Recent advances in Higgs physics and the Standard Model from ATLAS and CMS

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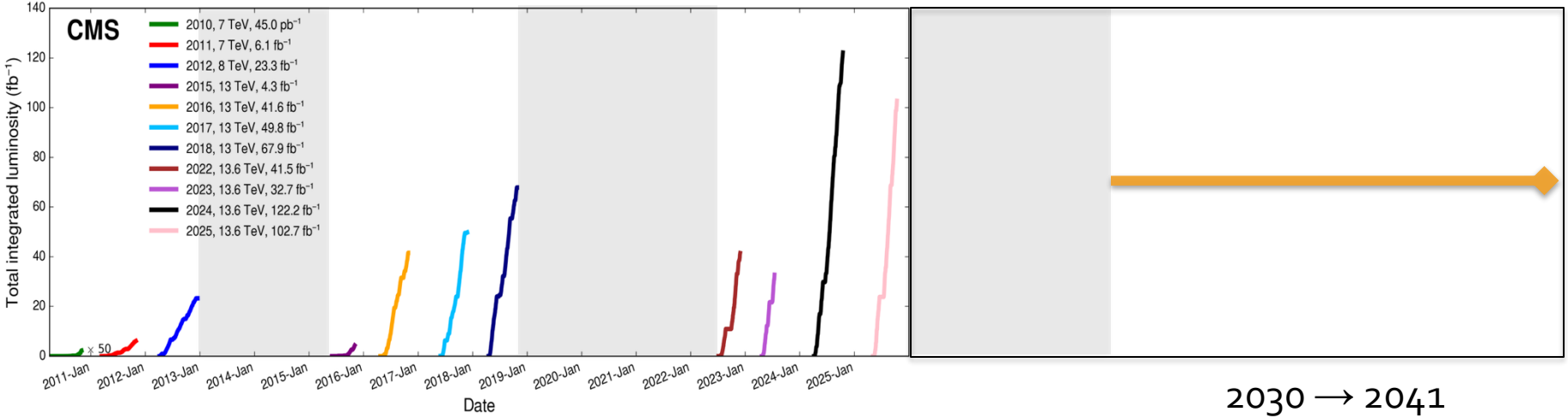
Brookhaven Forum, October 2025

The LHC roadmap: ~90% of the full dataset to come

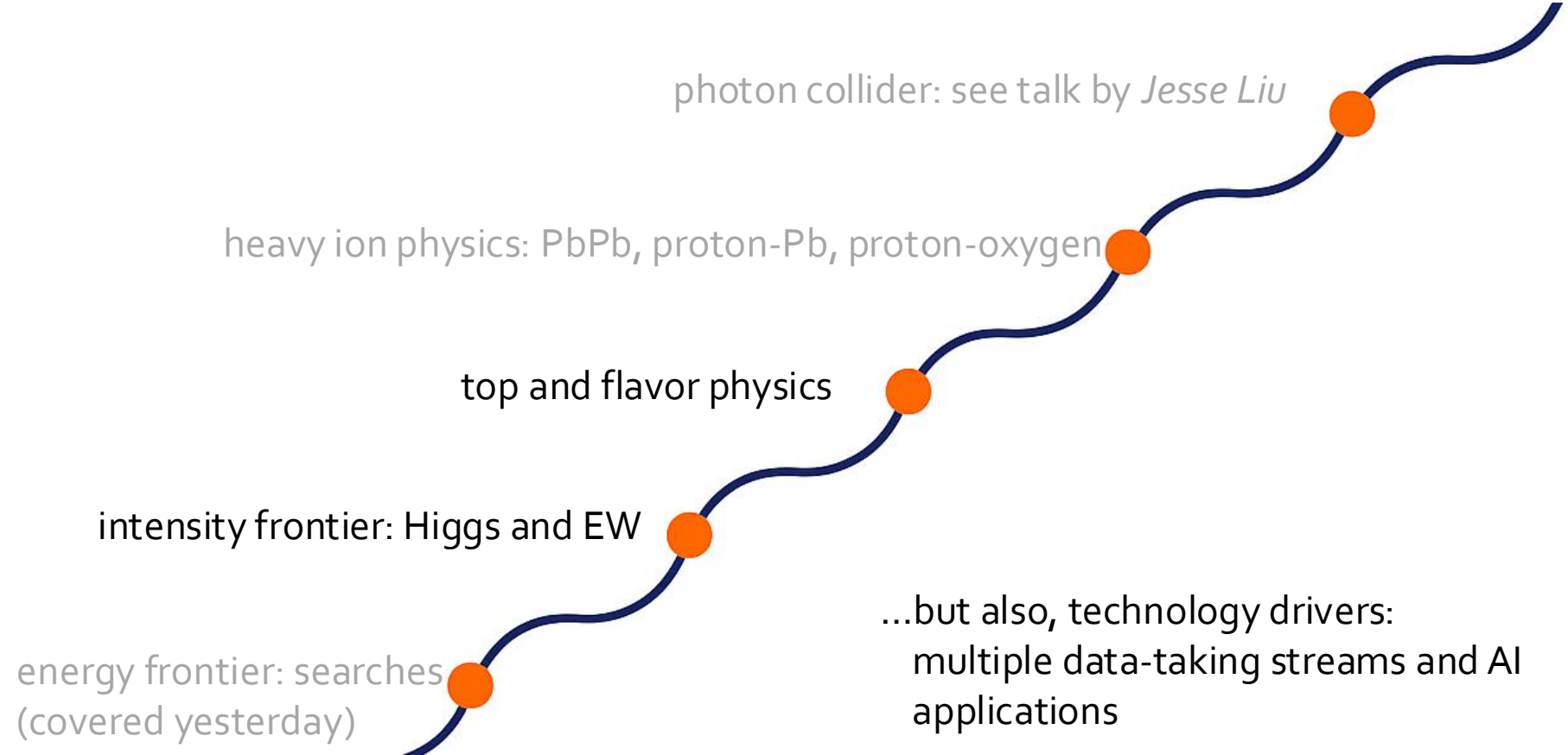
The goal is 3000 fb^{-1}



2030 ⟶ 2041

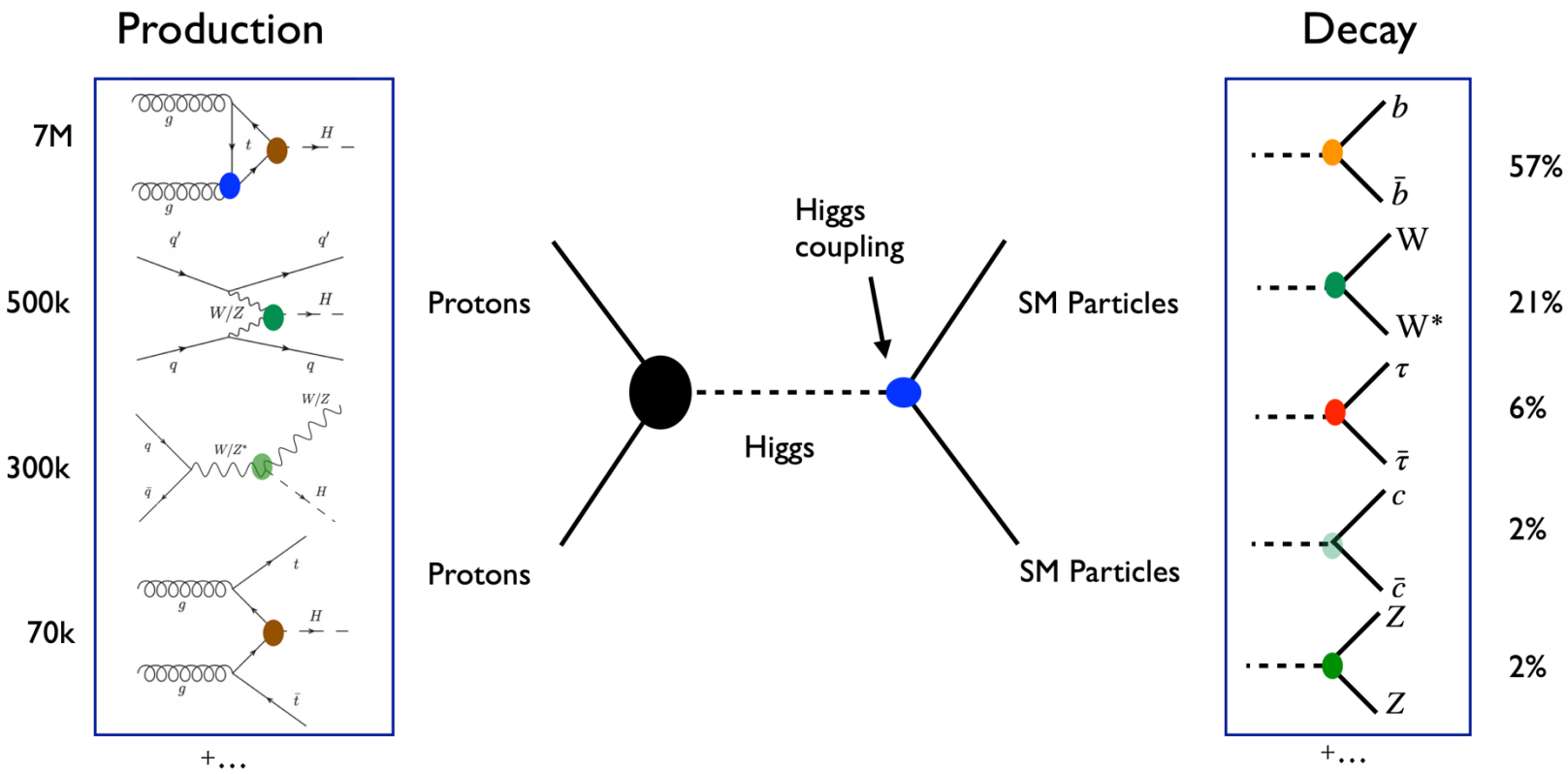
Run-1 Run-2 Run-3 Run-4

CMS/ATLAS: many experiments at once



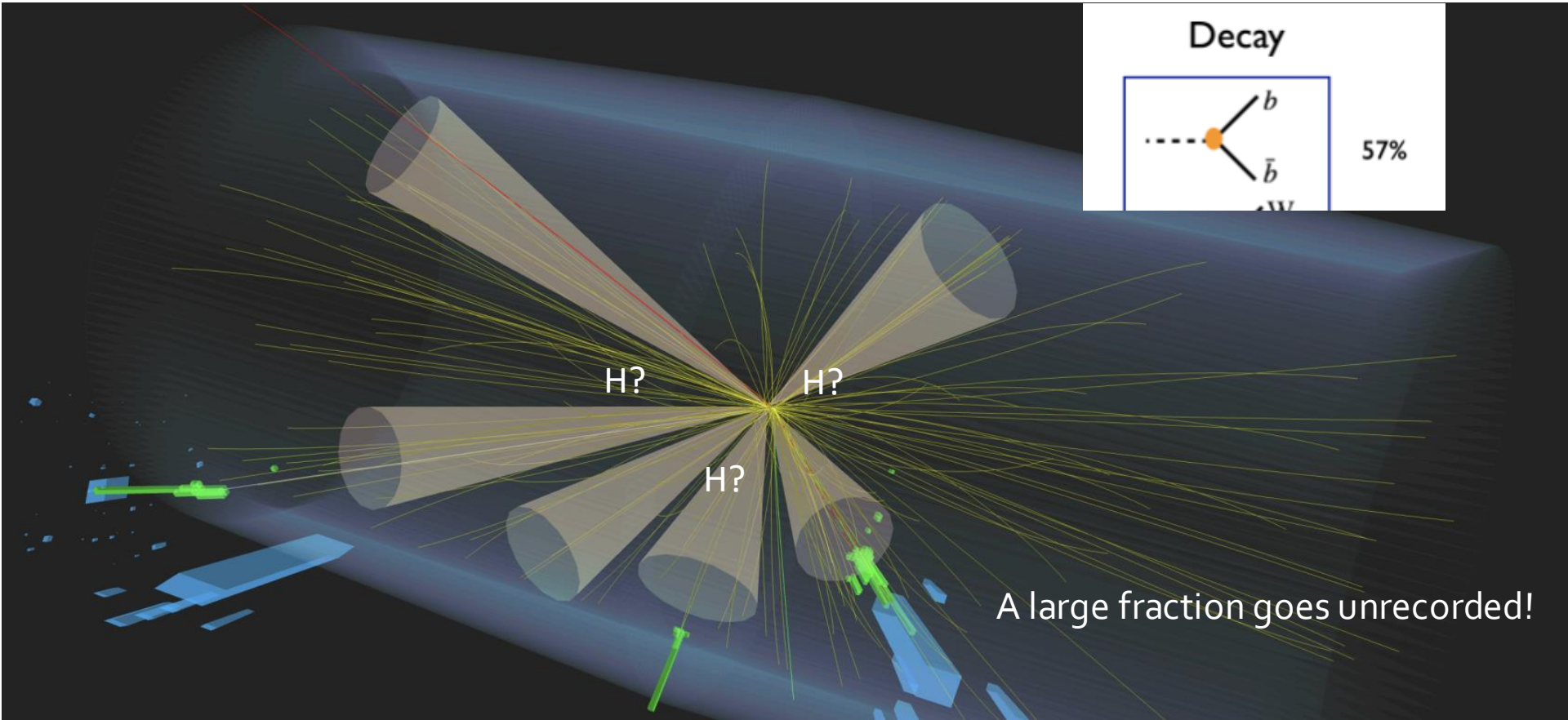
…but also, technology drivers:
multiple data-taking streams and AI applications

Example: a Higgs story

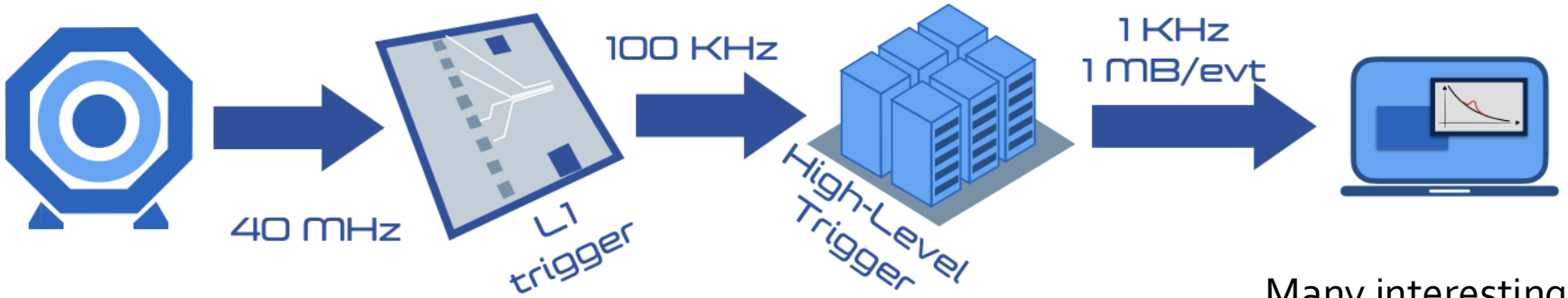


*Run-2 approx. numbers

Hadronic decays: key to target multi –H production



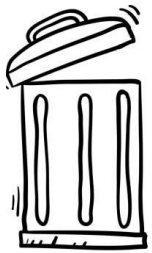
LHC's data-taking strategy



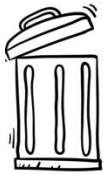
1MB/event
1 TB/sec

Many interesting processes at high p_T

+ very high p_T $H \to \bar{b}b$

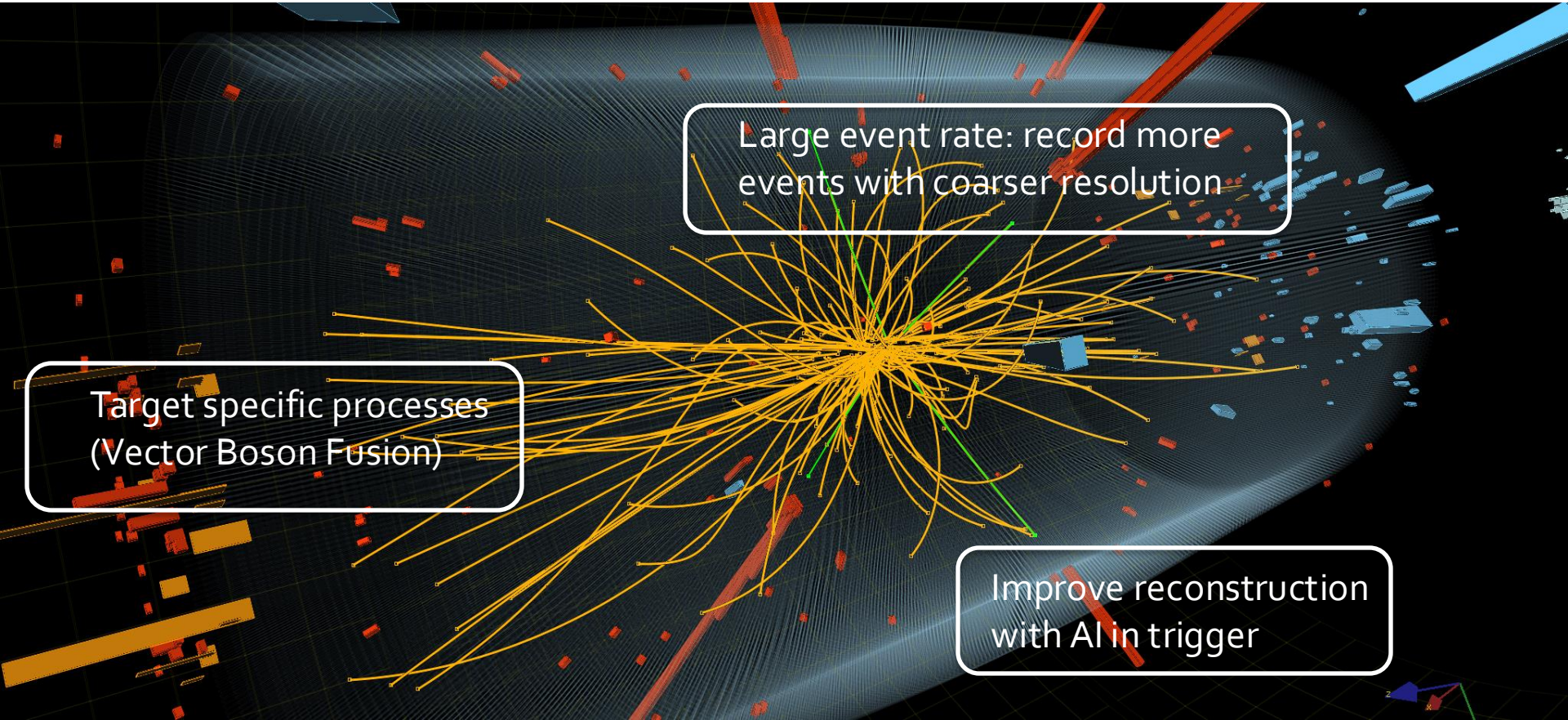


Low p_T $H \to \bar{b}b$

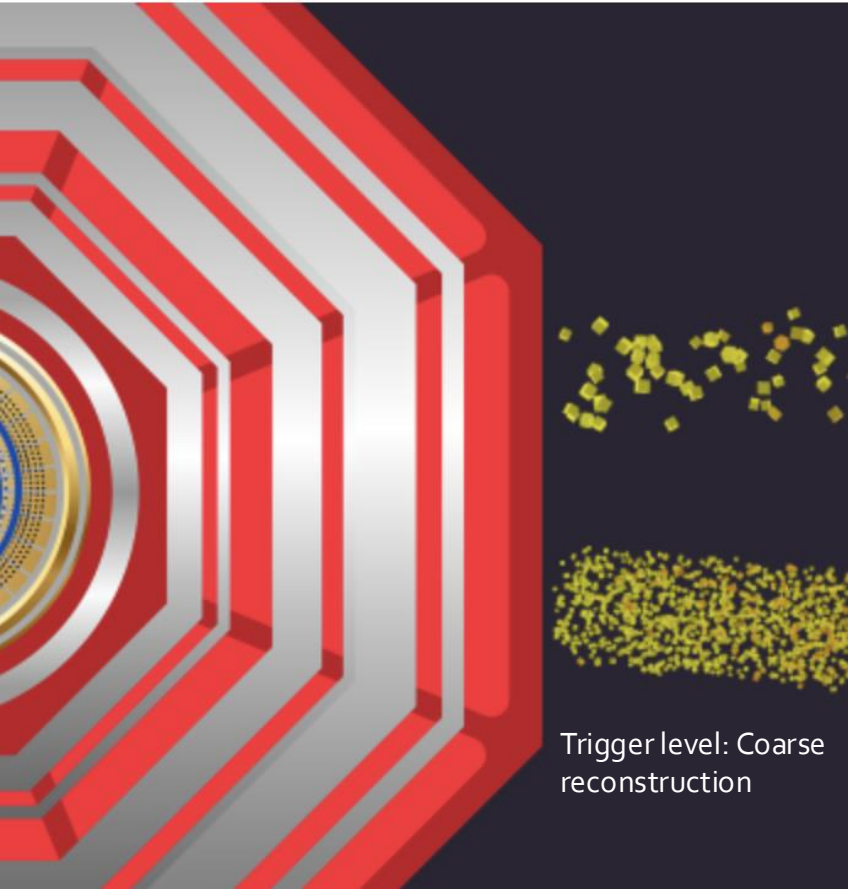


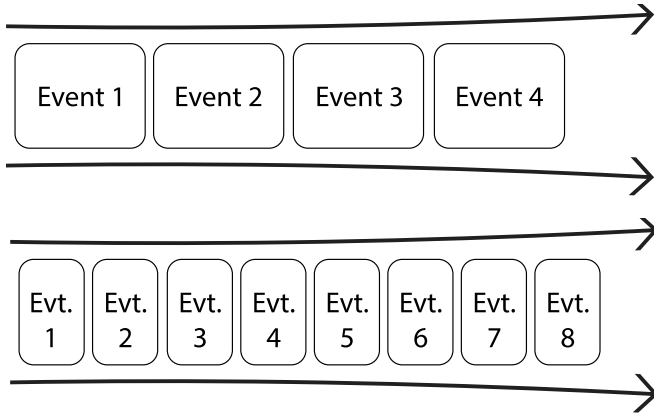
Medium p_T $H \to \bar{b}b$

How to target rare and low p_T processes



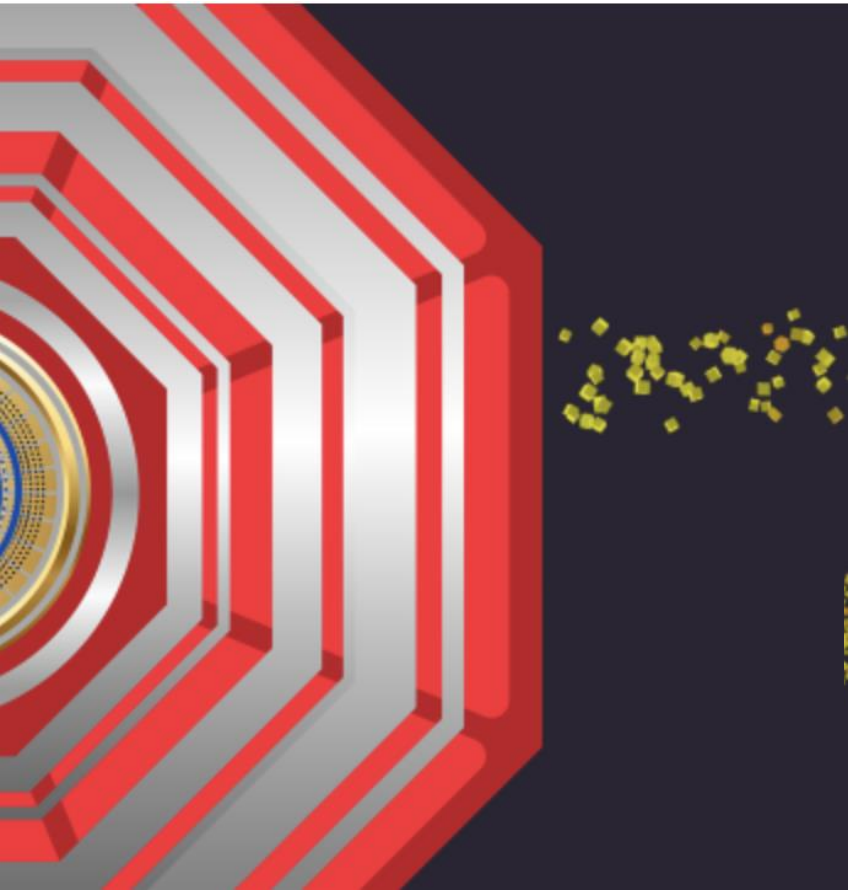
Technology drivers: adding a coarse stream

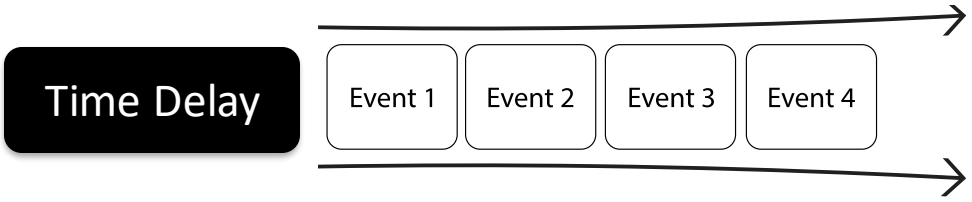




Trigger level analysis (ATLAS) or Scouting (CMS)

Technology drivers: delaying data processing



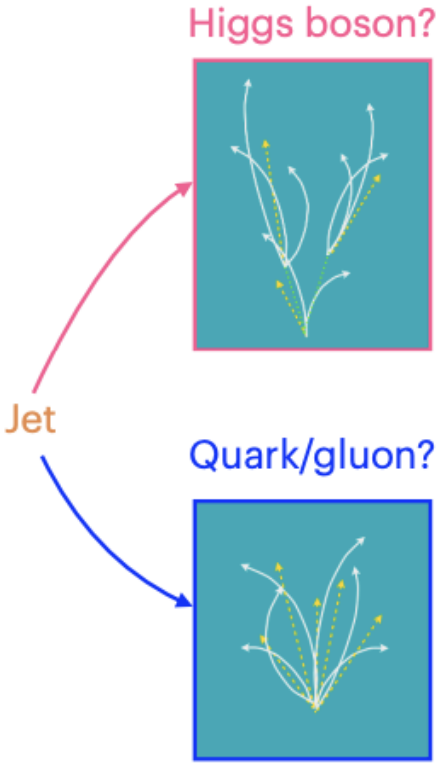


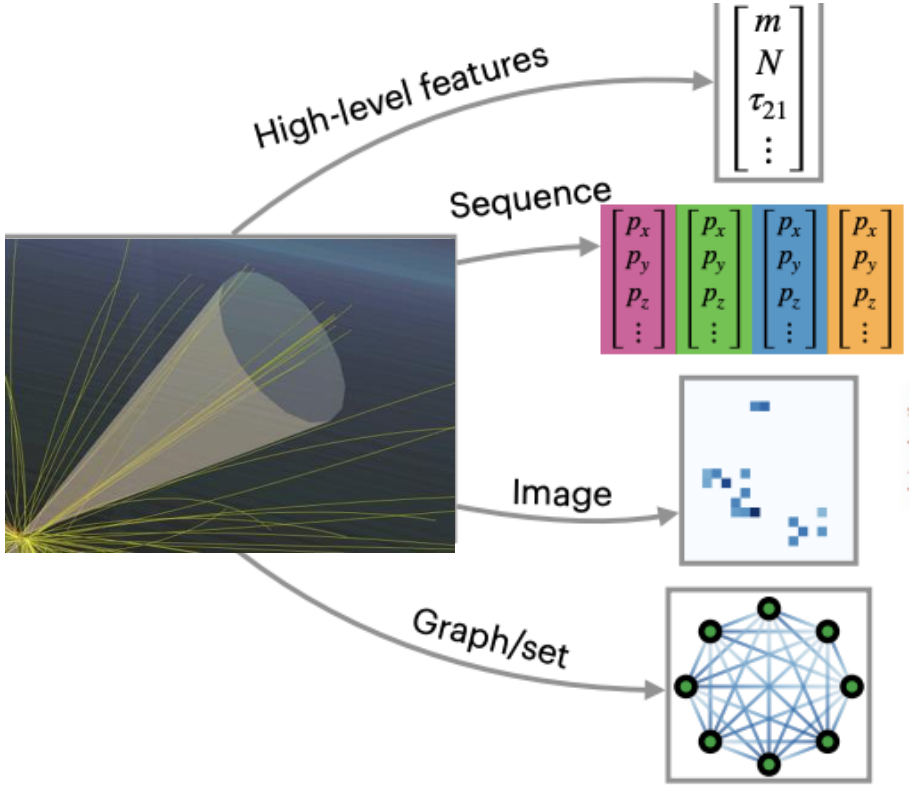
Delayed stream (ATLAS)
or Parking (CMS)

Work around computing constraints, target:

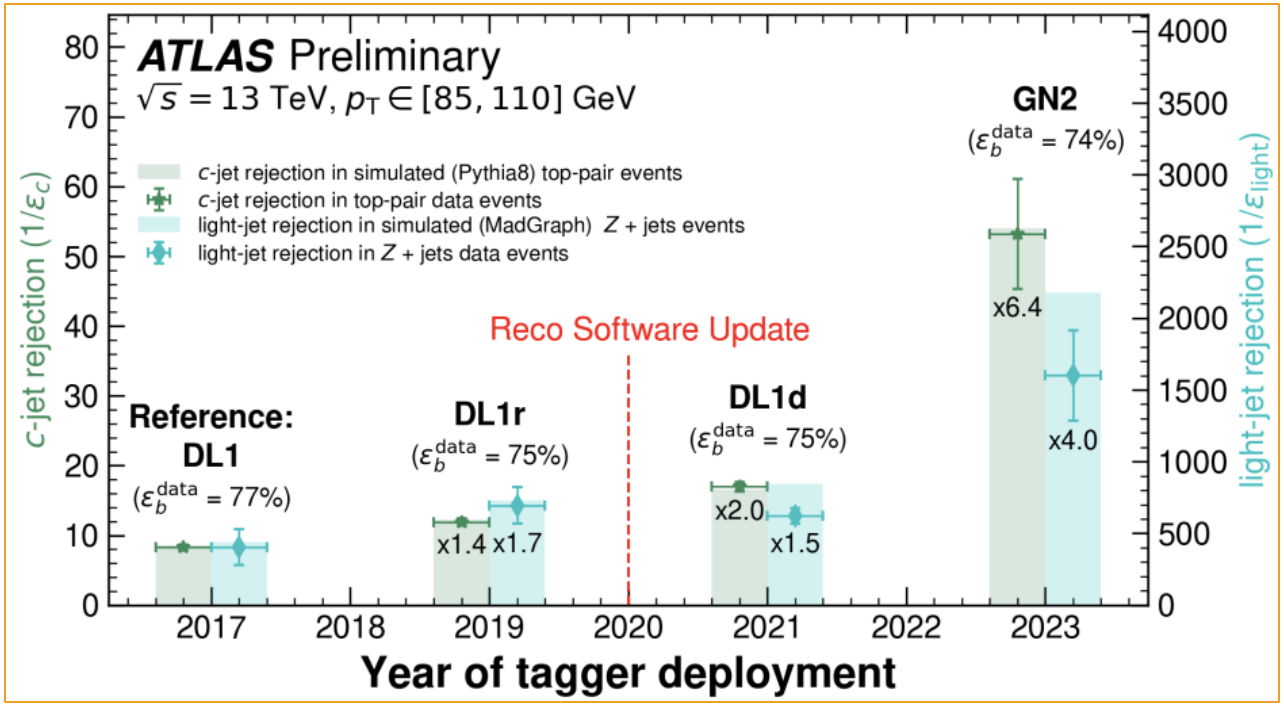
- 2 forward quarks
- 4 low p_T b-quarks
- 2 low p_T muons

Technology drivers: accelerating jet ID with ML



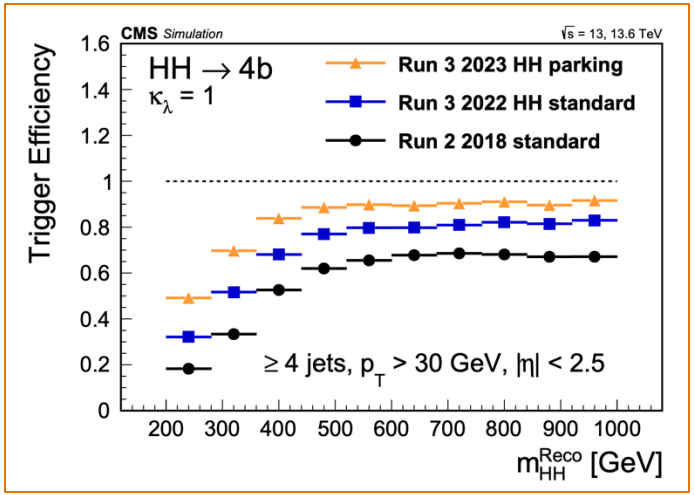


ATLAS SOTA transformer model for b-jet ID (GN2)



ATLAS-FTAG-2023-05

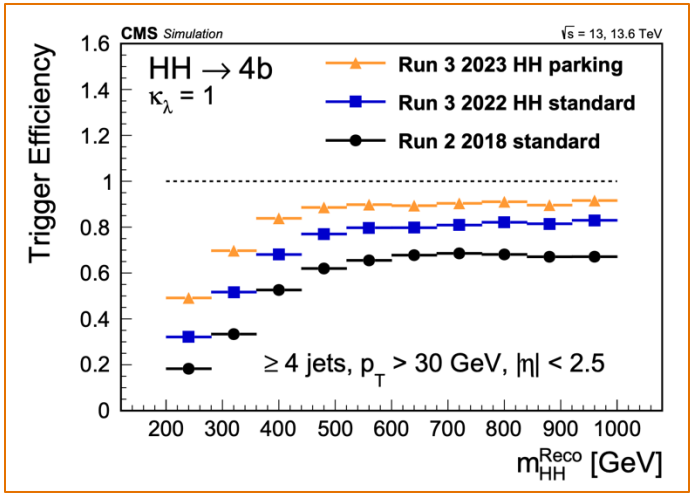
Impact on HH physics in Run-3



"Data Parking" and AI for b-jet tagging: × 1.2 signal efficiency

arXiv.2403.16134

Impact on HH physics in Run-3



"Data Parking" and AI for b-jet tagging: × 1.2 signal efficiency

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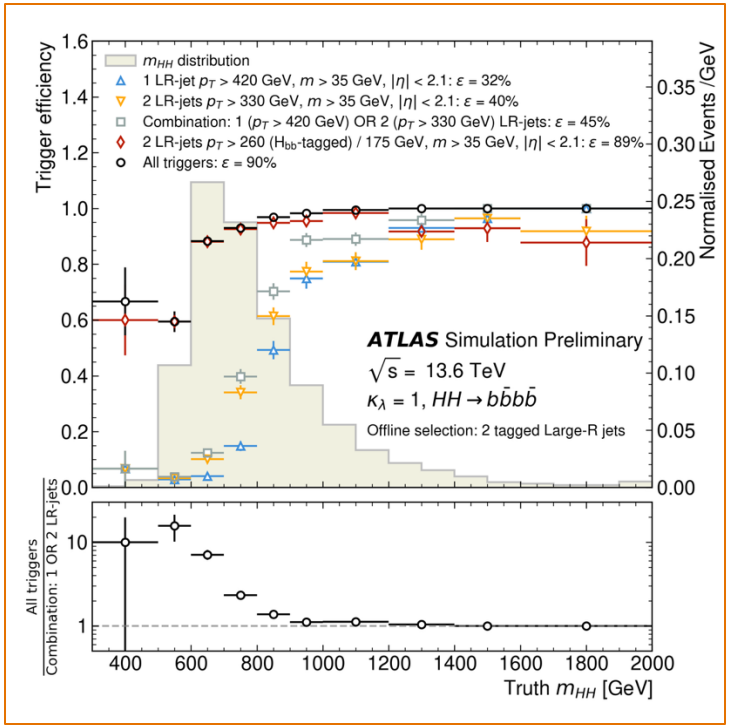
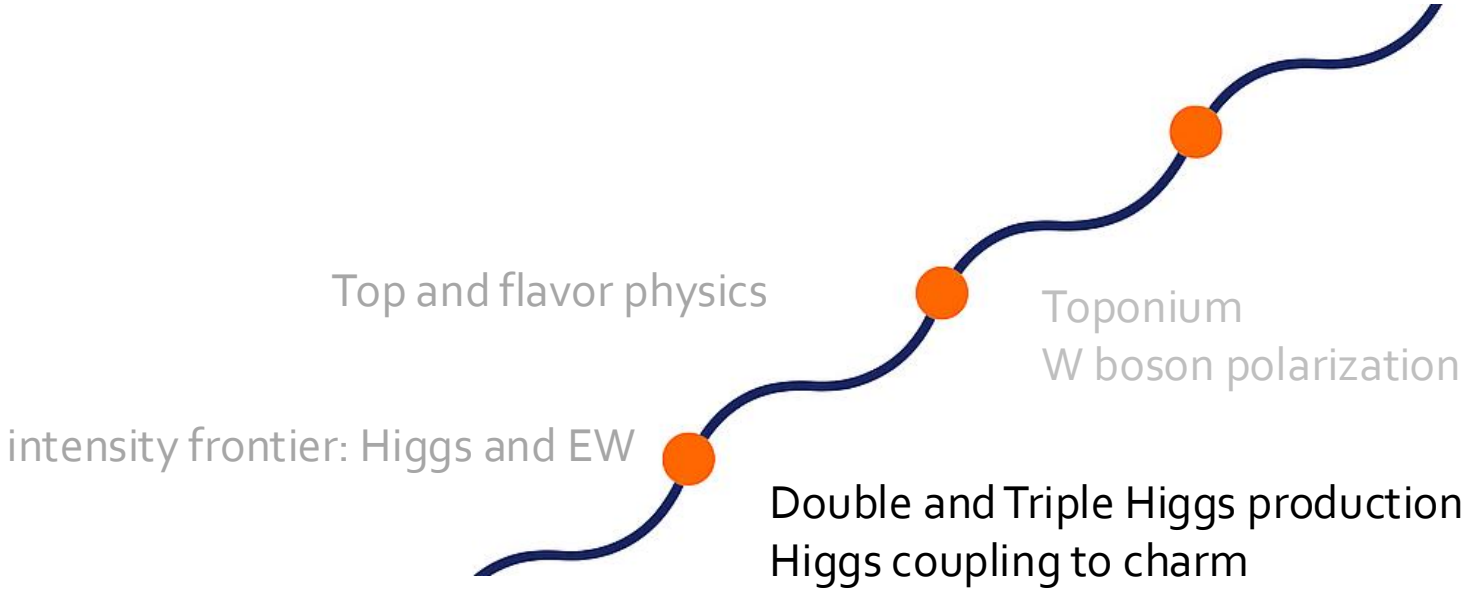


GN2 for bb-jet tagging in large radius-jets: up to ~90% signal efficiency

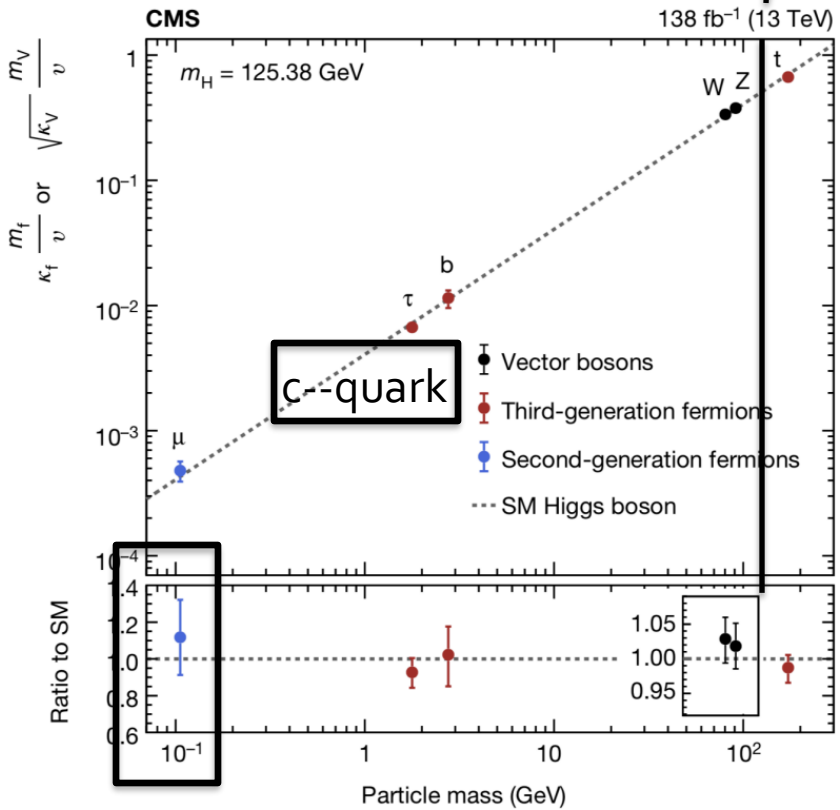
B-Jet Trigger Results ATLAS

Physics highlights



What is missing?

Higgs-Higgs interaction

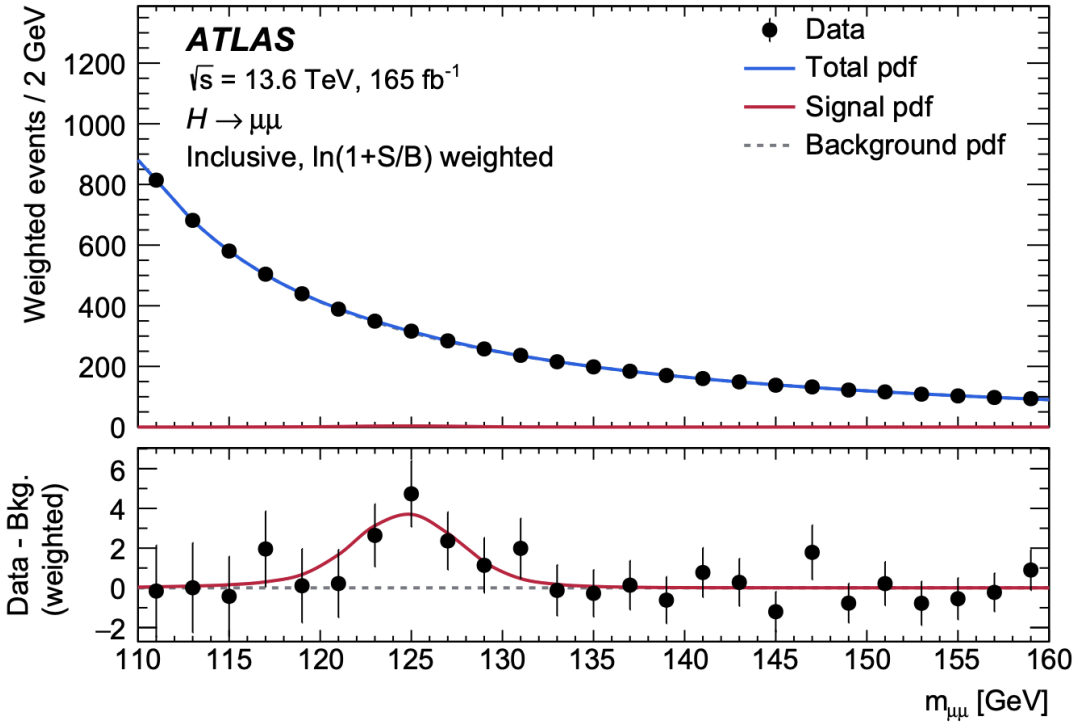


Precision $\mathrm{H} \to \mu\mu$ / $\mathrm{H} \to Z\gamma$

One step closer to second-generation fermions

- Challenging decay to muons! Low BR and large irreducible bkg.

arXiv:2507.03595

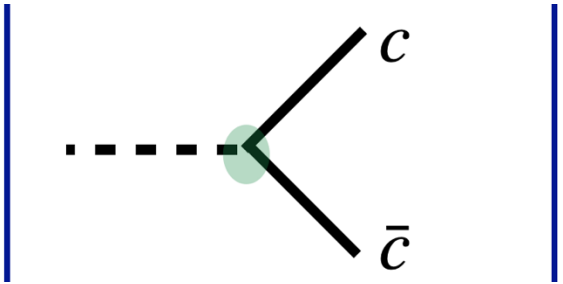


First evidence by the ATLAS experiment!

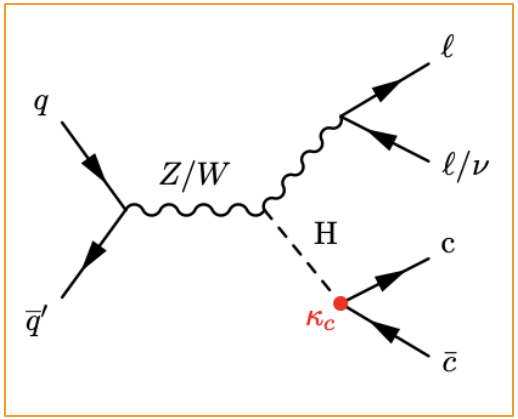
μ_H =1.6 ± 0.6 → 2.8σ (1.8σ) Run-3

μ_H =1.4 ± 0.4 → 3.4σ (2.5σ) Run-2+3

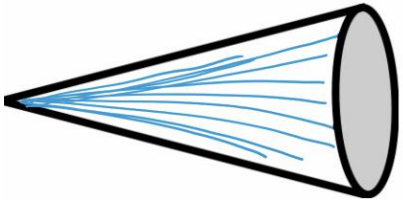
The challenging coupling to charm-quarks



2.9%

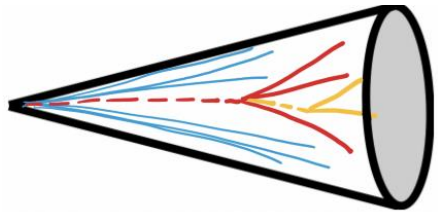


So far: $1.1 < |\kappa_C| < 3.4$



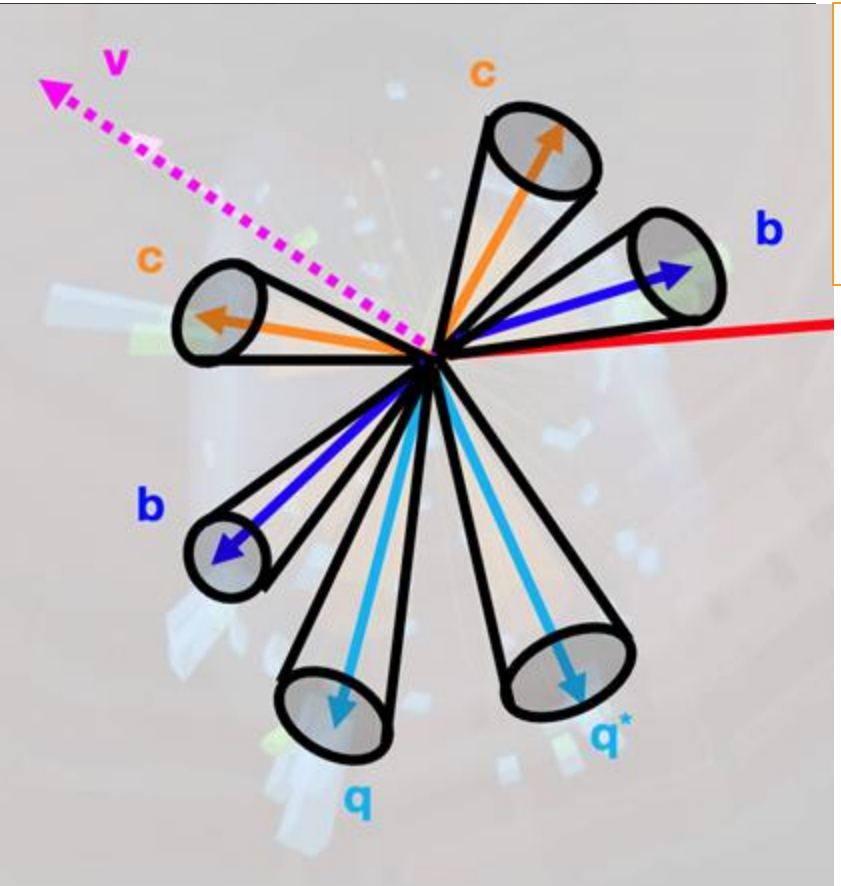
light (u,d,s,g)

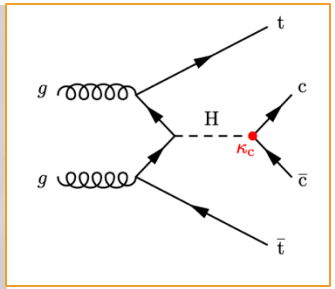
c-jet



b-jet

ttH(cc): complementary to VH(cc)



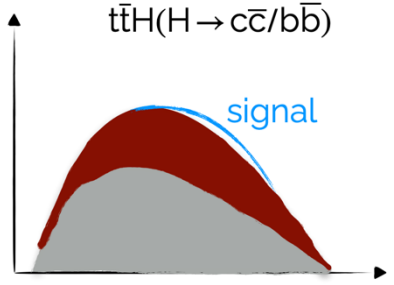


- Powerful jet-tagging: × 2 better than Run-2
- Event reconstruction: m_H, $m_{W(1)}$, $m_{W(2)}$, $m_{t(1)}$, $m_{t(2)}$
- Exploit correlations between objects in event

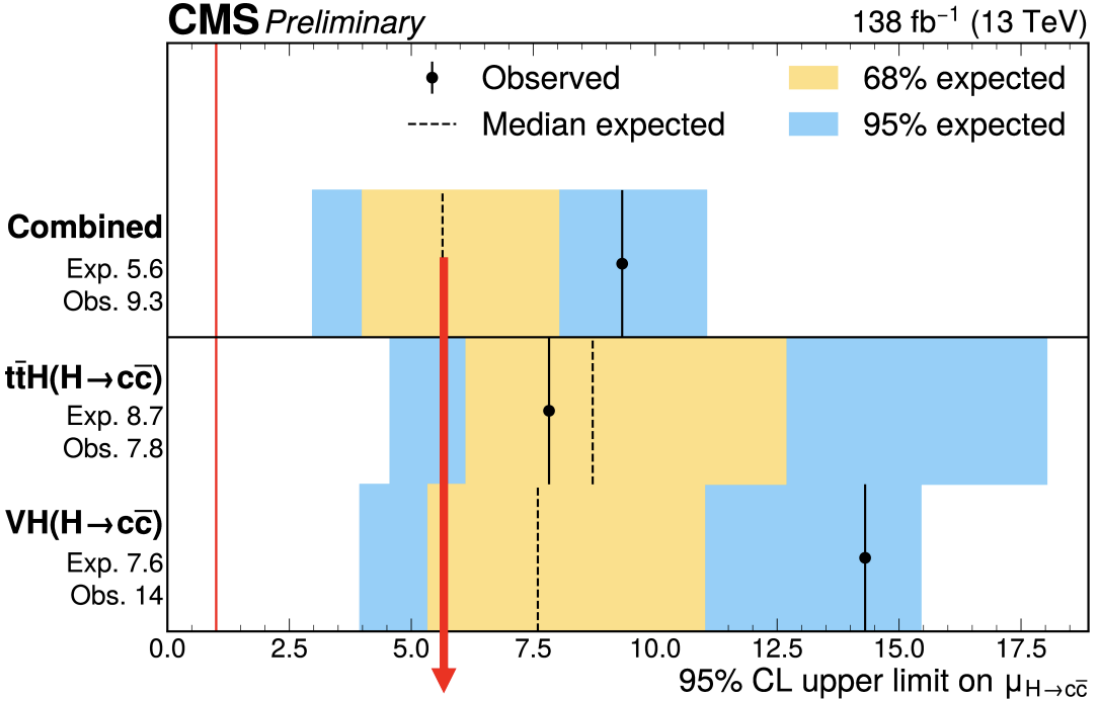
Recent *ttH*(cc) results

CMS-HIG-24-018

May 2025



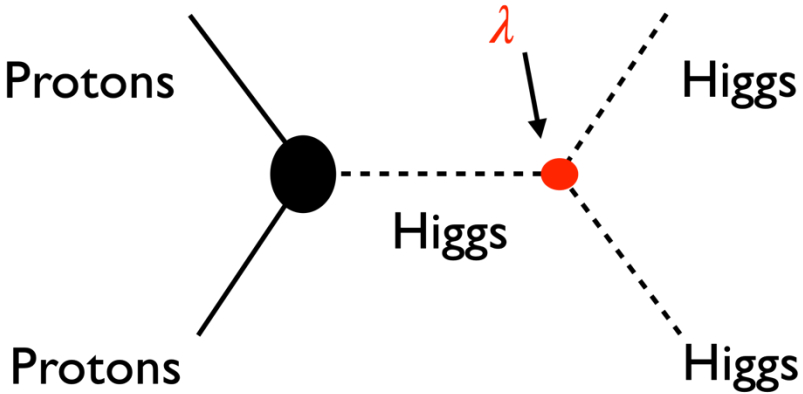
Fit discriminator instead of mass



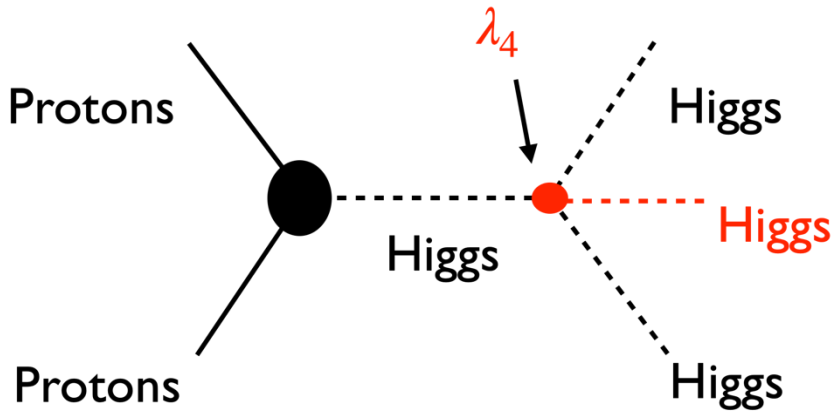
$\sigma_{(H \to cc)}$<5.6xSM; $|\kappa_c|$<2.7xSM
(Run2-only, CMS-only)

Doubling or Tripling the Higgs'es

$\sigma_{HH} \approx 31$ fb

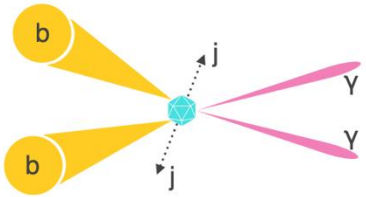


$\sigma_{HHH} \approx 0.1$ fb



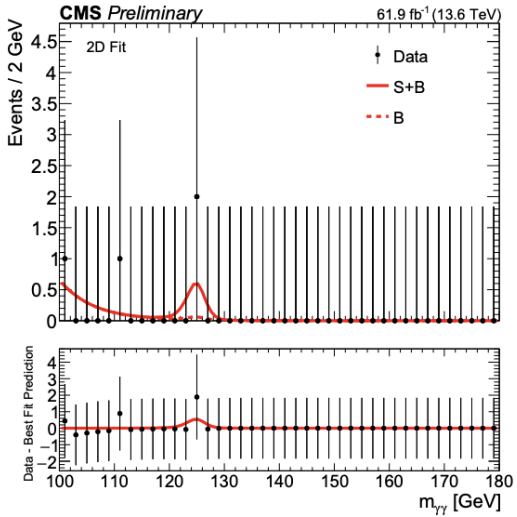
$$V(h+v) = V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_h^2}{2v} v\, h^3 + \frac{1}{4}\frac{m_h^2}{2v} h^4 + \ldots$$

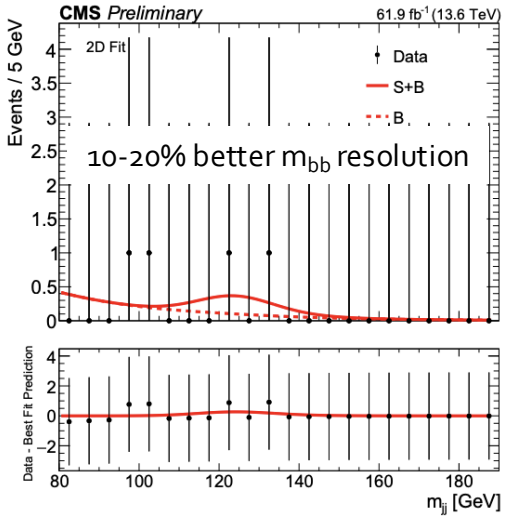
HH in Run-3: CMS $HH \rightarrow bb\gamma\gamma$ 2022-**2023**

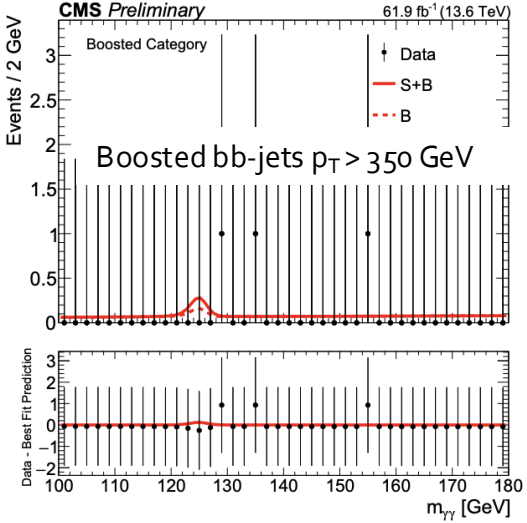


CMS-HIG-25-007

Oct. 2025





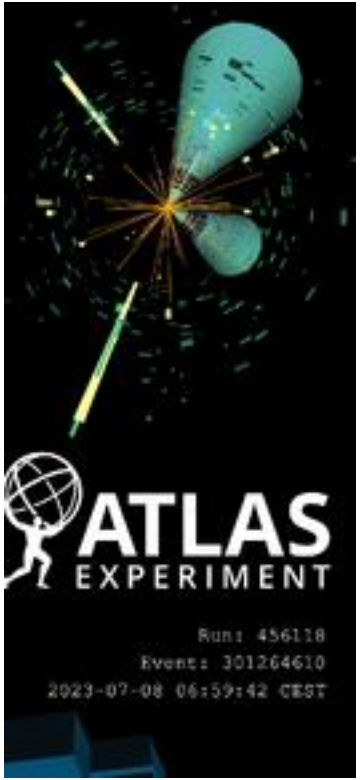


μ_{HH} < 11.0 (7.3) x SM obs. (exp) @ 95% confidence level
[assuming SM HH kinematics]

HH in Run-3: first results from ATLAS

arXiv:2507.03495

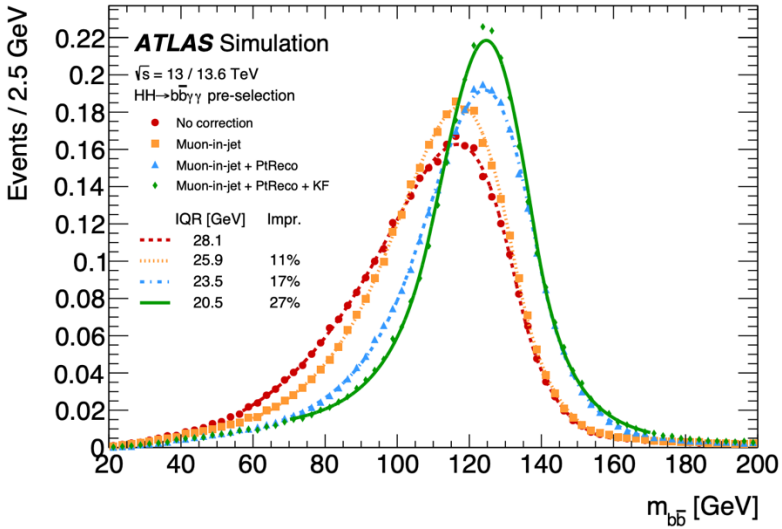
July 2025



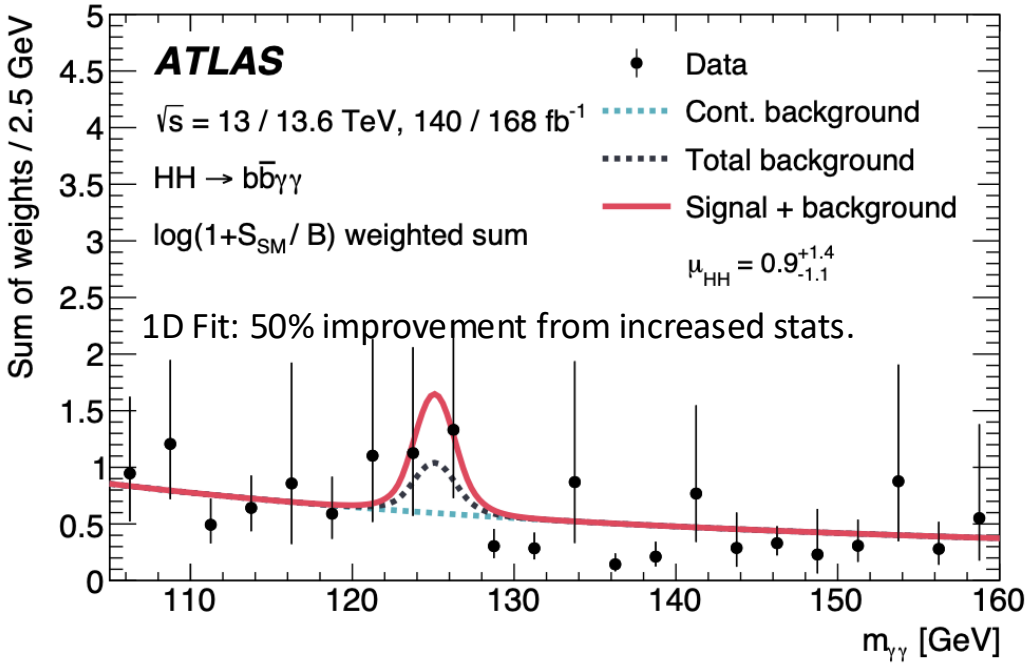
20% improvement: GN2 n-jet tagger

5% improvement: better mass resolution in $HH \rightarrow bb\gamma\gamma$:

constrain m_{bb} by making use of momentum balance with γγ (KF)



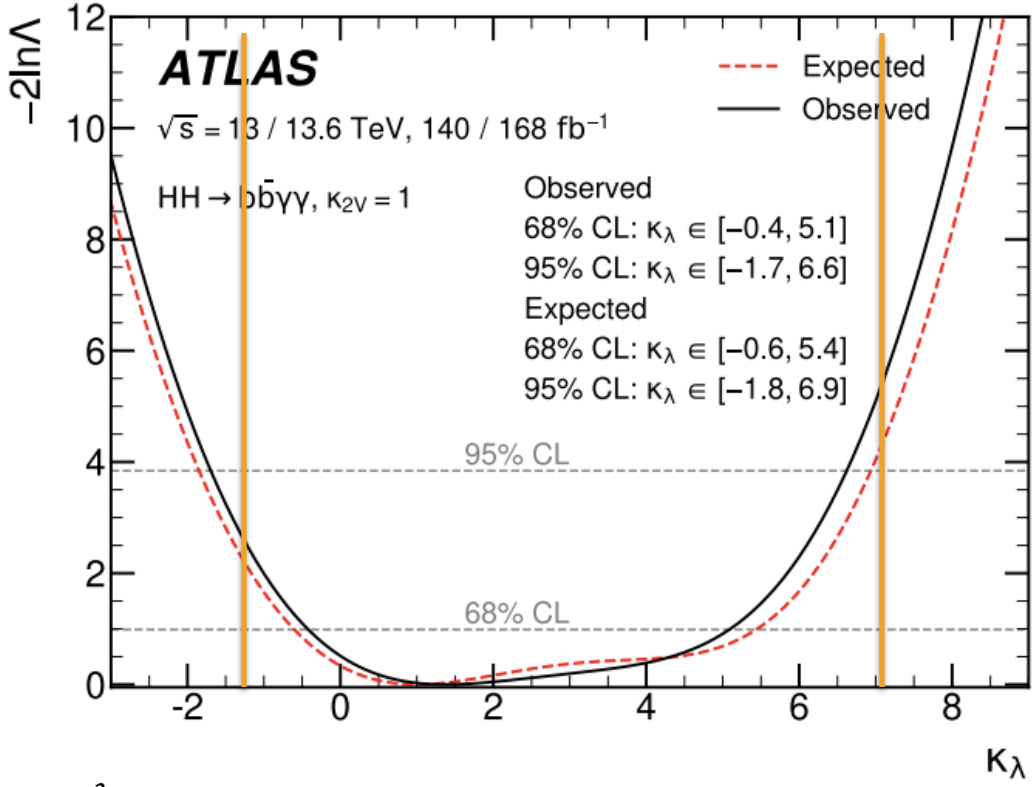
Run 2 + 2022-**2024**: $HH \rightarrow bb\gamma\gamma$



First glimpse at signal:
Obs: 0.8σ
Exp: 1.0σ

μ_{HH} < 2.6 x SM @ 95% confidence level
[assuming SM HH kinematics]

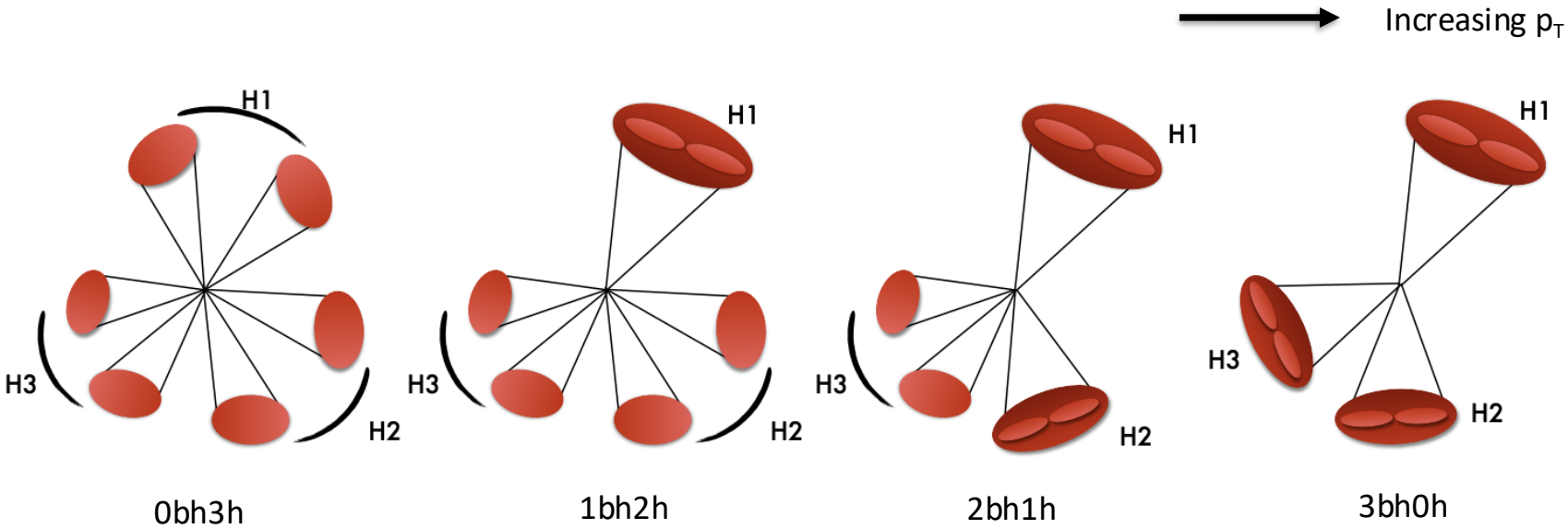
Translating into λ constraints



ATLAS: Phys. Rev. Lett. 133, 101801
CMS: PAS-HIG-20-011

$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$ **∈ [-1.7, 6.6]** – same sensitivity as channel-combination in Run-2!

H(bb)H(bb)H(bb)



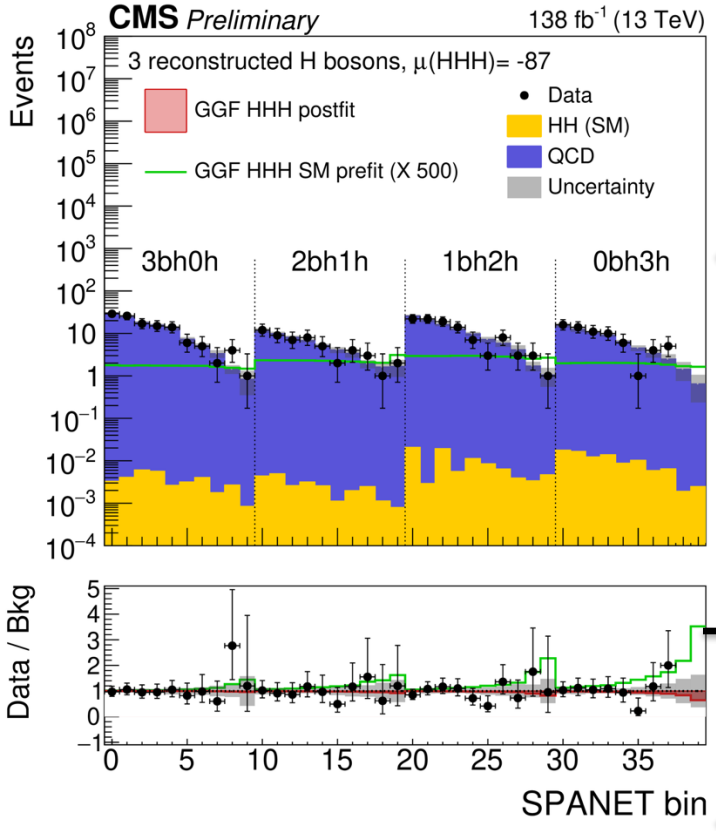
Pairing problem: which jet corresponds to H1, H2, H3 decay?

- Permutation symmetry of indistinguishable jets
- Assignment symmetry: two b's can be exchanged

HHH with SPANet

CMS-PAS-HIG-24-012

Oct. 2025

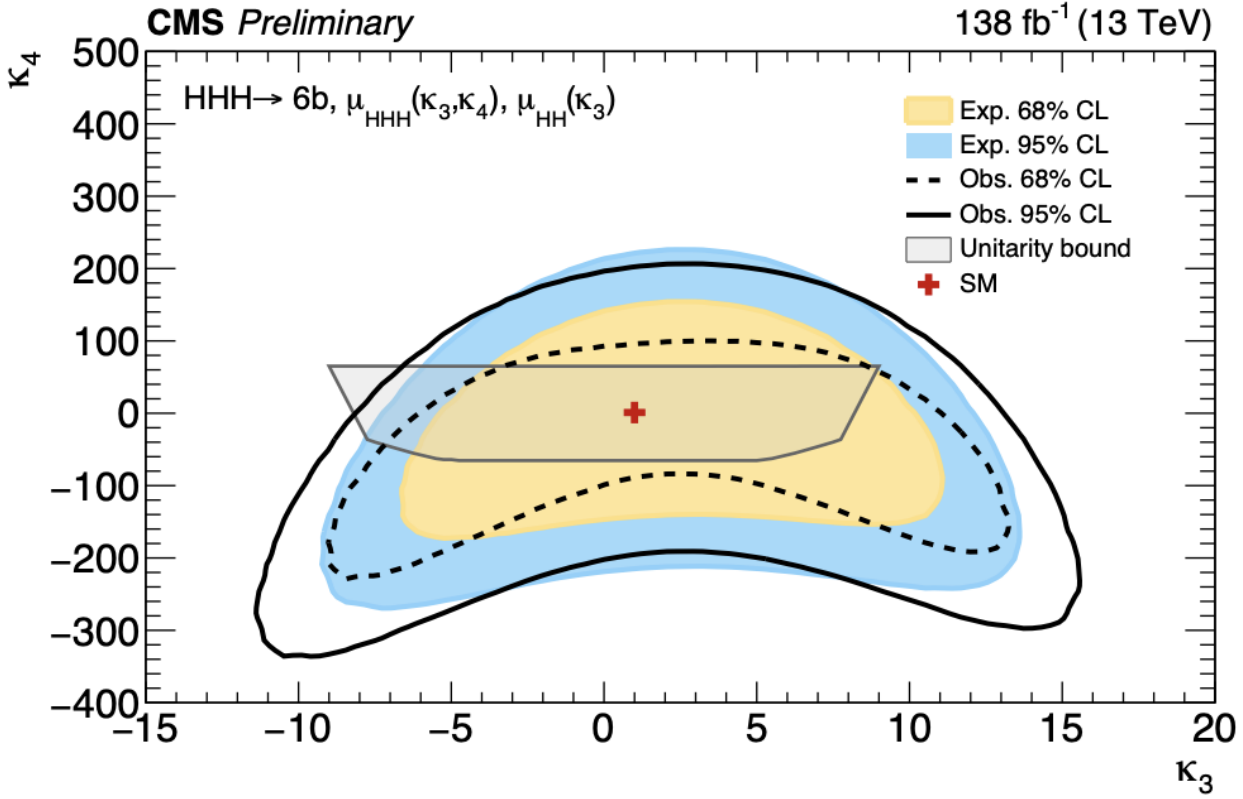


→ Pairing accuracy: ~60%

→ HHH signal, $\mu_{HHH} < 588\ (572)\ \times$ SM

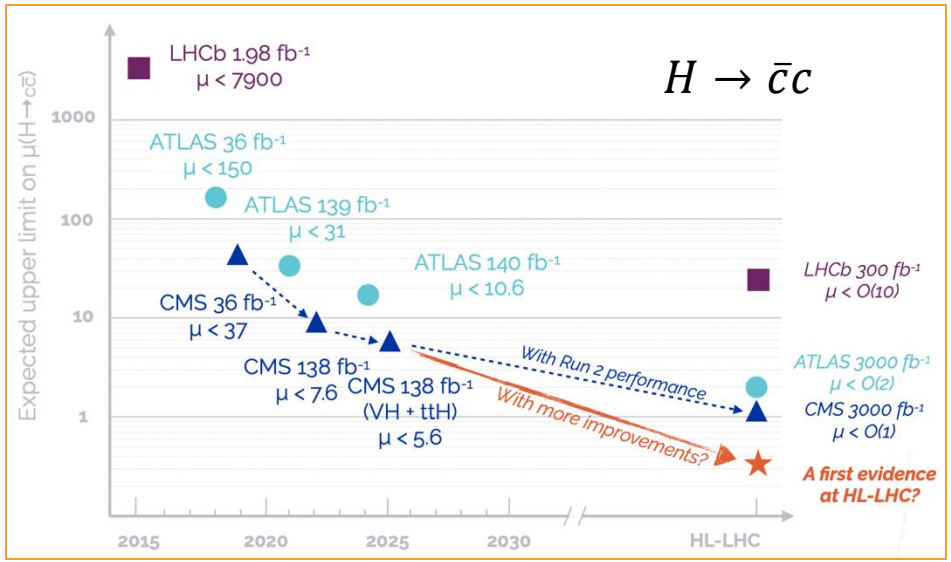
→ Bins in ML output score for classification

Interpreting HHH results

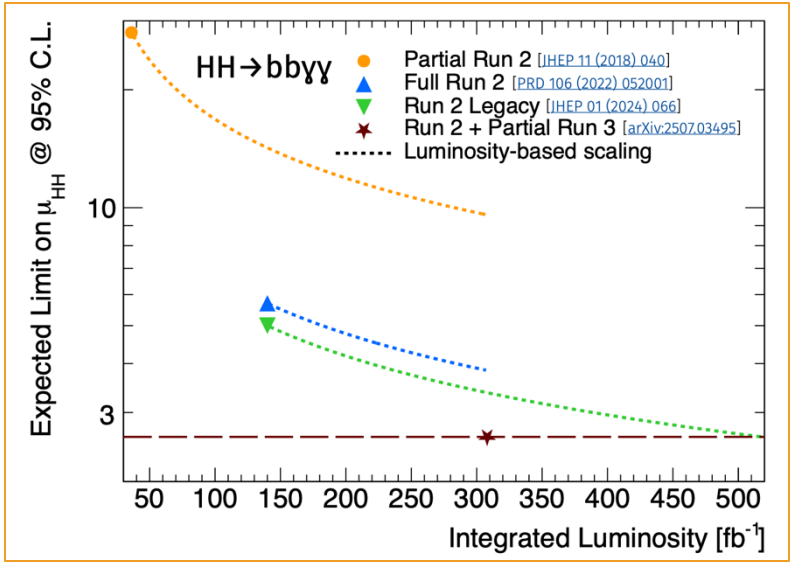


Inputs from theory needed: how to parametrize κ_4 in HH

Summarizing the Higgs path



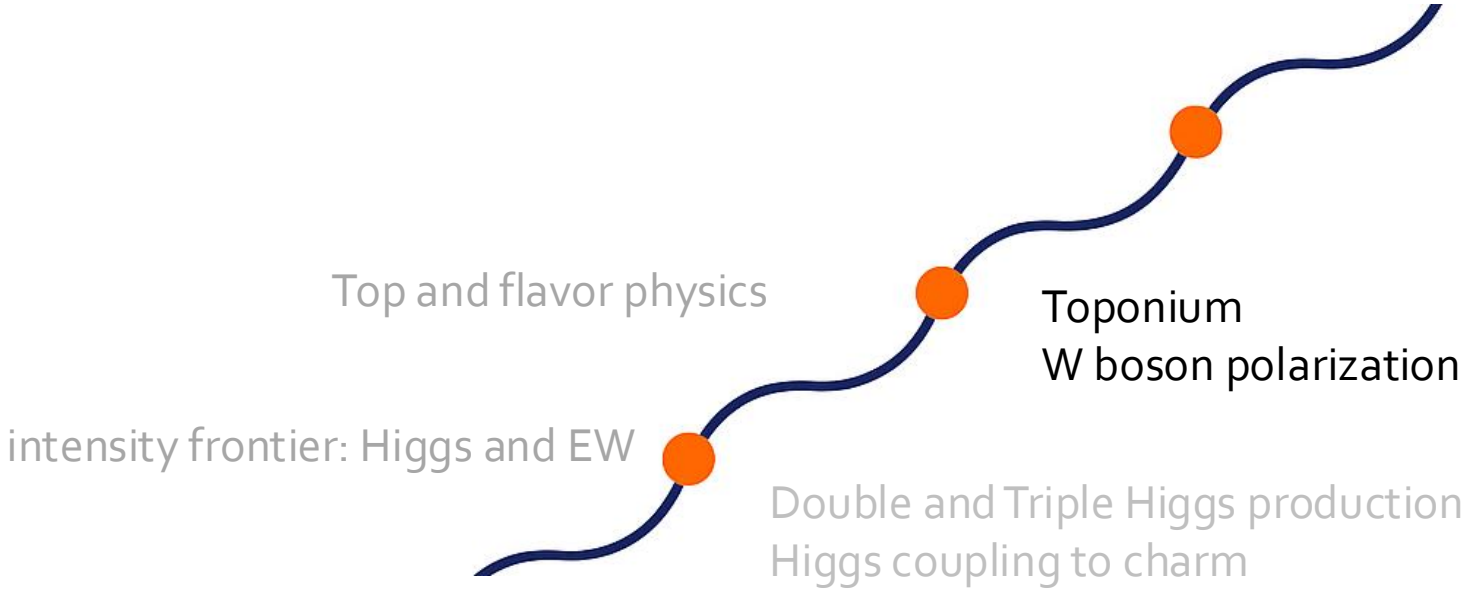
S. Wuchterl



B. Moser

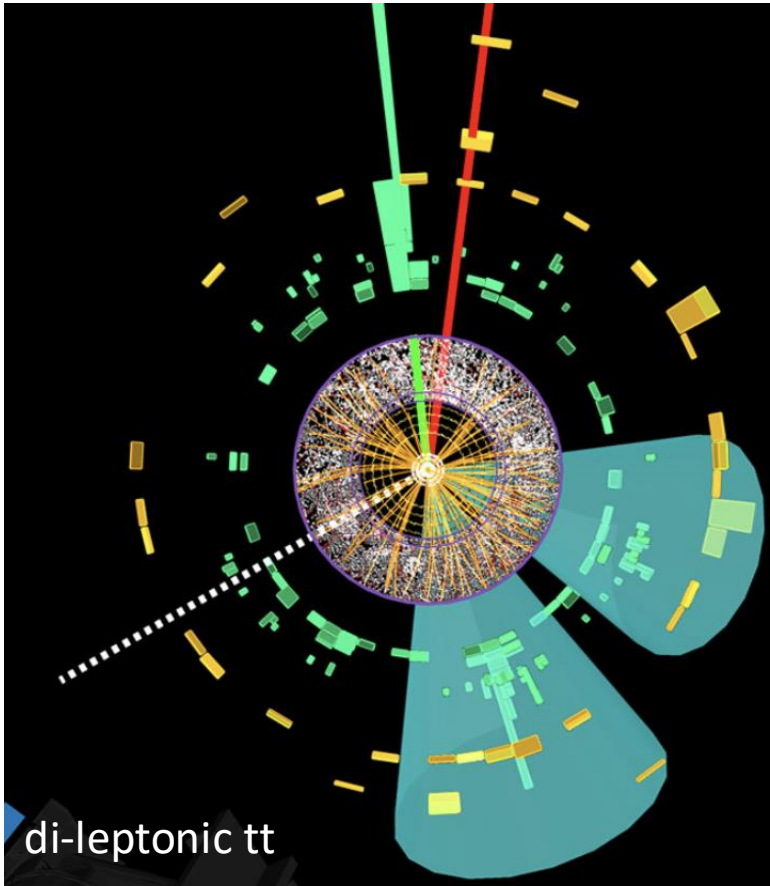
Consistently outperforming luminosity scaling / old projections!

Physics highlights



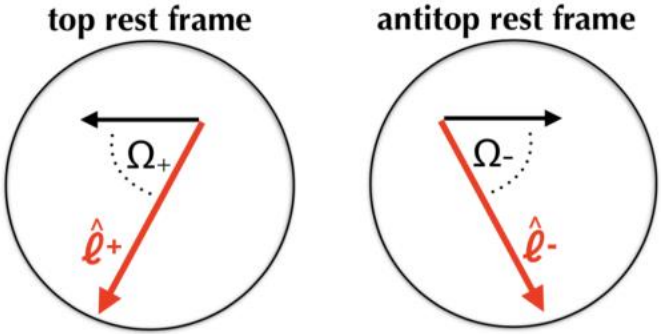
Top quark pair production at threshold

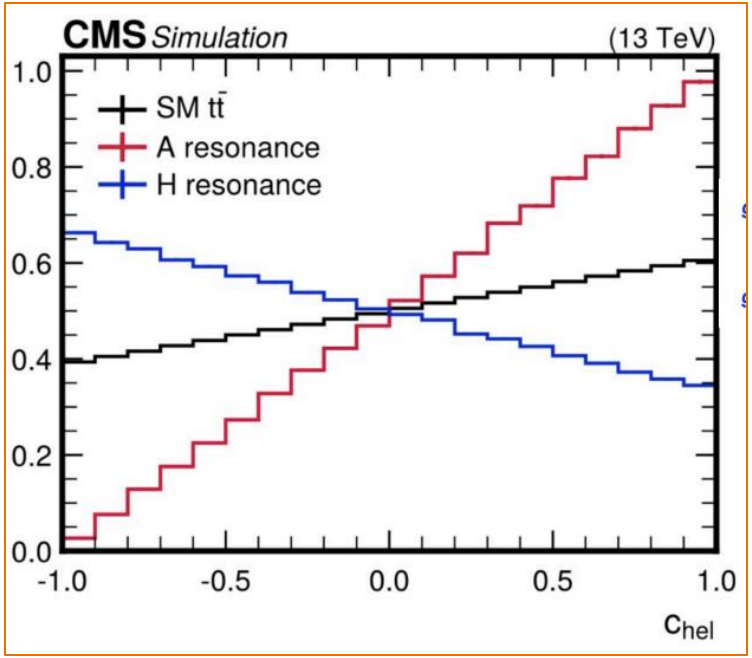
- Top: very short lifetime, decay before forming hadrons
- Still, a **quasi-bound state** at low $m_{tt\ (\sim 345\ GeV)}$ predicted by non-relativistic QCD
- Experimental resolution (~15-20%) makes it a challenging measurement



Need to enhance sensitivity to spin-correlations

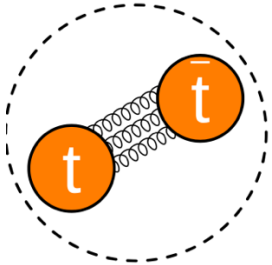
$$C_{\mathrm{hel}} = \hat{\ell}_{\mathrm{t}}^{+} \cdot \hat{\ell}_{\bar{\mathrm{t}}}^{-}$$



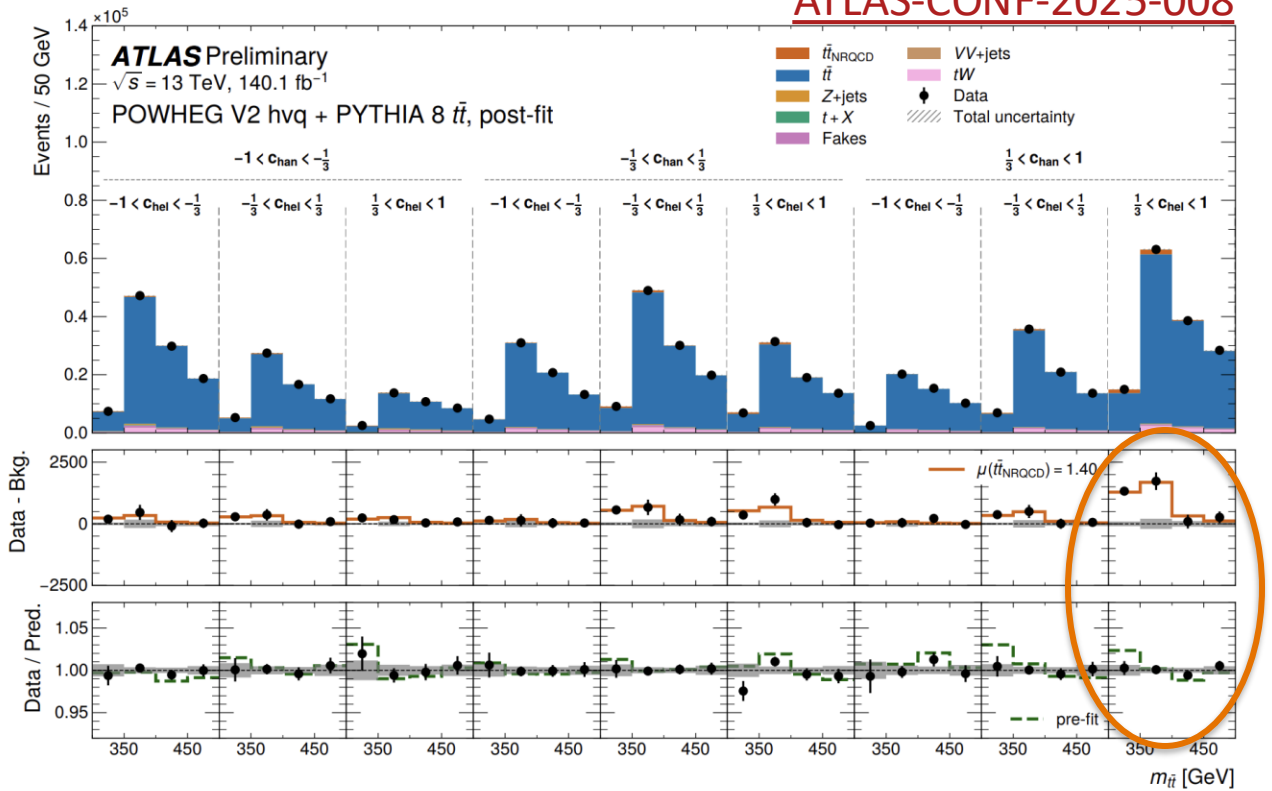


Separates between pseudo scalar hypothesis and SM

Top quark pair production at threshold: ATLAS

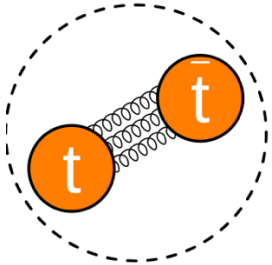


ATLAS-CONF-2025-008



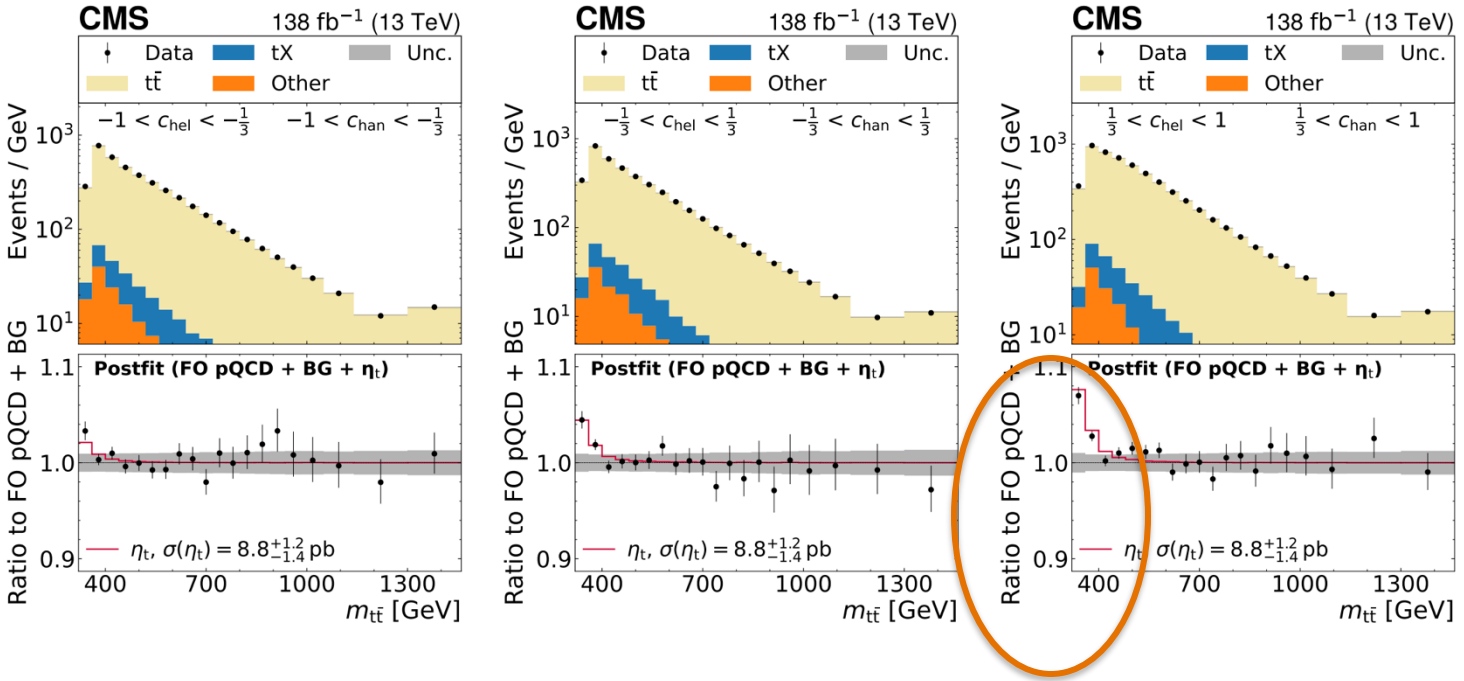
Model without quasi-bound-state rejected at 7.7σ (5.7σ)

Top quark pair production at threshold: CMS



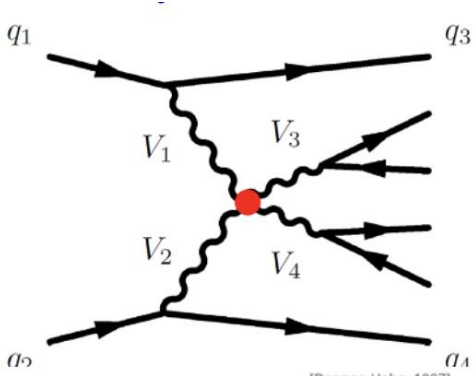
arXiv:2503.22382

Dominated by modeling uncertainties!



Excess above 5σ: cross-section $8.8\,^{+1.2}_{-1.4}\,\text{pb}$

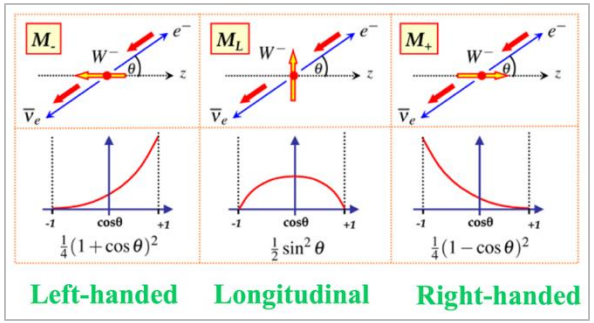
EW rare processes: Vector boson Scattering



VBS: unitarity conservation in longitudinally polarization modes, e.g.:

$$W_L^+W_L^- \to W_L^+W_L^-, \quad W_L^+W_L^- \to Z_LZ_L, \quad Z_LZ_L \to Z_LZ_L$$

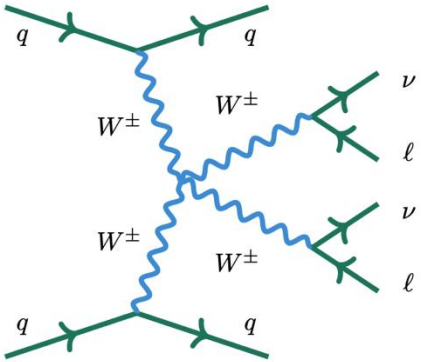
Longitudinal polarization: spin in parallel with the momentum

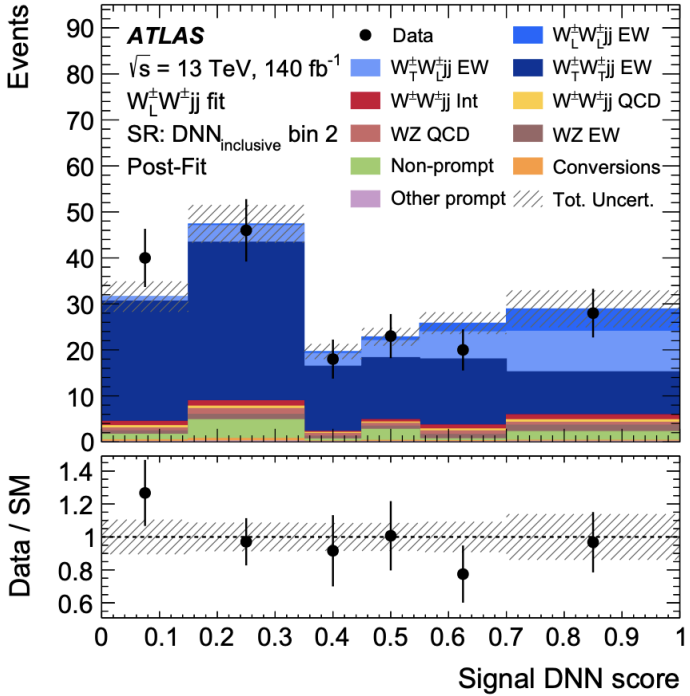


W bosons are their own polarimeters!
Polarization has effects on decay products

EW rare processes: longitudinally polarized W bosons

arXiv:2503.11317





First evidence for $W^{\pm}W^{\pm}{}_{L}jj$ (3.3σ)

Still statistically limited but first steps towards understanding EWSB

Summary

- LHC is our *only current* probe of Higgs and EW processes
- We have far surpassed our initial goals and learned how to squeeze so much more out of the data!
- A major upgrade is ahead that will extend our physics reach even further!