Constraining the Higgs Width @ HL-LHC

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(paper in preparation)

BOOST 2019

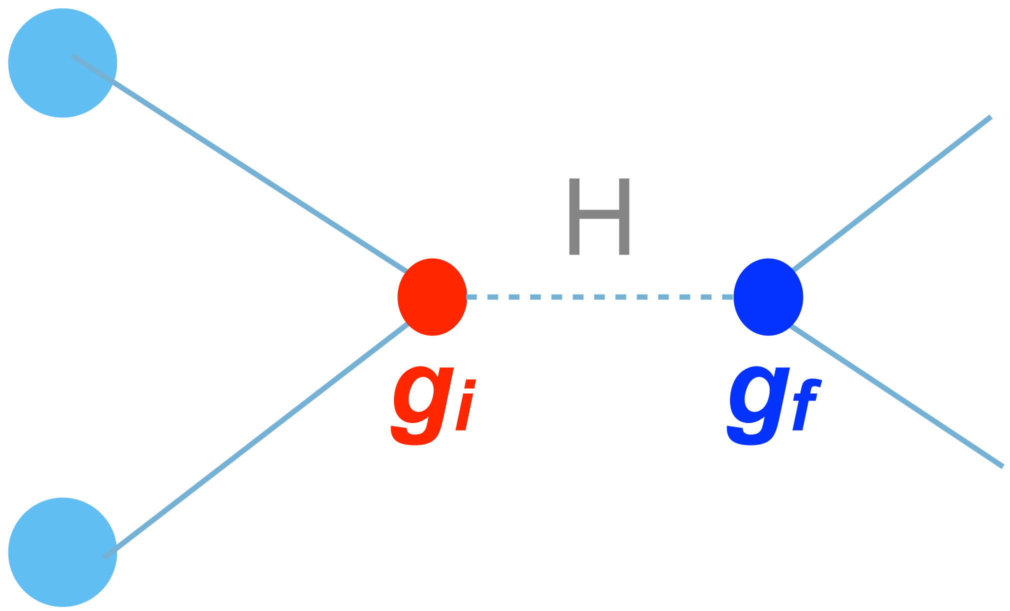
Overview

- Higgs Width: constraints and future prospects
- Proposal to constrain Γ_H
  - Higgs tagging
  - Measurement strategy
  - Projections @ 3000fb^{-1} HL-LHC

This is only a proof of concept

The Higgs Width: Γ_H

* Γ_{SM} = 4.2 MeV
* Total cross section depends on coupling strengths in production g_i and decay g_f stages, and width Γ_H



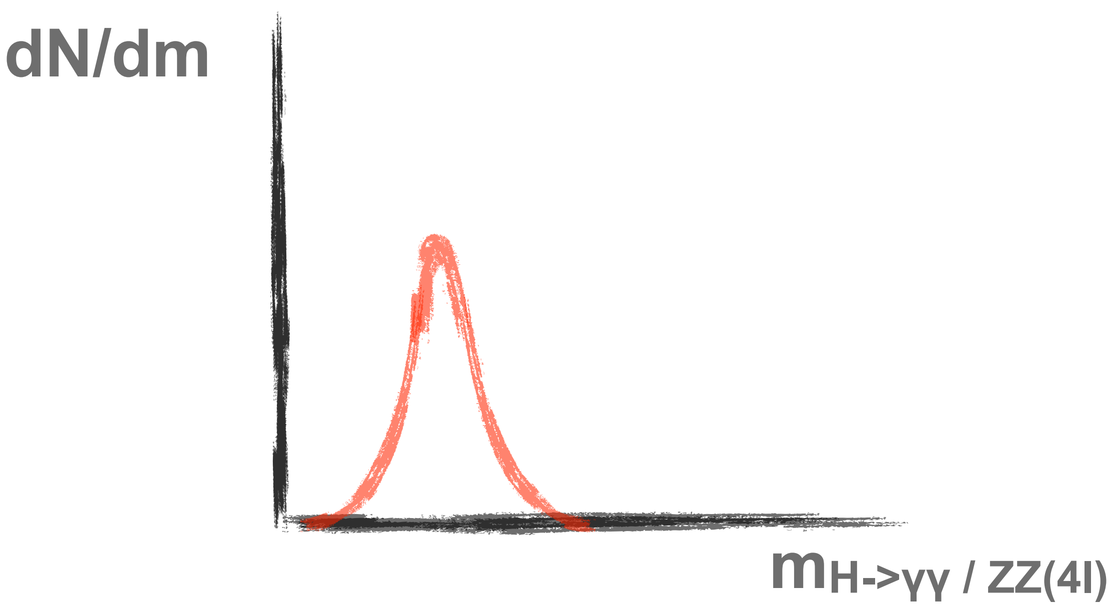
$$\sigma_{i \to H \to f} \sim \frac{g_i^2\, g_f^2}{\Gamma_H}$$ x m_H (if on-shell)

* How to extract Γ_H from an inclusive cross section measurement?

Γ_H @ LHC

Peak width:

$h \to \gamma\gamma/ZZ$

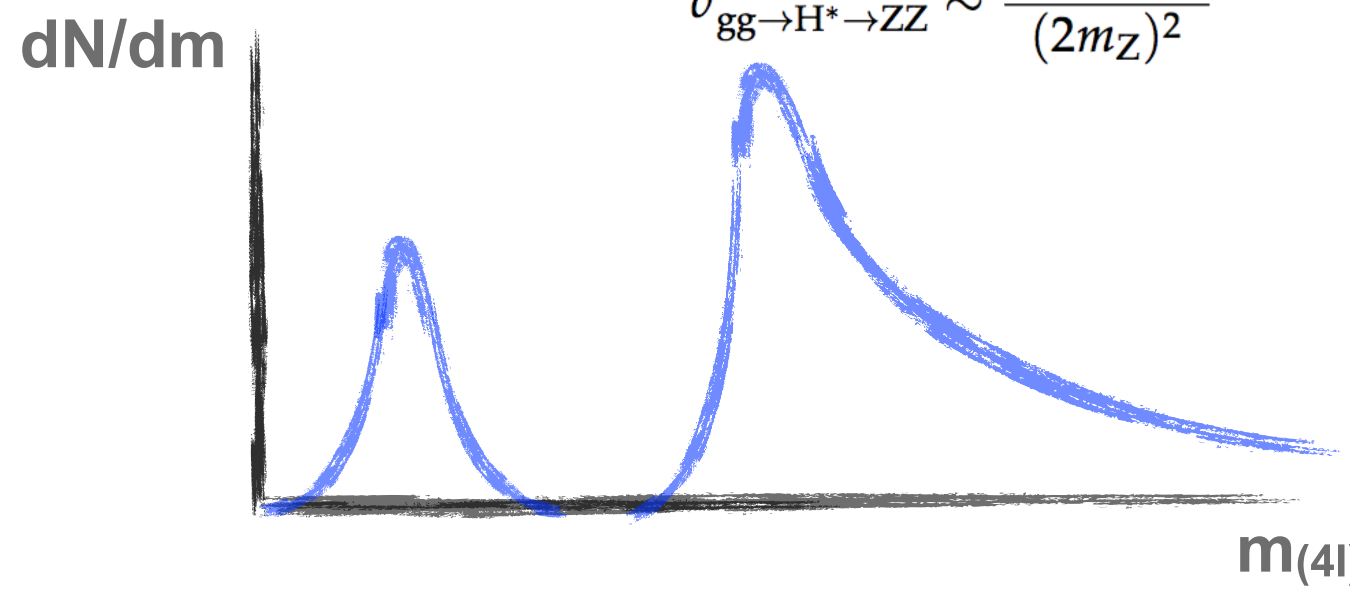


limited by detector res.

* $\Gamma_H < 1.1$ GeV (**$270\times\Gamma_{SM}$**)

On-shell/off-shell:

$$\mu = \frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}}$$



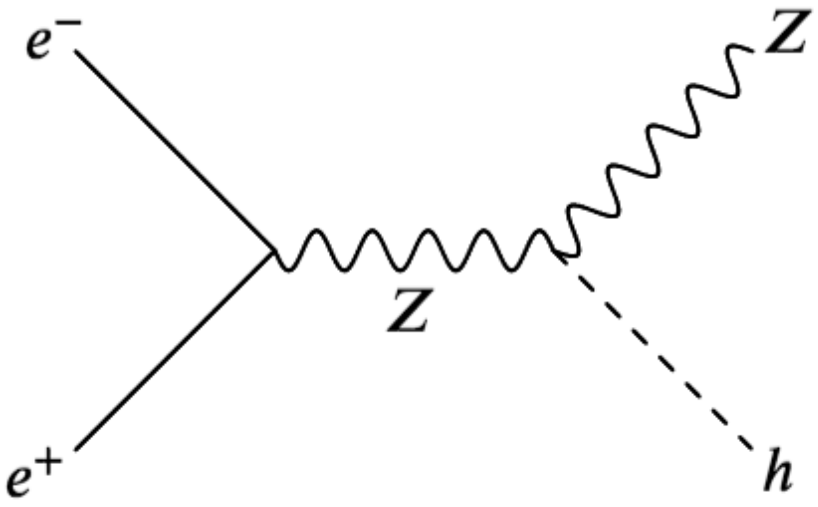
assume: $g^2_{ggH}g^2_{HZZ}{}^{(\text{on-shell})} = g^2_{ggH}g^2_{HZZ}{}^{(\text{off-shell})}$

* $\Gamma_H < 9.1$ MeV (**$2.2\times\Gamma_{SM}$**)

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

Γ_H @ Future Colliders

* Muon collider: great resolution $\delta\Gamma_H/\Gamma_{SM} \approx 0.05$
* Electron collider (e.g. ILC $\delta\Gamma_H/\Gamma_{SM} \approx 0.1$):



1. Measure Zh cross section from recoil mass.

$$\sigma(e^+e^- \to Zh) \propto g^2_{hZZ}$$

Γ_H @ Future Colliders

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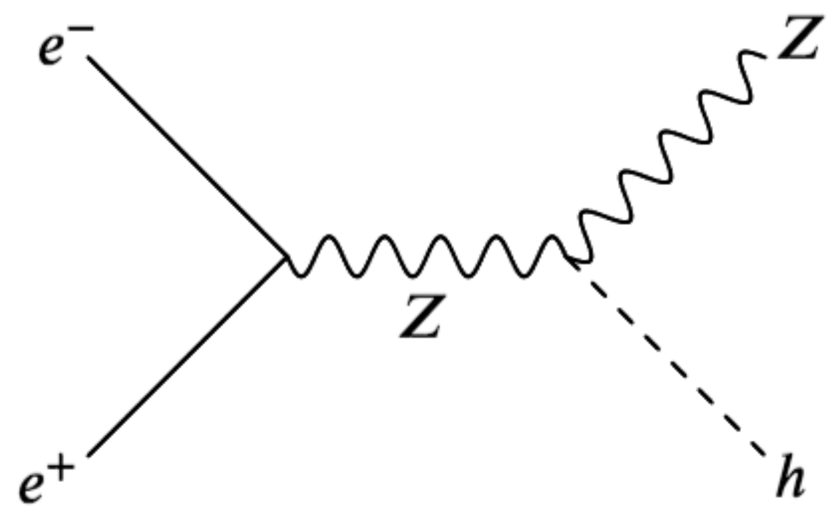


1. Measure Zh cross section from recoil mass.

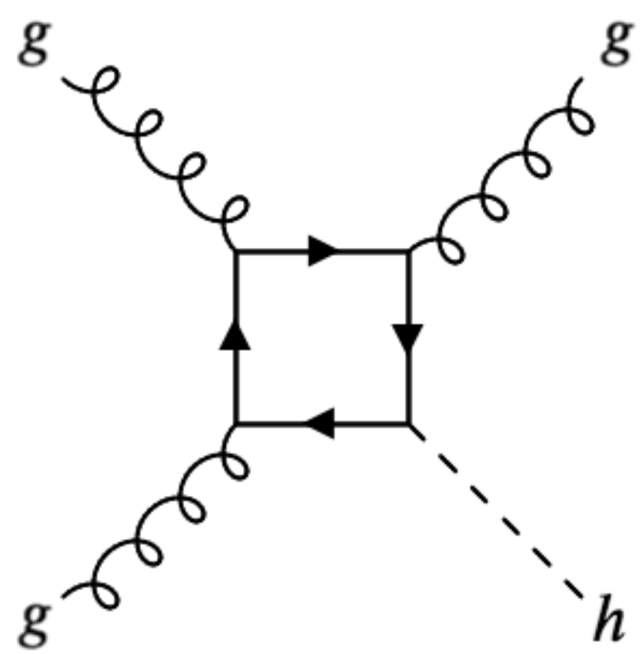
$$\sigma(e^+e^- \to Zh) \propto g^2_{hZZ}$$

2. Measure h→ZZ decay

$$\sigma_{Zh\to XX} \propto \frac{g^2_{hZZ}\, g^2_{XX}}{\Gamma_h} \longrightarrow \Gamma_h \propto \frac{g^4_{hZZ}}{\sigma_{Zh\to ZZ}}$$

Γ_H with boosted Higgs

* Similar way but now use Higgs+1jet:



1. Measure inclusive cross section from reconstructed m_h
2. Use existing measurements to constrain Γ_H:
   1. boosted h → bb
   2. W+h → bb
   3. W+h → WW

Γ_H with boosted Higgs

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

* See full math in backup

Γ_H with boosted Higgs

δσ/σ_{SM} = 0.09

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

δσ/σ_{SM} = 0.05

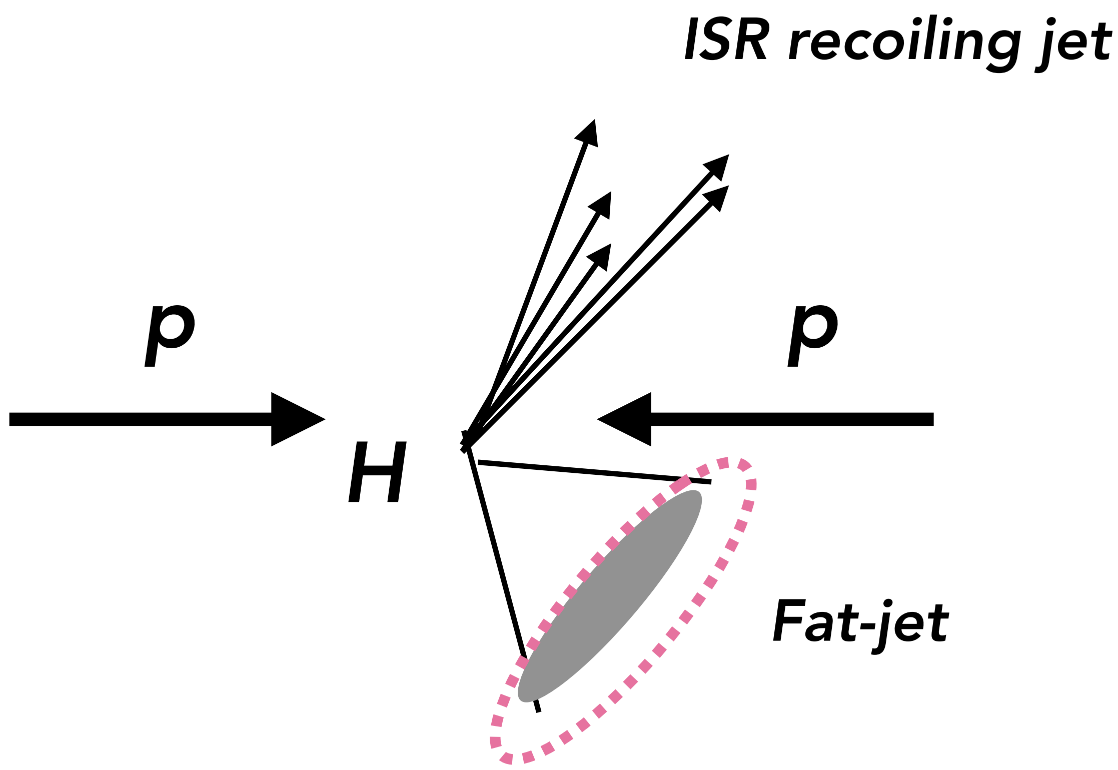
δσ/σ_{SM} = 0.25 **δ**$\sigma_{(gg=>h)}$

Γ_H with boosted Higgs

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

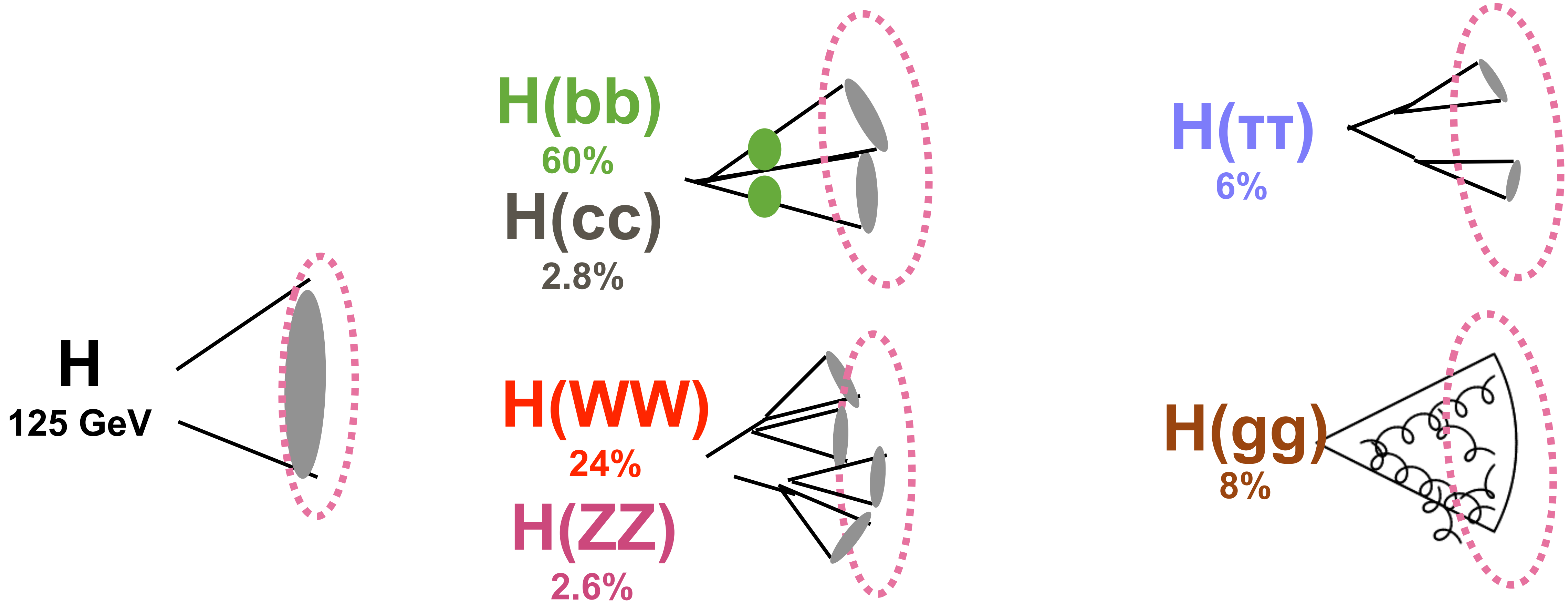
This talk is going to focus on how to measure this

Higgs + 1 jet topology



1. Assume LHC can trigger on jet p_T> 400 GeV
2. Tag Higgs jet for all decays
3. Fit Higgs mass

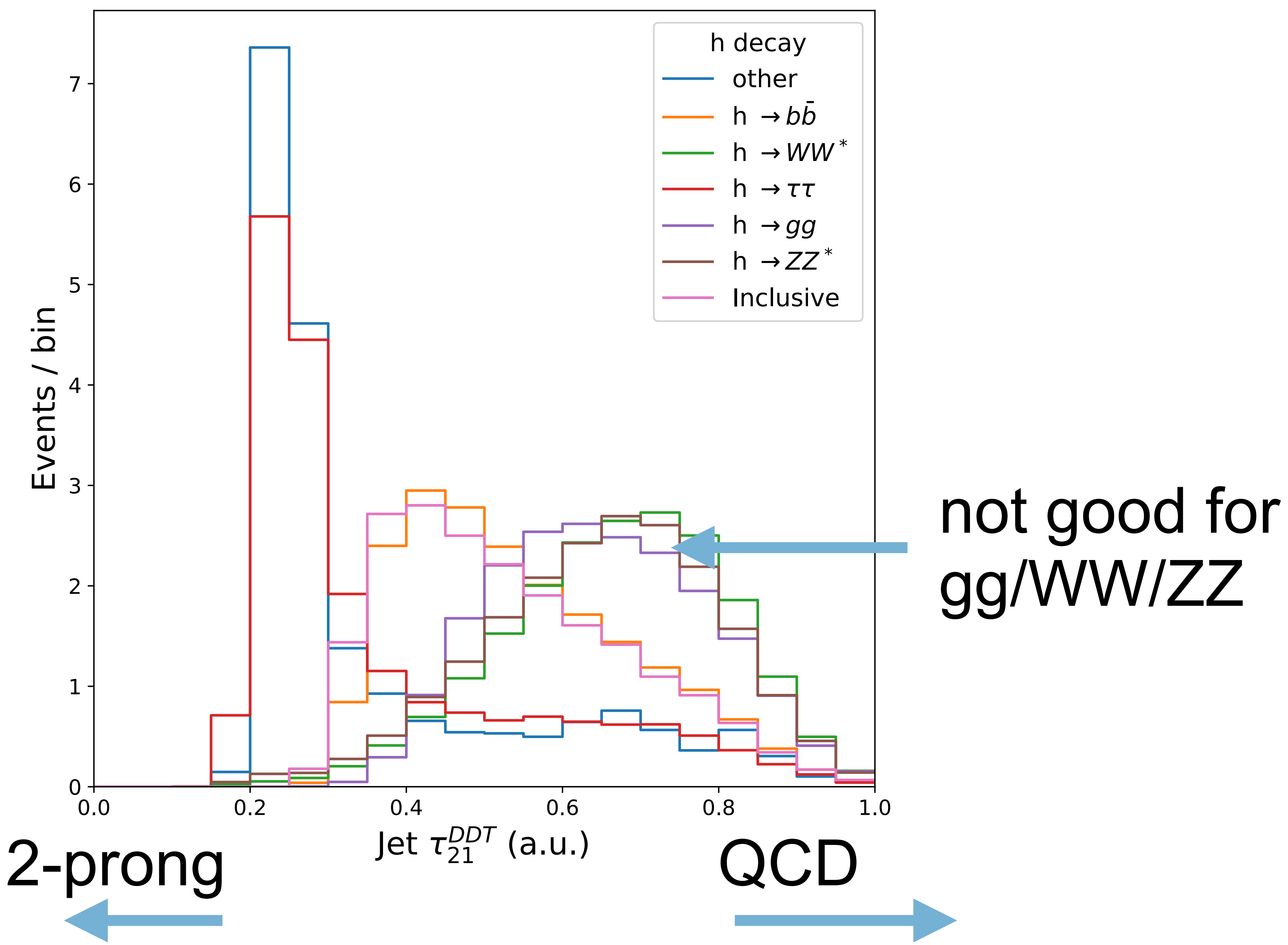
Higgs tagging



- Assume decay products fall within jet cone
- Focus on tagging visible Higgs decays
- Will discuss H=>gg and semi-visible/invisible decays later

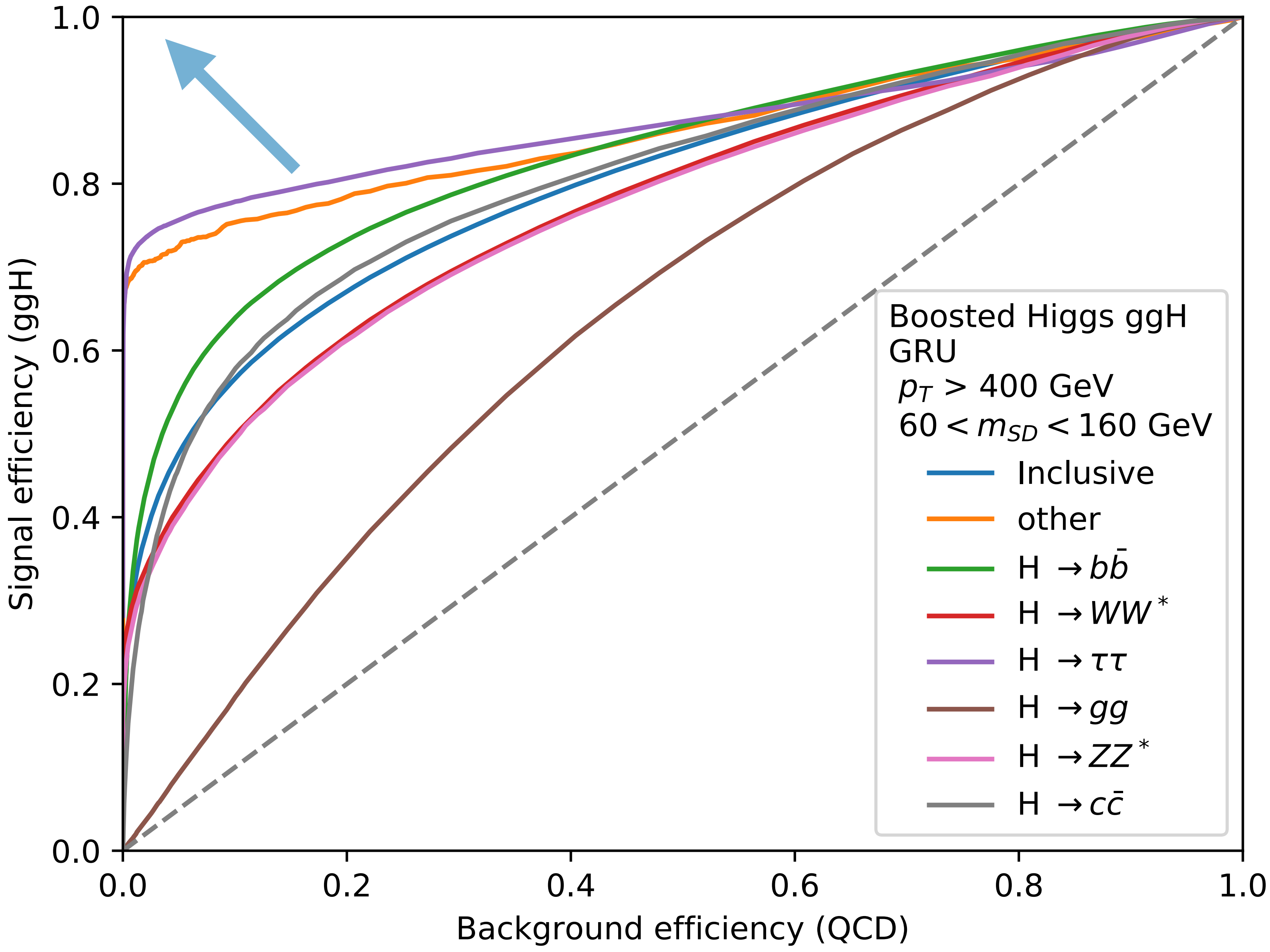
Jet substructure for Higgs

* Two-object symmetric decay for Higgs: τ_{21}?



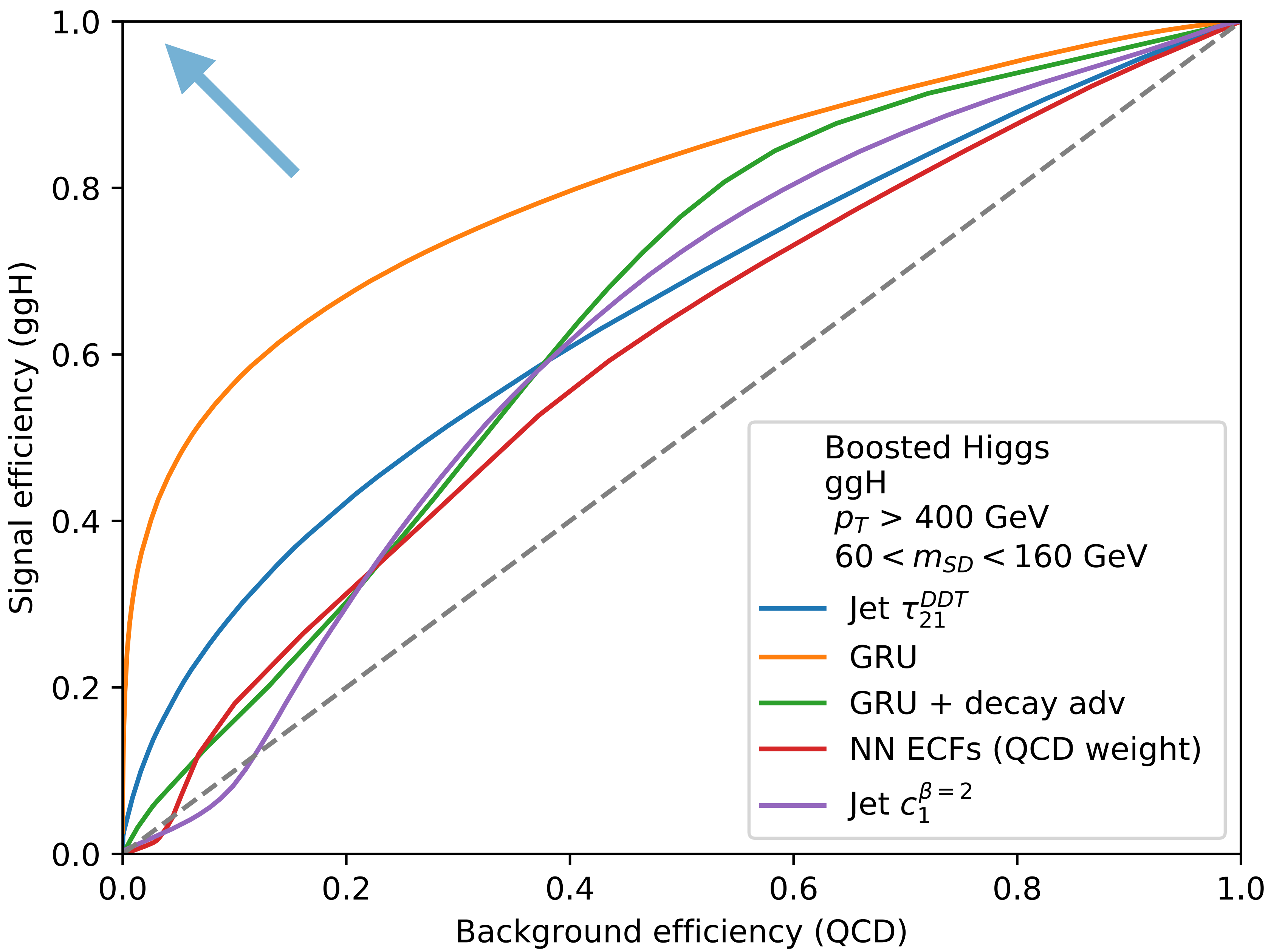
Simple RNN of particles

* Take 4-momenta + particle-ID of **jet constituents** (up to first 20 - ordered by p_T)
* Recurrent fully-supervised (GRU) + classifier layers



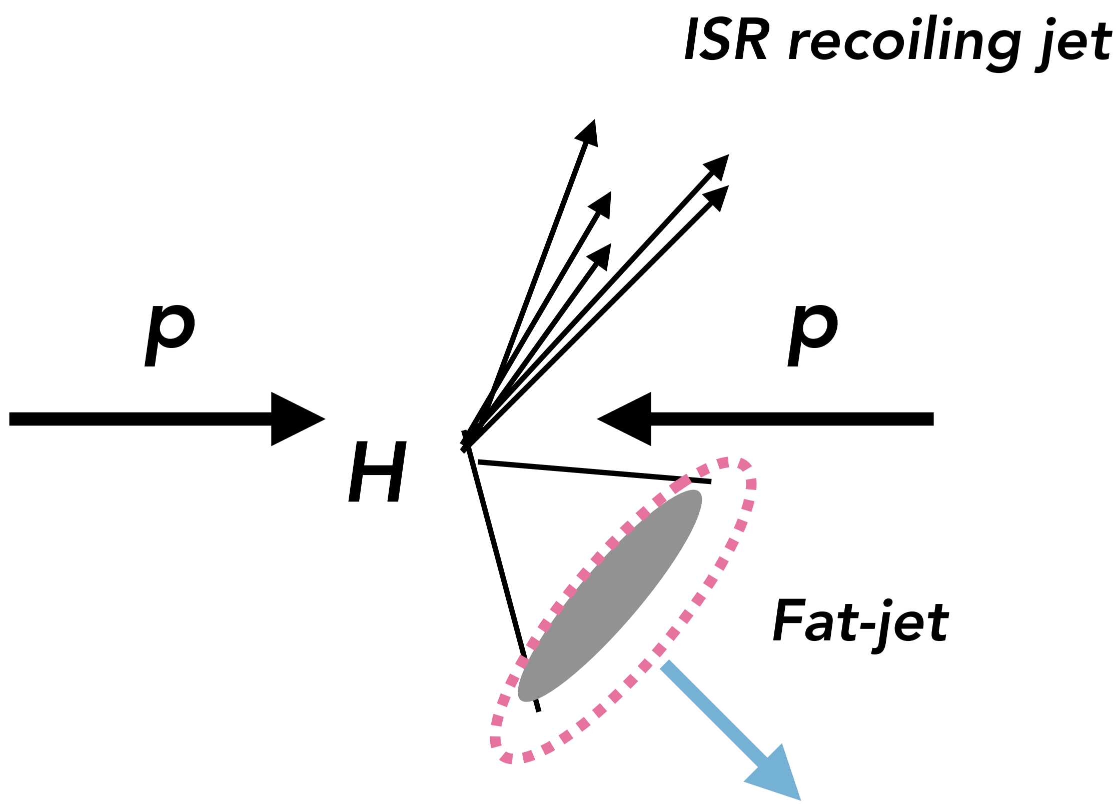
Higgs inclusive performance

* For h=>anything **GRU** has the best performance
* Use **jet τ_{21}** as a reference.



Higgs mass

- Next step is to select Higgs jet and fit mass

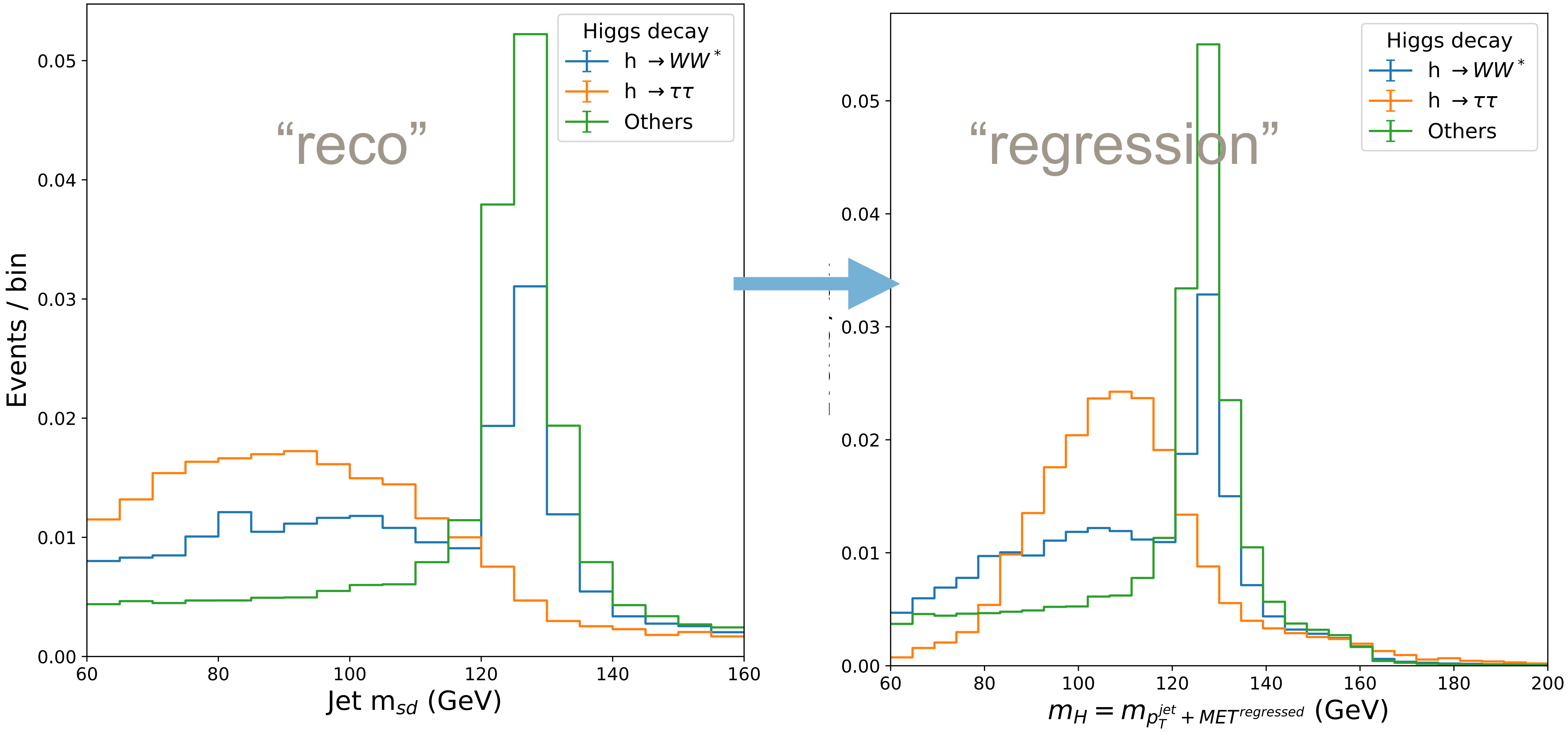


- Visible decays: Higgs can be leading p_T jet in the event
- invisible decays: neutrino will take away energy

- Take leading jet on (jet+neutrino).p_T instead.

Higgs mass

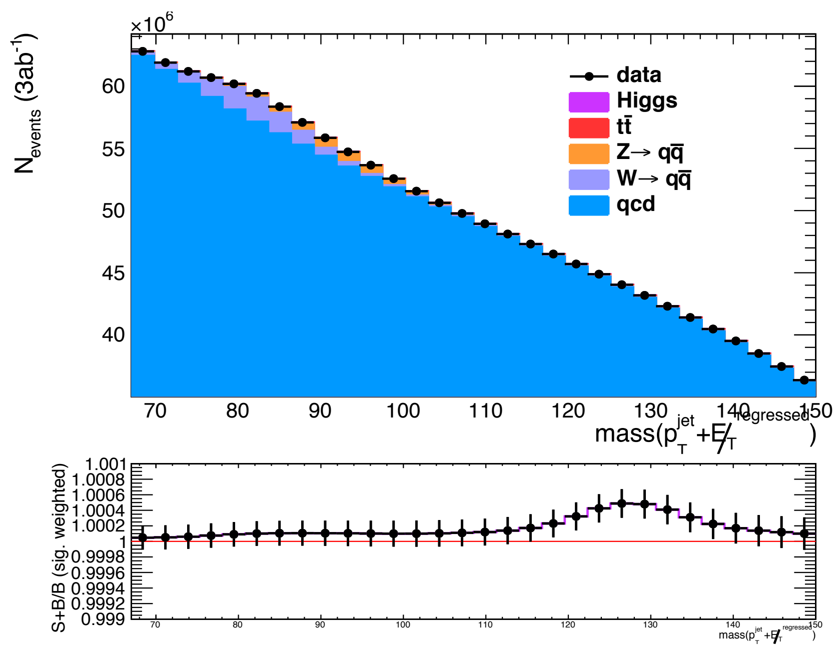
- Reconstruct Higgs mass as: **(jet+neutrino).M()**
  - Here "neutrino" = rough MET reconstruction
  - Assume same direction as jet *(take jet η/φ)*
  - MET Regression improves slightly signal resolution



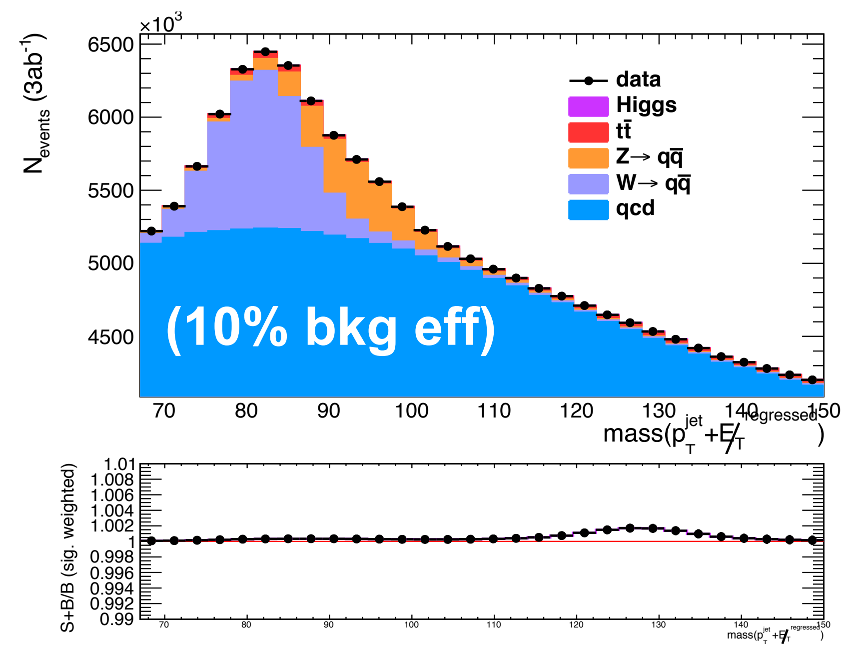
Fitting Higgs mass

- Fitting reconstructed mass in **bins of p_T**: [400-450],[450-500],[500-550],[550-inf]
- Consider 4 scenarios:

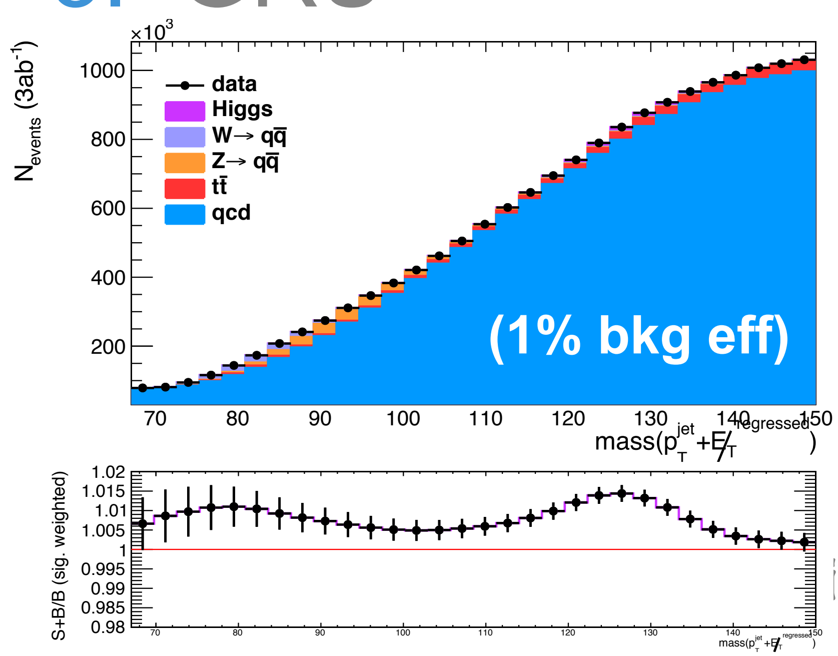
1. Just mass



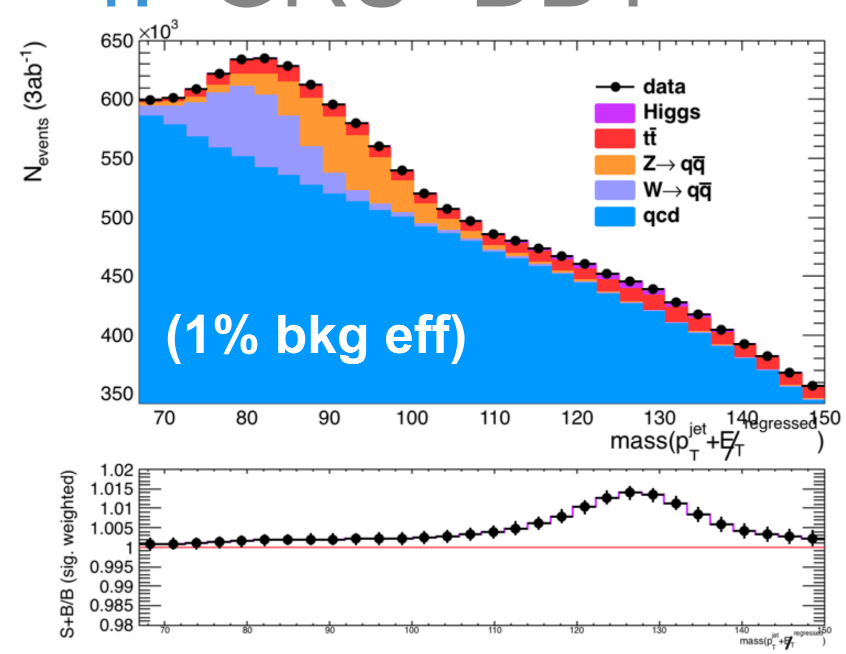
2. τ21 selection



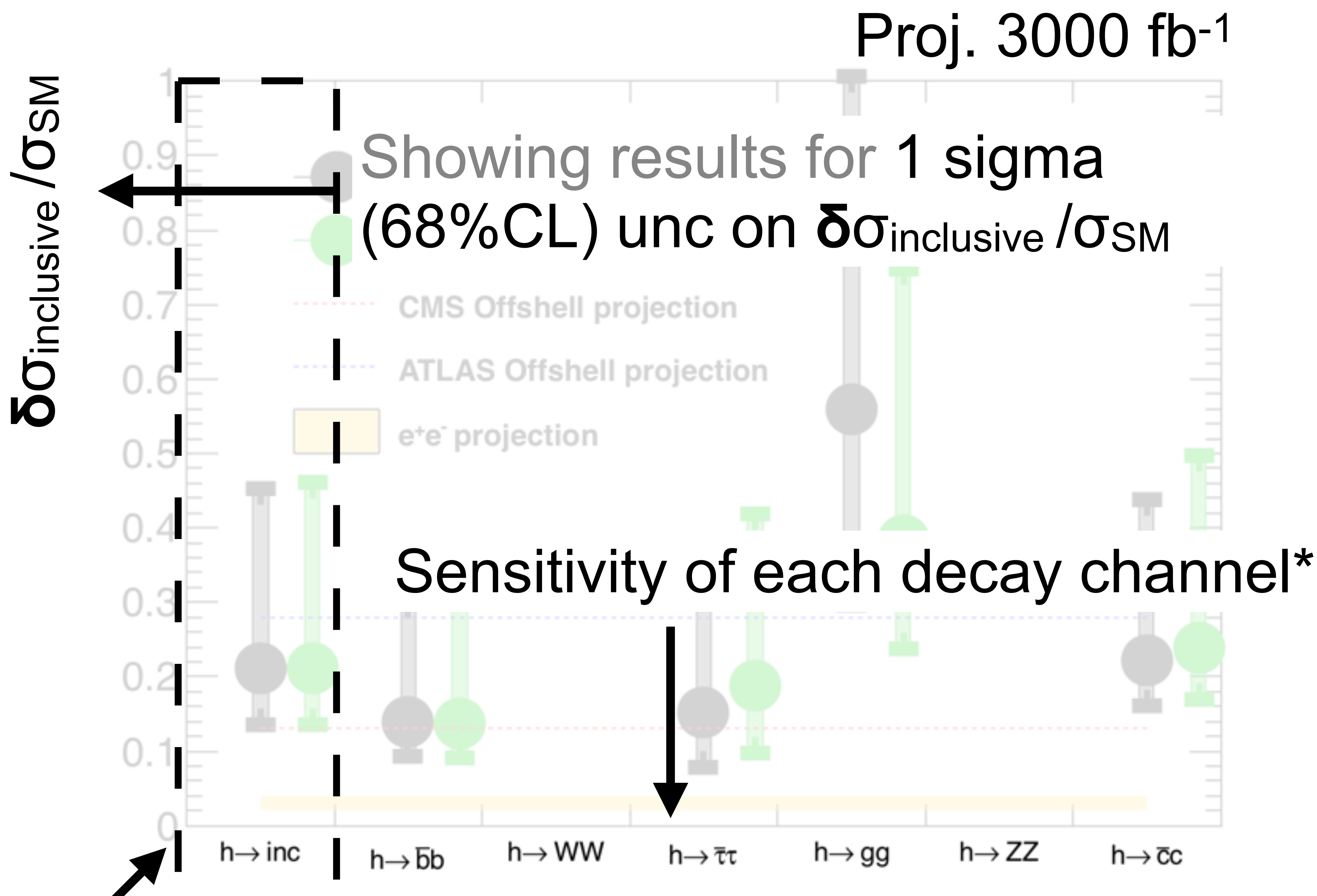
3. GRU



4. GRU+DDT



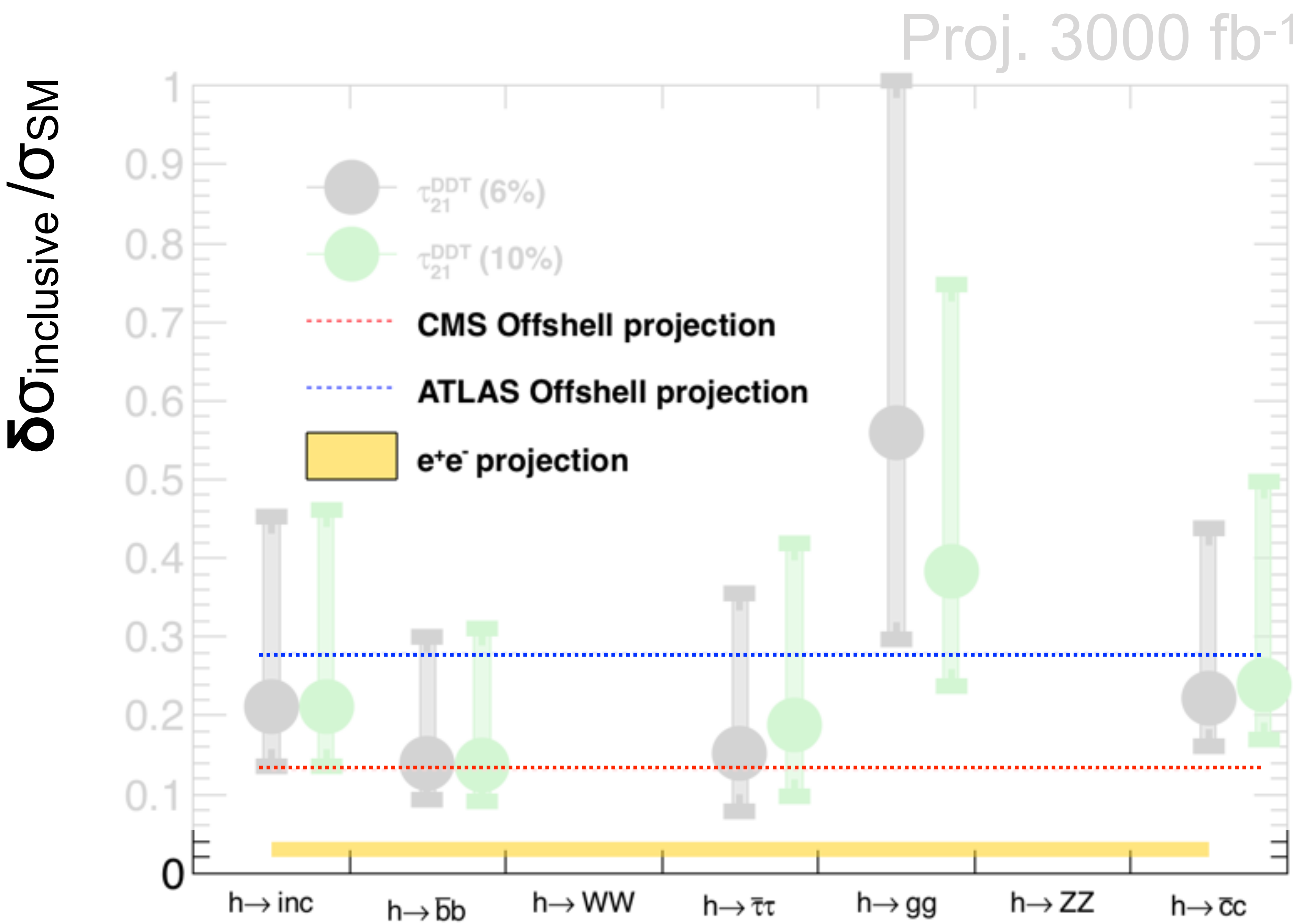
What the next plots show



Inclusive cross section

*(i.e. for each decay channel show with $\delta(\sigma_{xs}/(\sigma_{SM}*BR))=\delta\mu/BR$ with $\mu = \sigma_{xs}/\sigma_{SM}$)

What the next plots show



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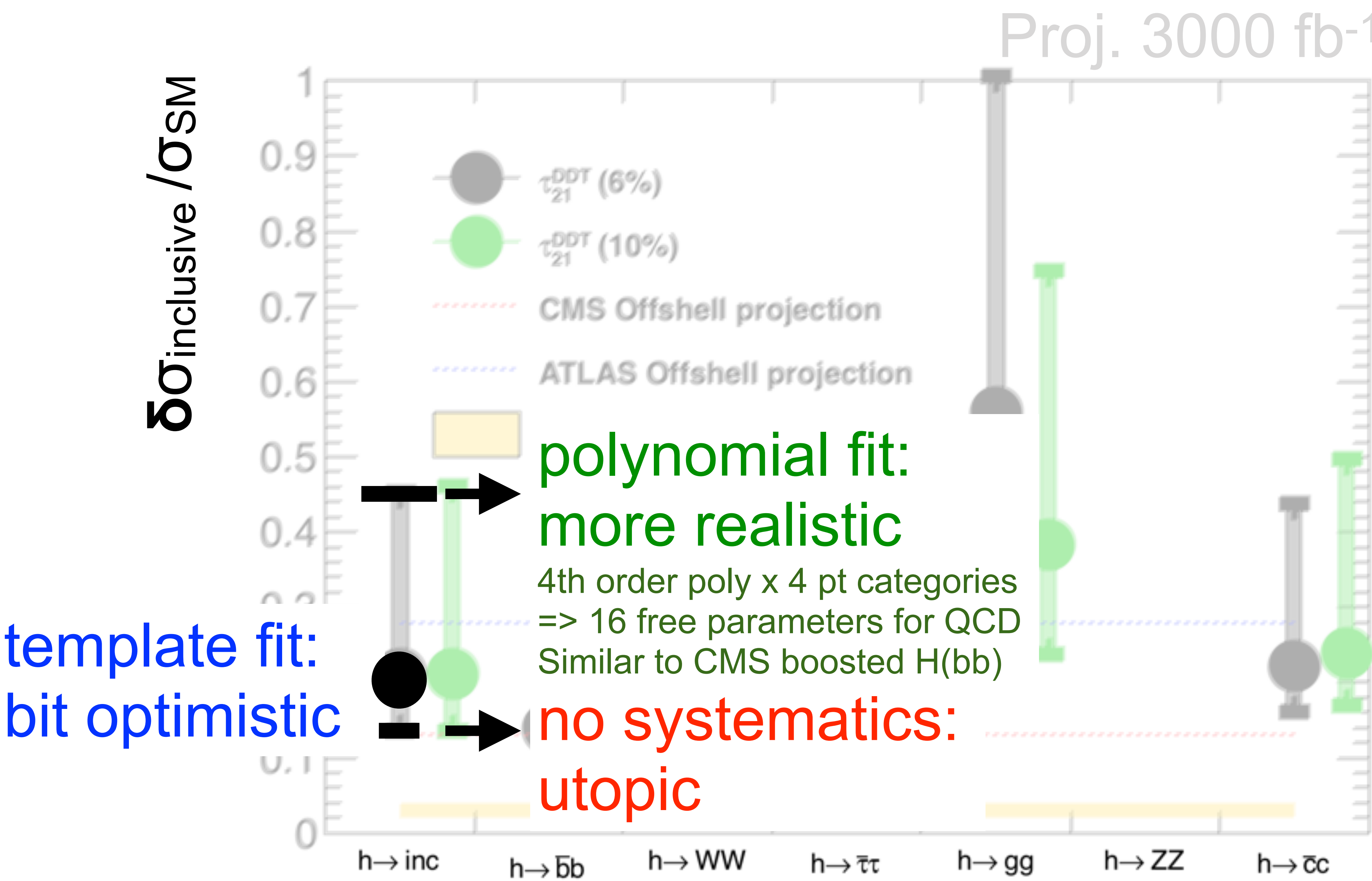
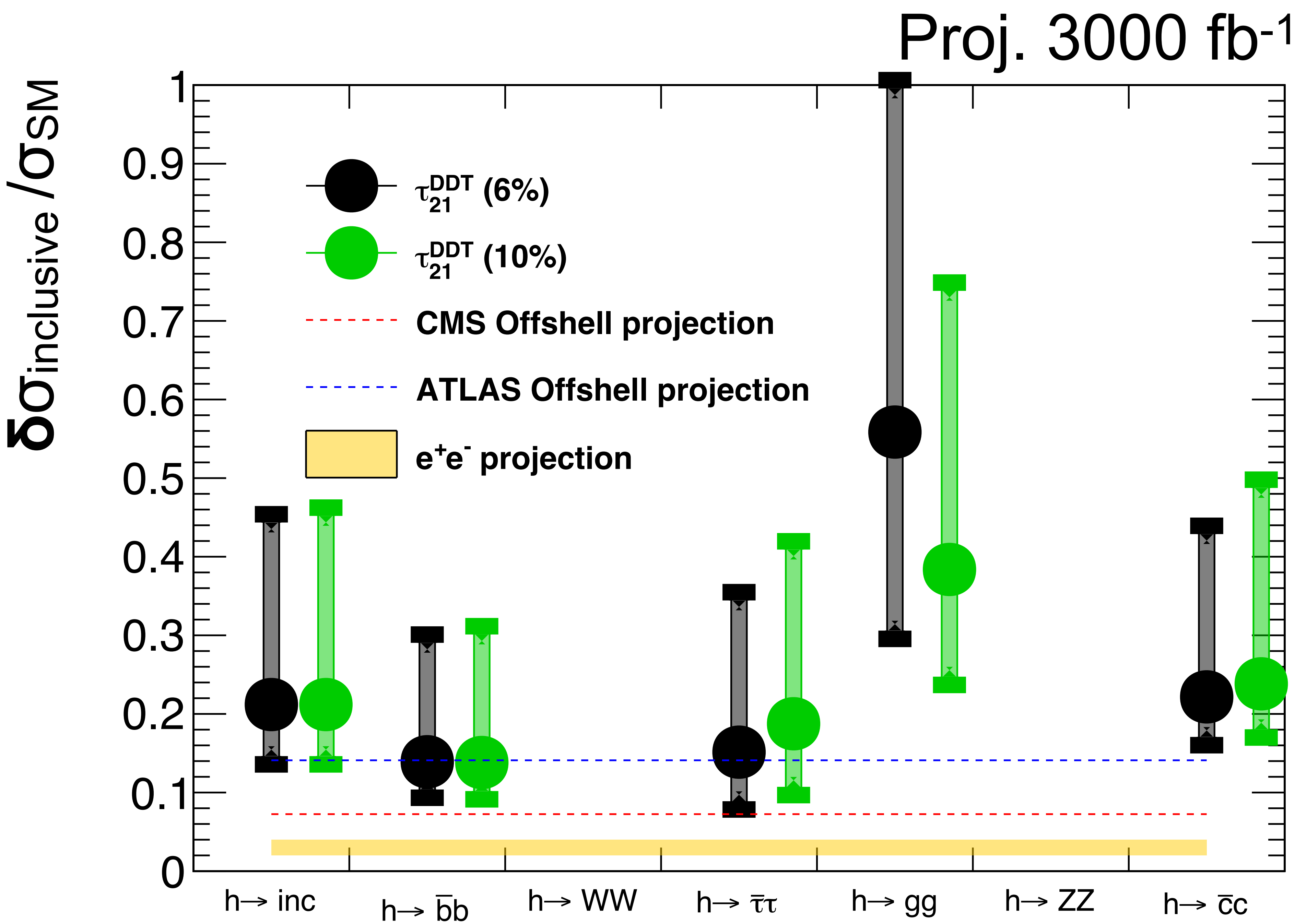


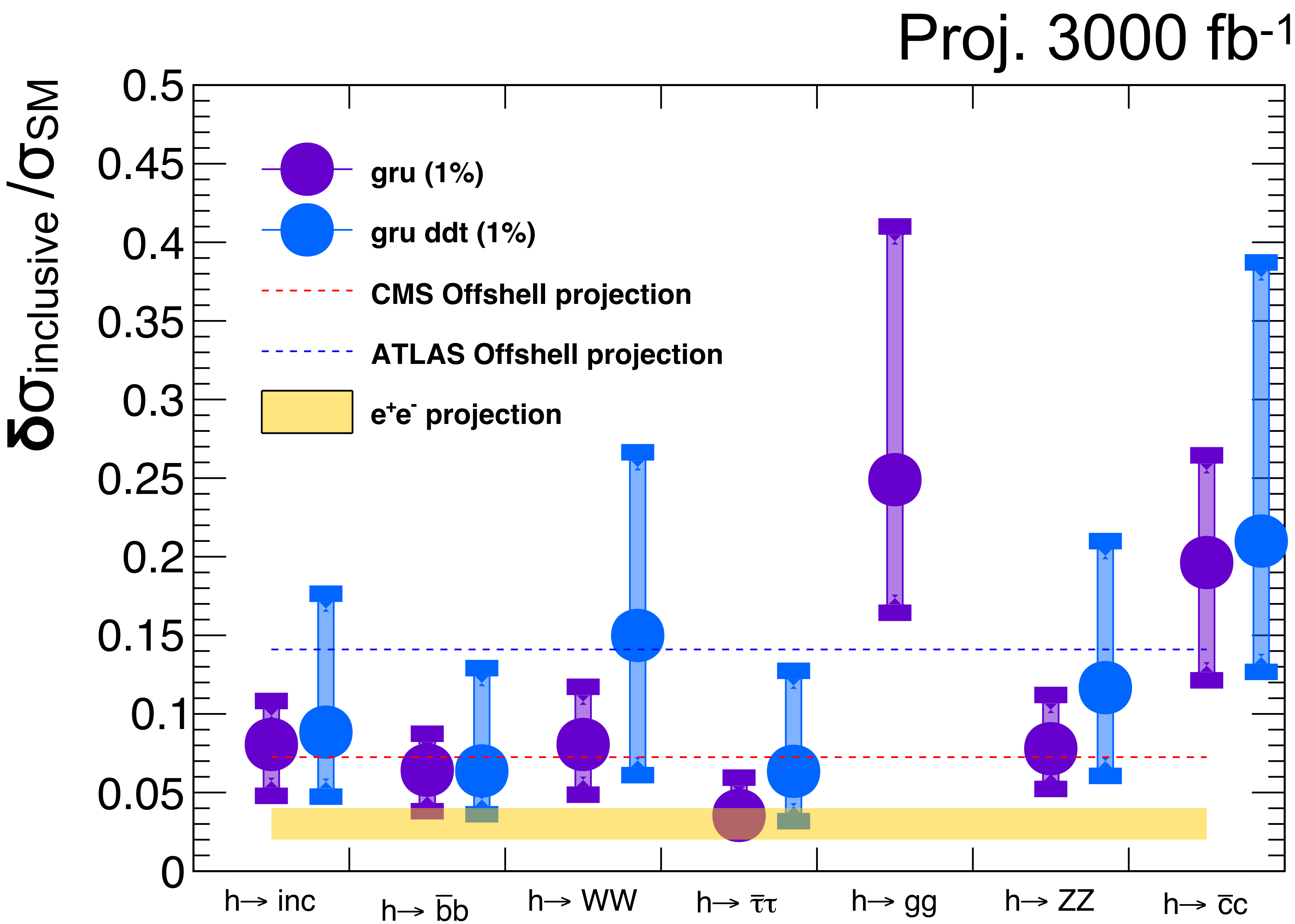
*(i.e. for each decay channel show with $\delta(\sigma_{xs}/(\sigma_{SM}*BR))$ with $\mu = \sigma_{xs}/\sigma_{SM}$)

Tau21



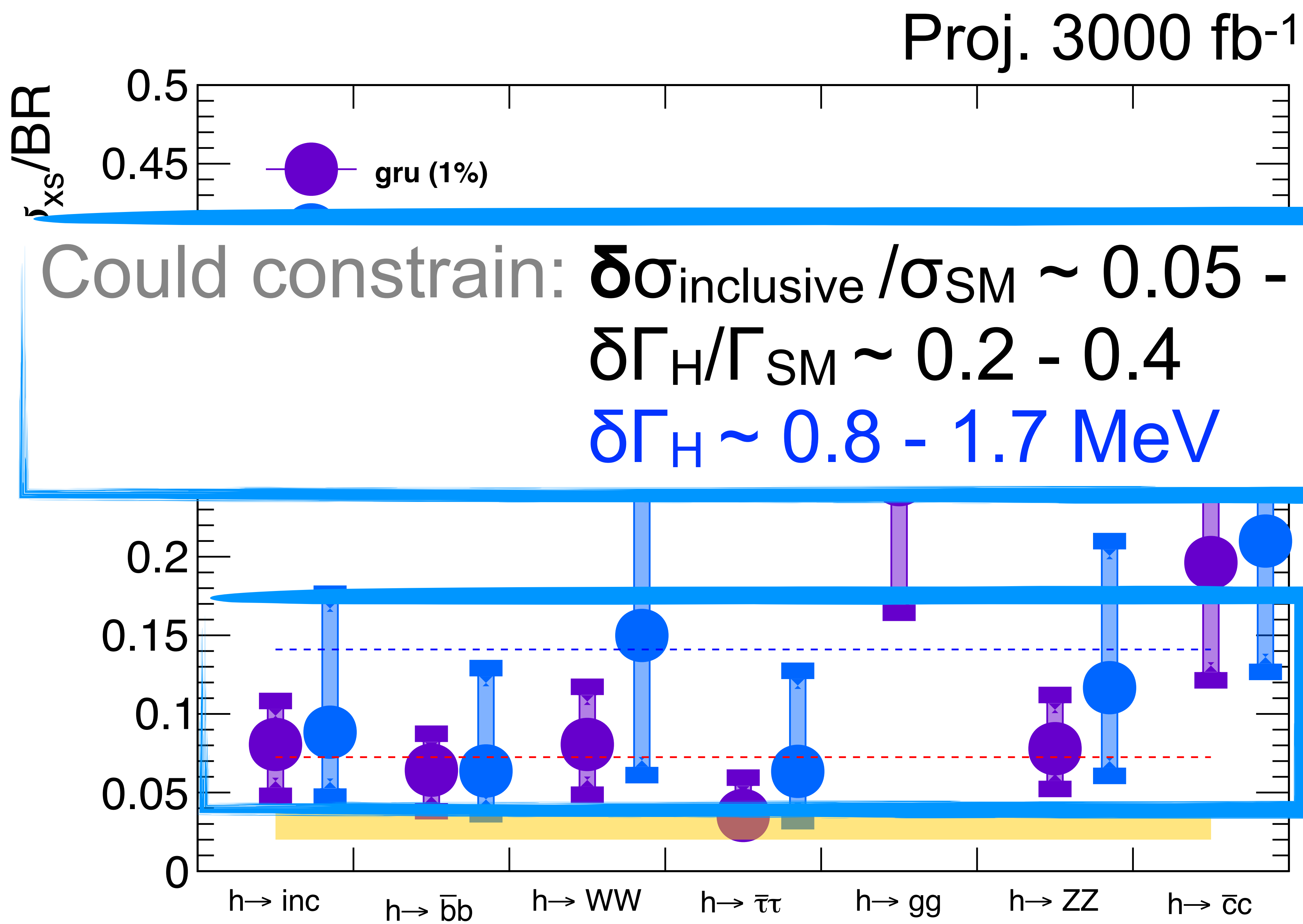
- Zooming in (h → WW/ZZ limit is around 3.)

GRU + GRU DDT



* Un-decorrelated version **(GRU)** is MUCH more challenging (really hard to fit sculpted shape of QCD)

GRU + GRU DDT



Could constrain: $\delta\sigma_{inclusive} / \sigma_{SM} \sim 0.05 - 0.17$

$\delta\Gamma_H / \Gamma_{SM} \sim 0.2 - 0.4$

$\delta\Gamma_H \sim 0.8 - 1.7$ MeV

Discussion

* This is only a **proof of concept** assuming Lorentz invariance
* Where can model dependence come in?
    * h=>gluons/h=>BSM that looks like bkg.: are the real challenge
    * h=>semi-visible decays:
        * Strategy for h(tau-tau/WW) works well => can be improved
    * h=>invisible & h=> long lived decays
        * Bounded by h->invisible (4% in VBF)
* Signal efficiency measurement is an open question

Summary

- Proposal to **measure inclusive Higgs at high-pT @ LHC**
- Could **constrain Γ_H at level comparable to on-shell/off-shell** measurements ($\delta\Gamma_H$ ~0.8-2 MeV)
- Hope to initiate discussion on: boosted H(gg) tagging/ how to recover invisible/semi-visible H decays

More material

Γ_H with boosted Higgs

1. Measure $\sigma(gg \to h) \propto g_{gg}^2$ from reconstructed h mass.
2. Measure boosted h → bb $\quad \sigma(ggh \to \bar{b}b) \propto \frac{g_{gg}^2 g_{\bar{b}b}^2}{\Gamma_h}$
3. Measure W+h → bb $\quad \sigma(W+h \to \bar{b}b) \propto \frac{g_{WW}^2 g_{\bar{b}b}^2}{\Gamma_h}$

Take ratio: $\quad \frac{\sigma(W+h \to \bar{b}b)}{\sigma(ggh \to \bar{b}b)} \propto \frac{g_{WW}^2}{g_{gg}^2}$

$$\sigma(gg \to h) \times \frac{\sigma(W+h \to \bar{b}b)}{\sigma(ggh \to \bar{b}b)} \propto g_{WW}^2 \quad (*)$$

4. Measure W+h → WW $\quad \sigma(W+h \to WW) \propto \frac{g_{WW}^4}{\Gamma_h}$
5. Replace g_{WW} from (*)
6. Get total width:

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

Results & interpretation

- Projections @ **13 TeV / 3ab^{-1}**

$$\mu_\Gamma = \mu^2_{ggh} \frac{\mu^2_{Wh\to\bar{b}b}}{\mu^2_{ggh\to\bar{b}b}\mu_{W+h\to WW}}$$

$$\delta\mu^2_\Gamma = 4\delta\mu^2_{ggh} + \delta\mu^2_{W+h\to WW} + 4\delta\mu^2_{W+h\to bb} + 4\delta\mu^2_{ggh\to bb}$$

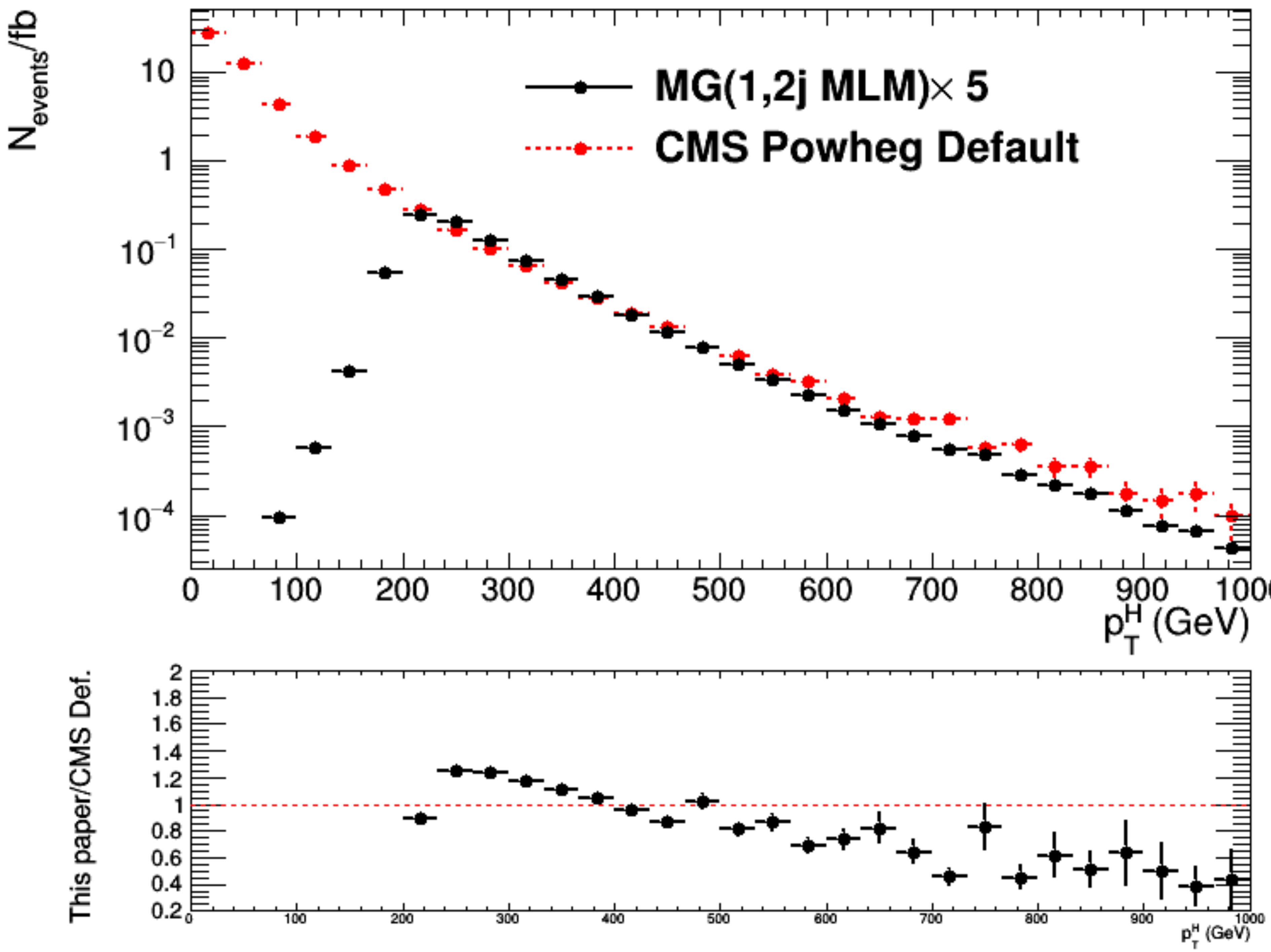
- How to get $\delta\Gamma_H/\Gamma_{SM}$ @ 68%CL:
  1. Inclusive H: **$\delta\mu_{(ggh)}$ (%) = XX ~ [0.05-0.1]**
  2. Boosted h(bb) $\delta\mu_{(ggh\text{->}bb)}$ (%) ~ 0.25* $\delta\mu_{(ggh)}$
  3. W+h(bb) $\delta\mu_{(W+h\text{->}bb)}$ (%) = 0.09
  4. WBF+h(WW) $\delta\mu_{(W+h\text{->}WW)}$ (%) = 0.05

FTR-18-011

- Final unc:
  - $\delta\Gamma_H/\Gamma_{SM}$ ~sqrt(0.05^2+4*0.09^2+4*(1+0.25^2)*(XX^2))
    - **range: [0.27-0.35]**

Higgs pT

* Slope follows more conservative approach close to LHCXS WG



Higgs mass

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  * Visible decays: Higgs is leading p_T jet in the event
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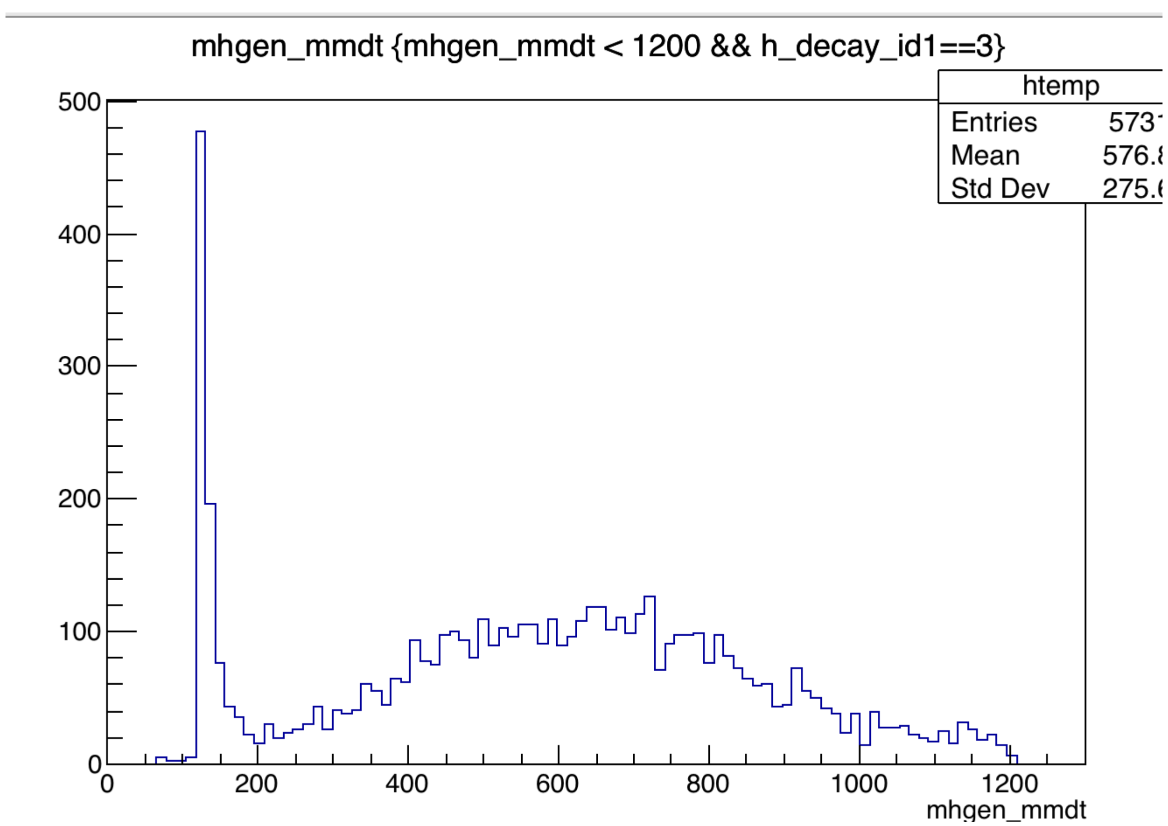
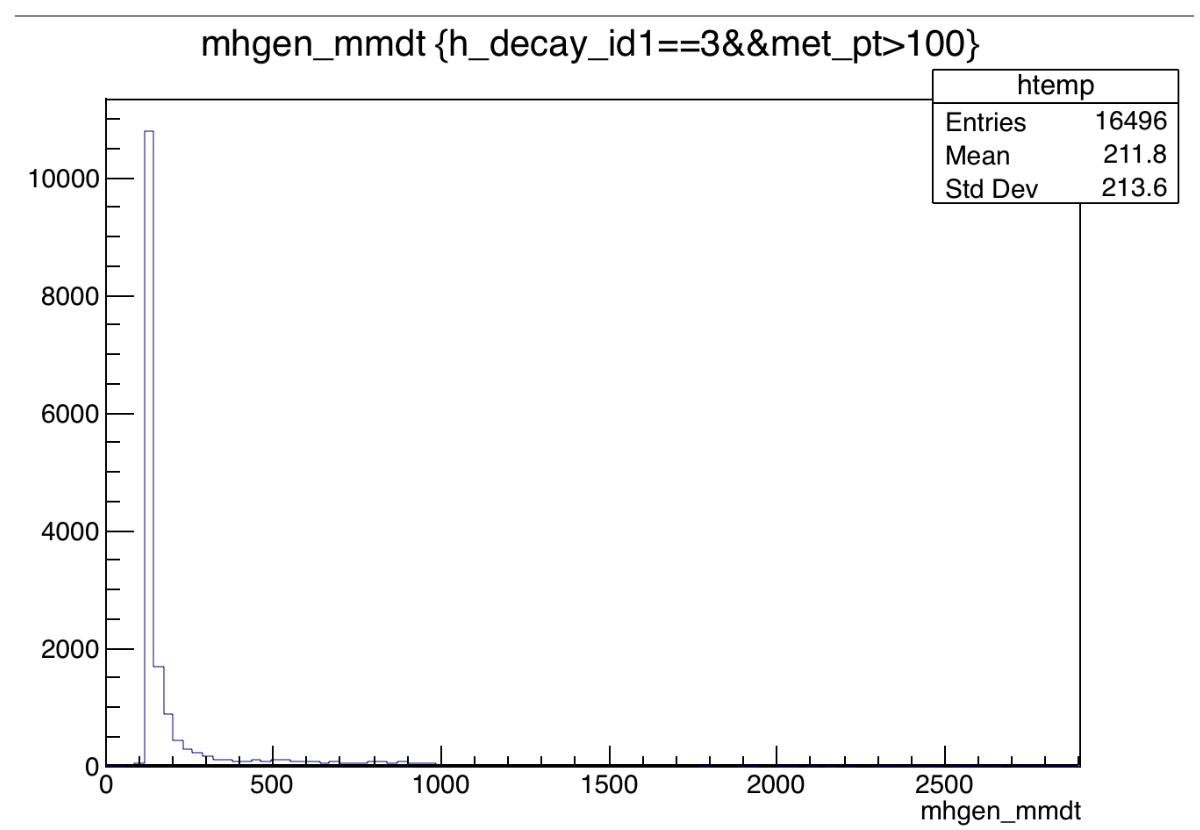
  * Take leading jet on (jet+neutrino).p_T instead.

* h(tautau) when taking leading p_T jet

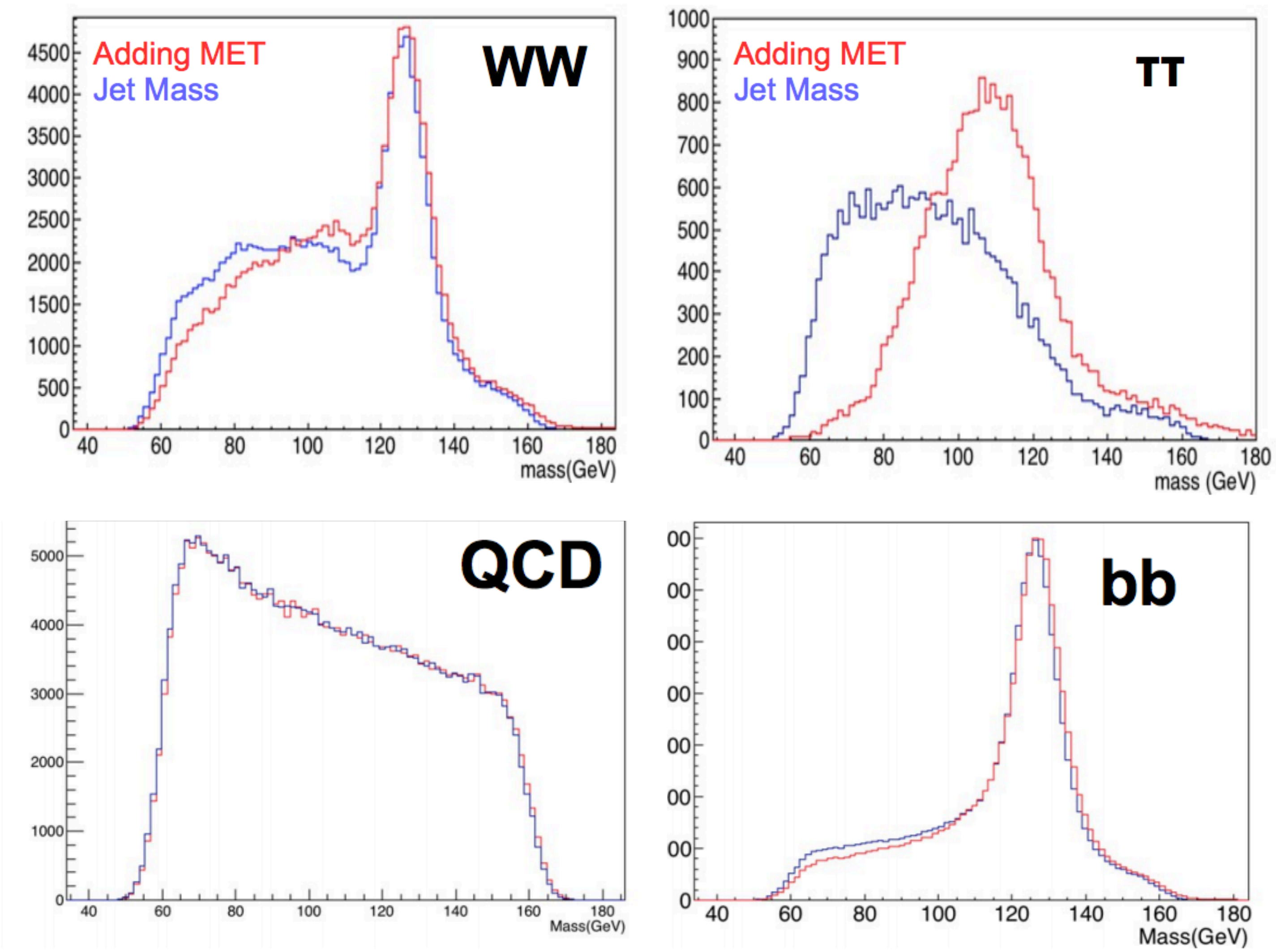


* h(tautau) when taking leading jet on (jet+neutrino).p_T

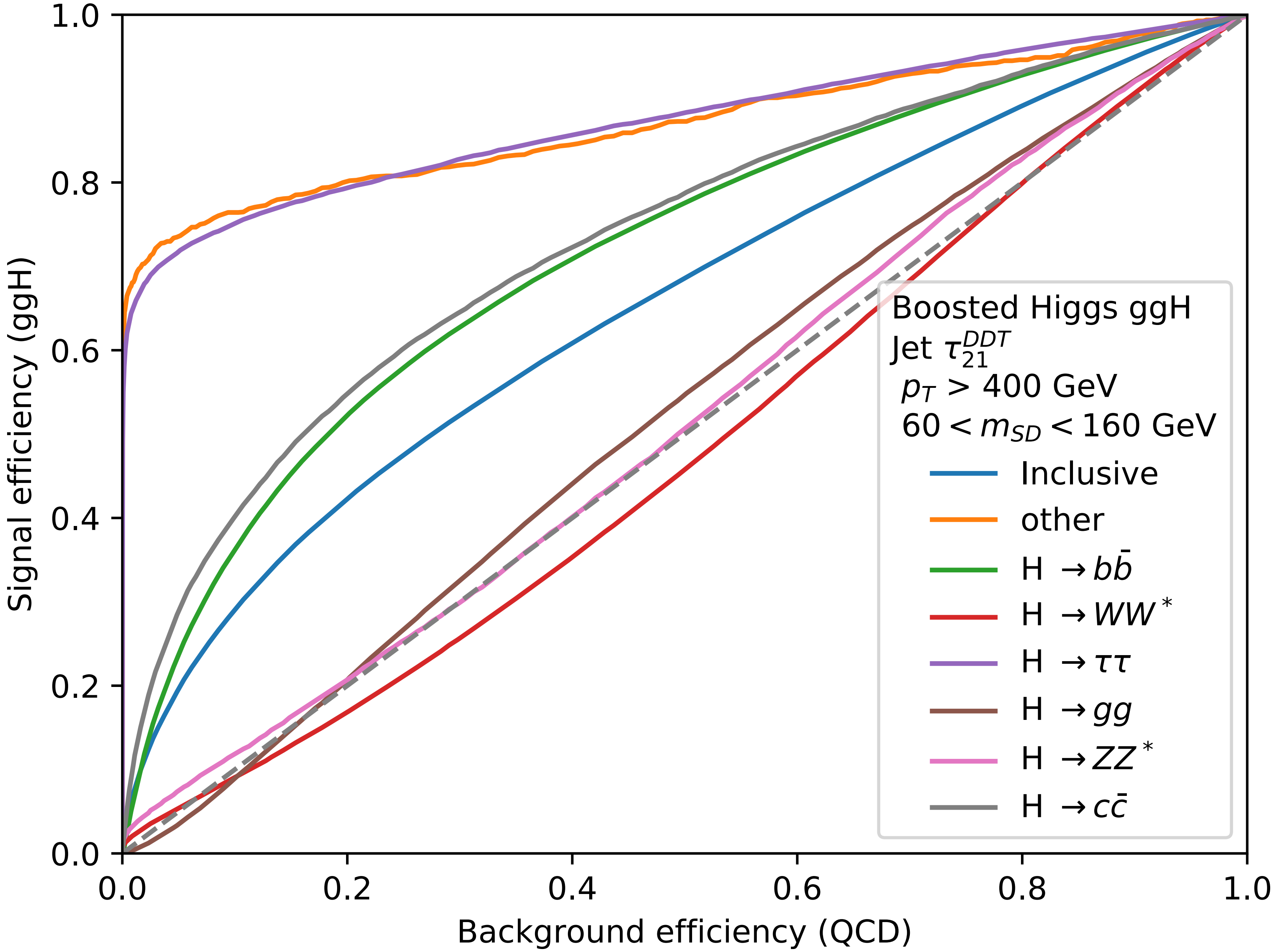


Higgs mass

- Ταkε the regressed *MET* and use jet η/φ
  - WW/tau-tau: yields a pretty clear improvement in the mass distribution
  - For QCD and b-jets effect is small

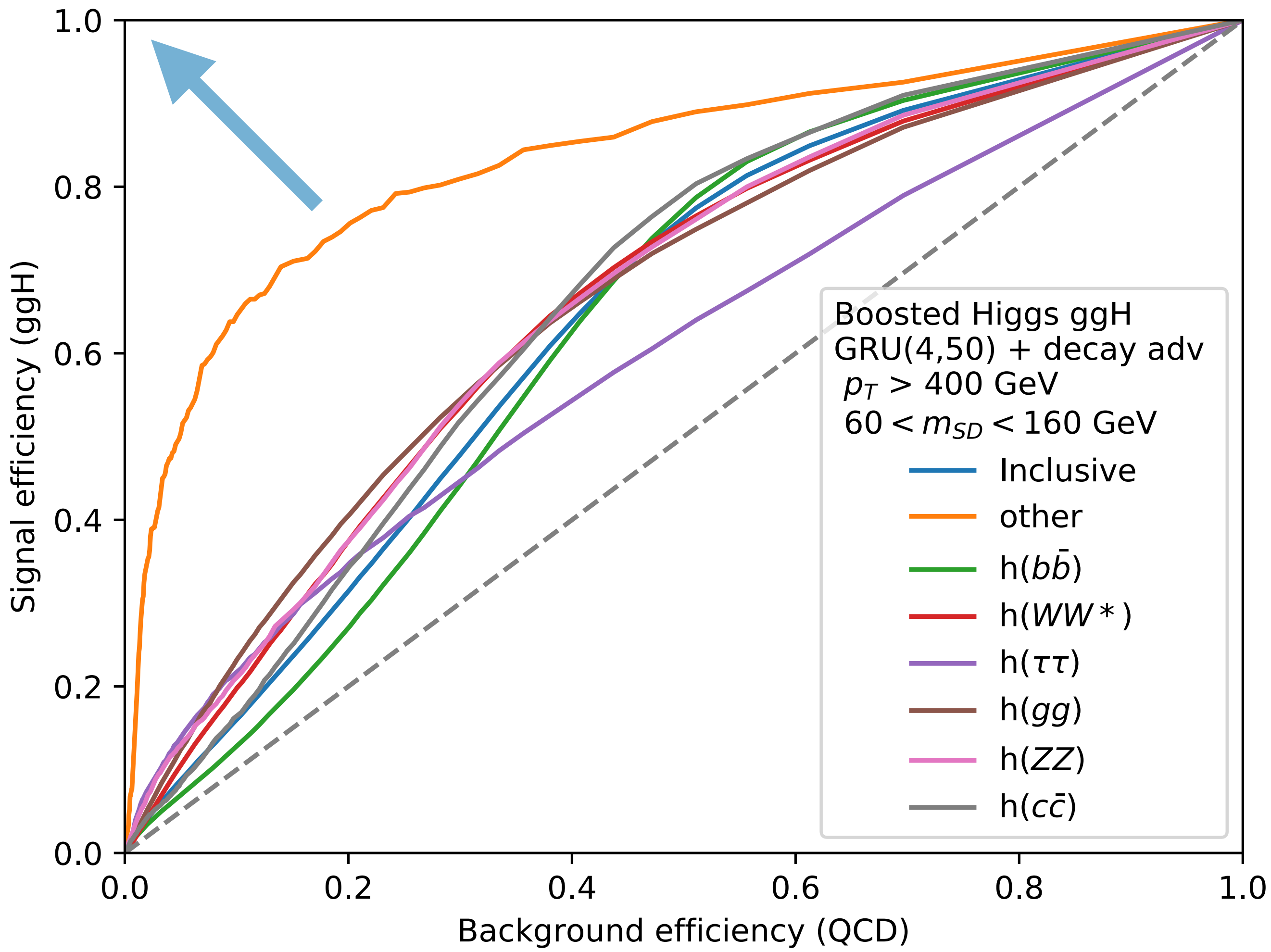


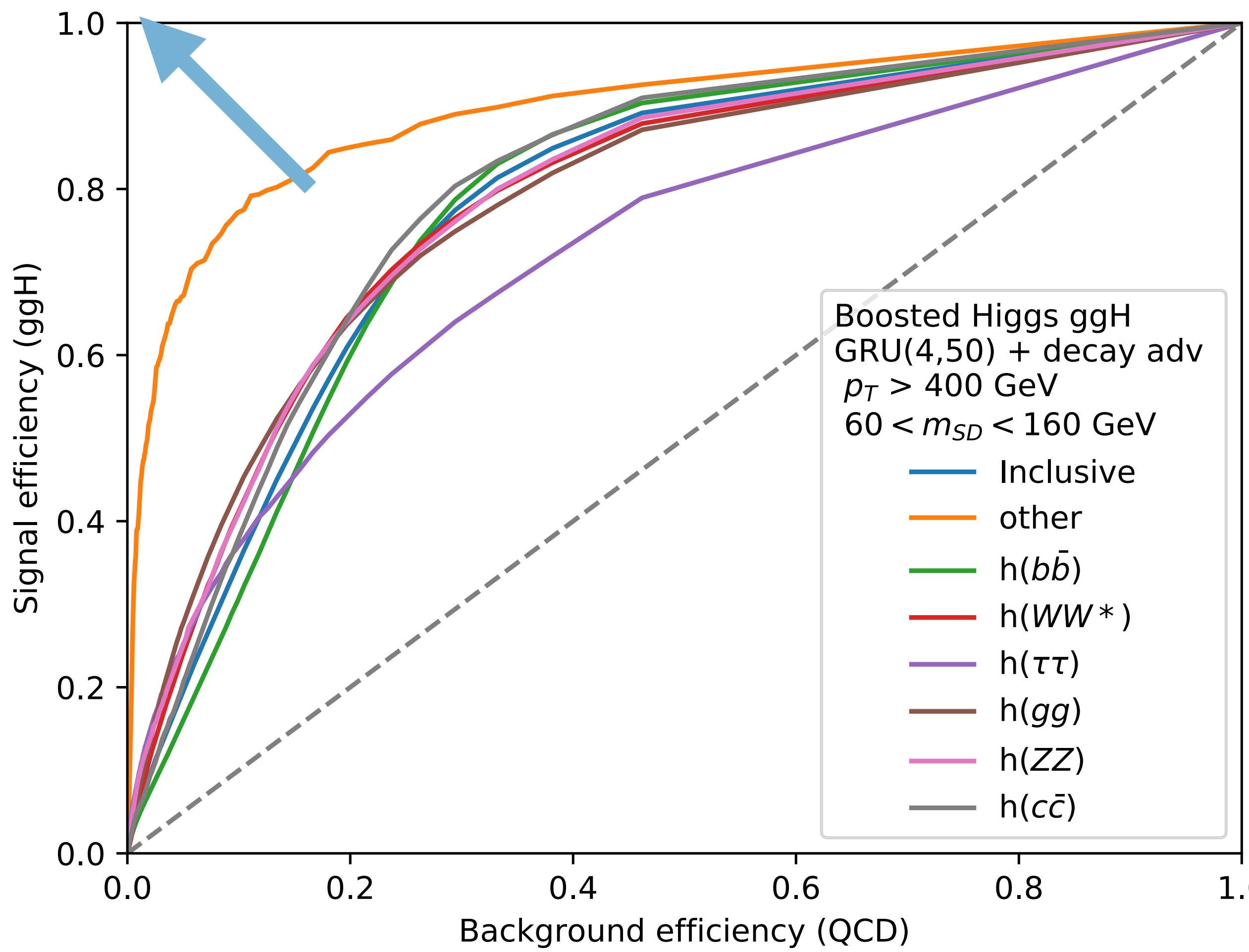
Tau21


Boosted Higgs ggH
Jet τ_{21}^{DDT}
p_T > 400 GeV
$60 < m_{SD} < 160$ GeV
Inclusive
other
H $\to b\bar{b}$
H $\to WW^*$
H $\to \tau\tau$
H $\to gg$
H $\to ZZ^*$
H $\to c\bar{c}$
Signal efficiency (ggH)
Background efficiency (QCD)
0.0
0.2
0.4
0.6
0.8
1.0

Minimizing bias against decay

- Attempt to add adversarial to minimize bias against h decay.
- Does not really work: i.e. performance reduces to **h(gg)**



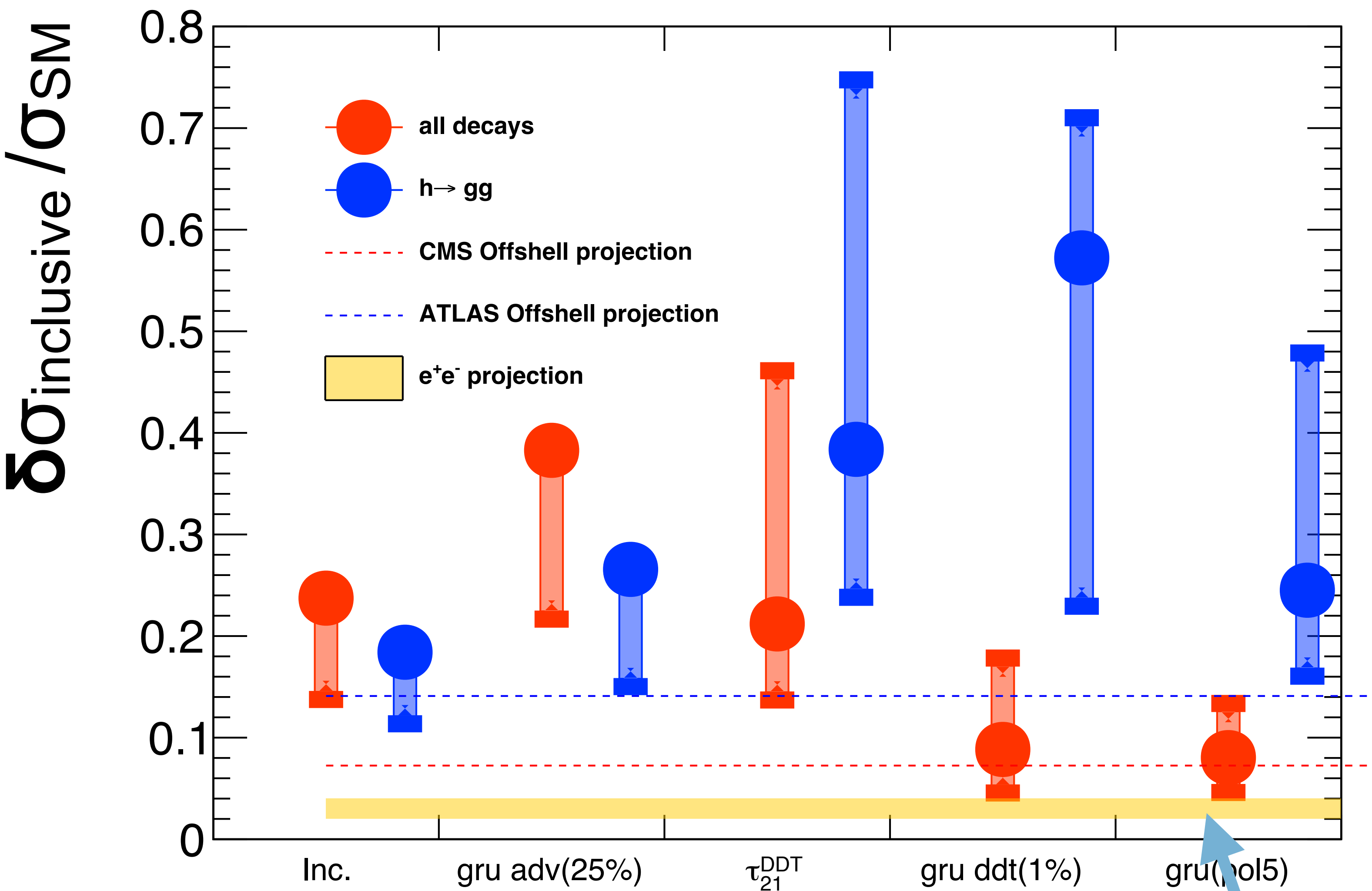


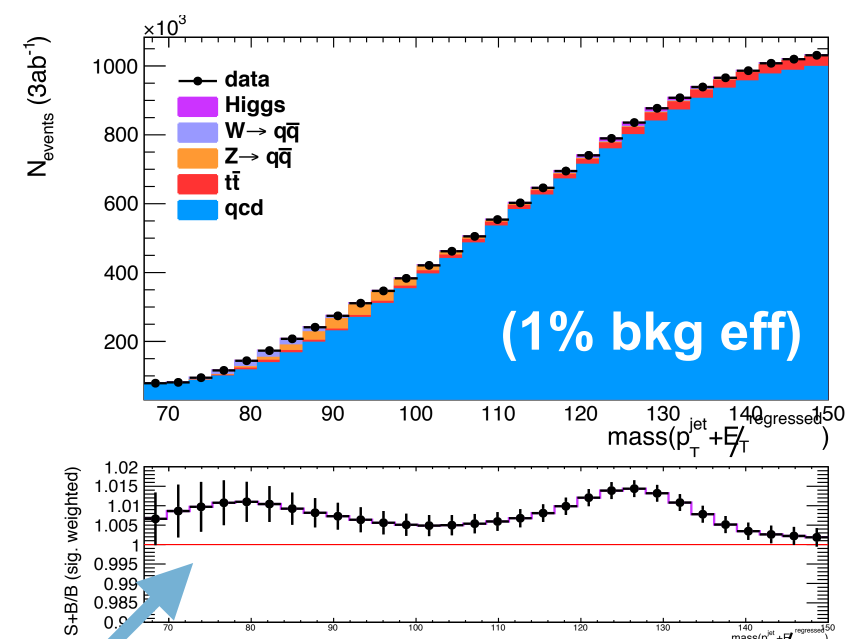
Fit details

* Systematics
  * Systematics on W/Z/top normalization
  * Shape systematics on W/Z/H
* Backgrounds
  * QCD estimate:
    * Template fit (optimistic approach)
    * Polynomial fit - 4th order - (# of parameters similar to current approaches e.g. CMS boosted H(bb))
  * Non-DDT versions are non-realistic…

h to gluons

- Are the real challenge
- Trained adversary to minimize bias against H decay => brought sensitivity back to level of h=>gg

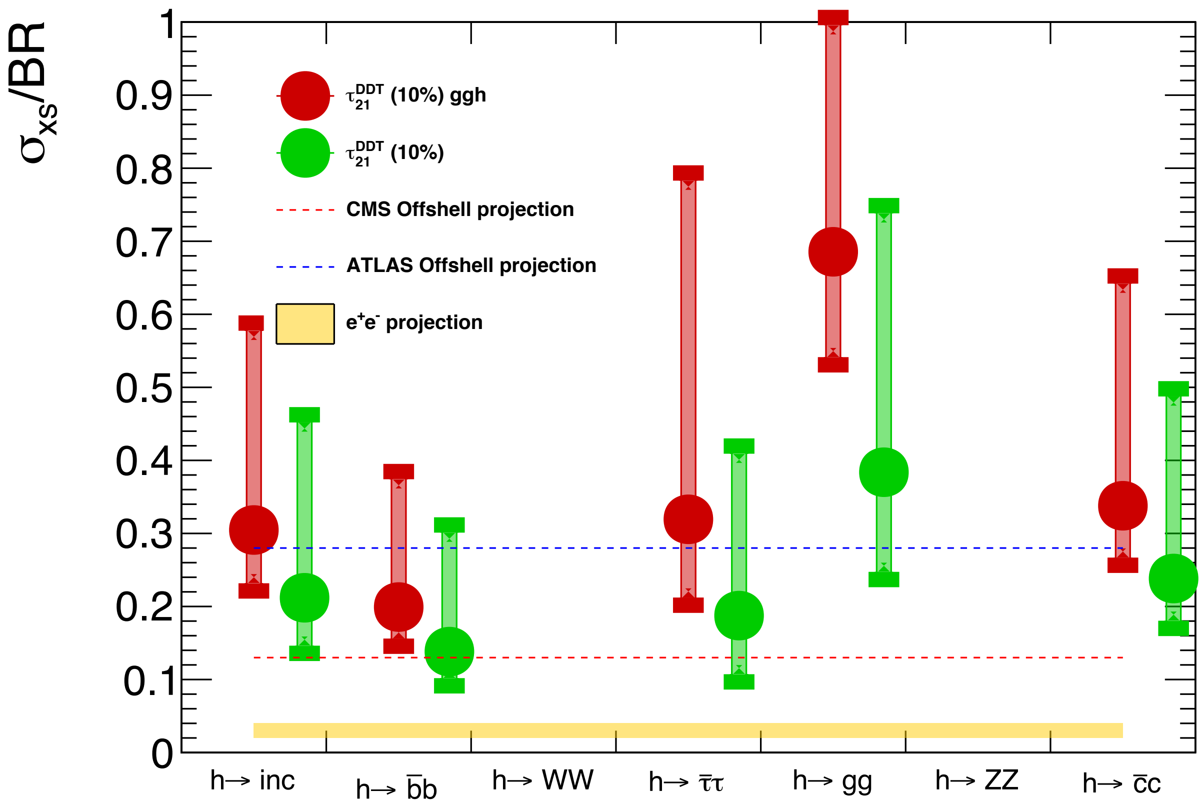


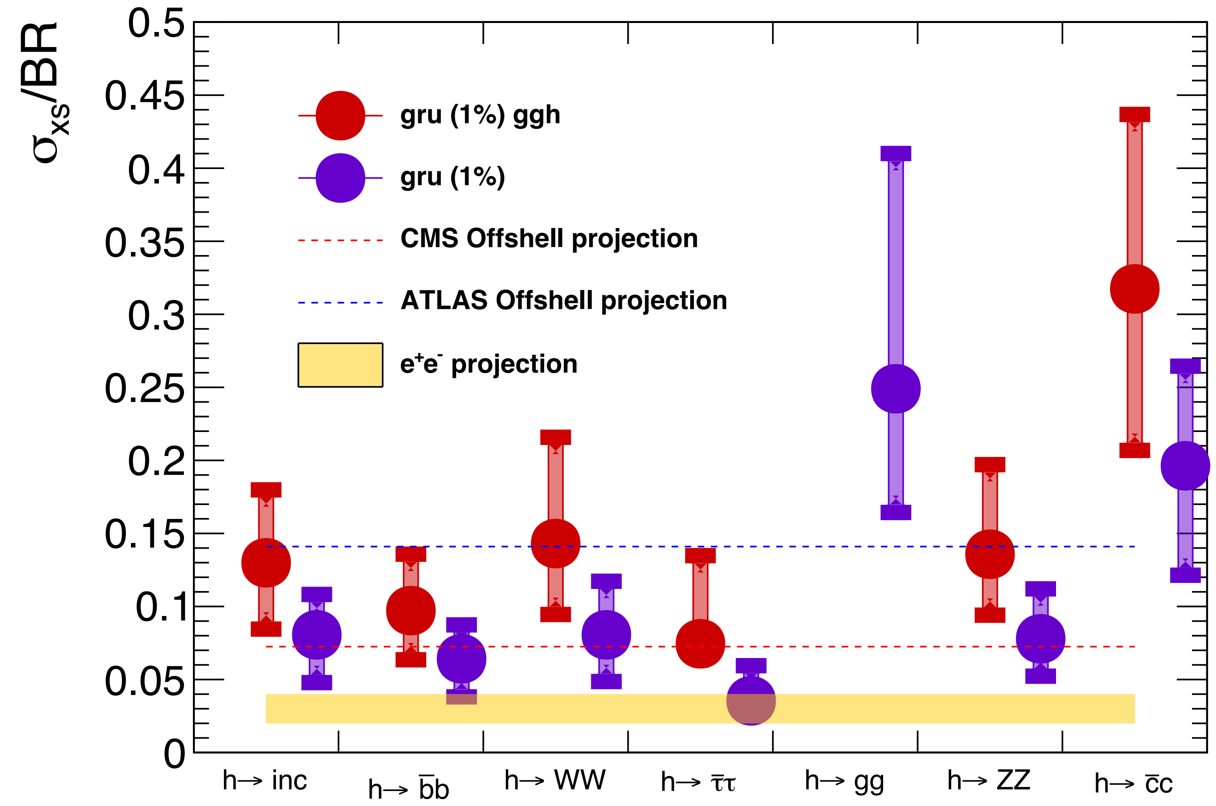


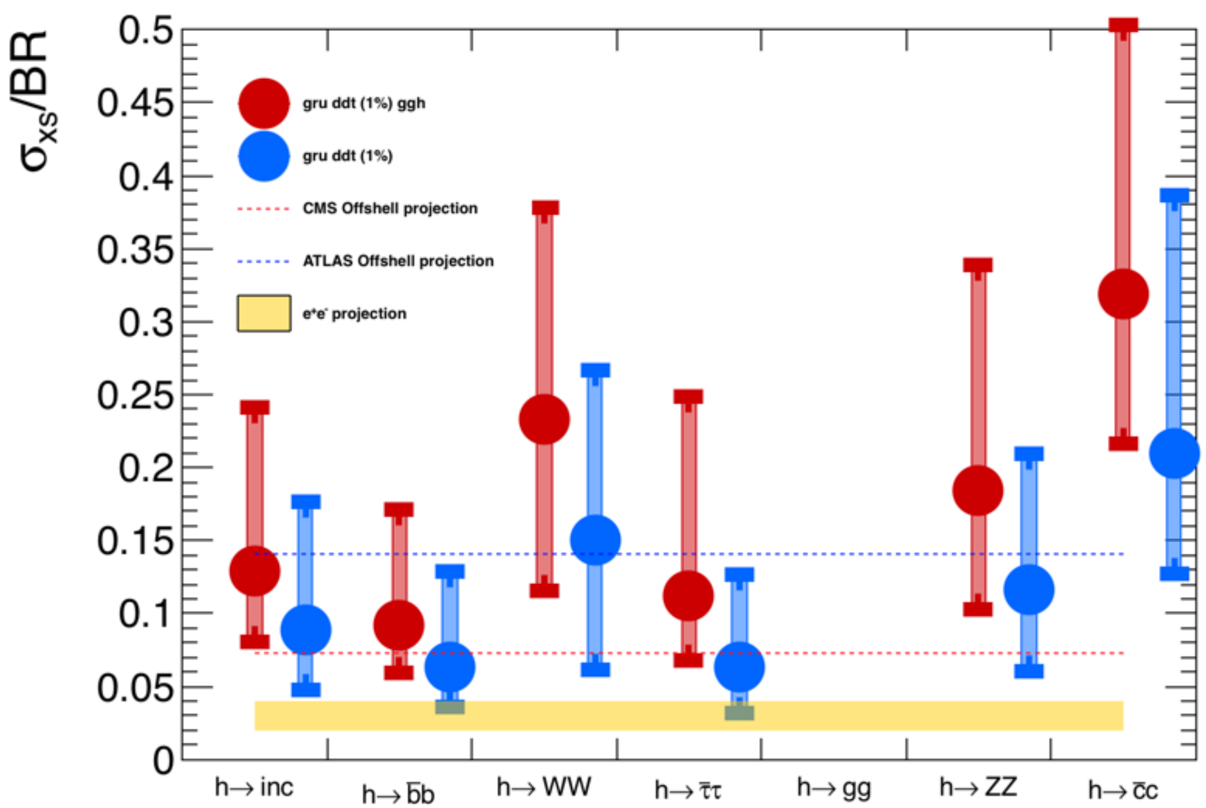
For GRU, sensitivity comes from VH

GGH only

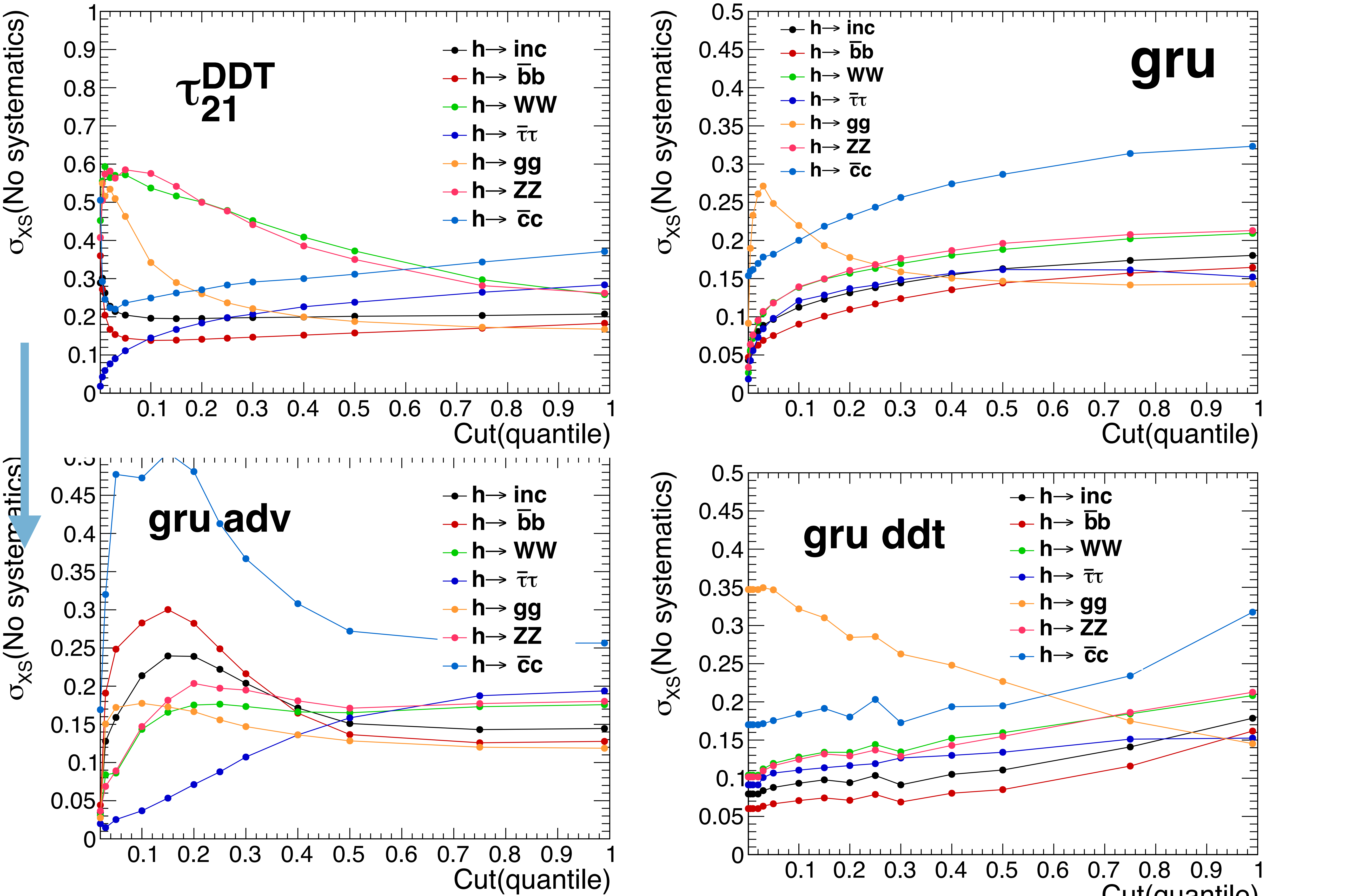
- For GRU, hgg comes from VH



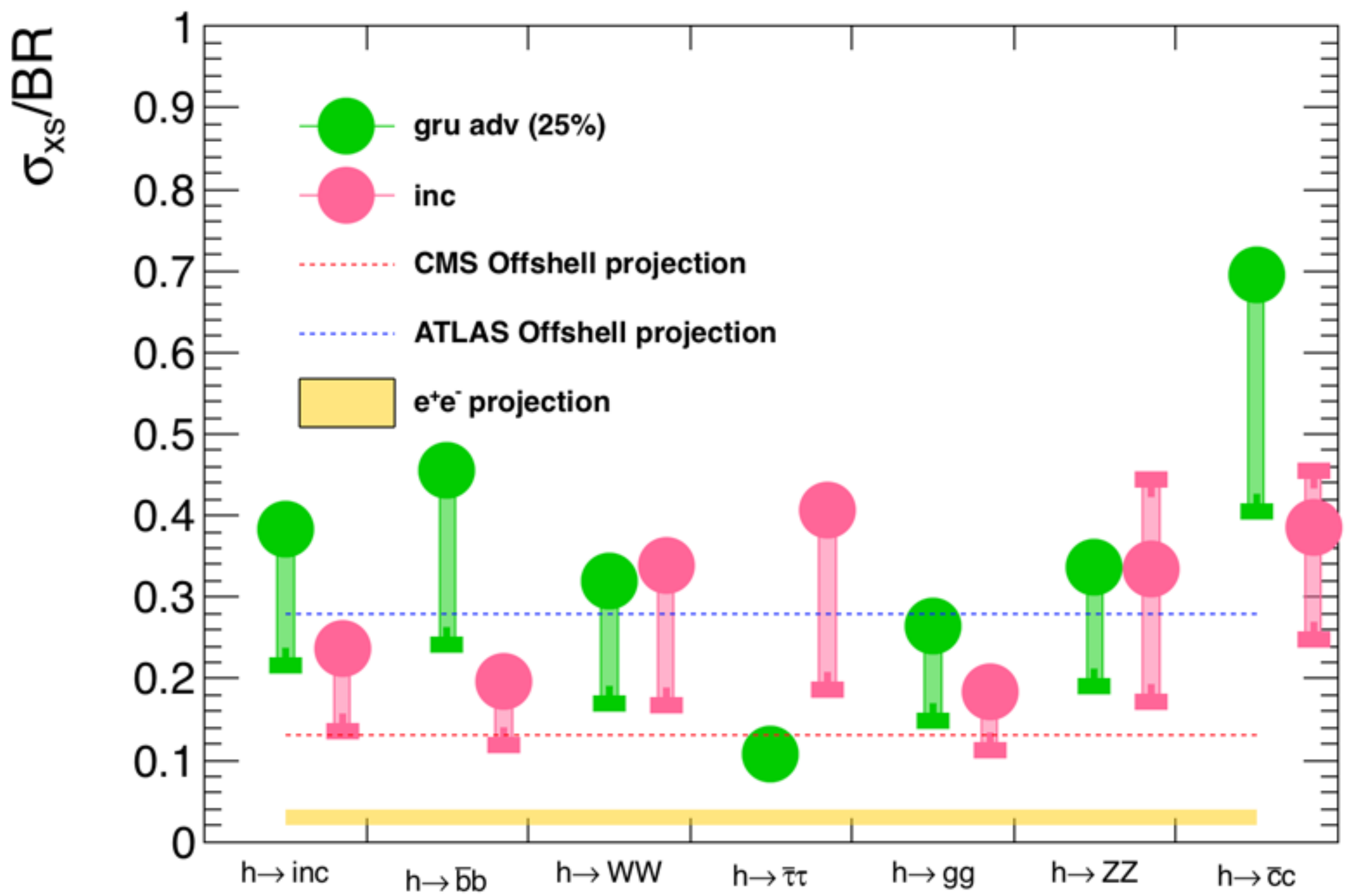




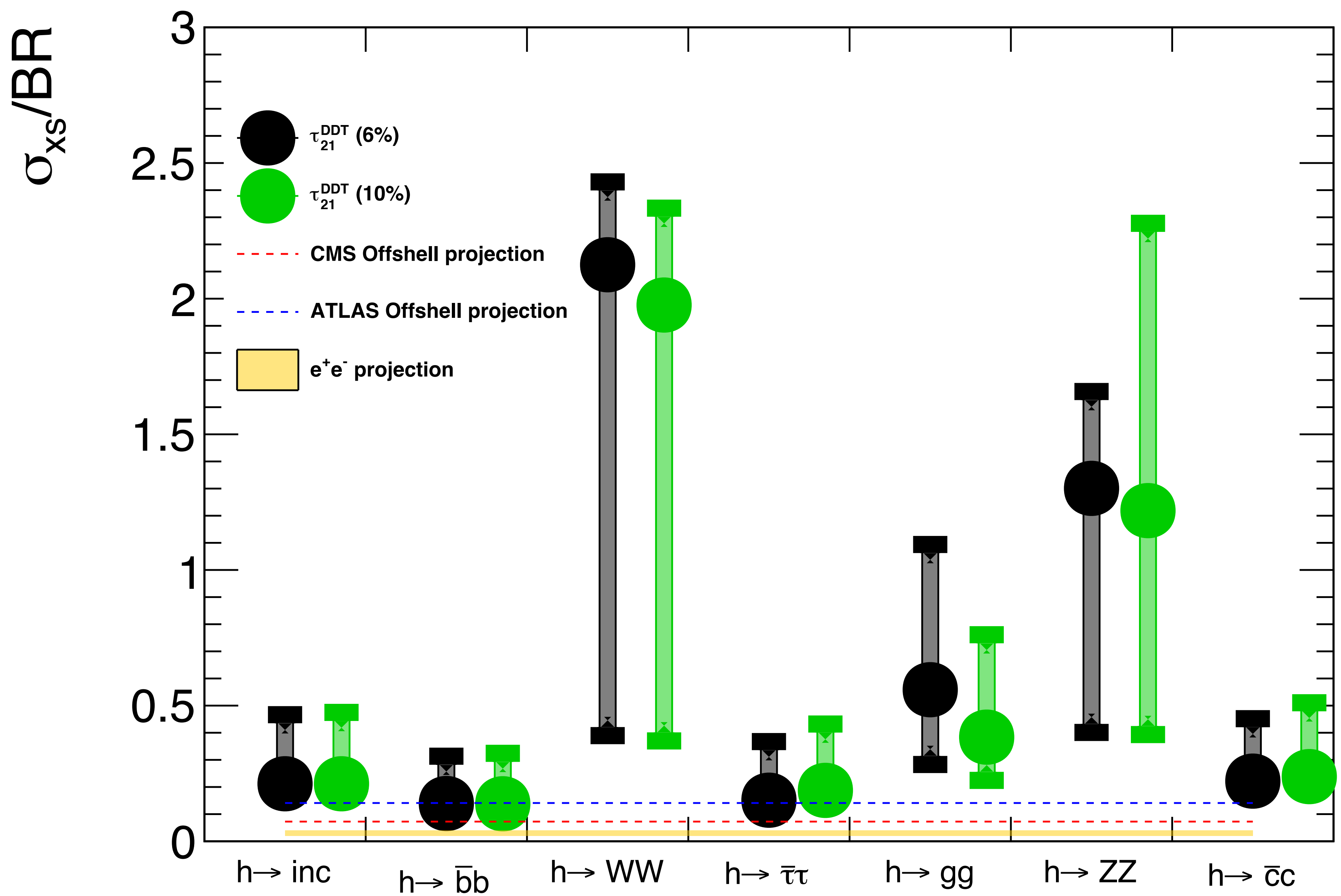
Scans


τ_{21}^{DDT}
gru
gru adv
gru ddt
σ_{XS}(No systematics)
Cut(quantile)
h→ inc
h→ $\bar{b}$b
h→ WW
h→ $\bar{\tau}\tau$
h→ gg
h→ ZZ
h→ $\bar{c}$c

Just mass and GRU+Adv.

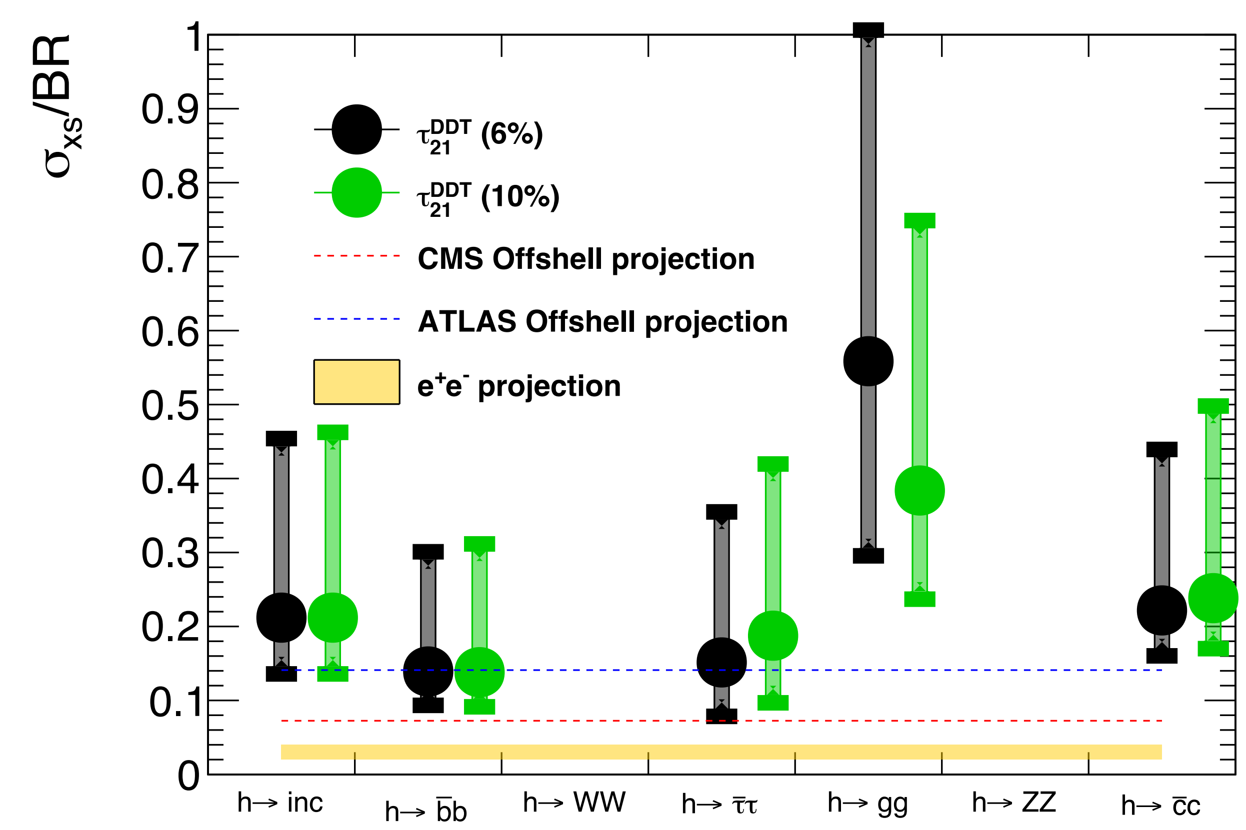


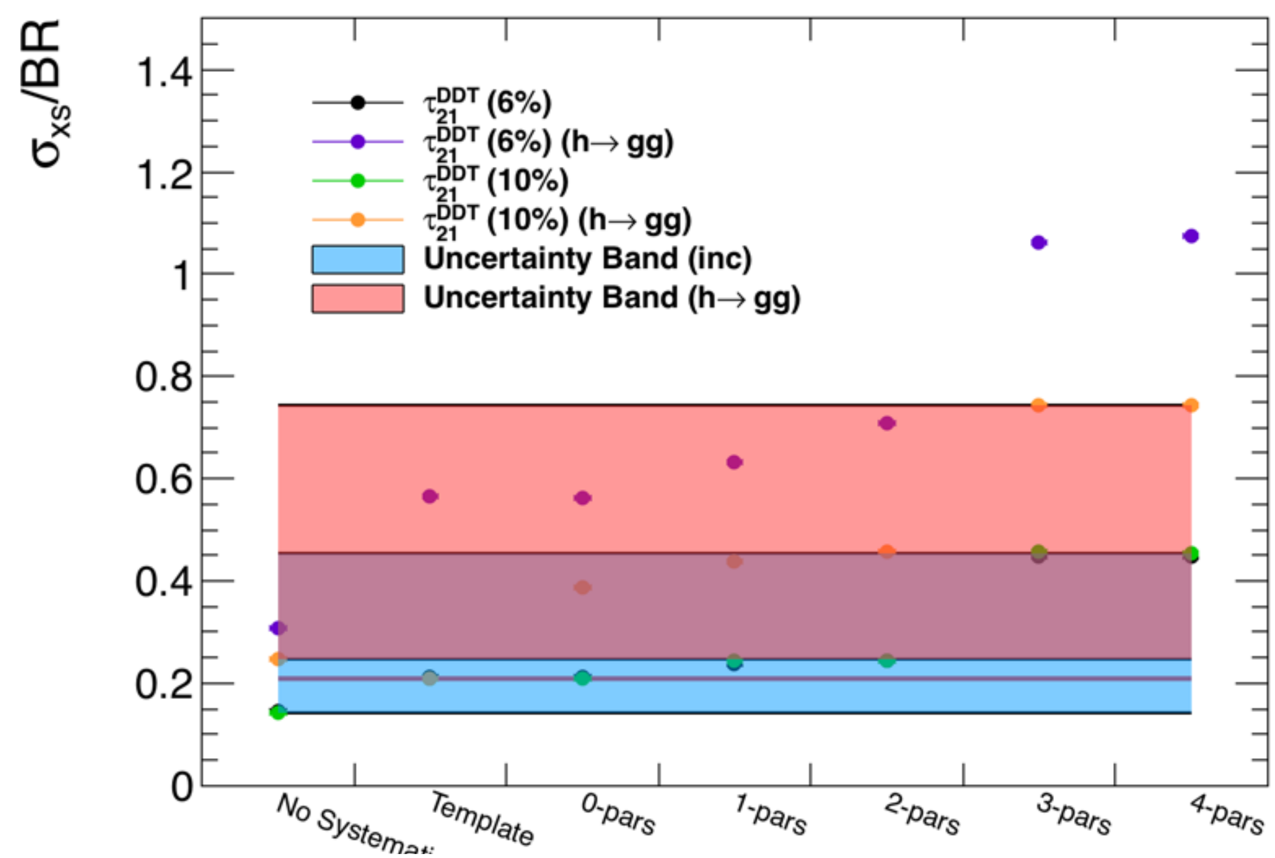
Tau21 (WW/ZZ)

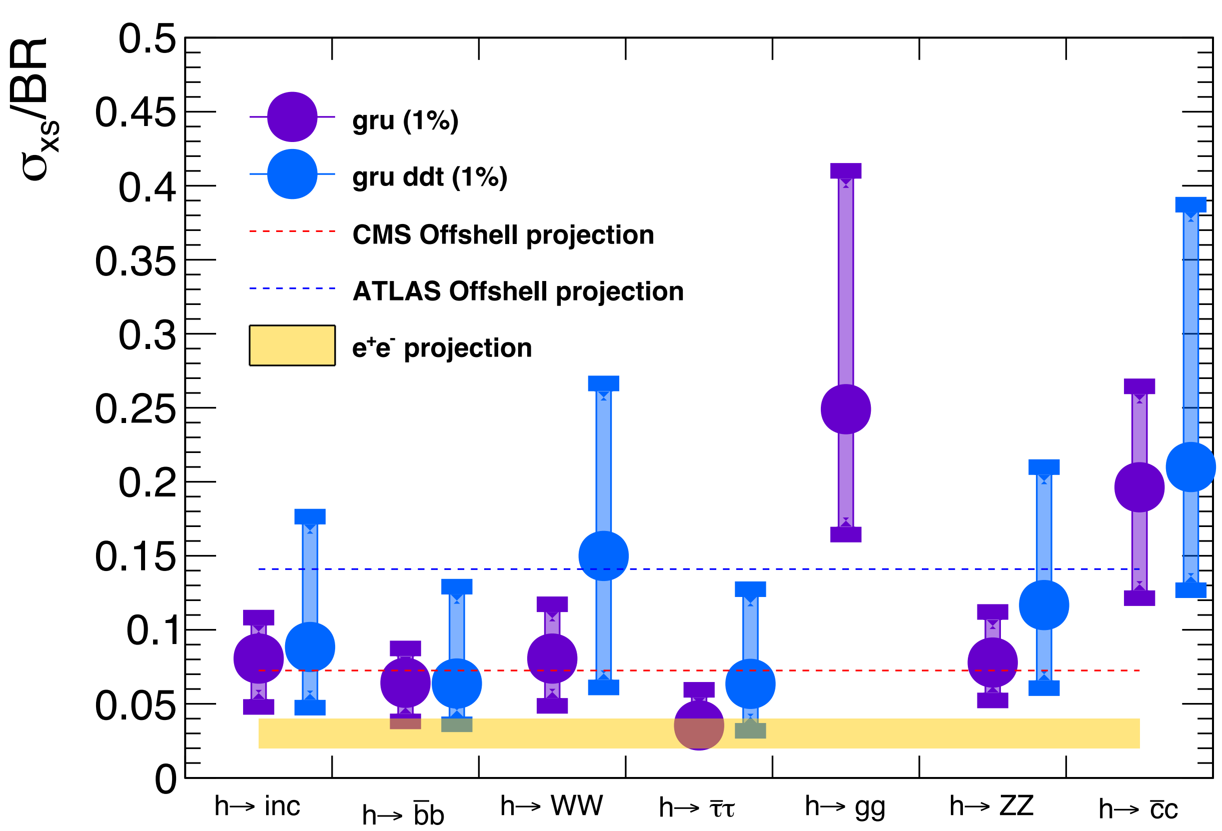


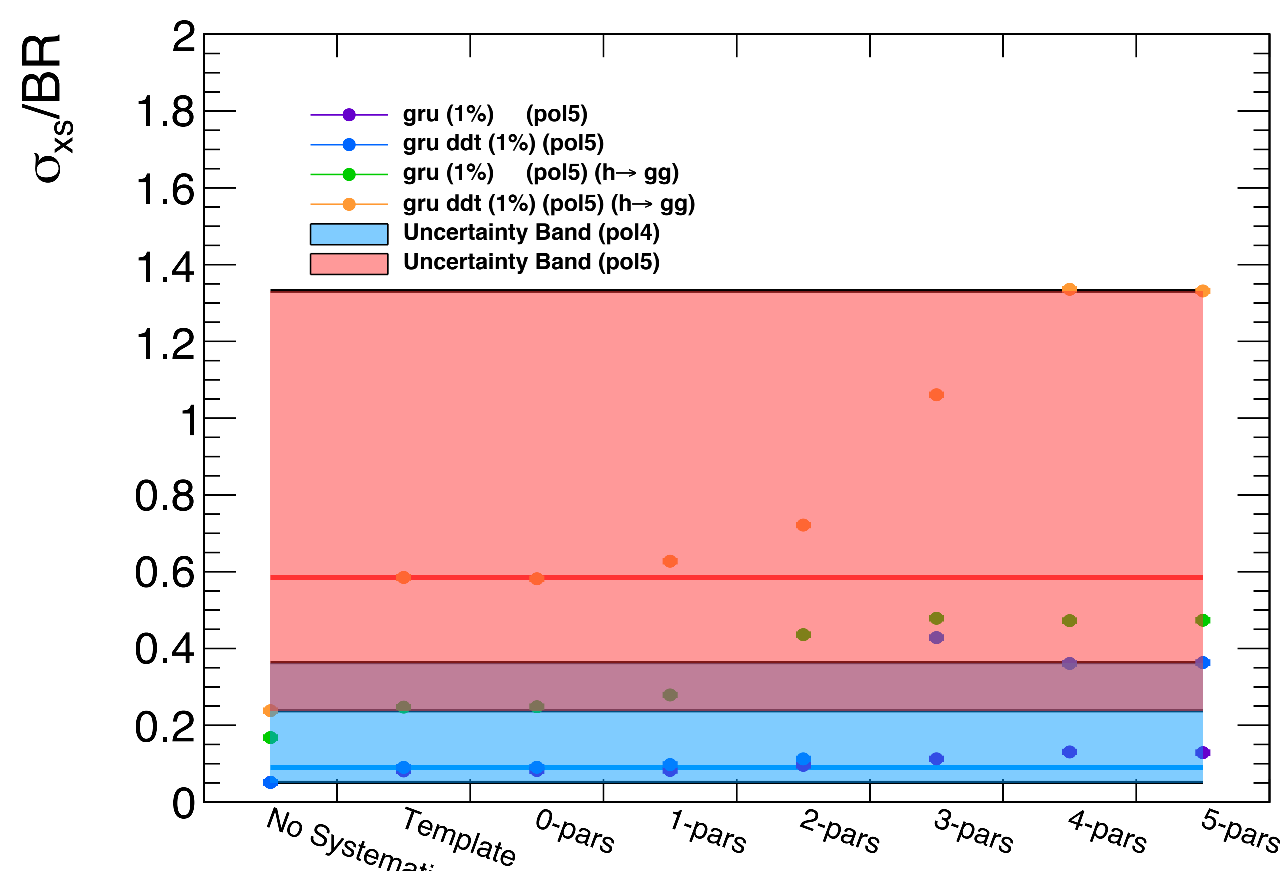
σ_{xs}/BR
3
2.5
2
1.5
1
0.5
0
τ_{21}^{DDT} (6%)
τ_{21}^{DDT} (10%)
CMS Offshell projection
ATLAS Offshell projection
e+e- projection
h→ inc
h→ $\bar{b}$b
h→ WW
h→ $\bar{\tau}\tau$
h→ gg
h→ ZZ
h→ $\bar{c}$c

Variation of the fit

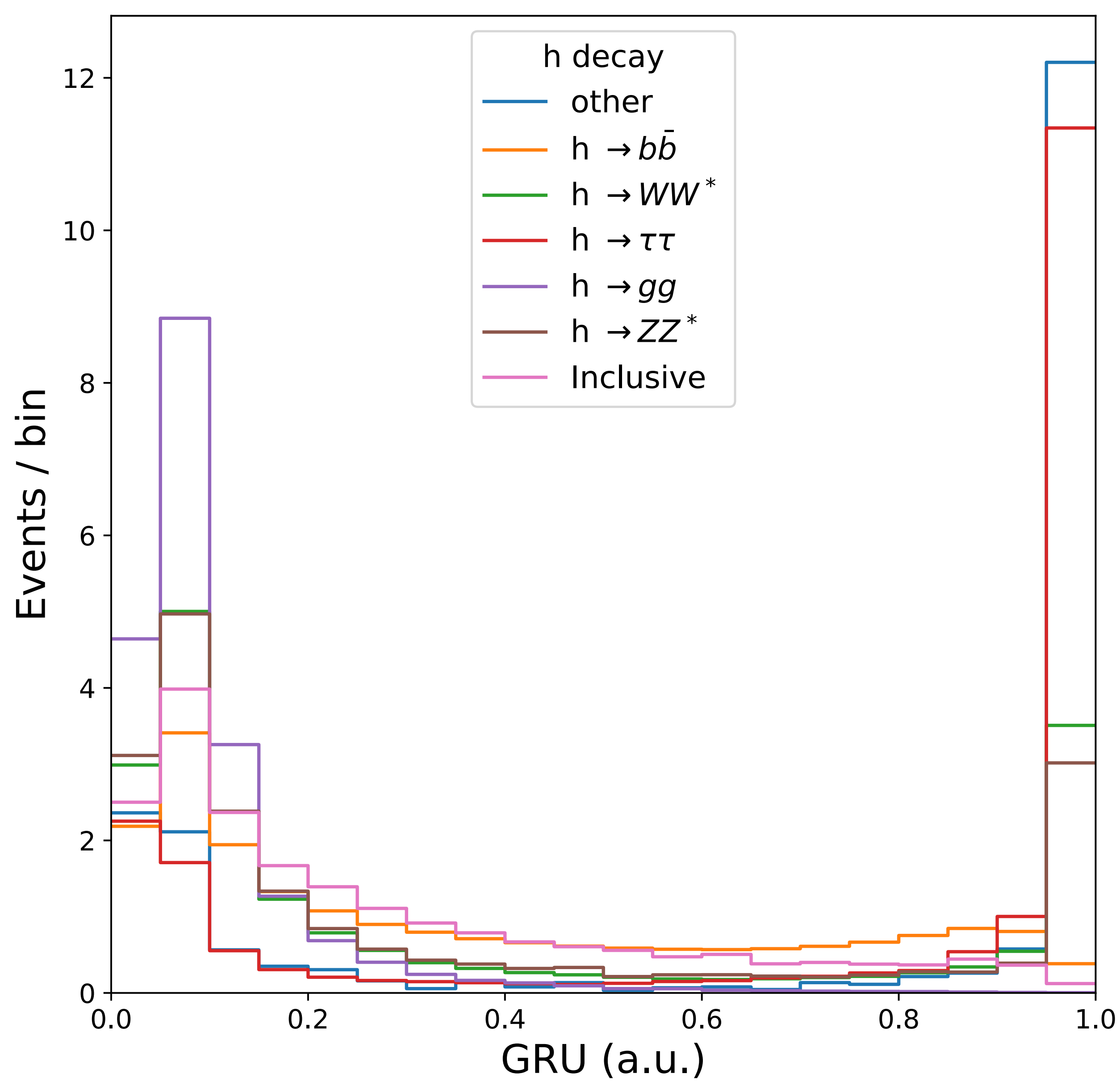


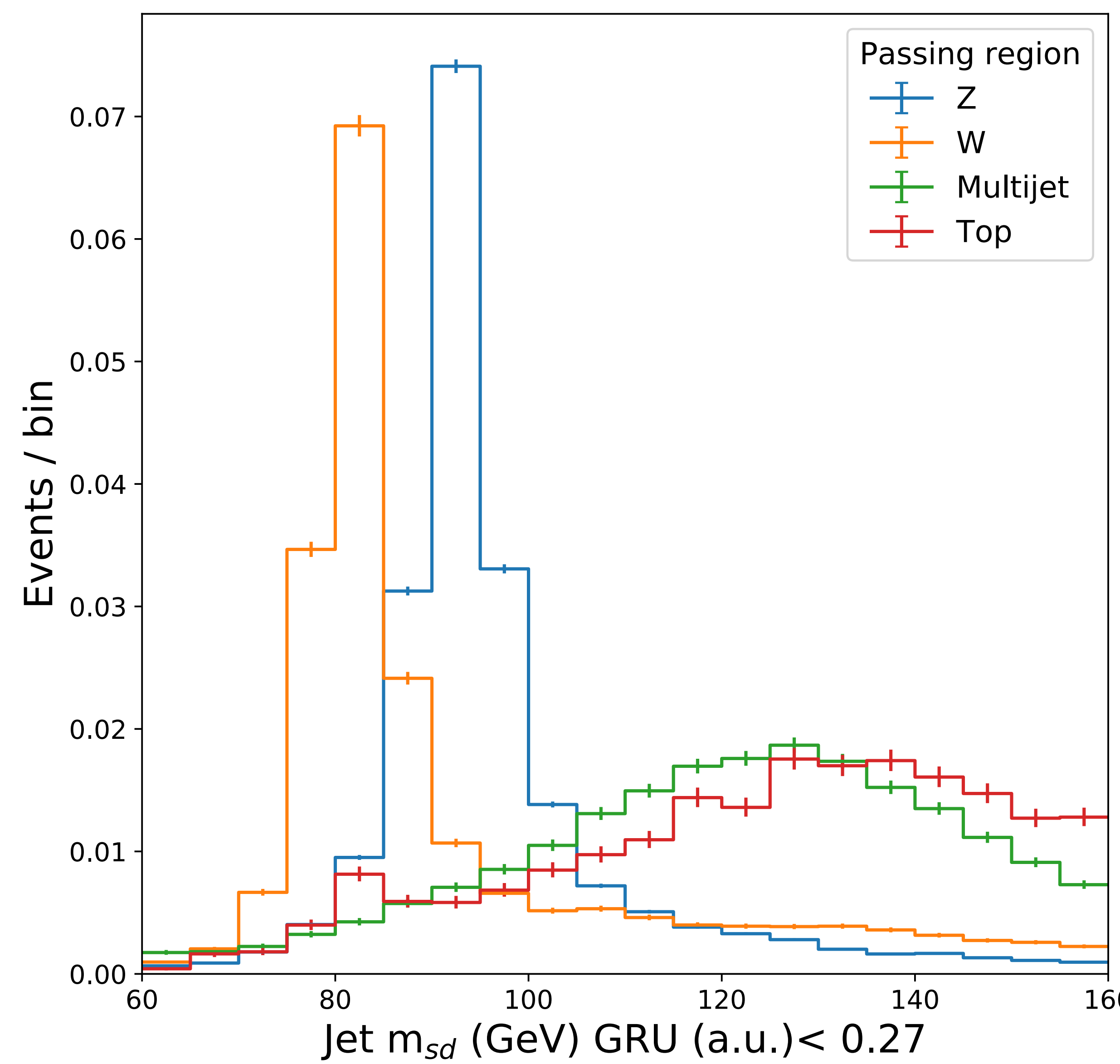






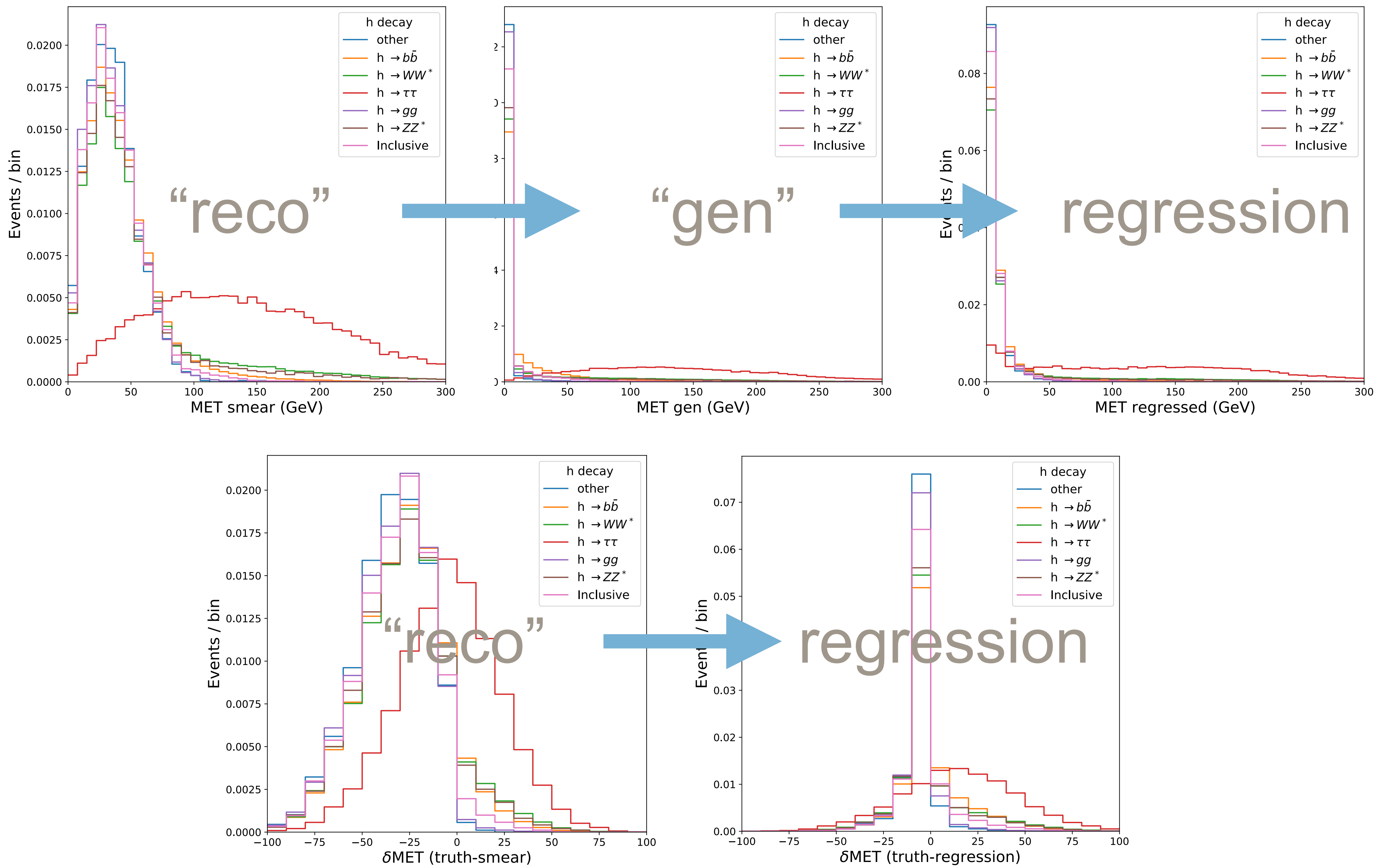
GRU response





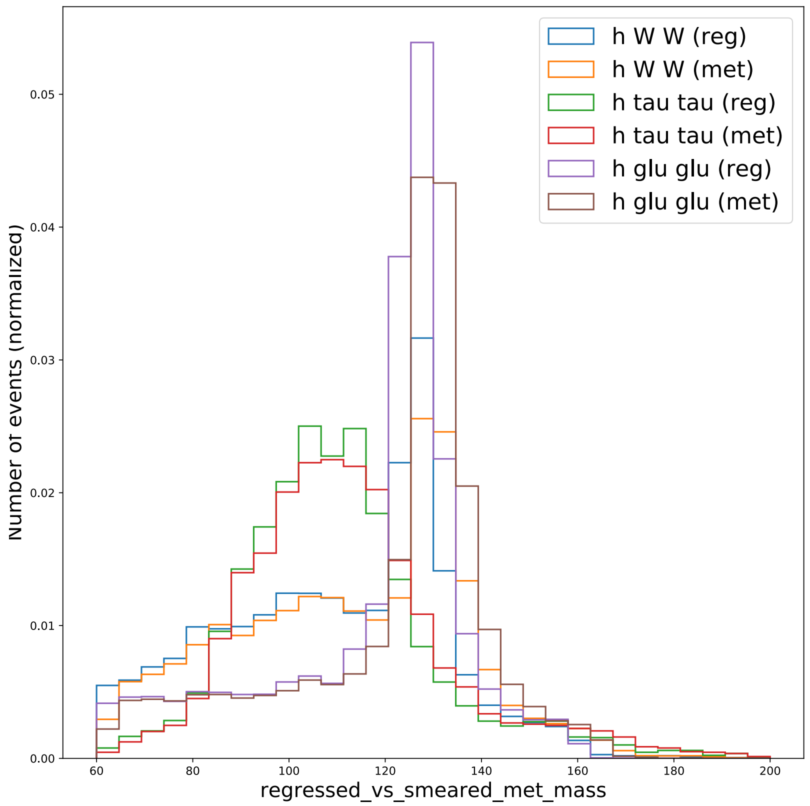
MET regression

- Perform **regression on MET.pT** using kinematic inputs of jet/MET/ECFs

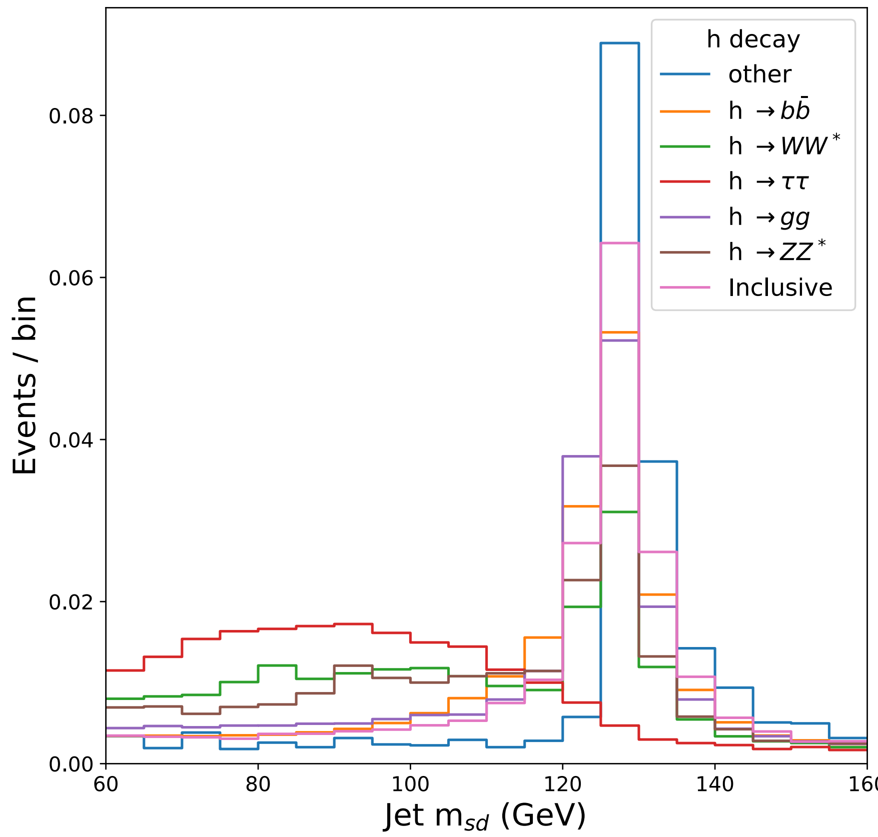


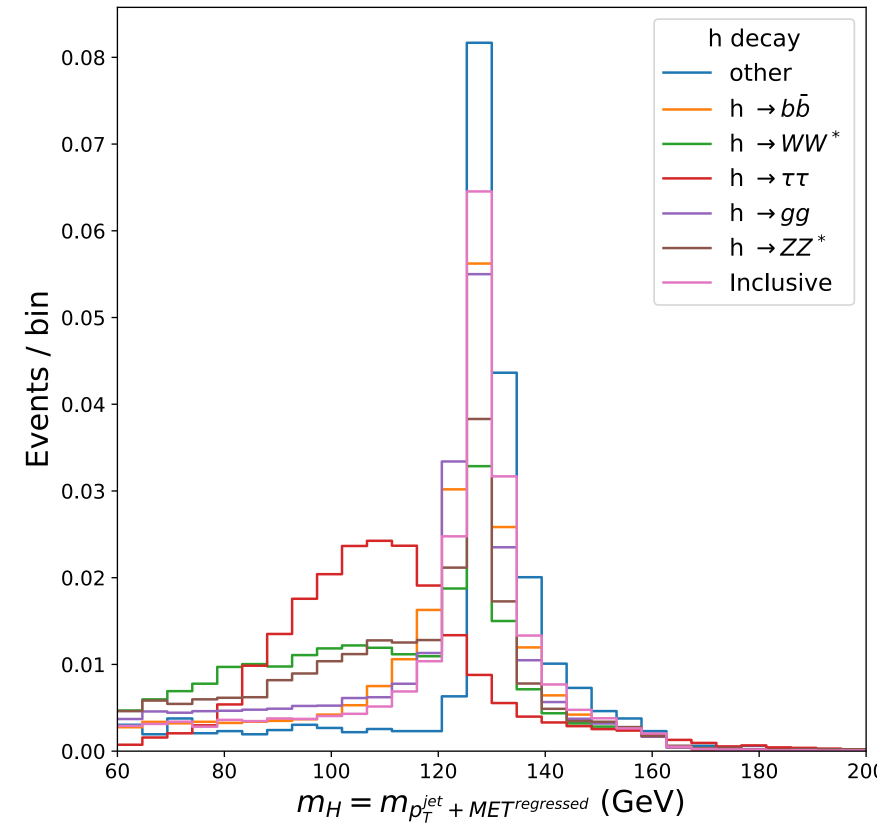
Mass reconstruction

“reco” vs “regressed”



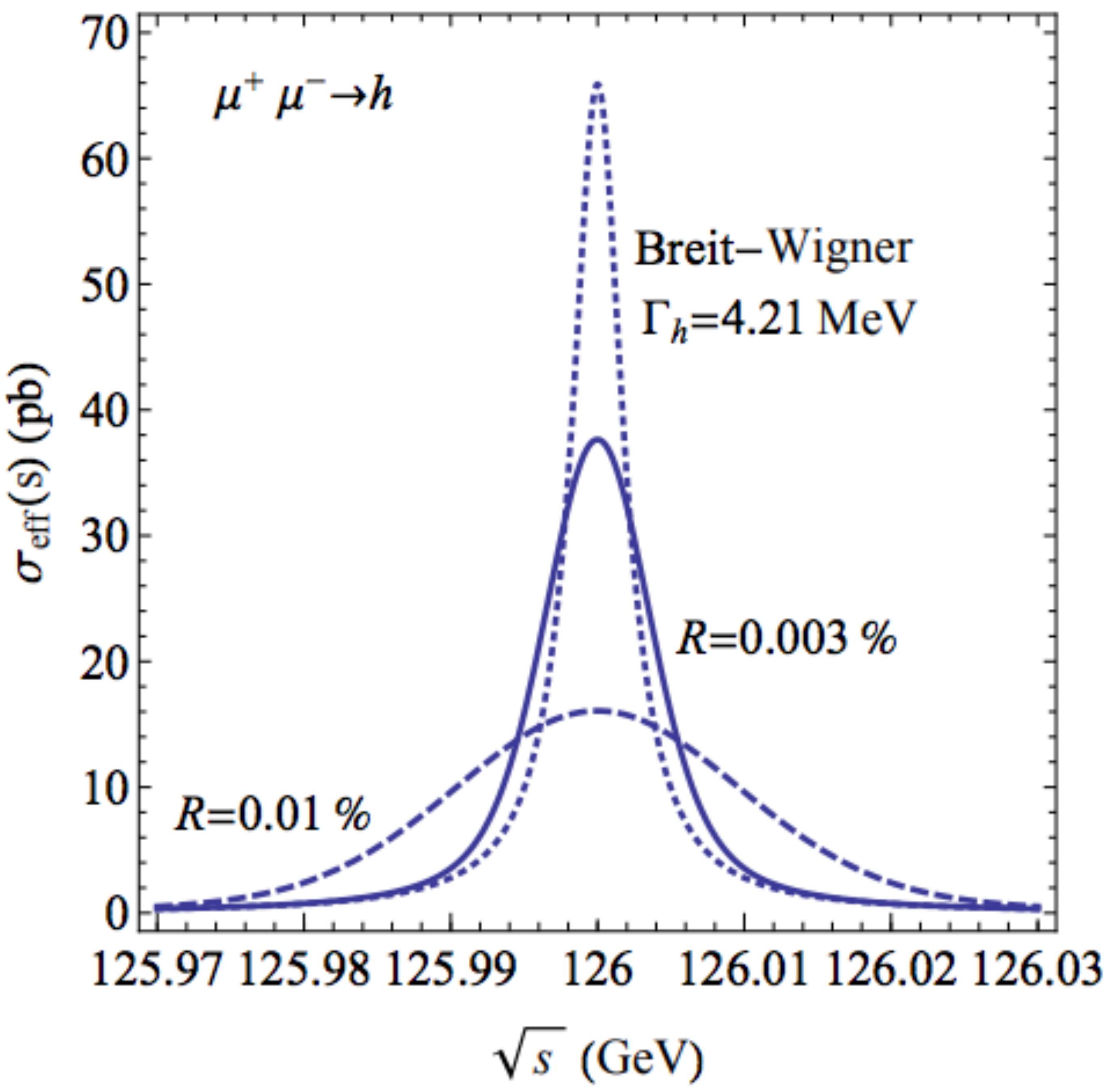
“reco” → regression





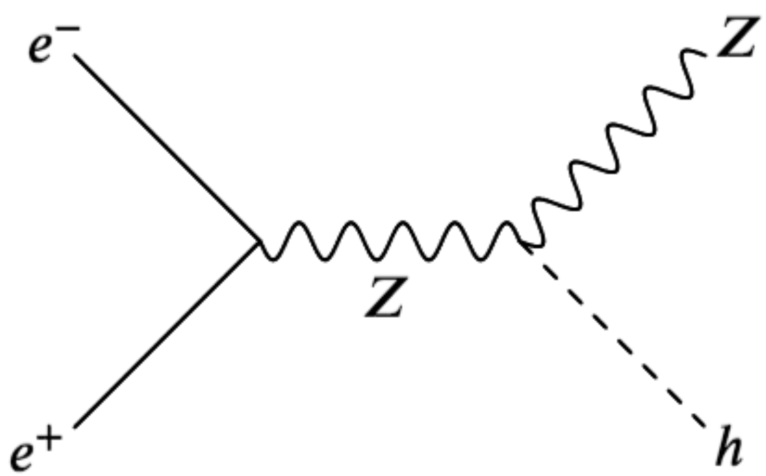
Γ_H @ Muon Colliders

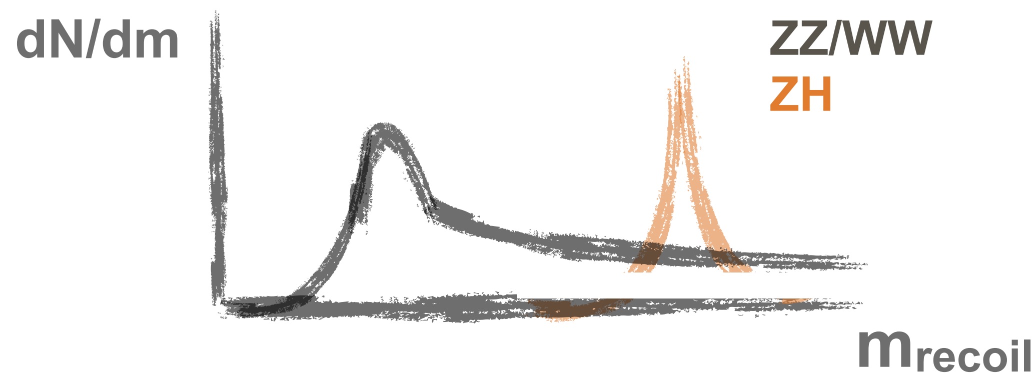
* Muon collider: great resolution $\delta\Gamma_H/\Gamma_{SM} \approx 0.05$
* Scan against collider energy sqrt(s):



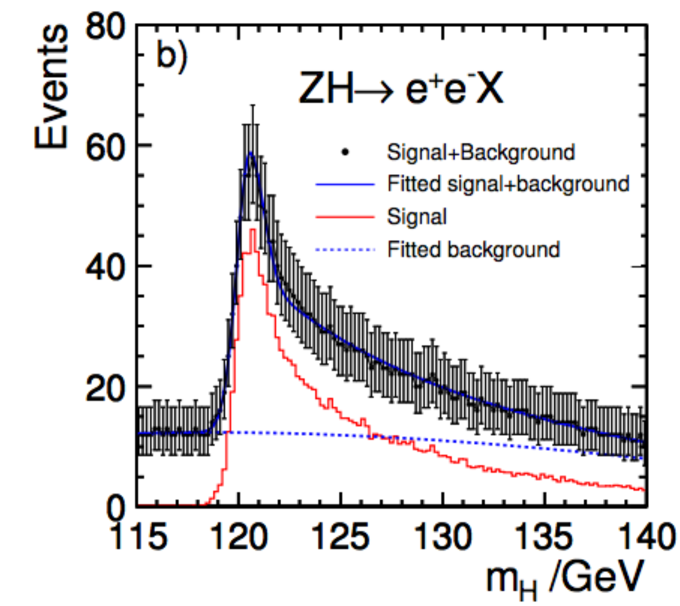
Γ_H @ Electron Colliders

1. Measure $\sigma(e^+e^- \to Zh) \propto g^2_{hZZ}$ by tagging ZH and recoil mass:





$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



2. Measure h→XX decay $\sigma_{Zh\to XX}$

$$\sigma_{Zh\to XX} = \sigma(e^+e^- \to Zh) \times \mathrm{BR(h \to XX)} \propto g^2_{hZZ}\frac{g^2_{hXX}}{\Gamma_h}$$

3. Get total width:

$$\Gamma_h \propto g^2_{hZZ}\frac{g^4_{hZZ}}{\sigma(e^+e^- \to Zh) \times \mathrm{BR(h \to ZZ)}}$$

$$\propto \frac{g^2_{hZZ}}{\mathrm{BR(h \to ZZ)}}$$