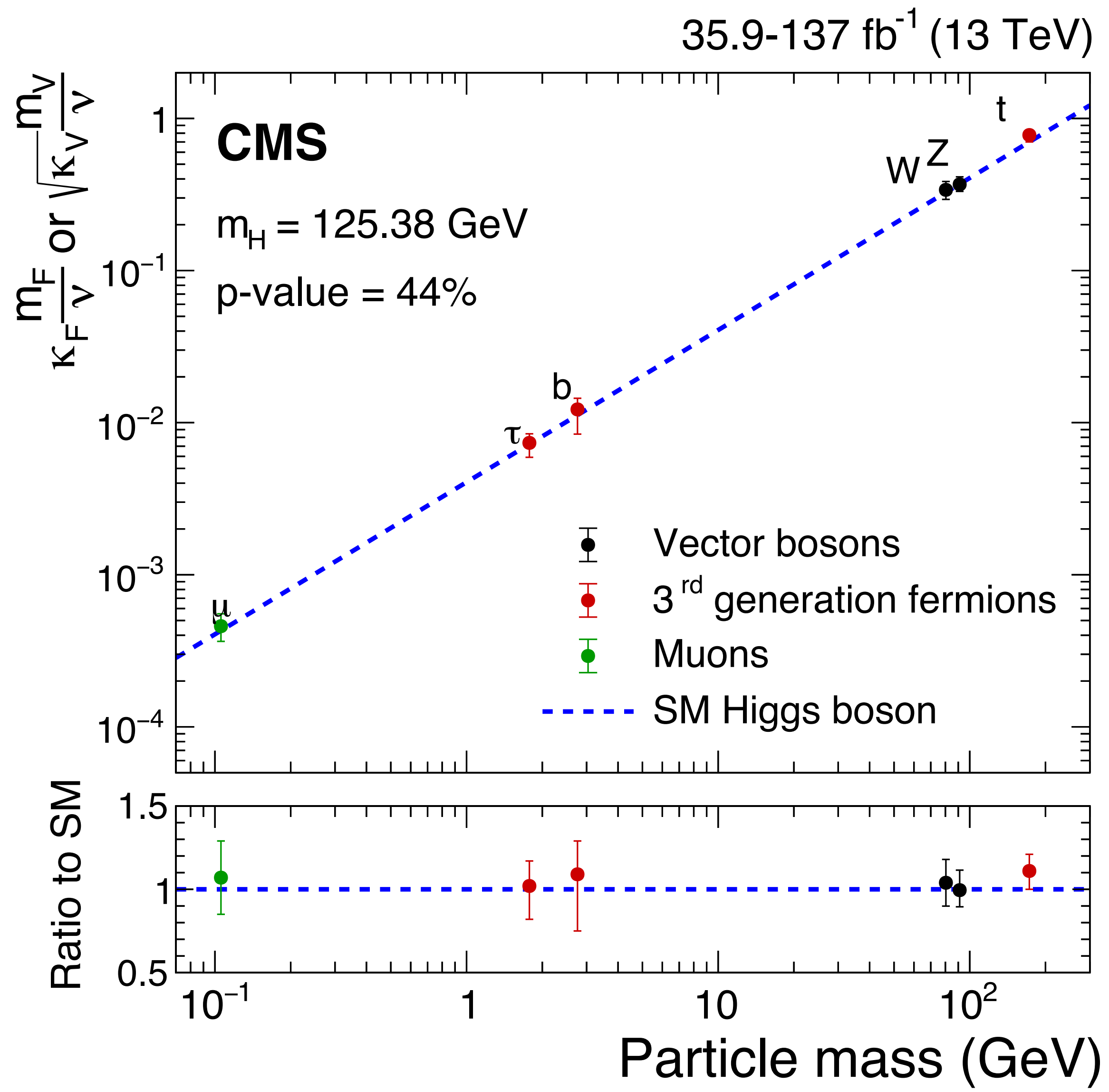
New trigger strategies targeting HH events at the CMS experiment in Run 3

Stephane Cooperstein (University of California San Diego),
on behalf of the CMS Collaboration

Higgs boson measurements ~today

- Millions of Higgs bosons have now been produced at the LHC, enabling
  - Per-mille precision on Higgs boson mass
  - Measurement of most Higgs boson couplings, even rare decays such as $H \rightarrow \mu\mu$.
- This unprecedented data set opens a *new frontier in exploration of H sector*:
  - The Higgs self-interaction!
  - ***What can we expect for Run-3?***



Why the H self-coupling matters

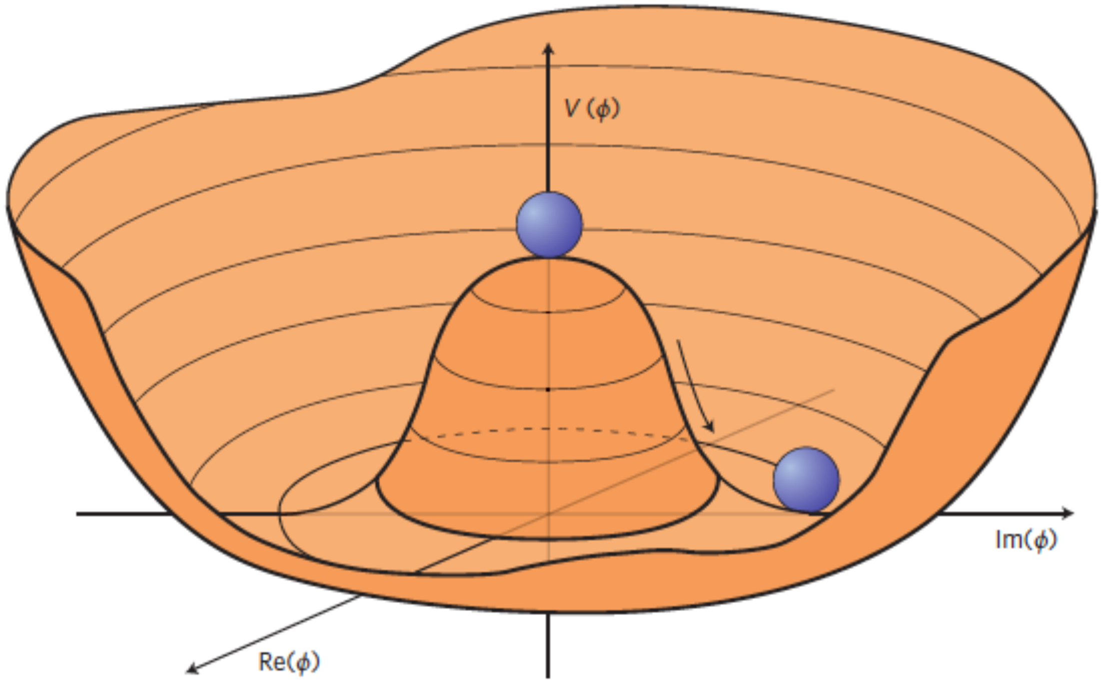
- Shape of H potential is probably the most important unmeasured parameter in the SM.
  - ❖ Implications for stability of the universe, baryogenesis, …

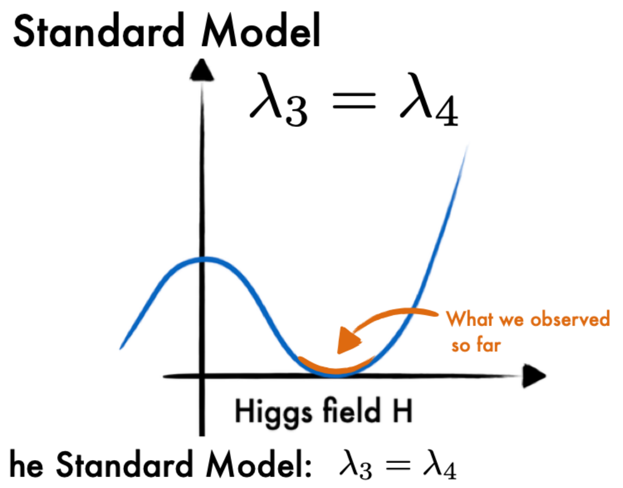
H boson mass term

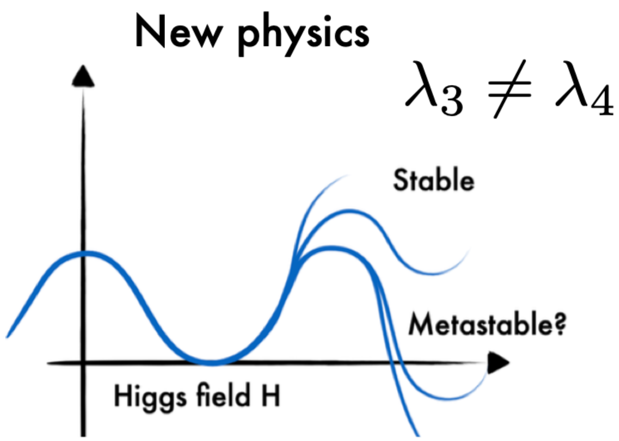
H trilinear and quartic self-interactions

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

- Higgs boson discovery confirms the (quadratic) shape close to the minimum, but we know little to nothing about most of the potential.







HH at the LHC

The driving channels for HH at LHC

4b: largest rate, but very large backgrounds

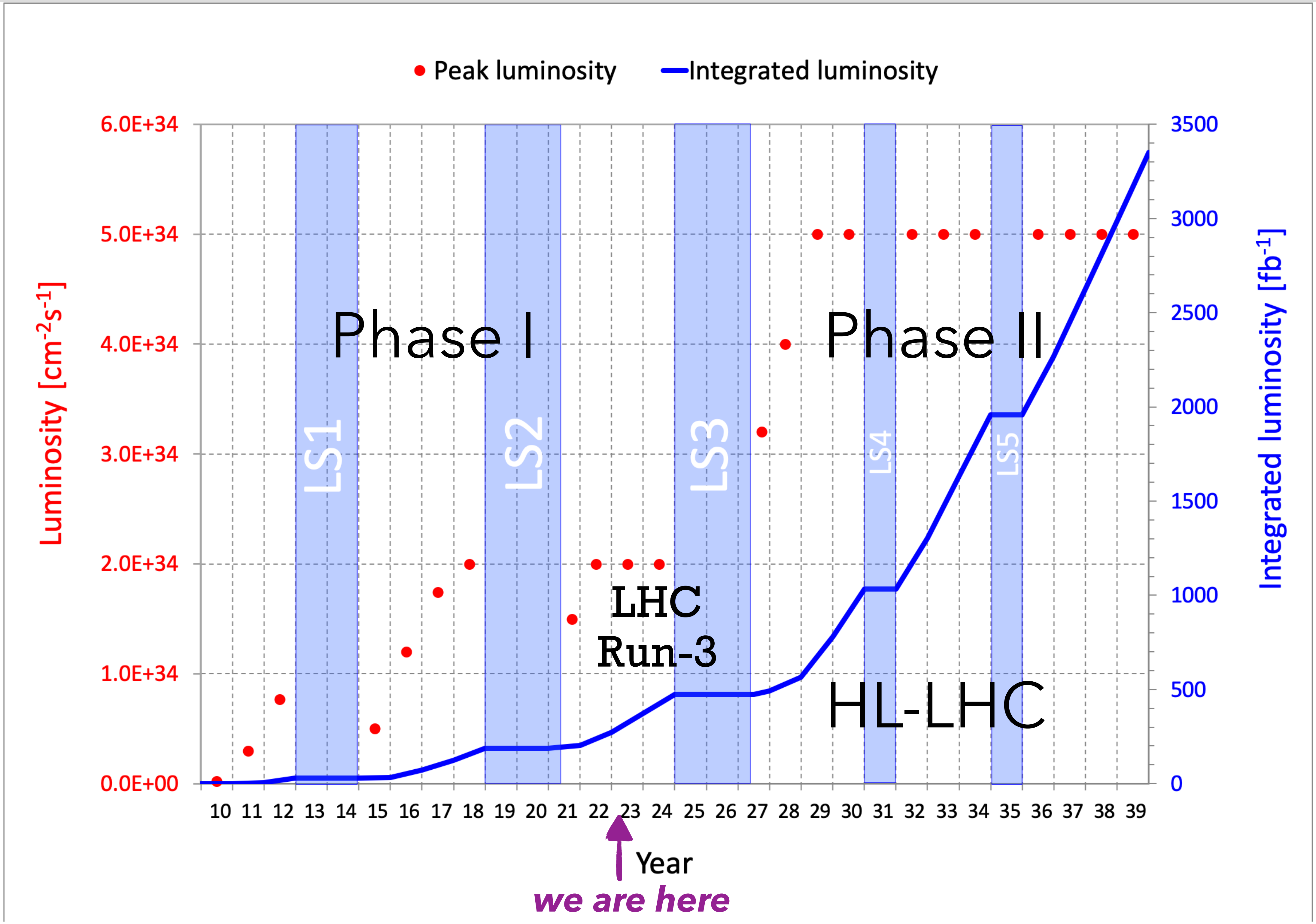
2b2τ: strongest compromise between rate and background contamination

2b2γ: "golden channel", but very small rate

HH final state branching fractions

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

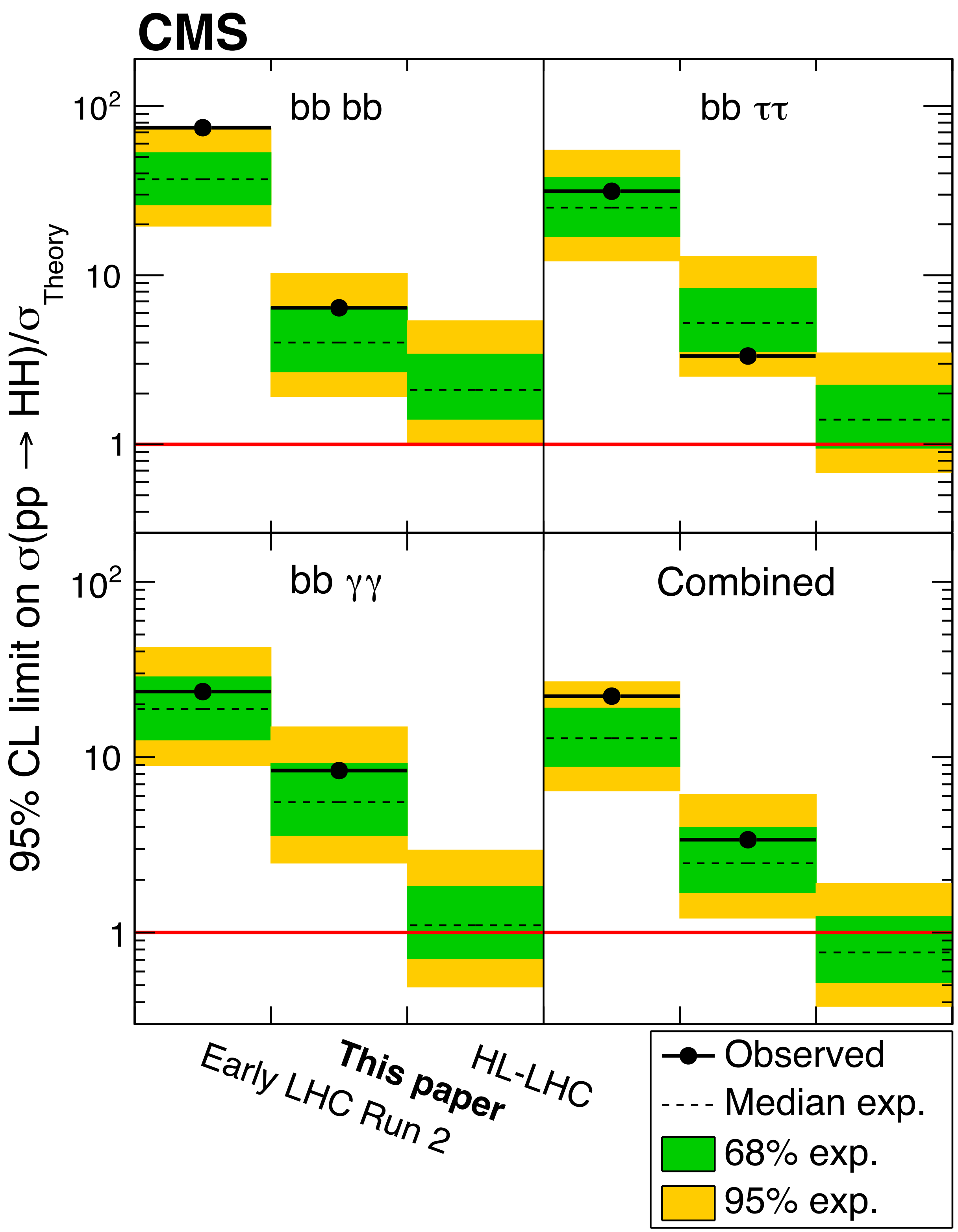
(HL-)LHC schedule



- Era of rapid total integrated luminosity and center-of-mass energy increases is ~over
  ⇒ ***to make the most of the incoming data we need innovation!***

Where we stand today

- Huge progress made in probing HH with Run-2 data
  - ❖ 95% C.L. upper limits on HH production rate of ~3 x SM
- Improvements in precision during Run-2 going well beyond increase in data set
  - ❖ Multiple novel methods, including many ML applications
- With 3000 fb^{-1}, expect visible SM HH signal, precision on λ at ~50% level
  - ❖ Can we manage to measure HH sooner….and better?

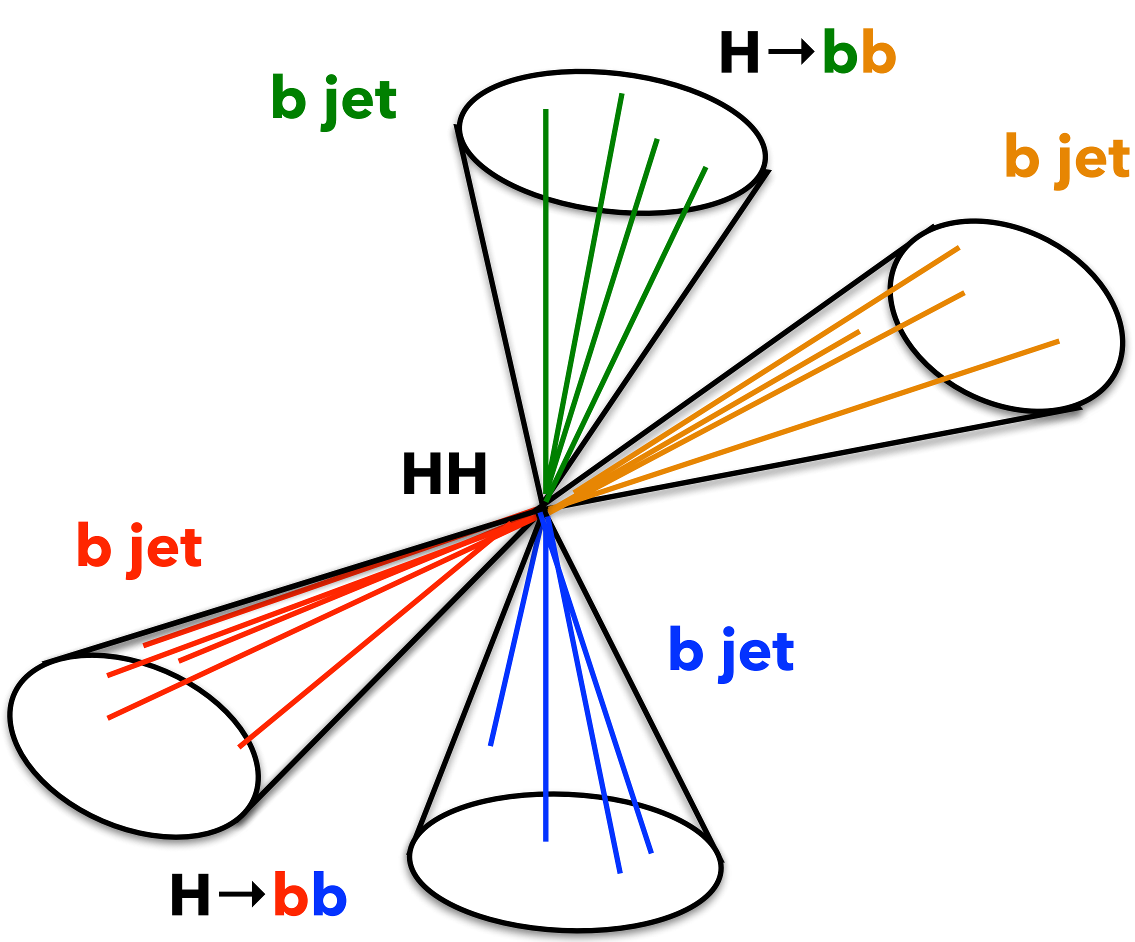


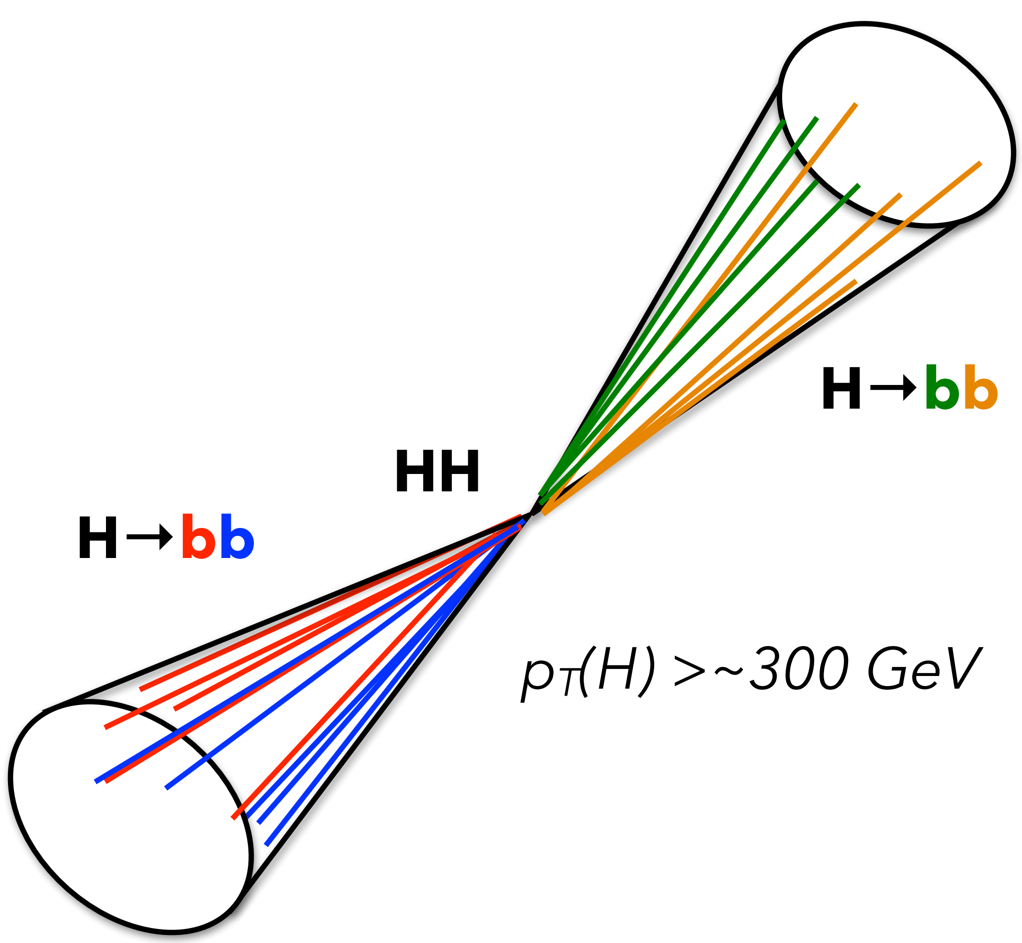
Nature 607 (2022) 60

Outline for today

- LS2 Insights: Trigger Limitation in HH Physics
  - *Identified trigger as a key limitation for HH→4b scope* using Run-2 data
  - HH→4b trigger efficiency in Run-2 (expected for SM HH) was approximately 18%
- Challenges with Run-2 Data Analysis
  - Innovations in analysis could only take us so far – data not collected due to trigger limitations cannot be recovered (~80% of all HH→4b events!)
- Advancements in Run-3 trigger: *dedicated trigger-level ML for jet flavor tagging*
  - Application of state-of-the-art ML for jet flavor tagging (ParticleNet)
  - Implemented within the CMS trigger system since the beginning of Run-3
  - Expect significant improvement in Run-3 HH physics reach

HH→4b signal topology



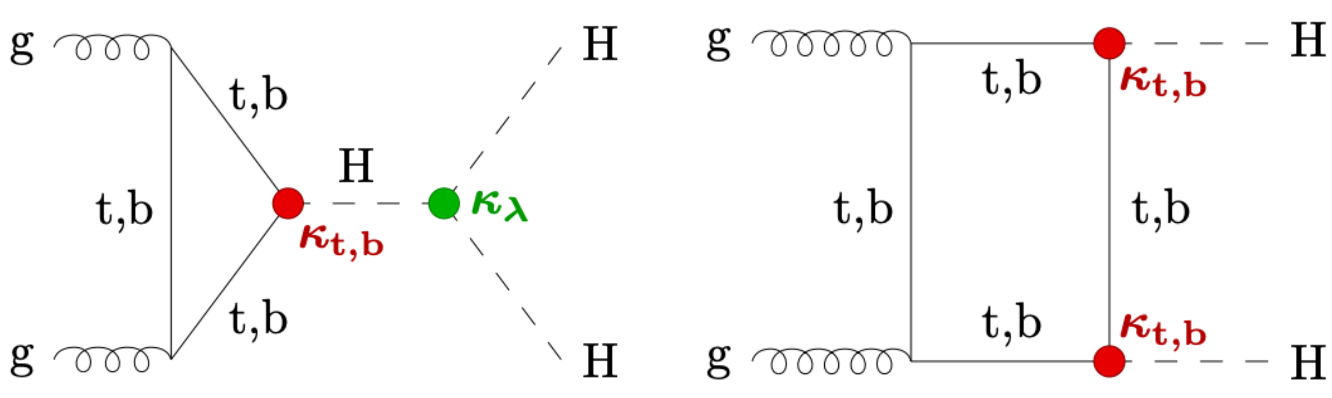


- Fully hadronic multijet final state ⇒ huge backgrounds at LHC
- At **high p_T(H), H decay products are highly collimated in lab frame**
  - Reconstruct H→bb as single large-radius jet
  - Reconstruction of such decays is ***key to maximizing sensitivity to HH→4b*** signal

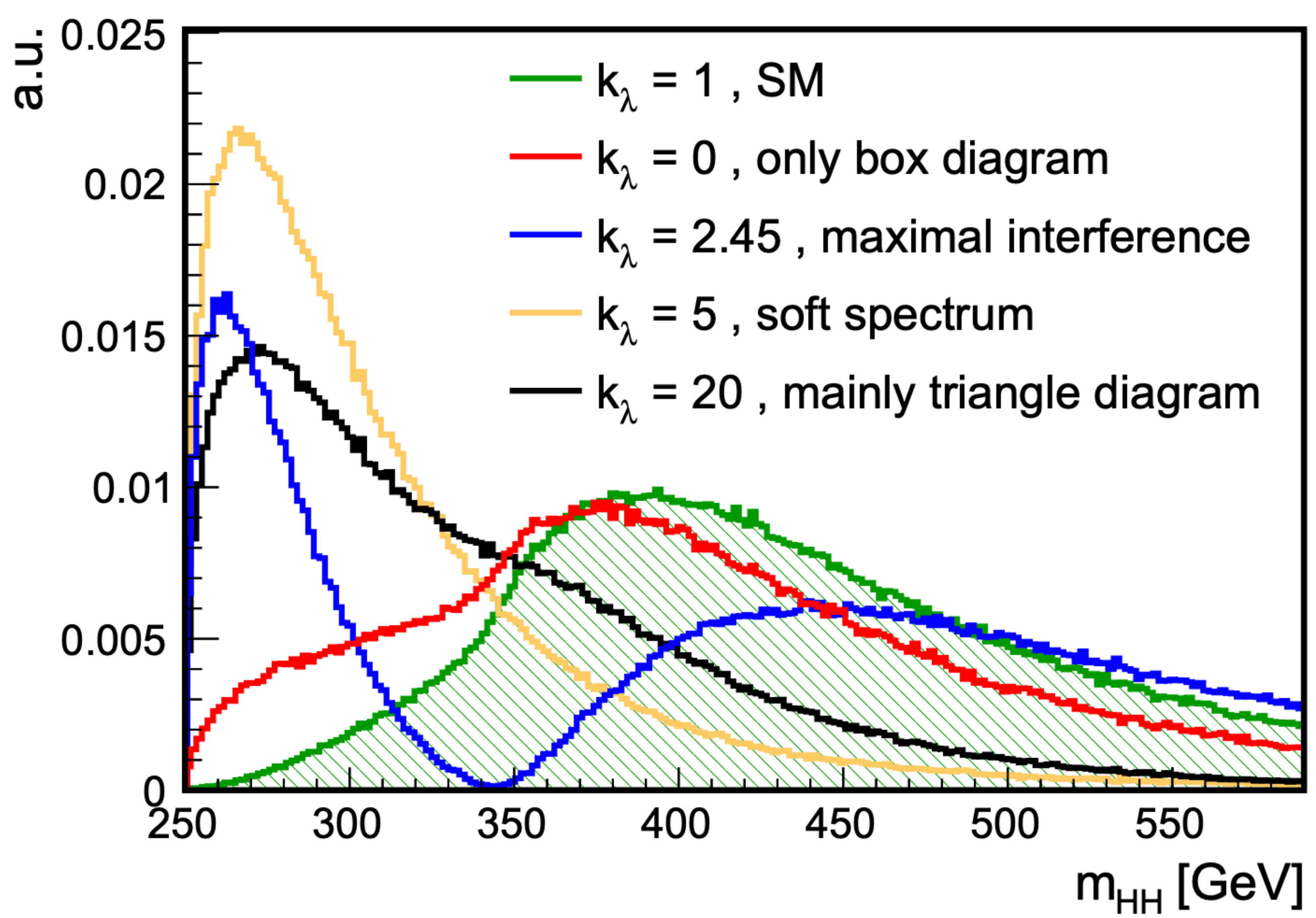
Signal evolution with λ

- HH production driven by two diagrams that destructively interfere
  - ❖ variations in λ change HH kinematics significantly
  - ❖ ~1000 times less HH than single-H events expected at LHC
- Critical to efficiently select potential signals throughout λ range of interest ([-10,10])
- ***We have designed the new HH triggers to be as efficient as possible for range of λ scenarios***
  - ❖ Low m_{HH} ⇒ low jet p_T's
  - ❖ Critical to keep trigger jet p_T thresholds as low as possible, to maximize acceptance throughout λ range

HH production at leading order



Evolution of HH kinematics when varying Higgs self-coupling λ



The challenge: trigger system

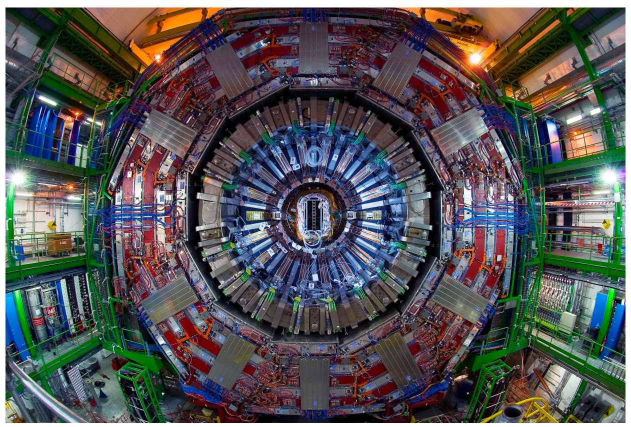
40 MHz

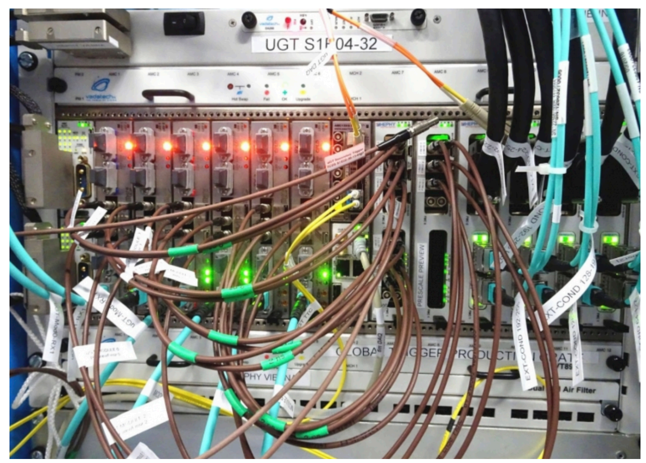
110 KHz (<4μs)

~5 KHz (<0.5s), ~15 GB/s

for HH4b: 30-35 Hz

collision event → Level-1 Trigger → High-Level Trigger (HLT) → Data storage





(partial detector readout)

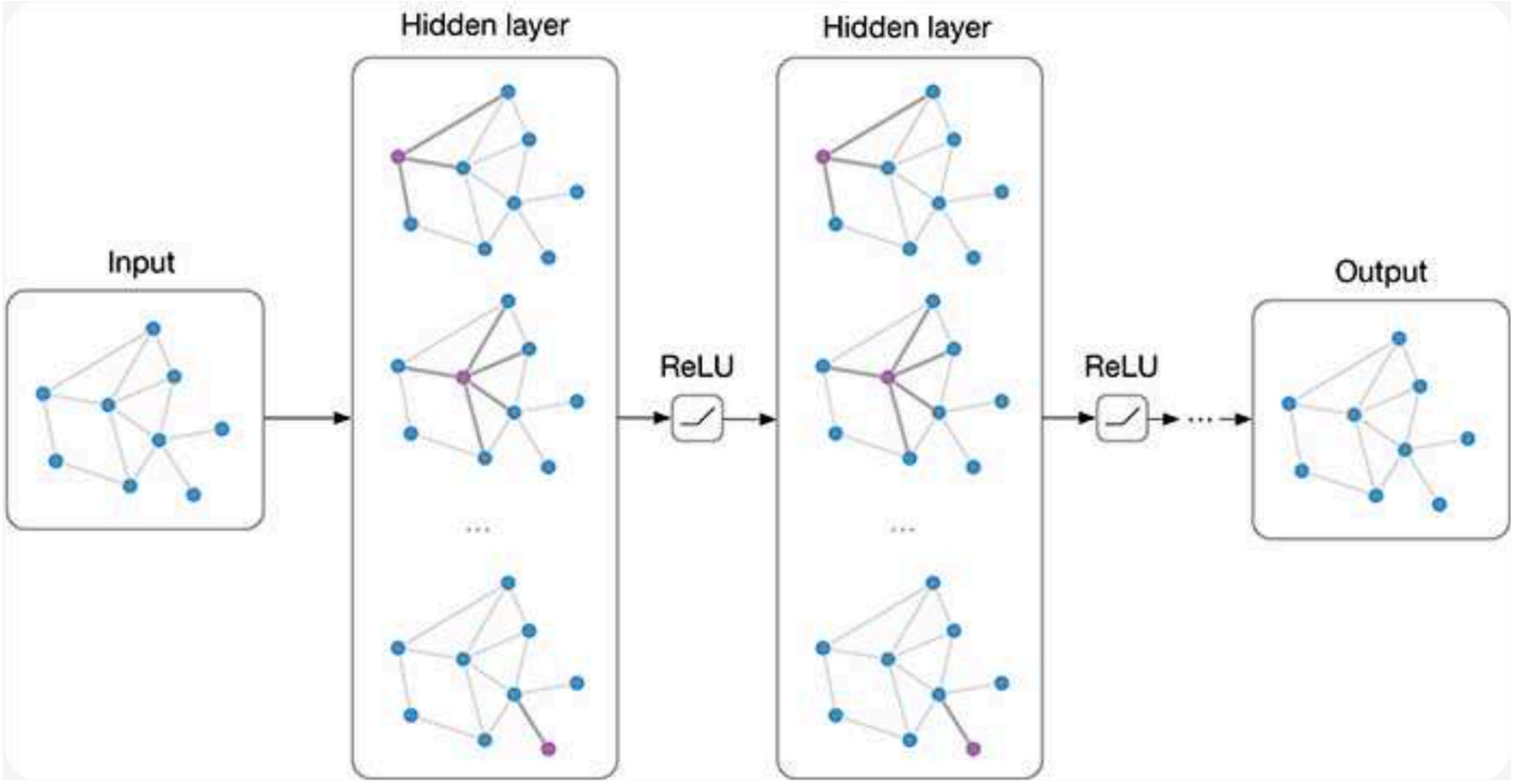
(full detector readout)

- Main handle to reduce HH→4b trigger rate is b-tagging in HLT
- Jet b-tagging is particularly challenging at trigger level:
  - Degraded inputs: highly simplified track reconstruction, less precise calibrations, etc.
  - Low latency requirements (~milliseconds)

Trigger efficiency, HH→4b signal	
Run-2	**18%**

Graph neural networks

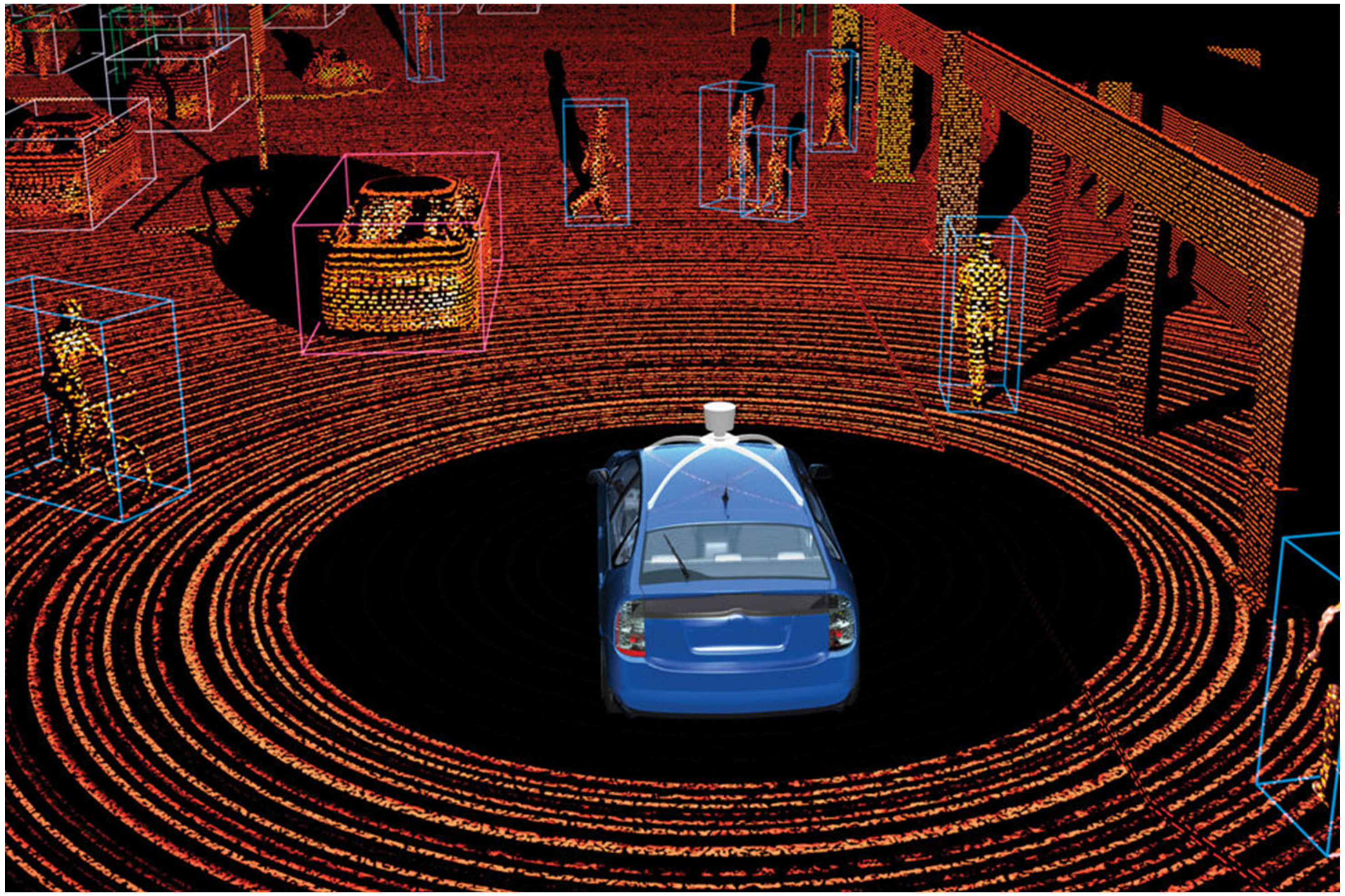
- Graph networks emerging in the last years as the new sharp tool in jet physics



- A data structure type naturally suited to jet physics:
  - ❖ Consider jets as collection of particles and vertices forming nodes in a graph, with edge features giving relations among jet constituents
  - ❖ The more the data structure is suited to the problem, the more efficient the ML

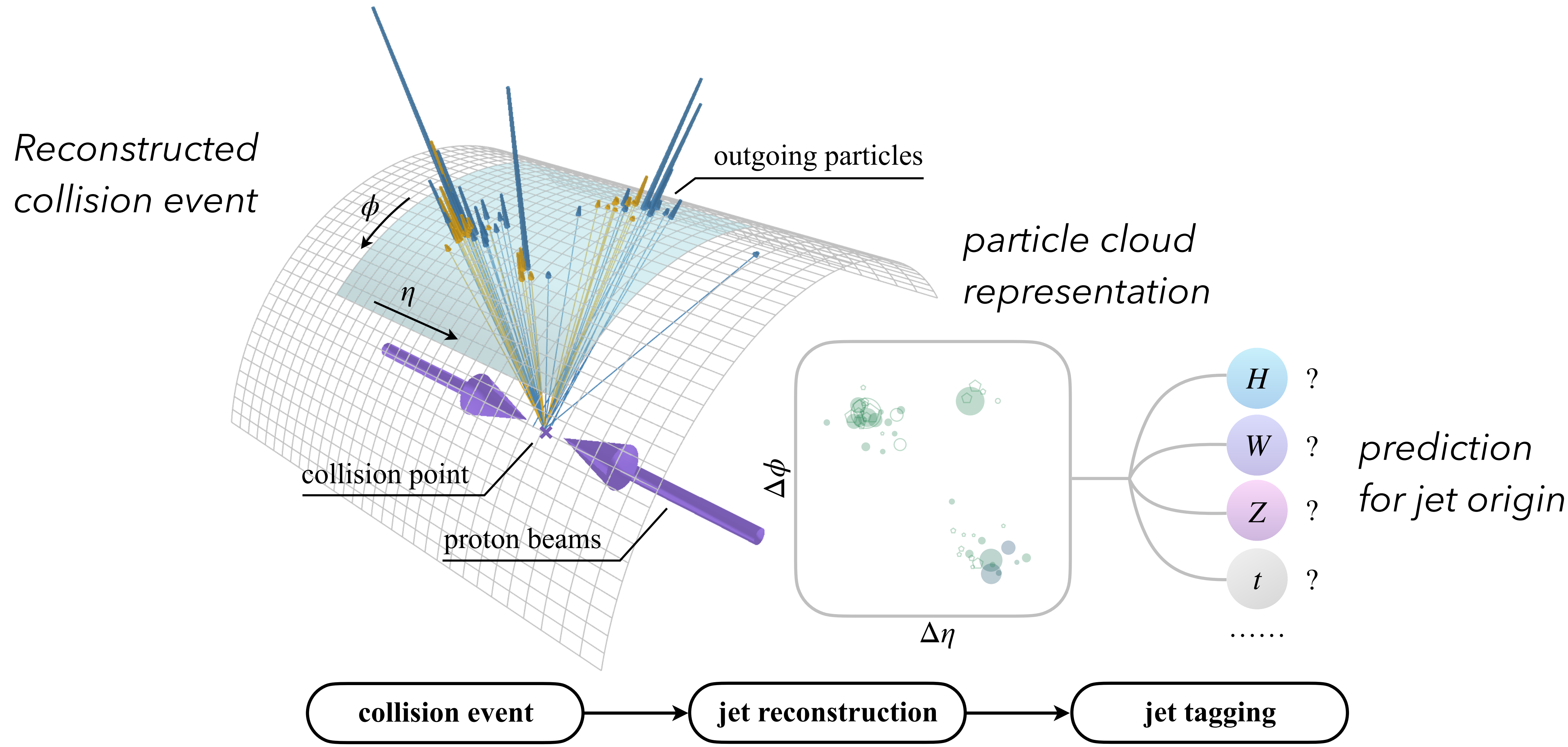
Point clouds: representing multidimensional data

- *Represent shapes with unordered set of points in space ⇒ natural representation as input to graph-based neural networks*
  - *Self-driving cars* : efficiently represent complex and dynamic outside environment as given by LiDAR (laser imaging using time of reflected light to return)
  - Computer-aided design (CAD): store a design in any level of detail while minimizing size of data



Self-driving car representation of space with point cloud

Particle cloud: a point cloud for the LHC

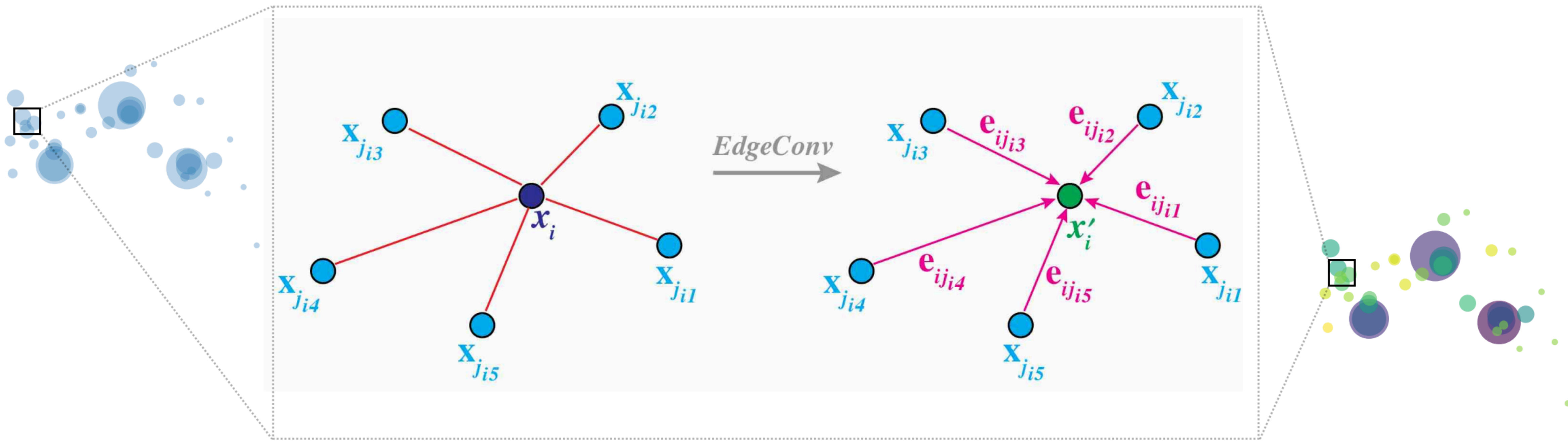


- Represent jet as unordered set of particles (particle cloud) with variety of features:
  - Spatial (η/φ), pT, impact parameter, charge, …

- ***Learn nature of the jet and its properties from particle features and correlations***

arXiv:2202.03772

Edge convolution

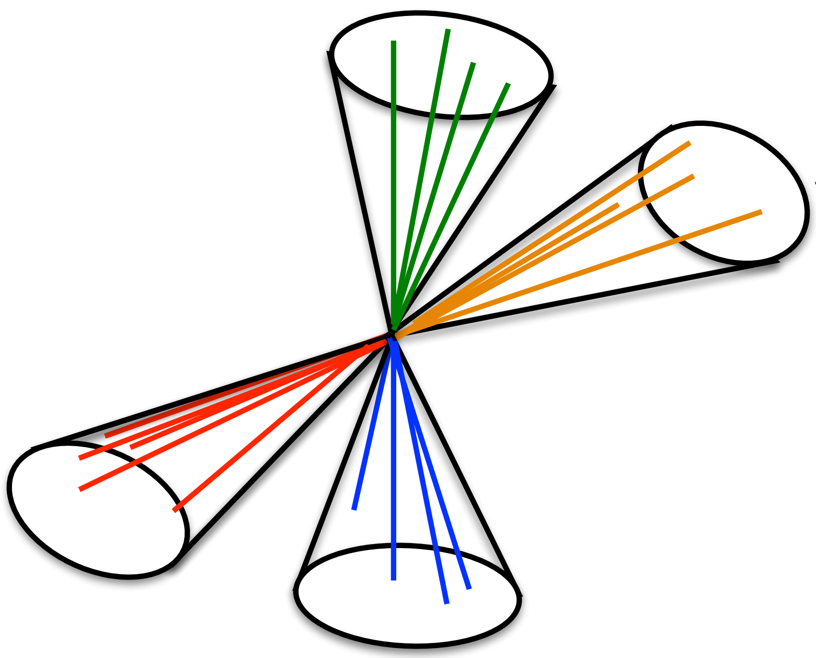


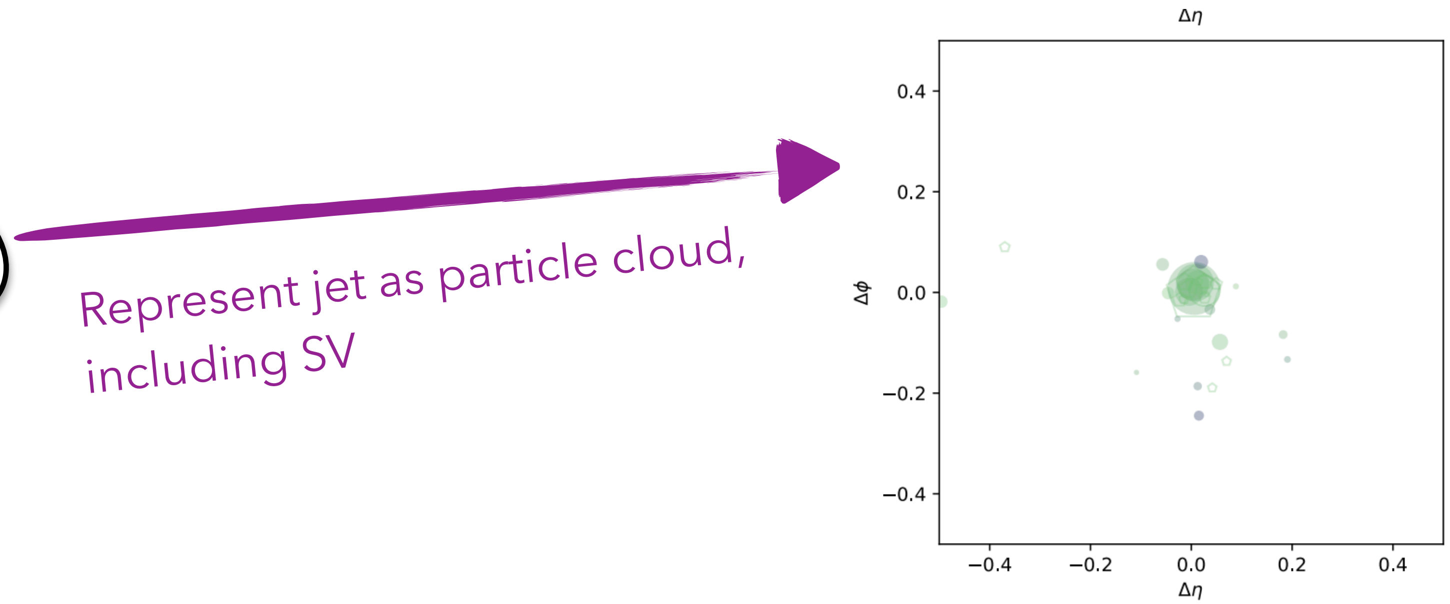
- To apply ML to a particle cloud, need a differentiable function to pass information, learn given task (e.g. b-jet classification)

- EdgeConv:
  - An abstraction of convolutional layer as applied in image-based AI (e.g. ResNet)
  - For each node in the graph (particle), calculate a new node representation based on N nearest neighbor nodes
  - Output of each EdgeConv operation is a graph (stackable)

A particle cloud-based jet tagger: ParticleNet

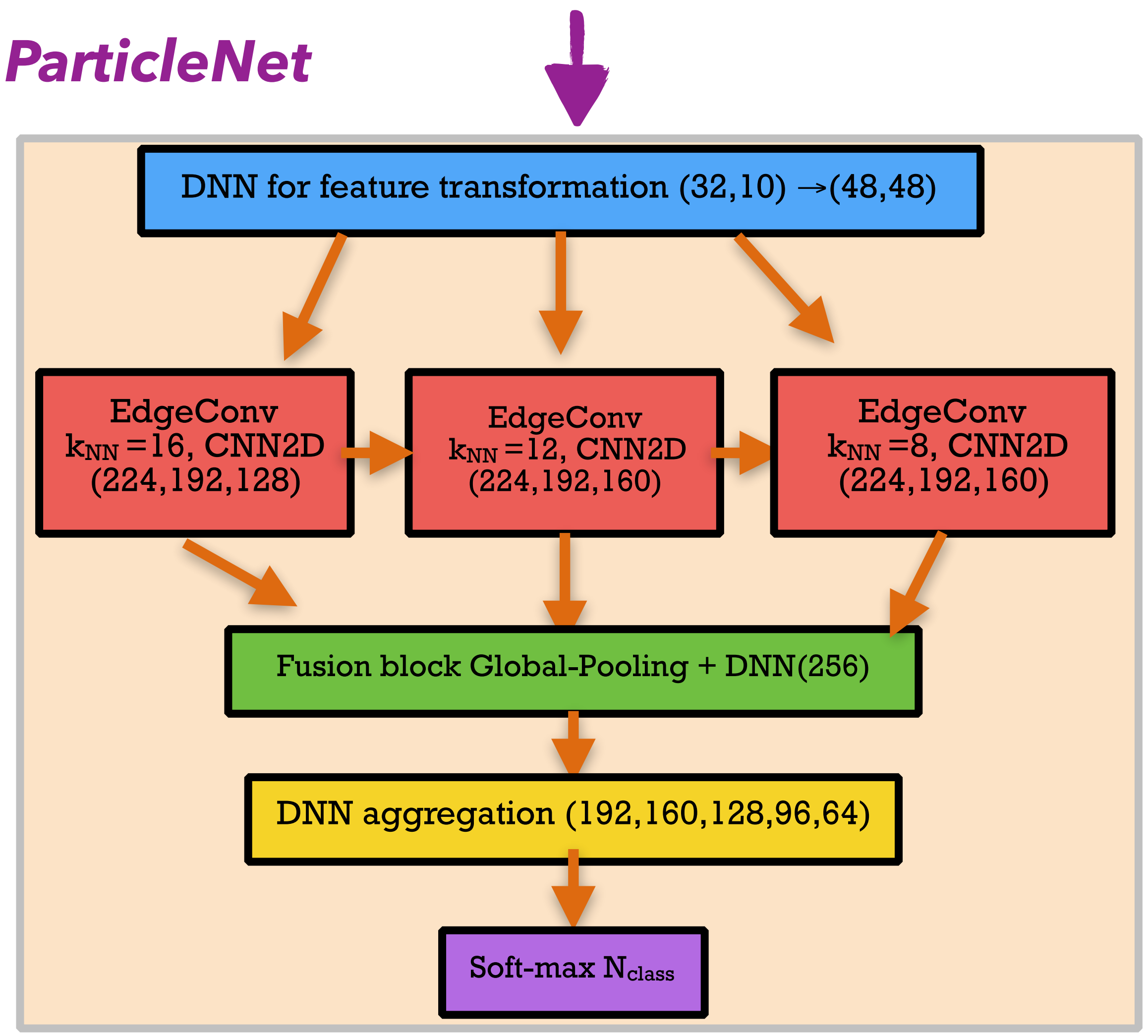
HH→4b candidate event





Is it a b jet?

ParticleNet

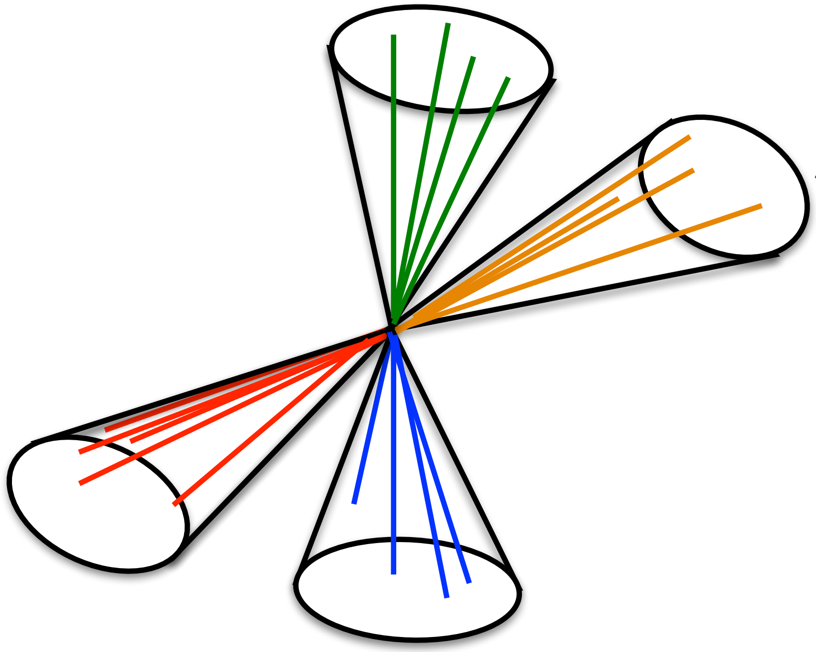


- Putting it all together into ML for b-jet tagging: ParticleNet

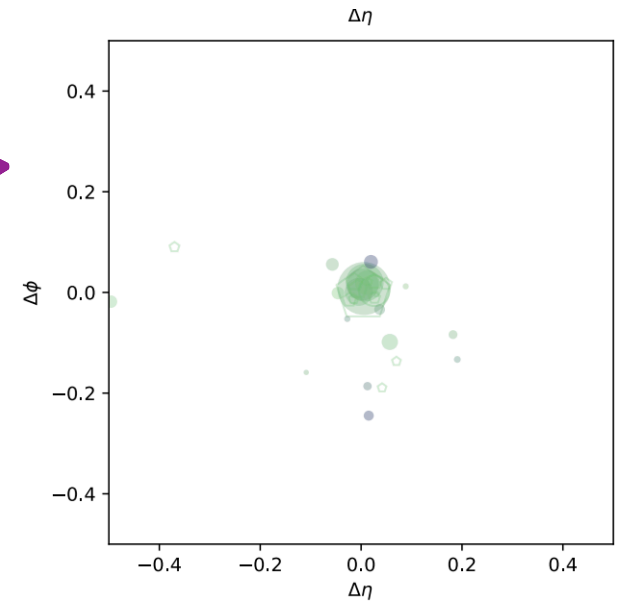
Phys. Rev. D 101, 056019

A particle cloud-based jet tagger: ParticleNet

HH→4b candidate event



Represent jet as particle cloud, including SV



Is it a b jet?

ParticleNet

Represent jet as graph built from particles and vertices

Pass information among graph nodes via stacked EdgeConv layers

Condense graph representation into set of features to feed to deep neural network (DNN)

Output set of jet class probabilities

- Putting it all together into ML for b-jet tagging: ParticleNet*

Jet origin probabilities

p(b)

p(c)

p(uds)

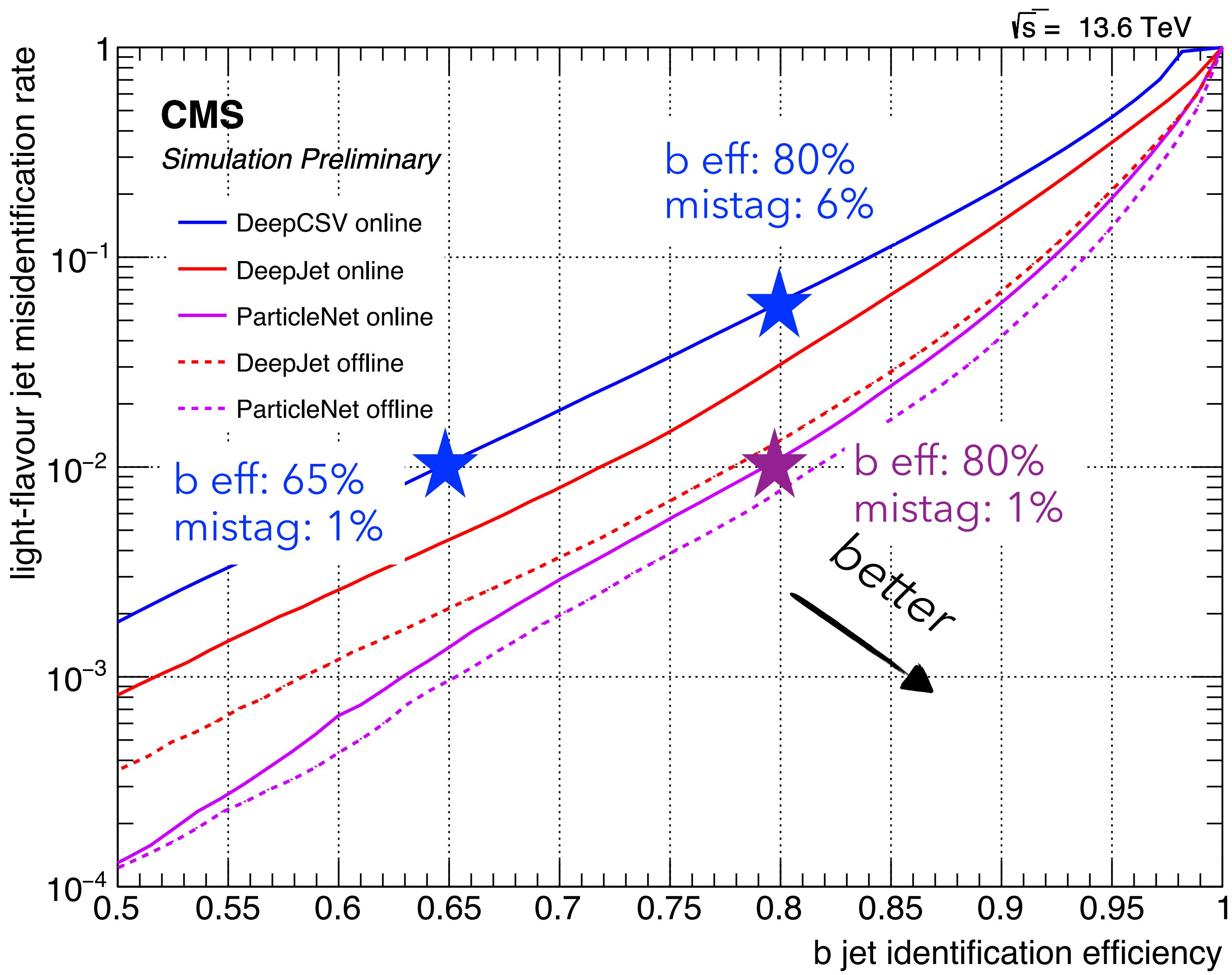
p(g)

Phys. Rev. D 101, 056019

Online b-tagging performance of ParticleNet

- ***We developed a b-tagging algorithm, based on particle clouds, for the CMS trigger system***
  - *First such network in trigger system*
  - *First generation of online b-taggers trained on HLT-level jets*
    - Previous algorithms were suboptimal (no HLT jet training)
  - Design of network to *fit within trigger low-latency budget*

b-tagging performance at trigger level



CMS-DP-2023-021

A powerful new tool for CMS to select b jets at trigger level in Run-3

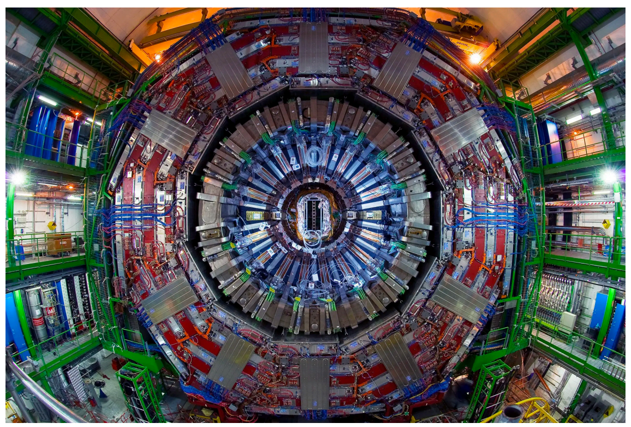
New Run-3 HH→4b trigger strategy

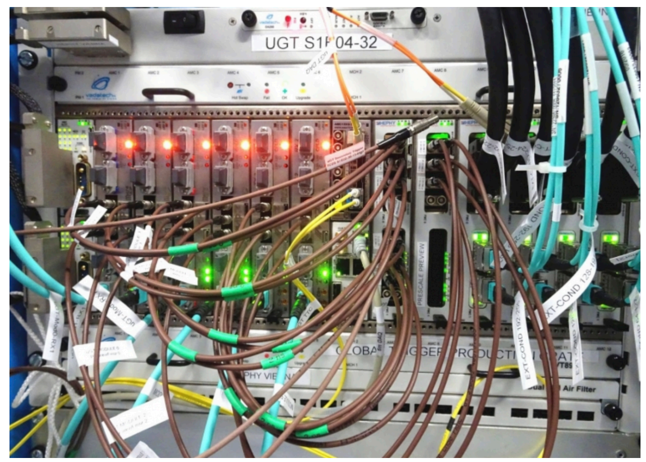
40 MHz

110 KHz (<4μs)

~5 KHz (<0.5s), ~15 GB/s
for HH4b: 30-35 Hz

collision event → Level-1 Trigger → High-Level Trigger (HLT) → Data storage





(partial detector readout)

(full detector readout)

- **Leveraging the highly improved online b-tagger (ParticleNet@HLT)**, we *redesigned Run-3 HH→4b trigger with much more inclusive selections*

Trigger efficiency, HH→4b signal	
Run-2	**18%**
Run-3	**42%**

*actual rate in 2022 was ~60 Hz after update to HCAL calibrations

A new opportunity for 2023: data parking

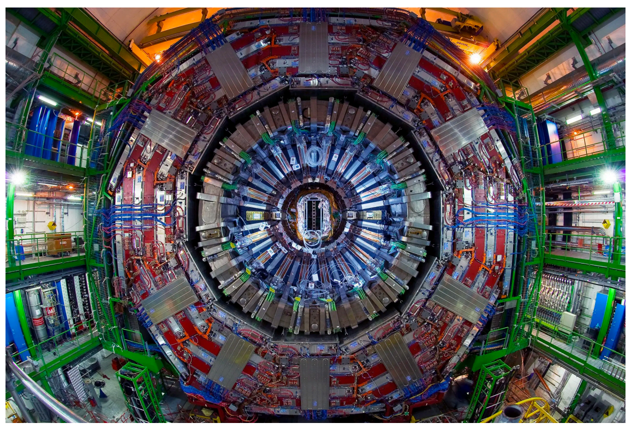
40 MHz

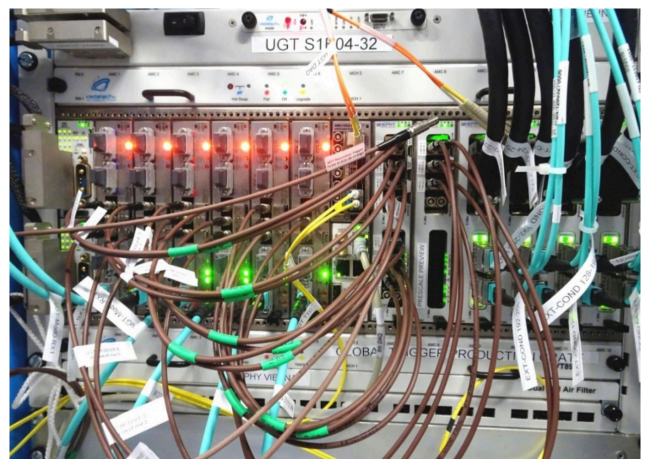
110 KHz (<4μs)

~5 KHz (<0.5s), ~15 GB/s

for HH4b: ~150 Hz

collision event → Level-1 Trigger → High-Level Trigger (HLT) → Data storage





(partial detector readout)

(full detector readout)

- In 2023, opportunity for higher rate (150 Hz) in delayed data stream (“data parking”) ⇒ even looser thresholds
- Absolute HH→4b ***signal efficiency improved by 300%****
  - *Efficiency gain even larger for HH→4b signals with λ other than SM*

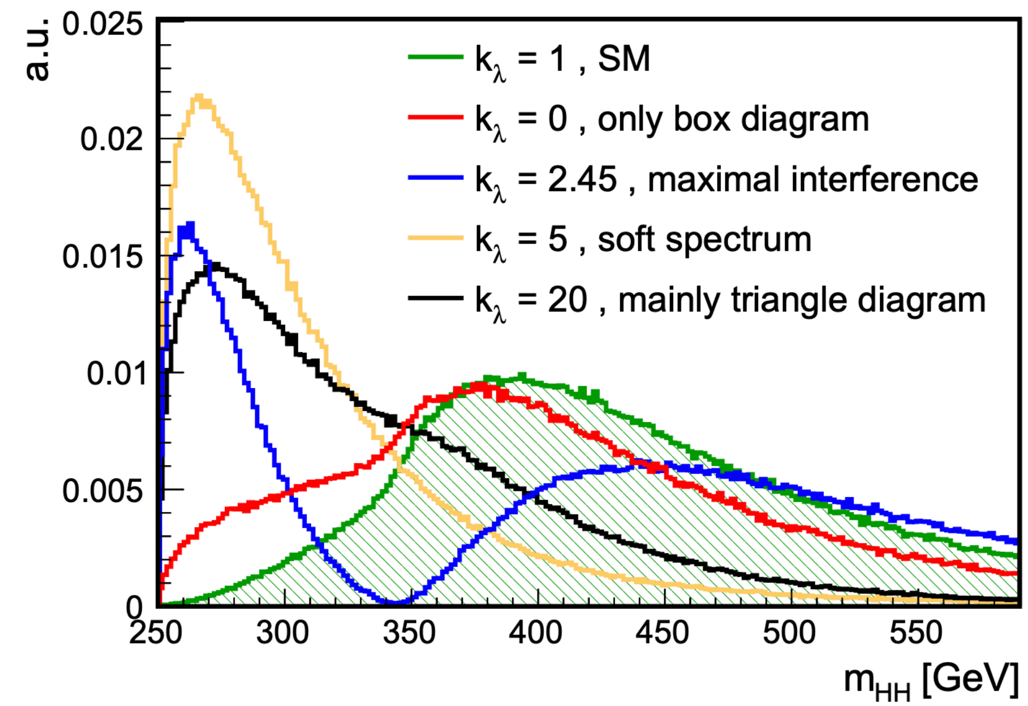
**N.B. more background too - room to explore for Run-3!*

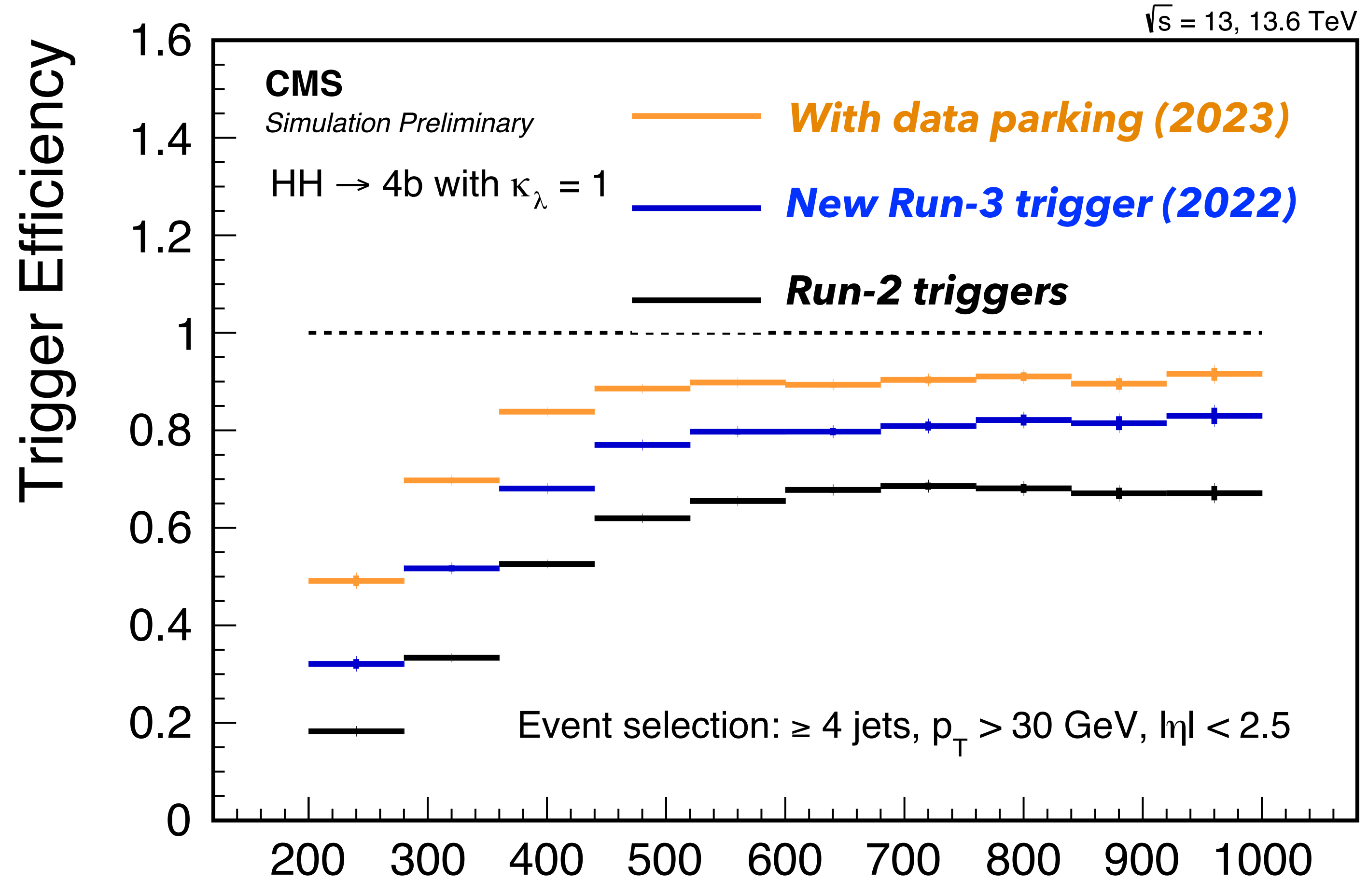
Trigger efficiency, HH→4b signal	
Run-2	**18%**
Run-3	**42%**
Run-3 (parking)	**55%**

Efficiency recovery vs. m_{HH}

- *Efficiency gain is particularly large for lower m_{HH} events*, which are critical in constraining λ

- With many more HH→4b events saved in Run-3, we have much more room to explore
  - ❖ Can HH→4b become a leading channel in constraining λ?



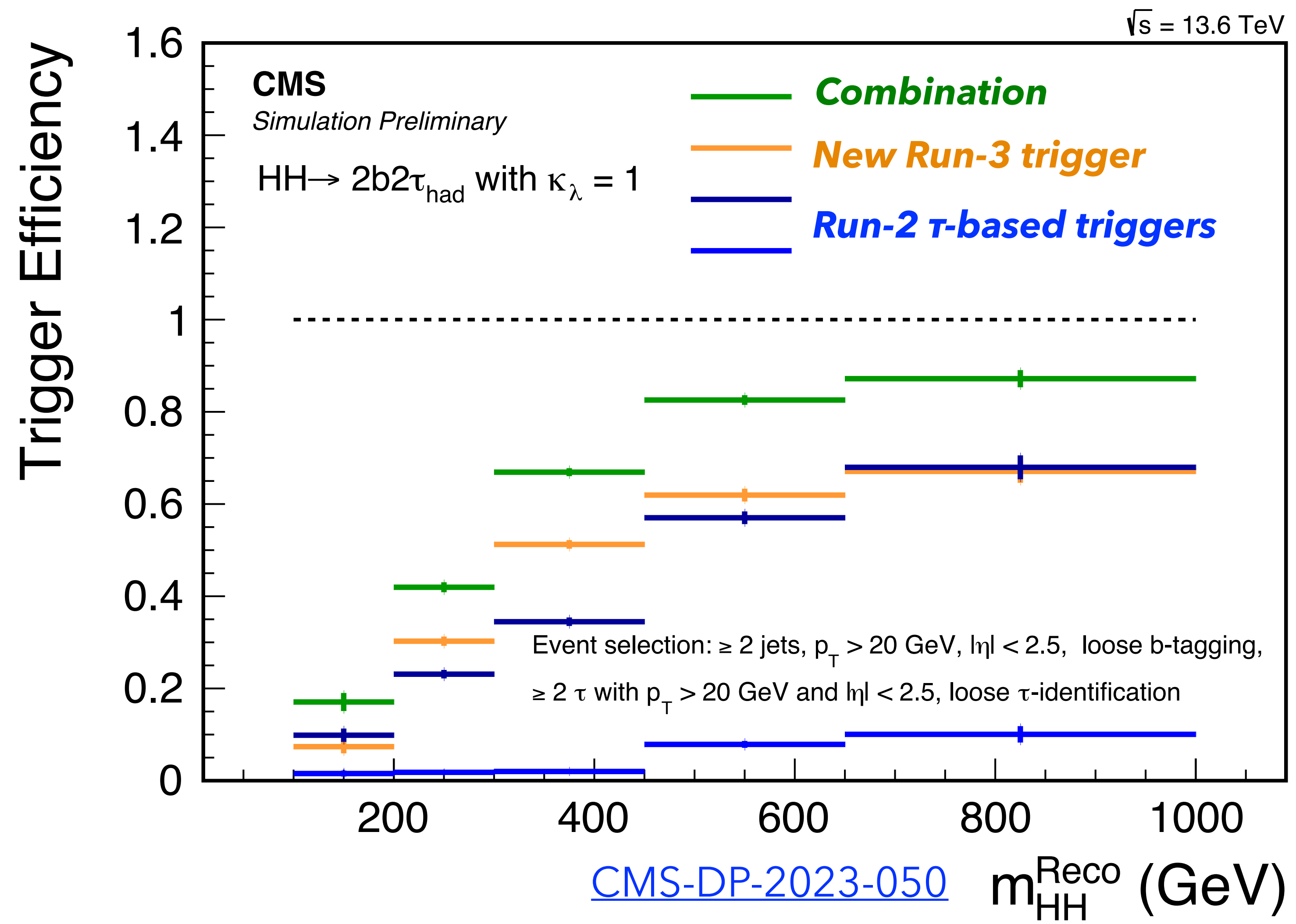


CMS-DP-2023-050

Improving HH→bbττ as well

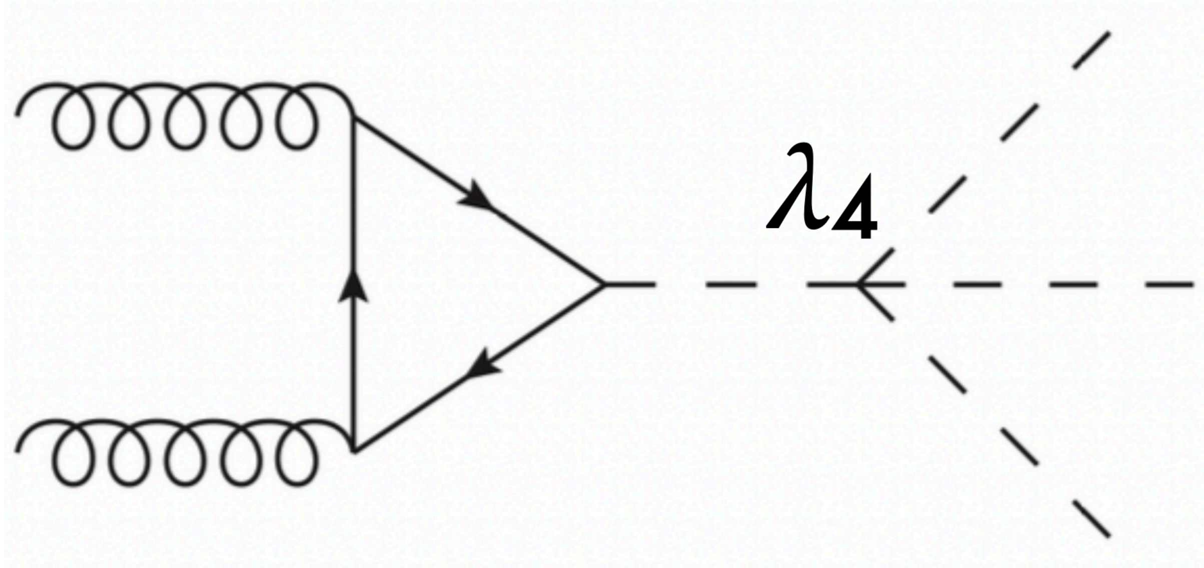
- ***New trigger is significantly more generic*** *than in Run-2, improving signal efficiency for a variety of analyses*
  - HH→bbττ, ttH(bb), resonance searches, …
- ***In particular, it also improves signal efficiency in key HH→bbττ fully hadronic channel by about 70%.***

HH→bbττ trigger efficiency



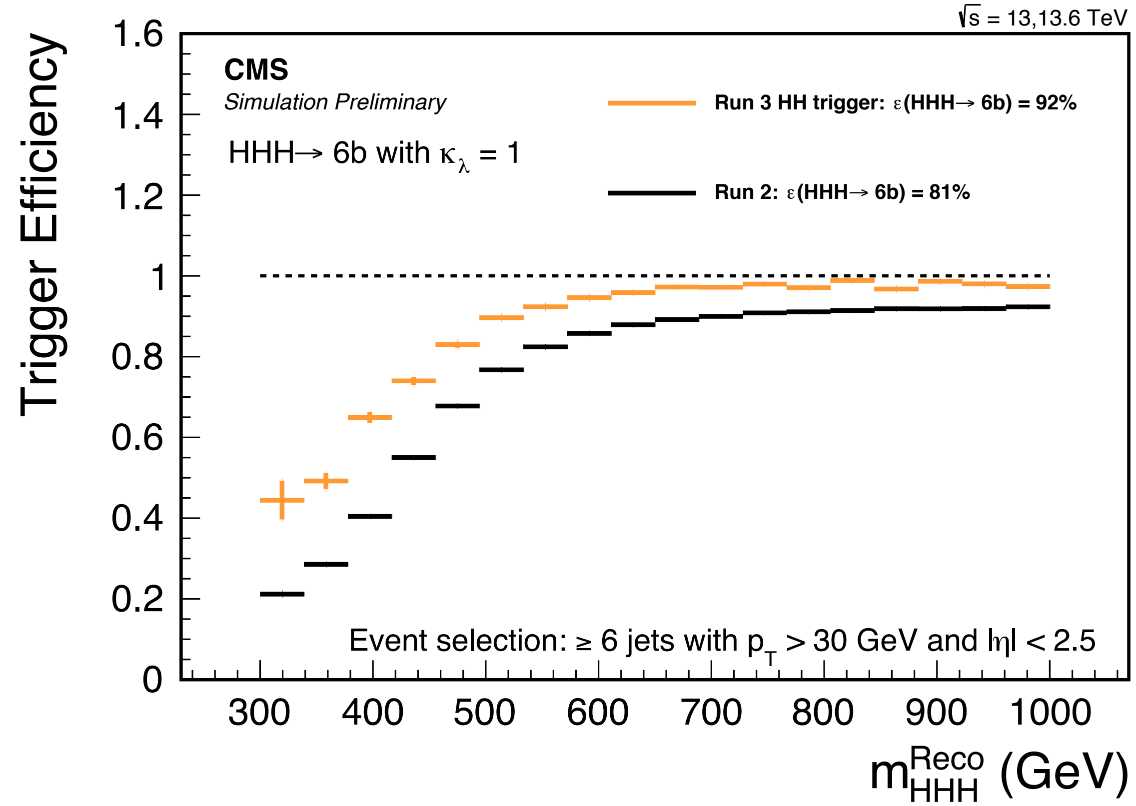
CMS-DP-2023-050

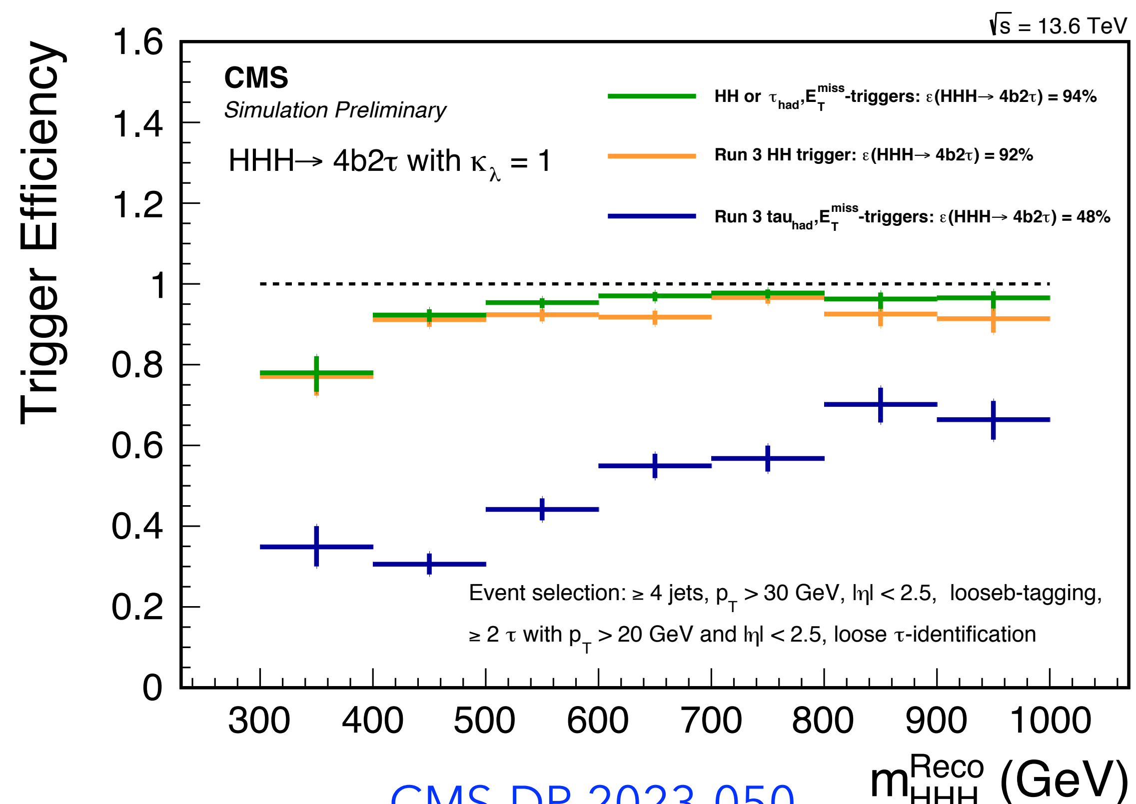
...and HHH!



- The latest place to explore: HHH production
  - SM production rate is very (very) small, but large enhancement when varying λ_4
  - See Marko's talk this morning for more details

- *New HH→4b triggers also substantially improve the trigger efficiency for HHH signals*

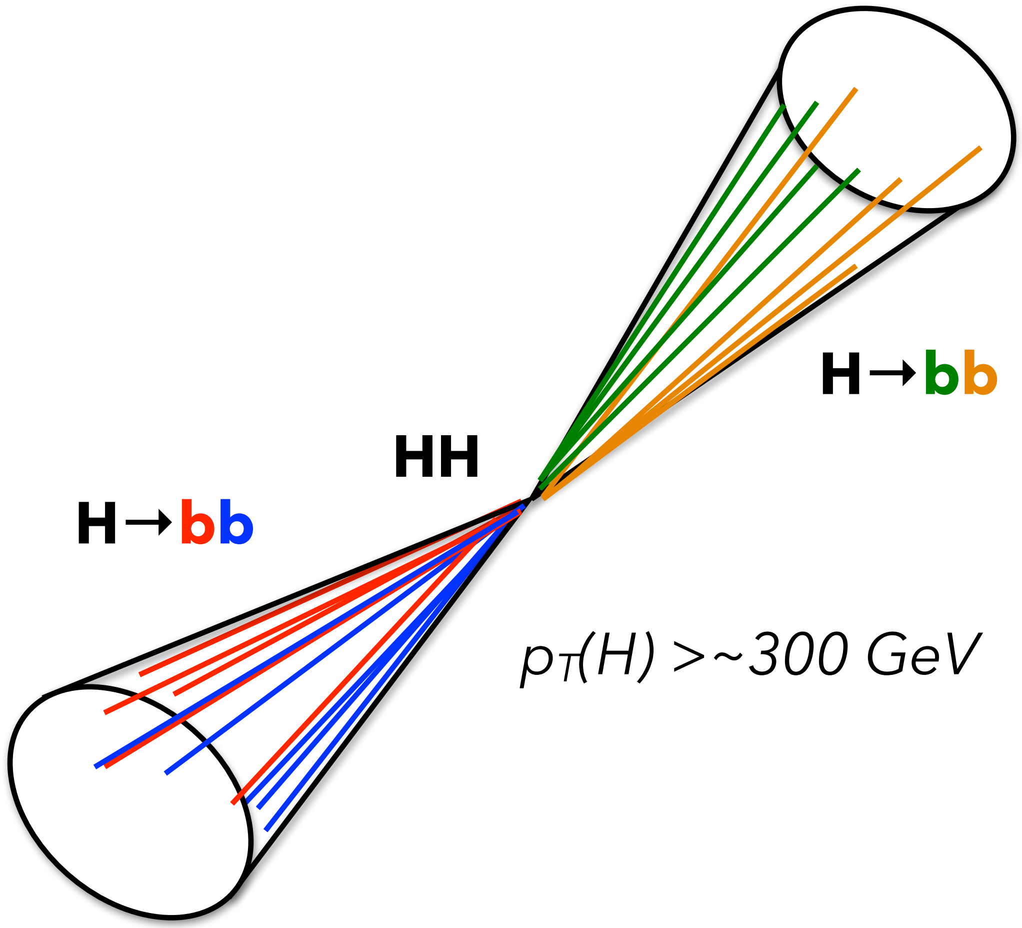




CMS-DP-2023-050

Merged H→bb triggers

- *We have similarly deployed a dedicated training of ParticleNet@HLT for merged bb-jet tagging at HLT*
- Basis for new merged-H triggers, deployed since start of Run-3, which will very significantly expand available phase space
  - ❖ Run-2 analyses were strongly limited by trigger acceptance
  - ❖ Merged HH→4b channel alone had sensitivity comparable to 2b2τ and 2b2γ, despite these limitations in trigger
- *Expect a general large expansion in general high-p_T(H) physics reach for Run-3*
  - ❖ *…coming soon :)*



Validating in data

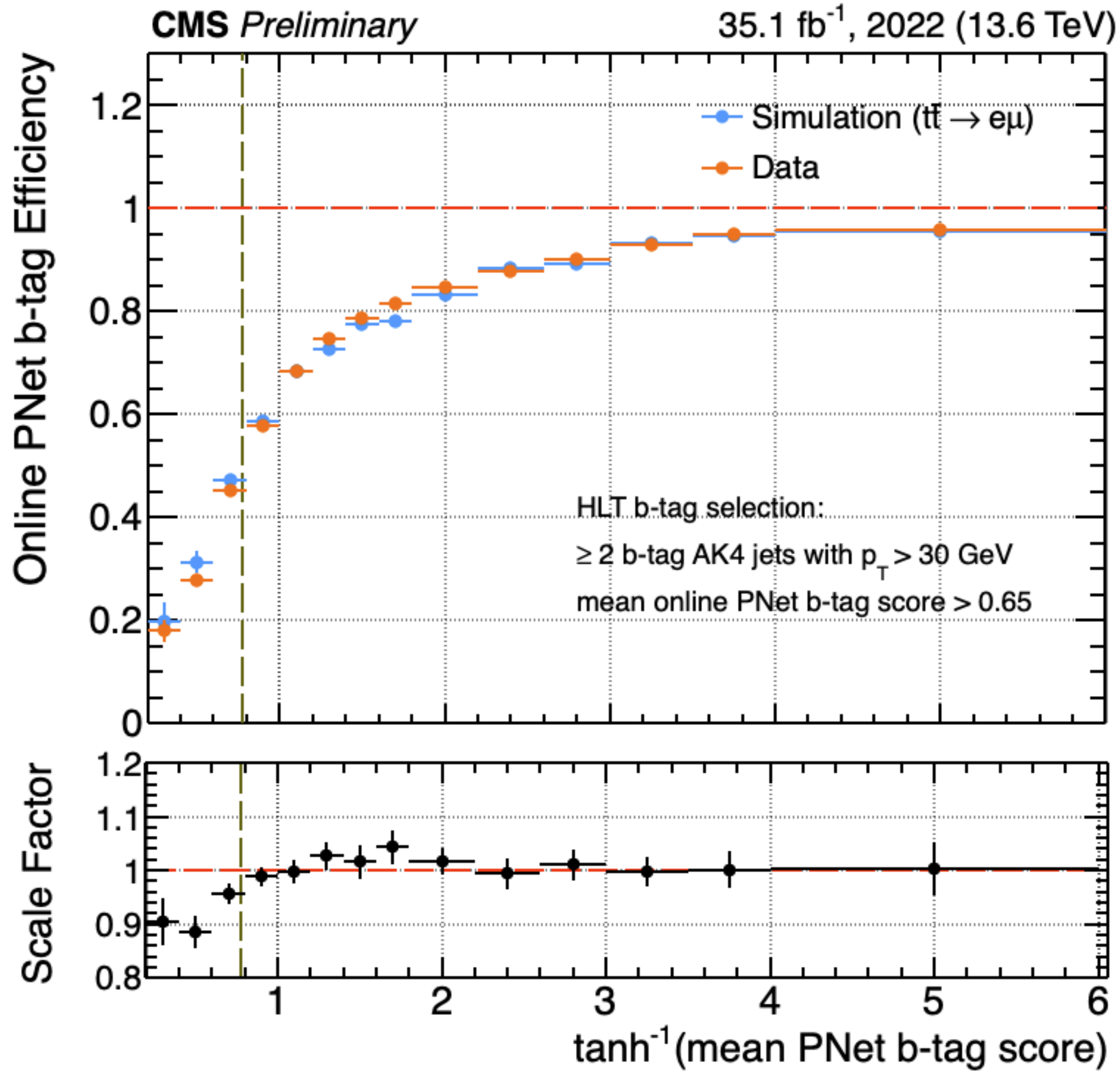
- Two years (2022+2023) of successful data-taking with new HH triggers

- We have now also validated the HLT jet b-tagging performance relative to the full offline reconstruction, in data and simulation

- Performance in data is well predicted by simulation ⇒ ***high confidence that the predicted gains in HH/HHH are representative of the data***

- Similar studies in progress for online merged H→bb tagging performance

new for today



Further improvements for HH Run-3

- Focus today has been on new trigger developments for Run-3
  - First priority, further innovations don't matter if we don't collect the data :)

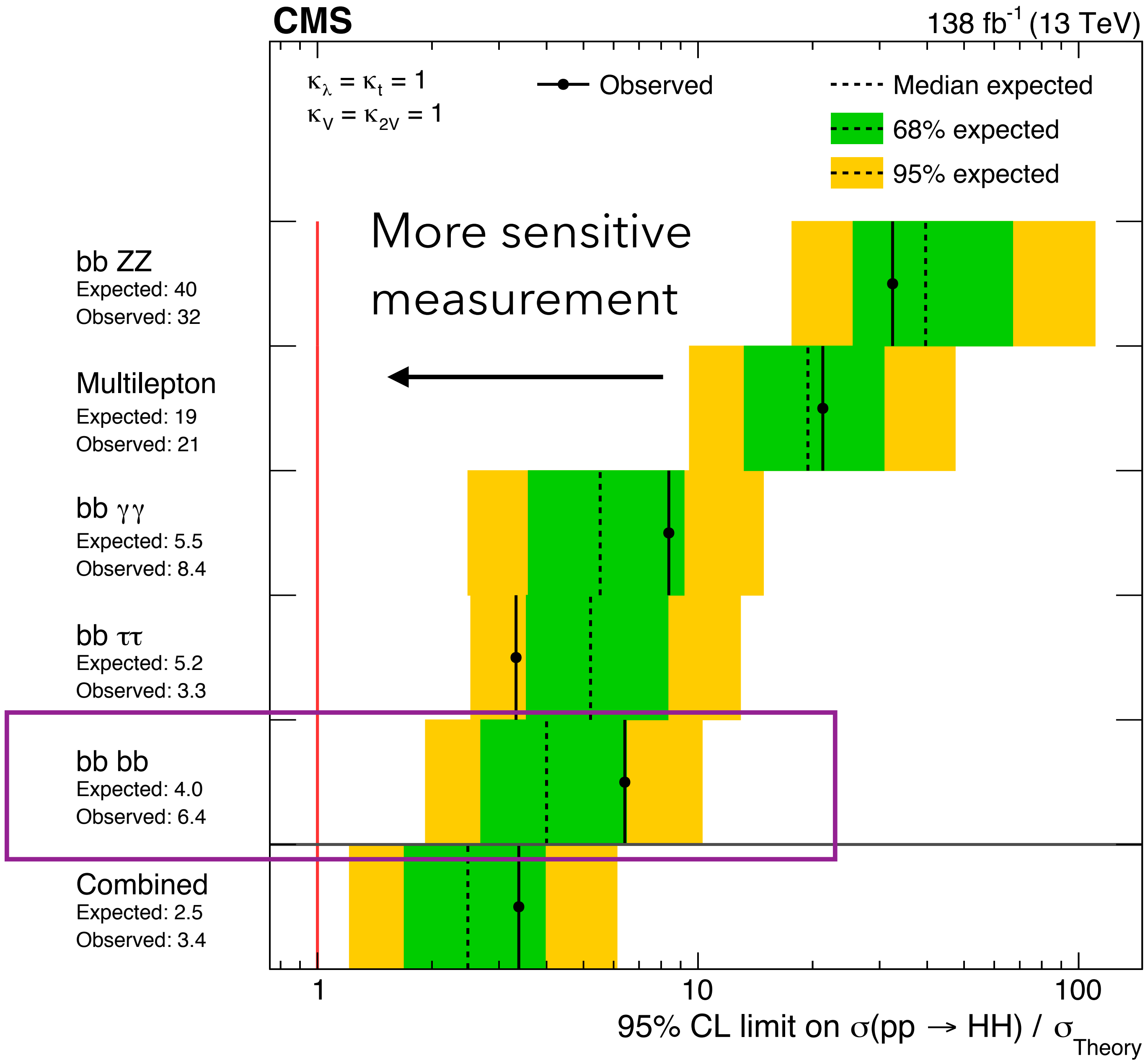
- However, this is *just one piece in a multi-faceted effort to maximize HH reach for Run-3*
  - Improvements in offline b-jet identification and p_T regression
  - New methods for tau identification and reconstruction
  - …

- Let's see together how far we can push the HH frontier with Run-3 data!

Additional Material

- Despite significant trigger limitations, HH→4b was one of the driving channels in Run-2 HH, honing in on SM…

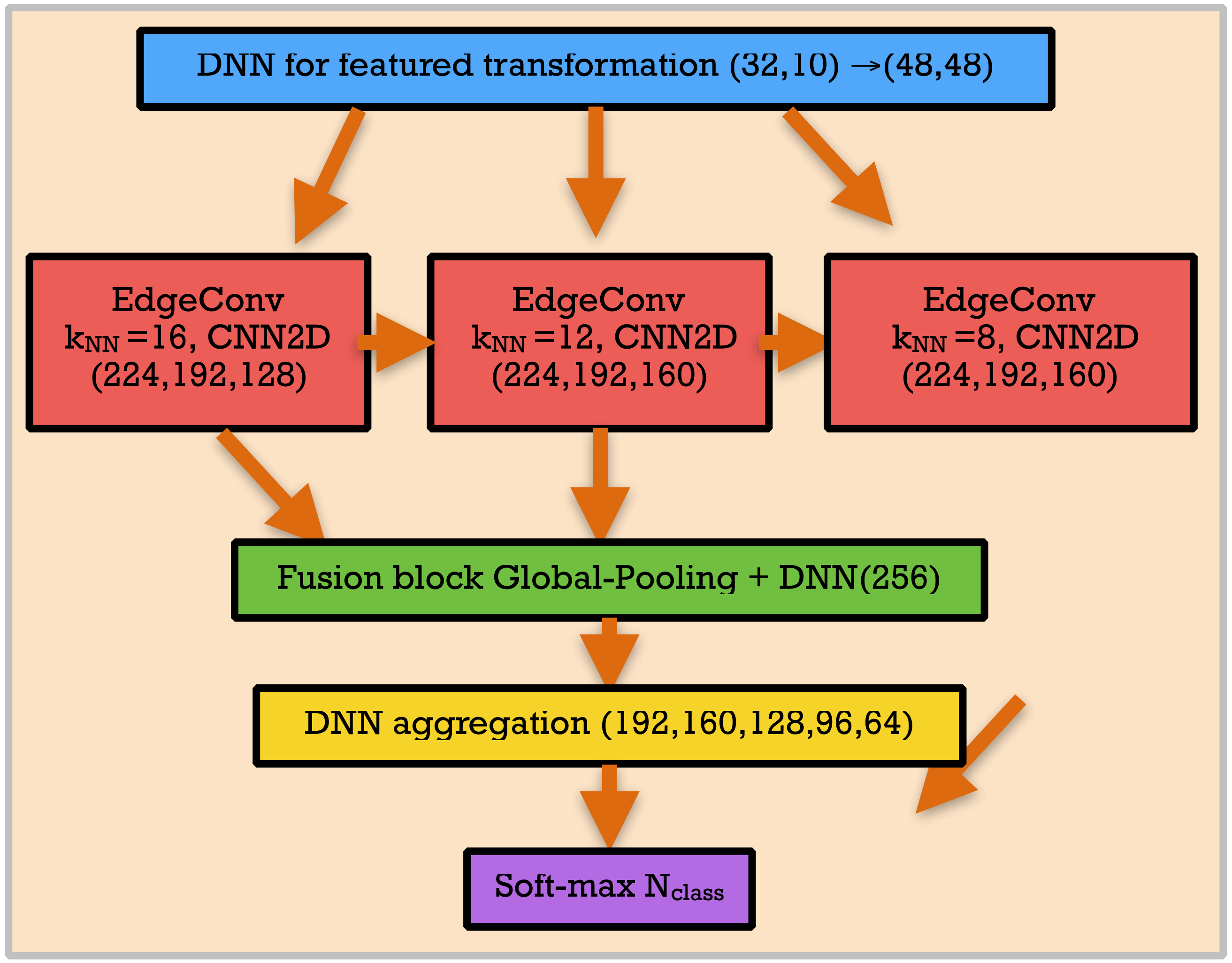
- HH→bbττ is another leading channel that should improve substantially from our new algorithms.



Nature 607 (2022) 60-68

Network architecture, inputs

ParticleNet general architecture



- Input features from:
  - ❖ PF candidates (up to 50): similar to Run-2 classifier + dedicated PF e/μ/γ inputs
  - ❖ SV vertices (up to 5)
  - ❖ Lost tracks (up to 5)
    - Good quality tracks not matched to PF candidate, important for tau reconstruction.
- Unify tasks (jet flavor classification, tau ID+reco, jet energy regression) by combining into single loss function.

$$L = \mathrm{CatEntropy}(x, x_{\mathrm{truth}}) + \lambda \times \log(\cosh(y - y_{truth})) + \gamma \times [\rho_{0.16}(z - z_{\mathrm{truth}}) + \rho_{0.84}(z - z_{\mathrm{truth}})]$$

Classification

Regression (p_T, m_X)

Quantile regression

$$\rho_\tau(z) = \begin{cases} \tau z, & \text{if } z > 0; \\ (\tau - 1)z, & \text{otherwise,} \end{cases}$$

Input features

- **PF candidates** (up to 50 per jet) :
  - ❖ Common between charged and neutral:
    - $\log(p_T)$, $\log(E)$, η, $\Delta\eta(i,jet)$ $\Delta\varphi(i,jet)$, charge, PFID, H/E, $E_{CALO}/E_{PF,}$ P_T projected || or ⊥ to jet axis
  - ❖ Specific to charged particles:
    - PV association, Trk χ^2 and quality, Δz & Δxy vs PV, $N_{pix\text{-}hit}$ $N_{strip\text{-}hit,}$ $N_{lost\text{-}hit,}$ Δ3d impact, decay length

- **Secondary vertices** (up to 5 per jet):
  - ❖ $\log(p_T)$, M_{SV}, $\Delta\eta(i,jet)$, $\Delta\varphi(i,jet)$, N_{track}, χ^2, Δxy, Δz

- PF candidate specific features:
  - ❖ Electrons: $\sigma_{i\eta i\eta}$, $\sigma_{i\varphi i\varphi}$, R9, $\Delta\varphi$(SC,trk.), $\Delta\eta$(SC,trk.)
  - ❖ Photons: $\sigma_{i\eta i\eta}$, R9, eVeto
  - ❖ Muon: isGlobal, χ^2, segment compatibility, N_{hit}, $N_{station}$

- Good quality tracks not associated with PF candidate (“**lost tracks**”)
  - ❖ Input features the same as those specific to PF charged candidates.

Training sample

- General philosophy: sample jet kinematic phase space as much as possible, mix processes to protect from process-specific biases

- AK4 PUPPI jets from a mix of Run-2 2018UL MINIAODSIM v2 samples: QCD, ttbar, H/HH(bb/cc/ττ/μμ/ee), DY(ττ/μμ/ee), W+jets

- About 80M AK4 PUPPI jets with raw p_T>15 GeV, |η|<2.5, and matched with generator-level jet.
  - 65% for training, 20% for validation, 15% for testing.
  - Jets sampled such that distribution in jet p_T and η is ~uniform such that network output is decorrelated.

Bins for uniform resampling:

```
jet_pt_raw: [15, 20, 25, 30, 38, 48, 60, 76, 97, 122, 154, 195, 246, 311, 393, 496, 627, 792, 1000]
jet_eta: [-2.5, -2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5]
```

Jet truth classes

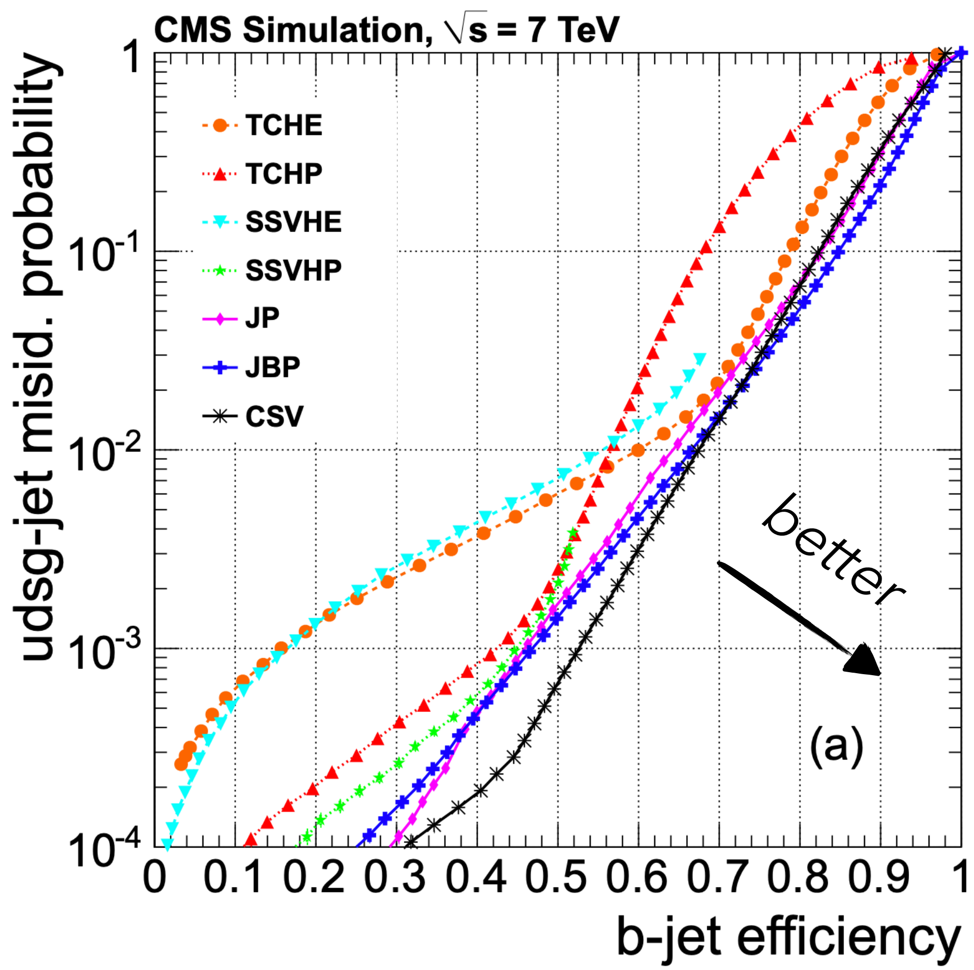
- Classify jets based on truth-level:
  - Hadron flavor for heavy flavor jets (b, c)
  - Parton flavor for udsg
  - Matching $\Delta R(j,\text{lep.})$ with prompt GEN lepton from H/W/Z decay.

- Ensure orthogonality among classes, giving priority to lepton classes.

Truth classes	selection	weight
μ jets	GEN μ with $p_T > 8$ GeV from $H/W/Z/\tau$ decays $\Delta R(j,\mu) < 0.4$	1
e jets	GEN e with $p_T > 8$ GeV from $H/W/Z/\tau$ decays $\Delta R(j,e) < 0.4$	1
τ_h jets	GEN τ_h with $p_T^{vis} > 15$ GeV from $H/W/Z/\tau$ decays $\Delta R(j,\tau) < 0.4$	1.5
b-jets	Not $\mu/e/\tau_h$ + hadron-flavor = 5	2
c-jets	Not $\mu/e/\tau_h$ + hadron-flavor = 4	2
uds jets	Not $\mu/e/\tau_h$ + hadron-flavor = 0 + abs(parton-flavor) = 1,2,3	4
gluon jets	Not $\mu/e/\tau_h$ + hadron-flavor = 0 + abs(parton-flavor) = 21	6

Evolution of b-tagging in CMS

- *Rely on a few observables*:
  - ❖ Track impact parameters
  - ❖ Secondary vertices (SV)
- First single-variable algorithms, later multi-dimensional likelihoods

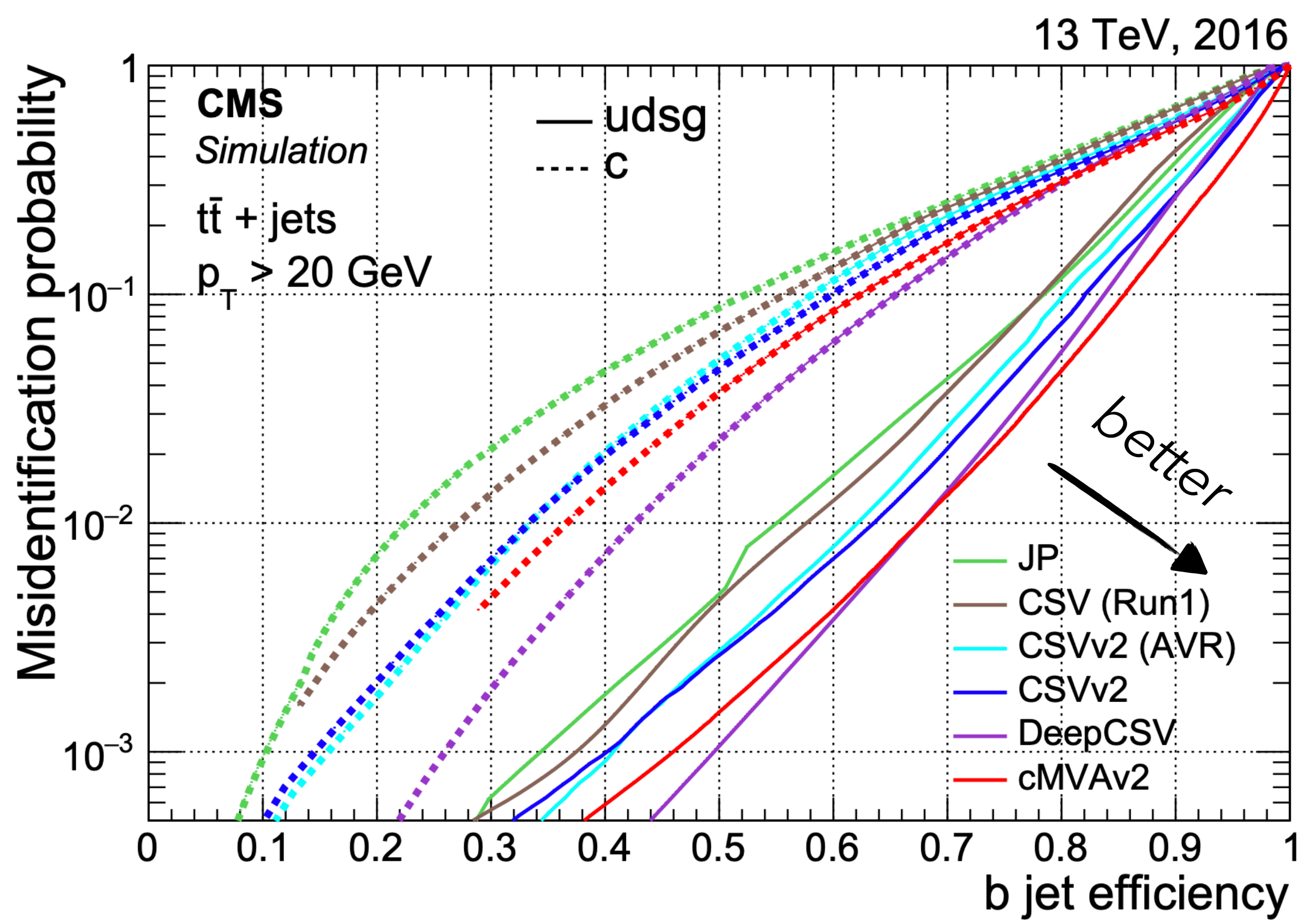


JINST 8 (2013) P04013

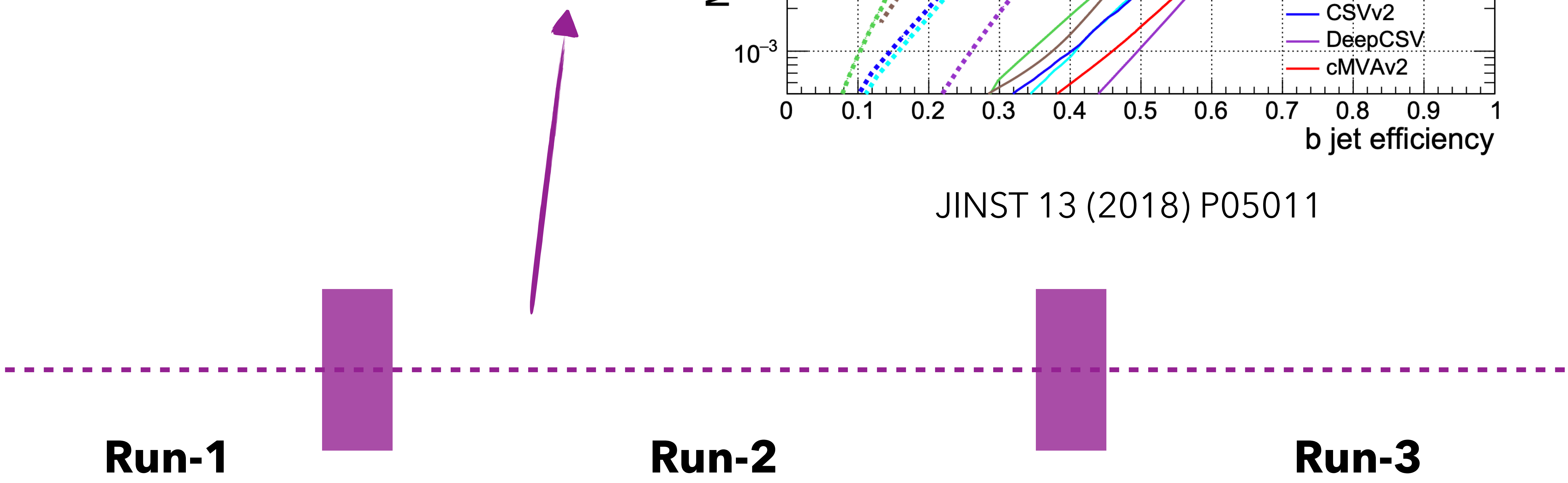
Run-1 **Run-2** **Run-3**

Evolution of b-tagging in CMS

- *Combine increasing number of high-level input variables into multivariate algorithms:*
  - *Single layer neural network: CSVv2*
  - *Deep neural network with several hidden layers of 100 nodes: DeepCSV*

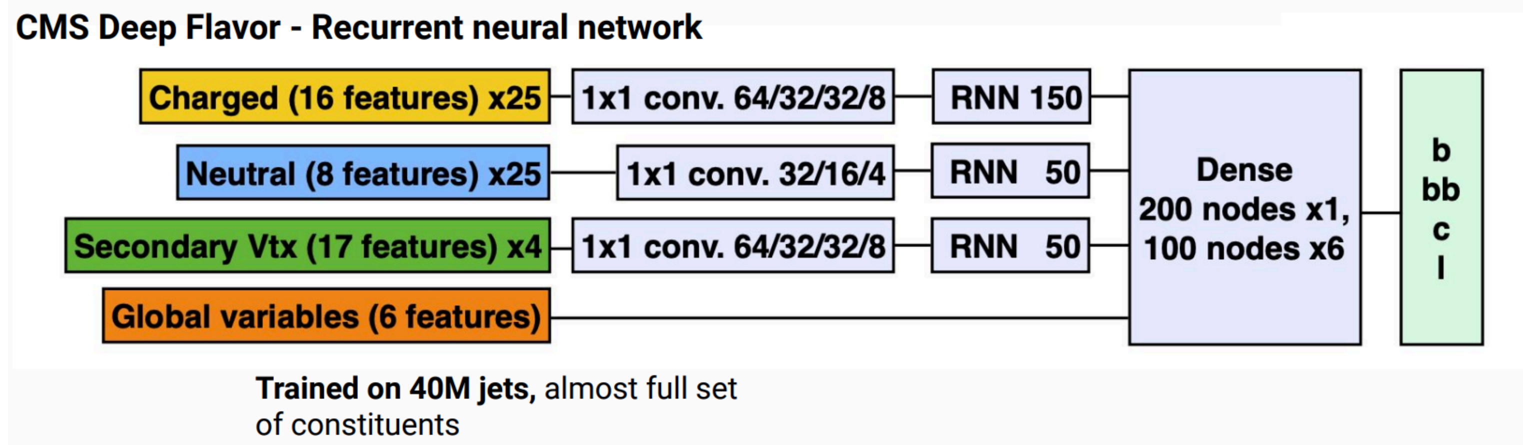


JINST 13 (2018) P05011



Evolution of b-tagging in CMS

- **A paradigm shift**: *much larger networks, low-level input features based on jet particular constituents*
  - ❖ Training on 40M jets!



- New inner tracking detector with additional innermost layer also key to pushing b-tagging performance further