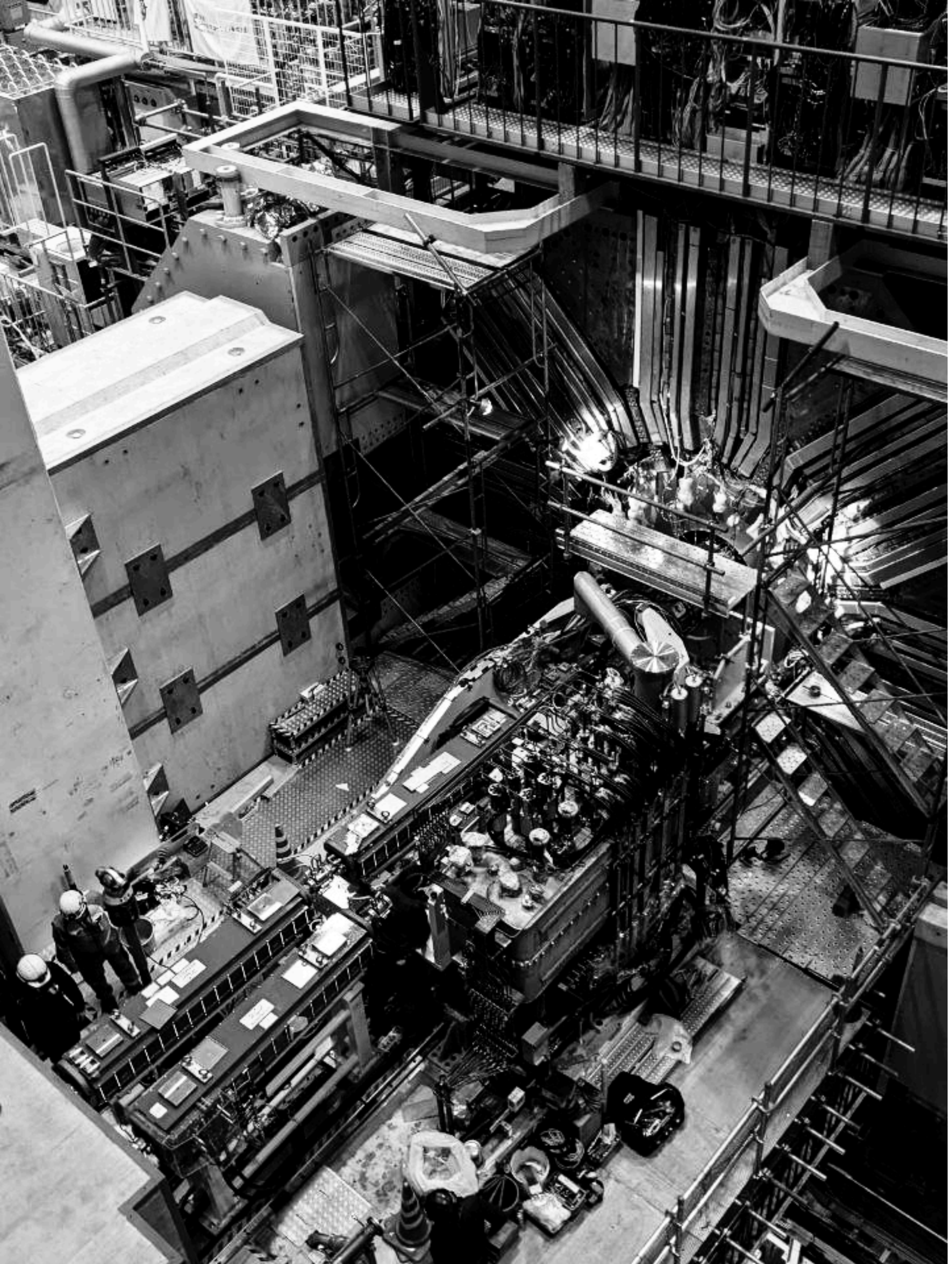


62ND INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS

HEXAQUARKS AT BELLE II

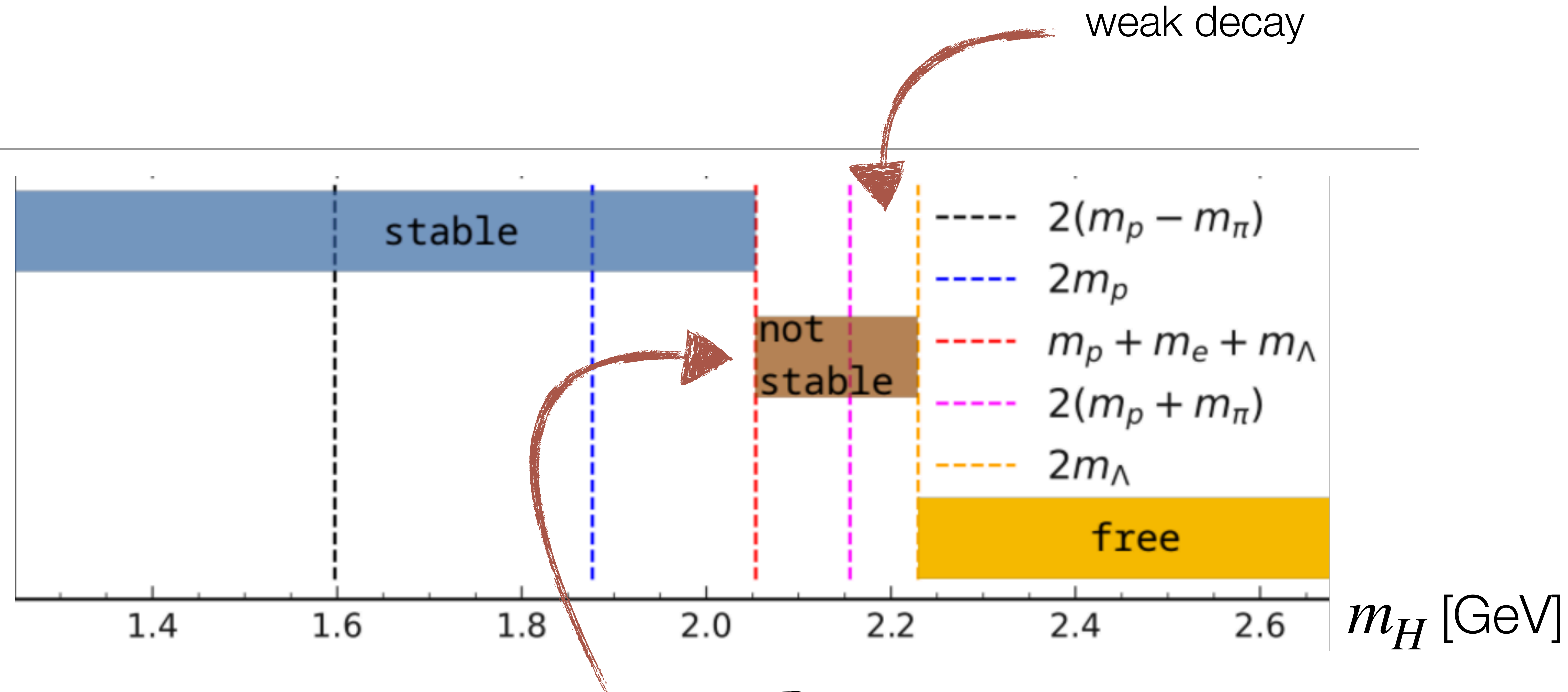
FELIX M. KEIL

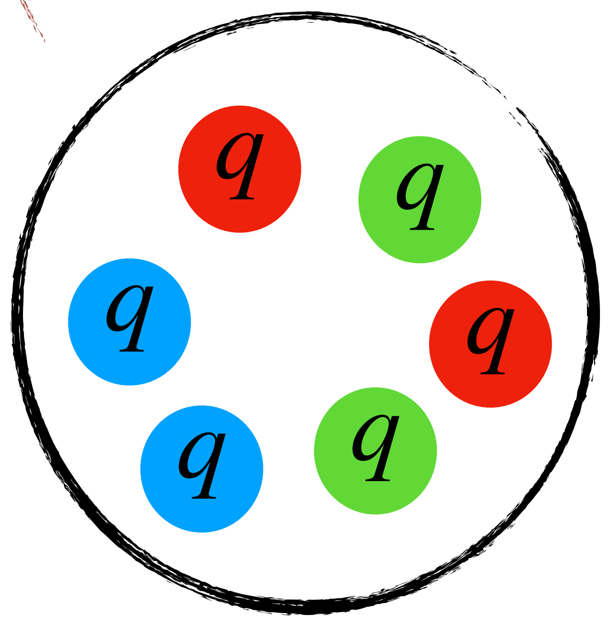
Bundesministerium für Forschung, Technologie und Raumfahrt

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

What?

- Doubly strange six-quark state
- Spinless and flavor-singlet
- udsuds content (like $2\Lambda^0$)
- LQCD & ALICE & NAGARA $\rightarrow$ Binding Energy $\lesssim 7$ MeV





Hexaquark/H-Dibaryon?

H-DIBARYON TIMELINE

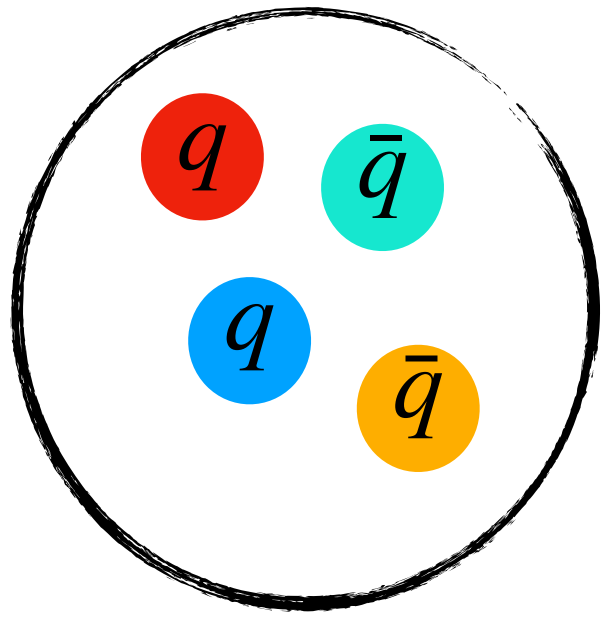
- 1977: H-Dibaryon (R.L. Jaffe) proposed
- 1999: Stable Dibaryon (Kochelev) proposed
- 2003: Sexaquark (Farrar) proposed
- 20xx: H-Dibaryon?

Why?

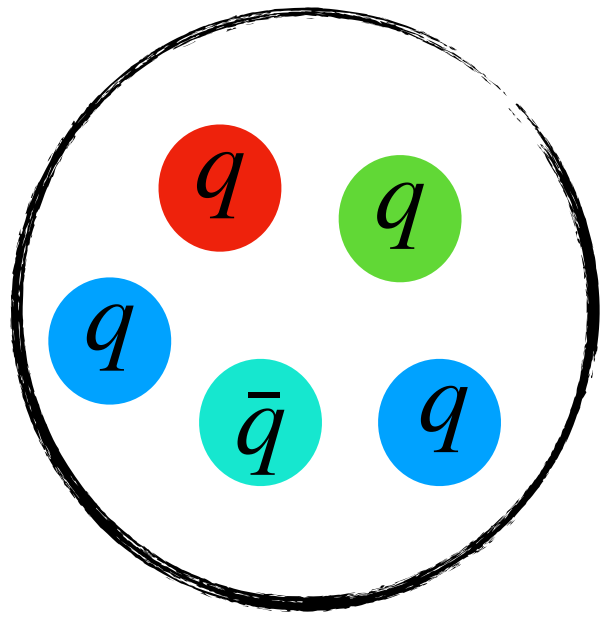
- Discoveries:
  - X(3872) at Belle,
  - Tetraquarks at LHCb,
  - Pentaquarks at LHCb,
  - Why not **six-quark** states?

- Influence on **neutron star** EoS
- Understand $\Lambda - \Lambda$ interaction better
- New particle = Cool 😎

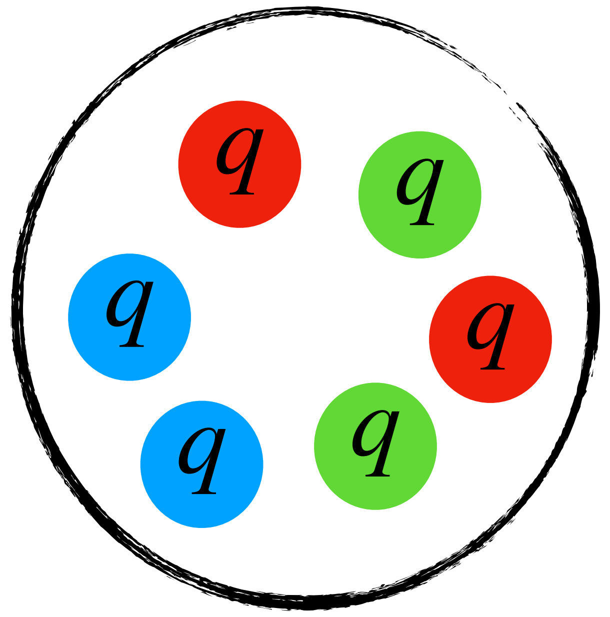
QCD: No limit on number of quarks!



Tetraquark

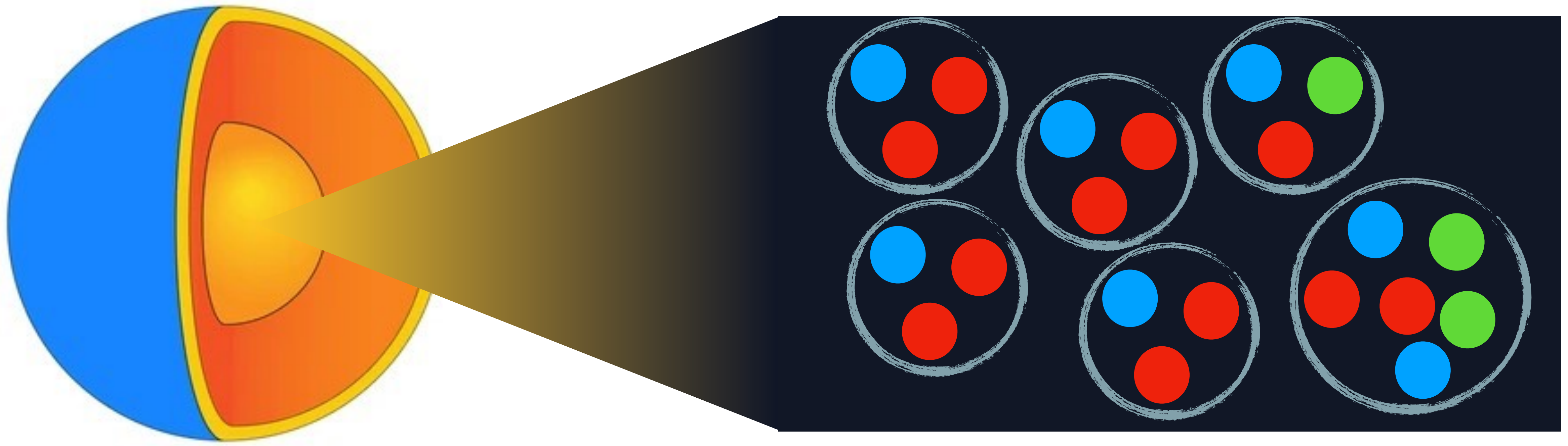


Pentaquark



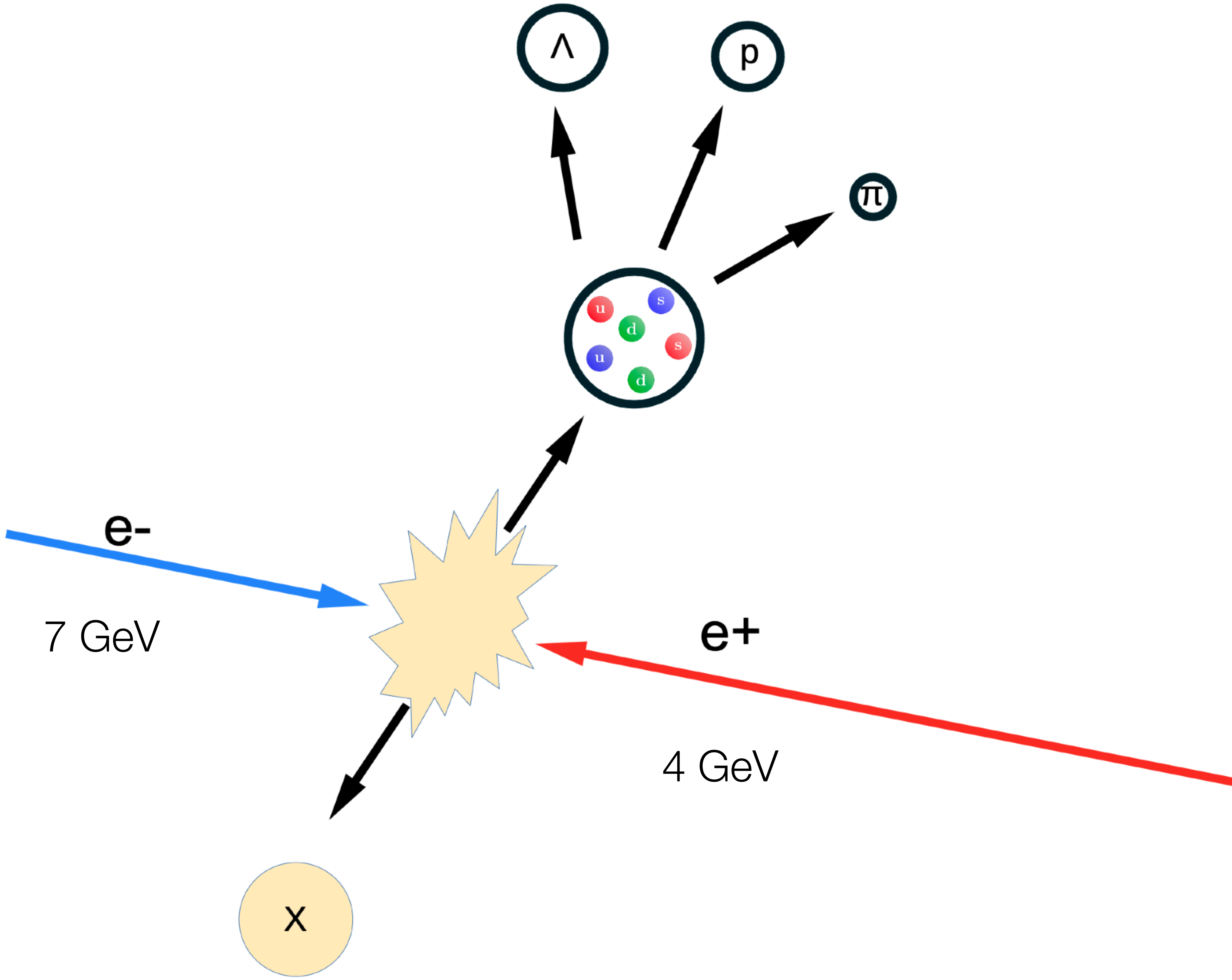
Hexaquark/H-Dibaryon?

Neutron star



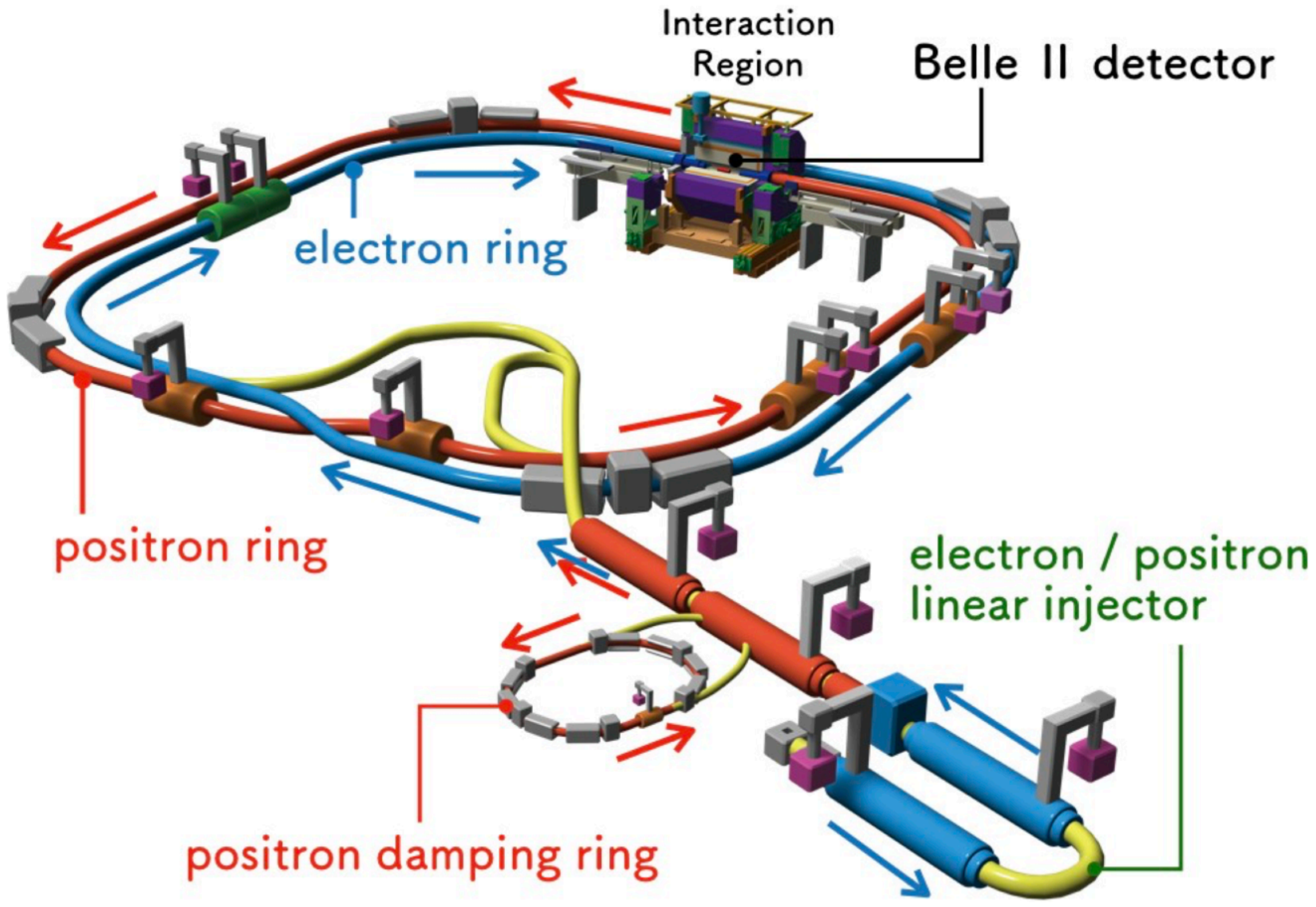
How? - High Luminosity Frontier

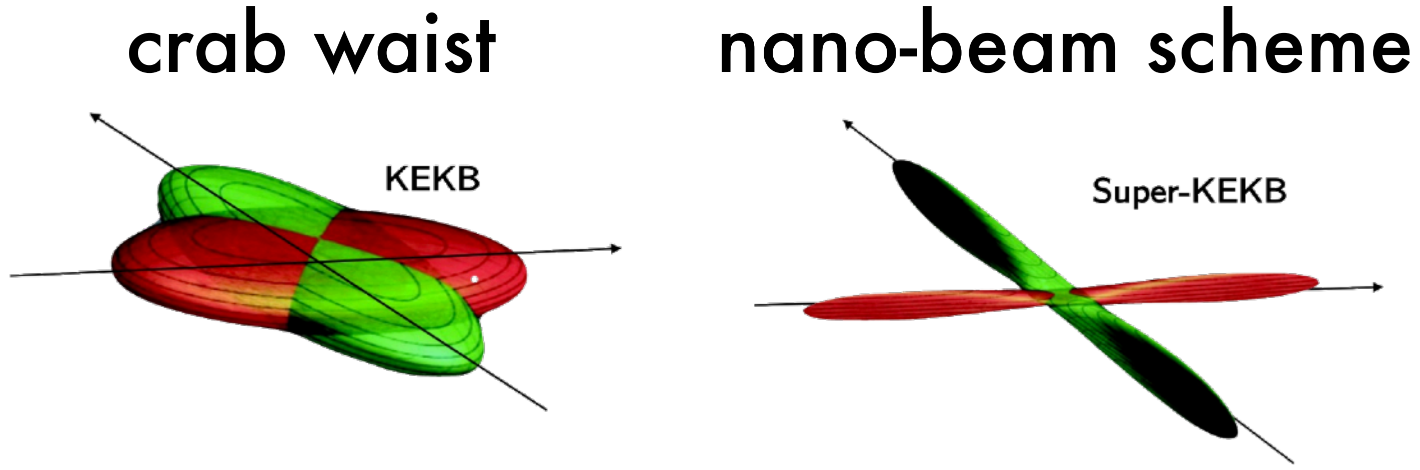
- $H \rightarrow \Lambda\, p\pi^-$
- Requirement:
  - High density of quarks
  - Good reconstruction of Λ and tracking of $p\ \pi^-$
  - Lots of data ⇔ high luminosity
  - Optimal having $\Upsilon(1,2,3S)$



⇒ B-Factories (eg. **SuperKEKB + Belle II**) are optimal for such decay channels

Briefly: SuperKEKB & Belle II

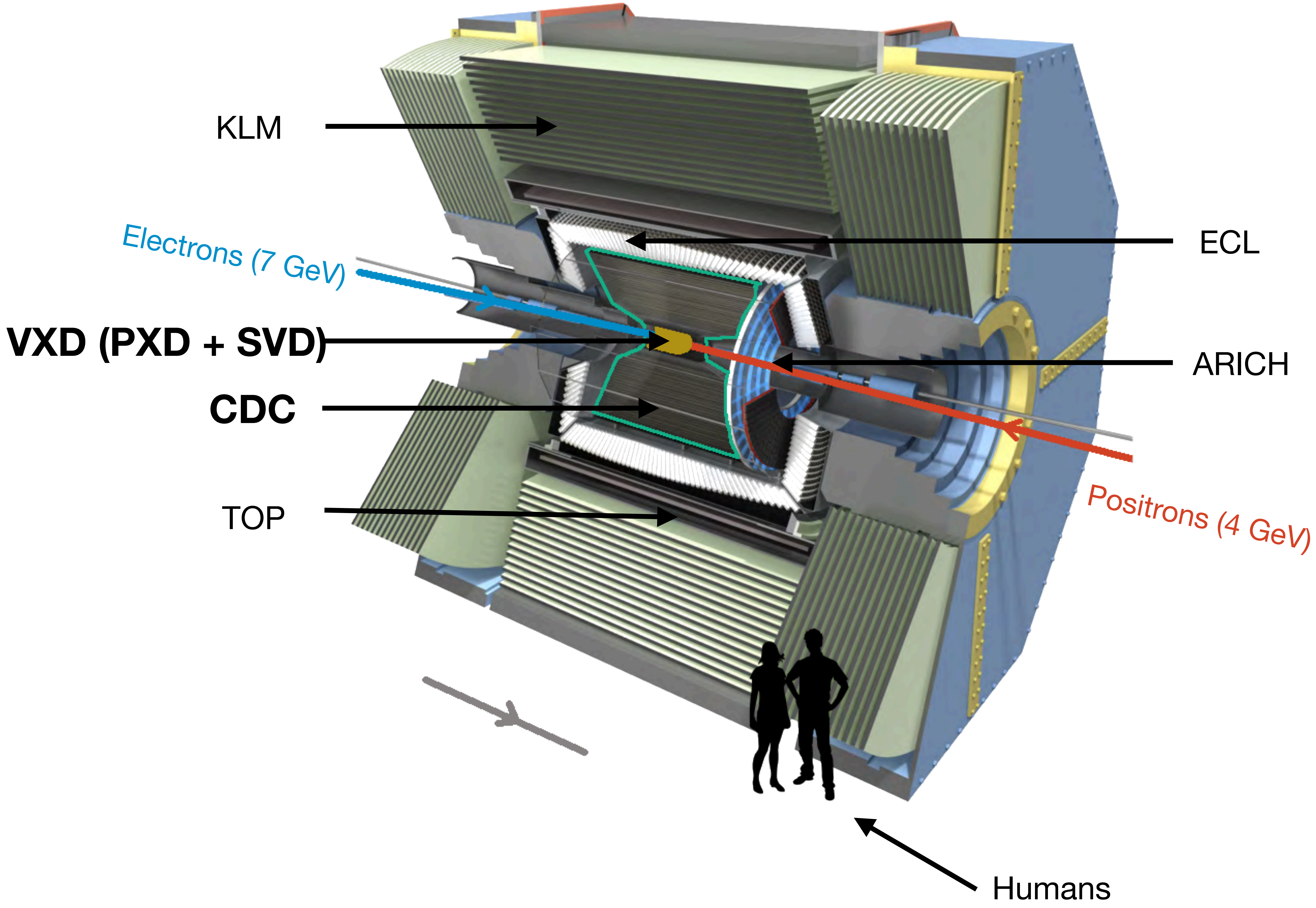




→ x30 instant. luminosity

~$5.1 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

SuperKEKB



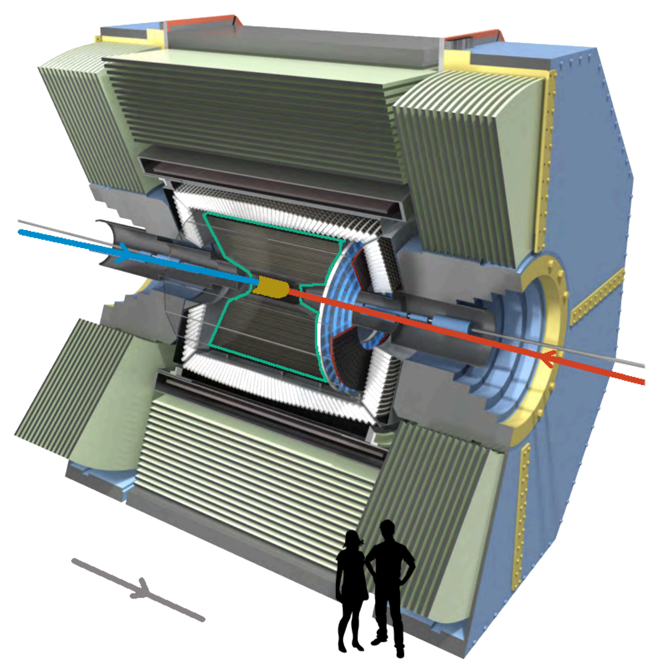
Belle II

How? - Analysis Outline

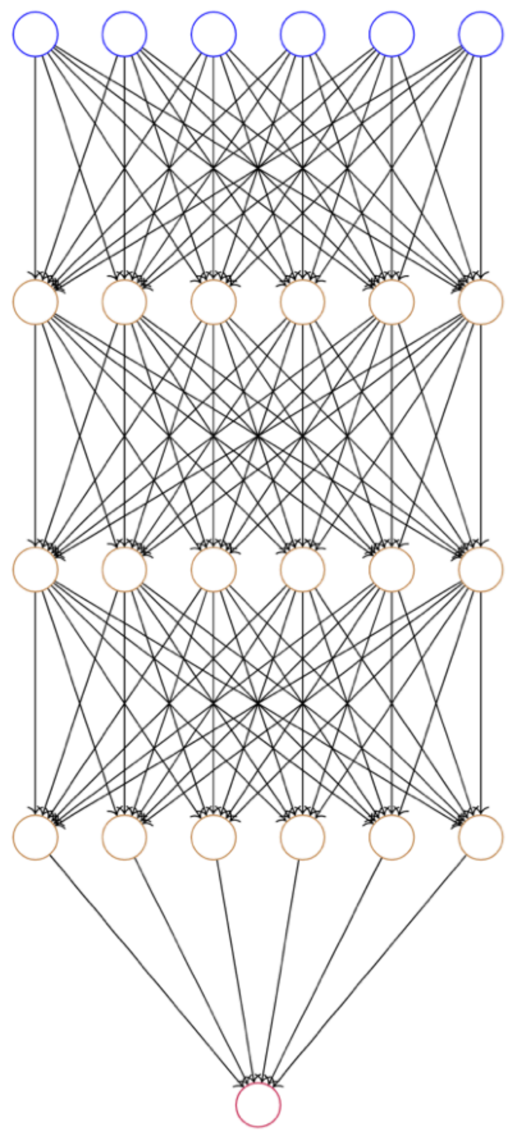
MC

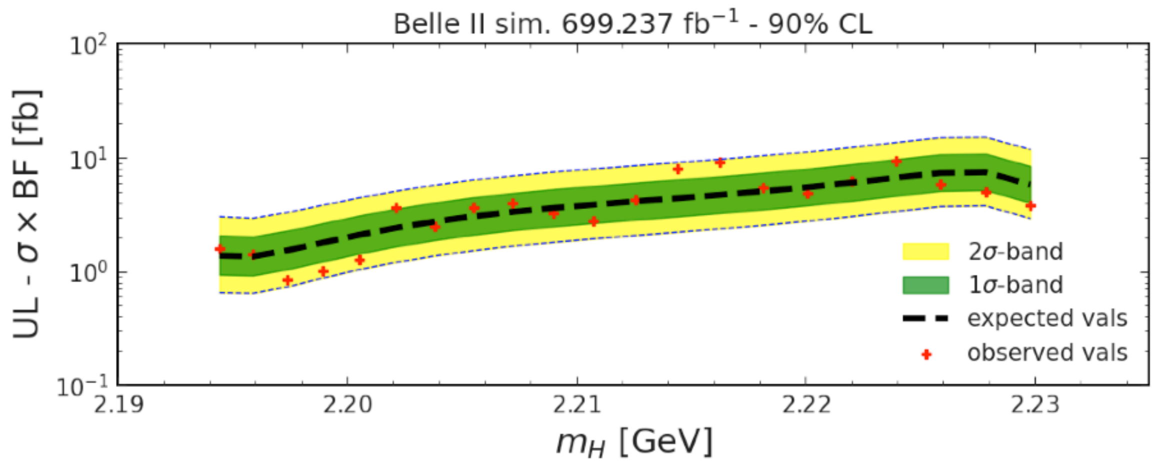
Reconstruction

Reconstruction



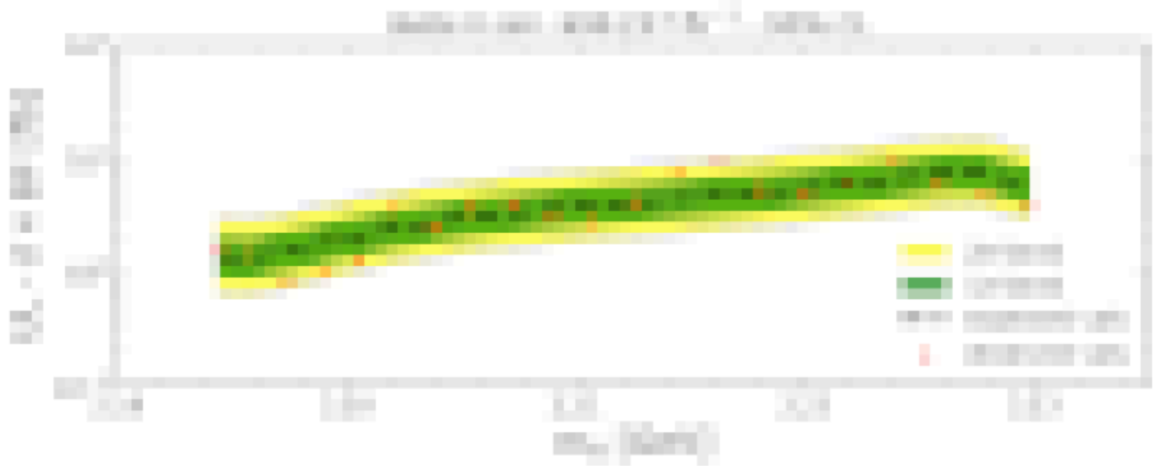
Neural Network





Fit + Inference

Fit + Inference

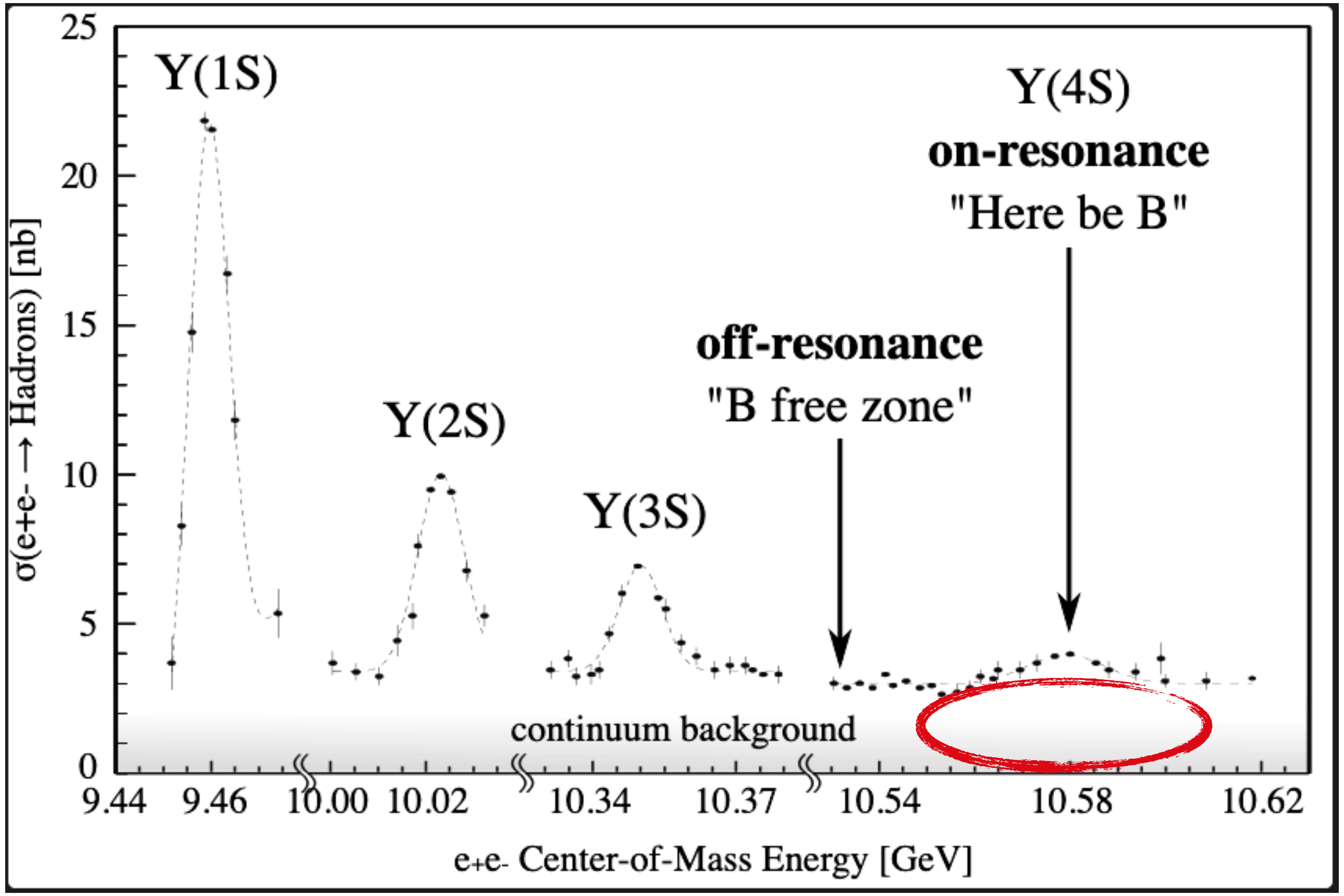


How? - Analysis Outline

How?

- SuperKEKB + Belle II tuned to $\Upsilon(4S)$
- ~~$e^+e^- \to Y(1,2,3S)$~~

→ **Continuum**



How? - Generation

MC

- From **continuum**

$$e^+e^- \to [H \to \Lambda\, p\pi^-] \;+\; X$$

- Replace $\Xi^0(1530)$ values with hypothesised parameters for **H** in Pythia.

  → Sensitive to strangeness

  → Unlikely to be a daughter-particle

- 26 masses in region $m_H \in [2.19,\, 2.23]$ GeV

KKMC

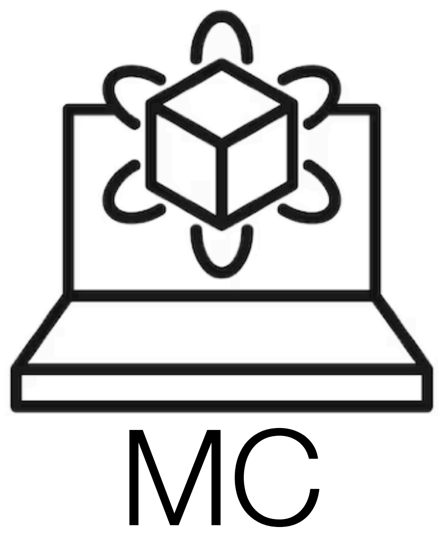
↓

Pythia

↓

EvtGen

How? - Reconstruction



- Belle II → Bottom-Up
  - Steering file

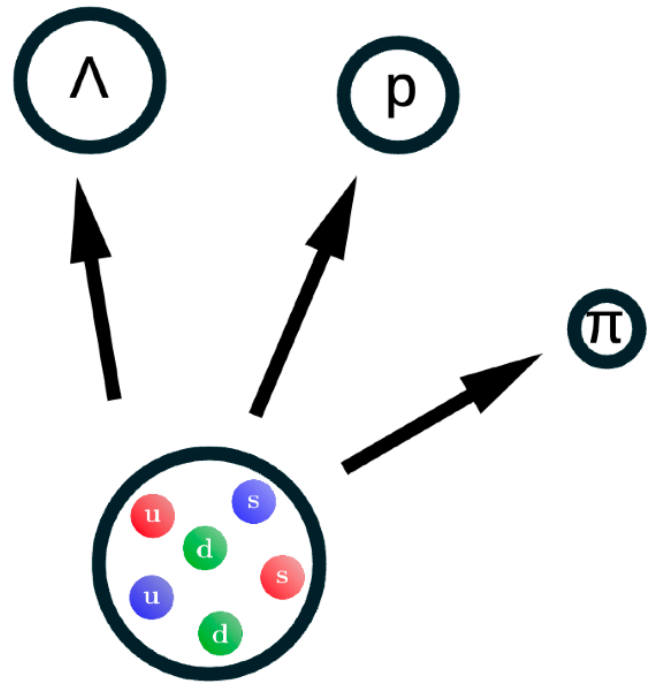
Build lists with FS

Combine lists + vertex fit

Write out new list + coarse selection

add PID weights

  - Neural Network - selection
  - Best Candidate - selection

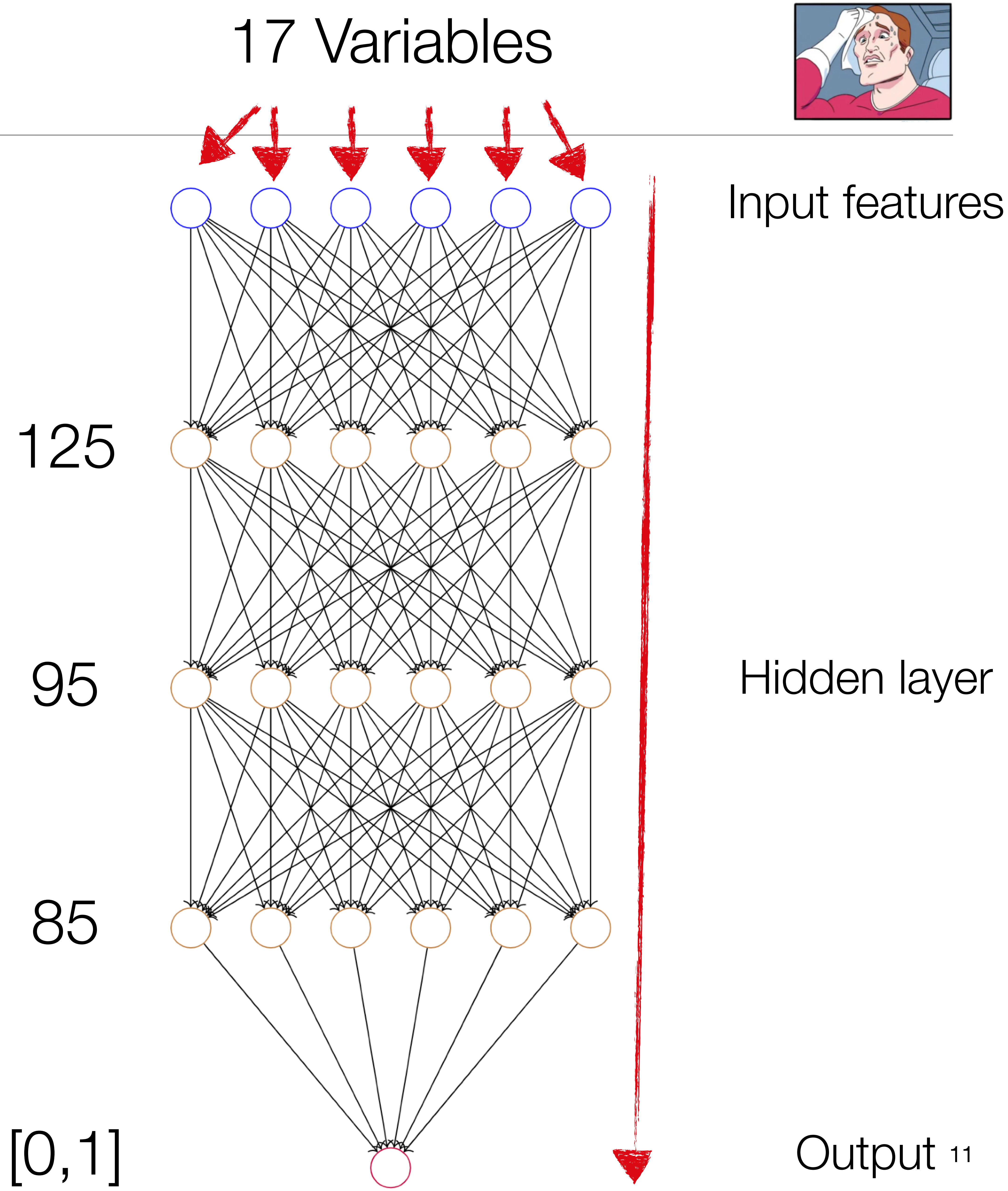


How? - Neural Network

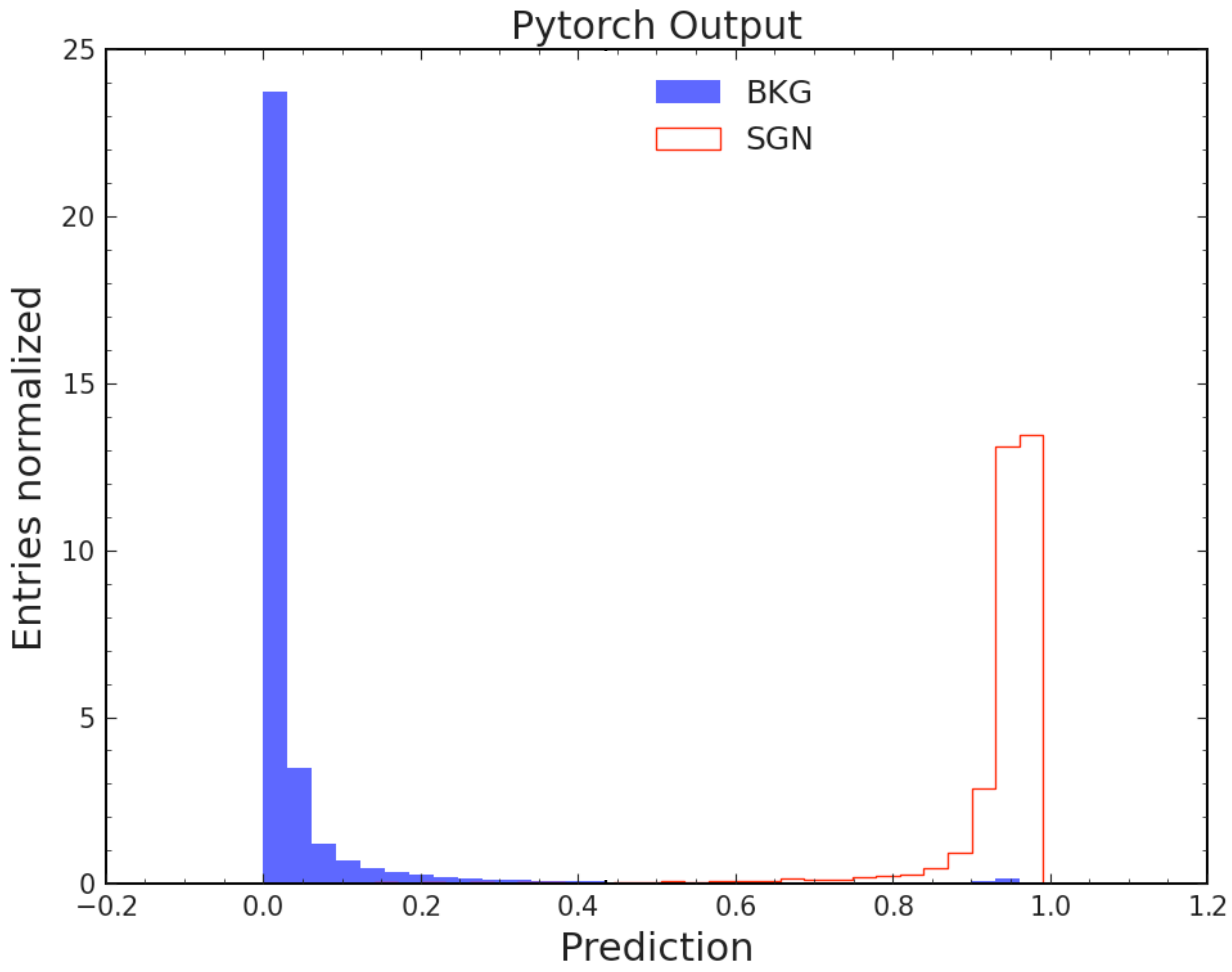
- Deep Neural Network
    - Hyperparameter tuned with Optuna
    - Variables selected via BDT importance
    - …

- Training + validation on BKG + every other signal mass-point

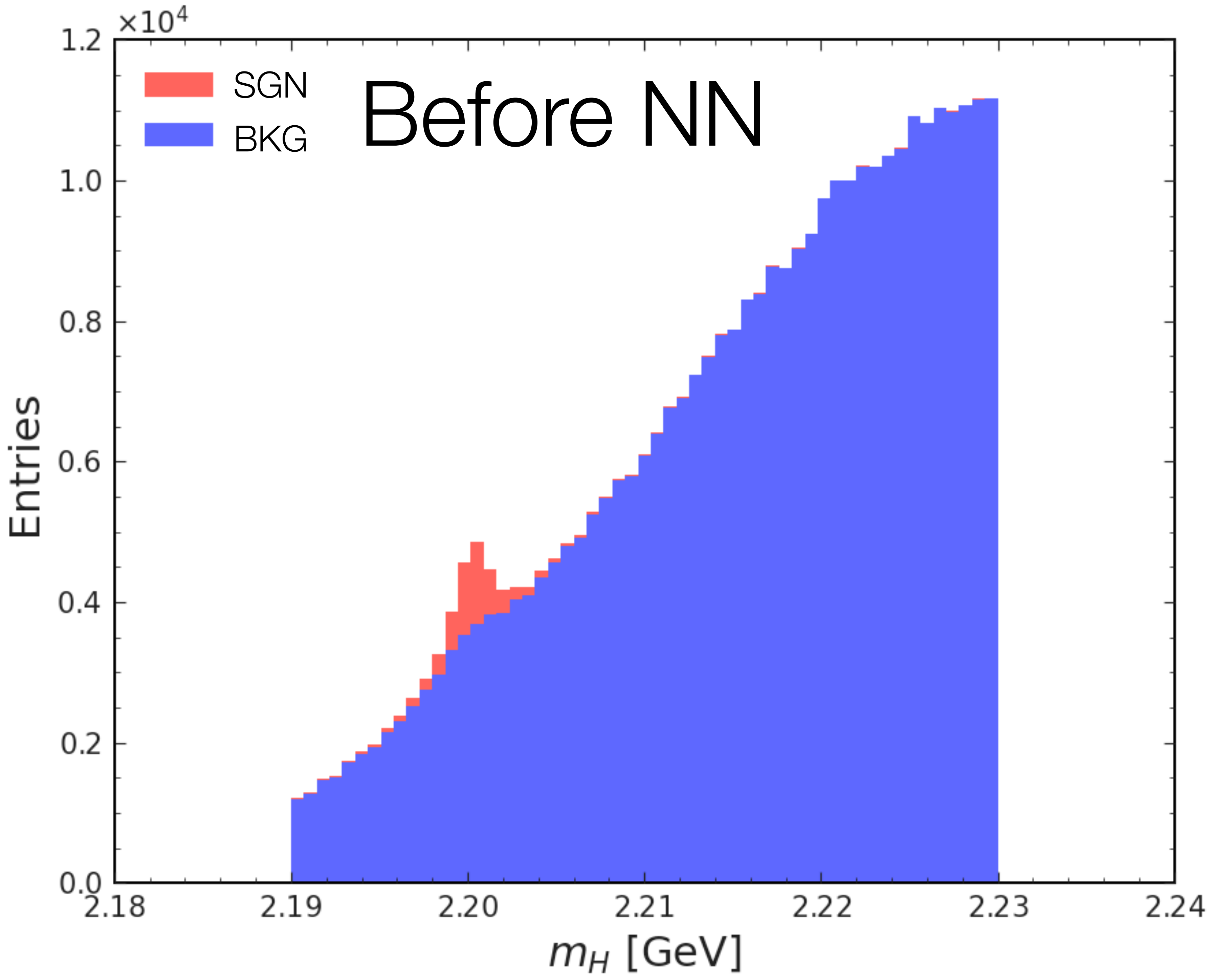
- Test on data the NN has not seen
  → BKG + signal mass-point(s) not used in training/validation



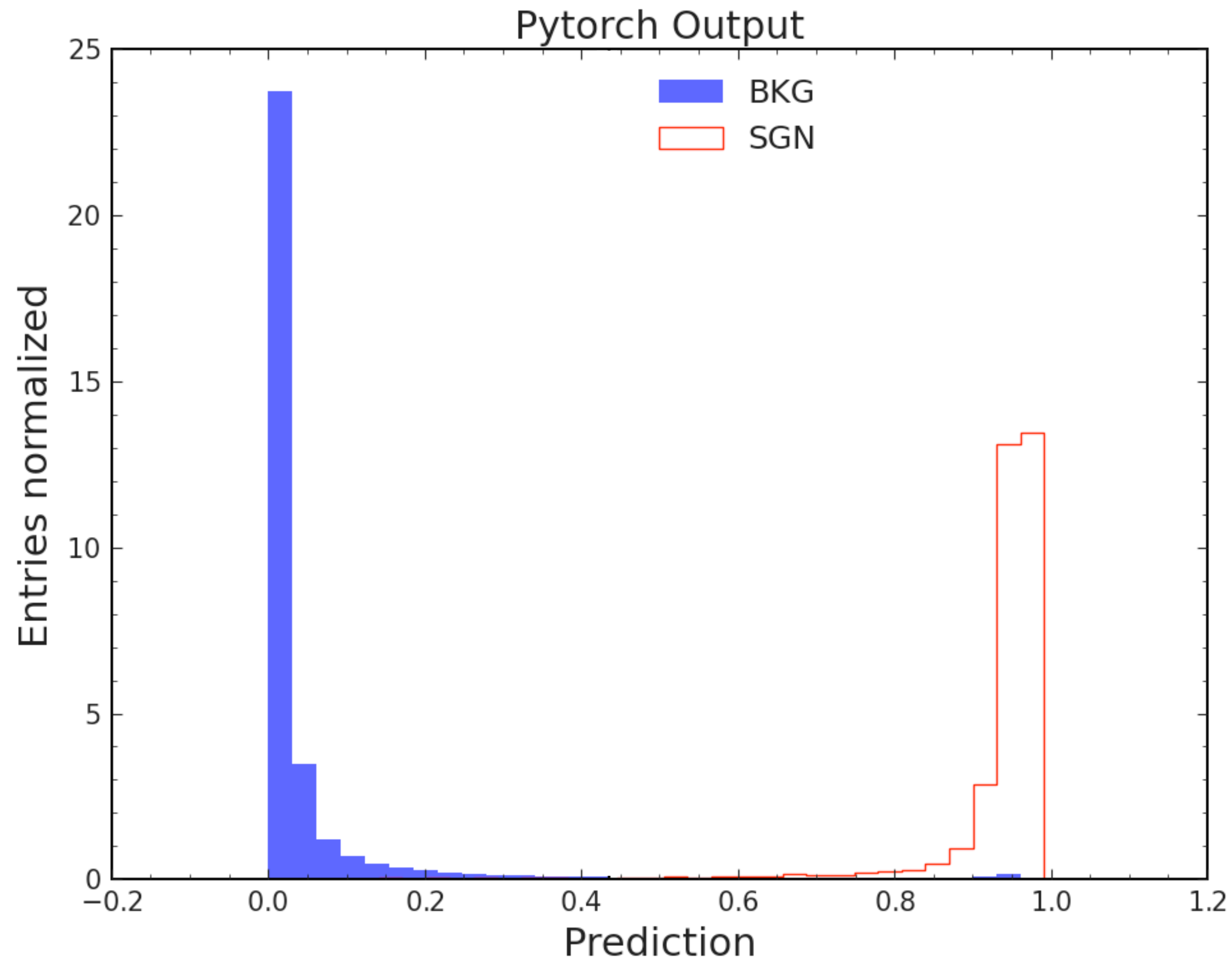
How? - Neural Network Evaluation

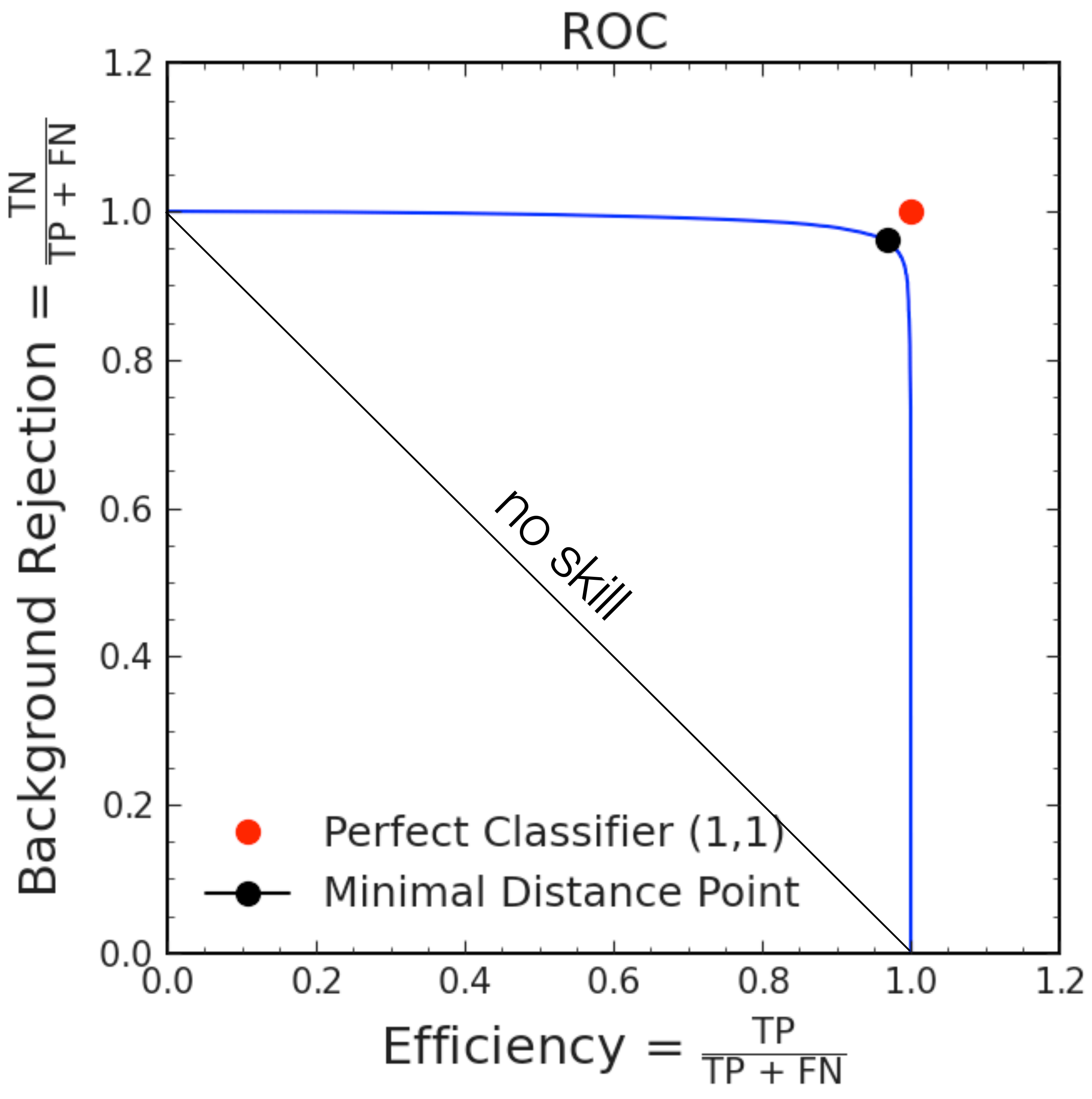


Test-set (not seen before)
BKG + 5000 artificial signals @ 2.200 GeV injected



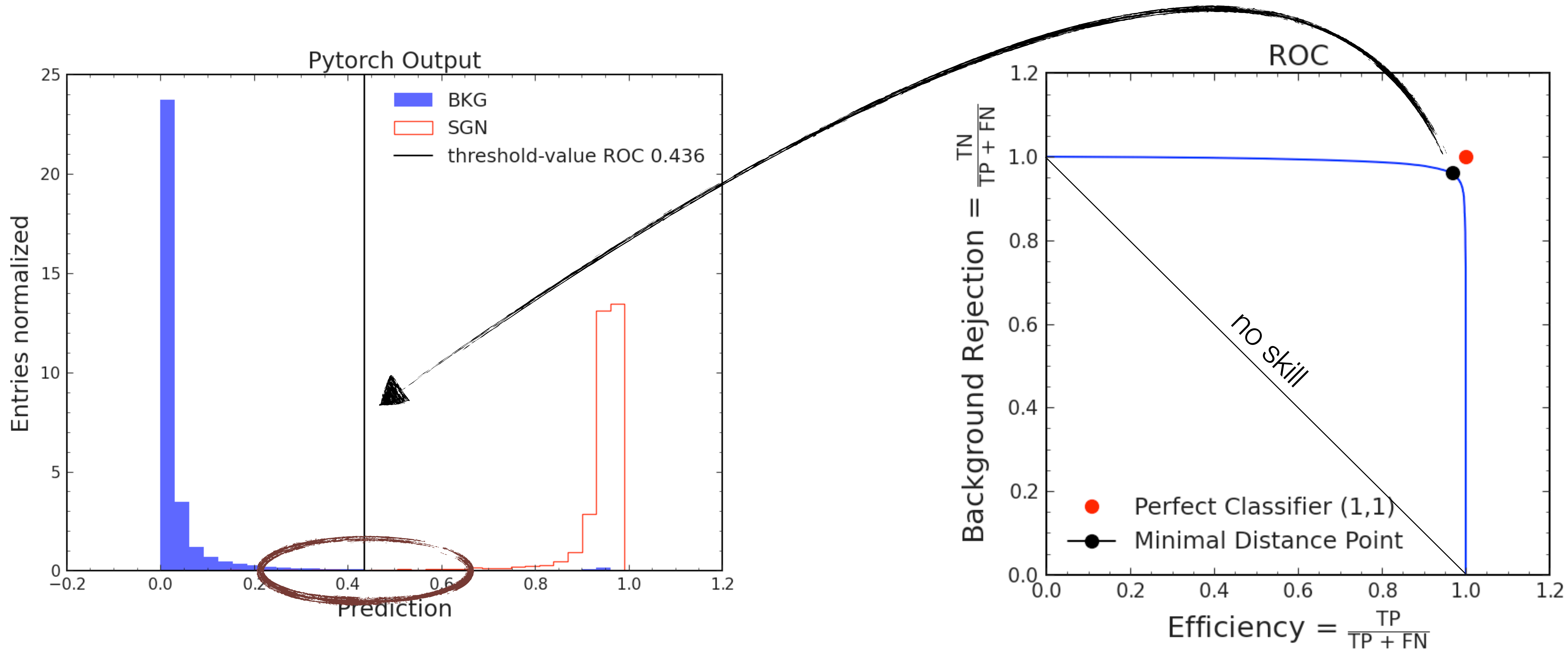
How? - Neural Network Evaluation



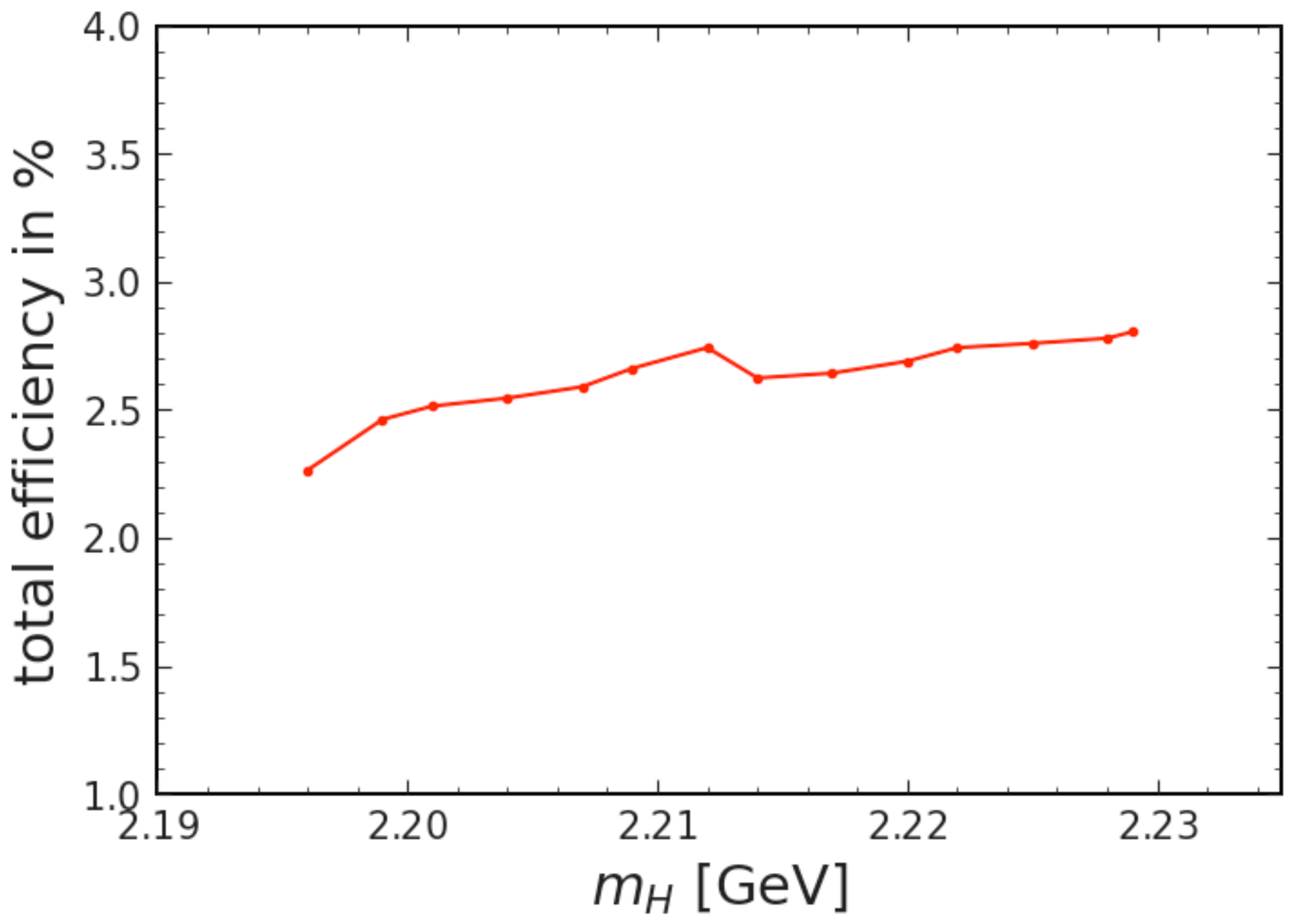


How? - Neural Network Evaluation

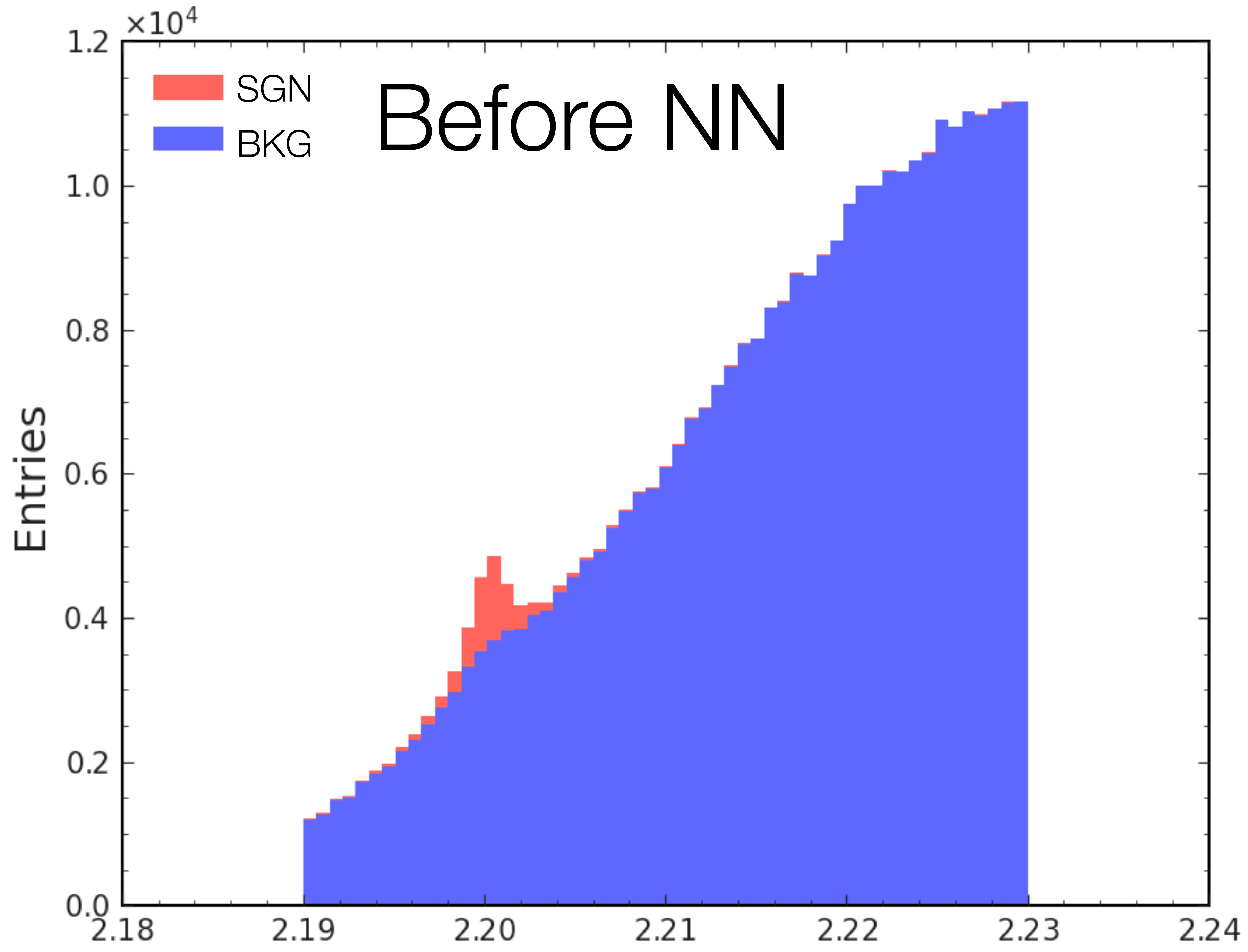
- Threshold in flat area → Network is stable

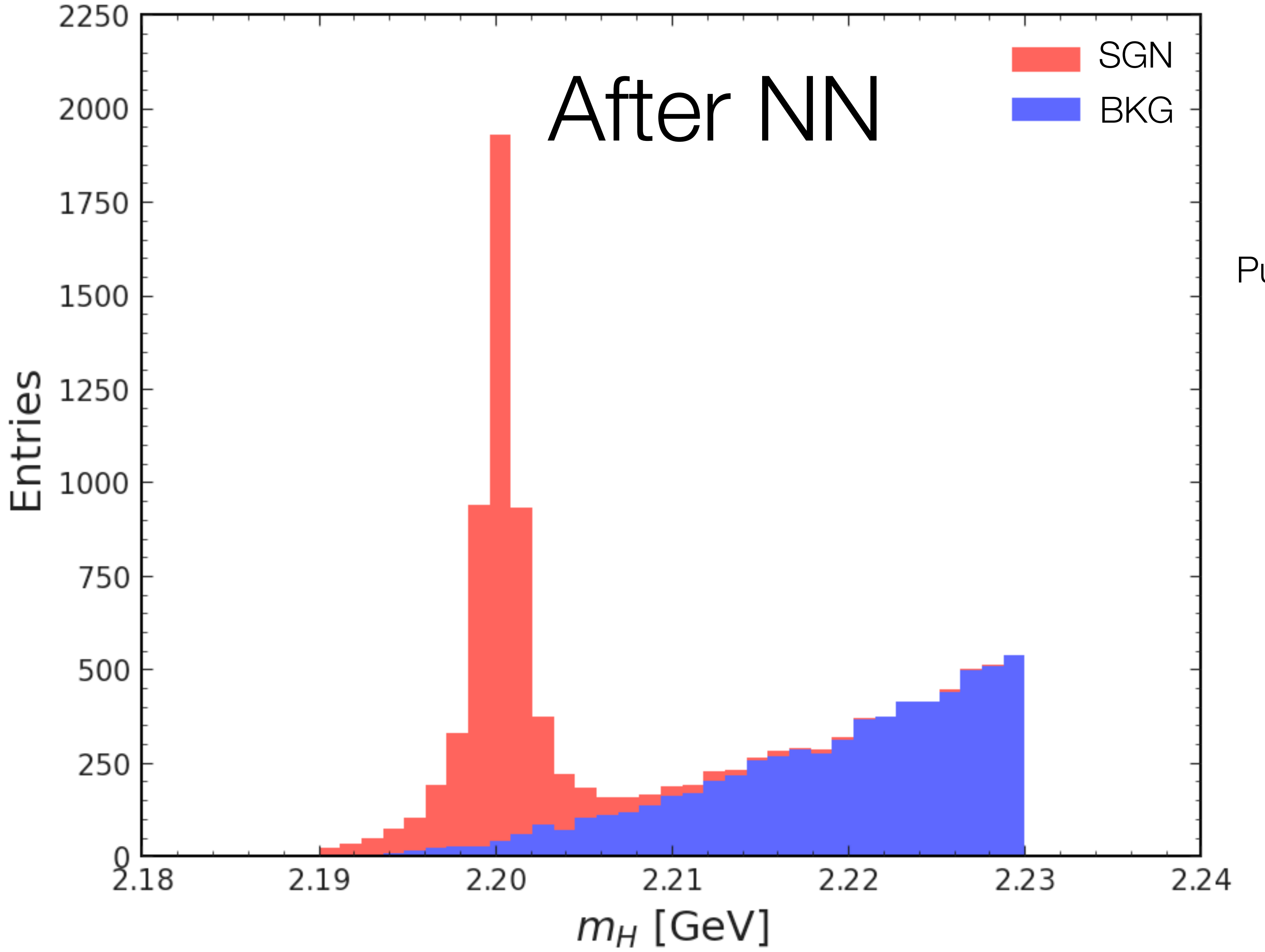


How? - Neural Network Evaluation



Total efficiency = Reconstruction-efficiency · NN-efficiency





$$\text{Purity} = \frac{TP}{TP + FP}$$

~ 90%

(2σ window)

How? - Inference

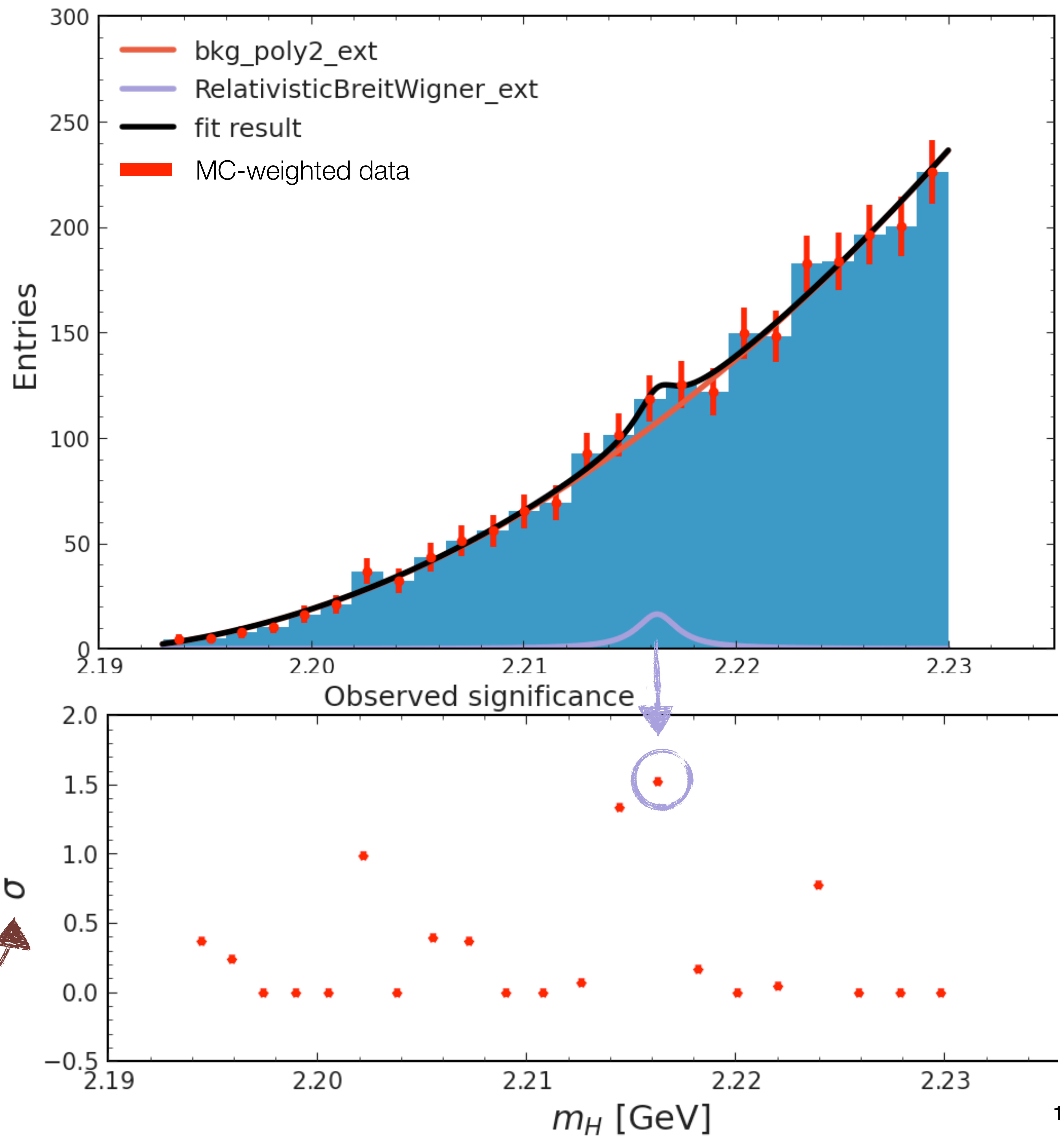
- Extended Unbinned Maximum Likelihood
- Keep it simple:

  SGN → Breit-Wigner profile

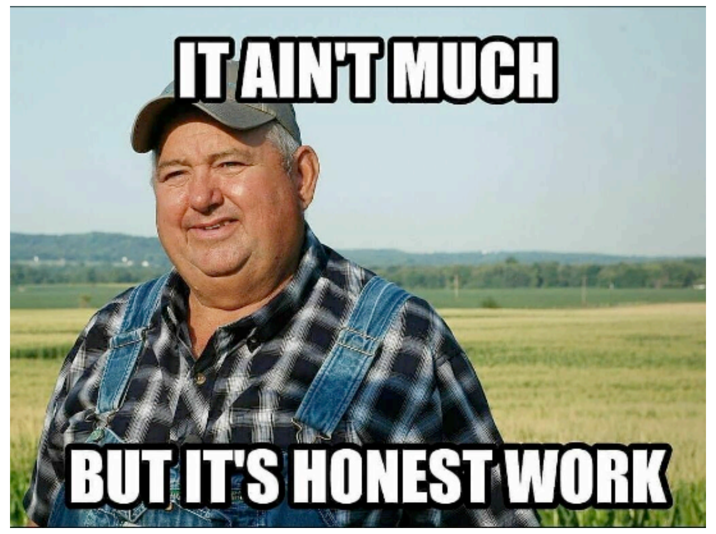
  BKG → 2[nd] order polynomial

- Fit on scaled BKG-only—MC
  → **No signal** injected here
  → Peak due to statistical fluctuation
  → Account for Look Elsewhere Effect (**LEE**)

Discovery significance



Results on MC



- Discovery significance ~ **0 σ**
- Upper Limits ~ **1-10 fb**
- Compare with on-resonance searches:

→ weak decay[1]:

BF($\Upsilon(1{,}2S) \to [H \to \Lambda p \pi] + X$) ~ $10^{-7} - 10^{-6}$

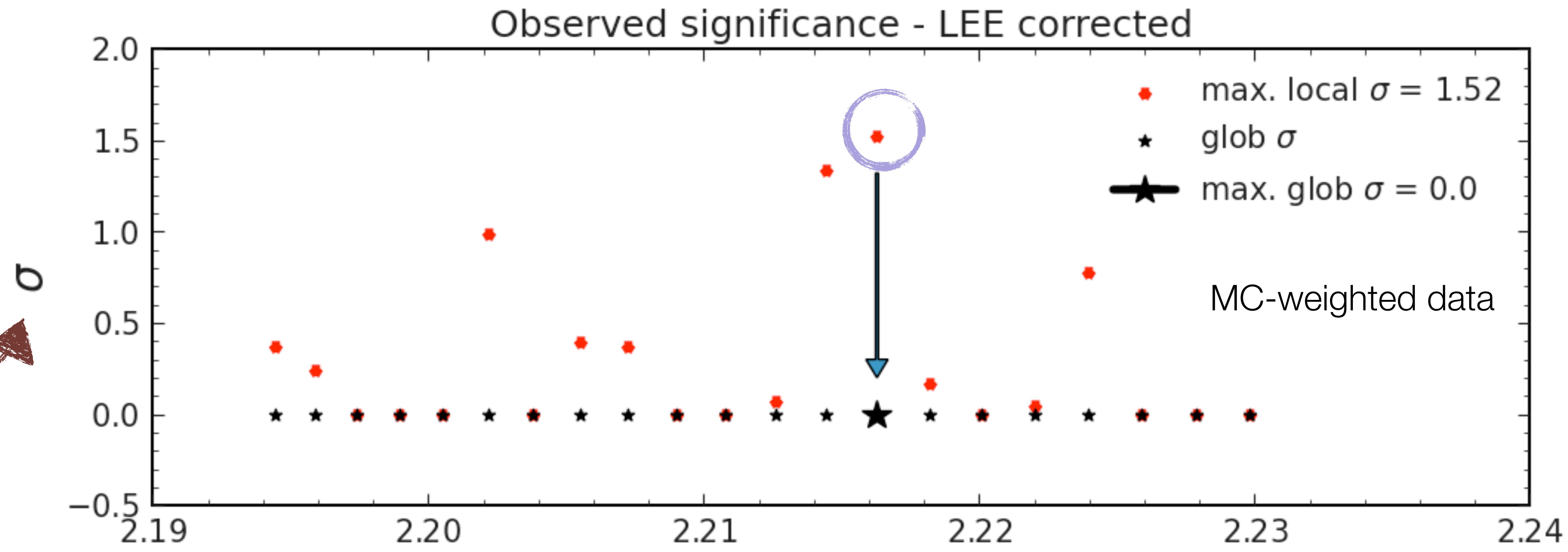
UL ~ 0.5 - 4 fb

→ stable (MC-only)[2]:

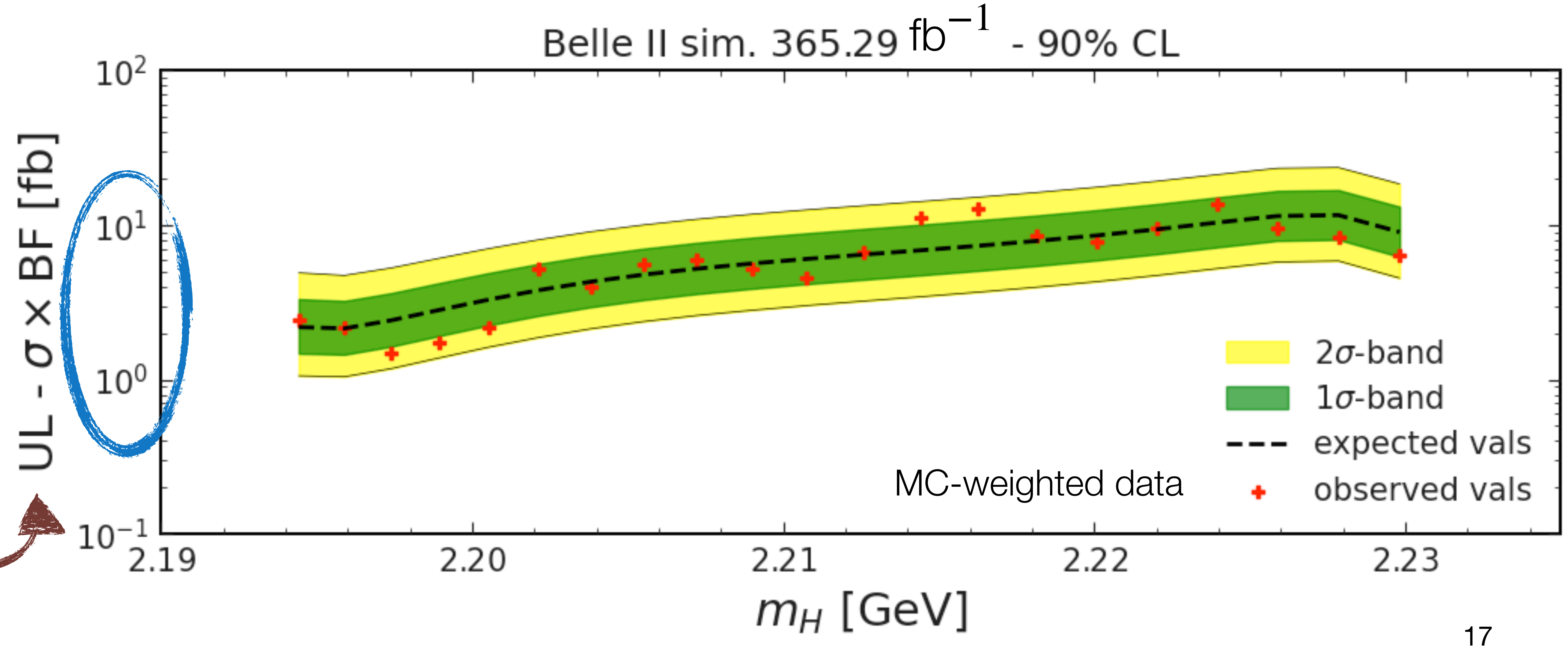
BF($\Upsilon(3S) \to S\Lambda\Lambda$) ~ $0.5 \cdot 10^{-7} - 3 \cdot 10^{-6}$

UL ~ 2 - 12 fb

Discovery Significance

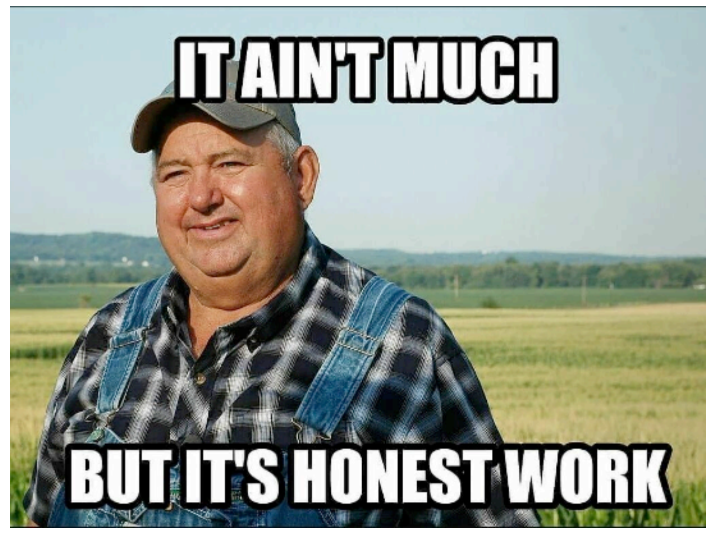


Upper Limit



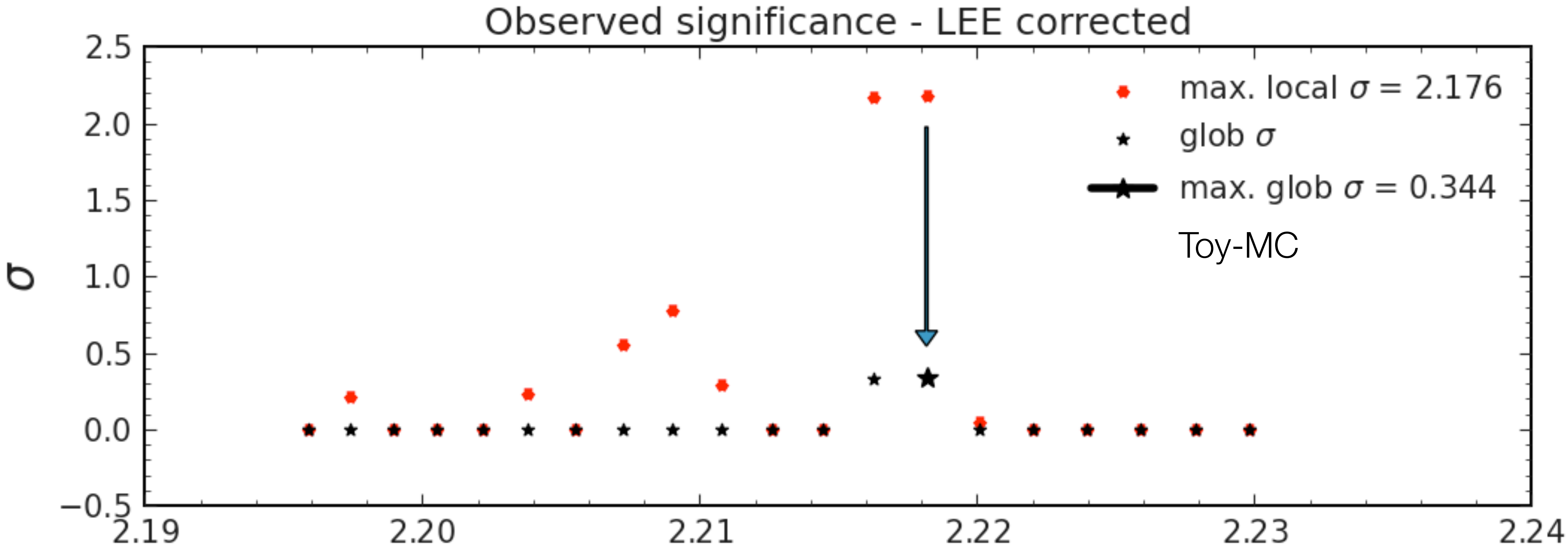
[1] https://arxiv.org/abs/1302.4028

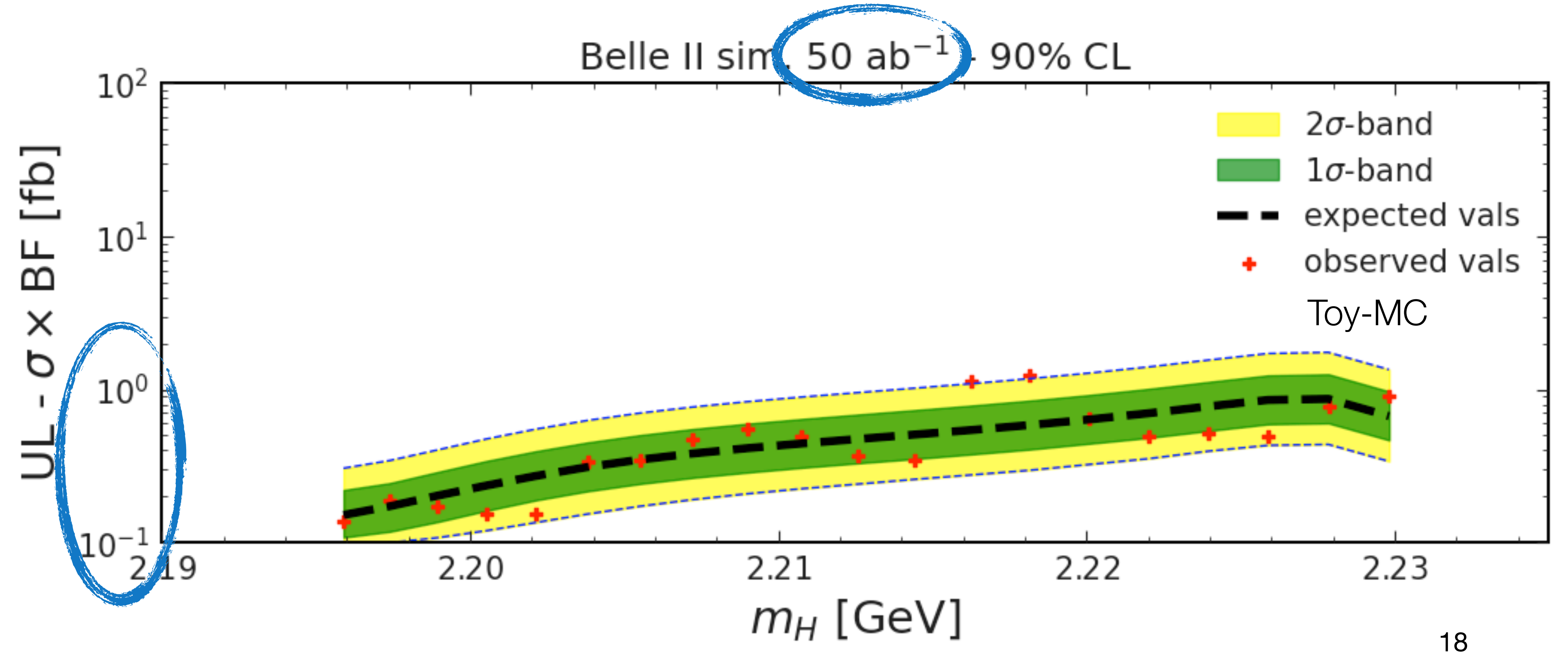
[2] https://b2-pubdb1.desy.de/pub_data/documents/2331/



Conclusion and Outlook

- **First search for a weakly decaying H-Dibaryon from continuum ready to unblind**
- Analysis-pipeline including Neural Networks **successful** for classification of this kind
- **UL of 1-10 fb** with current dataset available
- Luminosity **projection to 50 ab^{-1}** further reduces the UL by order of magnitude

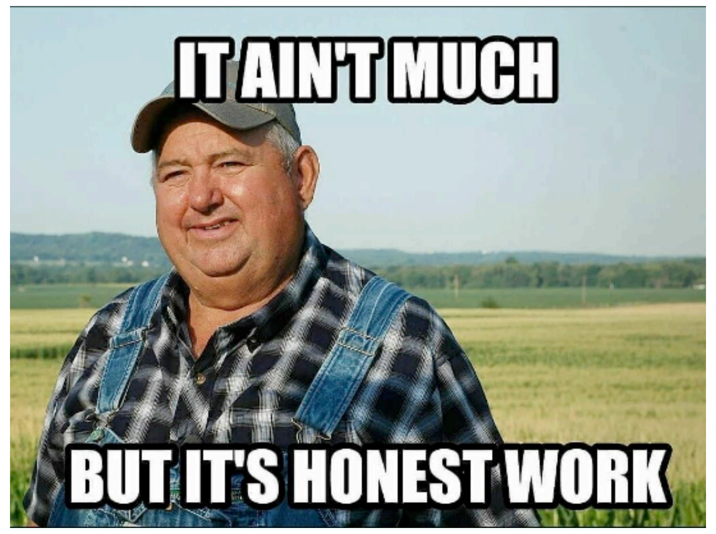




Thanks!

Backup

Results on MC

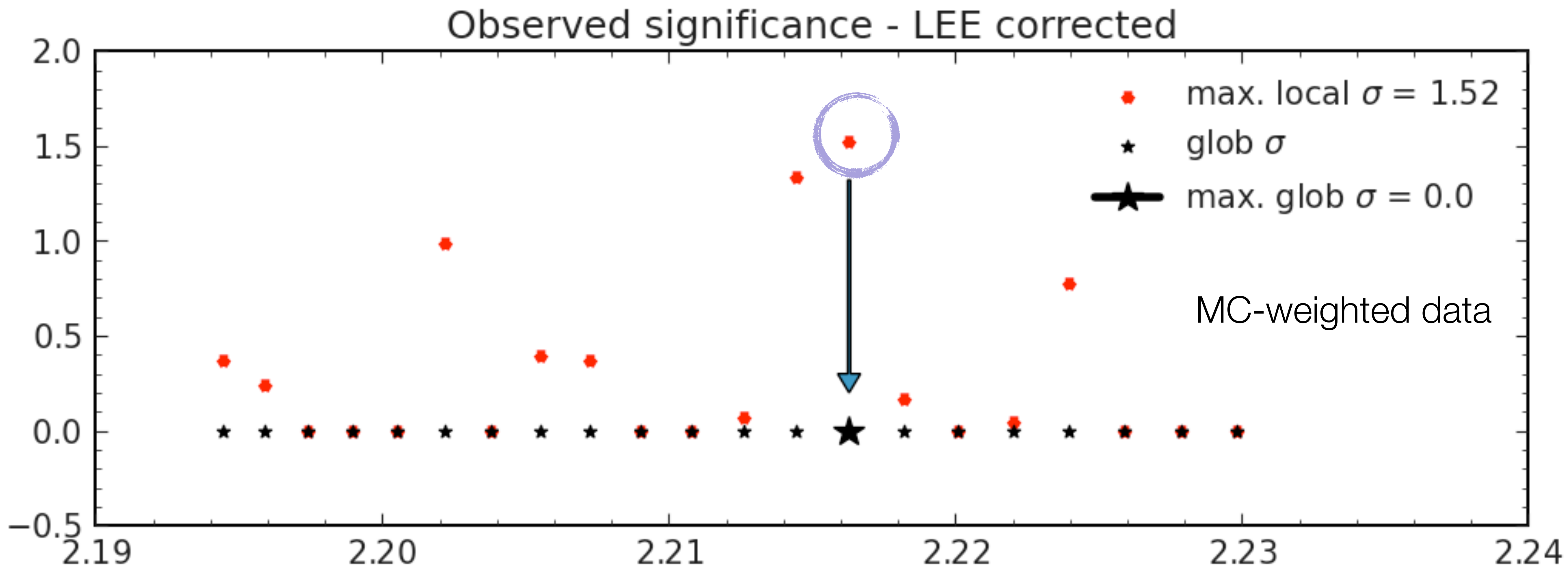


- Discovery significance ~ $\mathbf{0}\ \boldsymbol{\sigma}$
- Upper Limits ~ $\mathbf{6 \cdot 10^{-7} - 3 \cdot 10^{-6}}$
- Compare with on-resonance searches:

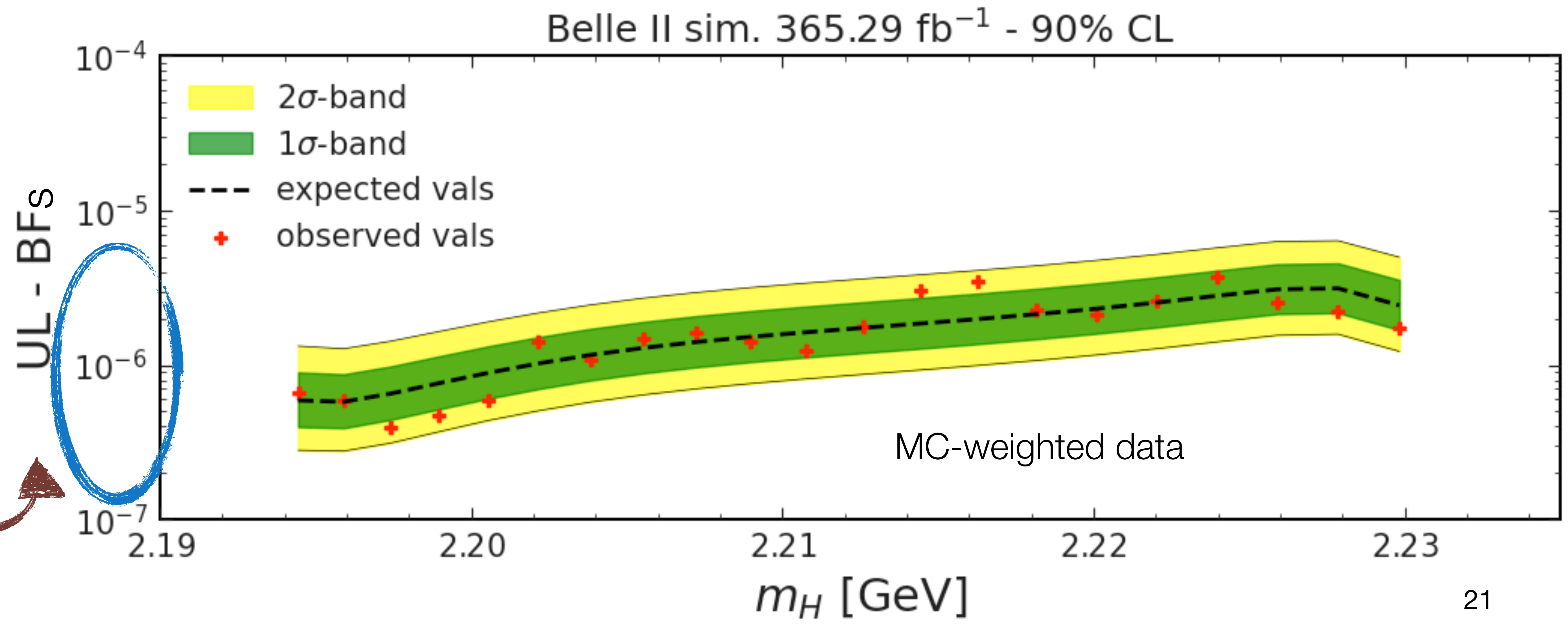
→ weak decay[1]:
BF($\Upsilon(1{,}2S) \to [H \to \Lambda p\pi] + X$)
UL ~ $10^{-7} - 10^{-6}$

→ stable (MC-only)[2]:
BF($\Upsilon(3S) \to S\Lambda\Lambda$)
UL ~ $0.5 \cdot 10^{-7} - 3 \cdot 10^{-6}$

Discovery Significance



Upper Limit



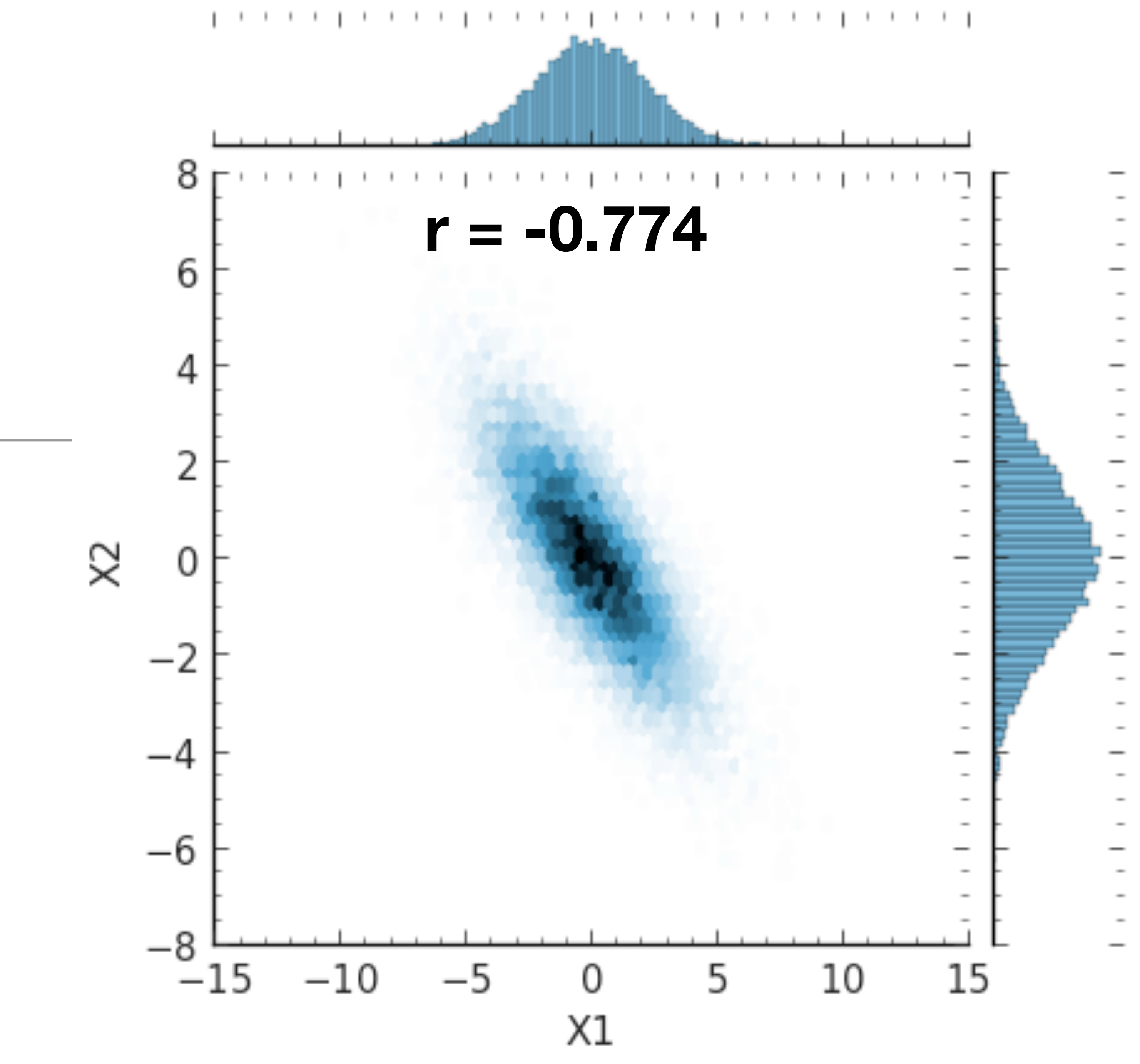
[1] https://arxiv.org/abs/1302.4028
[2] https://b2-pubdb1.desy.de/pub_data/documents/2331/

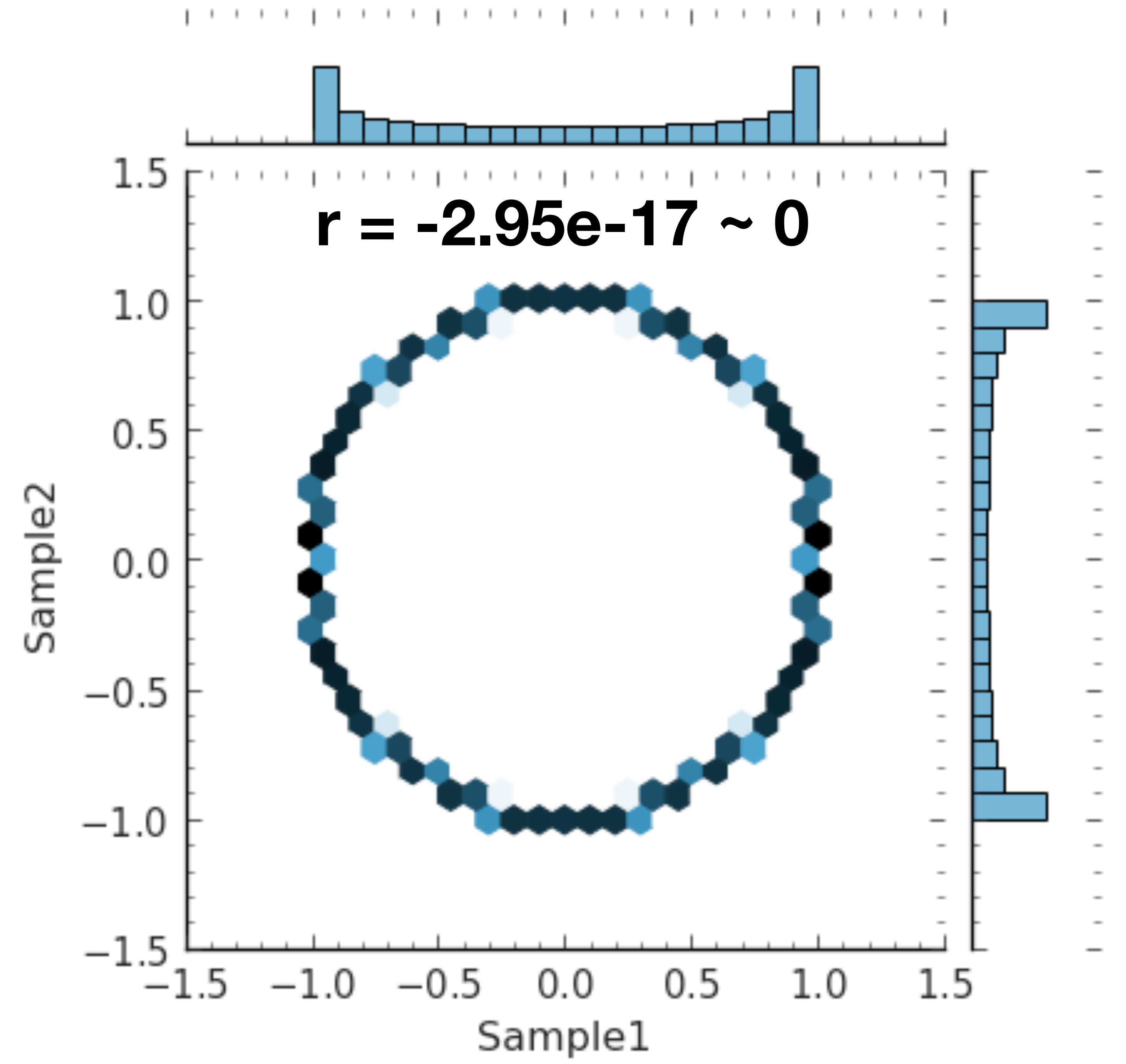
$$r_{xy} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2}\sqrt{\sum (y_i - \bar{y})^2}}$$

$$r_{xy} \in [-1,1]$$

Backup - Correlations

- Important when using NN and or fitting PDFs
- Classic: Pearson Coefficient
  But: Linear only
- Better: Uniform Distributions (flat)
- If uncorrelated
  → **uniformly distributed** in the 2D-plane
  → $n_{expect} = N/n^2$ events





Backup - Correlations

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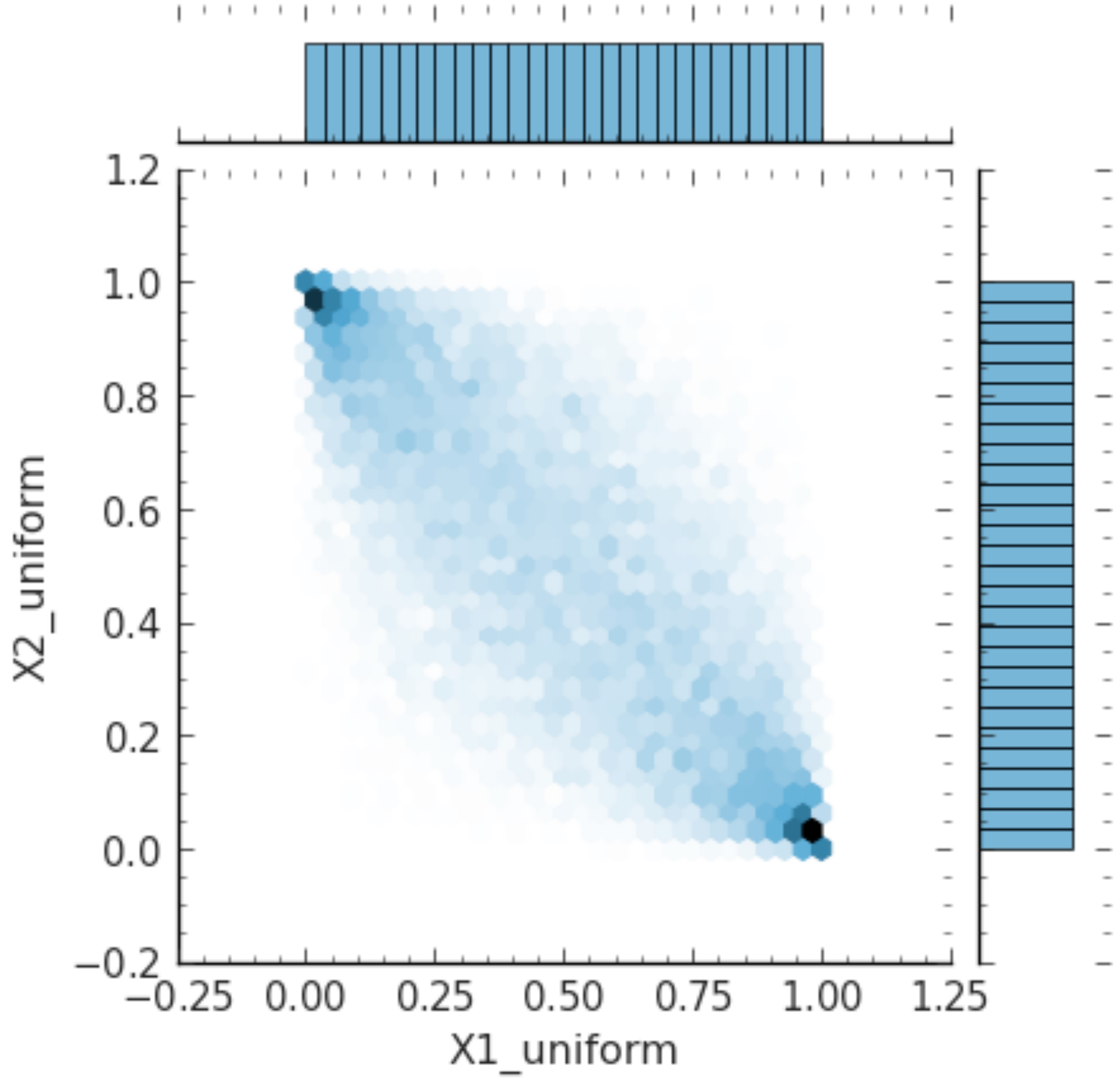
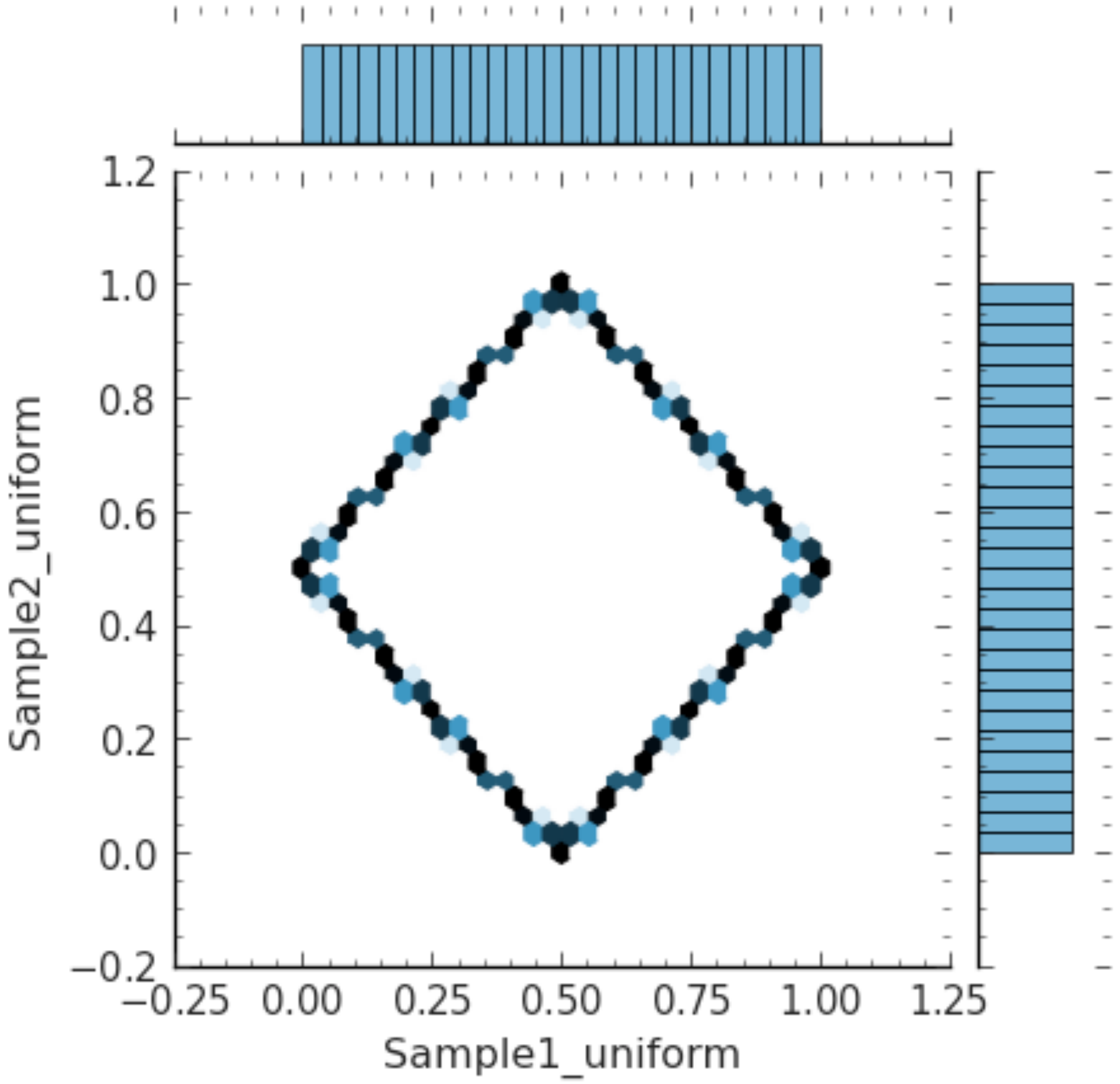


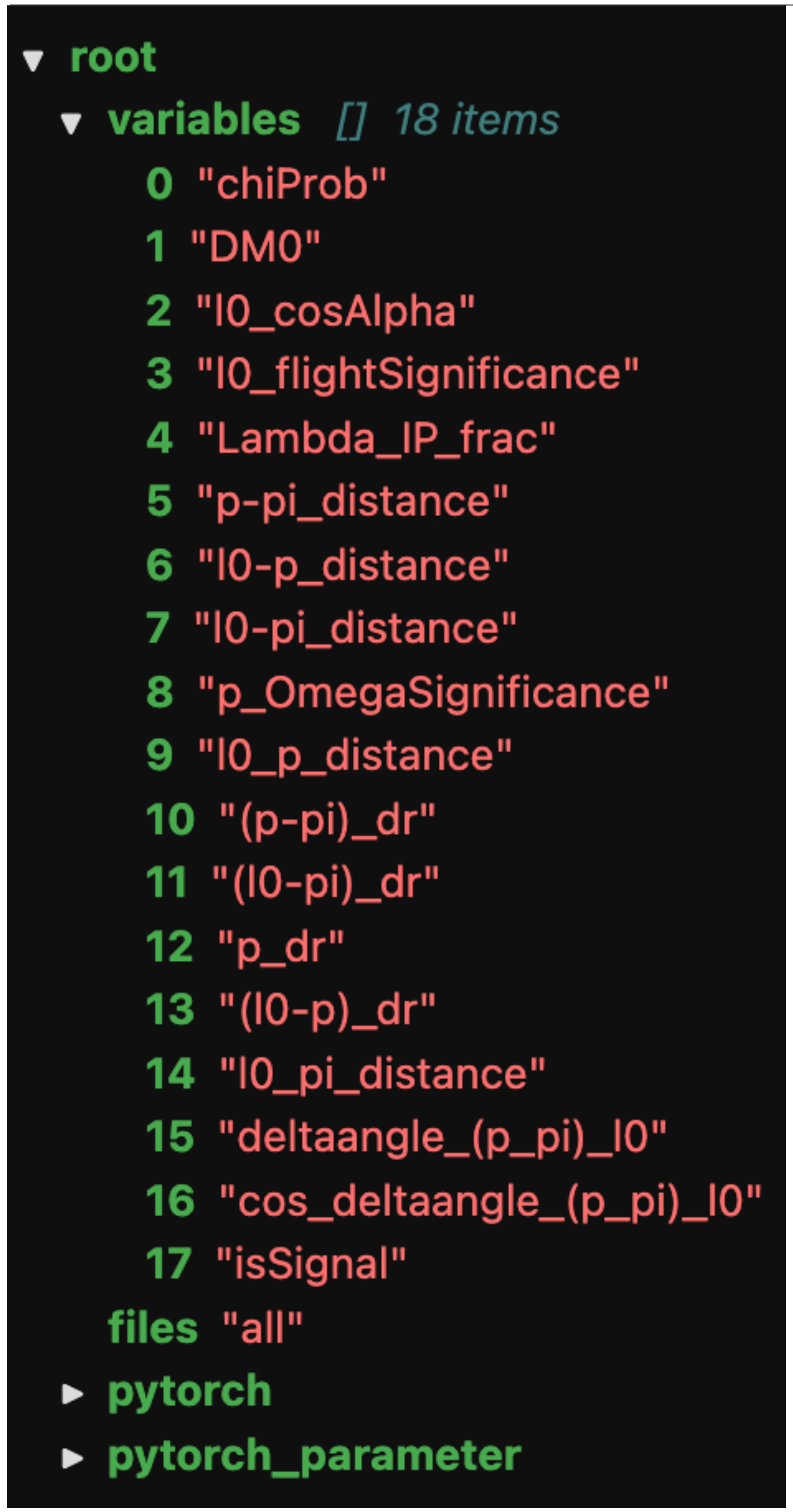


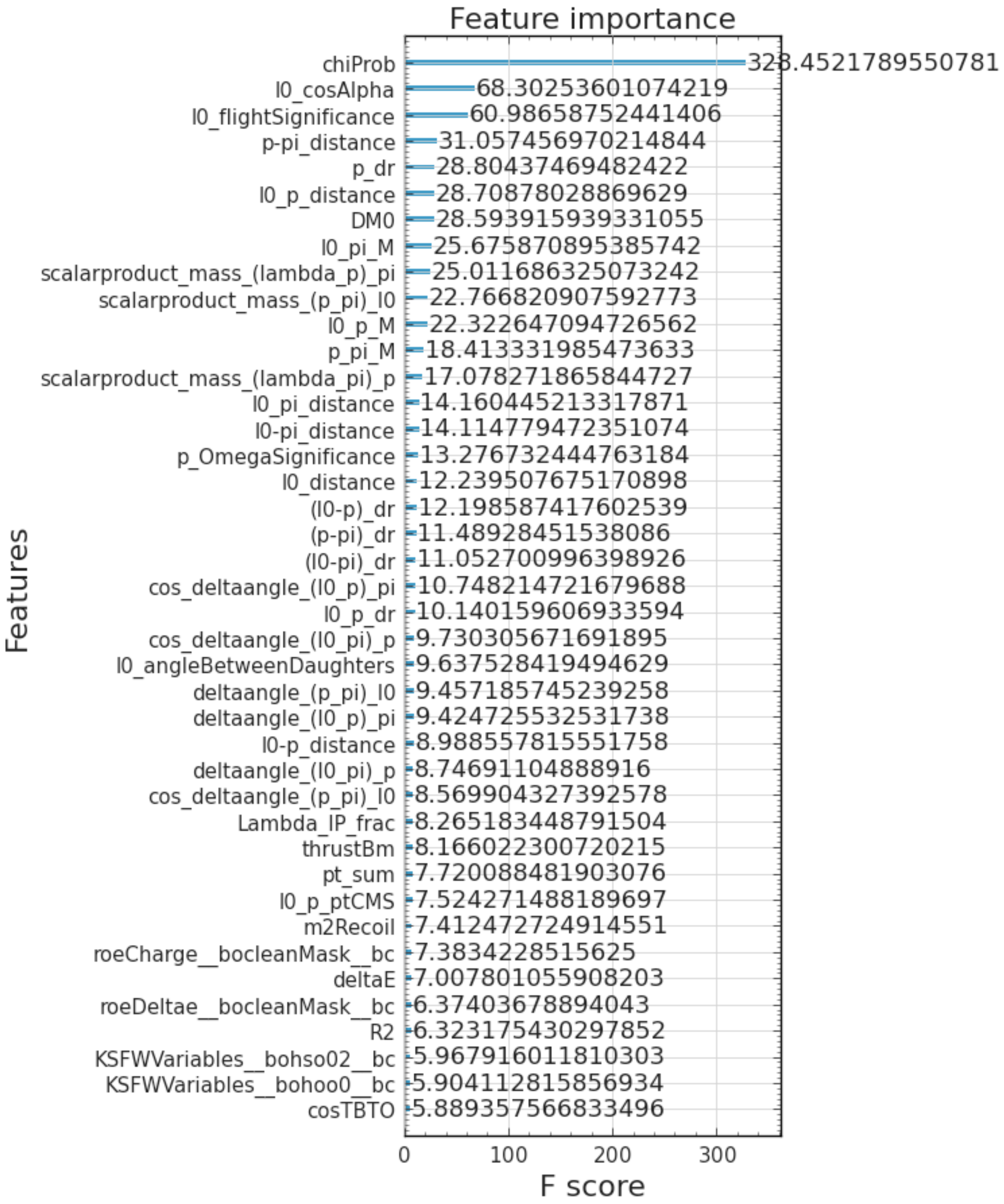
Backup - Correlations

- Important when using NN and or fitting PDFs
- Better: Uniform Distributions (flat)
- If uncorrelated → **uniformly distributed** in the 2D-plane → $n_{expect} = N/n^2$ events

How? - Correlations

Backup - Variables





Backup - Systematics

Luminosity - 0.5%

Signal Efficiency - 10.0%

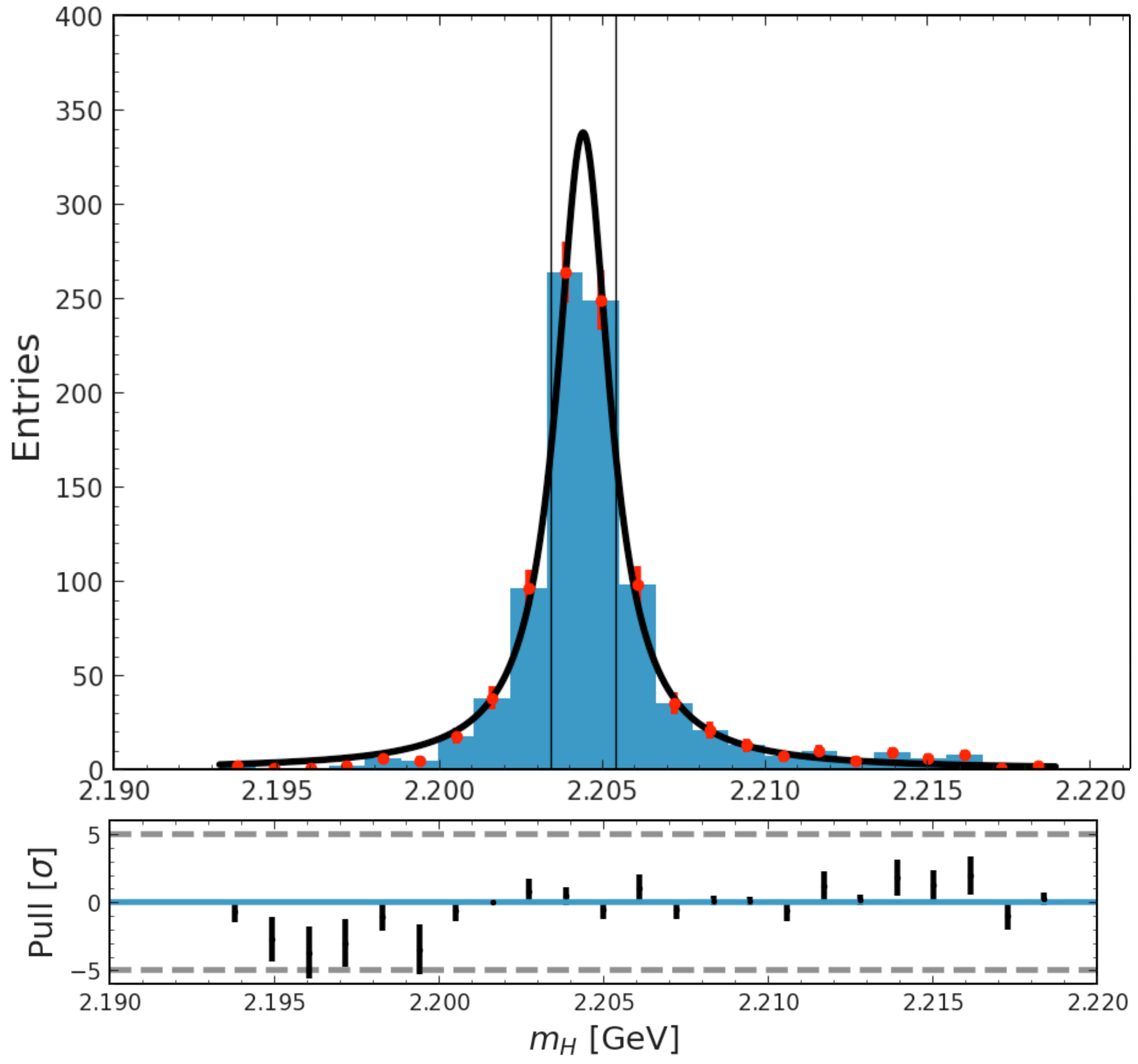
BF($\Lambda \to$ pπ) - 0.5%

NN efficiency - 1.0%

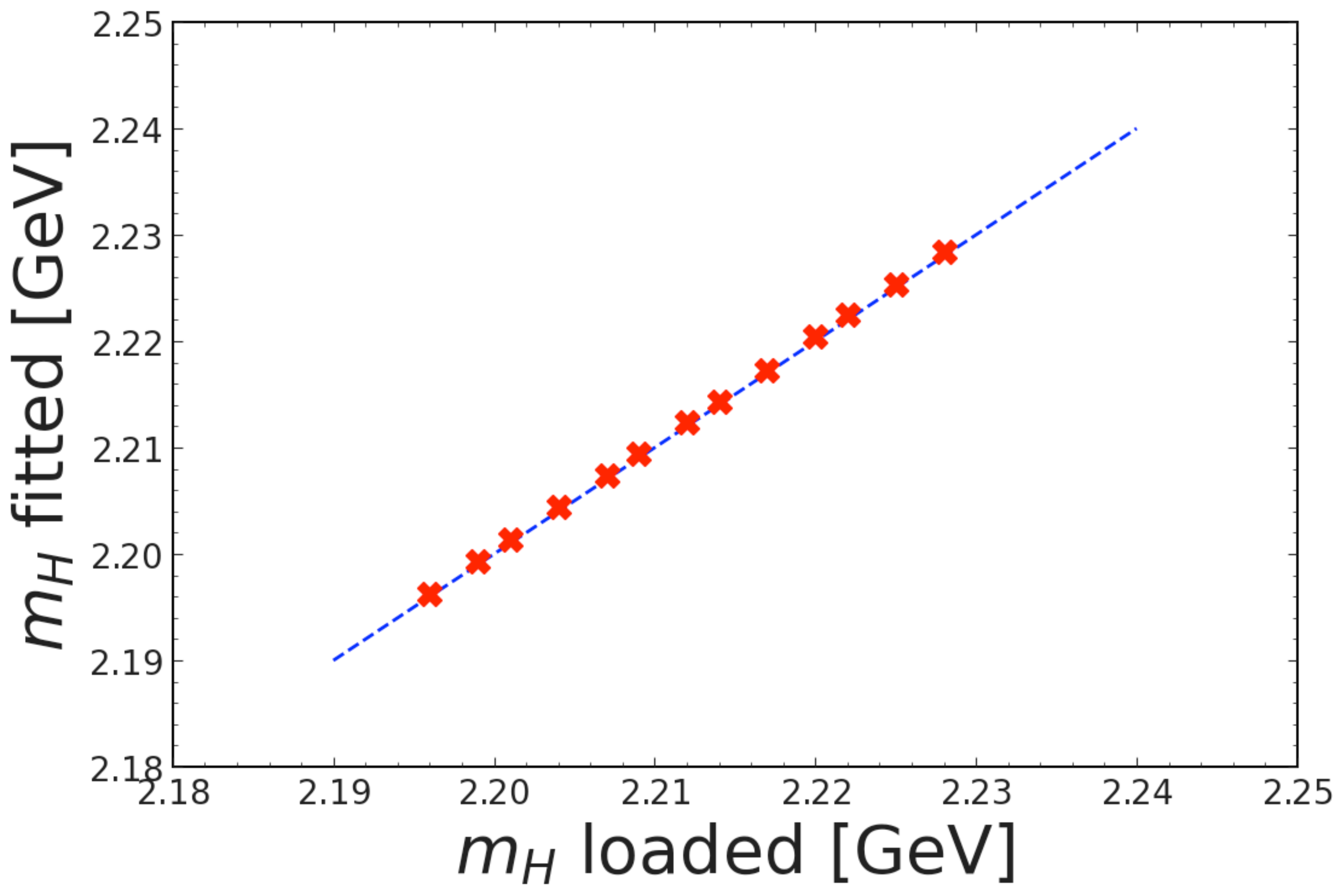
quadrature sum - 10.1%

$$\sigma(e^+e^- \to q\bar{q}) \cdot \text{BF}(q\bar{q} \to H + X) \cdot \text{BF}(H \to \Lambda p \pi) = \frac{N_{sig}}{\mathscr{L} \cdot \epsilon \cdot \text{BF}(\Lambda \to p\pi)}$$

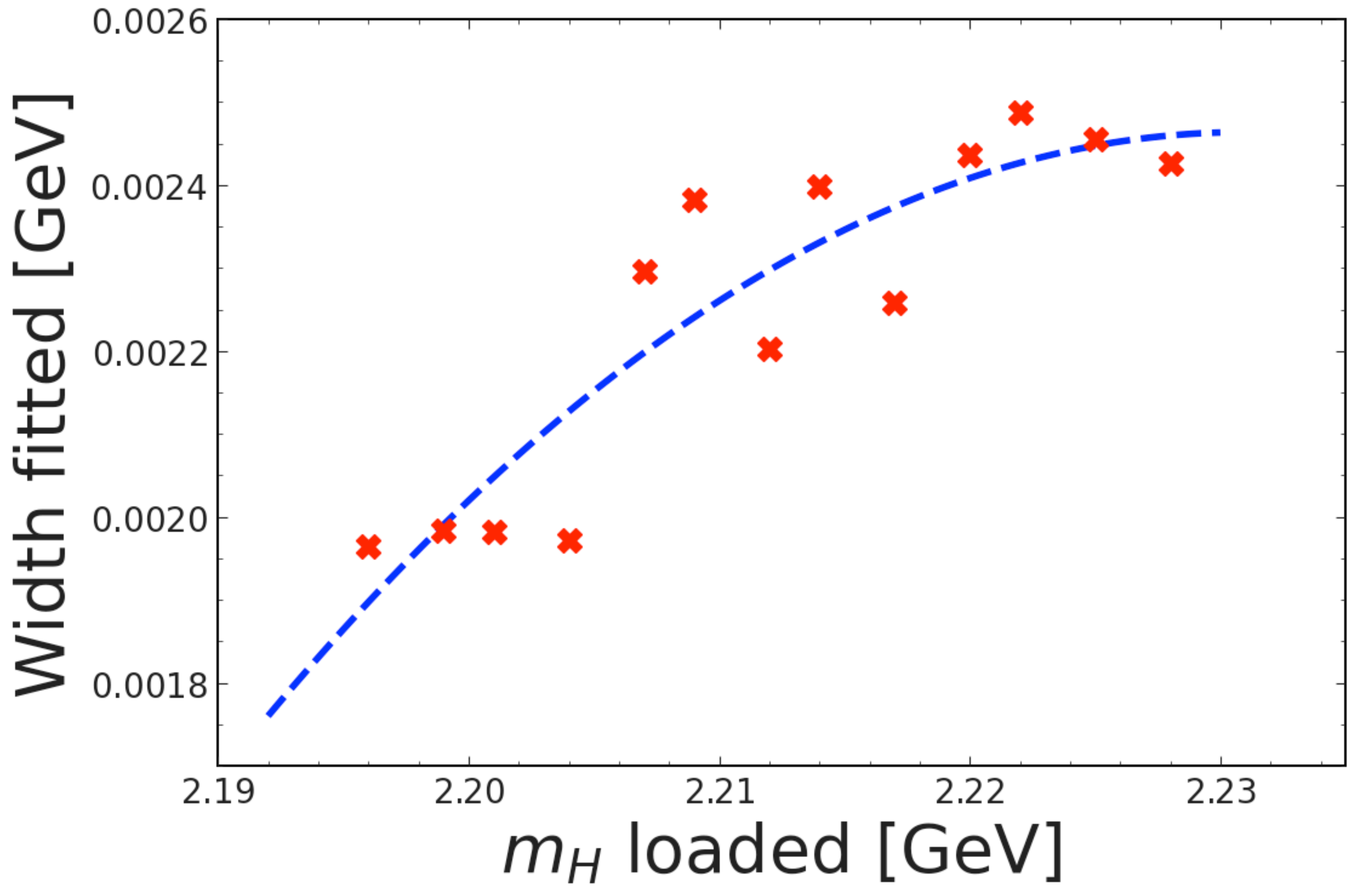
Raw-Fit



Entries
400
350
300
250
200
150
100
50
0
2.190
2.195
2.200
2.205
2.210
2.215
2.220
Pull [σ]
5
0
−5
m_H [GeV]



m_H fitted [GeV]
2.25
2.24
2.23
2.22
2.21
2.20
2.19
2.18
m_H loaded [GeV]



Width fitted [GeV]
0.0026
0.0024
0.0022
0.0020
0.0018
2.19
2.20
2.21
2.22
2.23
m_H loaded [GeV]

Test statistics

$$\tilde{t}_\mu = \begin{cases} -2\ln\left(\frac{L(x;\mu,\hat{\hat{\Theta}}}{L(x;0,\hat{\hat{\Theta}}))}\right), & \mu < 0 \\ -2\ln\left(\frac{L(x;\mu,\hat{\hat{\Theta}}}{L(x;\mu,\hat{\Theta}))}\right), & \mu \geq 0 \end{cases}$$

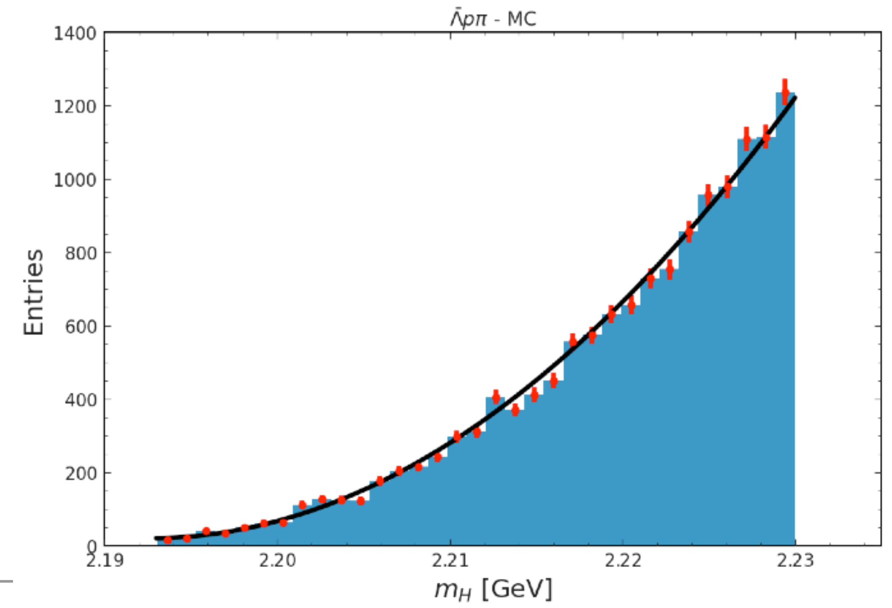
← Discovery

$$\tilde{q}_\mu = \begin{cases} -2\ln\left(\frac{L(x;\mu,\hat{\hat{\Theta}}}{L(x;0,\hat{\hat{\Theta}}))}\right), & \tilde{\mu} < 0 \\ -2\ln\left(\frac{L(x;\mu,\hat{\hat{\Theta}}}{L(x;\mu,\hat{\Theta}))}\right), & 0 \leq \tilde{\mu} \leq \mu \\ 0, & \tilde{\mu} > \mu \end{cases}$$

← Upper Limit

Look elsewhere effect

Sample from this



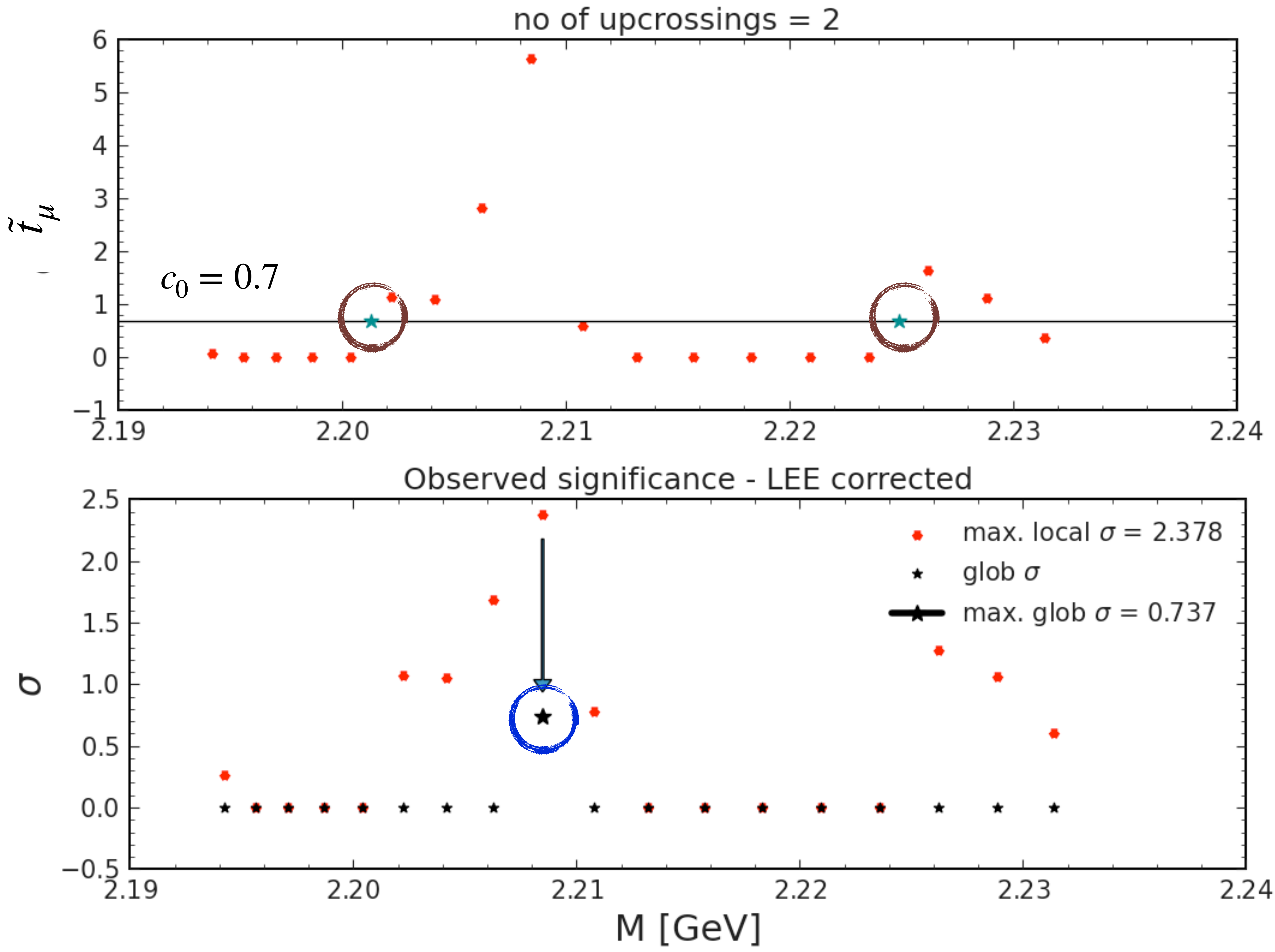
- Essentially:
  one can relate number of "upcrossings" N_{c_0} to σ_{global}

- Count N_{c_0} from toy studies

  - c_0 as low as possible

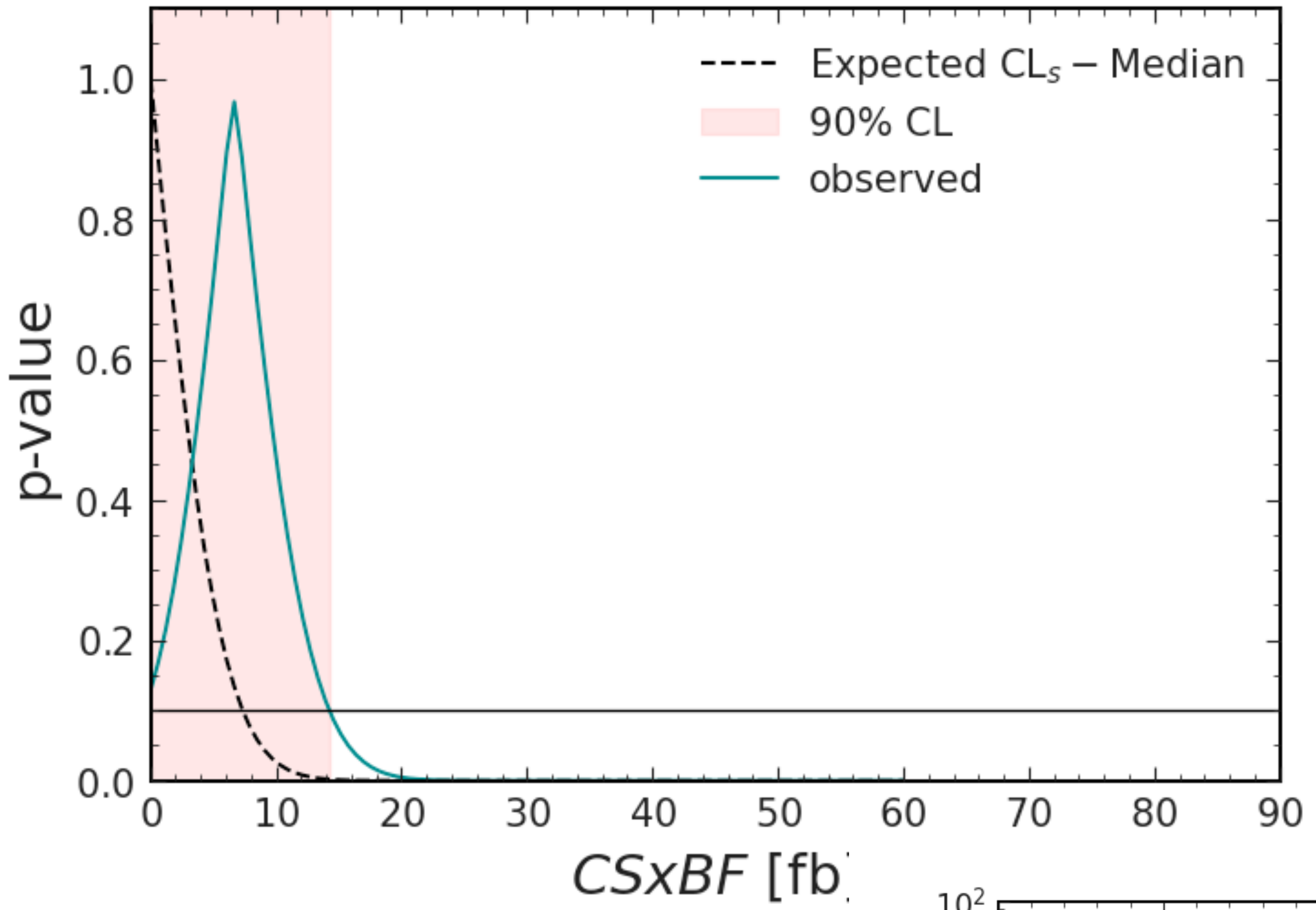
  - Reasonable sample size

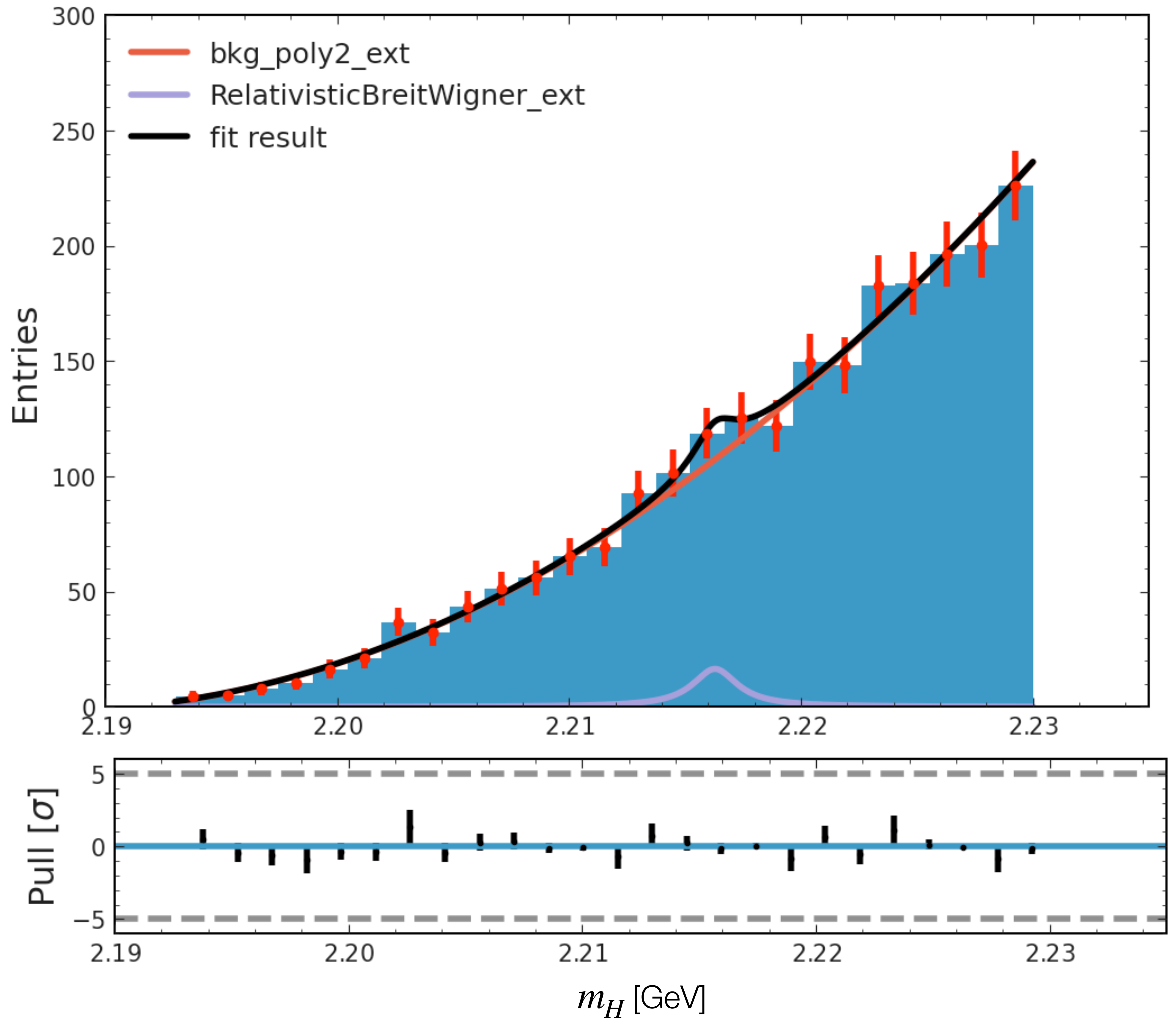
- $p_{global} \approx p_{local} + N_{c_0}\, e^{\frac{u_{ref} - u}{2}}$

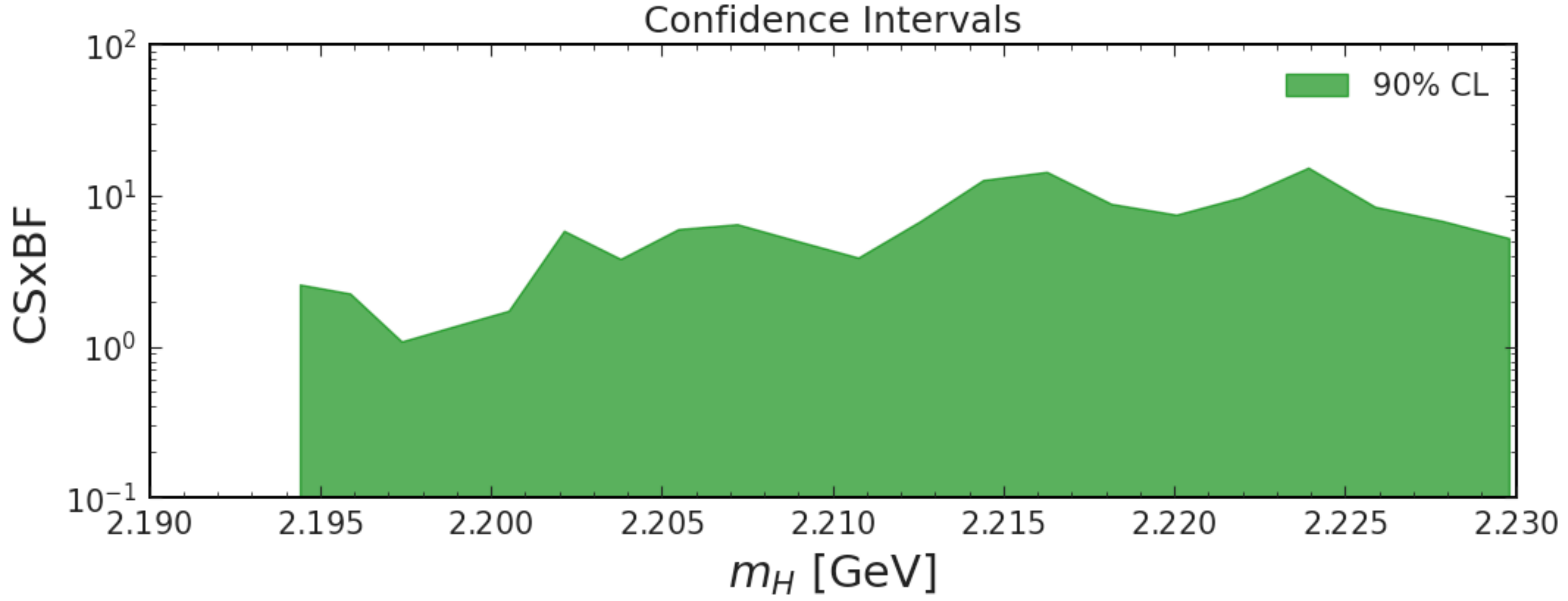


$u = \sigma^2_{local,max} \quad u_{ref} = 0.7^2 \quad N_{c_0} = 1.86$

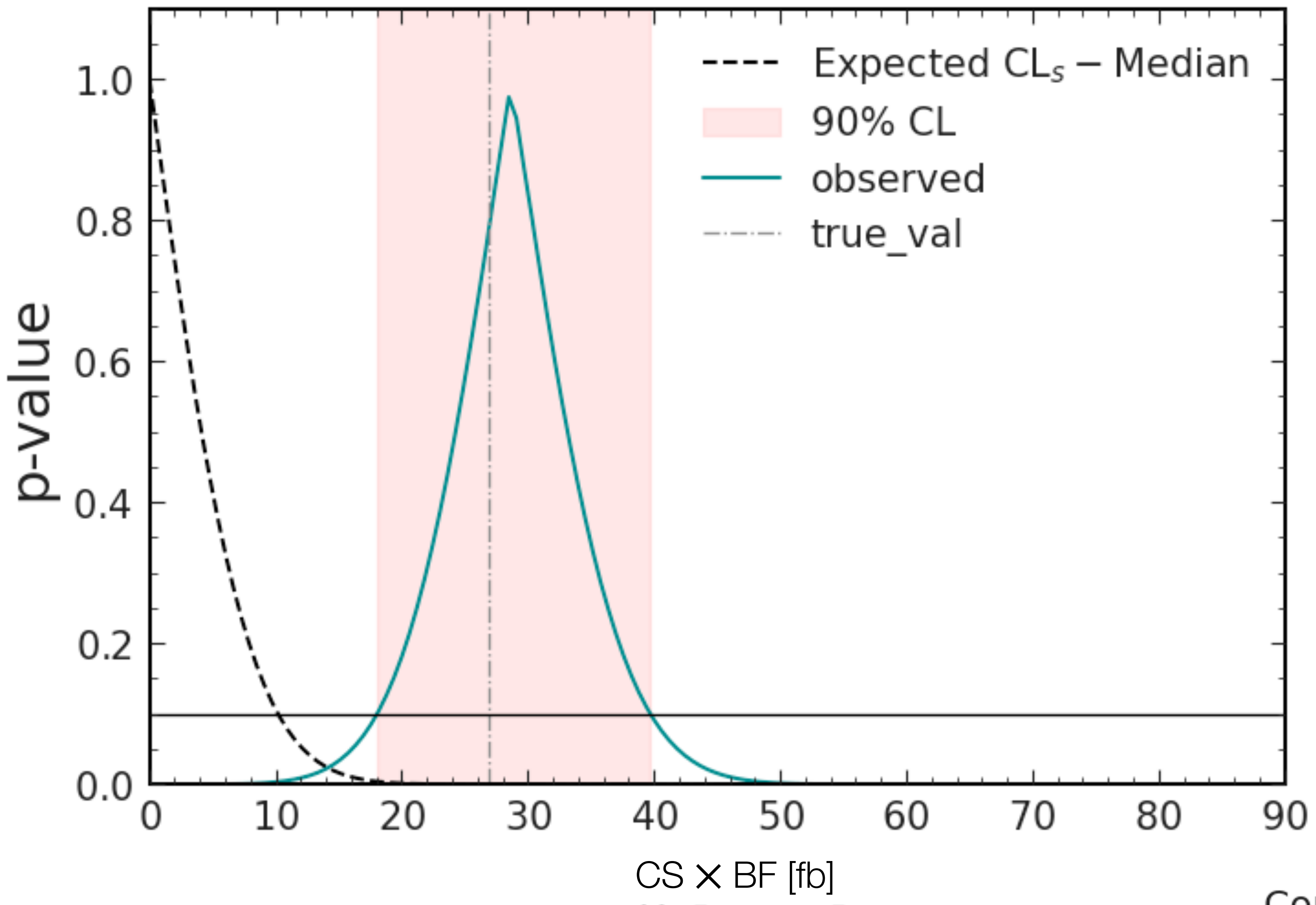
Confidence Intervals - MC-scaled

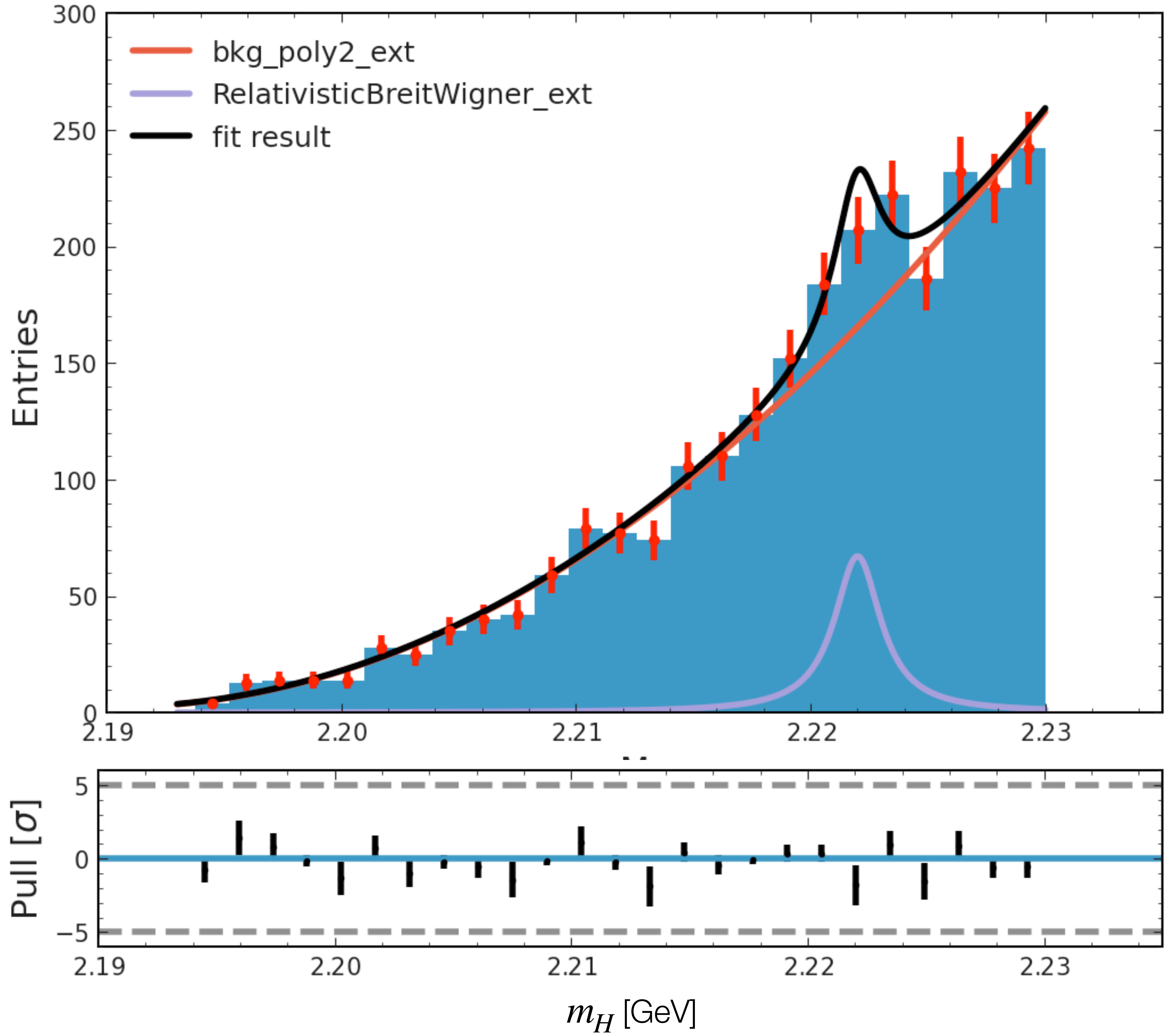


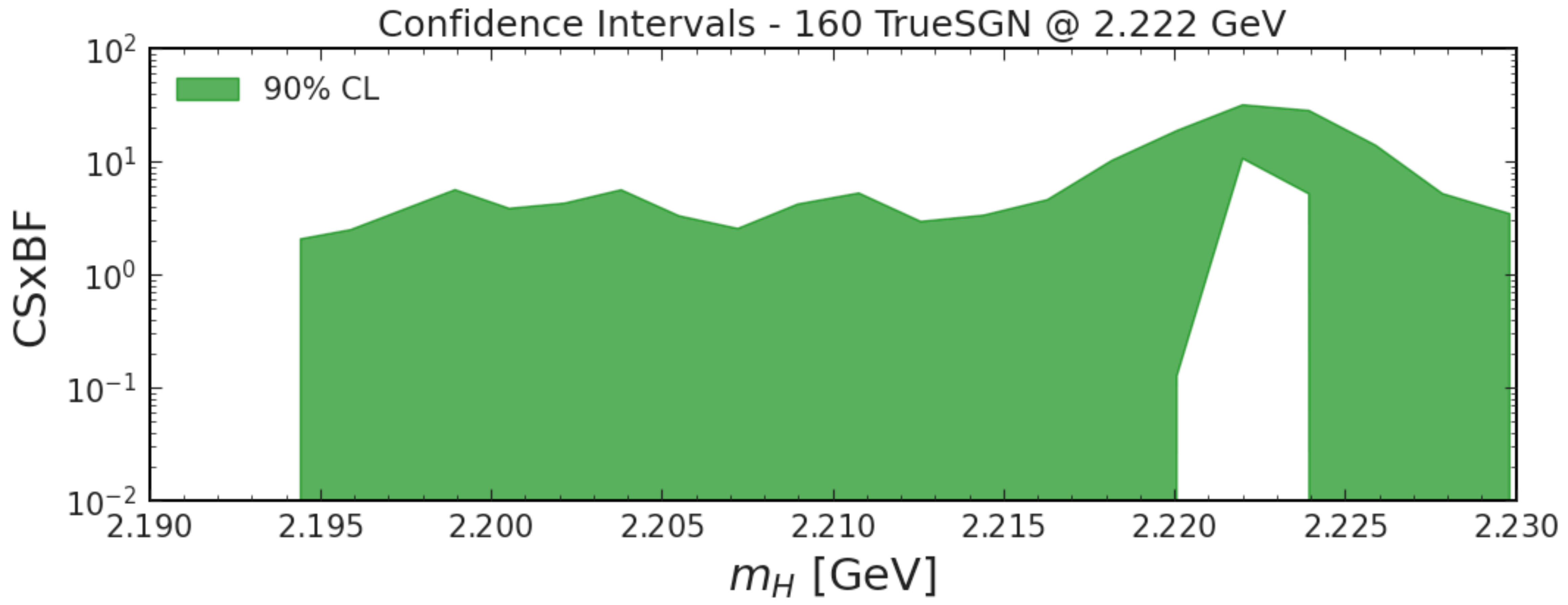




Confidence Intervals - SGN loaded







Conference End

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