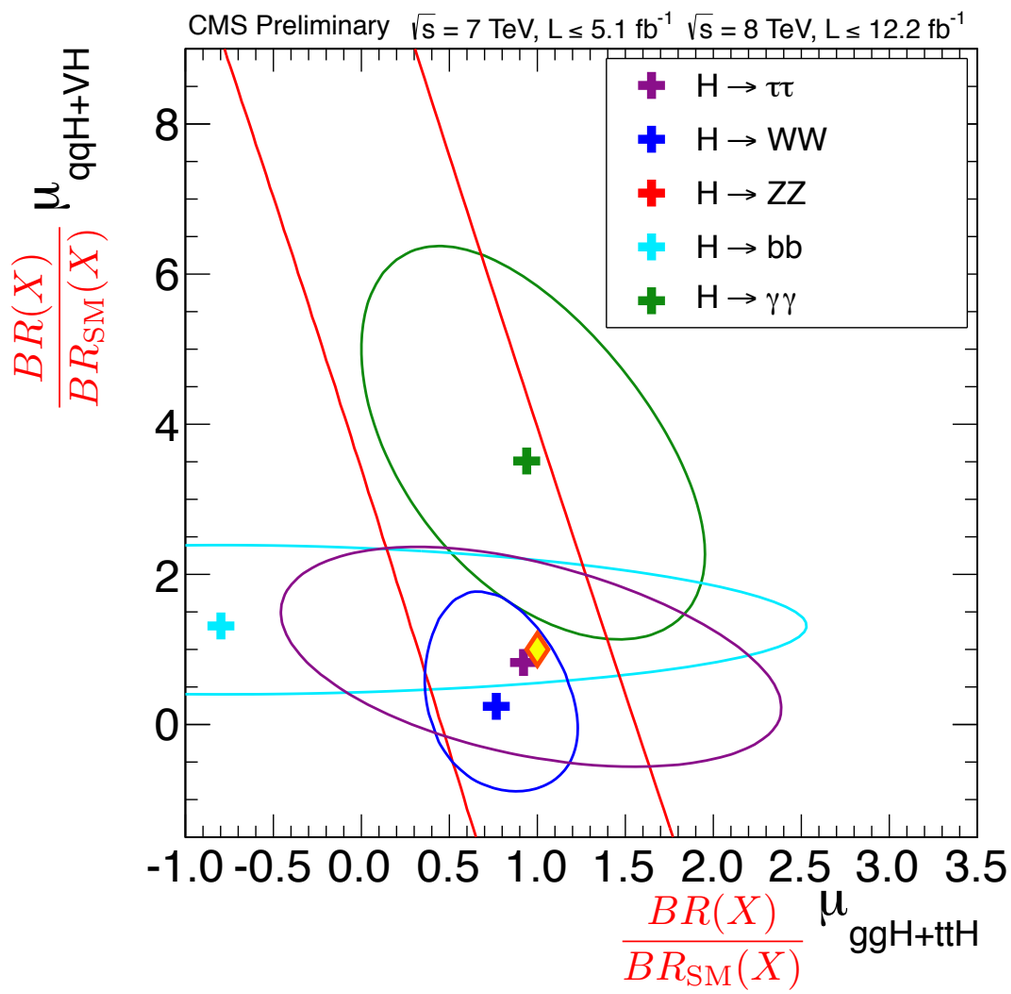
Signal strength for discovery: **a single μ**

$$L(\mu, \hat{\hat{\theta}})$$

Studying production modes: **one μ_i for every production mode and decay channel**

$$L(\mu_i, \mu_j, \hat{\hat{\theta}})$$

no discrimination power with the current categories in this channel alone



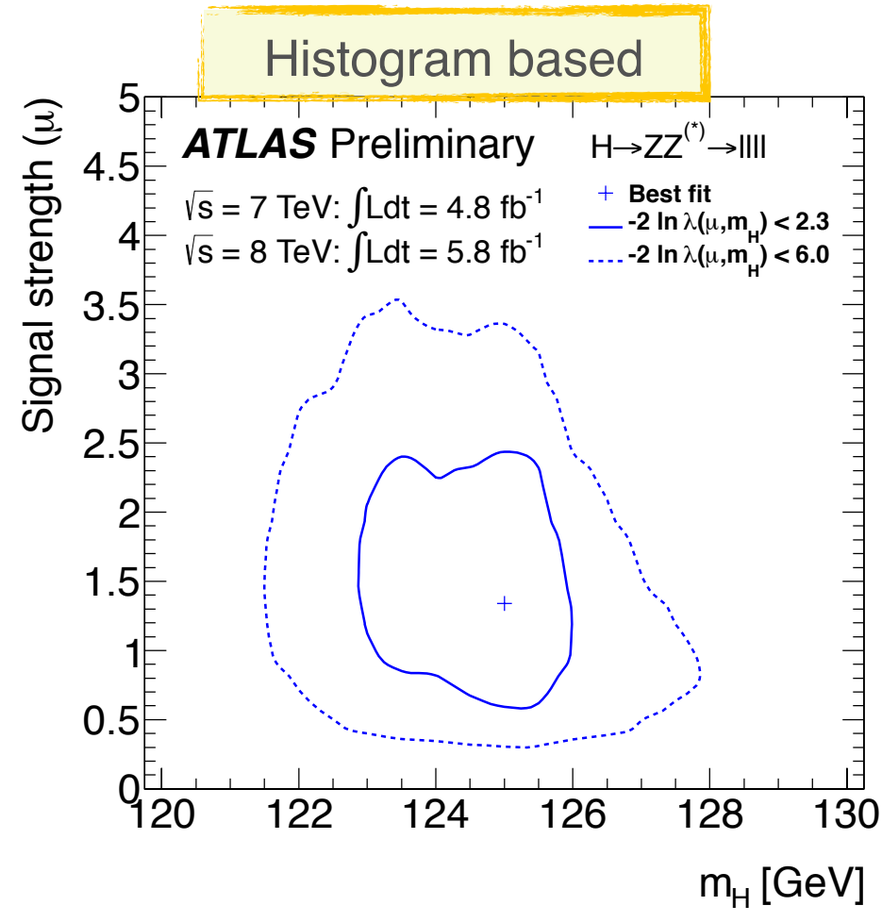
For coupling studies: **every μ_i is parametrized in terms of theory parameters κ**

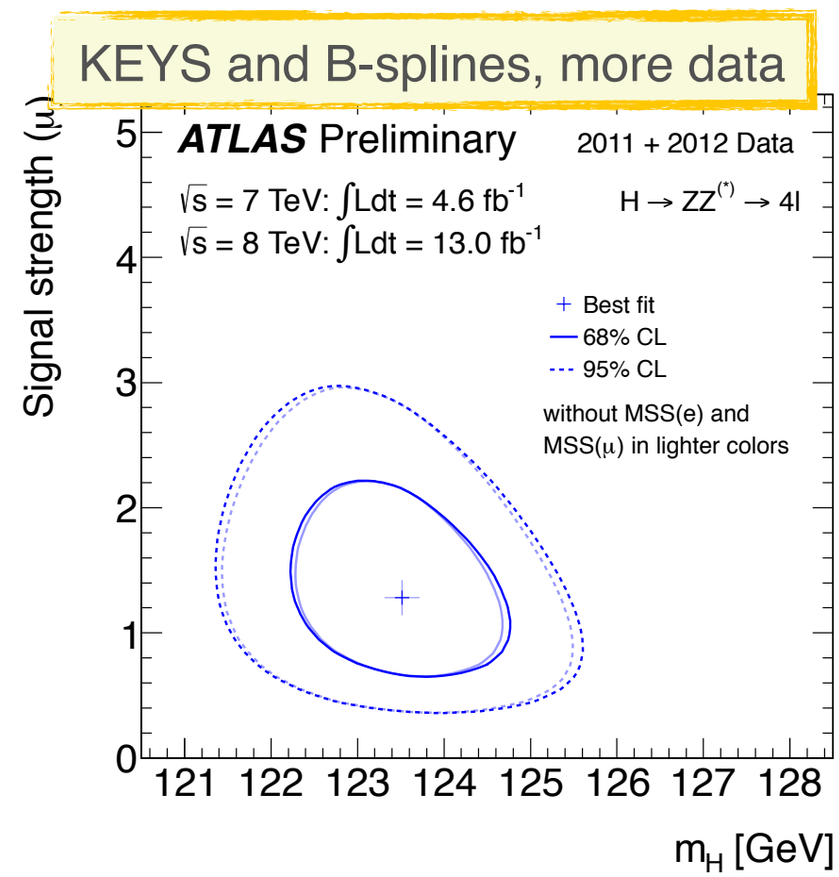
$$L(\mu_i(\boldsymbol{\kappa}), \mu_j(\boldsymbol{\kappa}), \hat{\hat{\theta}})$$

Motivation

Difficult to converge on ad-hoc analytic parametrization of ZZ and reducible background and signal.

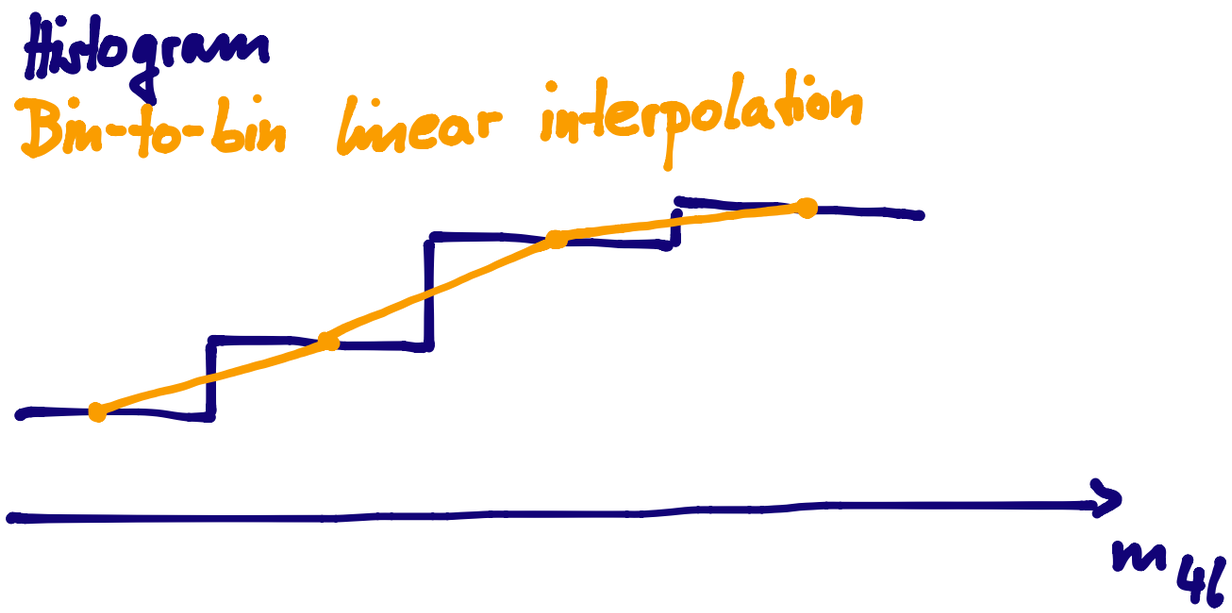
- ➡ want to mix HistFactory style inputs for ZZ and reducible background with unbinned signal parametrized in m_H
- ➡ solution ParamKeysPdf + linearly interpolated HistFactory-style backgrounds
- ➡ unbinned datasets





Continuous Parametrization in m_H

Background histograms are linearly interpolated between bins.

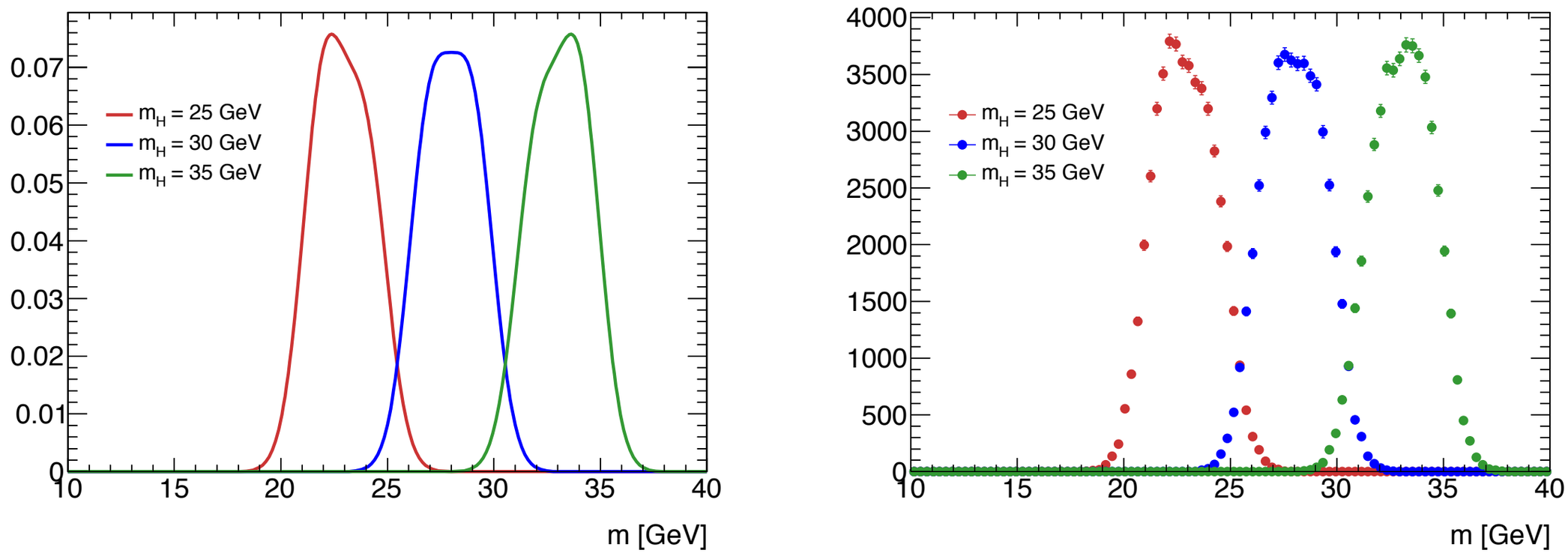


New method for **signal** parametrization based on KEYS PDFs and B-splines.

- ➡ RooParamKeysPdf in the RooStats development branch:

  `https://root.cern.ch/svn/root/branches/dev/roostats`

Example Model (no ATLAS data here)



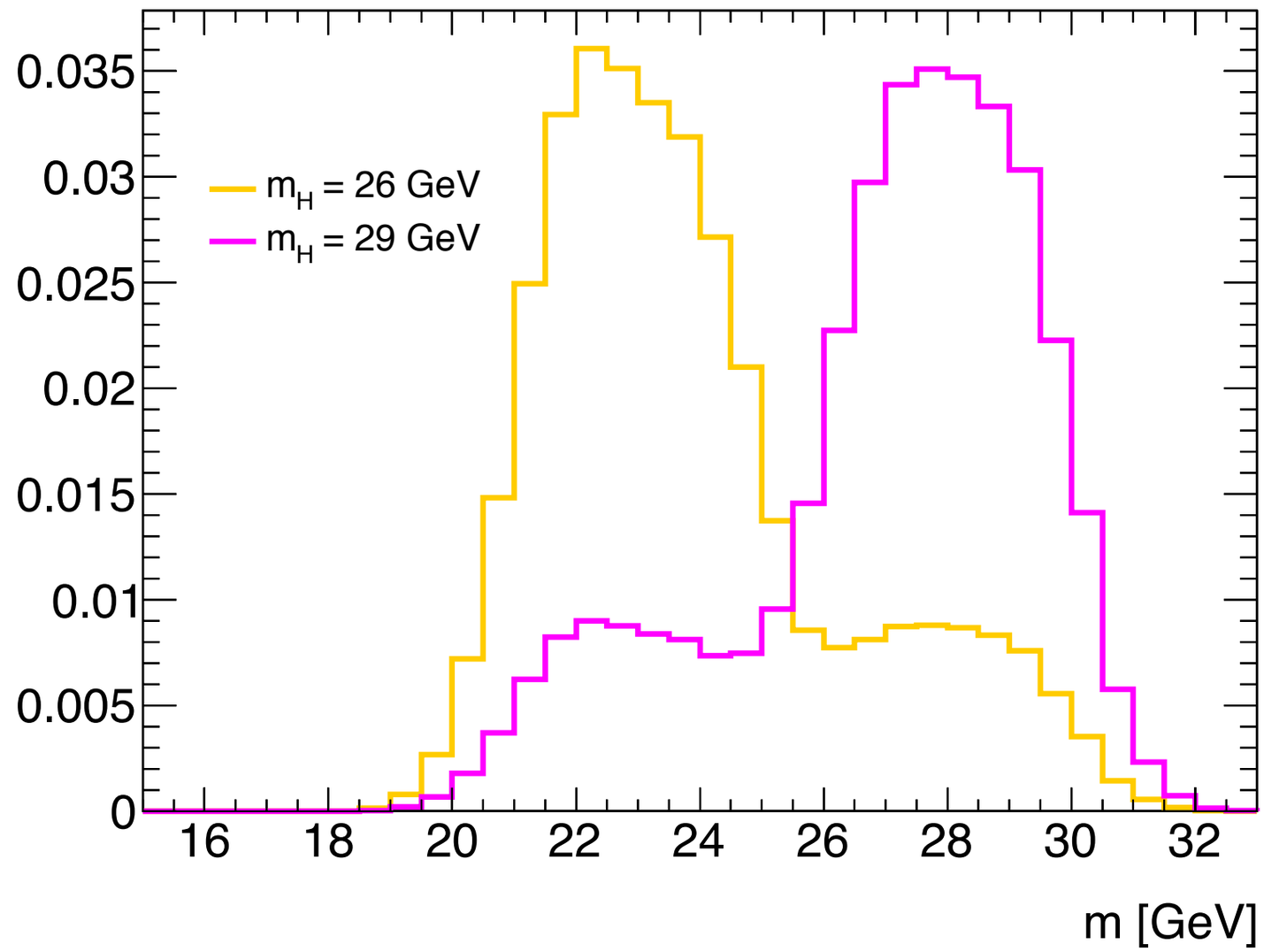
(a) (b)

Figure 1: Illustration of the example model that is used in this note. There are three MC samples available with $m_H = 25$, 30 and 35 GeV. All three samples have a slightly different shape. (a) True model. (b) Generated MC samples from the true model.

Vertical Interpolation: Not an Option for a High Resolution Channel

From physics, want: Shapes move left and right when changing m_H.

Vertical Interpolation: Bin heights move up and down creating unphysical effects.



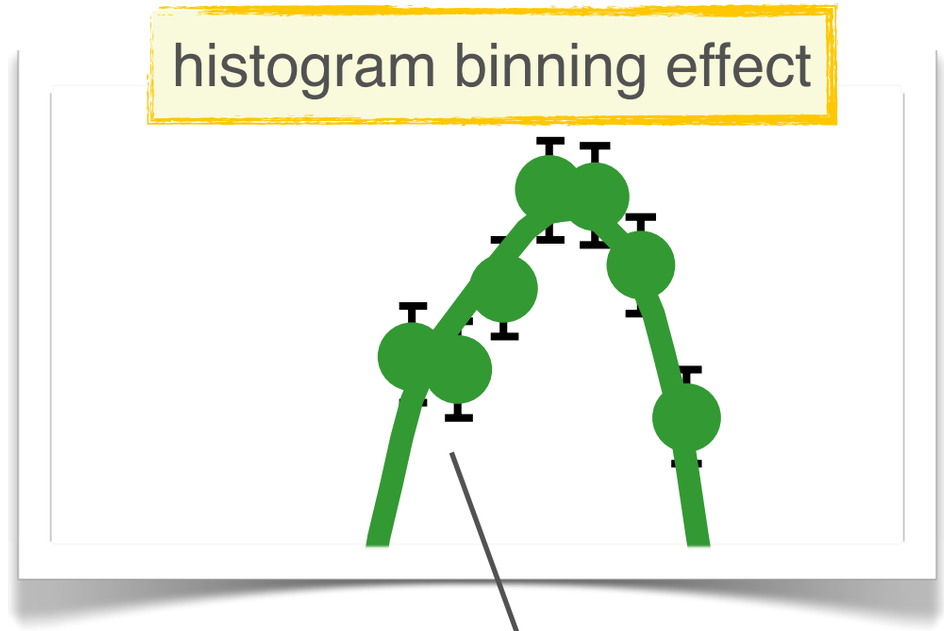
There are other interpolation options as mentioned before, which can in principle be built directly into the model.

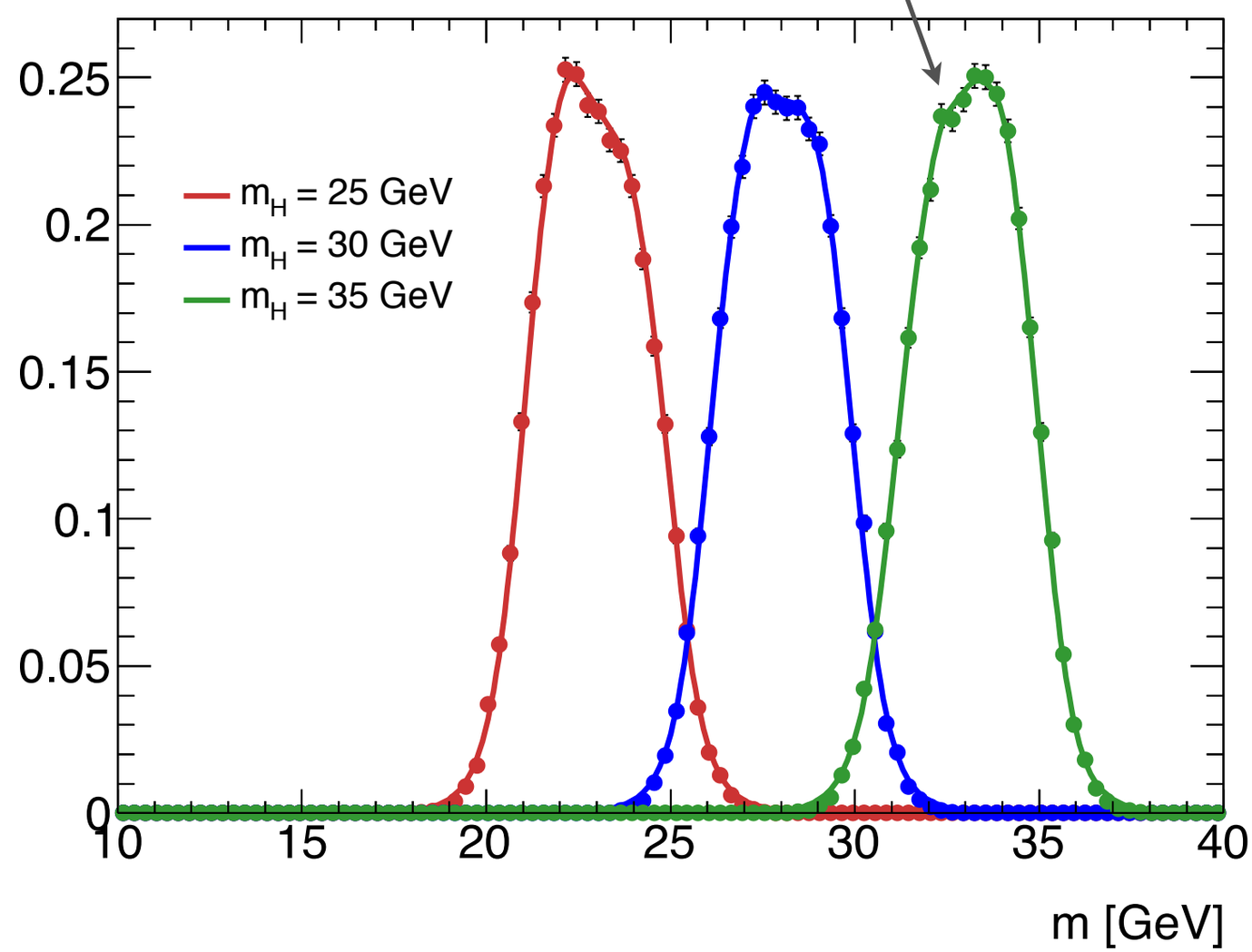
KEYS PDFs

MC samples in histograms shown as points.

KEYS PDFs overlayed.

- ➡ variable width kernels
- ➡ no discretization in observable

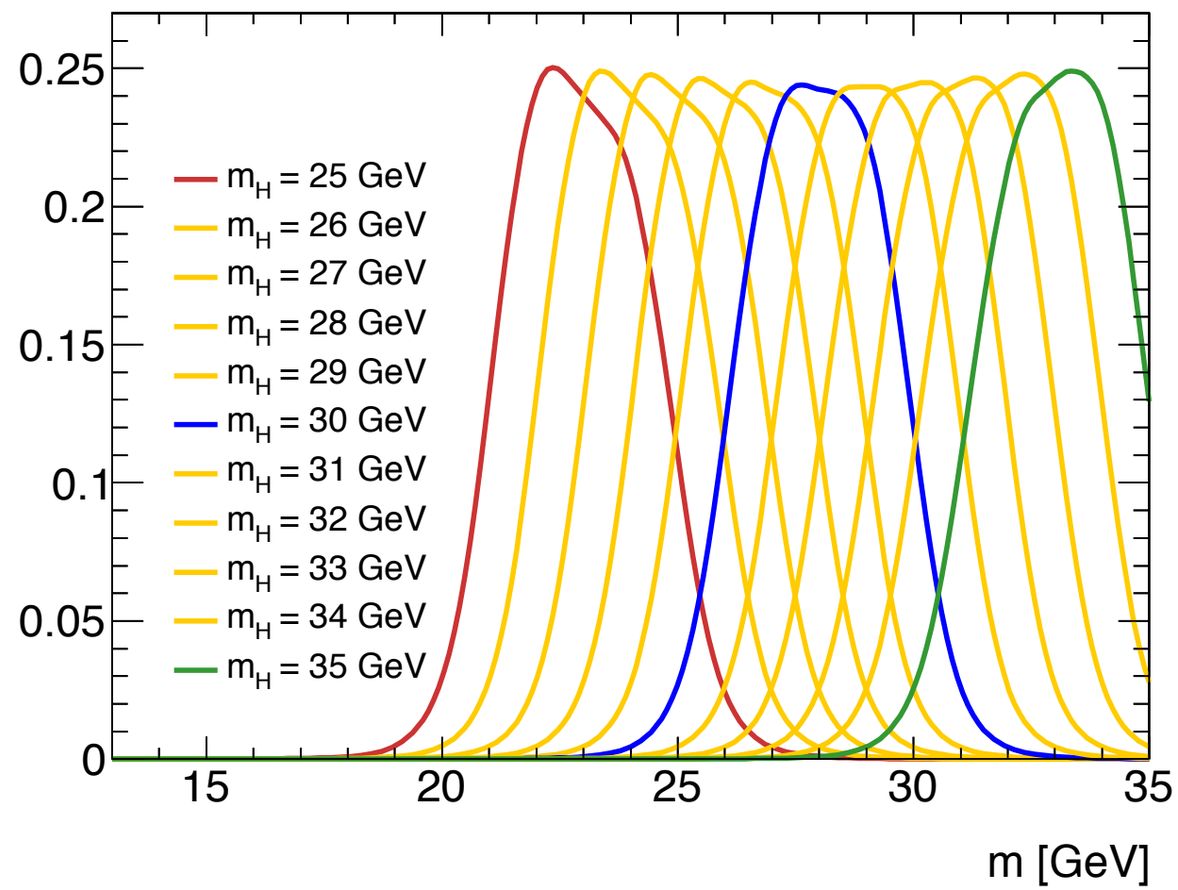




Combining KEYS and B-splines

With KEYS, can make use of:

$$f(m_{\text{inv}}|m_H + \Delta) \approx f(m_{\text{inv}} + \Delta|m_H)$$



Using KEYS PDFs and B-splines:

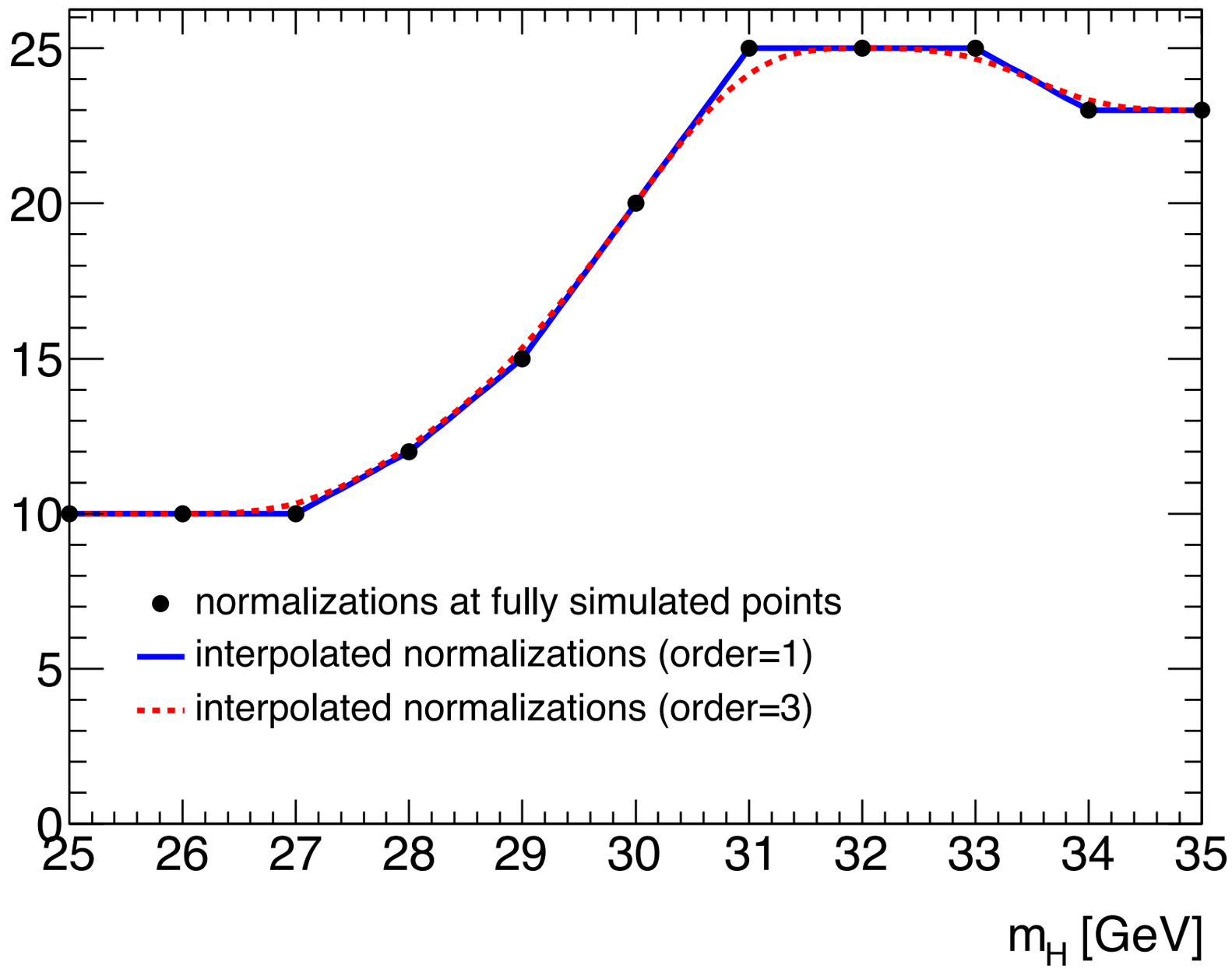
To obtain the signal shape at m_H, all f_j are first shifted by $\Delta m_{\text{inv},j} = m_H - m_j$ and then interpolated according to

$$f_{\text{total}}(m_{\text{inv}} \mid m_H) = \sum_j w_j(m_H)\ f_j(m_{\text{inv}} \mid m_H - m_j)$$

where the coefficients $w_j(m_H)$ are B-spline basis functions.

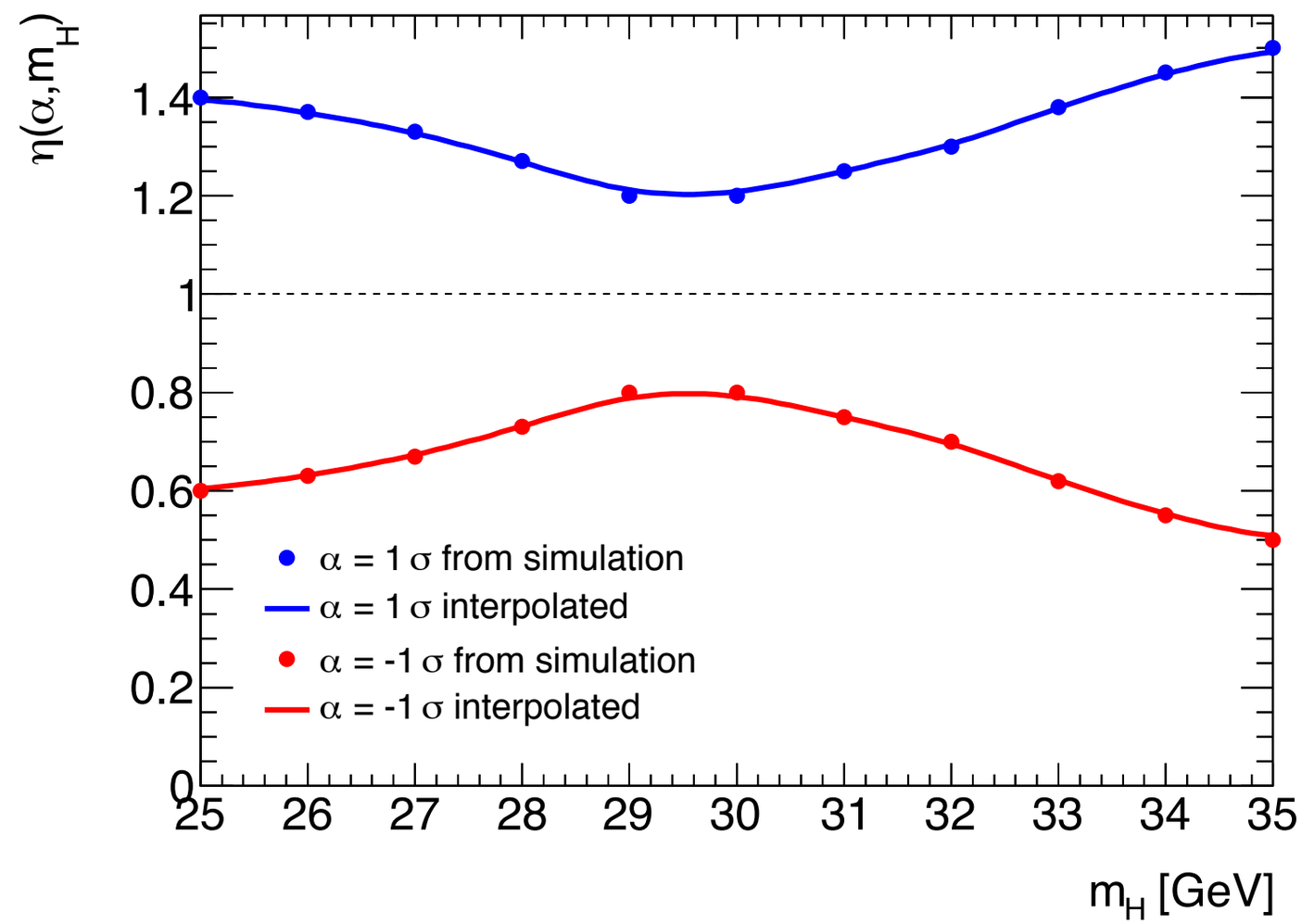
Normalization

B-splines interpolate signal normalizations in m_H.



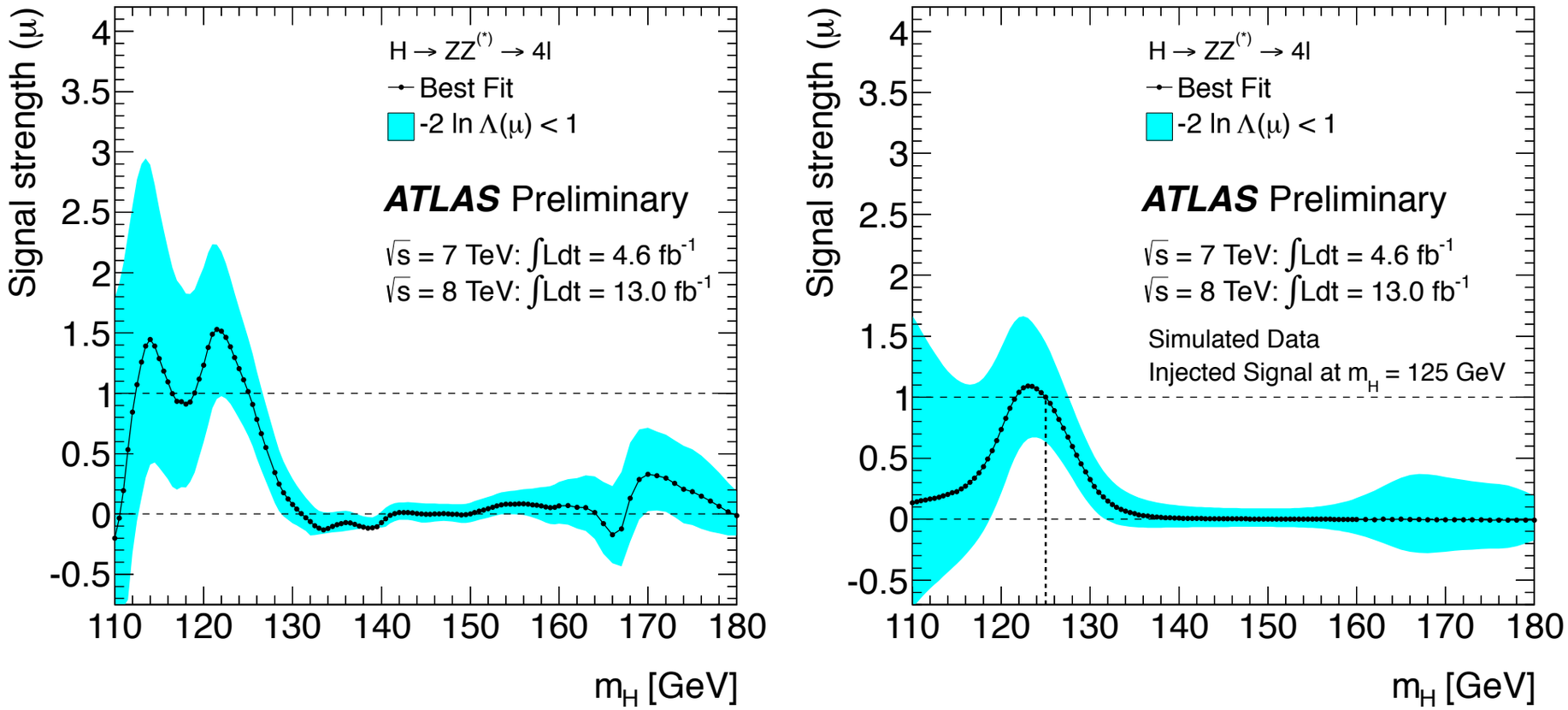
Parametrizing Response Functions

One “dynamic” B-spline interpolates response function in m_H.



PLOTS OF THE (PROFILED) LIKELIHOOD

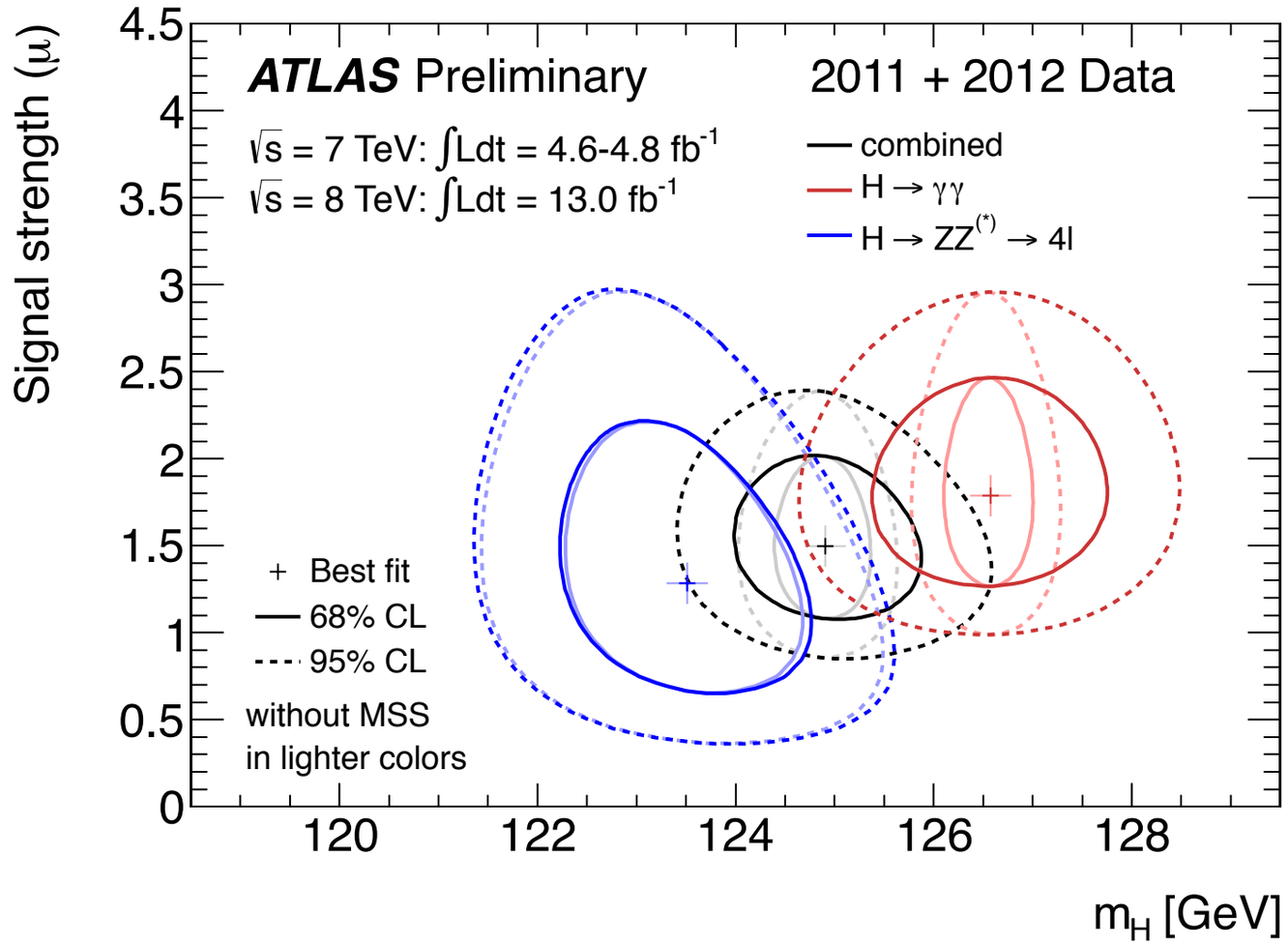
Signal Strength with this Model and more Data



(a) (b)

Figure 14: (a) The signal strength parameter $\mu = \sigma/\sigma_{SM}$ obtained from a fit to the data is presented for the combined fit to the 2011 and 2012 data samples. (b) The signal strength μ is shown as a function of m_H when a simulated SM Higgs boson signal with $m_H = 125$ GeV is injected onto simulated backgrounds.

Mass Discrepancy



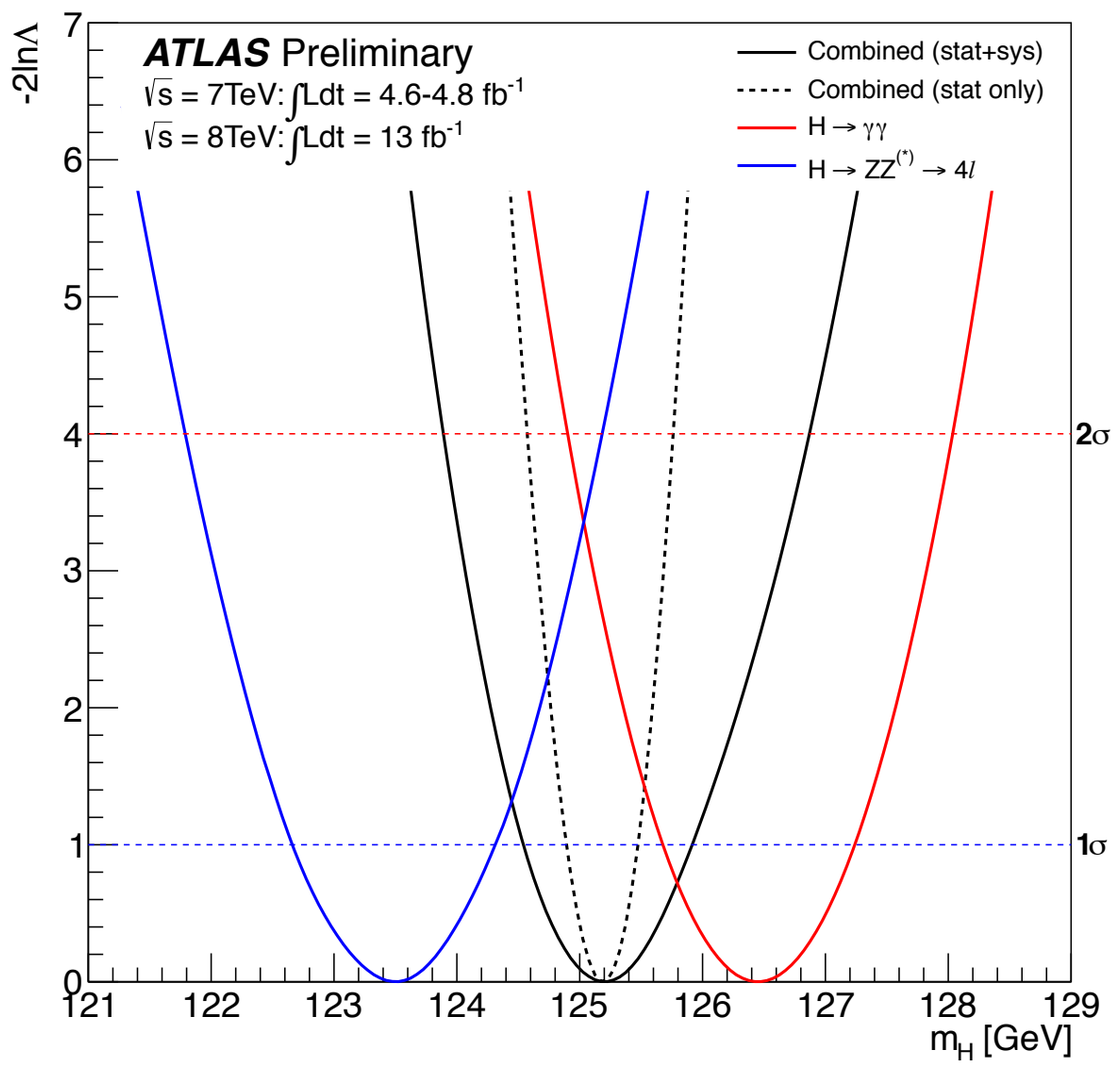
Mass Scale Systematics consists of many components. As correlated, we treat:

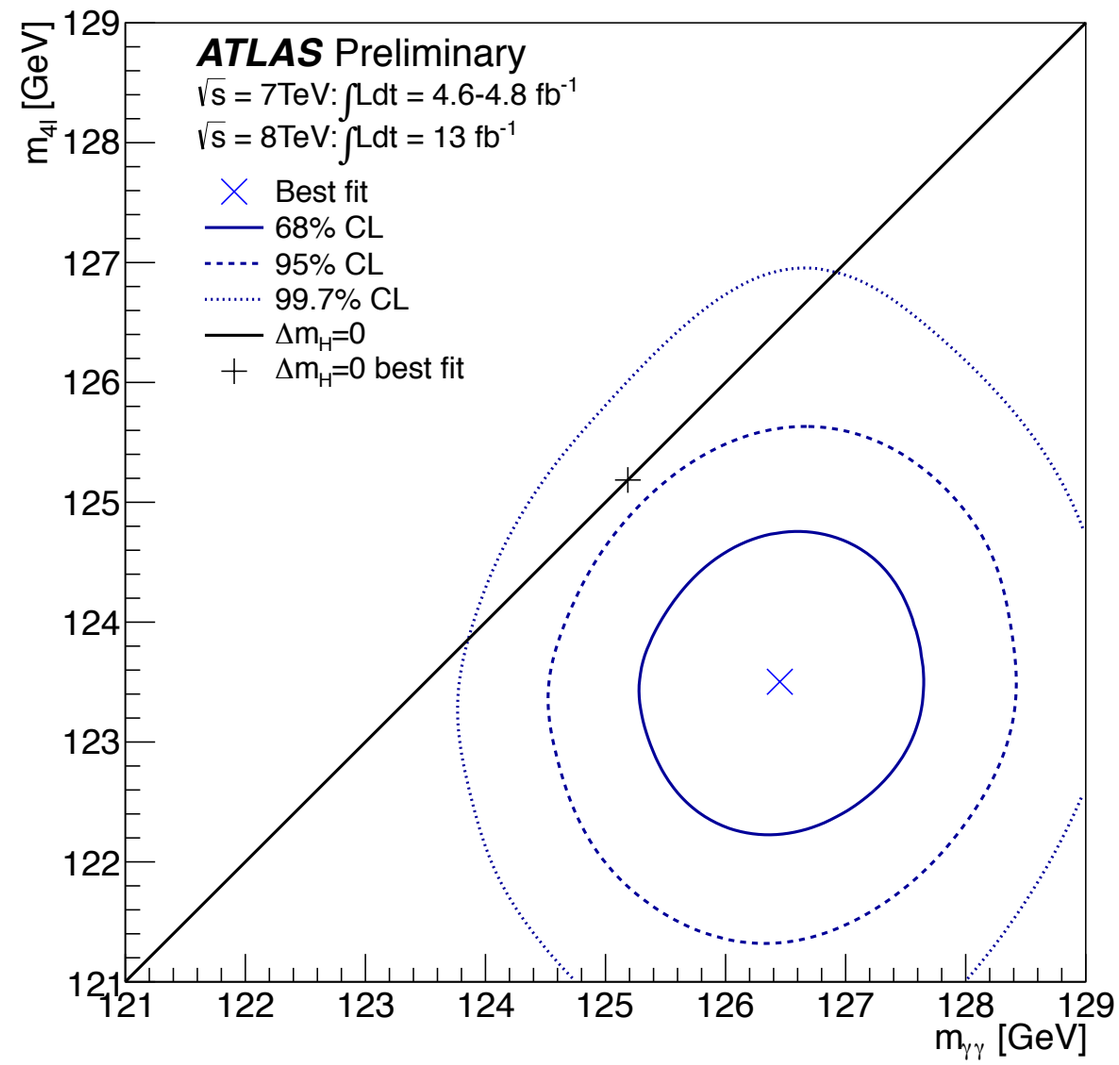
absolute energy scale calibration from Z peak

+0.4% +0.3%

Mass Compatibility

Continuous m_H parametrization in the γγ and 4l channel allow to make these studies:

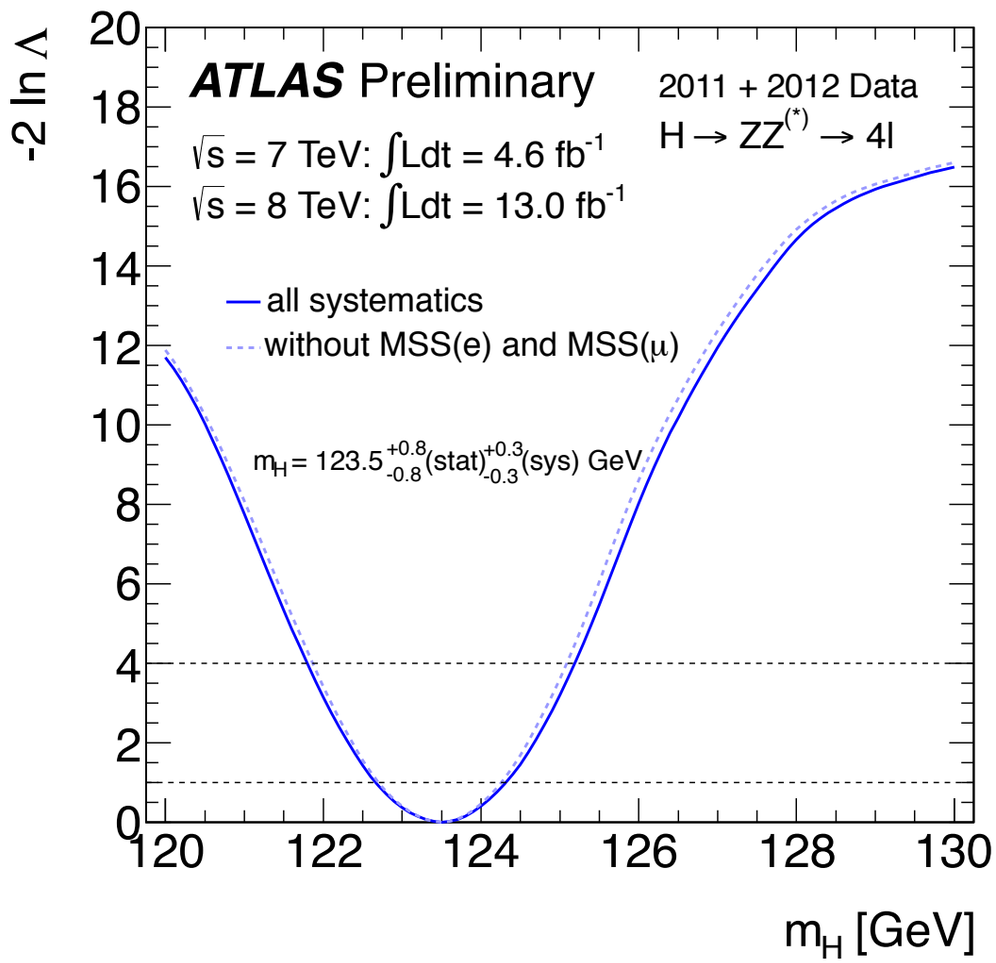




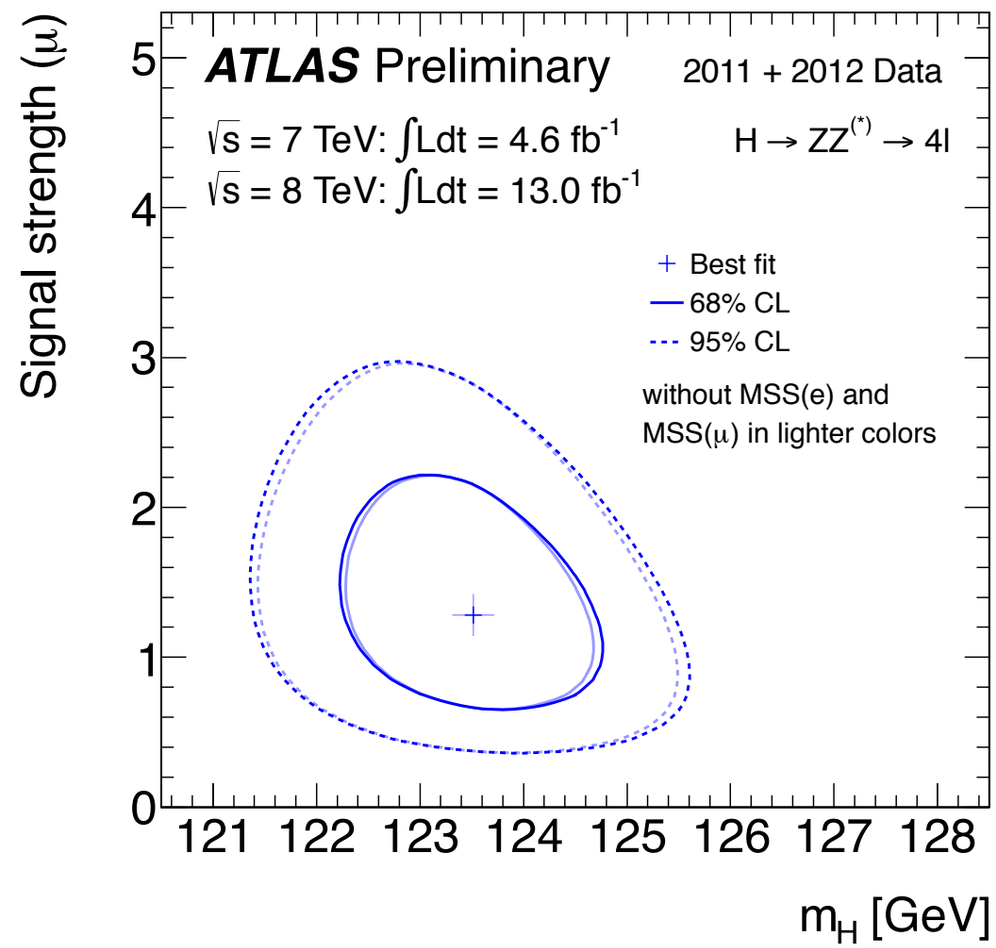
Conclusion

Shown an overview of the ATLAS $H \rightarrow ZZ^* \rightarrow 4l$ likelihood and some subtleties associated with high resolution and low count channels.

An alternative to modeling with histograms and analytic functions was shown.



(a)



(b)

For signal modeling, RooParamKeysPdf available in the RooStats development branch:

https://root.cern.ch/svn/root/branches/dev/roostats

BACKUP

From Marumi Kado (talk in Mainz):

$H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ Mass Scale Systematic Uncertainties

Main Mass Scale systematic uncertainties (considered in also ICHEP studies) :

Source	Relative Mass Scale Effect
Absolute Energy scale calibration from Z	0.3%
Upstream material simulation inaccuracies	0.3%
Pre-Sampler energy scale	0.1%

Further investigation and extensive checks lead to find additional sources of systematic uncertainties :

- LAr Strips relative calibration (0.2%)
- Photon energy resolution (0.15%)
- Calibration of the high gain (0.15%)
- Mis-classification due to fake conversions (0.13%)
- Backgound modeling (0.1%)
- Lateral shower development simulation (0.1%)
- Effect of PV choice (0.03%)

Main 4l Mass Scale systematic uncertainties :

Source	Relative Mass Scale Effect
Absolute Energy scale calibration from Z	0.4%
Low transverse energy electrons	0.2%
Muon momentum scale	0.2%

Further investigation and extensive checks have not lead to additional substantial sources of systematic uncertainty :

- Measurement with MS and ID alone
- Local detector biases checked event by event
- Local resolution effects checked using event-by-event error;
- kinematic distributions in agreement with expectation
- FSR simulation
- Different mass reconstruction using Z-mass constraint (+400 MeV shift)

46

Spin/CP

Candidate events in the region 115 GeV < m4l < 130 GeV are used. To improve the overall sensitivity, this mass region is split into two bins of high and low signal over background (S/B): low - 115 – 121 and 127 – 130 GeV, and high - 121 – 127 GeV. The sensitivity improvement of this two region split is estimated to be ~ 6% for all hypotheses tested.

BDT or MELA discriminant.

HistFactory model.

0+ / 0-

2+ / 2-

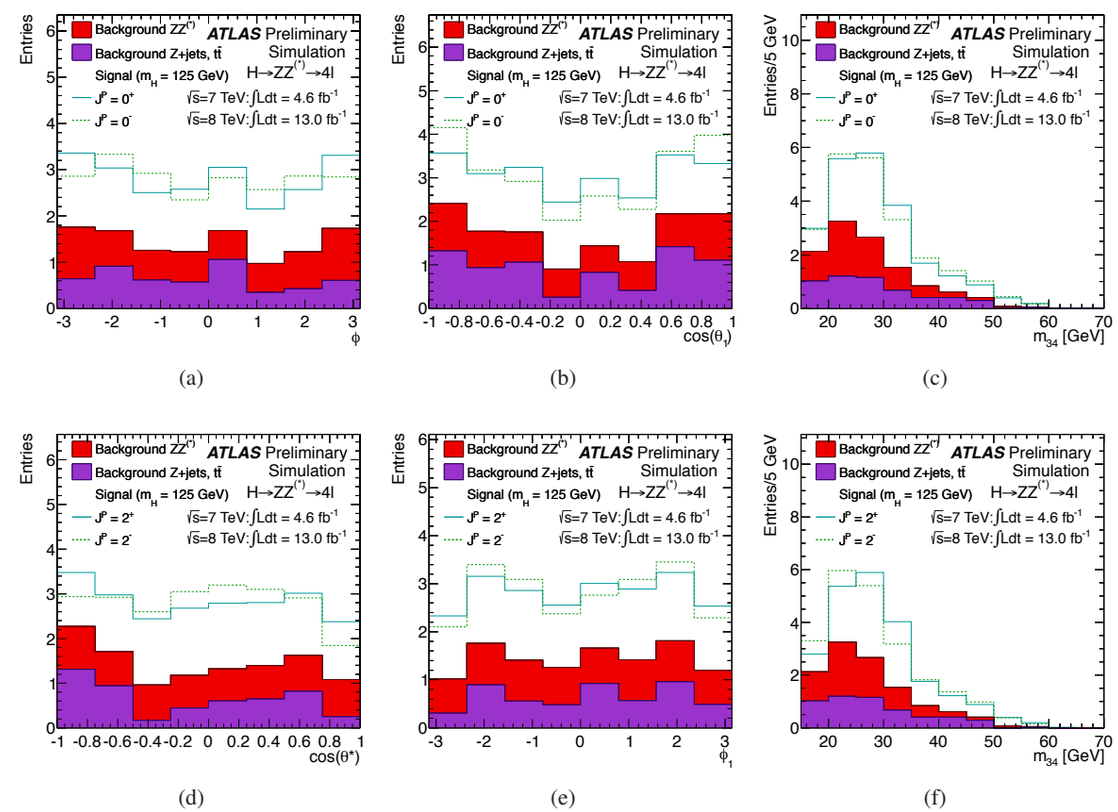


Figure 6: Expected distributions for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV for $m_{4\ell} = 125$ GeV including backgrounds in the mass range 115 GeV $< m_{4\ell} <$ 130 GeV comparing two pairs of spin/parity J^P states. Comparison of 0^+ versus 0^- hypotheses: (a) Φ, (b) $\cos\theta_1$, and (c) m_{34}, and comparison of 2^+_m versus 2^- hypotheses: (d) $\cos\theta^*$, (e) Φ_1, and (f) m_{34}.

Parametrizations of Response Function

Requirements:

- ➡ smoothly approaching zero
- ➡ continuous also in 1st and 2nd derivative for MIGRAD minimization

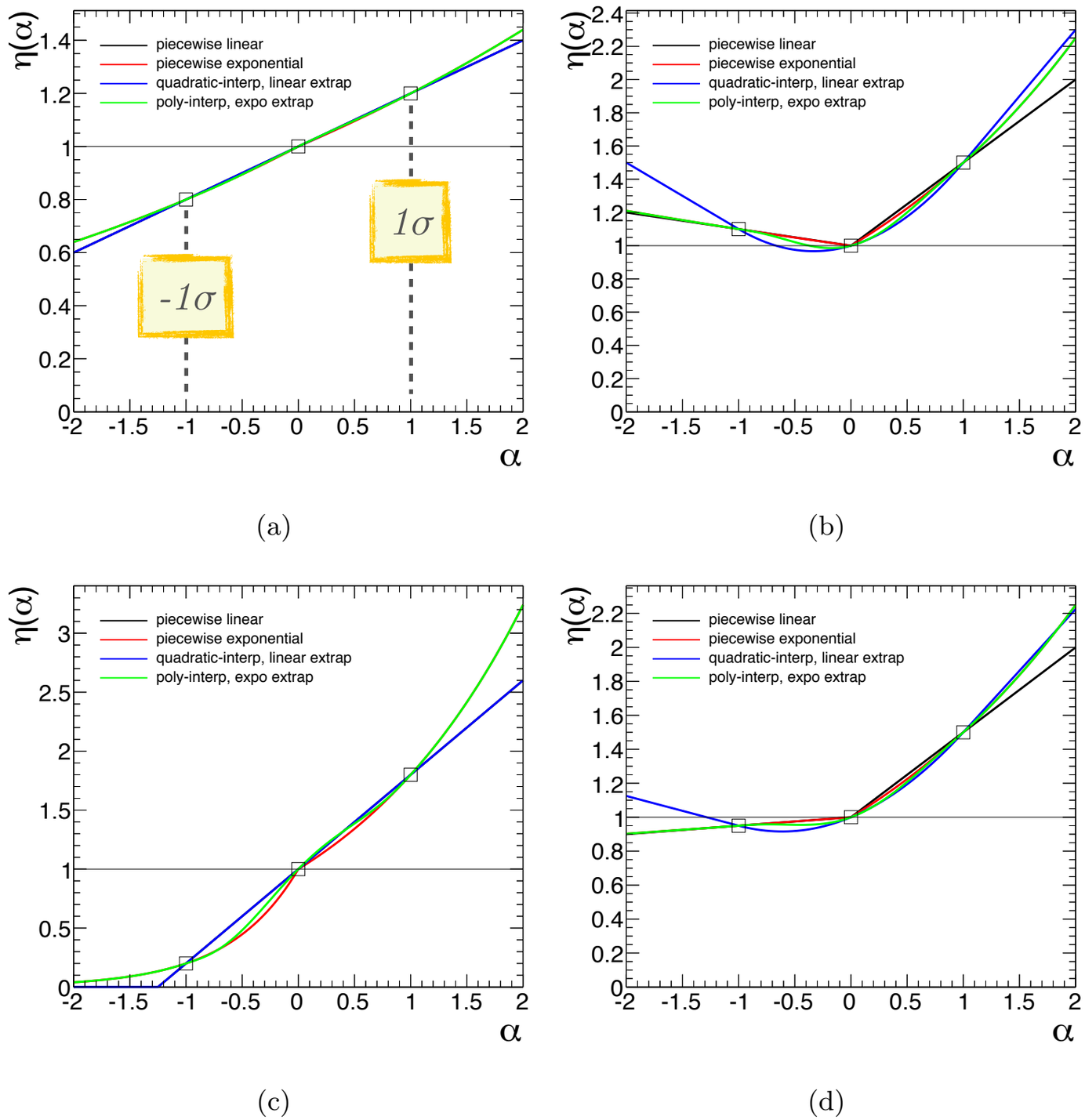


Figure 1: Comparison of the three interpolation options for different $\eta^{\pm}$. (a) $\eta^{-} = 0.8$, $\eta^{+} = 1.2$, (b) $\eta^{-} = 1.1$, $\eta^{+} = 1.5$, (c) $\eta^{-} = 0.2$, $\eta^{+} = 1.8$, and (d) $\eta^{-} = 0.95$, $\eta^{+} = 1.5$