Potential of di-Higgs observation via a calibratable jet-free *HH*(4*b*) search framework

arXiv:2508.15048

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(Peking University)

TeV 物理前沿专题研讨会暨第 31 届

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Key points of this talk

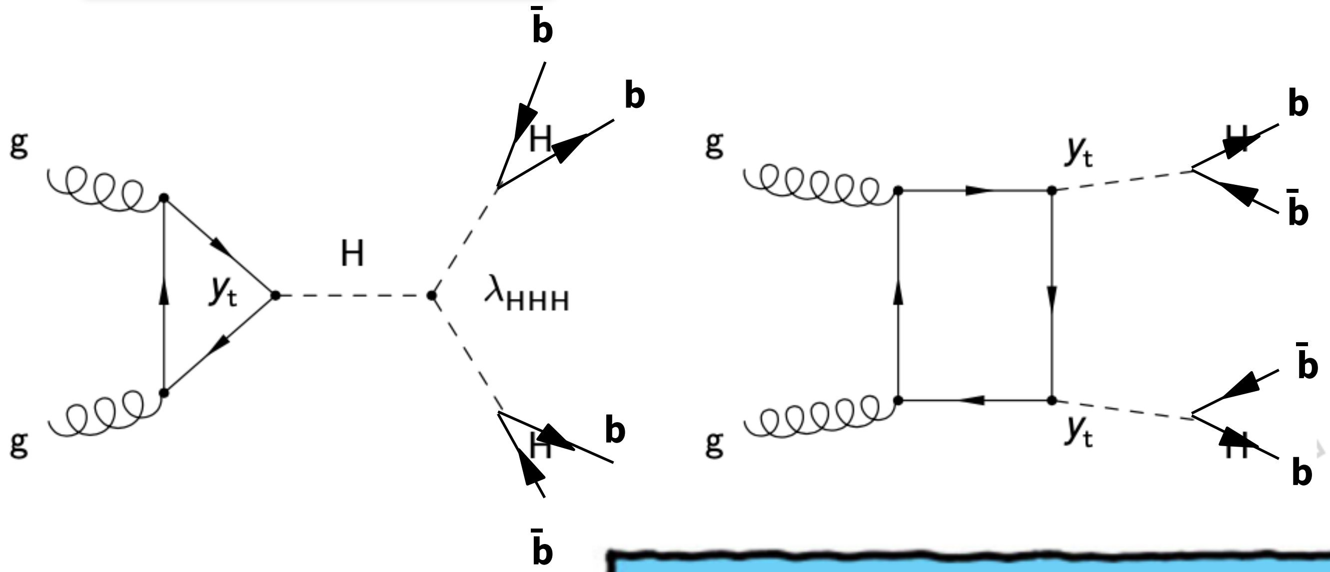
TL;DR

- ➔ We find that CMS/ATLAS can achieve >5× sensitivity improvement for di-Higgs in the *HH*→4*b* final state, with potential to observe HH even before the HL-LHC
- ➔ This gain is driven entirely by AI engineering
  - ❖ **"scaling up" improves performance** (larger models, larger datasets) and training **directly on low-level objects** (going beyond modularized objects like jets)
- ➔ We validated the method's reliability
  - ❖ successfully reproduced two prior CMS results
- ➔ We aim to deliver this within the next three years. If successful, it will be transformative for the LHC, reshaping expectations for what physics measurements are achievable

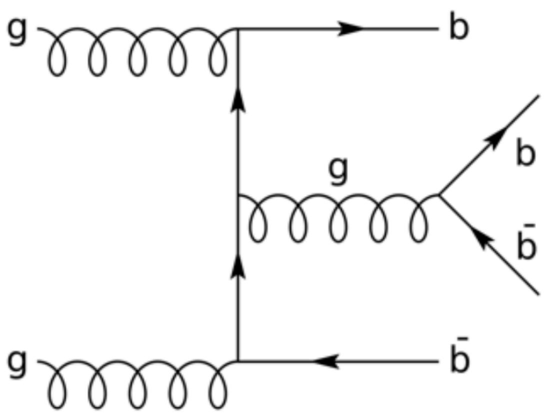
based on arXiv:2508.15048

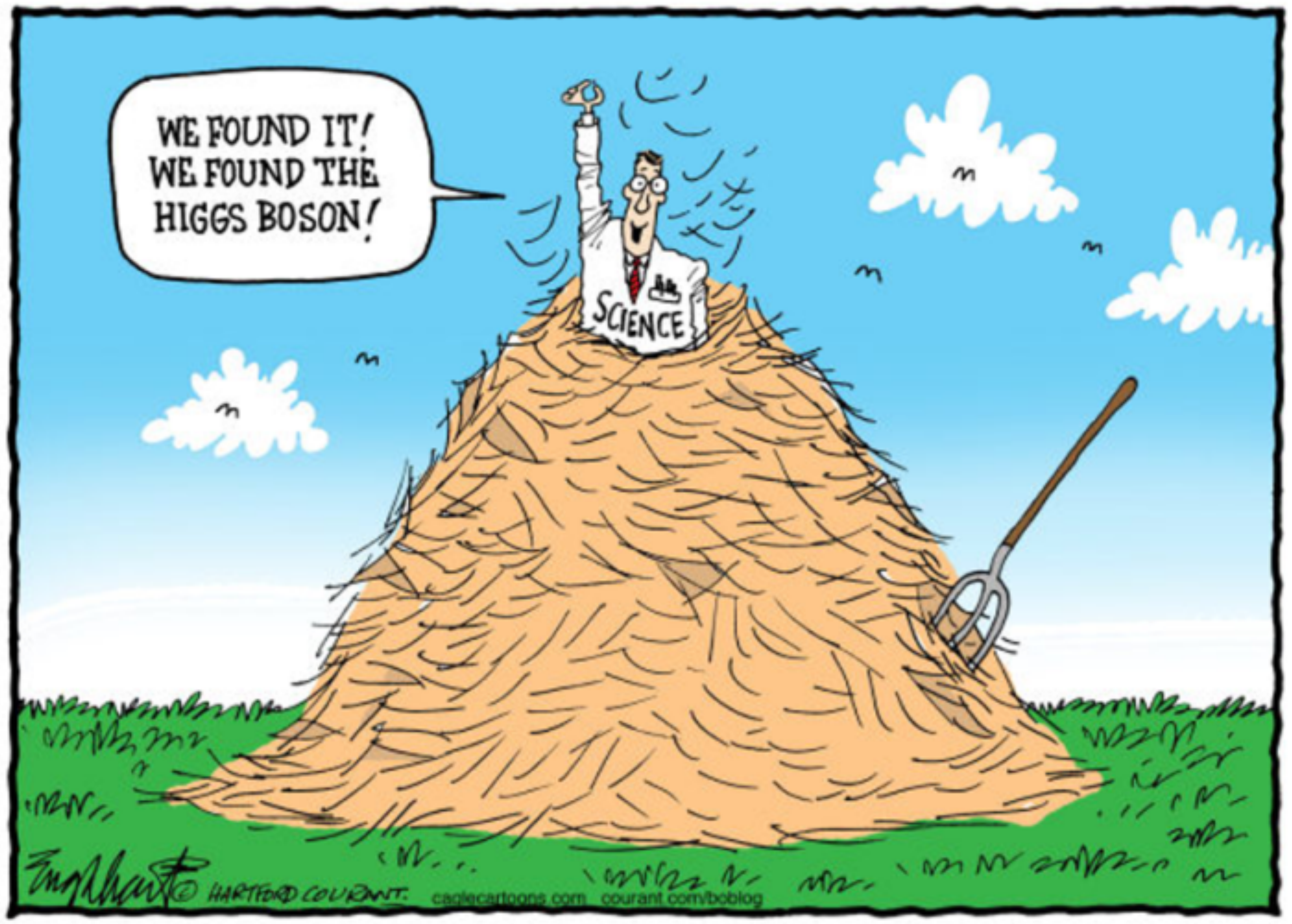
Illustrative view of the *HH*(4*b*) search

_HH_(4*b*) signal



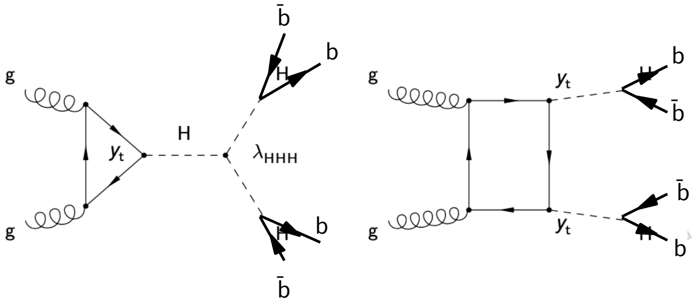
QCD background

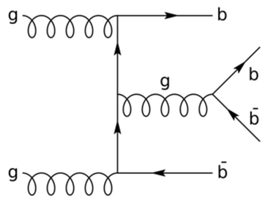




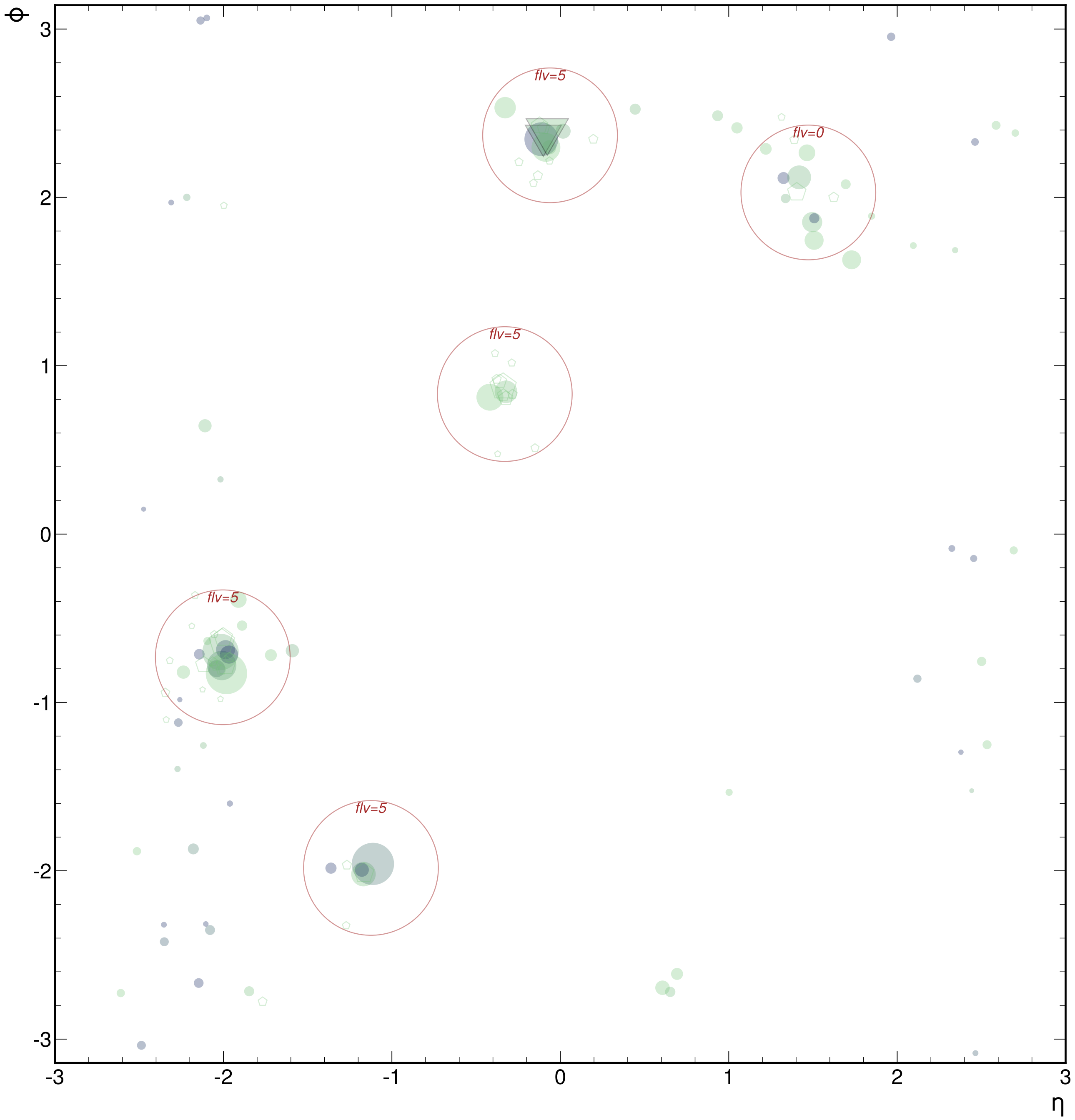
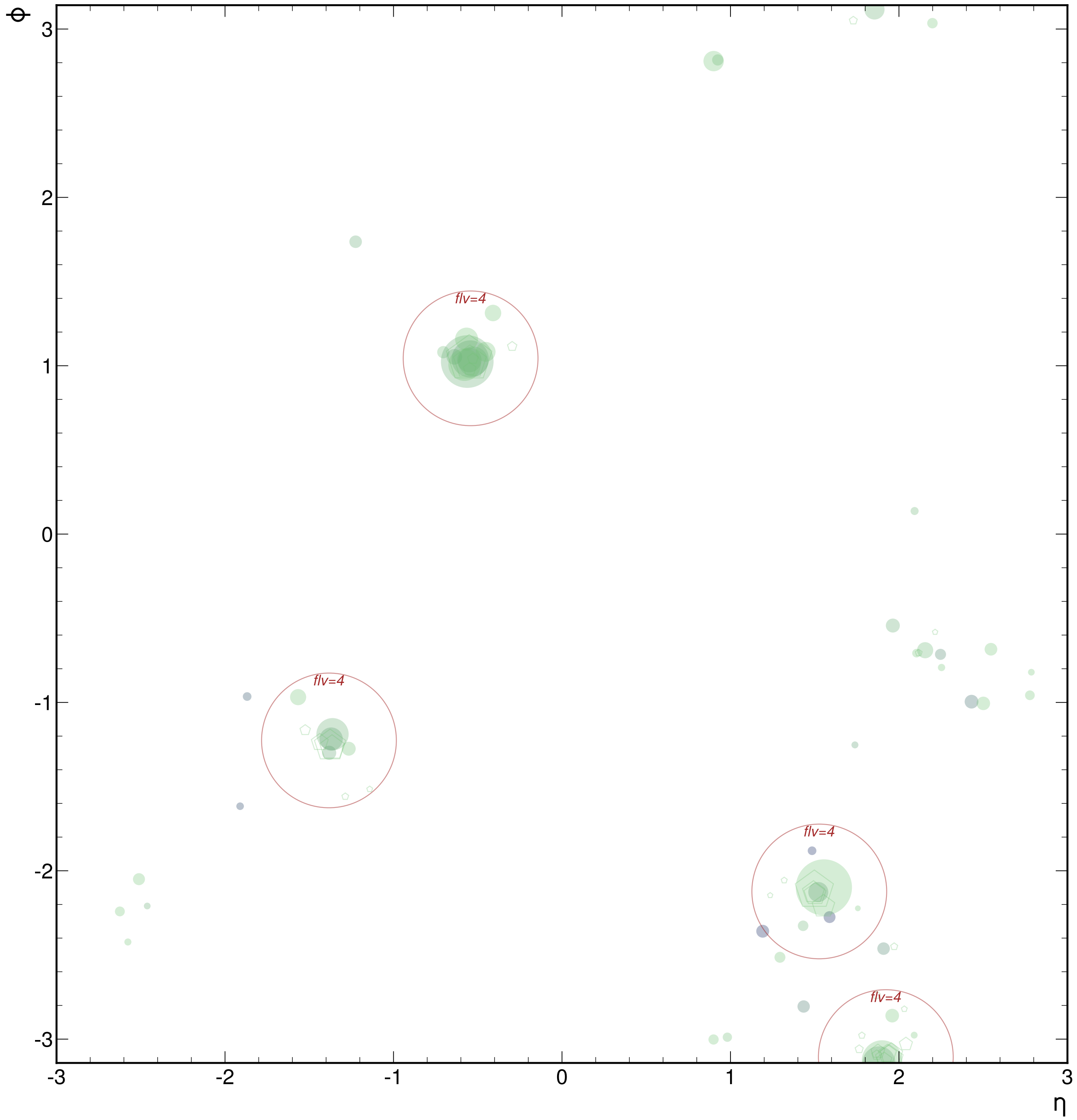
Illustrative view of the *HH*(4*b*) search

***HH*(4*b*) signal**





QCD multijet bkg.

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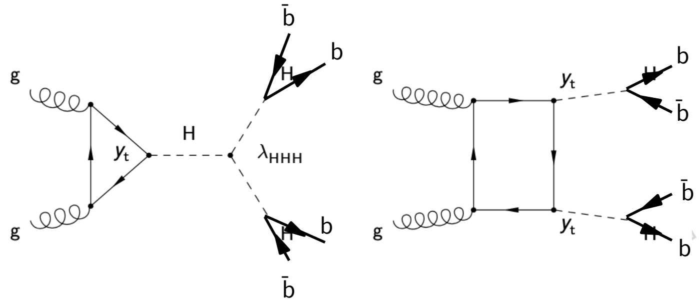

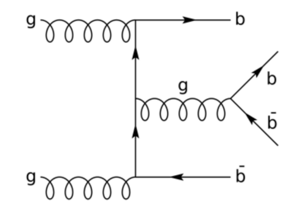

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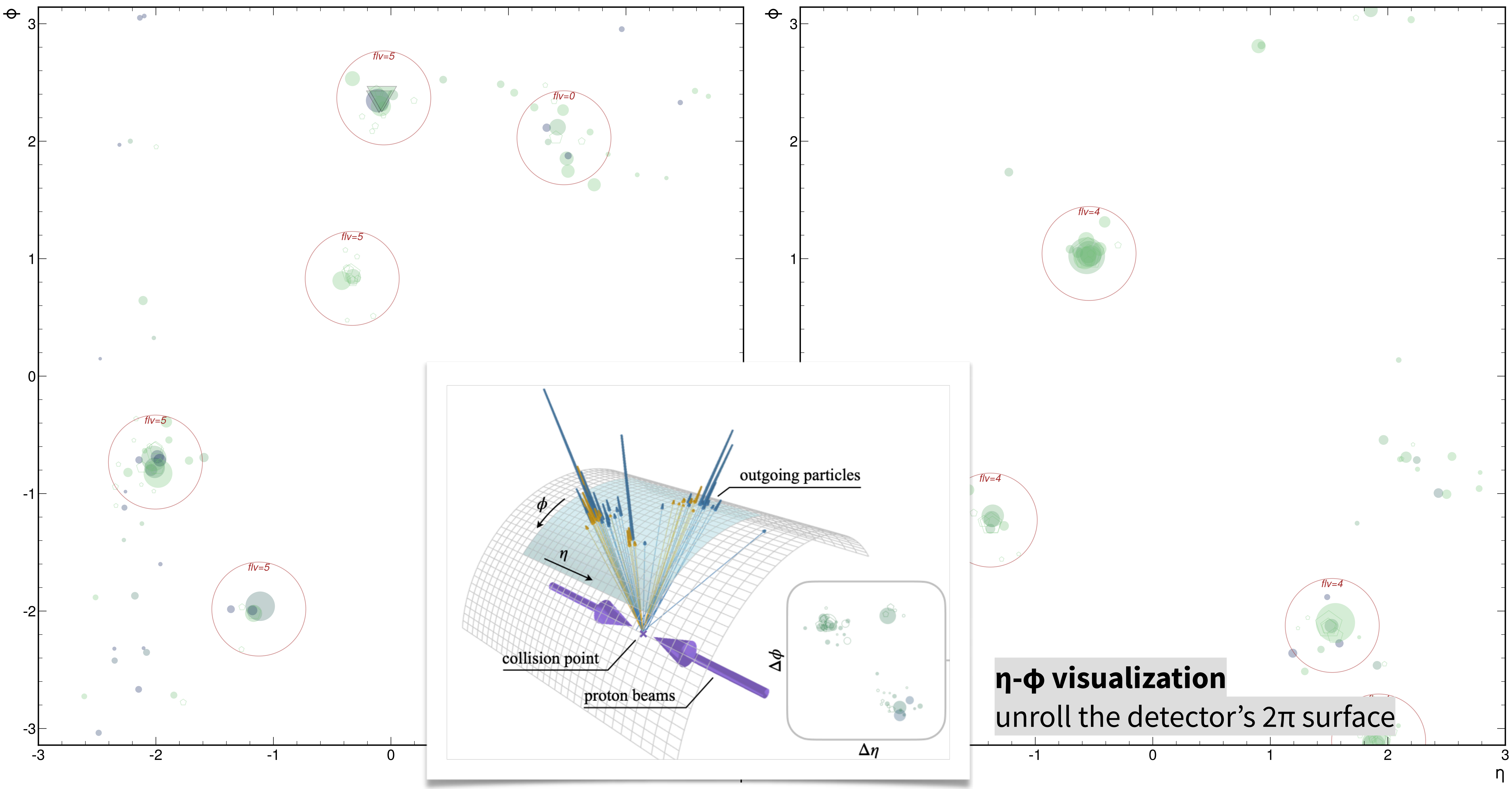
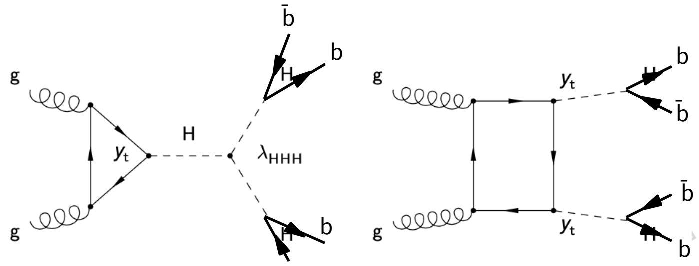


η-φ visualization
unroll the detector's 2π surface

Illustrative view of the *HH*(4*b*) search

***HH*(4*b*) signal**



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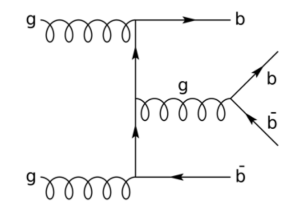

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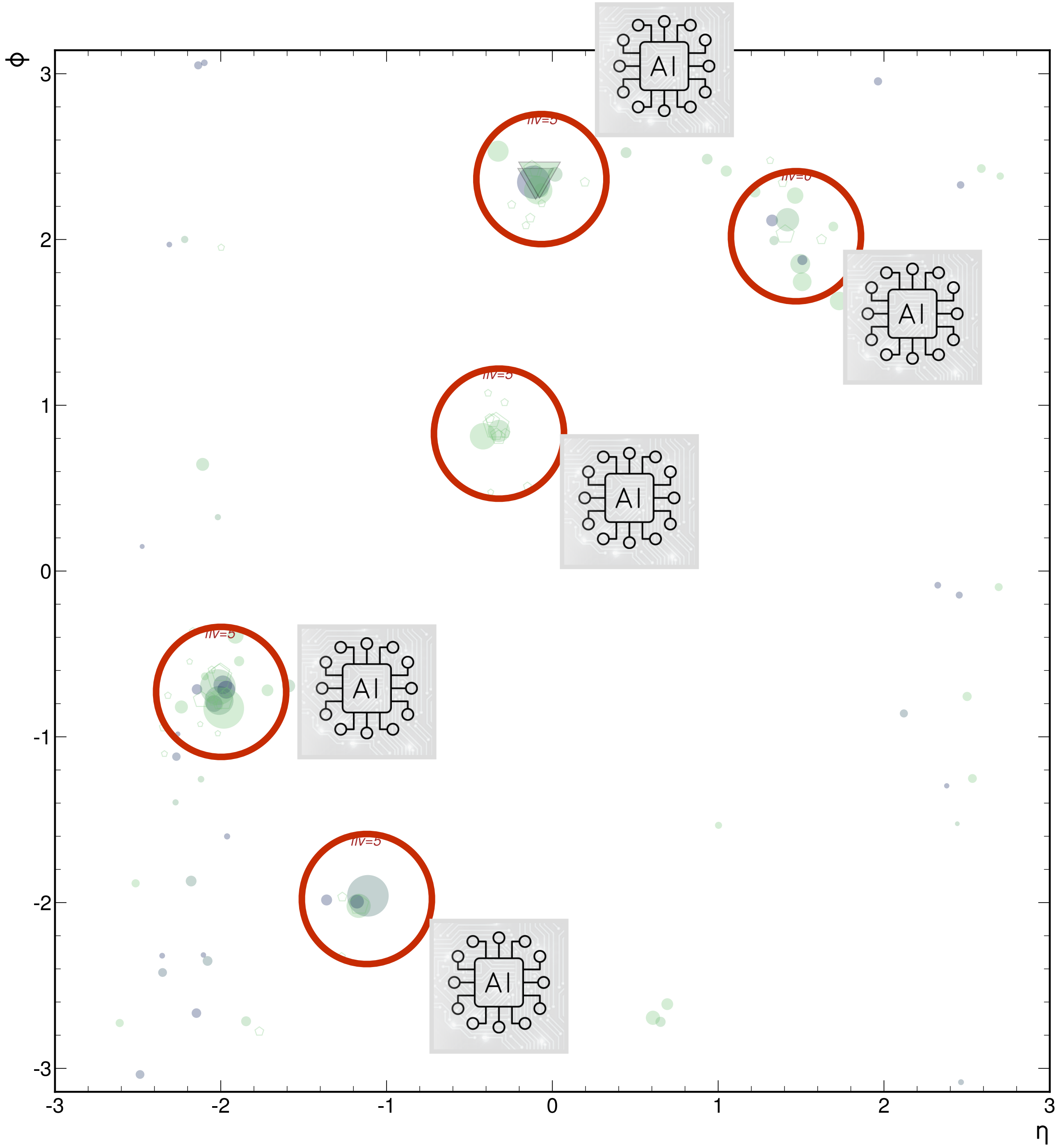

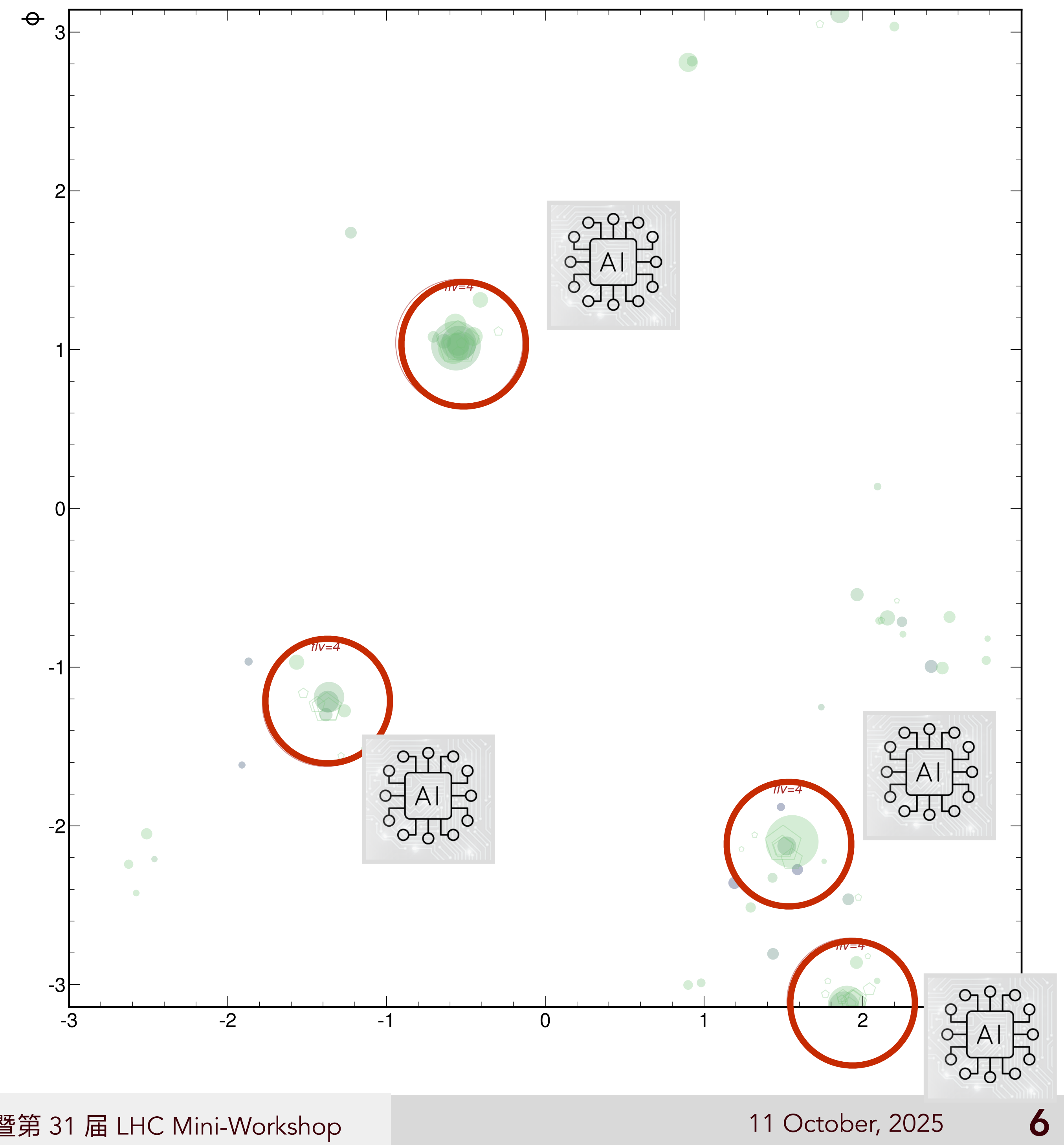

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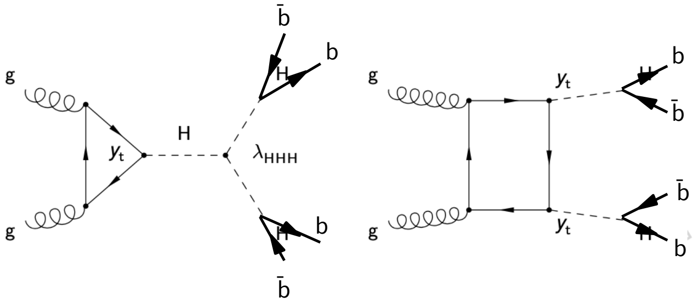

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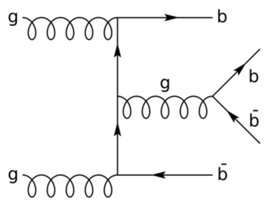

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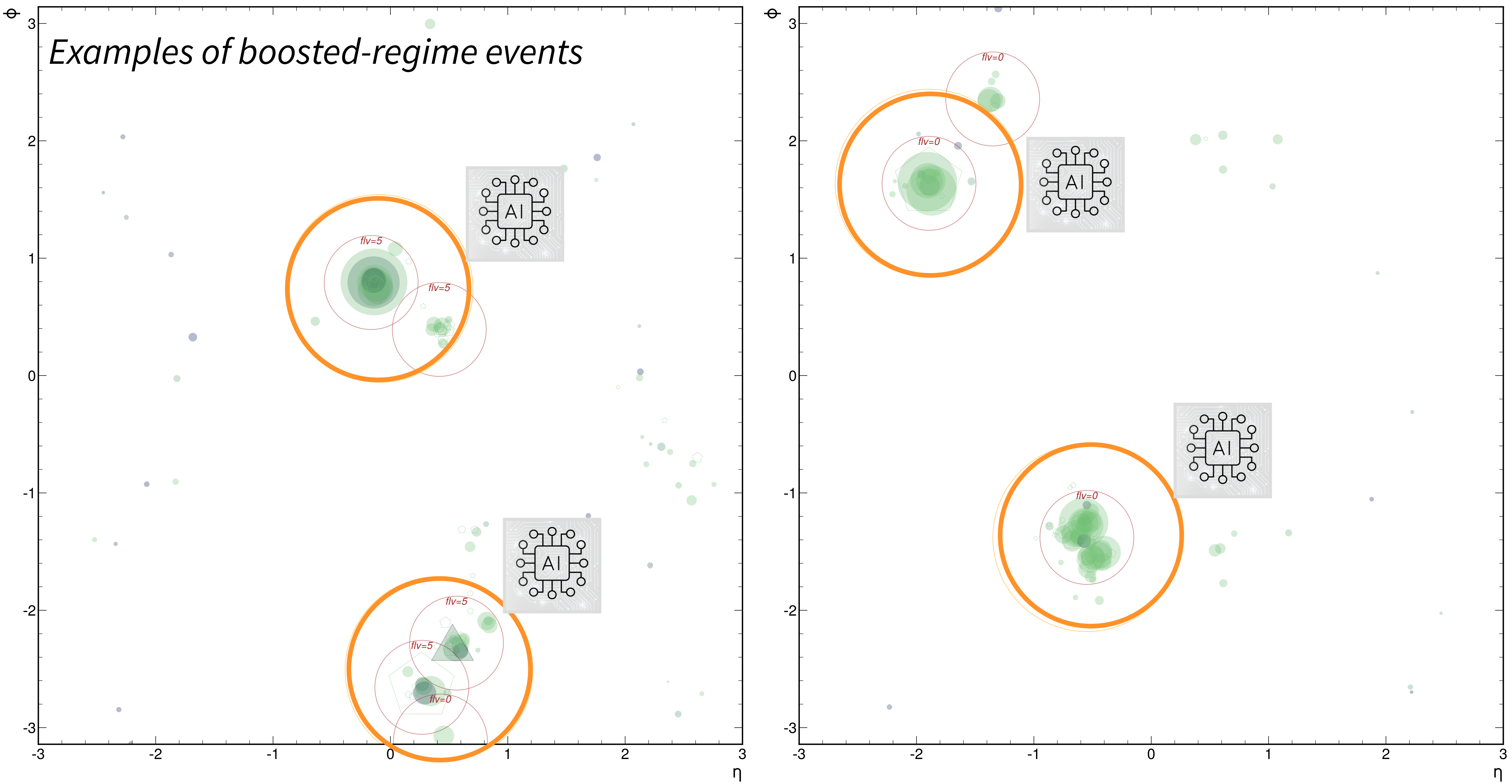
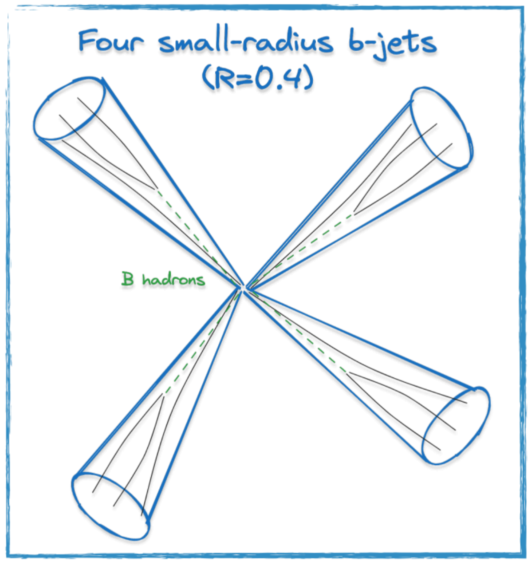


Resolved vs boosted?

Resolved regime



ATLAS papers:
1. ggF+VBF resolved
2. VBF boosted

PRL 129 (2022) 081802

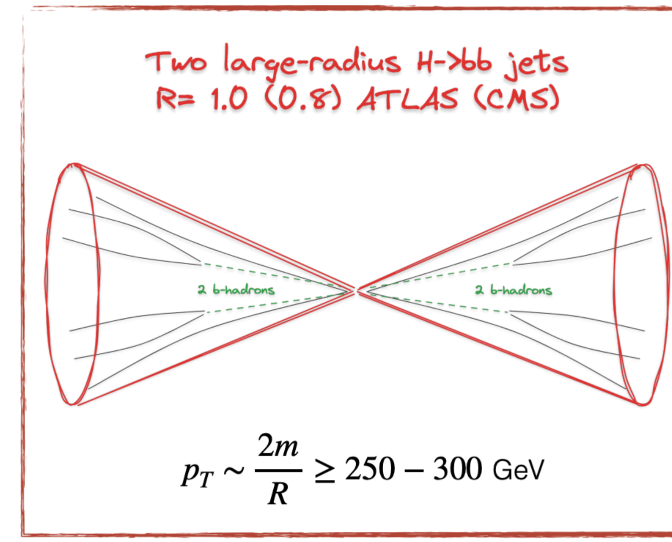
results website

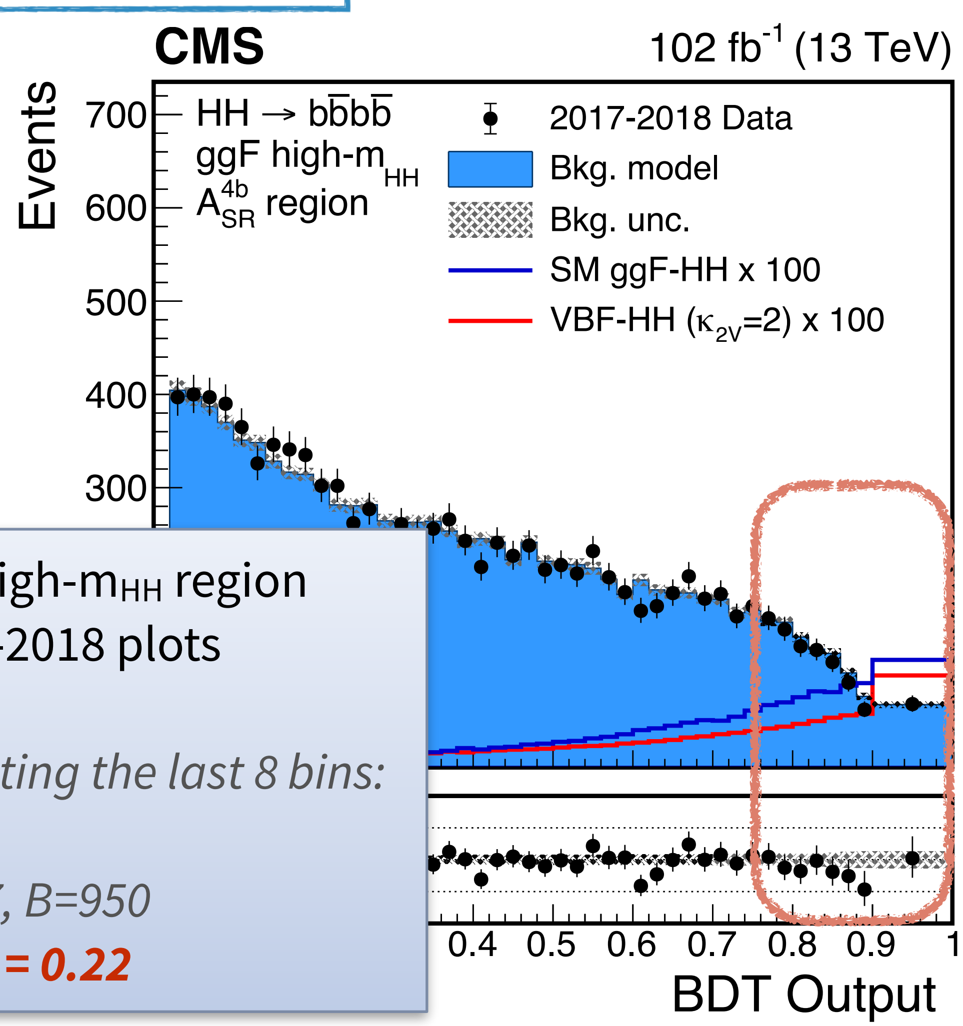
CMS papers:
1. ggF+VBF resolved
2. ggF+VBF boosted
3. ZZ/ZH in 4b resolved

PRL 131 (2023) 041803

results website

Boosted regime



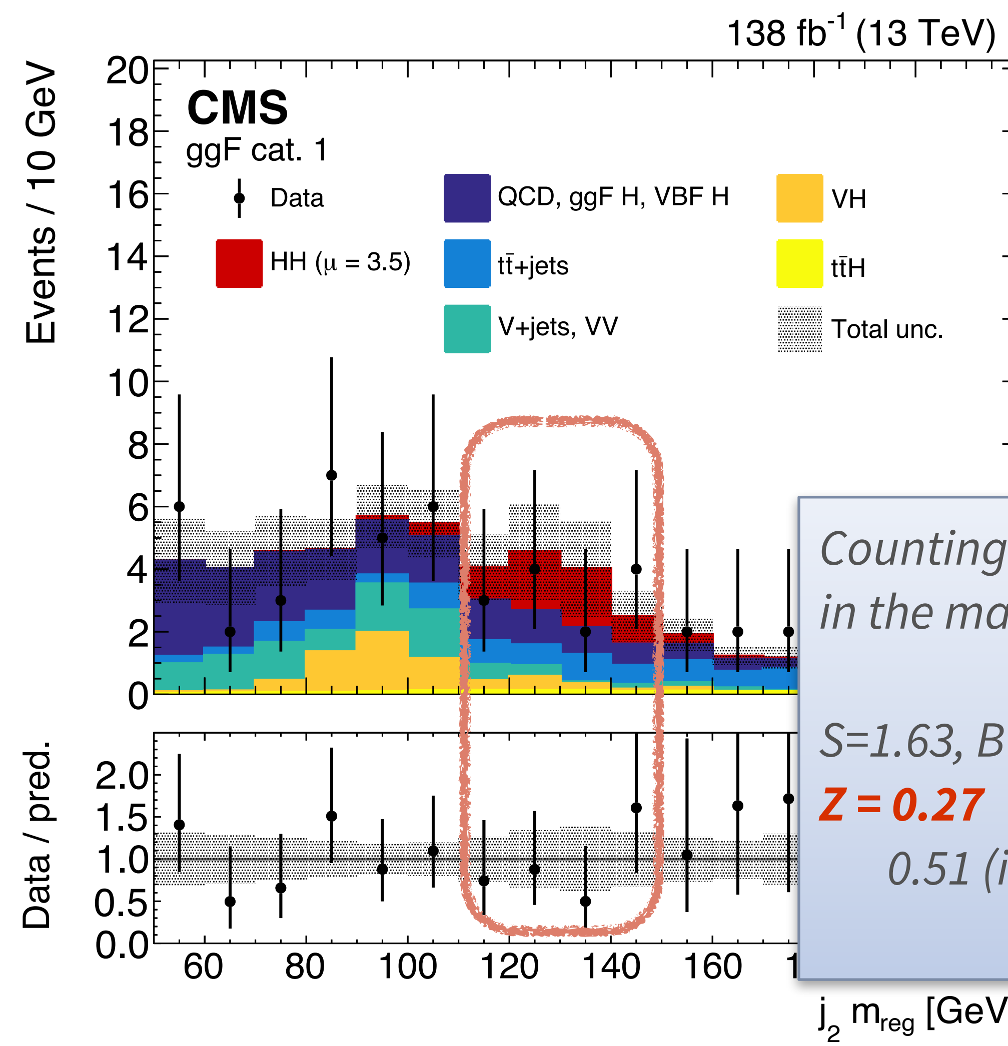


the high-m_{HH} region
2017-2018 plots

Counting the last 8 bins:

S=6.7, B=950

S/√B = 0.22



Counting the 4 bins in the mass window:

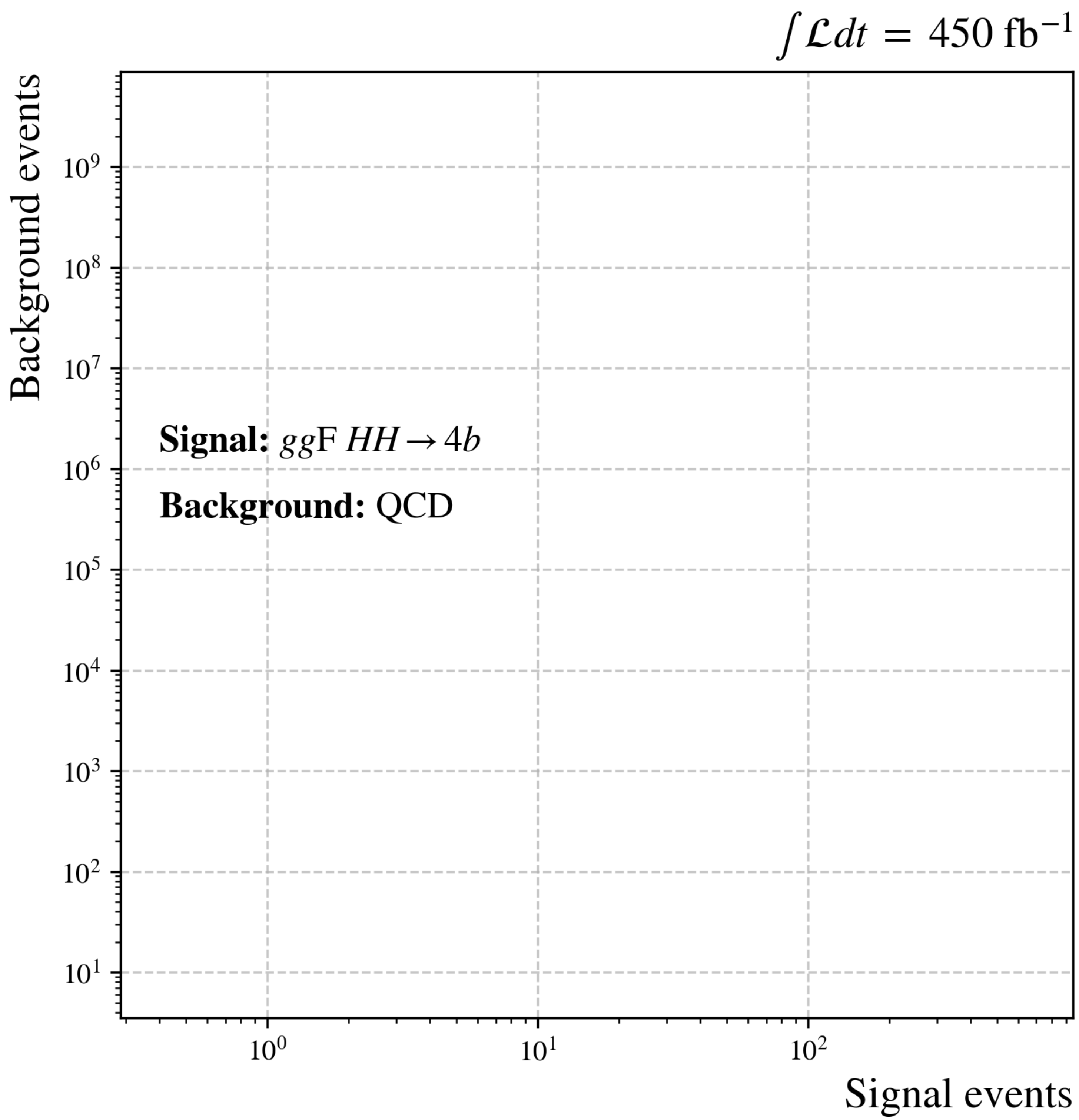
S=1.63, B=9.5, σ_B=4.9

Z = 0.27

0.51 (if B is certain)

Reproducing CMS's *HH*→4*b* results

→ First, reproduce CMS's ***HH*→4*b*** results using our highly realistic Delphes simulation



introducing the N(signal) vs N(bkg.) canvas

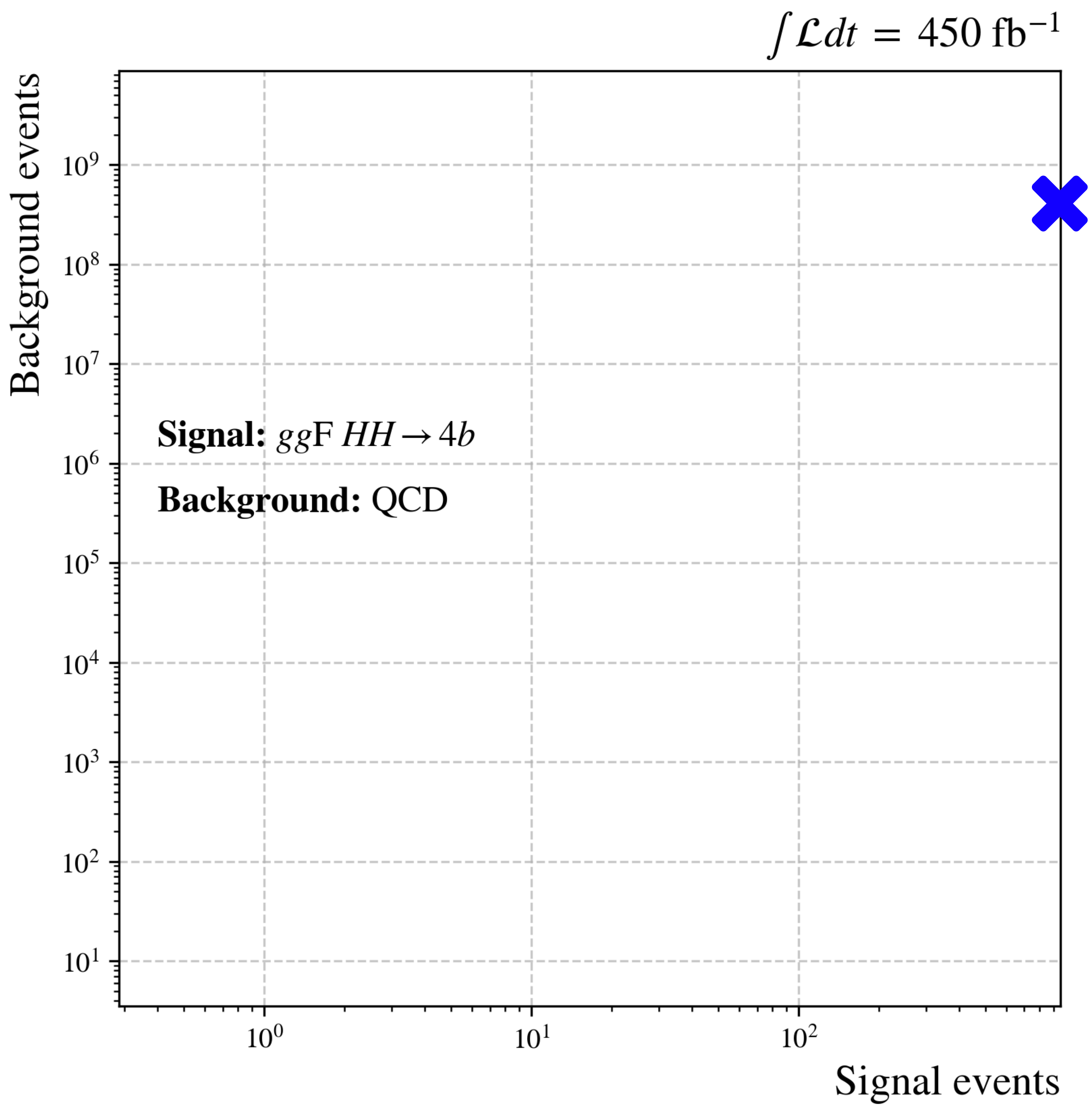
Concept:

✦ each "cut" can be visualized as a point on this canvas.

✦ **a "dynamic cut" forms a curve**—effectively a ROC curve scaled by total signal/bkg. event counts

Reproducing CMS's *HH→4b* results

➔ First, reproduce CMS's ***HH→4b*** results using our highly realistic Delphes simulation



Events (100 fb^{-1}) passing resolved *HH4b* triggers

Mimic CMS's 2018 trigger ("4j3b"):

- ✦ H_T (AK4 p_T>30 GeV) > 330 GeV
- ✦ four jet p_T > 75/60/45/40 GeV
- ✦ ≥ 3 b-tagged jets (SophonAK4 loose b-tag WP: ε_l = 10%)

After trigger selection (under 450 fb^{-1})**:**

Signal (ggF *HH4b*): 960
Bkg. (QCD multijets): 3.5e8 (rate@2e34 ≈ 18 Hz)
pretty realistic!

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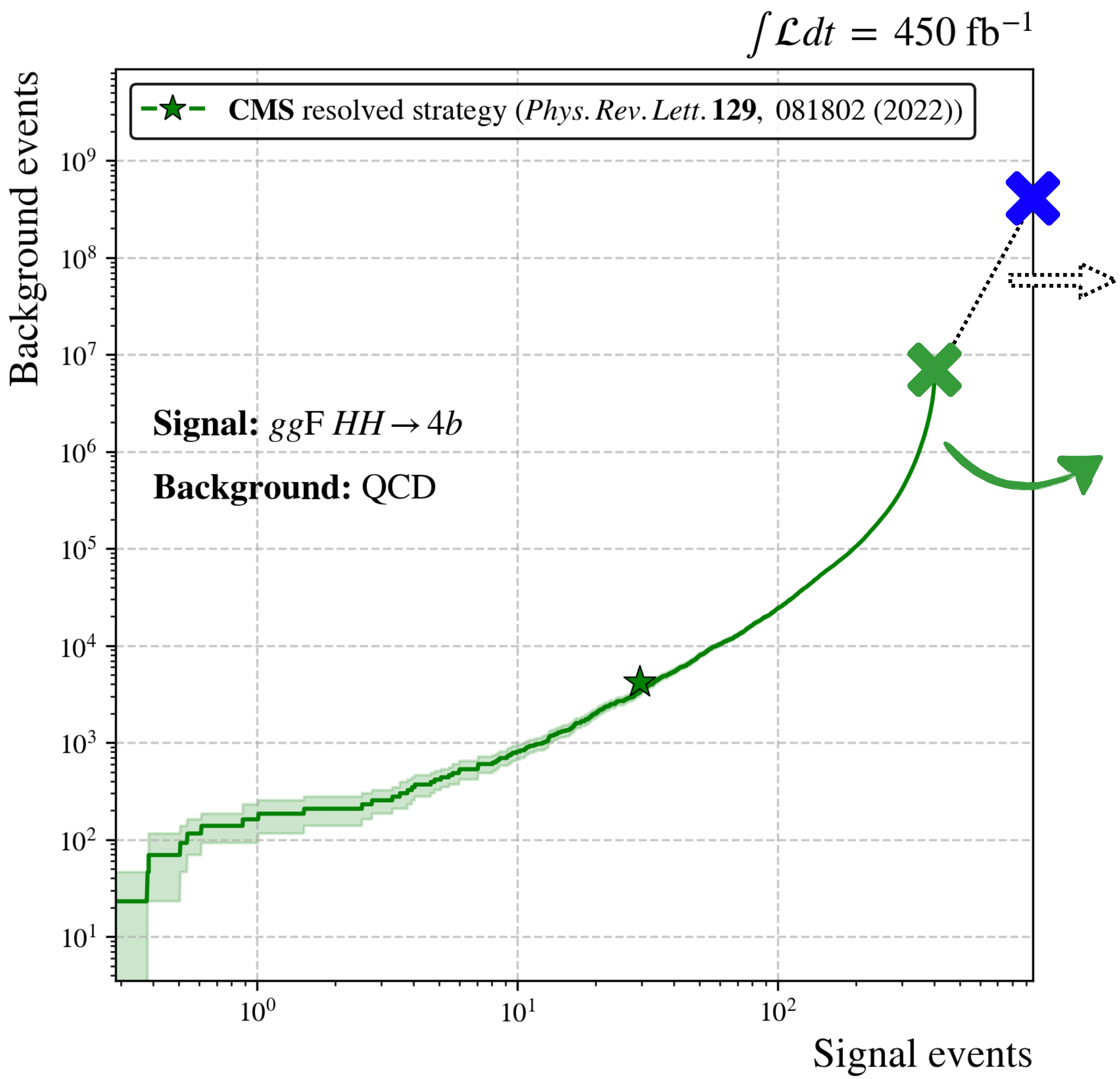

Further require all four leading jets to be b-tagged at *medium WP* (ε_l = 1%)

Then train a ParT classifier, using four jets' kinematic inputs to distinguish signal events vs QCD.
(ParT algorithm constructs ΔR, m_{ij} of all jet pairs, effectively enabling jet-pair association.)

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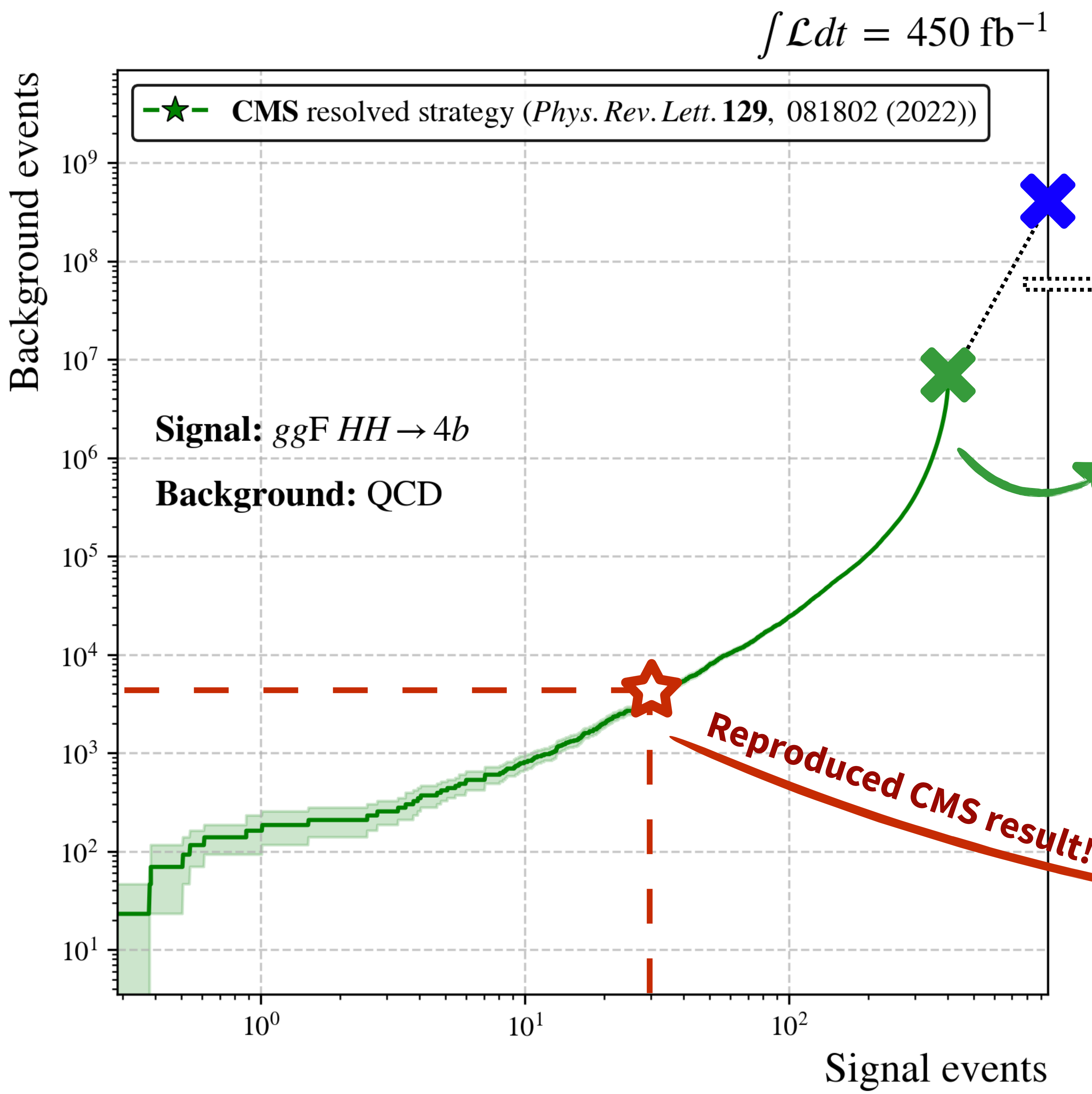

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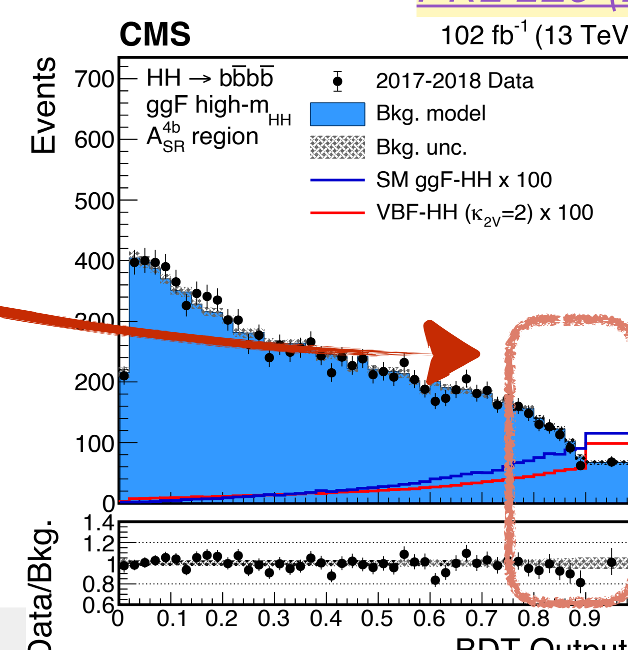
PRL 129 (2022) 081802



S=6.7
B=950

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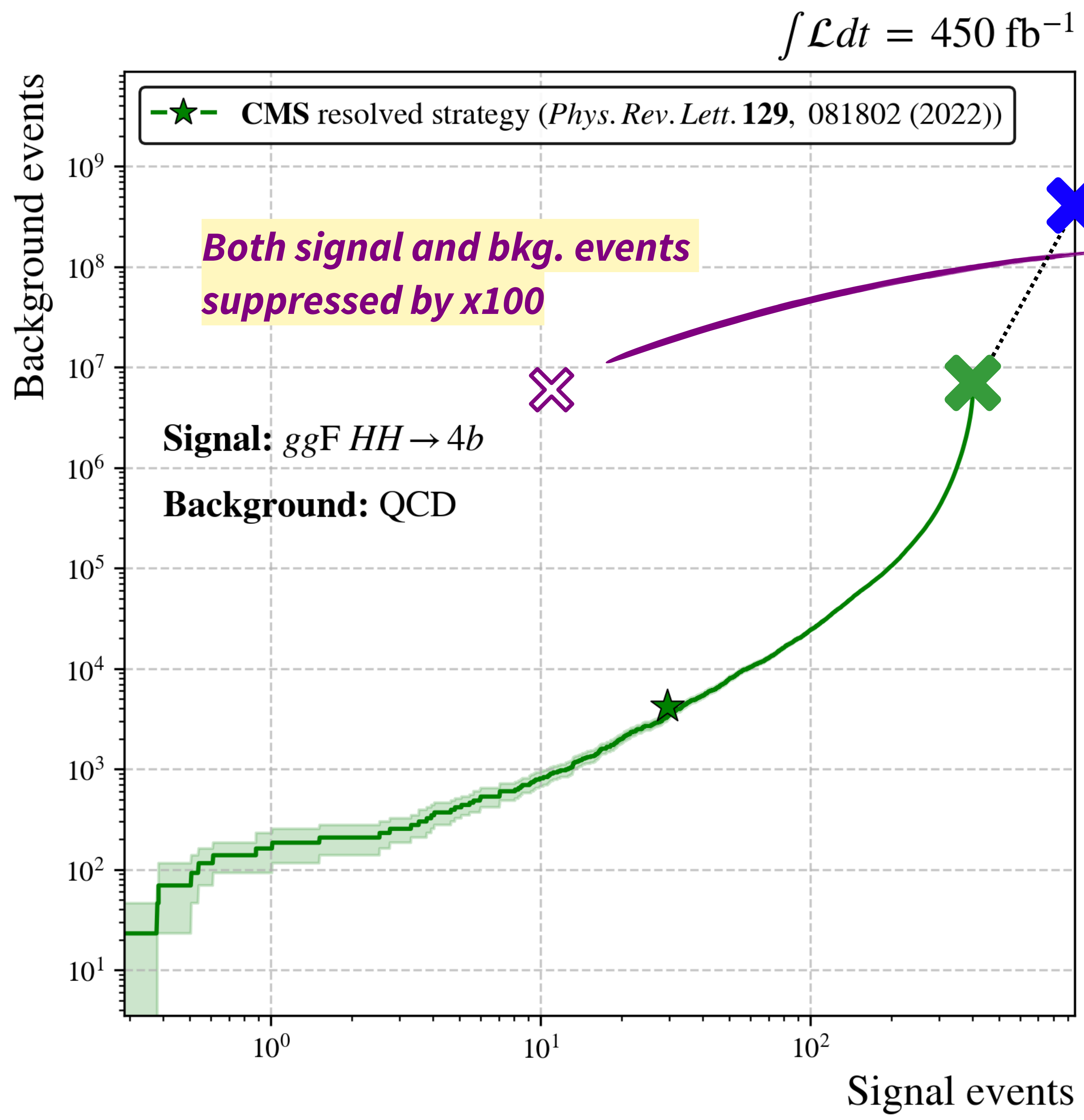
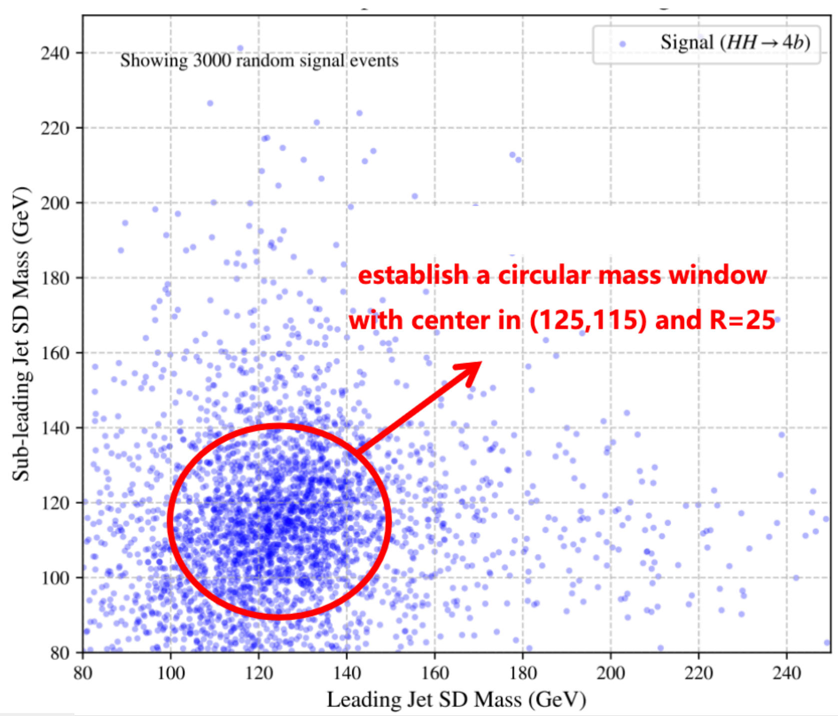


Then, we reproduce boosted *HH4b* results

① **Events (100 fb^{-1}) passing boosted-jet triggers**

Mimic CMS's typical boosted-jet trigger:
- ✦ H_T (AK8 p_T>200 GeV) > 800 GeV
- ✦ leading AK8 jet trimmed mass > 50 GeV

② **And further require two leading jets to have soft-drop masses within the circle:**
- centered at (125, 115) with *R*=25 GeV



Reproducing CMS's *HH*→4*b* results

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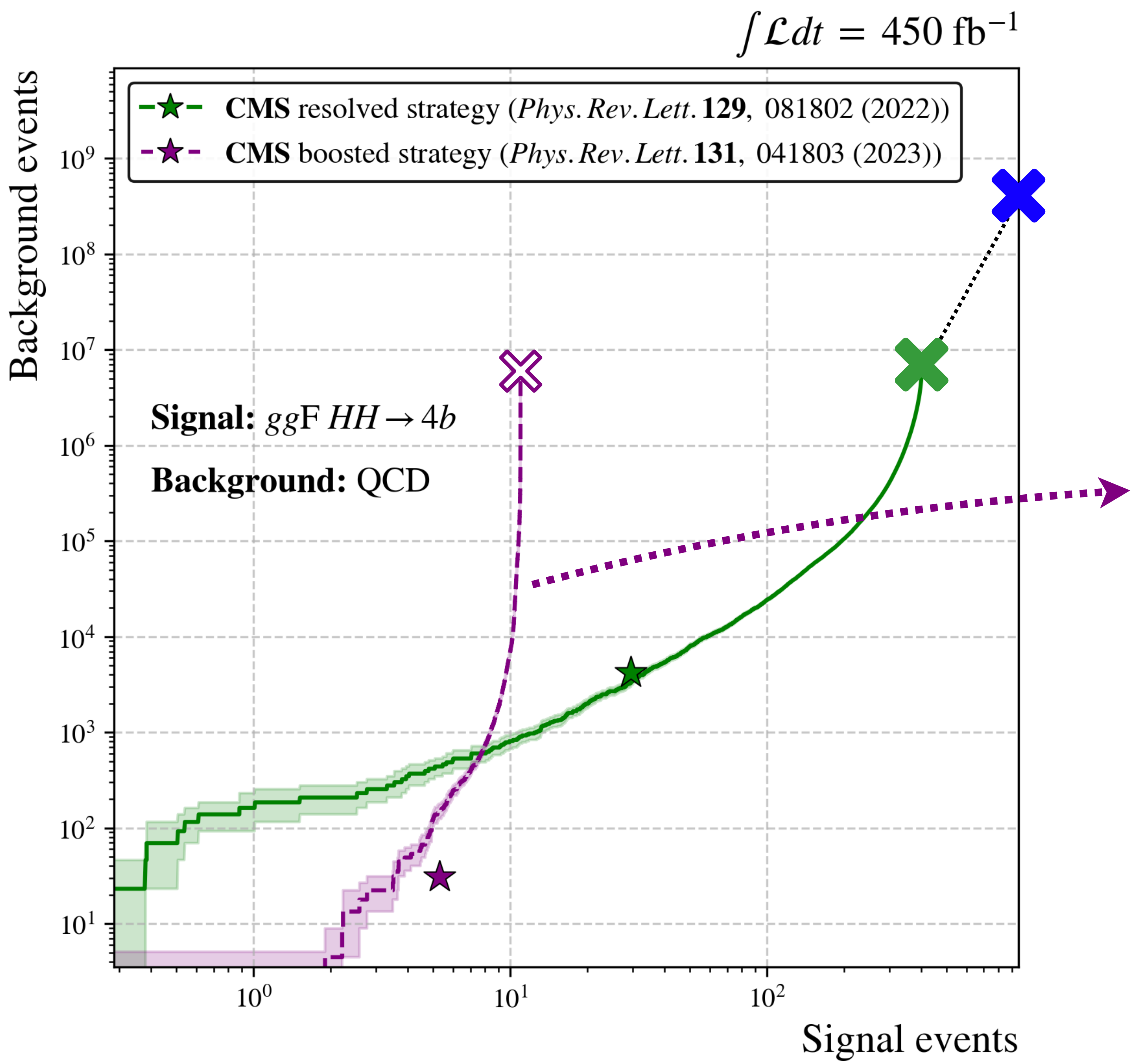

But the QCD suppression power is "astonishingly" powerful

using the sum of two AK8 jets' **Sophon (AK8) XbbvsQCD scores** as the discriminator

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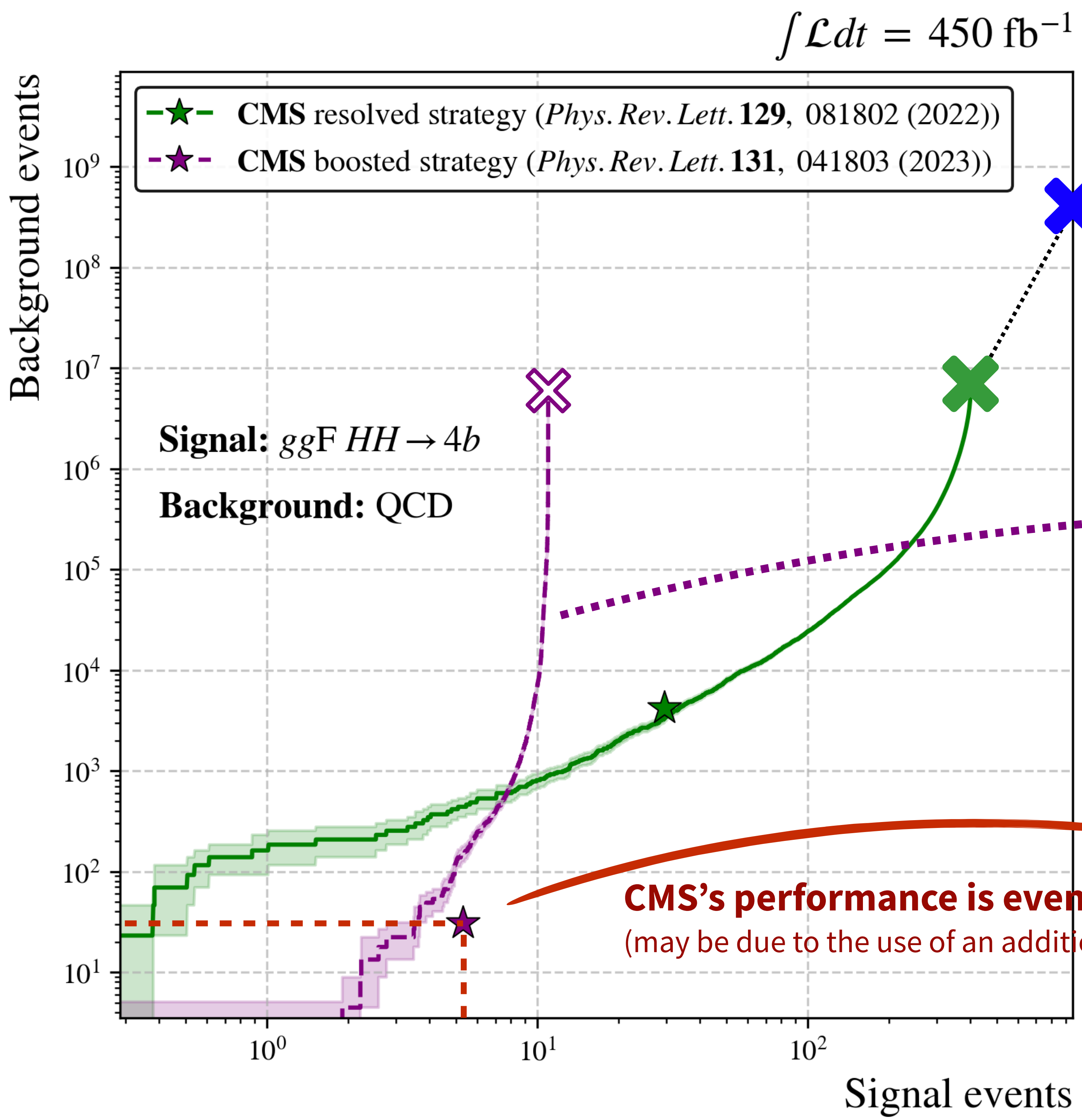
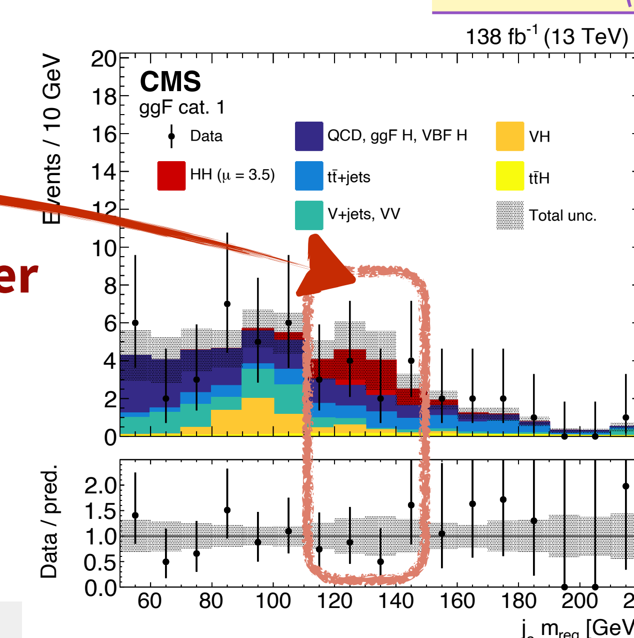


CMS's performance is even stronger
(may be due to the use of an additional BDT)

But the QCD suppression power is "astonishingly" powerful

using the sum of two AK8 jets' **Sophon (AK8) XbbvsQCD scores** as the discriminator

PRL 131 (2023) 041803



S=1.63

B(QCD)≈4.1

Reproducing CMS's *HH→4b* results

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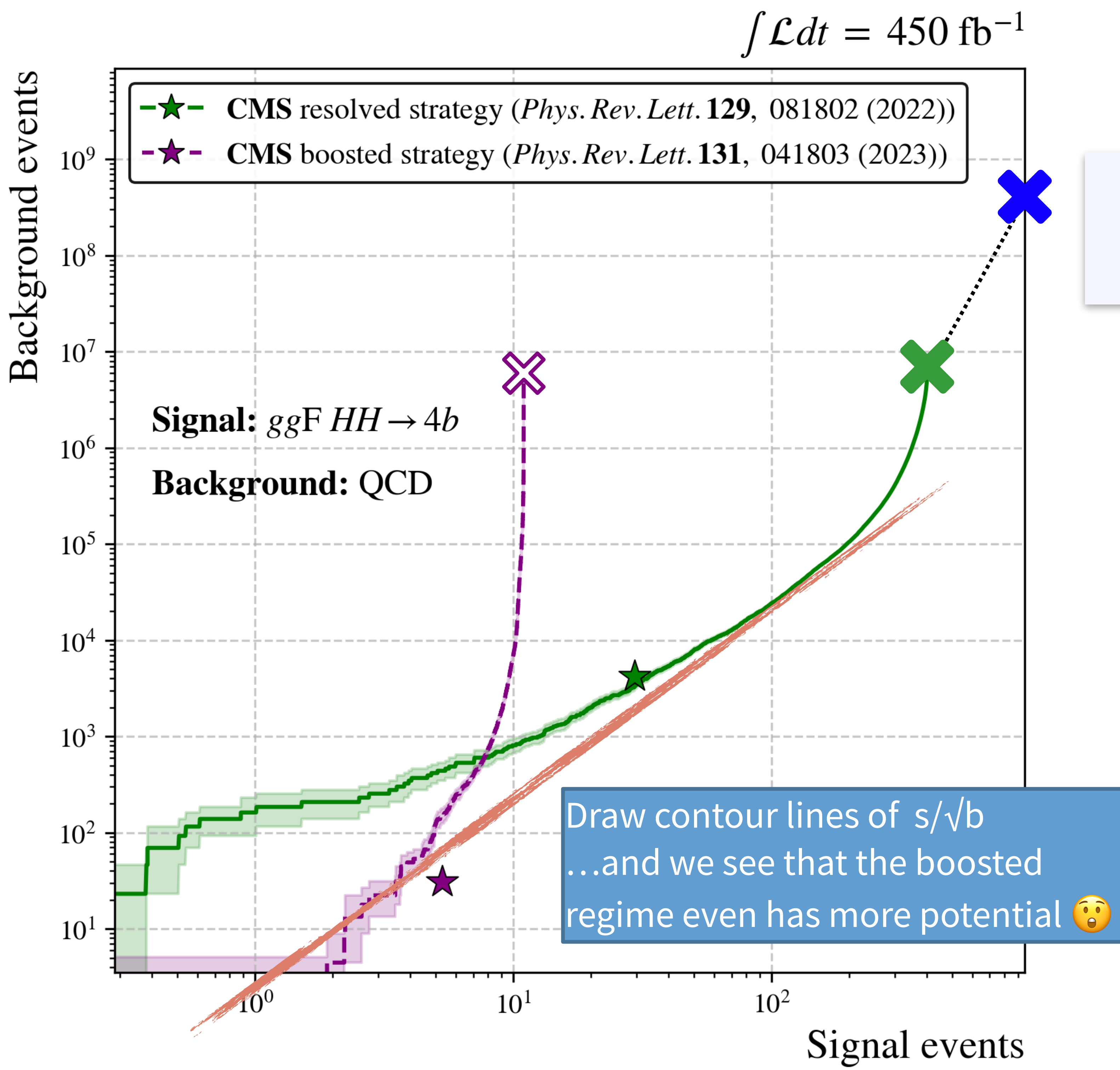

Remarks from comparison of CMS's resolved & boosted analyses

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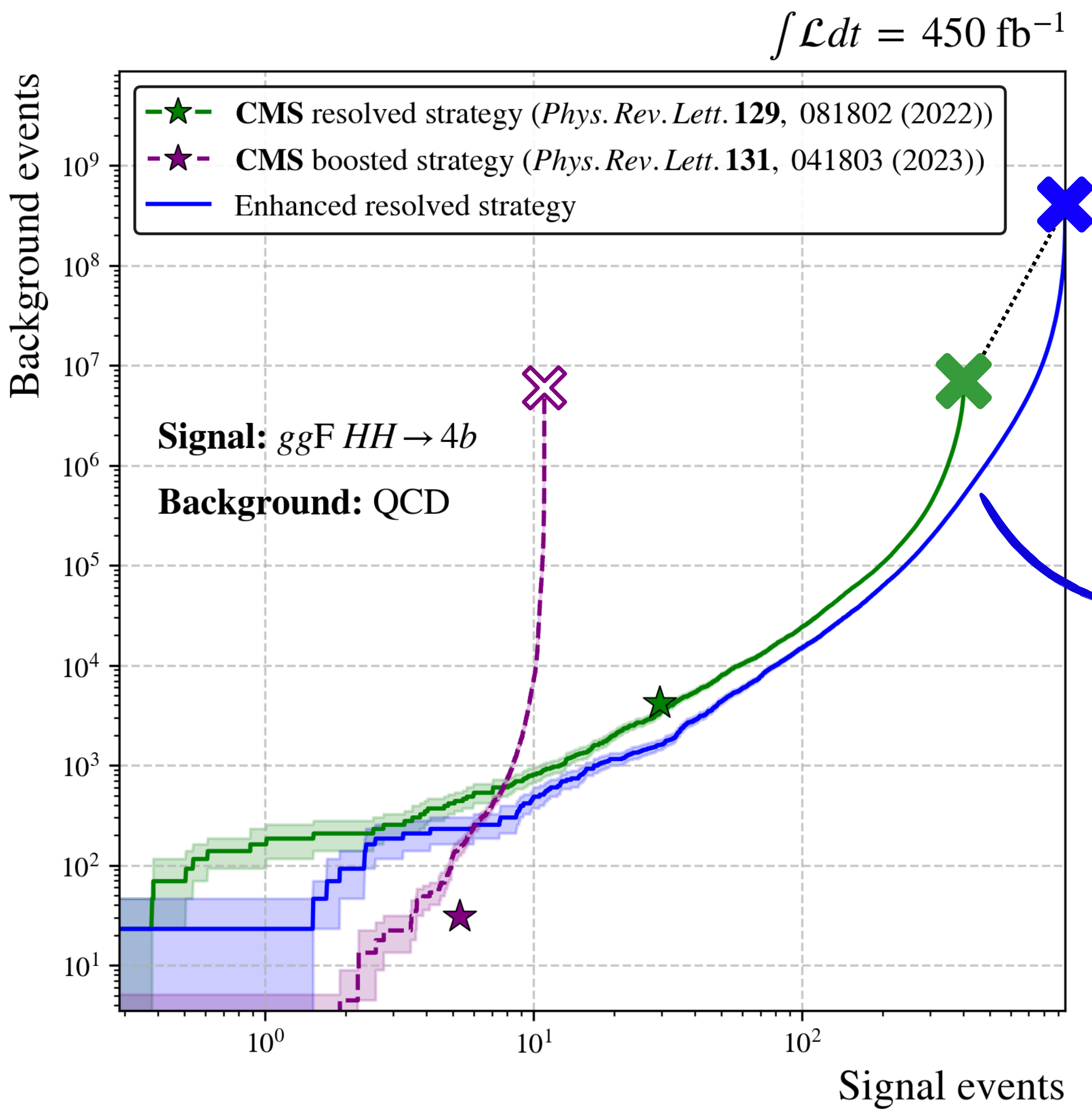

Remarks from comparison of CMS's resolved & boosted analyses

But… can we improve the resolved-regime strategy?
😕 Unfortunately, if we insist on using AK4 jets in the resolved regime, we yield only marginal gains.

Here, we benchmark the best achievable performance relying on small-*R* jets

Train a ParT on events passing resolved triggers, utilizing full AK4 jet information—including tagging scores

Reproducing CMS's *HH*→4*b* results

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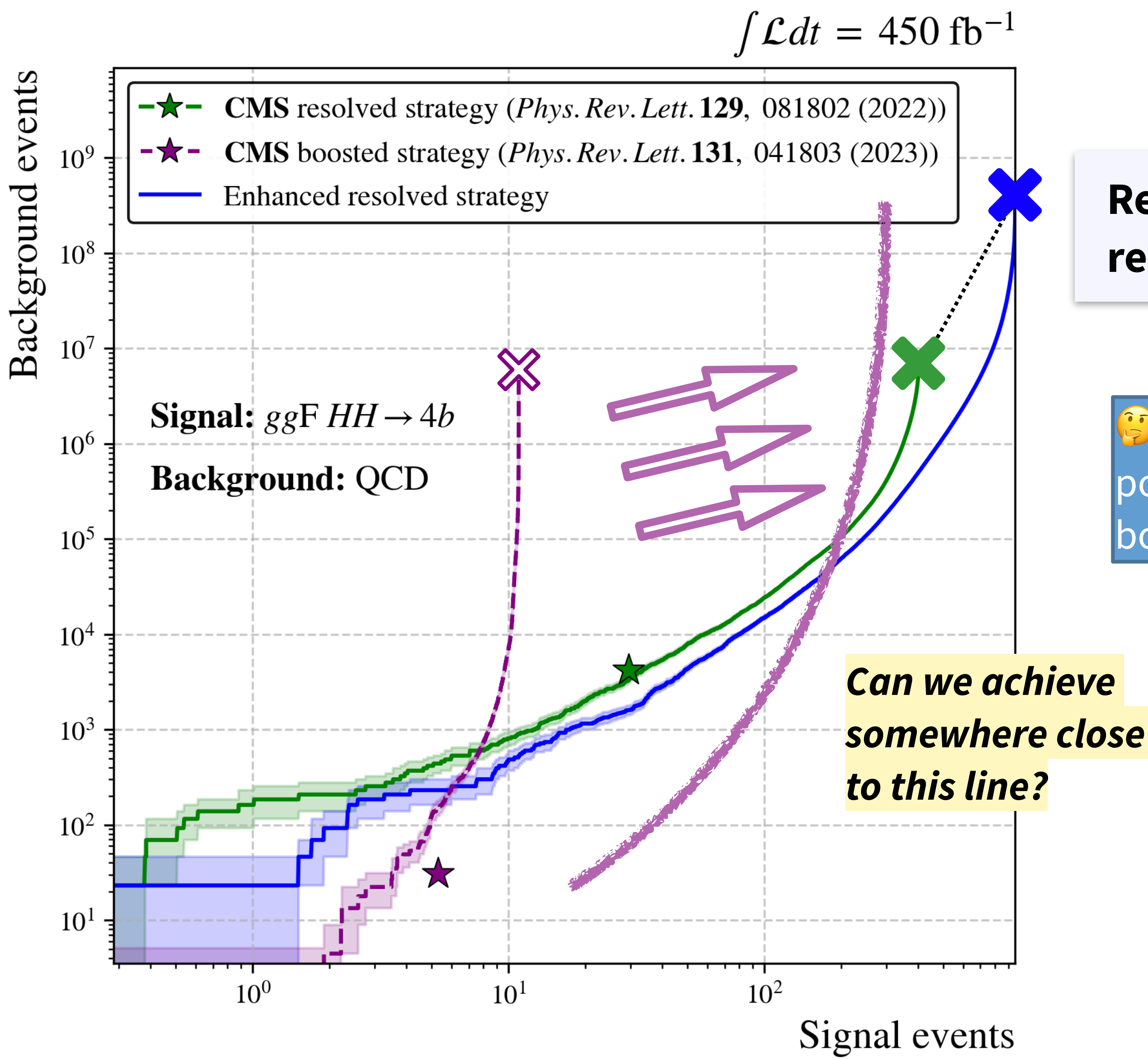

Remarks from comparison of CMS's resolved & boosted analyses

🤔 Naively, the strong discriminative power should generalize across all boosting conditions.

Reproducing CMS's *HH→4b* results

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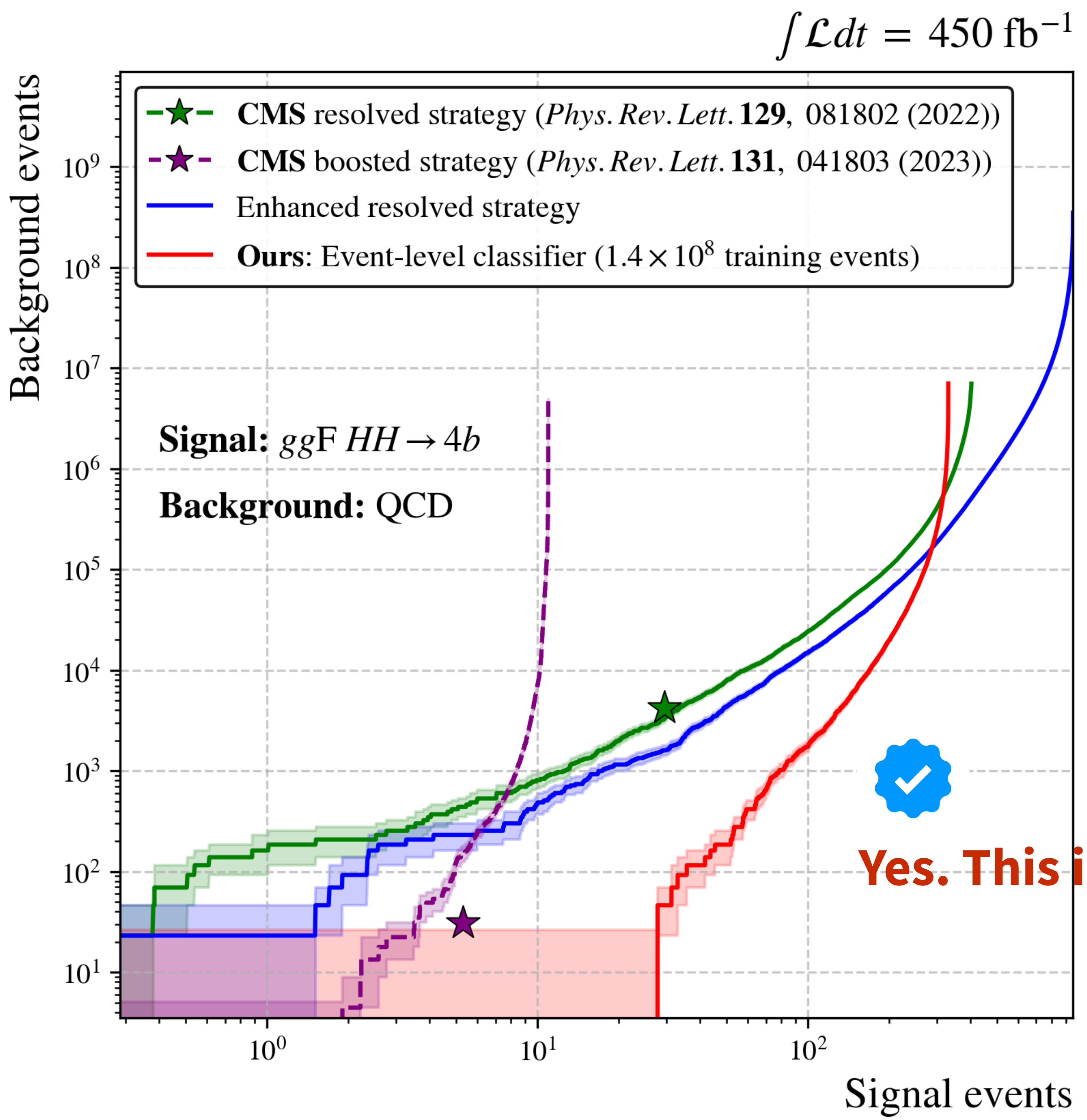


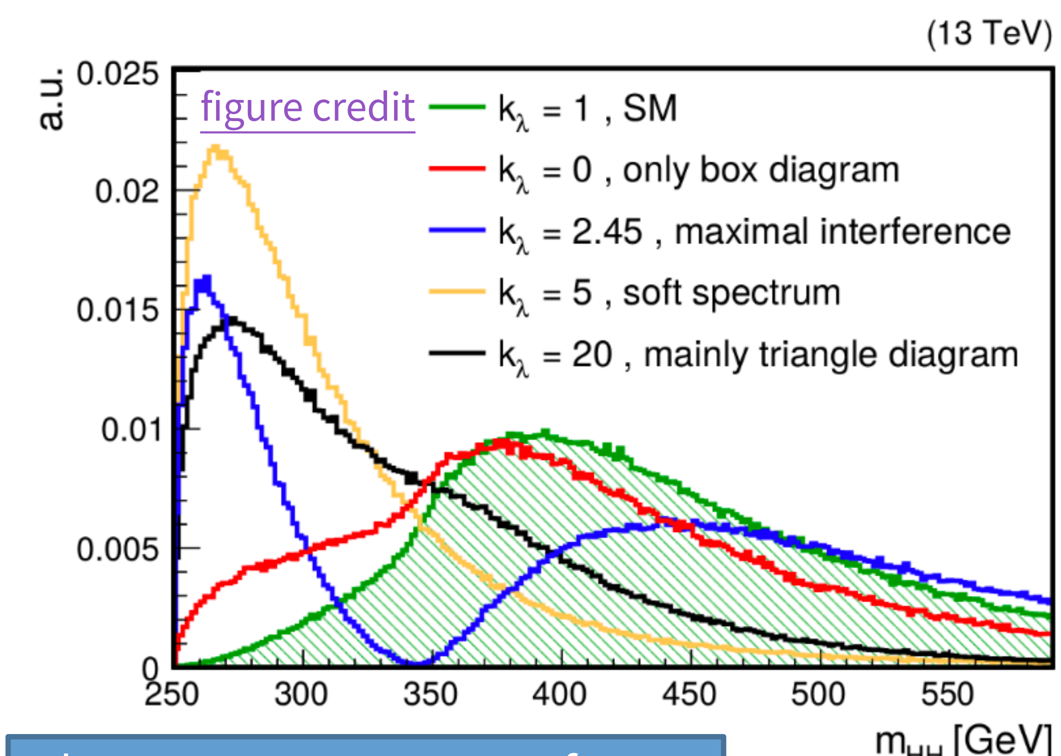
Yes. This is achievable.

Introducing our *HH4b* strategy

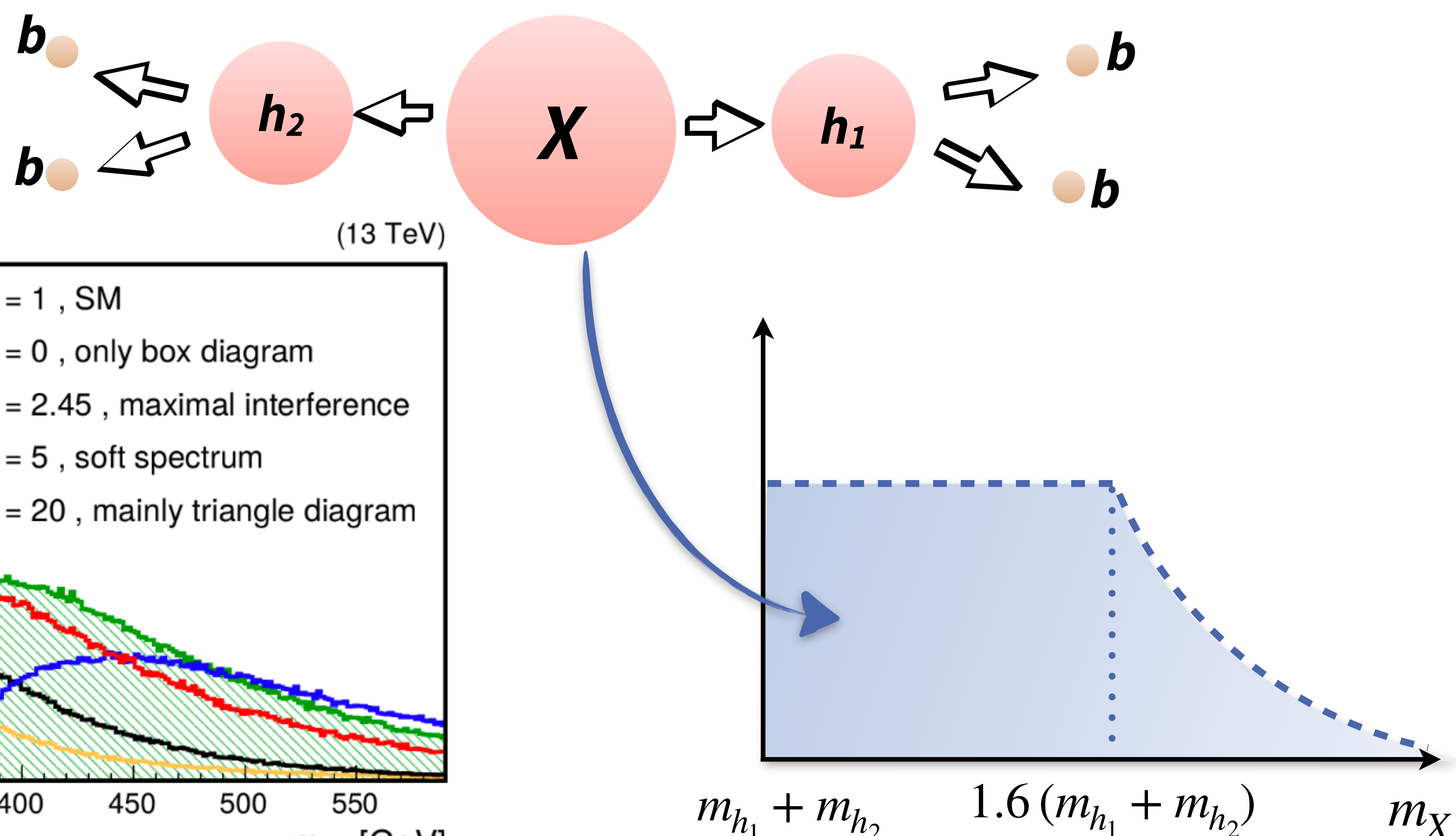
Analysis strategy: training a $X\to h_1h_2\to 4b$ vs bkg. classifier

➔ Train "$X\to h_1h_2\to 4b$" signal versus QCD and $t\bar{t}$ (passing the "4j3b" resolved trigger!)

- h_1 and h_2 masses: uniformly distributed in [40, 200] GeV
- X mass → taking various HH→4b topologies as a reference
- using full-event particle-level inputs



Take m_{HH} spectrum as a reference



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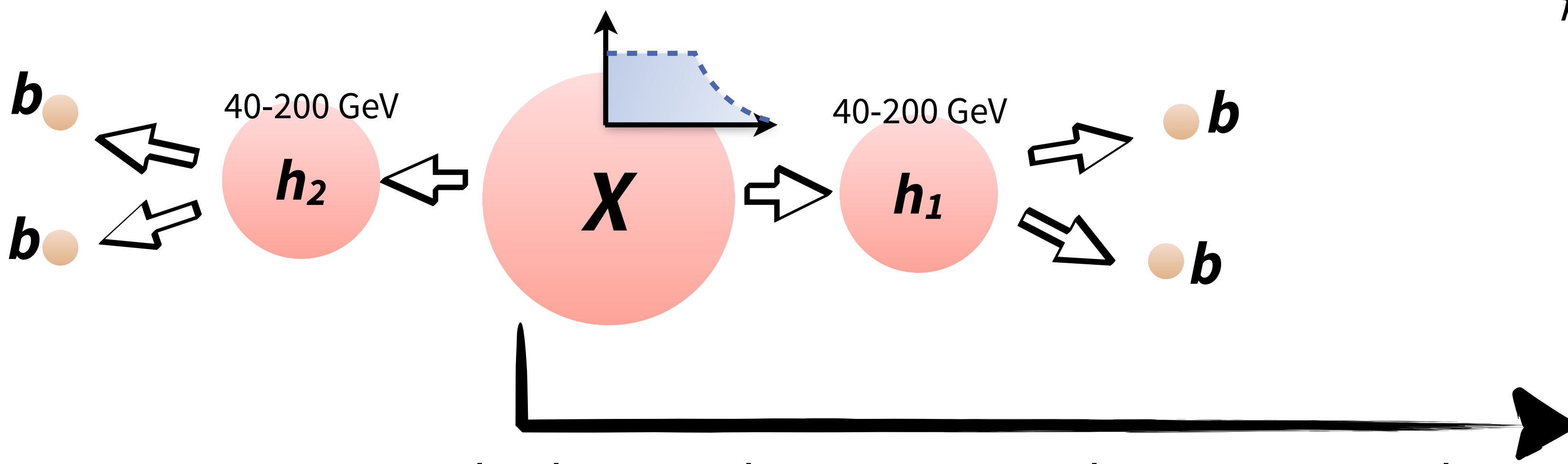
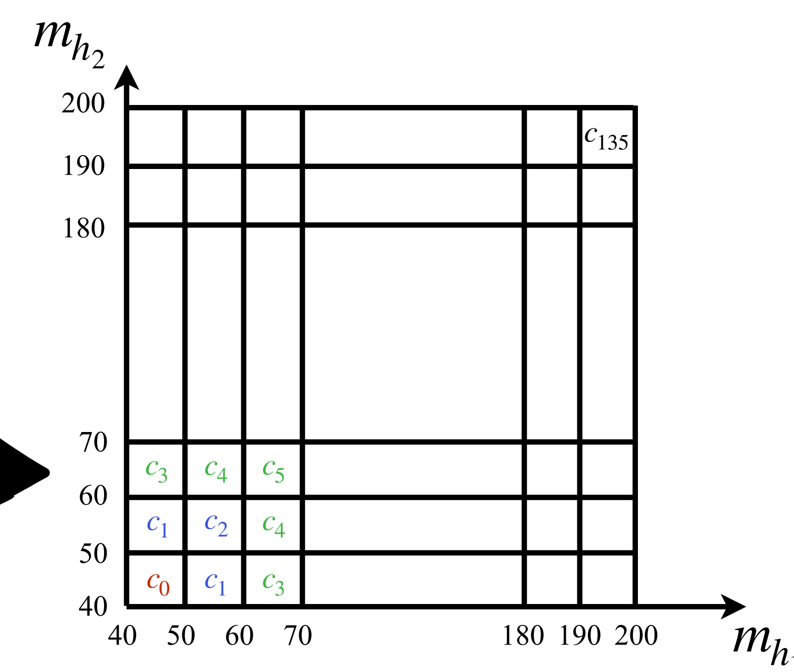
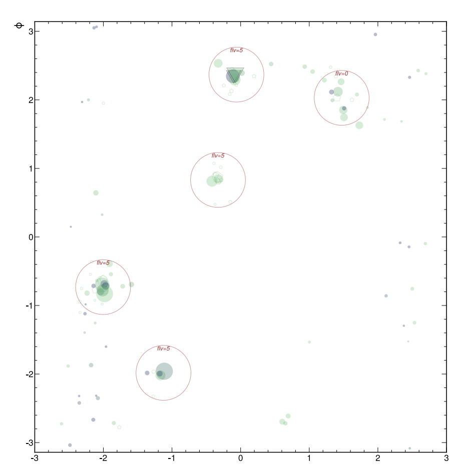


Split the signal training samples into 136 grids (classes), based on (m_{h_1}, m_{h_2})

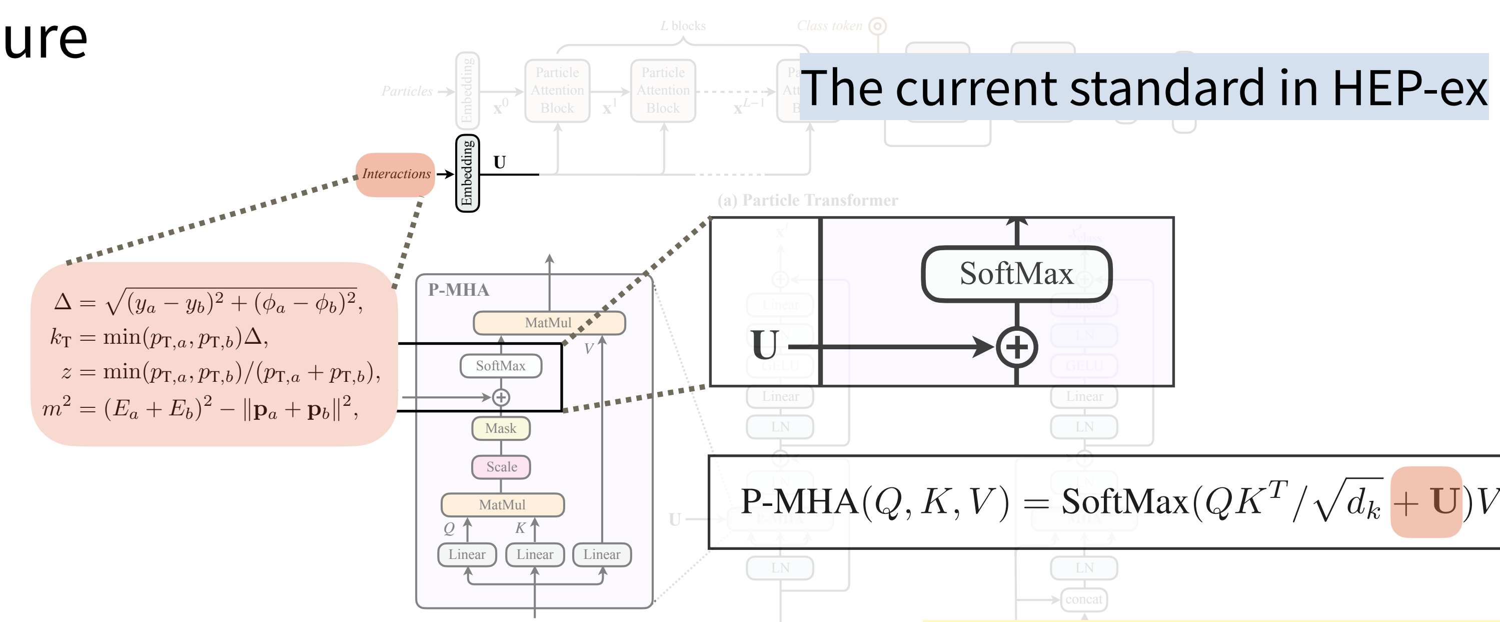


Train a "136+2 class" classifier

- on full-event reconstructed particle inputs (pileup-mitigated)
- using a **Particle Transformer** architecture

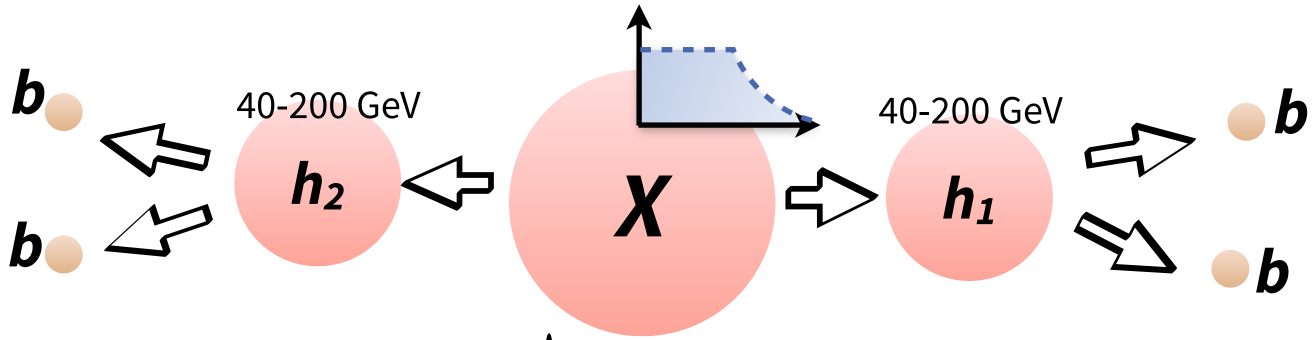


full-event particles



H. Qu, CL, S. Qian. ICML 2022

Analysis strategy: training a $X \to h_1 h_2 \to 4b$ vs bkg. classifier



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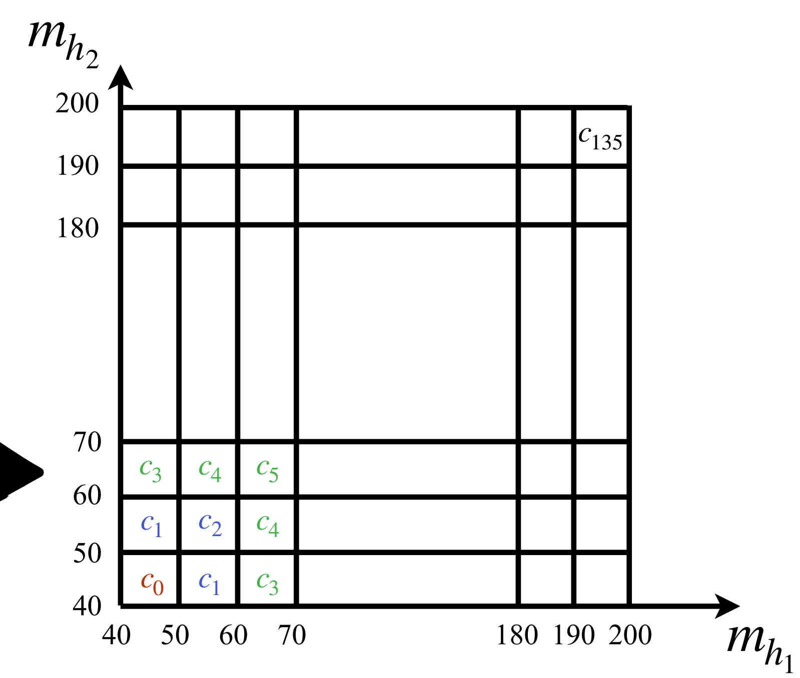
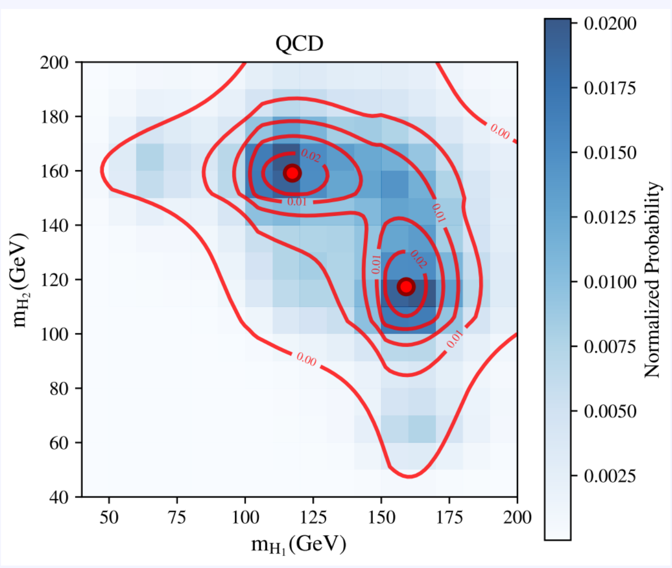


The "136+2" classifier offers two analysis tools

A powerful bkg-veto classifier

- p_{sig} = the sum of 136 signal-class scores, defining **discr = $p_{sig} / (p_{sig} + p_{QCD} + p_{ttbar})$** provides a powerful background-veto discriminant
- naturally mass-decorrelated due to the flat prior of (m_{h_1}, m_{h_2})

An (m_{h_1}, m_{h_2}) estimator

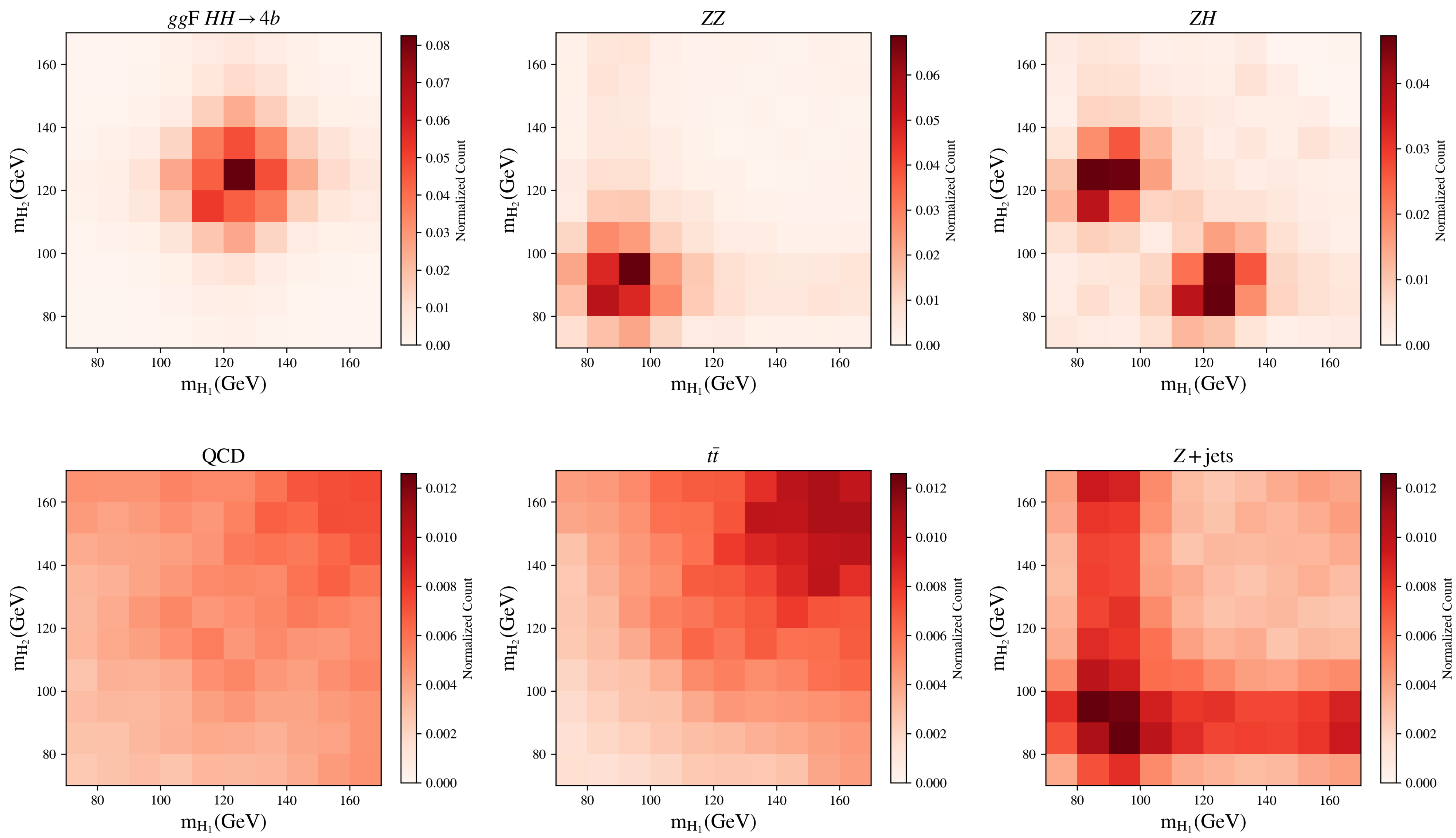


- 136-grid NN output estimated a discrete probability density ratio (by Neyman–Pearson lemma)
- **Perform a fit to extract the most probable point $(m^0_{h_1}, m^0_{h_2})$**

Mass distributions

➔ Distributions on (m_{h_1}, m_{h_2}) plane after selection

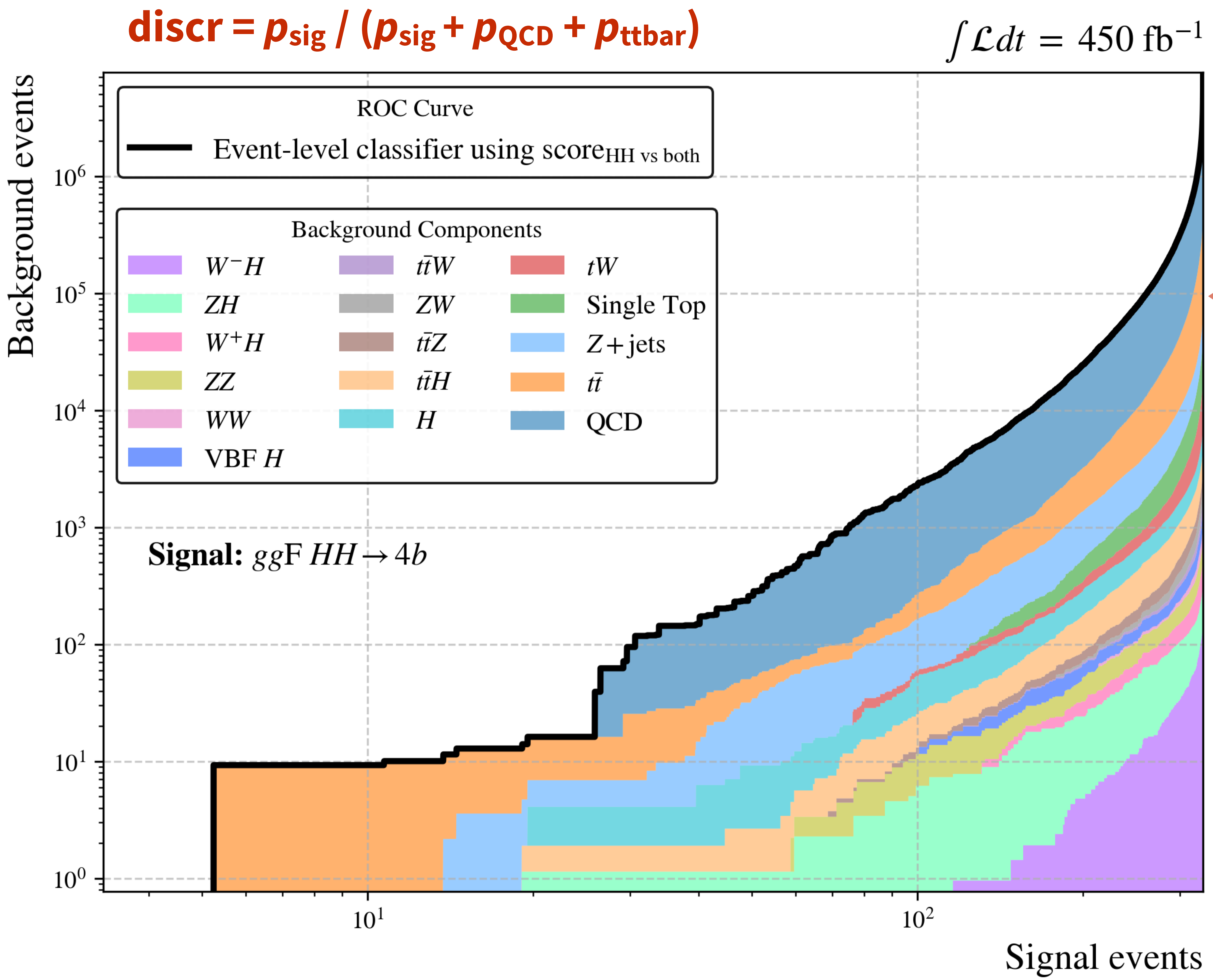
discr = p_{sig} / (p_{sig} + p_{QCD} + p_{ttbar}) > 0.9

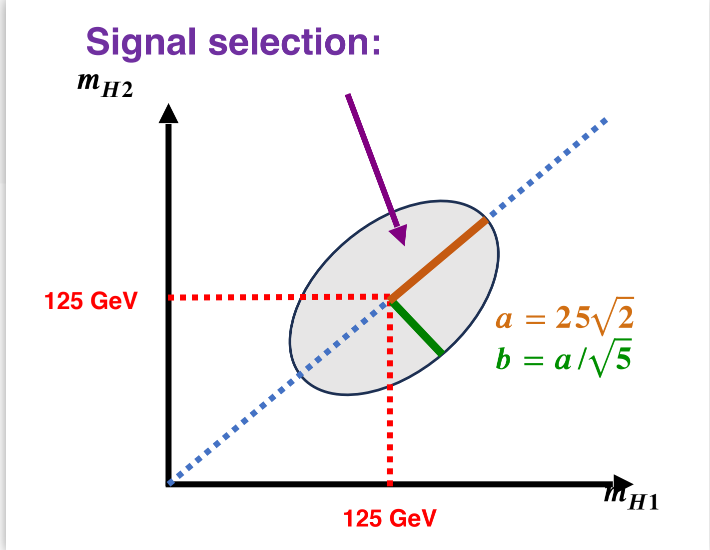


Expected shapes

- **smooth QCD and $t\bar{t}$ spectrum**
- single-Z/H: form ridge-like structures
- ZZ/ZH/HH: 2D peak-like structures

Effect of analysis selection

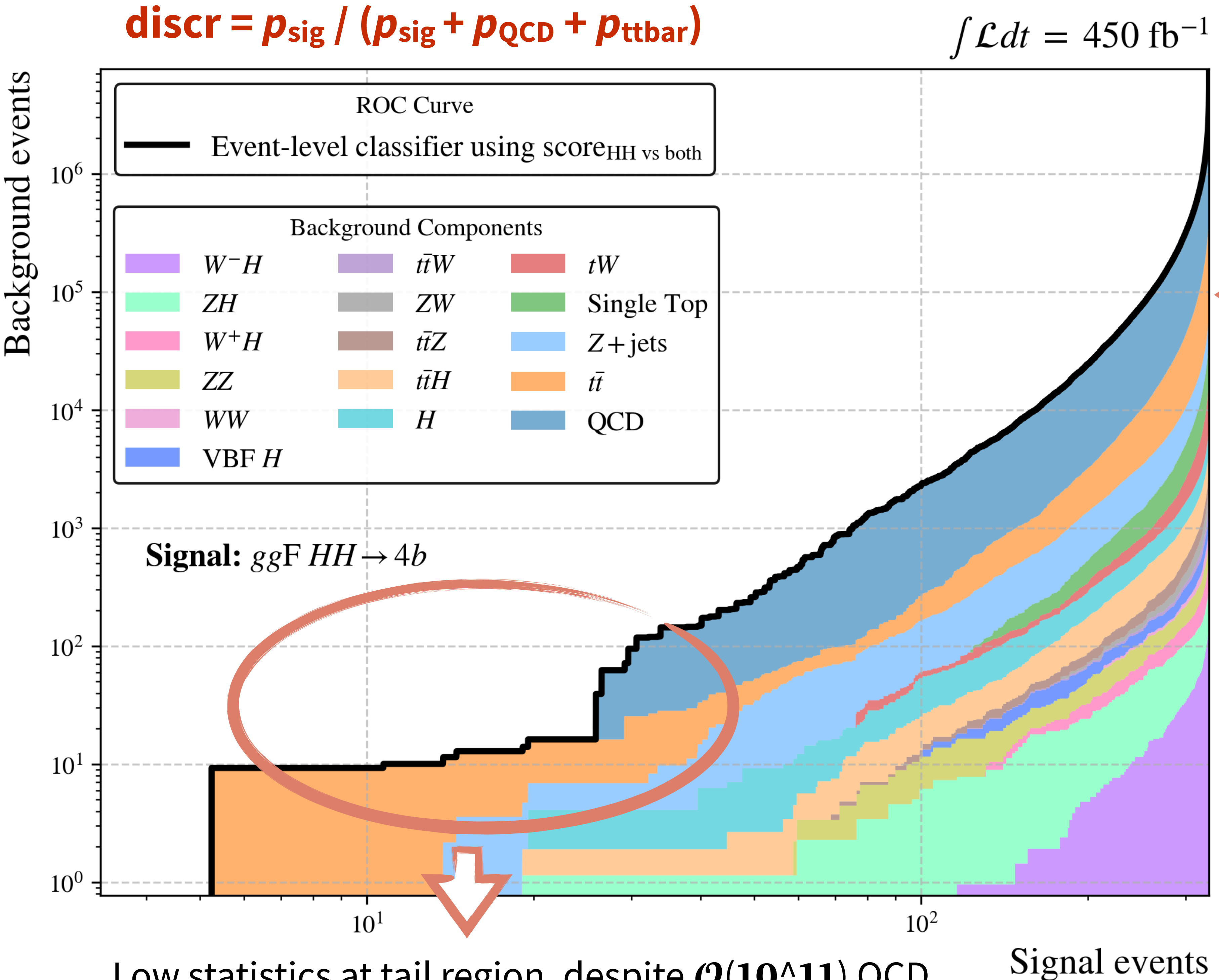


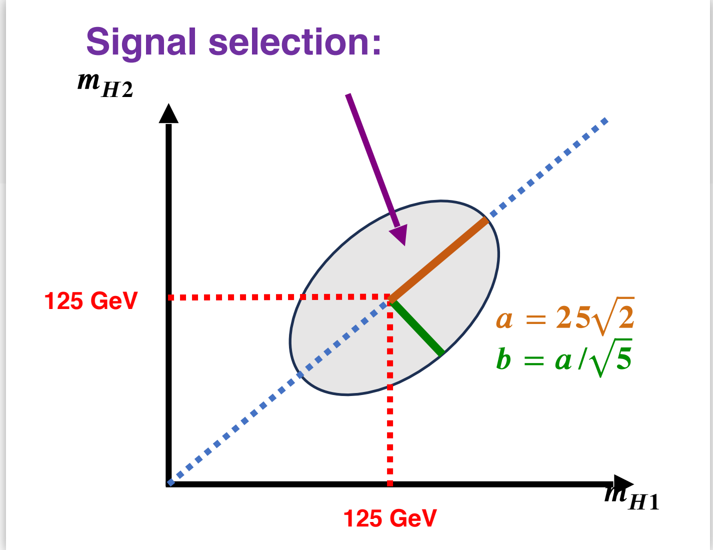


Select events in the HH mass window, and count the yields of each physics process

Effect of analysis selection

$\text{discr} = p_{\text{sig}} / (p_{\text{sig}} + p_{\text{QCD}} + p_{\text{ttbar}})$

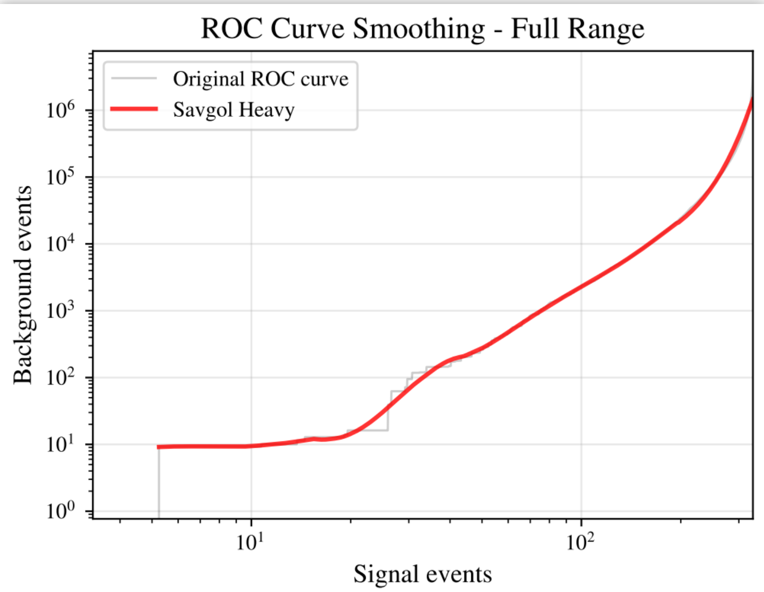




Select events in the HH mass window, and count the yields of each physics process

Low statistics at tail region, despite $\mathcal{O}(10^{11})$ QCD events before trigger selections are generated

smoothed ROC curve



Expected result

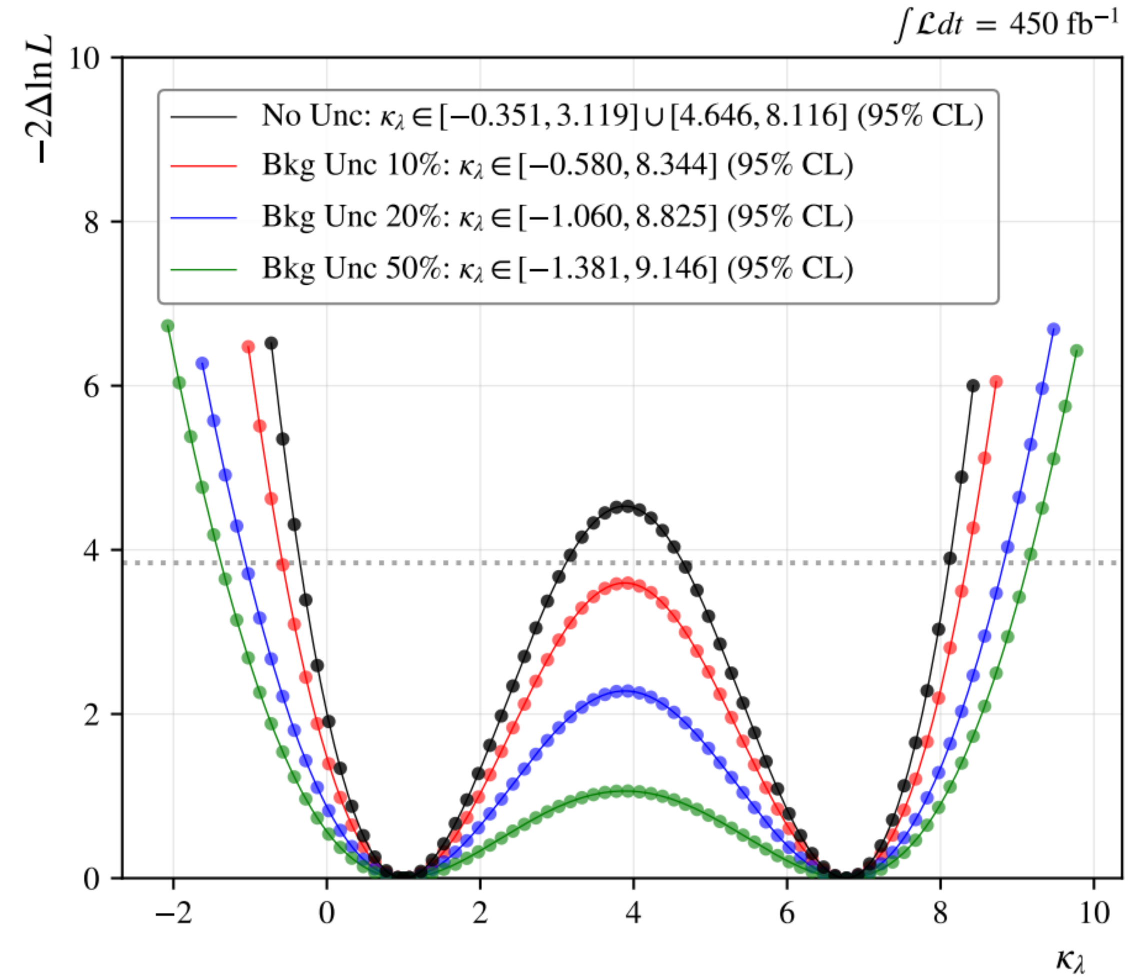
- The significance is calculated for each points at smoothed ROC:

$$Z_A = \sqrt{2\left\{(s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right] - \frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right\}}$$

- Best significance at **S = 20.5 and B = 15.2**
- Different settings for $\boldsymbol{\sigma_b}$ are considered
  - 0%, 10%, 20%, 50%

Background (signal) uncertainties	SM significance (σ)	95% CL κ_λ range
0% (0%)	4.5	$[-0.35, 3.1] \cup [4.6, 8.1]$
10% (10%)	4.1	$[-0.58, 8.3]$
20% (20%)	3.3	$[-1.1, 8.8]$
50% (20%)	1.8	$[-1.4, 9.1]$

TABLE I. Summary of the expected SM di-Higgs statistical significance and 95% CL constraints on κ_λ under different signal and background uncertainty scenarios, for an integrated luminosity of 450 fb^{-1}.

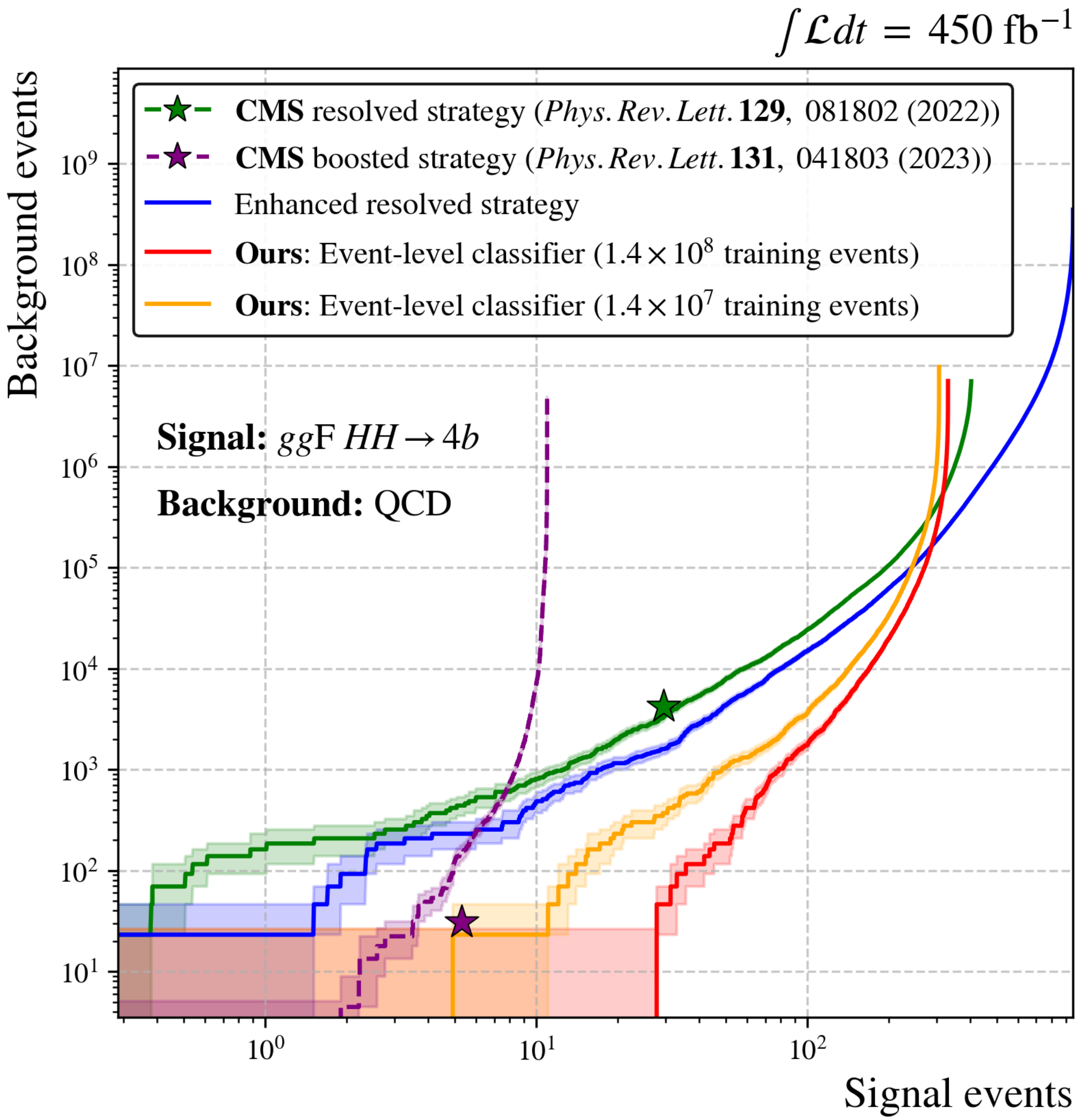


- >5x improvement in significance over existing approach!

Validity of the new method?

Further investigation into the classifier

1 **What does it take to train a powerful classifier? Data size is important!**



- The nominal model (denoted SophonHH) is trained on the **full dataset of 140M events**
  - ParT with 10M parameters (4x default size)
- To study data dependence, we also trained on reduced subsets: **1/10 (14M)** of the full dataset.
- Number of training batches scale down accordingly to avoid overfitting (by 5x)

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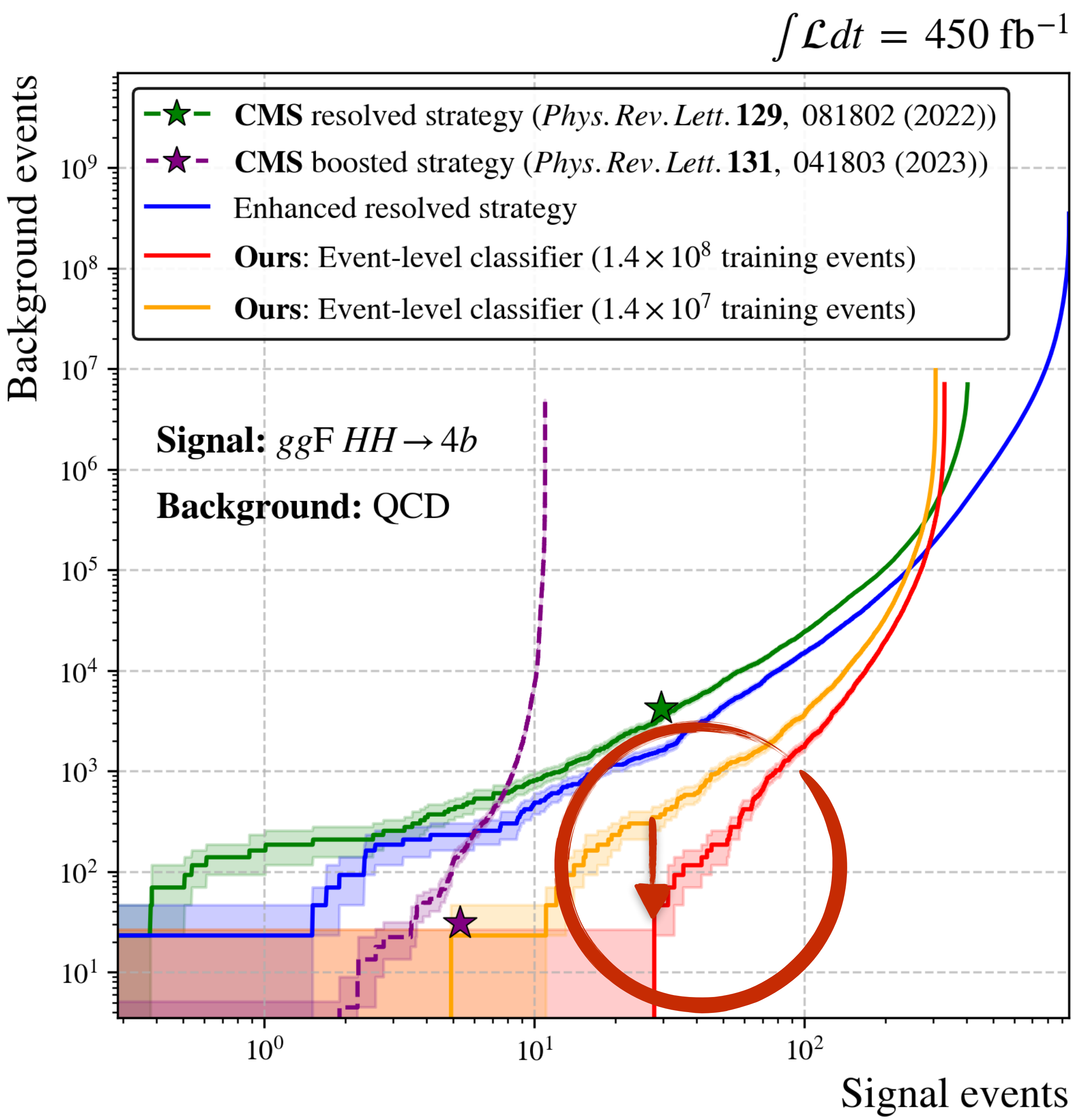

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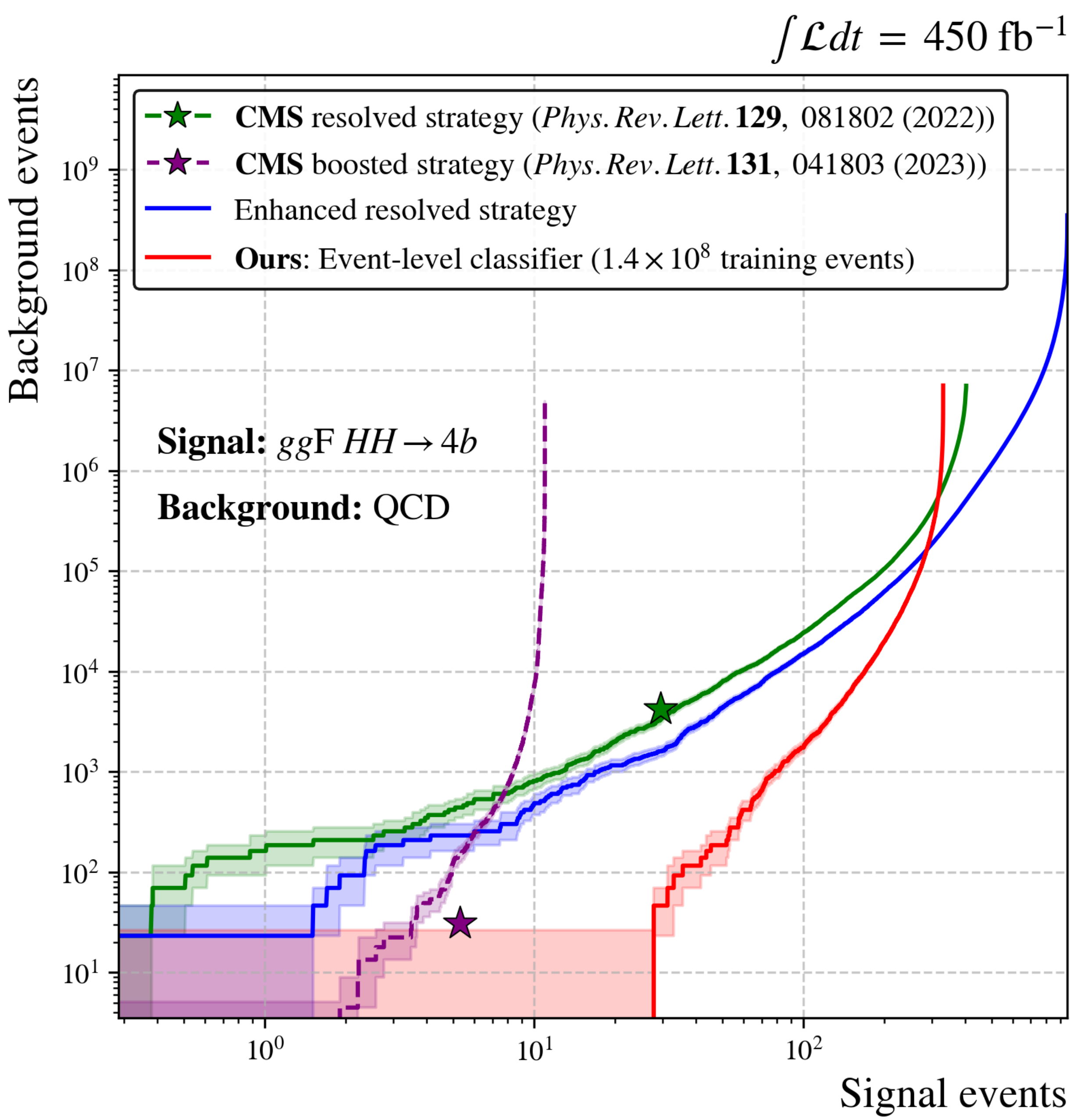
Data size is crucial to the classifier's performance!
From 13M to 130M: bkg rejection improved by 4-8x

Further investigation into the classifier

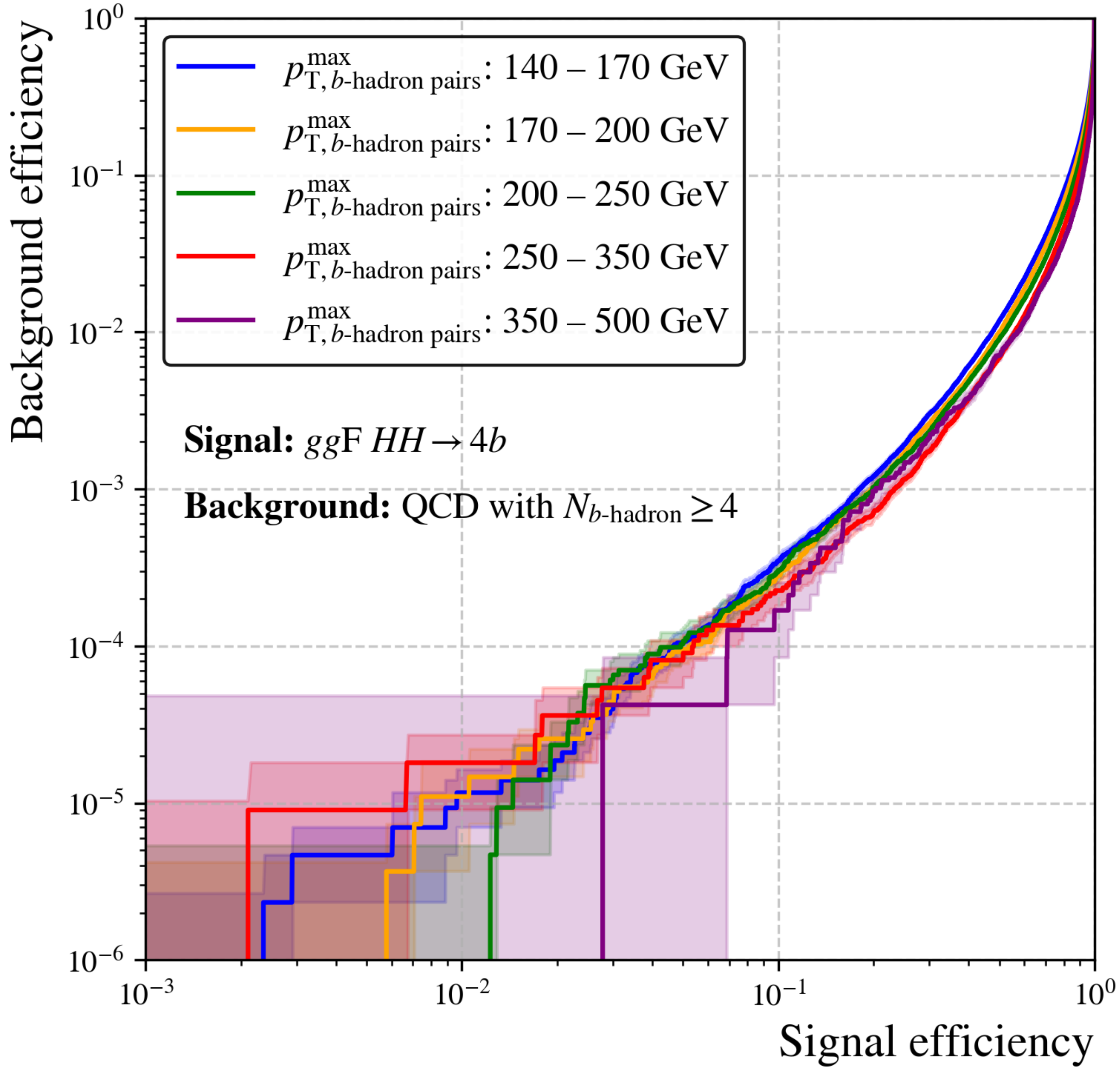
2 Is the QCD background truly irreducible? -No



- From signal vs QCD ROC curves, we observe that we can **suppress QCD bkgs to a non-negligible level,** even in the resolved regime.
- Using solely jet-based info, it's challenging to reach the same stage
- **Soft radiation pattern matters in vetoing QCD!**

Further investigation into the classifier

3 Should HH4b vs bkgs have a similar separation power across all Lorentz boost conditions? –Yes



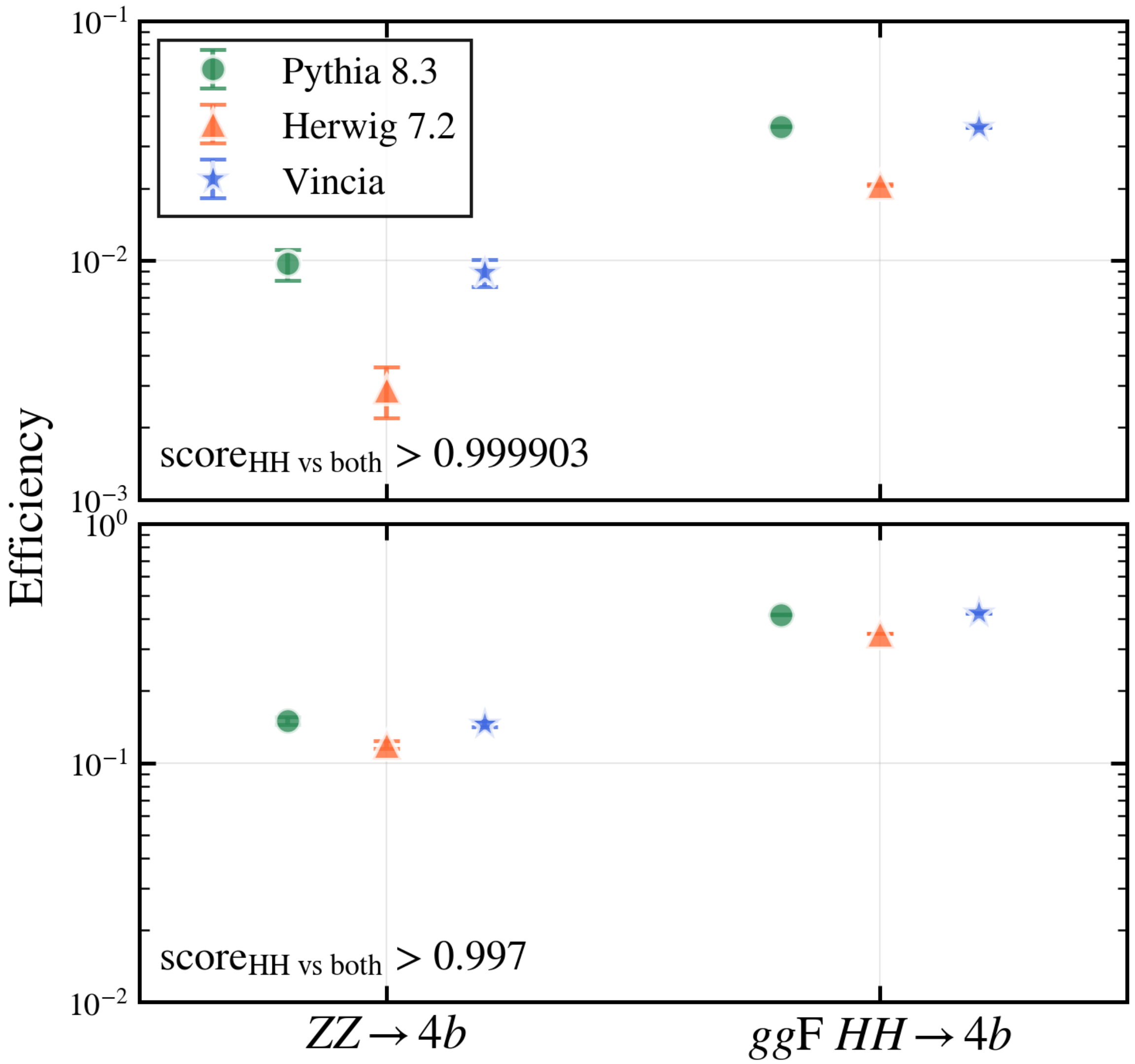
- Focus on ggHH signal vs QCD that contains exactly 4 gen-*b*-hadrons
- Use the **maximum p_T vector sum of all b-hadron pairs** as an indicator to characterize the event's Lorentz boost
- Result: **separation ability is consistent across different boosting conditions**!

Further investigation into the classifier

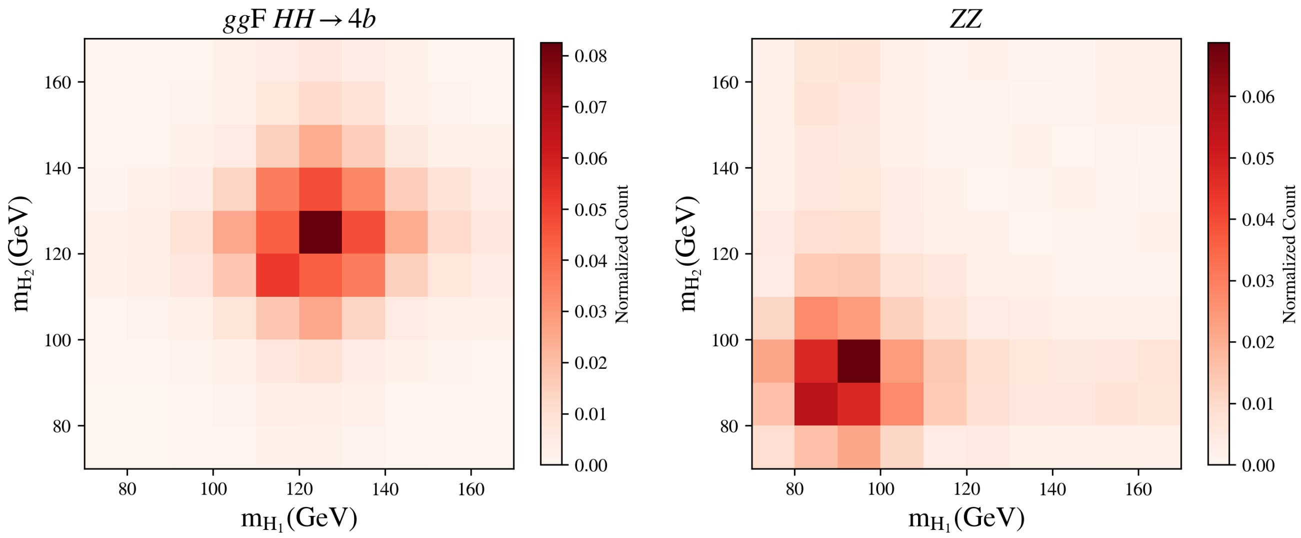
4

Robustness across hadronization models, ZZ vs HH

Comparing the efficiencies of Pythia 8.3, Herwig 7.2 and Vincia



- Tighter classifier working points enlarge discrepancies, most notably between Herwig 7.2 and the others
- No significant efficiency loss is observed
- **Similar behavior between and HH vs ZZ** (allowing to use ZZ→4b as a "calibration candle")



Summary & outlook

arXiv:2508.15048

- ➔ Take home:
  - ❖ We show that CMS/ATLAS can achieve >5× sensitivity improvement for di-Higgs in the *HH*→4*b* final state, with potential to observe HH even before the HL-LHC
  - ❖ This gain is driven entirely by AI engineering
    - ‣ “scaling up” improves performance; training directly on low-level objects
  - ❖ also validated the method’s reliability
- ➔ These findings challenge the conventional understanding of di-Higgs!
- ➔ Aim to deliver this search within the next three years

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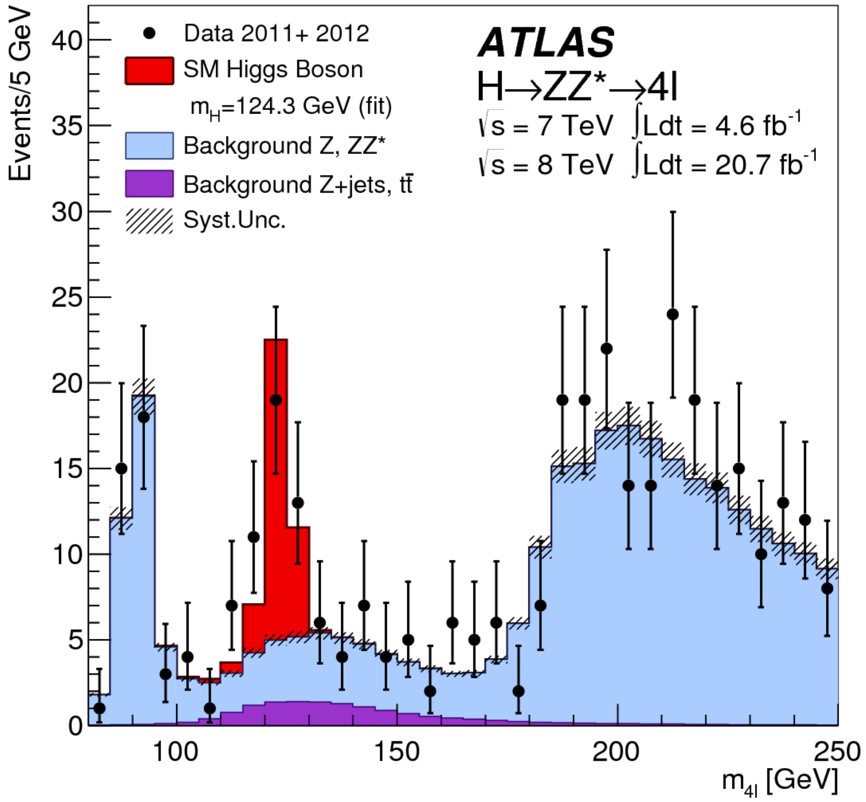
A conceptual sketch
- We are using advanced AI to make the fully hadronic channel “clean”
- As clean as H→4ℓ observation 🙂



Backup

Interlude: Our journey toward a "more realistic Delphes"

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H. Qu, CL, S. Qian, ICML 2022*

February '22

JetClass [data card]

Realistic particle-level features:
(+impact params d0, dz, d0_err, dz_err)

⇒ enable realistic flavour-tagging

CL et al. arXiv:2405.12972*

May '24

JetClass-II [data card]

emulate **pileup** ($\langle\mu\rangle$=50) &
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March '25

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[SophonAK4], [Sophon (AK8)**]**

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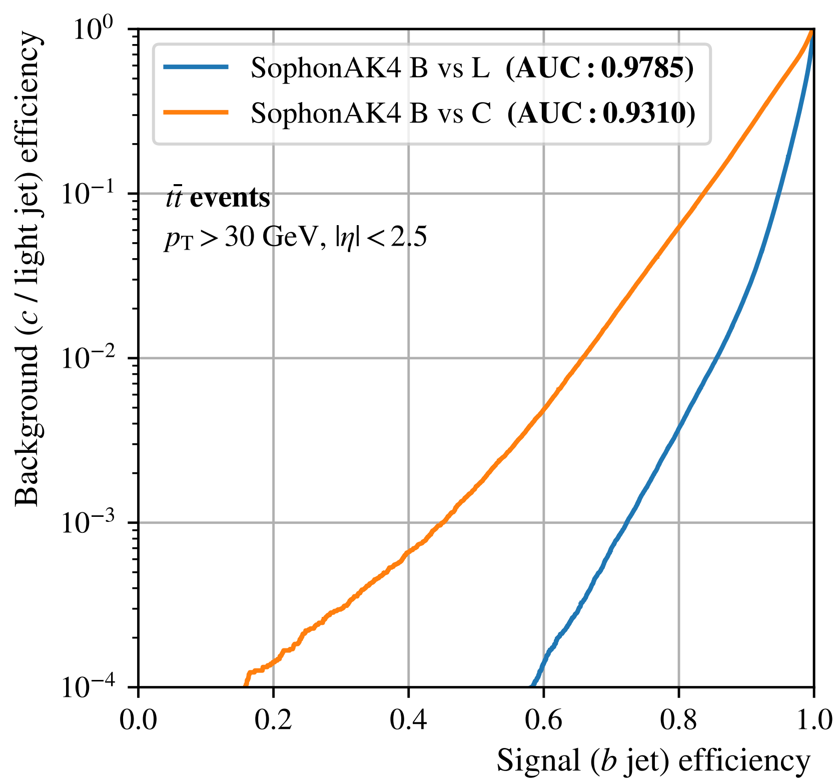

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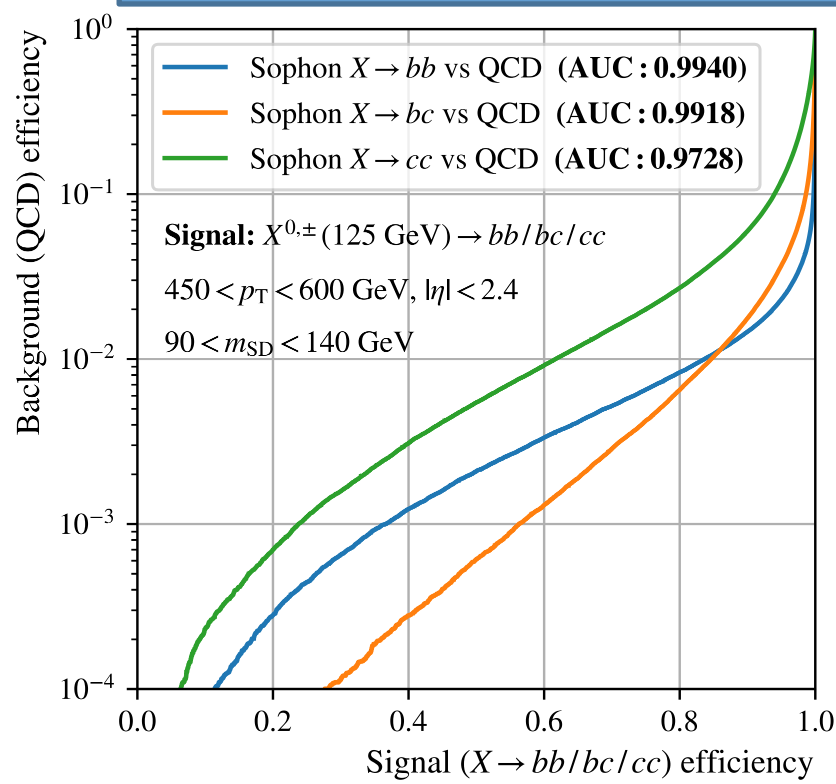
Performance of X→bb vs QCD tagging



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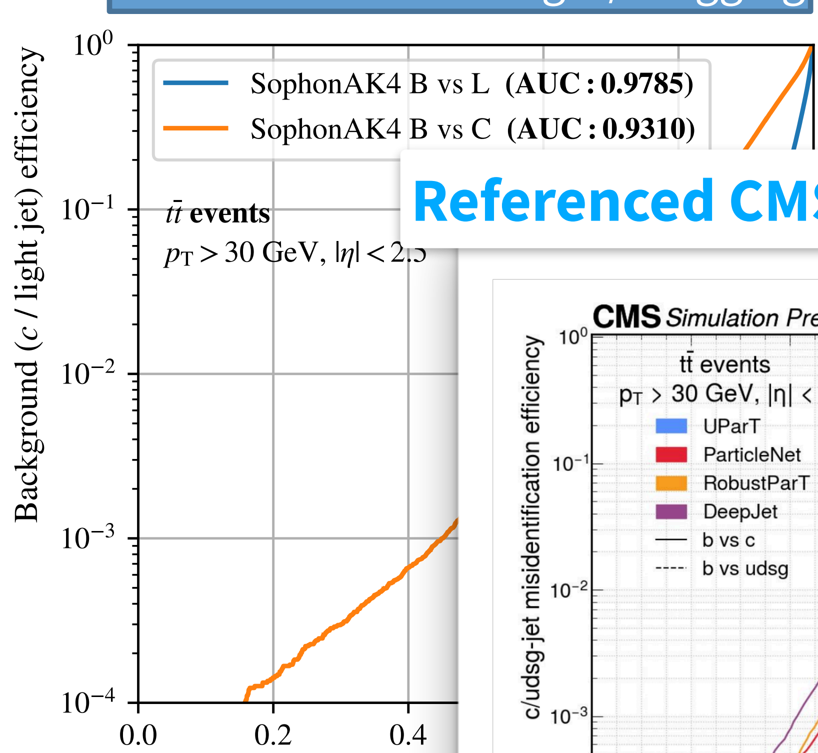

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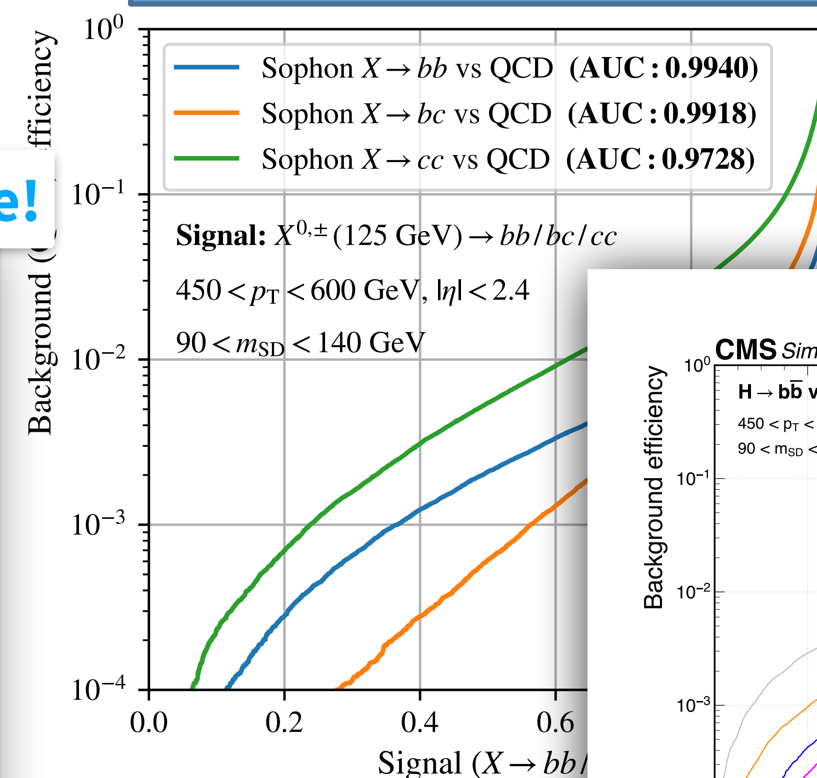
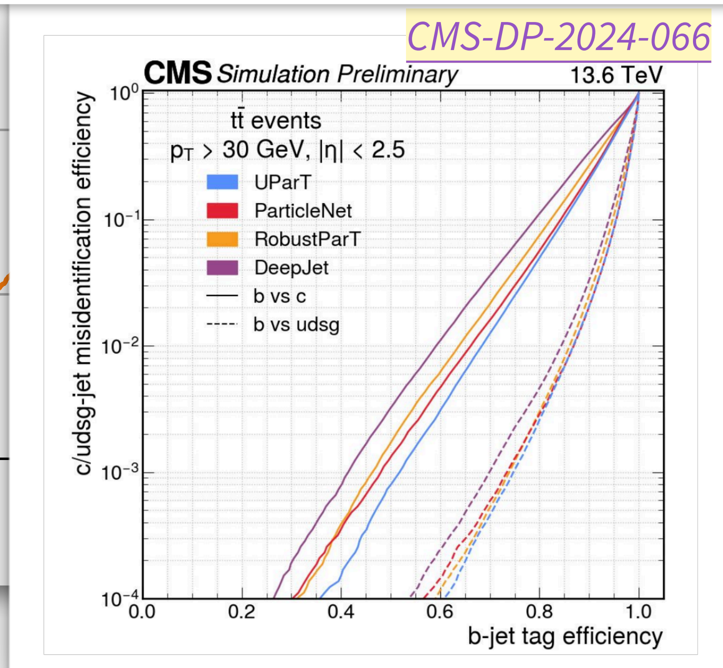
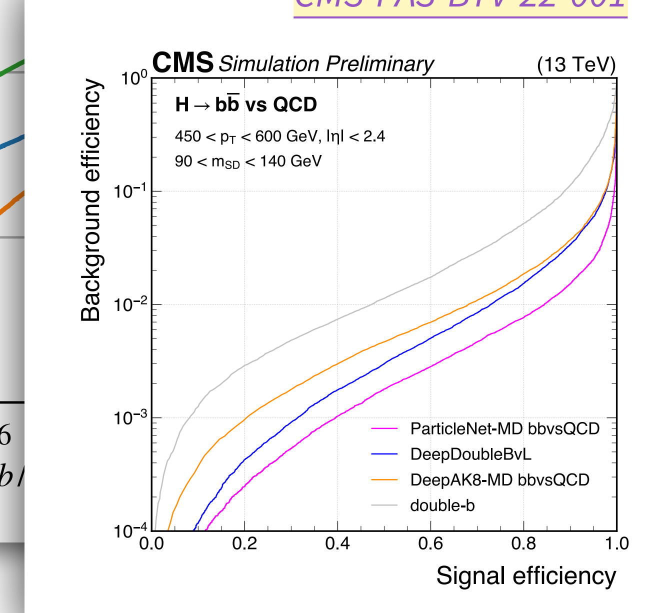


Referenced CMS performance!

CMS-DP-2024-066



CMS-PAS-BTV-22-001



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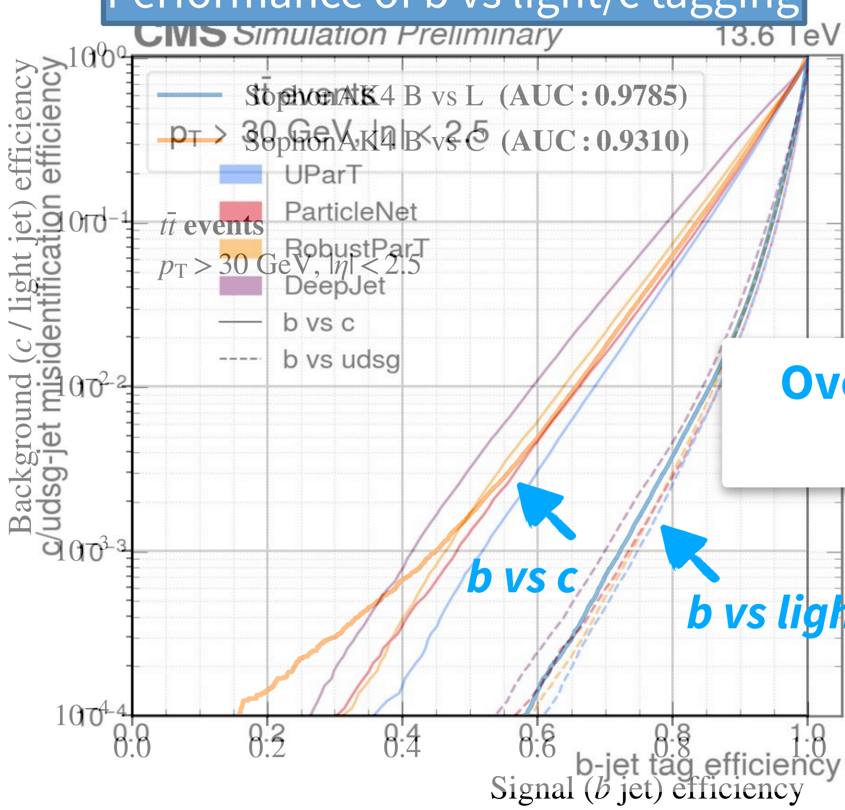

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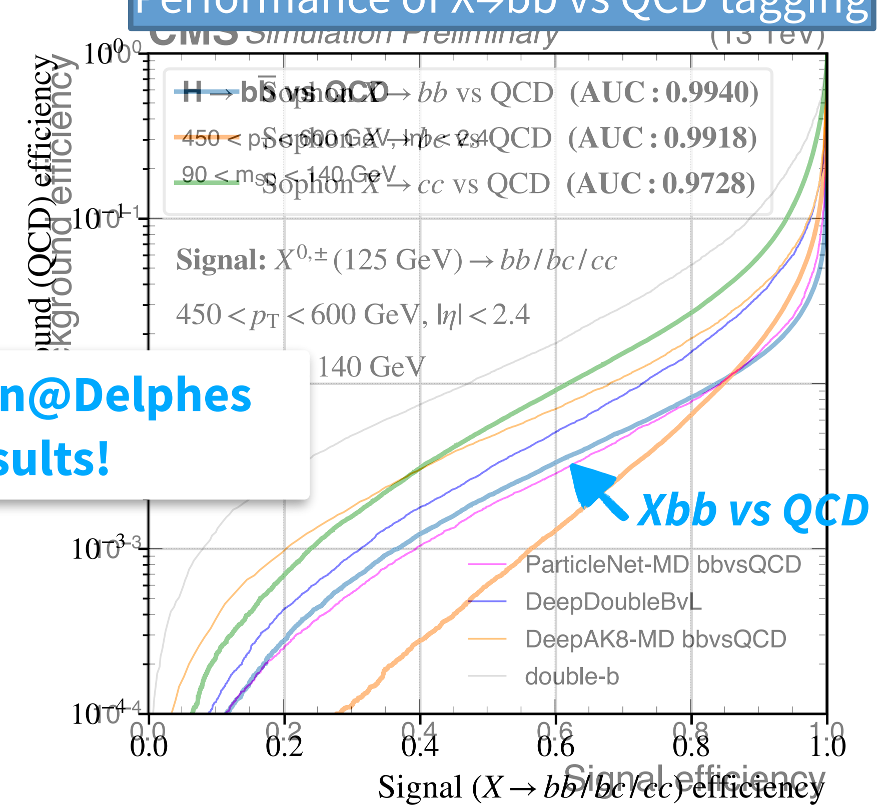


Overlaying Sophon@Delphes and CMS results!

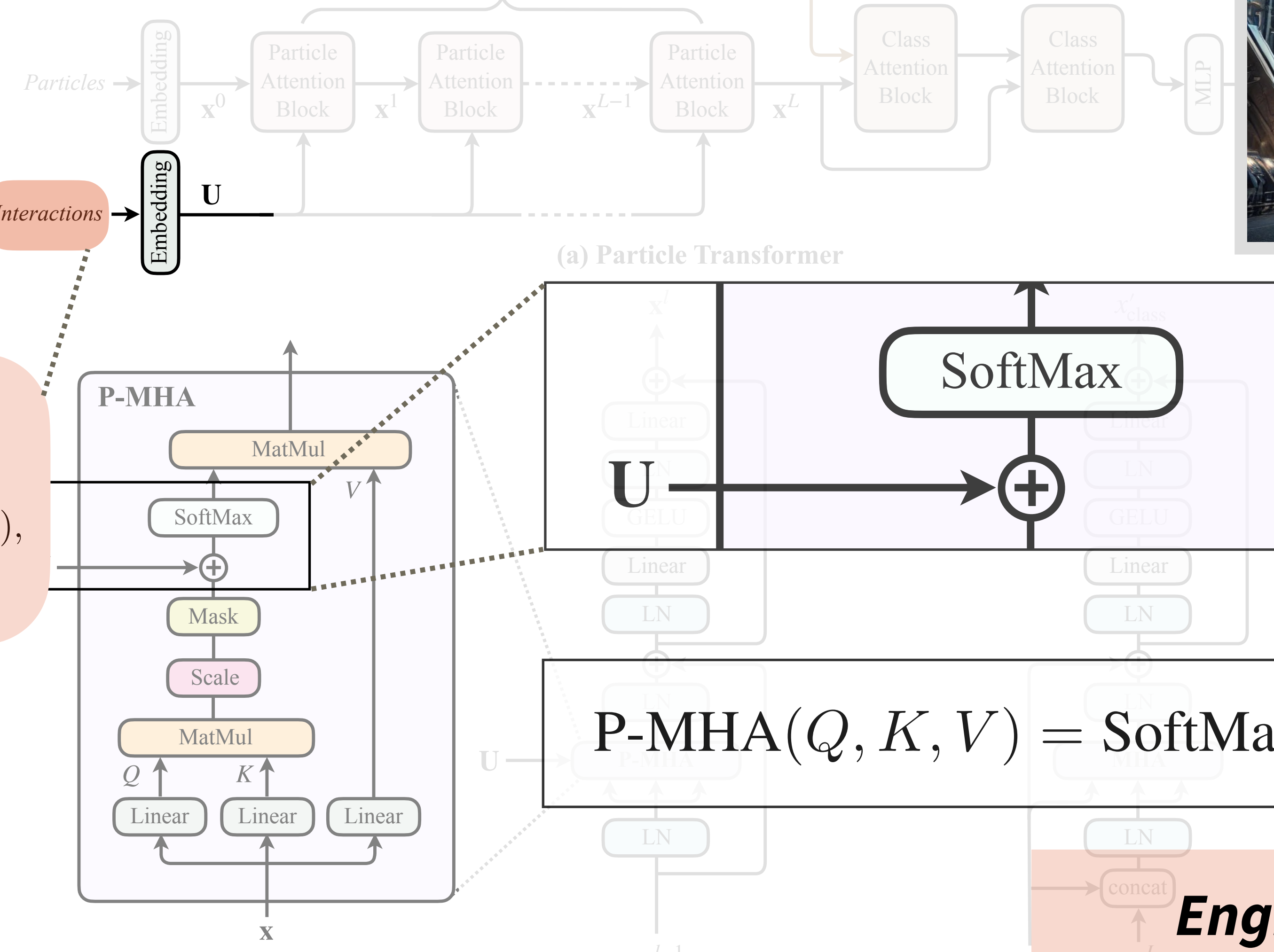
Sophon/SophonAK4 is really close to CMS's state-of-the-art taggers

Particle Transformer

➔ Transformer tailored for particle physics

❖ featuring its "attention bias" that **embed pairwise features respecting different levels of Lorentz symmetry**

H. Qu, CL, S. Qian. ICML 2022



$$\Delta = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},$$
$$k_T = \min(p_{T,a}, p_{T,b})\Delta,$$
$$z = \min(p_{T,a}, p_{T,b})/(p_{T,a} + p_{T,b}),$$
$$m^2 = (E_a + E_b)^2 - \|\mathbf{p}_a + \mathbf{p}_b\|^2,$$

$$\text{P-MHA}(Q, K, V) = \text{SoftMax}(QK^T/\sqrt{d_k} + \mathbf{U})V,$$

- Now a new standard in the HEP field

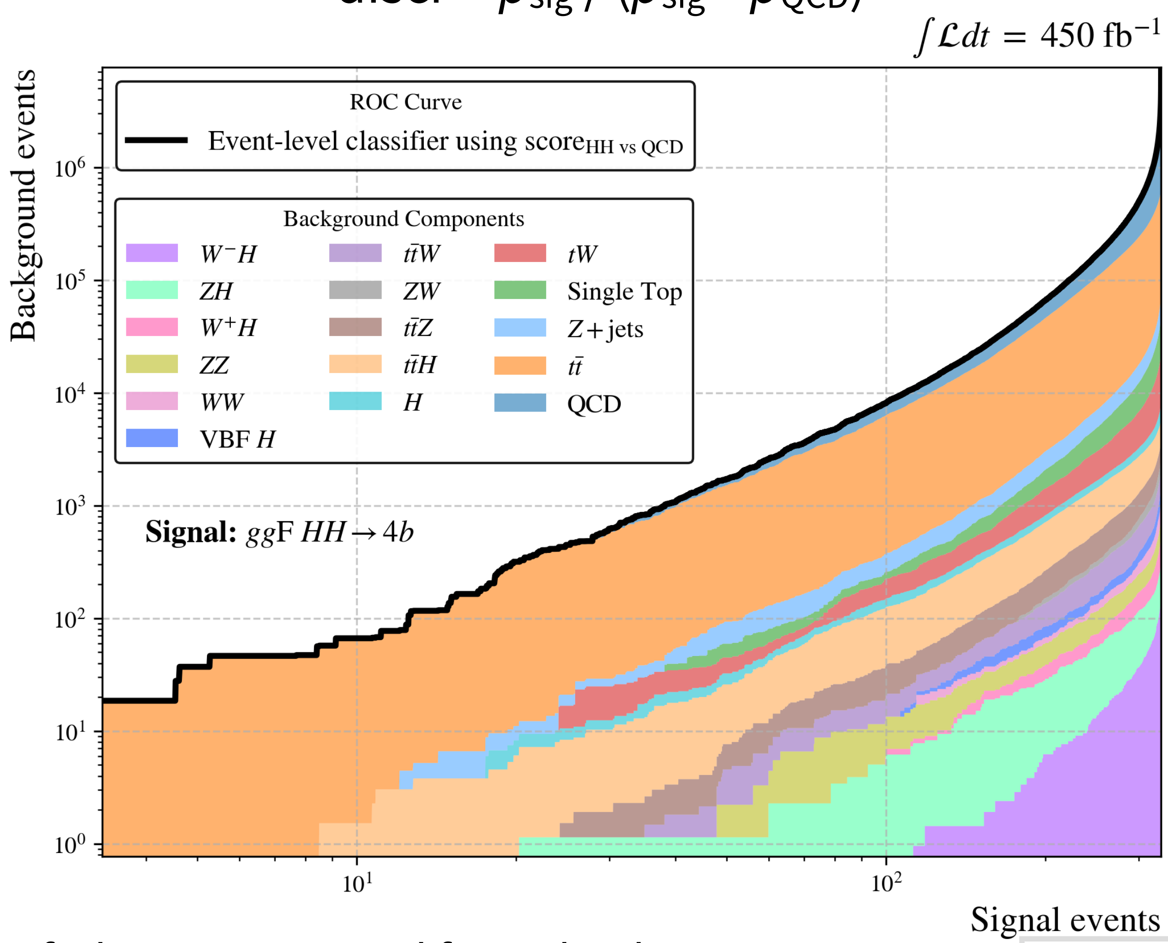
Engineering blueprint

Plain Transformer + Inductive bias from "jet symmetries"

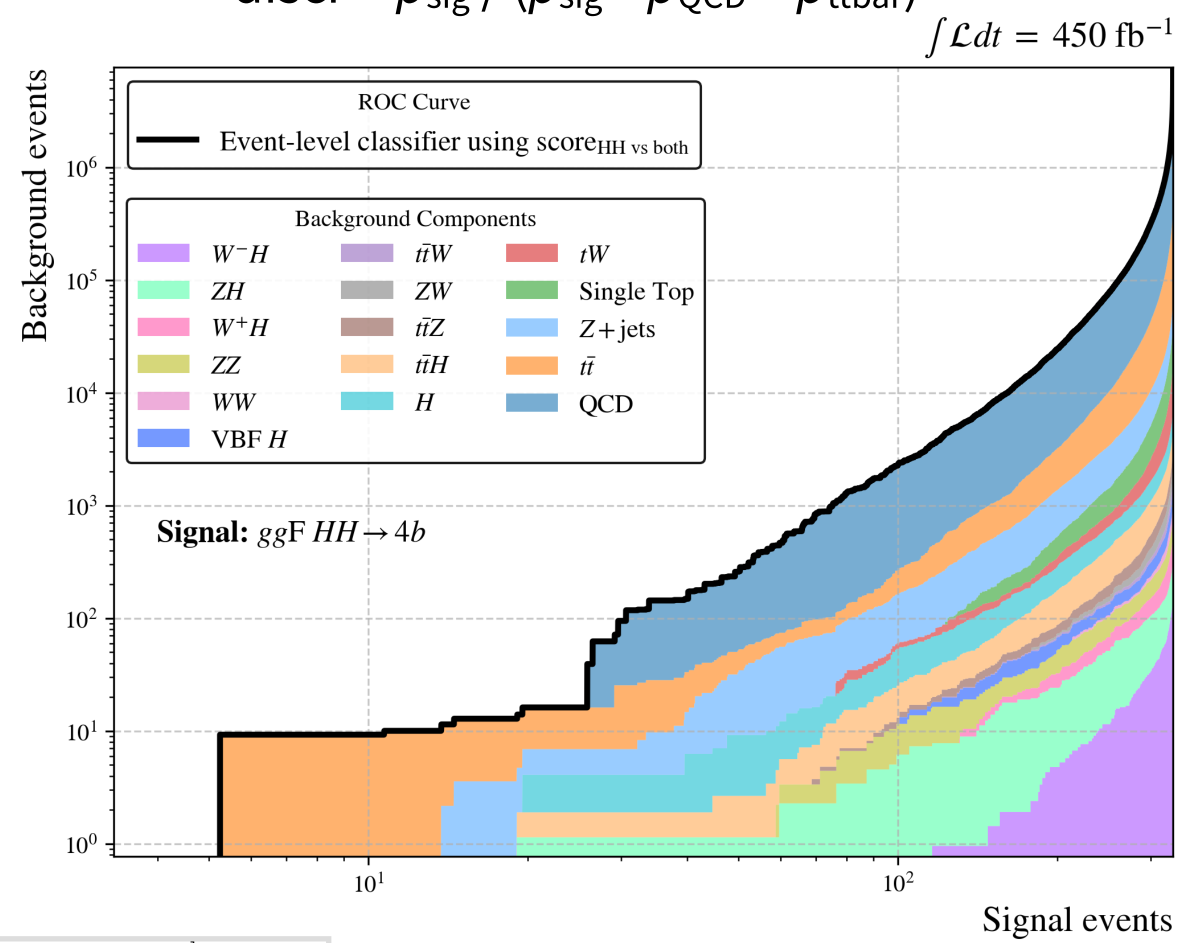
Further investigation into the classifier

Which background dominates? QCD or ttbar?

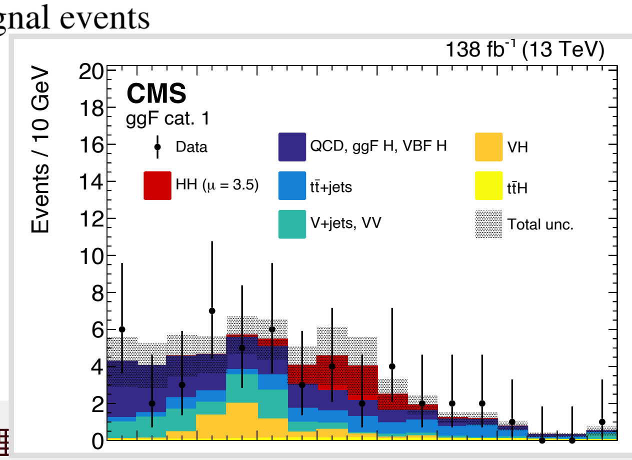
discr = p_{sig} / (p_{sig} + p_{QCD})



discr = p_{sig} / (p_{sig} + p_{QCD} + p_{ttbar})



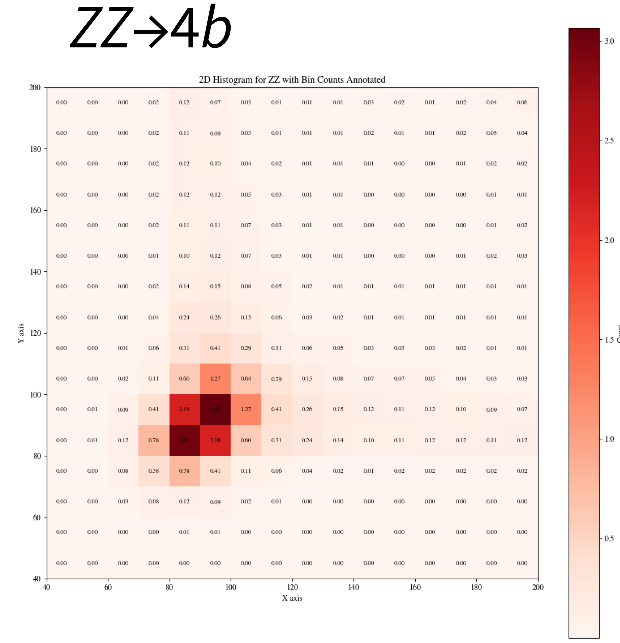
- If ttbar is not vetoed from the discriminant definition, it becomes dominant
- Suggest that boosted-channel search can be further improved by incorporating a top-like jet veto (currently using a XbbvsQCD discriminant)



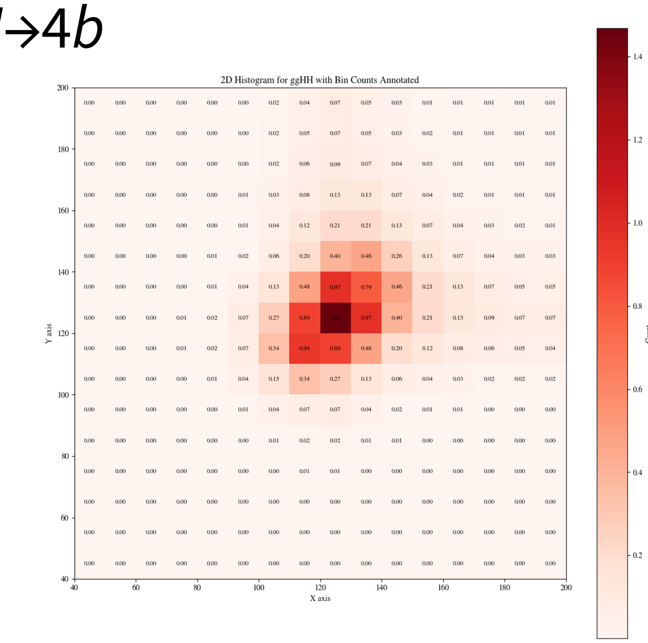
Calibration strategy

We assume their MC-to-data scale factors, peak shifts, and smearing effects are the same

ZZ→4b



HH→4b



A valid strategy

ZZ→4b extraction
(with SF, peak shifts and smearing obtained from the fit)

⇔

HH→4b extraction
(using shared factors)

An even safer strategy

extracting fake "ZZ→4b" obtained from event mixing
(with SF, peak shifts and smearing obtained from the fit in a different phase space)

⇔

ZZ→4b extraction
(using shared factors)

⇔

HH→4b extraction
(using shared factors)

Validation region

Sample production

- ➔ QCD:
  - ❖ Pythia-generated
  - ❖ for resolved studies: only kept events passing the resolved "4j3b" trigger → enabled GEN-level filters to improve event-generation efficiency: GEN H_T and GEN jet p_T cuts (looser than reco-level cuts to avoid over-removing phase space)
  - ❖ use the Pythia calculated cross-section
- ➔ Z(qq)+jets
  - ❖ generated by MadGraph LO with the addition +0/1/2 jets and MLM matching with partons. Z→qq decay implemented in MadGraph
  - ❖ for resolved studies: only kept events passing the resolved "4j3b" trigger → use matrix-element-level cuts, on $p_{T,j1/2/3}$ and H_T
  - ❖ use the MadGraph calculated cross-section
- ➔ ttbar, single-top, tW, $t\bar{t}W$, $t\bar{t}Z$, WW, WZ, ZZ
  - ❖ generated by MadGraph LO with the addition +0/1/2 jets, or +0/1 jet, or 0 jet (depending on the processes)
  - ❖ consider inclusive "boson -> fermion fermion" decay modes
  - ❖ use the highest-order cross sections recommended
- ➔ ggF Higgs, VBF Higgs, VH, $t\bar{t}H$ & ggHH signal
  - ❖ generated by Powheg at NLO
  - ❖ consider inclusive decay
  - ❖ use the Powheg cross sections

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