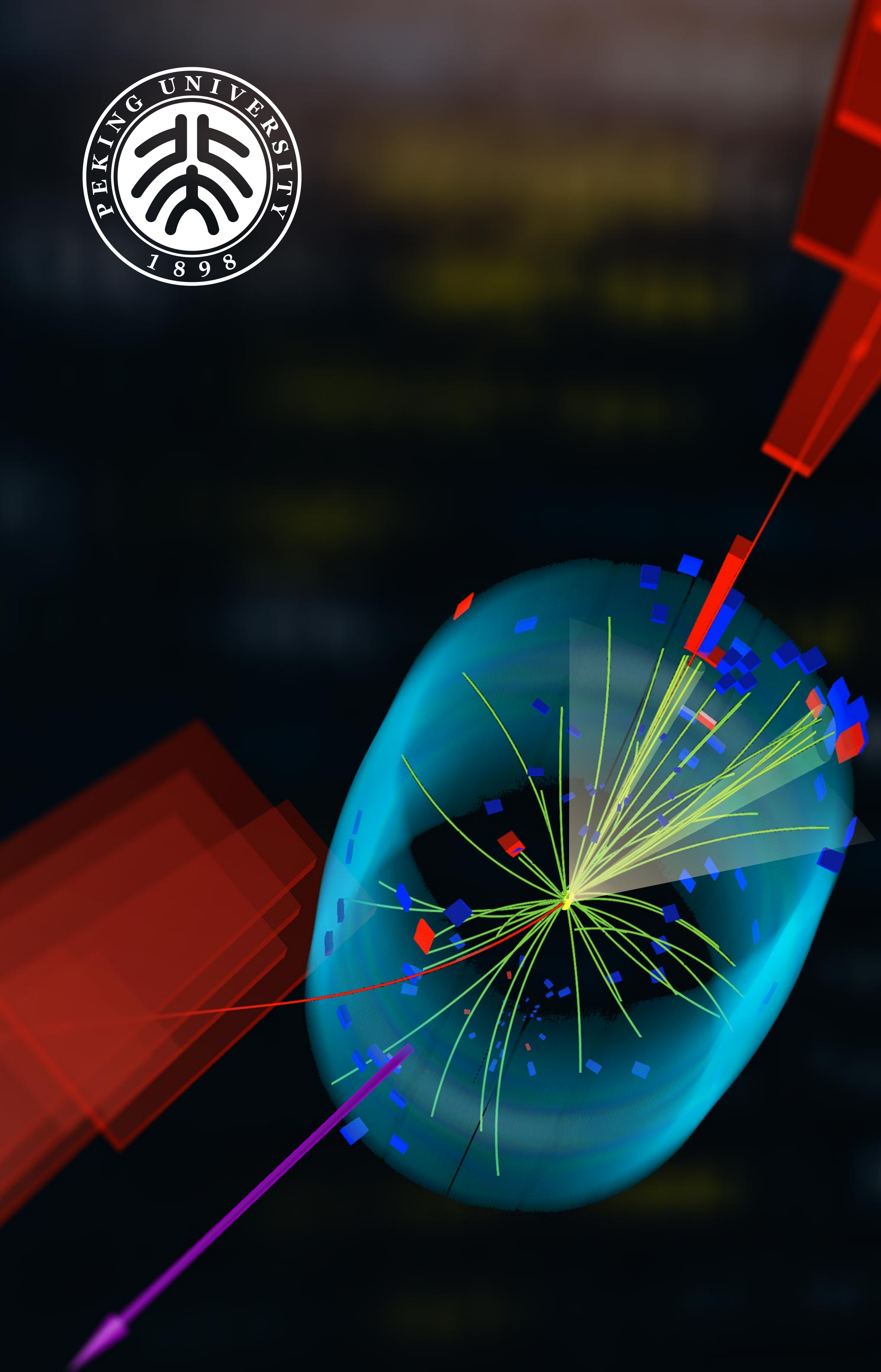


CMS new physics search highlights

— A lens on recent experimental innovations

Congqiao Li (李聪乔) *(Peking University)*

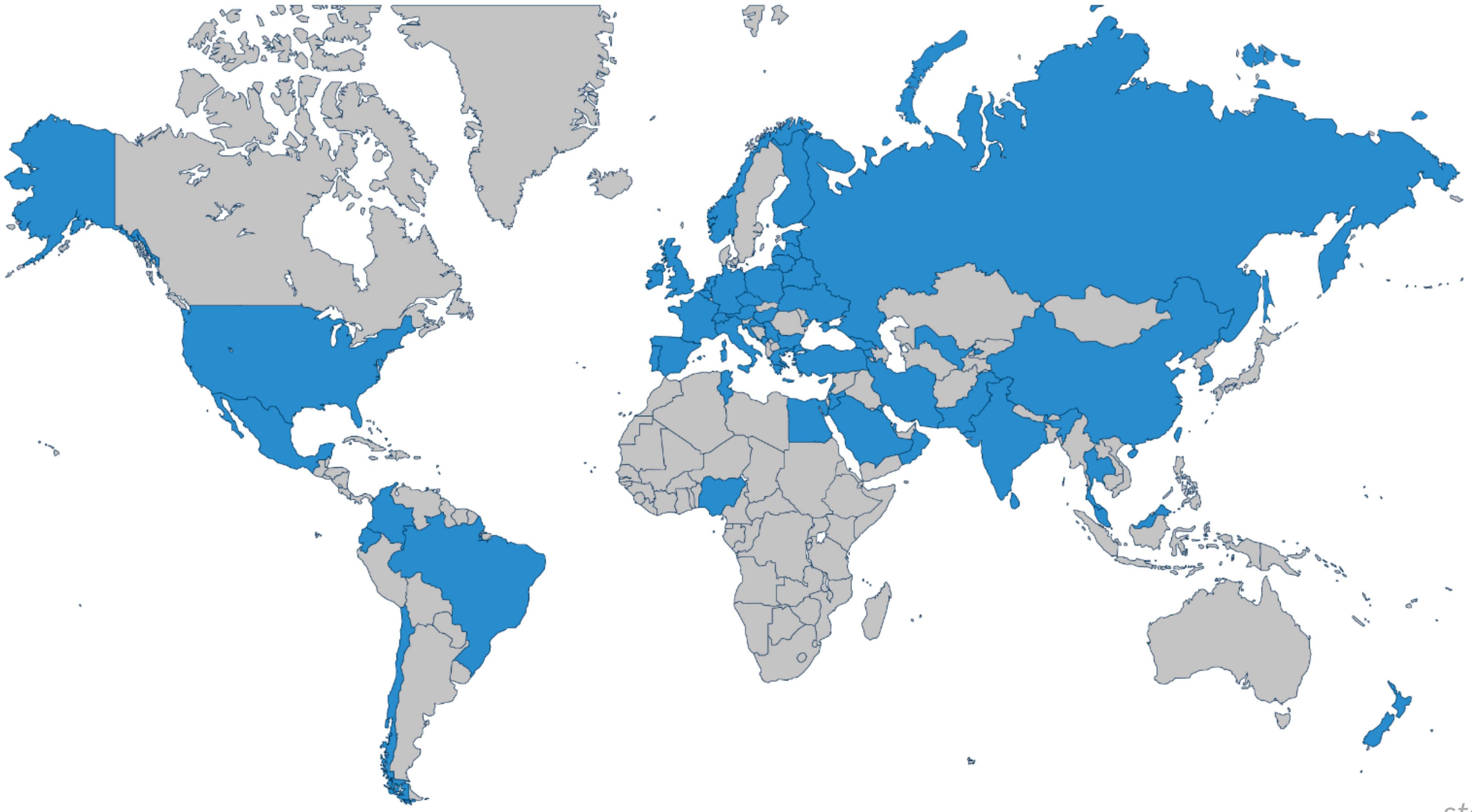
on behalf of the CMS Collaboration

第十七届 TeV 工作组学术研讨会 · 南京

16 December, 2023

The CMS collaboration

3394	1102	282	247	57
PHYSICISTS (1228 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS



stat. from link

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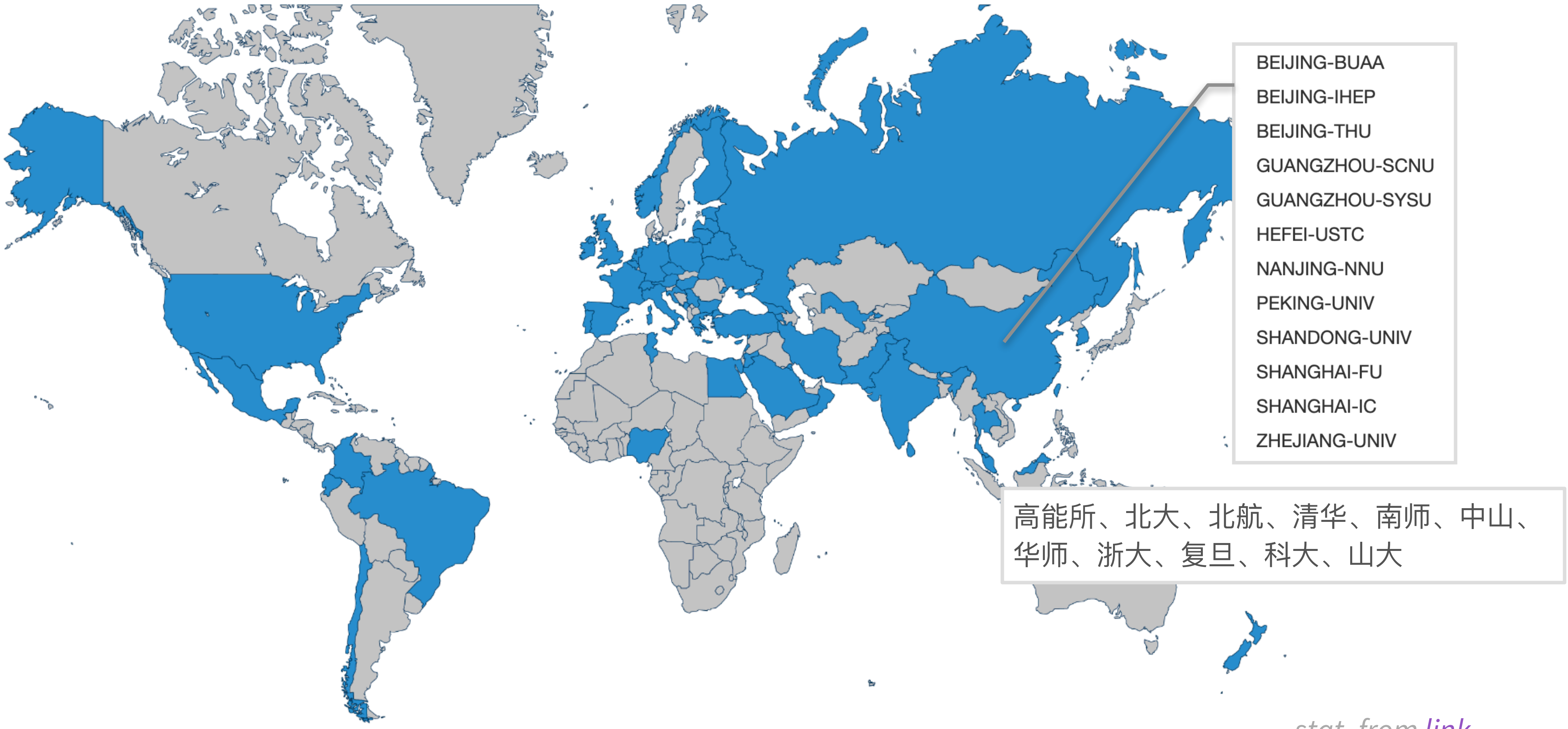

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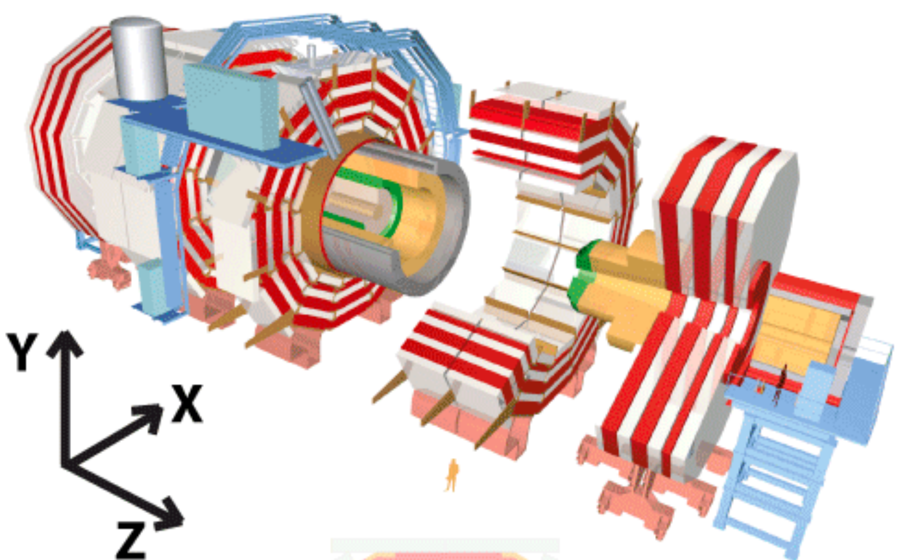
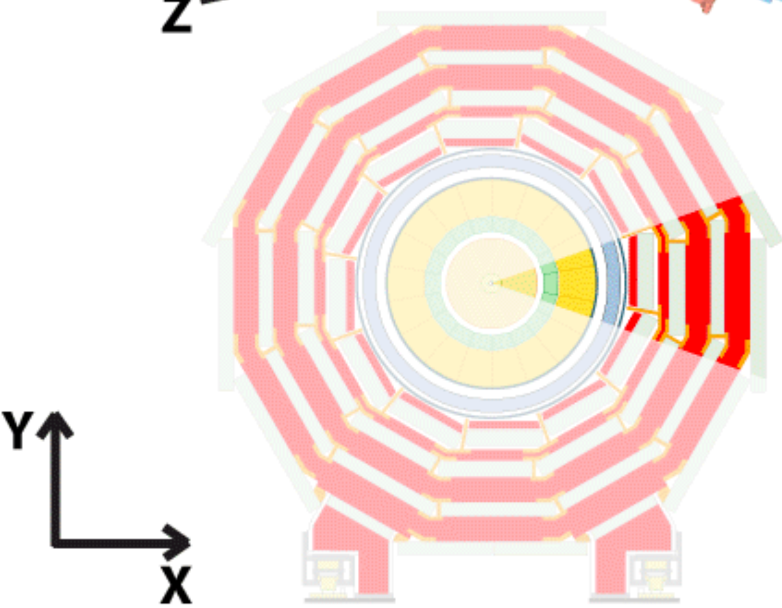
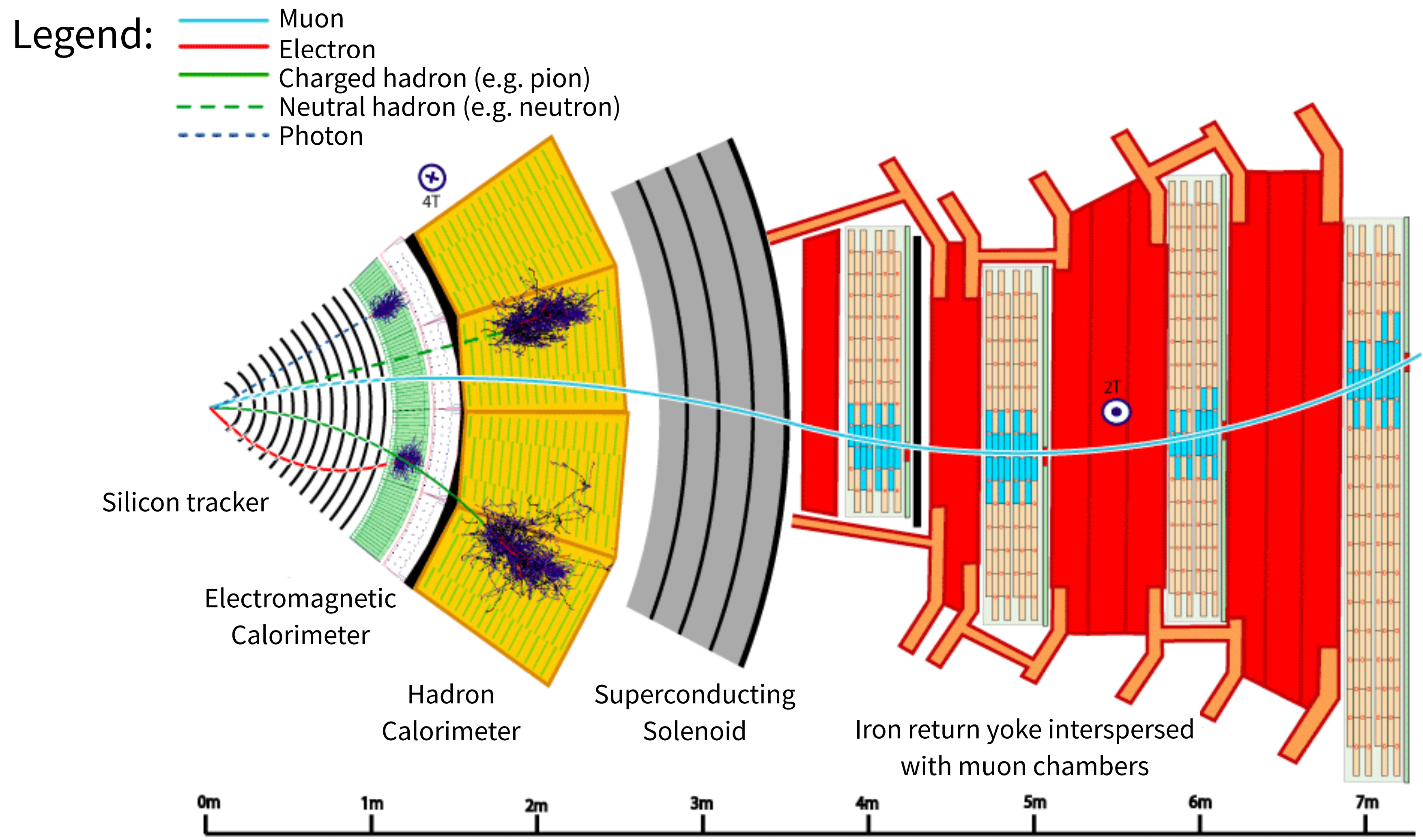
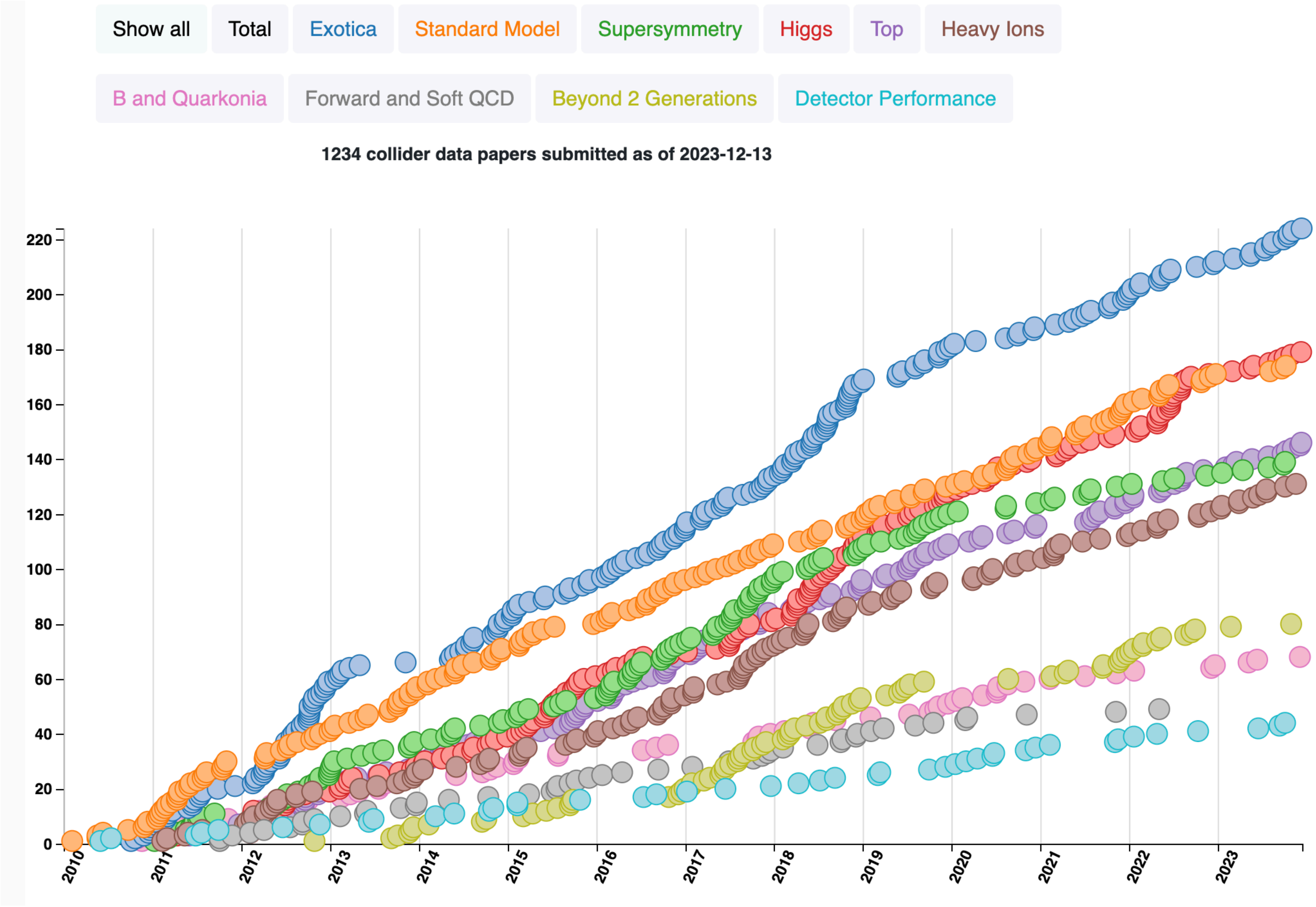
The CMS detector



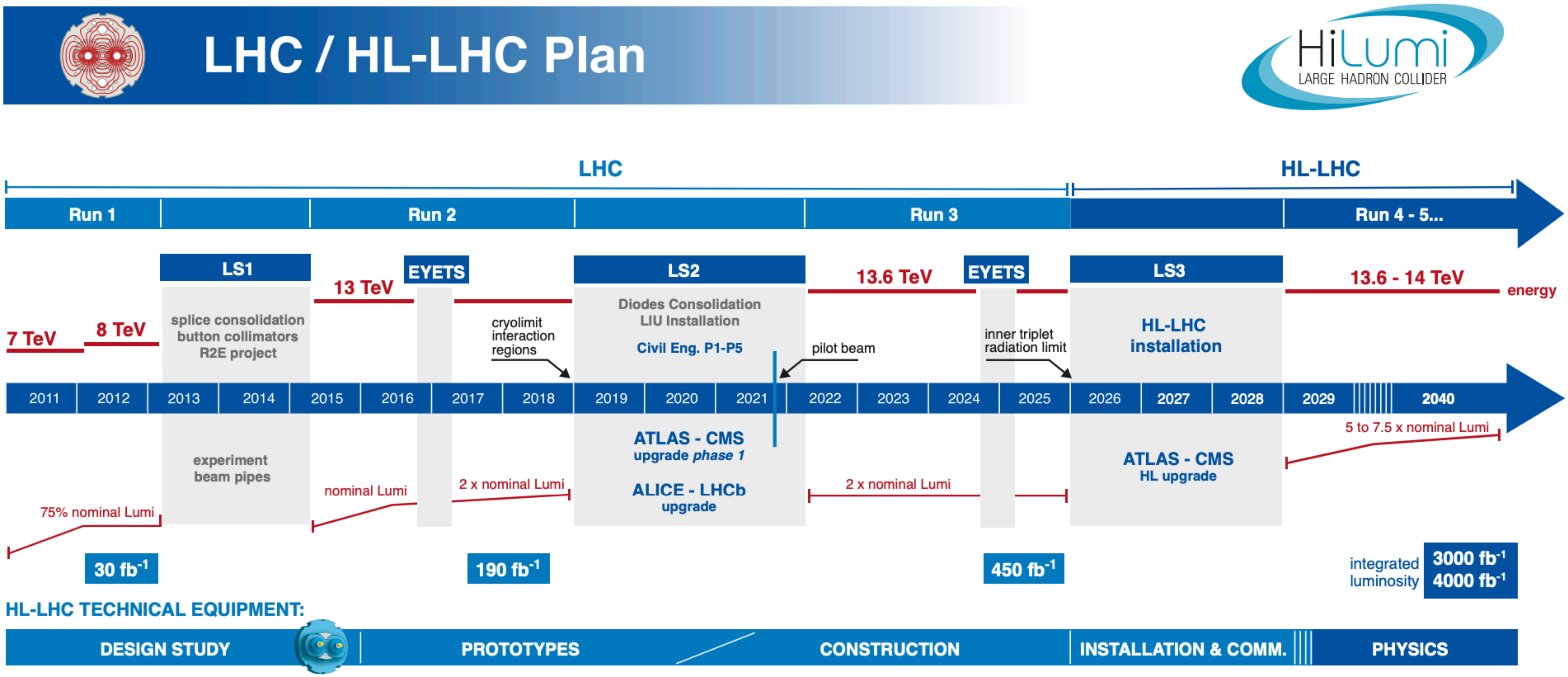




CMS publications

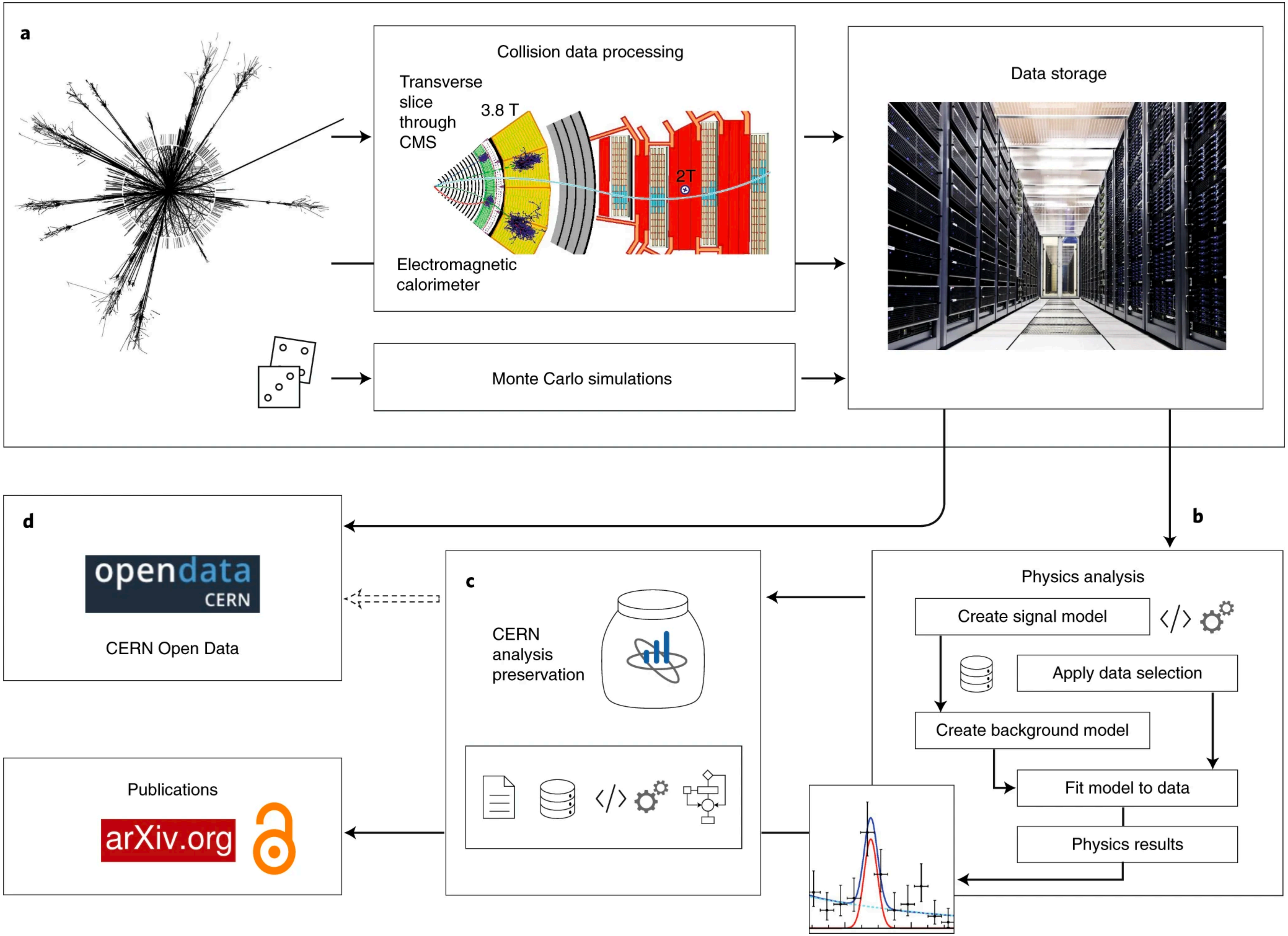


LHC / HL-LHC schedule



Typical CMS experiment workflow

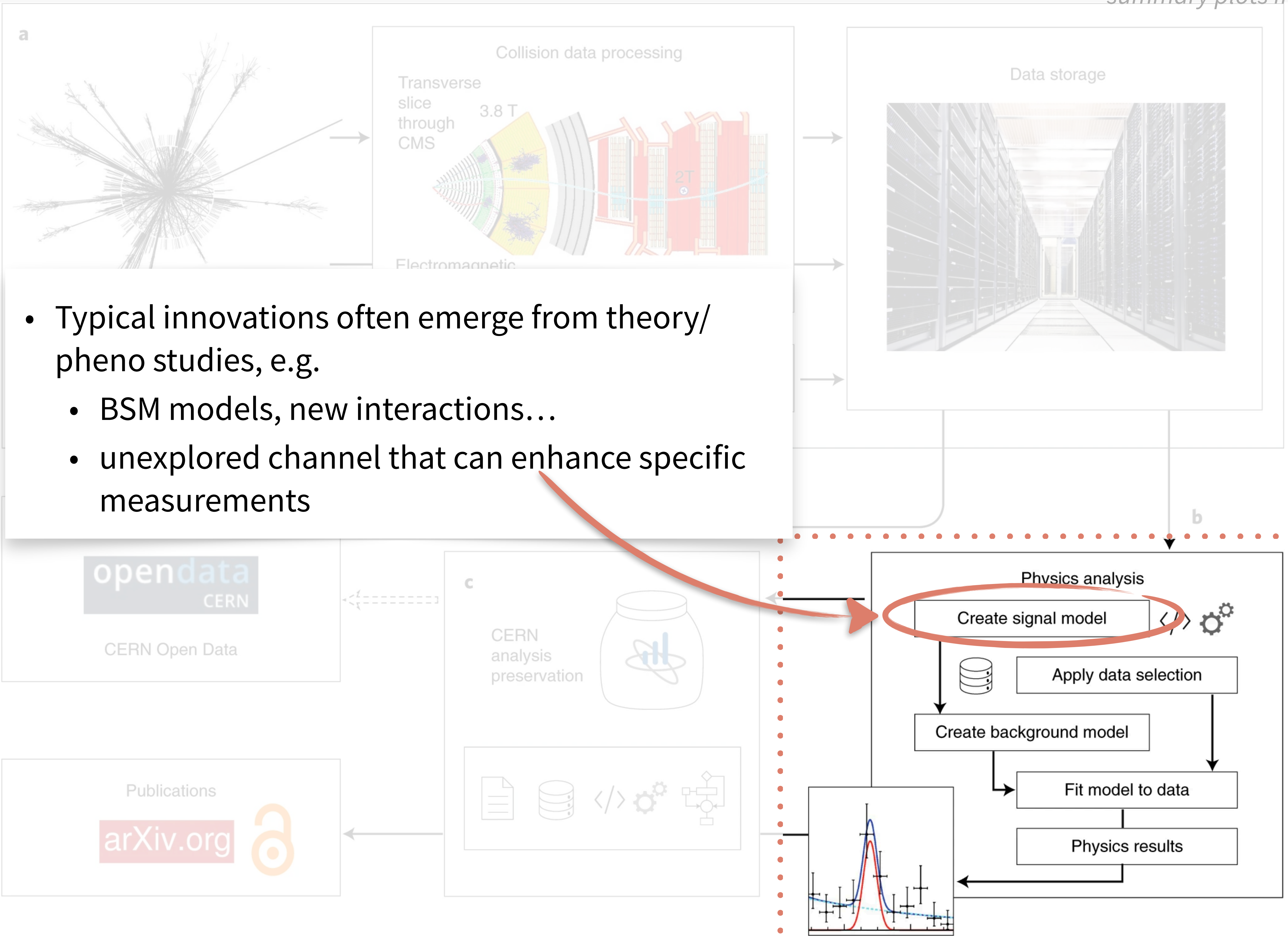
borrow the figure from link



Typical CMS experiment workflow

summary plots from link

- Typical innovations often emerge from theory/pheno studies, e.g.
  - BSM models, new interactions…
  - unexplored channel that can enhance specific measurements



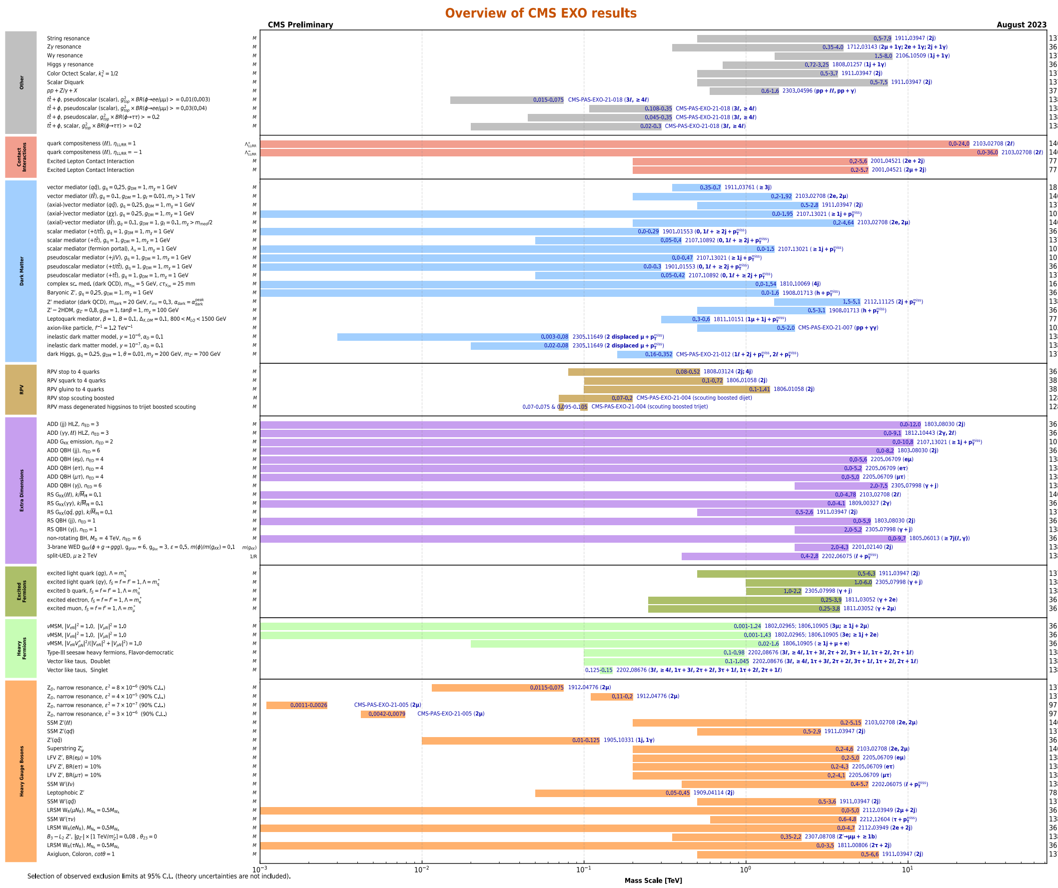
Typical CMS experiment workflow

summary plots from link

Theory-oriented BSM searches:
pseudo-scalar particles (ALPs)
SUSY, LFV, LLPs, lepto-quarks, …

See selected CMS result overview →

But not our main focus today!



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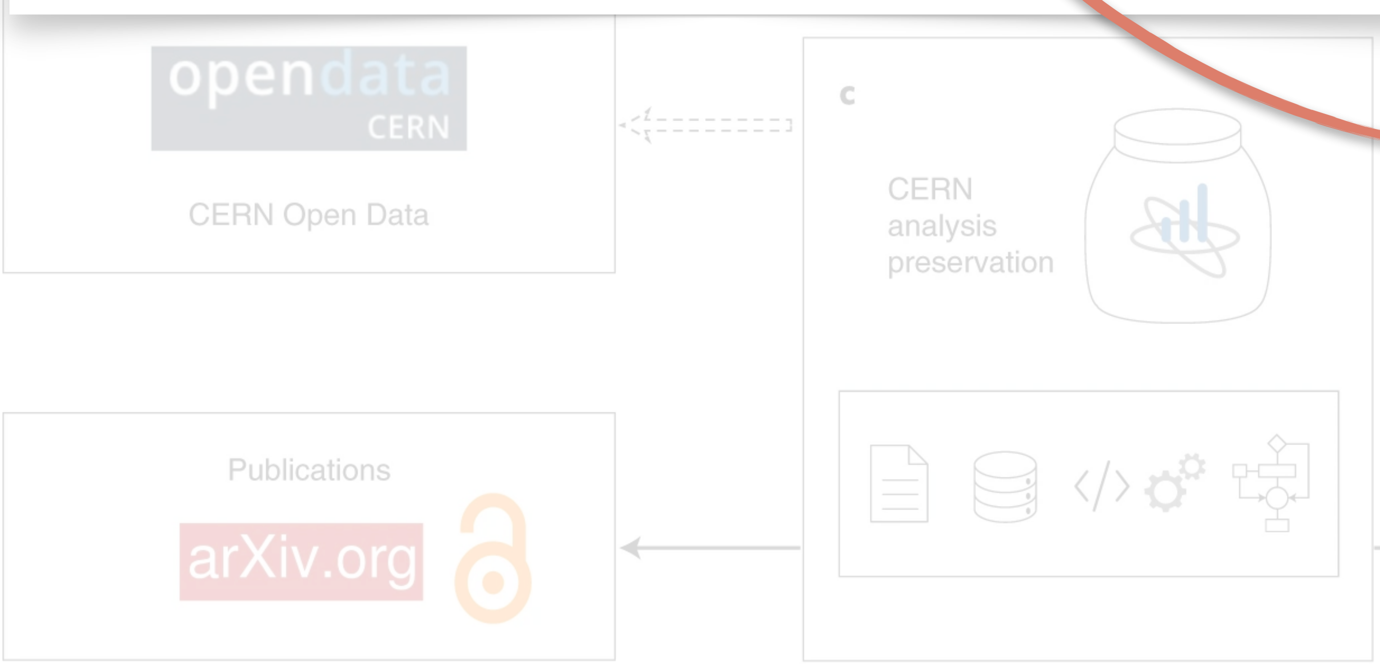
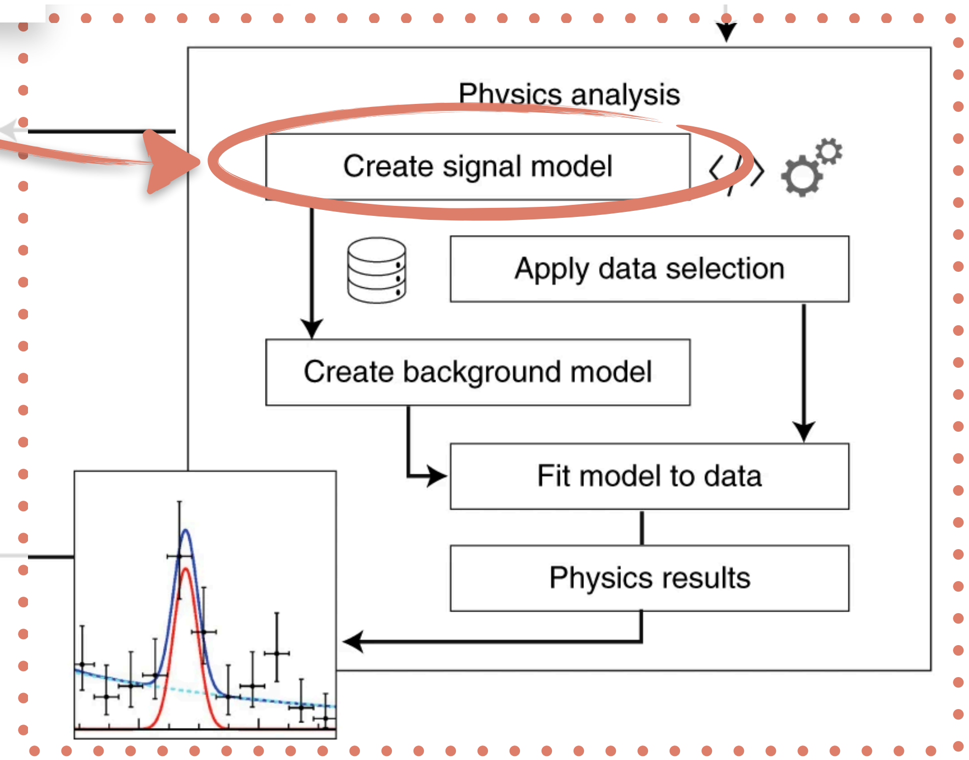
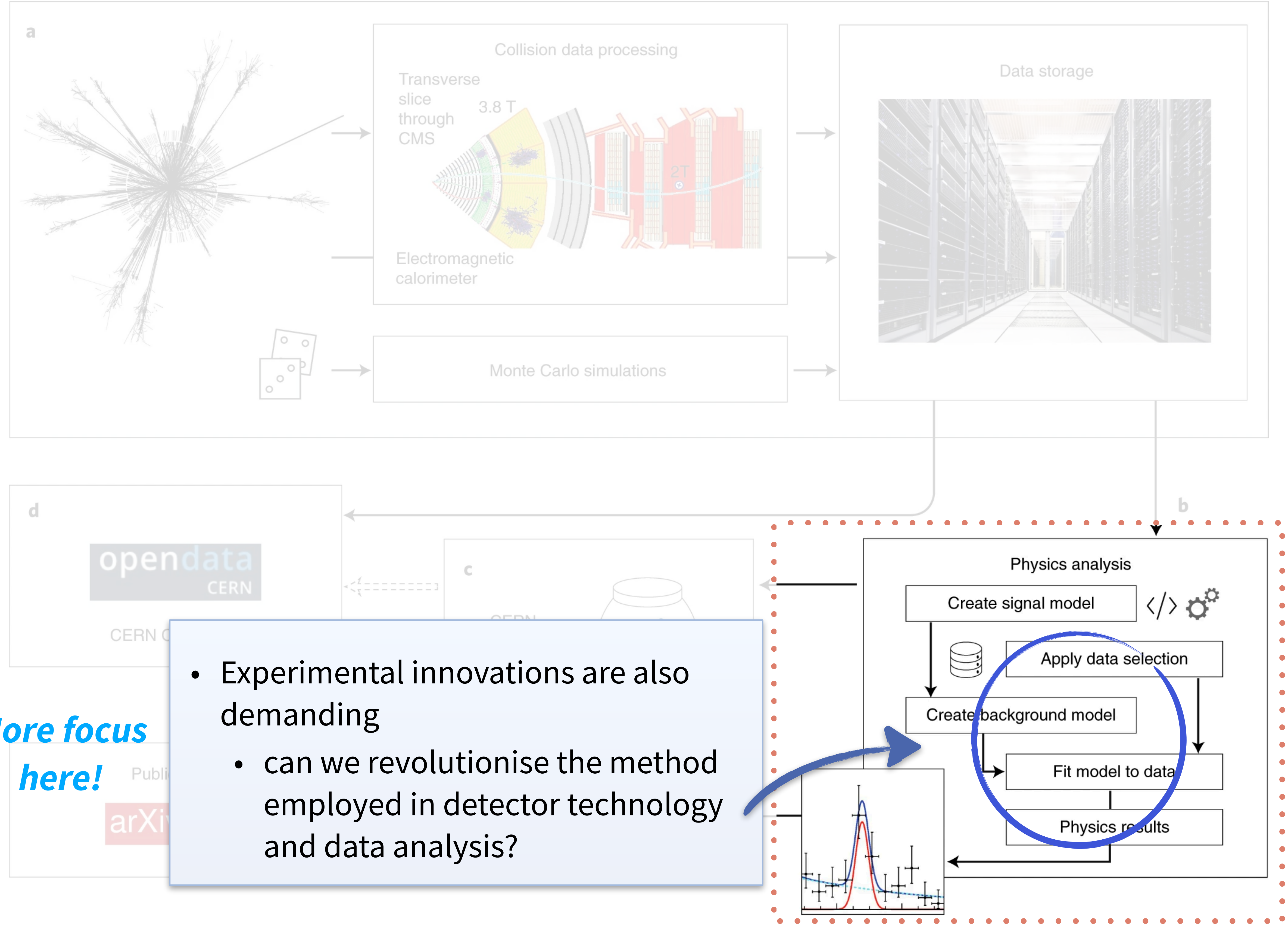




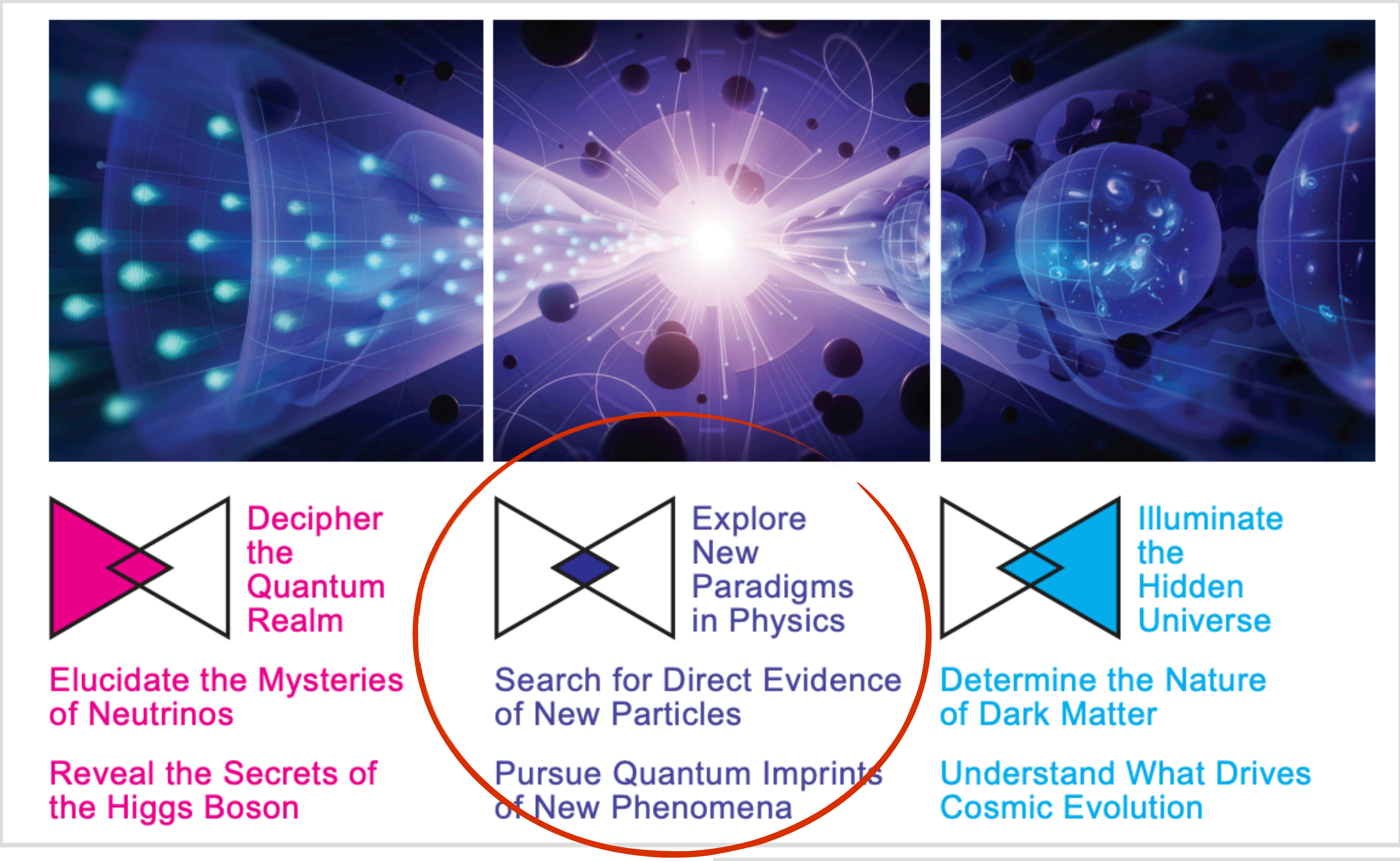
Highlight: experimental innovations



More focus here!

- Experimental innovations are also demanding
  - can we revolutionise the method employed in detector technology and data analysis?

Highlight: experimental innovations



from 2023 P5 report

The most direct way of answering these questions is by discovering new fundamental particles. If these are very massive they can only be produced directly in high-energy colliders, as the higher the collider energy the higher the mass that can be produced. Another possibility is that these particles are produced at lower energy but very rarely, for example in decays of known particles such as the Higgs boson. This requires accelerators that produce very high numbers of particles, including neutrino experiments with their high intensity beams and massive detectors.

These complementary approaches provide access to an extensive theoretical parameter space that covers both higher mass scales and new physics that is weakly coupled to the Standard Model. Overall, these searches can be broadly categorized into those that are guided by specific theoretical ideas, searches driven by questions resulting from experimental data (e.g. dark matter), and searches that are model-agnostic and perform a general exploration of the unknown. Together, these approaches provide comprehensive coverage of the Beyond the Standard Model (BSM) landscape and have the potential to yield groundbreaking insights into the universe.

- theory-motivated search
- experimental data-driven search
- model-agnostic search

Focus of this talk

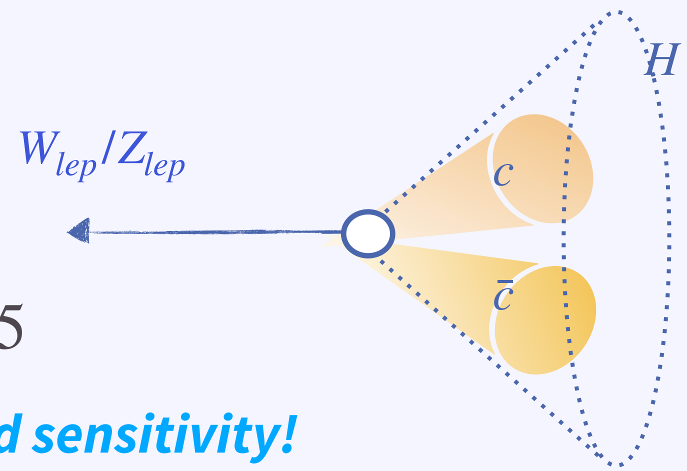
- ➔ In addition to sharing new CMS results, we want to highlight more on experimental innovations achieved these years
  - ❖ broadly driver by the rapid advancement in machine learning
- ➔ Cover two aspects
  - ❖ modern deep learning to process low-level data
  - ❖ model-agnostic resonance search
- ➔ Hope to share experimental insights with the broader HEP community

Modern deep learning for low-level input

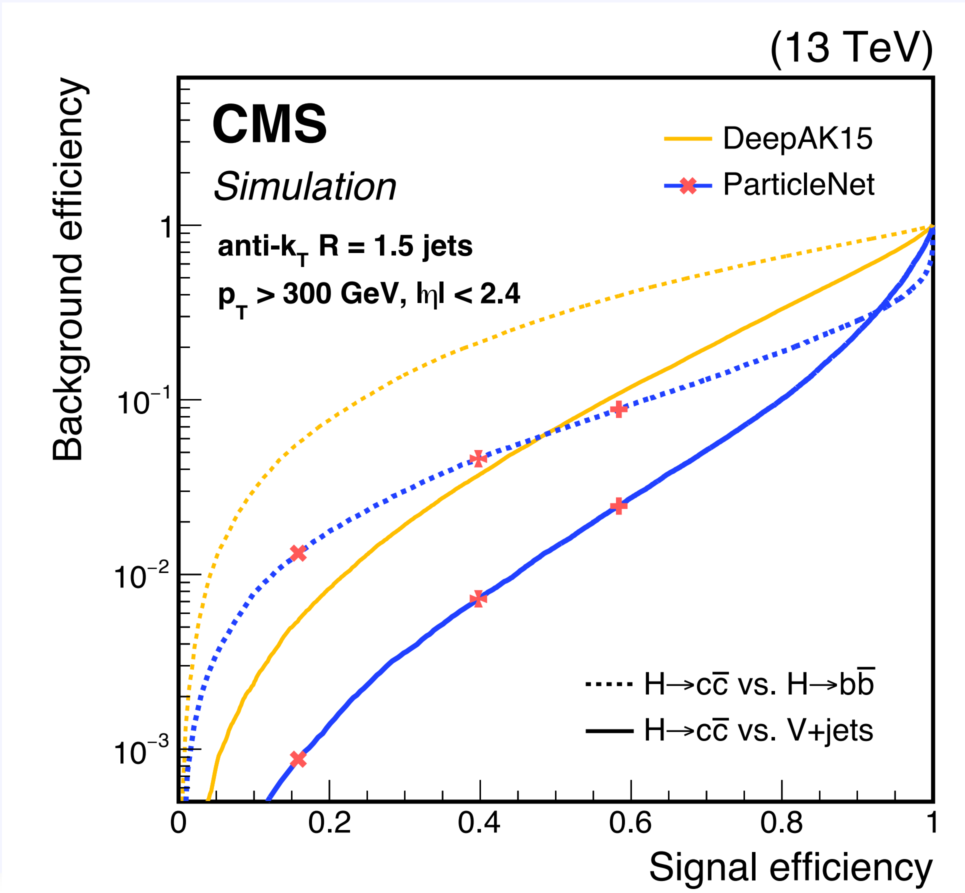
Recent CMS results in Higgs sector

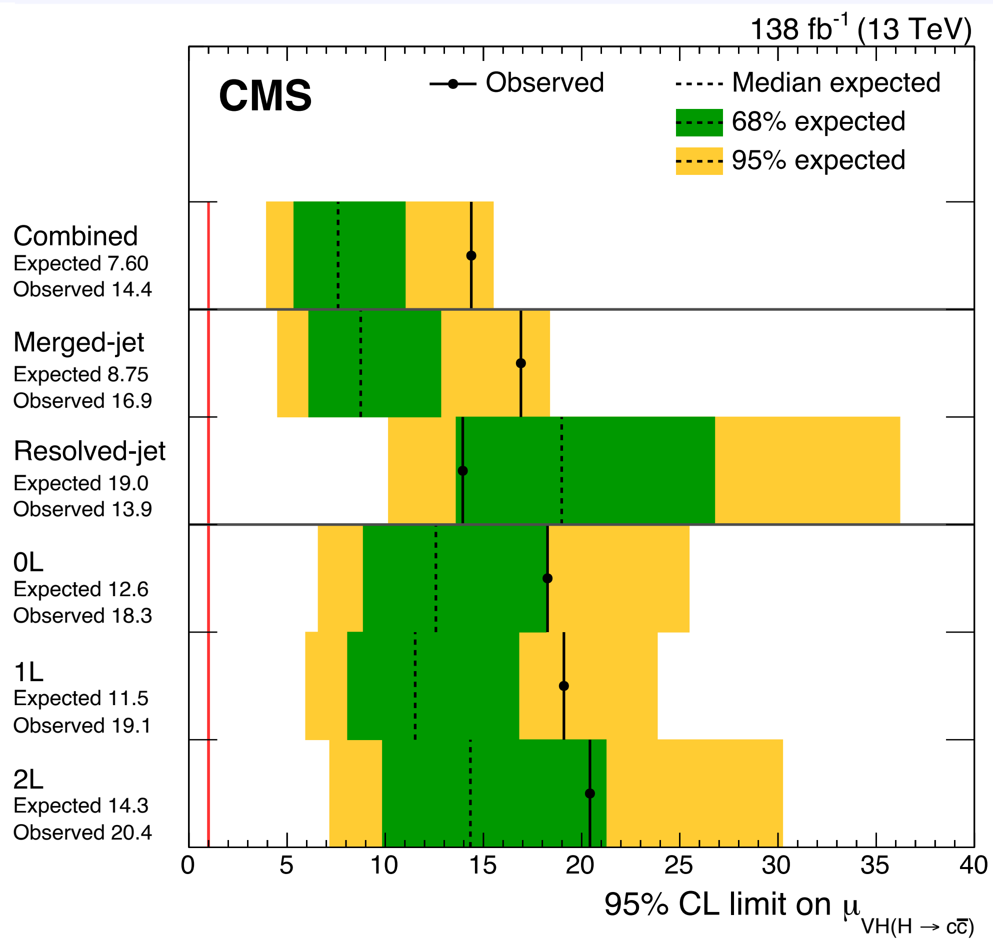
PRL 131 (2023) 061801

- ➔ We start with two recent CMS results
- ➔ CMS measures κ_c via VH(→cc̄) production mode, including the merged-jet topology
  - ❖ in merged-jet topology: leveraging advanced jet neural network (ParticleNet) to identify H→cc̄ jets and reconstruct H mass
  - ❖ obtain the most stringent direct limit (95% C.L.) on κ_c: $1.1 < |\kappa_c| < 5.5$
    - ATLAS results: $|\kappa_c| < 8.5$ [EPJC 82 (2022) 717]



largely improved sensitivity!



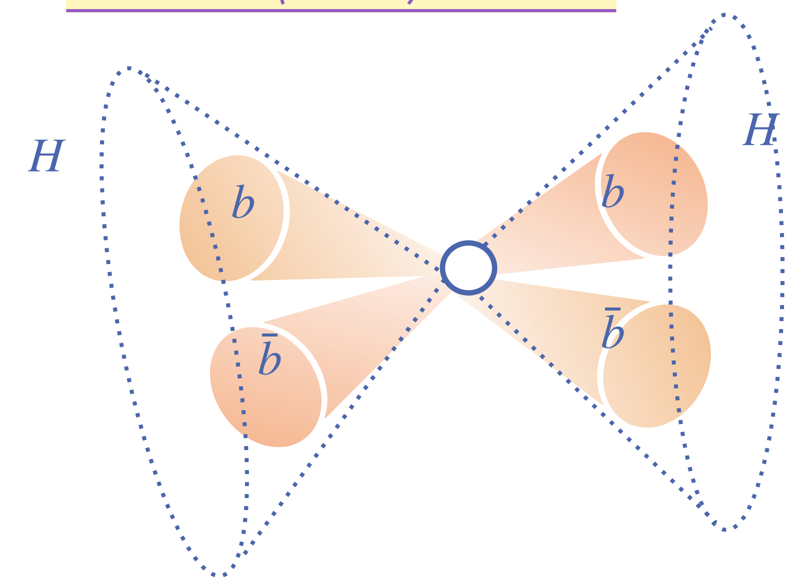


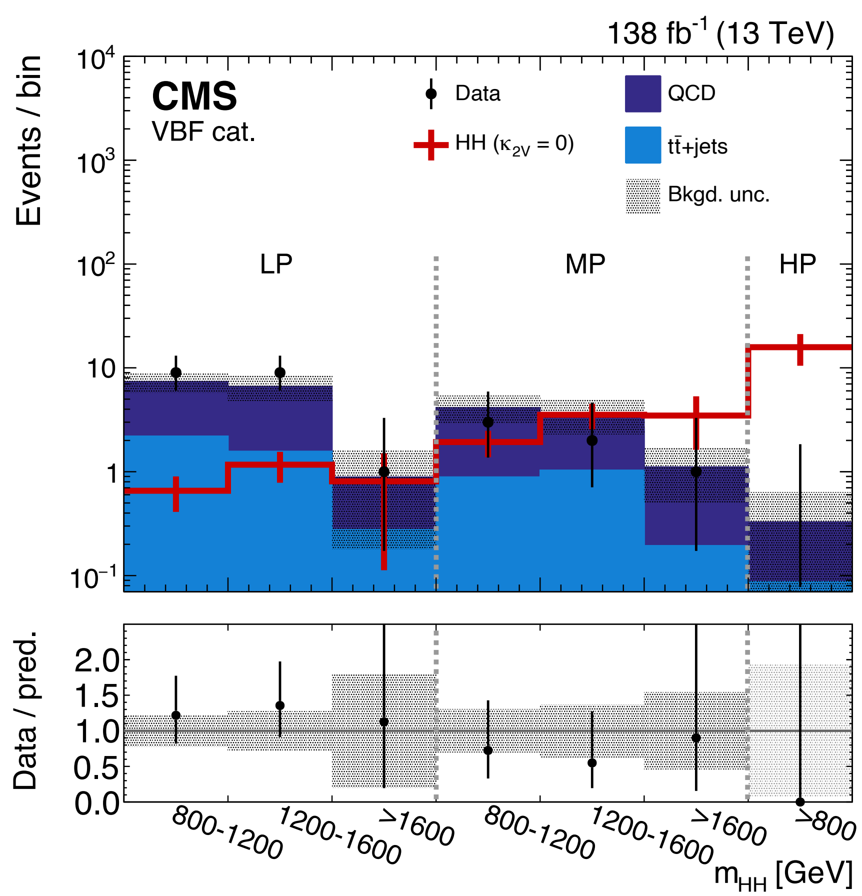
Recent CMS results in Higgs sector

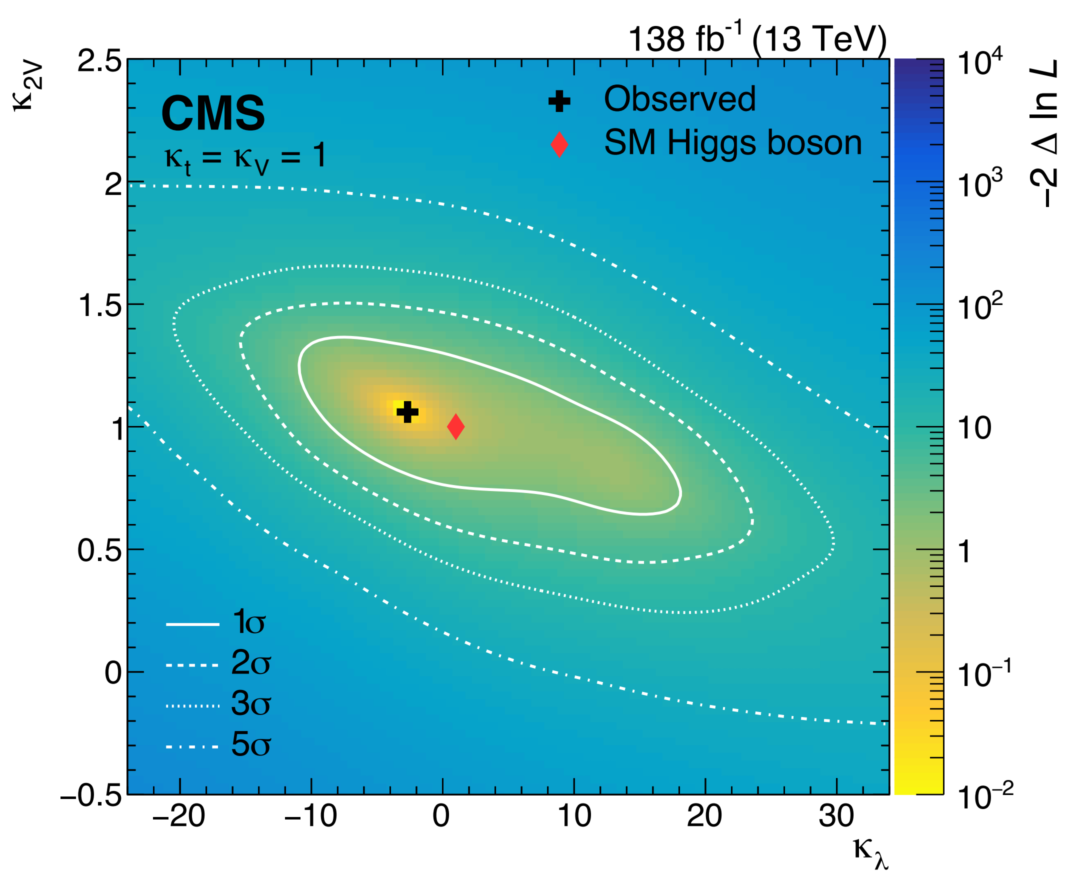
PRL 131 (2023) 041803

➔ Higgs self-coupling & quartic VVHH coupling (κ_{2V}) measured via HH→4b channel

- novel boosted-jet phase space explored by CMS
- advanced NN (ParticleNet) for $H\to b\bar{b}$ jet identification and mass regression
- ***first time*** excluding $\kappa_{2V} = 0$ (by 6.3 σ)



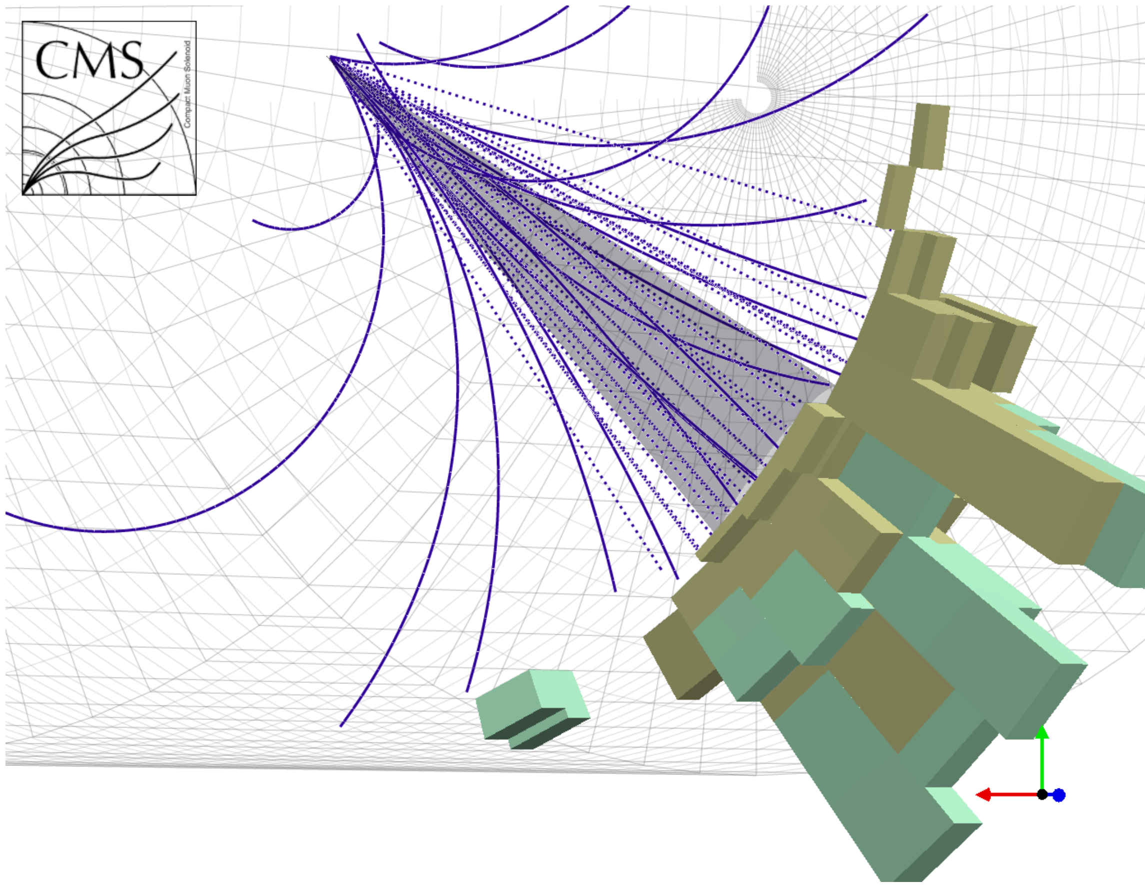




Interpreting the improvement

➔ **Sophisticated** networks have huge experimental potential when dealing with **complex** hadronic boosted-jet final states

- **sophisticated**: modern NN designs brought by the ML era (since ~2015)
- **complex**: a boosted jet contains O(50-100) constituents



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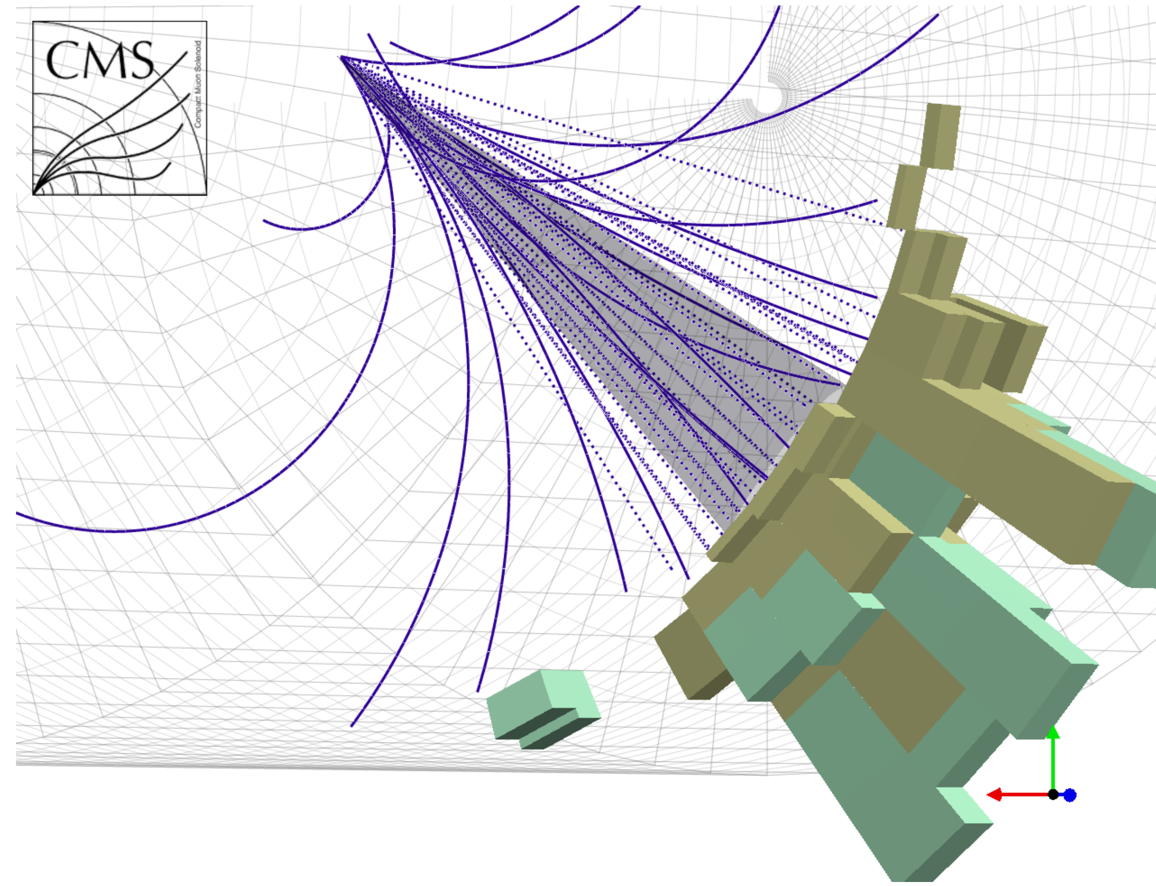
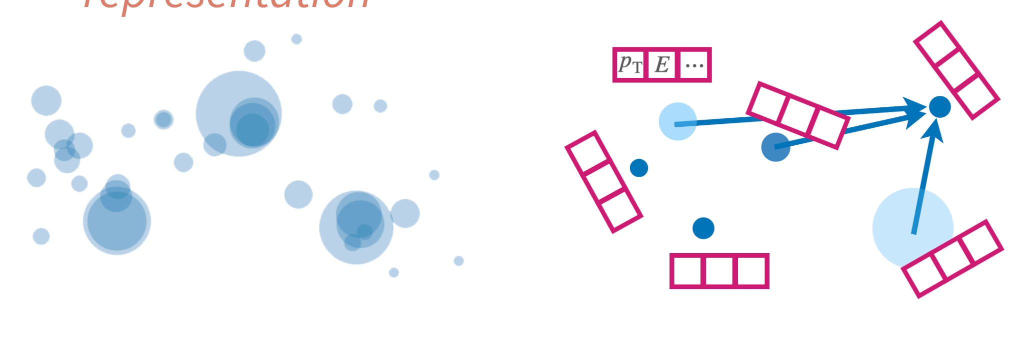


→ “ParticleNet” is a benchmark algorithm that leads the experimental advancement

- sensitivity highly improved (~2-5 greater background rejection)
- view a jet as a point cloud
- allow message passing between neighbouring particles

point cloud representation



ParticleNet: Jet Tagging via Particle Clouds

Huilin Qu (UC, Santa Barbara), Loukas Gouskos (CERN)

Feb 22, 2019

250 citations

PRD 101 (2020) 056019

Philosophy of “event selection” and advanced NNs

➔ A theoretical upper bound exists to the “optimal event selection”

- signal and bkg cannot be 100% distinguished: overlapping between signal and bkg phase space; ambiguity caused by detector resolution/reconstruction efficiency…
- but an optimal selection exists, and it is defined on the signal and bkg likelihood ratio (although intractable due to its complexity)

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  - ❖ but an optimal selection exists, and it is defined on the signal and bkg likelihood ratio (although intractable due to its complexity)
- ➔ The big question for experimentalists: where is that limit, and how close are we now?
  - ❖ this is still an open question - current results imply that the data we collected at the LHC has not been fully explored (especially for hadronic final states)

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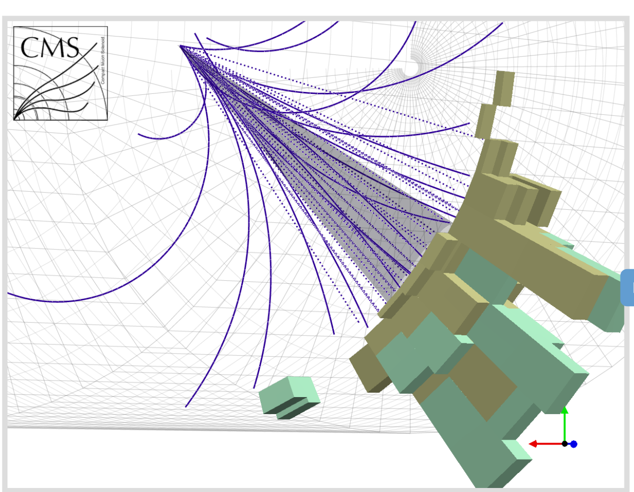
➔ The big question for experimentalists: where is that limit, and how close are we now?

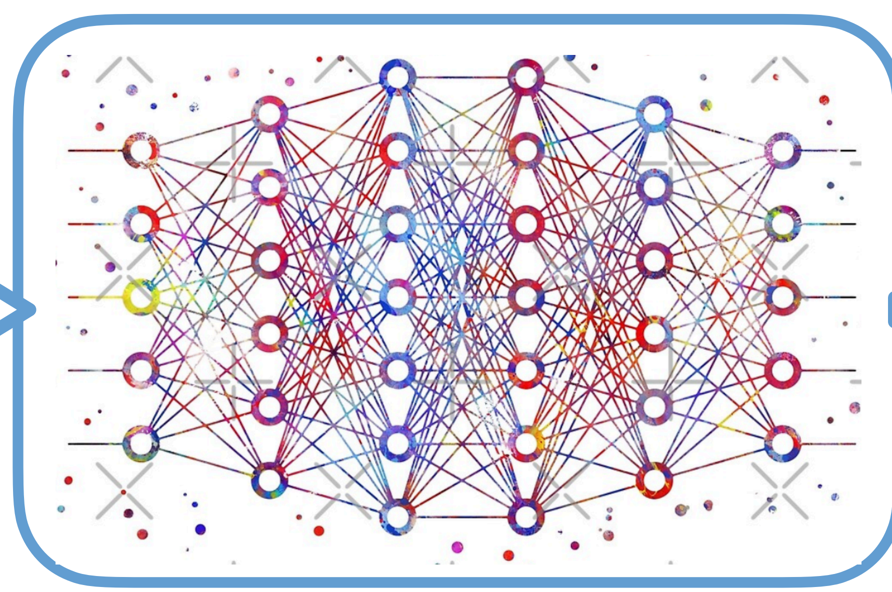
- this is still an open question - current results imply that the data we collected at the LHC has not been fully explored (especially for hadronic final states)

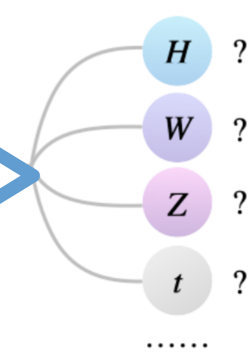
➔ Advanced NN can serve as a powerful fitter to approach the theoretical limit

- the training target of NN guarantees an optimum in classification/regression under present NN’s capability
- better NN: better data representation (an ML+physics problem [backup])



A jet described by its constituent particles





original of the jet?

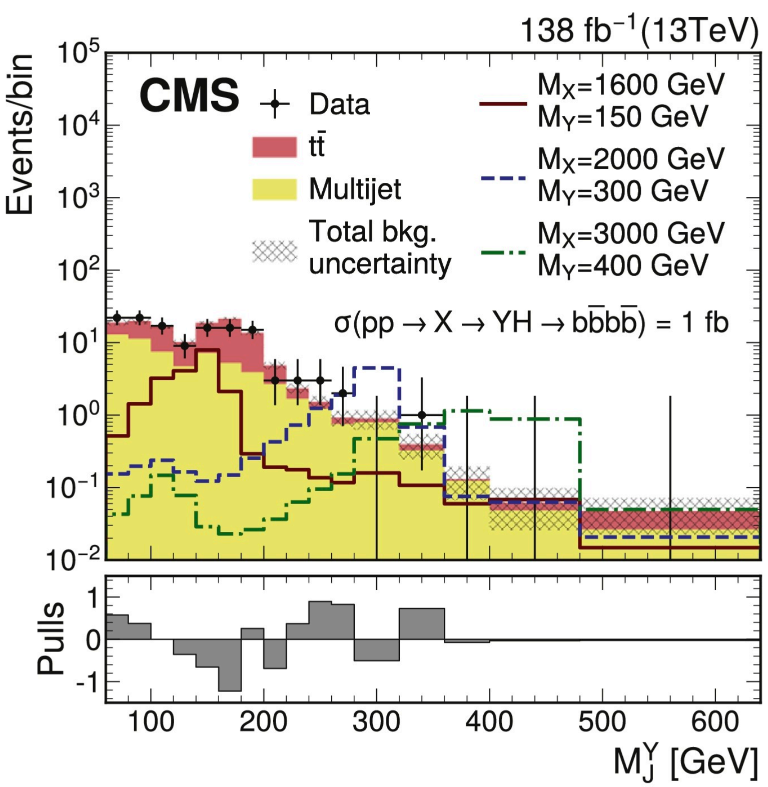
other jet properties?

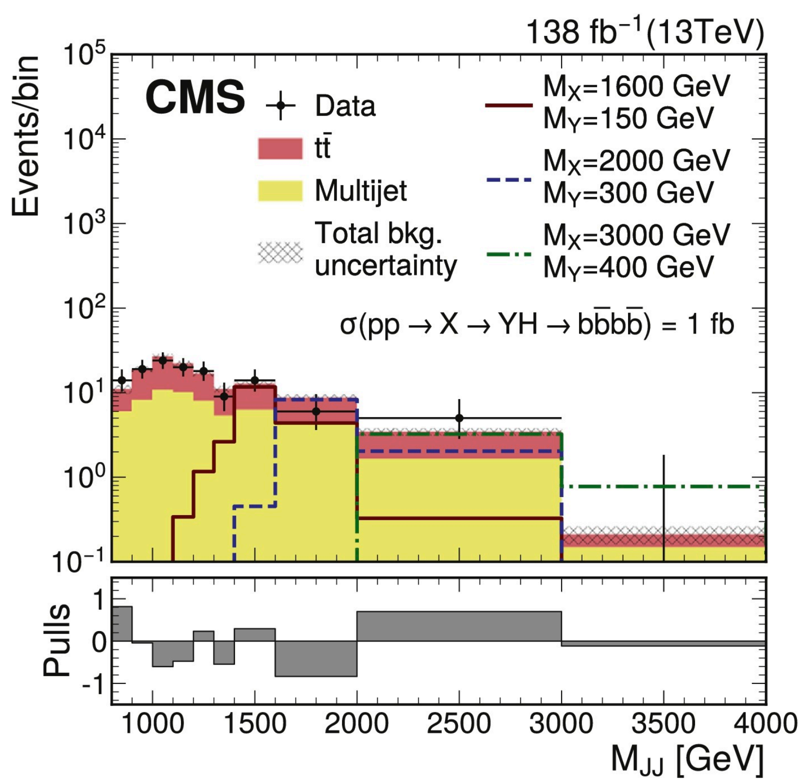
Selected CMS BSM searches (X → YH → b$\bar{b}$b$\bar{b}$)

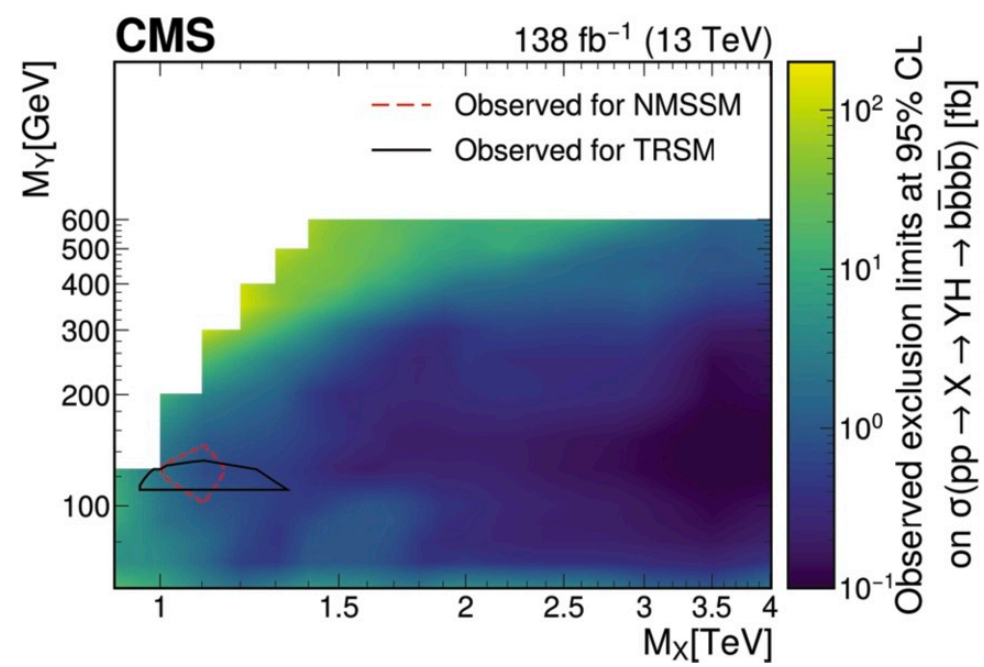
PLB 842 (2023) 137392

➔ Search for scalar particles in X→YH→b$\bar{b}$b$\bar{b}$ final states

- reconstruct H and Y in each in a large-R jet
- use advanced NN (ParticleNet) to select H→b$\bar{b}$ and Y→b$\bar{b}$ jets
- maximum likelihood fit on (m_{JJ}, m_J^Y), model-independent constraint on the cross-section





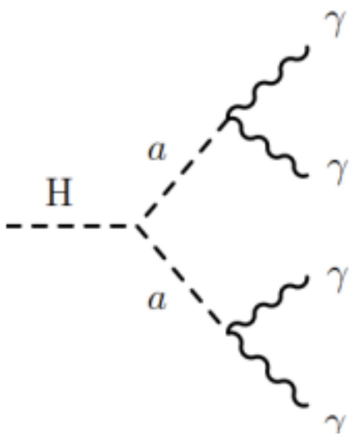


Selected CMS BSM searches (H → AA → 4γ)

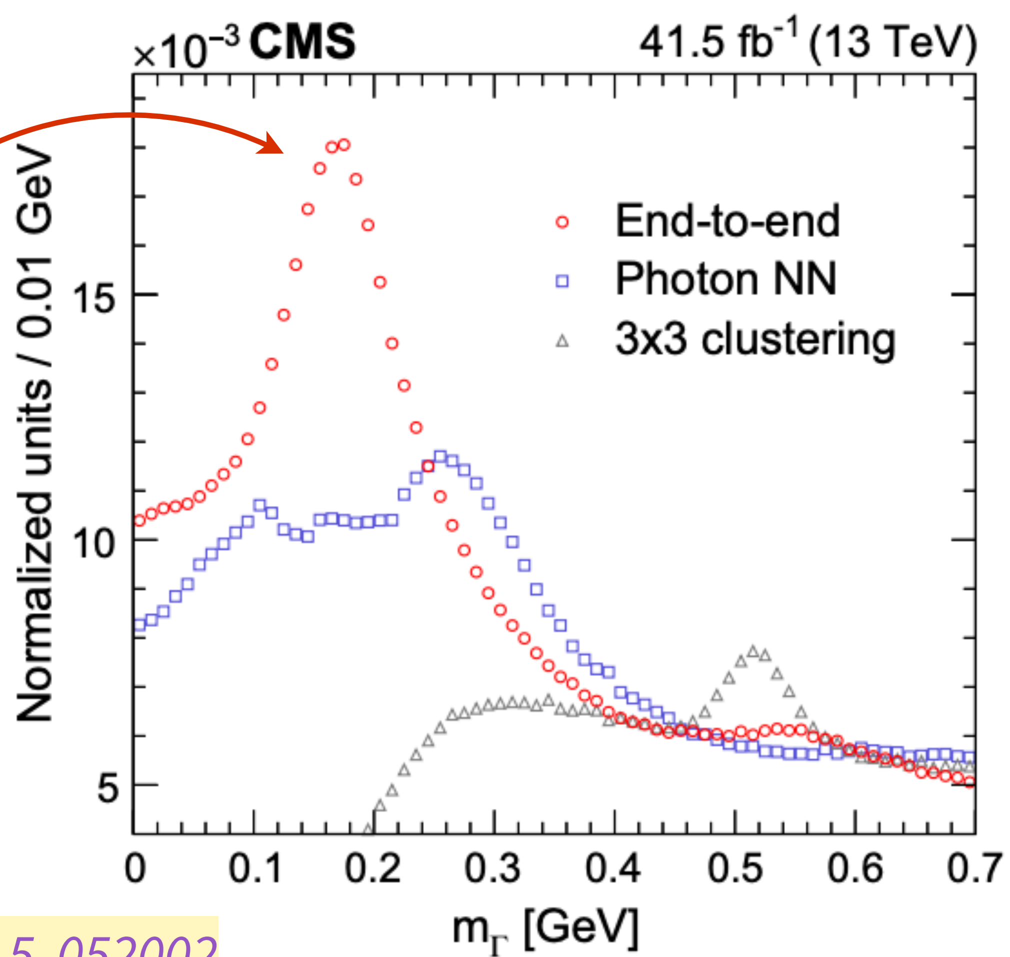
PRL 131 (2023) 101801

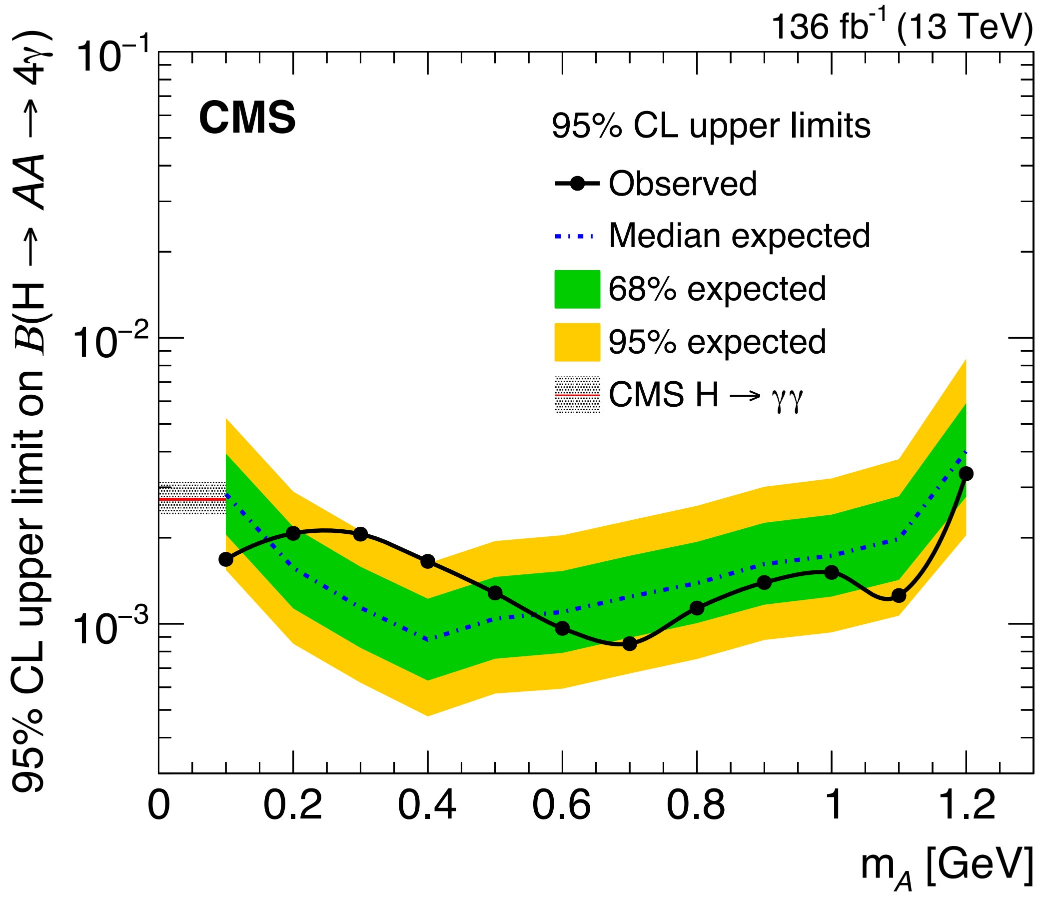
➔ Search for low mass (0.1–1.2 GeV) ALPs

- first direct search for Higgs exotic decay to ALPs with ALP to 2γ
- **merged** γγ reconstructed as a single photon-like object Γ, regress on $m(\Gamma)$ using low-level ECAL energy deposit as input
- set limit on $B(H \to AA \to 4\gamma)$



prominent π^0 peak





$m(\Gamma)$ regressor algorithm:

PRD 108 (2023) 5, 052002

Modern model-agnostic searches

Modern model-agnostic searches

➔ Begin of journey in the modern (machine-learning-based) model-agnostic searching scheme at LHC

Anomaly Detection for Resonant New Physics with Machine Learning

Jack H. Collins (Maryland U. and Johns Hopkins U.), Kiel Howe (Fermilab), Benjamin Nachman (UC, Berkeley and LBL, Berkeley)

May 7, 2018

PRL, 121 (2018) 24, 241803

161 citations

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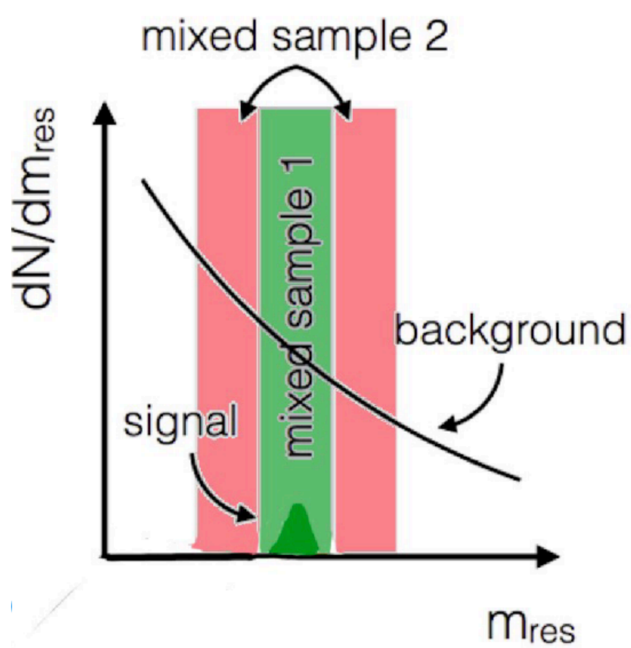
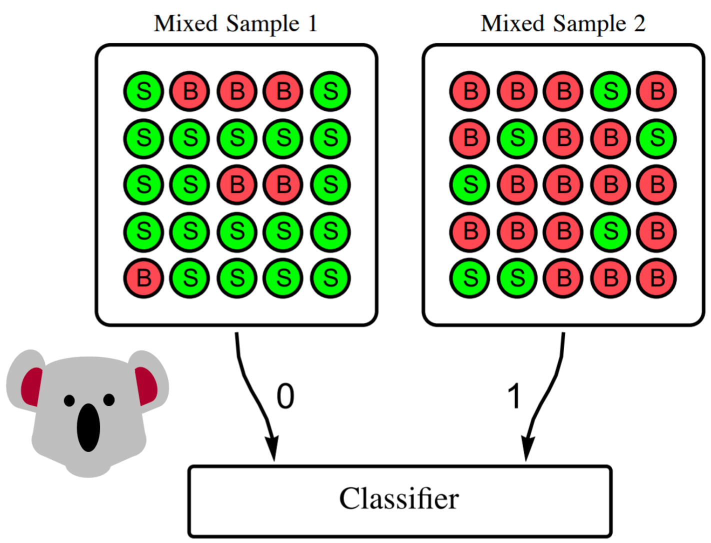
- ➔ A "general method" for resonant search with minimal requirements
  - ❖ resonance localised in a mass window
  - ❖ can be reconstructed by two hadronic large-*R* jets
- ➔ General strategy:
  - ❖ scan on the mass spectrum → apply model-independent selection → purify the signal
- ➔ With no significant evidence of new physics found at LHC, a broader search strategy will be a meaningful

Weakly-supervised approach

JHEP 10 (2017) 174





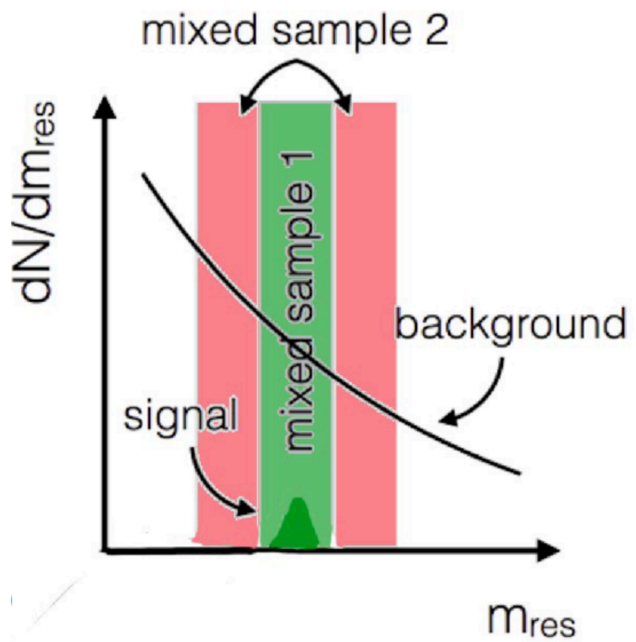
Equivalent effect for training **S** vs **B**

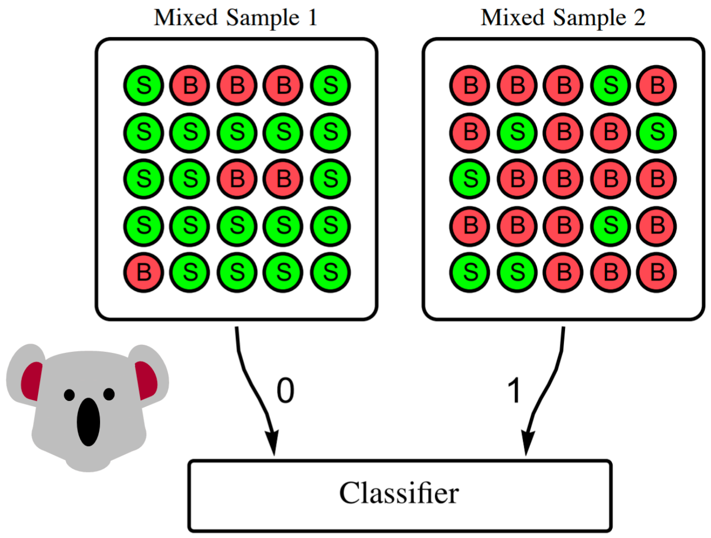
➔ Proposed "CWoLa (classification without labels) Hunting"

- allow to detect anomalies purely from data
- train a classifier for mass window vs mass sideband (mixed sample 1 vs 2)
- can prove that the effect is equivalent to training S vs B

Weakly-supervised approach

JHEP 10 (2017) 174





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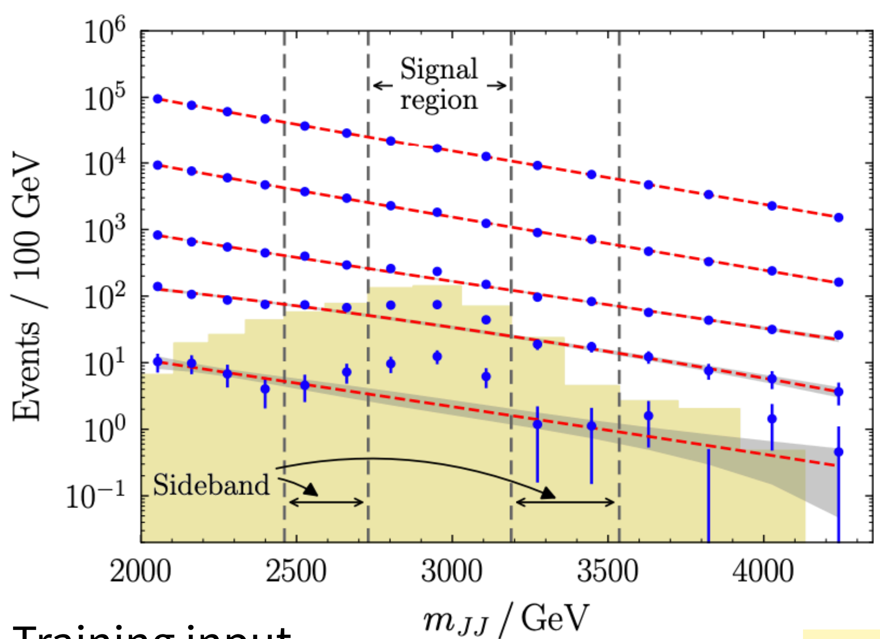
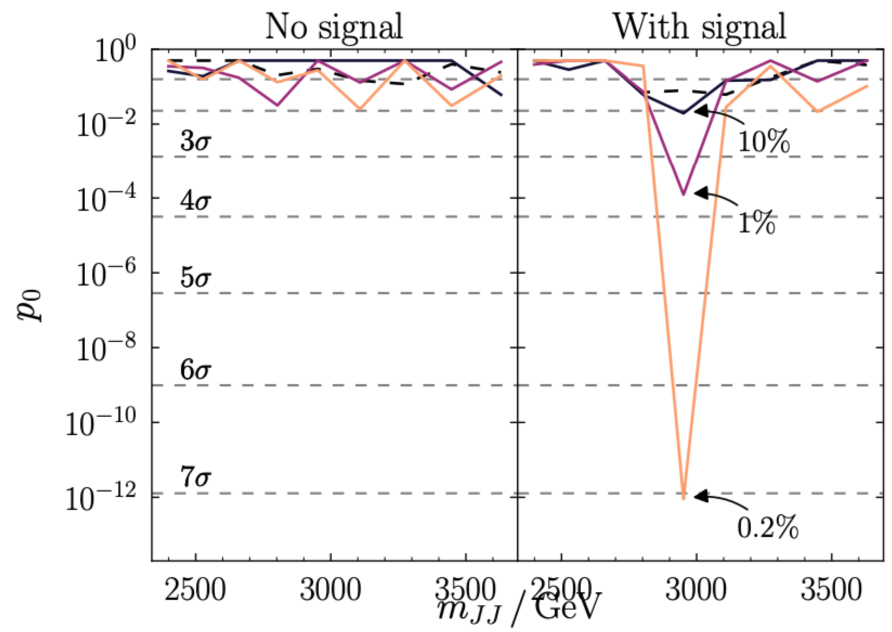




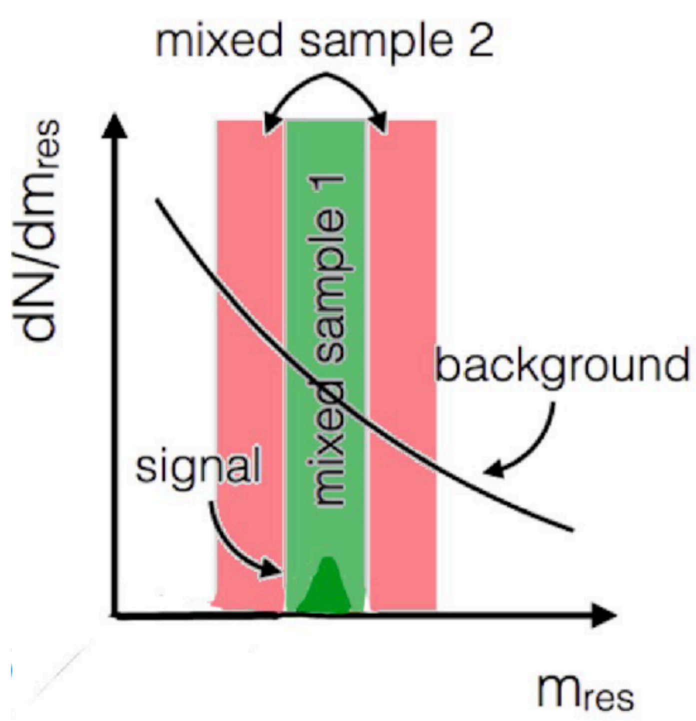
Training input

$m_J, \sqrt{\tau_1^{(2)}/\tau_1^{(1)}}, \tau_{21}, \tau_{32}, \tau_{43}, n_{\rm trk},$

PRL, 121 (2018) 24, 241803

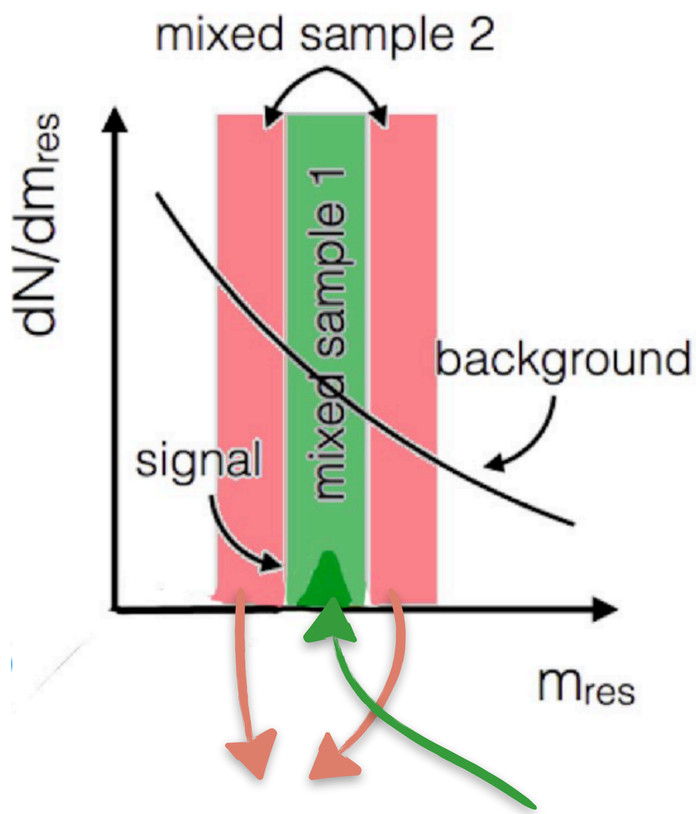
PRD, 99 (2019) 1, 014038

Improved methods



- ➔ Improvement made to the weakly-supervised scheme
  - **CWoLa**: train mixed sample 1 vs 2, i.e. taking sideband as the background *PRD, 99 (2019) 1, 014038*

Improved methods



First, train an NN to generate input events conditioned on m_{res}

Then, generate events in the mass window → i.e. interpolate background from sideband

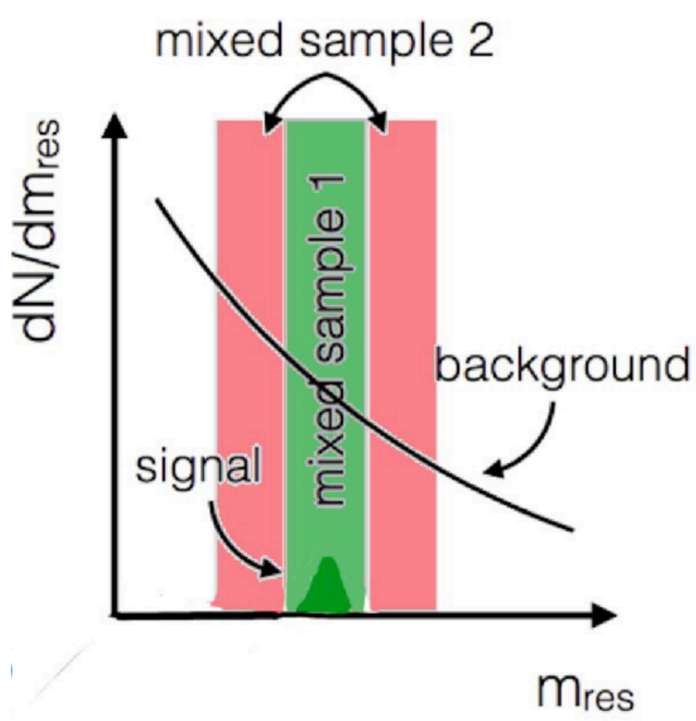
Finally, train a classifier over mixed sample 1 vs generated background

➔ Improvement made to the weakly-supervised scheme

- **CWoLa**: train mixed sample 1 vs 2, i.e. taking sideband as the background
- **CATHODE** (Classifying Anomalies THrough Outer Density Estimation): interpolate background from the sideband

PRD, 106 (2022) 5, 055006

Improved methods



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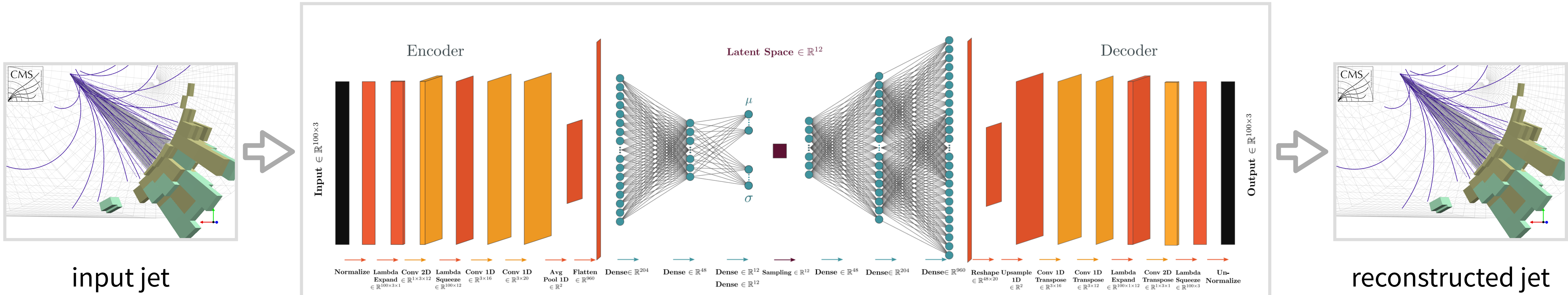
- **CWoLa**: train mixed sample 1 vs 2, i.e. taking sideband as the background
- **CATHODE** (Classifying Anomalies THrough Outer Density Estimation): interpolate background from the sideband
- **Tag N' Train**: apply autoencoder preselection on each fatjet → target resonance from anomalous dijet

JHEP 01 (2021) 153

A view on (variational) autoencoder for anomaly detection



input jet

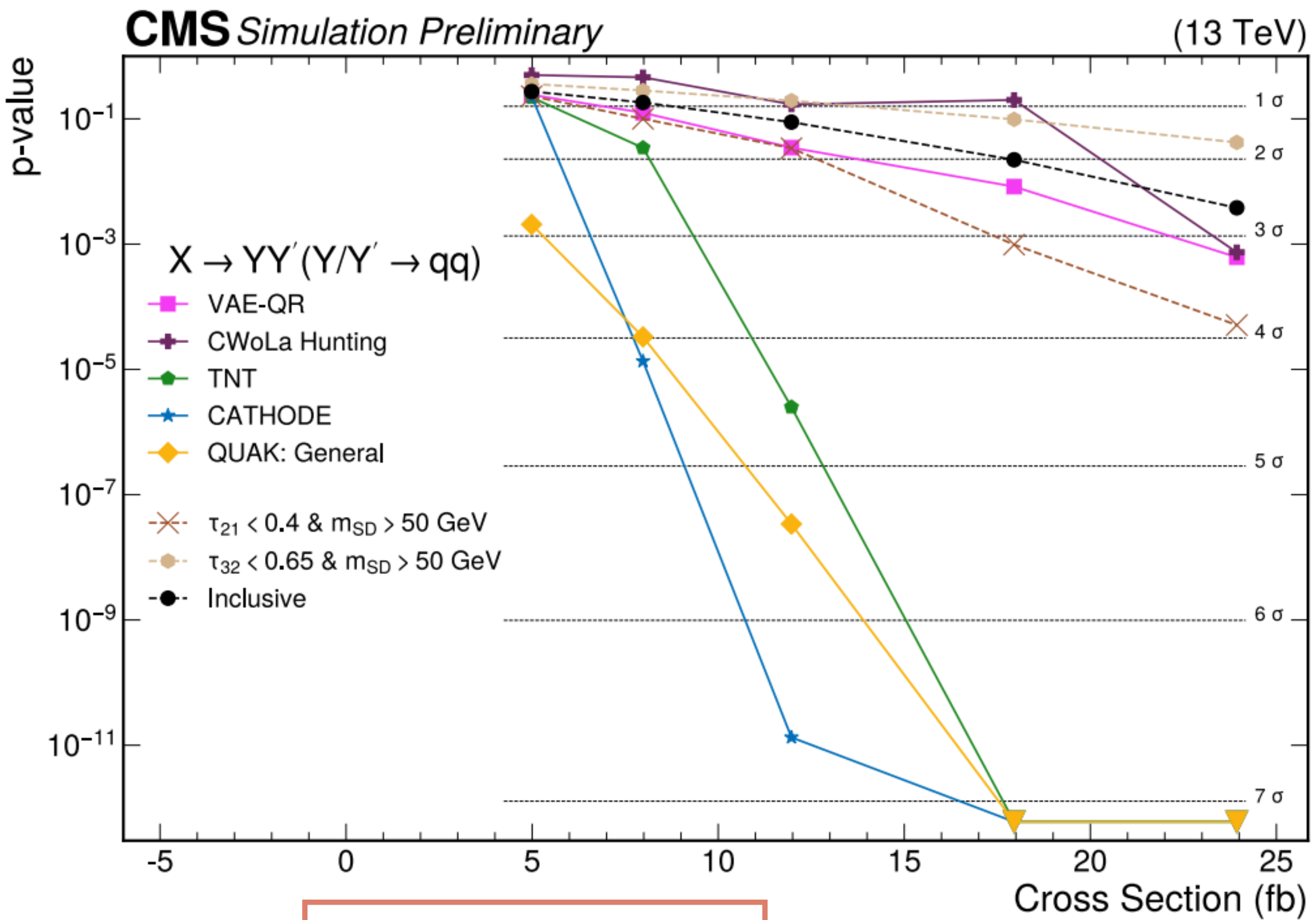
a compressed jet representation

reconstructed jet

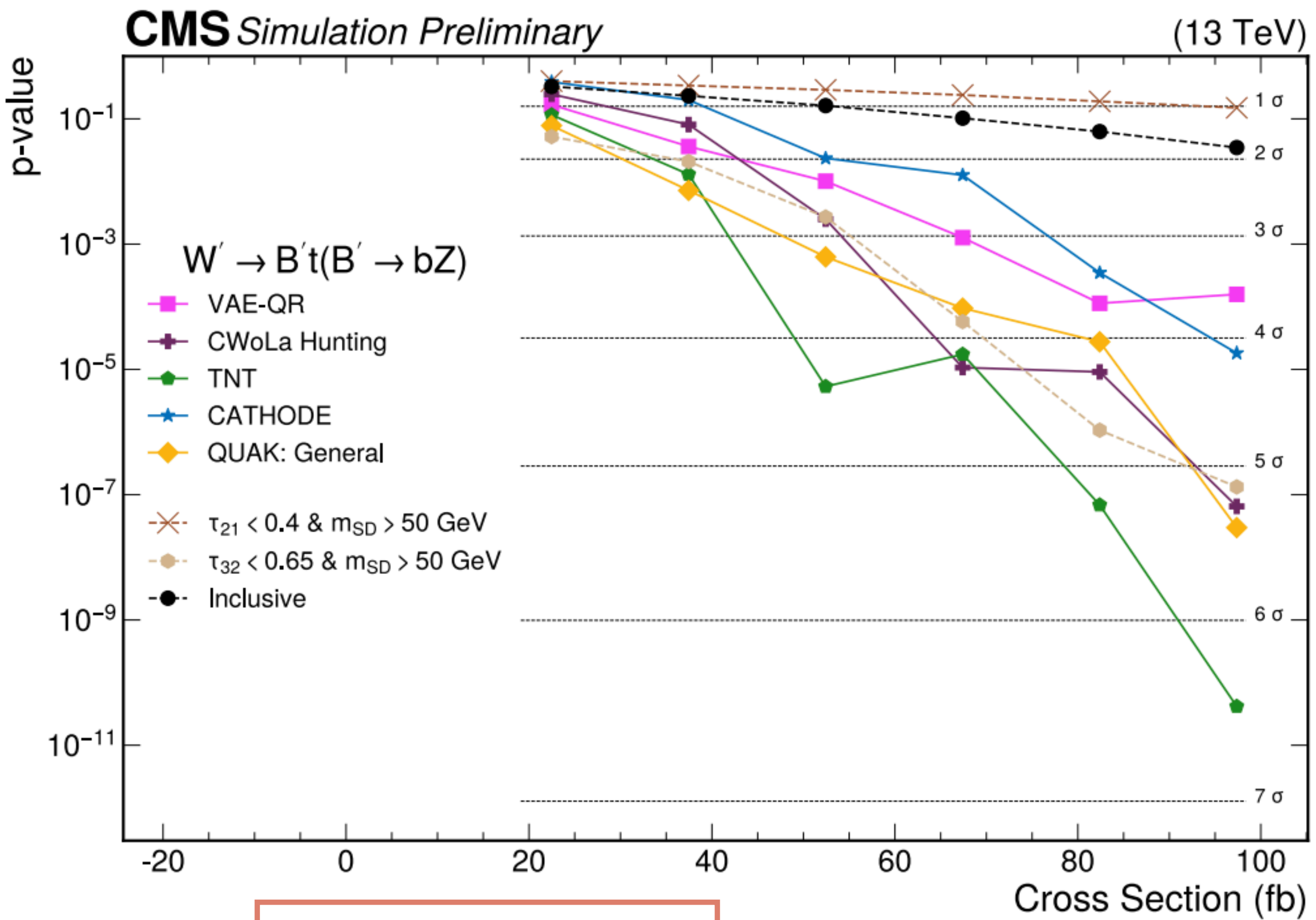
Training on SM background jet
→ **anomalous jet will produce outlier latent scores** → make selection on the score

CMS model-agnostic resonant search

CMS-NOTE-2023-013



2-prong + 2-prong

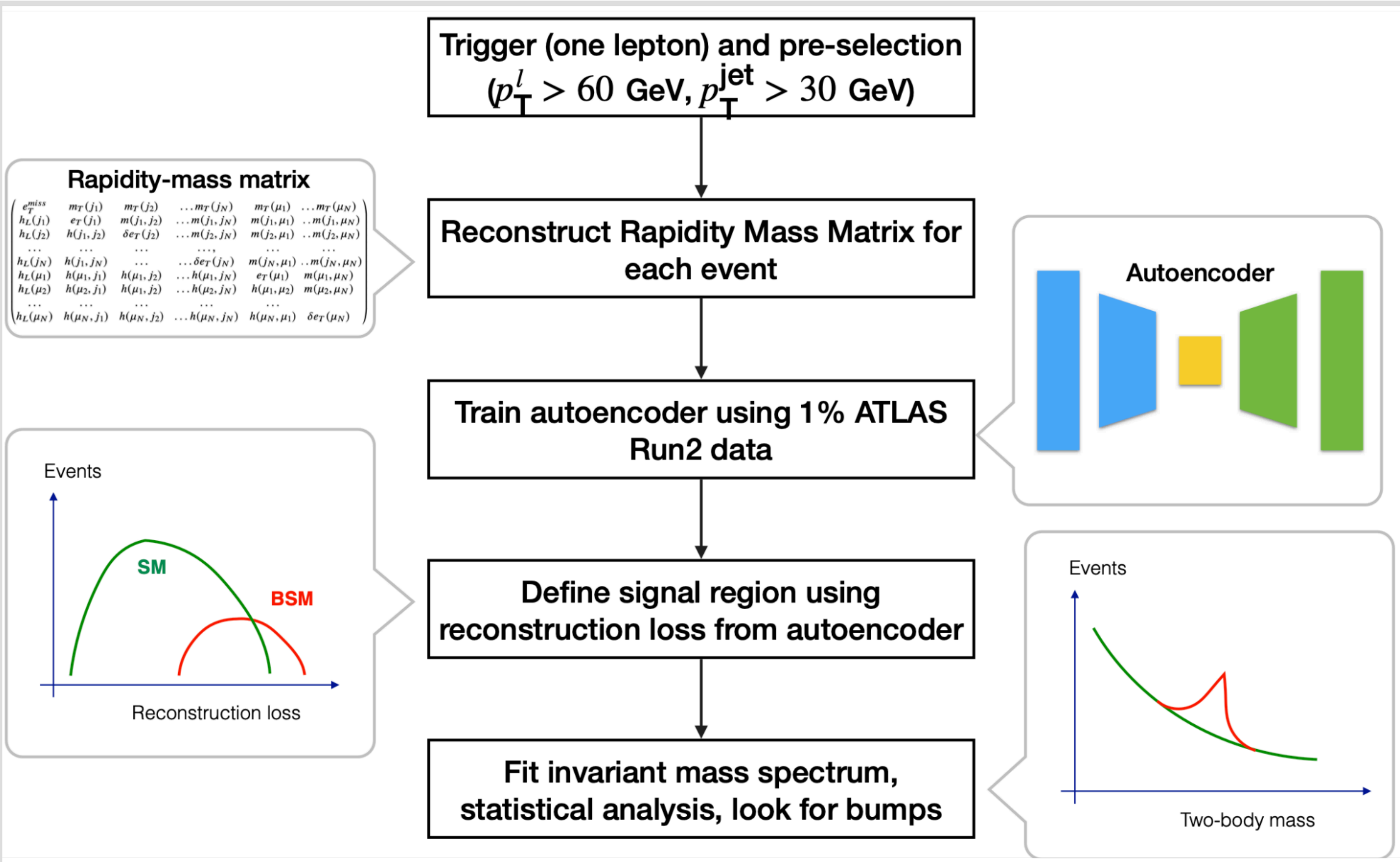


3-prong + 3-prong

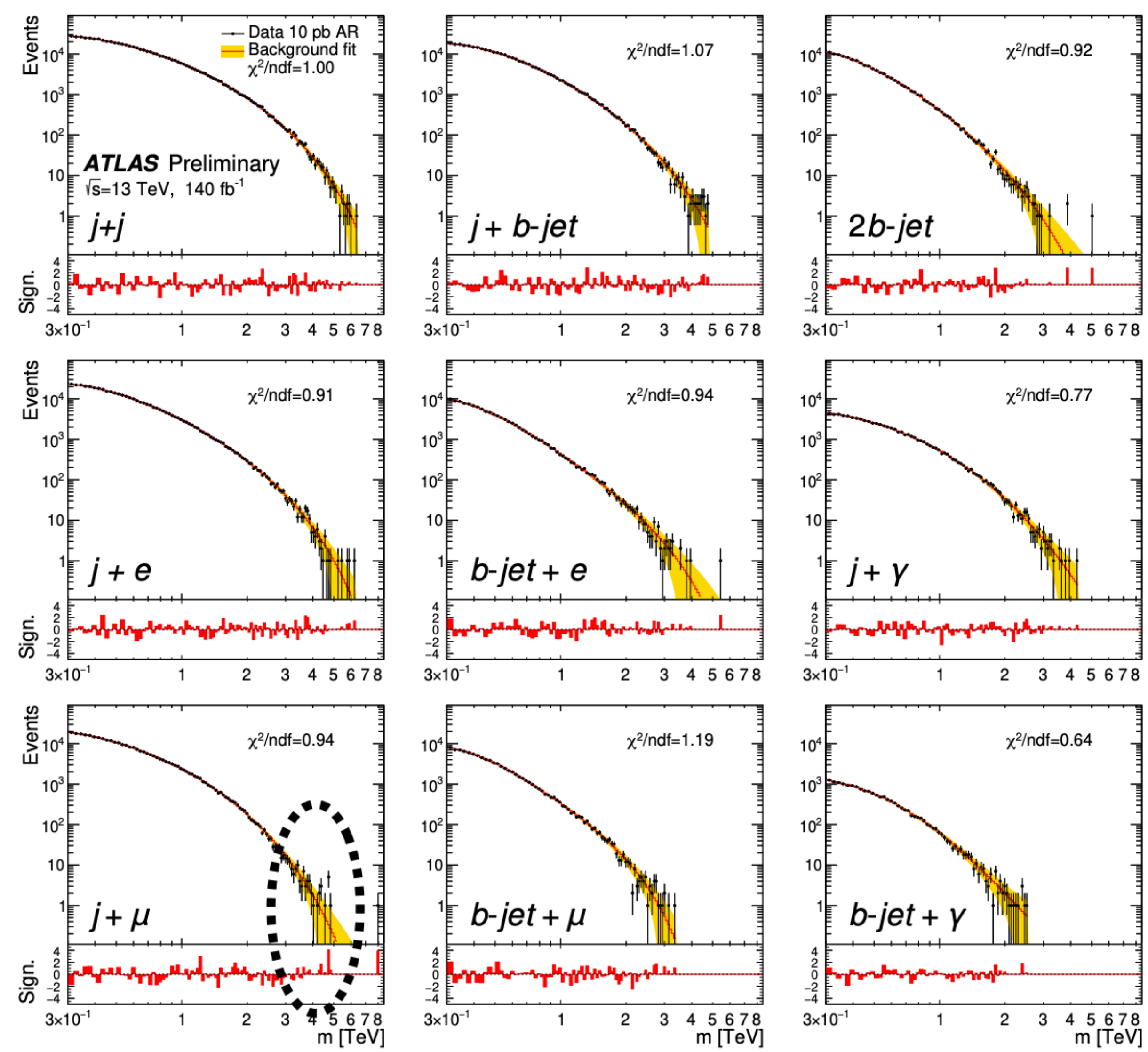
- ➔ CMS systematically test all model-agnostic approaches to search for resonance
  - ❖ first performed on toy data (from simulation)
  - ❖ achieve comparable/better performance than conventional search using jet substructure selection (τ_{21}, τ_{32})

➔ Intermediate release results - to perform on data

ATLAS's model-agnostic search



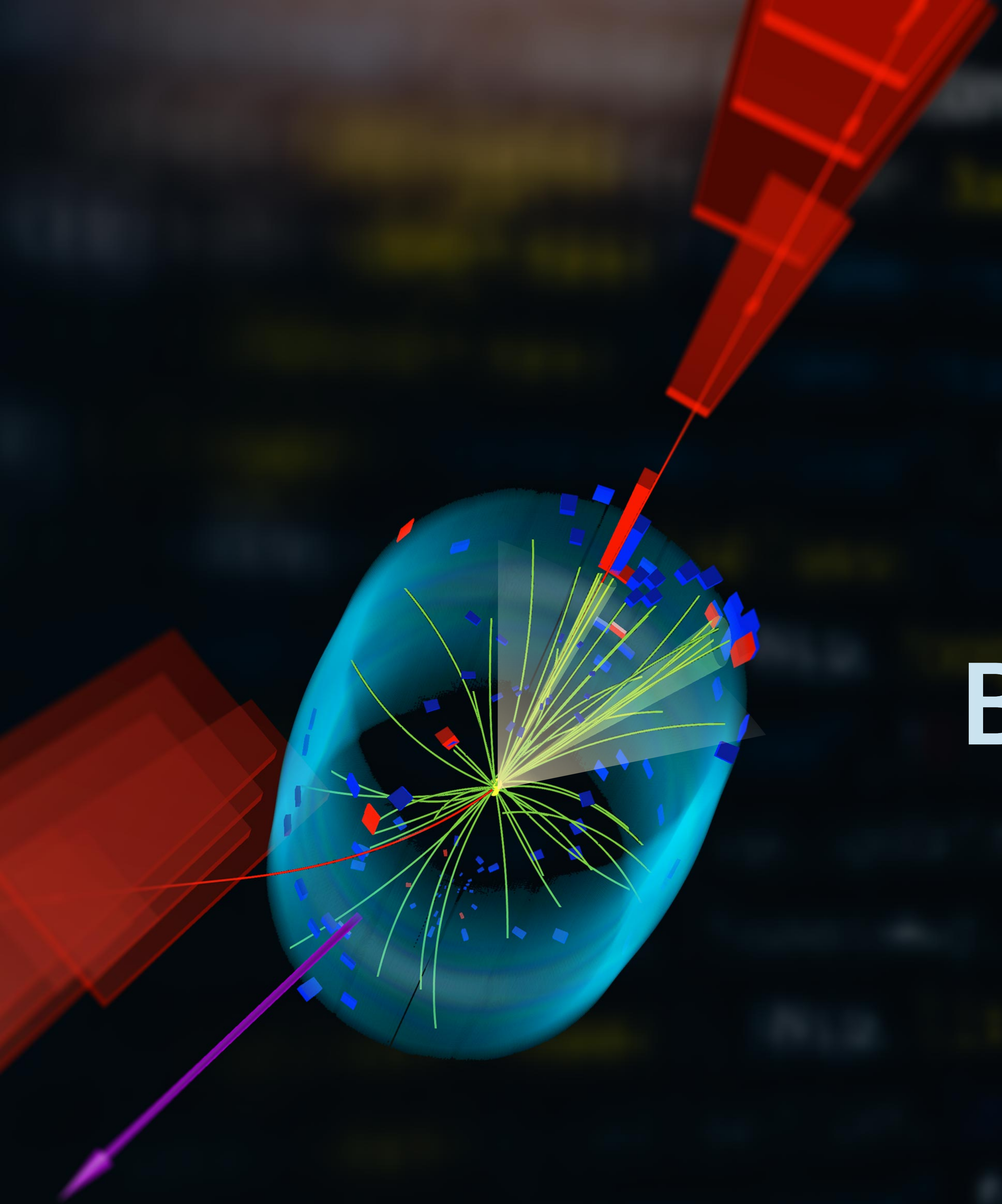
arXiv:2307.01612



- ➔ ATLAS applies full-event-level anomaly detection
- ➔ Train "autoencoder" and select on the score
- ➔ Search in 9 invariant masses including di-jet, di-b-jet, with three anomaly regions

Conclusion

- ➔ We introduce the latest CMS results from an angle of experimental innovations
  - ❖ these aspects can be meaningful to a wide HEP community:
    better use/analysis of the collected LHC data → accelerate our next HEP discovery!
- ➔ We share two innovations to showcase how they might **bring general impacts** to our physics programme
  - ❖ advent of advanced NNs to process low-level data → change the way we put selections/define observables, leading to substantial sensitivity improvements
  - ❖ advent of modern model-agnostic search → transform searching paradigm of BSM particles and still achieving optimal sensitivity
- ➔ Novel results including **Run 3 data** to bring more excitement
  - ❖ improvement foreseeable brought by more collected data + improved strategies
- ➔ Upgrade to HL-LHC is making good progress

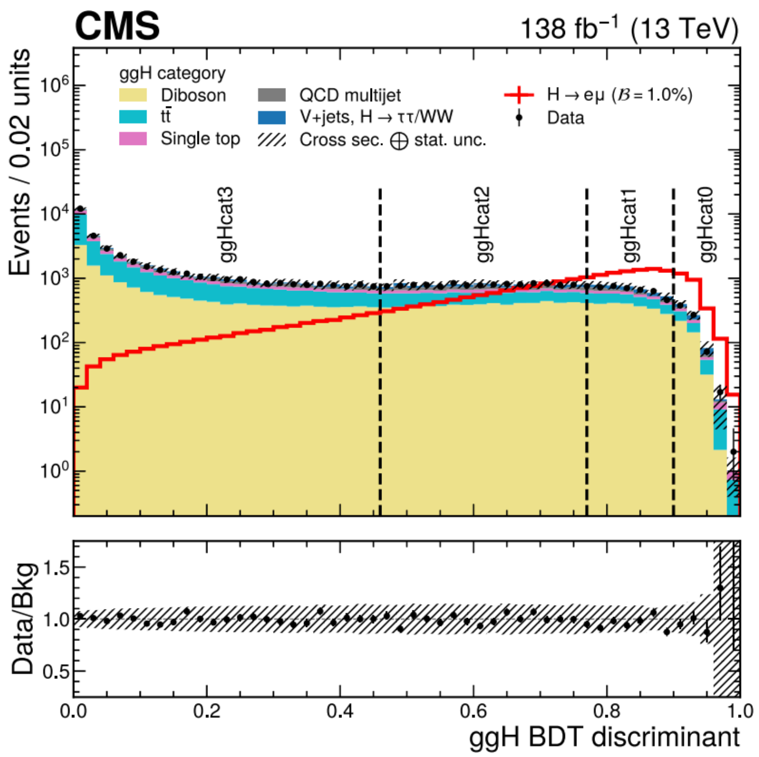


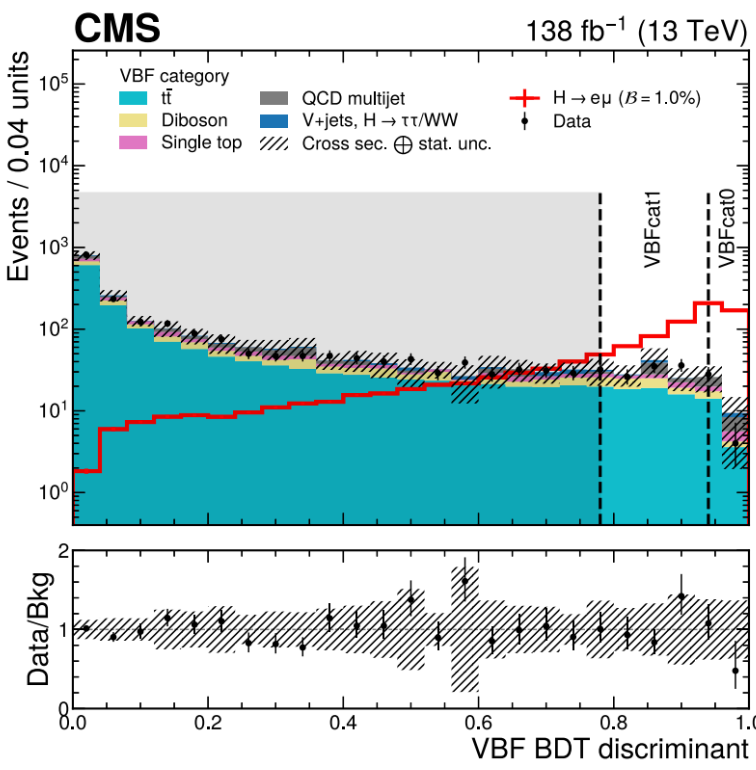
Backup

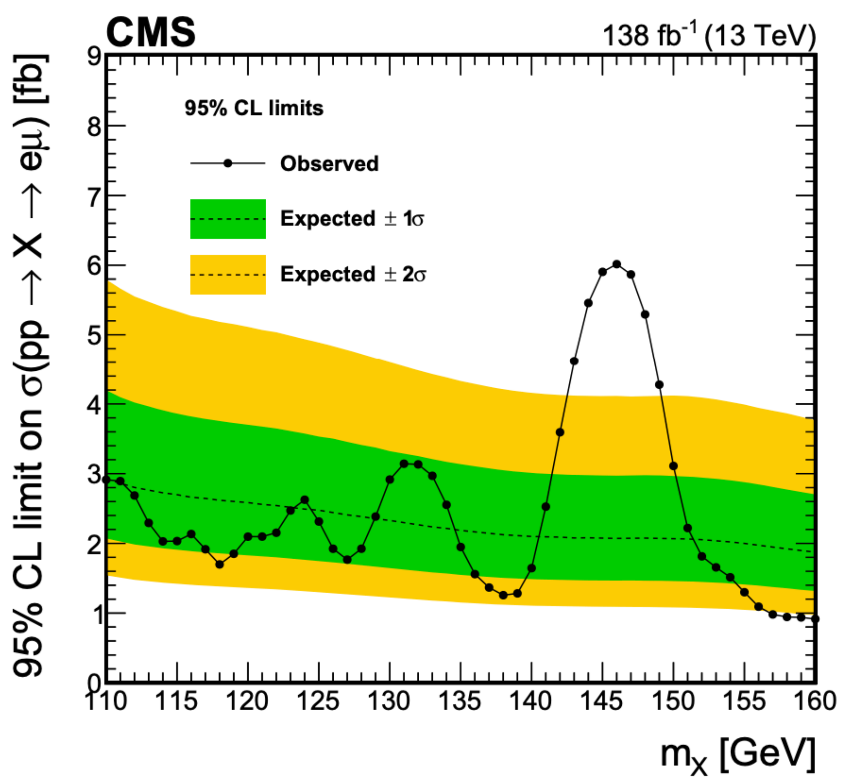
Lepton flavour violating

PRD, 108 (2023) 7, 072004

- ➔ Search LFV signature for H→eμ, also extending to *X*→eμ (m_X: 100-160 GeV)
  - ❖ type III 2HDM predicts additional scalar bosons *X*, with LFV decays
- ➔ Fitting $m_{e\mu}$ distribution in signal regions (classified by BDT)
- ➔ Largest excess: 3.8σ (2.8σ) local (global) at 146 GeV



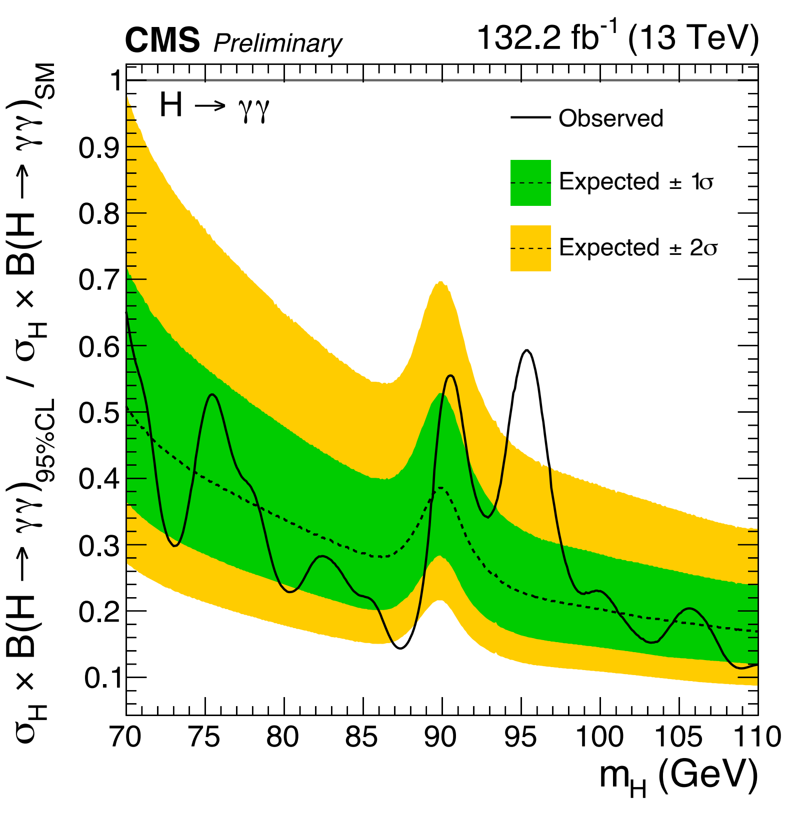


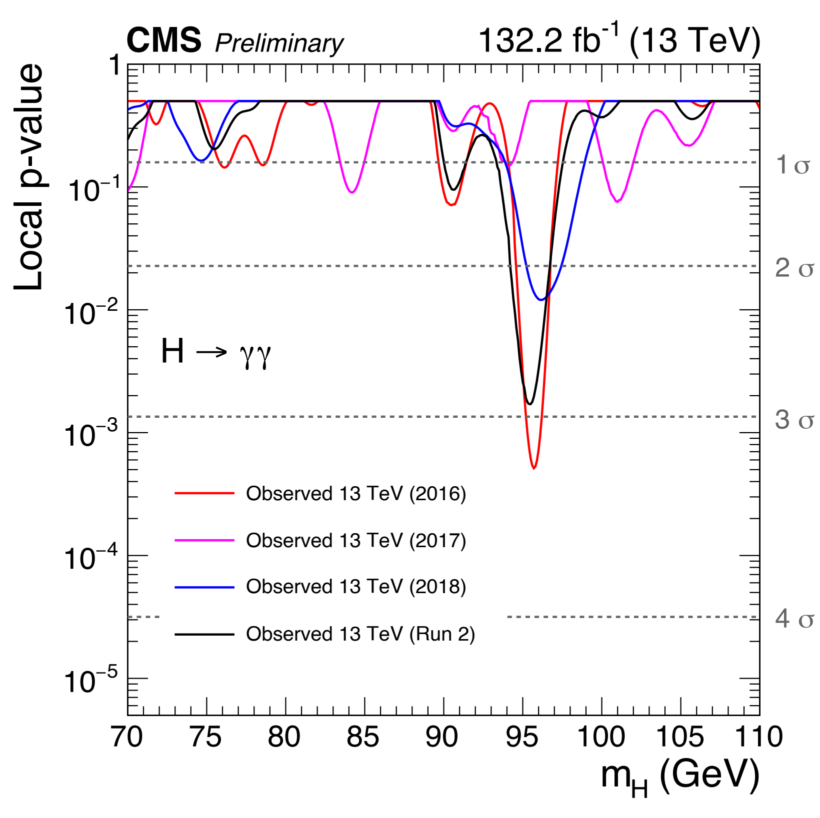


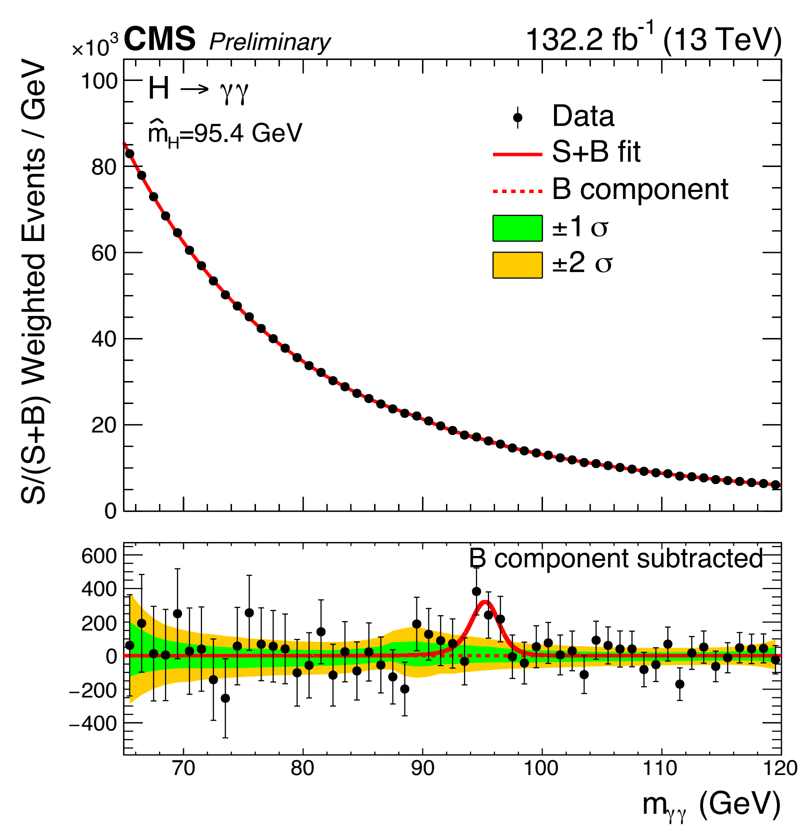
New resonance in γγ final state

CMS-PAS-HIG-20-002

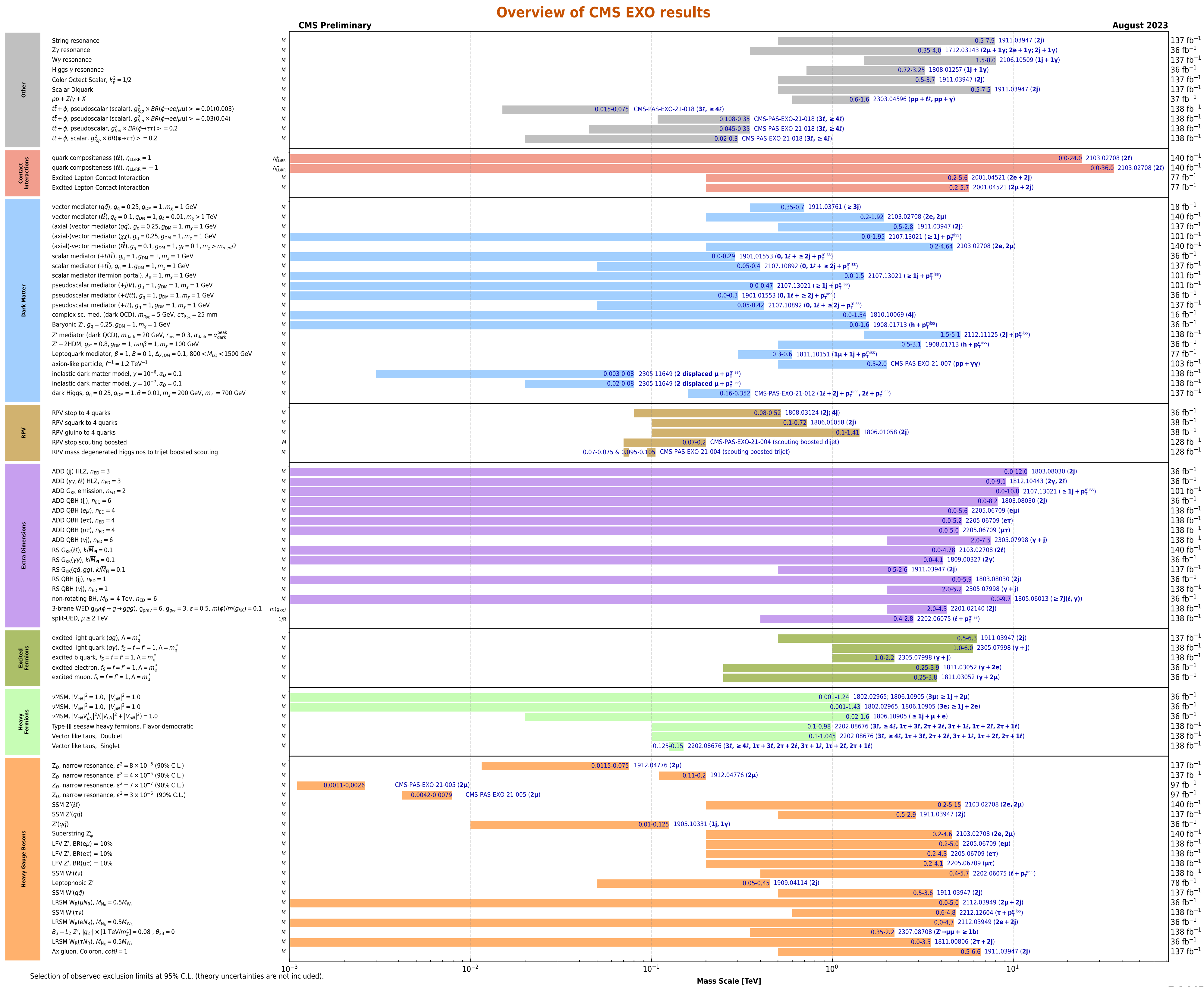
- ➔ Search for new resonance in the clean γγ final state
- ➔ Categories: 1 VBF + 3 classes defined by di-photon BDT
- ➔ Test statistic based on profile likelihood ratio constructed from the mass spectrum: 2.9σ local (1.3σ global) at 95.4 GeV







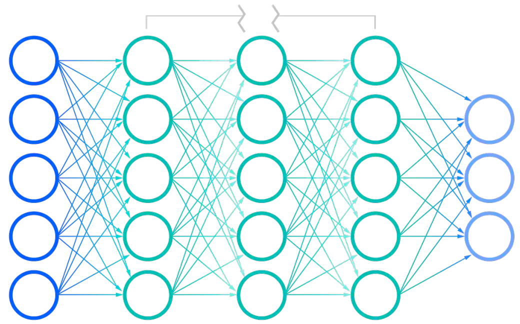
CMS exotic search results

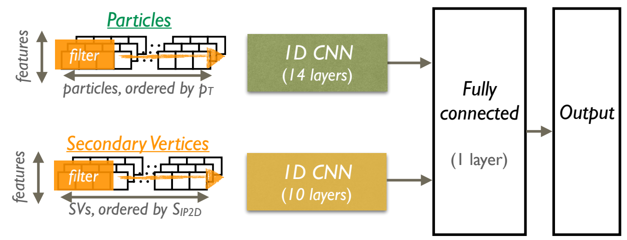


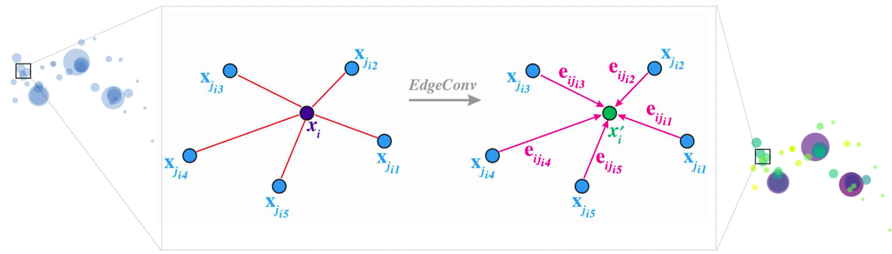
summary plots from link

Evolution of jet NNs

feed-forward NN *(high-level inputs)* • • • ▶ • • • *1D/2D CNN, RNN* *(low-level inputs)* • • • ▶ • • • *graph NN* *(low-level inputs)* • • • ▶ • • • *??*







Shallow networks

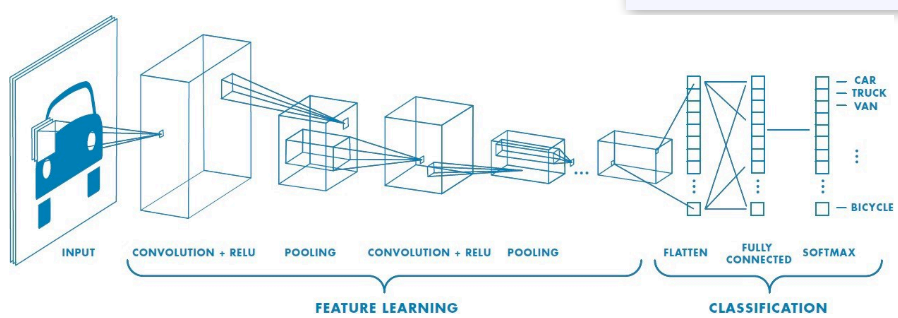
- ✦ Using high-level features directly as input to a shallow network

Deep NN with low-level inputs

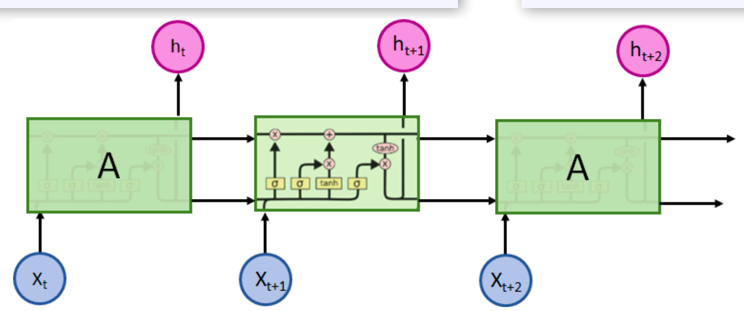
- ✦ Using particle-level features
- ✦ Input data structure determines the type of networks
  - jet as a *image (fixed-grid data structure)*
  - jet as a *sequence* → 1D CNN or RNN

Graph structure

- ✦ Graph neural networks
  - treat a jet as a permutational-invariant set of particles (or, point cloud)
  - build "edges" between particles
- ✦ Transformer networks
  - modern architectural designs; like a full-connected graph



Typical CNN

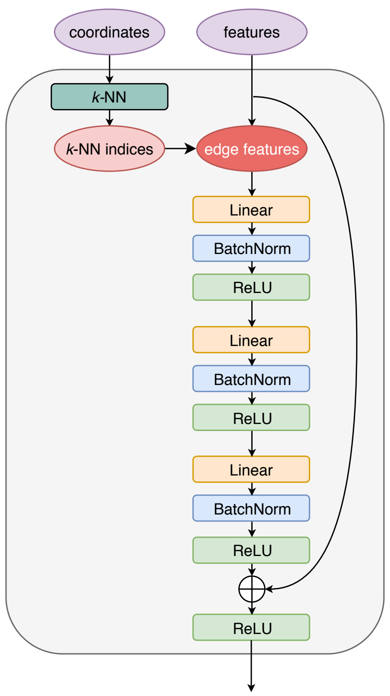


Typical RNN

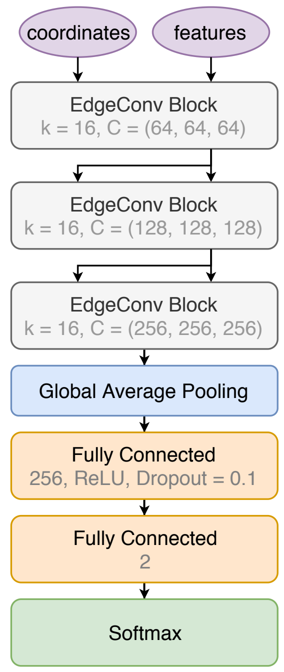
Typical graph

ParticleNet architecture

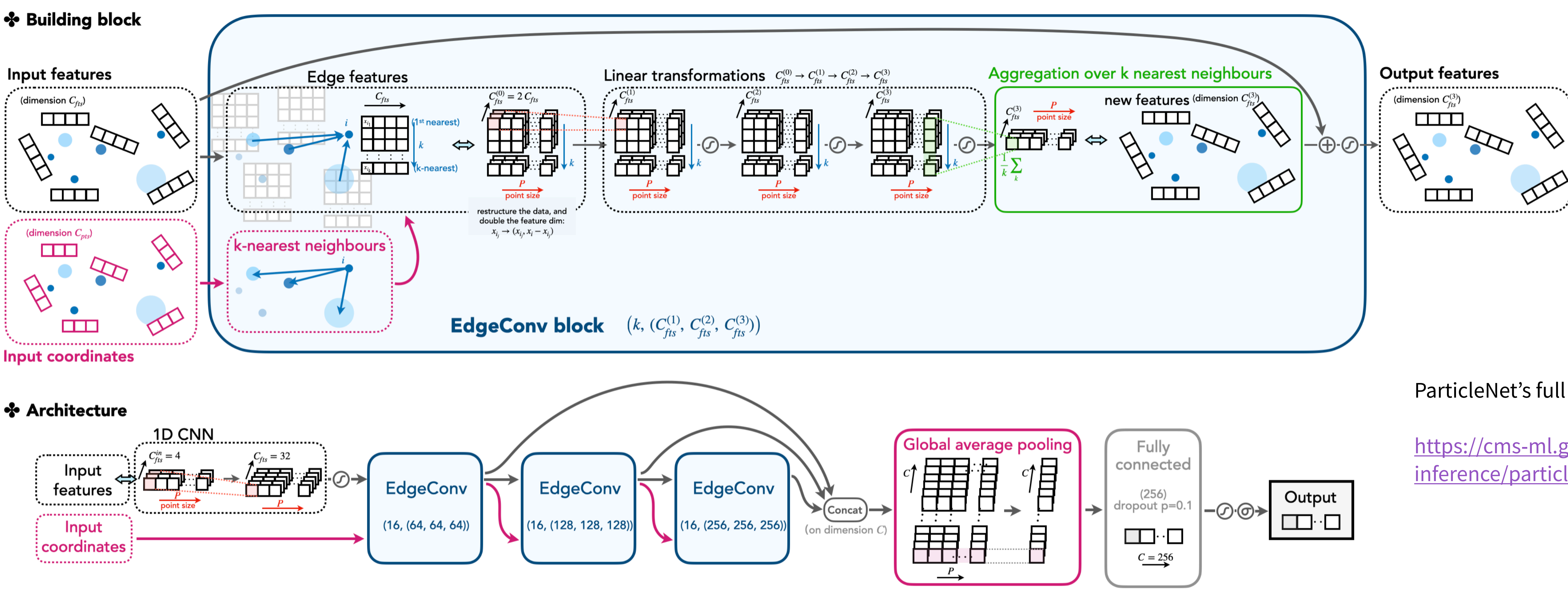
EdgeConv block



ParticleNet full architecture



[H. Qu, L. Gouskos, PRD 101, 056019 (2020)]



ParticleNet's full architecture

[https://cms-ml.github.io/documentation/inference/particlenet.html]