New potentials in boosted-jet regimes through inclusive jet model pre-training

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Based on: arXiv:2502.xxxxx and arXiv:2503.xxxxx.

Outline

Outline

How inclusive boosted jet models transform the HEP researches

Experimental impact

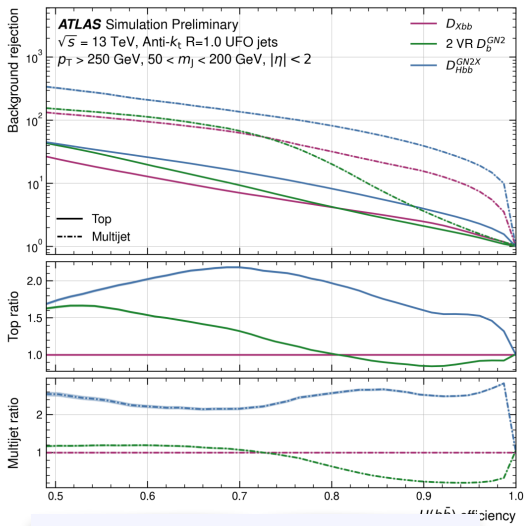
1

➔ Similar cases for large-R jet tagging

(Congqiao's talk yesterday)

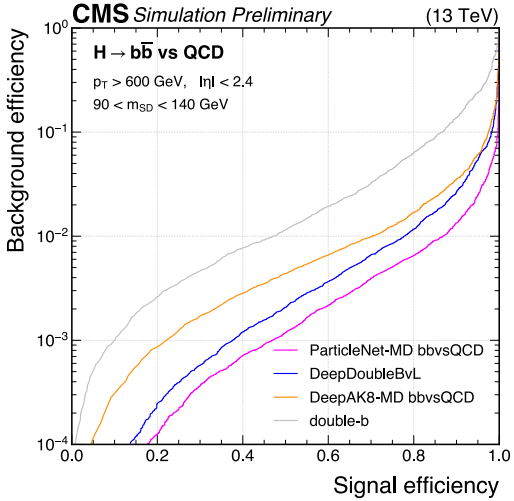
- more complex tasks! (o(30-100) particles within a large cone size)
- believed to have larger benefits from DNN algorithm improvements

ATL-PHYS-PUB-2023-021



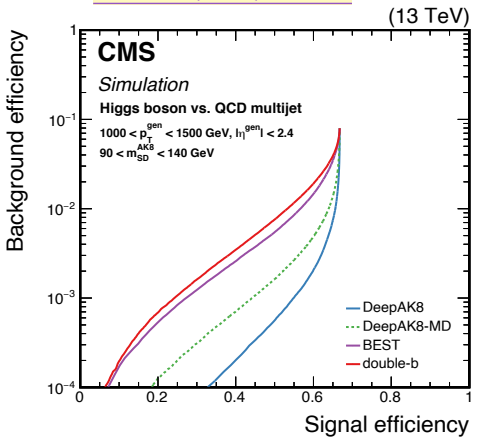
Transformer-based GN2X tagger:
~x3 📈 QCD and x2 top background rejection

CMS-PAS-BTV-22-001



DeepAK8 → ParticleNet:
x5 📈 QCD background rejection

JINST 15 (2020) P06005



Comparing with early approaches
Another **~x5** 📈 improvement achieved

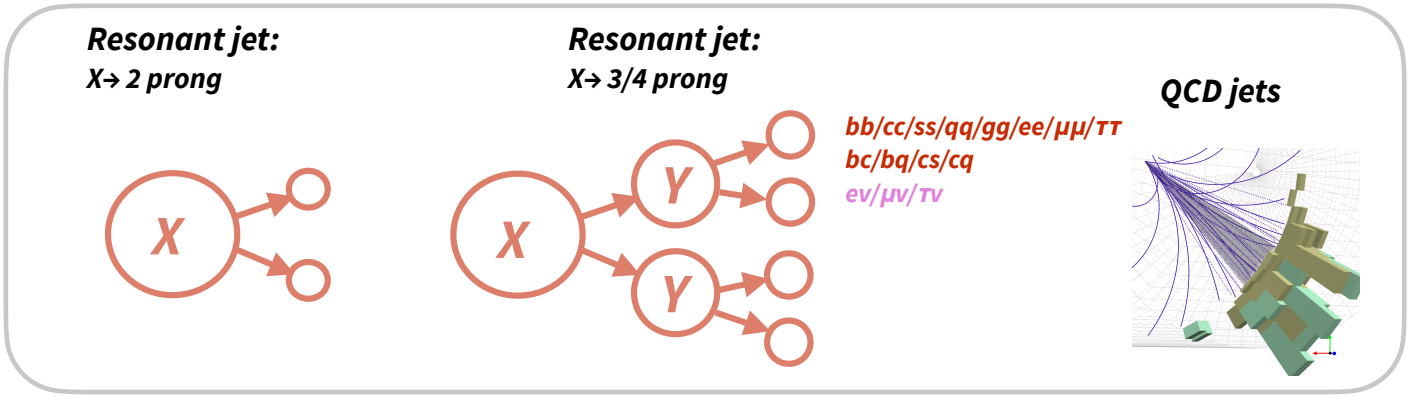
Sophon, a very recent inclusive boosted jet model

Introducing Sophon

arXiv:2405.12972

https://github.com/jet-universe/sophon

- ➔ **Signature-Oriented Pre-training for Heavy-resonant ObservatioN**
- ➔ the model is based on Particle Transformer (**ParT)** architecture
- ➔ a pre-trained model on a newly developed comprehensive dataset: **JetClass-II**
  - ***finely categorized labels:***



contributed final states: ***bb/cc/ss/qq/gg/ee/μμ/ττ bc/bq/cs/cq*** *all combination of Y decays, resulting to 4-prong or 3-prong*

(credit slides)

Key property: we do not focus on any specific *X* and *Y* masses
Their masses are variables: ranges from 20-500 GeV

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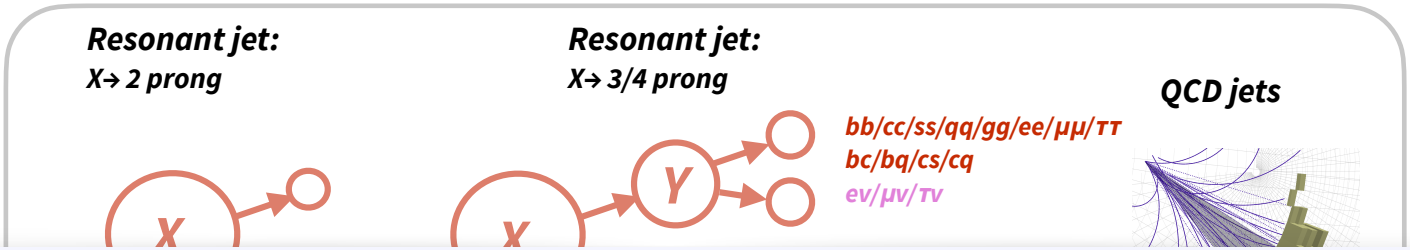


All final states!

Major types	Index range	Label names
Resonant jets: $X \to 2$ prong	0–14	bb, cc, ss, qq, bc, cs, bq, cq, sq, gg, ee, $\mu\mu$, $\tau_h\tau_e$, $\tau_h\tau_\mu$, $\tau_h\tau_h$
Resonant jets: $X \to 3$ or 4 prong	15–160	$bbbb$, $bbcc$, $bbss$, $bbqq$, $bbgg$, $bbee$, $bb\mu\mu$, $bb\tau_h\tau_e$, $bb\tau_h\tau_\mu$, $bb\tau_h\tau_h$, bbb, bbc, bbs, bbq, bbg, bbe, $bb\mu$, $cccc$, $ccss$, $ccqq$, $ccgg$, $ccee$, $cc\mu\mu$, $cc\tau_h\tau_e$, $cc\tau_h\tau_\mu$, $cc\tau_h\tau_h$, ccb, ccc, ccs, ccq, ccg, cce, $cc\mu$, $ssss$, $ssqq$, $ssgg$, $ssee$, $ss\mu\mu$, $ss\tau_h\tau_e$, $ss\tau_h\tau_\mu$, $ss\tau_h\tau_h$, ssb, ssc, sss, ssq, ssg, sse, $ss\mu$, $qqqq$, $qqgg$, $qqee$, $qq\mu\mu$, $qq\tau_h\tau_e$, $qq\tau_h\tau_\mu$, $qq\tau_h\tau_h$, qqb, qqc, qqs, qqq, qqg, qqe, $qq\mu$, $gggg$, $ggee$, $gg\mu\mu$, $gg\tau_h\tau_e$, $gg\tau_h\tau_\mu$, $gg\tau_h\tau_h$, ggb, ggc, ggs, ggq, ggg, gge, $gg\mu$, bee, cee, see, qee, gee, $b\mu\mu$, $c\mu\mu$, $s\mu\mu$, $q\mu\mu$, $g\mu\mu$, $b\tau_h\tau_e$, $c\tau_h\tau_e$, $s\tau_h\tau_e$, $q\tau_h\tau_e$, $g\tau_h\tau_e$, $b\tau_h\tau_\mu$, $c\tau_h\tau_\mu$, $s\tau_h\tau_\mu$, $q\tau_h\tau_\mu$, $g\tau_h\tau_\mu$, $b\tau_h\tau_h$, $c\tau_h\tau_h$, $s\tau_h\tau_h$, $q\tau_h\tau_h$, $g\tau_h\tau_h$, $qqqb$, $qqqc$, $qqqs$, $bbcq$, $ccbs$, $ccbq$, $ccsq$, $sscq$, $qqbc$, $qqbs$, $qqcs$, $bcsq$, bcs, bcq, bsq, csq, $bce\nu$, $cse\nu$, $bqe\nu$, $cqe\nu$, $sqe\nu$, $qqe\nu$, $bc\mu\nu$, $cs\mu\nu$, $bq\mu\nu$, $cq\mu\nu$, $sq\mu\nu$, $qq\mu\nu$, $bc\tau_e\nu$, $cs\tau_e\nu$, $bq\tau_e\nu$, $cq\tau_e\nu$, $sq\tau_e\nu$, $qq\tau_e\nu$, $bc\tau_\mu\nu$, $cs\tau_\mu\nu$, $bq\tau_\mu\nu$, $cq\tau_\mu\nu$, $sq\tau_\mu\nu$, $qq\tau_\mu\nu$, $bc\tau_h\nu$, $cs\tau_h\nu$, $bq\tau_h\nu$, $cq\tau_h\nu$, $sq\tau_h\nu$, $qq\tau_h\nu$
QCD jets	161–187	$bbccss$, $bbccs$, $bbcc$, $bbcss$, $bbcs$, bbc, $bbss$, bbs, bb, $bccss$, $bccs$, bcc, $bcss$, bcs, bc, bss, bs, b, $ccss$, ccs, cc, css, cs, c, ss, s, others

The CKM matrix and current measurement results

- The Cabibbo–Kobayashi–Maskawa (CKM) matrix quantifies the strengths of the flavour-changing weak interactions. According to the latest SM global fit result [1]:

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97435 & 0.22501 & 0.003732 \\ 0.22487 & 0.97349 & 0.04183^{+0.00079}_{-0.00069} \\ 0.00858 & 0.04111 & 0.999118 \end{pmatrix},$$

  where the primary contribution to the precision of $|V_{cb}|$ ($\sim 2\%$) is from semileptonic decays of B mesons to charm.

- A persistent tension exists between $|V_{cb}|$ results from inclusive and exclusive B decay methods [1]:
  - Inclusive: $(42.2 \pm 0.5) \times 10^{-3}$.
  - Exclusive to D and D^*: $(41.1 \pm 1.2) \times 10^{-3}$.

- The precision of $|V_{cb}|$ is found to be significantly affected by experimental uncertainties in flavor-tagging and mistagging efficiencies [2–4], especially under high-luminosity conditions. Reducing these uncertainties will be valuable to enhancing the unique opportunity to probe $|V_{cb}|$ via $W \to cb$ decays.

Our proposal for precise $|V_{cb}|$ measurement in the energy frontier

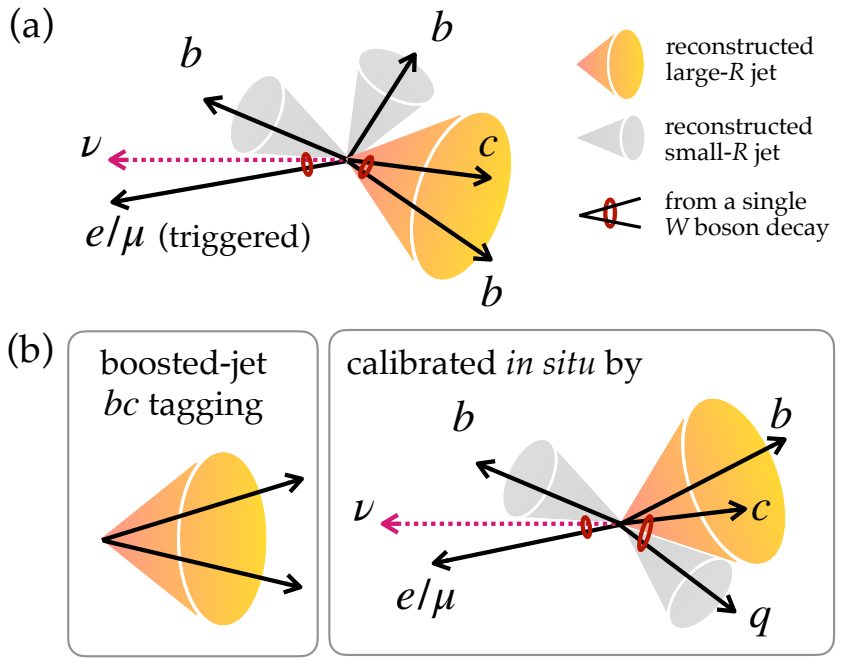
bc-tagging in boosted region

Benefits:

- Stronger background suppression: increasingly sophisticated deep learning techniques for boosted bb- and cc-tagging have brought substantial improvements in $H \to bb/cc$ measurements in CMS [5–8].

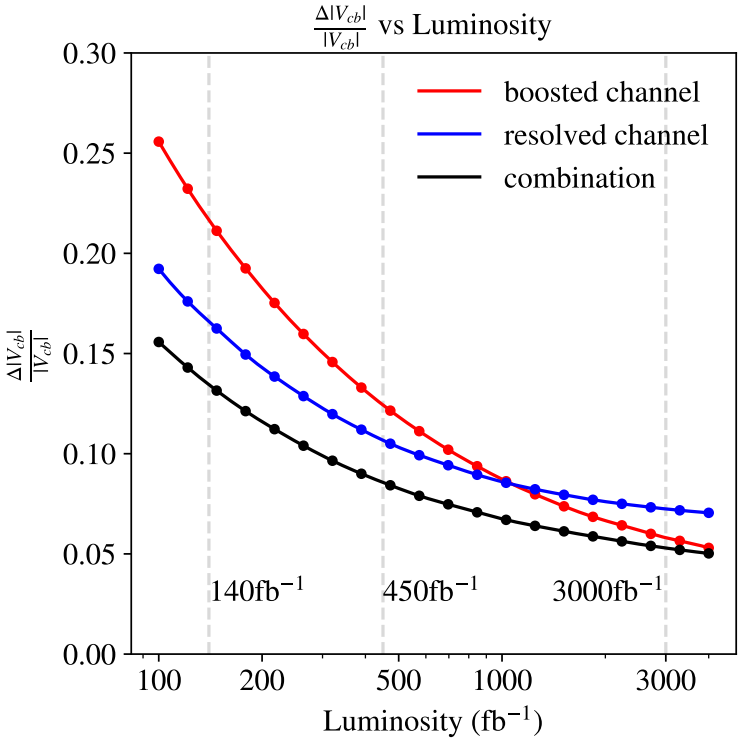
- Ability to facilitate *in-situ* calibration of the signal process, bypassing the calibration proxies [9, 10]:
  - The background is extremely dominated by "bc-matched" jets after tight bc-tagging.
  - The bc-tagger efficiency can be corrected using a shared unconstrained scale factor.

  This not only reduces uncertainty in boosted bc-tagging efficiency but also mitigates the dependence of remaining event selections on b/c flavor tagging, thereby enabling more precise extraction of $|V_{cb}|$ under high-luminosity conditions.



Outline

The high-lumi boosted regime surpasses the resolved one in $|V_{cb}|$ precision



Uncertainty contributions obtained by individually freezing $\vec{\nu}$ and λ in the fit.

Lumi. (chan.)	b/c-tag.	D_{bc}-tag.	Stat.
140 fb^{-1} (boosted)	0.036	0.100	0.191
140 fb^{-1} (resolved)	0.065	—	0.154
450 fb^{-1} (boosted)	0.036	0.056	0.106
450 fb^{-1} (resolved)	0.065	—	0.086
3000 fb^{-1} (boosted)	**0.035**	0.022	**0.041**
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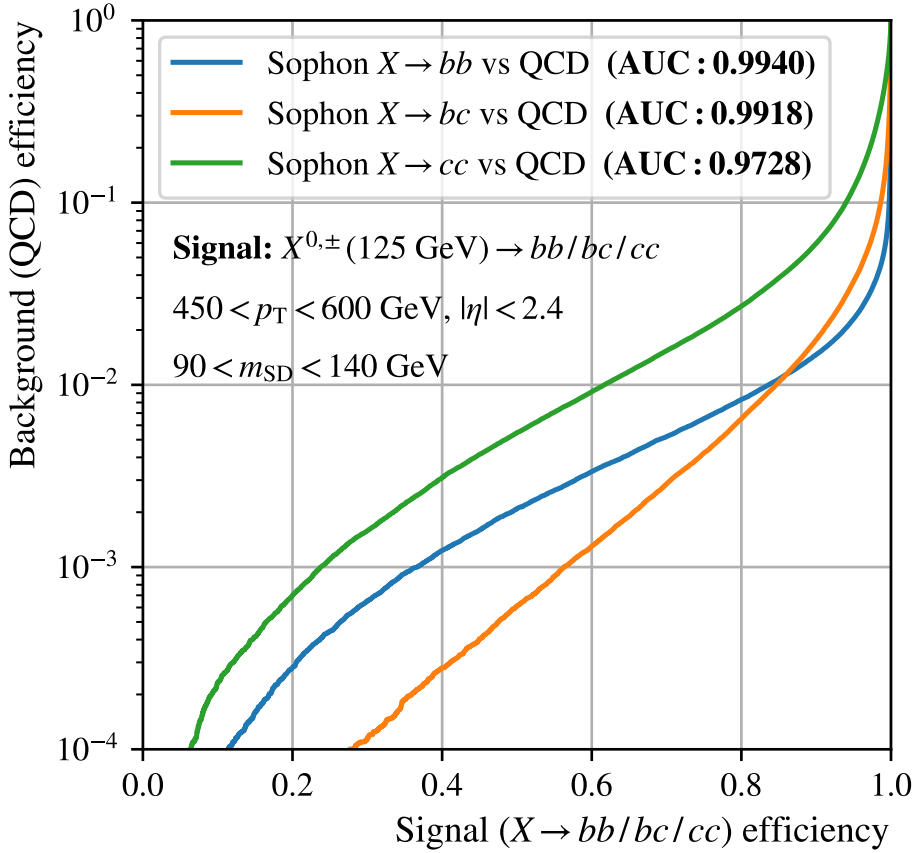
- The uncertainty under $140\ \text{fb}^{-1}$ is consistent with the preliminary expected result from ATLAS [11] at around $0.13\,(\text{syst.}) \oplus 0.13\,(\text{stat.})$.
- The boosted channel is predominantly limited by statistical uncertainty, while the contribution from flavor-tagging-related uncertainty is smaller than the resolved channel. As the luminosity increases, the boosted channel demonstrates a significant advantage in the overall uncertainty, surpassing the traditional resolved approach.

Outline

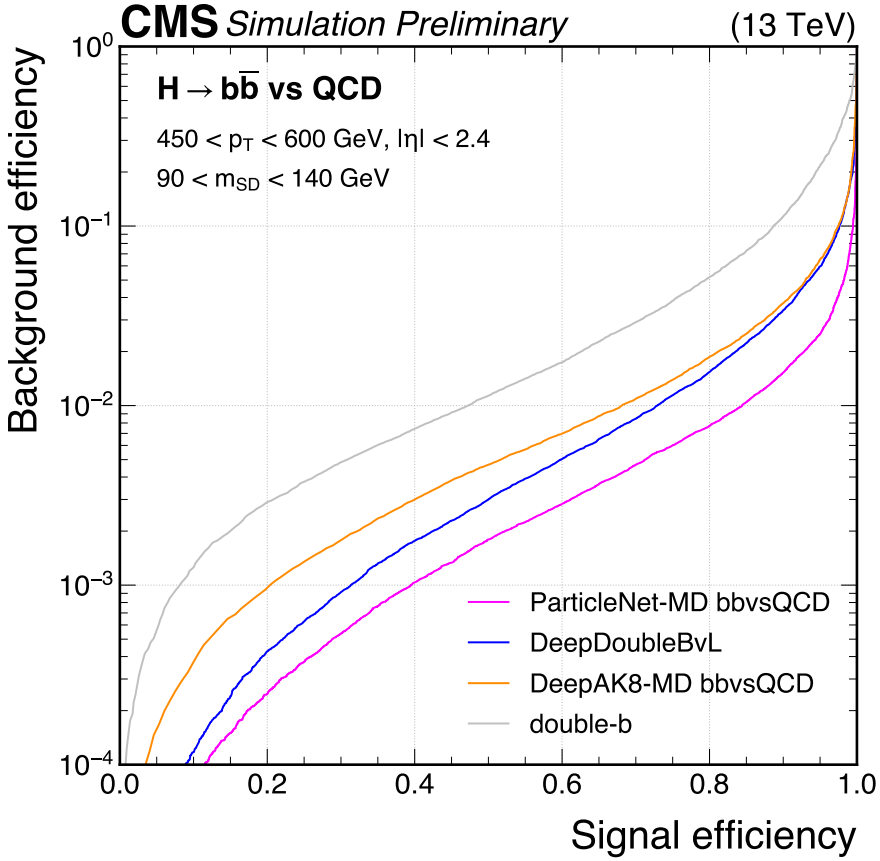
Performance of Sophon in various flavor tagging tasks

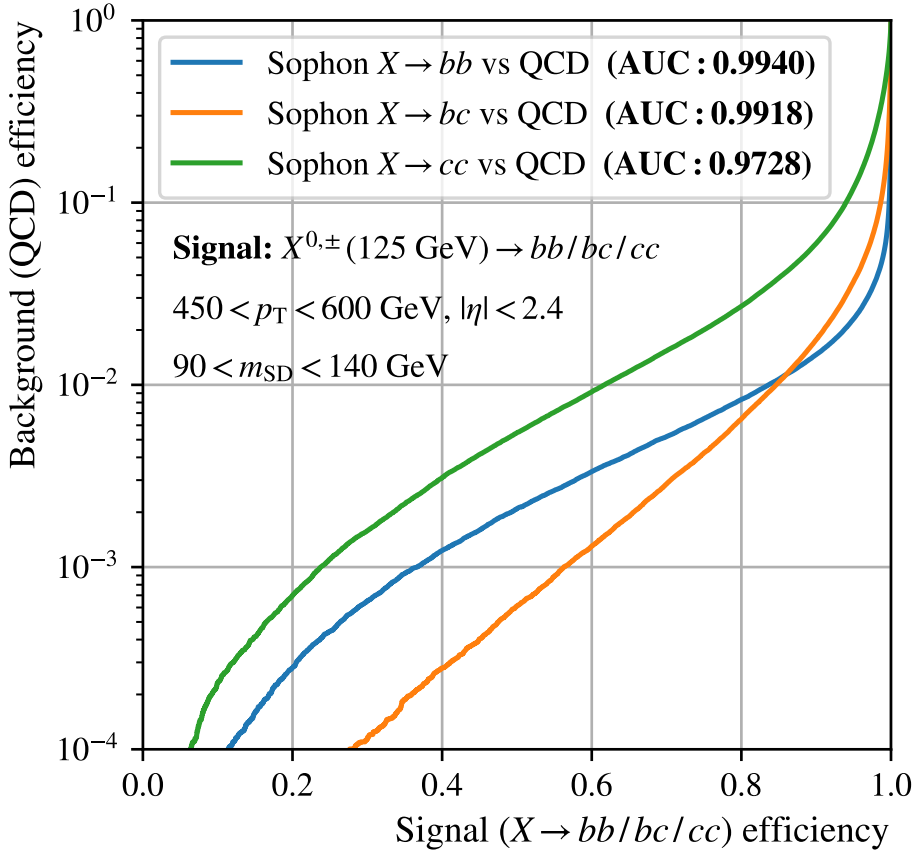
- bc tagging achieves an AUC between those of bb and cc tagging.
- At a tight working point, bc-tagging provides stronger QCD jet suppression compared to bb and cc, as QCD processes do not produce bc from gluon splitting.
- bb- and cc-tagging results are found compatible with CMS's state-of-the-art taggers ParticleNet-MD and GloParT.



Compared against state-of-the-art CMS taggers [12, 13] under consistency in signal and background definitions, jet selections, and discriminant definitions.

Performance of Sophon in various flavor tagging tasks





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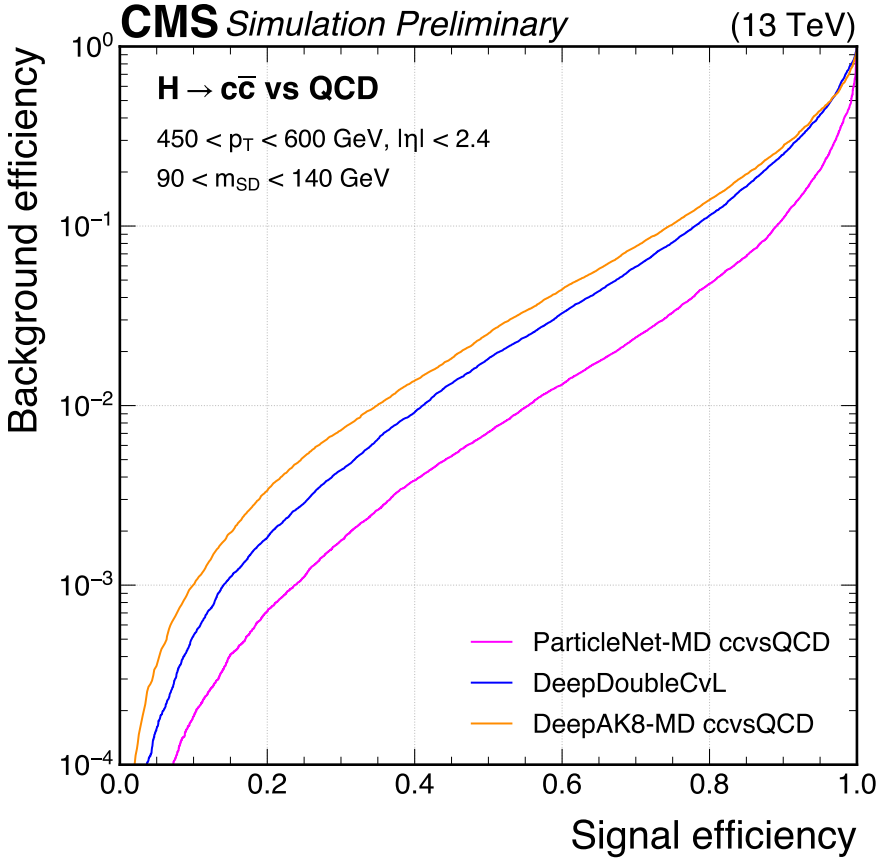

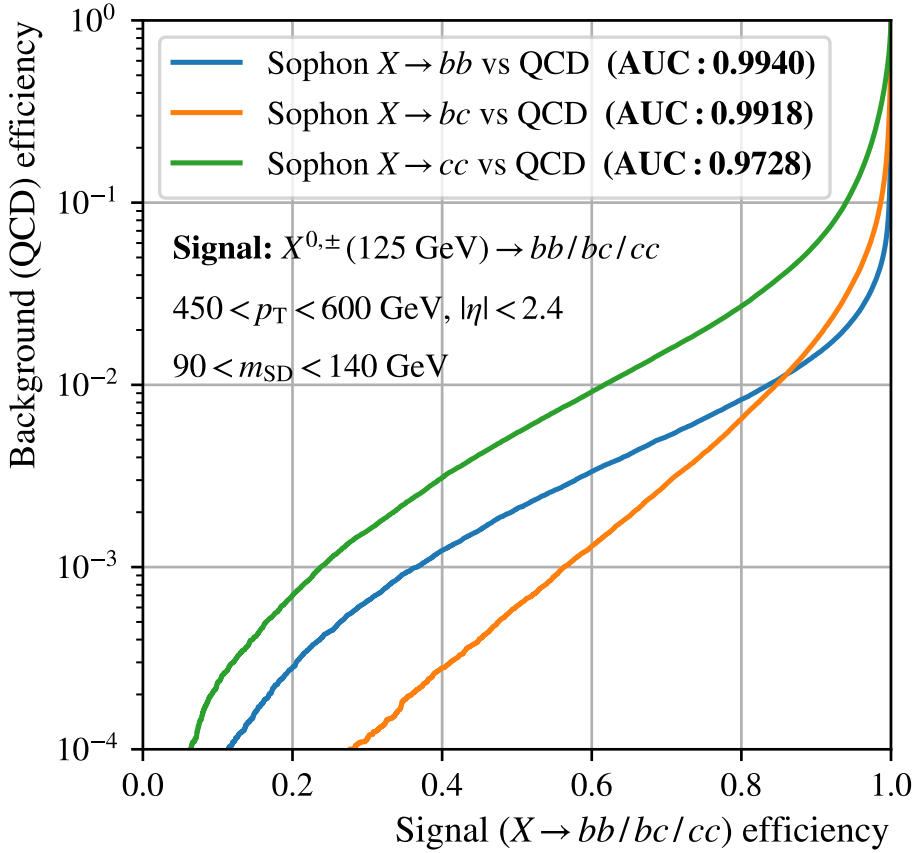

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MC simulation

Simulated datasets for LHC pp collision at $\sqrt{s} = 13$ TeV:

- Trigger: single isolated lepton ($p_{\mathrm{T}} > 24$ GeV for e or $p_{\mathrm{T}} > 32$ GeV for μ).
- Other SM processes: $W + \mathrm{jets}$ ($W \to \ell\nu$), tW ($W \to \ell\nu$), and semileptonic WW.
- Hard process: MG5_aMC@NLO v2.9.18 with SM at LO $\to$ scaled to higher-order calculations [14–17].
- Parton shower: Pythia 8.3 [18] with an NNLO PDF in NNPDF 3.1 [19].
- Fast detector simulation: Delphes 3.5 with the same configuration as JetClass-II:
  - Based on the default CMS card.
  - Account for track smearing according to CMS tracker resolution.
  - Include PU with an average of 50 vertices and apply the PUPPI algorithm [20].
  - Cluster anti-k_{T} jets with $R = 0.4$ and $R = 0.8$, with $p_{\mathrm{T}} \geq 25$ GeV and 200 GeV, respectively.
  - Yield 1.8×10^4 inclusive $W \to cb$ events for 140 fb^{-1}.

Event selection

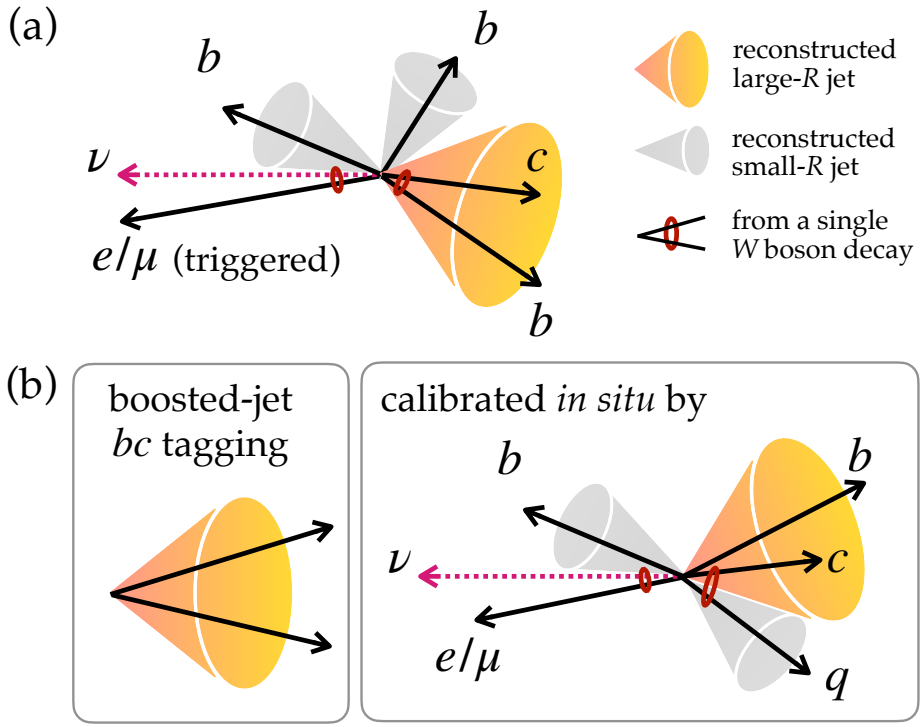
The boosted regime

Pre-selection:

- At least one $R = 0.8$ jet isolated from the trigger lepton.
- W candidate jet: the one with highest p_{T}, with $60 \leq m_{\mathrm{SD}}/\mathrm{GeV} \leq 110$ [21, 22].
- Only about 6% of signal events survives.

Event categorization:

- $t(bqq')$-matched (0.7%),
- $t(bc)$-matched (3.1%),
- $t(bq, q \neq c)$-matched (12.3%),
- $W(qq')$-matched (23.3%),
- non-matched (14.7%),
- QCD-originated (45.9%).



Event selection

The boosted regime

Two independent event selection strategies:

- For bc-content purification: define a discriminant

$$D_{bc} = \frac{g_{X\to bc}}{g_{X\to bc} + g_{X\to bq} + g_{X\to cs} + g_{X\to bqq} + g_{\mathrm{QCD}}}$$

  based on Sophon's 188 output scores $\vec{g}$.

- In parallel, train a multivariate classifier to distinguish $W(qq')$-matched-like W candidate jets from others without utilizing the Sophon's tagging information:
  - Model: Particle Transformer [23] (with pair-wise feature support)
  - Supposed categories: $W(qq')$-matched, "$t(bc)+t(bq)$"-matched, $t(bqq')$-matched, non-matched cases, and $W+\mathrm{jets}$ background
  - Input variables:
    - The triggered lepton, with its 4-vector;
    - Missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$;
    - Up to 5 $R=0.4$ jets exclusive to the triggered lepton and the W candidate jet, with their 4-vectors and flavor-tagging labels from SophonAK4.

Event selection

The boosted regime

For the 2nd classifier, before the Sophon D_{bc} selection:

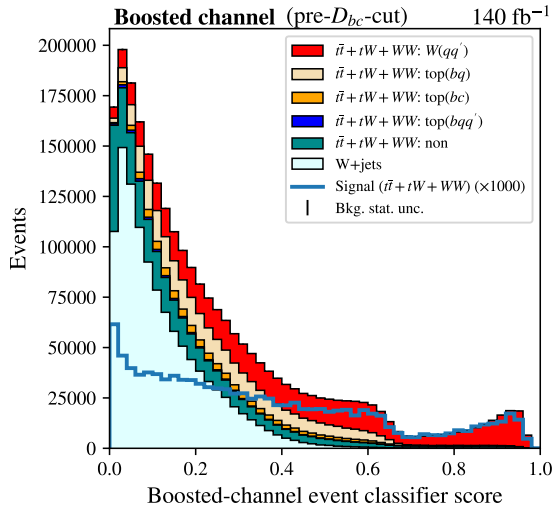
- Contributions from all background components are comparable (top figure).

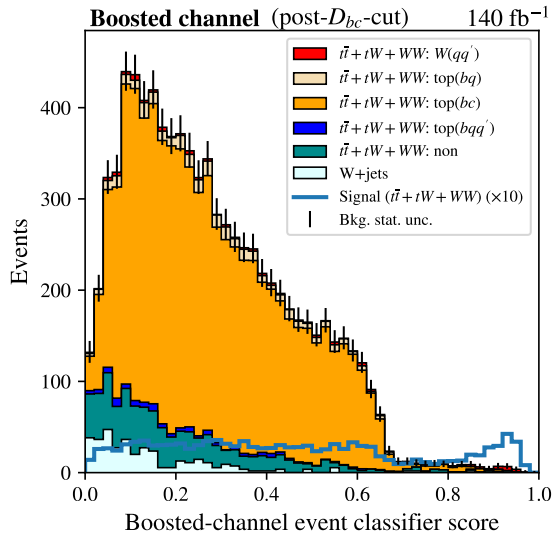
After a stringent Sophon D_{bc} selection:

- The background is predominantly composed of $t(bc)$-matched jets (bottom figure).

Main idea:

- Use event-level information fully independent of the W candidate jet content to construct another classifier.
- Pair the bc-matched background with the signal to calibrate the D_{bc} tagging efficiency: correct both yields using a shared, unconstrained scale factor.



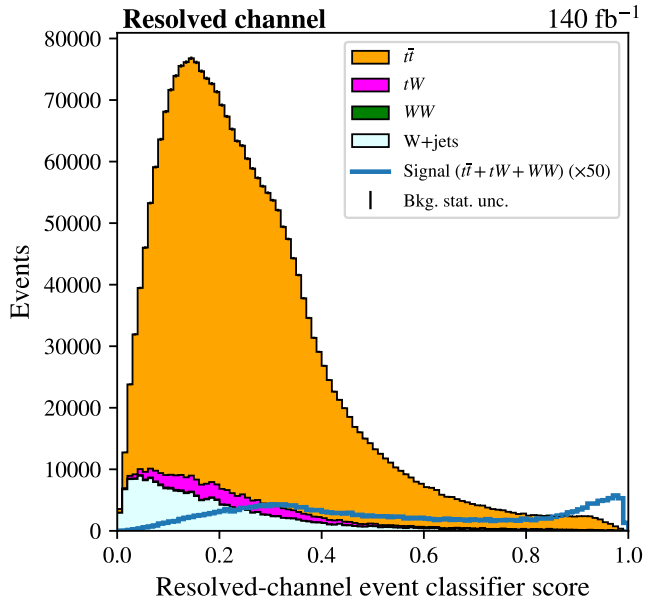


Event selection

The resolved regime (in comparison with the boosted regime)

For the resolved regime, the strategy is conventional, similar as Ref. [2]:

- Require exactly 1 lepton and at least 4 $R = 0.4$ jets exclusive to the triggered lepton, with at least 3 of them tagged as b/c.
- About 28% of the triggered signal events survive.
- A particle-transformer-based classifier similar to the boosted regime is trained to distinguish signal versus background events. The input variables are:
  - The trigger lepton (its 4-vector);
  - $p_{\mathrm{T}}^{\mathrm{miss}}$;
  - Up to 6 $R = 0.4$ jets exclusive to the triggered lepton (their 4-vectors and five SophonAK4 tagging labels).



Outline

The counting analysis for $|V_{cb}|$ extraction

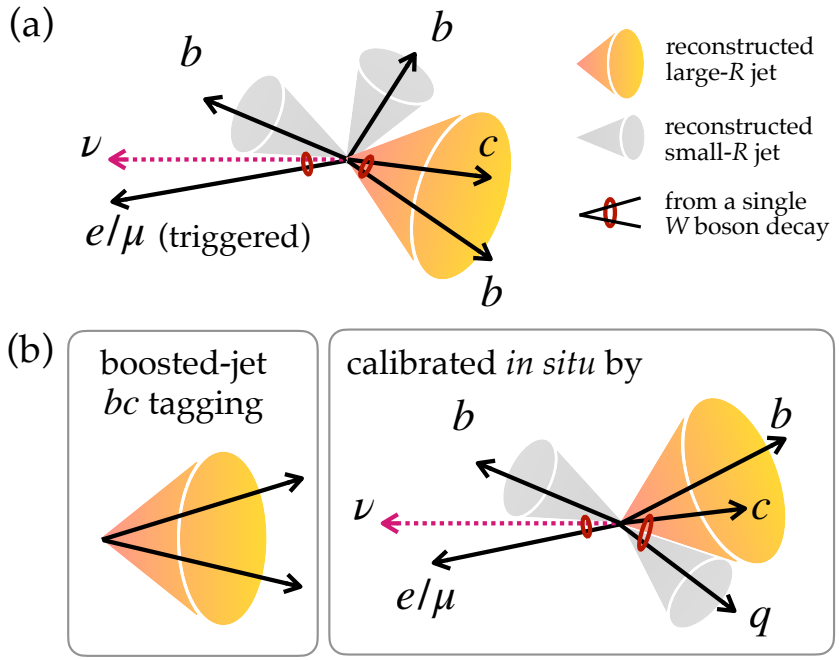
With uncertainty estimation and in-situ calibration

- Based on: events passing an optimized classifier score threshold.
- Three contributions to the total event count:
  - N_{s}: the predicted signal events count;
  - N_{b0}: the predicted background count without a hadronically decayed W boson;
  - N_{b1}: the predicted background count with a hadronically decayed W boson.
- Statistics: the signal strength $\mu = N_{\mathrm{s}}/N_{\mathrm{s}}^{\mathrm{SM}}$, theoretically $\mu = \left(\frac{|V_{cb}|^{\mathrm{obs}}}{|V_{cb}|^{\mathrm{SM}}}\right)^2$ in LO, and $N_{\mathrm{b1}} = \frac{1-\mu r}{1-r} N_{\mathrm{b1}}^{\mathrm{SM}}$, where $r := \frac{\Gamma(W\to bc)}{\Gamma(W\to qq')} = \frac{1}{2}(|V_{cb}|^{\mathrm{SM}})^2$, due to the CKM unitarity.
- Likelihood function: $\mathrm{Poisson}(\lambda = N_{\mathrm{s}}(\mu) + N_{\mathrm{b0}}(\mu) + N_{\mathrm{b1}})$ before integrating the nuisance.
- Nuisance parameters 1/2: $\vec{\nu}$ ($R = 0.4$ jet tagging uncertainty): The impacts of the $b/c/j$-jets tagged as B1/B2/C1/C2/N ($3 \times 5 = 15$ independent parameters) on the event count, with the tagging efficiencies varied but globally normalized to a constant event yield, delicately measured in $b/c/j$-enriched regions following a latest ATLAS work [24].

The counting analysis for $|V_{cb}|$ extraction

With uncertainty estimation and in-situ calibration

- Nuisance parameters 2/2: λ ($R = 0.8$ jet tagging efficiency in-situ calibration): An unconstrained scale factor λ is applied to both the signal and the $t(bc)$-matched background in the post-D_{bc}-cut region.
- Perform simultaneous fit for μ, $\vec{\nu}$, and λ.
- This shared-efficiency assumption is being validated by altering the parton shower model (Pythia → Pythia with Vincia and Herwig) and examining the stability of the post-D_{bc}-cut ratio signal to $t(bc)$-matched background.



The counting analysis for $|V_{cb}|$ extraction

Impacts of the nuisance parameters

The boosted channel:

- b-tagging efficiency is a predominant factor.
- The $W \to bc$ tagging is integrated within $R = 0.8$ jet techniques.
- The result is less affected by the $R = 0.4$ jet flavor tagging uncertainties.

The resolved channel:

- Multiple factors contribute significantly to the overall uncertainty.
- The classifier relies more heavily on identifying multiple b and c jets.

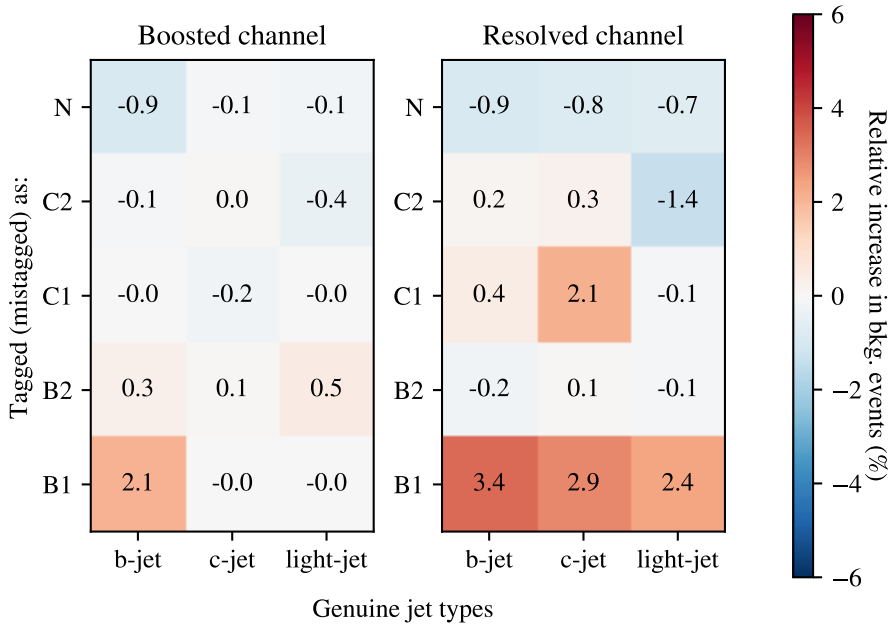
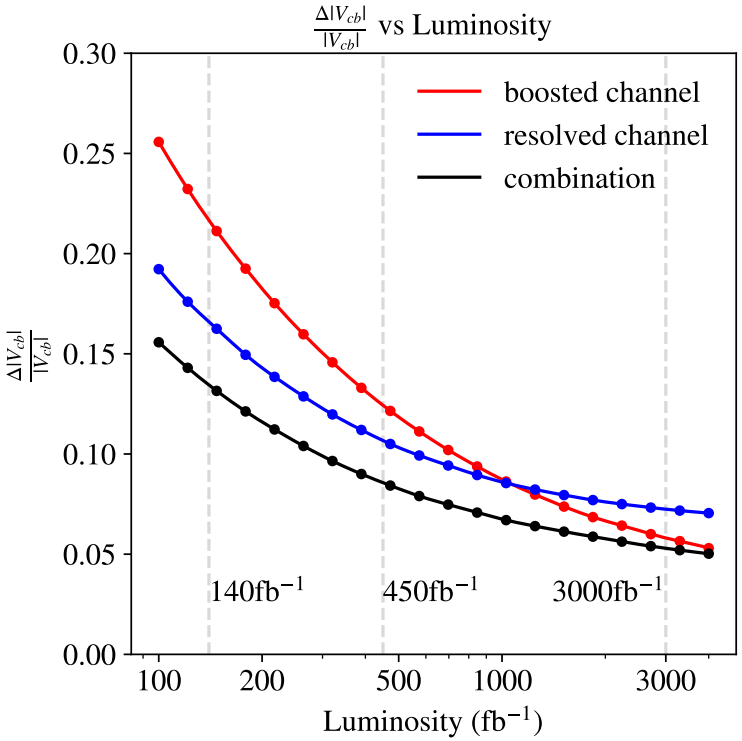


FIG. The relative increases in the background counts due to $+1\sigma$ variations in the 15 sources.

The high-lumi boosted regime surpasses the resolved one in $|V_{cb}|$ precision



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3000 fb^{-1} (resolved)	0.065	—	0.033

(Not a complete but a representative set of contributions considered.)

- The uncertainty under $140\ \text{fb}^{-1}$ is consistent with the preliminary expected result from ATLAS [11] at around $0.13\,(\text{syst.}) \oplus 0.13\,(\text{stat.})$.
- Under $3000\ \text{fb}^{-1}$, the orthogonalized combined precision reaches $\Delta|V_{cb}|/|V_{cb}| = \mathbf{0.051}$, representing a 30% reduction compared to resolved-only approach. A combination of ATLAS and CMS measurements can further reduce it to $\mathbf{0.036}$, sufficient to provide critical insights into resolving the $|V_{cb}|$ puzzle.

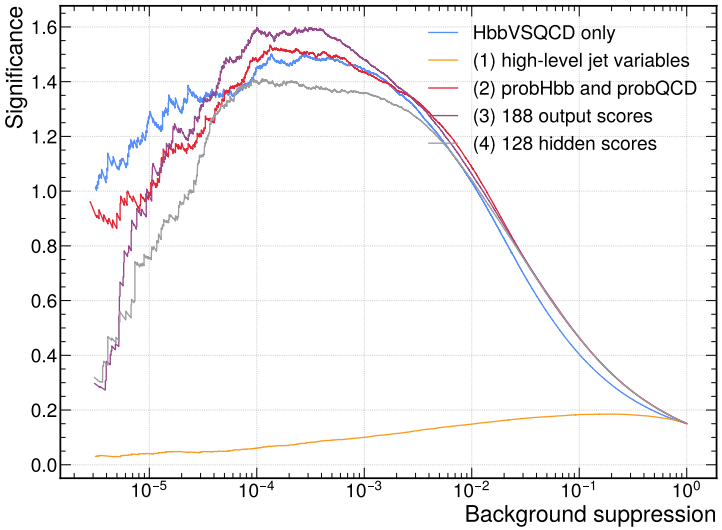
Outline

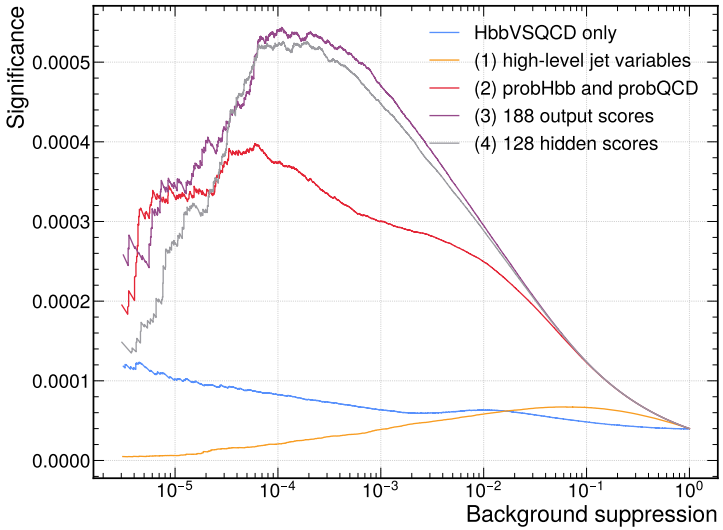
Summary and outlook

- We propose a novel approach for precise $|V_{cb}|$ extraction at the LHC, utilizing the boosted regime:
  - Employing an advanced boosted-jet bc-tagger via the Sophon model.
  - Creating an innovative *in-situ* calibration technique.
- This approach substantially improves the measurement precision over the conventional method.
- Recent advancements in deep learning algorithms for particle physics have enhanced sensitivity through well-established boosted channels such as bb and cc, revealing potential in exploring a broader range of boosted final states.
- This highlights the Sophon's philosophy: extending boosted-jet techniques to previously unexplored regions.
- It also suggests a more important role for boosted-regime searches in future LHC explorations.

Another possibility: boosted jet model fine-tuning for event selection

- Modern deep learning algorithms haven't been directly used for event-level selections, with less sophisticated jet information being utilized compared to what is available from advanced jet tagging models.
- By encoding the events incorporating a high-dimensional, comprehensive jet representation from successful pre-trained models with event-level physics objects (leptons, photons), a new-trained event-level classifier can show a more powerful background suppression capability under the same signal efficiency levels.
- This approach maintains the modularity of conventional analysis strategies, ensuring the feasibility of per-object calibrations.





Thanks for your attention!

And, welcome to Peking University for recent HEP workshops:

- Larger than Larger: Large AI Models at the Frontiers of Experimental High-Energy Physics. (1st on Jan 7, 2025, 2nd upcoming).
- Workshop on Quantum Entanglement at the Energy Frontier. (Apr 25–28, 2025; reports are welcome).

Outline

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