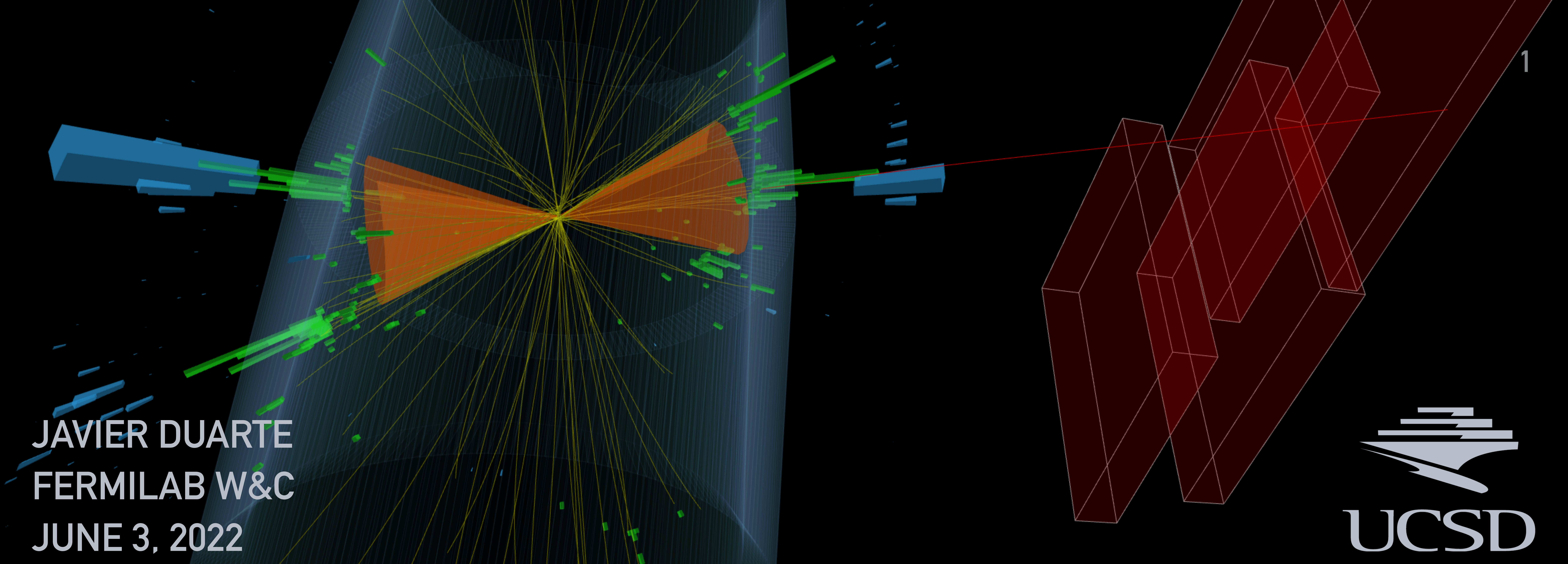

JAVIER DUARTE
FERMILAB W&C
JUNE 3, 2022

UCSD

ENABLING HIGGS COUPLING MEASUREMENTS WITH BOOSTED HH


D3
WRIGLEYVILLE
LINCOLN PARK
OLD TOWN
GOLD COAST
B
D1
WEST LOOP
D4
B
C
START
THE LOOP
D2
FINISH
D6
F
A
E
PILSEN
D5
CHINATOWN
BRONZEVILLE

- LHC+HL-LHC lifespan as the Chicago marathon
- 10 years since the Higgs discovery!

We are here!

Higgs discovery!

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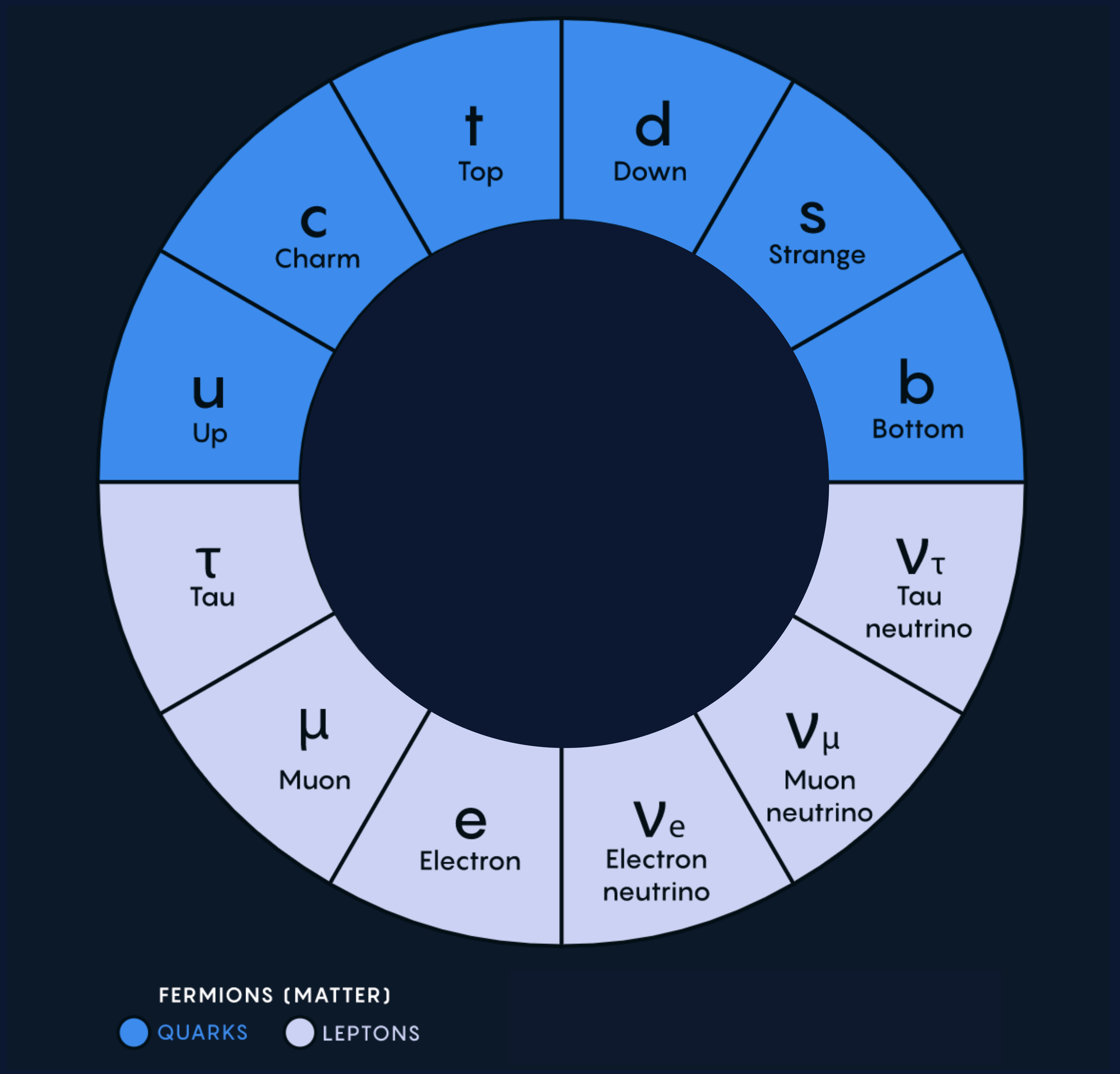
- But mile 10 is not mile 26.2!
  - ***Plenty of time for twists & turns***
  - Measuring Higgs self interaction necessary for establishing connection between the Higgs boson and *electroweak symmetry breaking*

We are here!

Higgs discovery!

Higgs self-interaction?

HIGGS BOSON IN THE STANDARD MODEL



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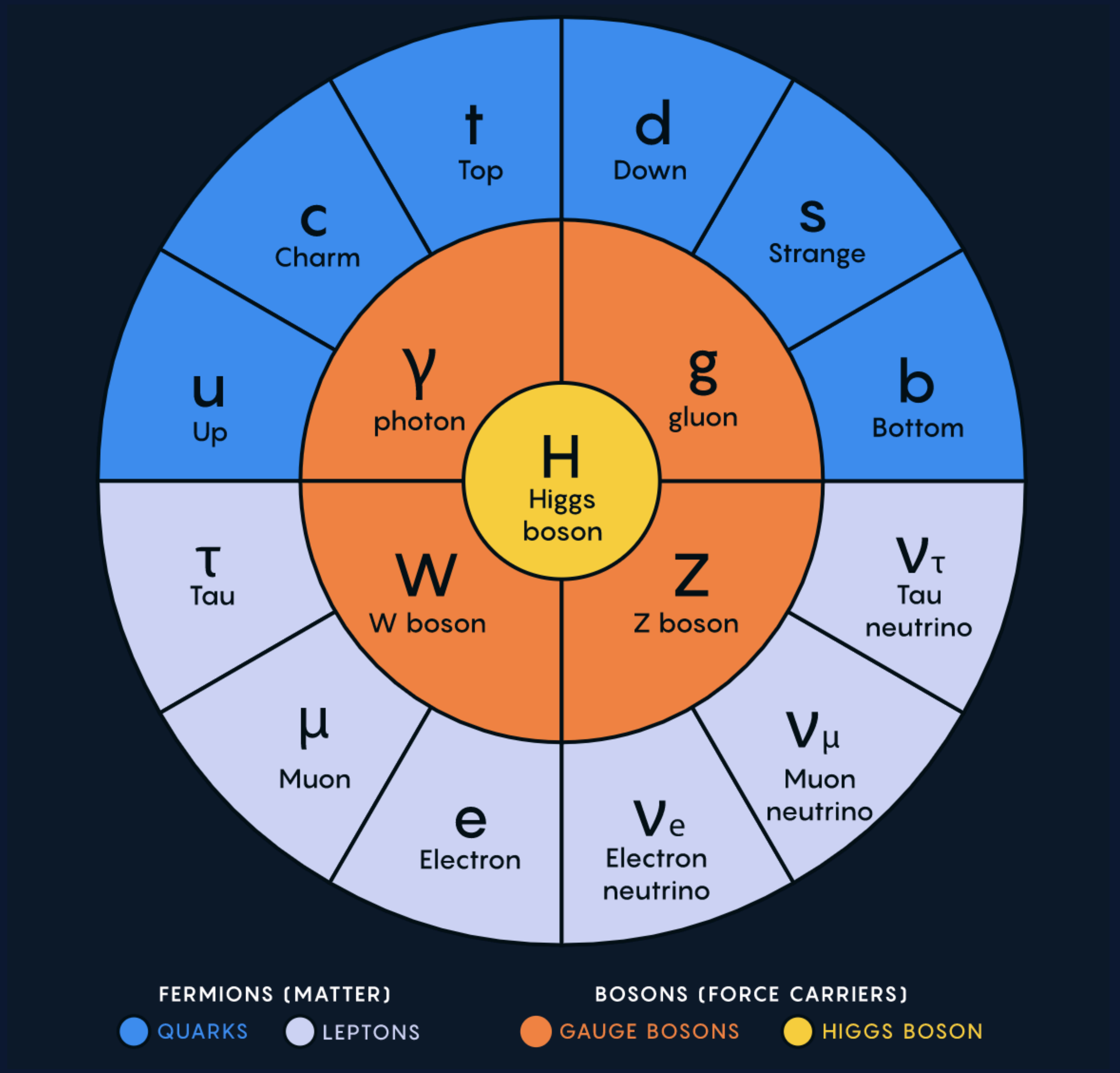

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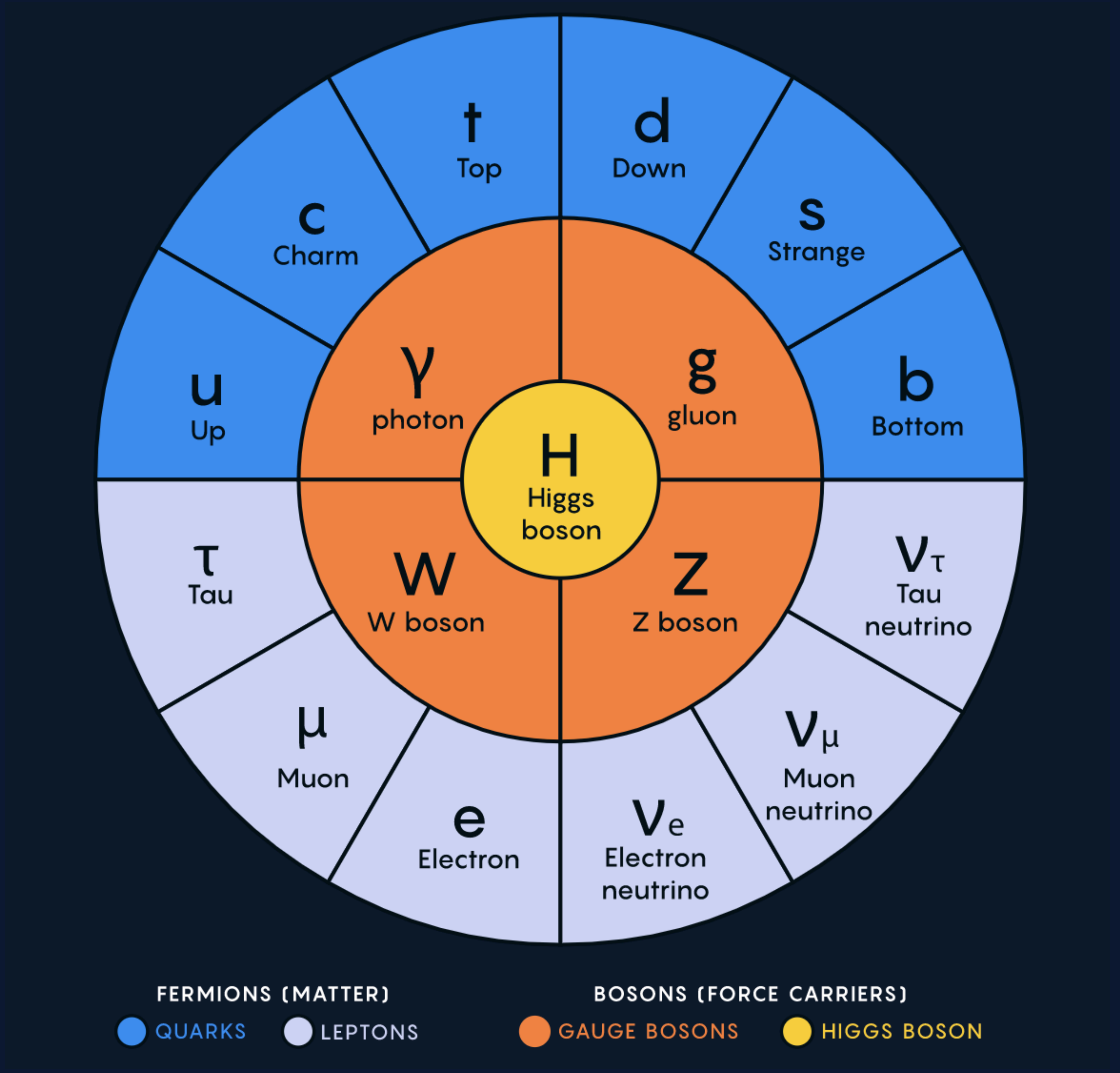

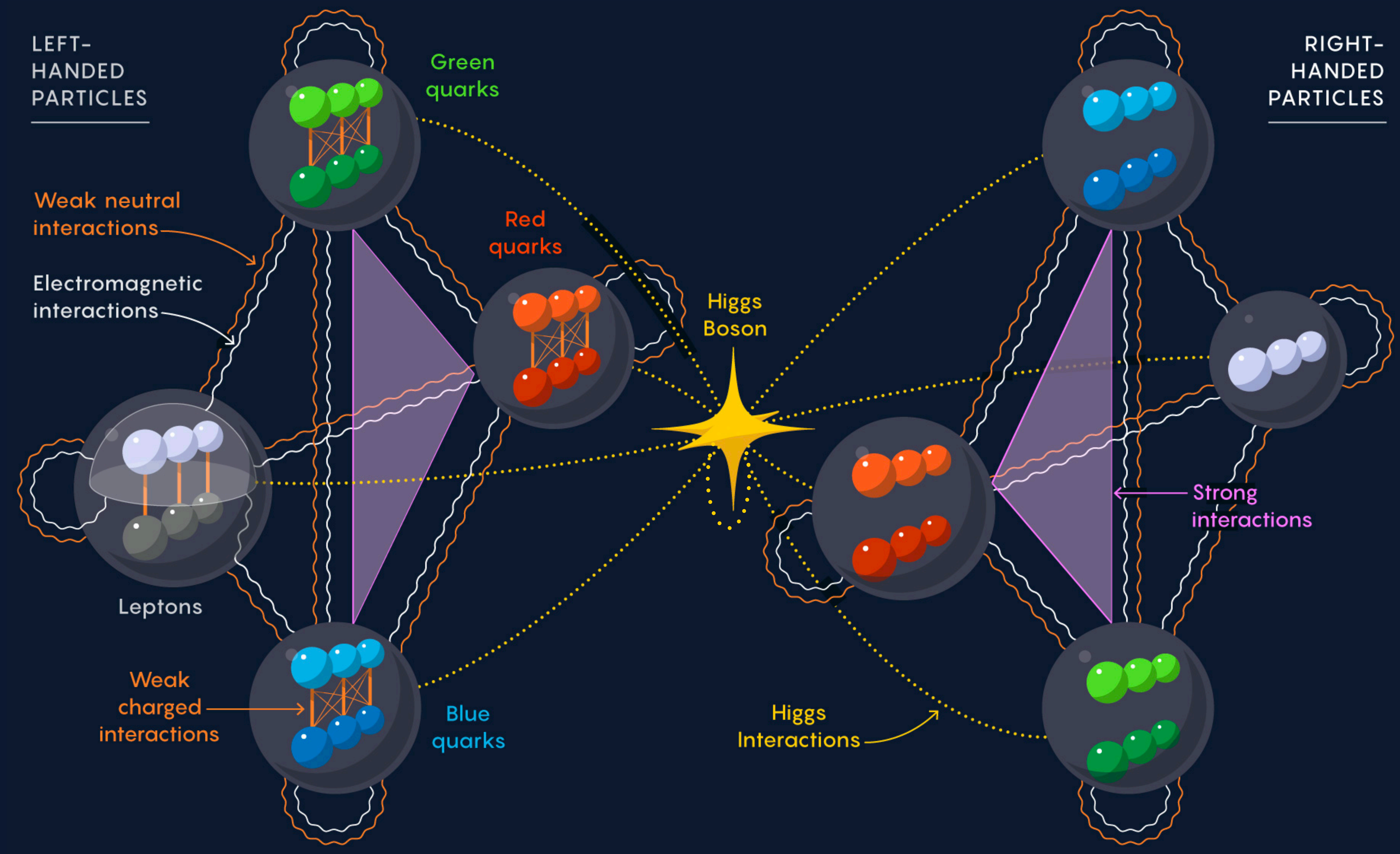

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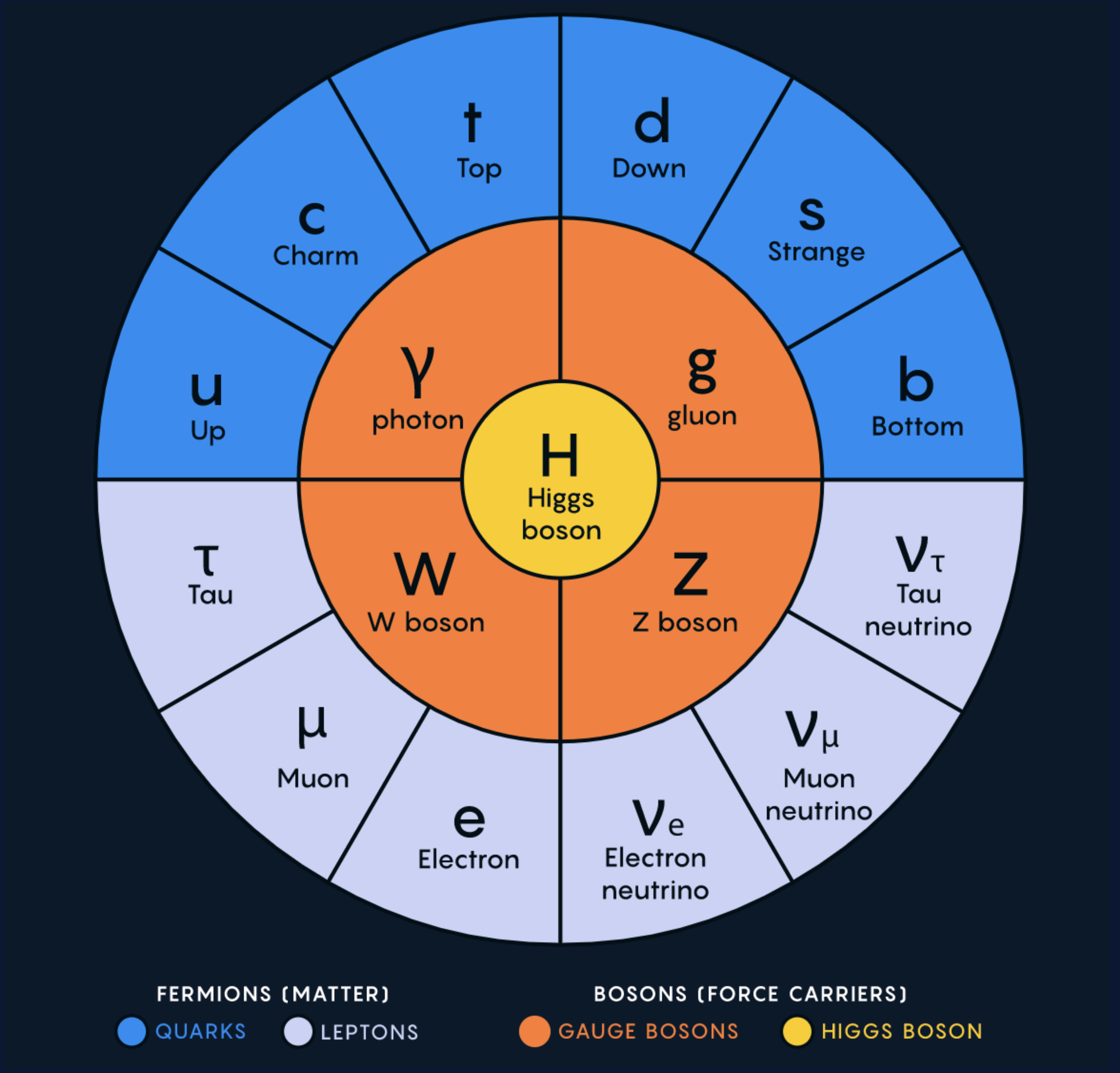

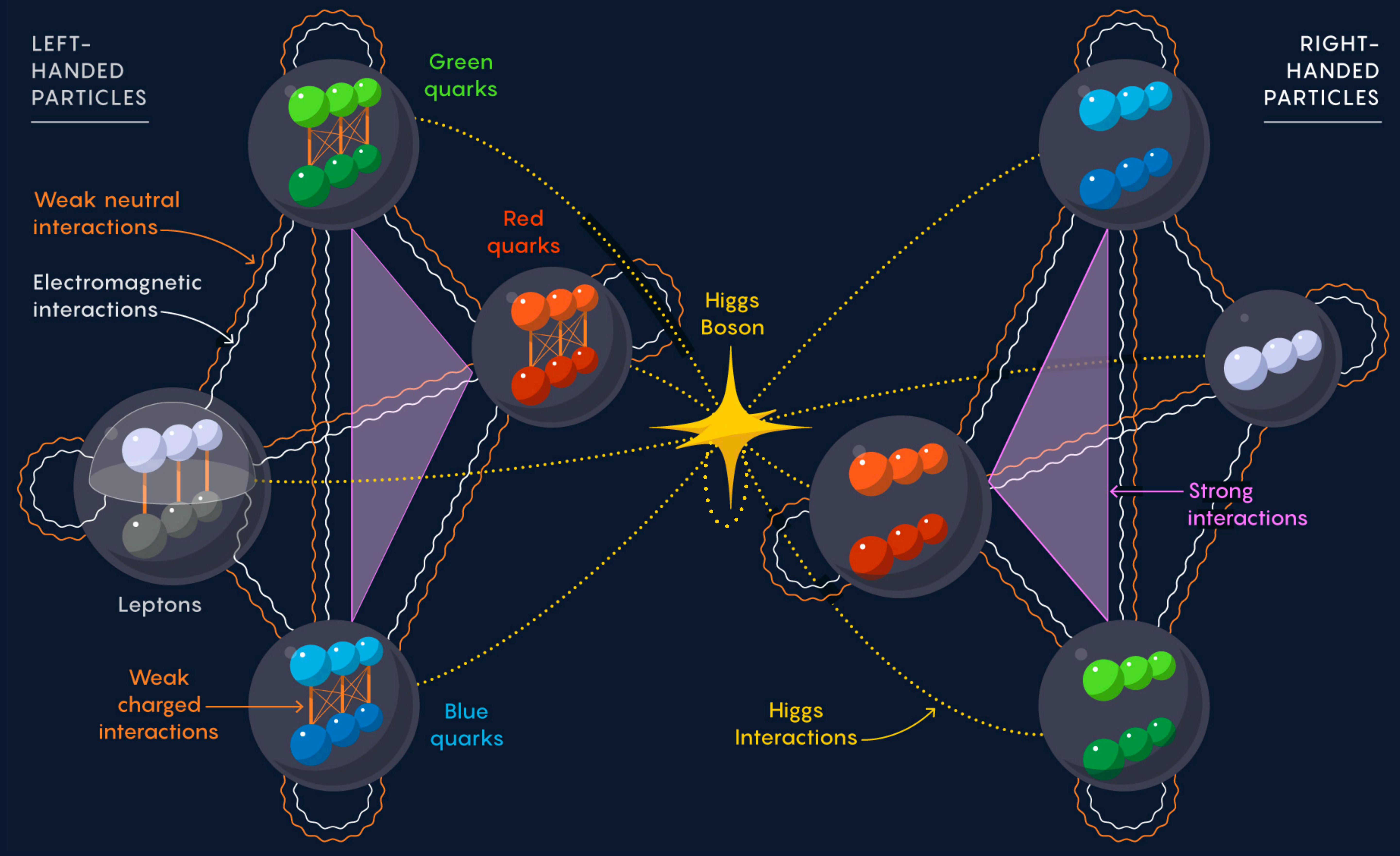

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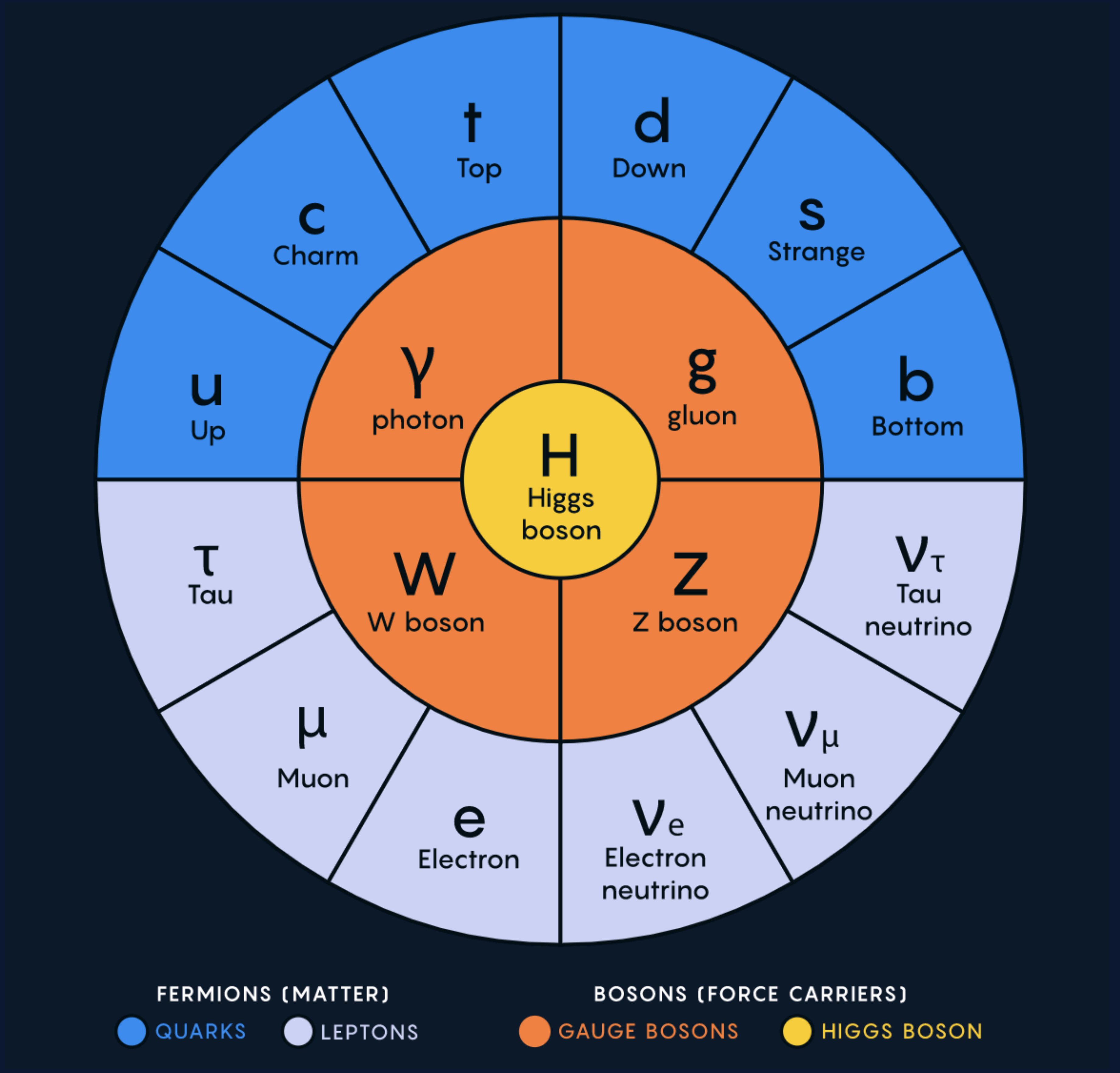
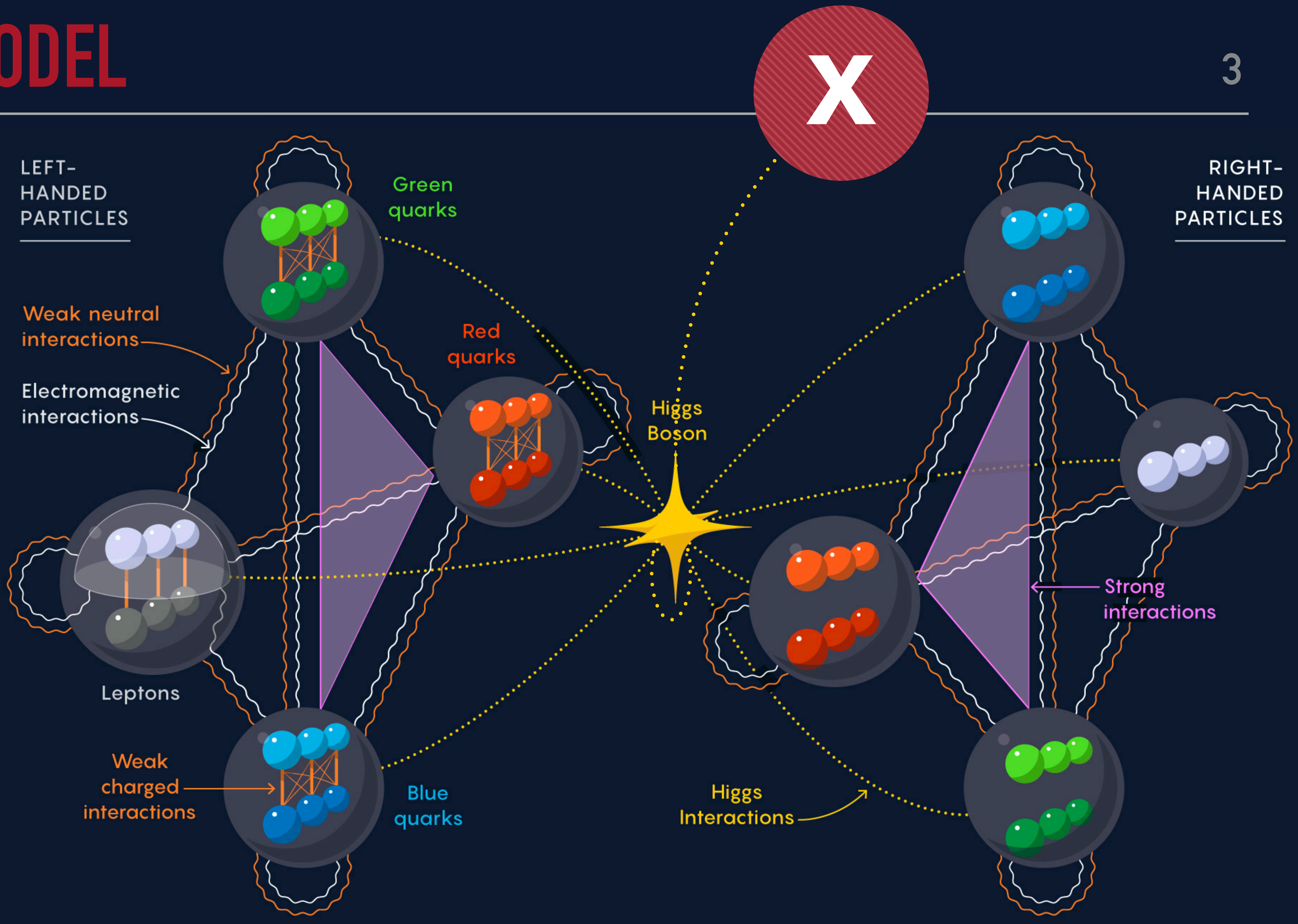
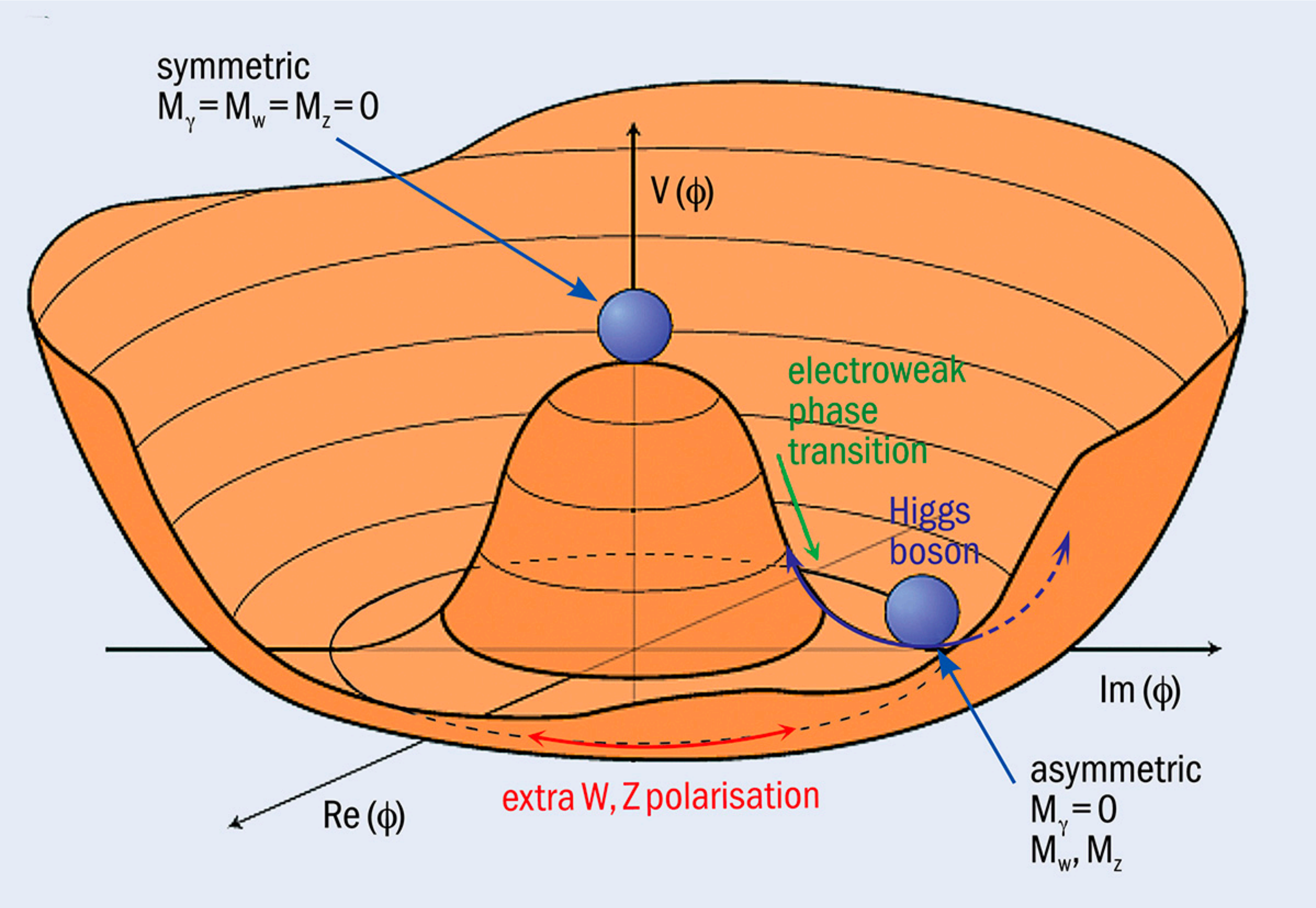




- But there has to be more to it! SM does not explain **dark matter**, **neutrino masses**, and the **matter-antimatter asymmetry**…
- Higgs boson is the ***centerpiece:*** all particles interact with it
- Measuring its couplings to other particles (and to *itself*) may give insight into BSM physics

ELECTROWEAK SYMMETRY BREAKING & THE HIGGS POTENTIAL

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$



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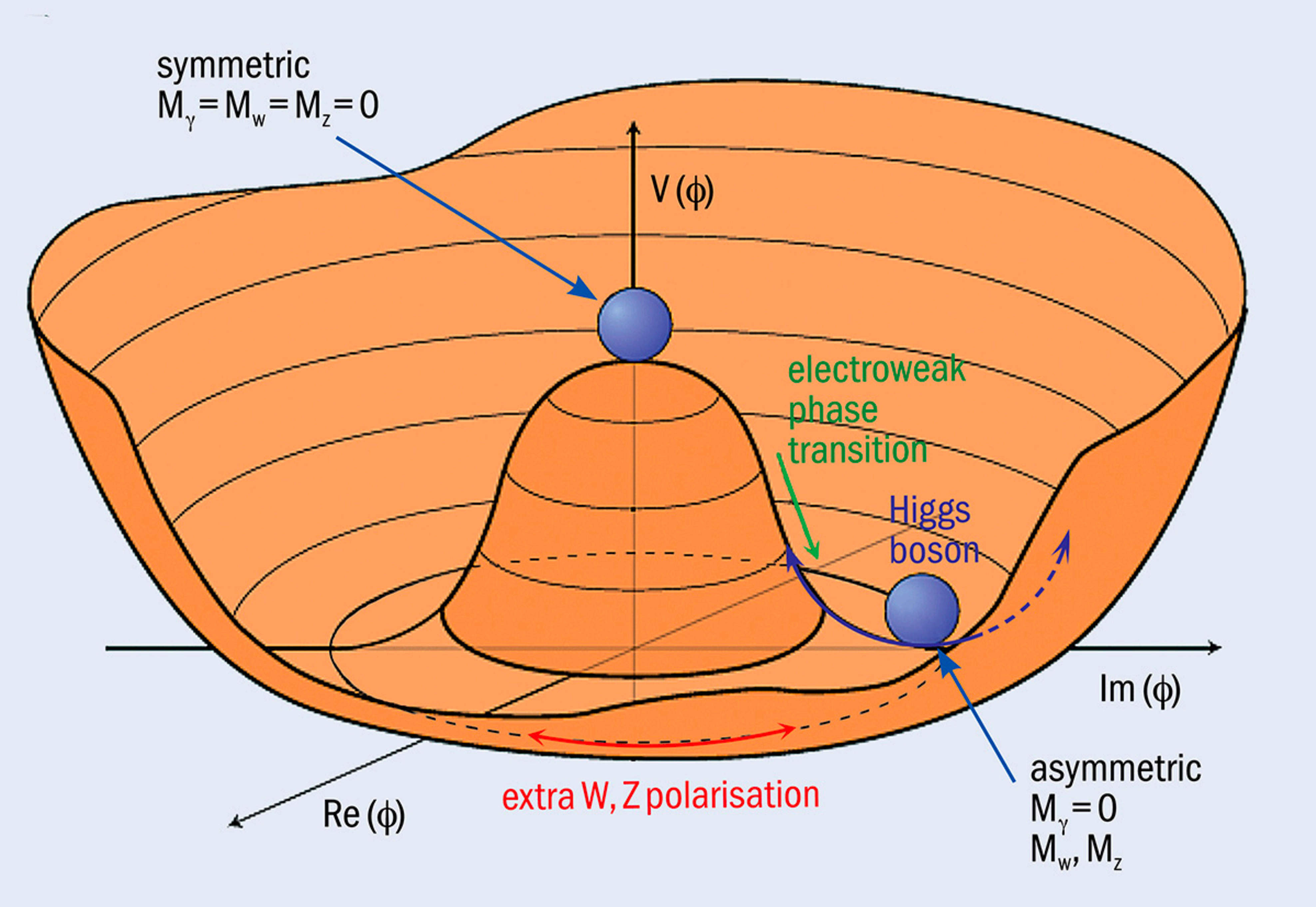

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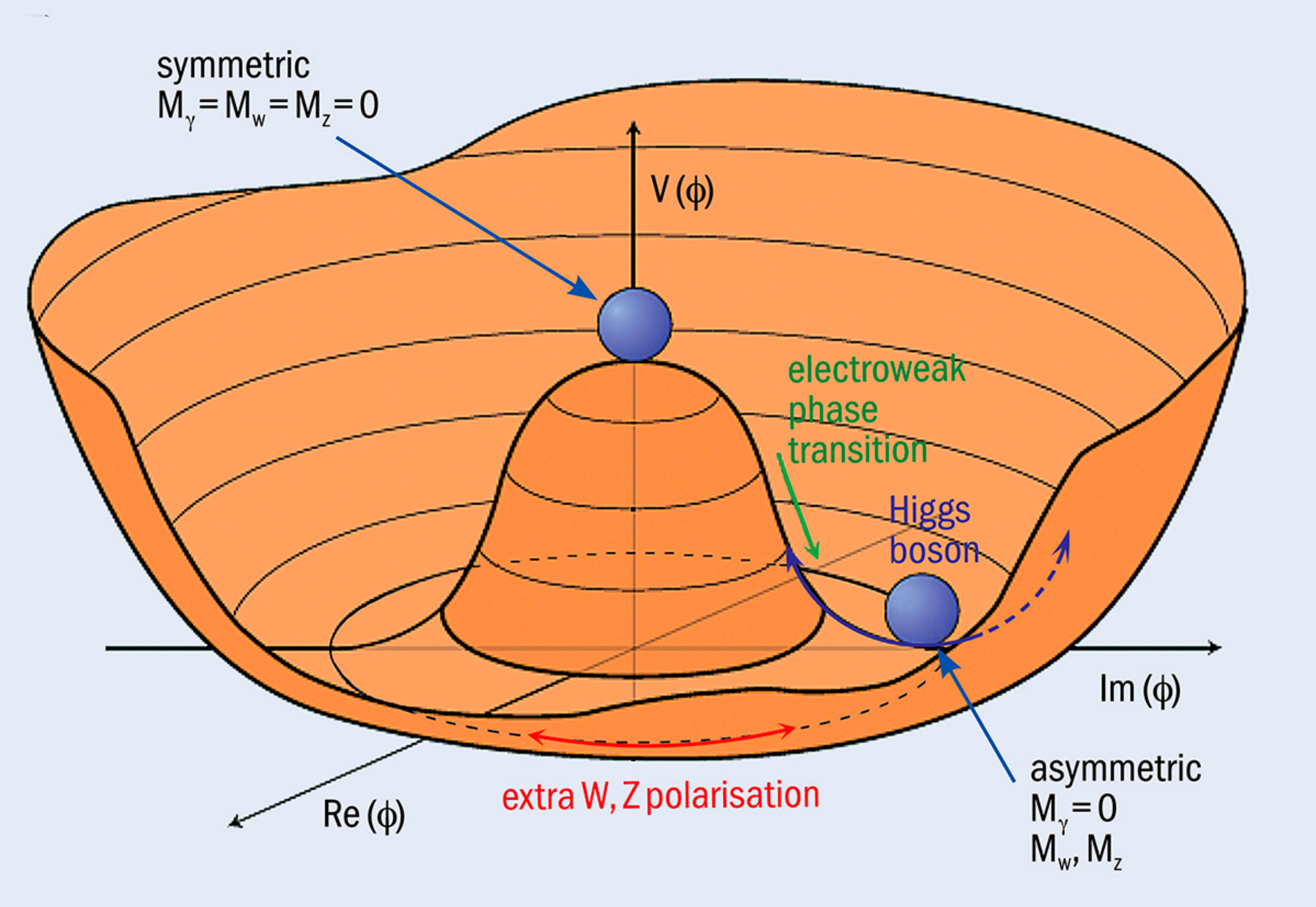

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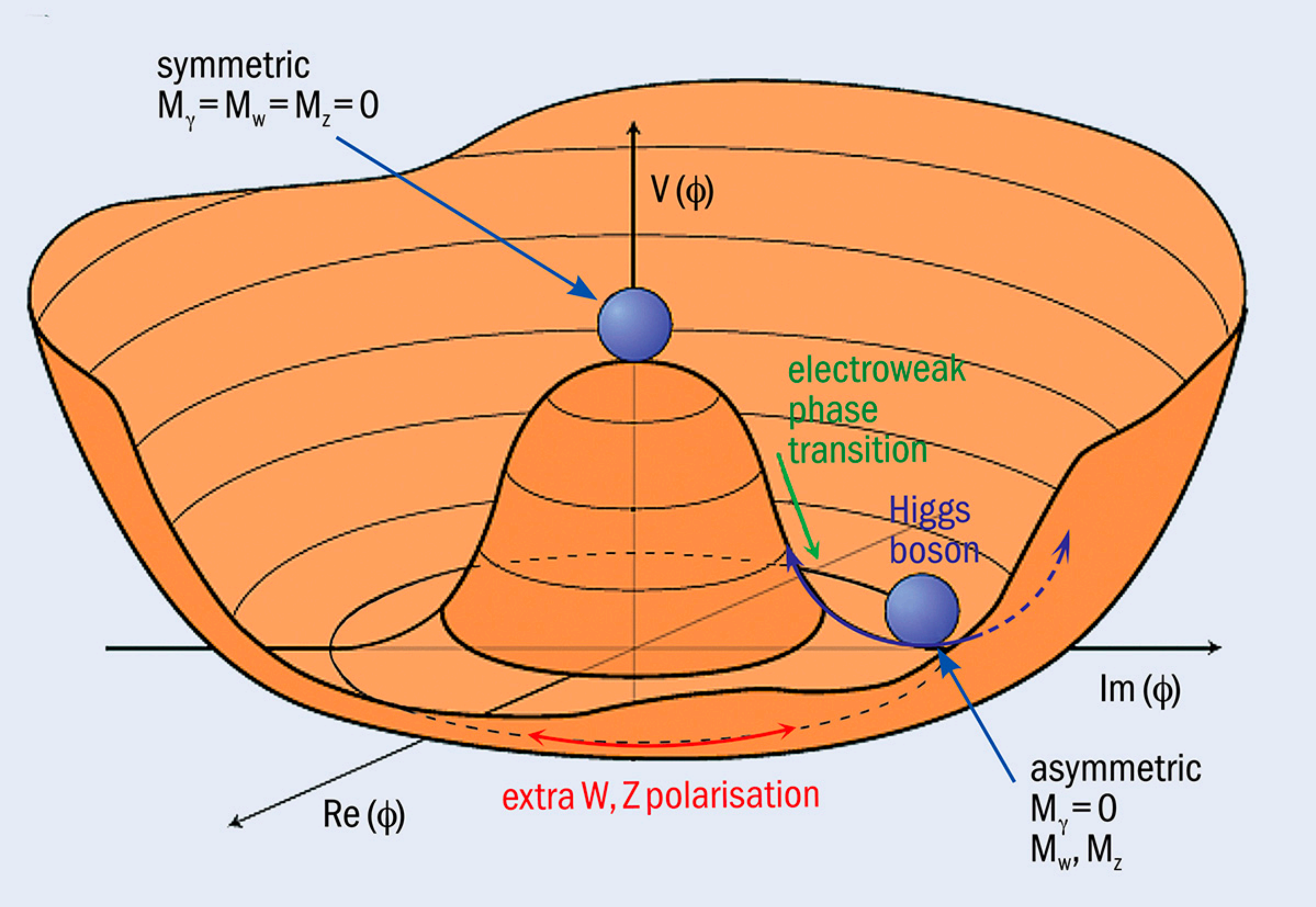
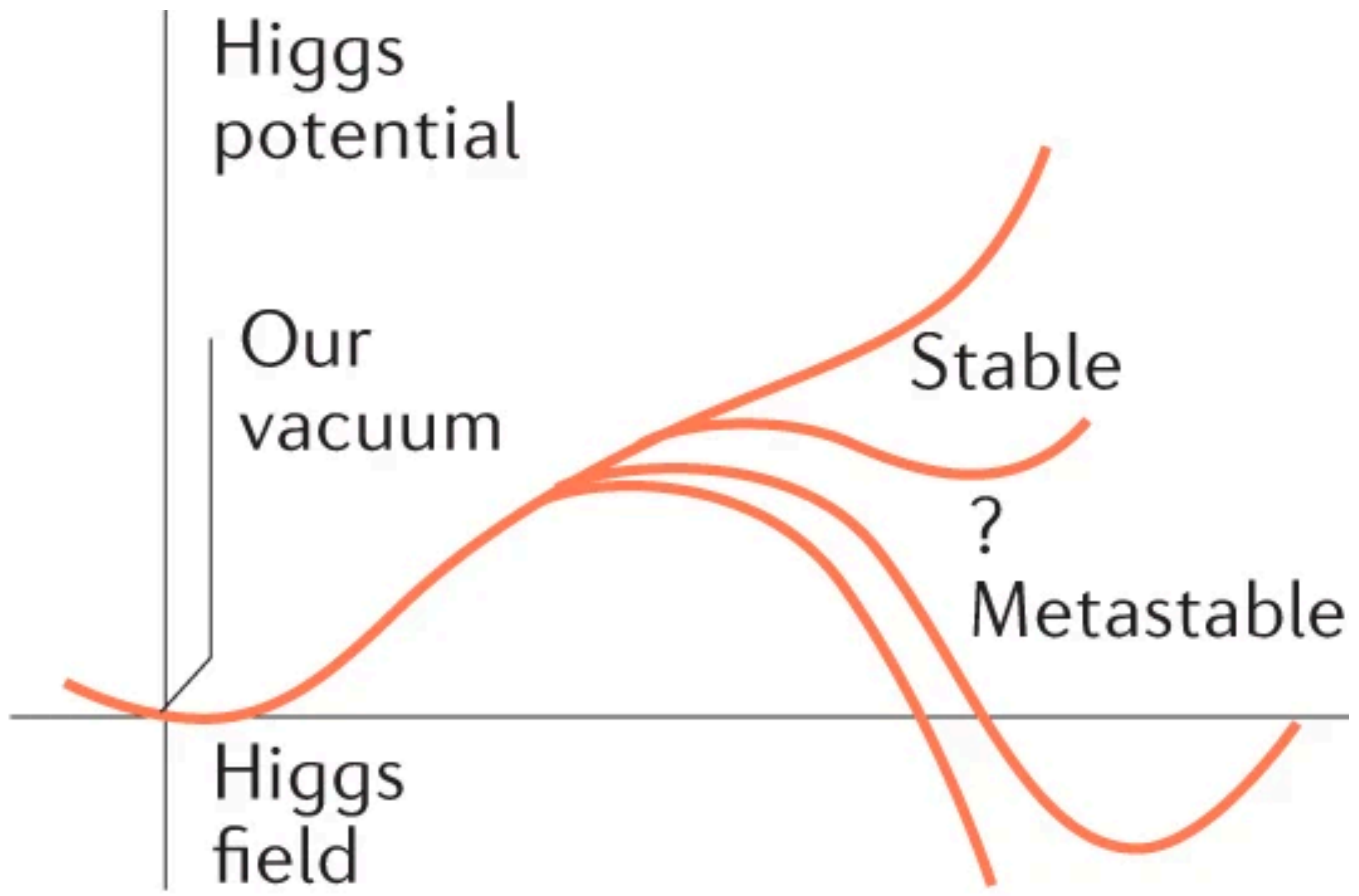
- Measurement of λ crucial for confirming this story of how electroweak symmetry breaking is realized
  - And the (meta)stability of our vacuum





(B)SM HIGGS COUPLINGS

$$\mathscr{L} \supset -\frac{m_t}{v}\bar{t}tH + \frac{m_{\mathrm{H}}^2}{2v}H^3 + \frac{m_{\mathrm{H}}^2}{8v^2}H^4$$

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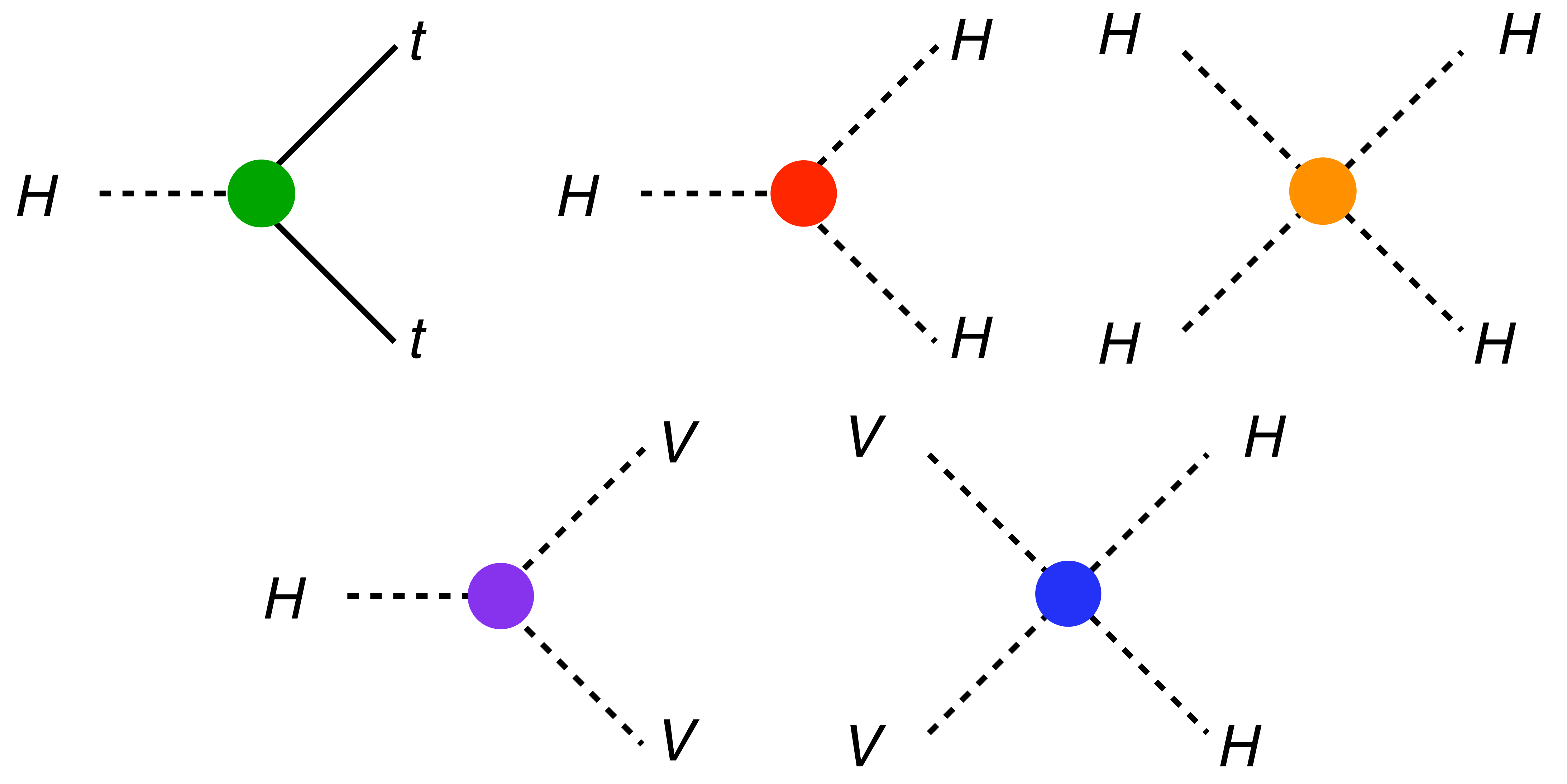

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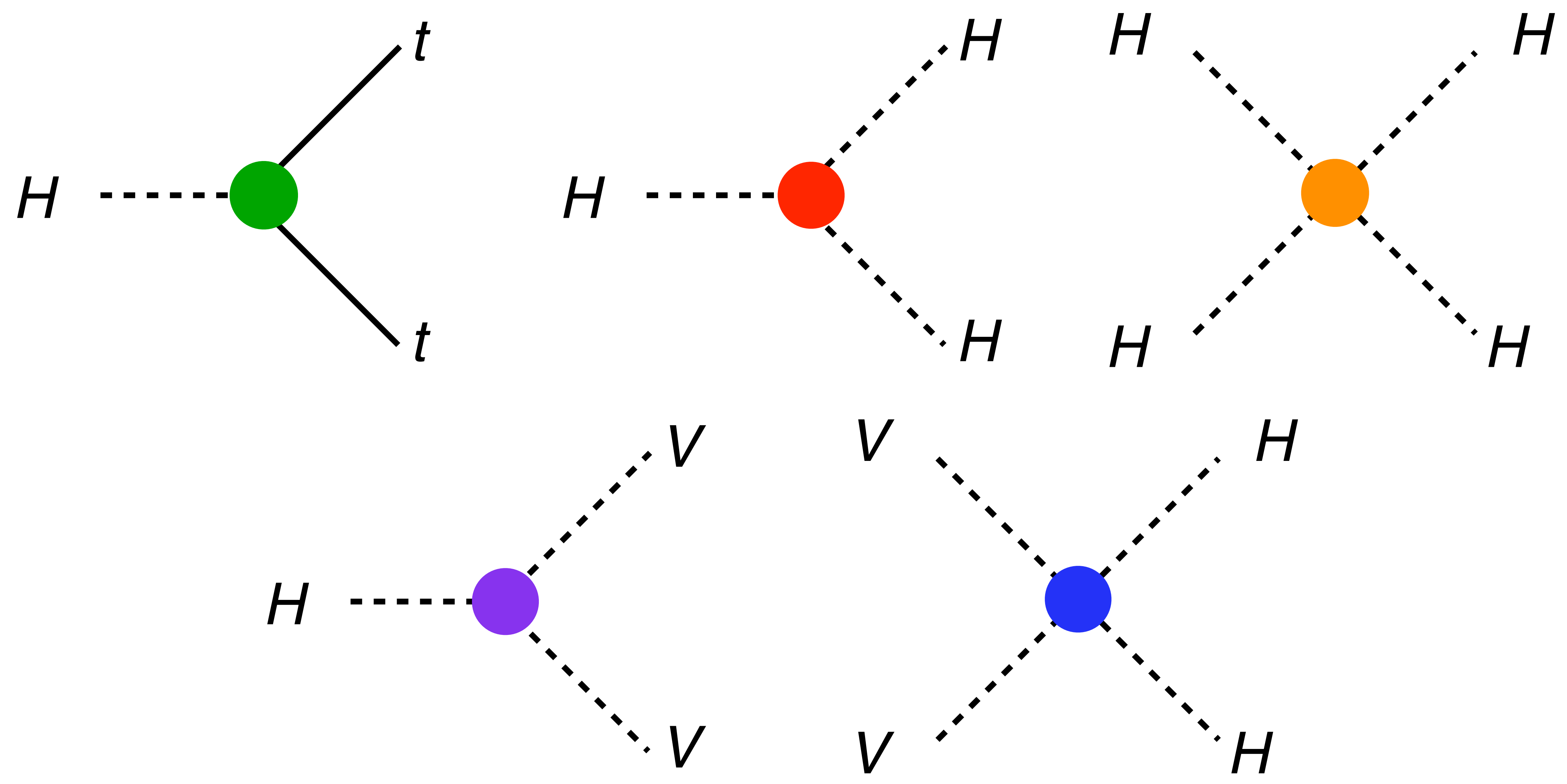

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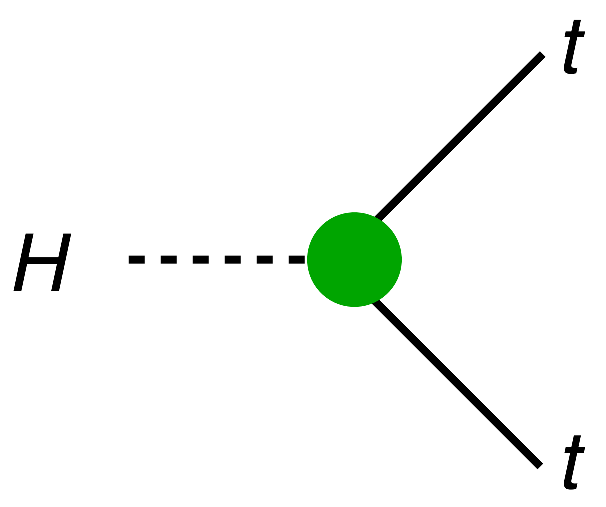

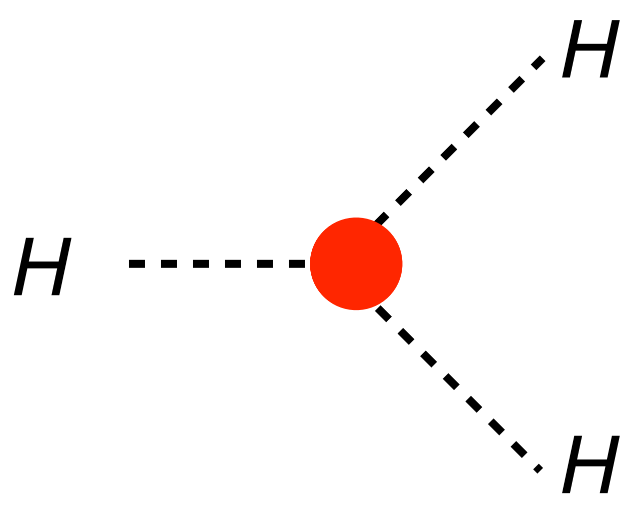

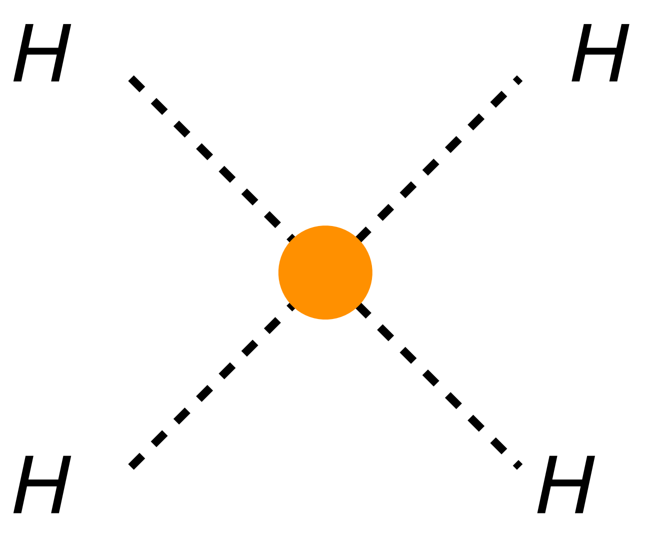

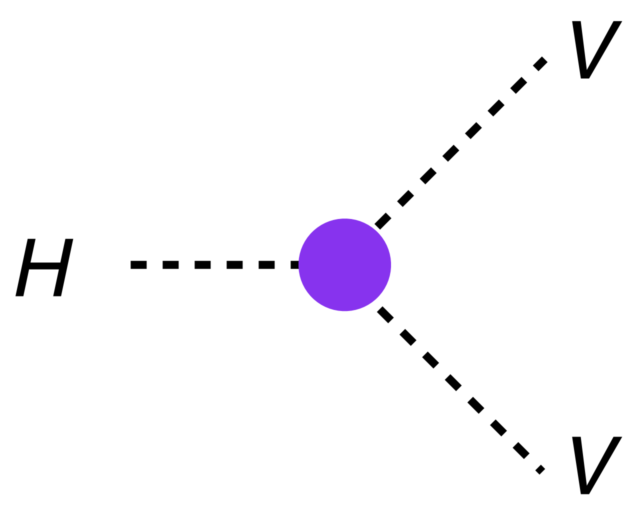

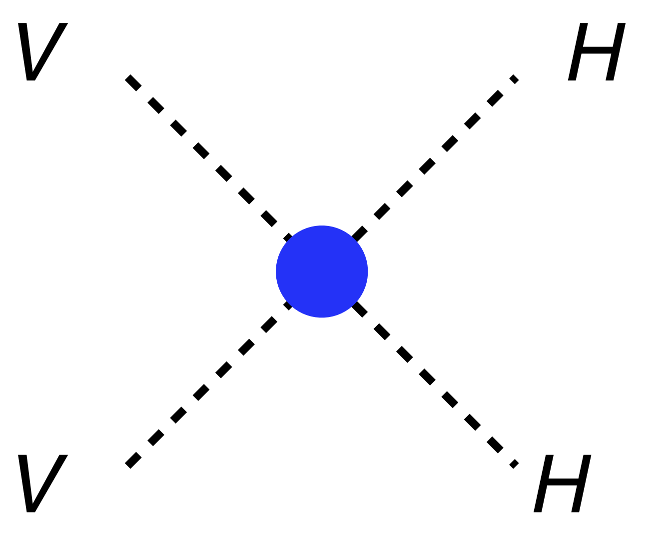

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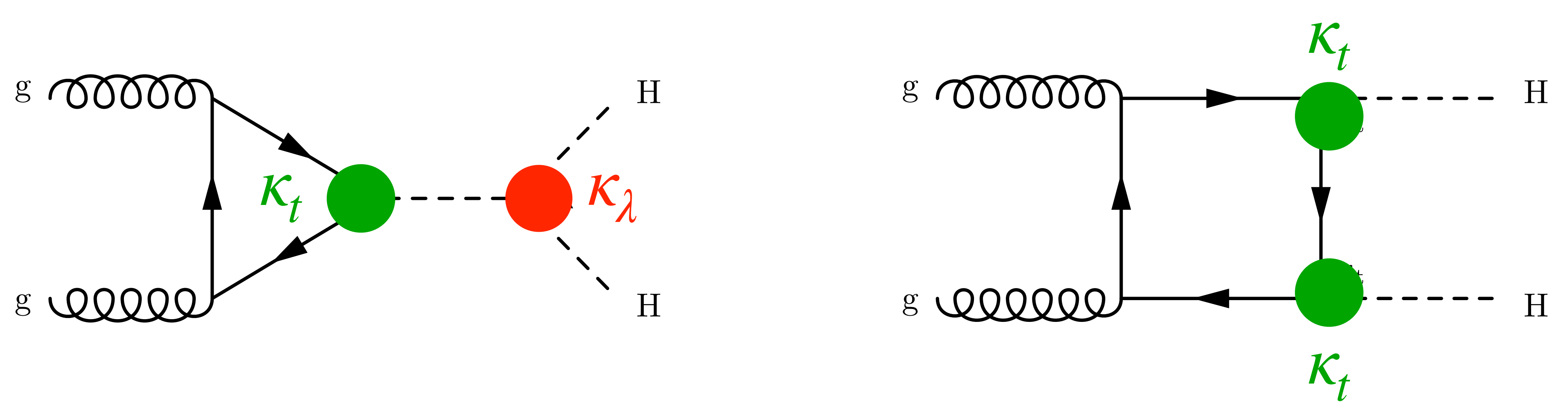
- Many BSM scenarios conceivable for interpreting results
    - Focus on modified couplings w.r.t. the SM: κ_λ, κ_V, κ_{2V}, and κ_t

HH PRODUCTION AT THE LHC

- Dominant gluon-gluon fusion (ggF) production mode (σ_{ggF} = 31.05 fb) gives best access to H self-coupling



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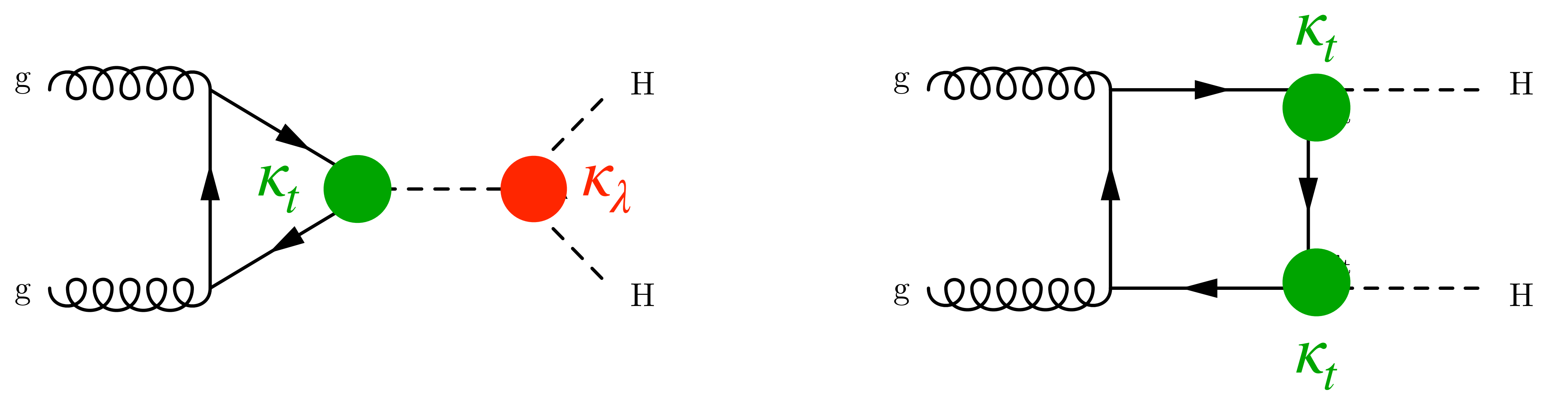

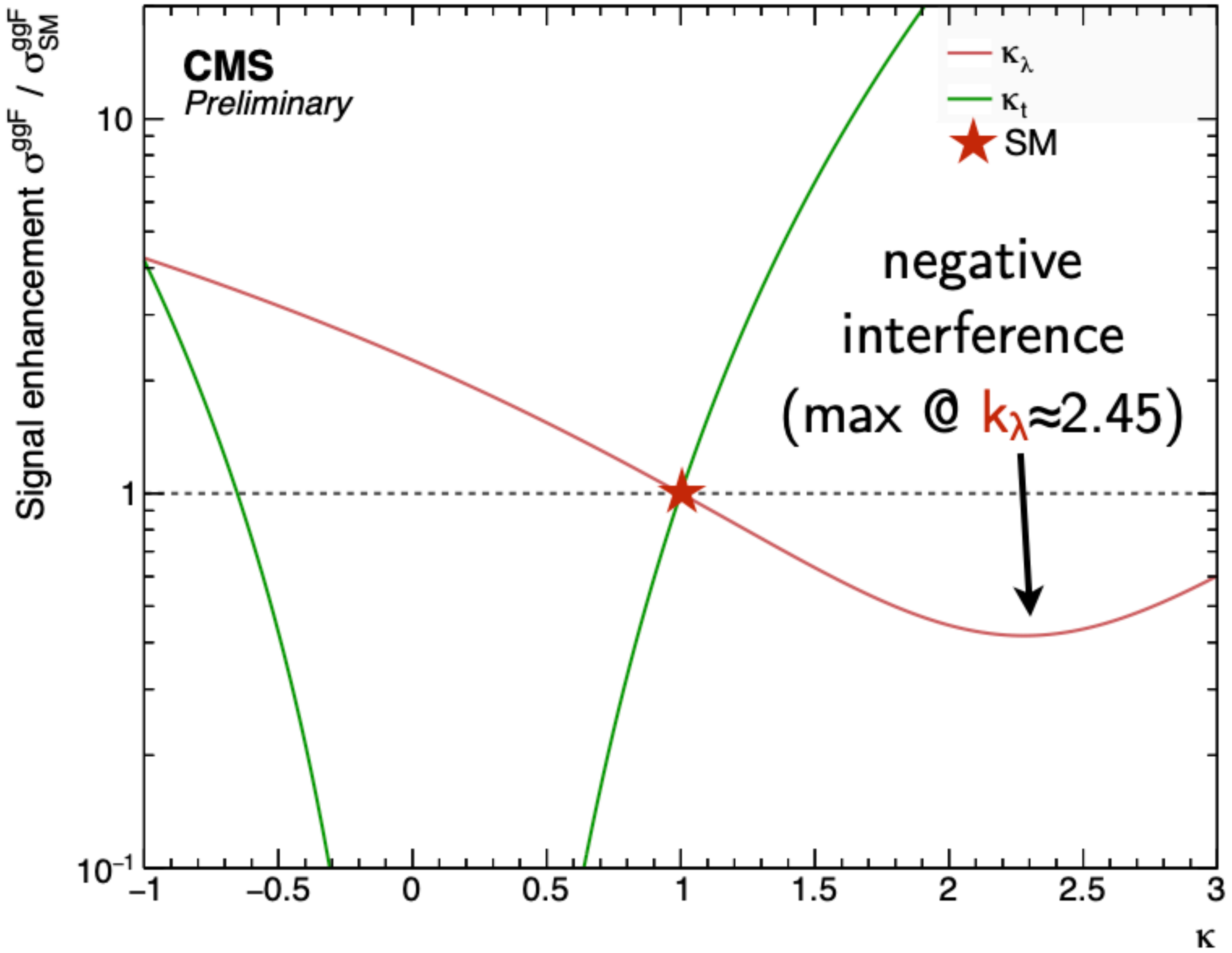

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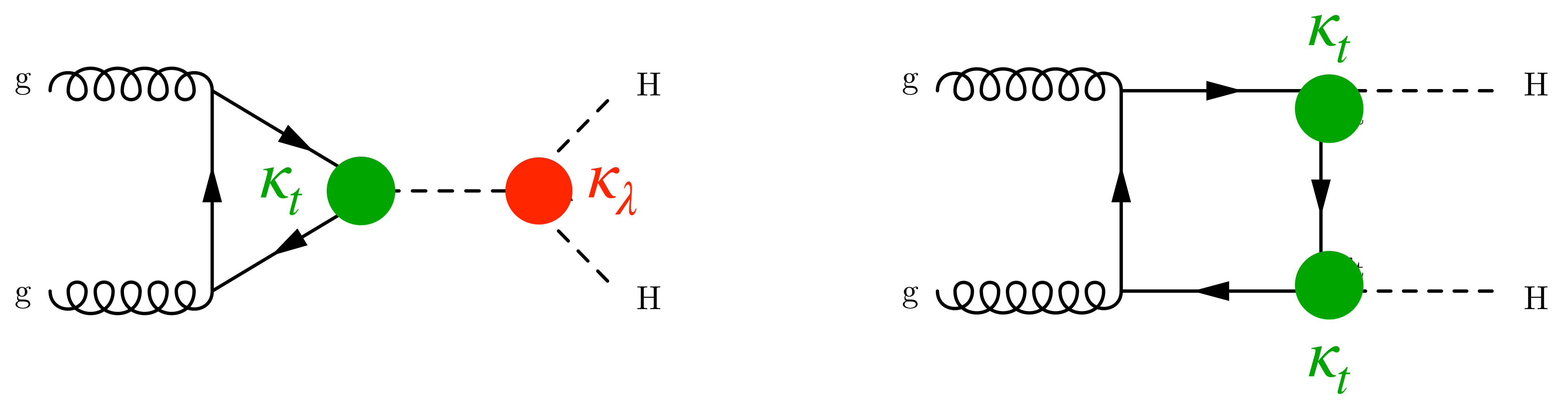

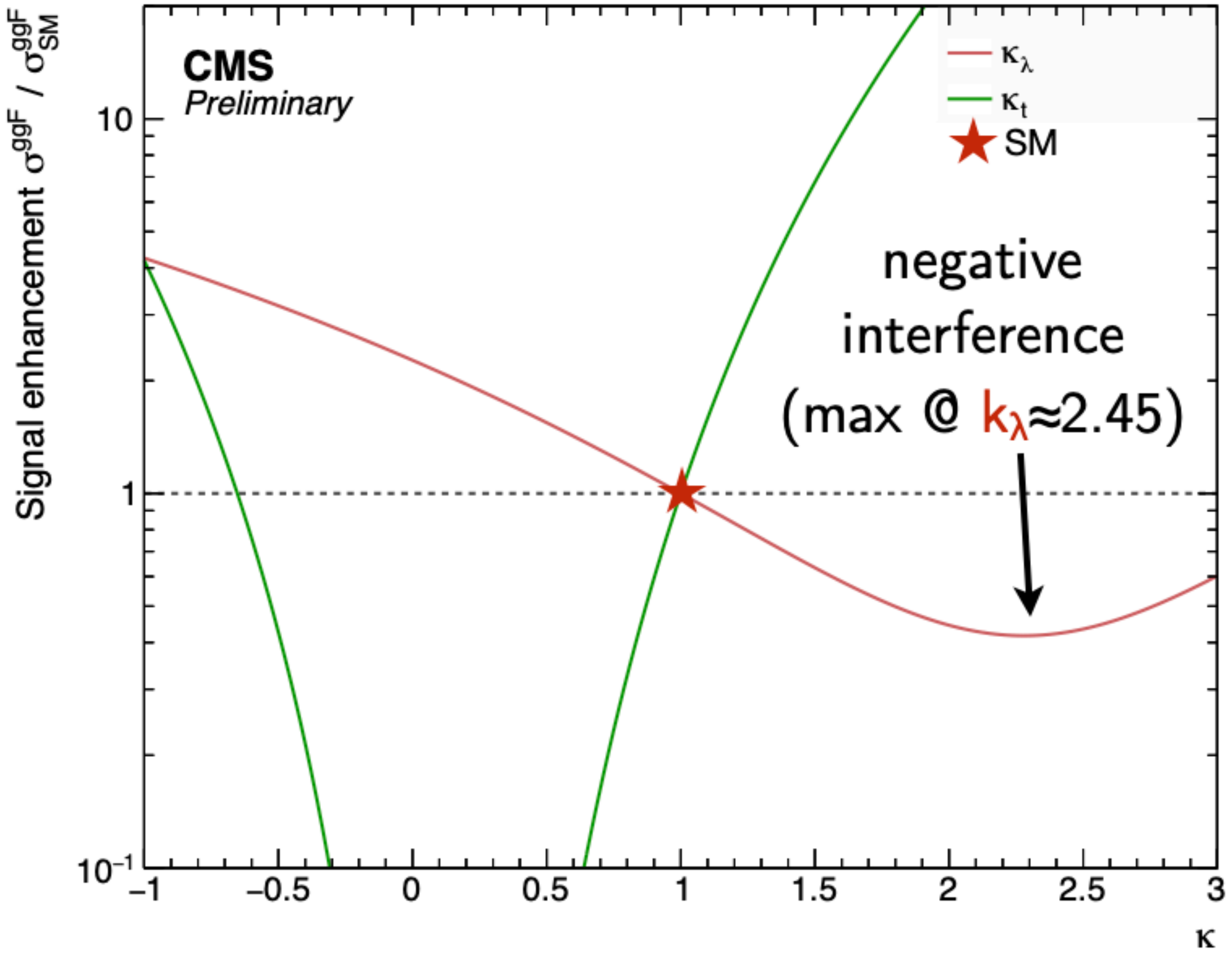

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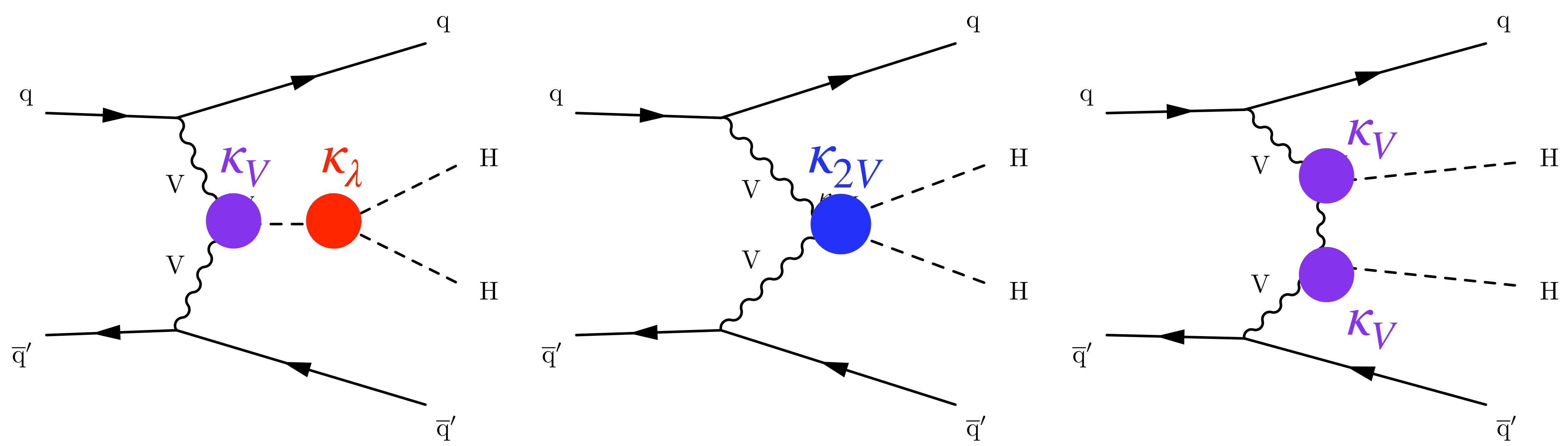

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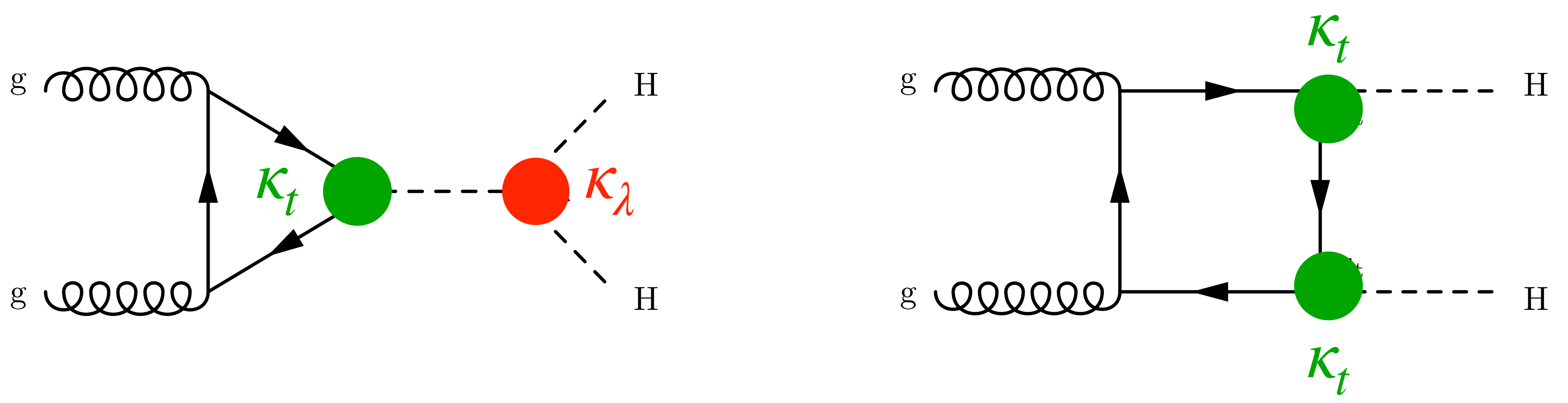

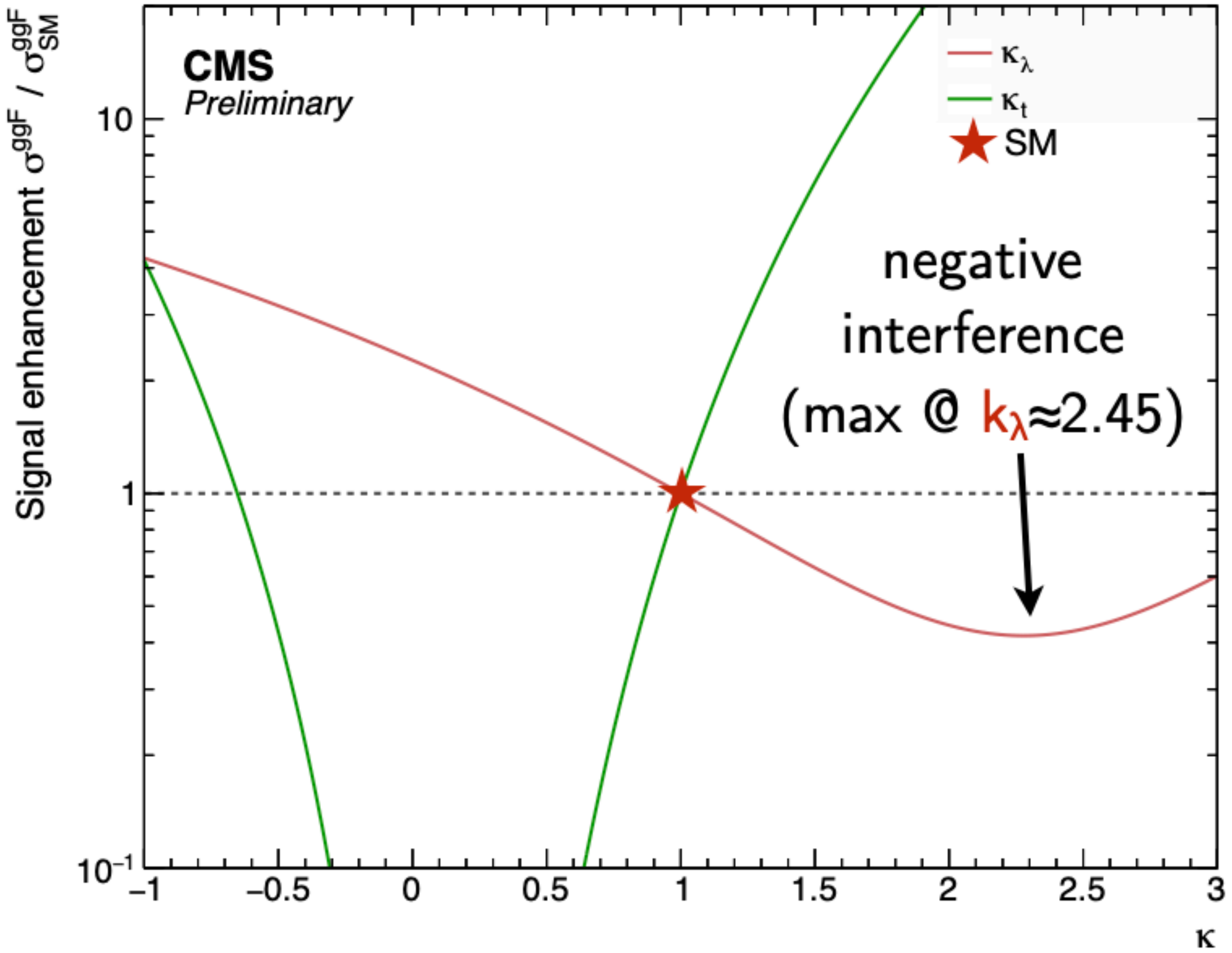

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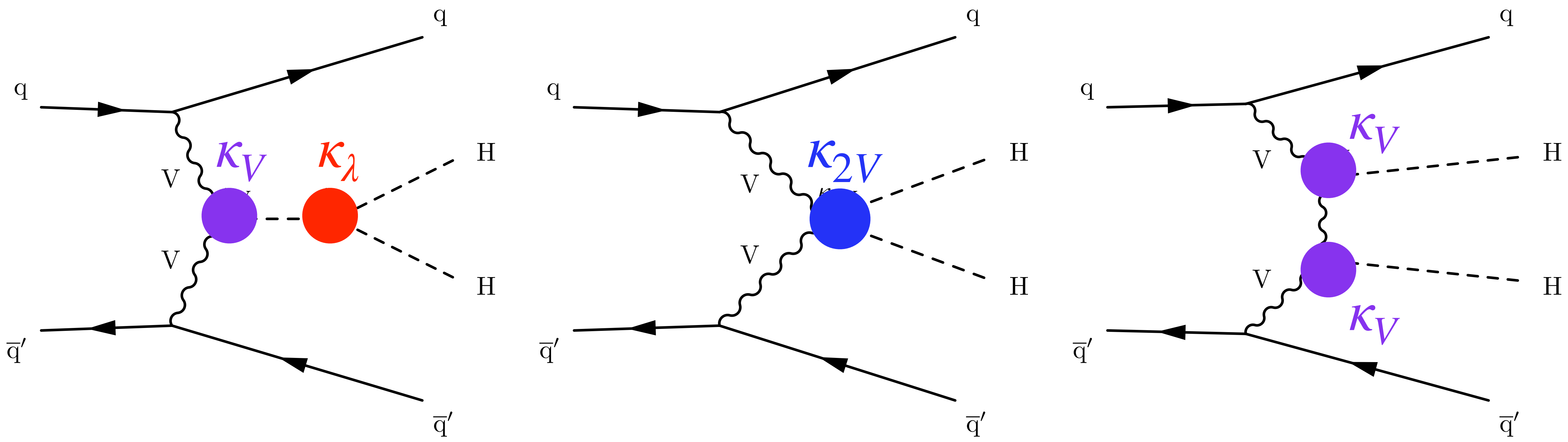
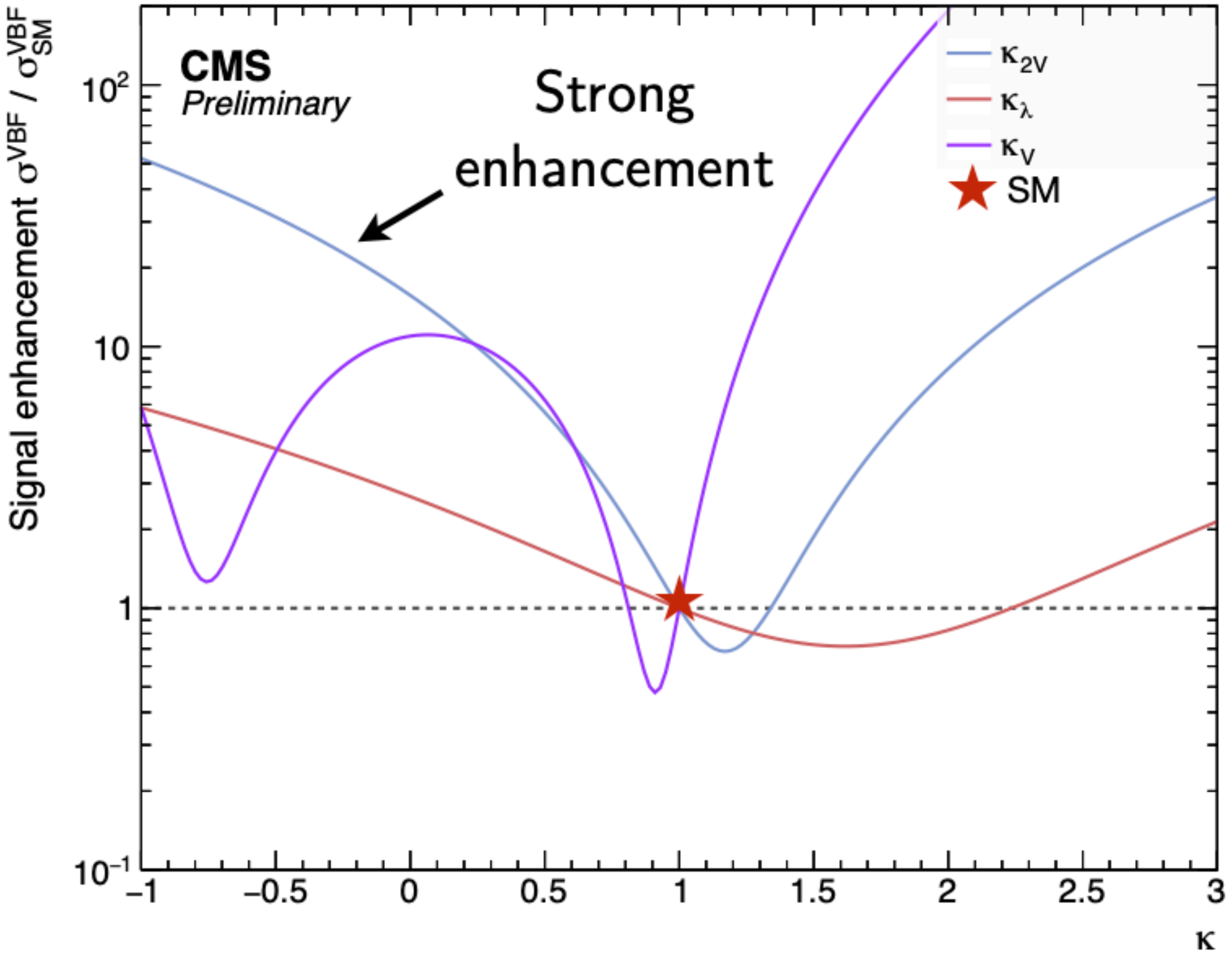
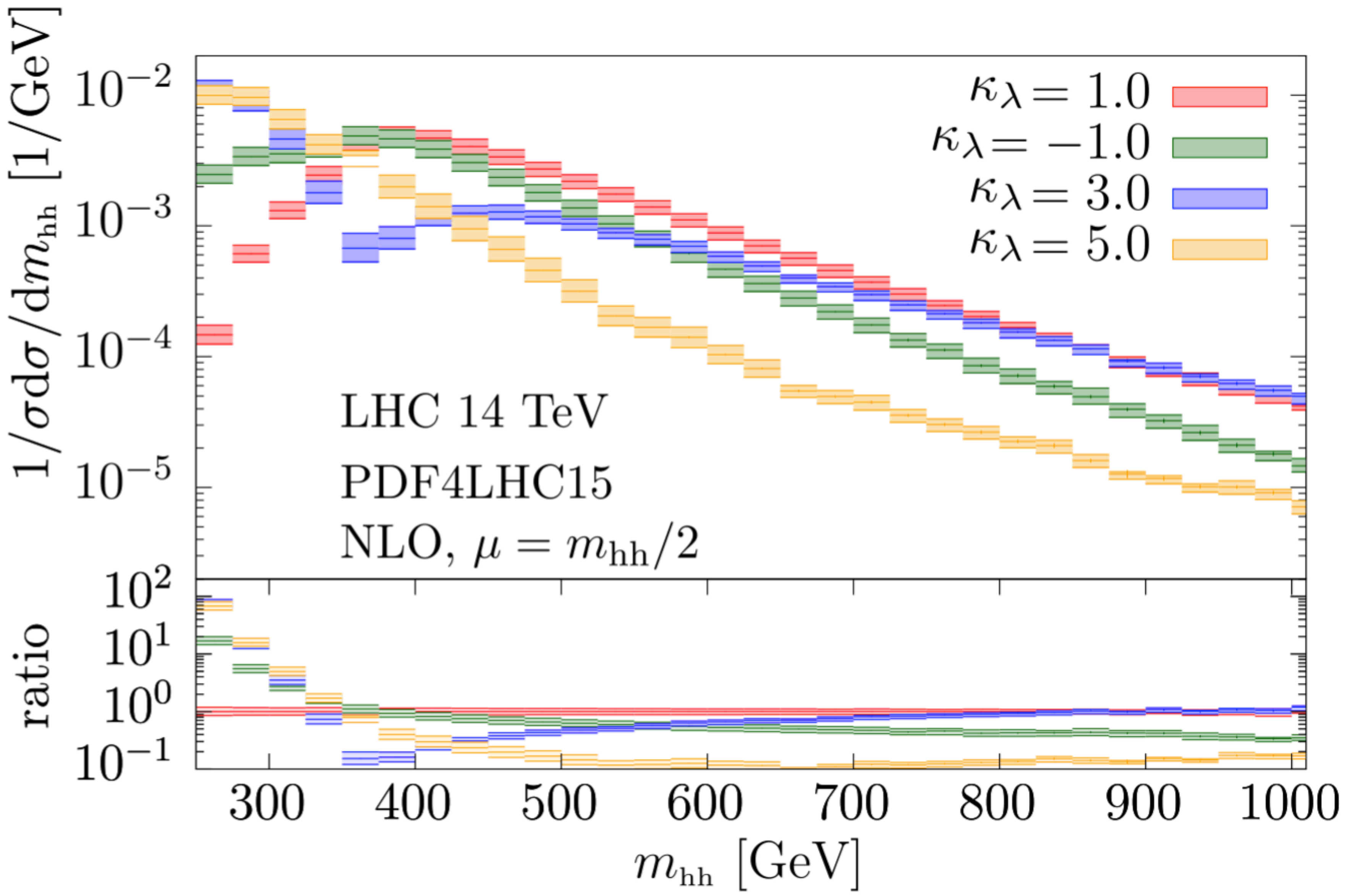


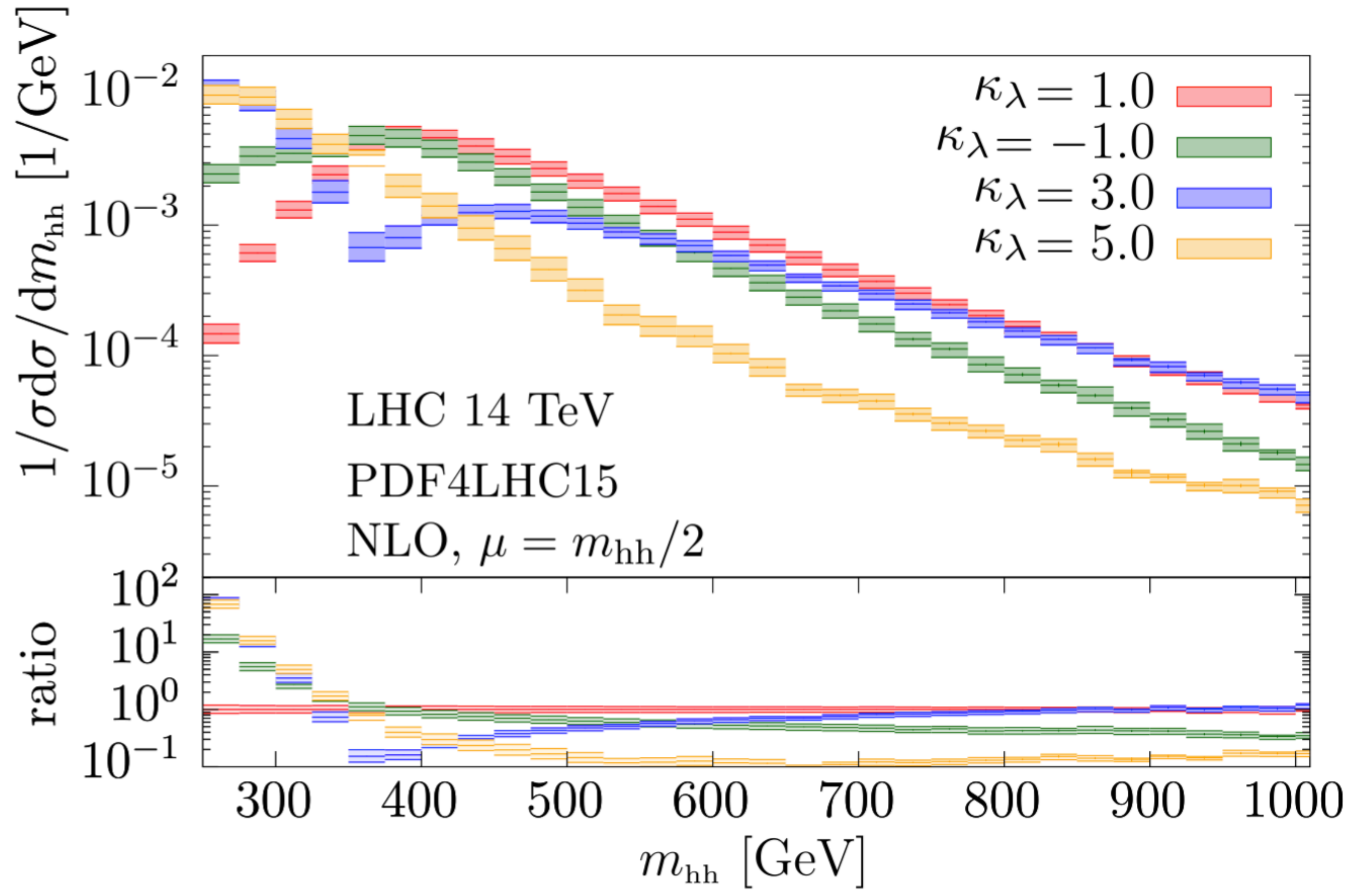


HH EVENT KINEMATICS



HH EVENT KINEMATICS

- Spectrum of m_{HH} depends on κ_λ
  - Softer for large $|\kappa_\lambda|$
  - Intermediate $|\kappa_\lambda|$ leads to harder m_{HH} spectrum and boosted ggF signatures, but overall cross section reduction due to interference



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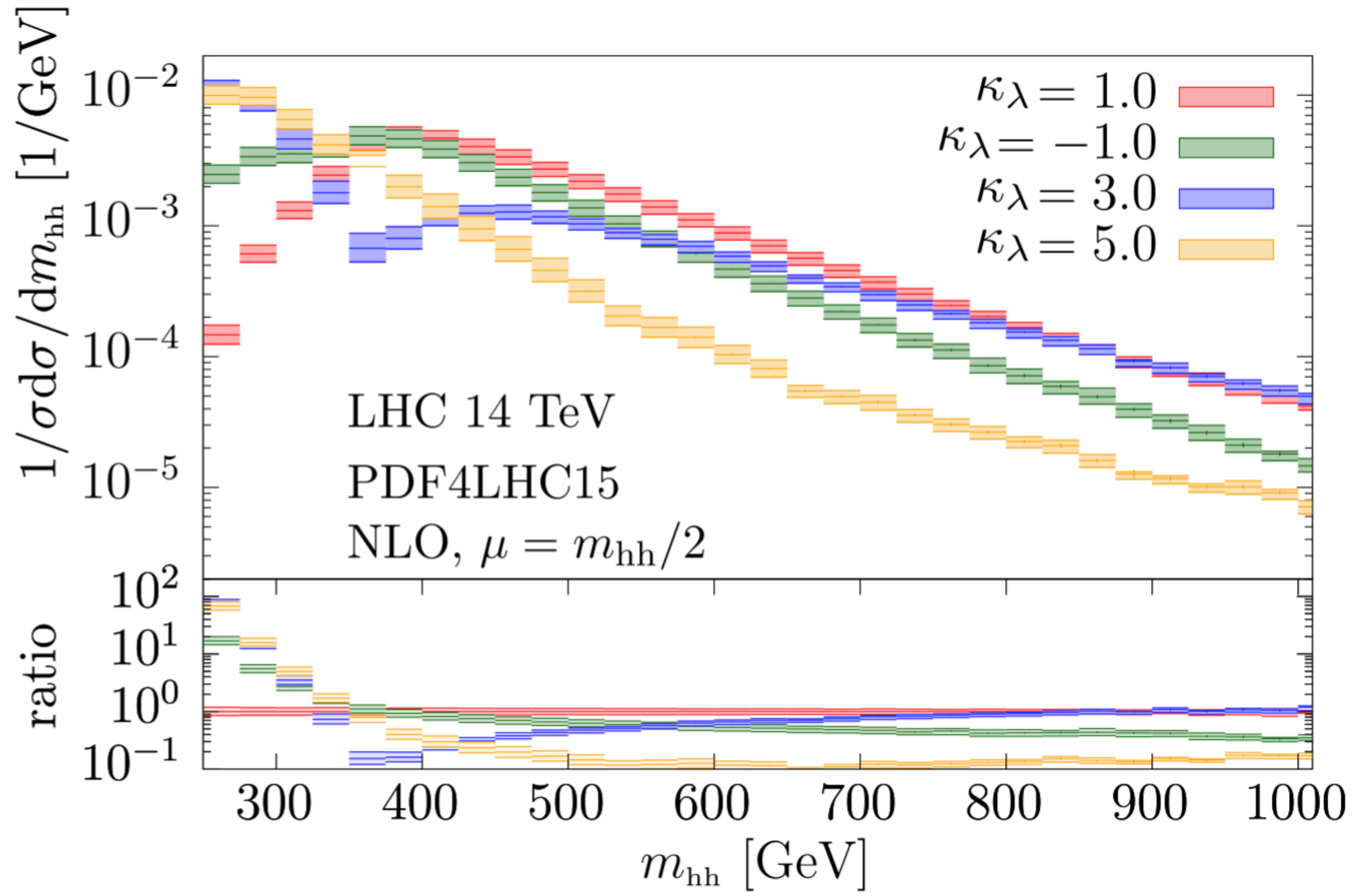
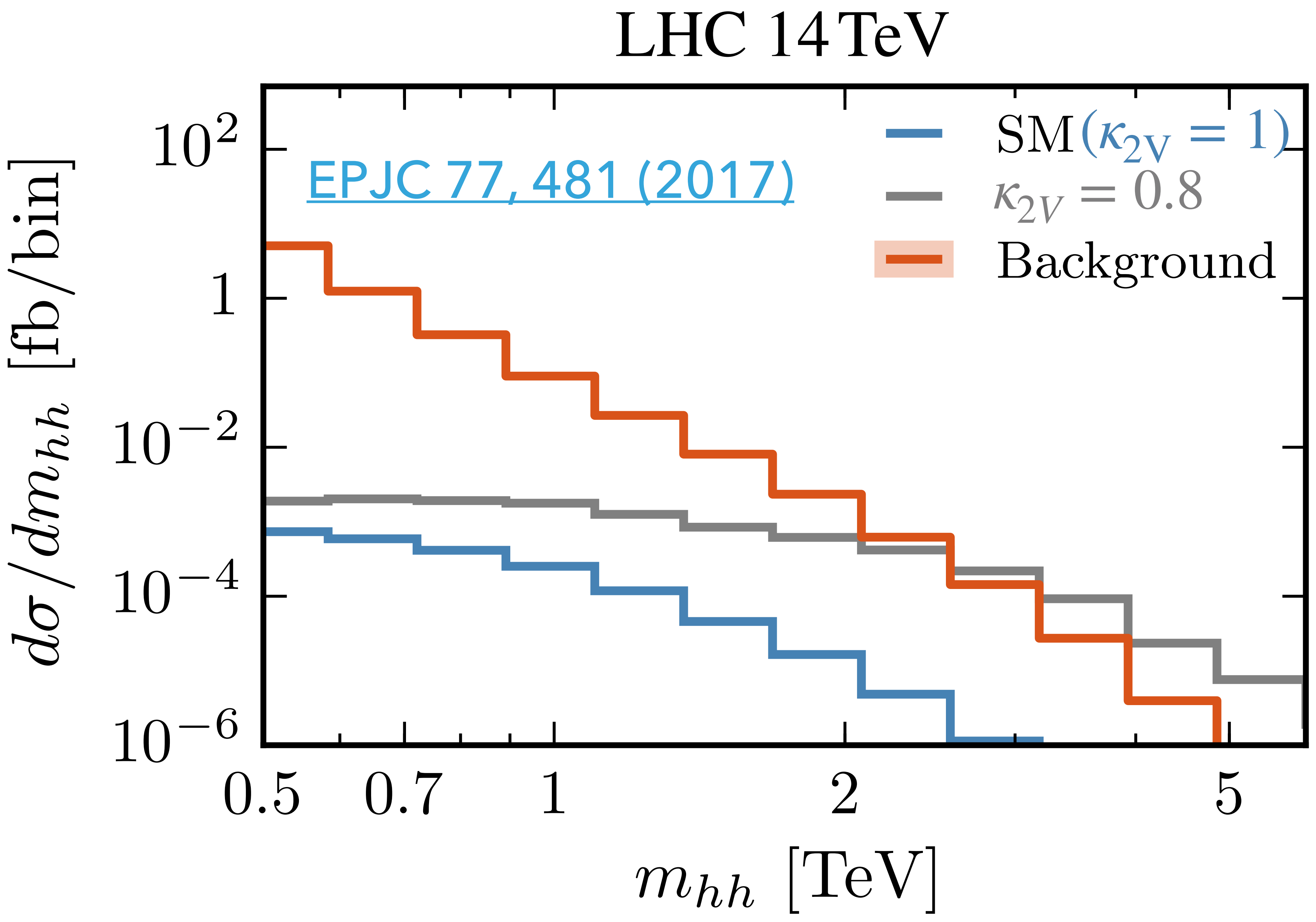
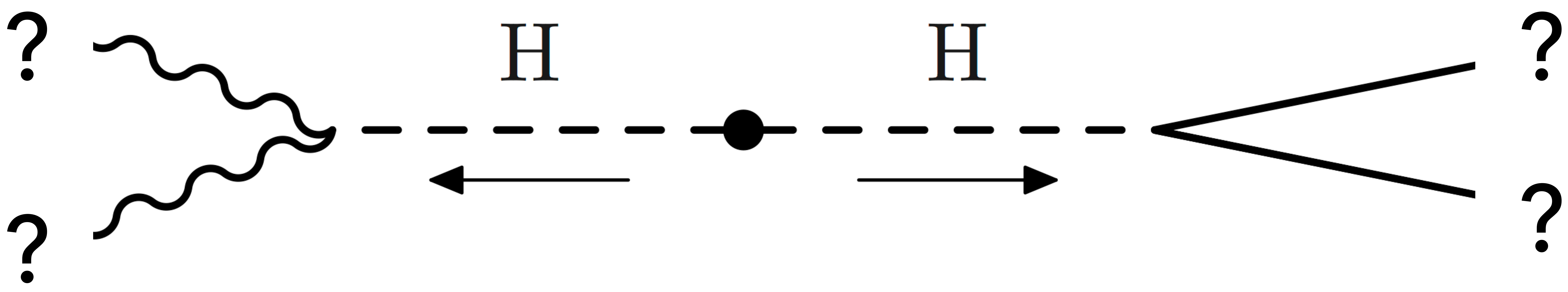
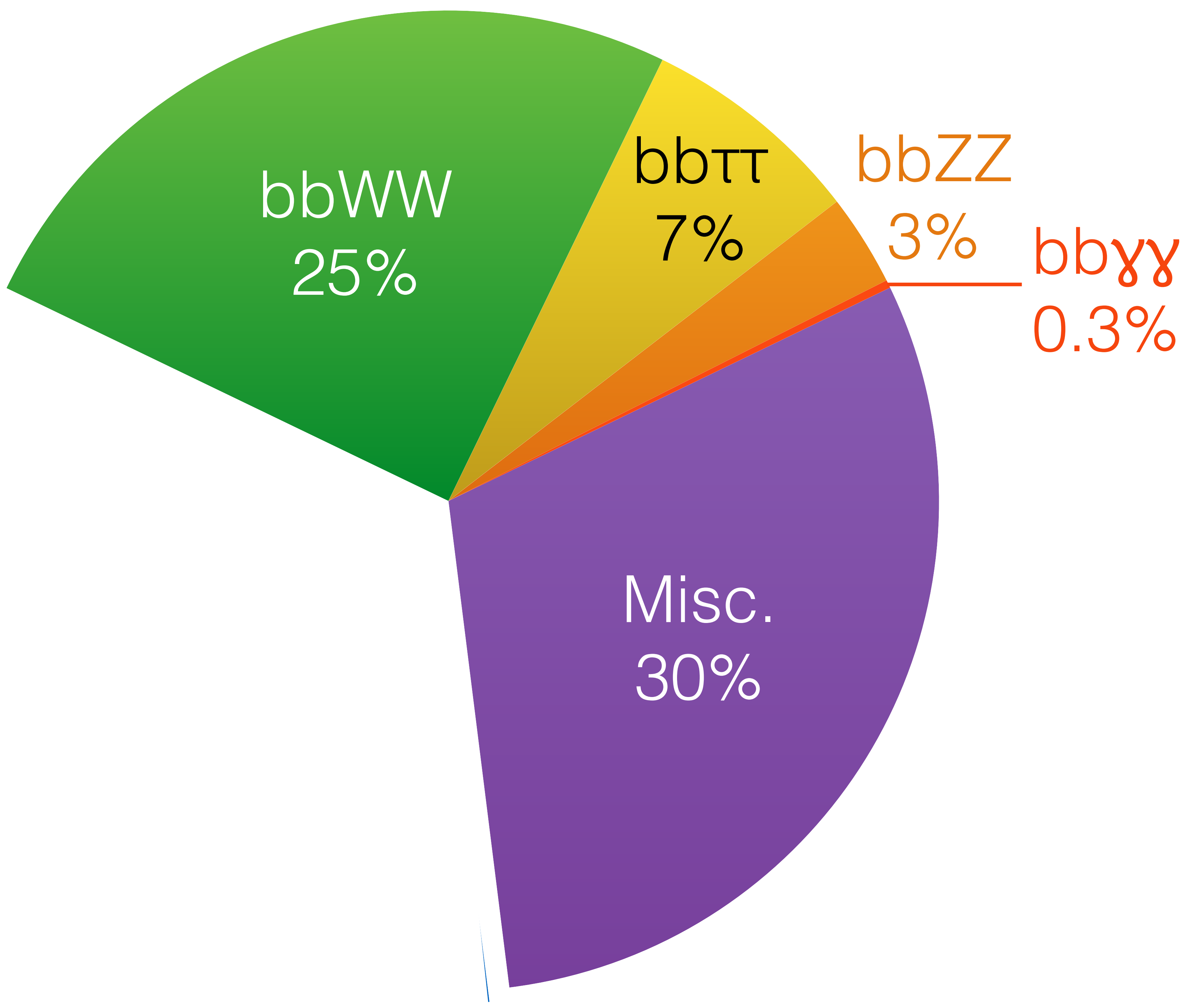


- Alternatively, smaller κ_{2V} leads to larger cross section, harder m_{HH} spectrum, and boosted VBF signatures



HOW DO WE DETECT HH PRODUCTION?





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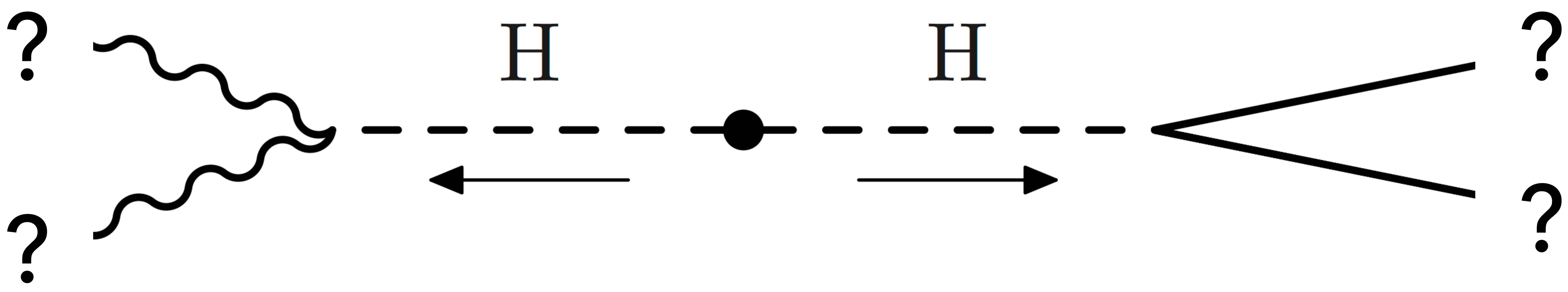
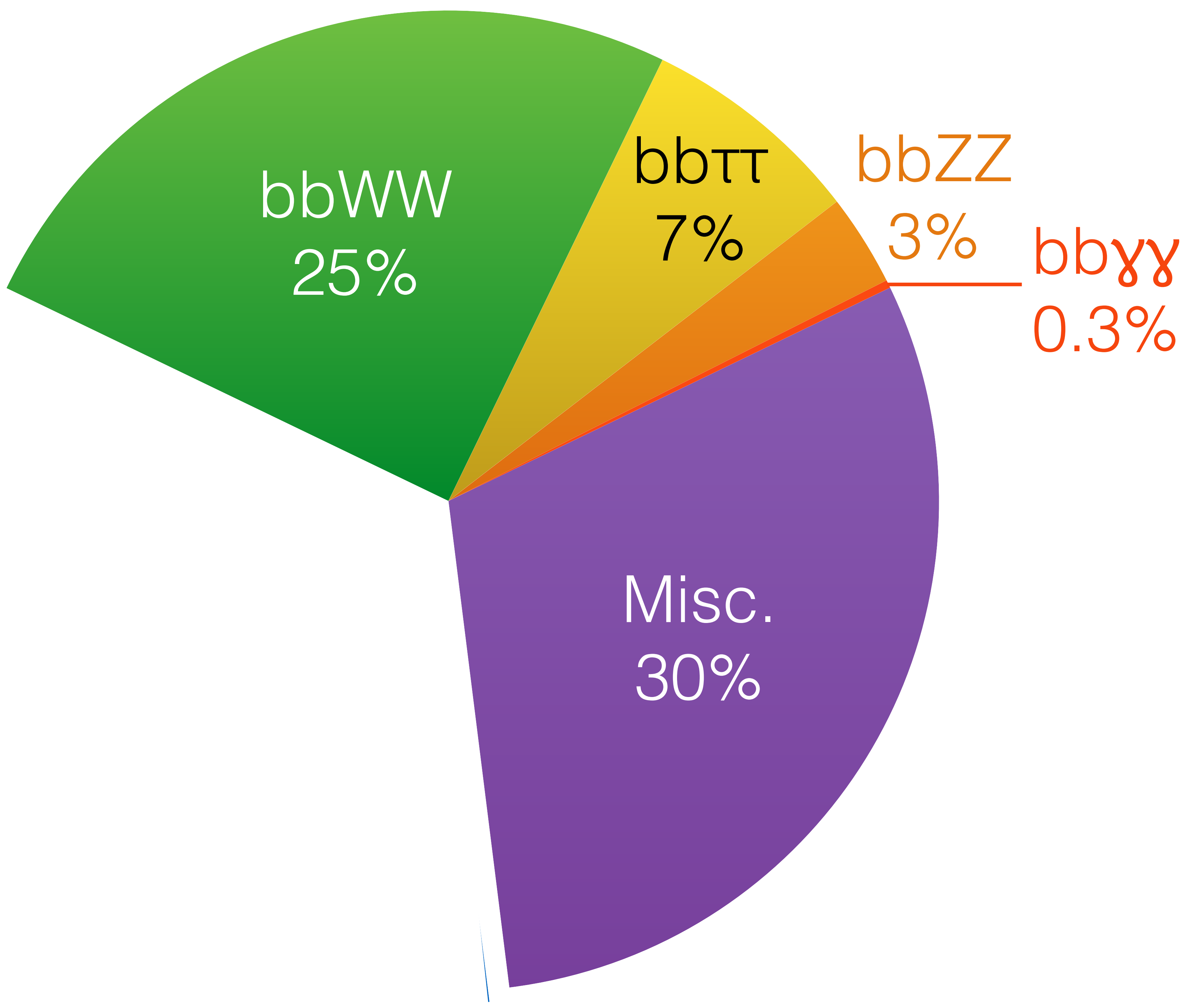


- bbɣɣ has small rate but is traditionally thought to be "golden channel"



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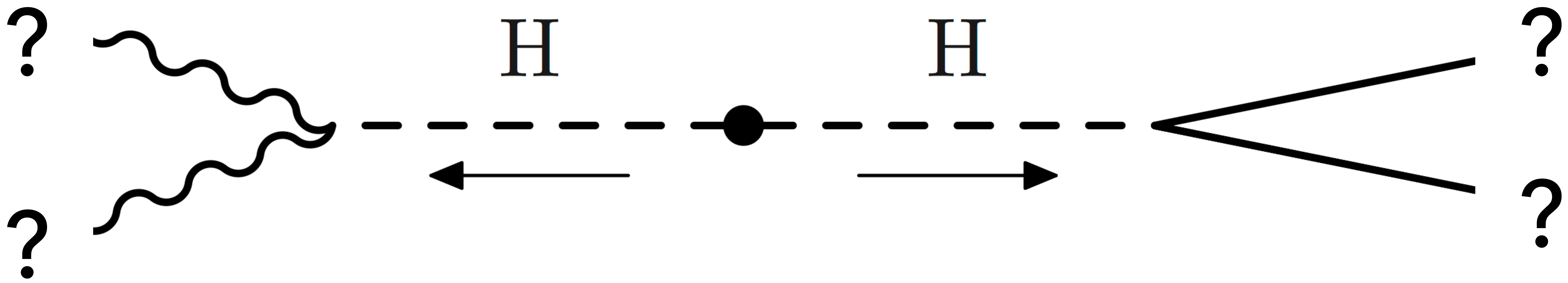

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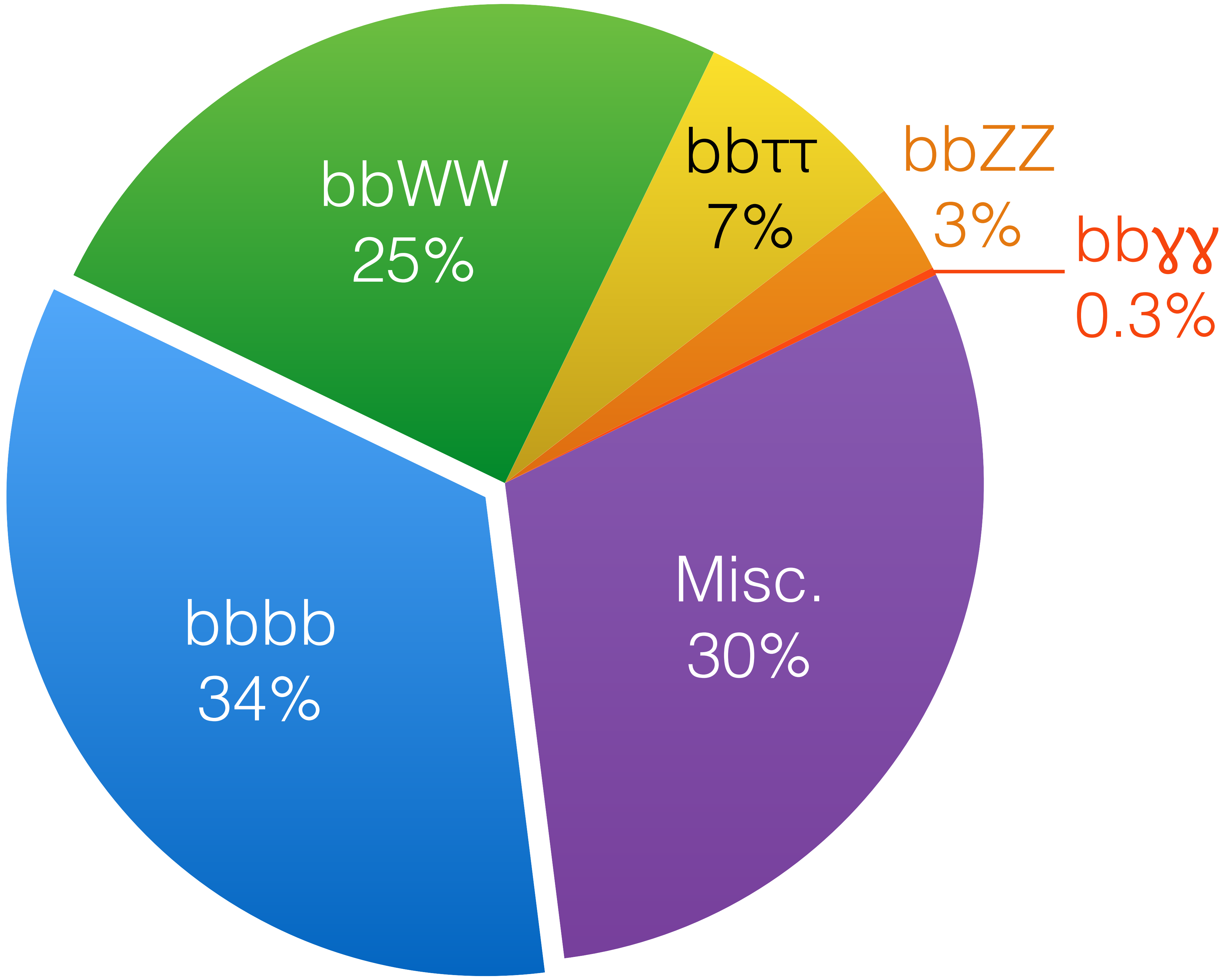
- bbbb is the largest fraction, but more challenging due to large backgrounds



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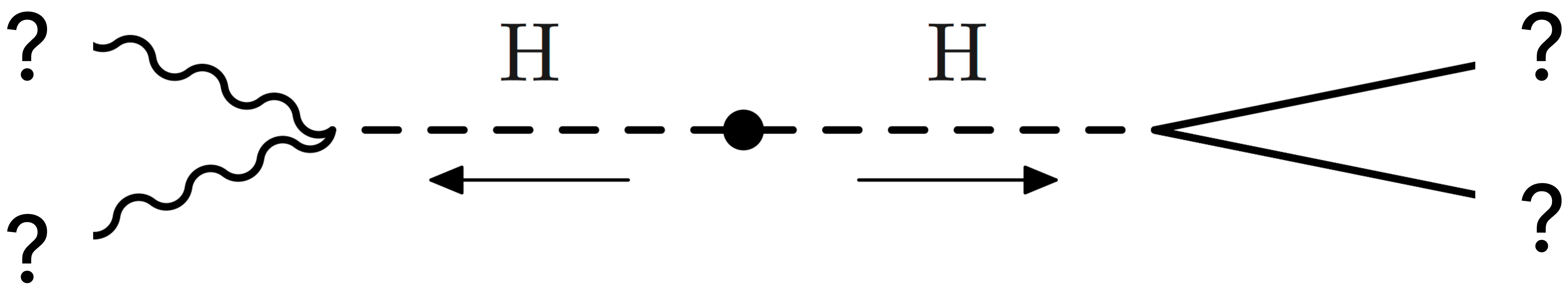
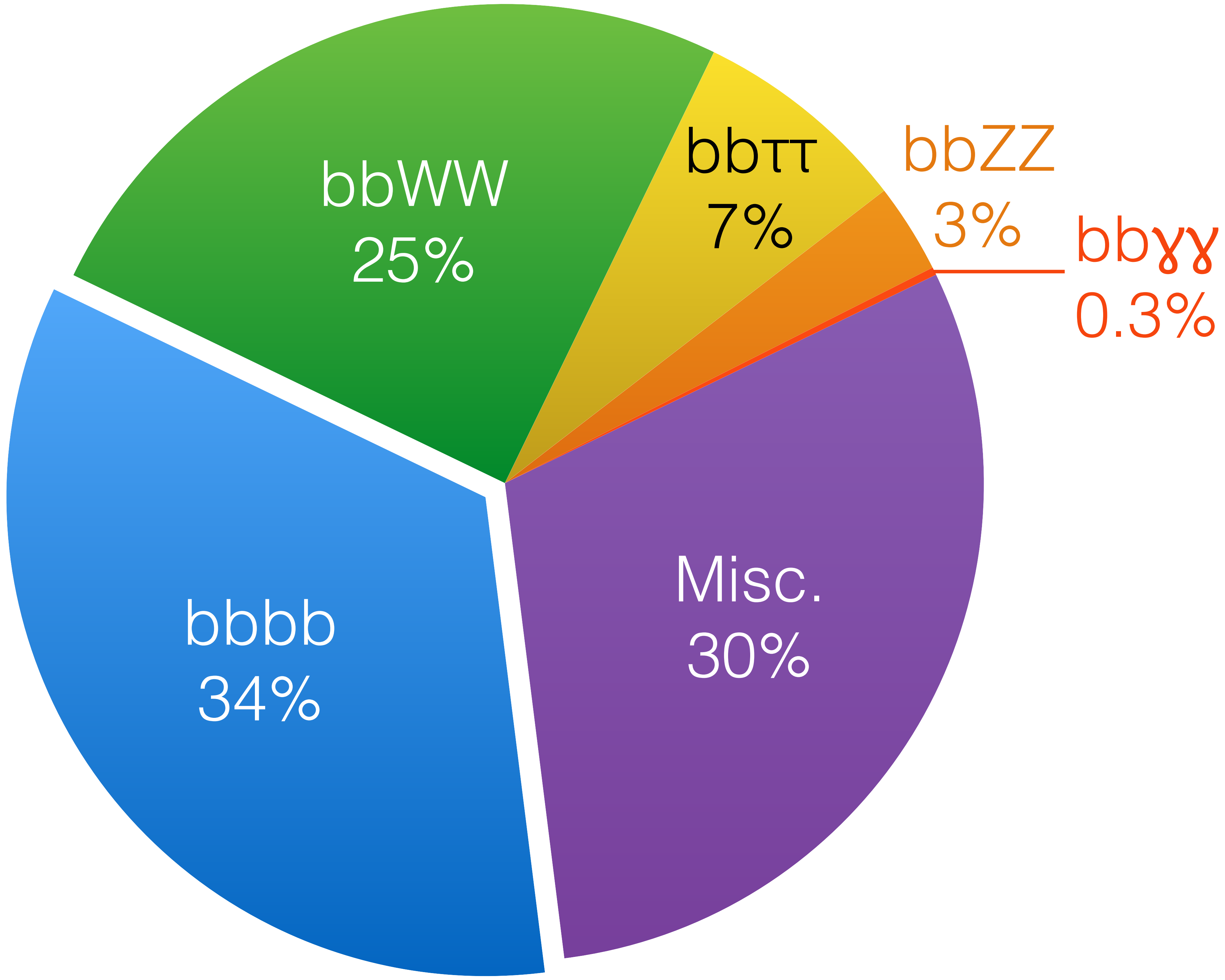
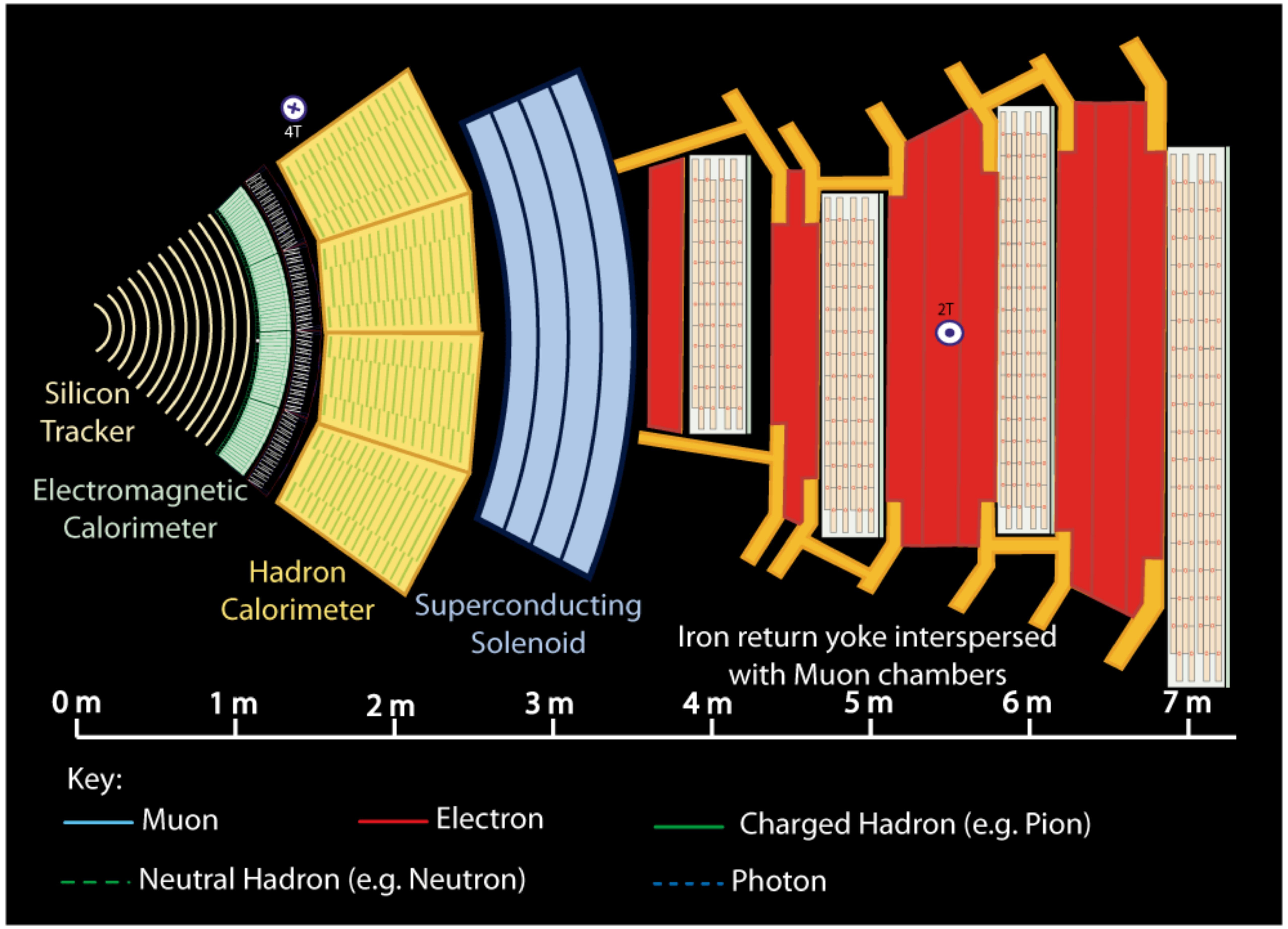


- bbγγ has small rate but is traditionally thought to be "golden channel"
- bbbb is the largest fraction, but more challenging due to large backgrounds
    - ***This talk***: using new tools & phase space to make bbbb channel ***among the most sensitive***



HOW CMS SEES QUARKS AND GLUONS

- Quarks and gluons interact via the strong force and are never seen in isolation
  → become *jets* of hadrons (bound states)



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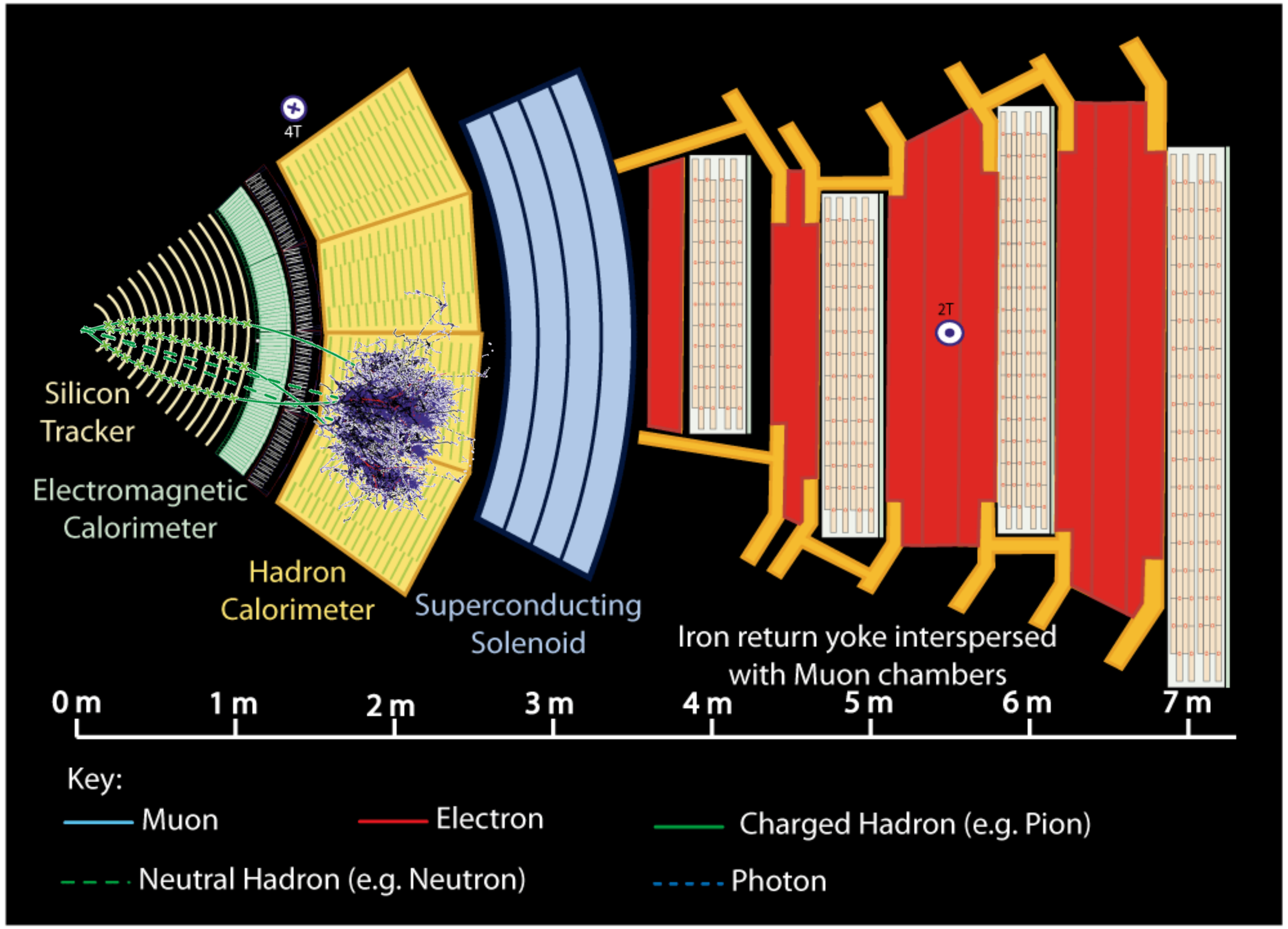

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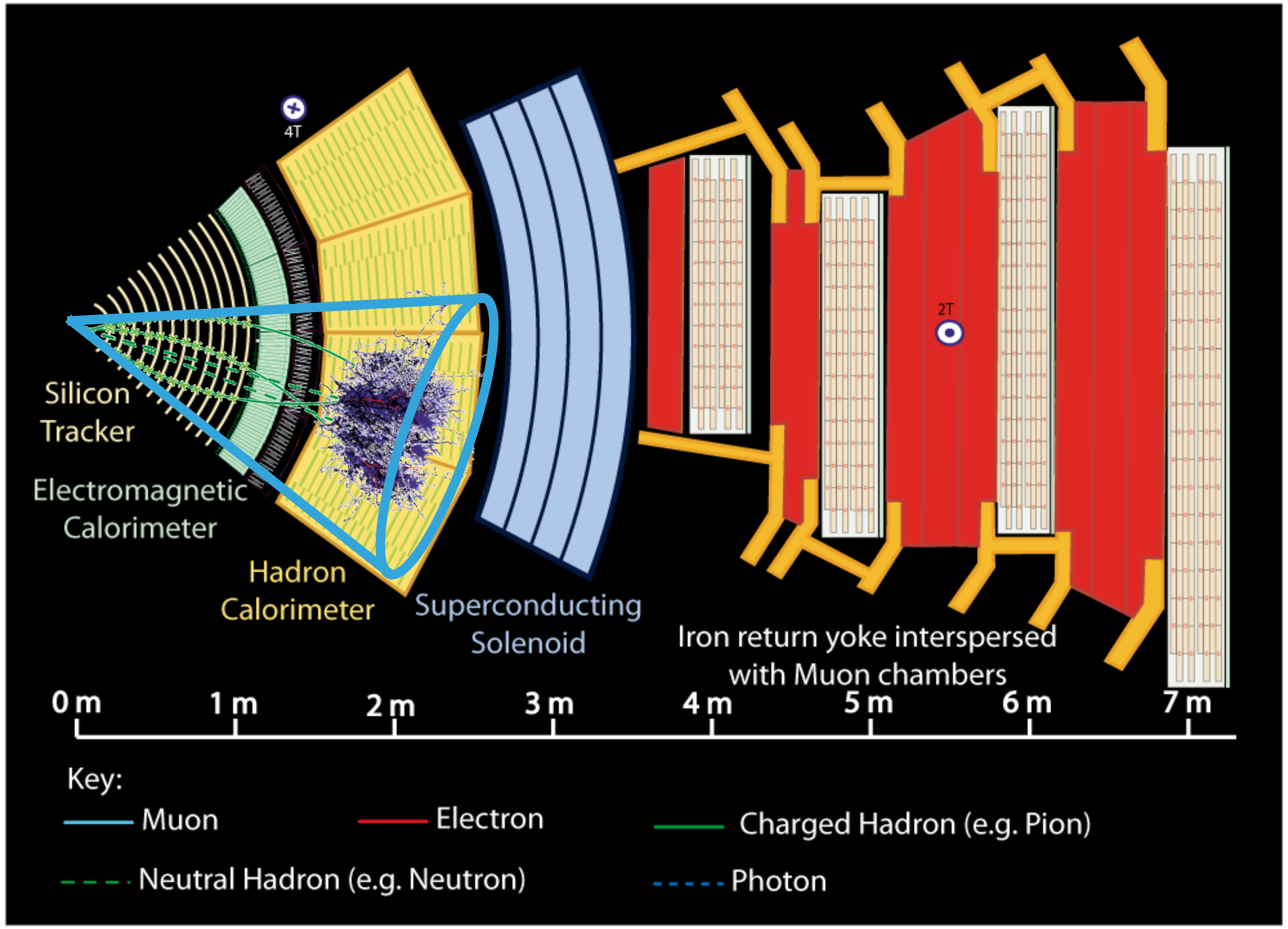
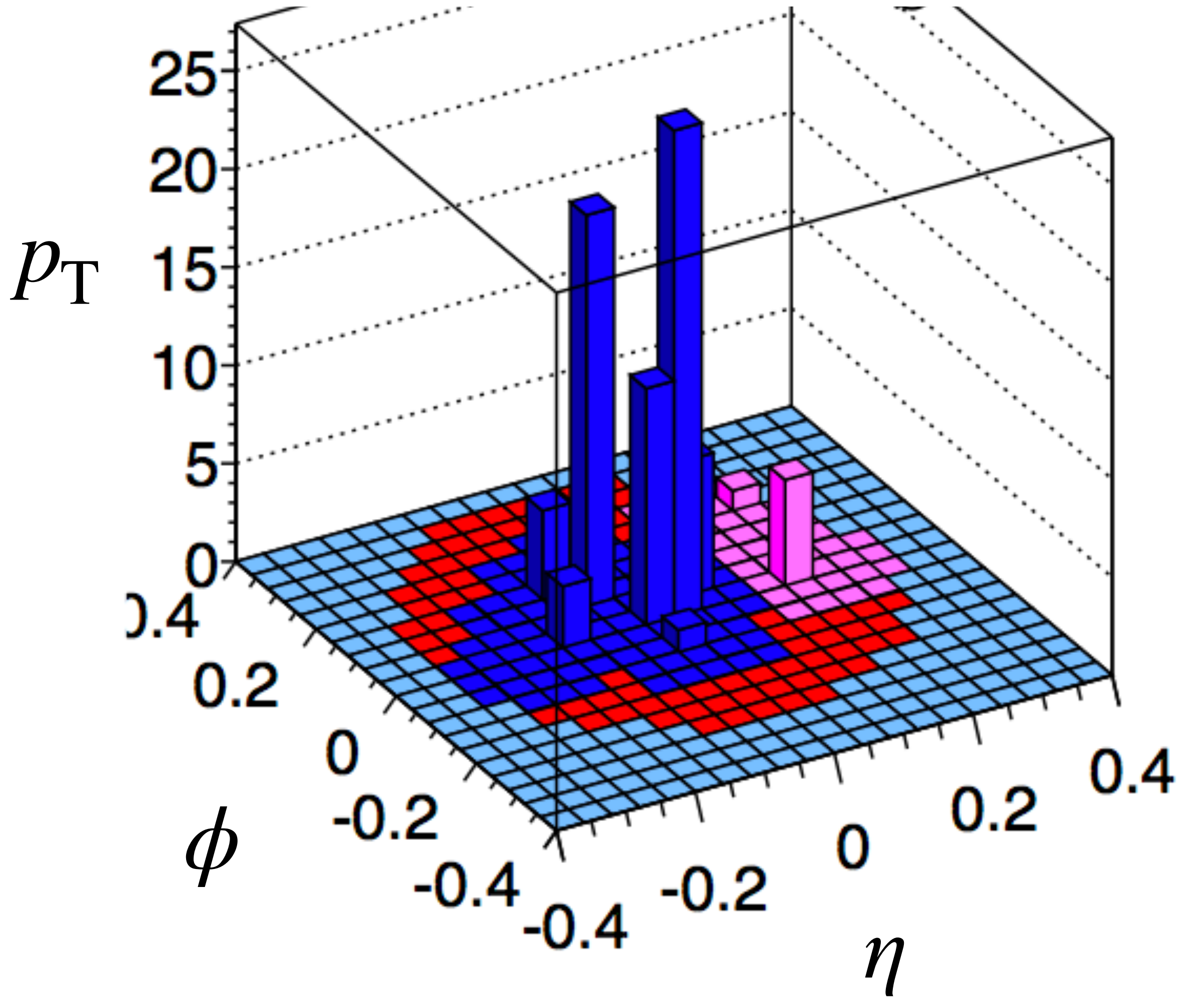
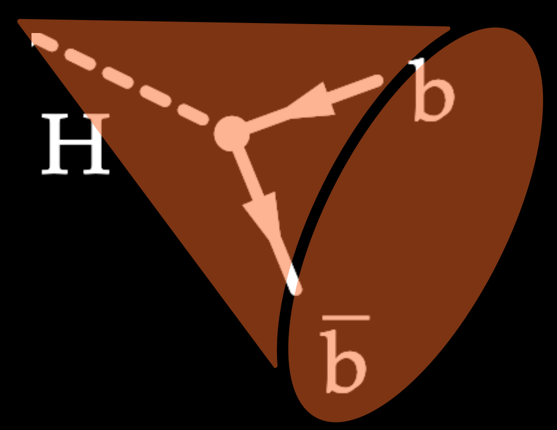
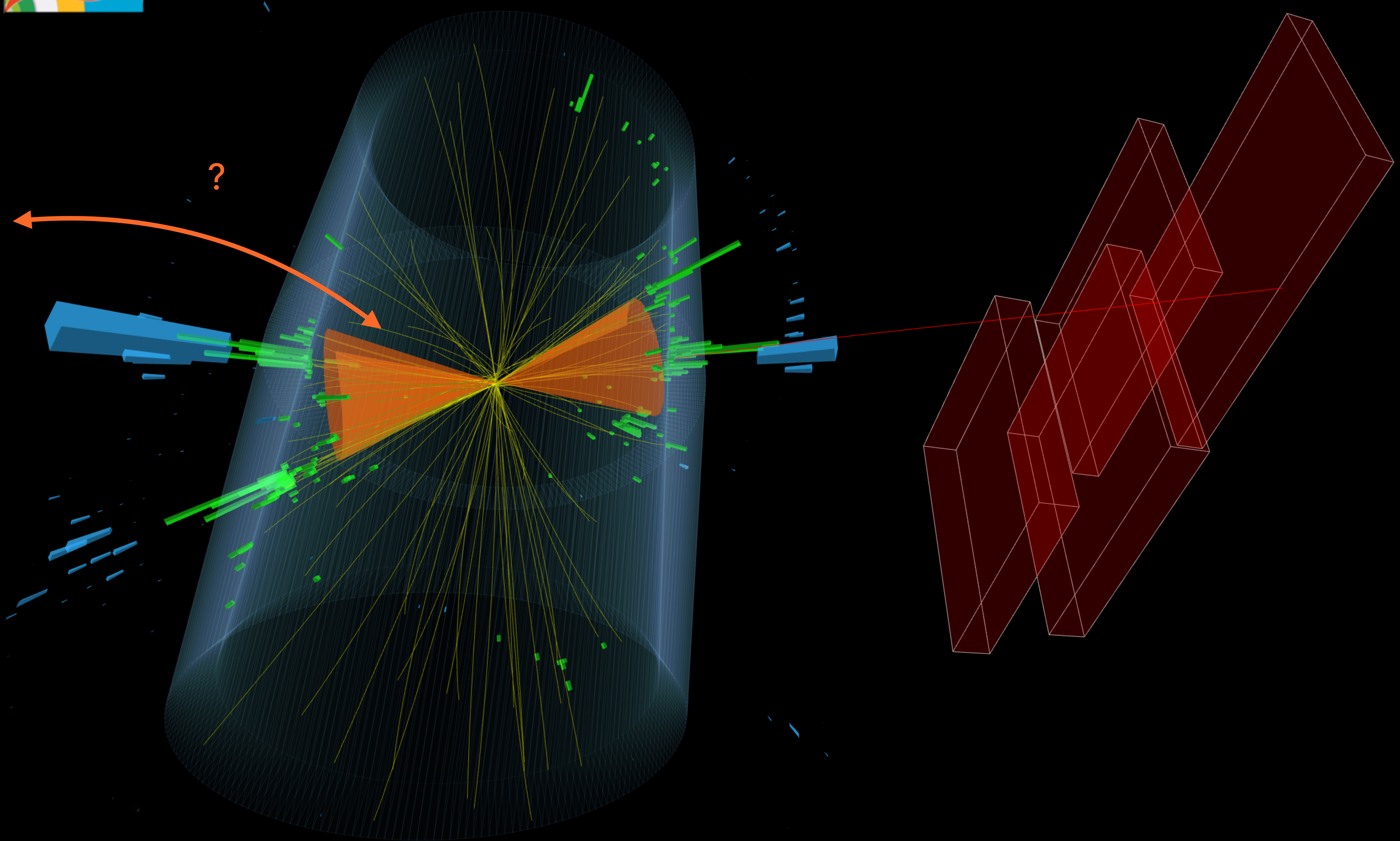


- Cluster the tracks and energy into a cone-shaped jet



Signal:


H
b
b̄


CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-13 16:51:13.749568 GMT
Run / Event / LS: 278803 / 465417690 / 259
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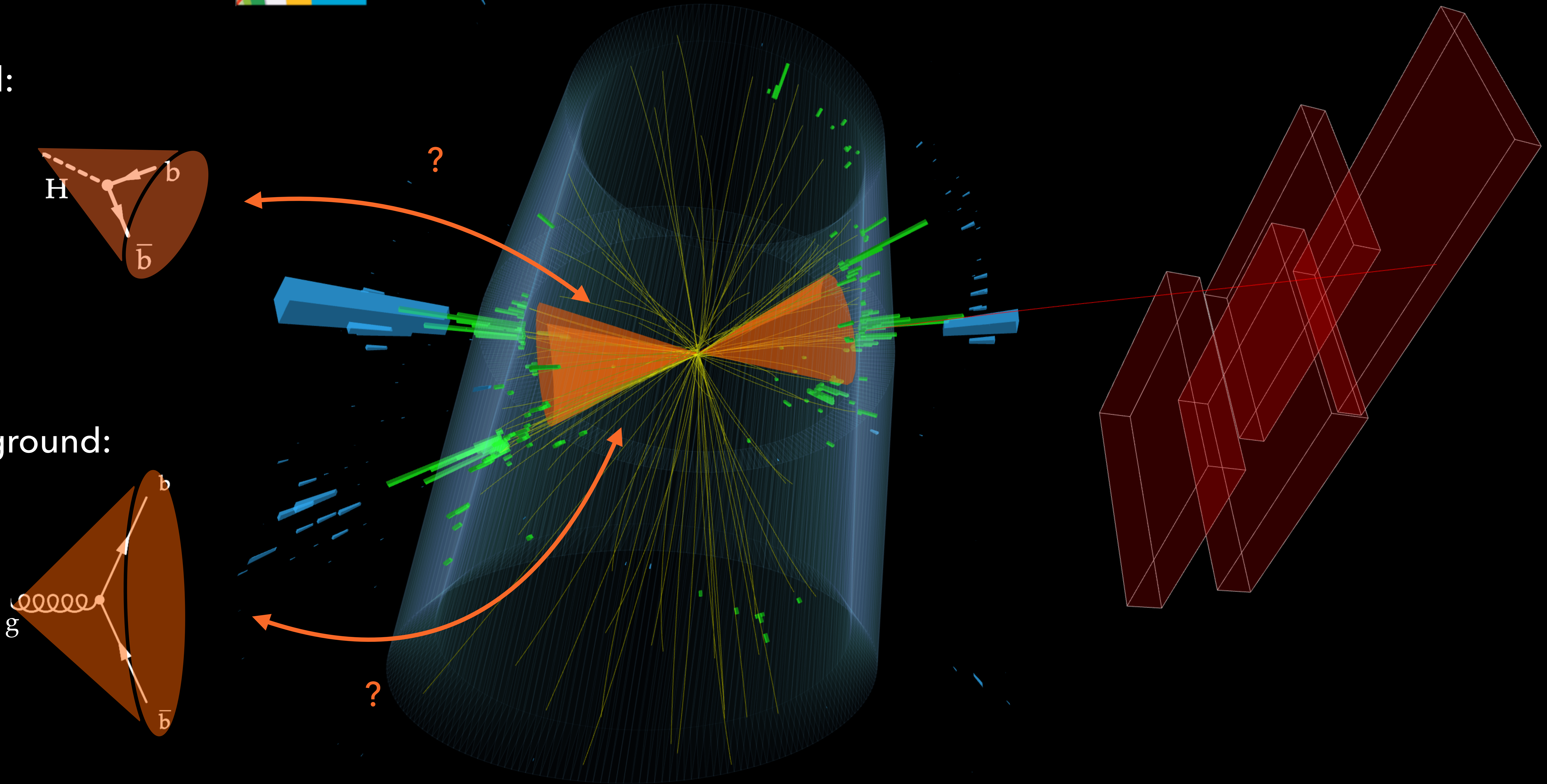


CMS
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Signal:
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Background:
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?
Can artificial intelligence help us?

I. HH PRODUCTION AT THE LHC

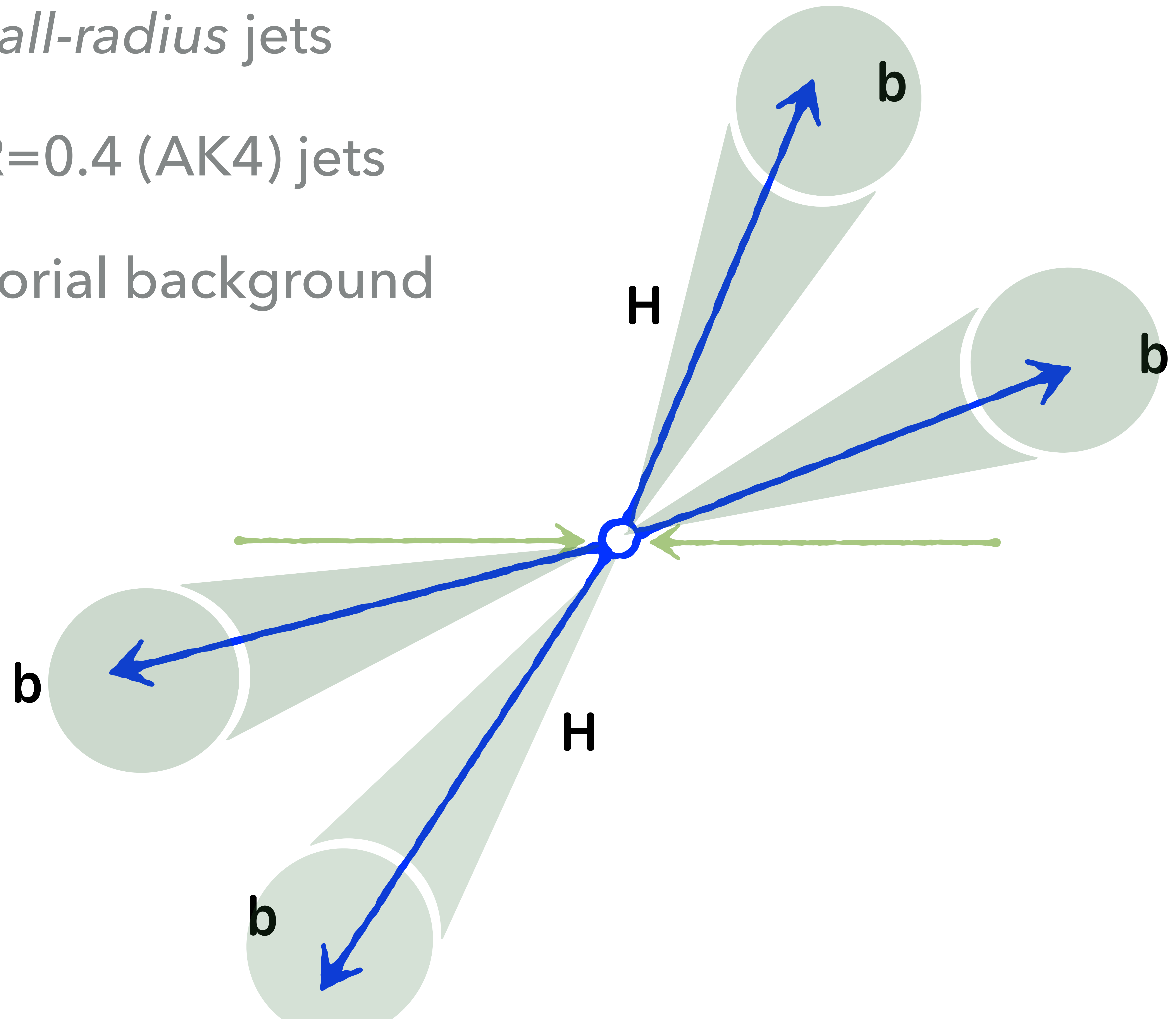
II. GNNS FOR JET PHYSICS

III. BOOSTED HH SEARCH

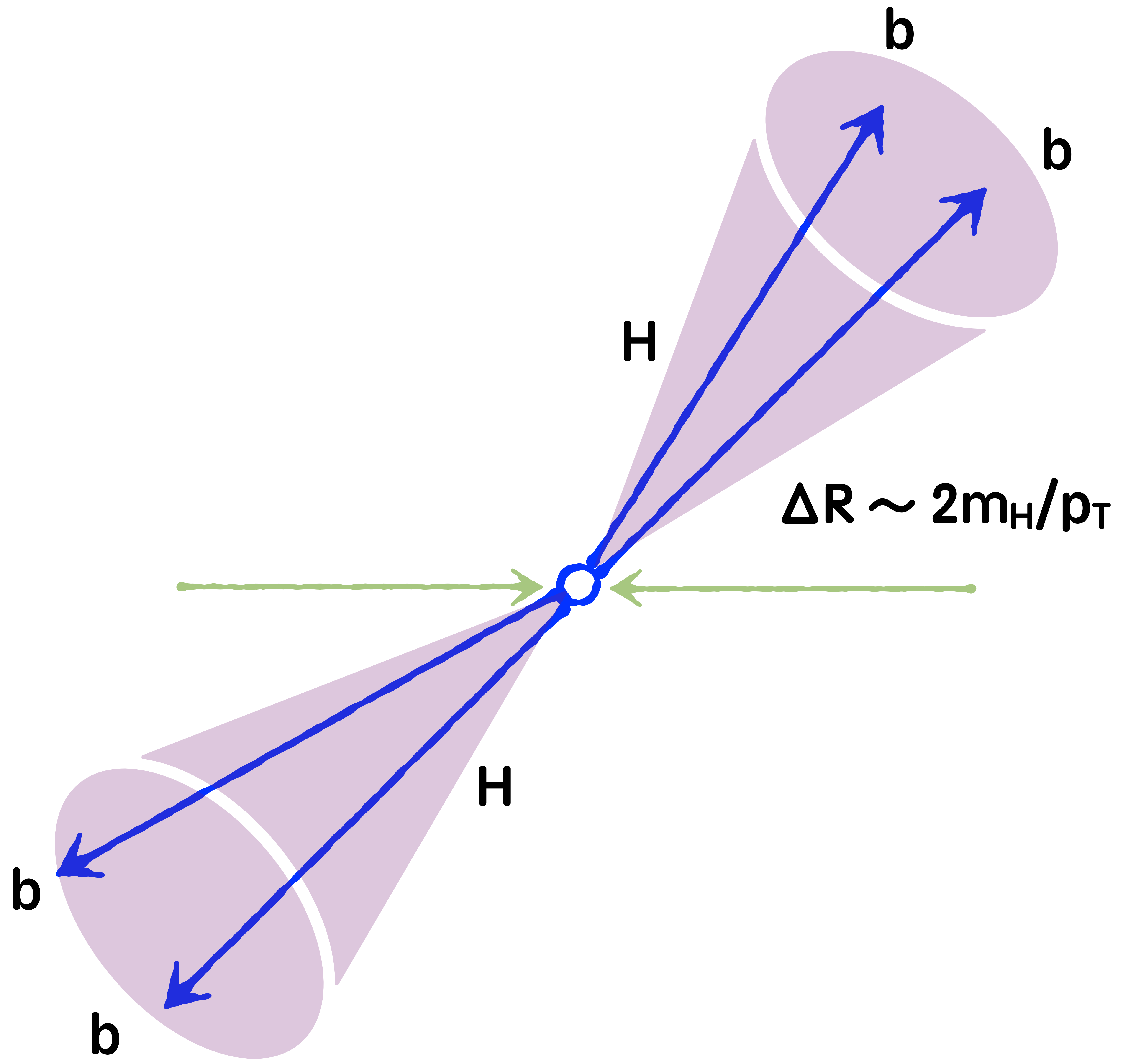
IV. OUTLOOK

LOW MOMENTUM (RESOLVED)

- At low momentum, the bottom quarks are resolved into separate *small-radius* jets
  - Anti-k_T algorithm with R=0.4 (AK4) jets
- Large QCD and combinatorial background

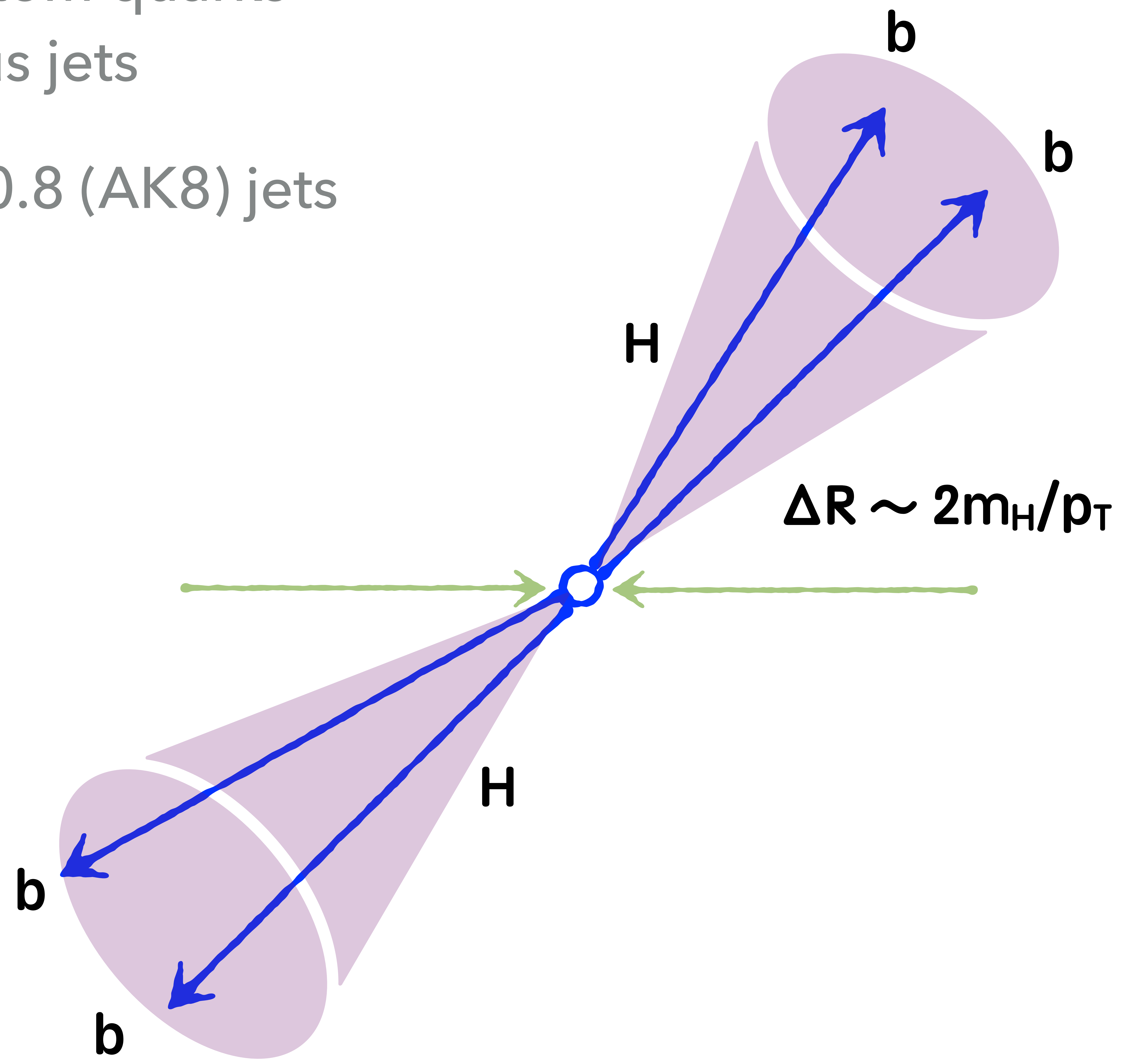


BOOSTING THE HIGGS



BOOSTING THE HIGGS

- At high momentum, the bottom quarks are ***boosted*** into large-radius jets
  - Anti-k_T algorithm with R=0.8 (AK8) jets



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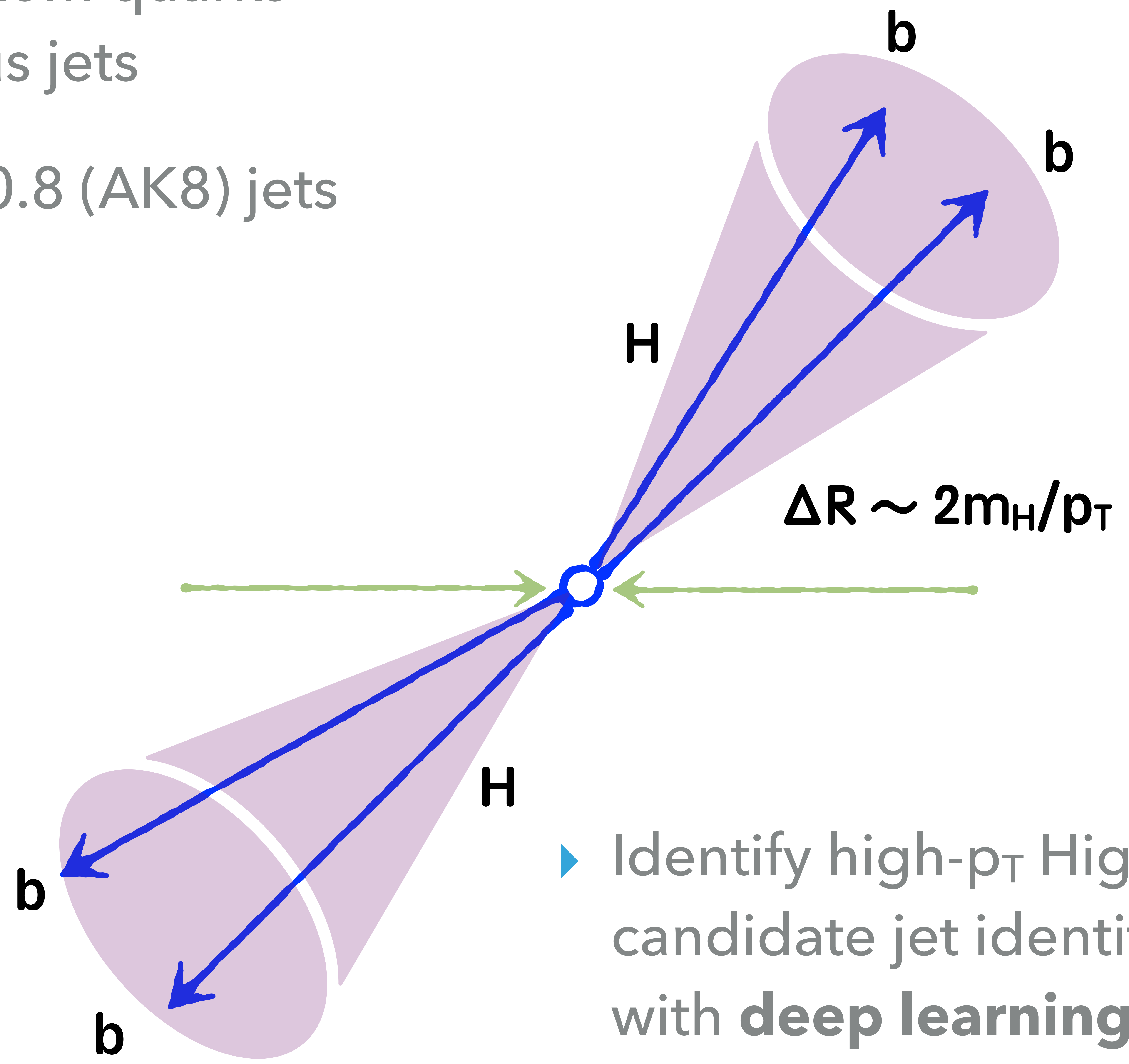

- Identify high-p_T Higgs candidate jet identified with **deep learning**

INNOVATING JET TAGGING WITH NEW JET REPRESENTATIONS

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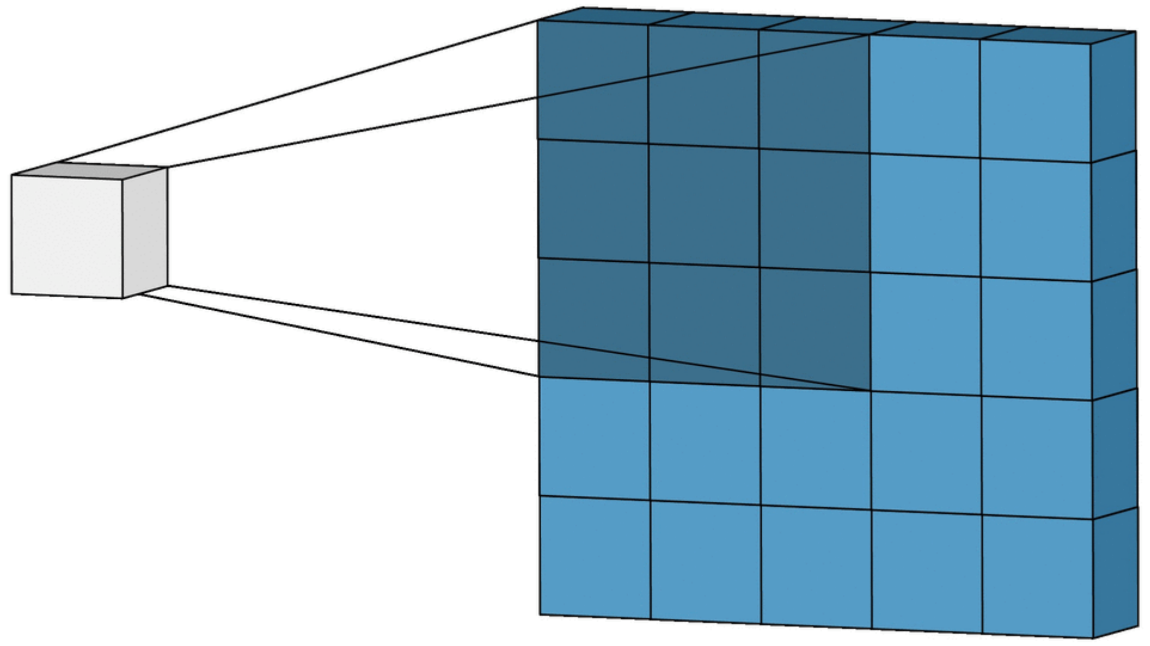

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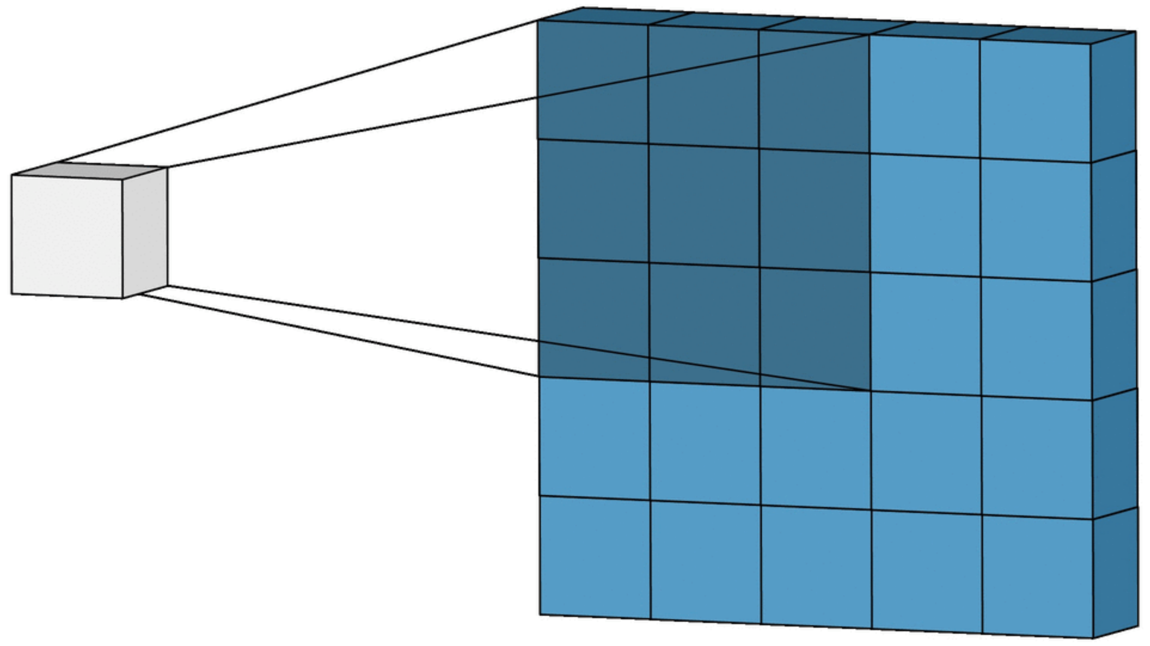
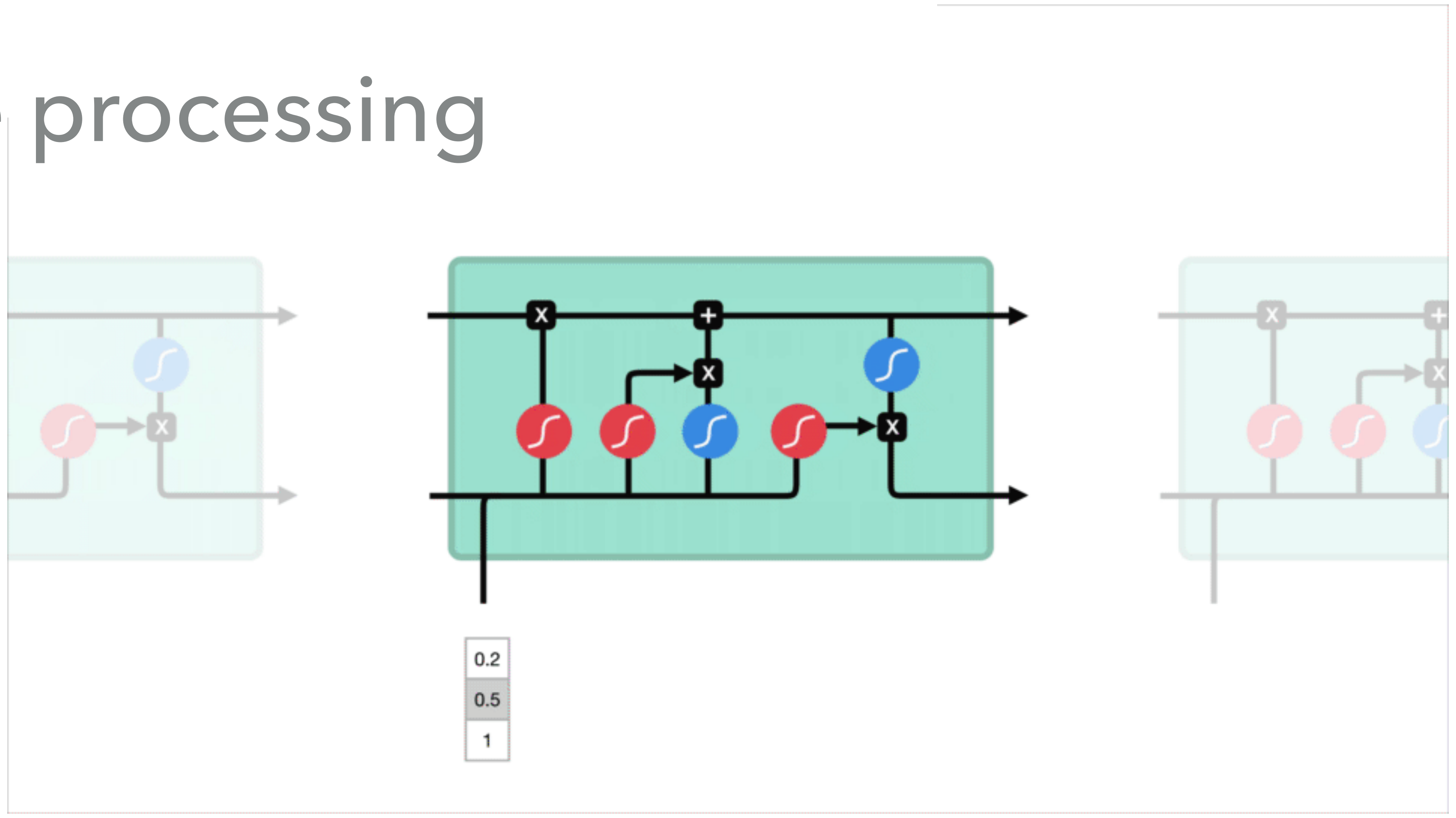


  - RNNs for language processing



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arXiv:2007.13681
arXiv:2012.01249

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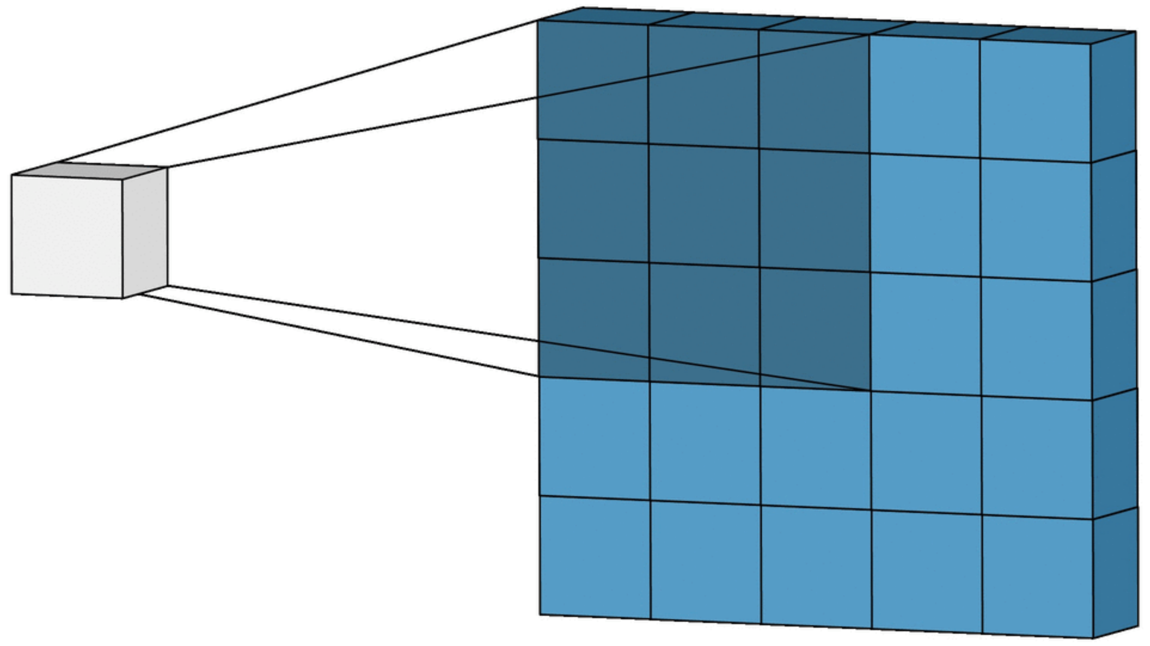

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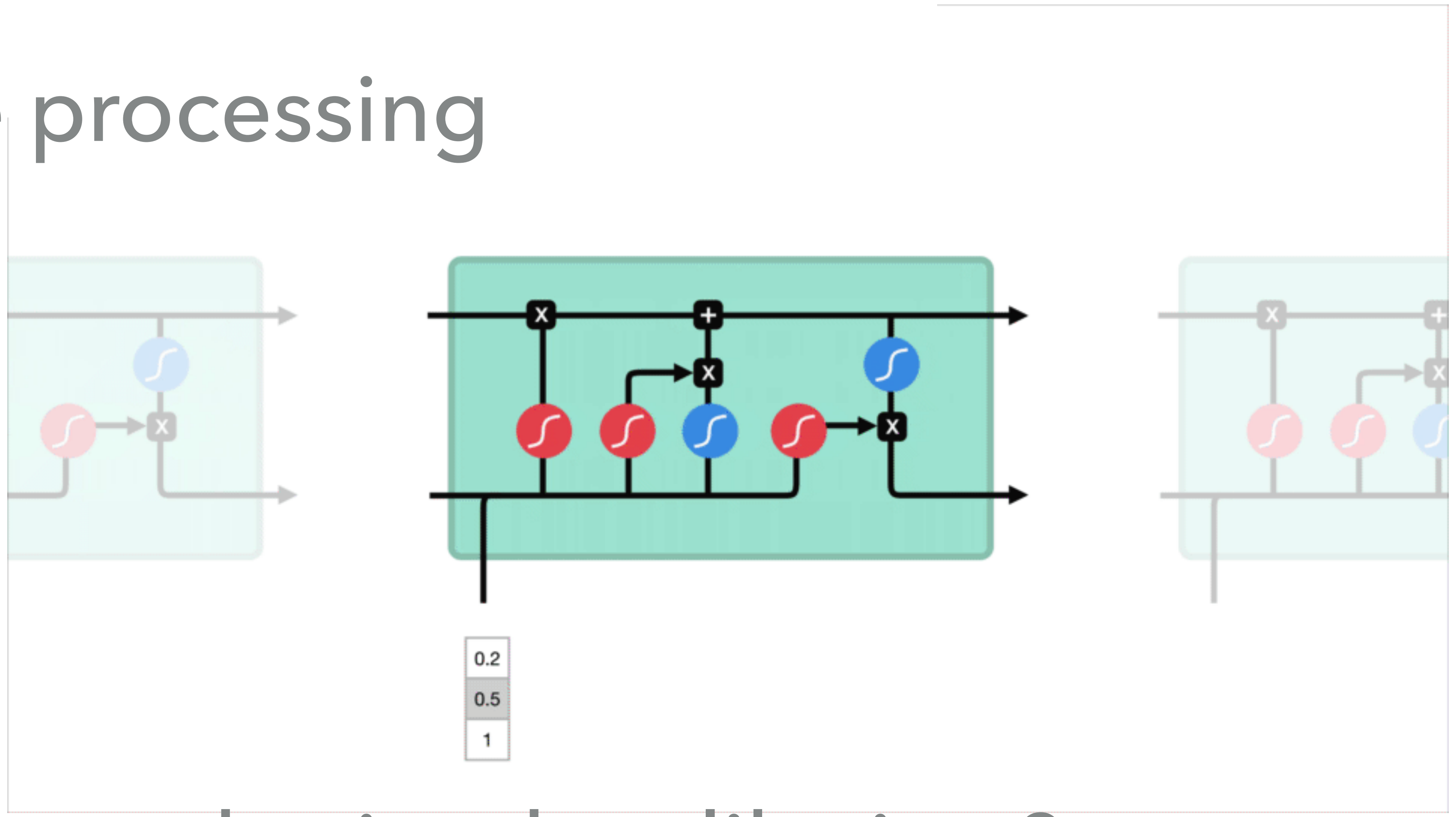

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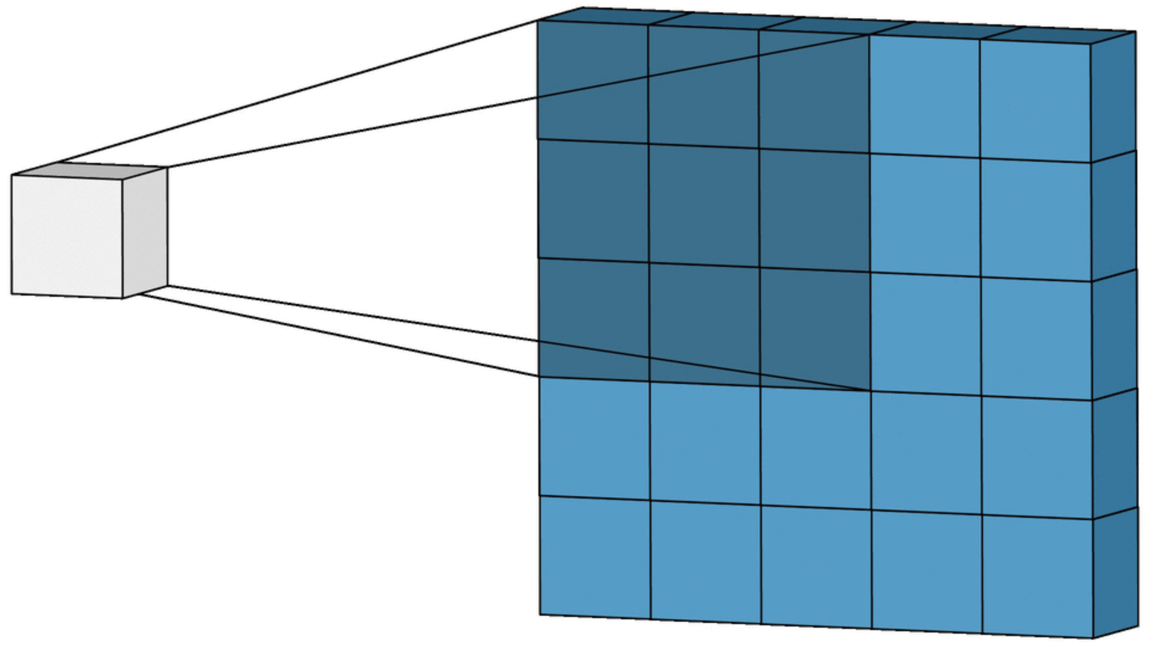

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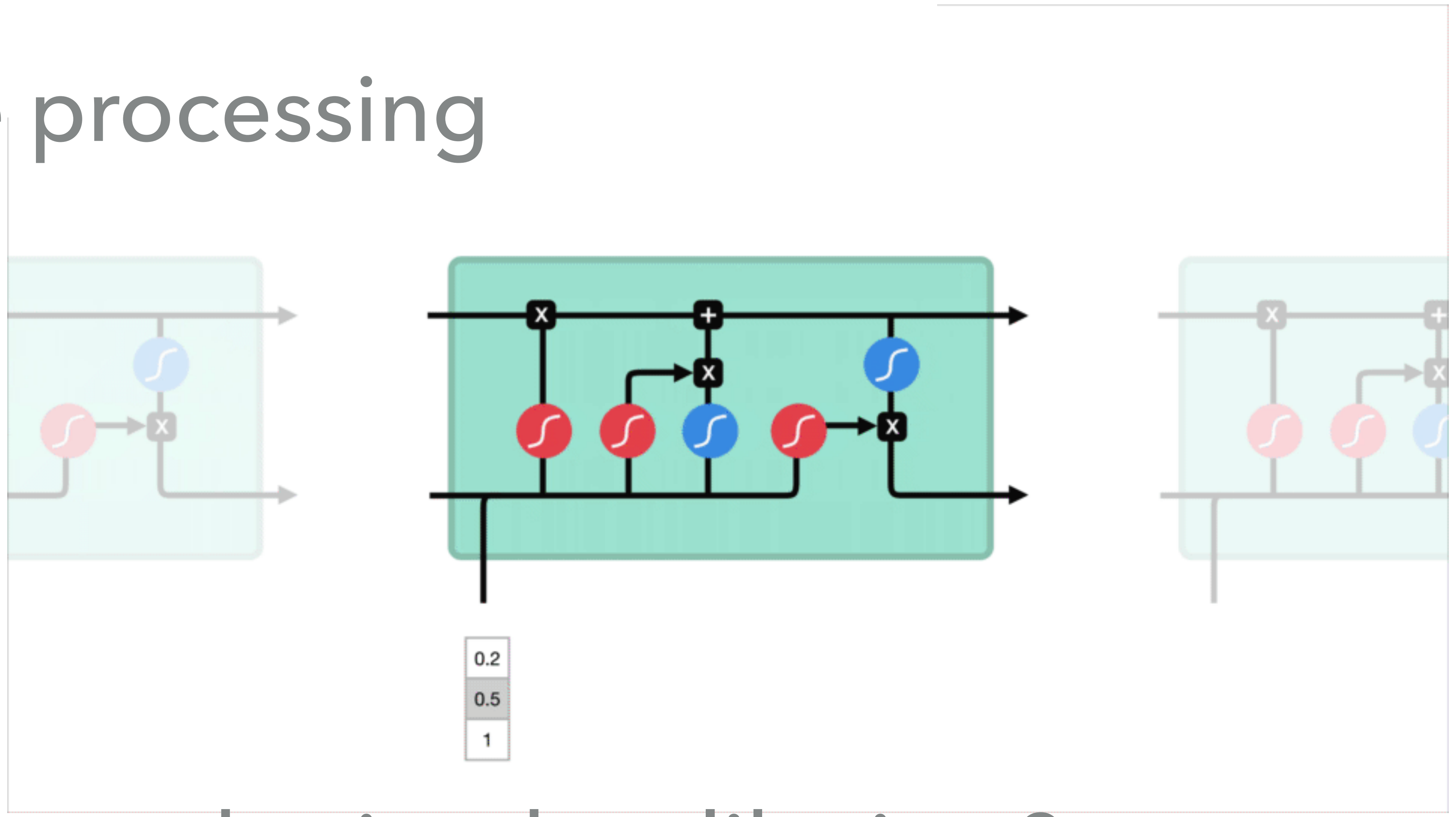
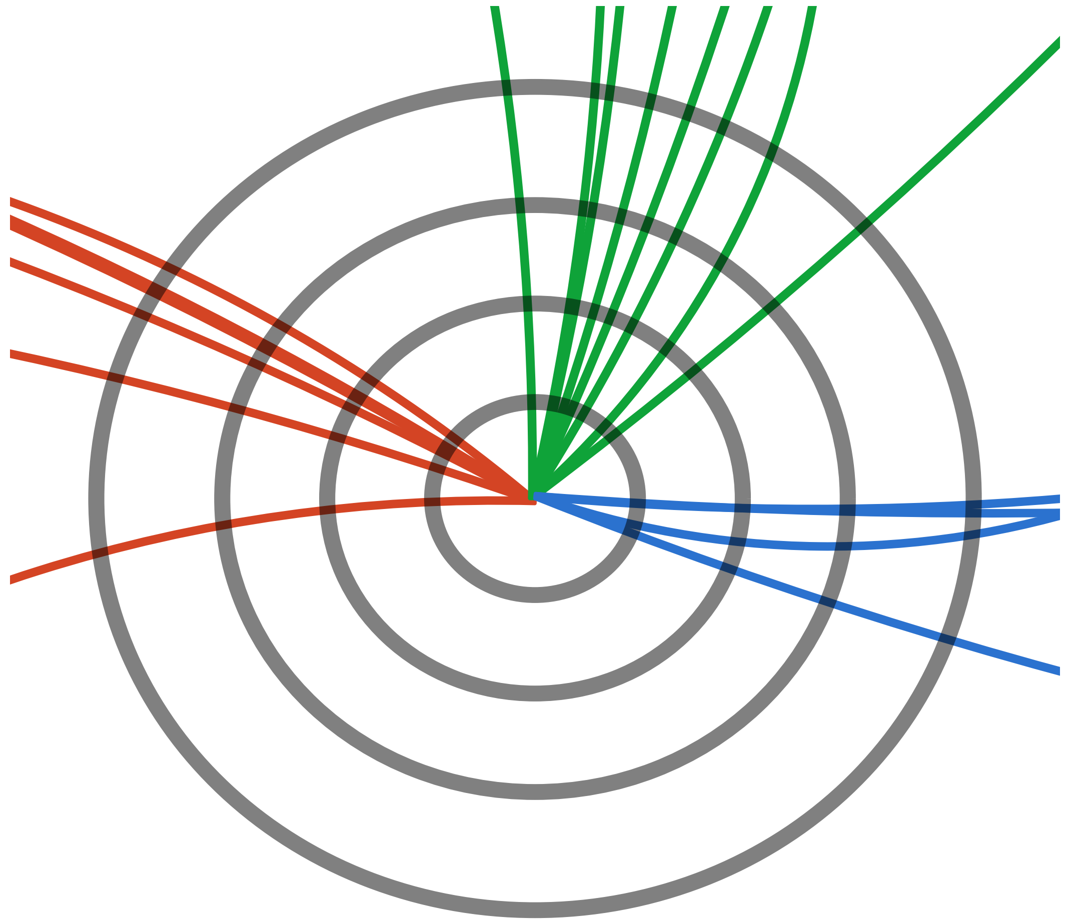


- Distributed unevenly in space
- Sparse
- Variable size
- No defined order
- Interconnections
  → Graphs



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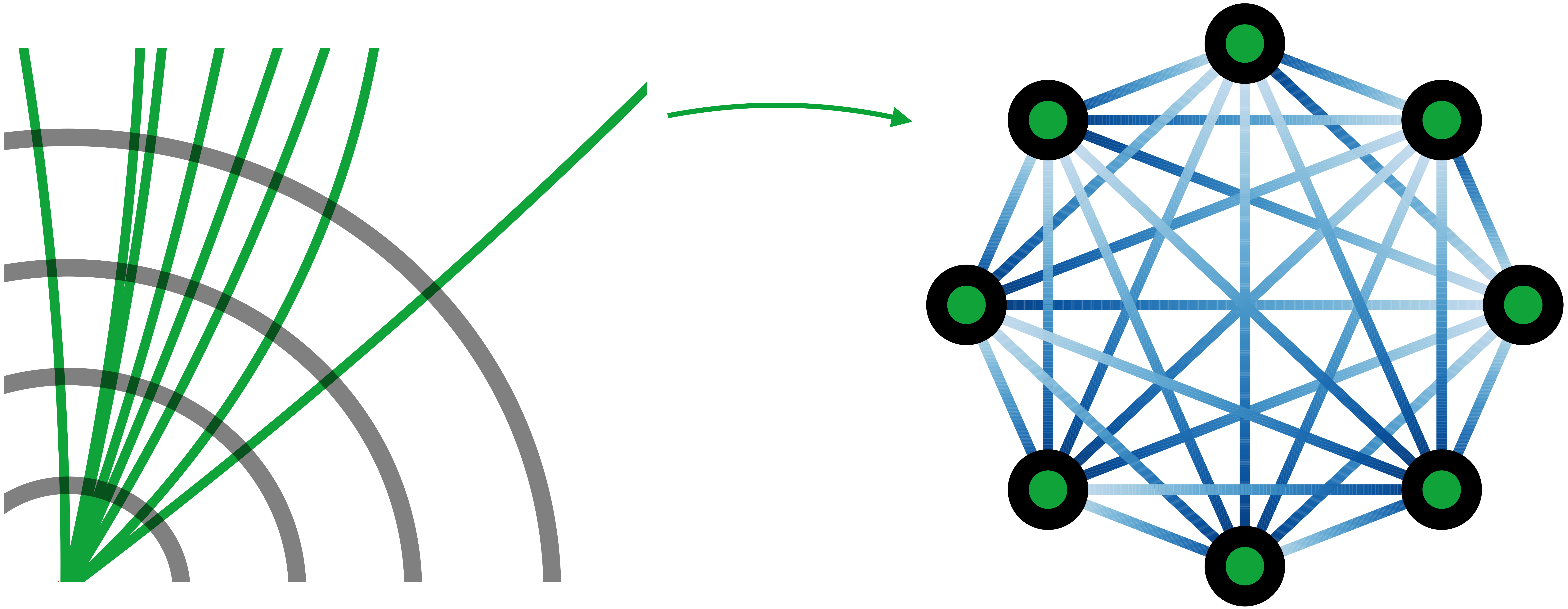
NODE, EDGE, GRAPH FEATURES IN HEP (E.G. JET)



NODE, EDGE, GRAPH FEATURES IN HEP (E.G. JET)

- Node features $\mathbf{v}_i$: particle 4-momentum

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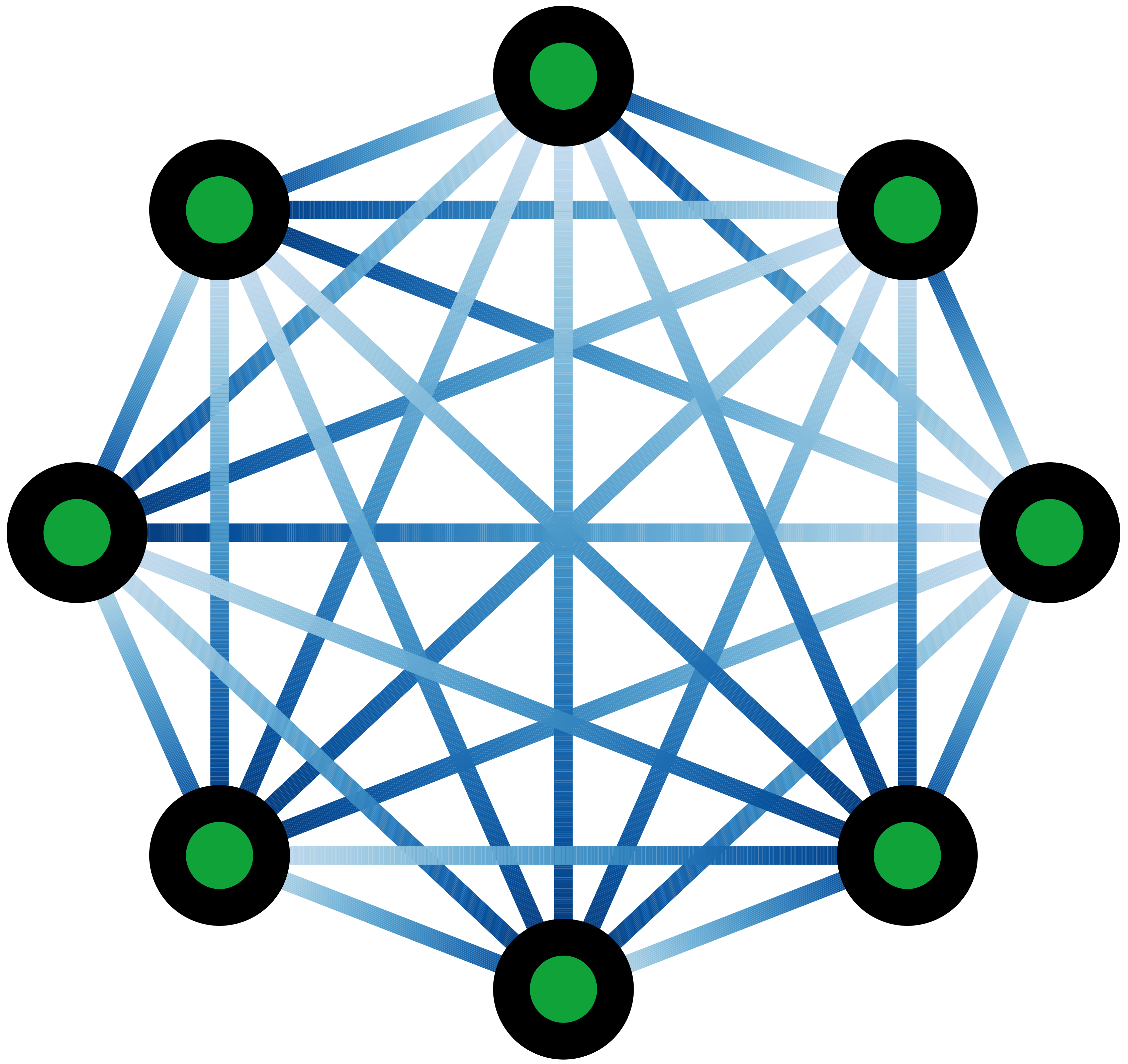

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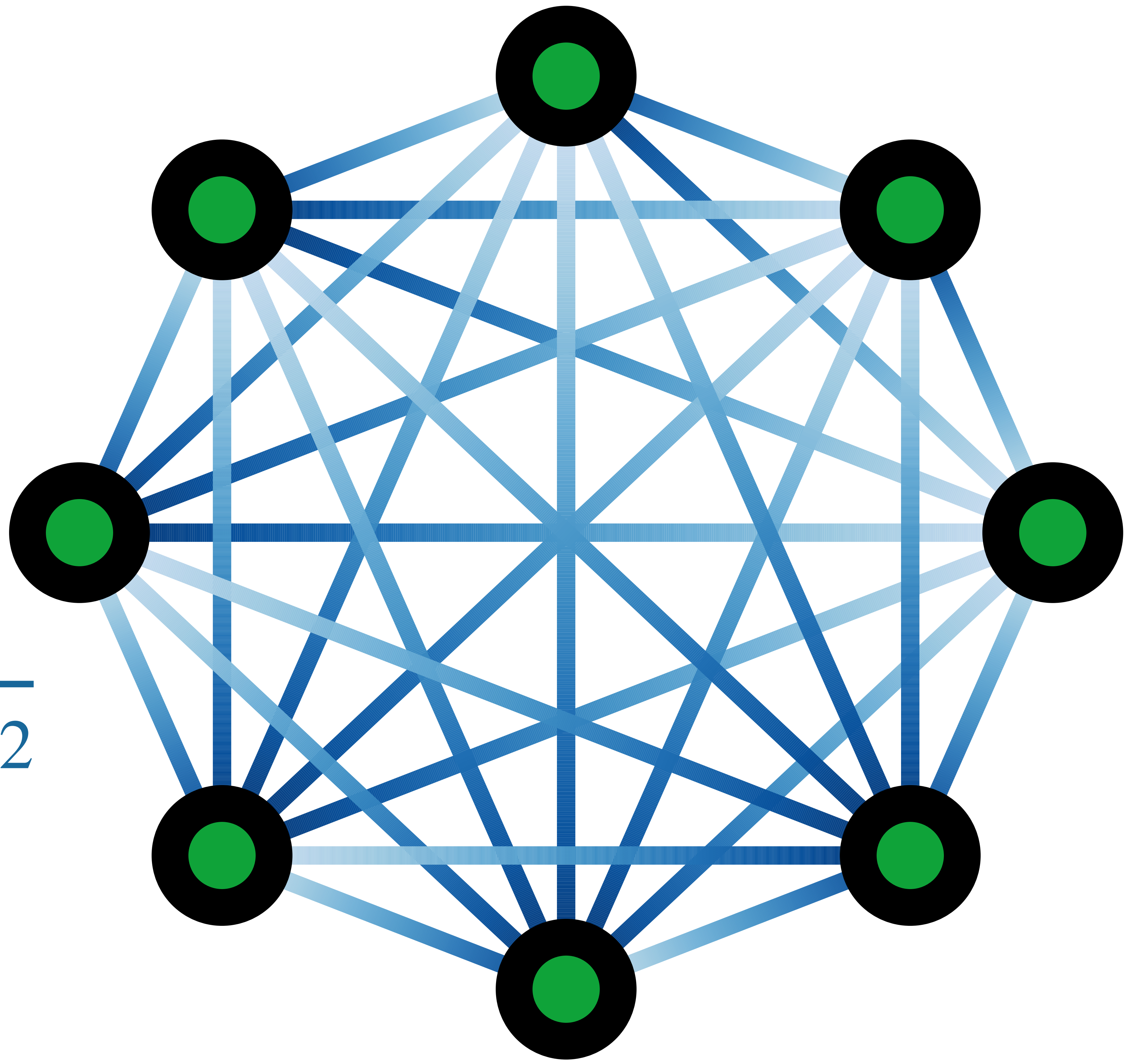

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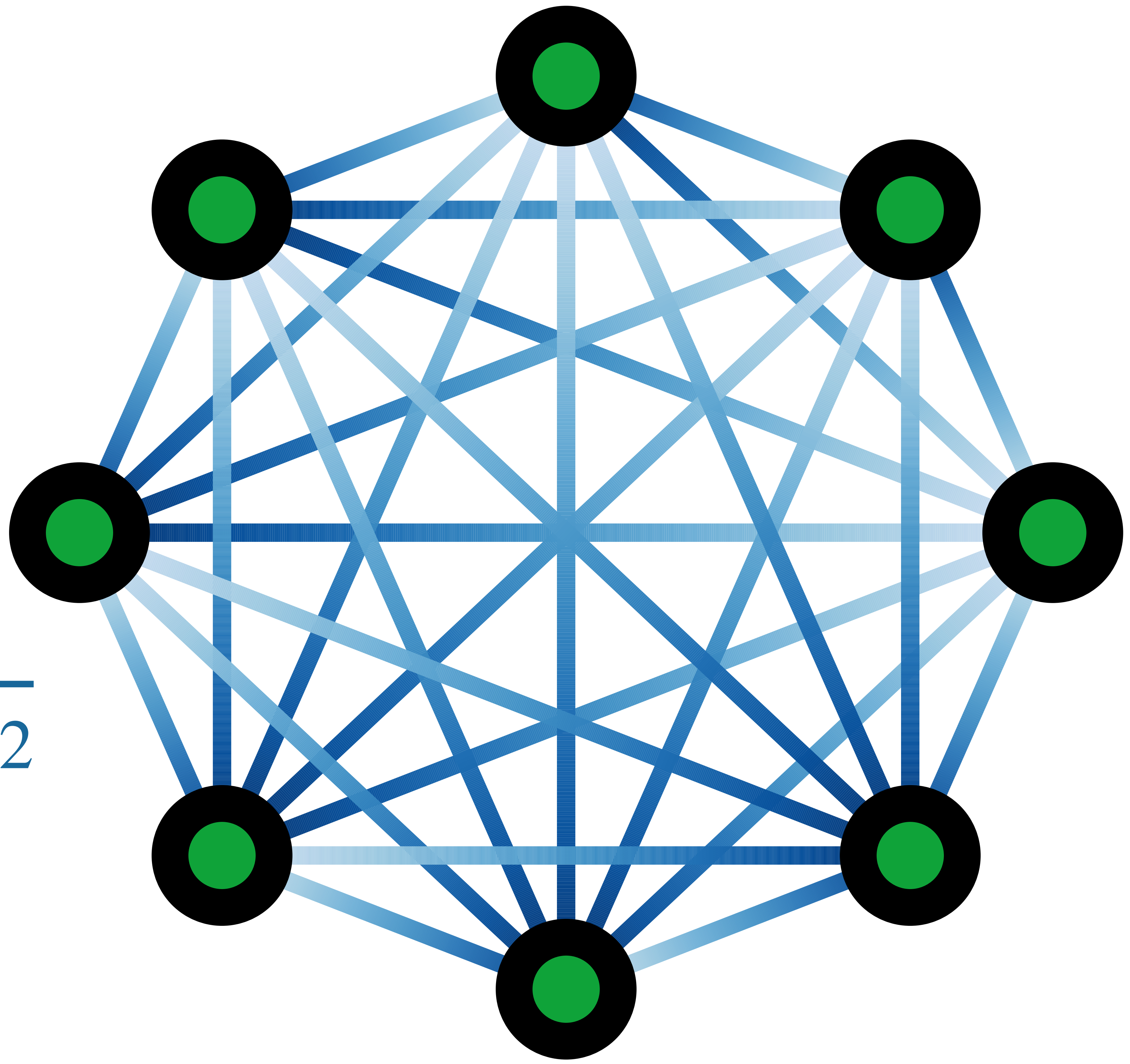

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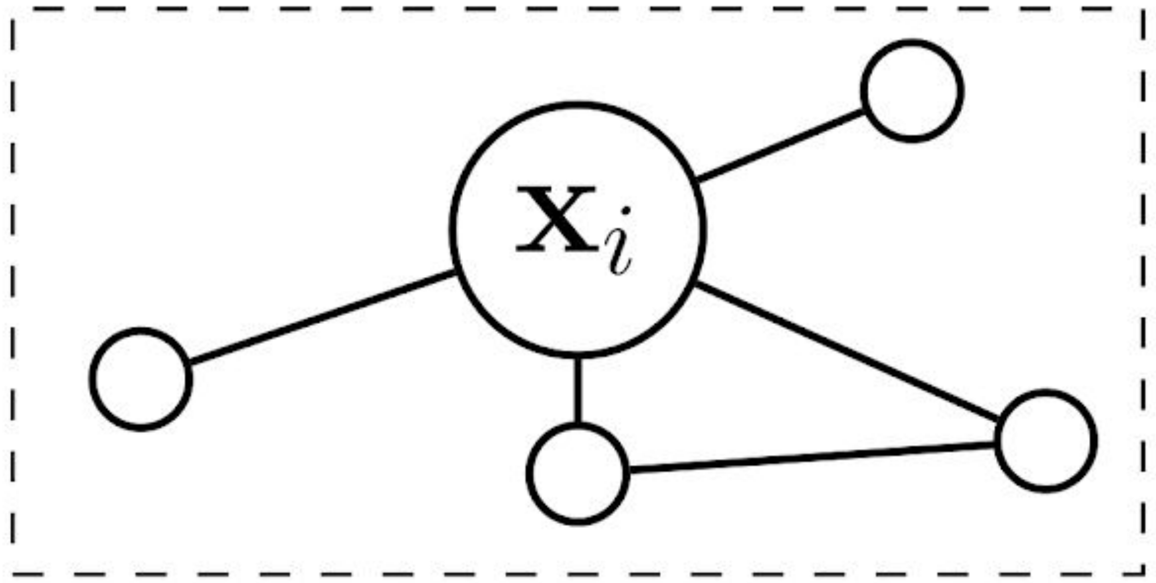
- Graph (global) features $\mathbf{u}$: jet mass

$$m = \sqrt{\sum_{i \in \mathrm{jet}} E_i^2 - p_{x,i}^2 - p_{y,i}^2 - p_{z,i}^2}$$

GNN'S MAIN INGREDIENT: MESSAGE PASSING

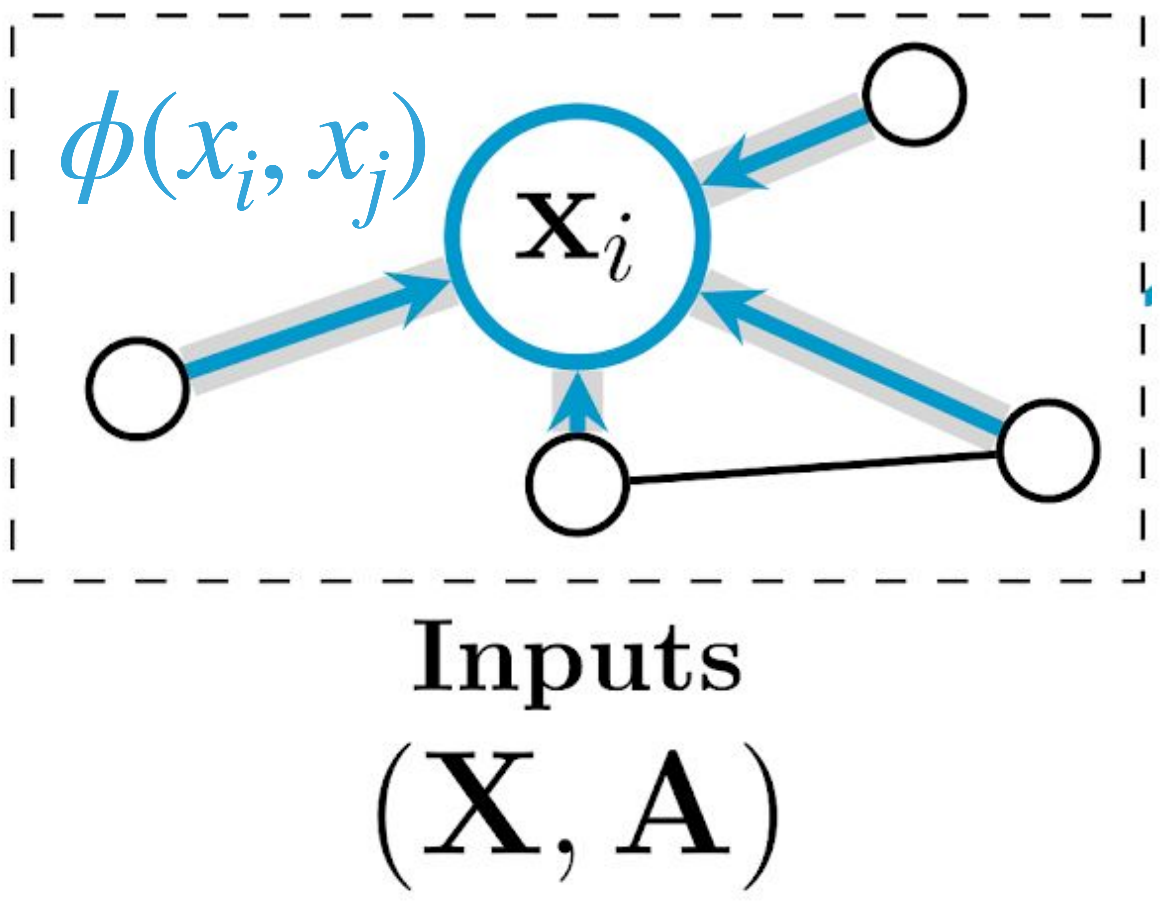


Inputs

$(\mathbf{X}, \mathbf{A})$

GNN'S MAIN INGREDIENT: MESSAGE PASSING

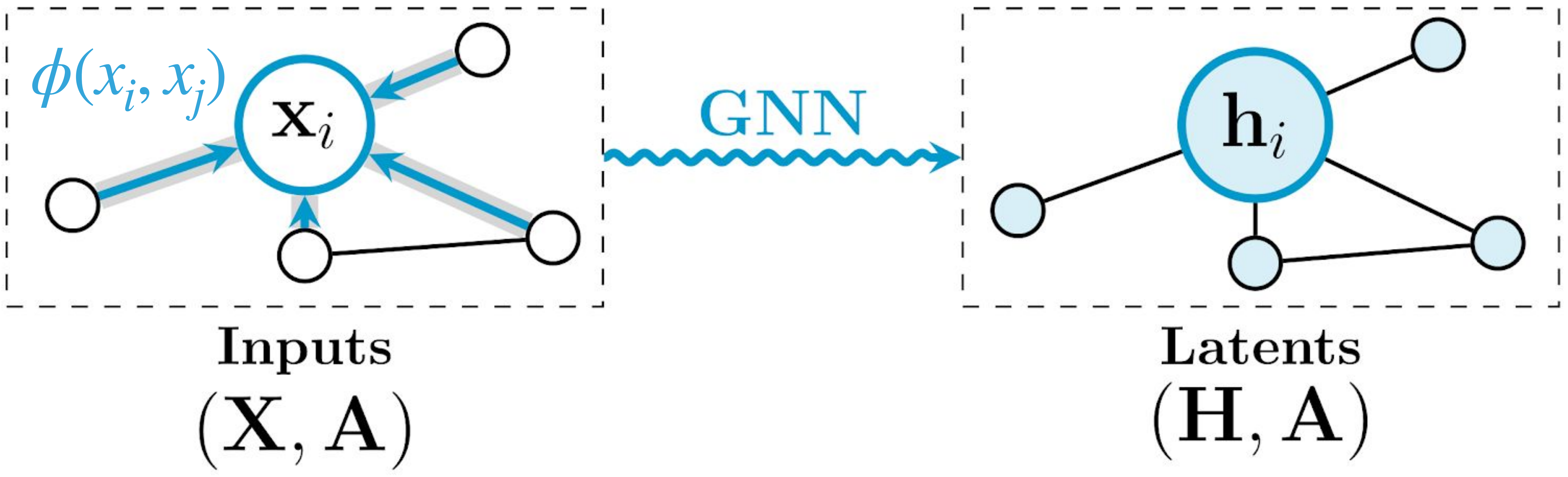
- For all neighbors j of node i compute a "message" via a NN: $\phi(x_i, x_j)$



GNN'S MAIN INGREDIENT: MESSAGE PASSING

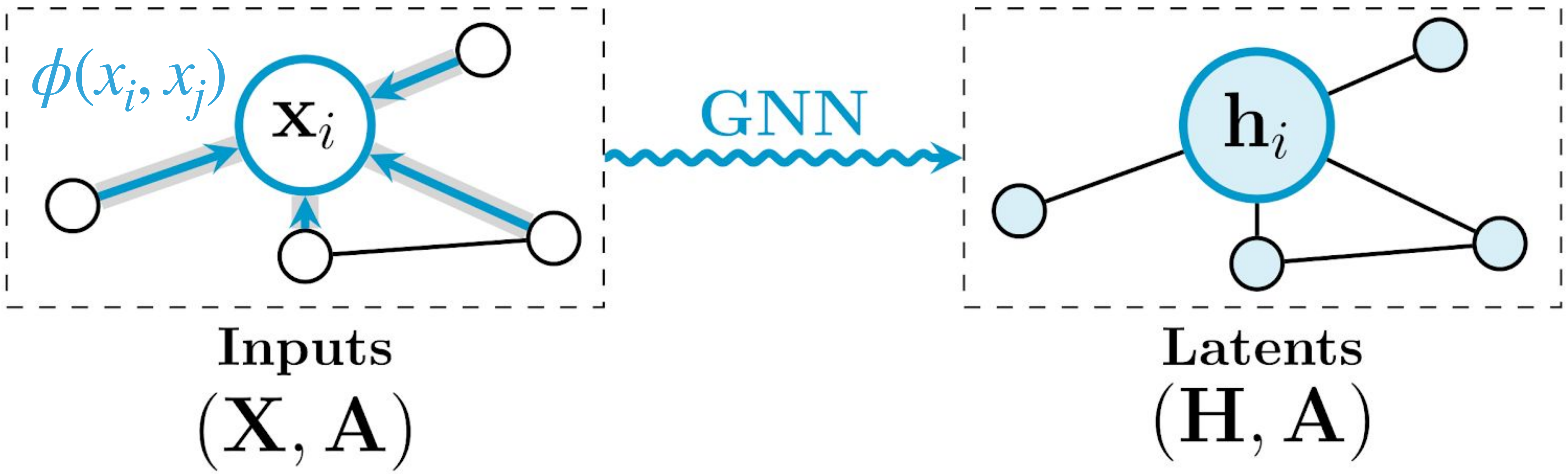
- For all neighbors j of node i compute a "message" via a NN: $\phi(x_i, x_j)$

- Update the node features by summing all messages:
  $$h_i = \sum_j \phi(x_i, x_j)$$



"message passing"

HOW TO USE GNNS IN HEP



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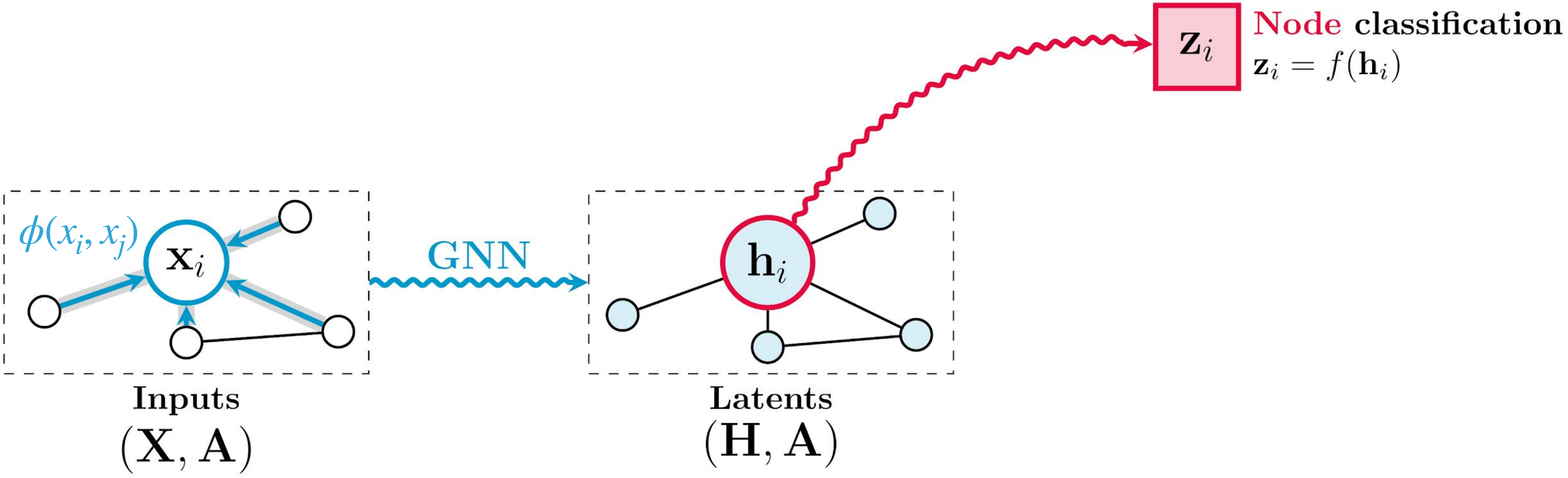
  - Identify "pileup" particles



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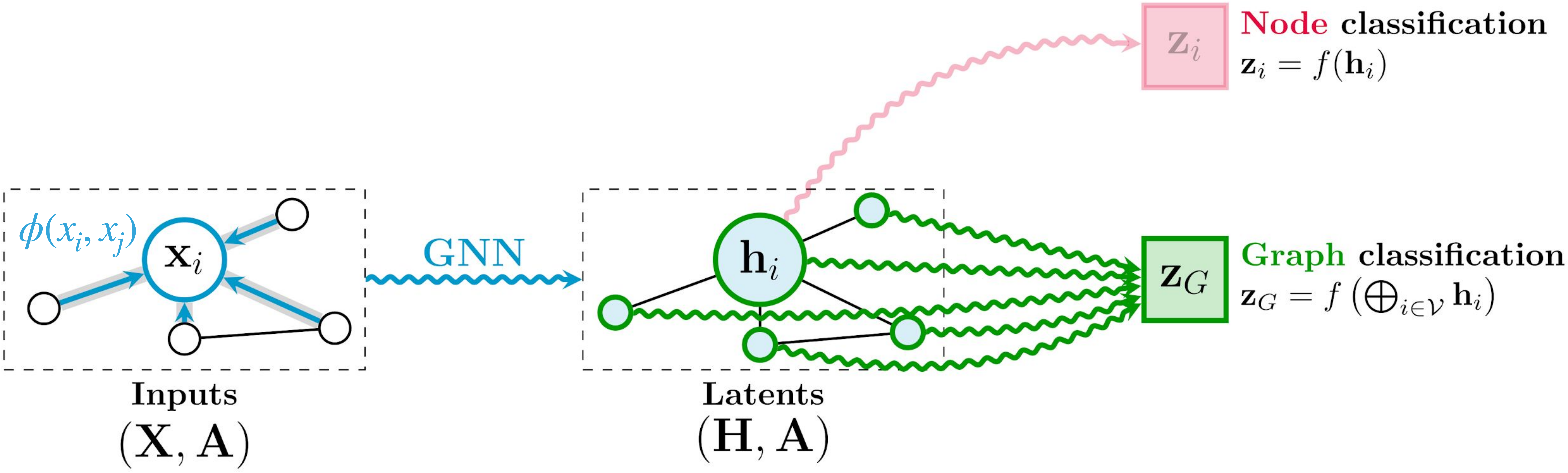

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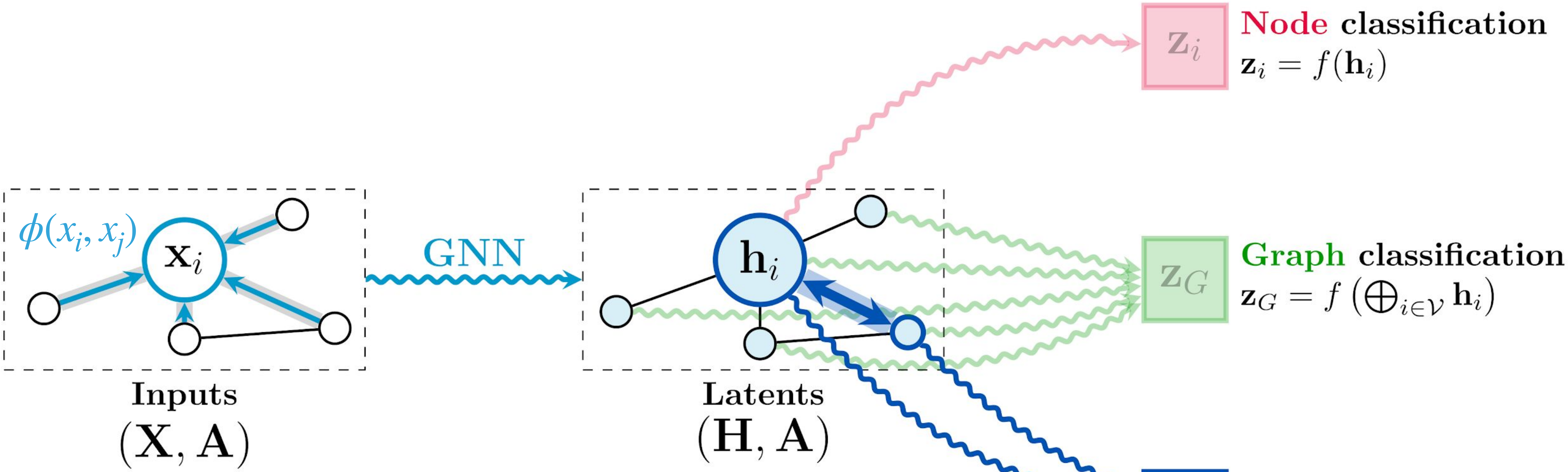
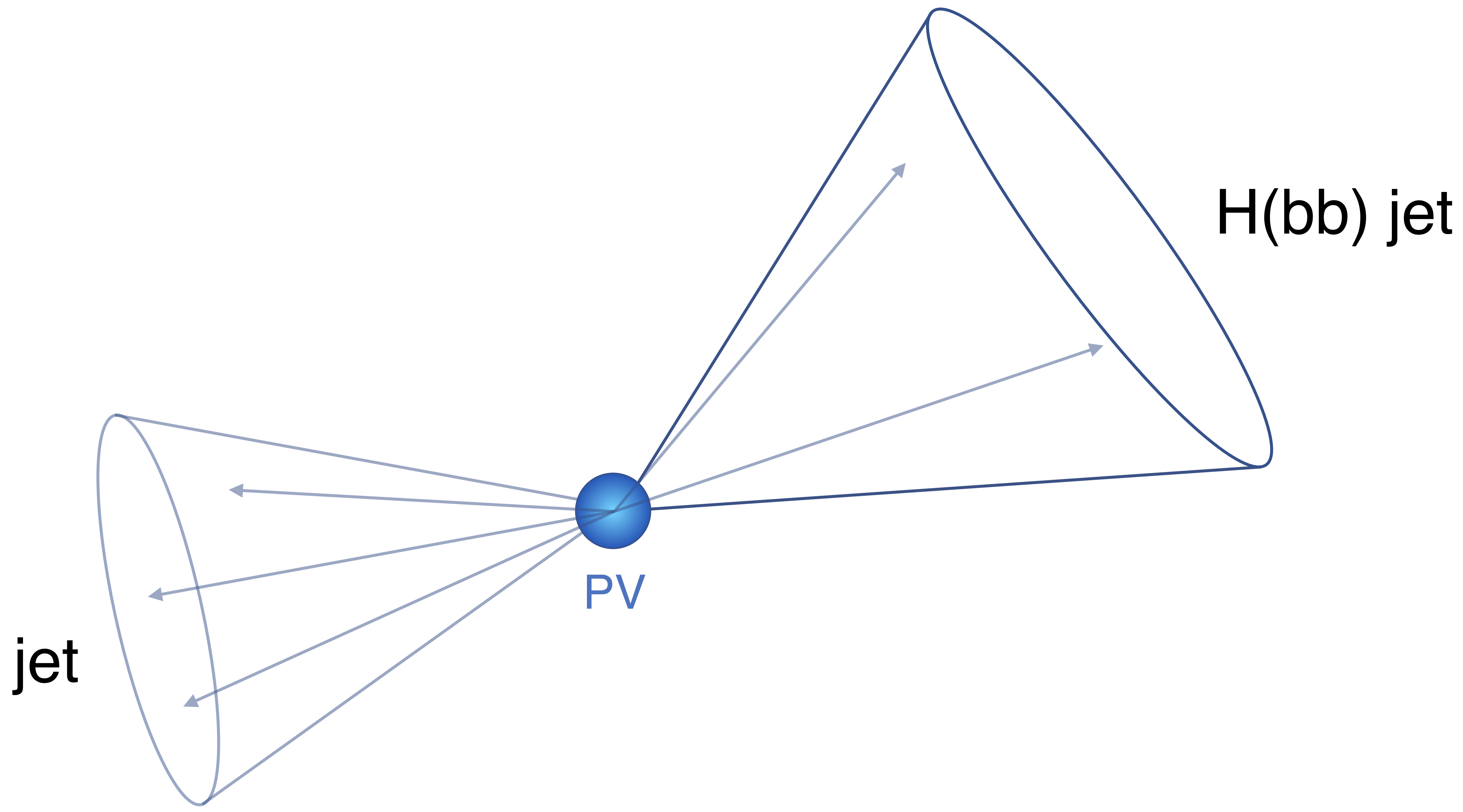


- Edge-level tasks
  - Identify good track doublets

BASICS OF HIGGS (DOUBLE-B) TAGGING

b hadrons have long lifetimes:
travel O(mm) before decay!



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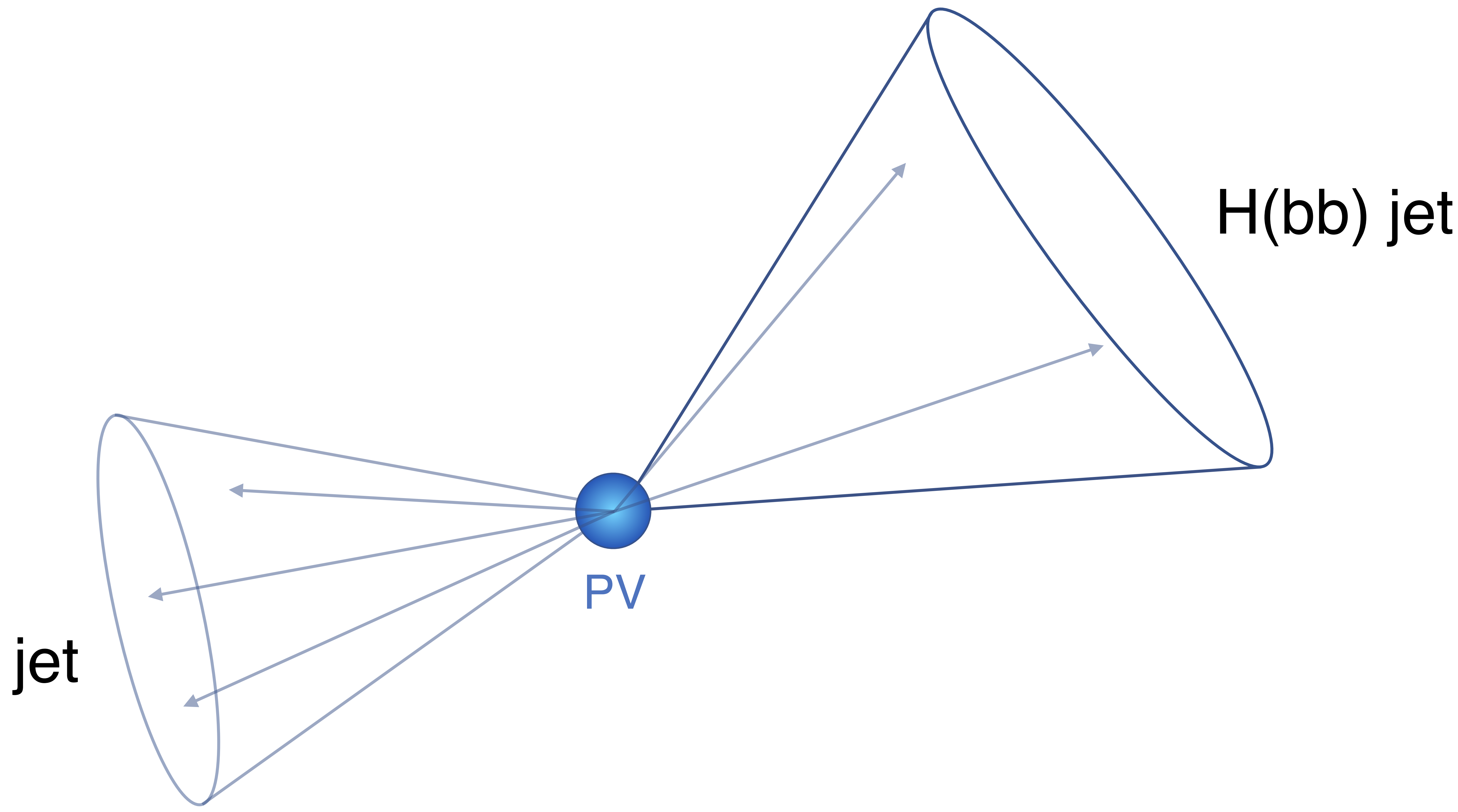

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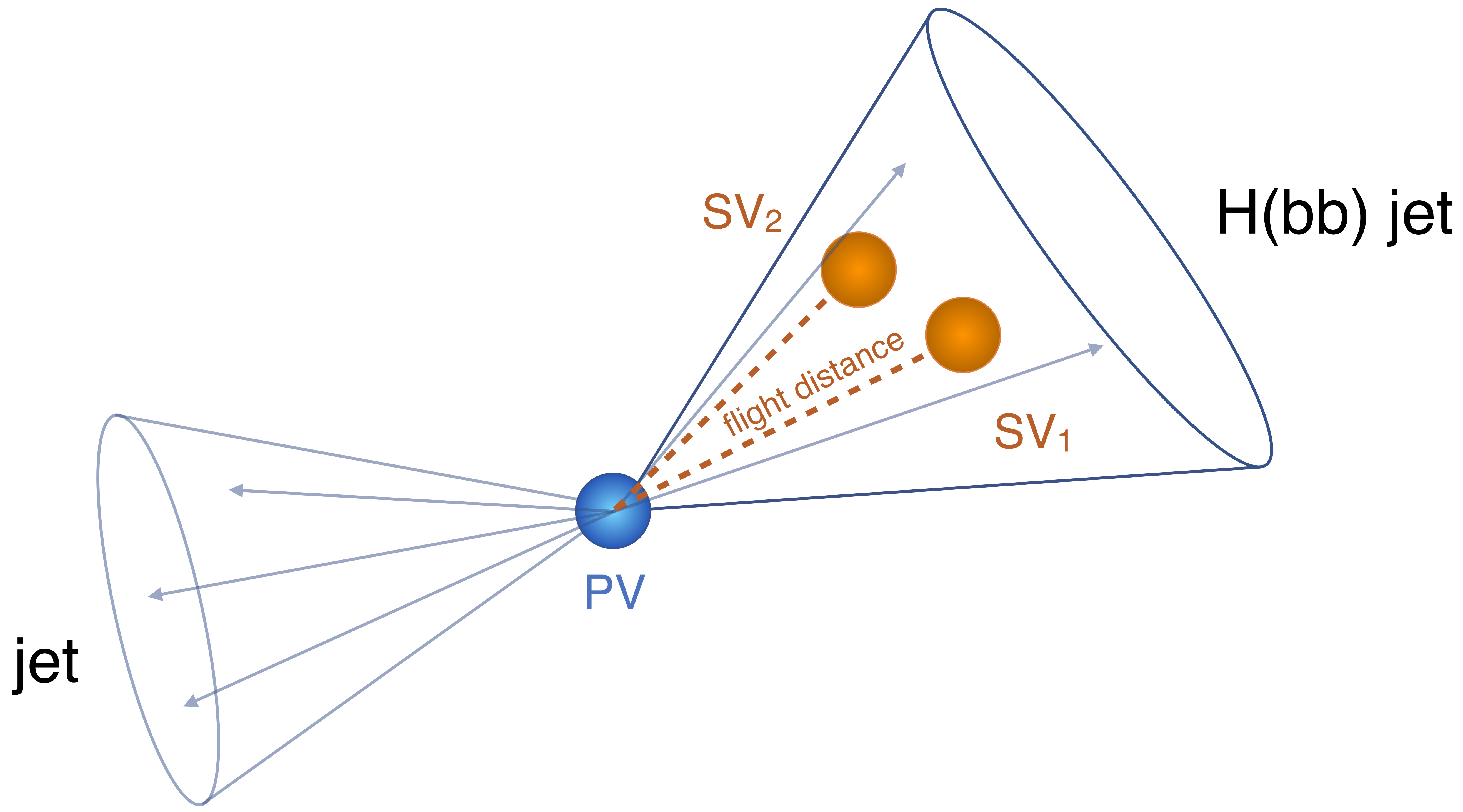

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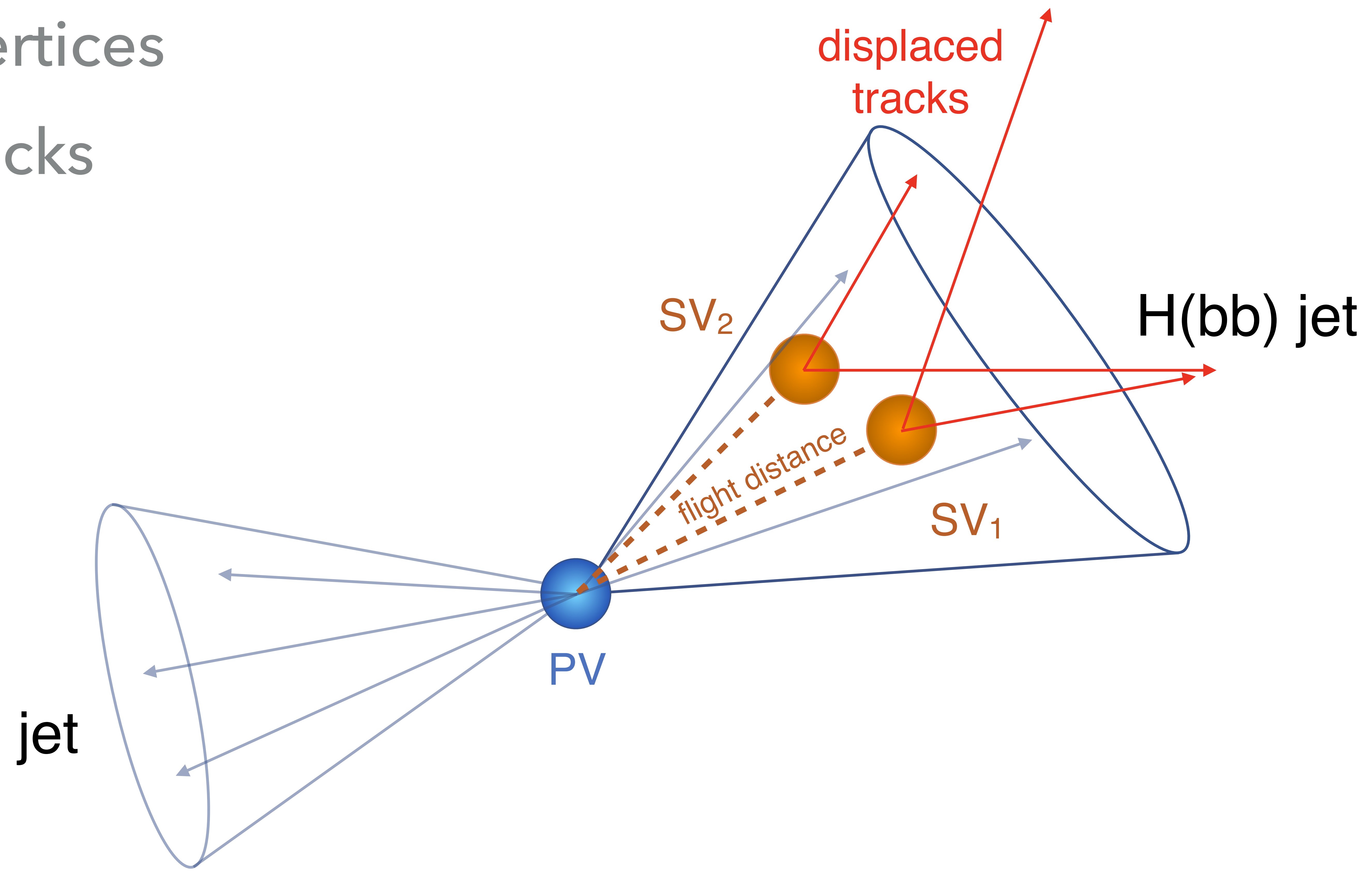

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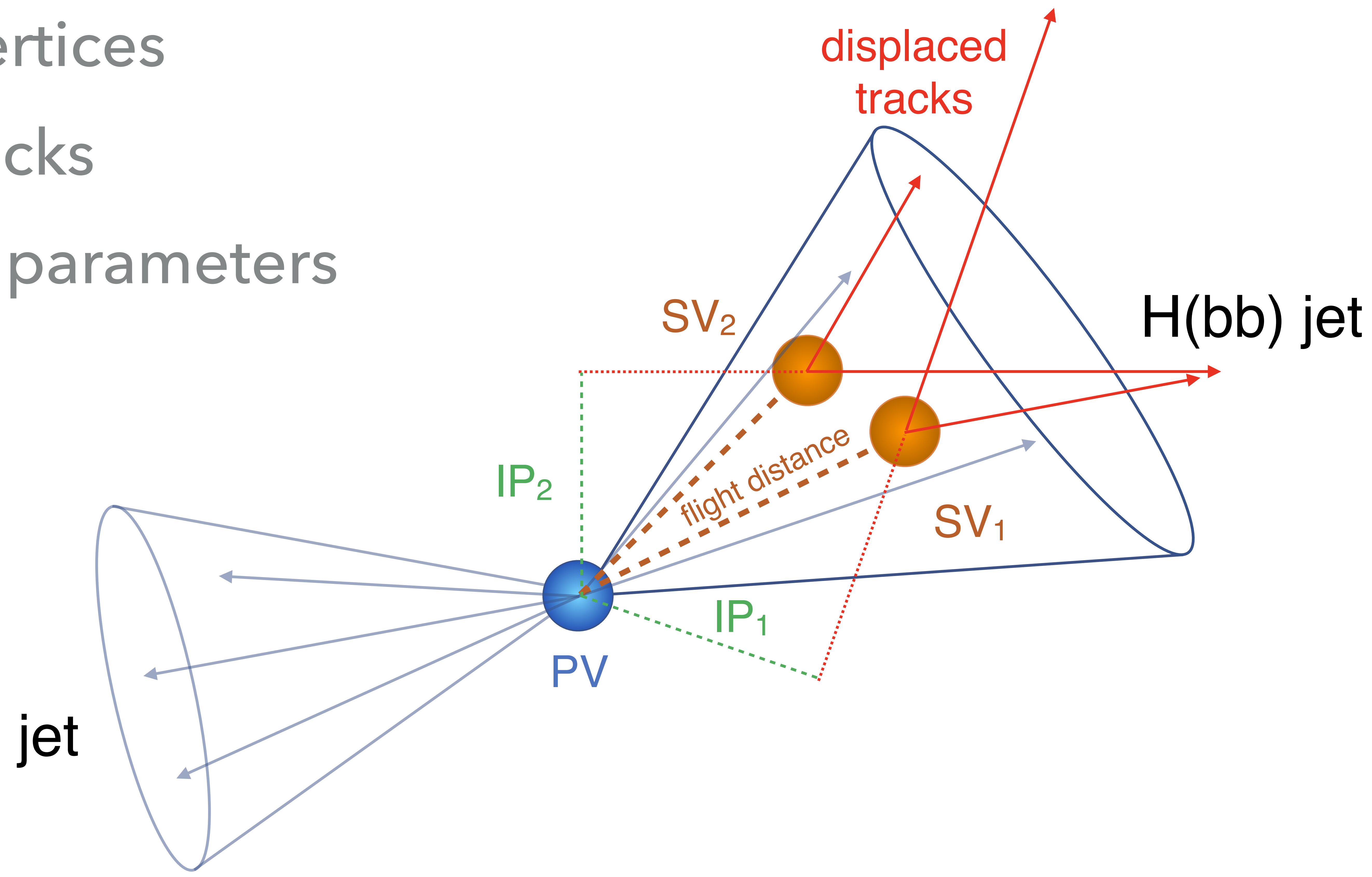

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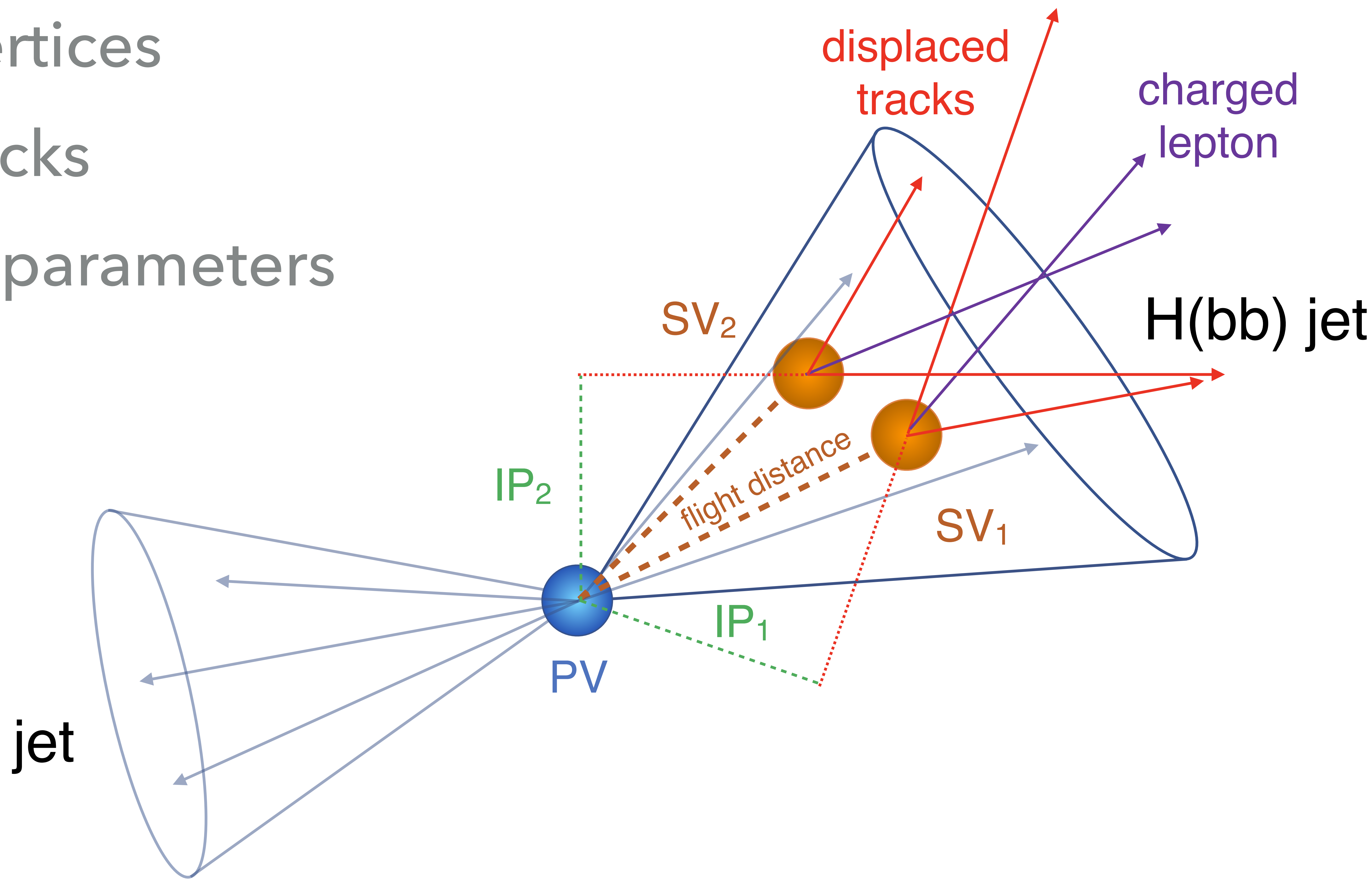

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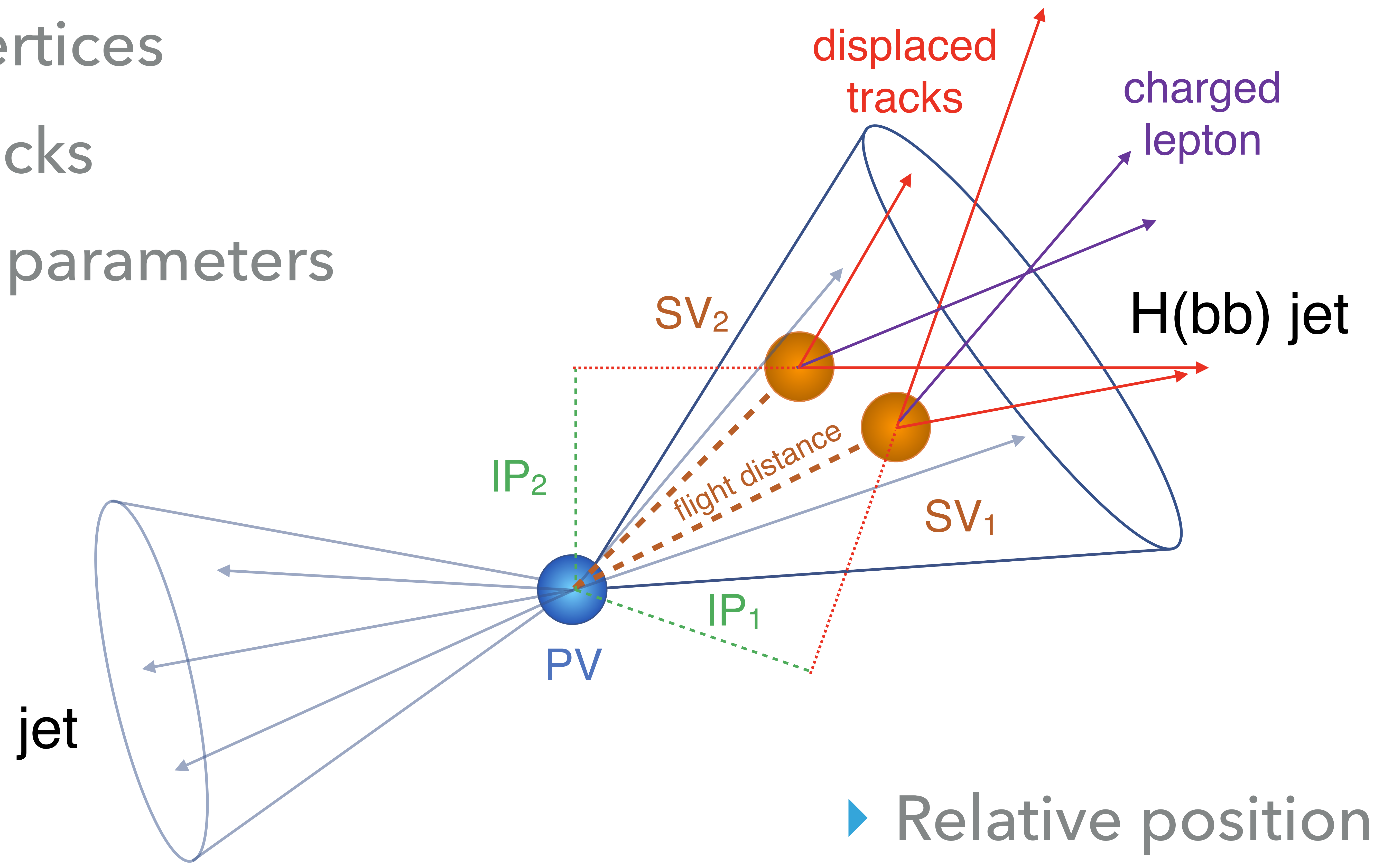
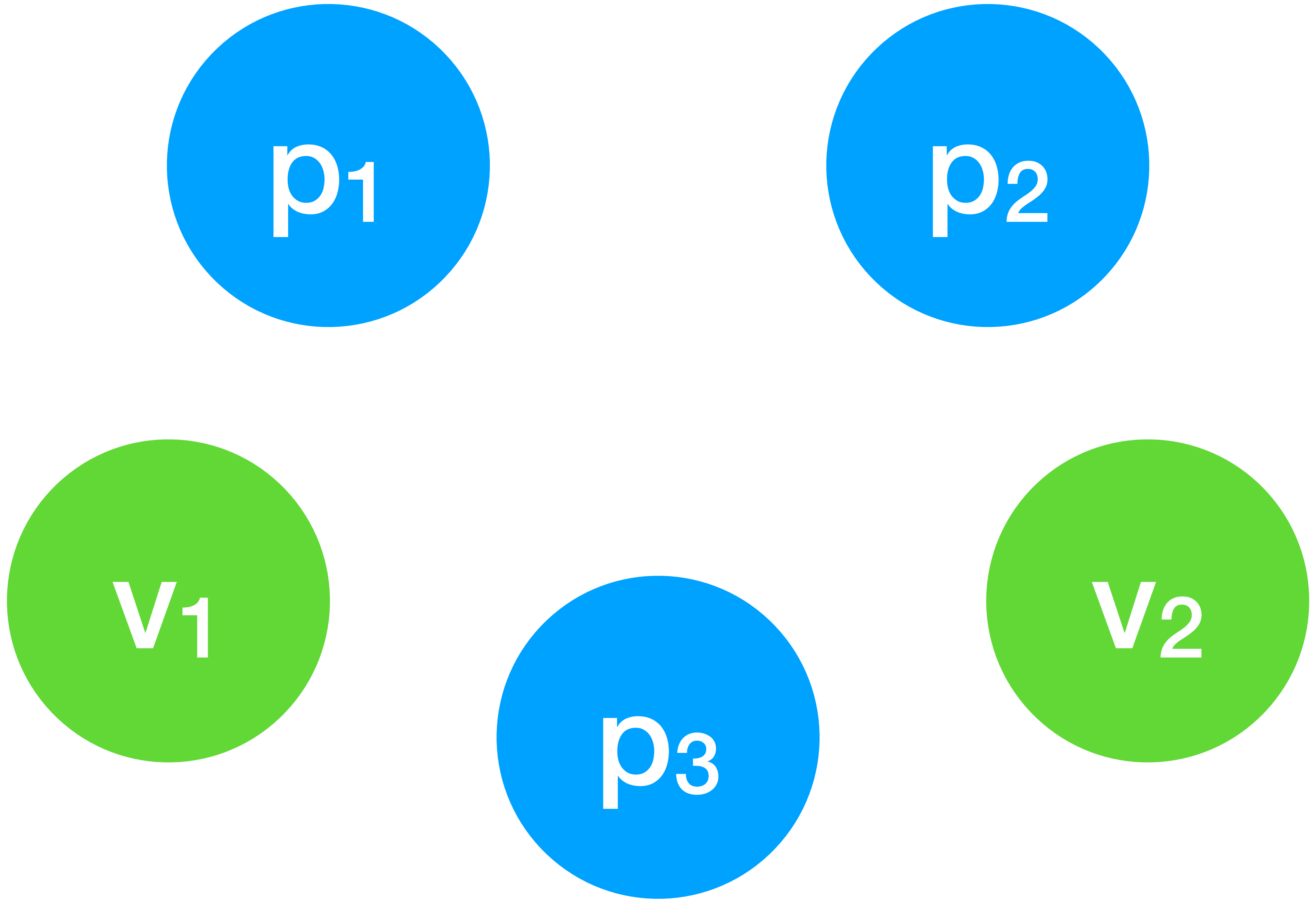


- Relative positions of SVs

PARTICLES AND SECONDARY VERTICES: TWO INPUT GRAPHS

$$p_i = [p_T^{rel}, \phi^{rel}, \eta^{rel}, \ldots, d_{3D}, \mathrm{cov}(p_T, p_T), \ldots]$$



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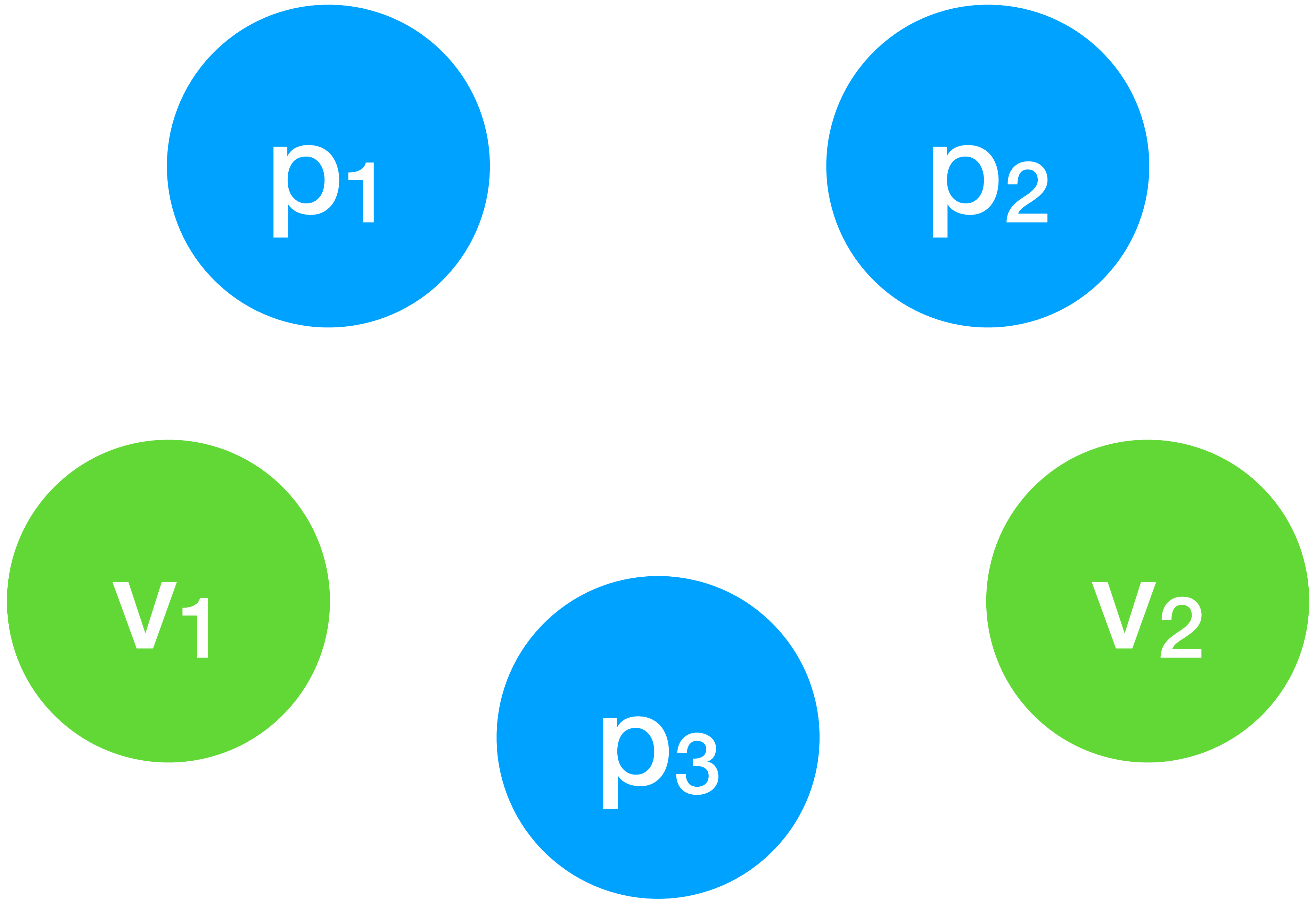

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arXiv:1909.12285

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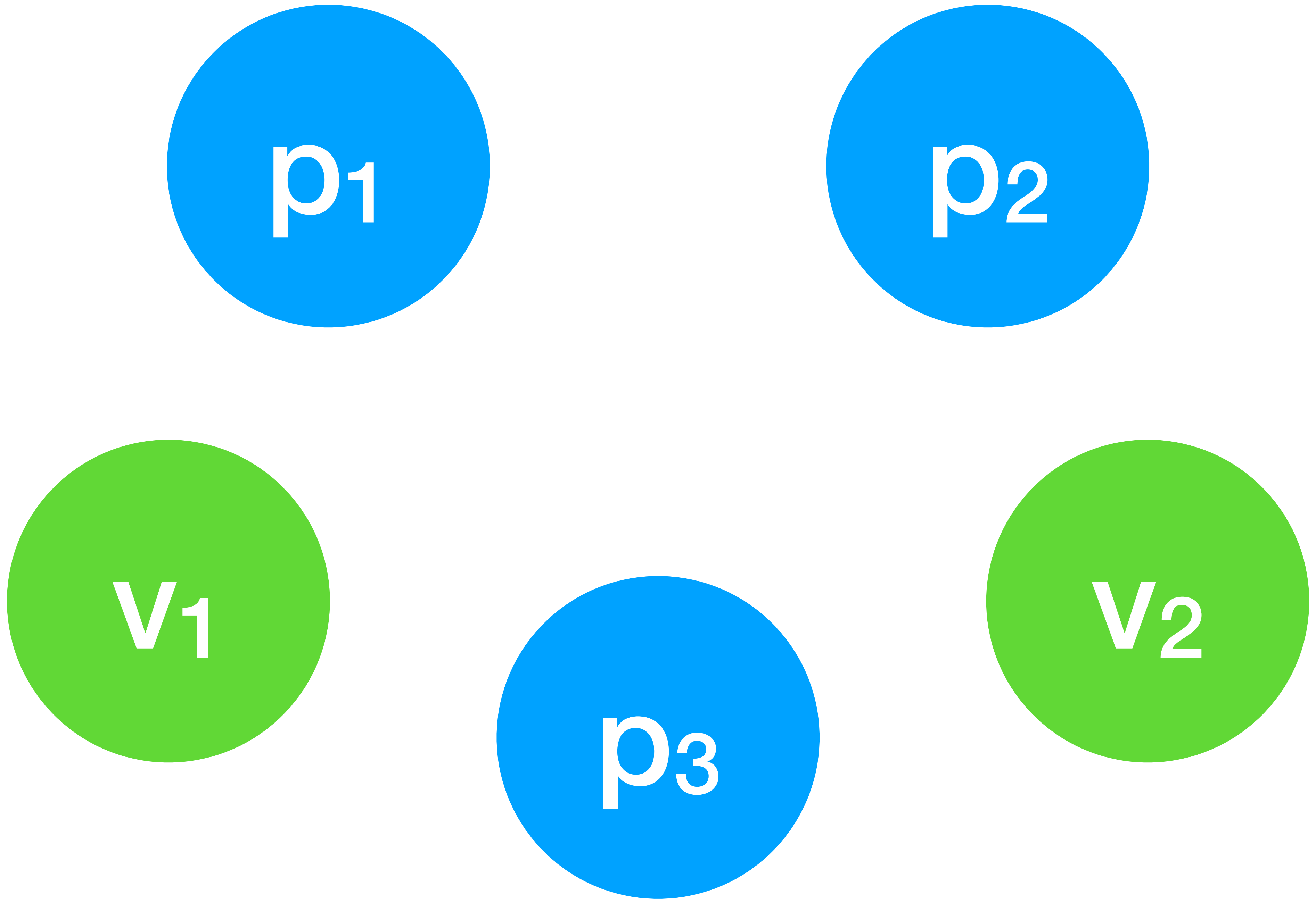

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- After embedding feature vectors in a common *latent space* (via a NN), *combined graph* can be constructed

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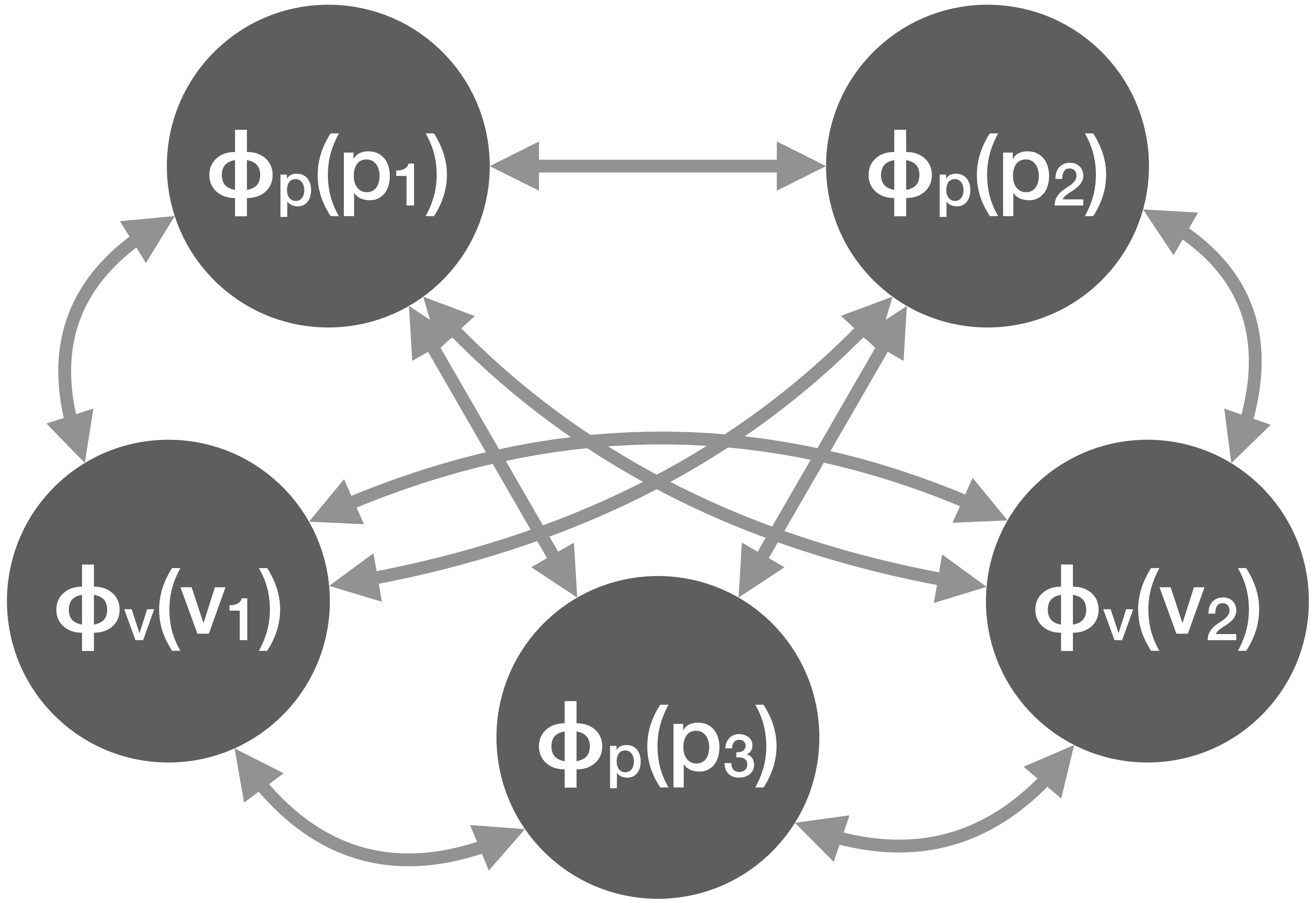

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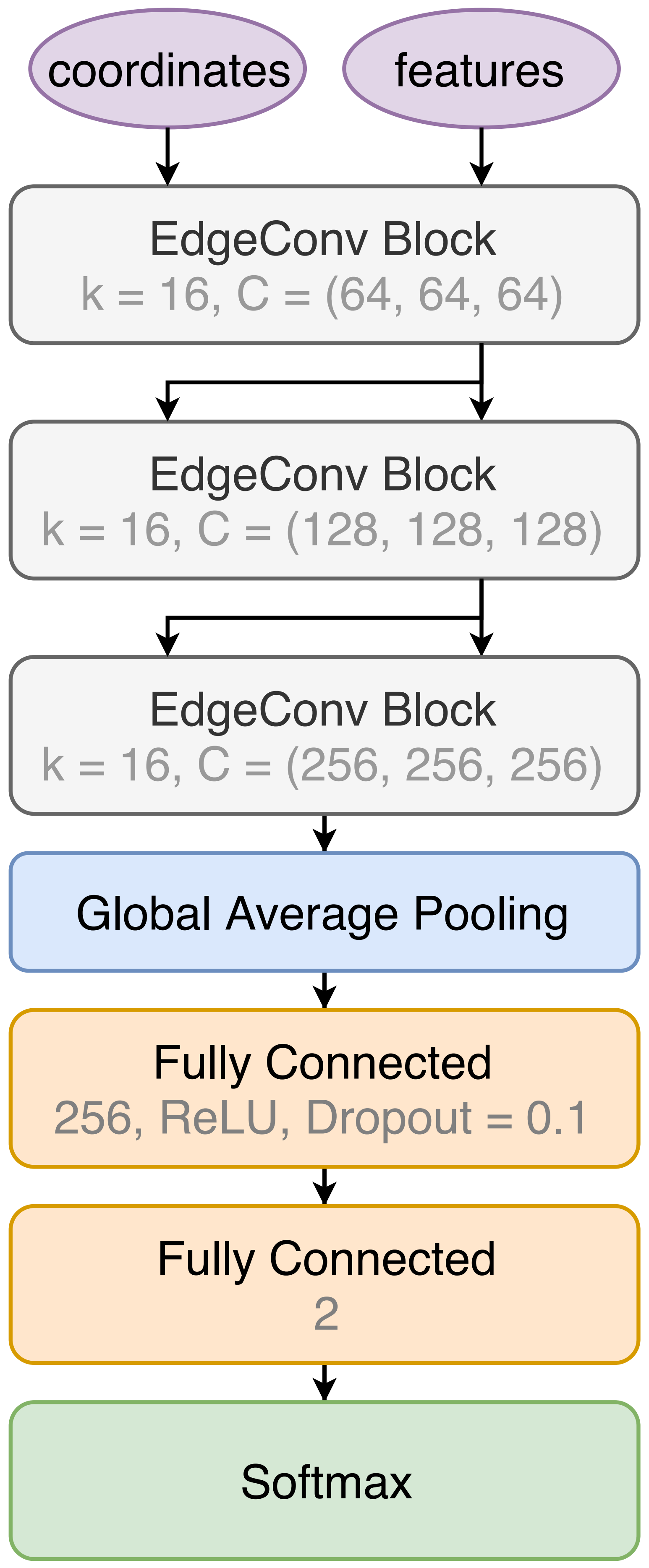
PARTICLENET: GNN FOR TAGGING H(BB) IN CMS

arXiv:1902.08570
CMS-DP-2020-002



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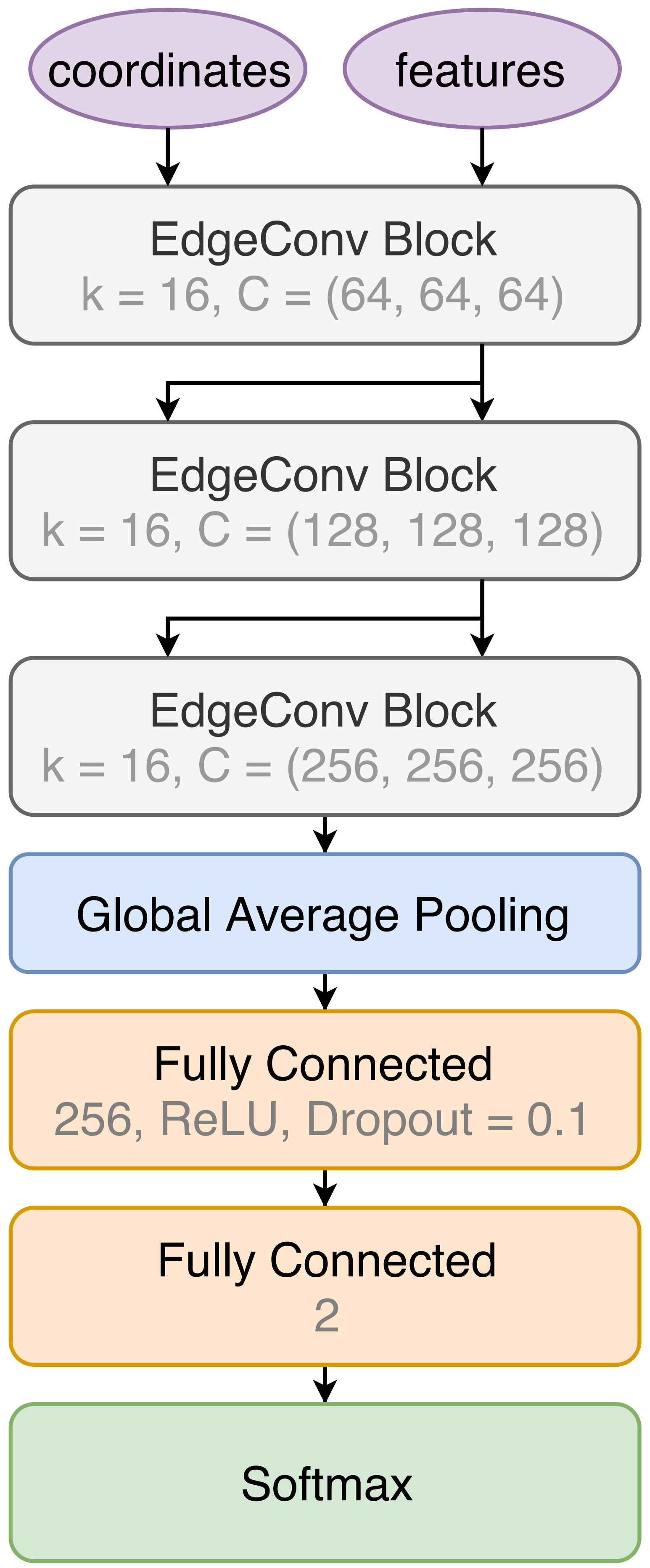

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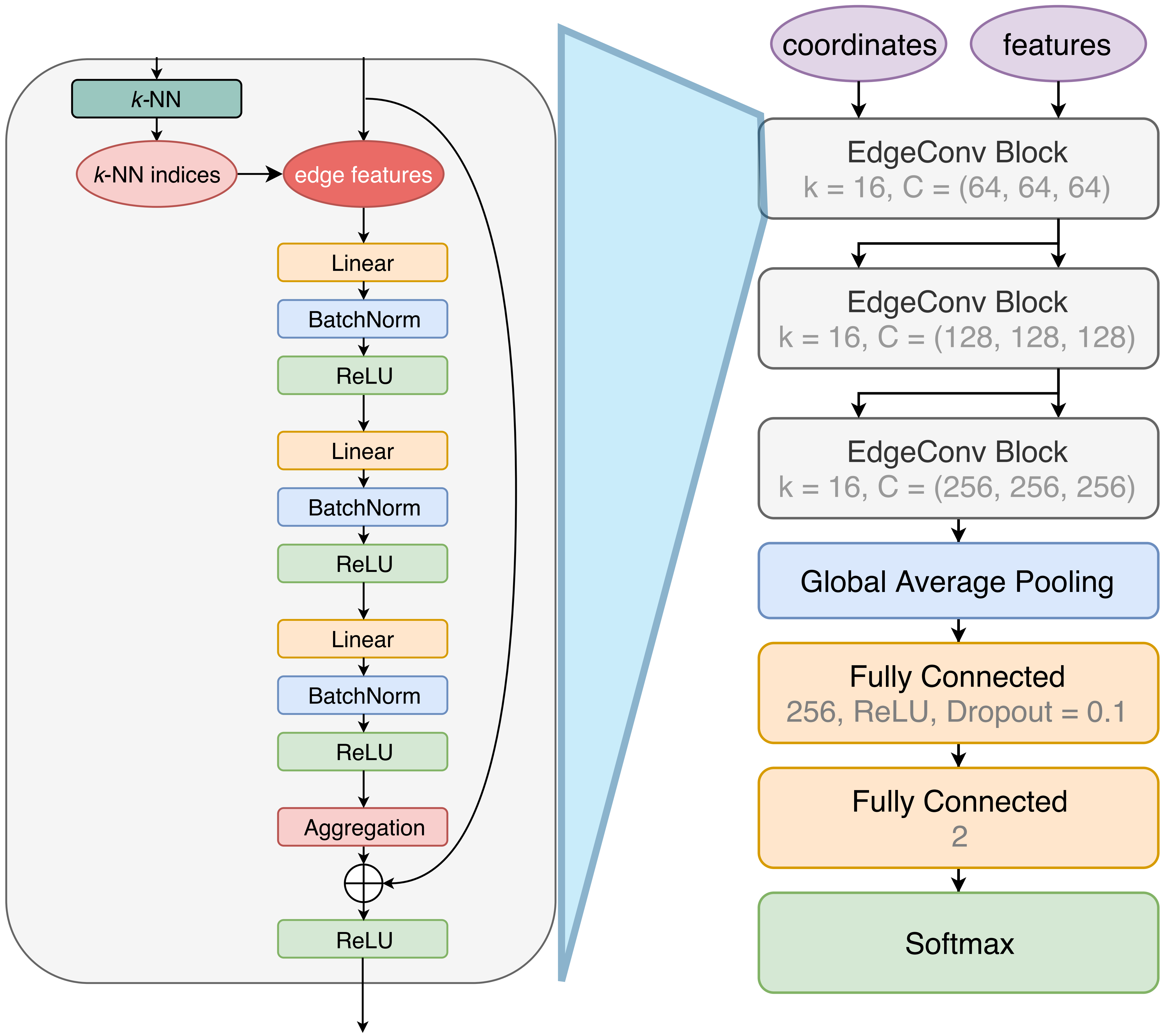

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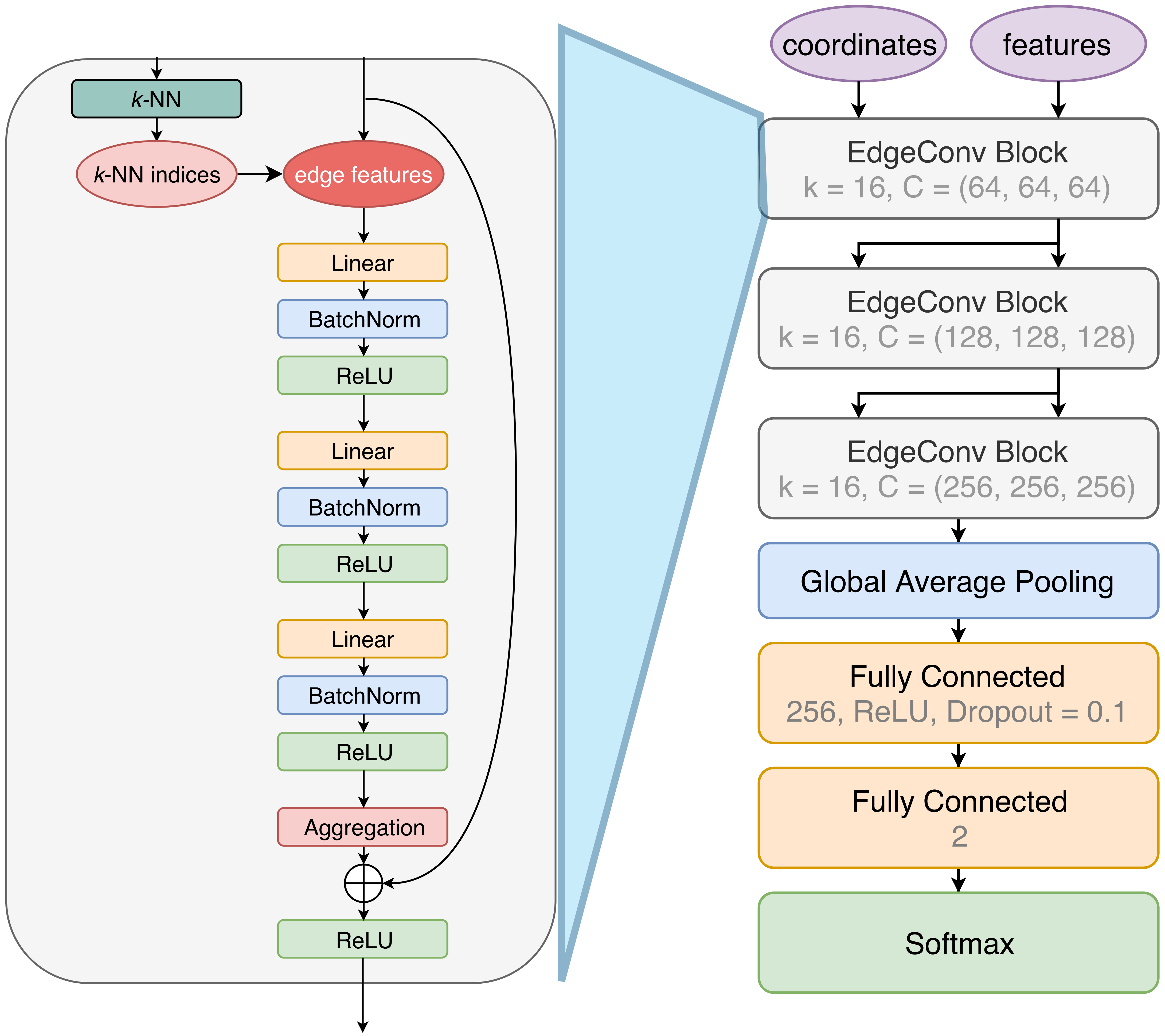

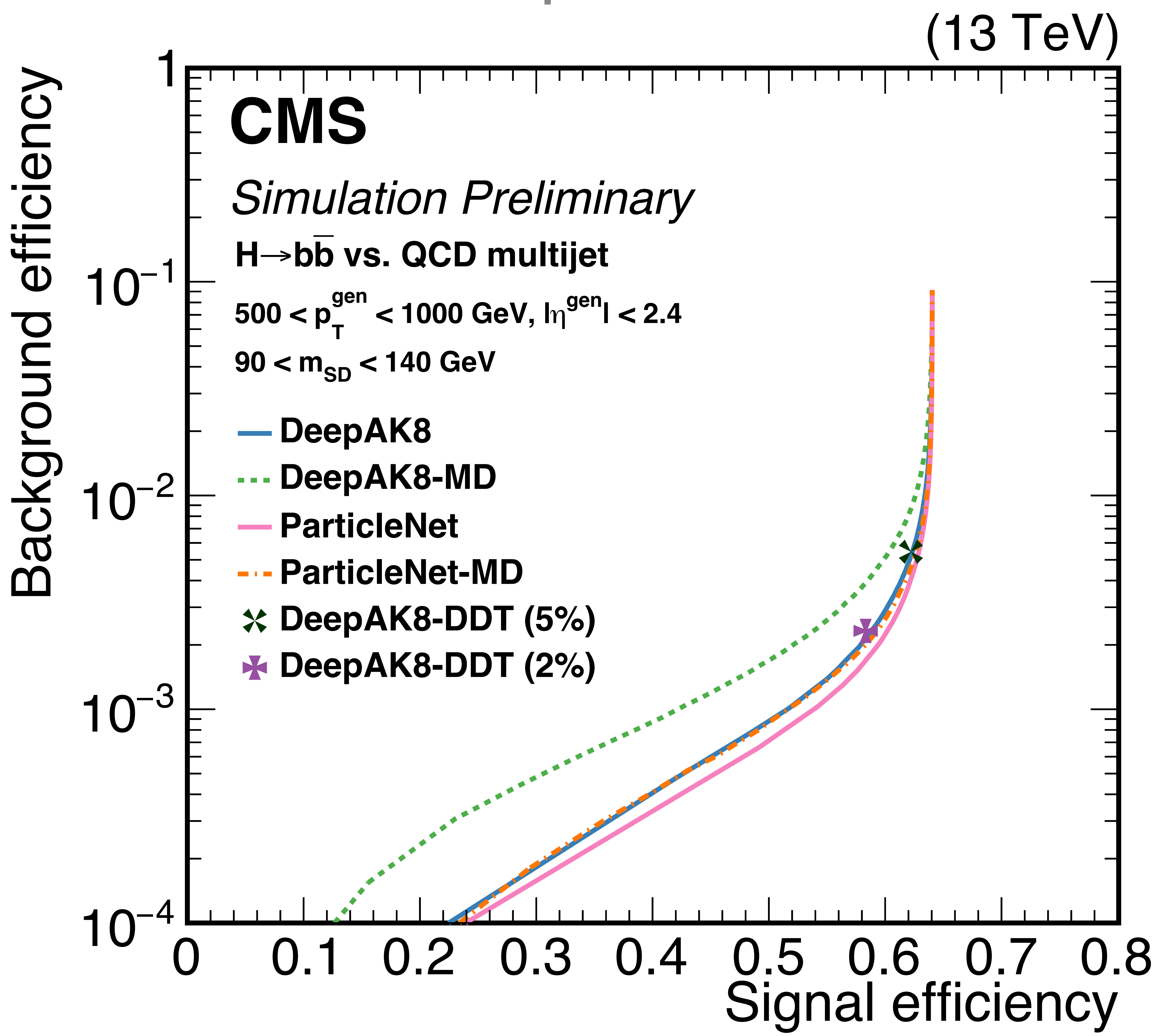

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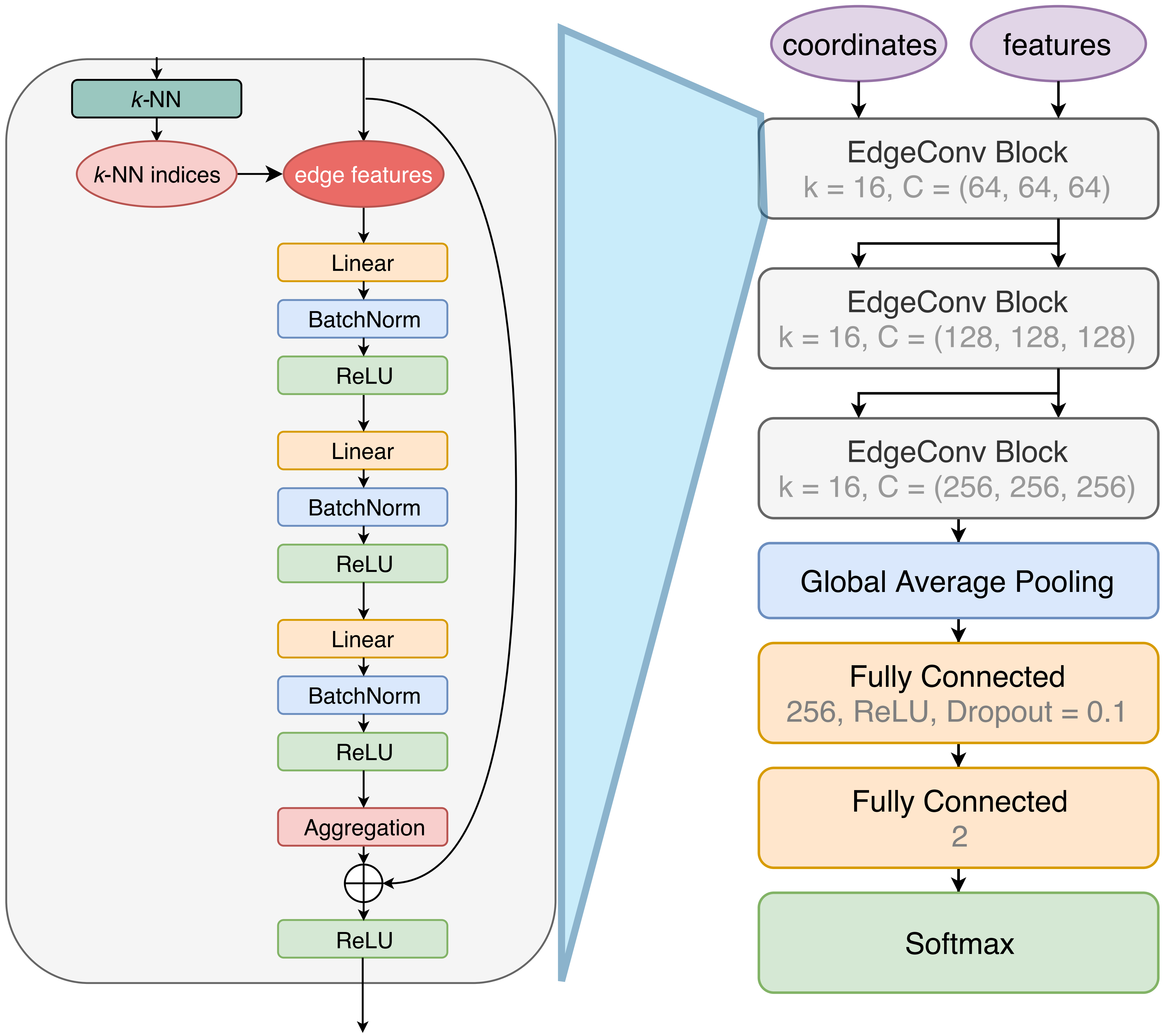
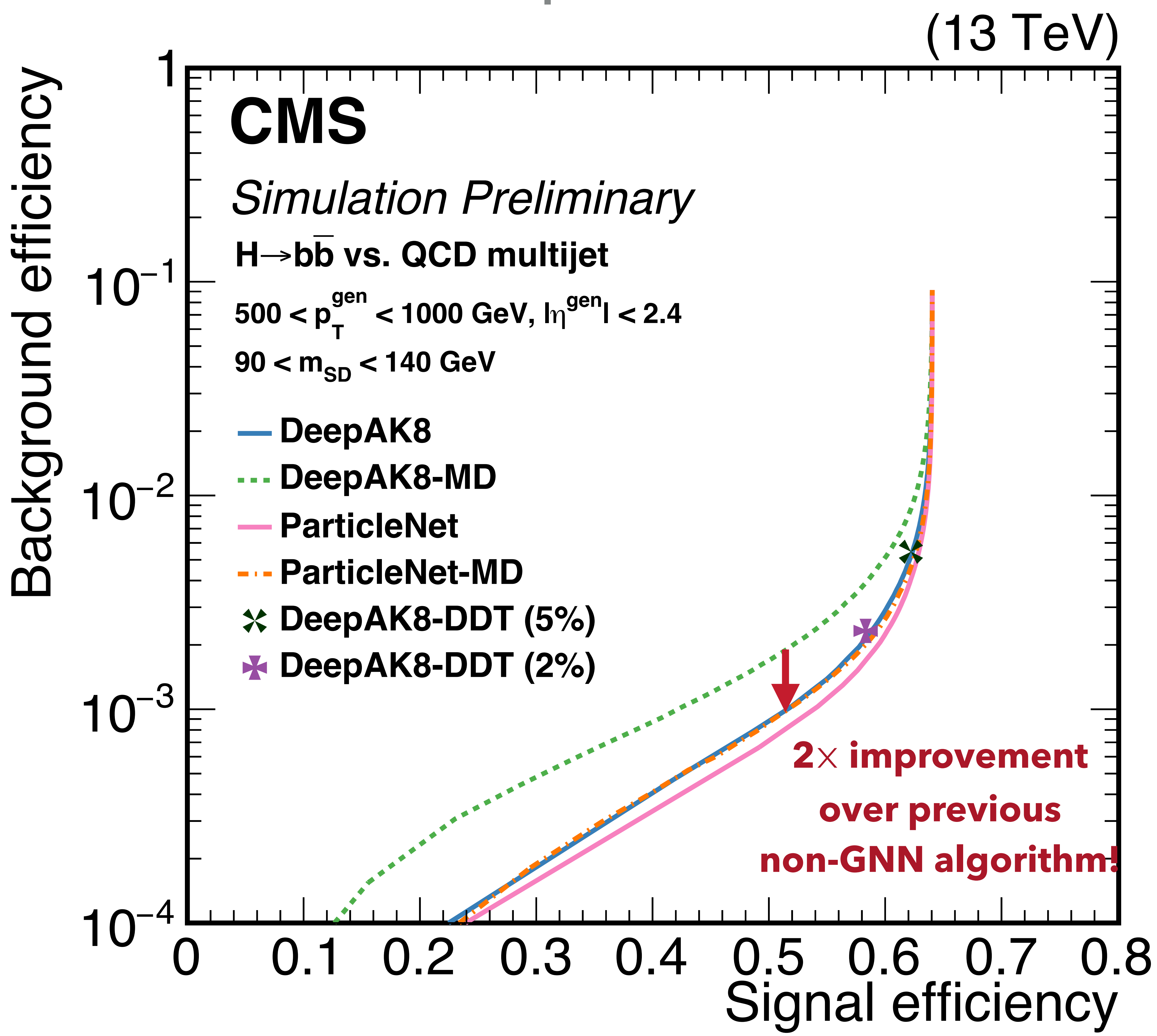
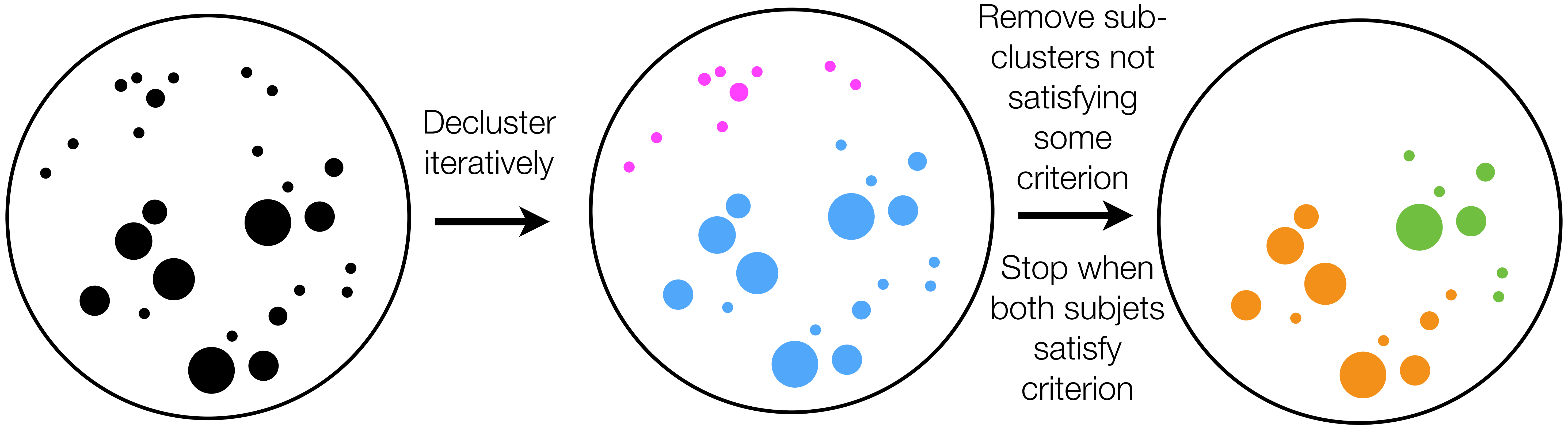


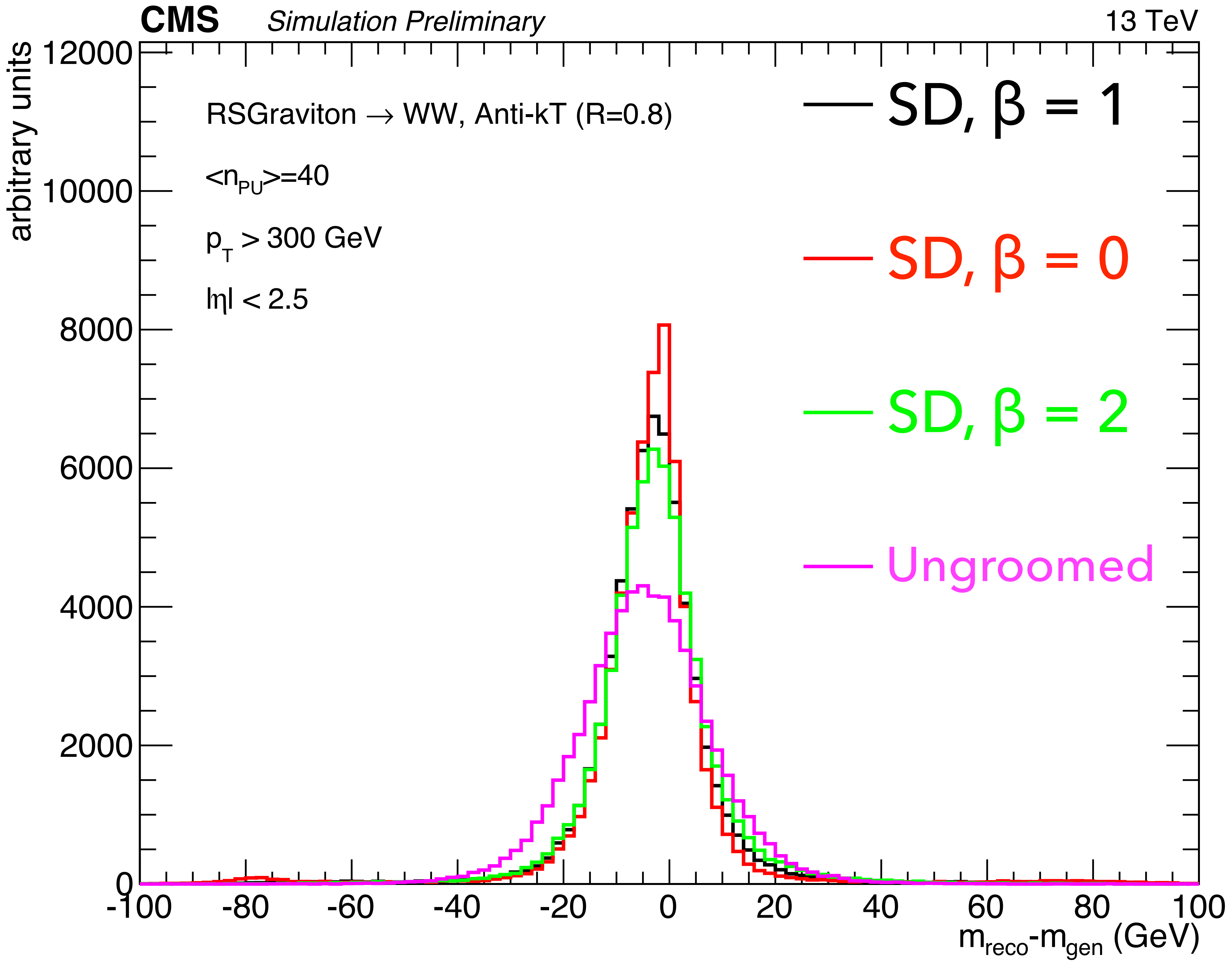


BEYOND JET TAGGING: JET MASS

arXiv:1307.0007
arXiv:1402.2657



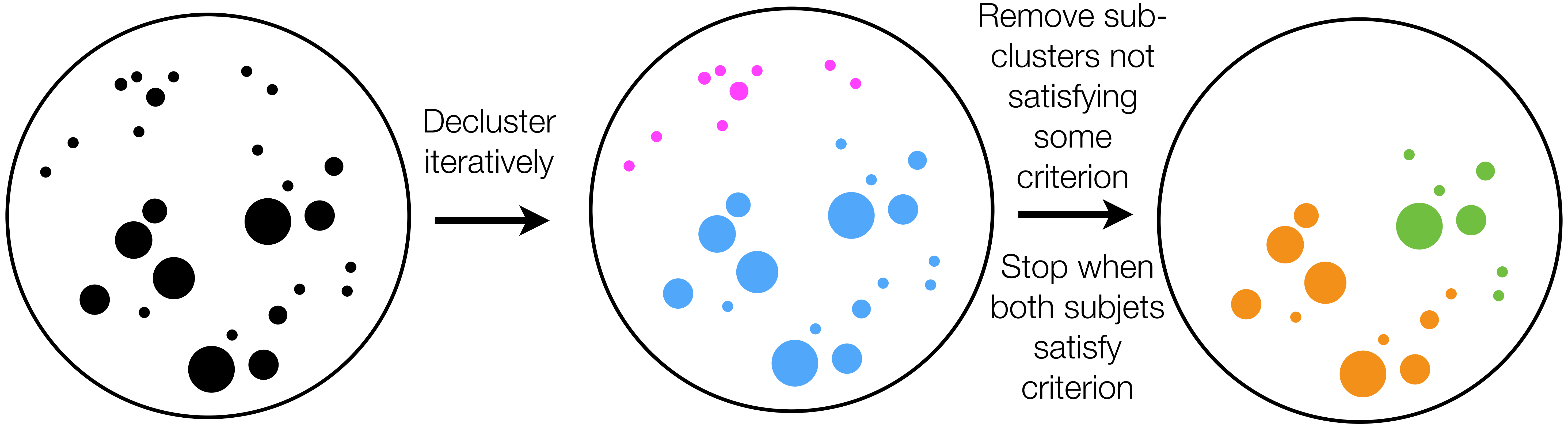
Soft Drop Condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



CMS: $z_{\text{cut}} = 0.1$, $\beta = 0$

BEYOND JET TAGGING: JET MASS

- An important property used to analyze Higgs boson jets is the ***soft drop mass***
  - Grooming removes soft/wide-angle radiation and improves mass resolution



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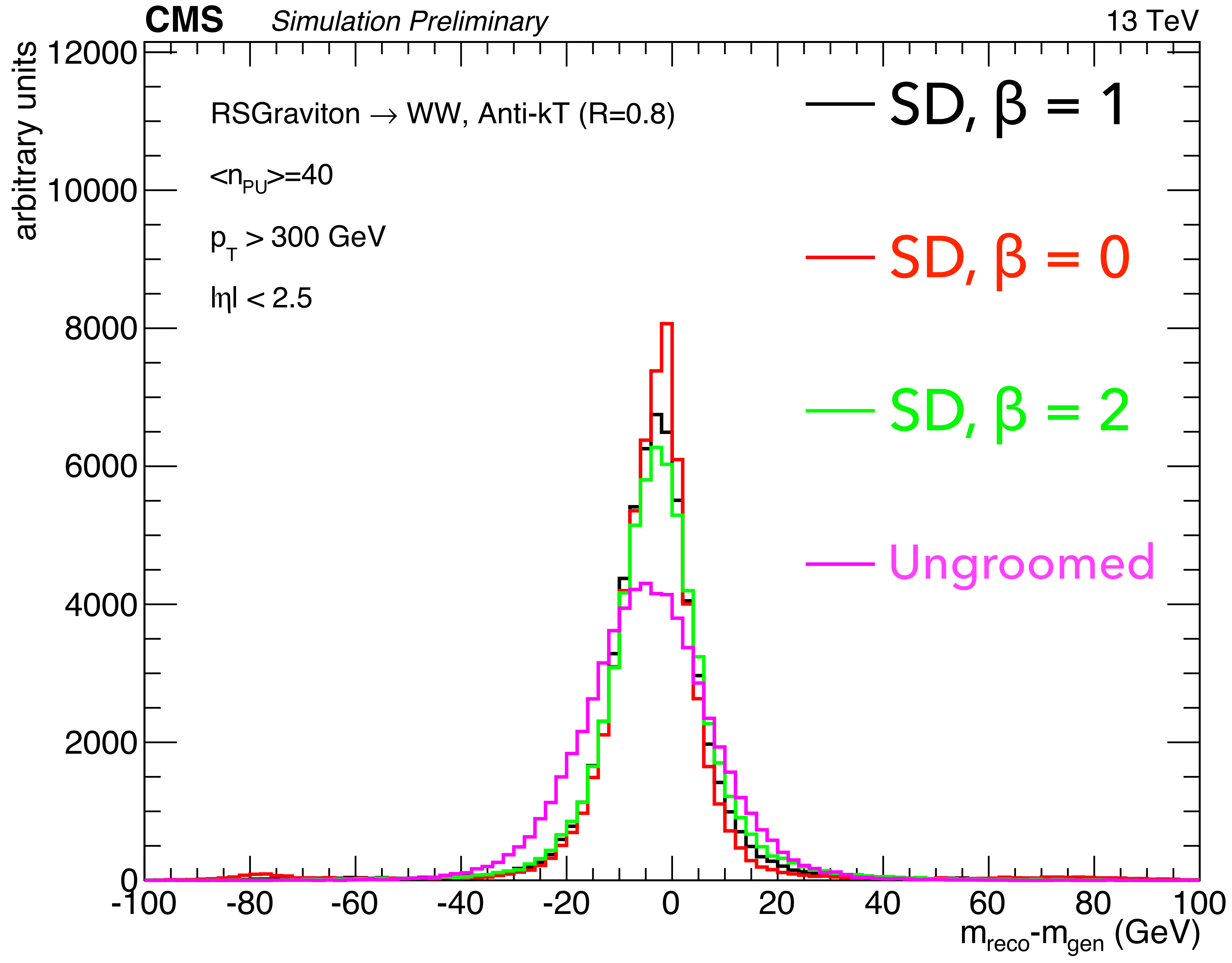

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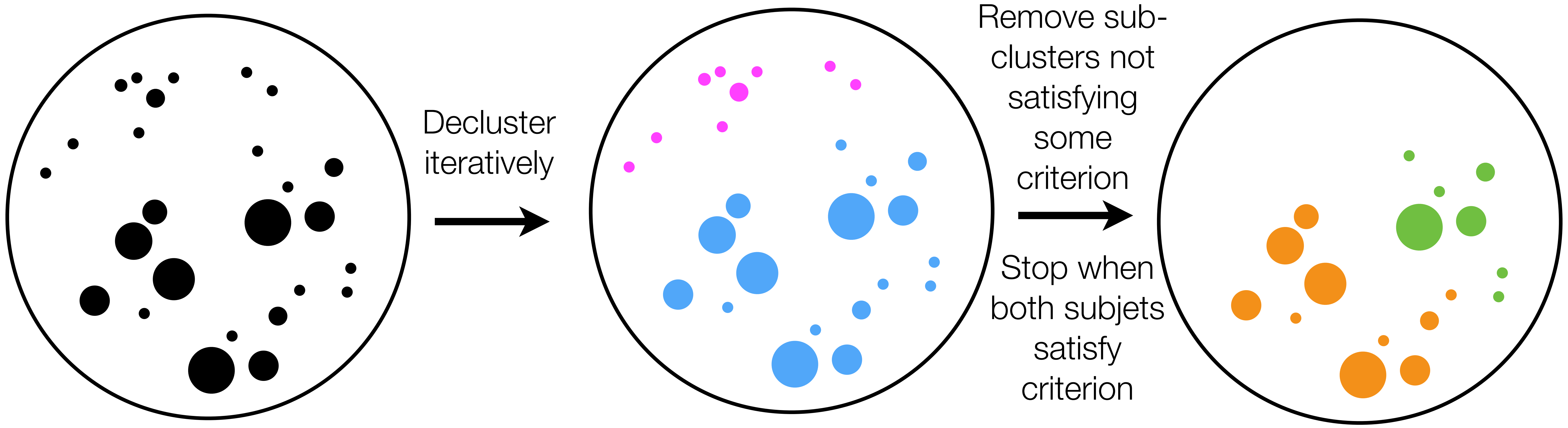
BEYOND JET TAGGING: JET MASS

- An important property used to analyze Higgs boson jets is the ***soft drop mass***
  - Grooming removes soft/wide-angle radiation and improves mass resolution
  - However, grooming can *over-prune* or *under-prune*
  - Can we do better with ML?



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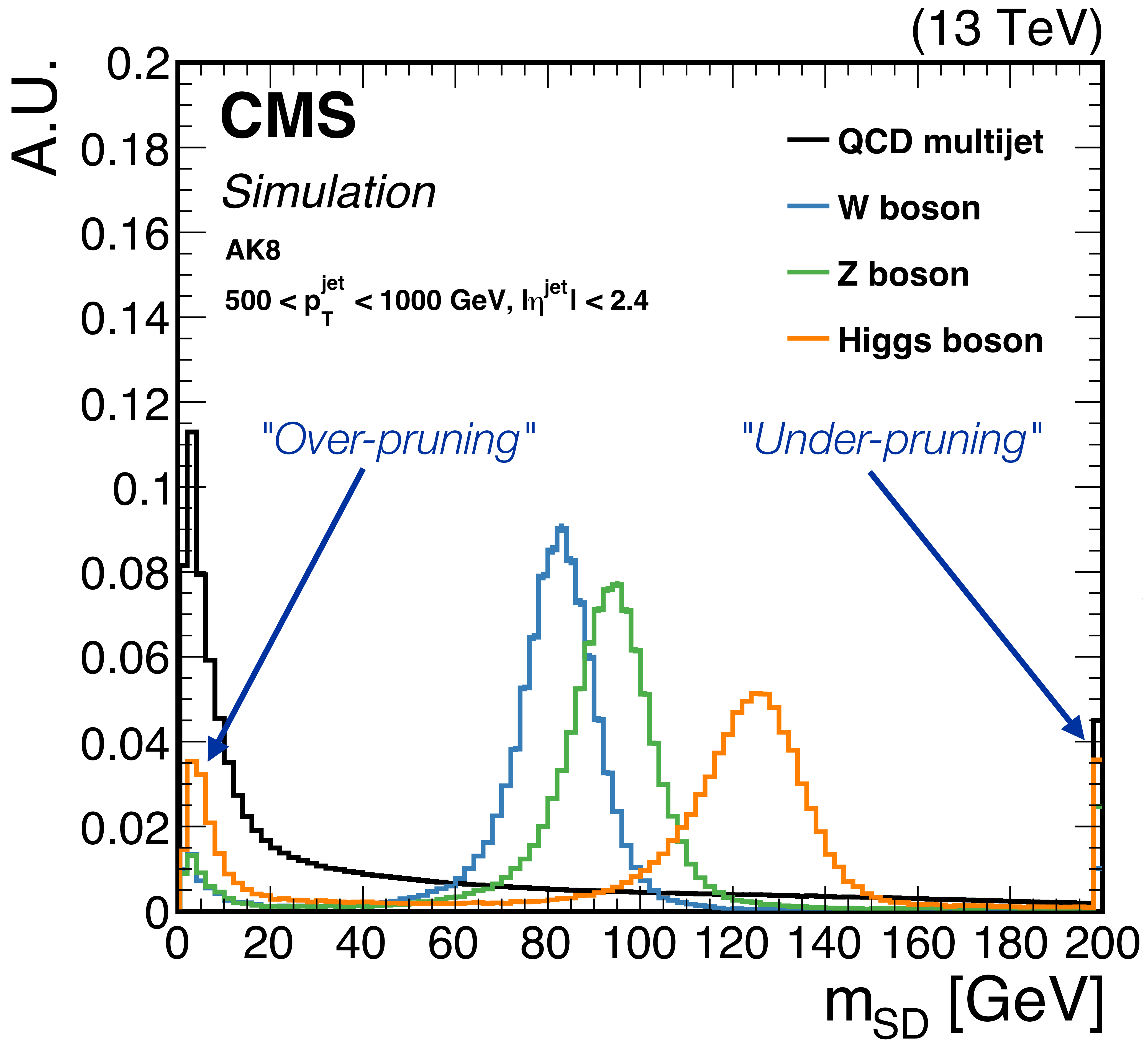

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- Training samples incorporate $X \to bb$, $X \to cc$, $X \to qq$ varying $m_X \in [15, 250]$ GeV

$$m_{\text{target}} = \begin{cases} m_{\text{SD}}^{\text{gen}} & \text{if jet is QCD} \\ m_{\text{X}} & \text{otherwise} \end{cases}$$

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- Minimize difference between output m_{reg} and target m_{target}

GNN FOR MASS REGRESSION IN CMS

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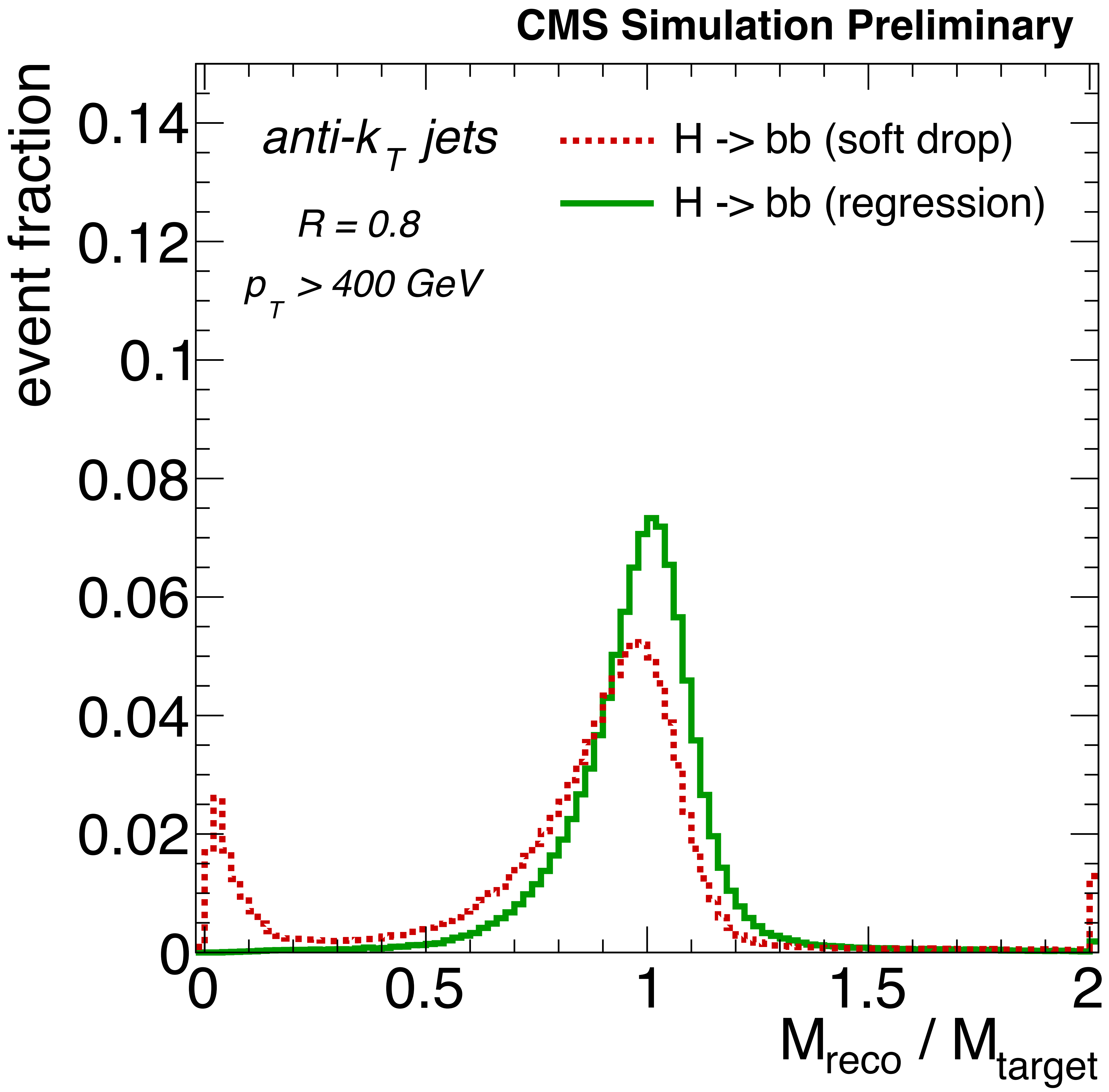
- Training samples incorporate X→bb, X→cc, X→qq varying $m_X \in [15, 250]$ GeV

$$m_{\text{target}} = \begin{cases} m_{\text{SD}}^{\text{gen}} & \text{if jet is QCD} \\ m_X & \text{otherwise} \end{cases}$$

- Minimize difference between output m_{reg} and target m_{target}
- Substantial scale and resolution improvement



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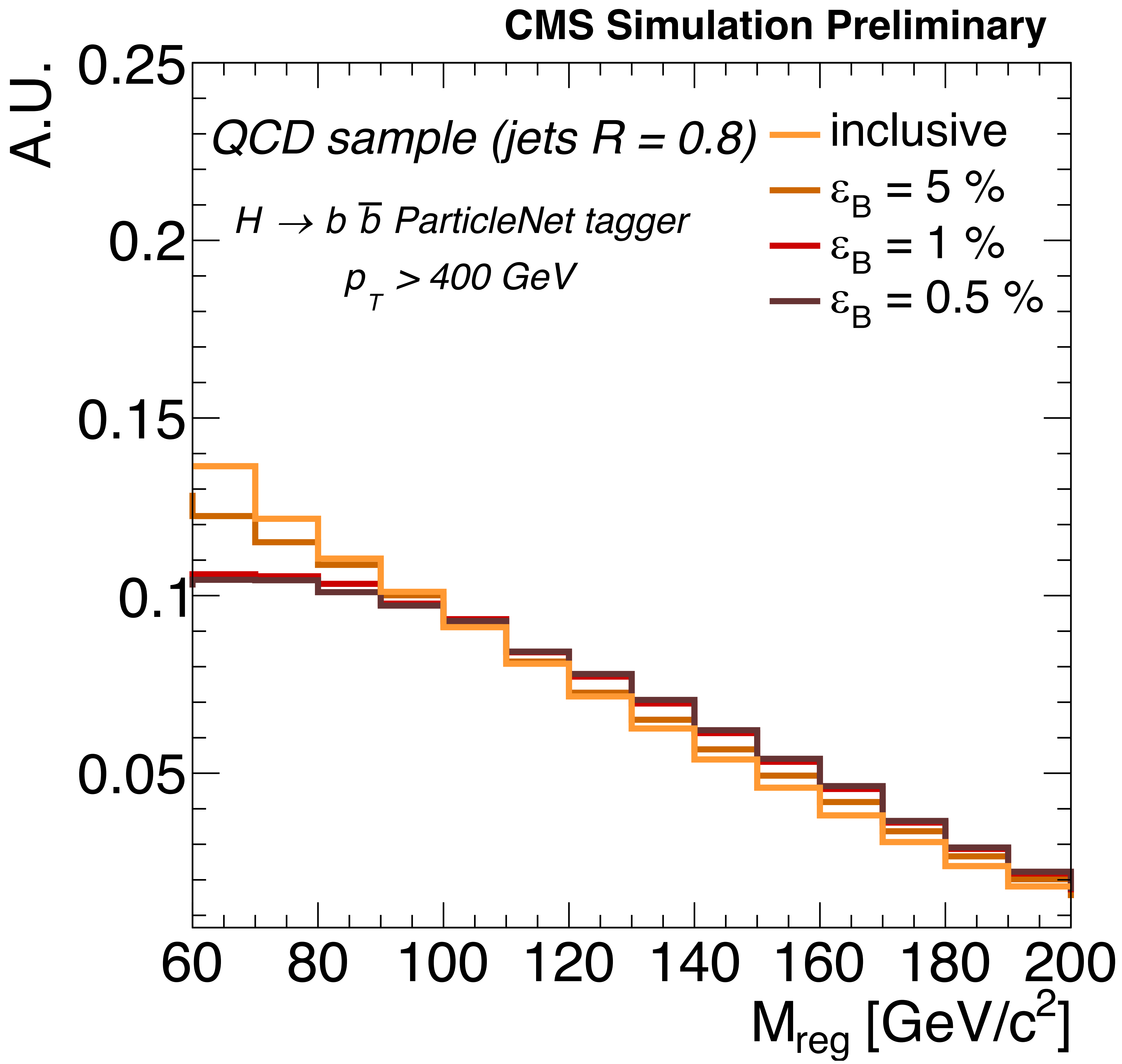
- No significant mass sculpting near m_H = 125 GeV for QCD background



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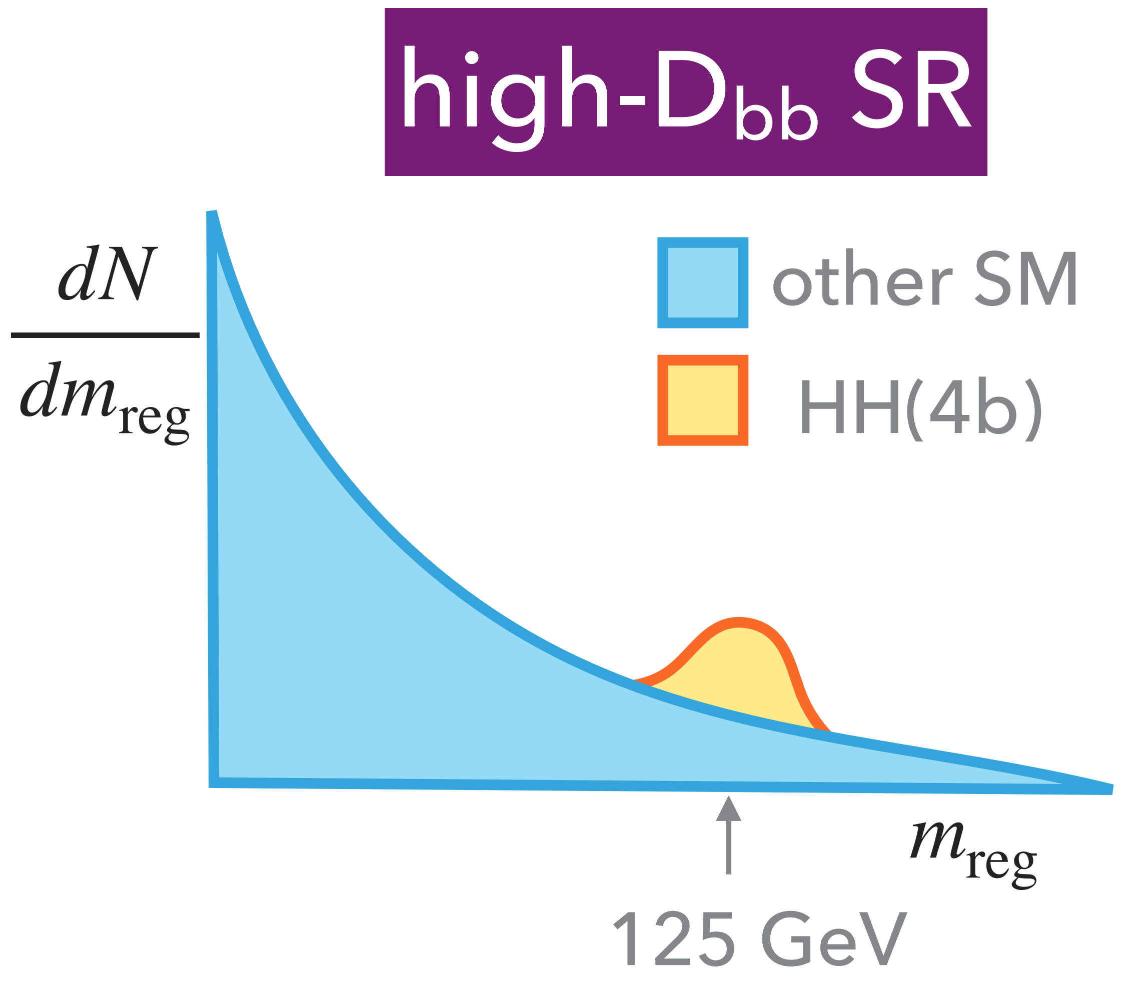

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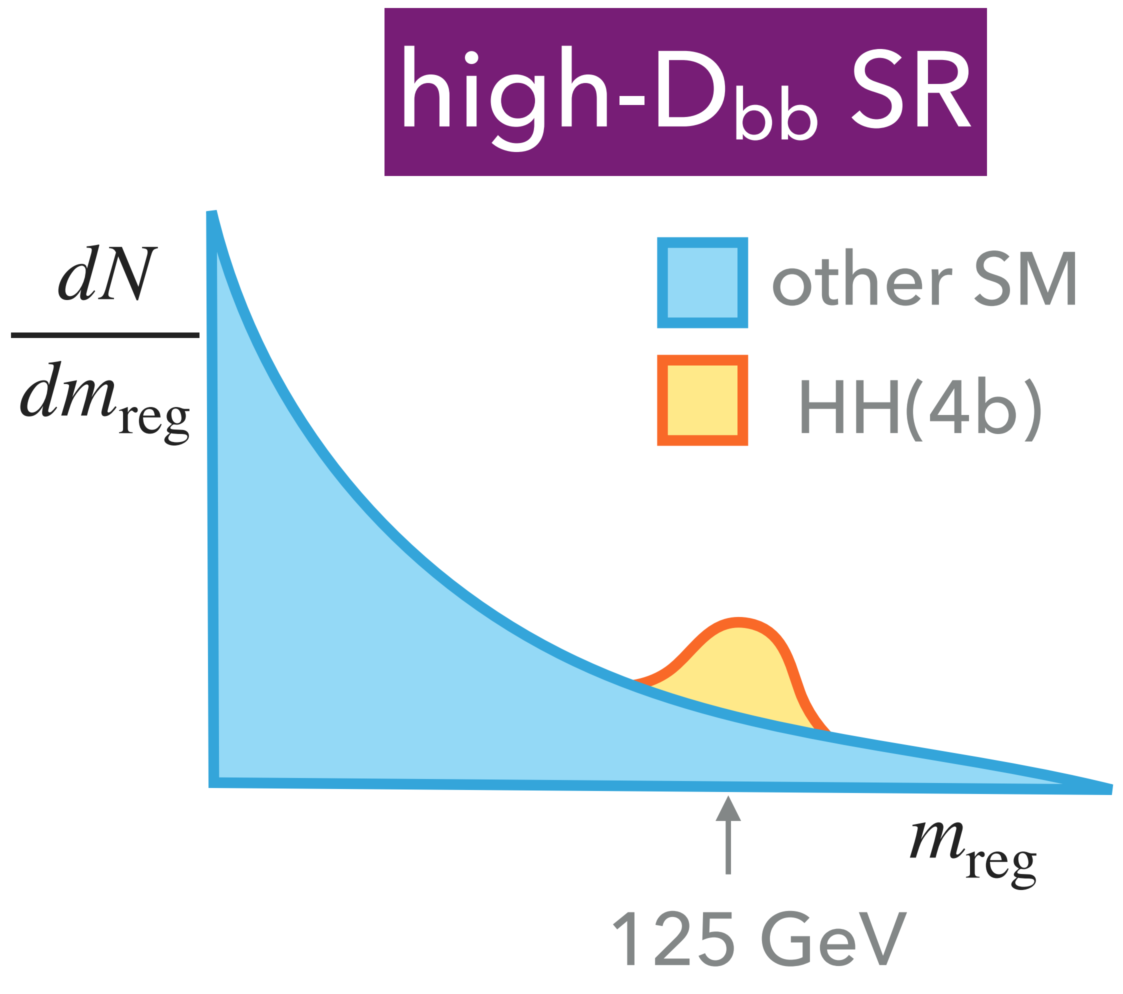

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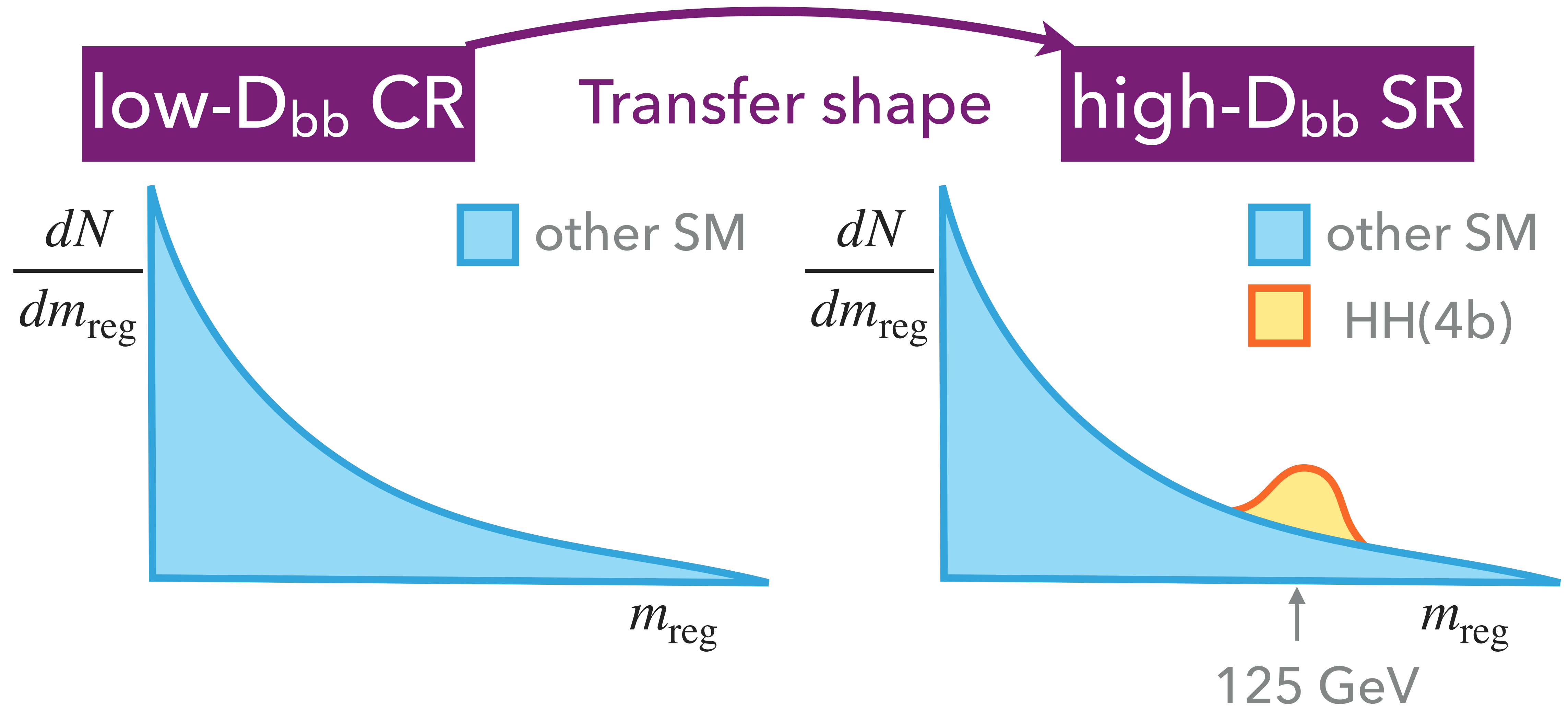

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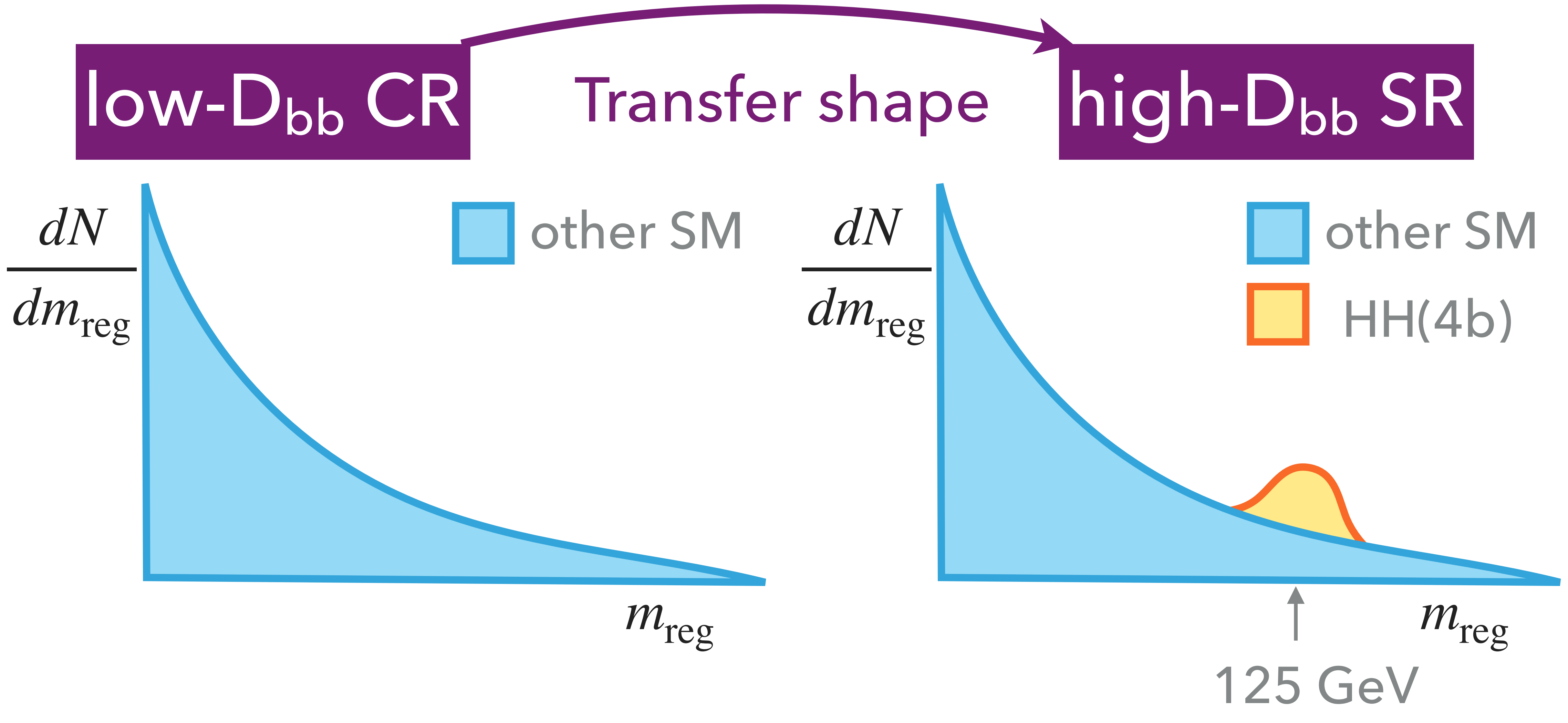
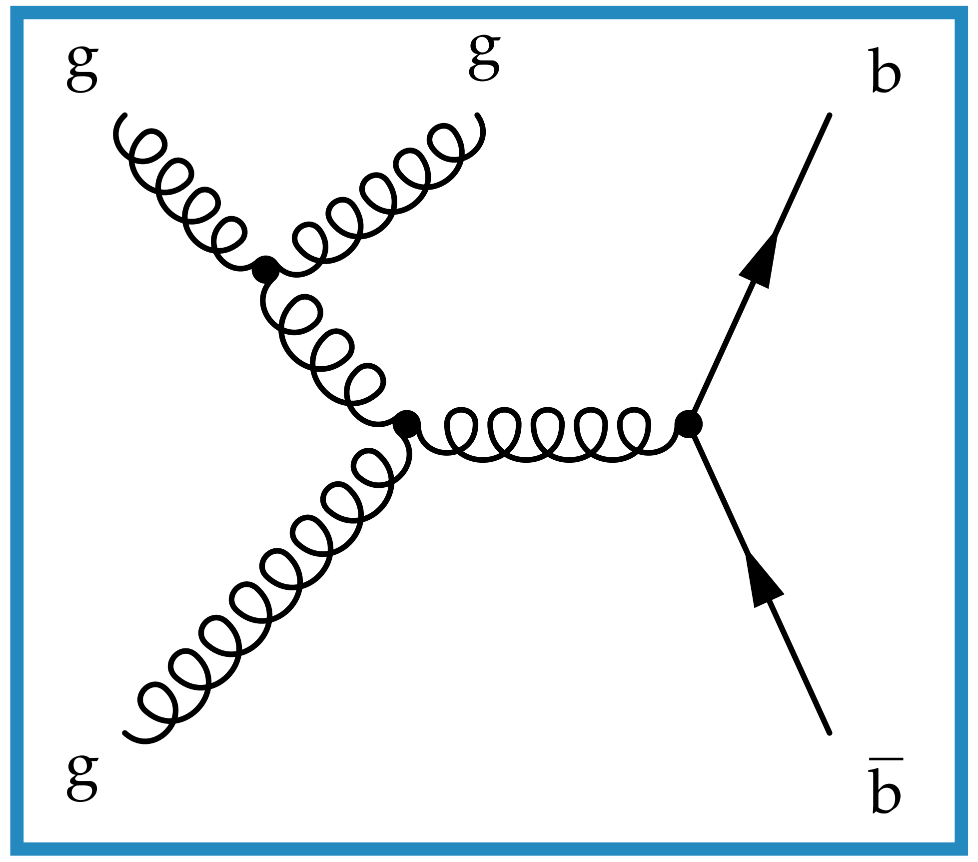
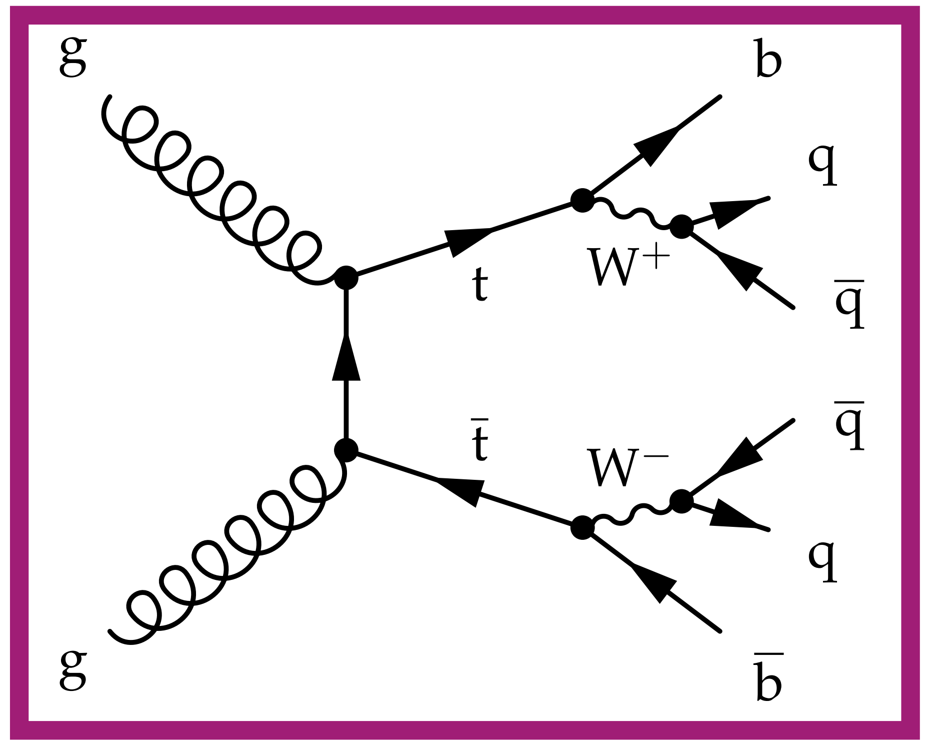
- Main backgrounds:



QCD

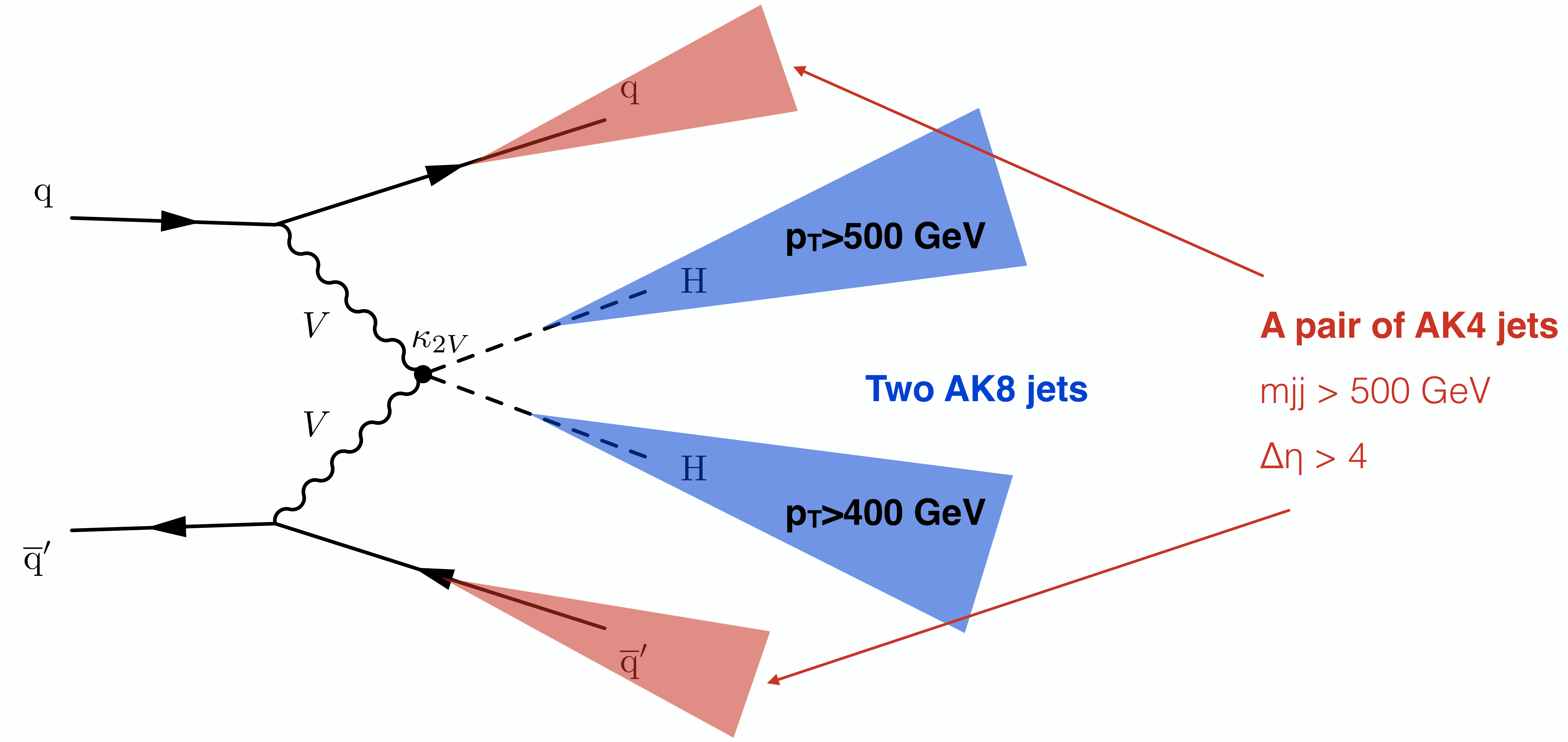


tt+jets



VBF: KINEMATIC SELECTON

- Two AK8 jets and two AK4 jets with $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 4$
  - Tight kinematic selection means we need **maximal** H identification efficiency



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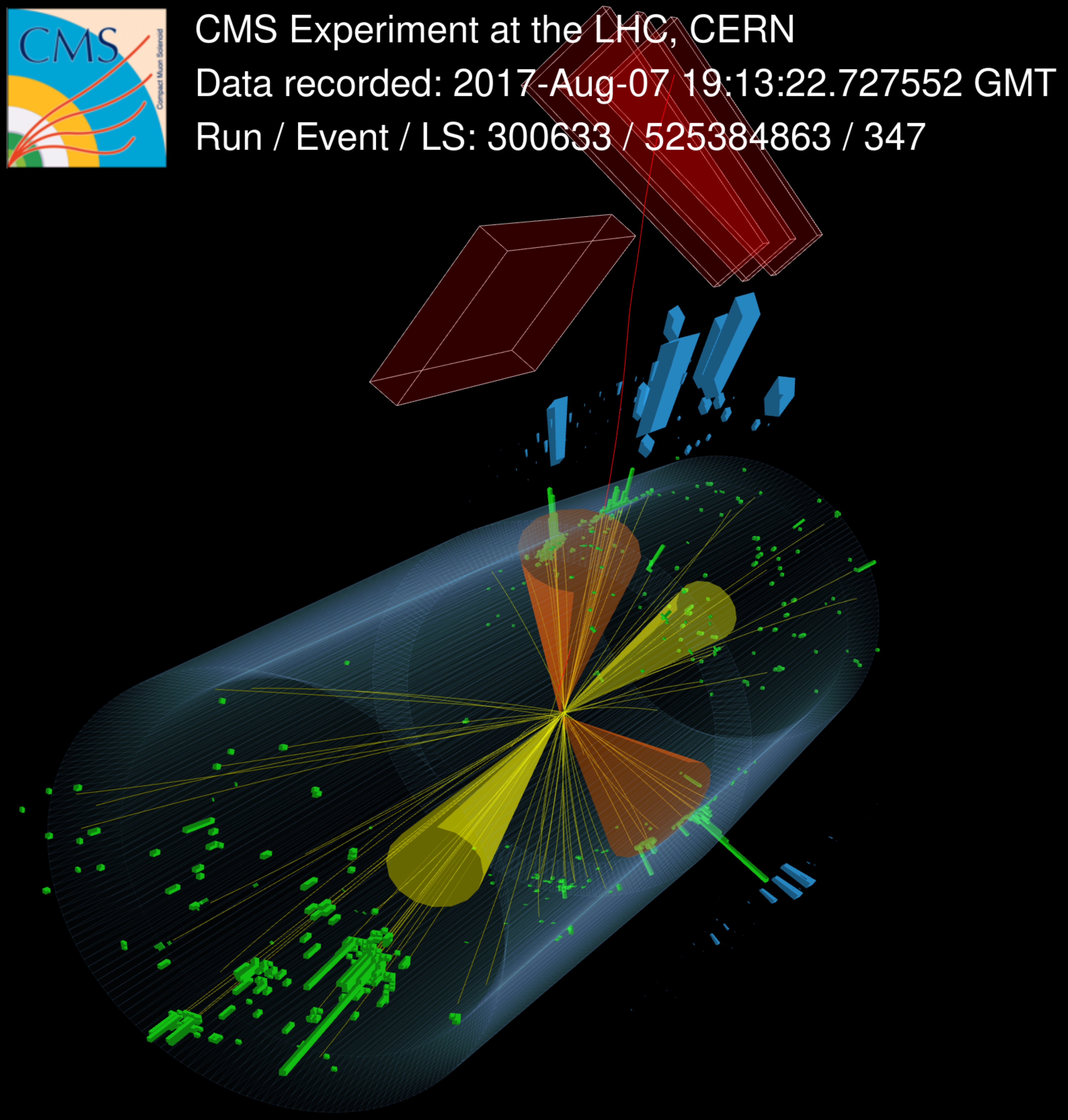

VBF: EVENT CATEGORIZATION

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- Three D_{bb} working points (WPs)
  - **Tight** WP: ε_S~60%, ε_B~0.3%
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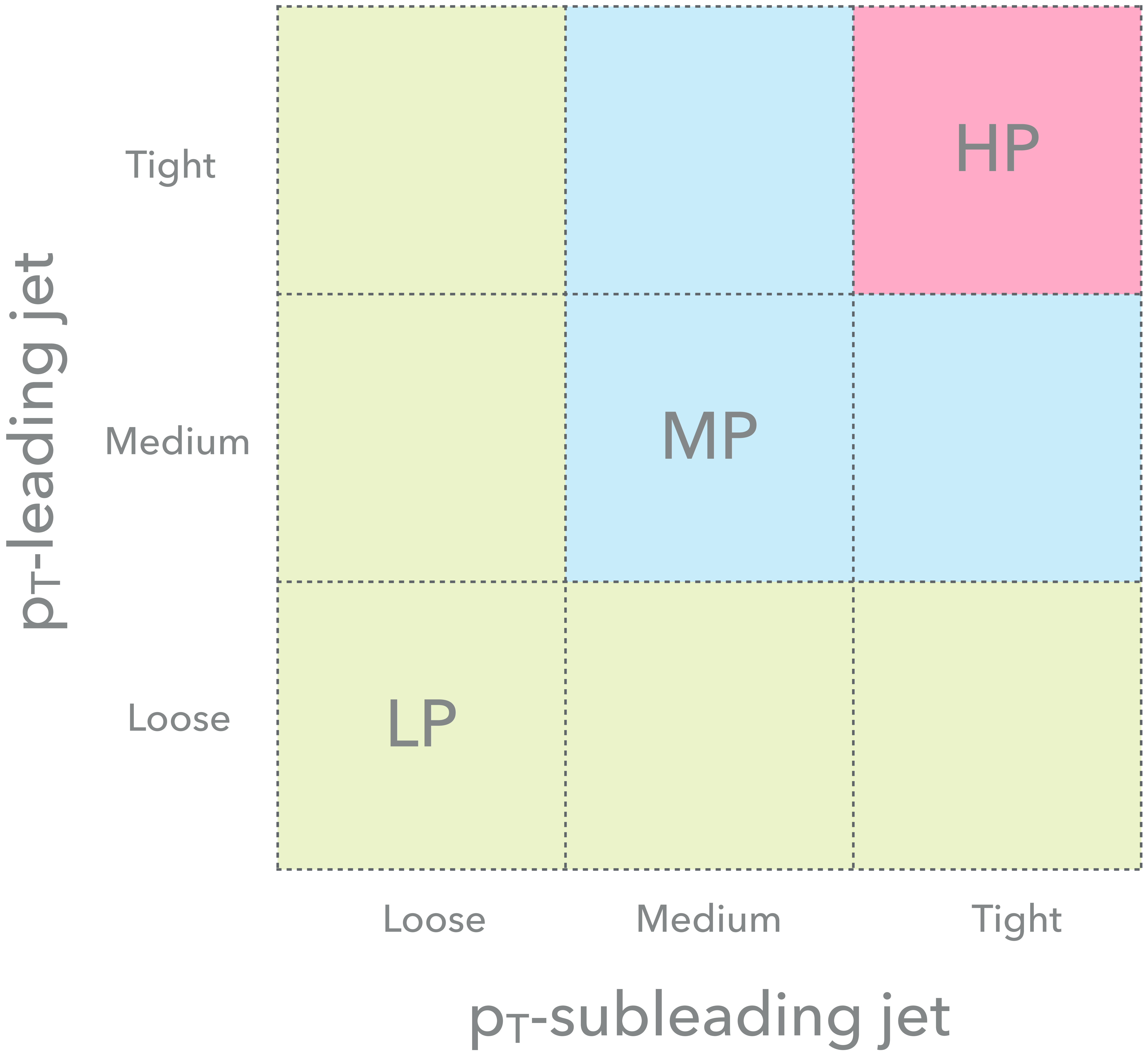
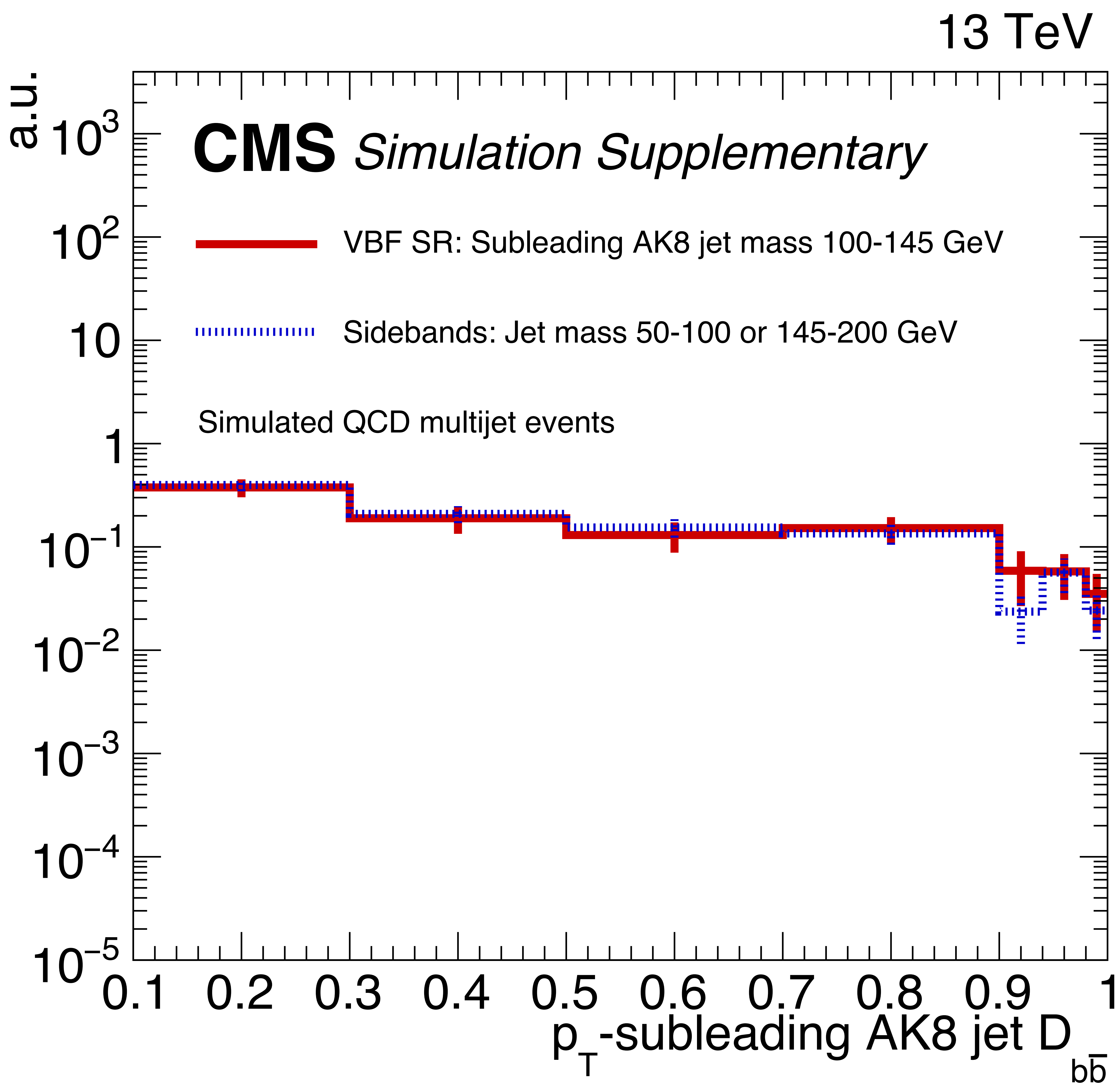
- Three exclusive regions based on WPs:
  - **High Purity (HP)**: Both Higgs candidate jets pass **tight** WP
  - **Medium Purity (MP)**: Both pass **medium** WP, but not tight WP
  - **Low Purity (LP)**: Both pass **loose** WP, but not medium WP



VBF: ESTIMATION OF THE BACKGROUND



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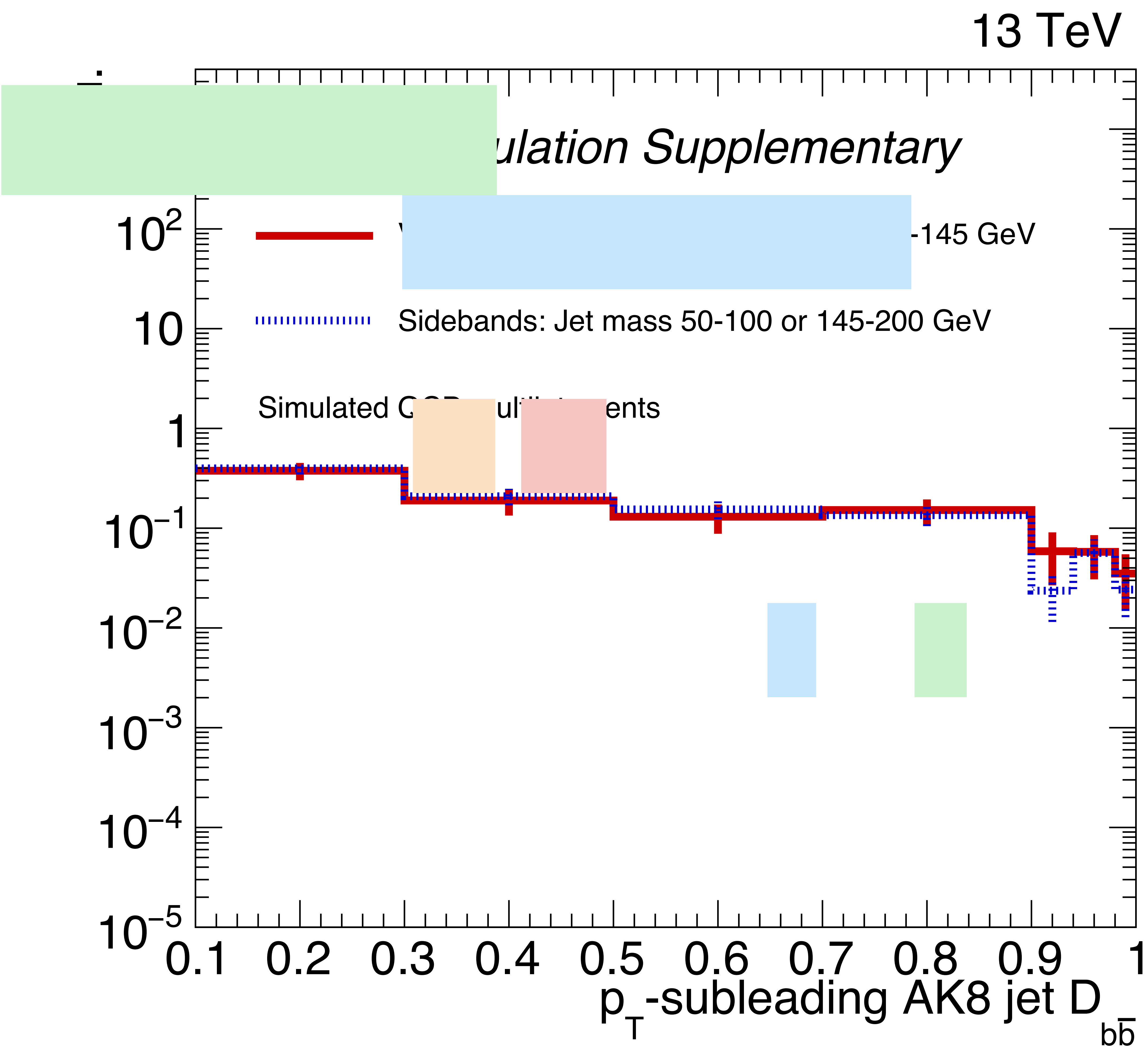

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- Key observation: D_{bb} score for QCD similar in sidebands and in search region
- ABCD method to estimate QCD background in search region D
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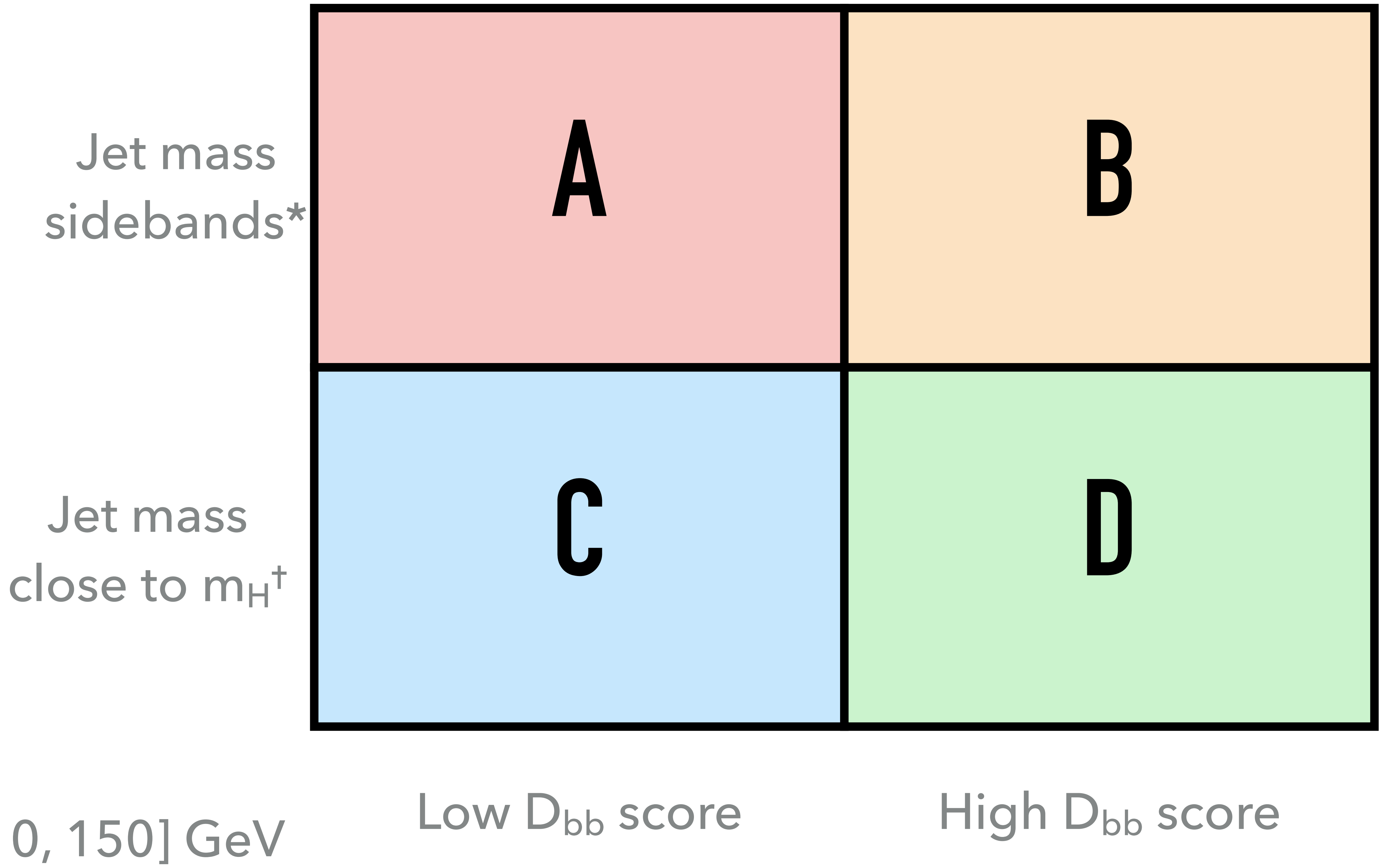

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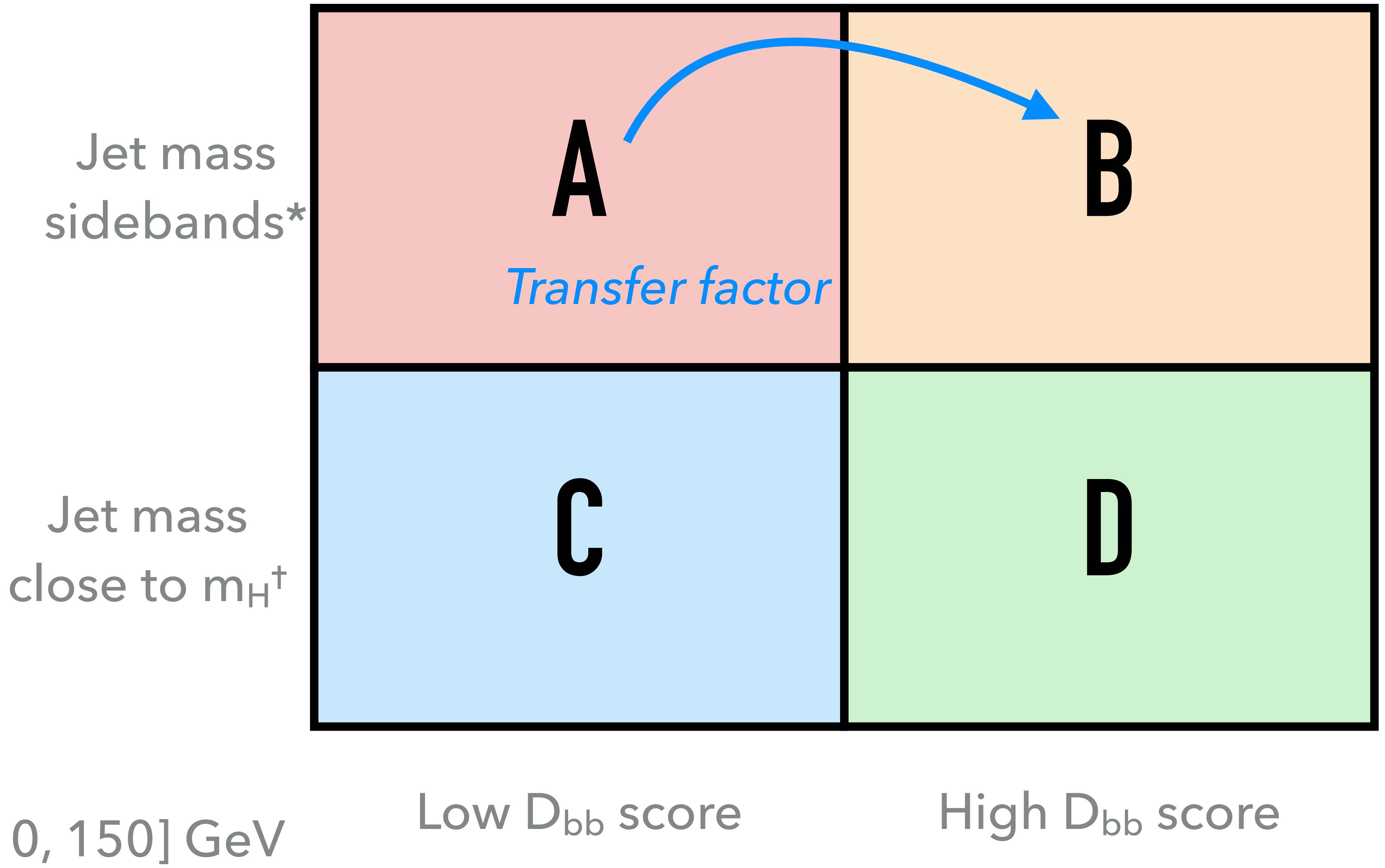
$$\left(\frac{N_B}{N_A}\right)$$



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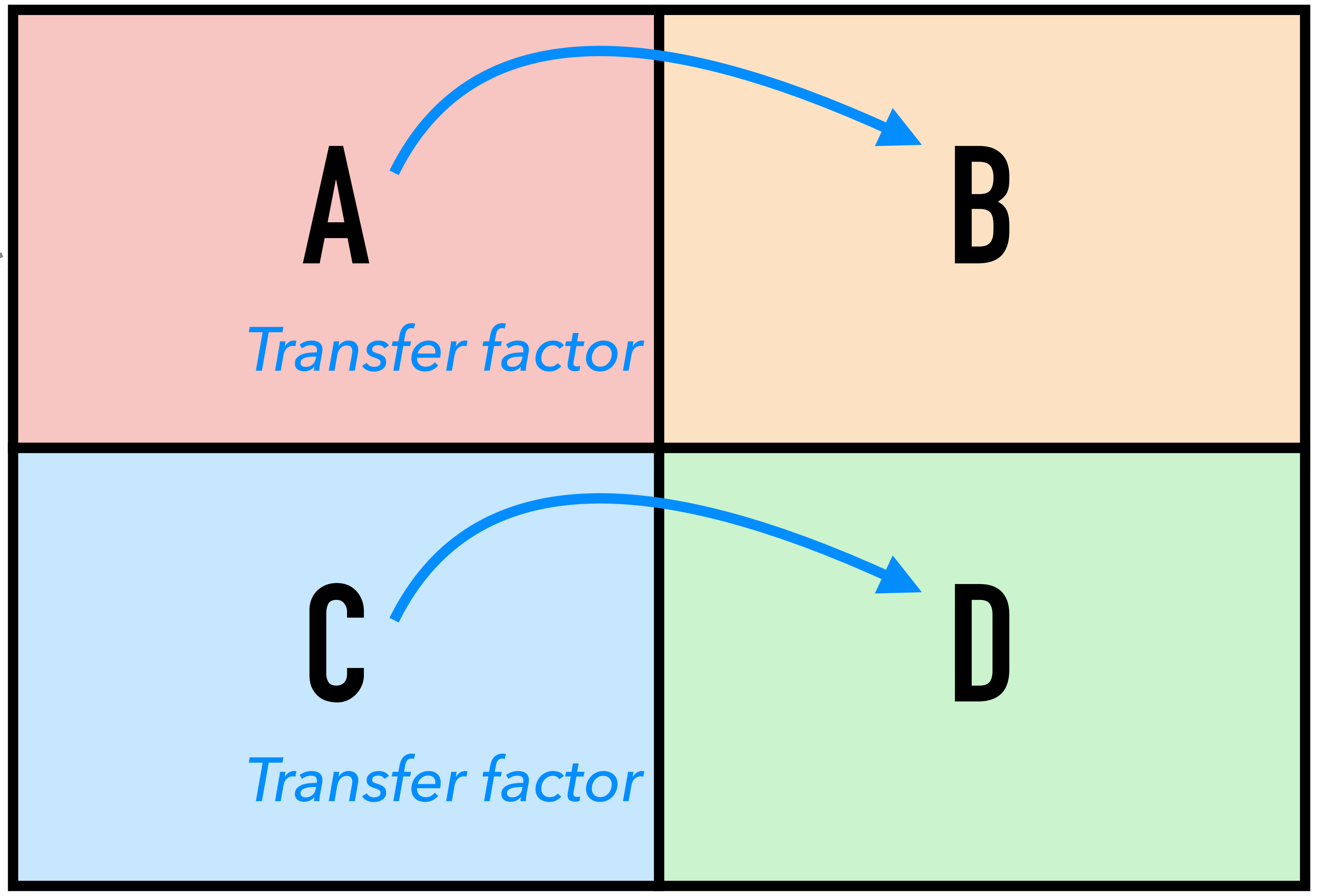
- TF applied to predict from C to D

$$N_D = \left(\frac{N_B}{N_A}\right) N_C$$

Jet mass sidebands*

Jet mass close to m_H†



Low D_{bb} score High D_{bb} score

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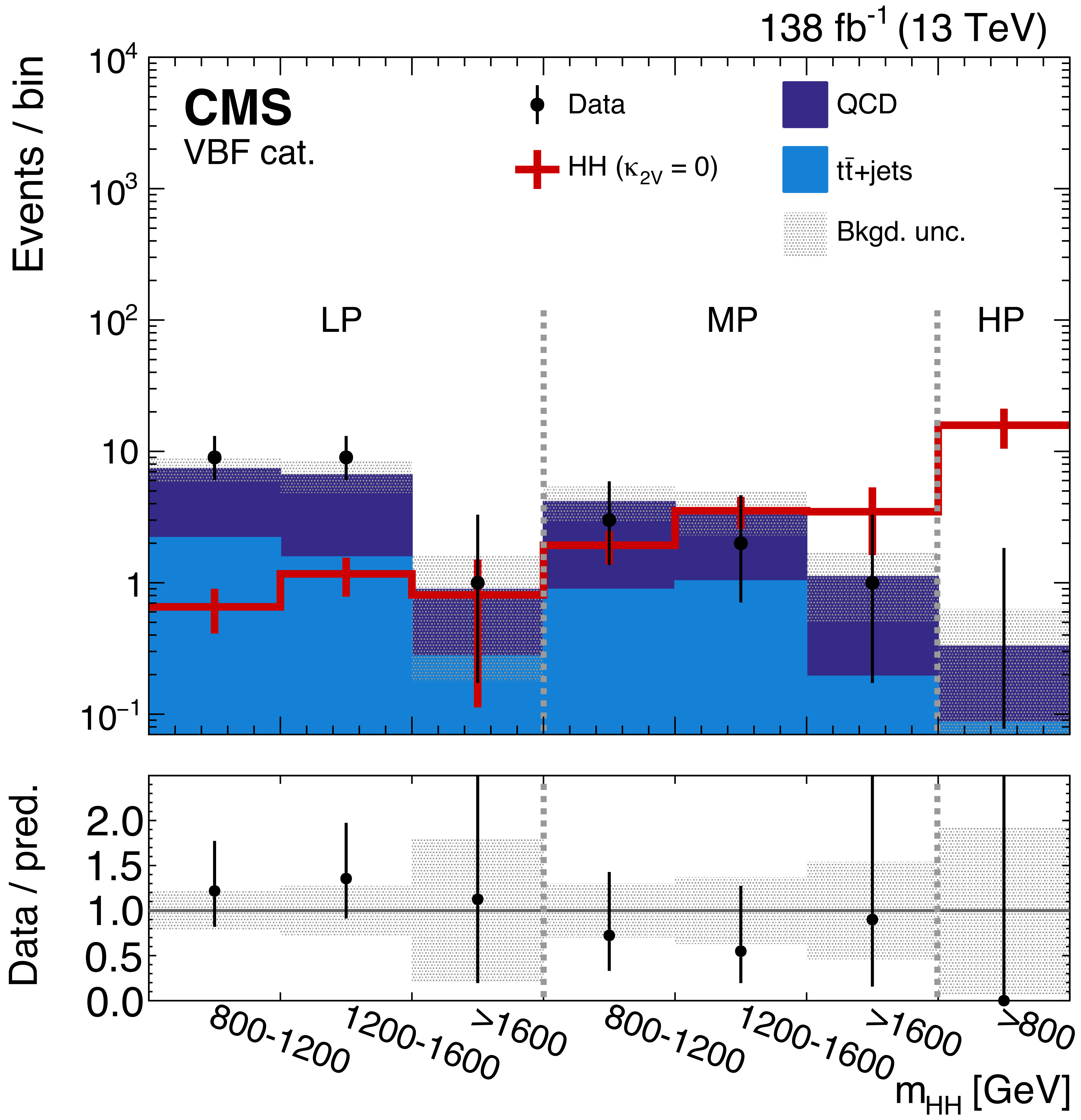
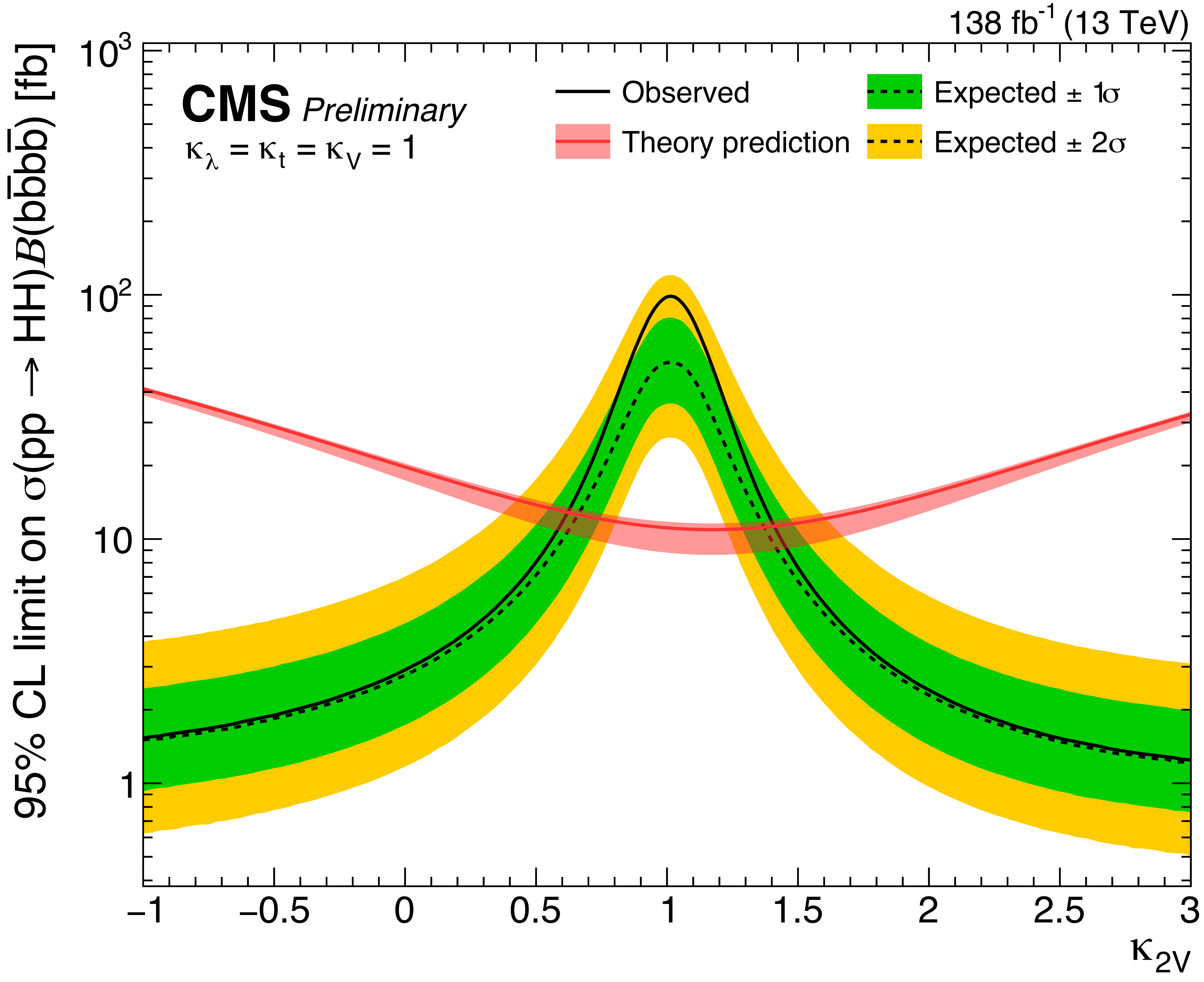
VBF: FIT RESULTS

- Three categories (LP, MP, HP) based on the D_{bb} discriminant of the H candidates
  - Categorize further in m_{HH}
- Data-driven QCD estimate
- Prediction agrees with observed data
  - Compare to expected contribution for $\kappa_{2V} = 0$ (other couplings at SM values)



HHVV COUPLING INTERPRETATION



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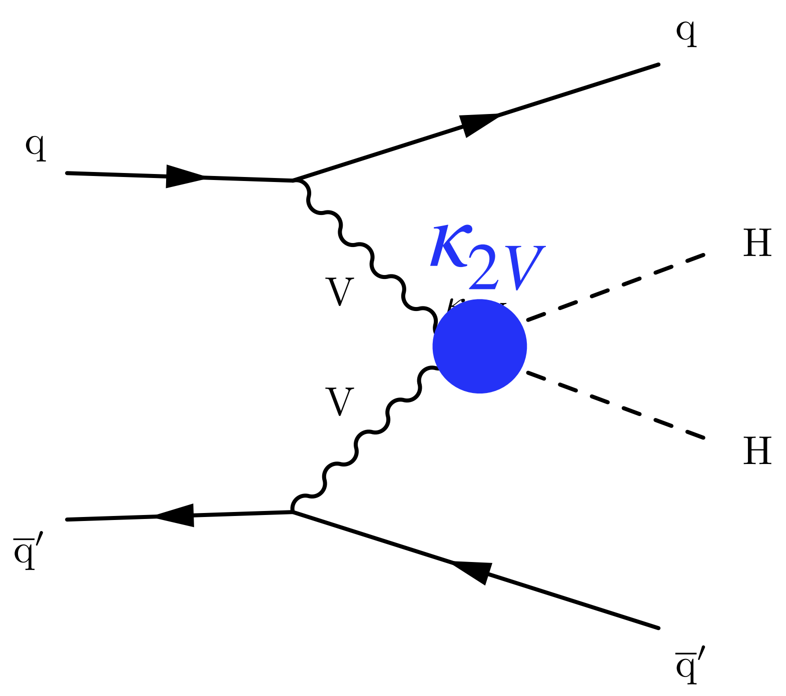
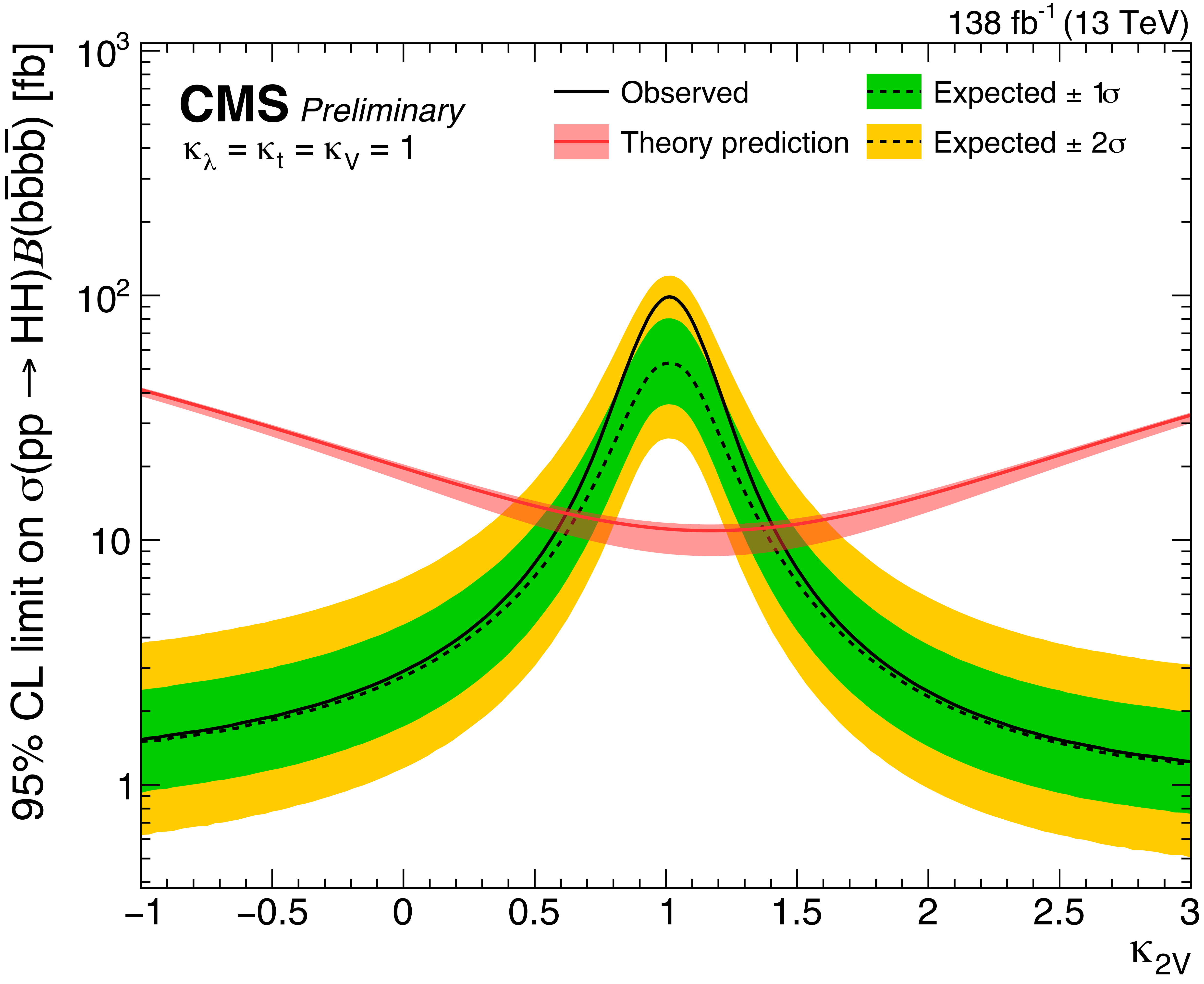
- ***Strongest constraints on κ_{2V} to date***: $0.62 < \kappa_{2V} < 1.41$ at 95% CL (all other couplings are SM)





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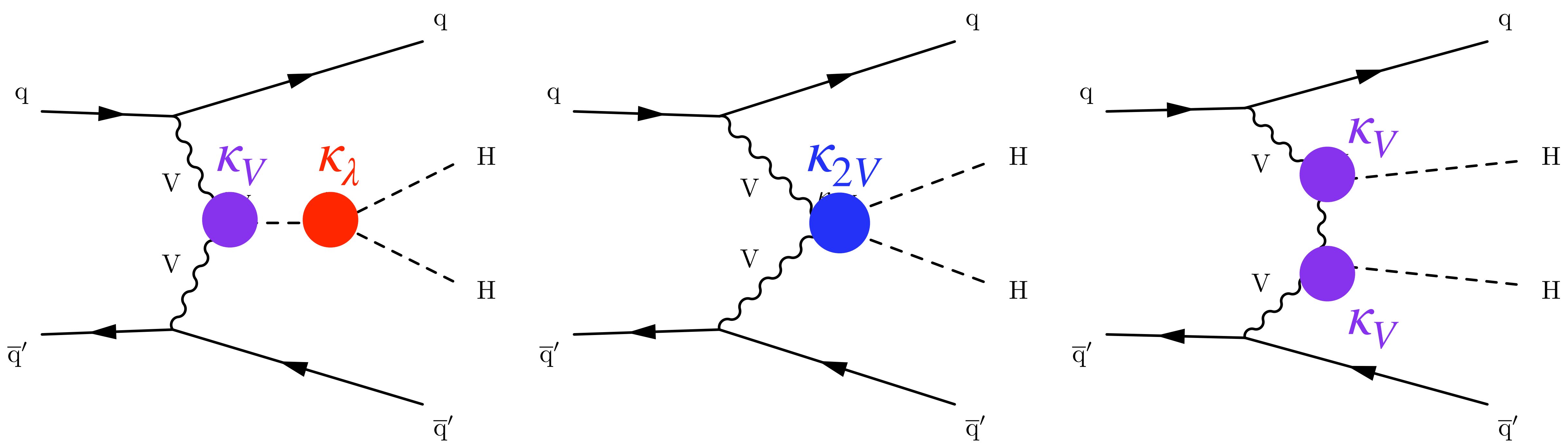

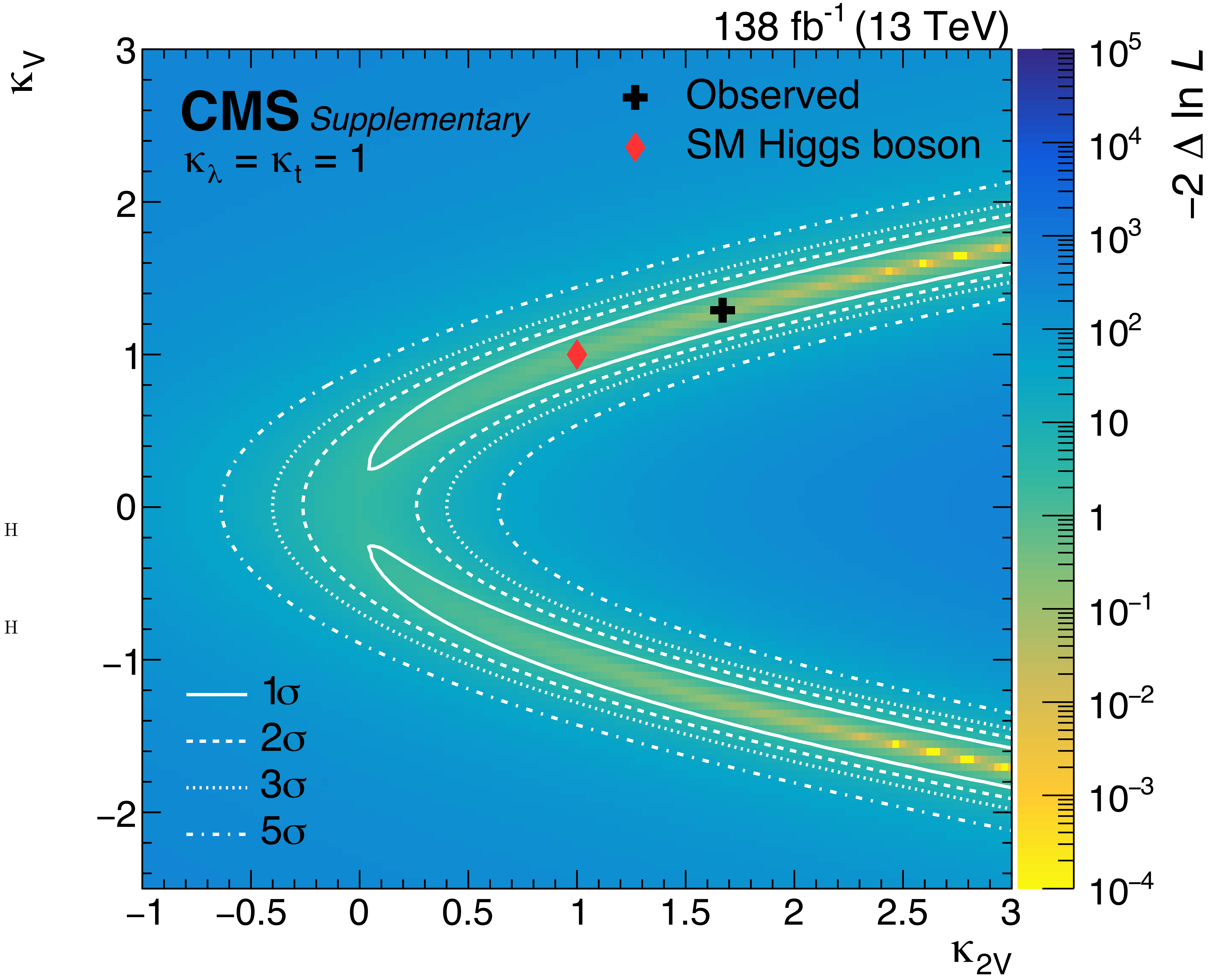

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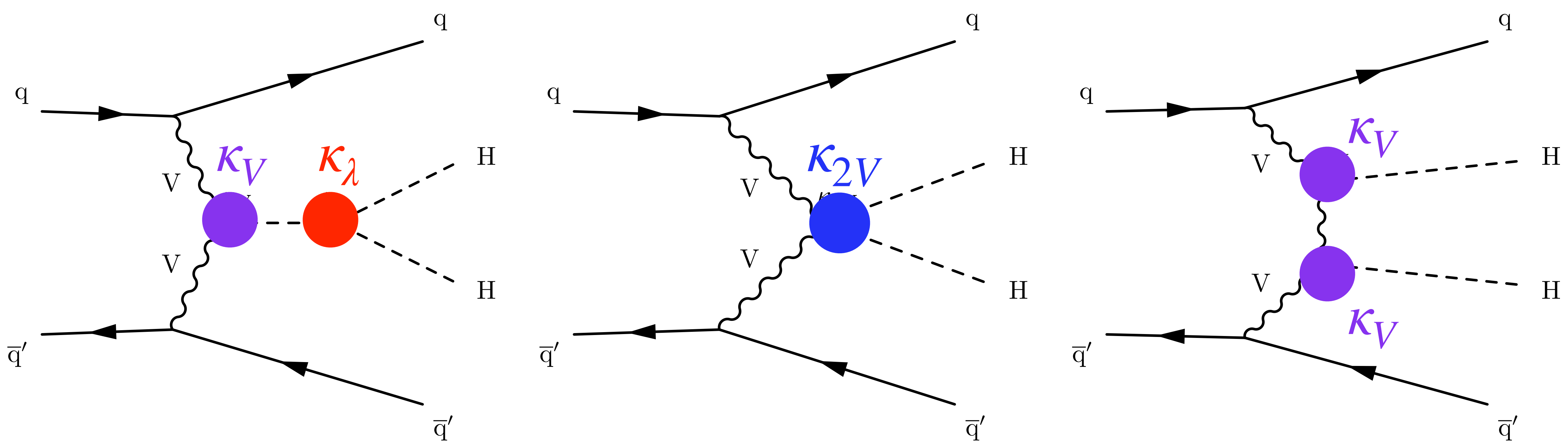

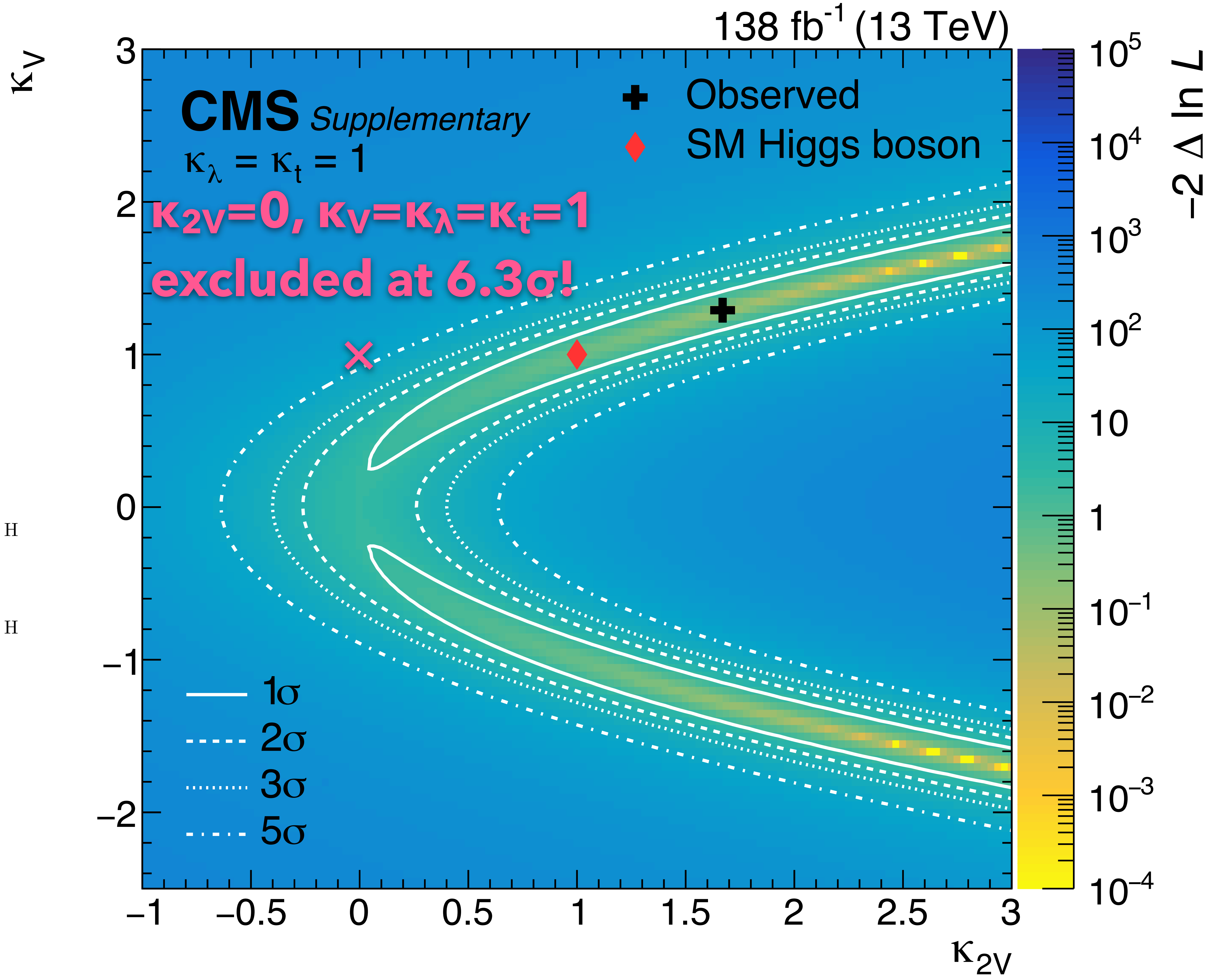

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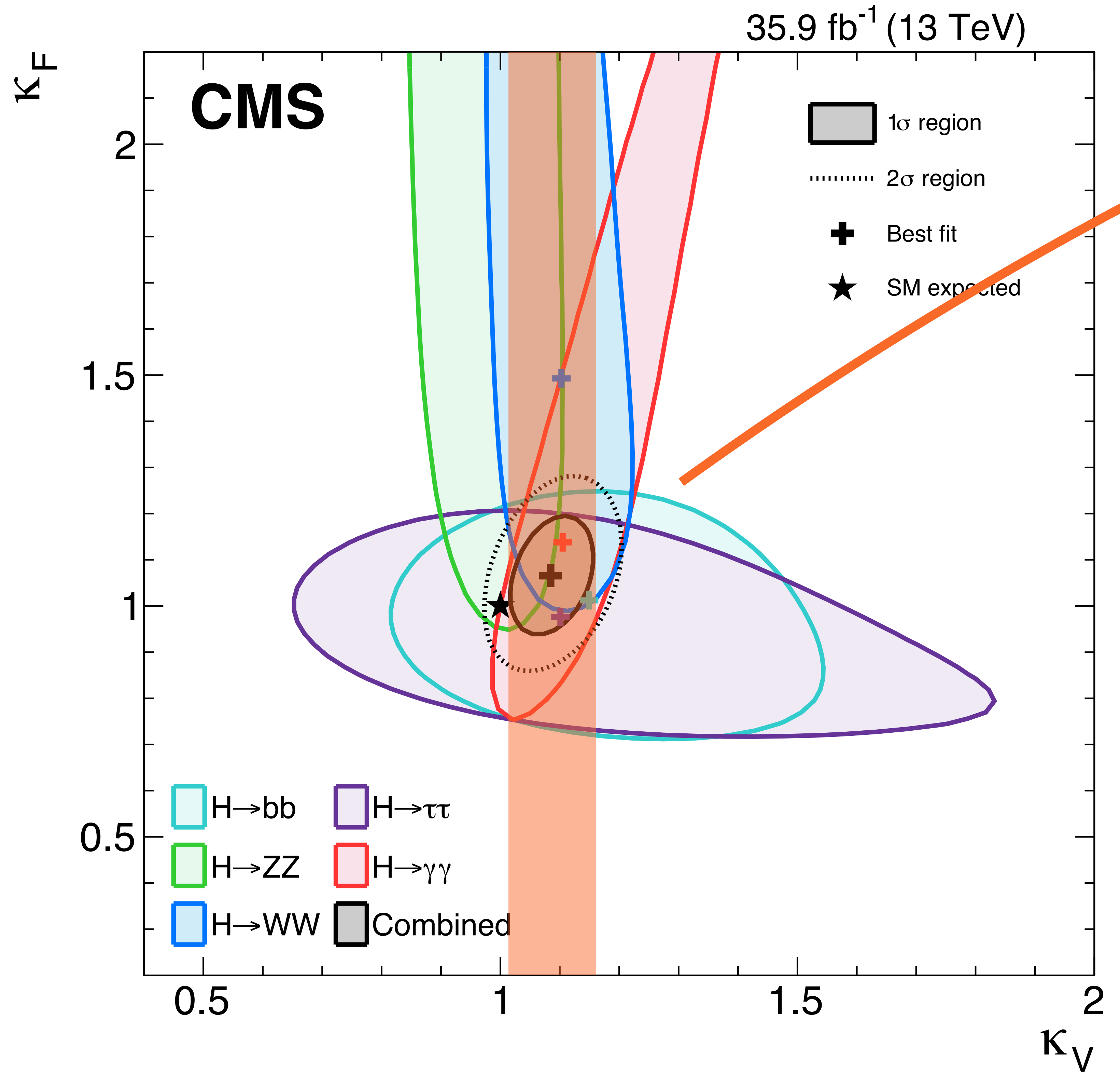
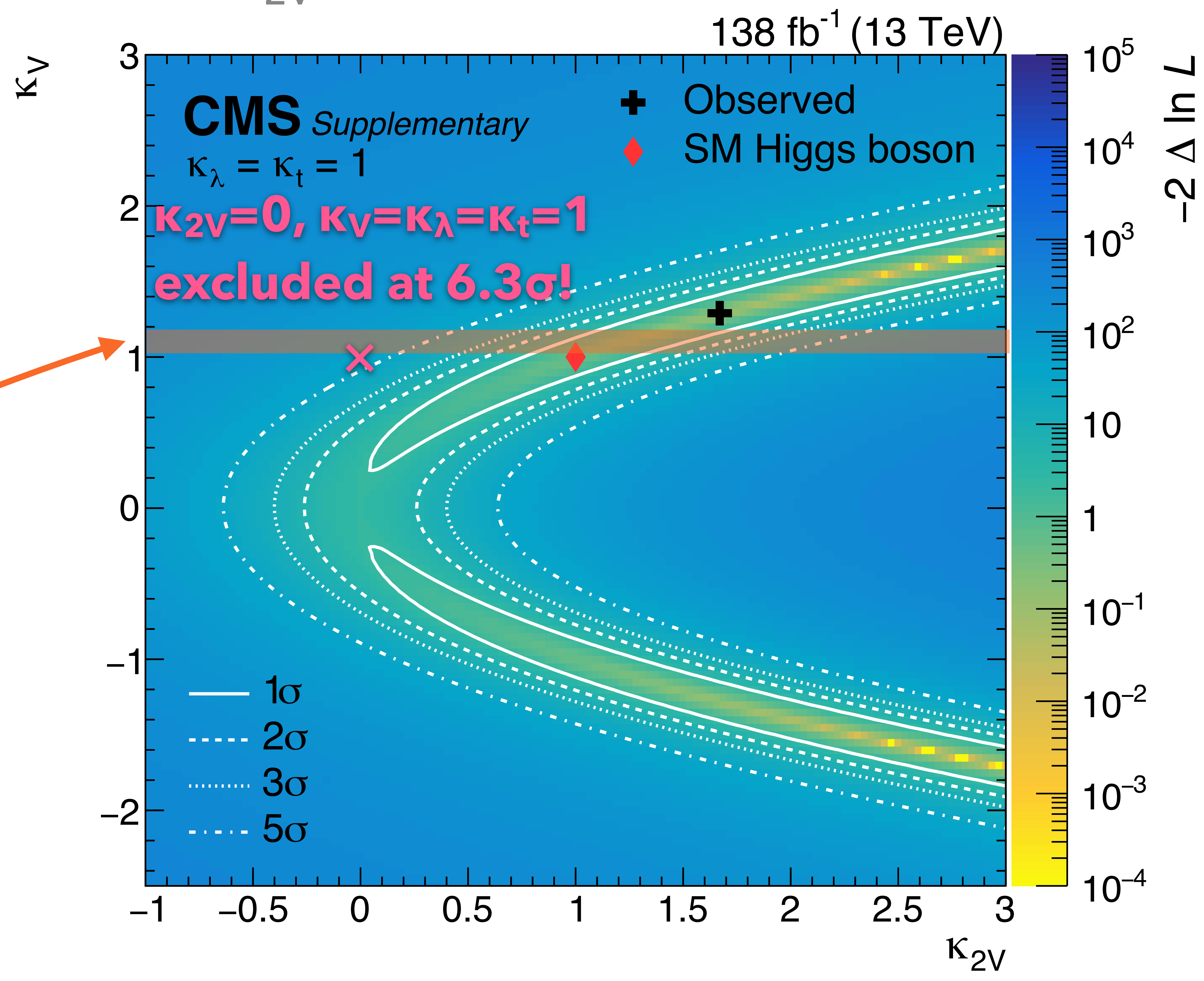
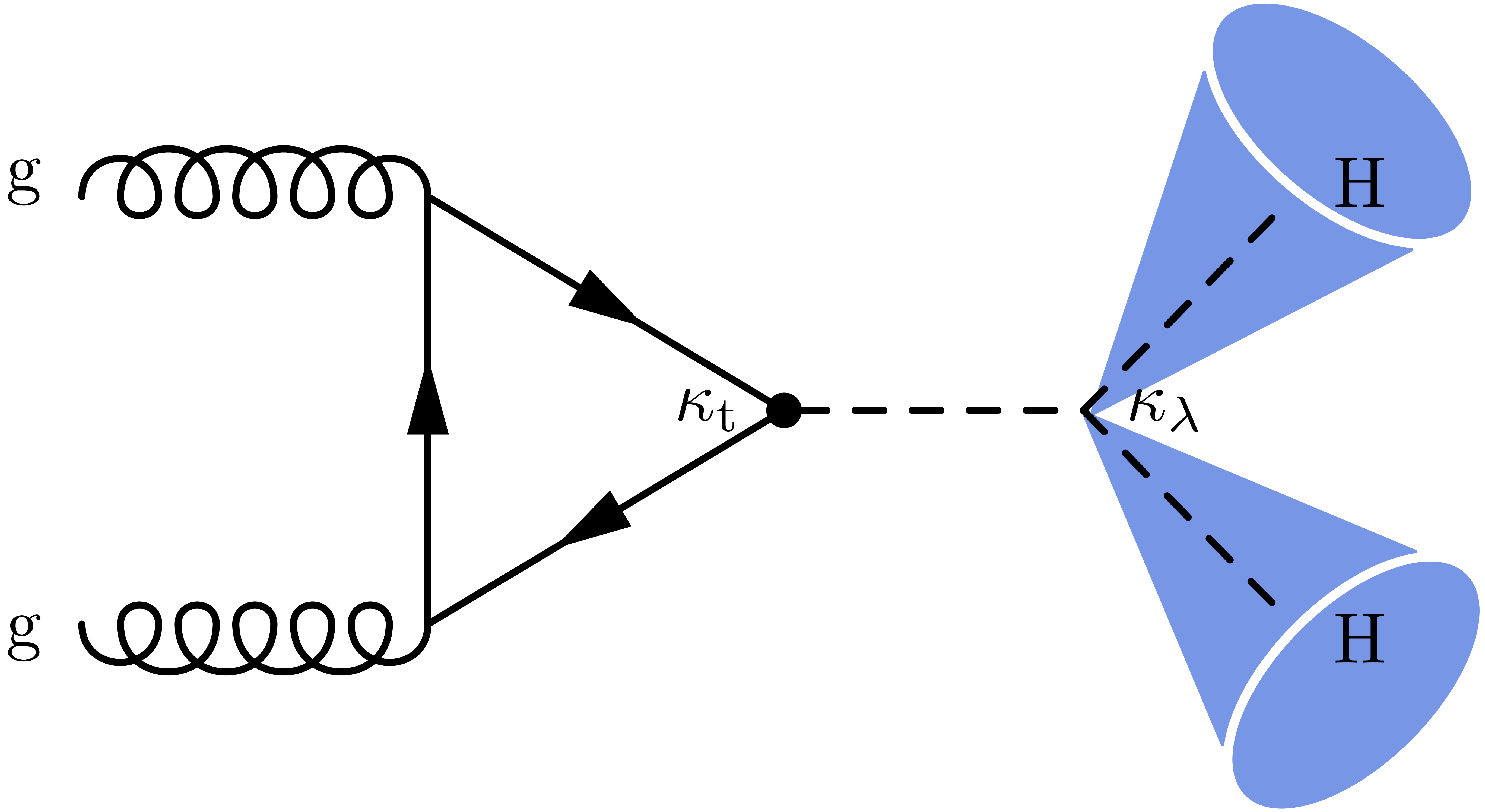
- $\kappa_{2V} = 0$ hypothesis highly disfavored with single-Higgs constraints on κ_V





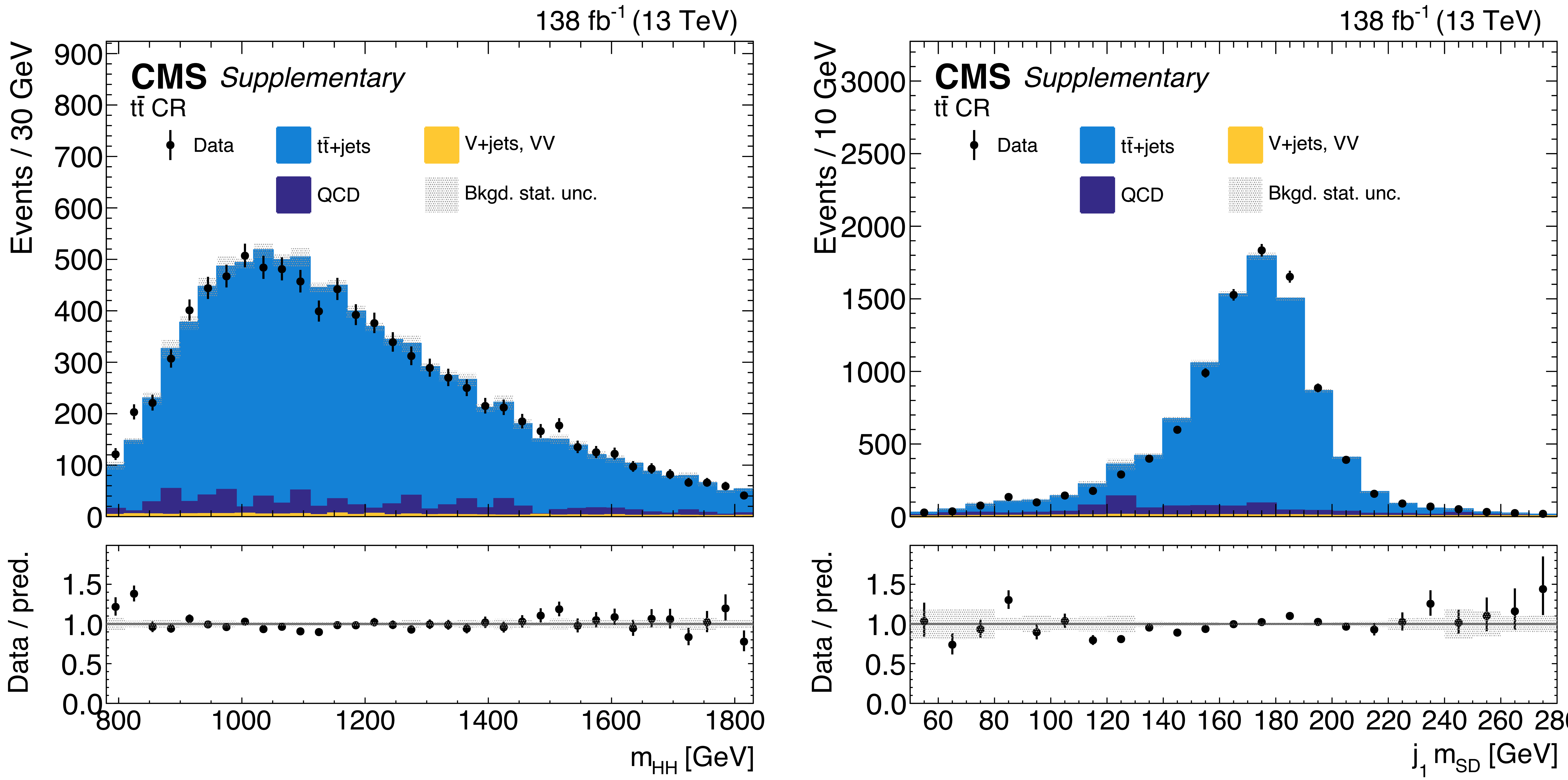
GGF: KINEMATIC SELECTON

- Two AK8 jets with $p_{\mathrm{T}} > 300$ GeV, sorted by D_{bb} score
  - Jet 1 $m_{\mathrm{SD}} > 50$ GeV, jet 2 $m_{\mathrm{reg}} > 50$ GeV
- Veto events passing VBF selection



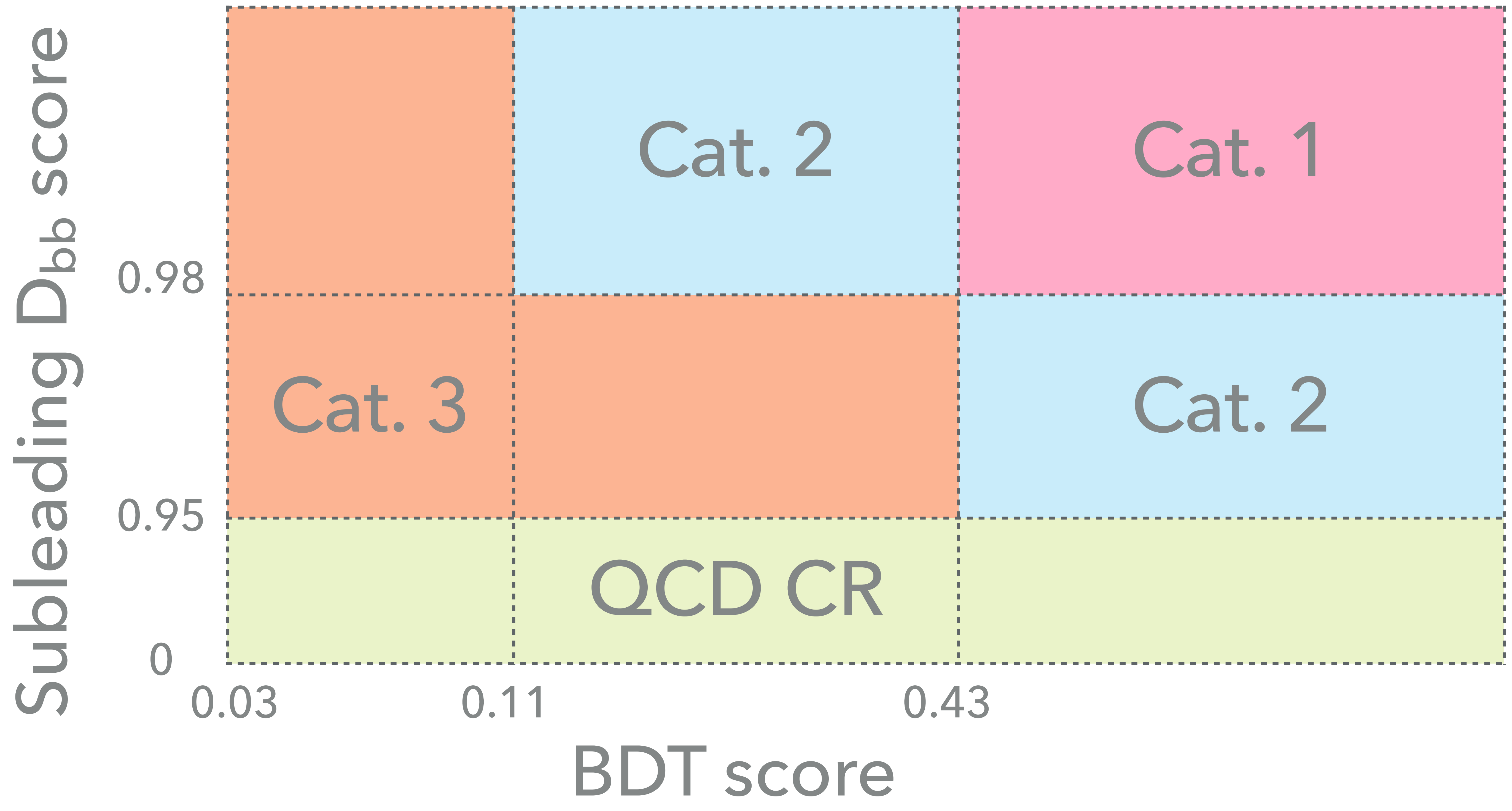
GGF: BOOSTED DECISION TREE FOR EVENT CATEGORIZATION

- A boosted decision tree is trained to select events using 17 input variables, including m_{HH}, $p_{T,j1}/m_{HH}$, jet 1 m_{SD}, jet 1 D_{bb}, …
- BDT has 2× better bkgd. rejection than cut-based: ε_B~0.05% for ε_S~15%



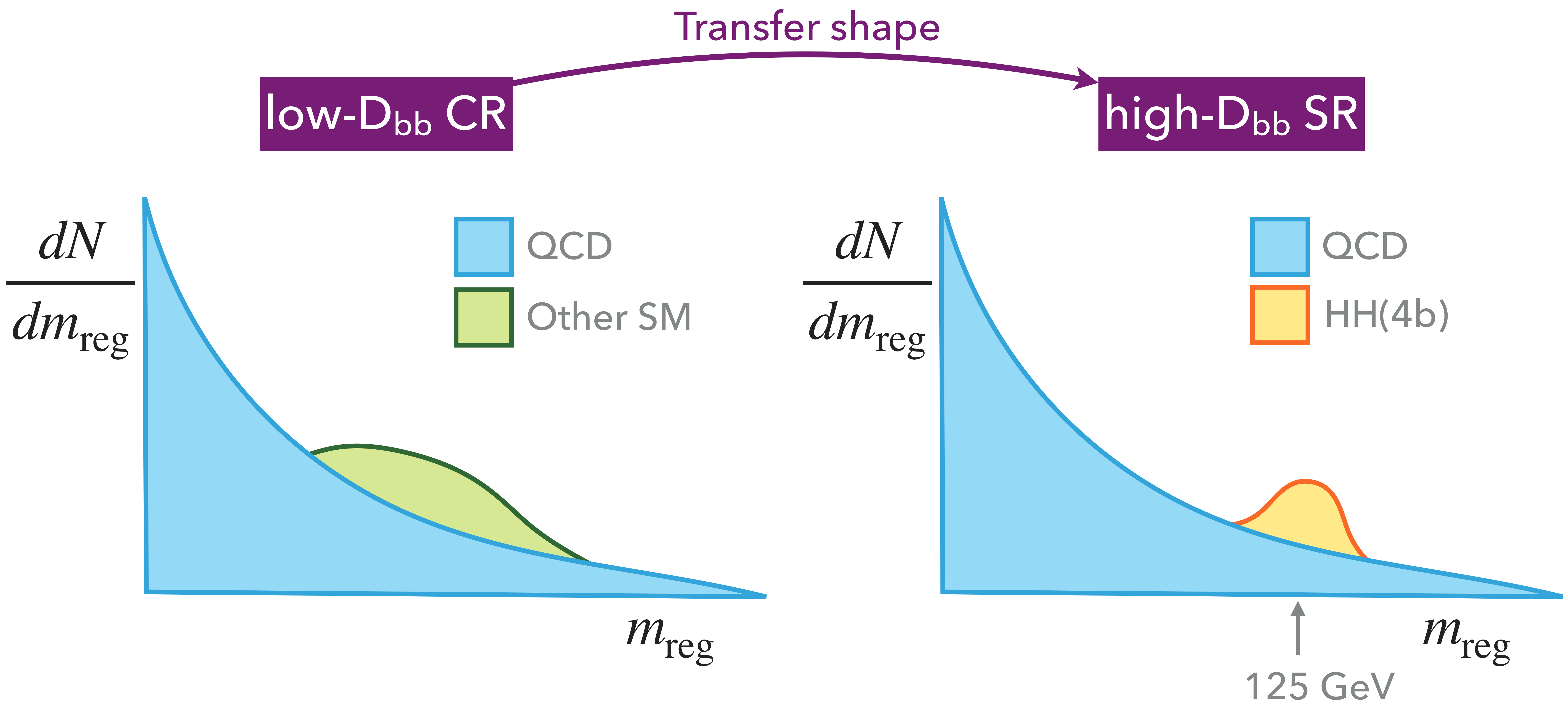
GGF: EVENT CATEGORIZATION

- Three signal region categories defined based on BDT score and subleading D_{bb} score
- QCD control region defined based on events that fail the D_{bb} selection



GGF: PREDICTING THE QCD BACKGROUND

- After accounting for other SM backgrounds, Derive the shape of the QCD background using the jets that fail the D_{bb} selection



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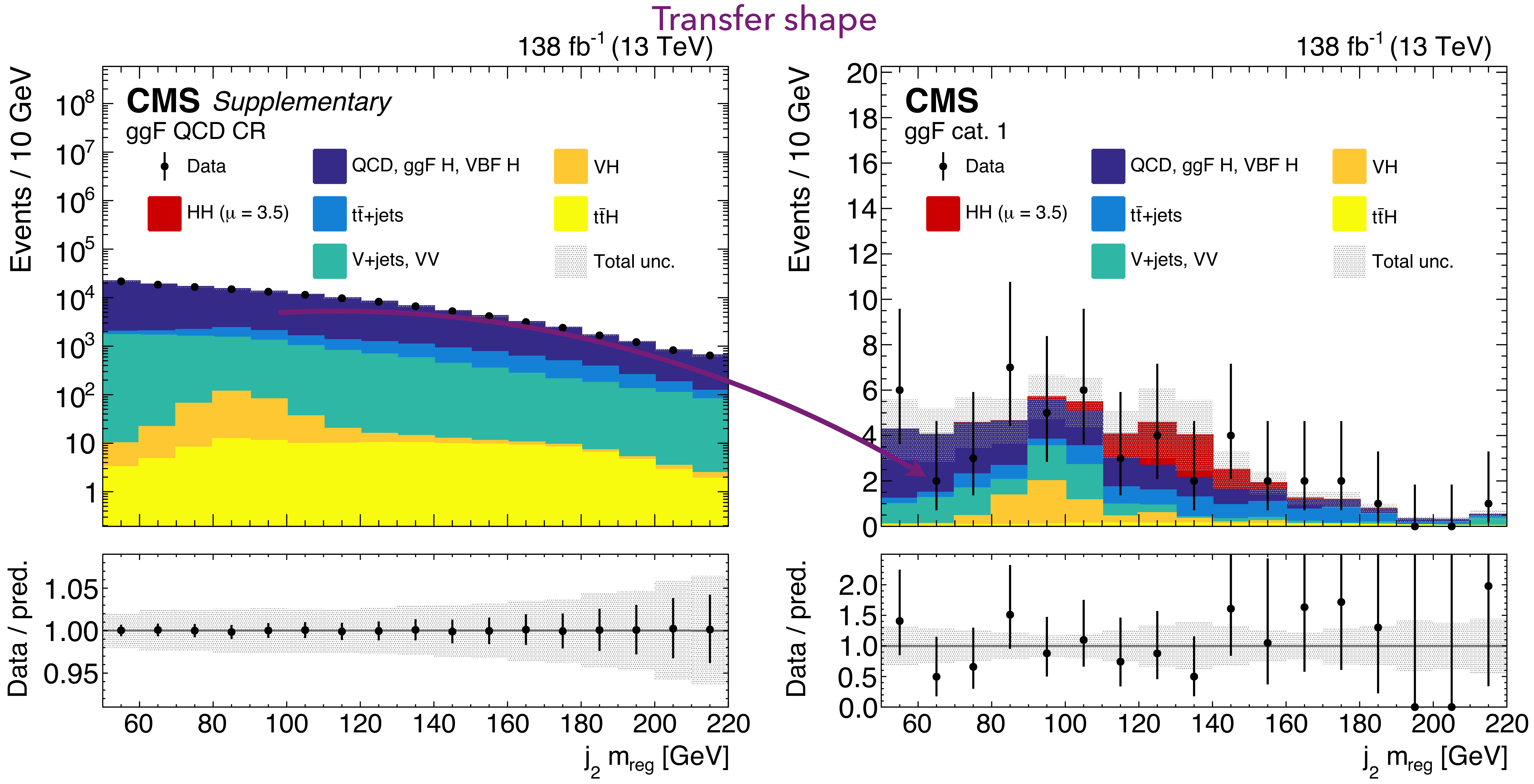

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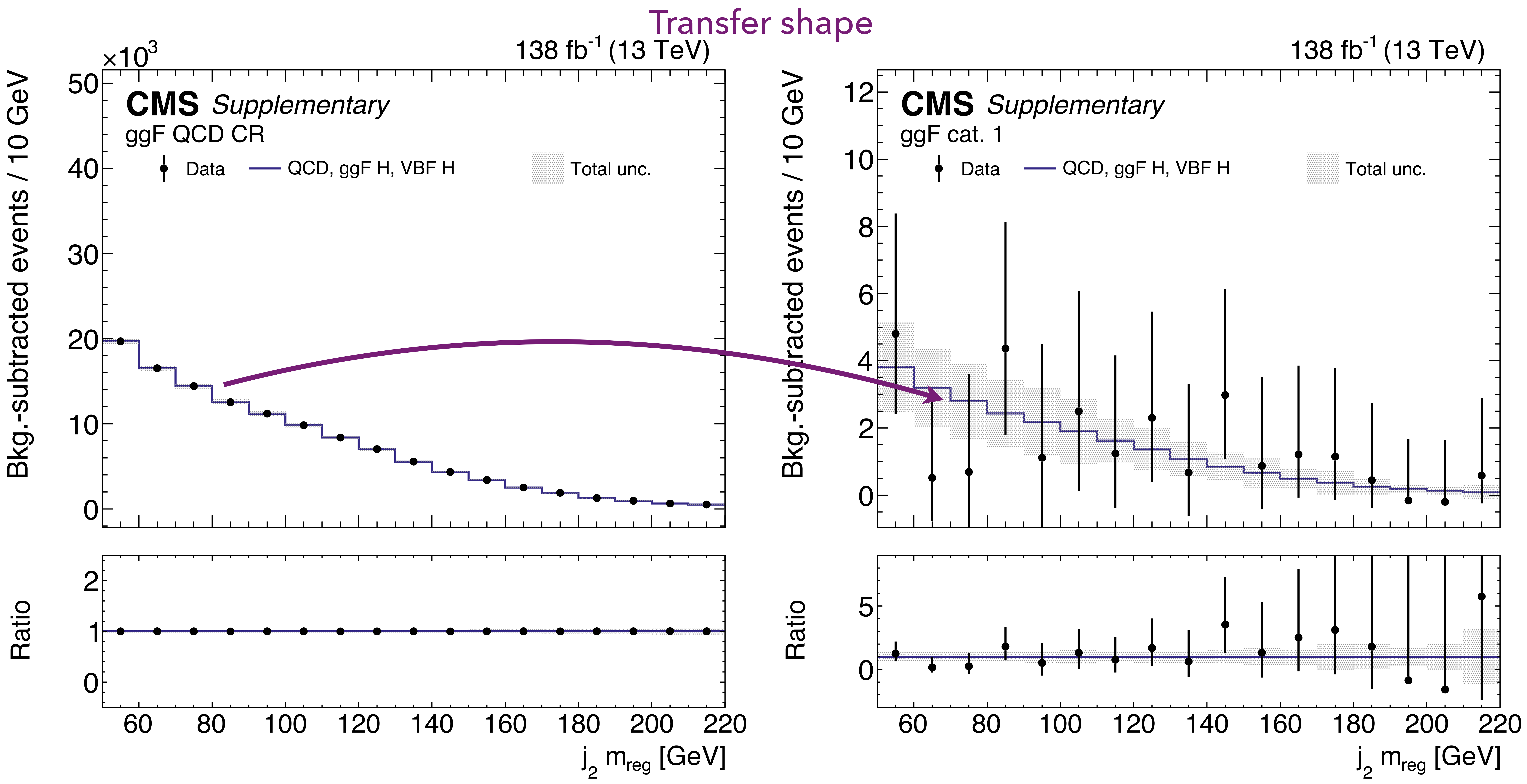

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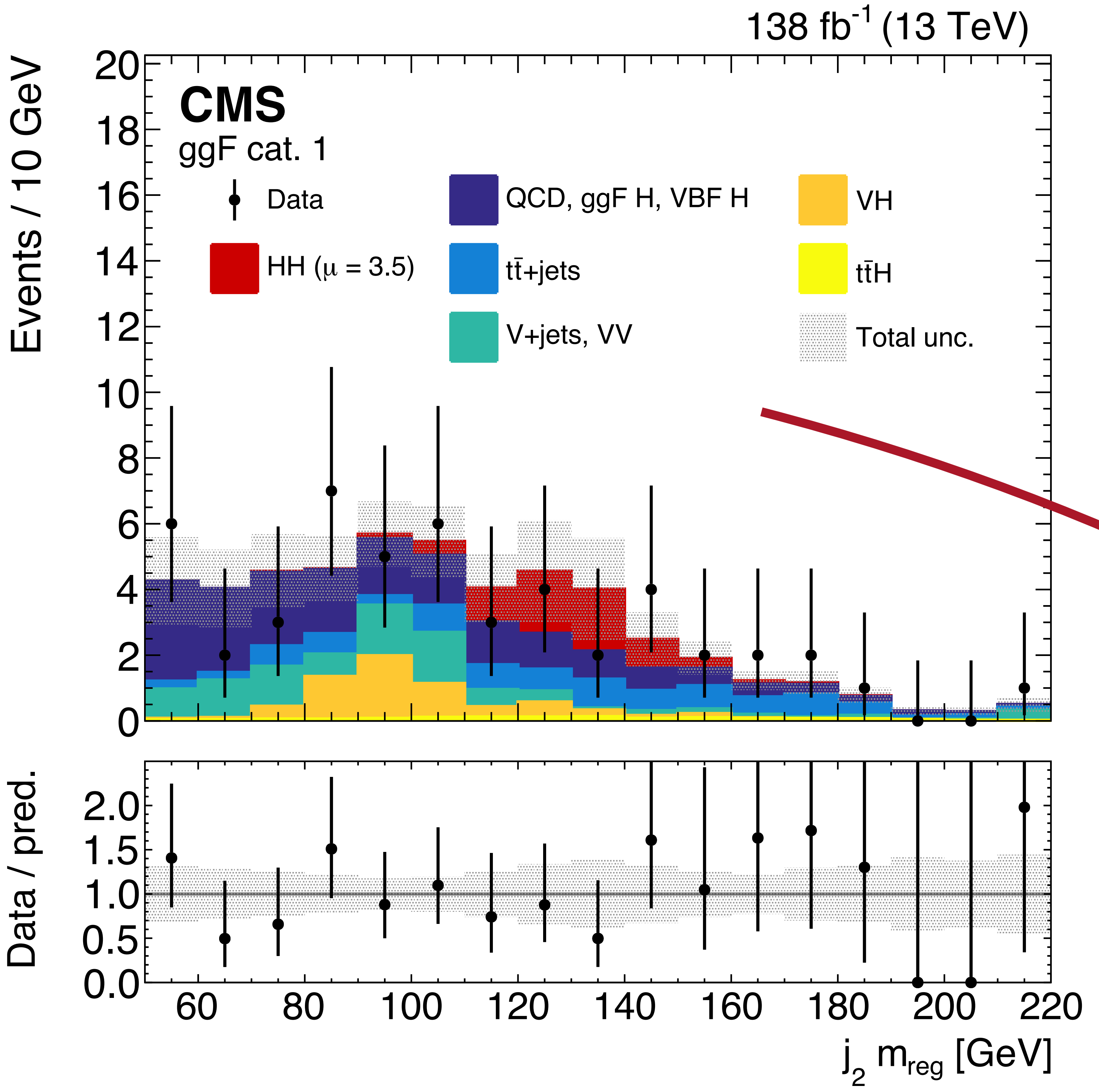
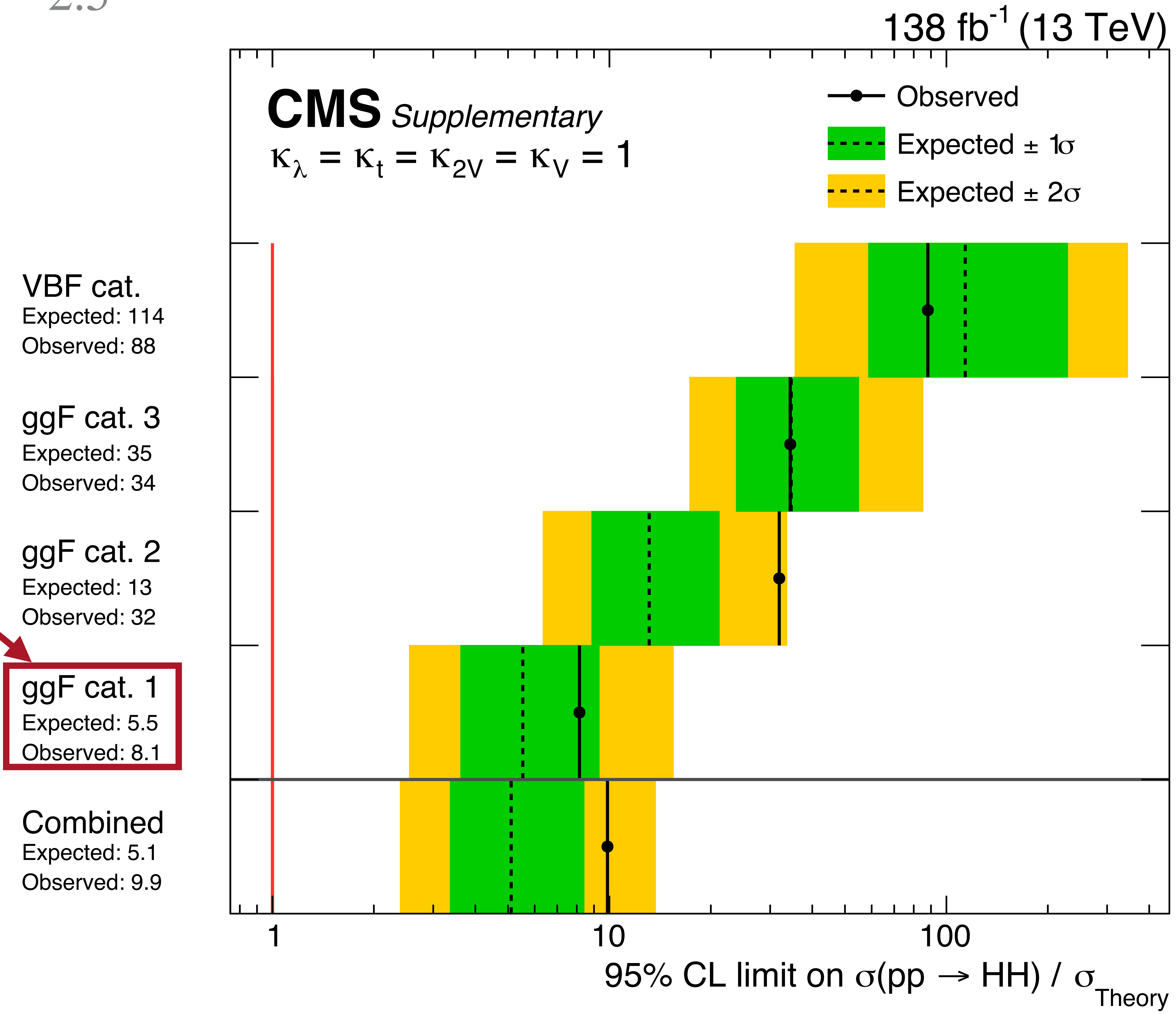


Most sensitive category for SM HH



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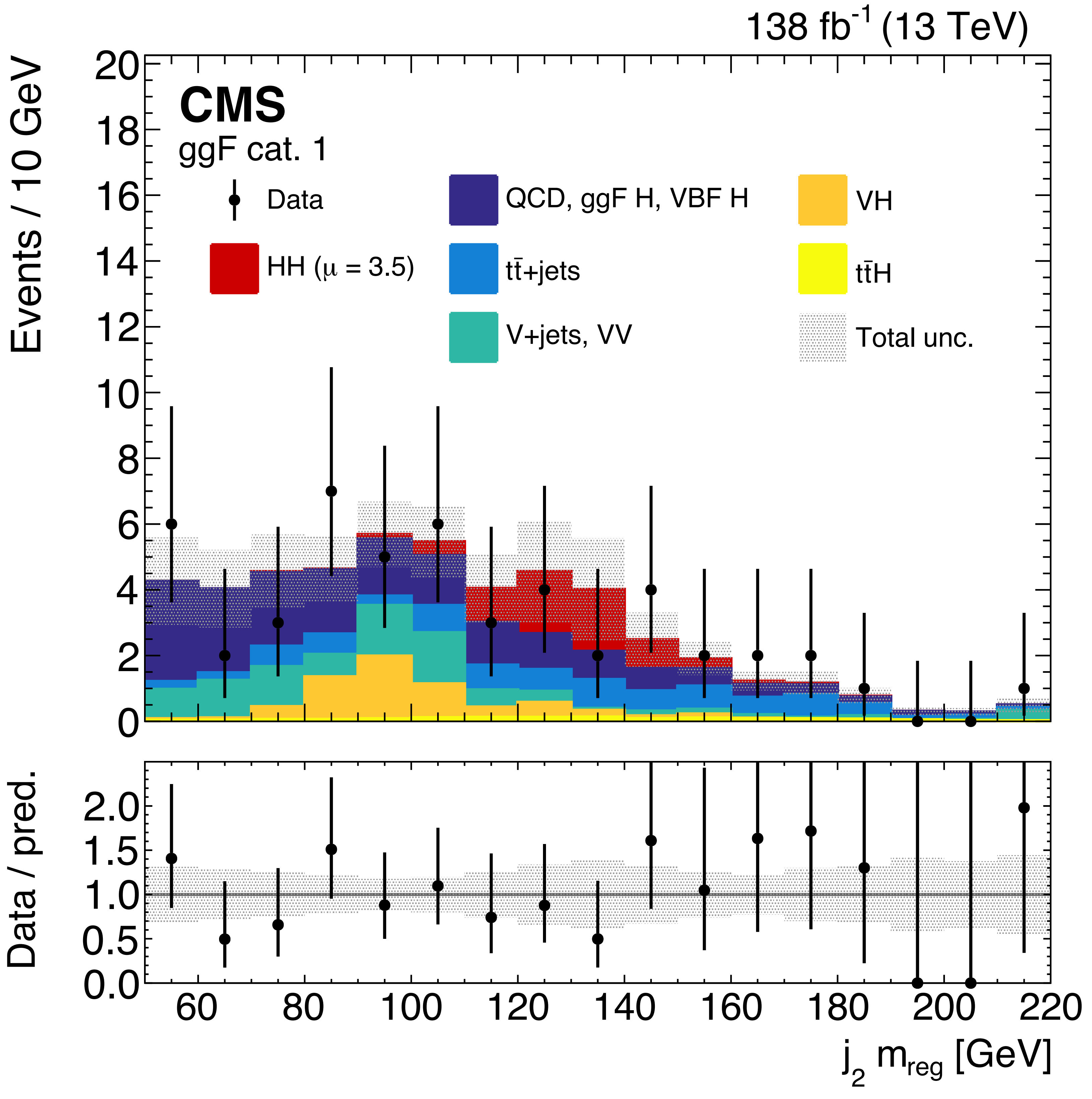

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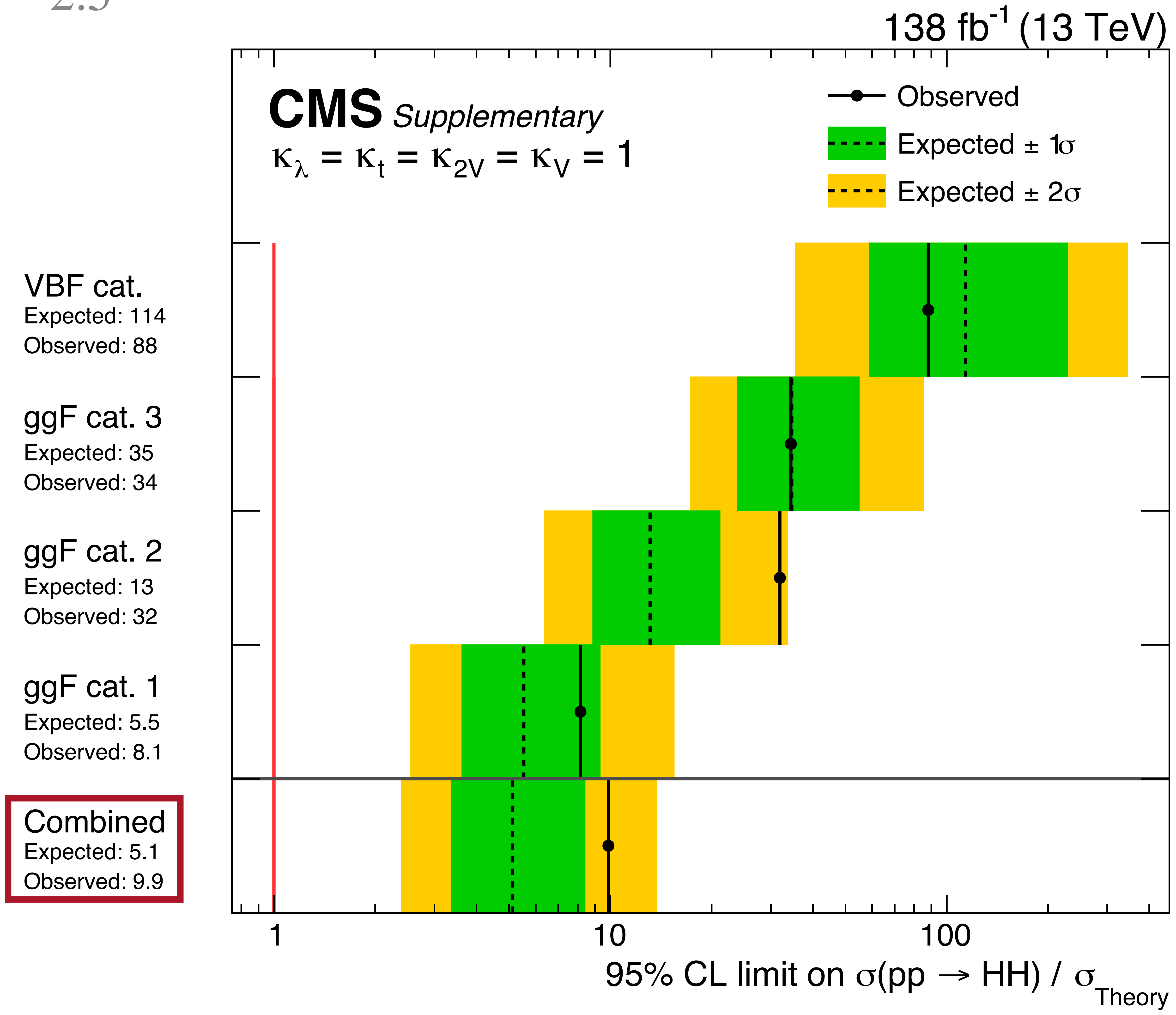
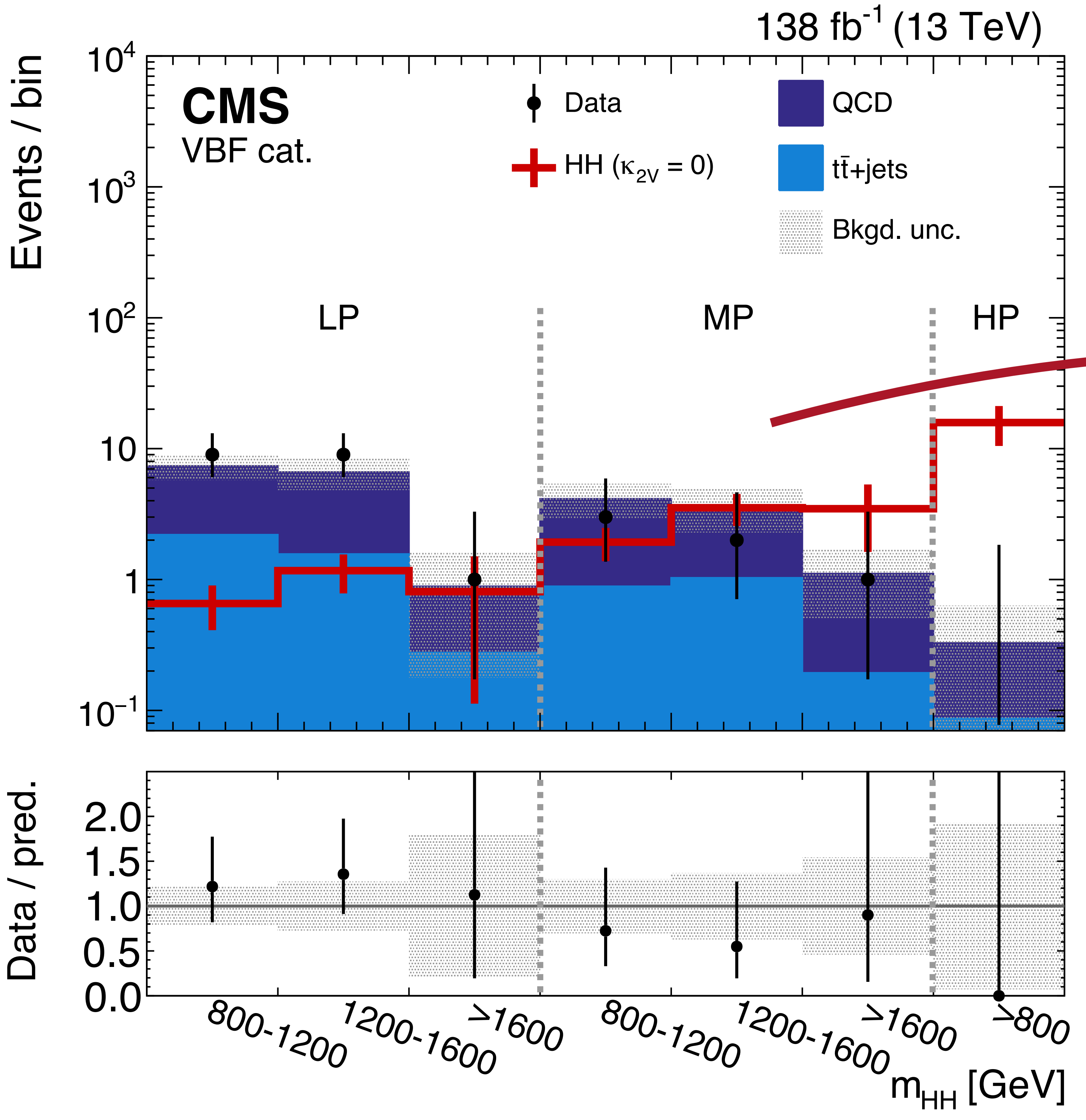


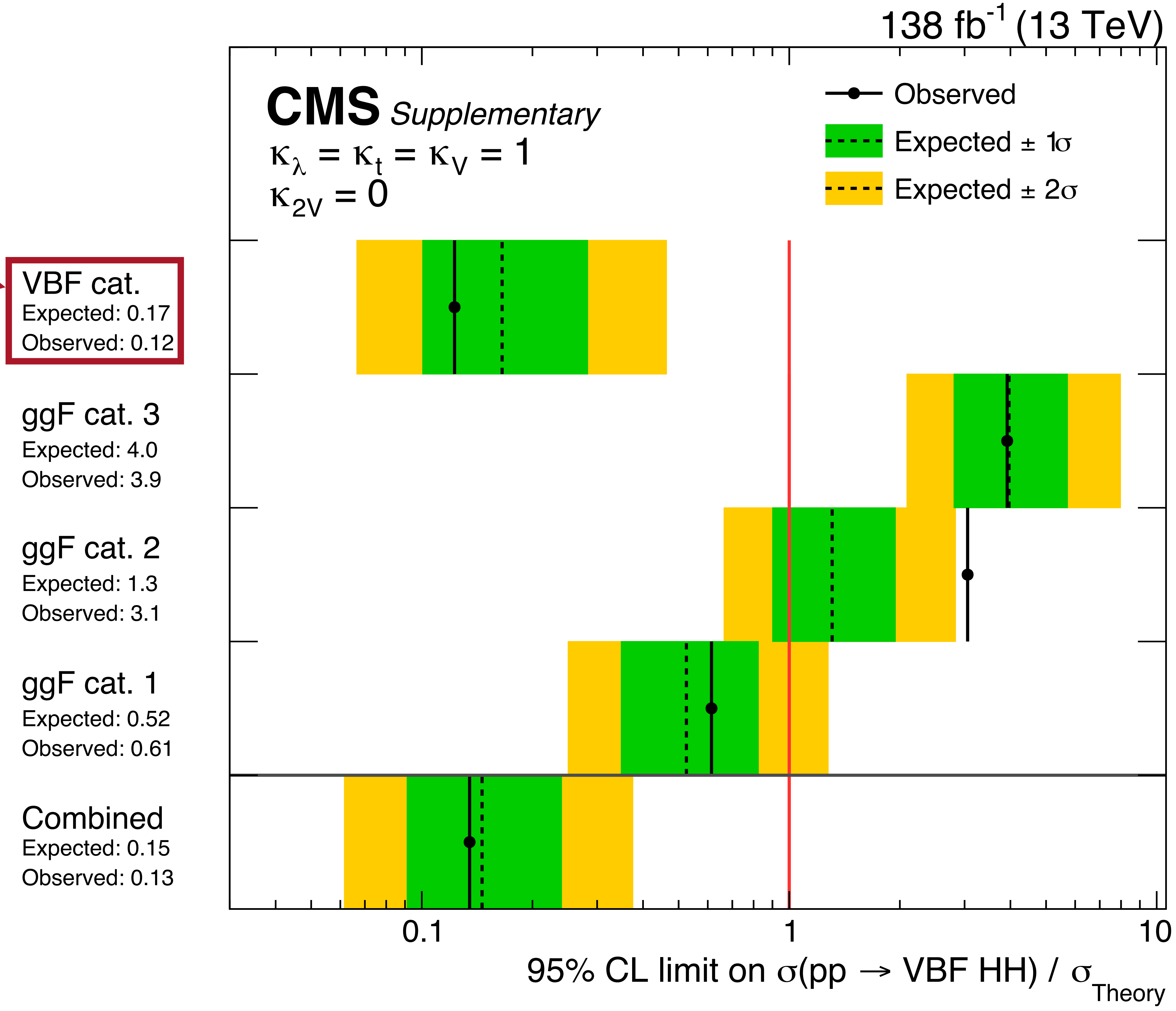
Observed (expected) 95% CL UL on HH: 9.9 (5.1) × SM!

VBF & GGF COMPLEMTARITY

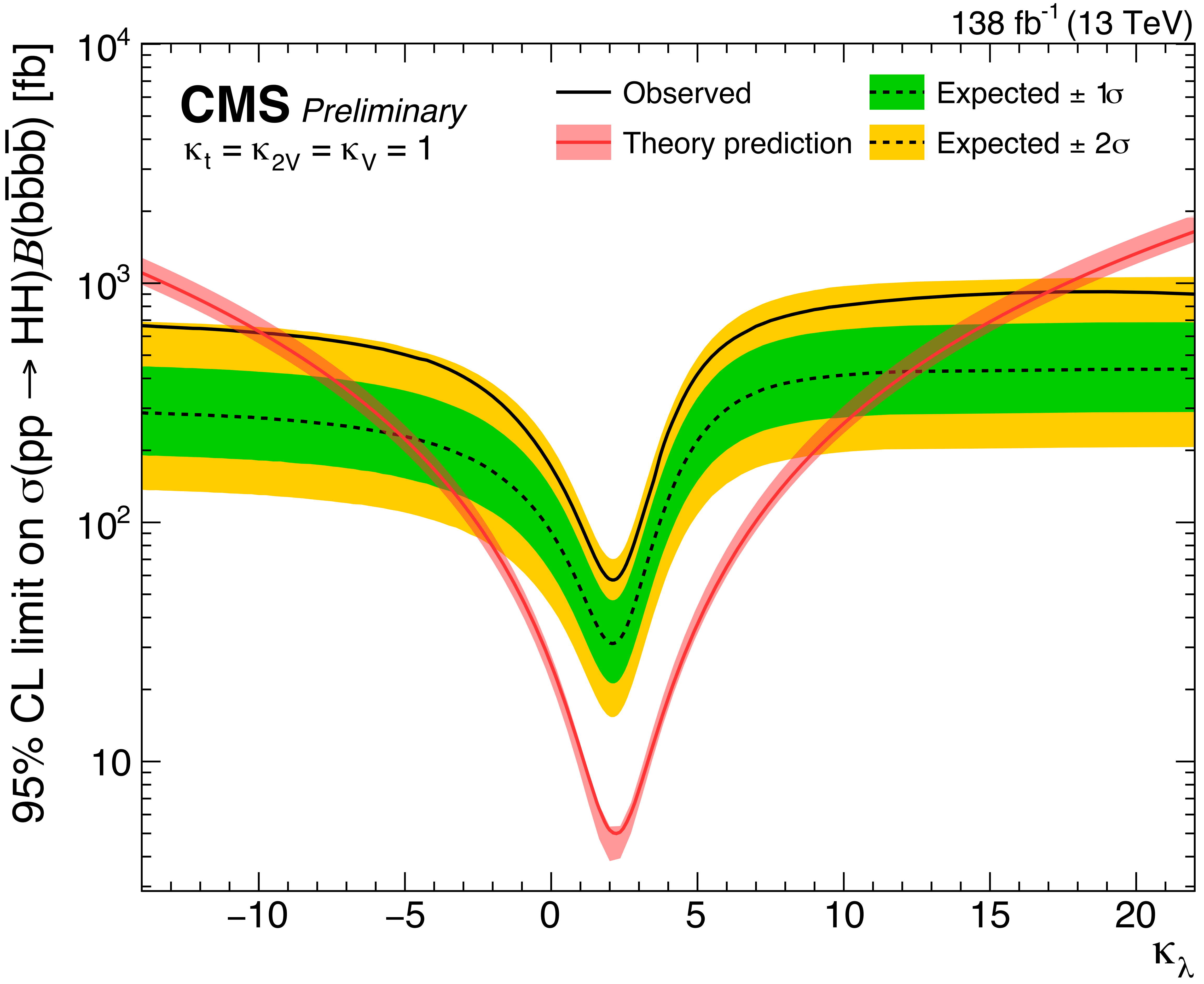
- While ggF categories dominate for inclusive SM HH signal, VBF category dominates for BSM VBF signal



Most sensitive category for BSM VBF

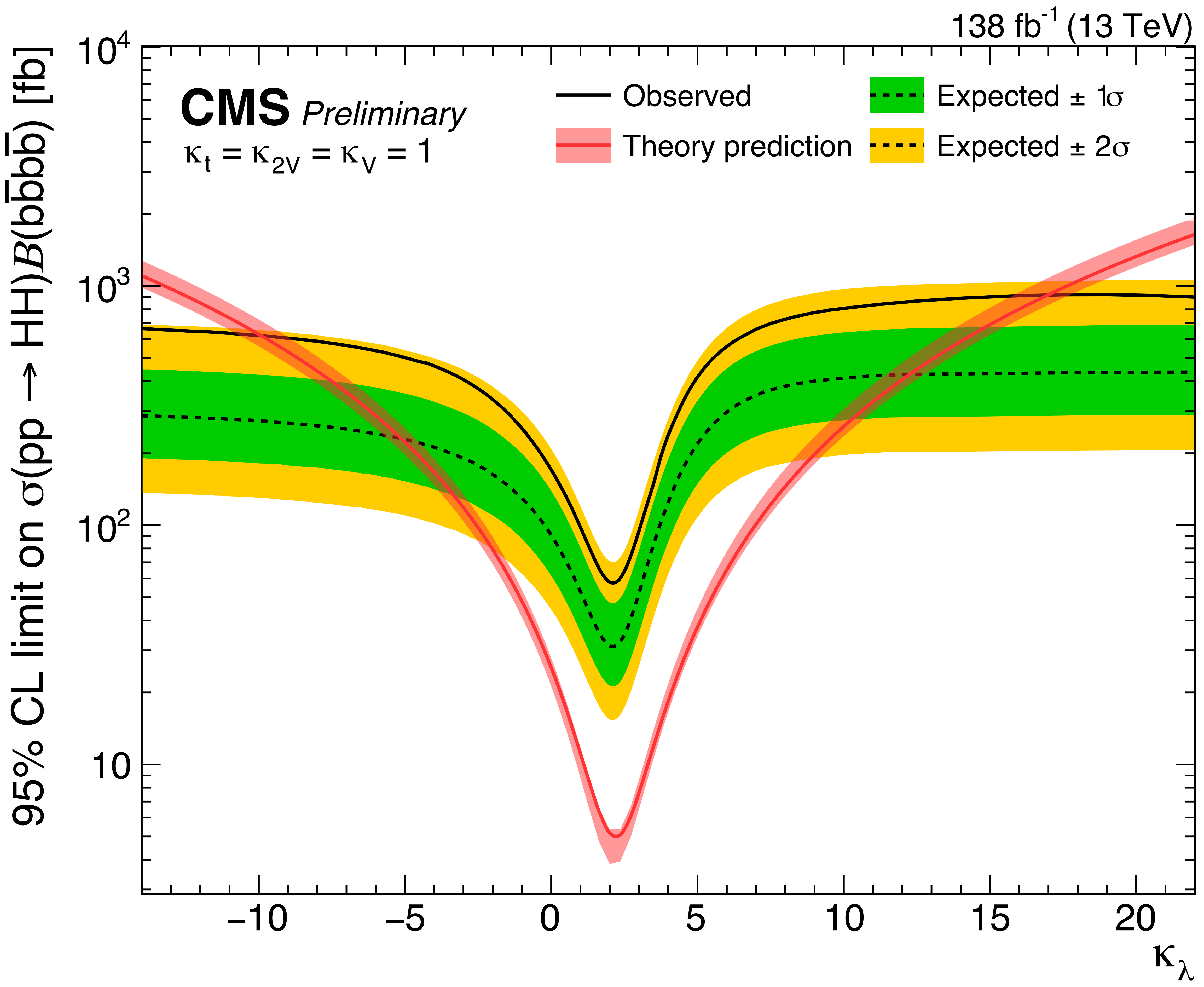


COMBINED RESULTS



COMBINED RESULTS

- Based on combined fit, κ_λ constrained to be in [-9.9, 16.9] at 95% CL



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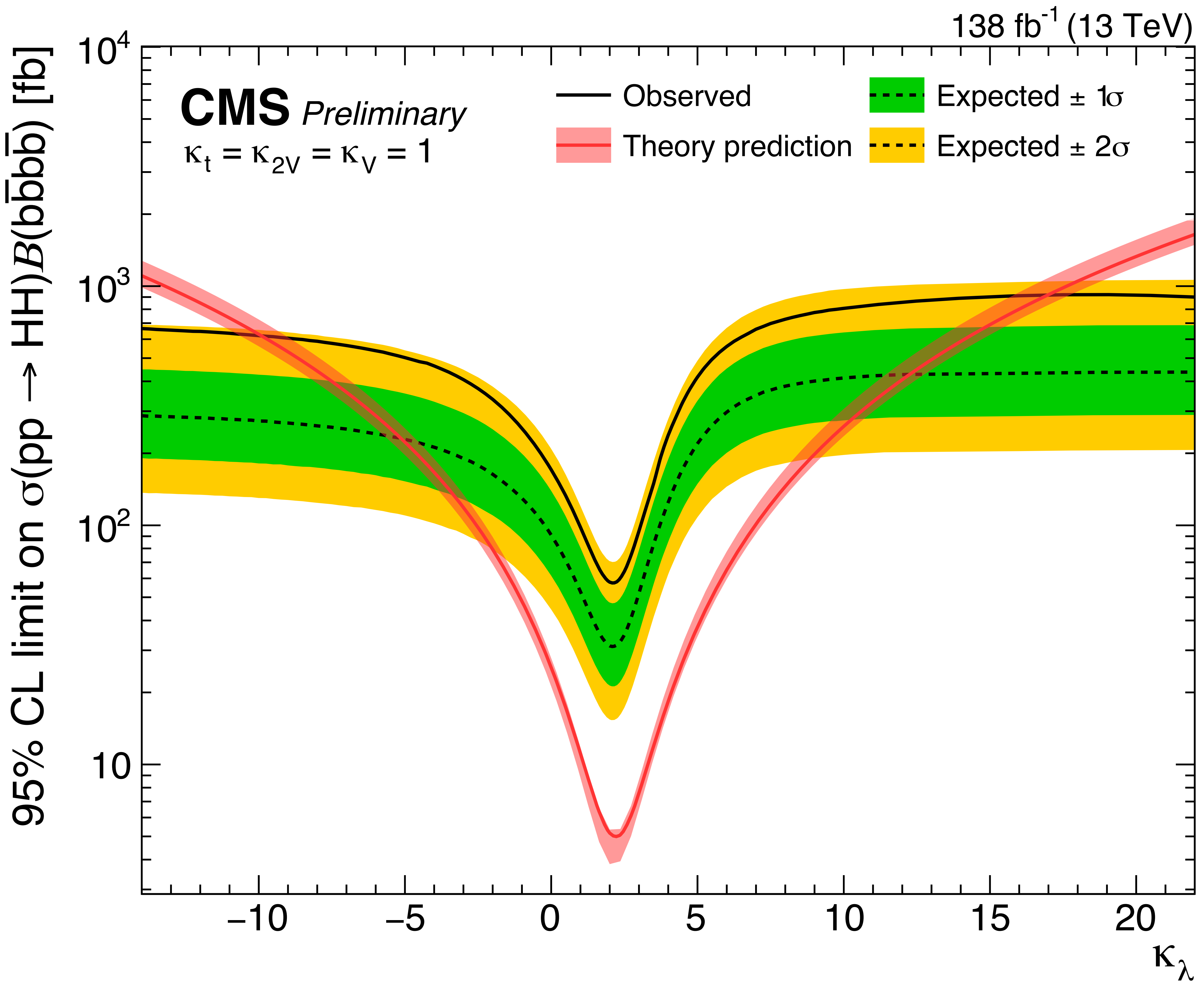
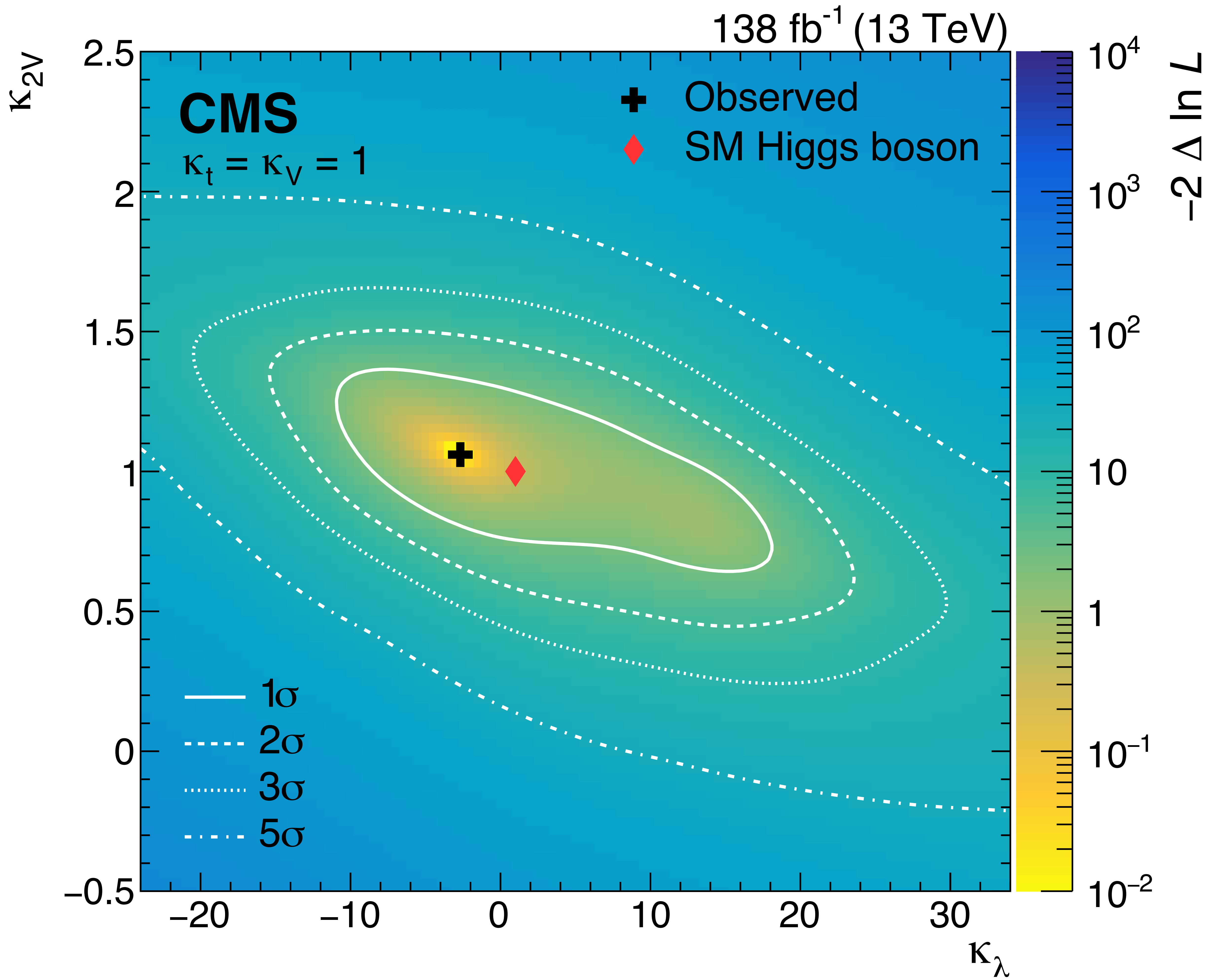
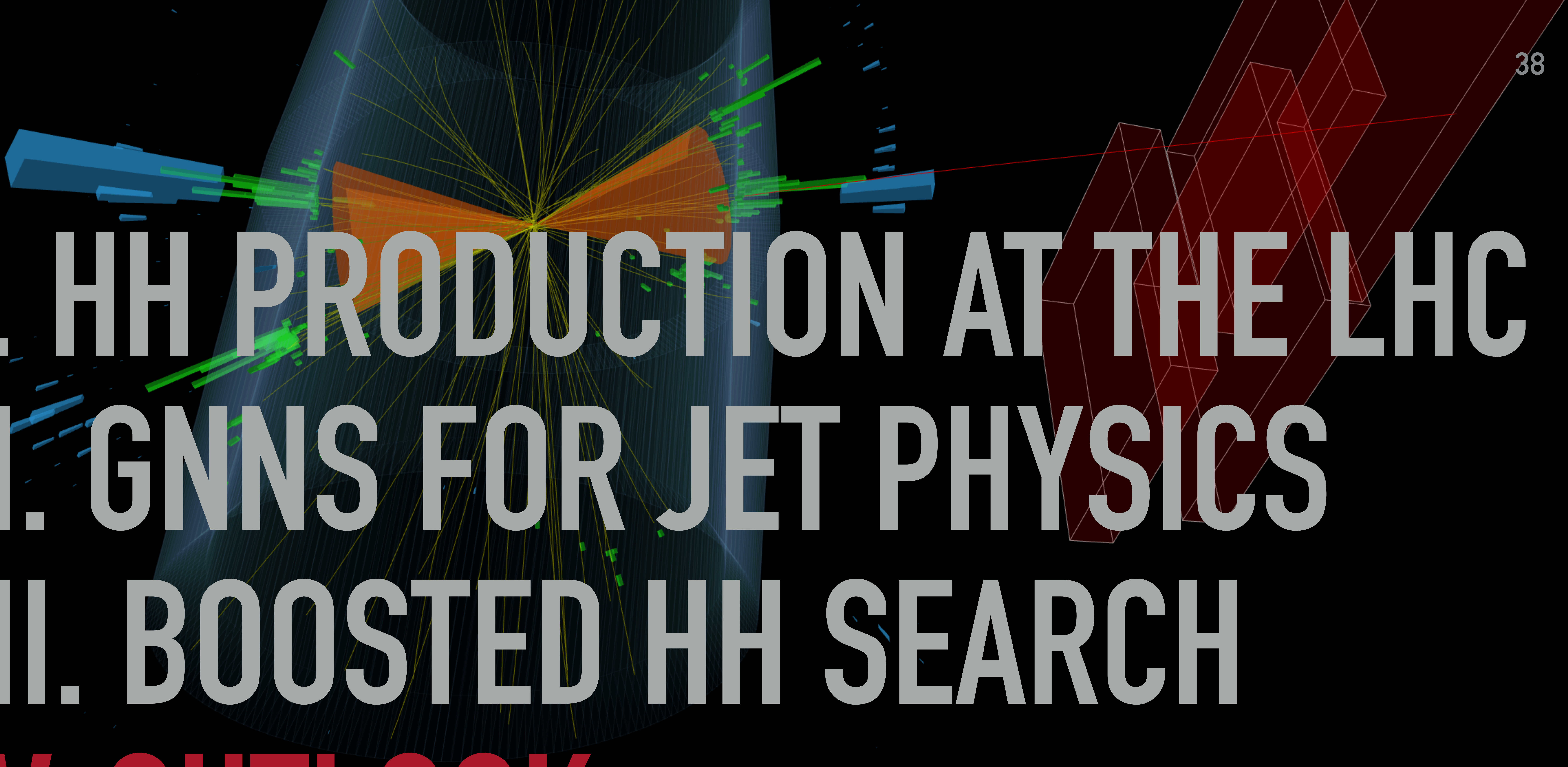
- 2D likelihood scan (κ_λ , κ_{2V}) shows complementarity between two channels







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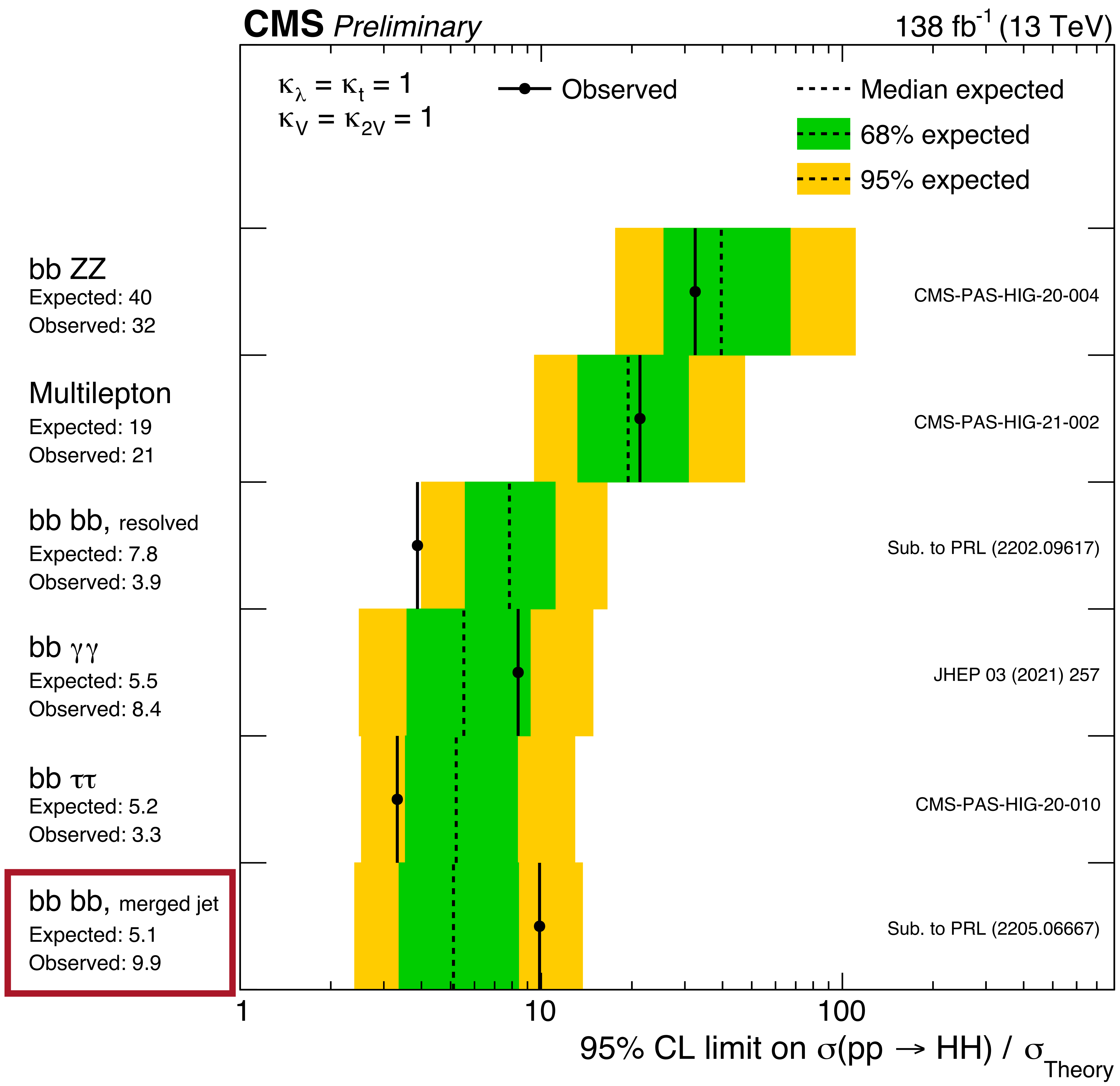
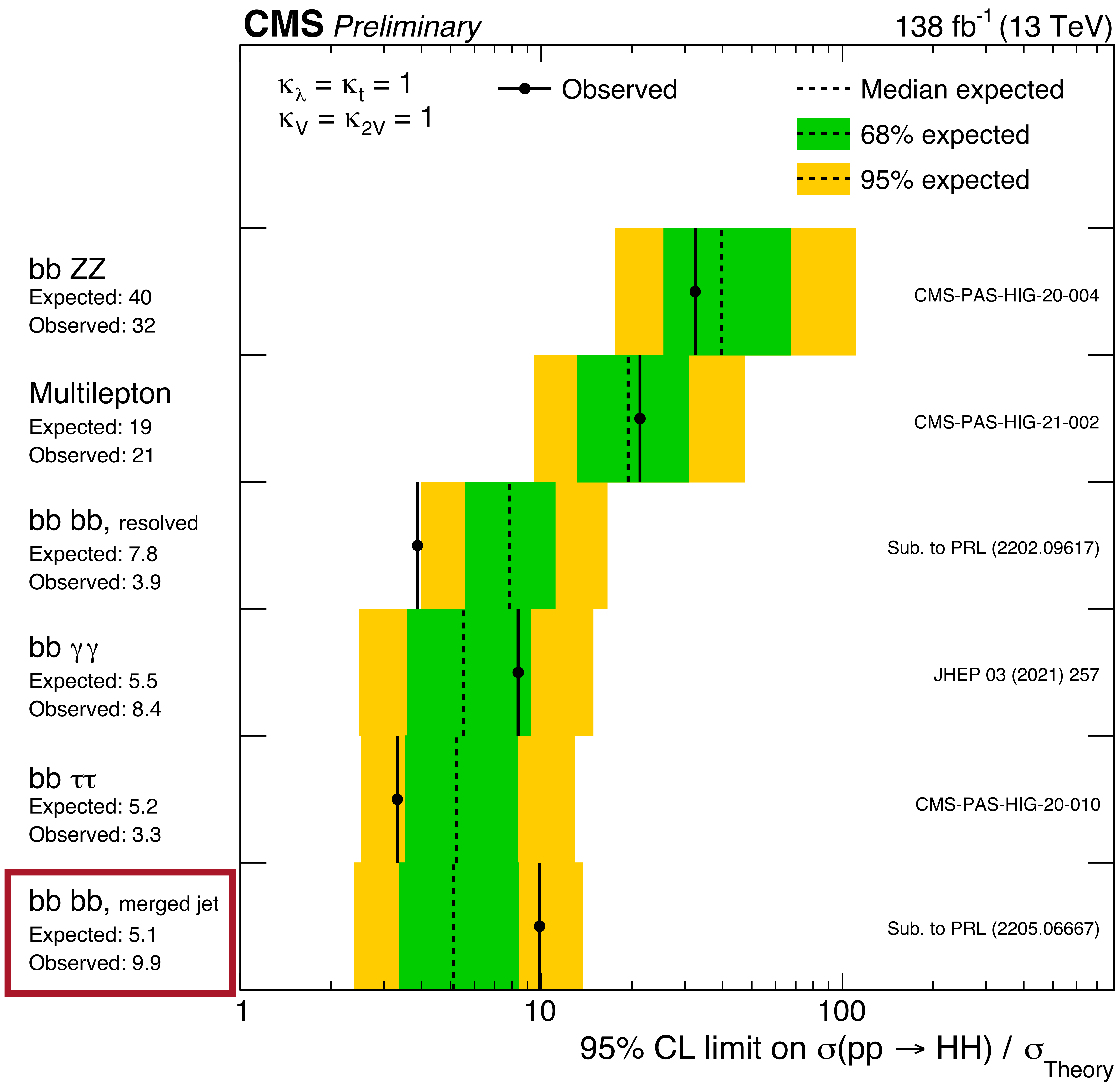
SIGNAL STRENGTH RESULTS IN CONTEXT

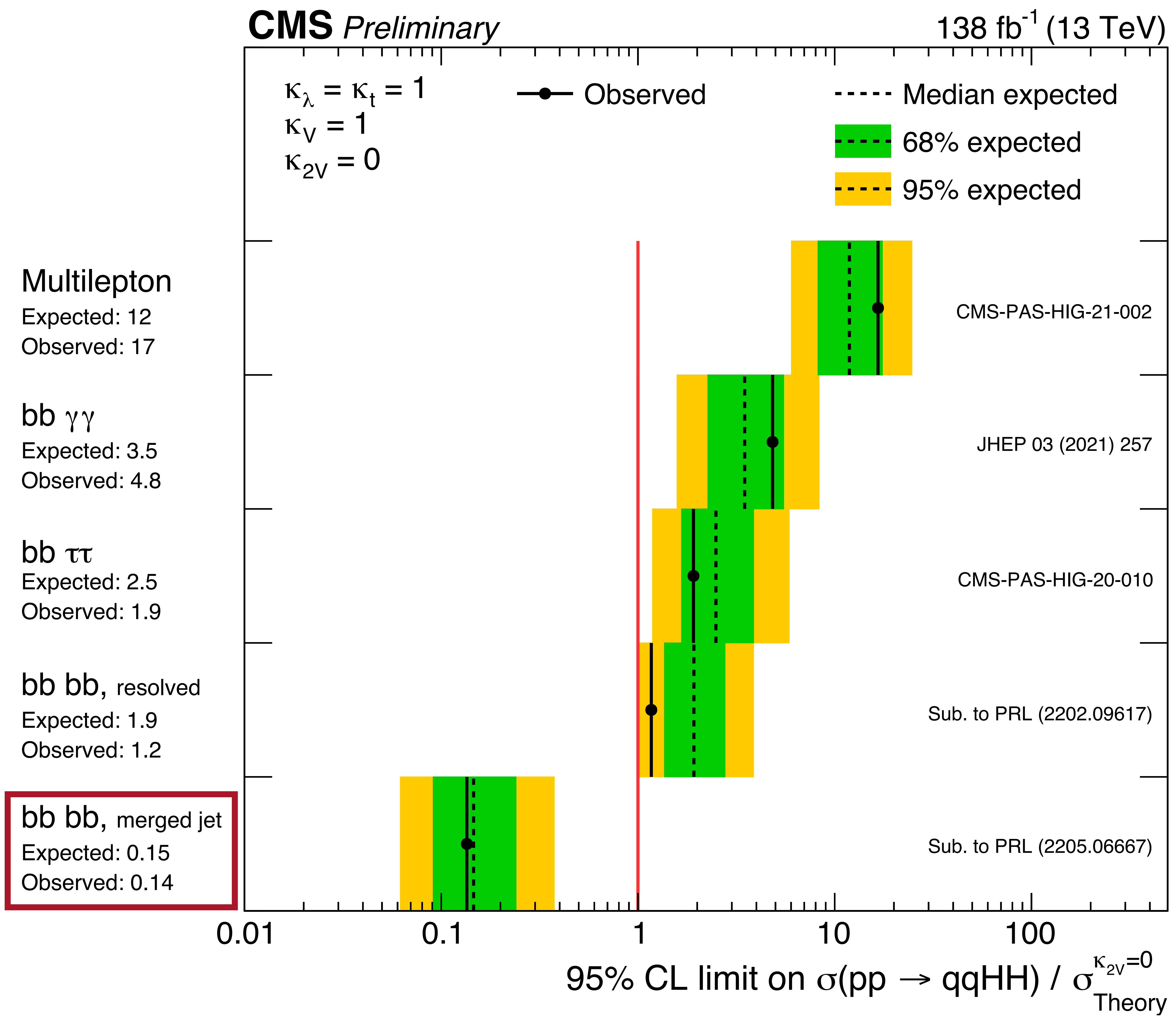
- Best sensitivity to SM ggF HH production



SIGNAL STRENGTH RESULTS IN CONTEXT

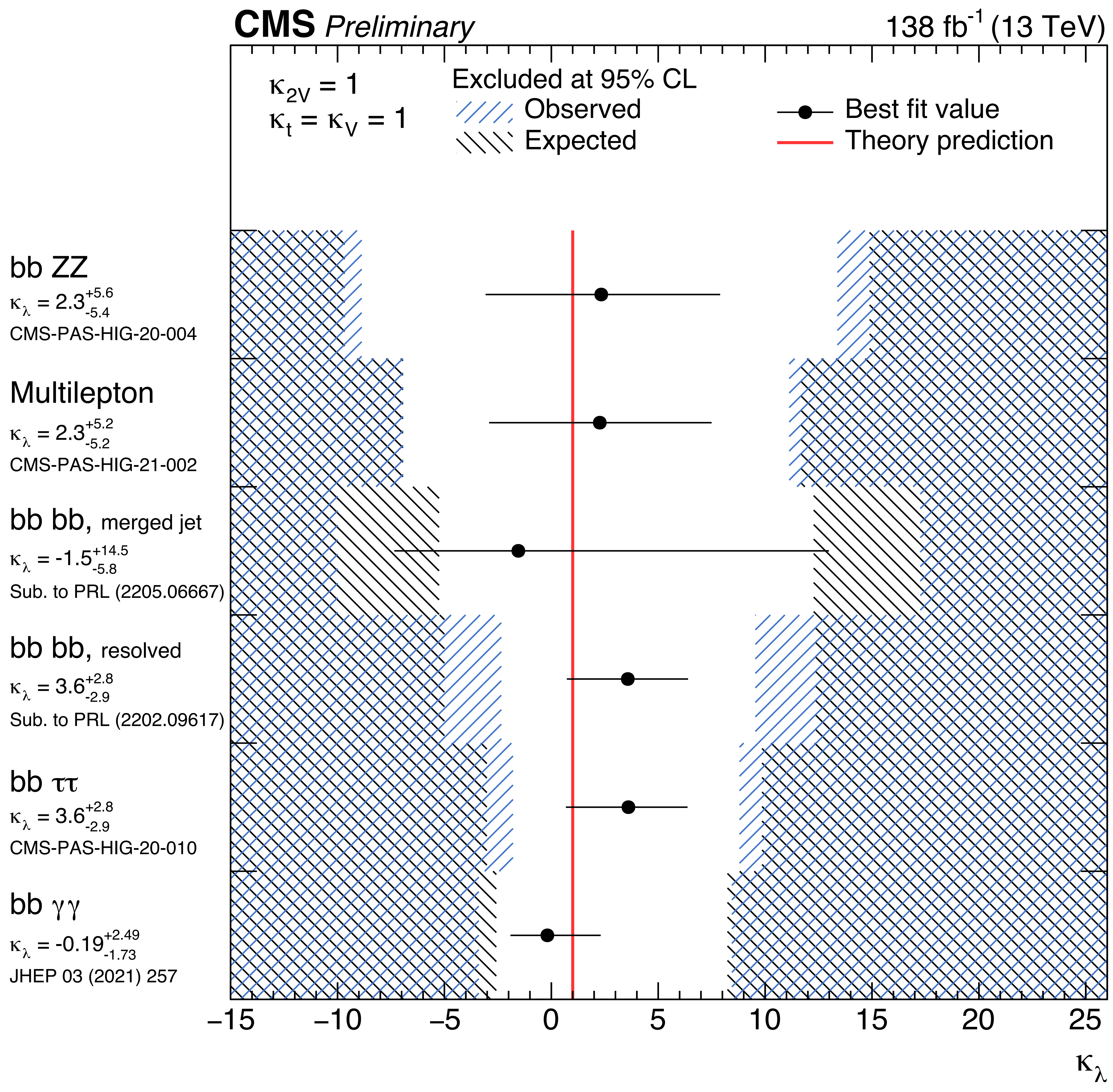
- Best sensitivity to SM ggF HH production and BSM VBF HH production

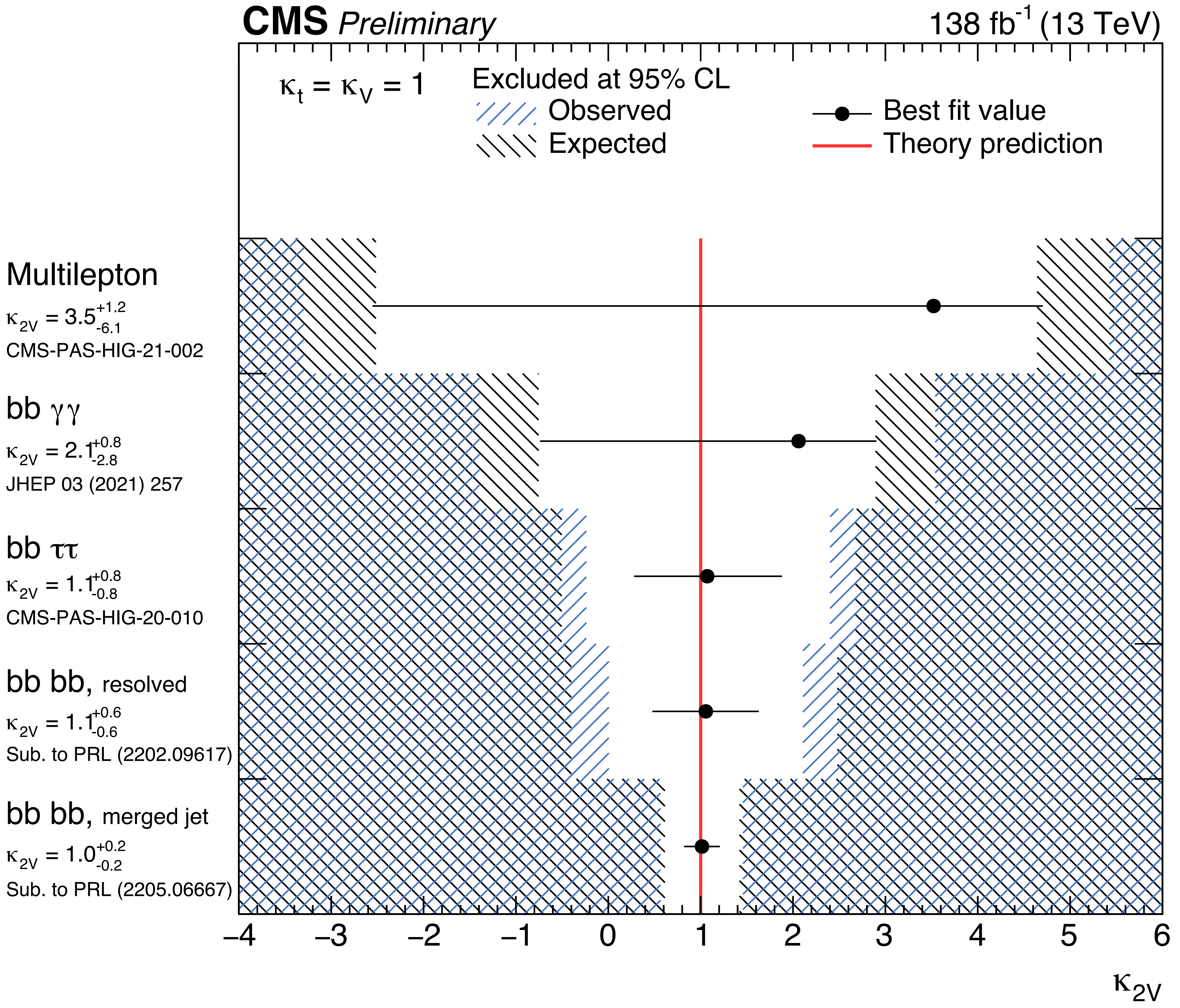




COUPLING RESULTS IN CONTEXT

- Best constraint on κ_{2V}





COUPLING RESULTS IN CONTEXT

CMSPublic/SummaryResultsHIG

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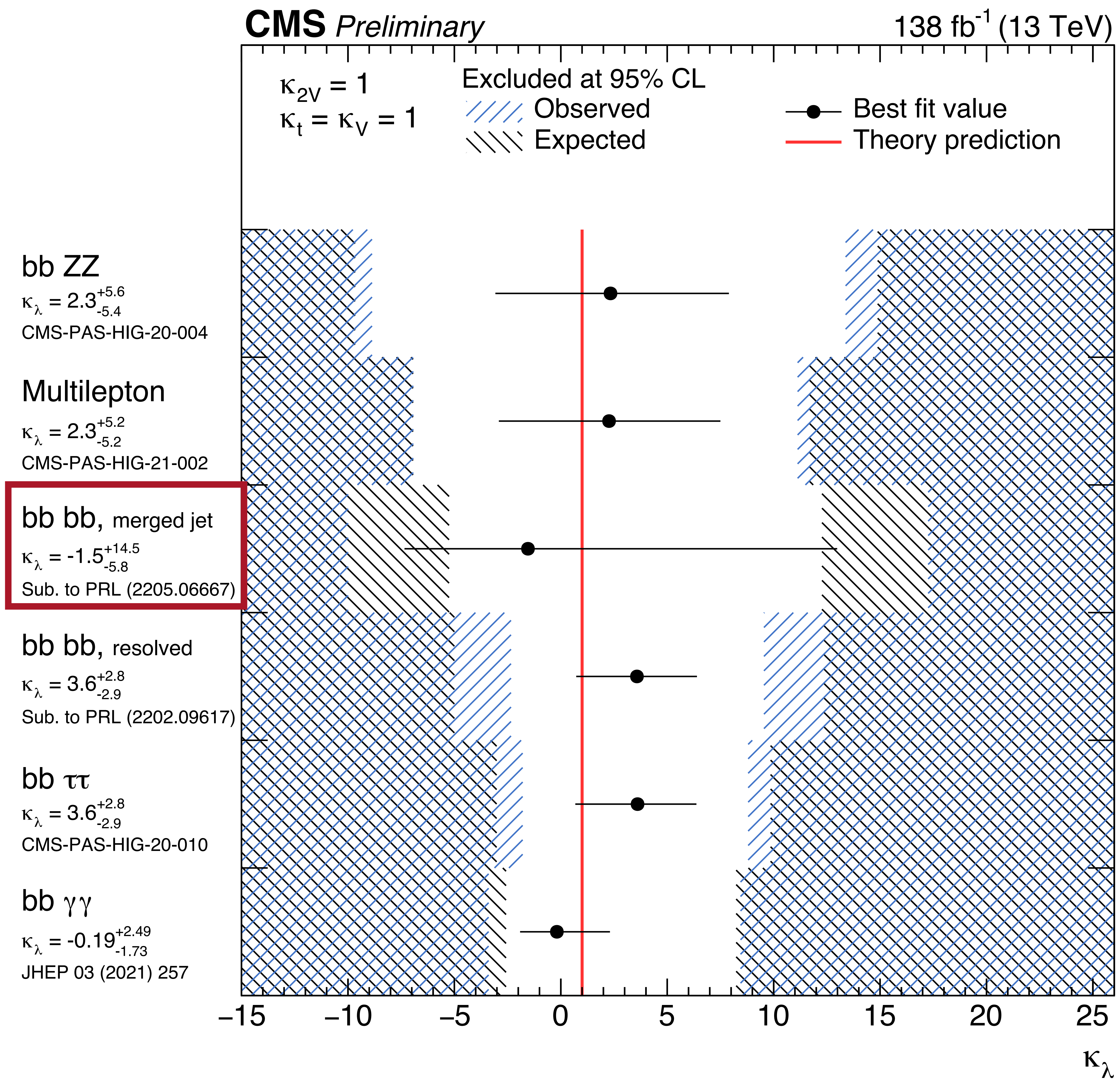

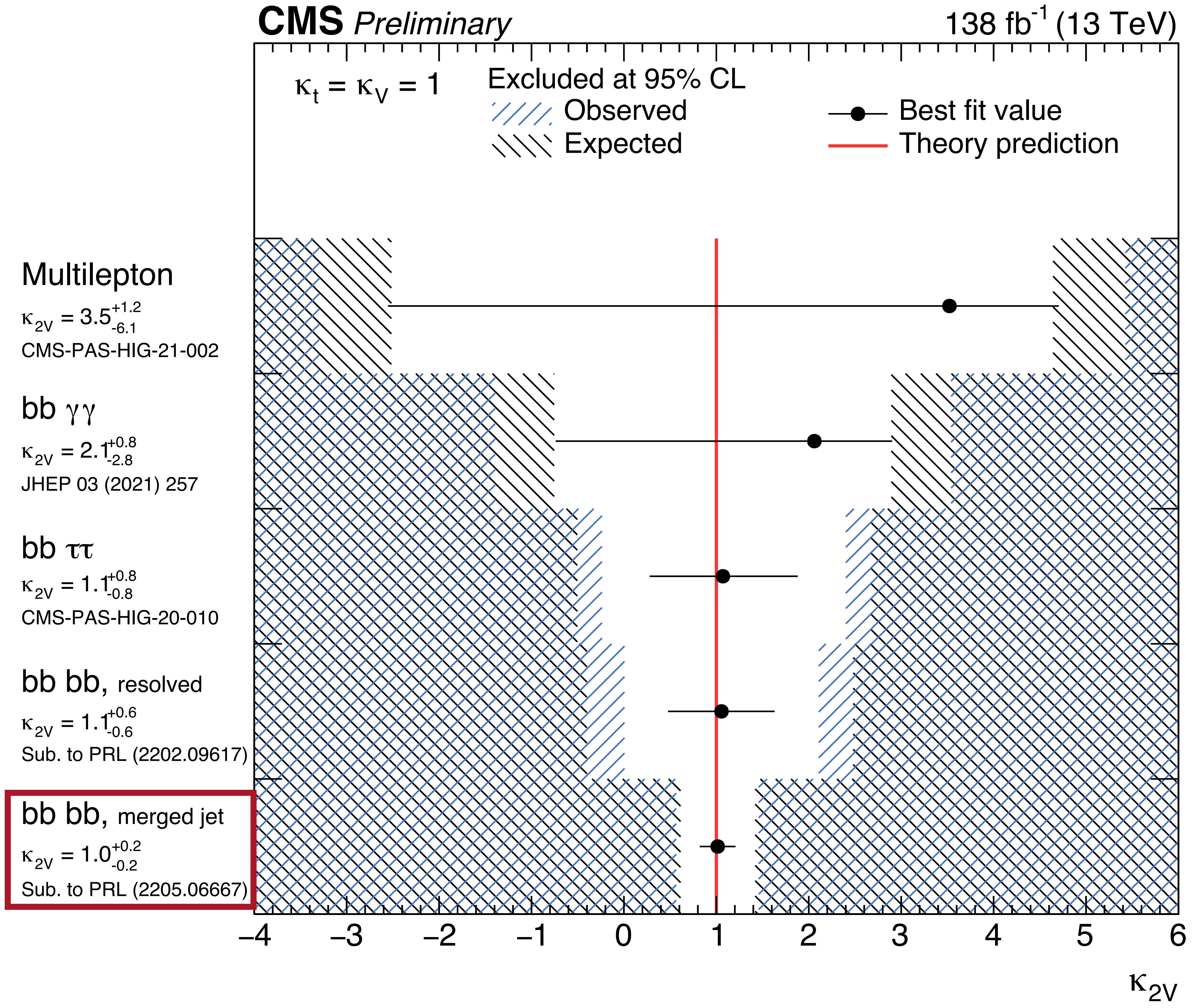

FUTURE HH PROJECTIONS

	Statistical + Systematic	
	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37
combined	3.0	2.6
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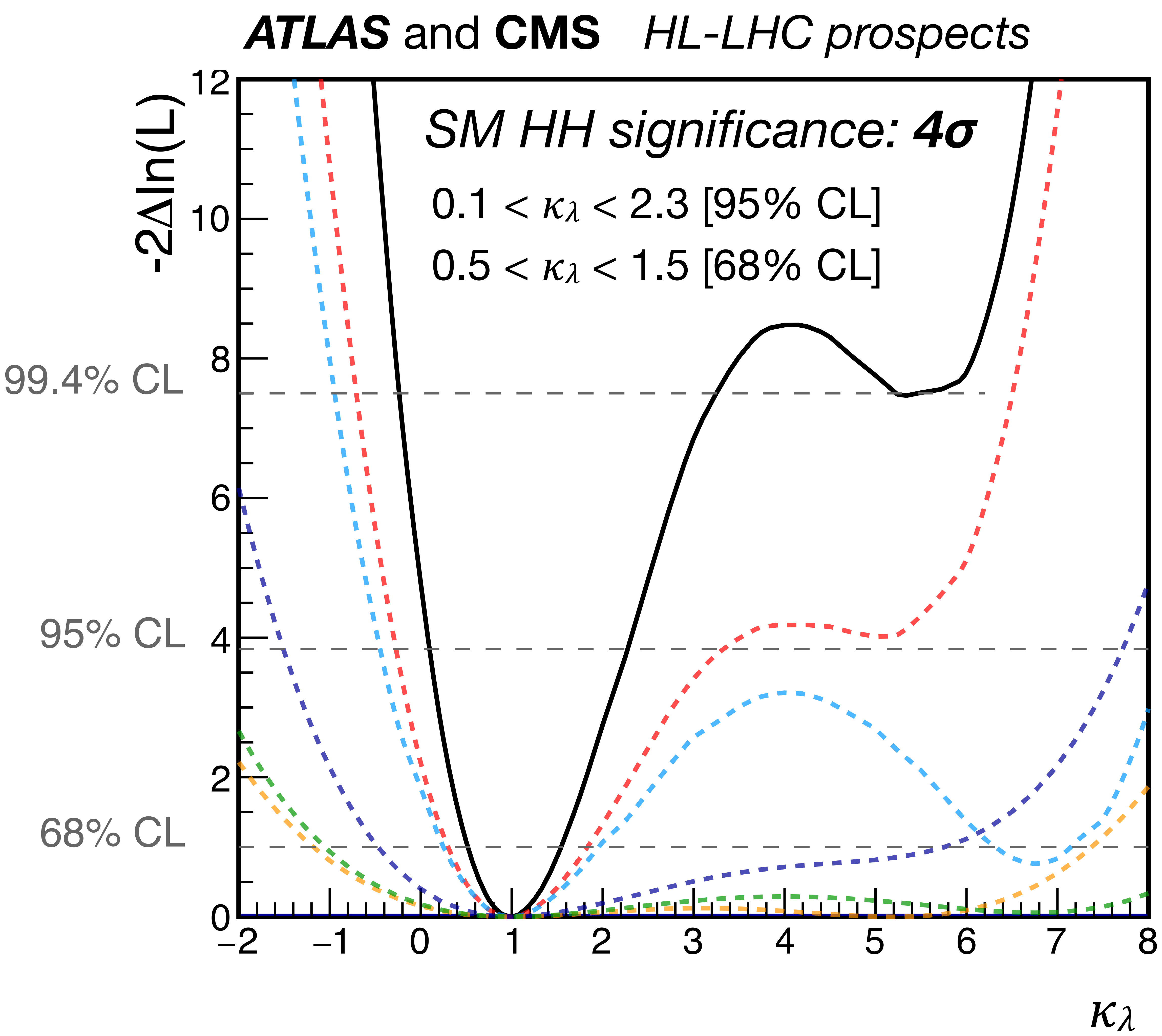

FUTURE HH PROJECTIONS

- Based on 2018 HL-LHC projection, SM HH significance is 4σ for 3000 fb^{-1}
- Boosted bbbb channels ***can put us over the edge of "discovery"***
- Plus many more ***improvements*** anticipated!

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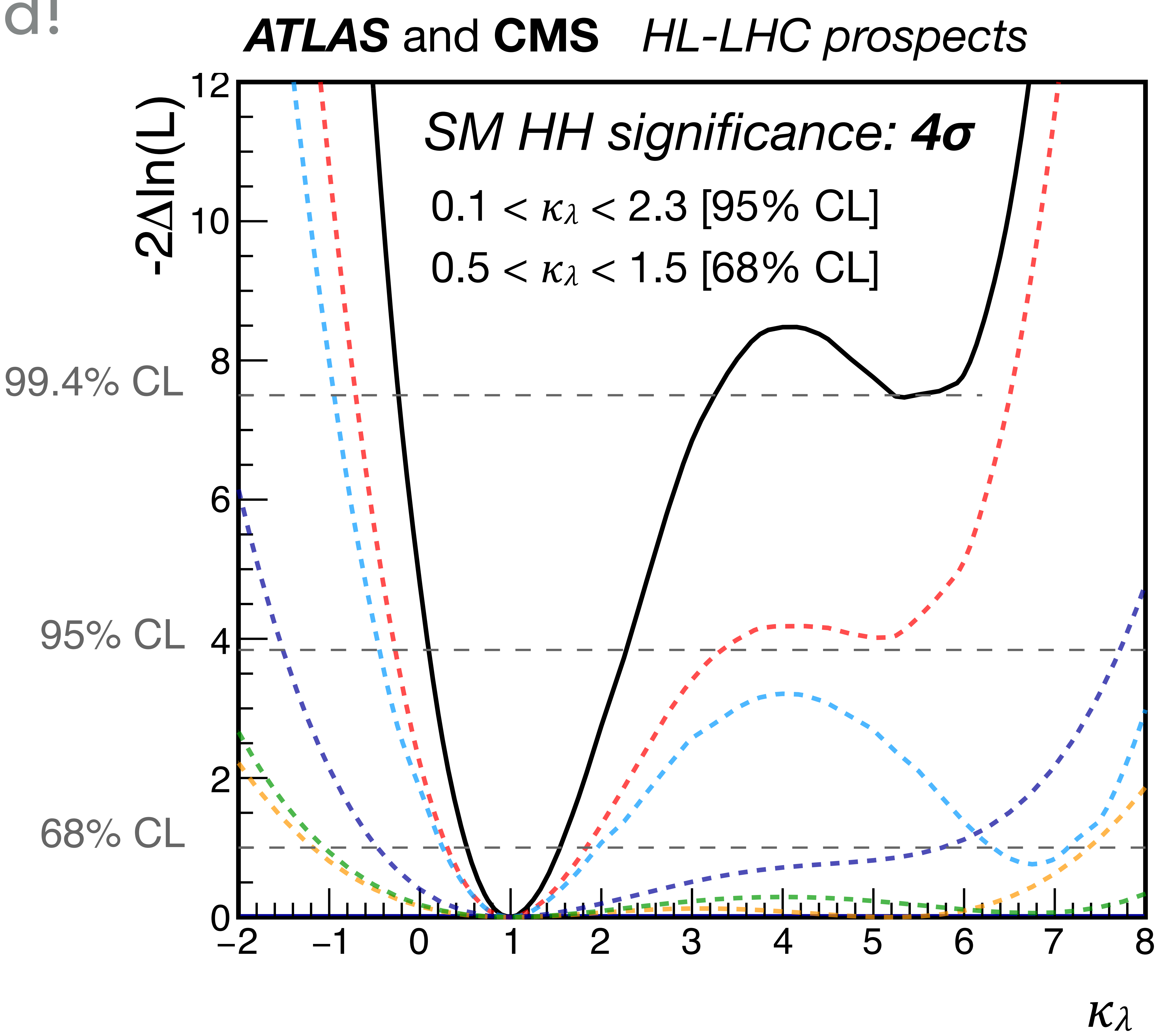

TRIGGER IMPROVEMENTS FOR RUN 3 AND HL-LHC

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CMS-DP-2022-XX

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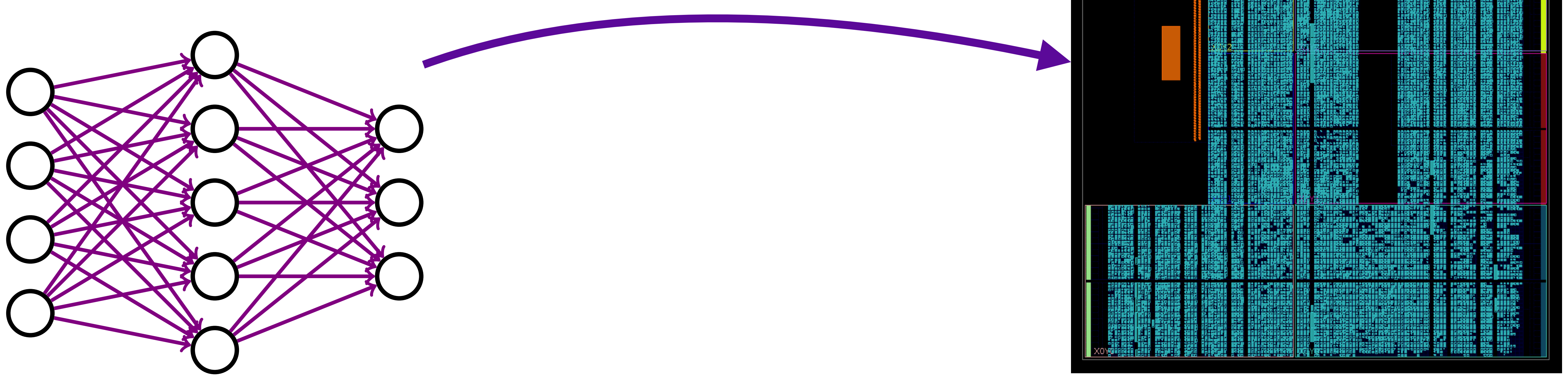

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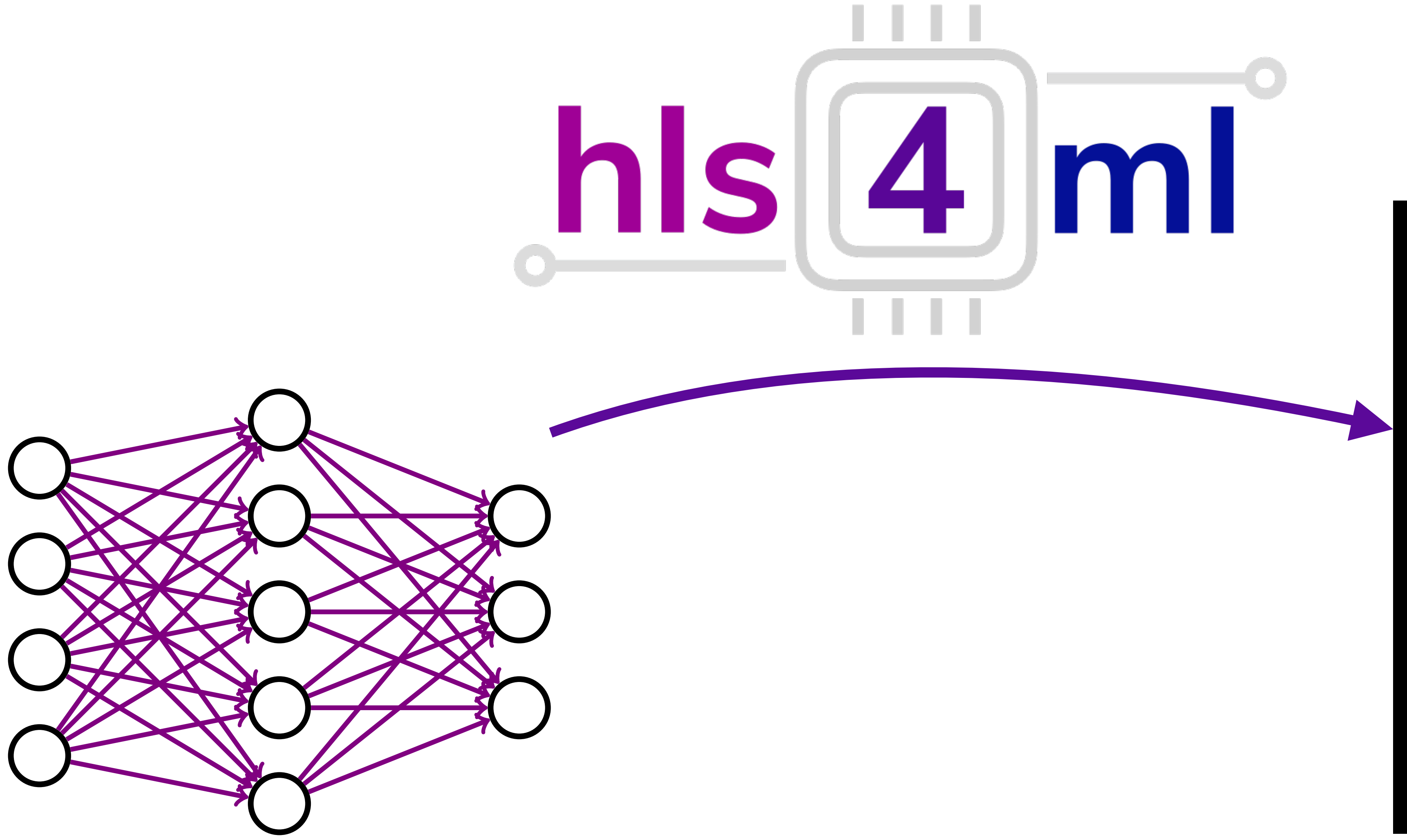
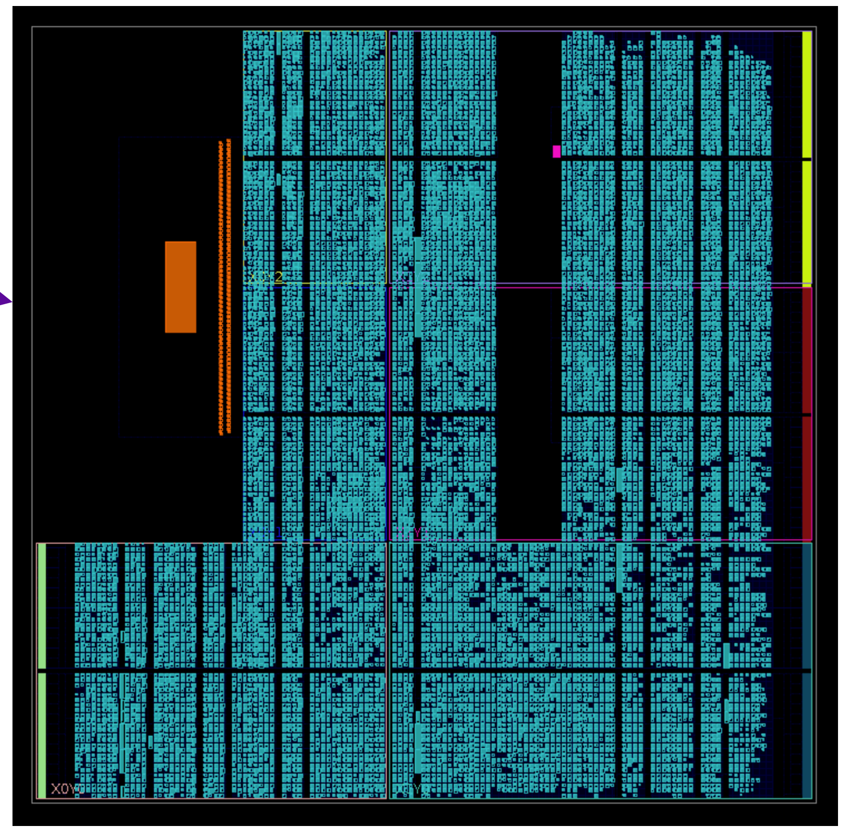
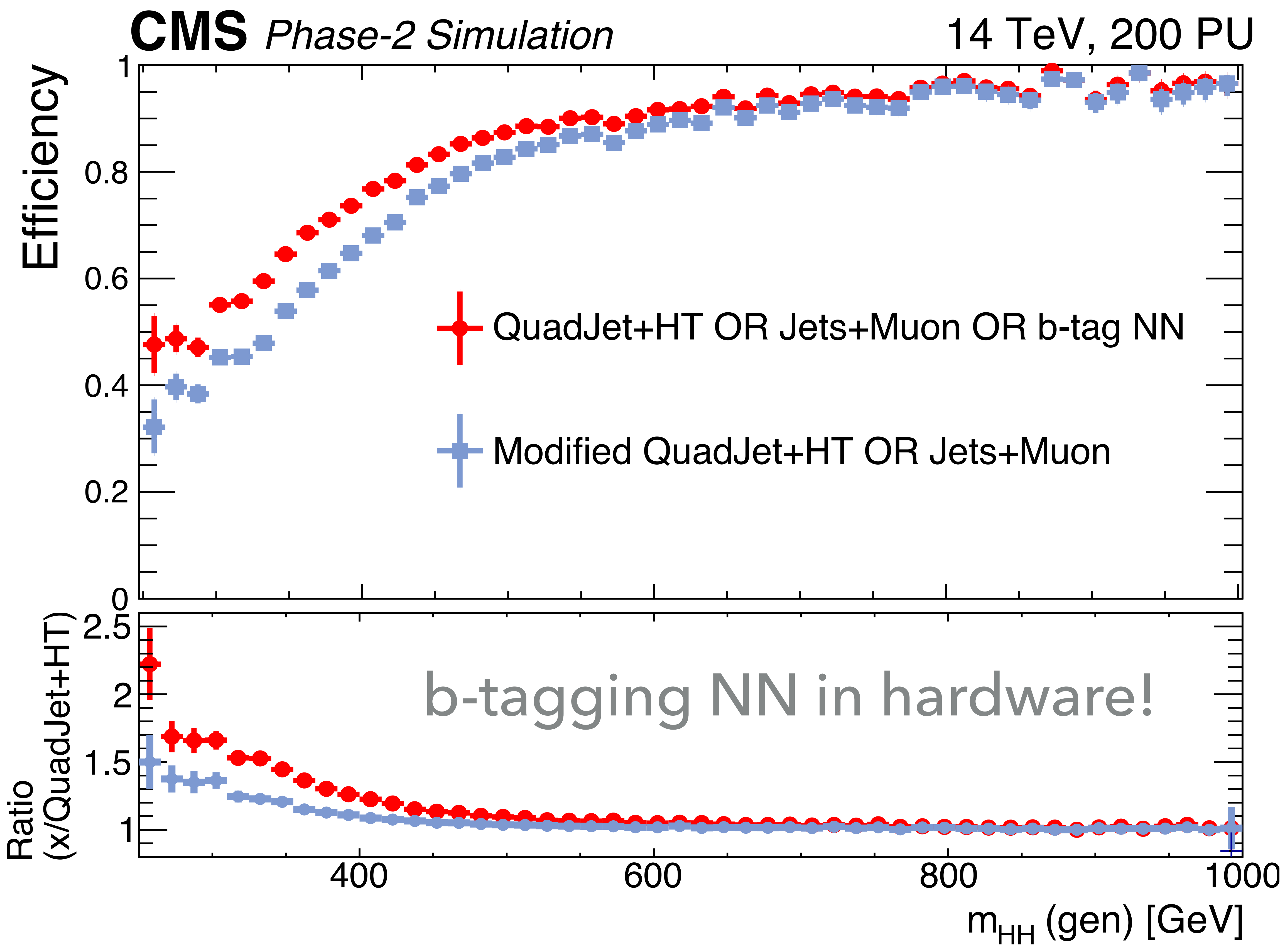
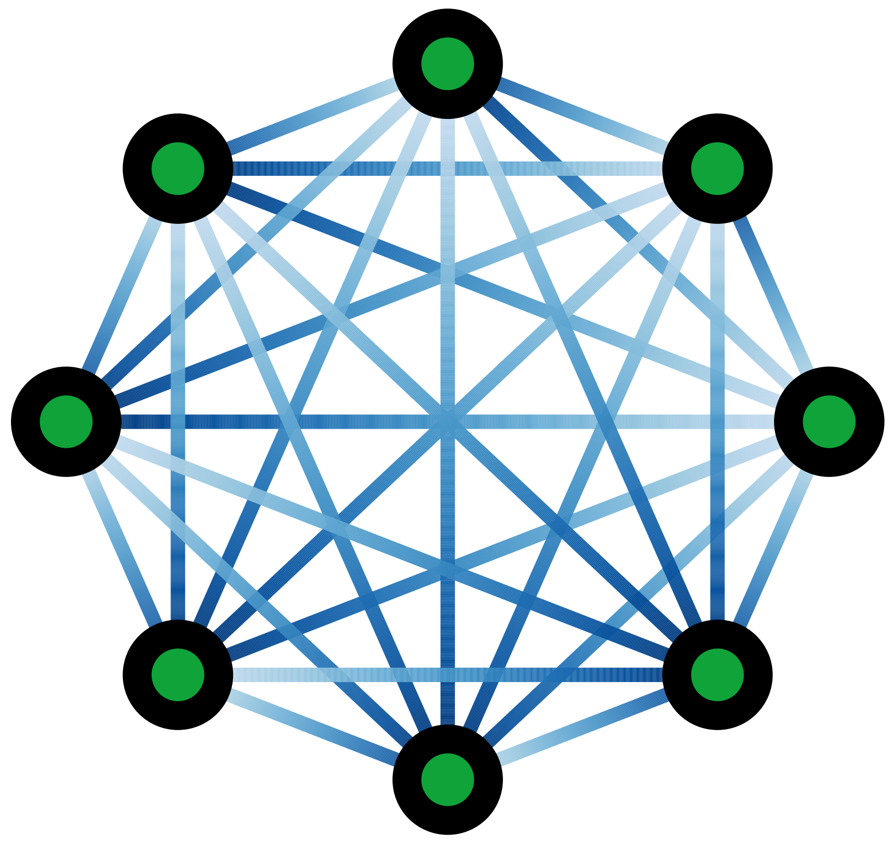




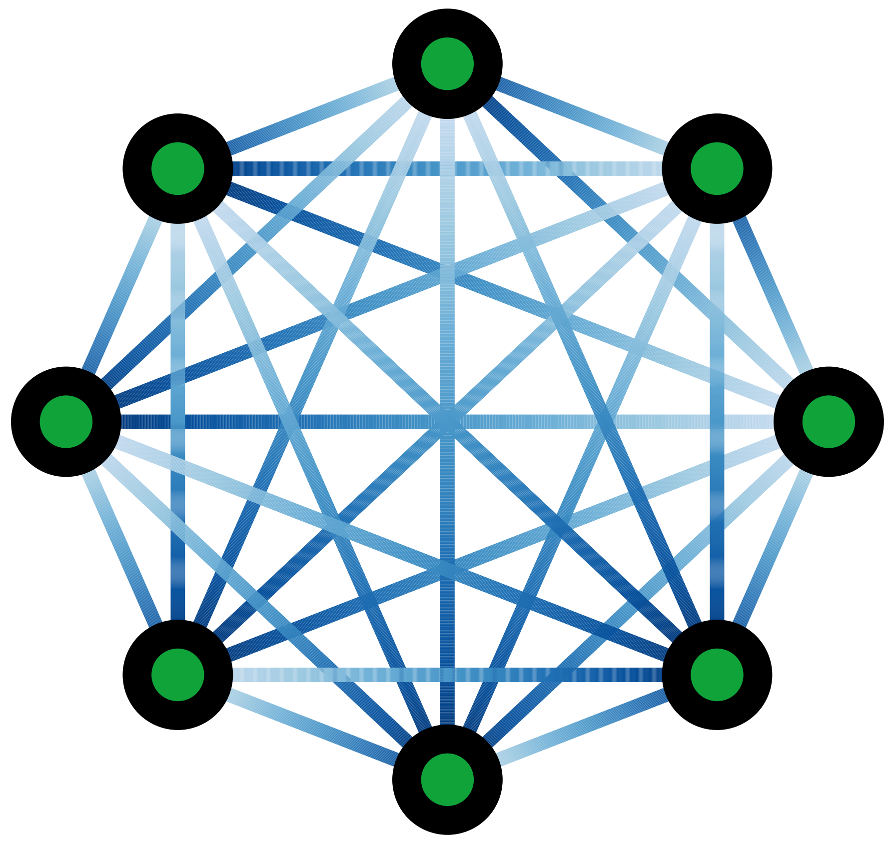


SUMMARY AND OUTLOOK



SUMMARY AND OUTLOOK

- GNNs, NNs that operate on graph-structured data, are state of the art for many HEP tasks including H(bb) tagging



SUMMARY AND OUTLOOK

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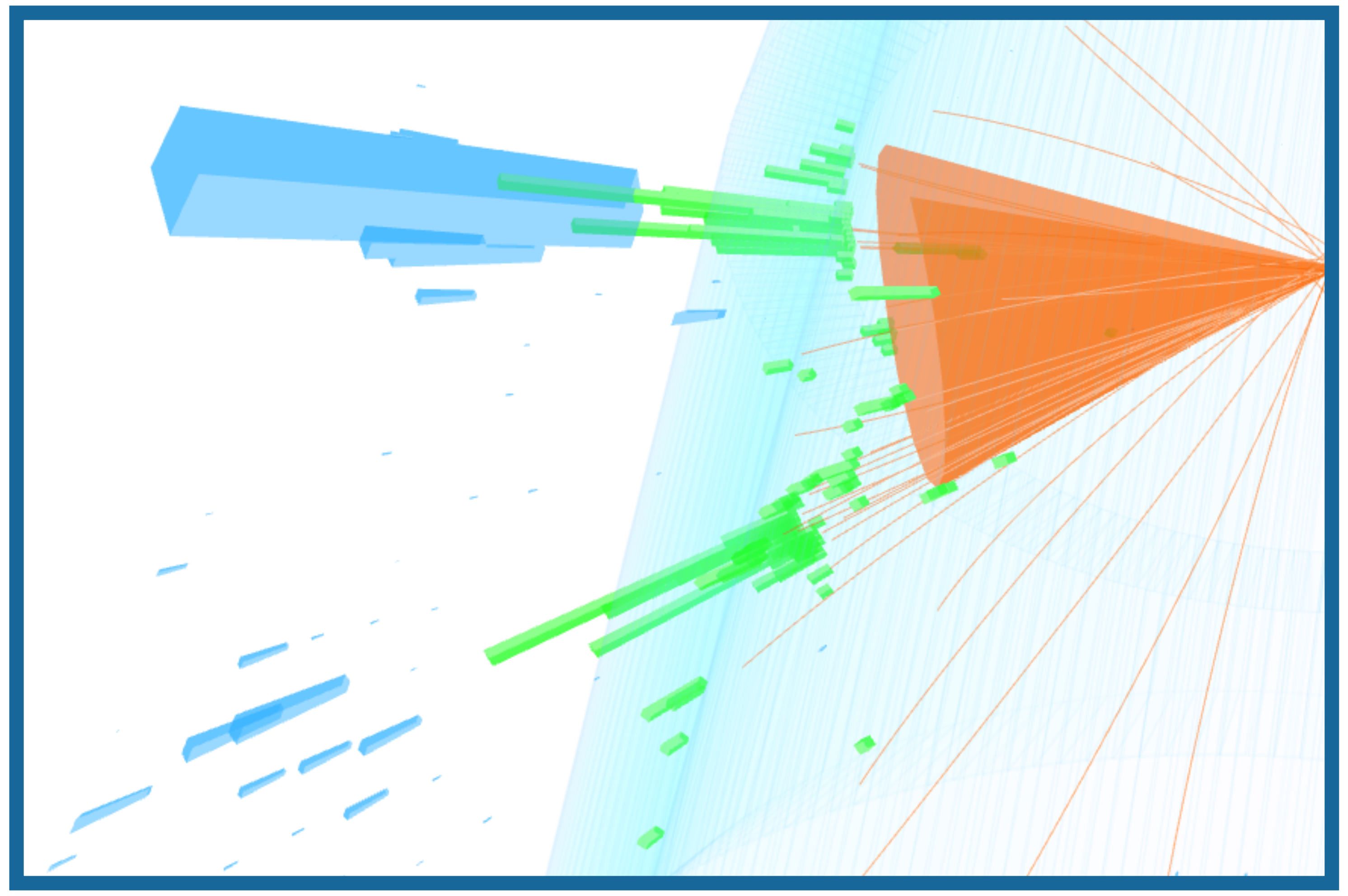
- Improving H(bb) tagging allows us to probe the high-p_T regime and measure Higgs couplings



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- CMS boosted HH search one of the first to use GNNs
  - 95% CL upper limit on HH production observed (expected) to be 9.9 (5.1) × SM
  - Strongest constraints on κ_{2V}: [0.62, 1.41]
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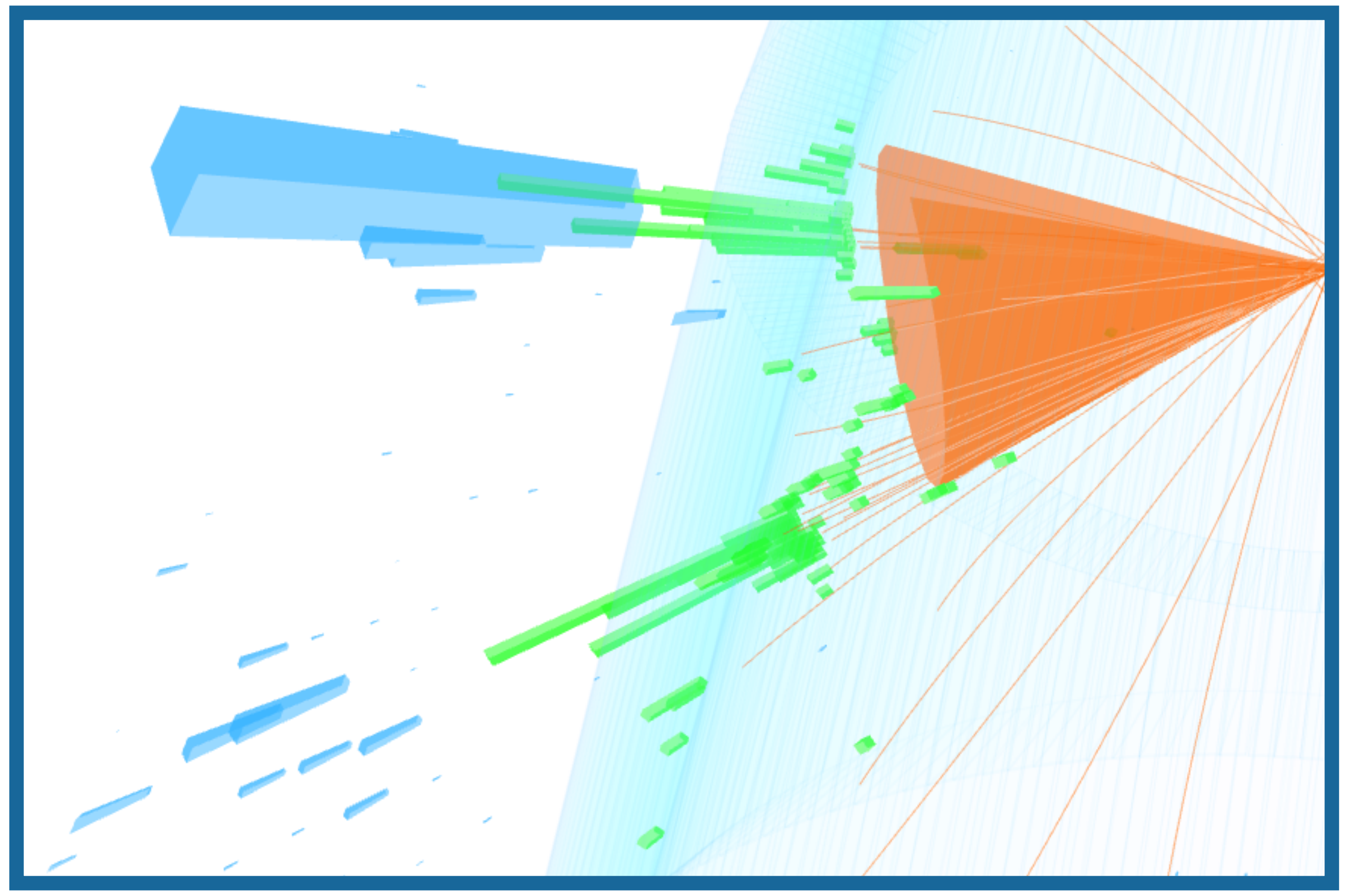

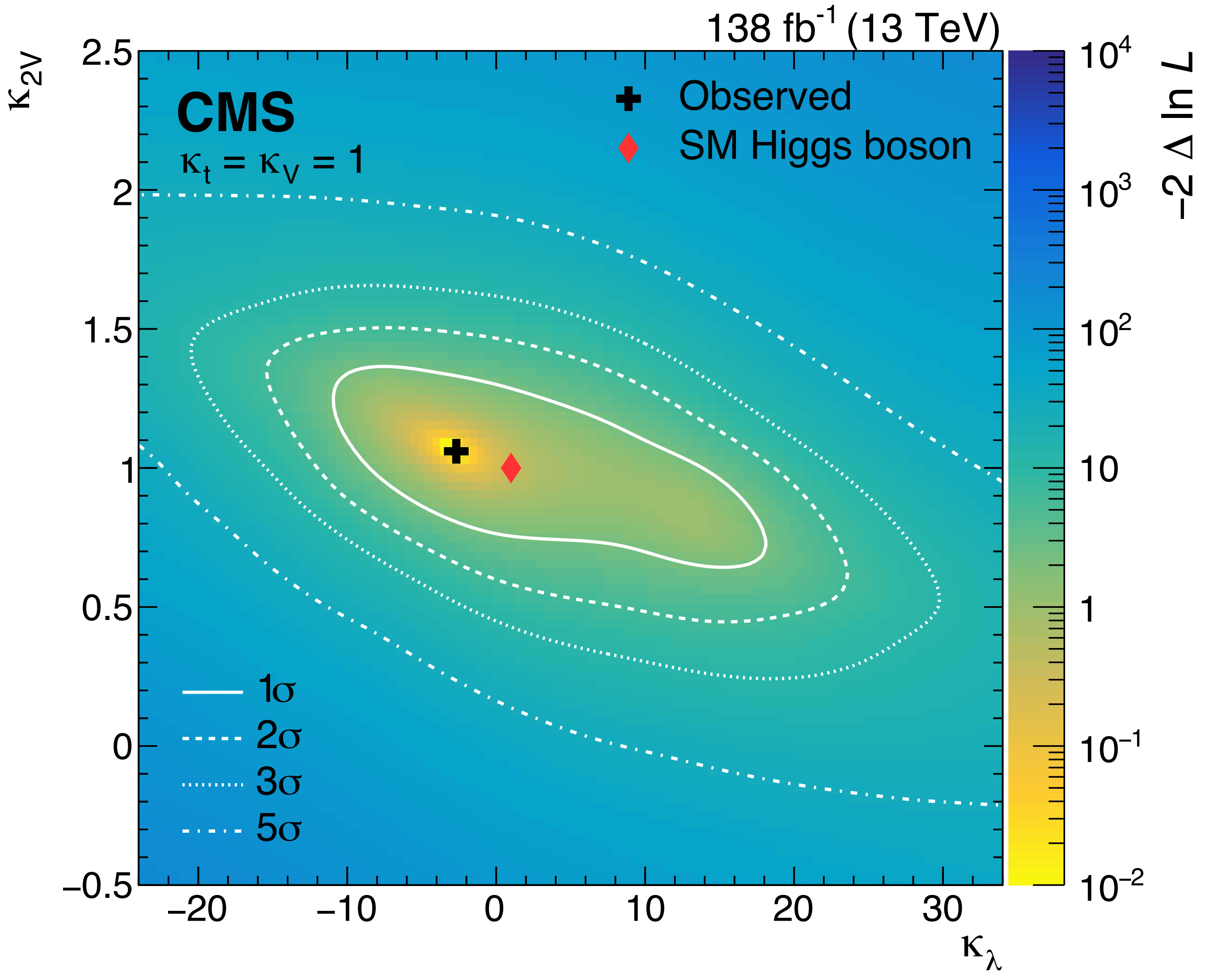

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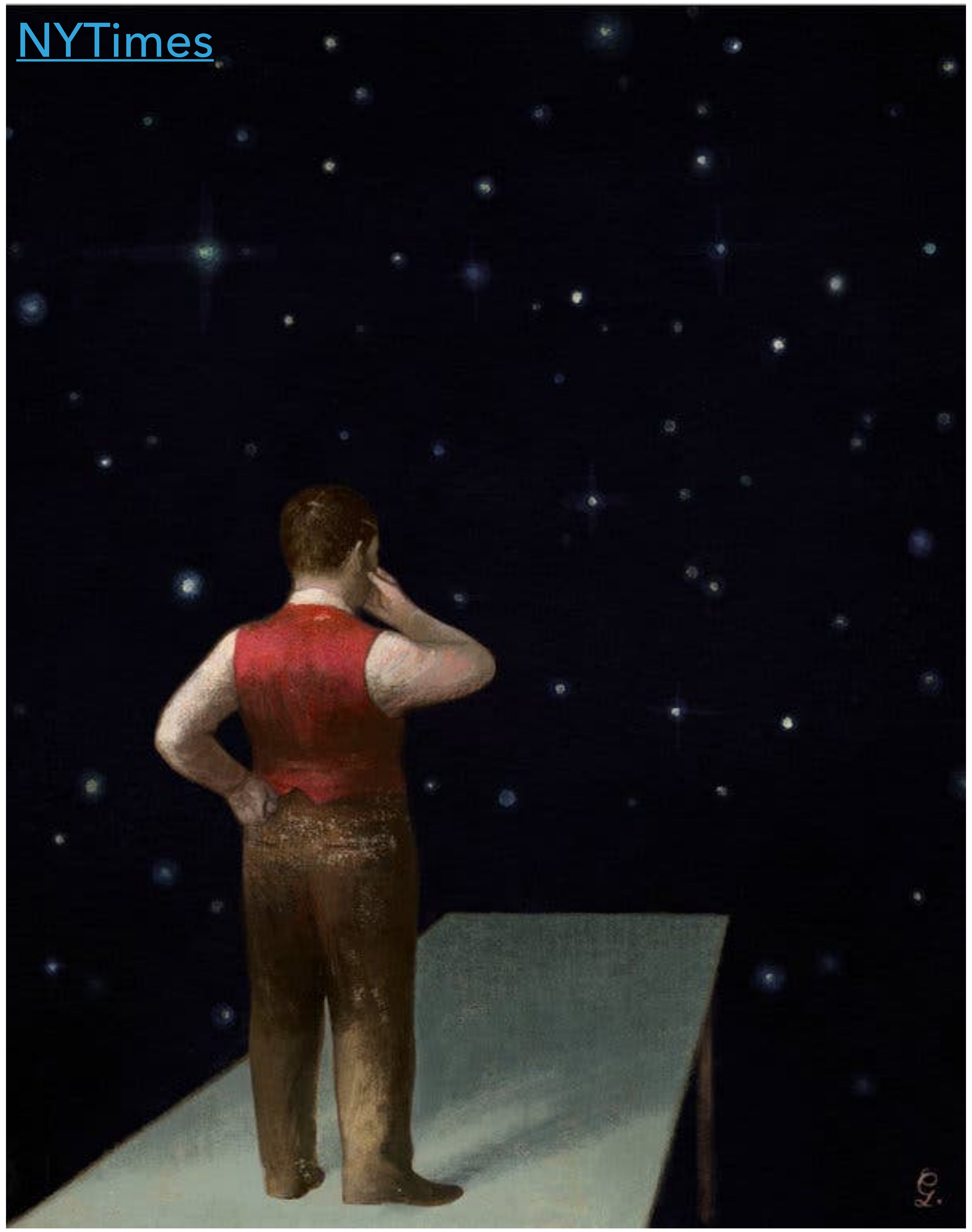
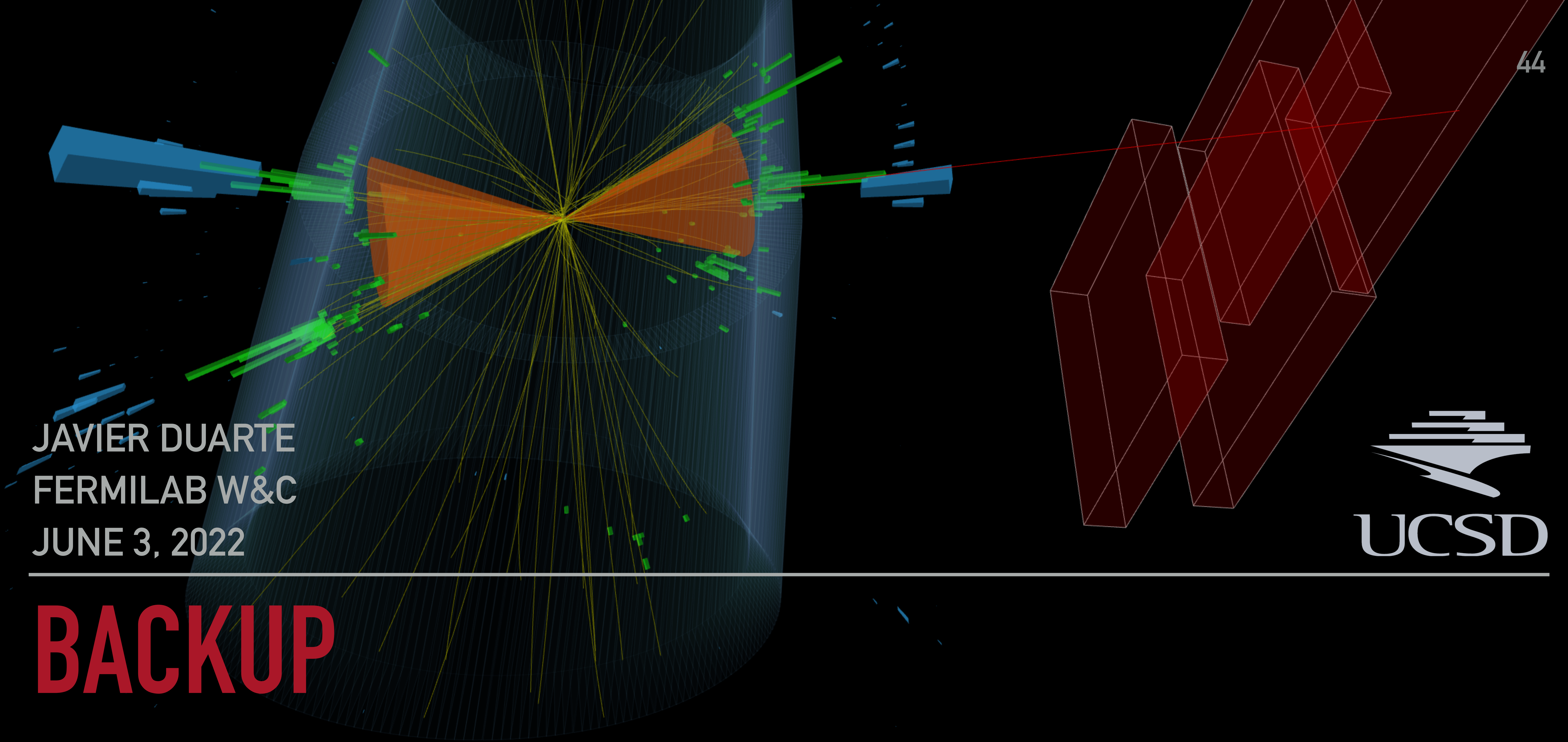


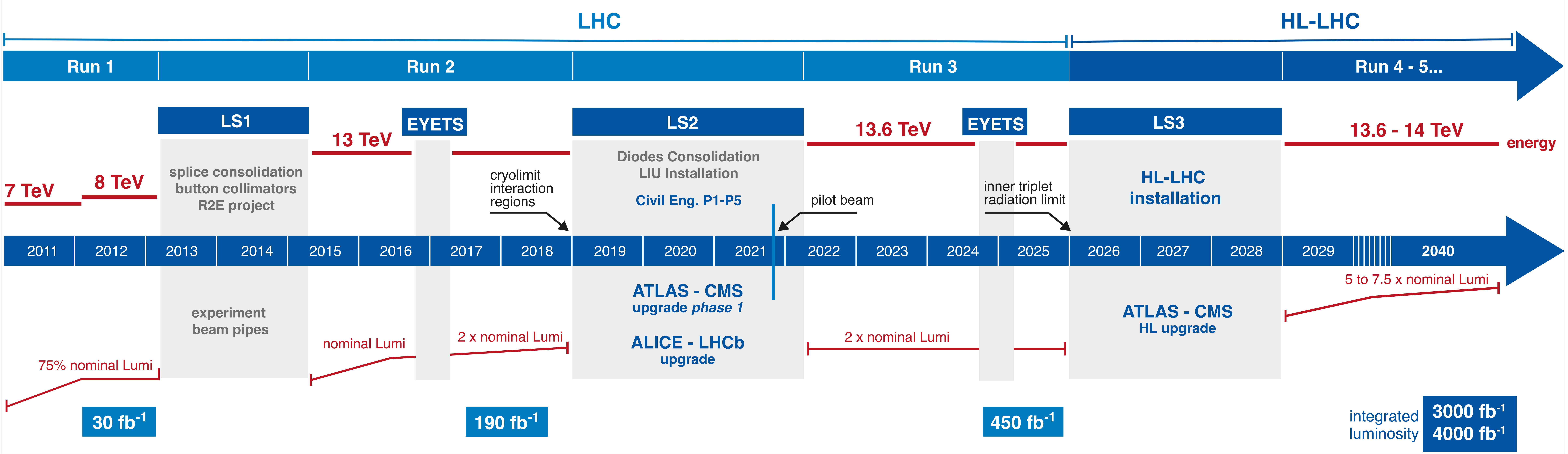


JAVIER DUARTE
FERMILAB W&C
JUNE 3, 2022

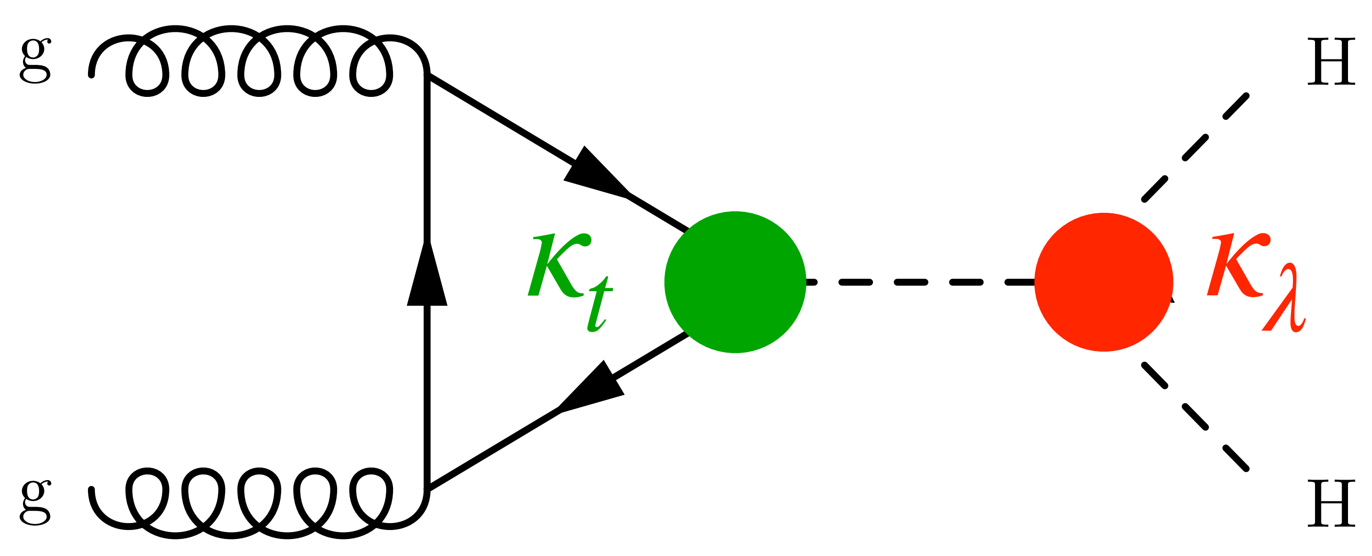
UCSD

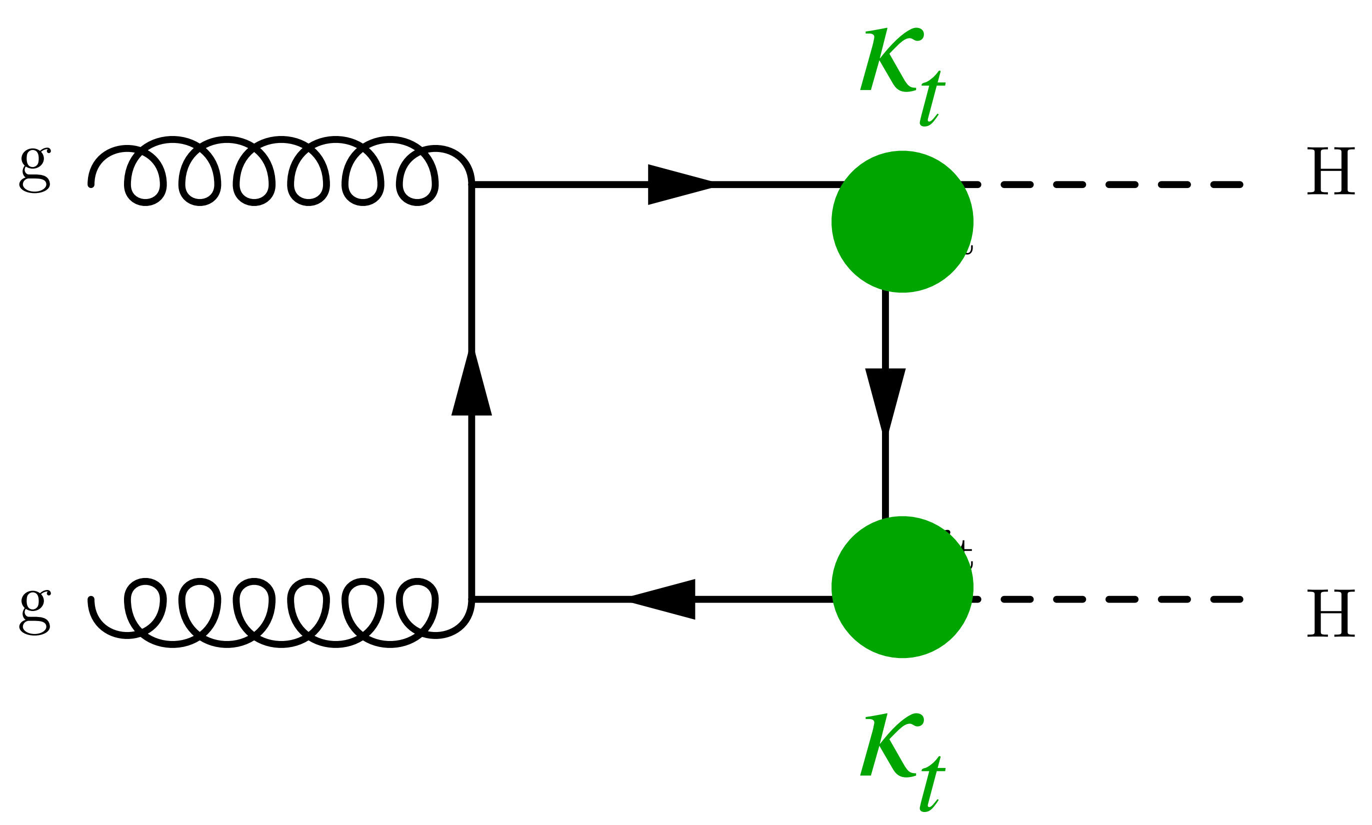
BACKUP

LHC + HL-LHC SCHEDULE



GGF HH INTERPRETATION





$$\mathcal{M} = \kappa_t{}^2\kappa_\lambda{}^2\mathcal{T} + \kappa_t{}^2\mathcal{B}$$

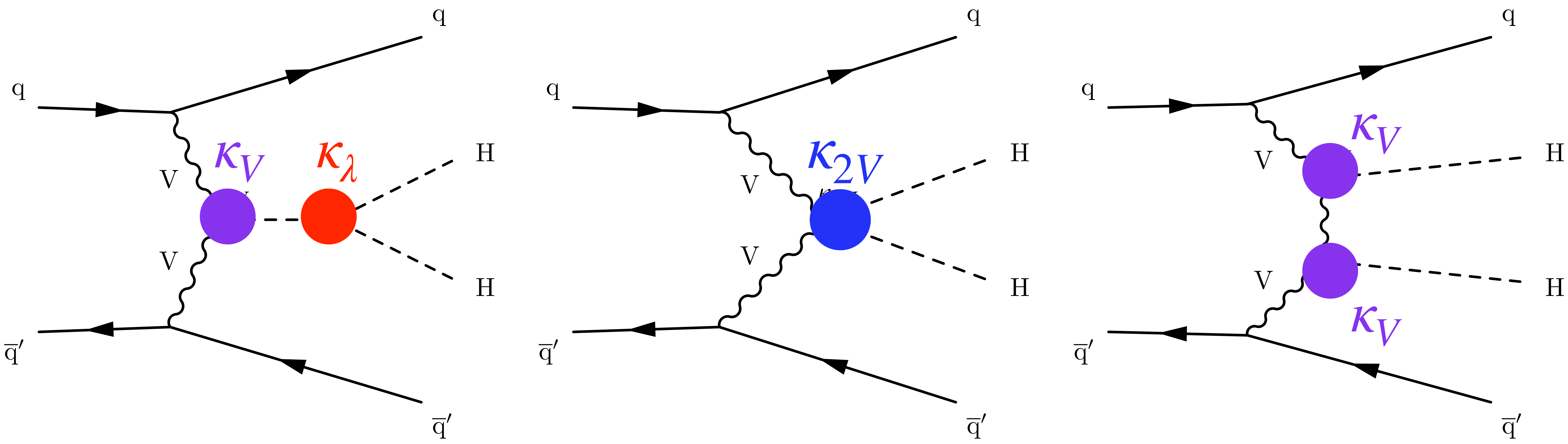
$$\sigma(\kappa_t, \kappa_\lambda) \sim |\mathcal{M}|^2 = \kappa_t{}^2\kappa_\lambda{}^2|\mathcal{T}|^2 + \kappa_t{}^4|\mathcal{B}|^2 + \kappa_t{}^3\kappa_\lambda|\mathcal{T}^*\mathcal{B} + \mathcal{B}^*\mathcal{T}|$$

$$= \kappa_t{}^2\kappa_\lambda{}^2 t + \kappa_t{}^4 b + \kappa_t{}^3\kappa_\lambda i$$

- Templates $(\kappa_\lambda, \kappa_t) = (1,1), (2.45,1), (5,1)$ chosen for continuous morphing

$$D_{\mathrm{ggF}}(\kappa_\lambda, \kappa_t) = \mu\ \mu_{\mathrm{ggF}} \sum_i^3 f^i_{\mathrm{ggF}}(\kappa_\lambda, \kappa_t) D^i_{\mathrm{ggF}}$$

VBF HH INTERPRETATION



$$\mathcal{M} = \kappa_V \kappa_\lambda \mathcal{A} + \kappa_V{}^2 \mathcal{B} + \kappa_{2V} \mathcal{C}$$

$$\sigma(\kappa_\lambda, \kappa_V, \kappa_{2V}) \sim |\mathcal{M}|^2 = \kappa_V{}^2 \kappa_\lambda{}^2 a + \kappa_V{}^4 b + \kappa_{2V}{}^2 c + \kappa_V{}^3 \kappa_\lambda i_{ab} + \kappa_V \kappa_{2V} \kappa_\lambda i_{ac} + \kappa_V{}^2 \kappa_{2V} i_{bc}$$

- Templates $(\kappa_{2V}, \kappa_V, \kappa_\lambda) = (1,1,1), (1,1,0), (1,1,2), (1,0,1), (1,2,1), (1.5,1,1)$ chosen for continuous morphing

$$D_{\mathrm{VBF}}(\kappa_{2V}, \kappa_V, \kappa_\lambda) = \mu\ \mu_{\mathrm{VBF}} \sum_i^6 f^i_{\mathrm{VBF}}(\kappa_{2V}, \kappa_V, \kappa_\lambda) D^i_{\mathrm{VBF}}$$

COMPACT MUON SOLENOID

- Specialized components to measure different particles
- 100 million channels