Using machine learning to constrain the Higgs total width

1910.02082

Phil Harris, Dylan Rankin (MIT)
Cristina Mantilla Suarez (Johns Hopkins)

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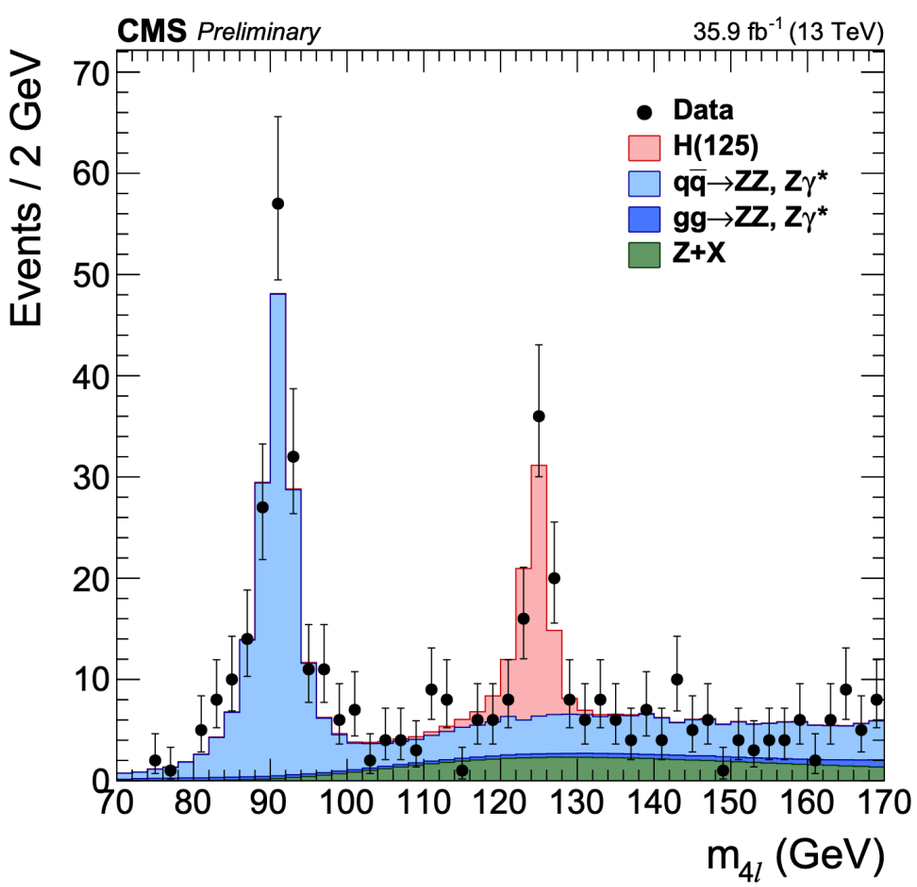
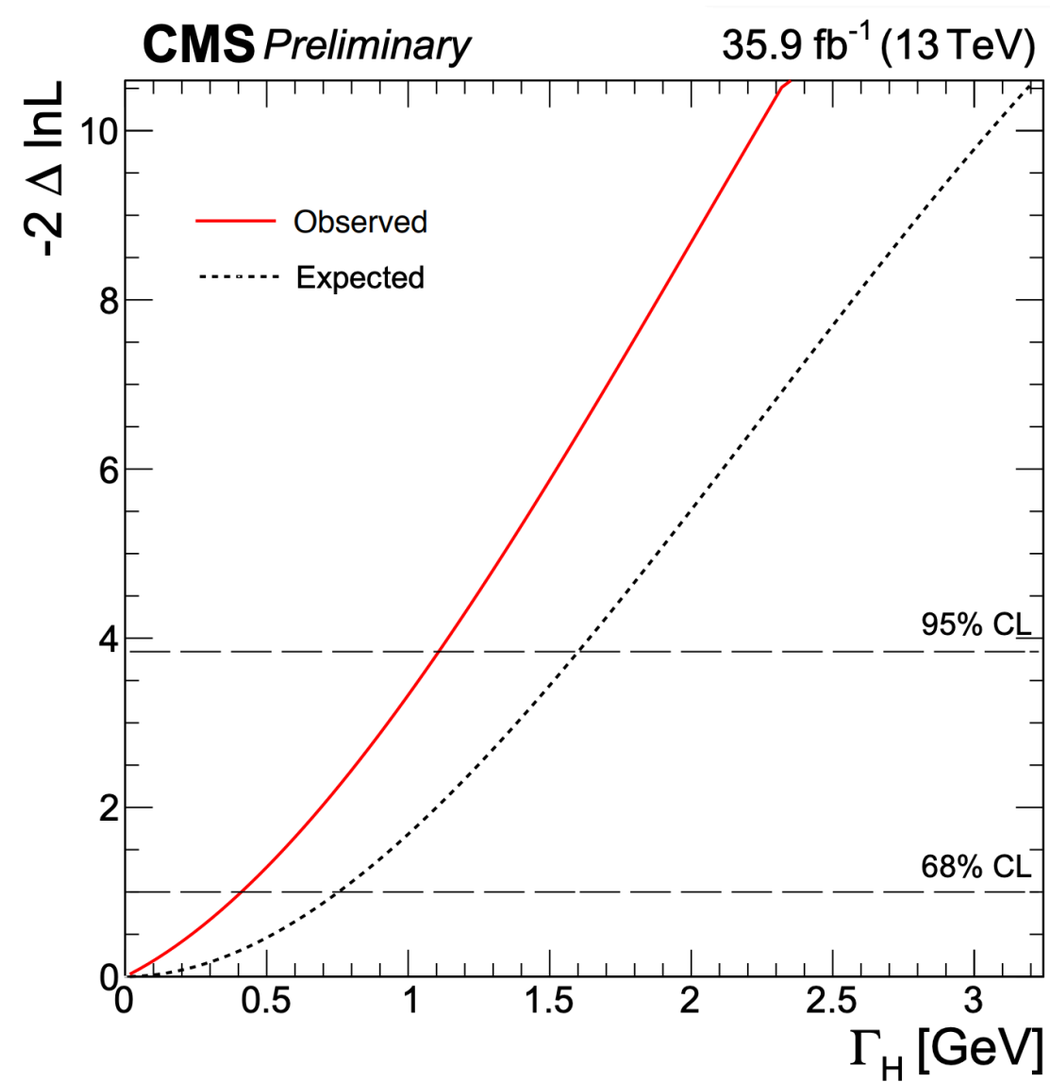
Introduction

- Higgs properties are crucial test of SM
- Inclusive Higgs cross section and Higgs width are poorly constrained
- Difficult measurement at hadron collider
- New proposed method along with machine learning can make competitive measurement possible

Constraints - LHC

- Peak width
  - Using h→γγ/ZZ*
- Limited by detector resolution
- **Γ_H < 1.1 GeV (270 × Γ_{SM})**
  - *HL-LHC*: $\delta\Gamma_H/\Gamma_{SM} \approx 80$



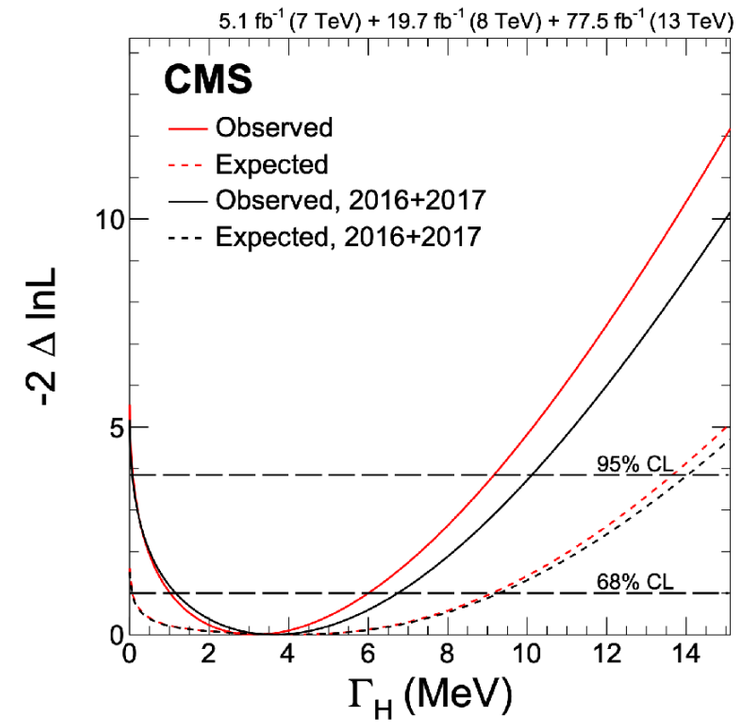


CMS-PAS-HIG-16-041

Constraints - LHC

- Off-shell measurement

$$\mu = \frac{\sigma^{\text{on-shell}}_{\text{gg}\to\text{H}\to\text{ZZ}^*} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_{\text{H}}\Gamma_{\text{H}}}}{\sigma^{\text{off-shell}}_{\text{gg}\to\text{H}^*\to\text{ZZ}} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{2m_{\text{Z}}}}$$

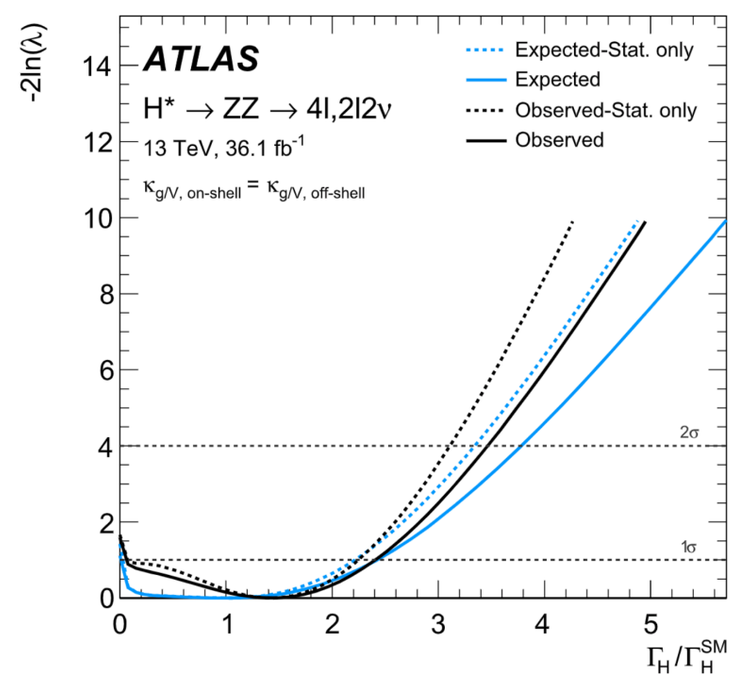


Phys. Rev. D 99 (2019) no.11, 112003

- Assumption: $g^2_{\text{ggH}} g^2_{\text{HZZ}}$ is the same on and off-shell

- **Γ_H < 9.1 MeV (2.2 × Γ_{SM})**

- *HL-LHC*: $\delta\Gamma_H/\Gamma_{SM} \approx 0.25$-$0.5$



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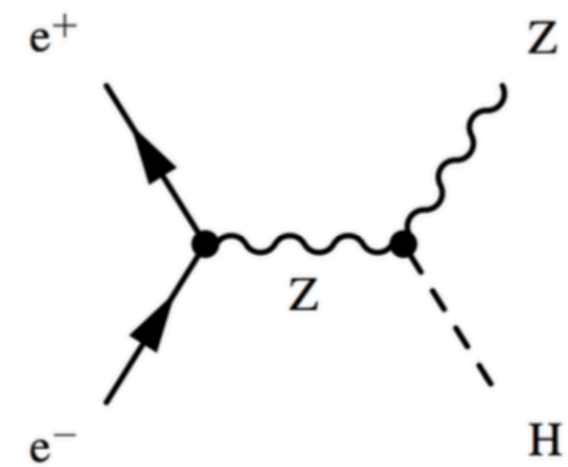
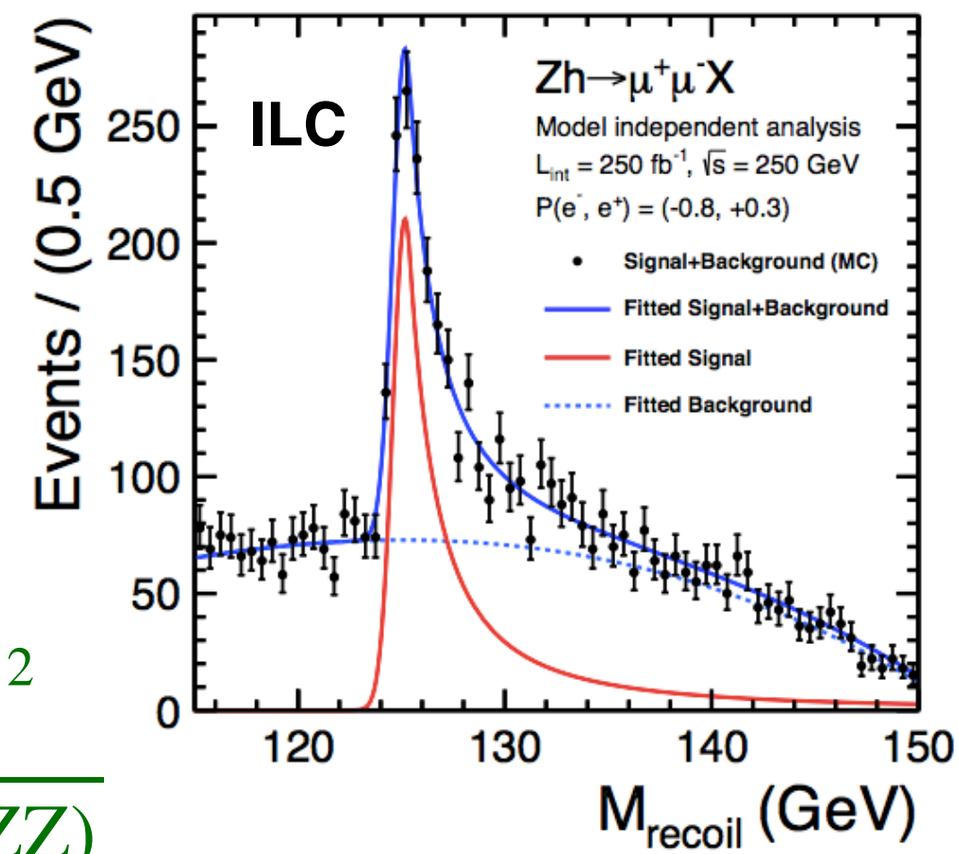
Contraints - Future

- Muon collider
  - $\delta\Gamma_H/\Gamma_{SM} \approx 0.05$
- **Electron collider : recoil method**
  - $\delta\Gamma_H/\Gamma_{SM} \approx 0.1$ [e.g. ILC]
  - *1) Measure* $\sigma(e^+e^- \to Zh) \propto g^2_{hZZ}$
  - *2) Measure* h→ZZ *decay*

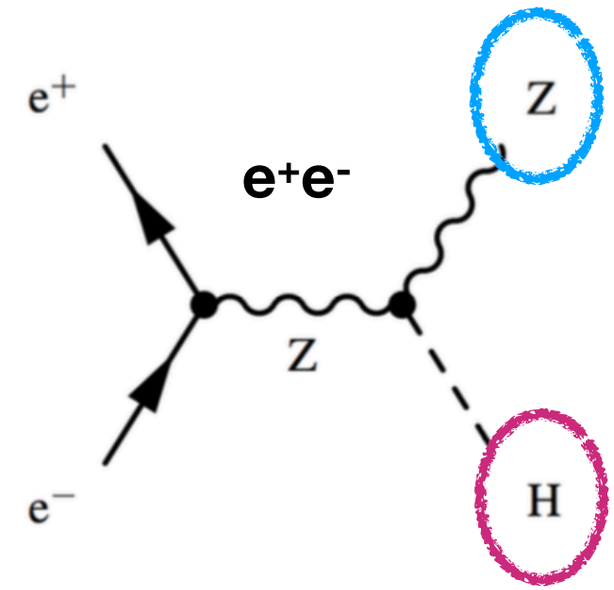


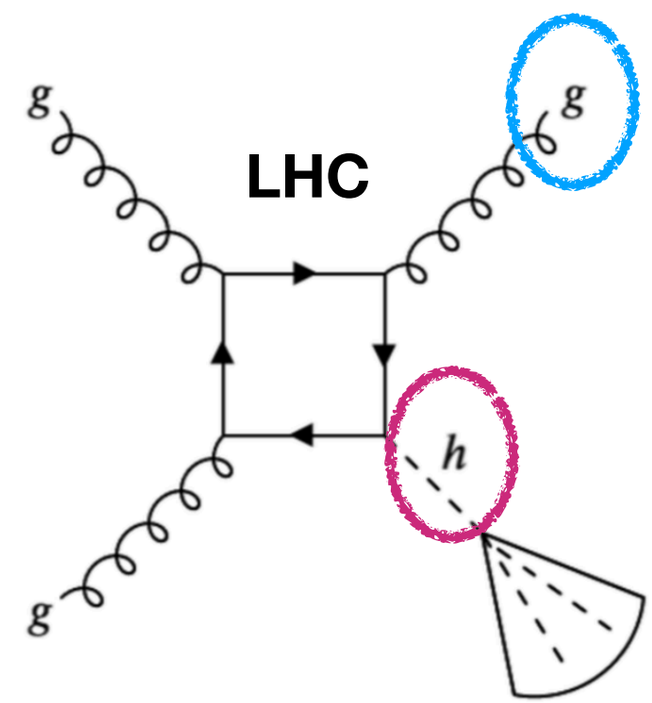


$$\sigma_{Zh\to XX} \propto \frac{g^2_{hZZ}g^2_{hXX}}{\Gamma_h} \rightarrow \Gamma_h \propto \frac{\left[\sigma(e^+e^- \to Zh)\right]^2}{\sigma(e^+e^- \to Zh \to ZZ)}$$

Γ_h @ LHC

- Similar method to recoil at electron collider
- Use Higgs + 1 jet instead of Zh
  - 1) Measure inclusive cross section from reconstructed m_h
  - 2) Complement with other measurements
    - Boosted h→bb
    - W+h→bb
    - W+h→WW





$$\Gamma_h \propto \frac{1}{\sigma(W+h\to WW)} \times \left(\sigma(gg\to h)\times\frac{\sigma(W+h\to bb)}{\sigma(gg\to h\to bb)}\right)^2$$

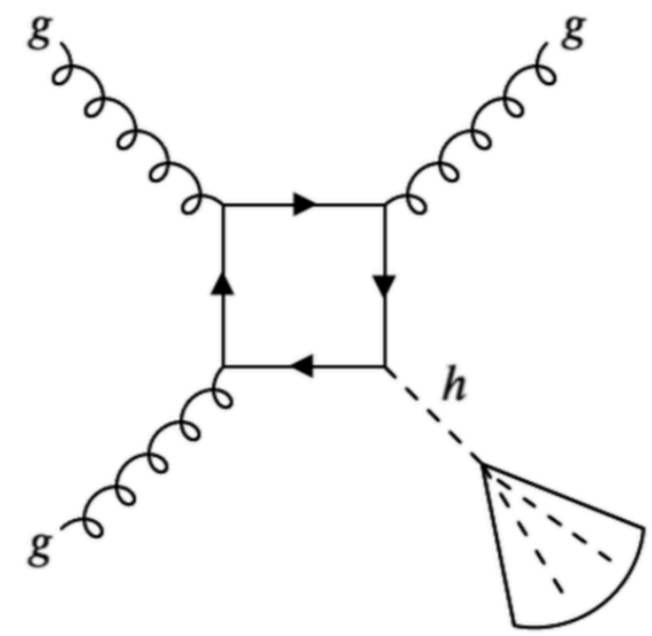
Γ_h @ LHC

$$\Gamma_h \propto \frac{1}{\sigma(W + h \to WW)} \times \left(\sigma(gg \to h) \times \frac{\sigma(W + h \to bb)}{\sigma(gg \to h \to bb)} \right)^2$$

$\delta\sigma/\sigma_{SM} = 0.05$

$\delta\sigma/\sigma_{SM} = 0.09$

$\delta\sigma/\sigma_{SM} = 0.25 \times \delta\sigma_{gg\to h}$

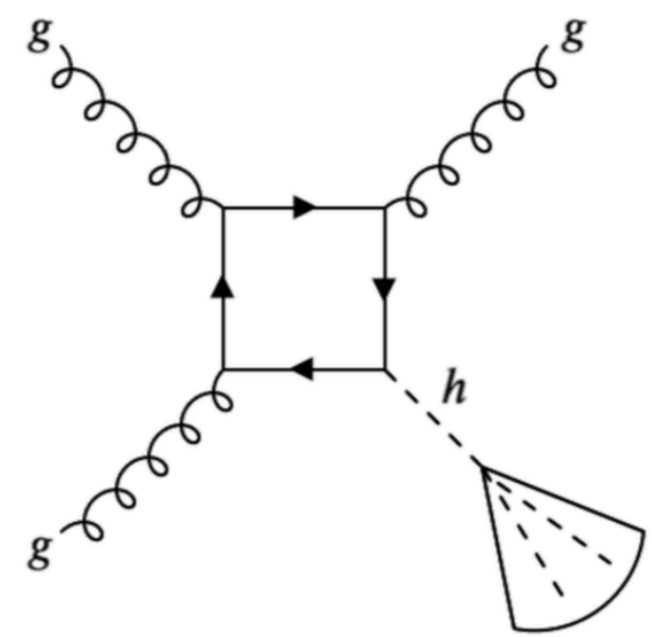


CMS-PAS-FTR-18-011

Γ_h @ LHC

$$\Gamma_h \propto \frac{1}{\sigma(W + h \to WW)} \times \left(\sigma(gg \to h) \times \frac{\sigma(W + h \to bb)}{\sigma(gg \to h \to bb)} \right)^2$$

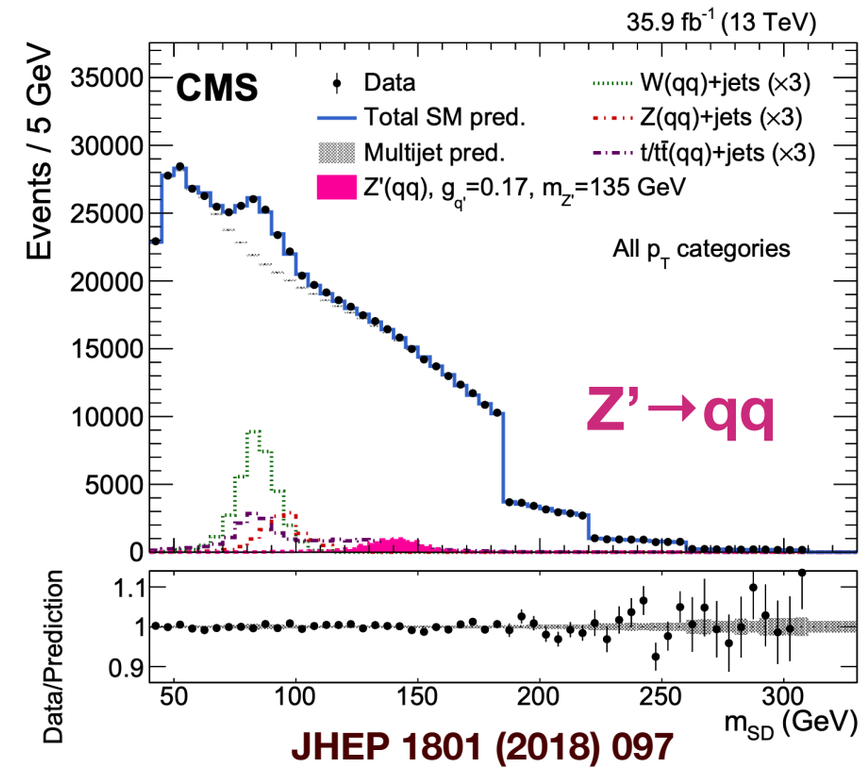
Can we measure inclusive Higgs cross section?
$\delta\sigma/\sigma_{SM}$ = ?

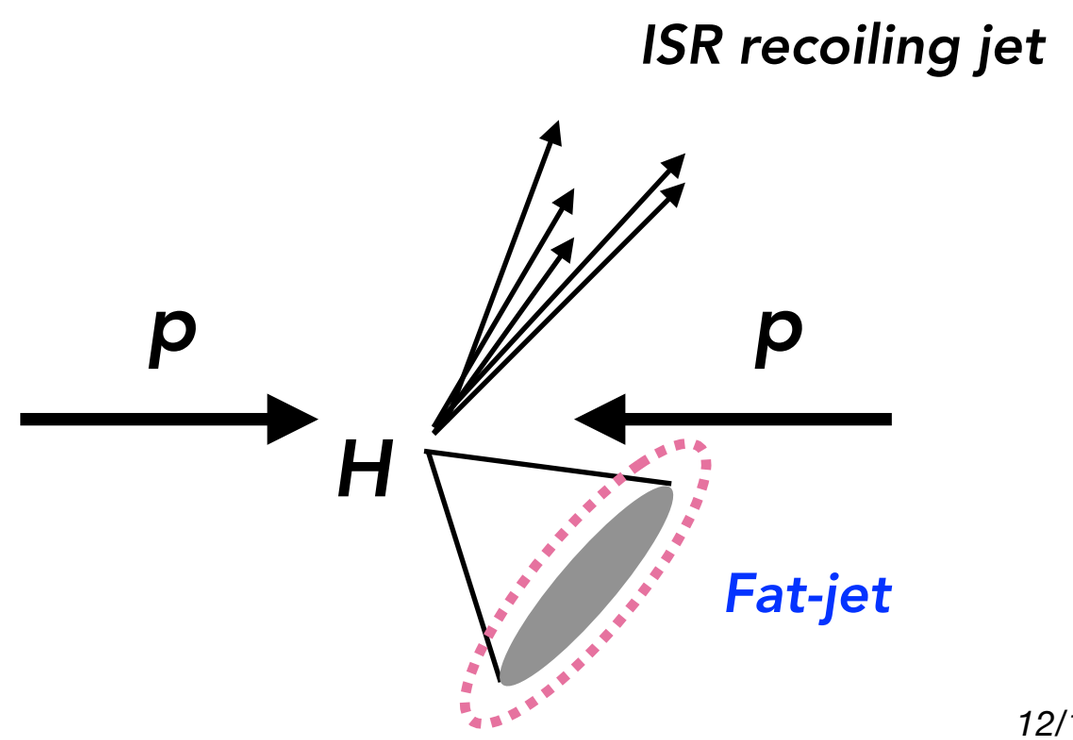


This is the challenge we need to solve

Measurement Strategy

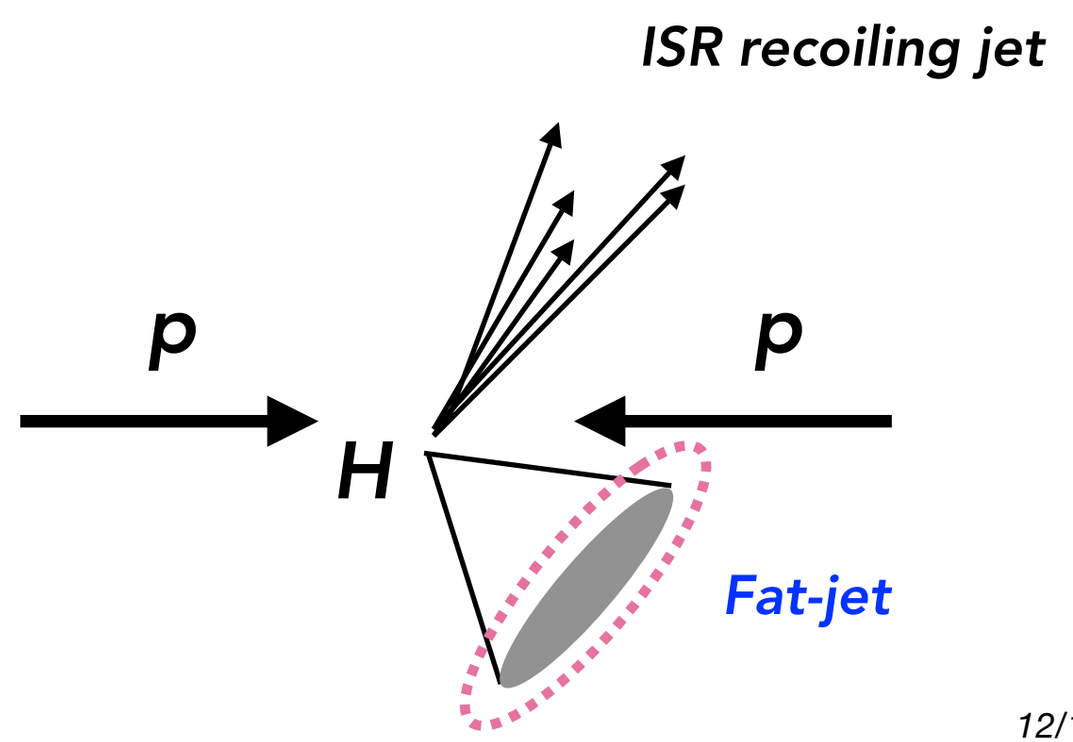
- Require high p_T jet
- Tag/select Higgs jet
- Fit mass





Measurement Strategy

- Require high p_T jet
  - Decay products contained in fat-jet
- Tag/select Higgs jet
  - Reduce background without bias
- Fit mass
  - Extract total cross section



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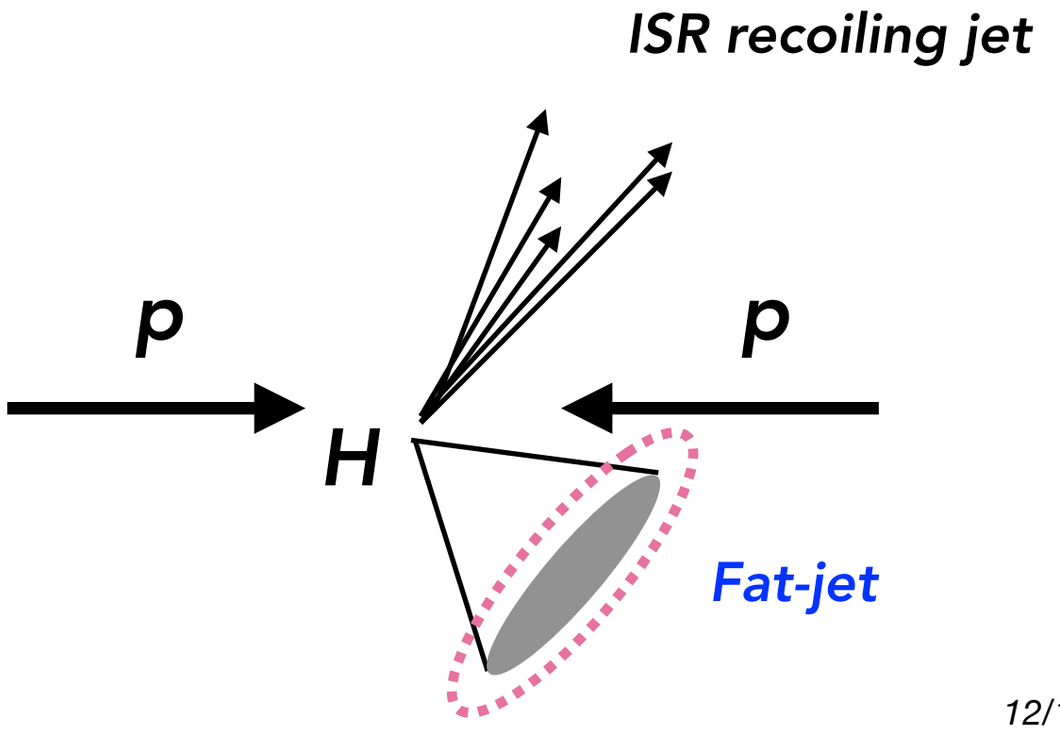
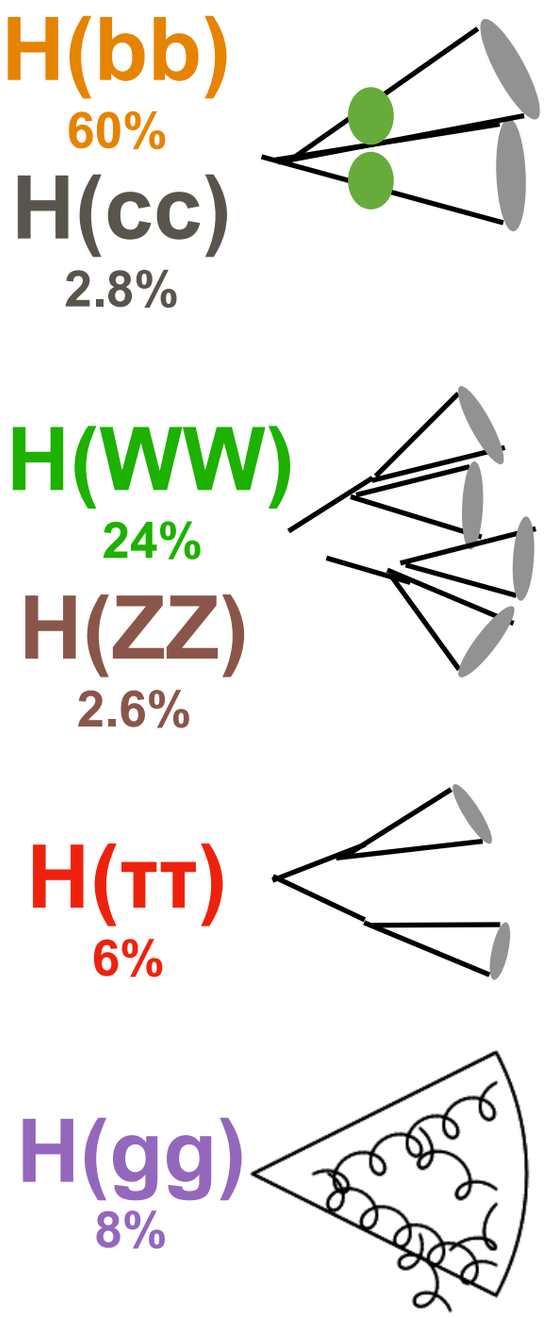
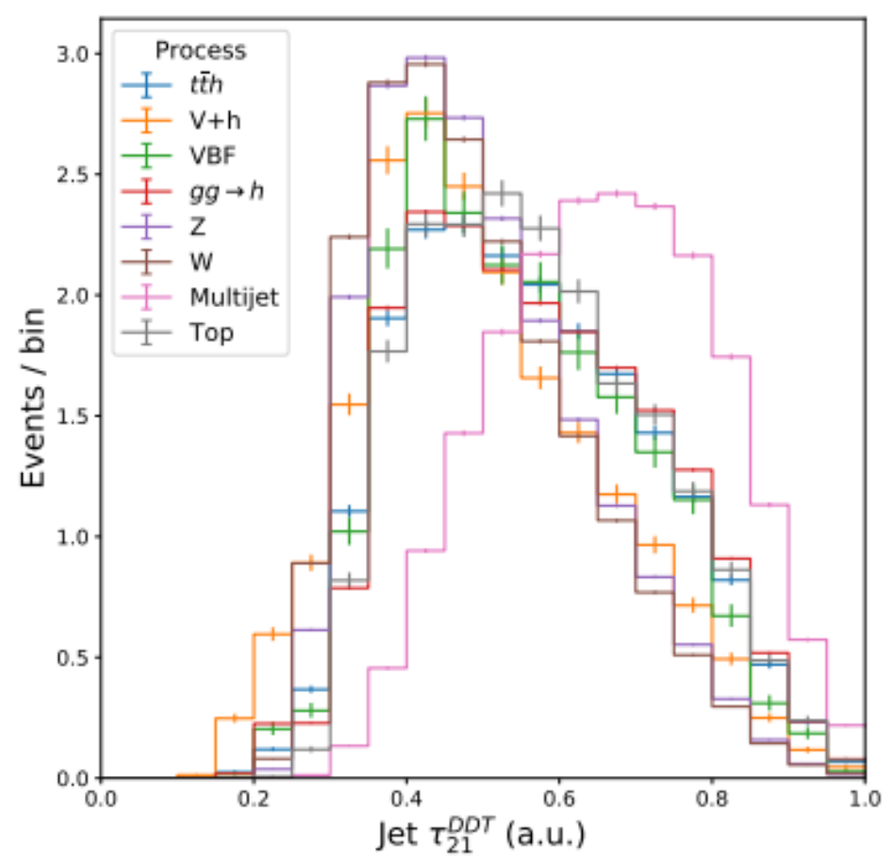
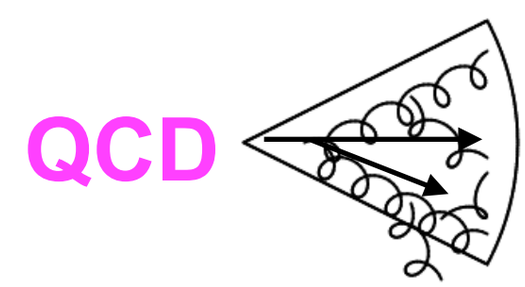


Higgs Tagging



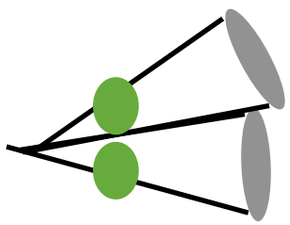
- Dominant background with minimal jet selection is QCD
- Can existing tools tag all Higgs decays simultaneously?





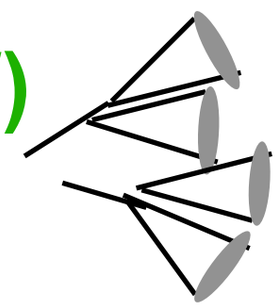
Higgs Tagging

H(bb)
60%



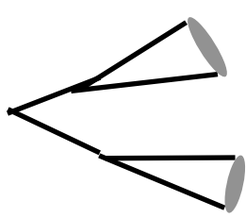
H(cc)
2.8%

H(WW)
24%

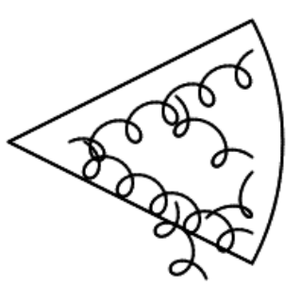


H(ZZ)
2.6%

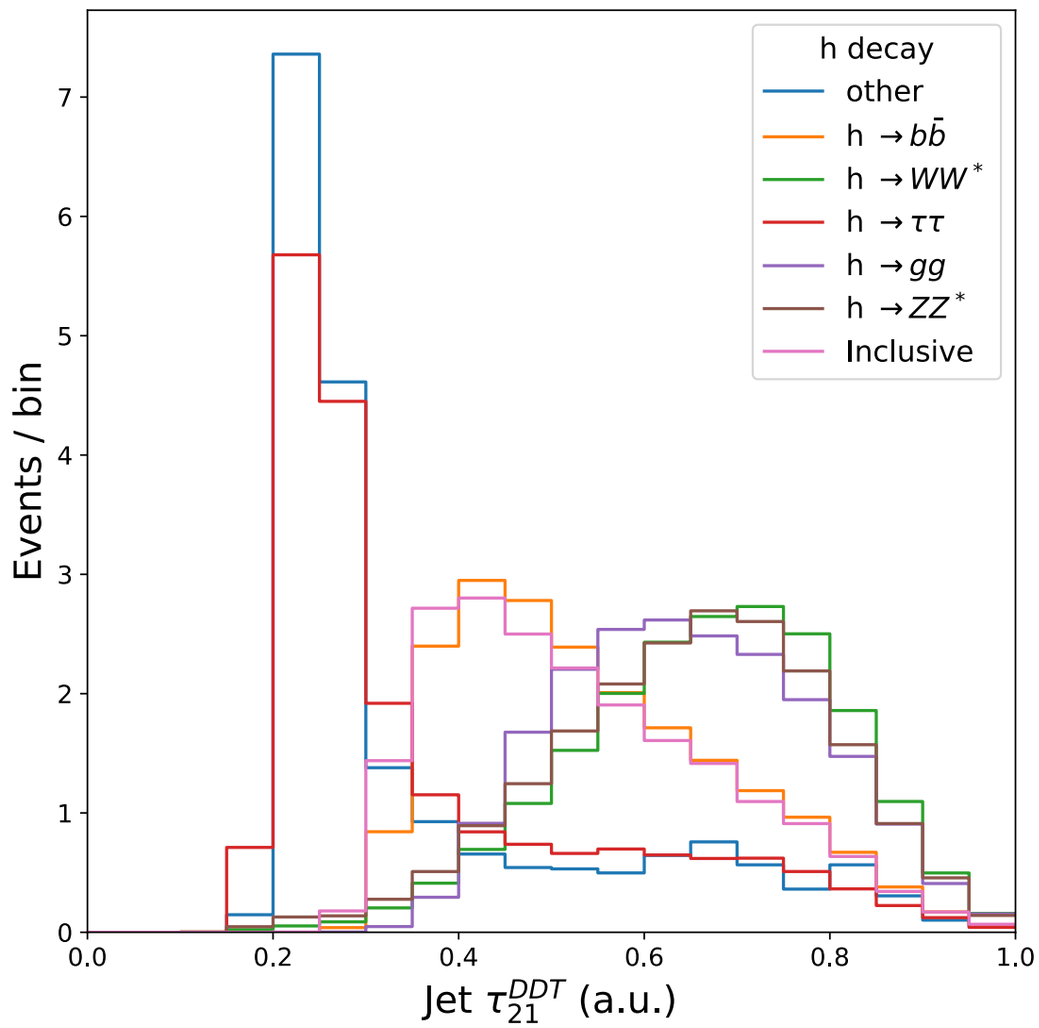
H(ττ)
6%



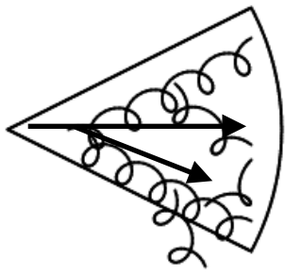
H(gg)
8%



- τ_{21} not optimal for **WW**/**ZZ**/**gg**
- Useful as a benchmark



QCD



Benchmark Comparison

- Jet p_T > 500 GeV
- Using τ_{21}^{DDT} for Higgs tagging

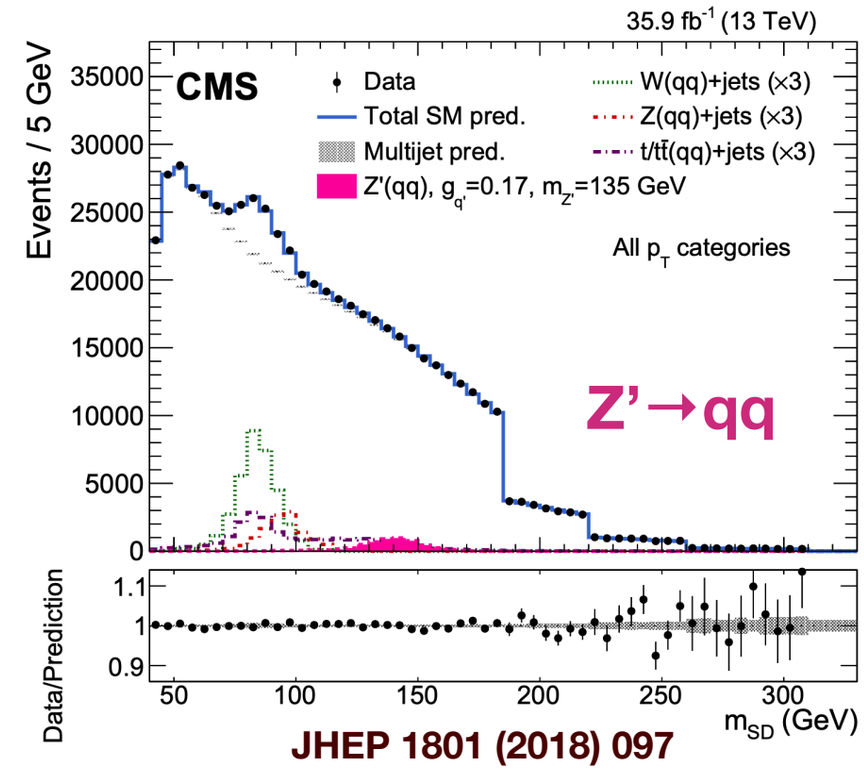
  → **$\Gamma_h < 7.8 \times \Gamma_{SM} = 32$ MeV**

  equivalently $\delta\sigma = 3.6 \times \sigma_{SM}$

- If lowered to jet p_T > 400 GeV

  → **$\Gamma_h < 19$ MeV ($\delta\sigma = 2.2 \times \sigma_{SM}$)**

$\Gamma_h \lesssim 10$ MeV from off-shell method



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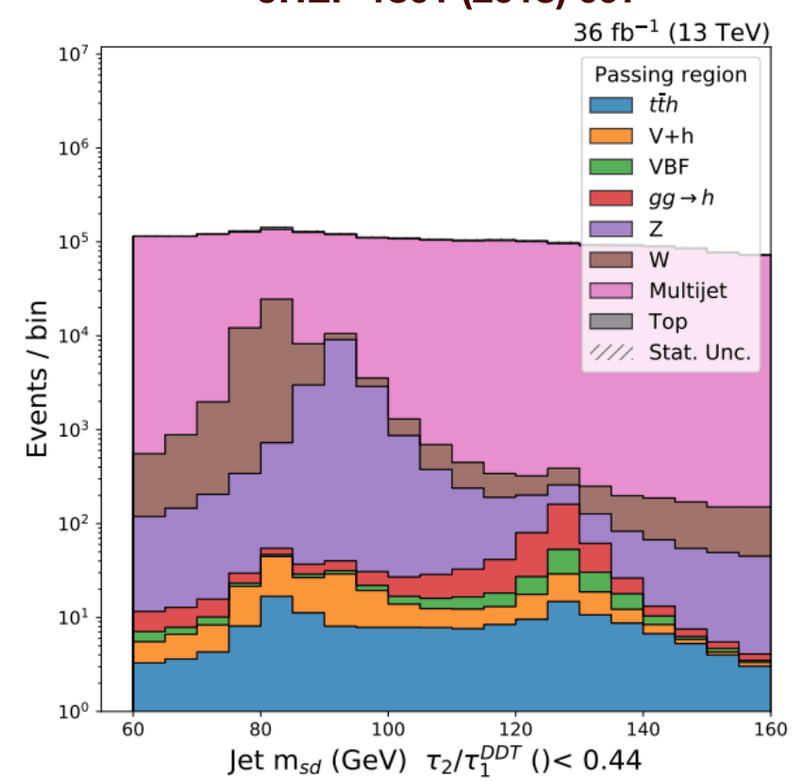
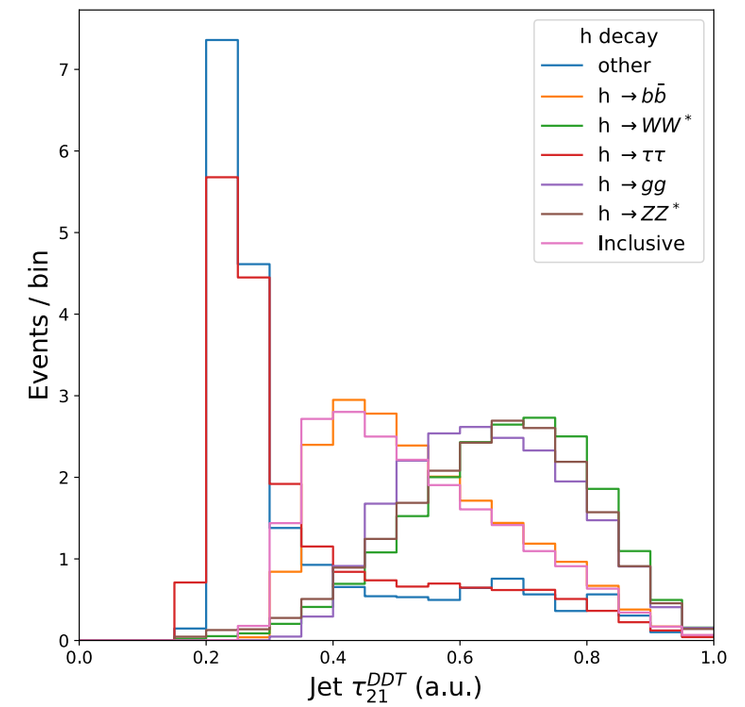
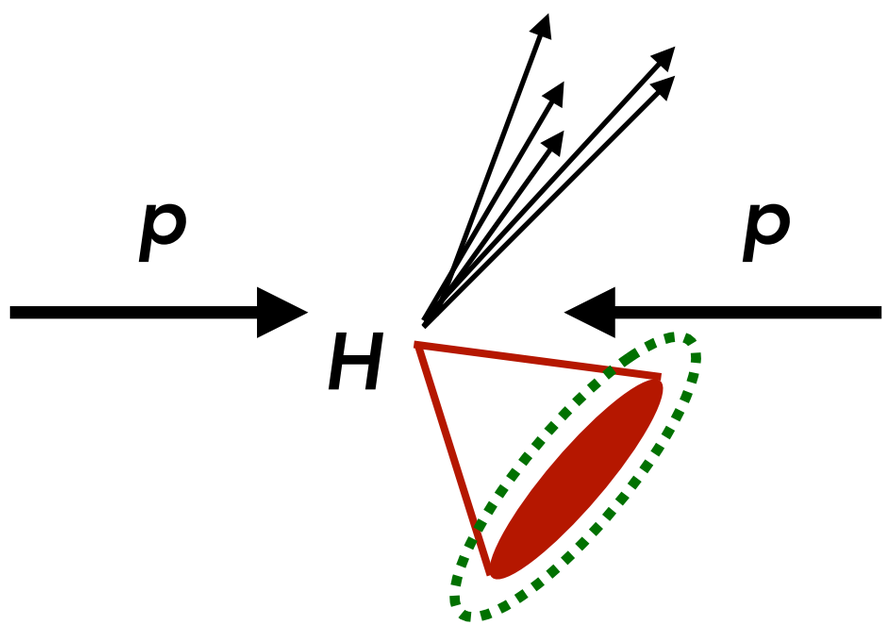
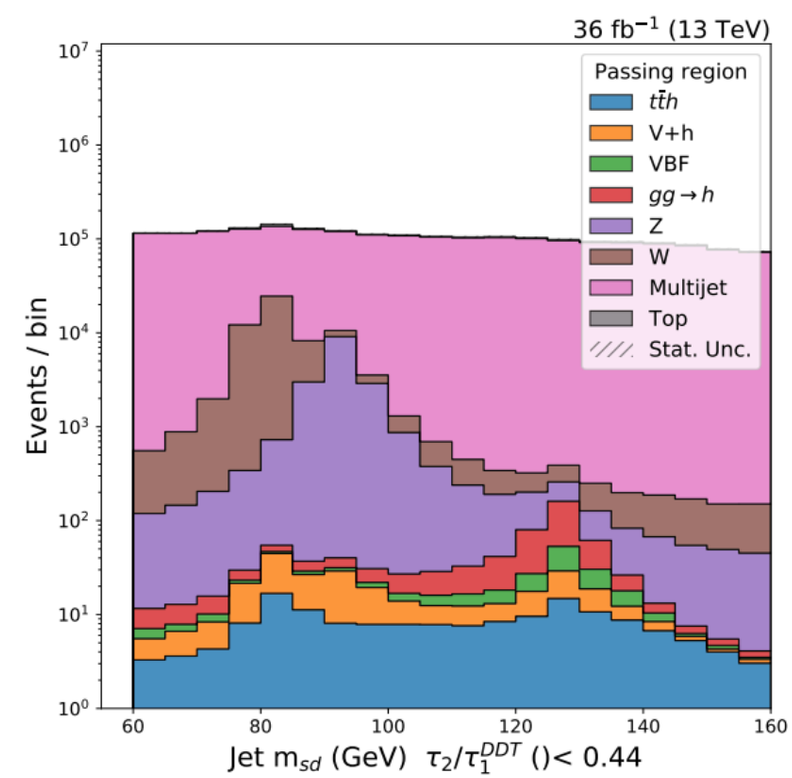


Can We Improve?

- Jet selection/mass reconstruction
- Improved tagger

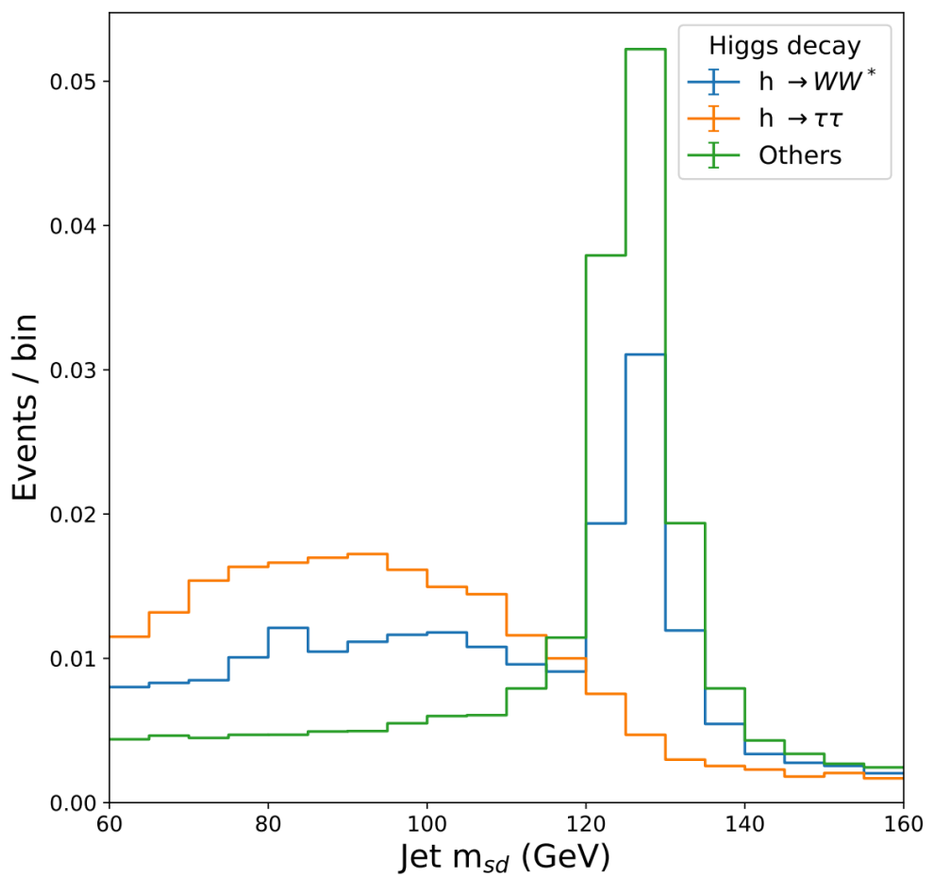


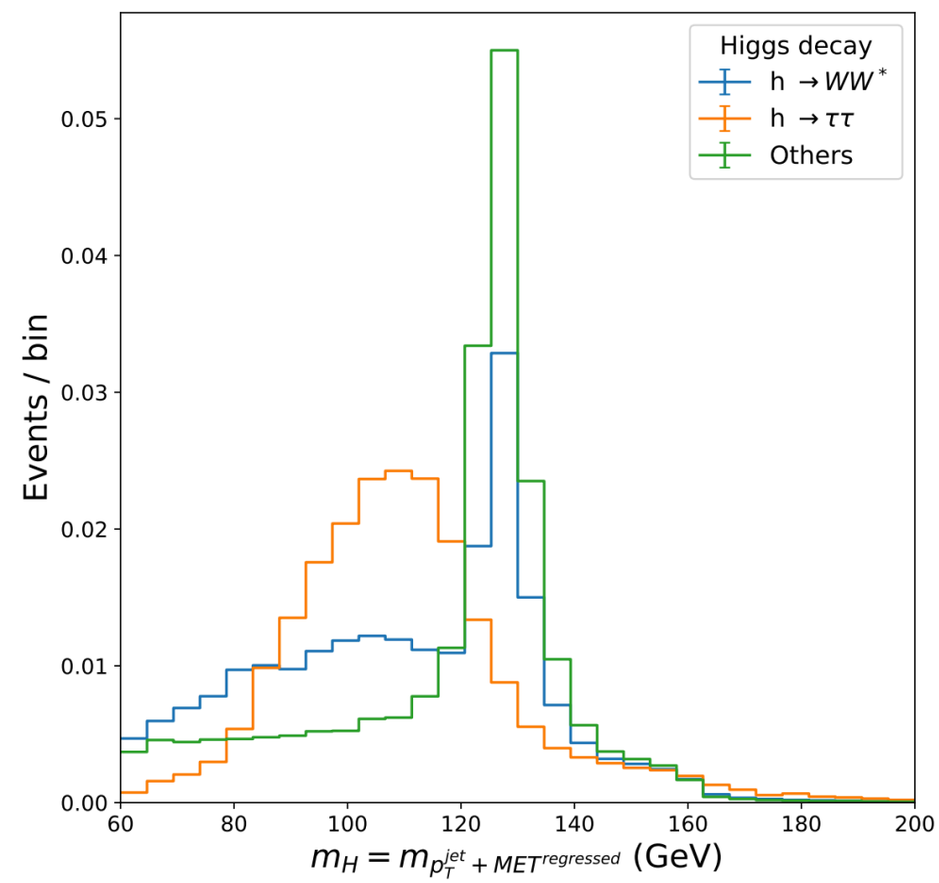




Jet Selection/Mass (MET)

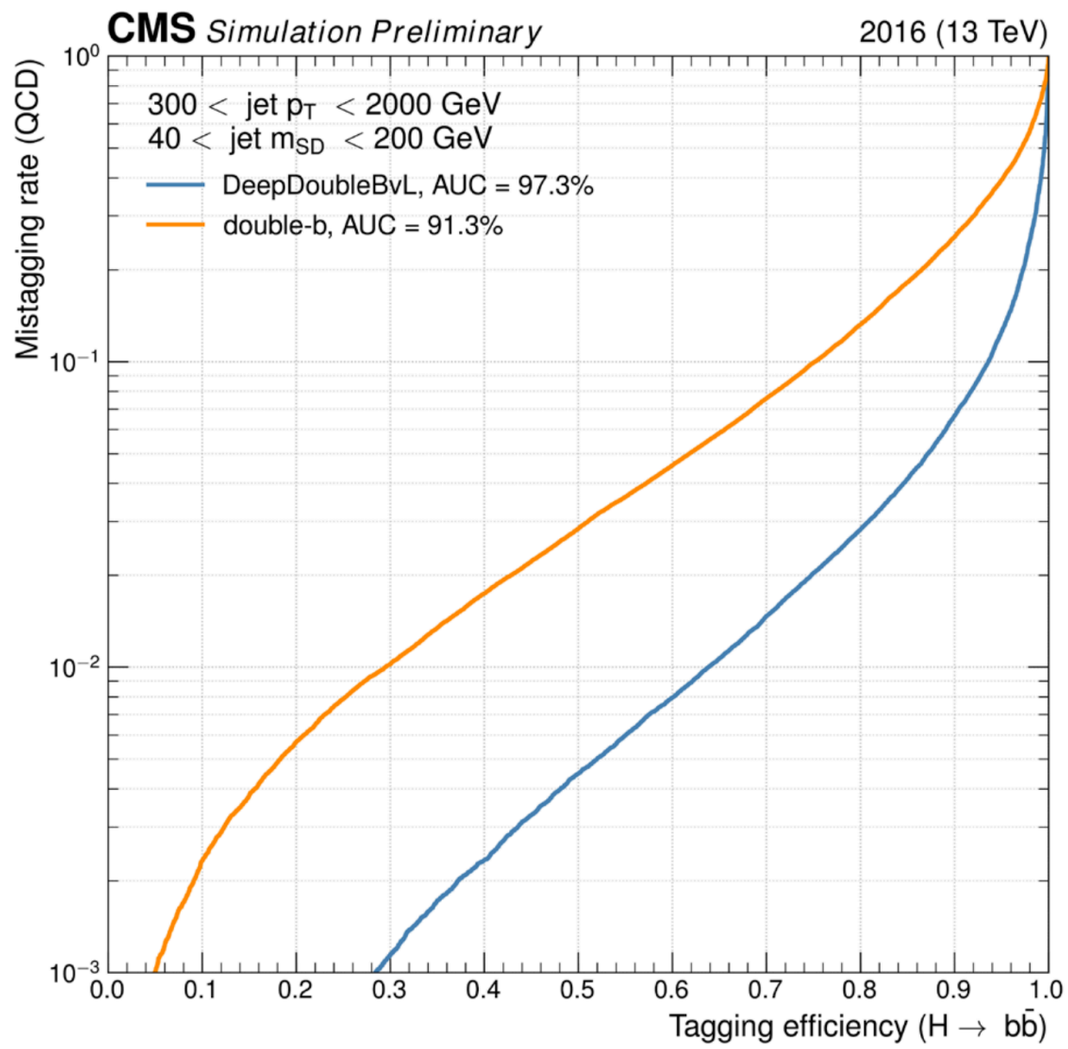
- Missing energy spreads/shifts jet mass peak
  - Simple MLP for regression of true MET (input: jet variables)
- Highest p_T jet not always Higgs jet
  - Especially WW, ττ
- Select jet using p_T of jet+MET^{reg} system





Higgs Tagging

- ML is a great tool for tagging Higgs jets (ex. h→bb)



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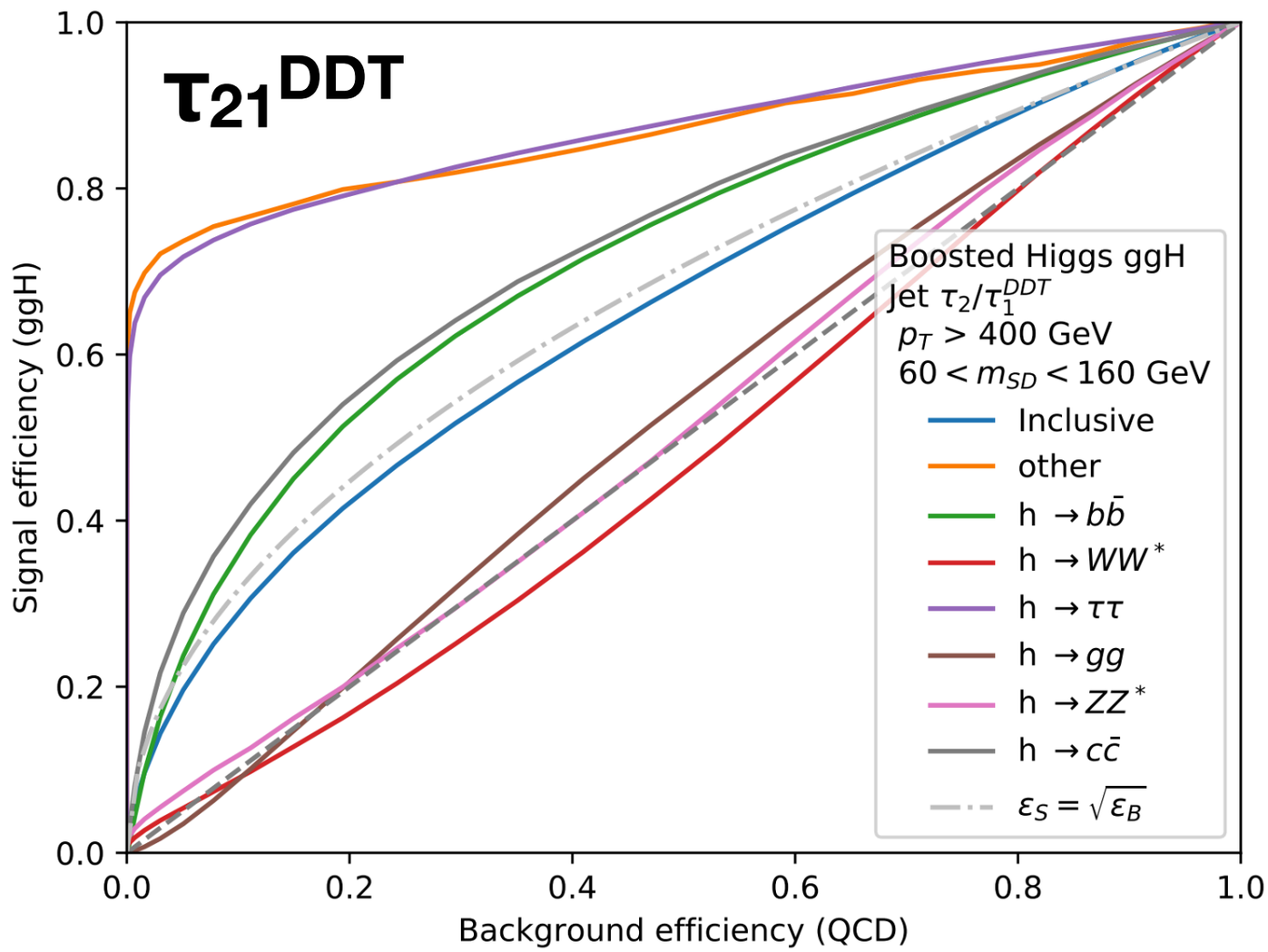
Higgs Tagging

- Design network to simultaneously tag all Higgs decays
  - GRU with 20 particle inputs (p_T, η, ϕ, ID)



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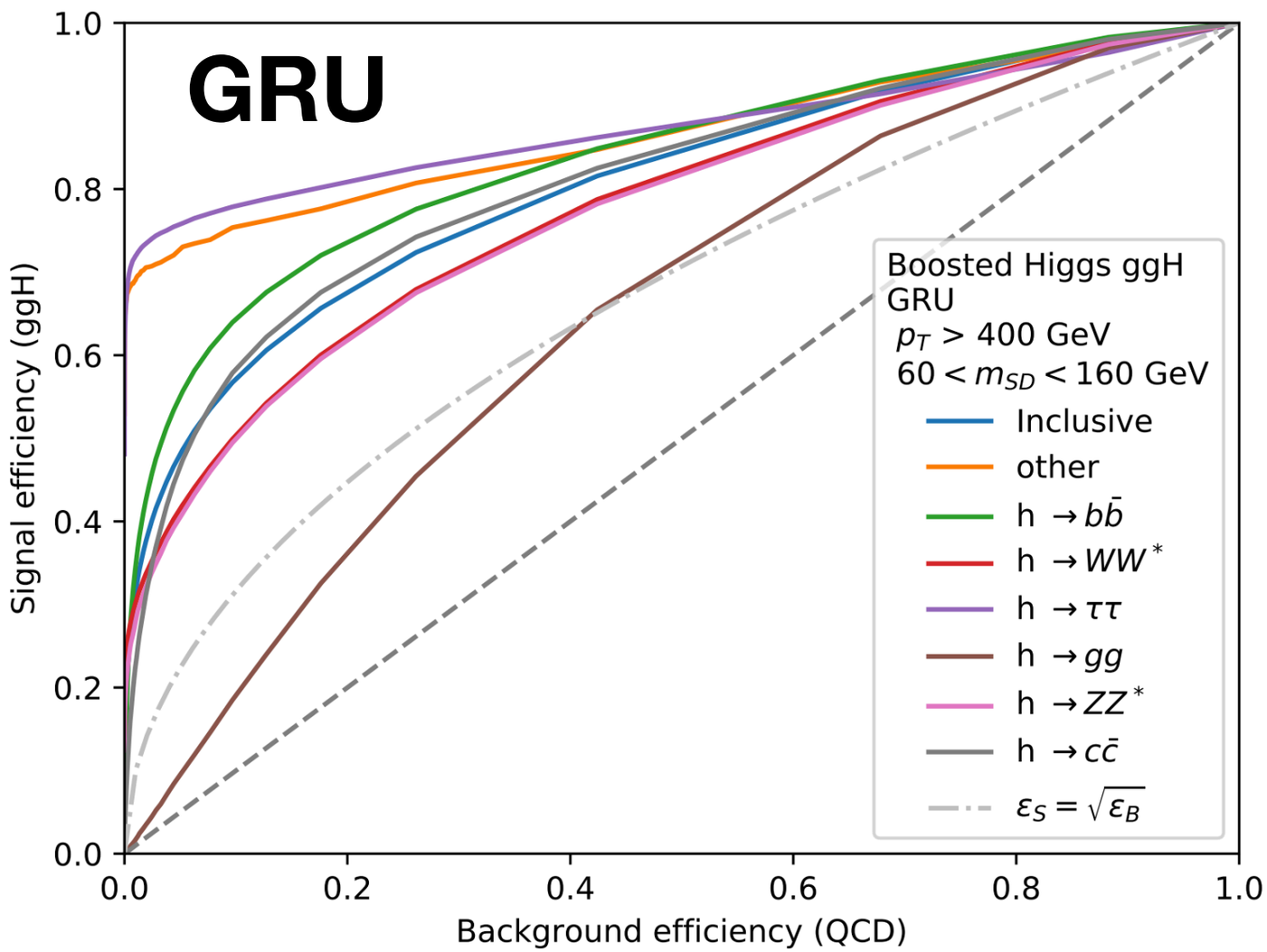
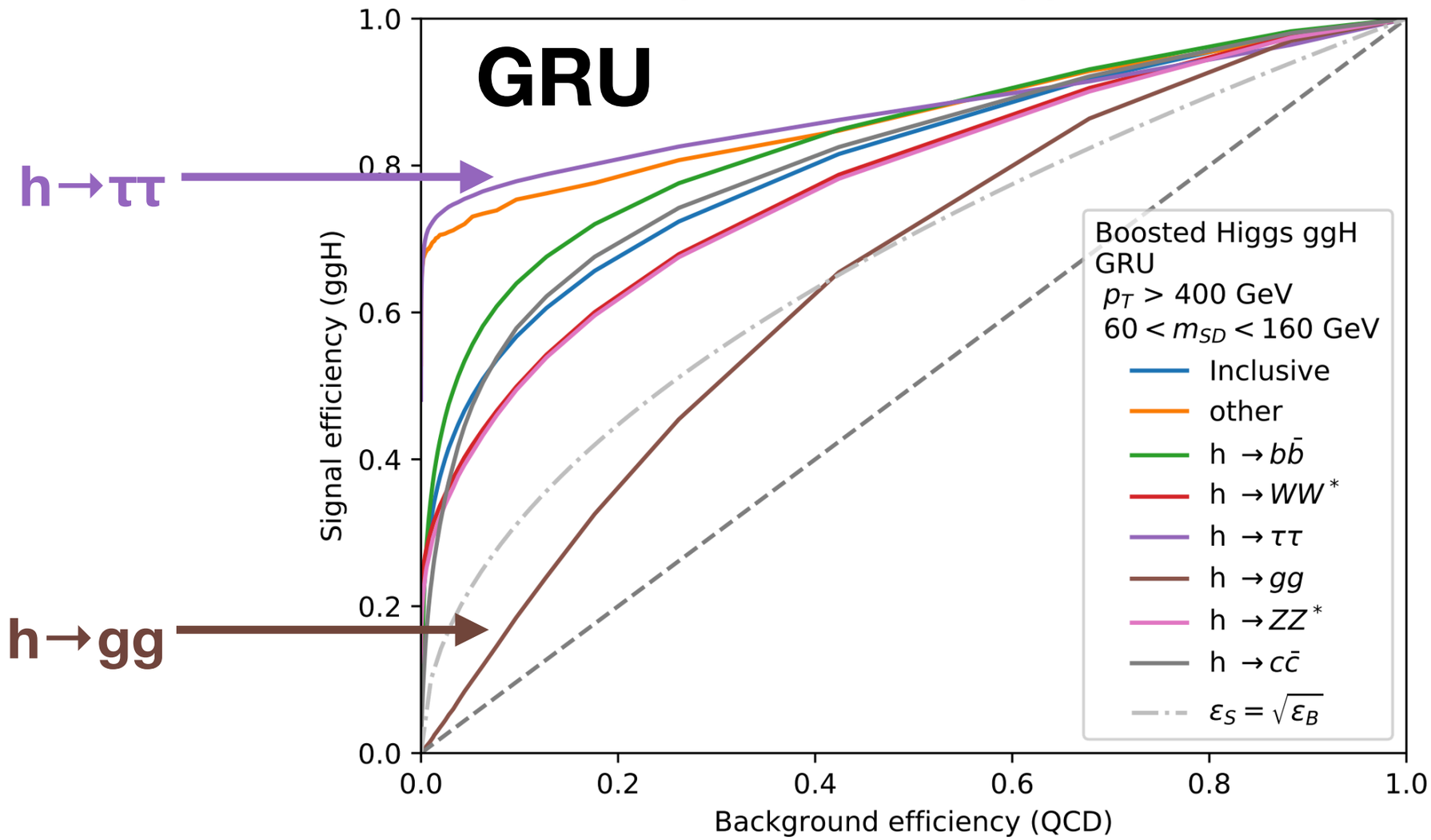


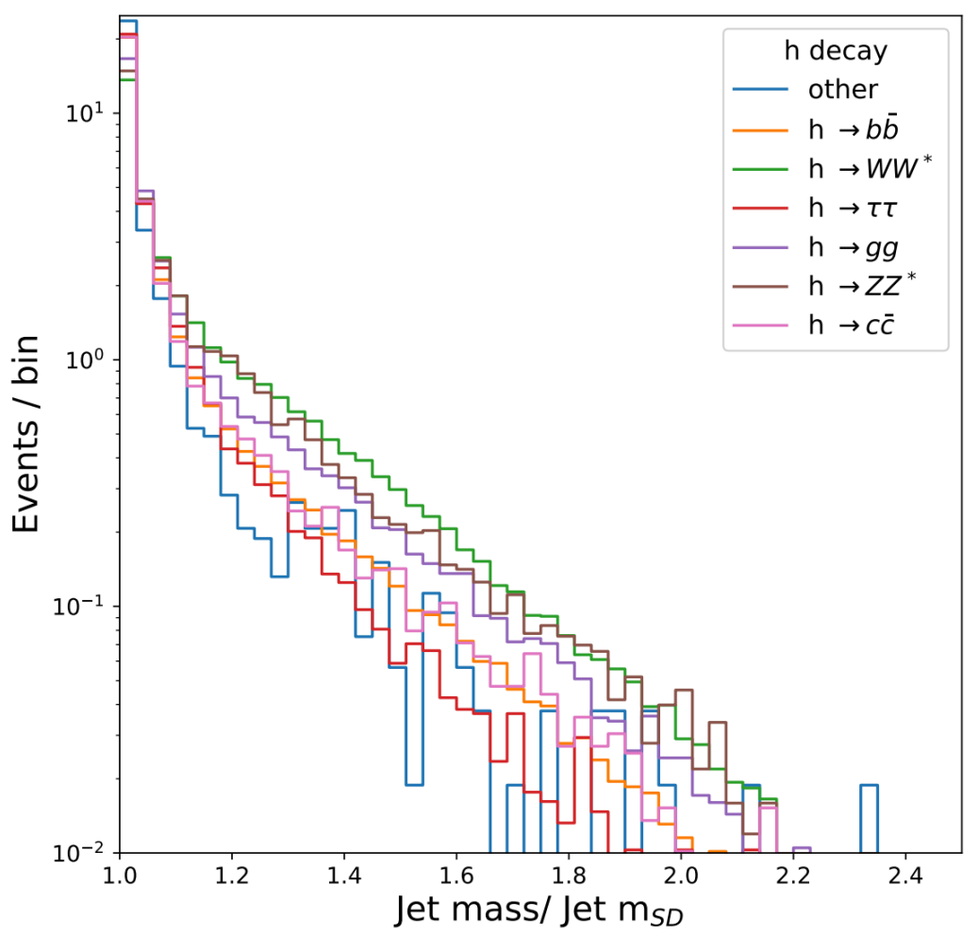
Higgs Tagging

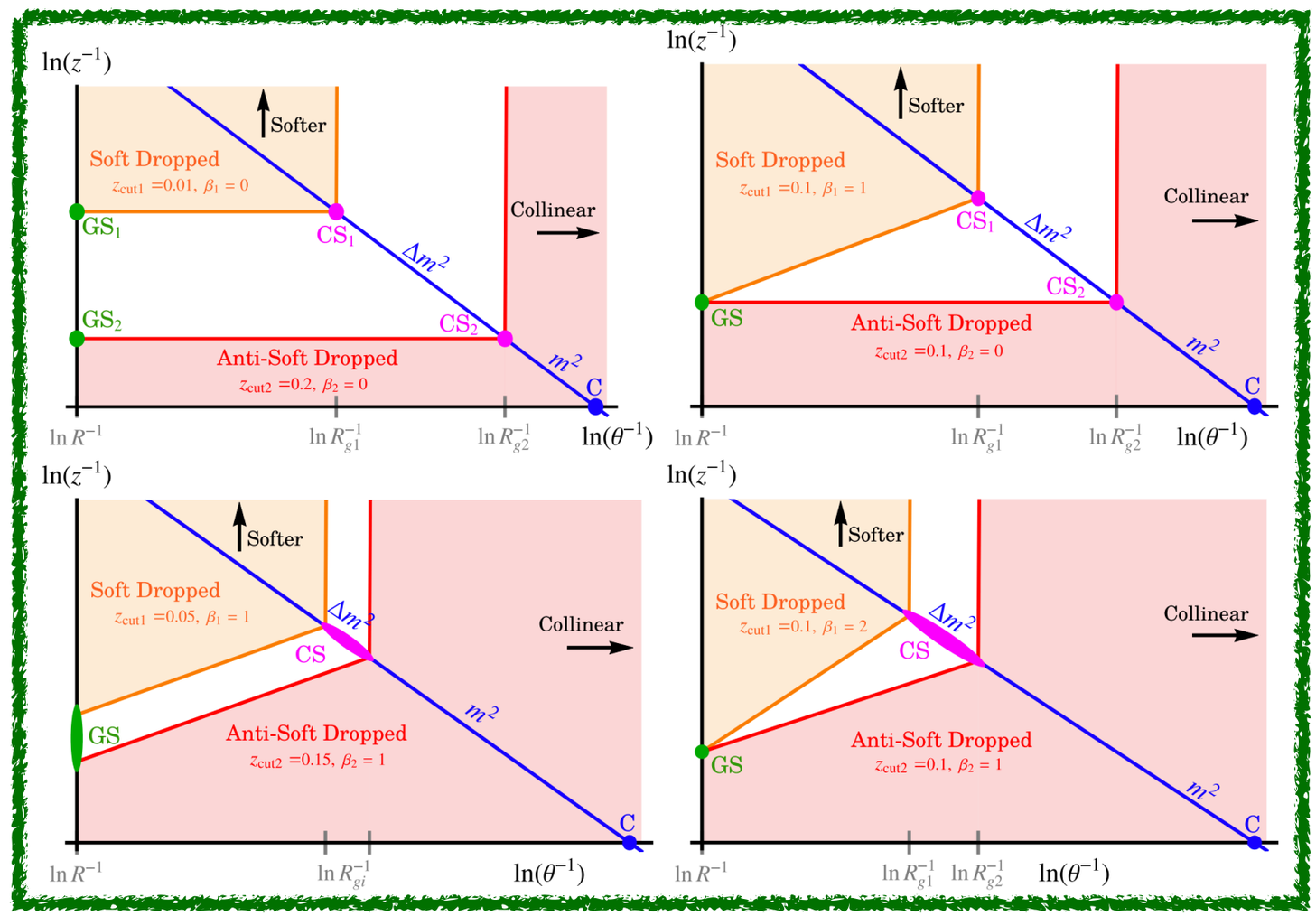
- Ideal case is uniform performance across decays
  - Avoid vertexing
- Similar performance excluding h→ττ and h→gg



Higgs Tagging - gg

- Particle content of h→gg jet similar to QCD jet
  - Dedicated GRU struggles to differentiate
- MLP with expert features - *jet mass ratios*
  - Similar concept to **collinear drop** [1907.11107], isolates color singlet





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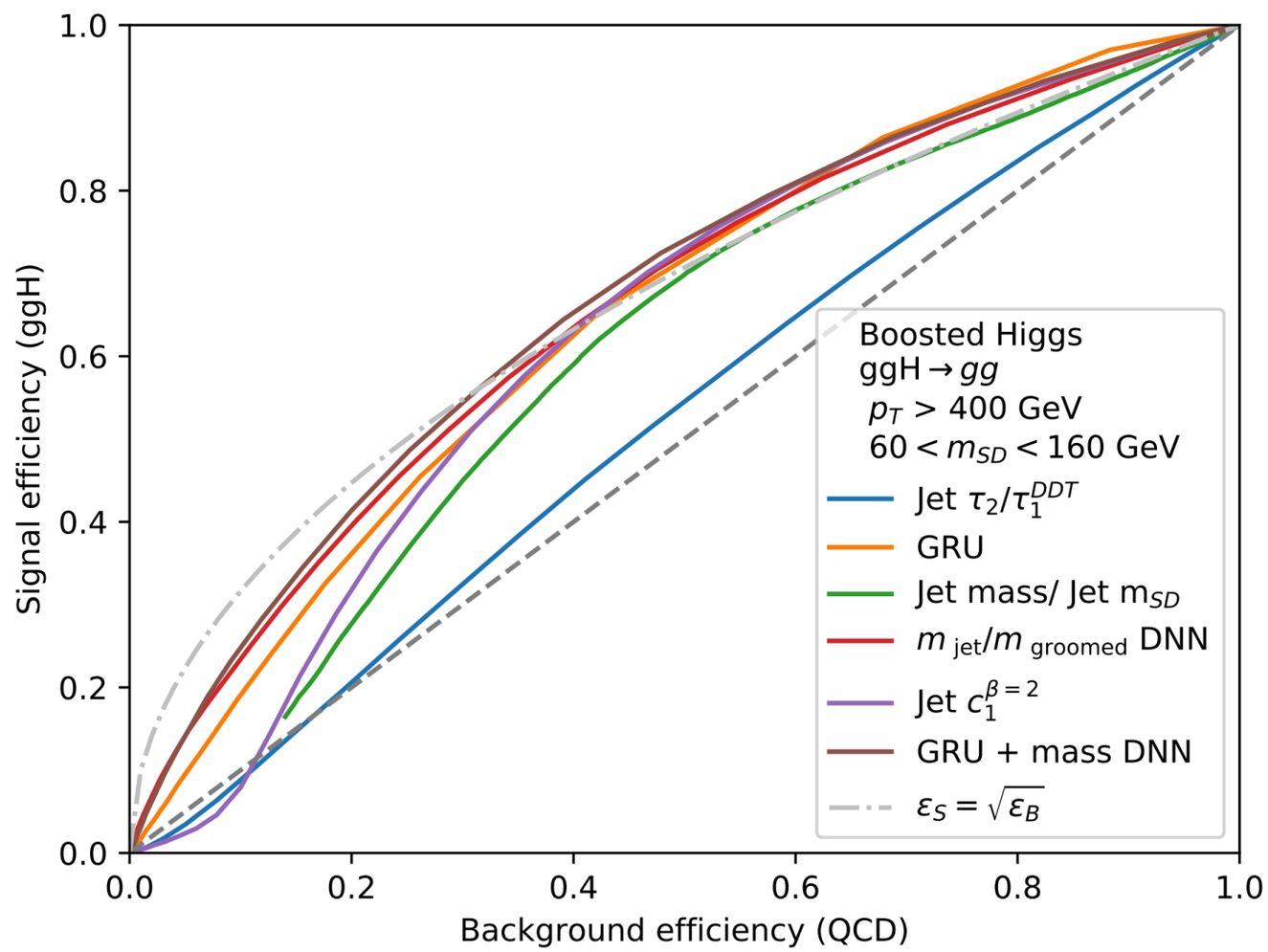
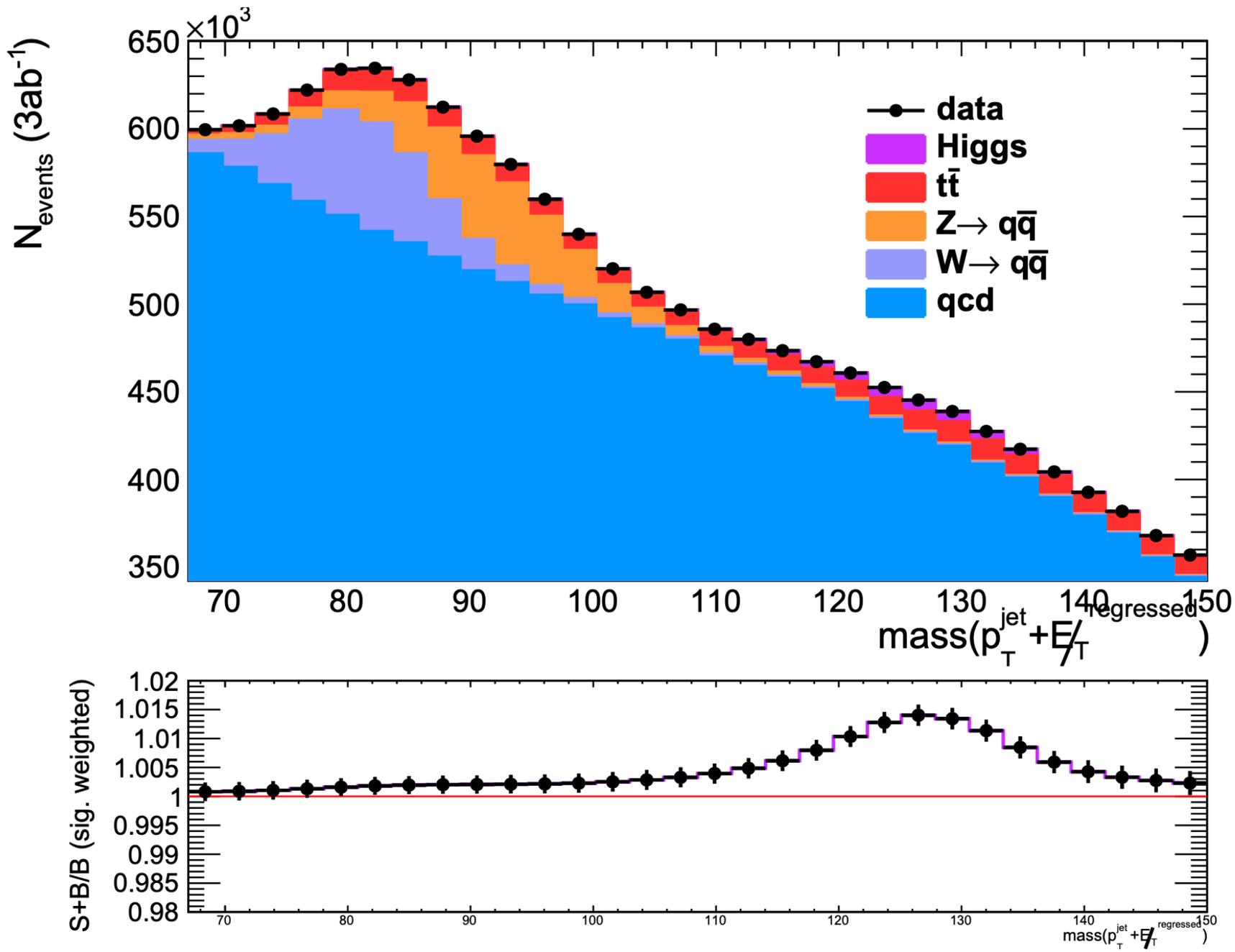
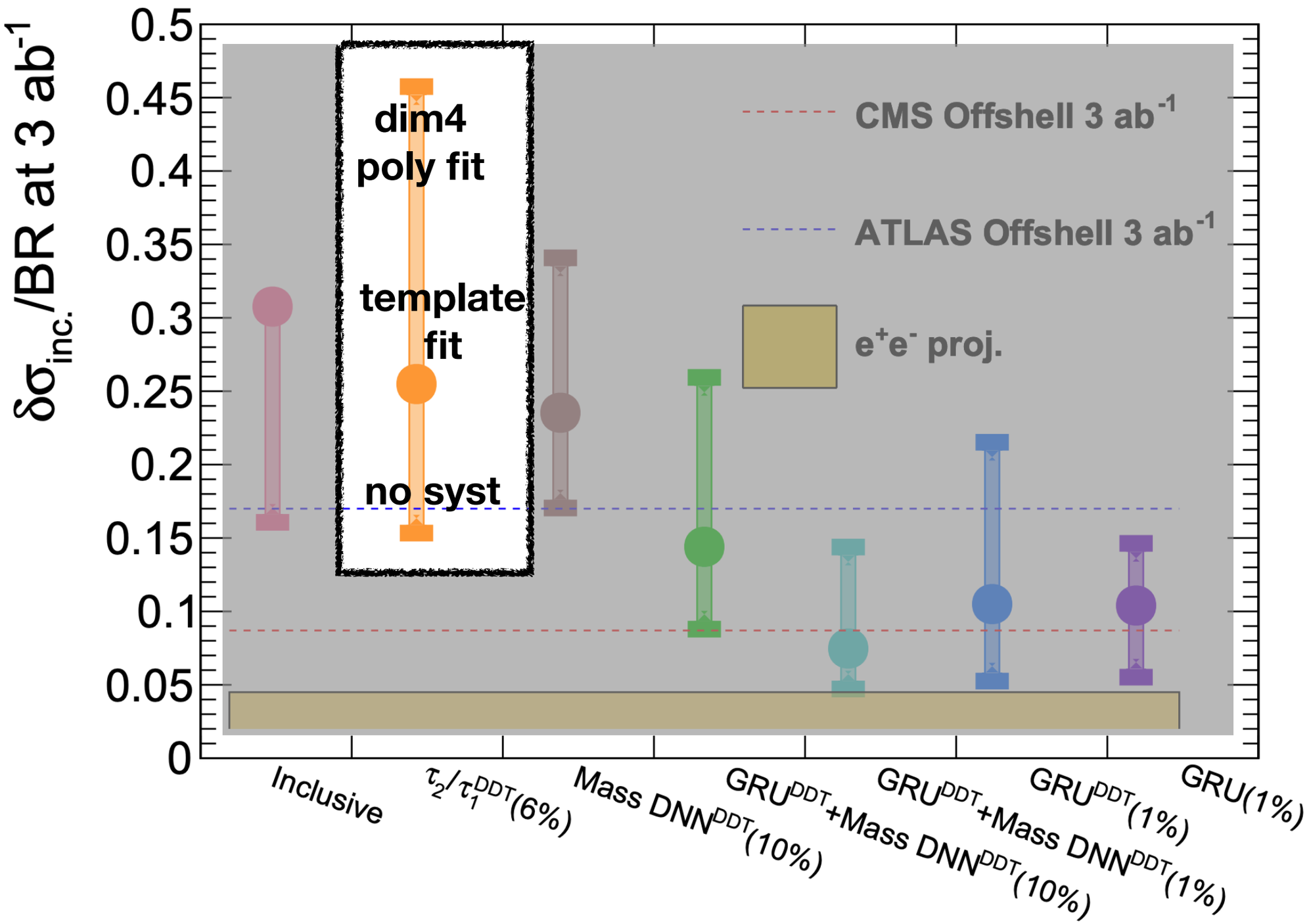


Sensitivity
GRU^{DDT}

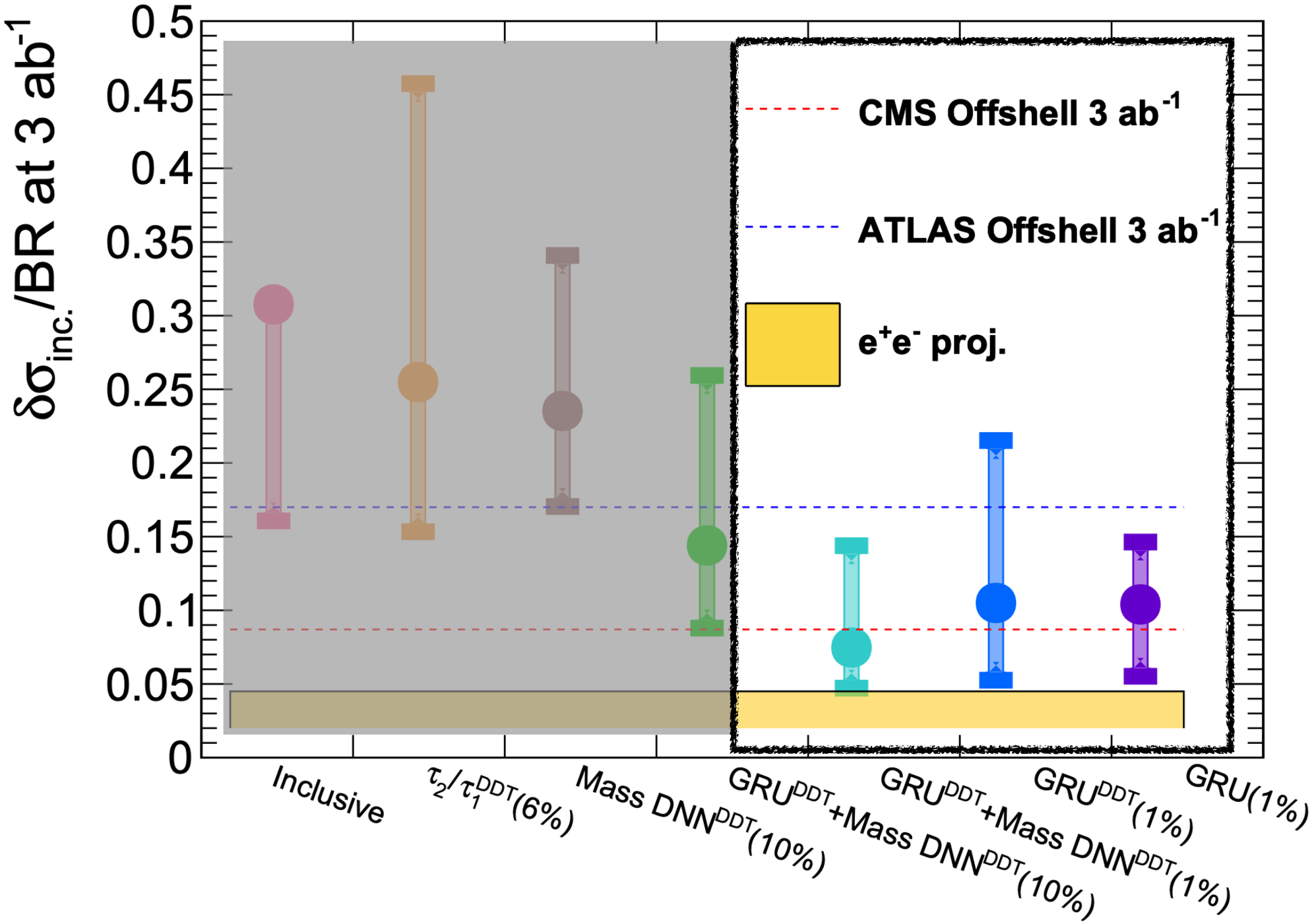
- GRU^{DDT}



Results


$\delta\sigma_{inc.}$/BR at 3 ab^{-1}
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
dim4
poly fit
template
fit
no syst
CMS Offshell 3 ab^{-1}
ATLAS Offshell 3 ab^{-1}
e^+e^- proj.
Inclusive
τ_2/τ_1^{DDT}(6%)
Mass DNN^{DDT}(10%)
GRU^{DDT}+Mass DNN^{DDT}(10%)
GRU^{DDT}+Mass DNN^{DDT}(1%)
GRU^{DDT}(1%)
GRU(1%)

Results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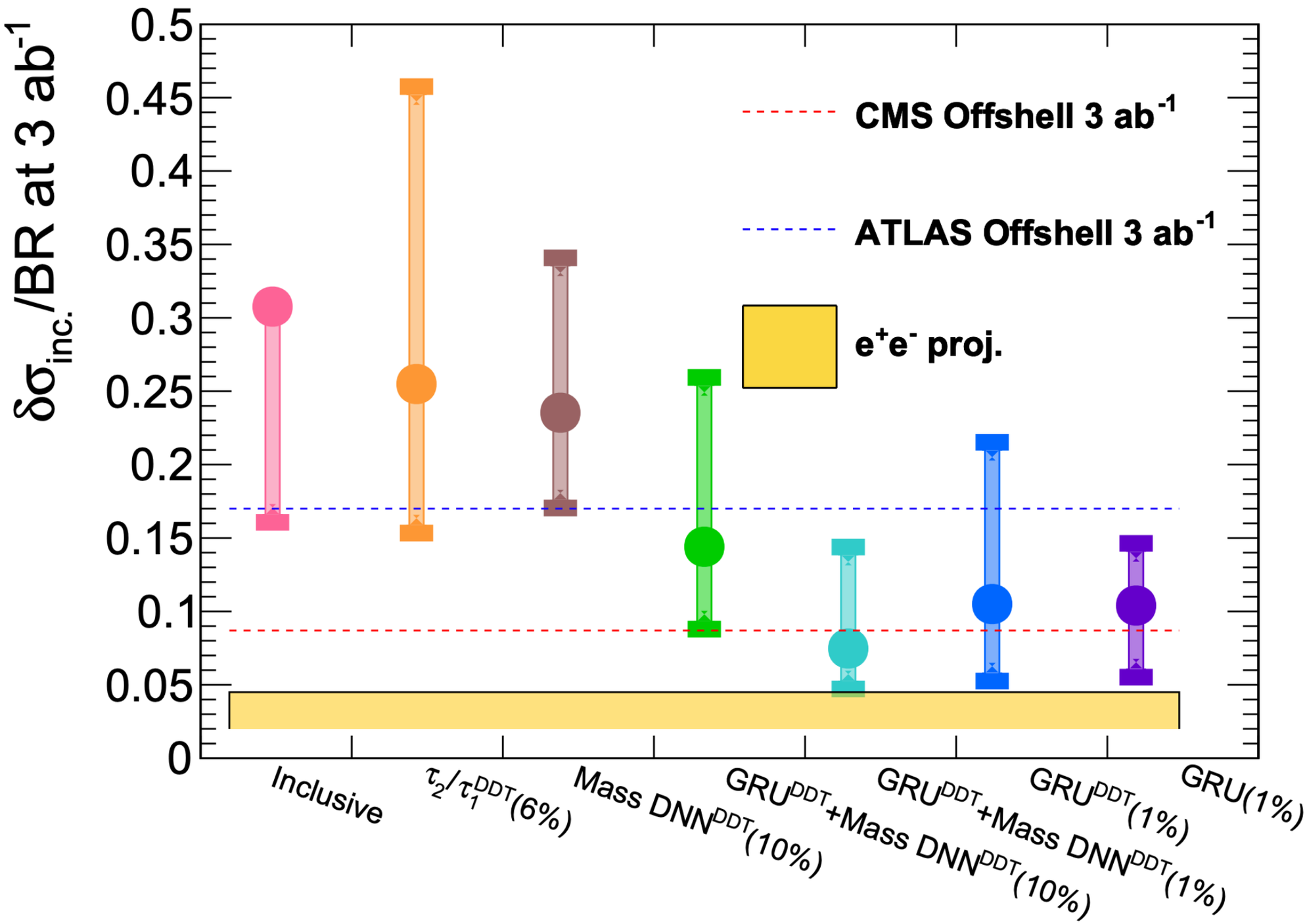
$\delta\sigma_{inc.}$/BR at 3 ab^{-1}
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0.45
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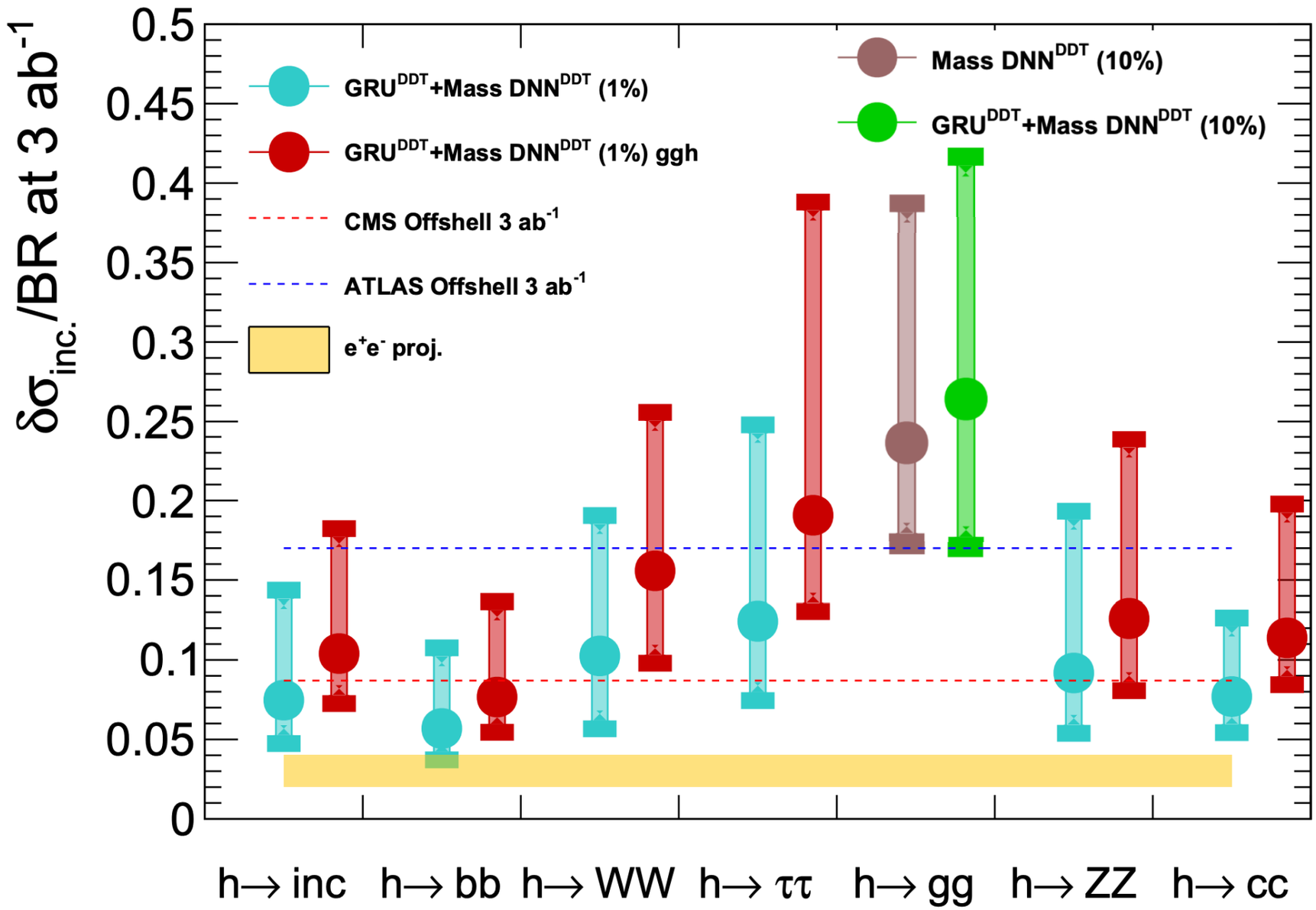
GRU^{DDT}(1%)
GRU(1%)

Results - GRU+DNN

- Tight GRU + DNN (1%) is good overall : **benchmark**



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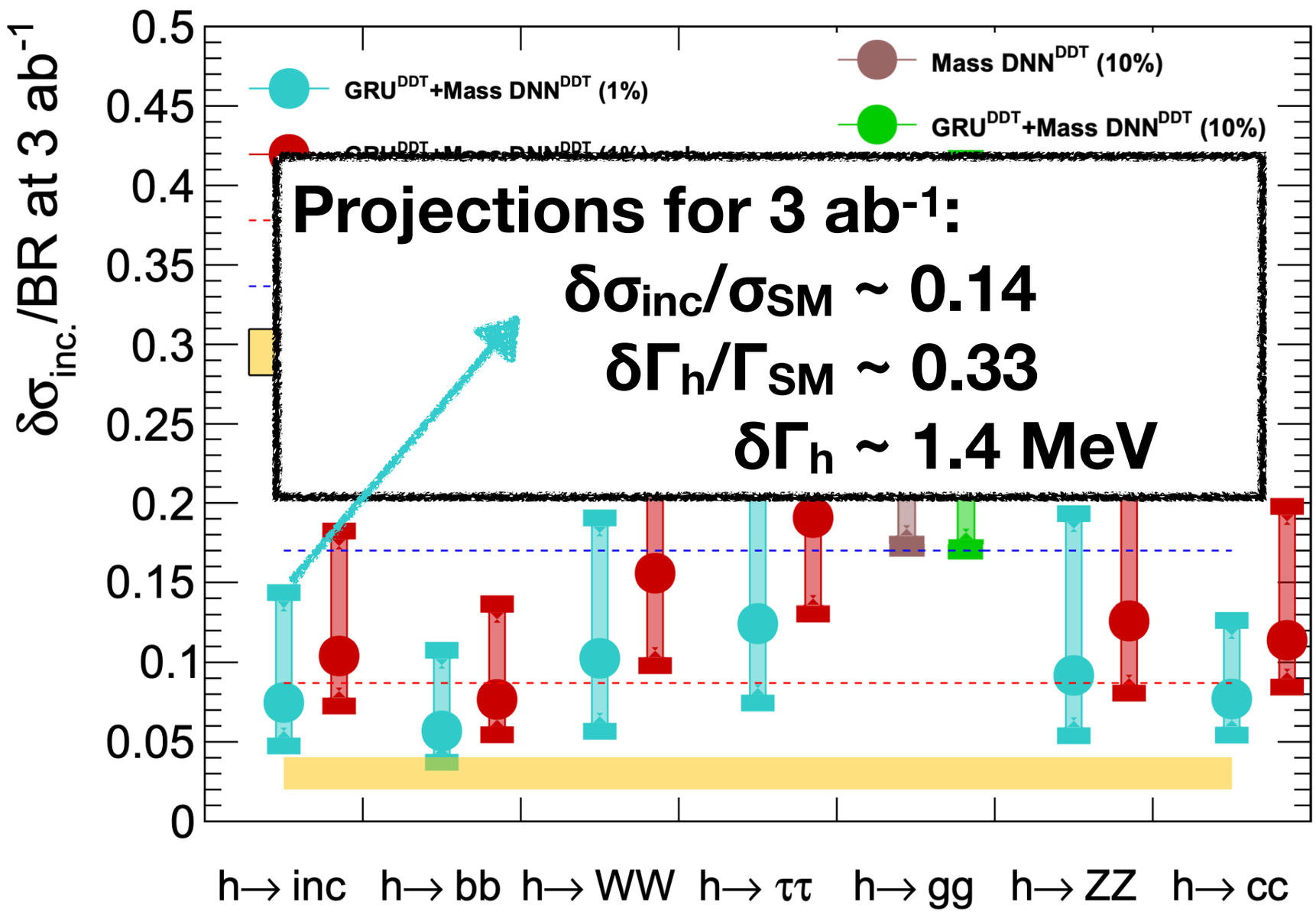
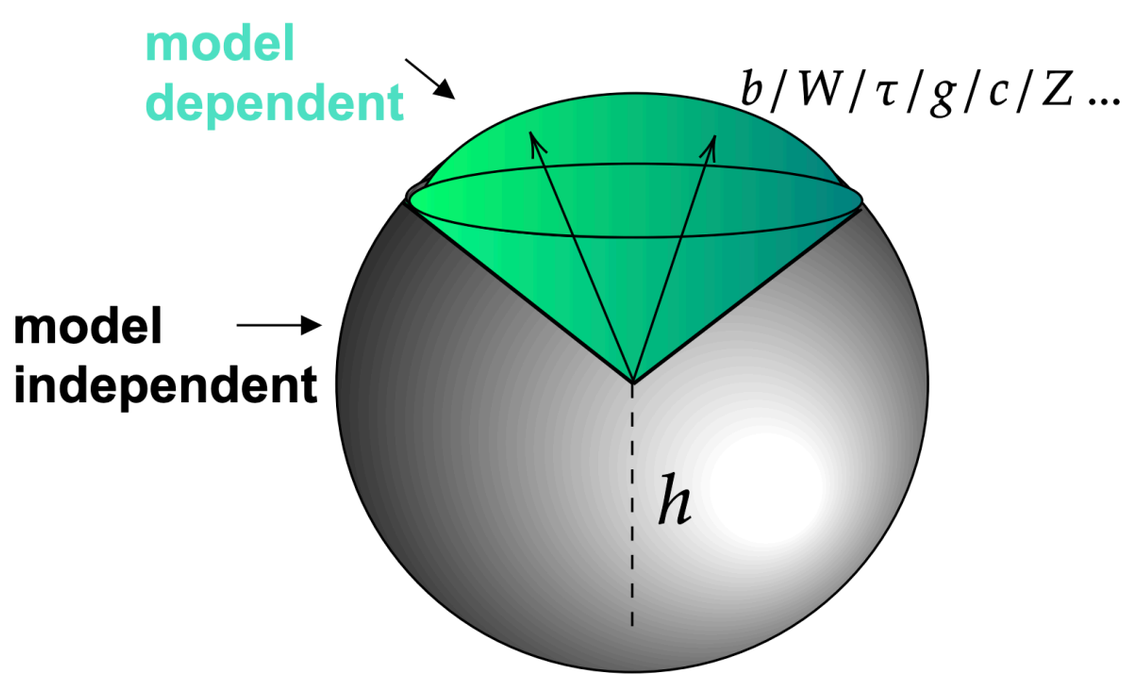


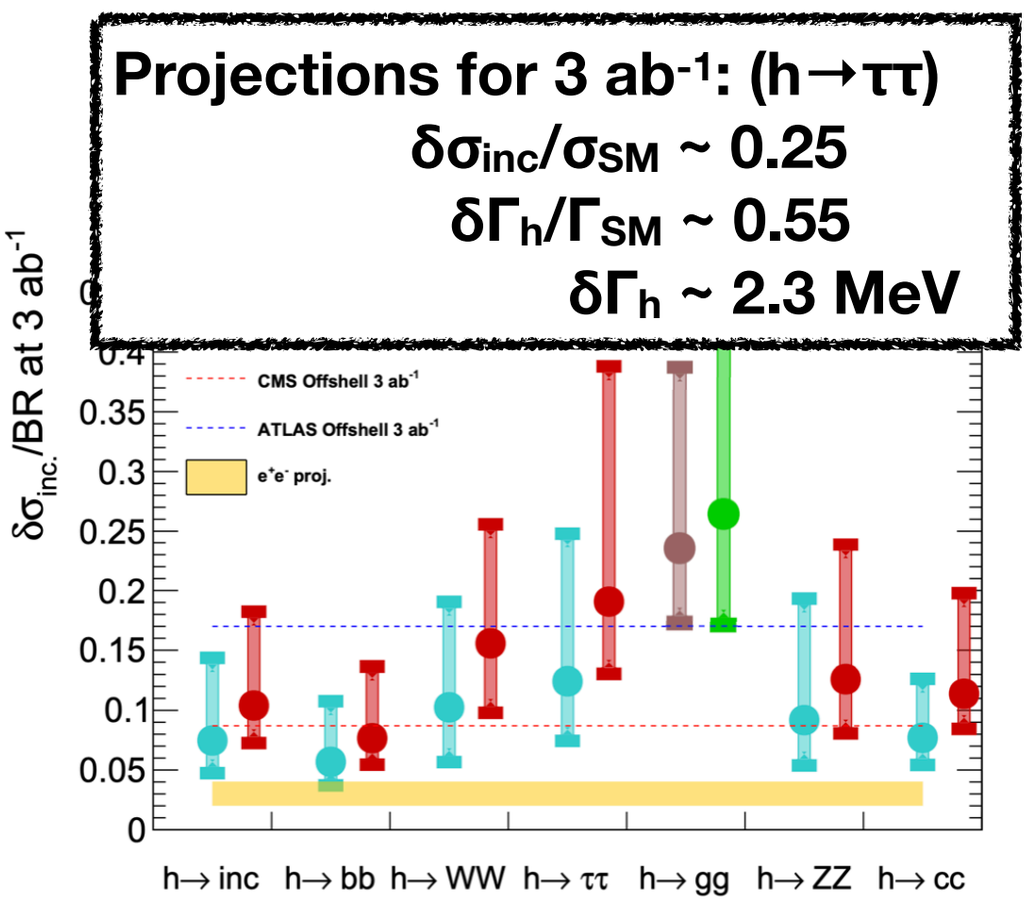
Biases/Assumptions

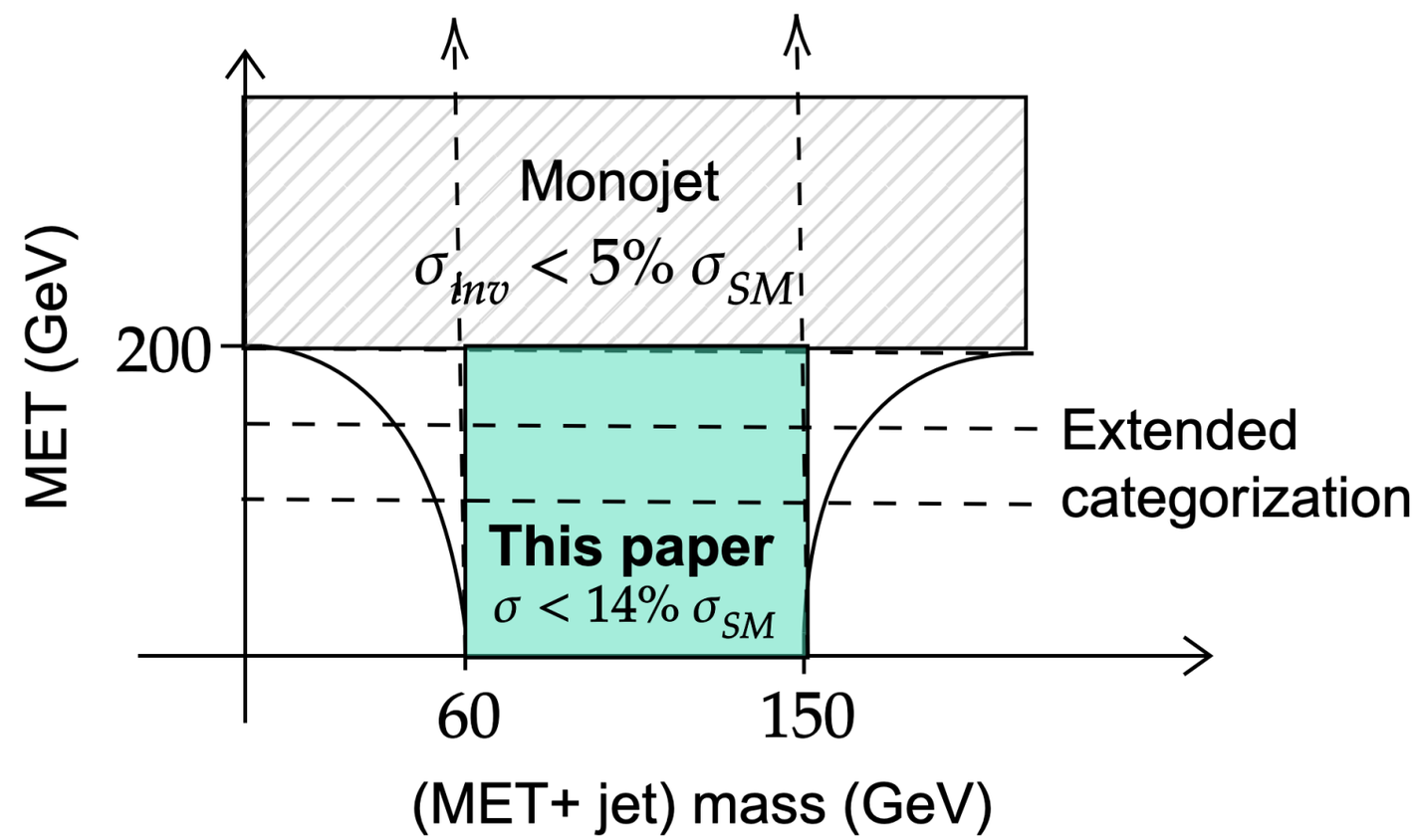
- Experimental challenges:
  - Jet $p_T > 400$ GeV
  - Fit convergence, necessary polynomial order
  - Signal efficiency (uncertainty and uniformity)
- Method assumptions:
  - Higgs decays can be reconstructed in single jet (semi-vis/invis?)



Semi-Visible/Invisible

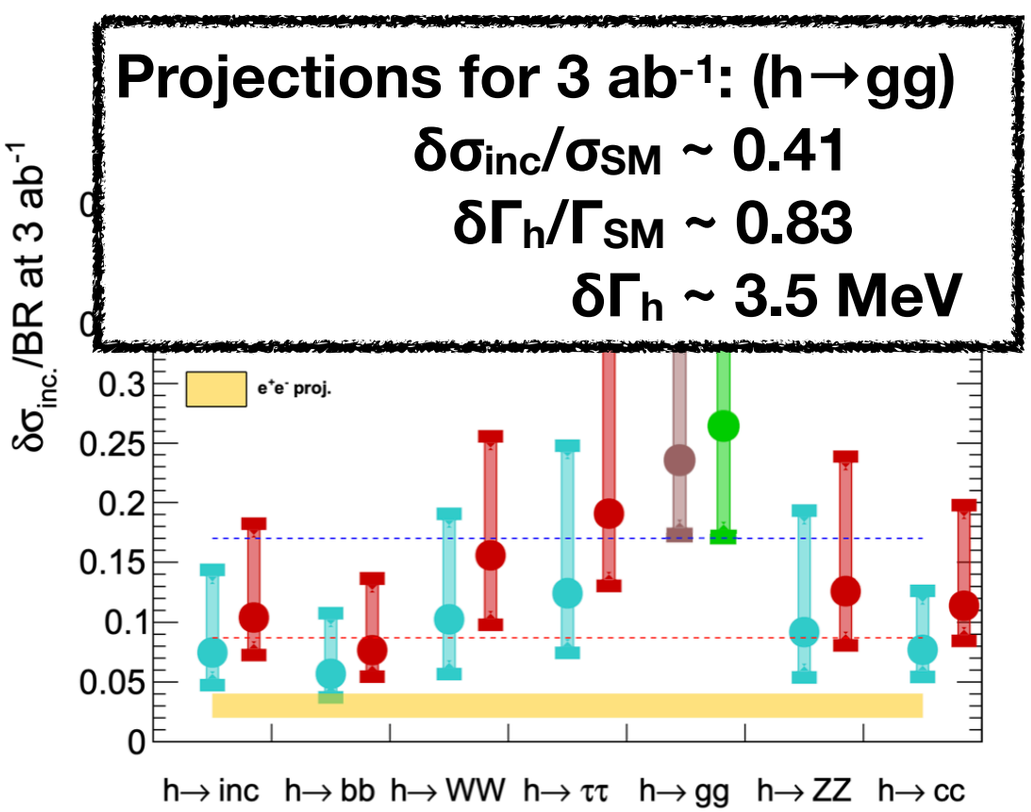
- SM semi-visible decays included in study (WW, ττ)
  - MET regression, MET + jet selection could be improved
- Further categorization possible using MET for fully invisible

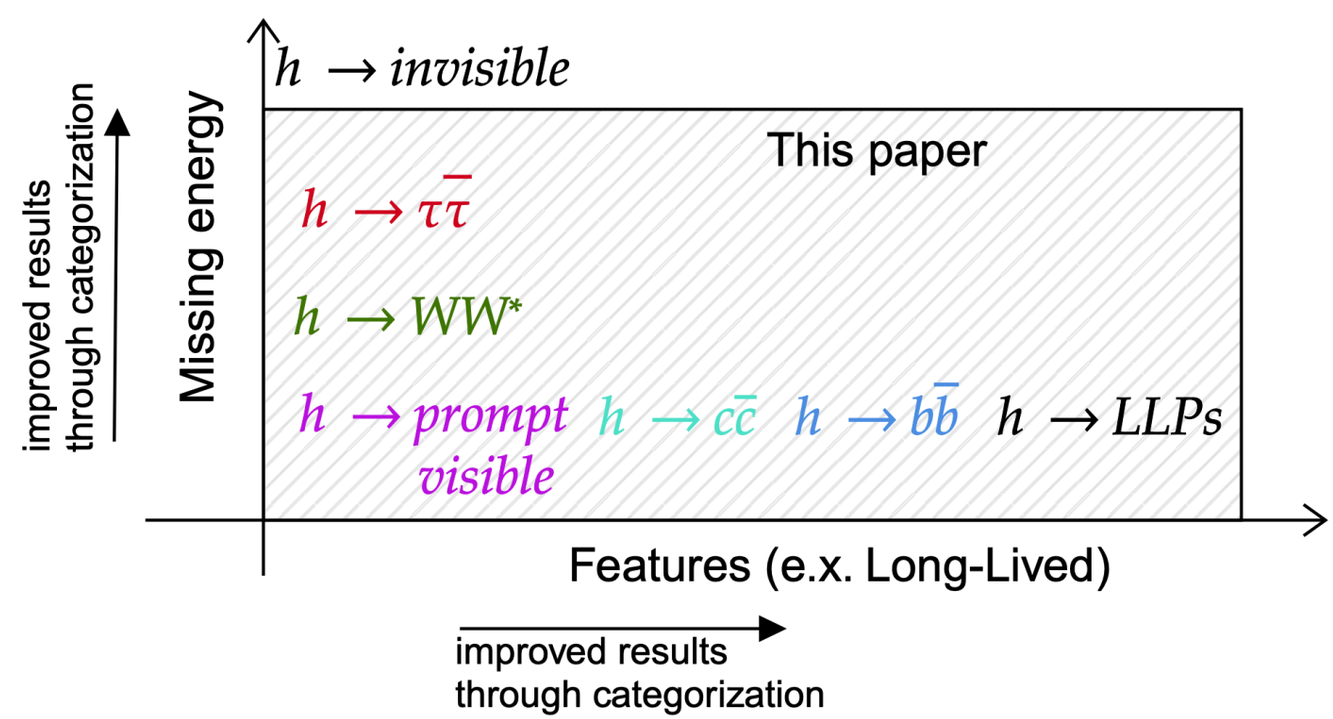




Other Signatures

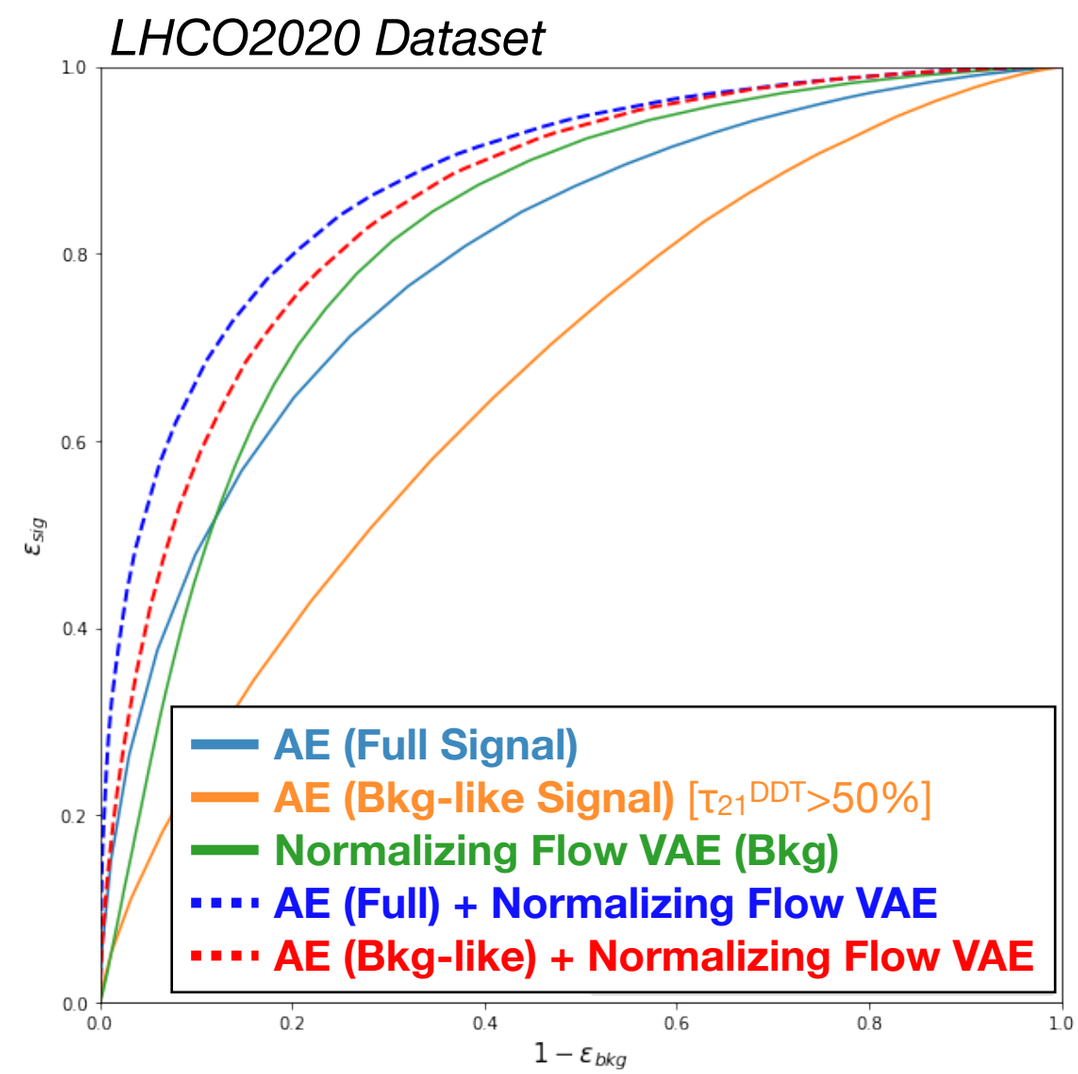
- h→gg difficult to handle
  - Some dedicated techniques show promise (mass DNN)
- Exotic decays
  - Prompt caught by tagger
  - LLP possible with further categories?





Improvements

- Improved tagger?
  - Better performance
    - Alternate architectures (VAE? Normalizing flow?)
  - Stability across decays
    - Investigated use of adversarial network (large reduction in performance)
- New ideas (from LHC olympics?) can have significant impact here



Sang Eon Park
Silviu Marian Udrescu
Andrew Tan

Conclusions

- Proposed method to measure Higgs width in high p_T events at LHC
- Constraints comparable to off-shell method possible
  - **$\delta\Gamma_h$ ~ 1.4 - 3.5 MeV**
  - Alternative measurements important
- Method has much room to grow, improvements possible
- Welcome suggestions/thoughts

BACKUP

Benchmark Comparison

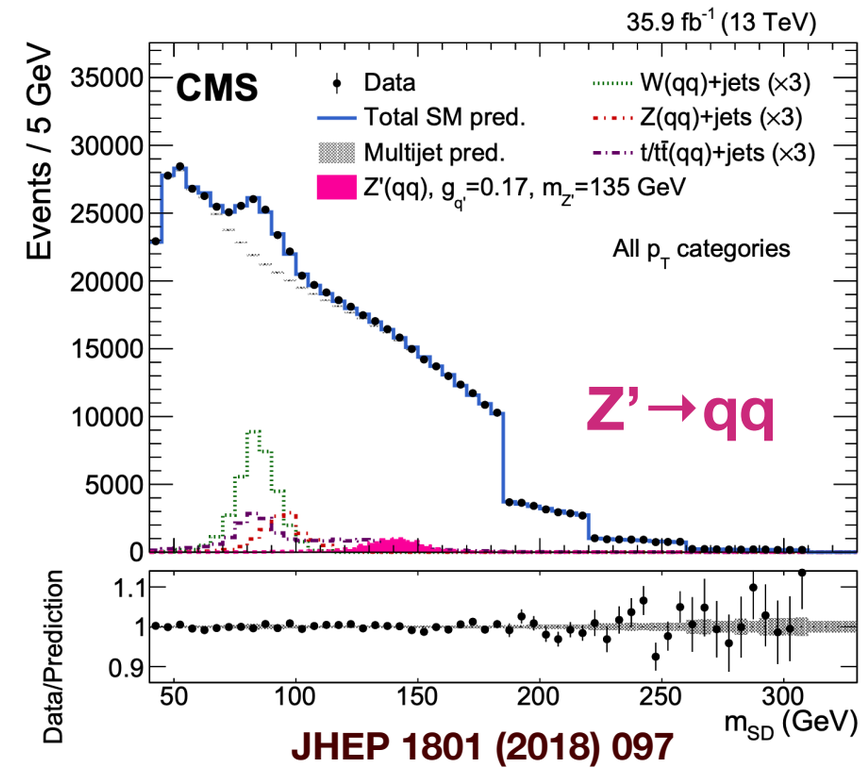
- Selection using hadronic triggers
  - Jet p_T > 500 GeV, Higgs candidate is highest p_T jet
- Using τ_{21}^{DDT} for Higgs tagging
- Fit jet mass using same procedure as boosted h→bb (Bernstein polynomial, predict multijet from failing data)

  → $\Gamma_h < 7.8 \times \Gamma_{SM} = 32$ MeV

  equivalently $\delta\sigma = 3.6 \times \sigma_{SM}$
- If lowered to jet p_T > 400 GeV

  → $\Gamma_h < 19$ MeV ($\delta\sigma = 2.2 \times \sigma_{SM}$)

$\Gamma_h \lesssim 10$ MeV from off-shell method



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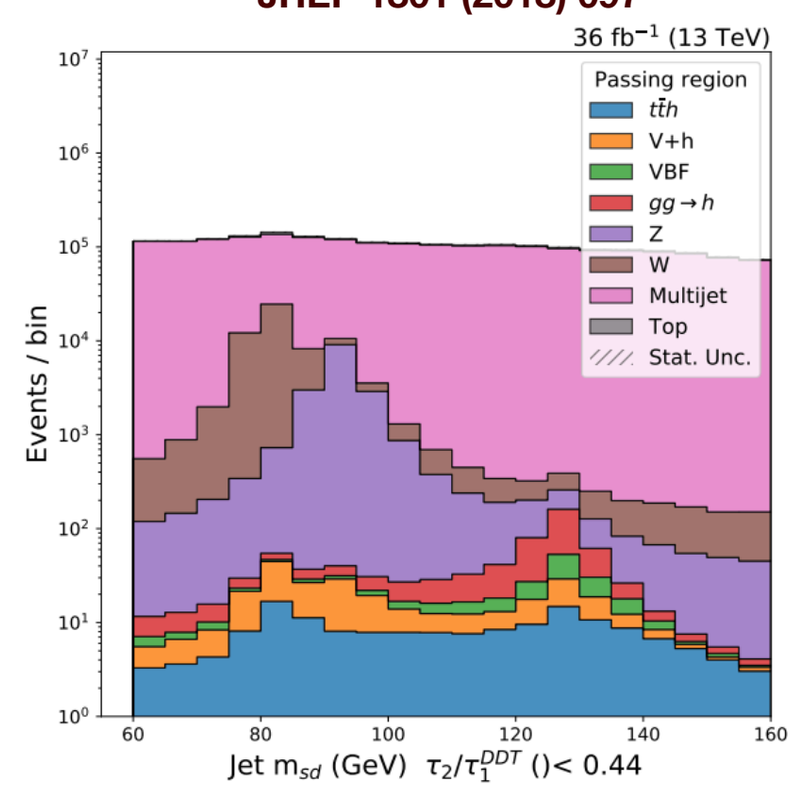


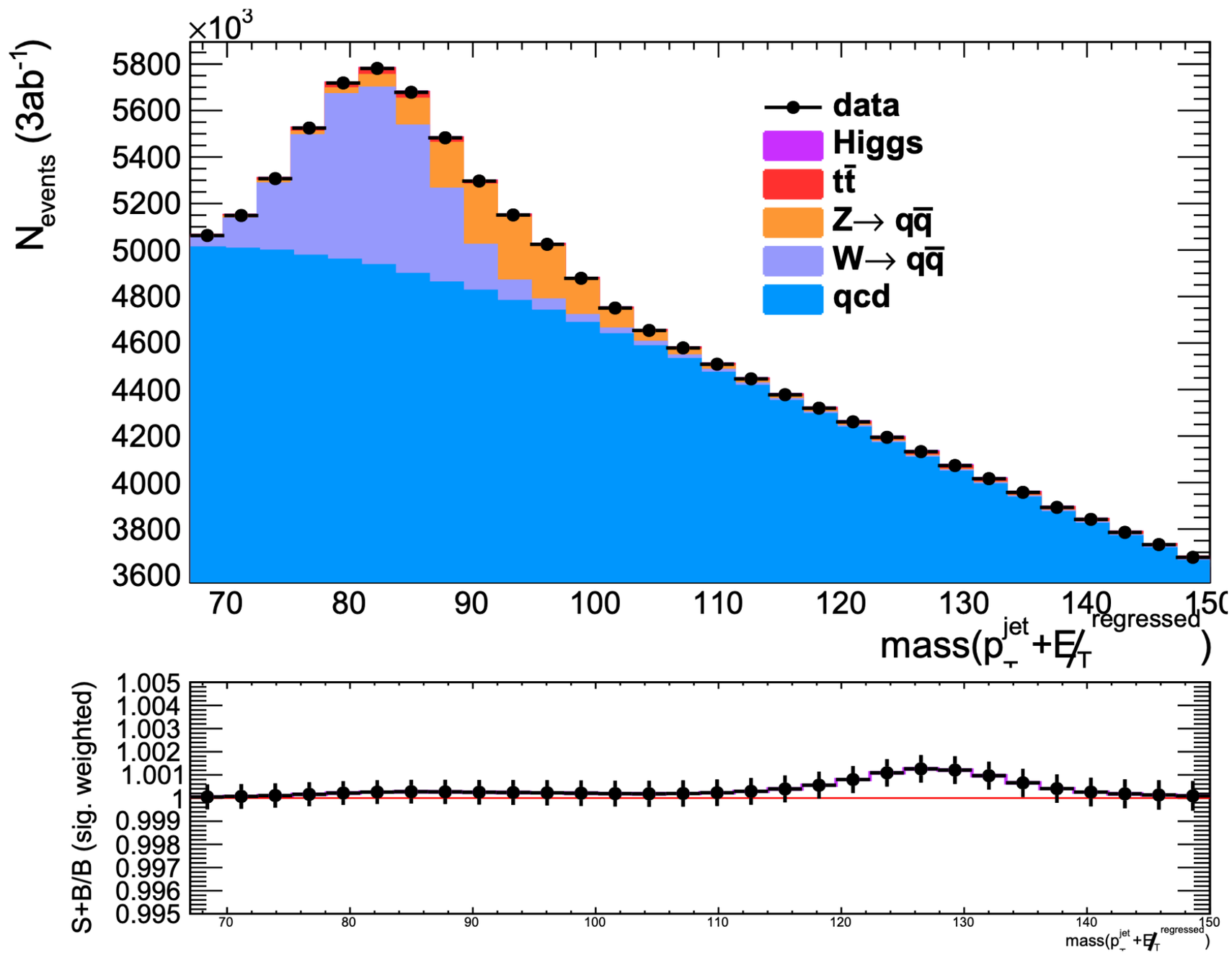
Benchmark @ 3000 fb^{-1}

- **This method: $\delta\sigma = 0.55 \times \sigma_{SM}$**
  - Without systematics: $\delta\sigma = 0.24 \times \sigma_{SM}$
- Off-shell projections:
  - CMS: $\delta\sigma = 0.09 \times \sigma_{SM}$
  - ATLAS: $\delta\sigma = 0.17 \times \sigma_{SM}$
- Electron collider projections
  - $\delta\sigma = 0.01 \times \sigma_{SM}$

Sensitivity

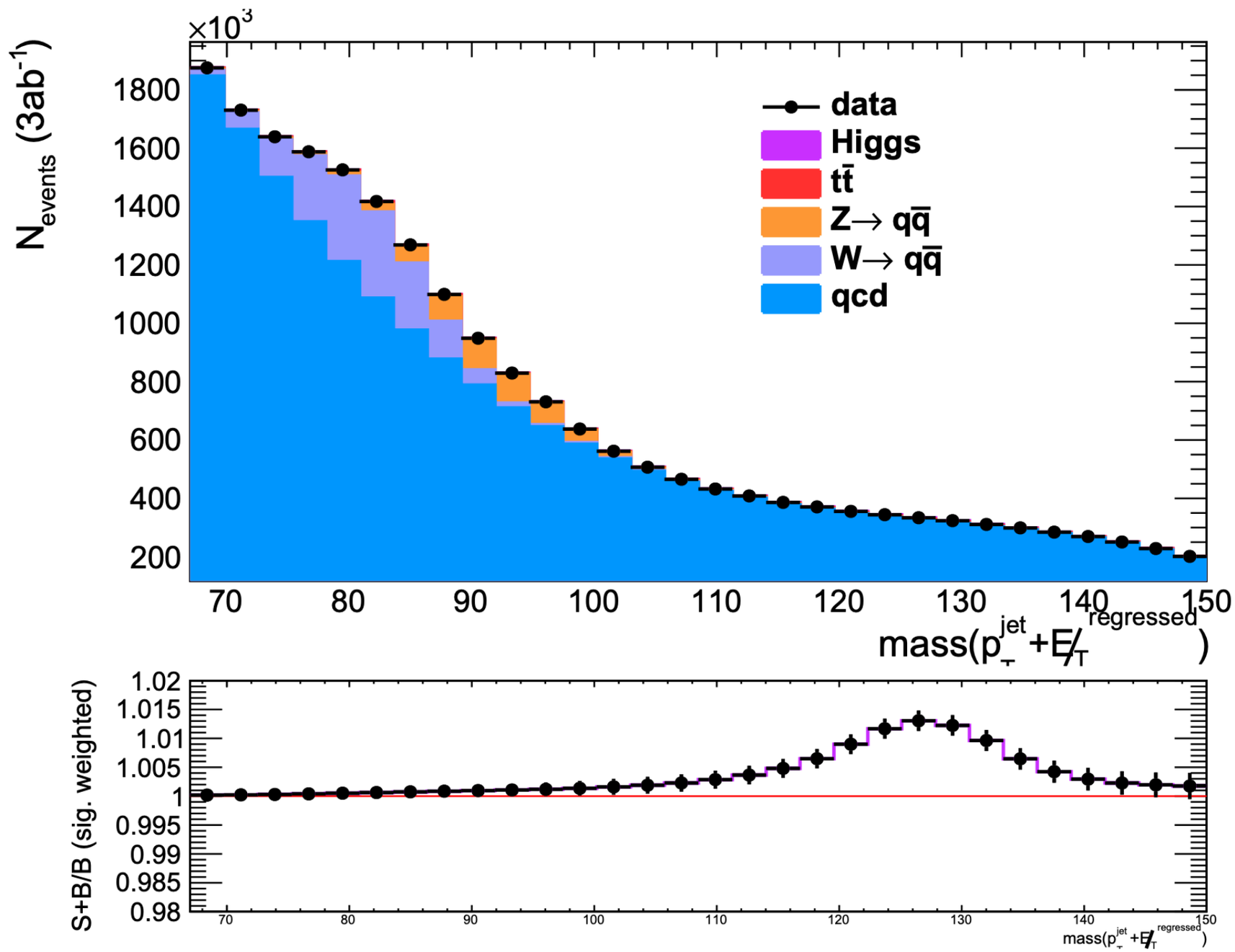
τ_{21}^{DDT}

- τ_{21}^{DDT}

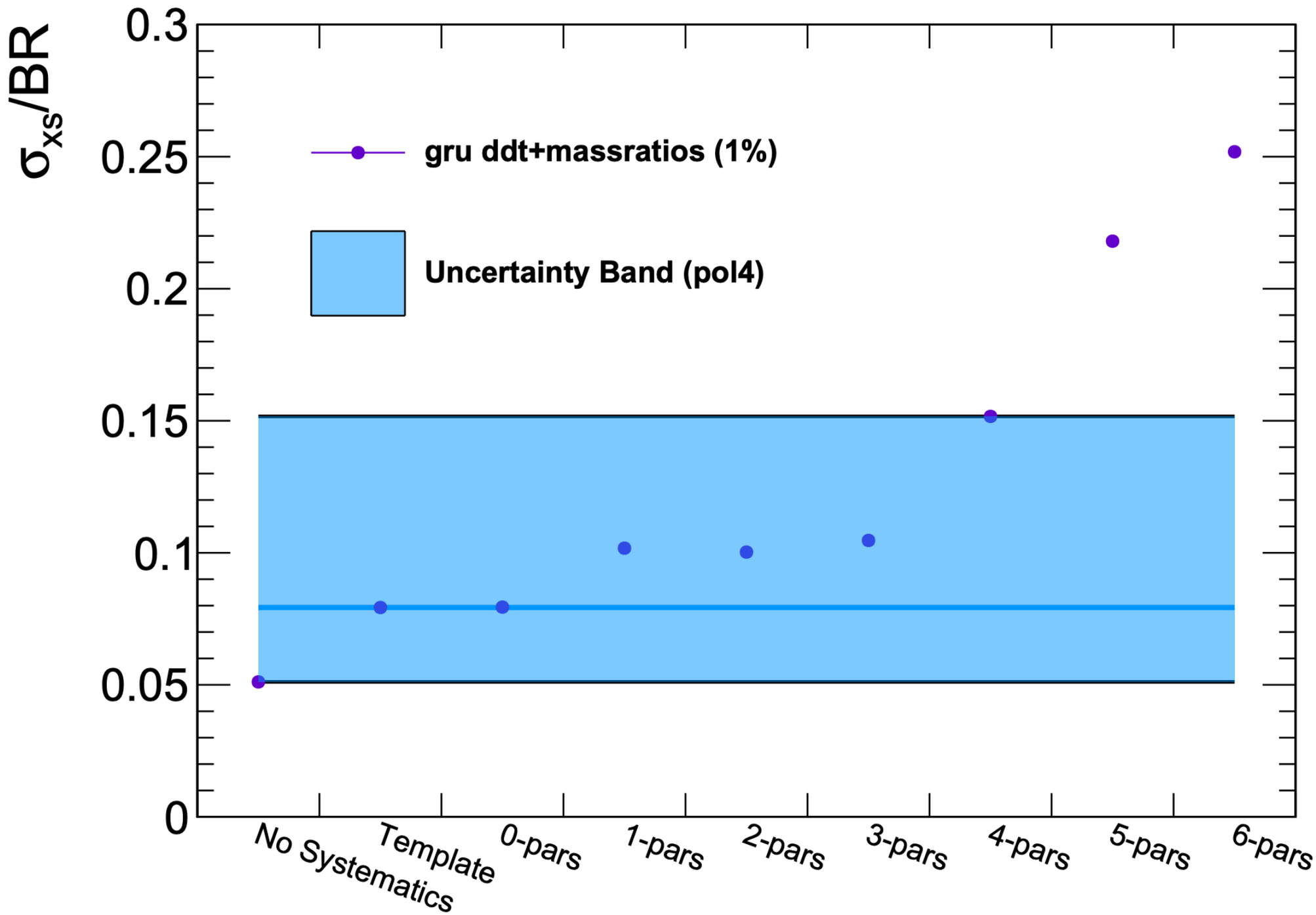


Sensitivity
GRU^{DDT}+Mass DNN^{DDT}

- GRU^{DDT}+Mass DNN^{DDT} (1%)

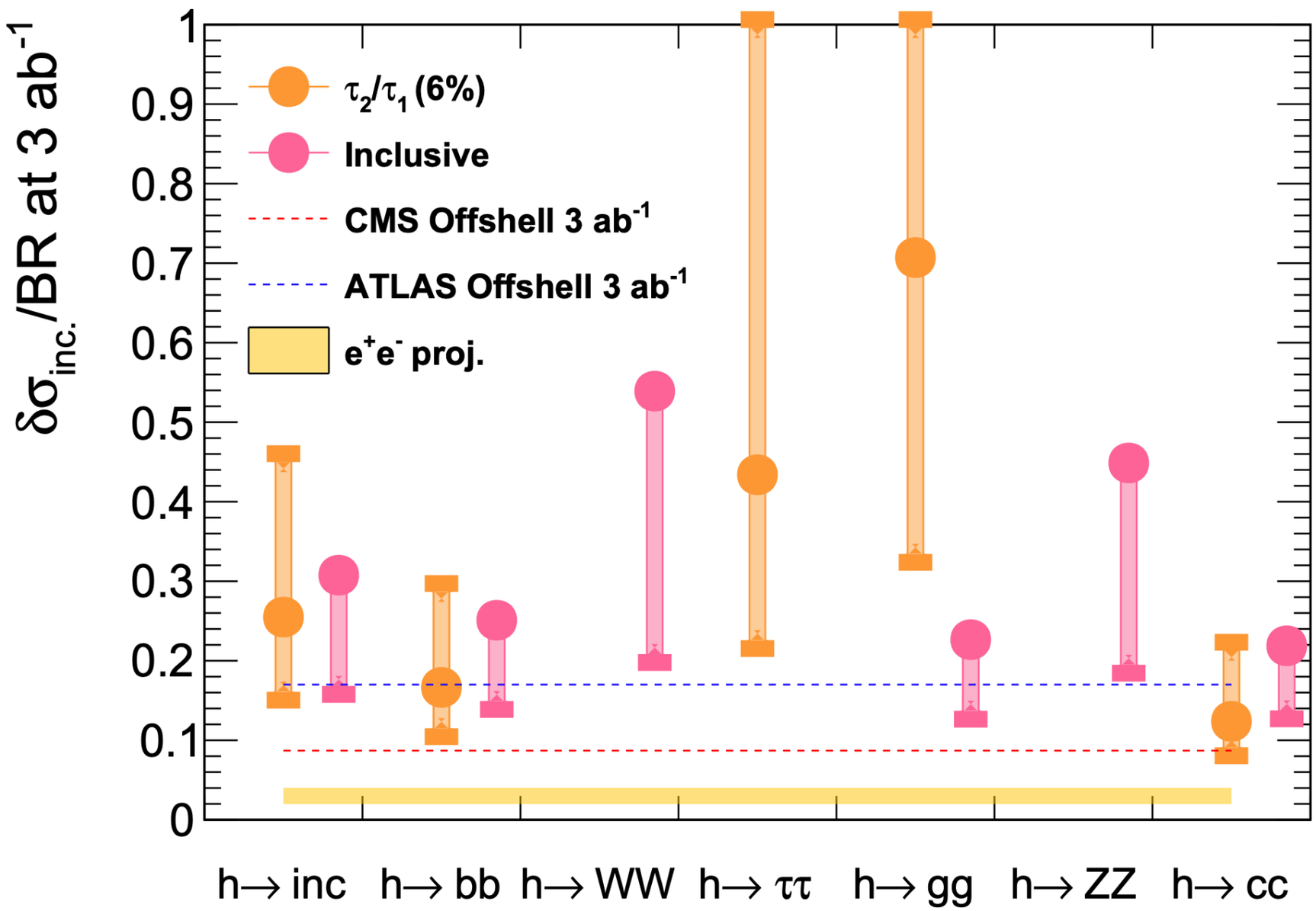


Fit Uncertainty



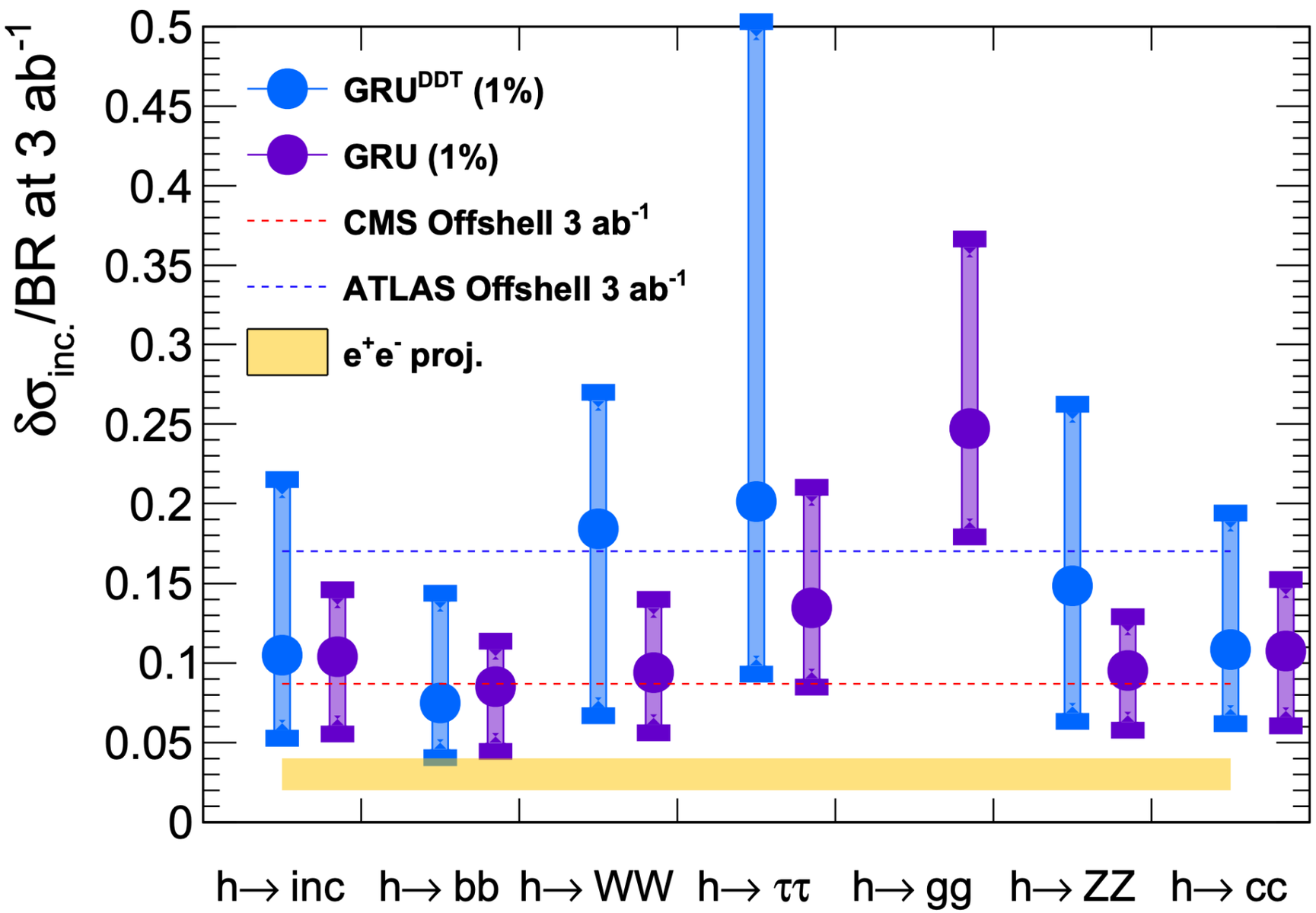
Results - Baseline

- Inclusive fits do not converge



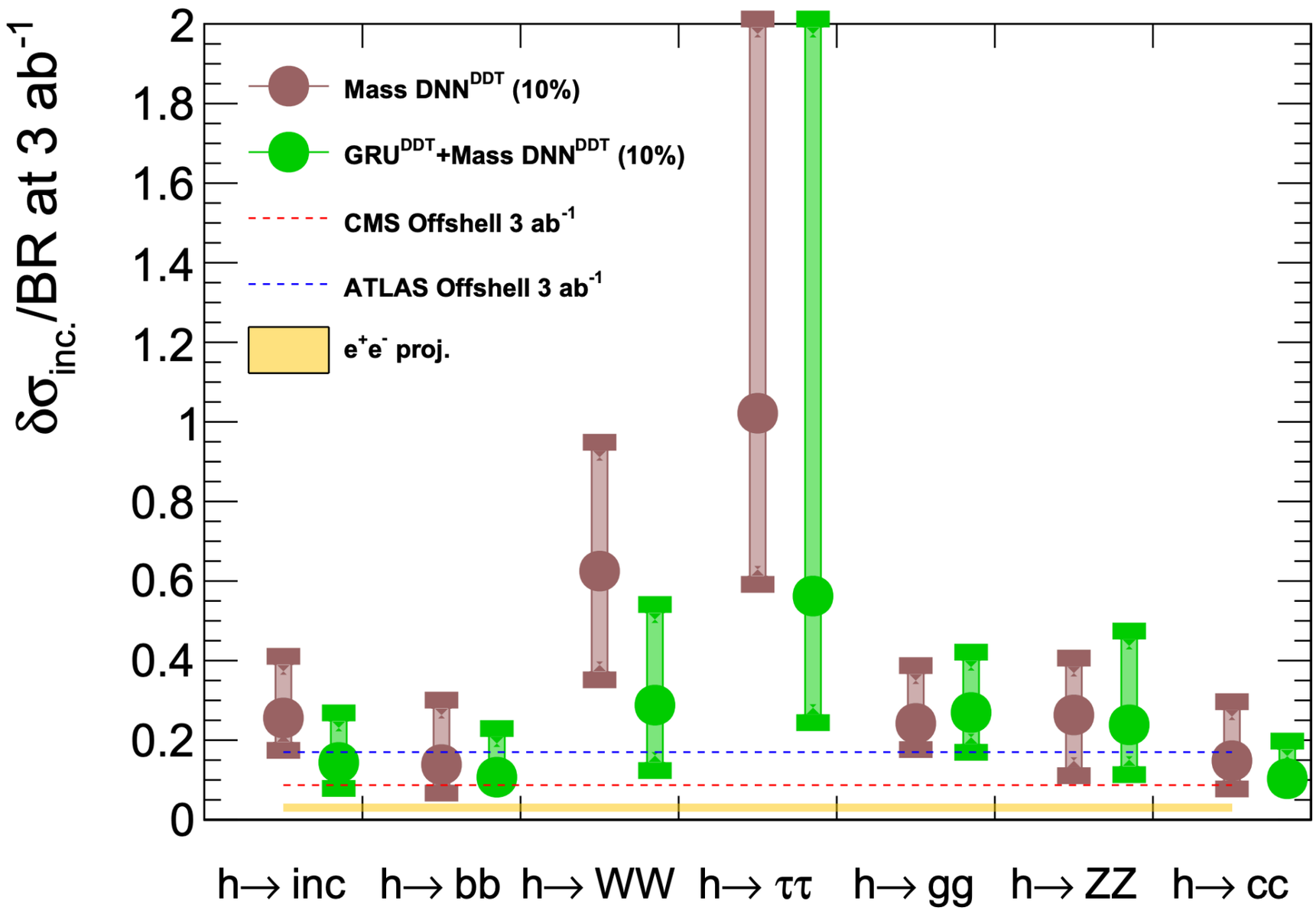
Results - GRU

- GRU has significant mass sculpting, fit is problematic



Results - GRU+DNN 10%

- Loose GRU + DNN (10%) able to select h→gg decays



Results - GRU+DNN 1%

- Tight GRU + DNN (1%) is good overall : **benchmark**