Overview of Recent LHC Results

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on behalf of the ATLAS, CMS and LHCb collaborations

Aspen 2024

Papers since Aspen 2023:

More than 250 papers submitted by ATLAS, CMS and LHCb!

I won't try to summarize 250 papers in 25 minutes.

Instead, will highlight a small selection of these beautiful results.

Recent results for each experiment linked here: ATLAS, CMS, LHCb,

Image: Juan Aliga

LHC Schedule

Run 1 | Run 2 | Run 3 | HL-LHC

2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | ... | 2045

Run 1: 7/8 TeV, 25 fb^{-1}

Run 2: 13 TeV, 140 fb^{-1}

Run 3: 13.6 TeV, 70 fb^{-1} so far, ~260 fb^{-1} expected

HL-LHC: 14 TeV, 3000 fb^{-1}

Significant increases in total integrated luminosity, but only marginal increases in energy.

LHC Schedule

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	...	2045

Run 1
7/8 TeV
25 fb^{-1}

Run 2
13 TeV
140 fb^{-1}

Run 3
13.6 TeV
70 fb^{-1} so far
~260 fb^{-1} expected

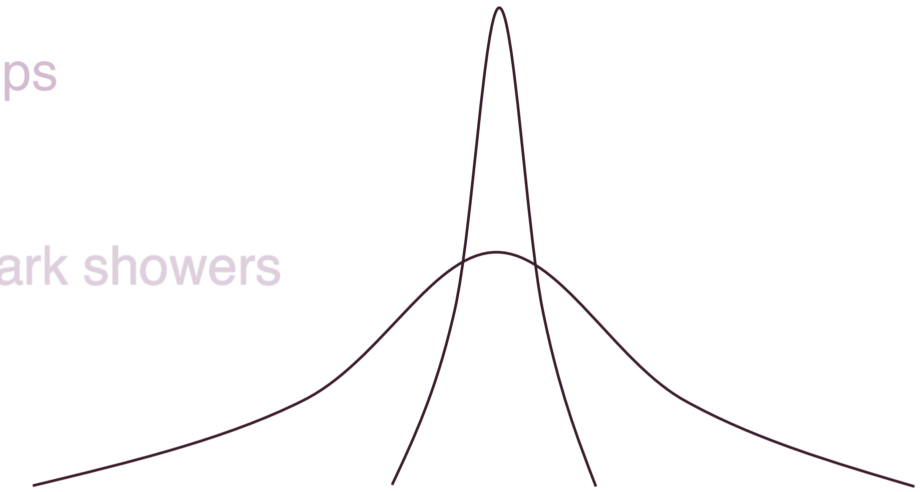
HL-LHC
14 TeV
3000 fb^{-1}

No large increases in the center of mass energy and no clear signs of new physics encourages more ***meticulous*** *and* ***creative*** *approaches*

Overview of Recent LHC Results

Results with the Full Run 2 dataset:

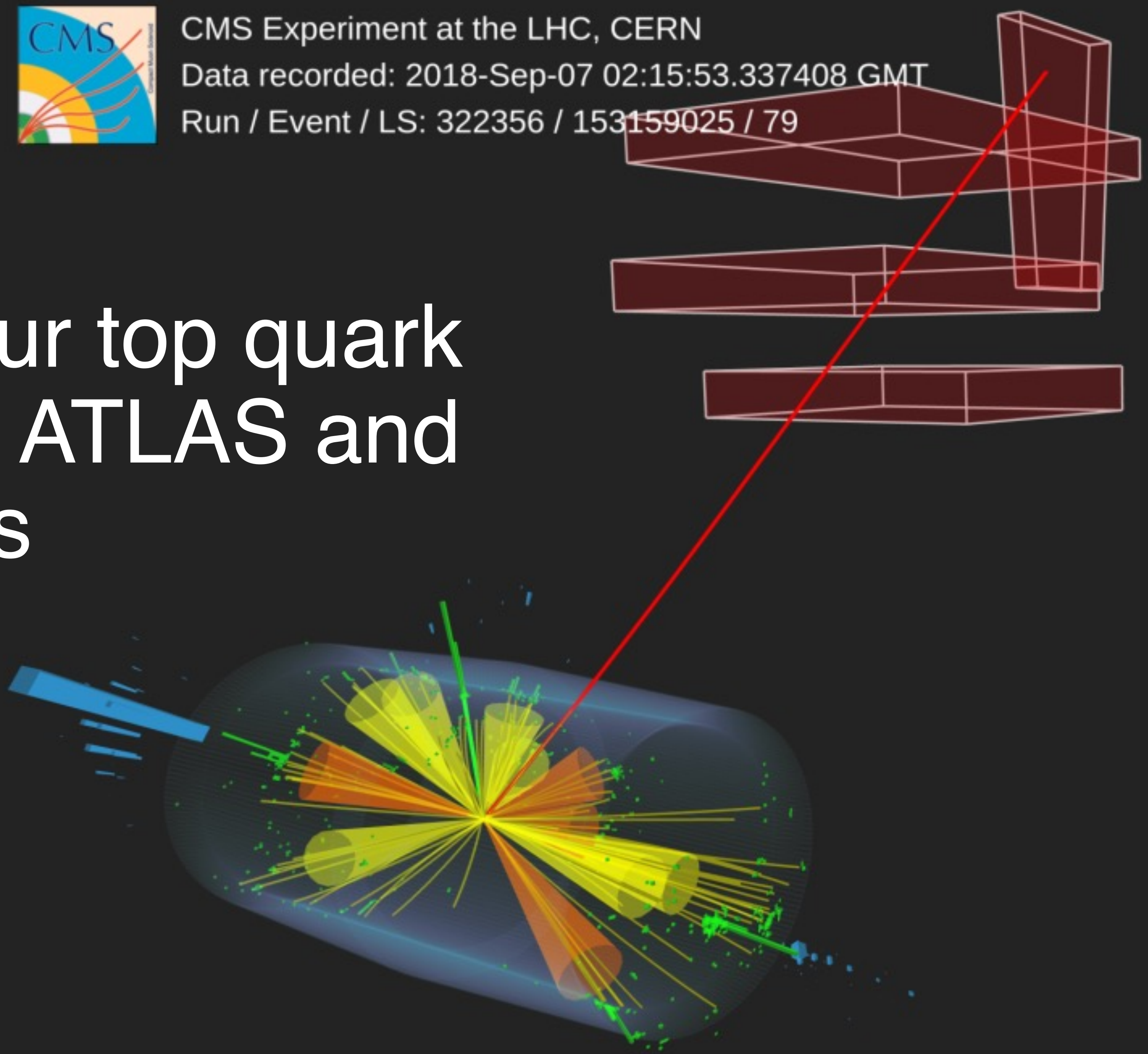
- Measurement of rare processes Observation of four tops
- Precision measurements R_K
- Searches for more complex and unusual signatures Dark showers
- New search techniques Anomaly detection searches



Small handful of Run 3 results:

- Measurements at 13.6 TeV & searches with new triggers - to be covered next year ☺

Rare Processes: Observation of four top quark production by the ATLAS and CMS Experiments

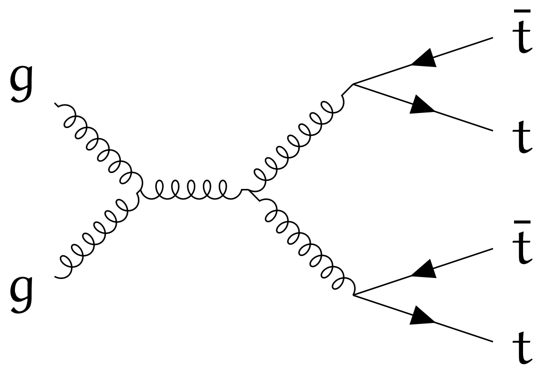


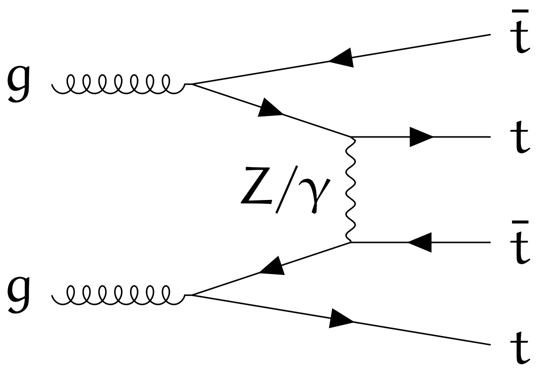
Four Top Production

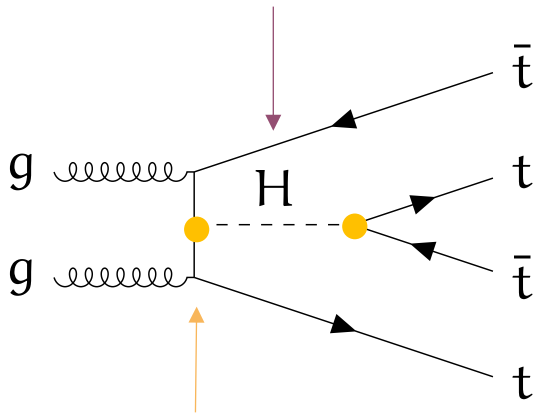
ATLAS: [Eur. Phys. J. C 83 (2023)](#)
CMS: [Phys. Lett. B 847 (2023)](#)

- Heaviest SM signature explored at the LHC!
- Very rare process: $\sigma(tttt)_{NLO+NLL'} = 13.4^{+1.0}_{-1.8}$ fb [arXiv:2212.03259]

Enhanced production for BSM models with heavy scalar or pseudo-scalar particles





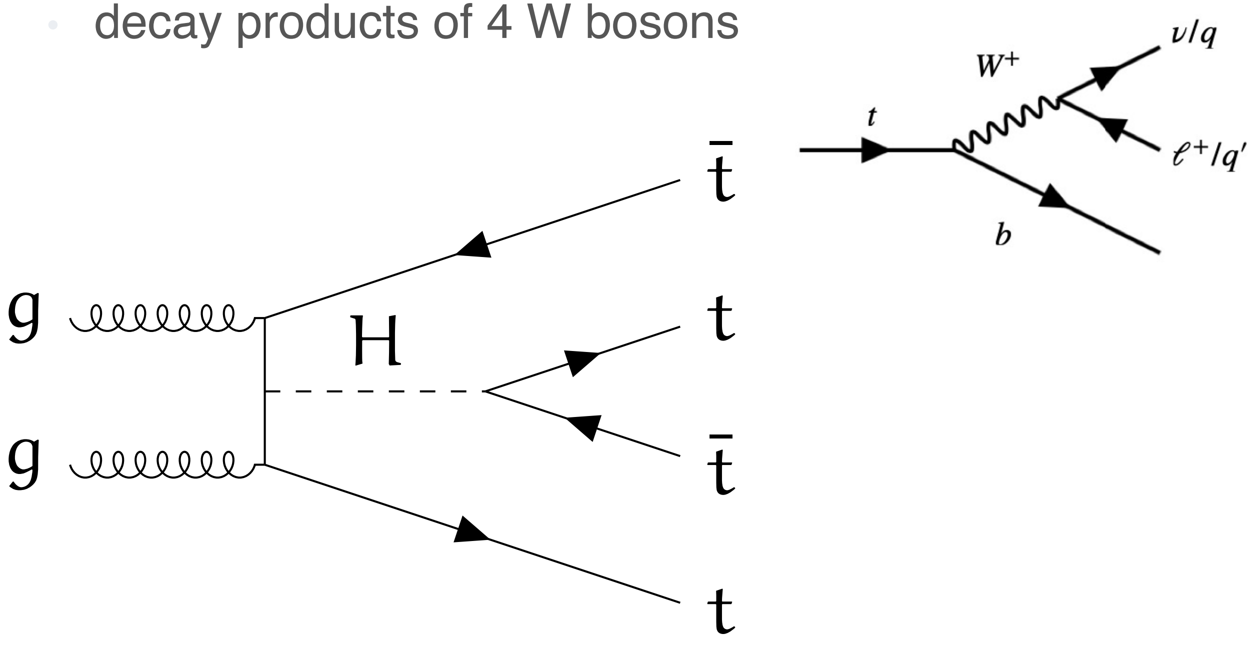


Sensitive to top Yukawa coupling

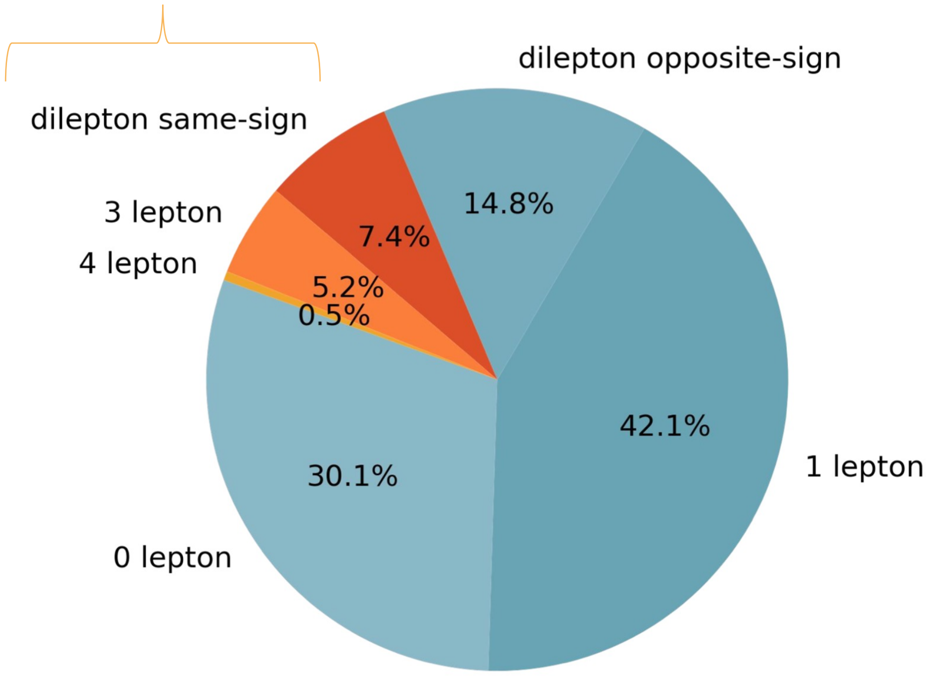
Four Top Production

High object multiplicity final state:

- 4 b-quarks leading to jets
- decay products of 4 W bosons



Same-sign and multilepton channels have highest sensitivities despite small branching fraction.



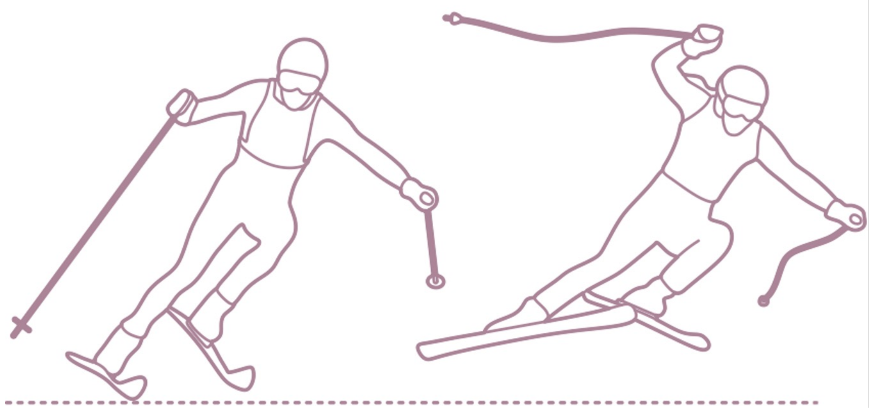
Main backgrounds in same-sign dilepton & multilepton channels: ttW, ttZ, ttH

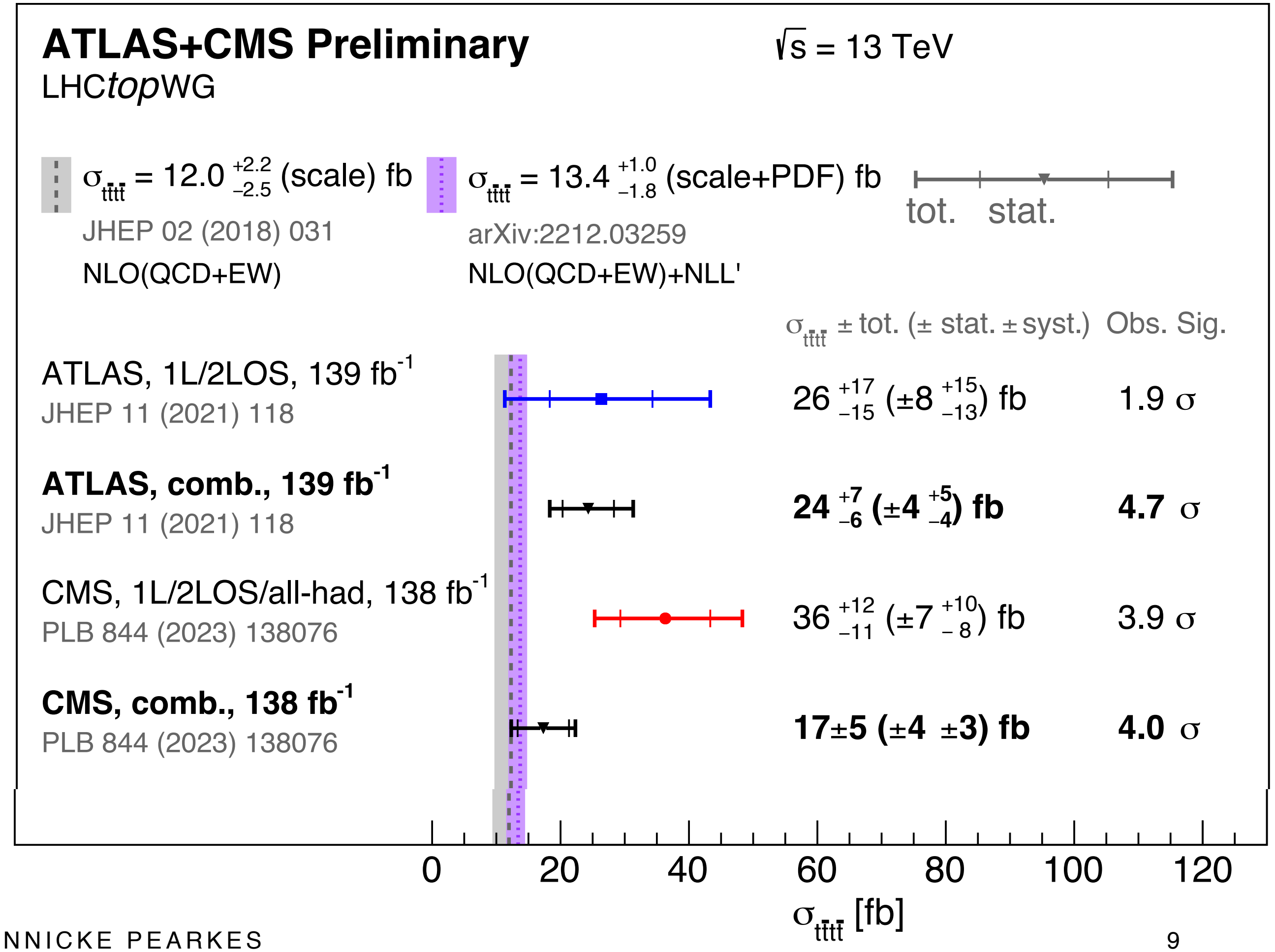
Initial Four Top Full Run 2 Results

LHCTopWG Summary Plots

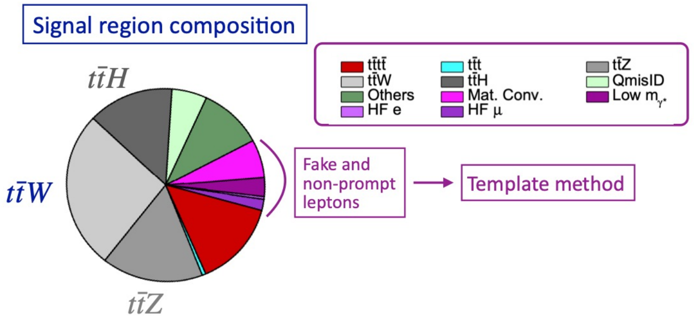
First iteration on full Run 2 dataset

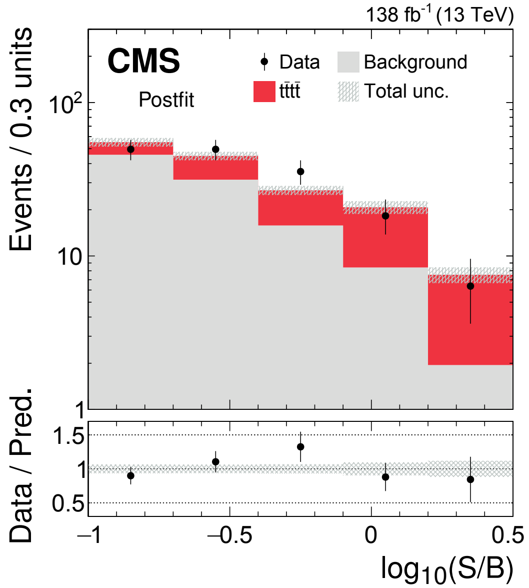
Race to 5σ with same-sign di-lepton and multilepton channels

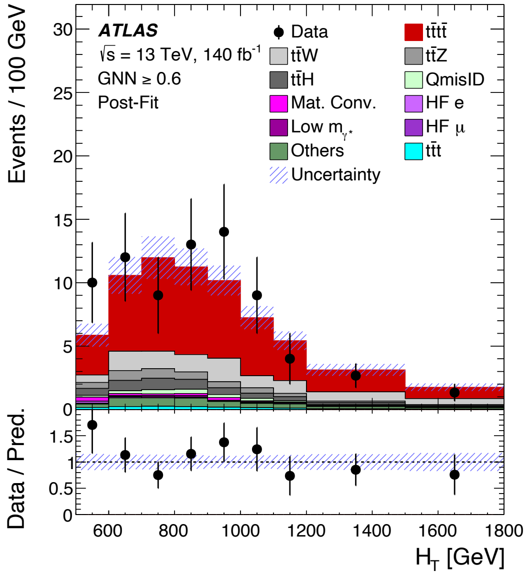




Four Top Production – Analysis Improvements







Widespread adoption of many dedicated ML techniques.

ATLAS

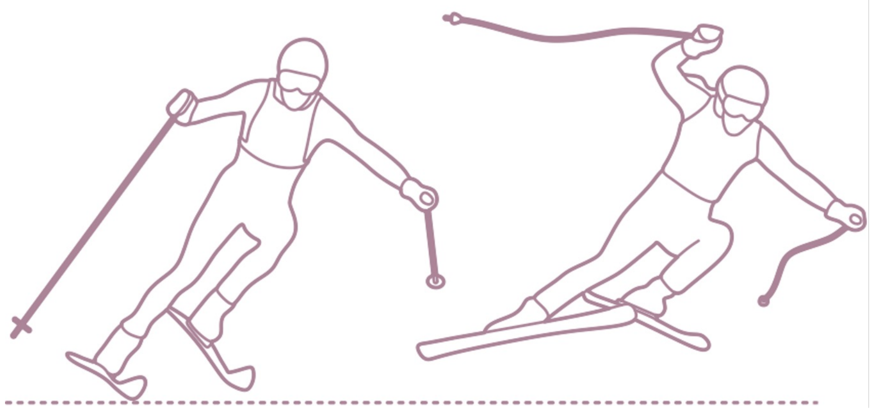
- Data-driven ttW+jets background estimate
- GNN for signal from background separation - 10% higher significance compared to prior BDT-based method
- DL1r b-tagging improves light/c-jet rejection
- Lowered p_T on lepton and jet selections

CMS

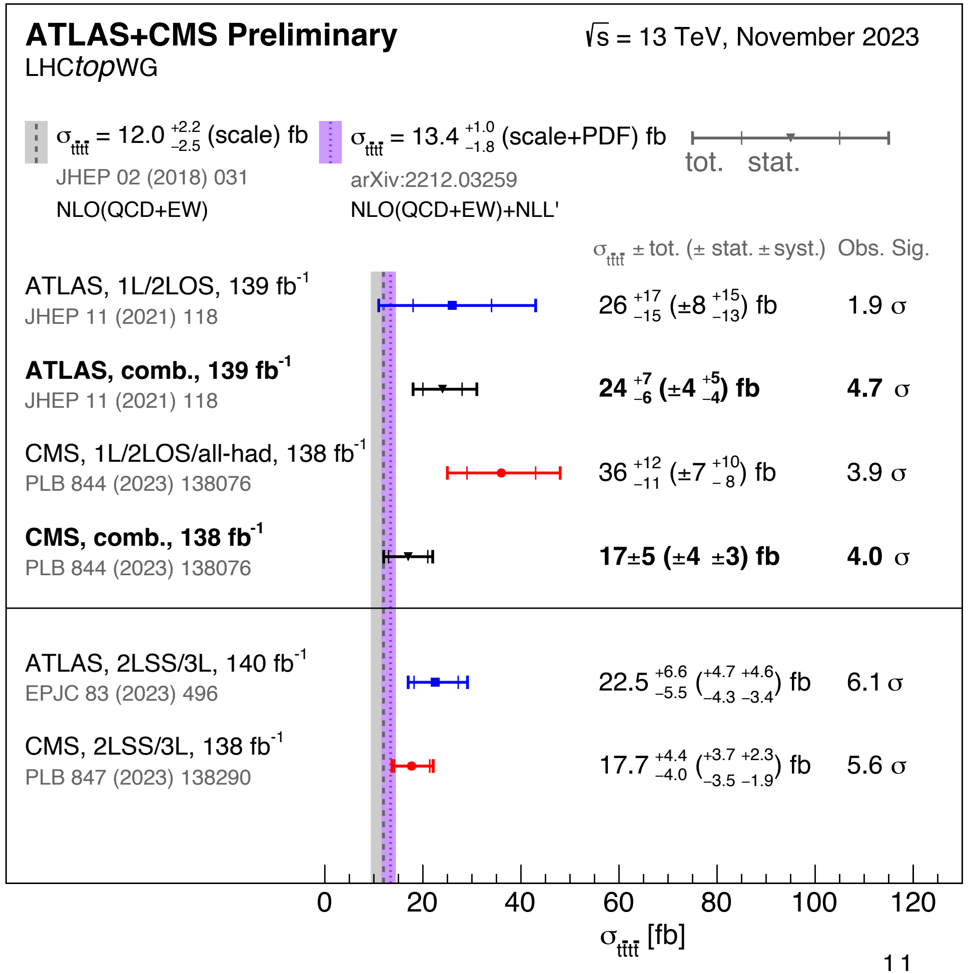
- Refined ttW / ttZ non-prompt control regions
- Improved multiclass BDTs for signal from background separation
- DeepJet b-tagging improved signal efficiency by 5-25%
- Improved lepton identification with tttt specific BDTs
- Lowered p_T on lepton and jet selections

Four Top Production - Results

Accumulation of many small improvements leads to large gains



[LHCTopWG Summary Plots](#)



More Rare Processes:

Tri-boson production:

WZγ observation at 6.3σ (5.0σ exp)

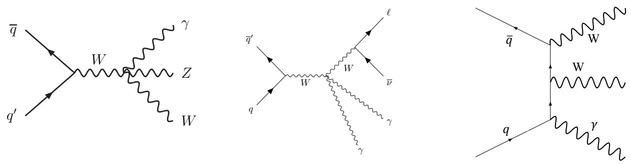
ATLAS: Phys. Rev. Lett. 132 (2024) 021802

W$\gamma\gamma$ observation at 5.6σ (5.6σ exp)

ATLAS: Phys. Lett. B 848 (2024) 138400

WWγ observation at 5.6σ (4.7σ exp)

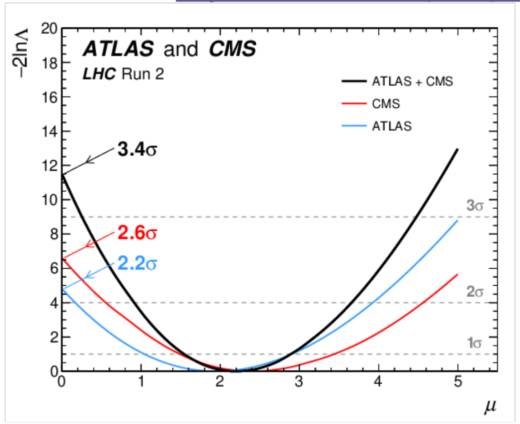
CMS: CERN-EP-2023-203



Higgs to Zγ:

Evidence at 3.4σ (1.6σ exp)

ATLAS+CMS: Phys. Rev. Lett. 132 (2024) 021803

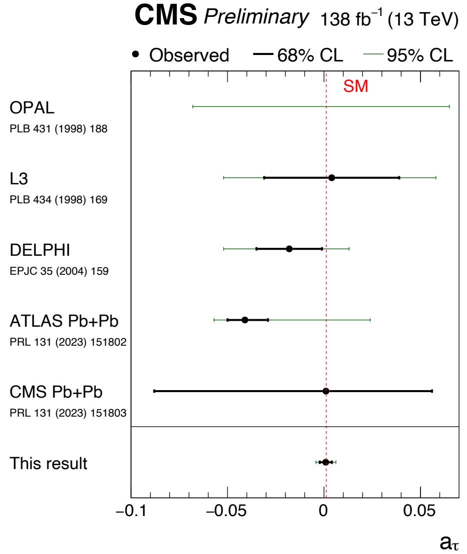


Observation of $\gamma\gamma \to \tau\tau$

CMS (pp) CMS-PAS-SMP-23-005

ATLAS (PbPb) Phys. Rev. Lett. 131 (2023) 15180

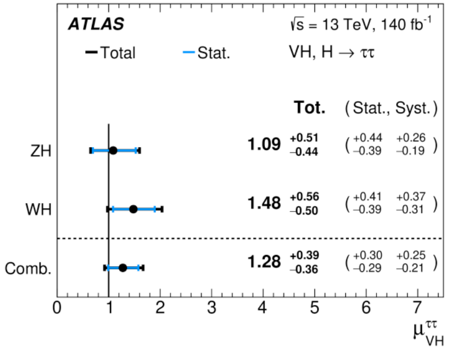
CMS (PbPb) Phys. Rev. Lett. 131 (2023)



VH($\tau\tau$):

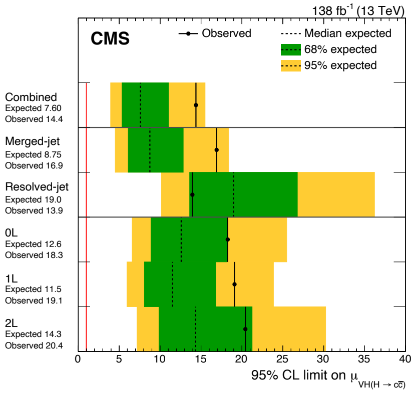
Evidence at 4.2σ (3.6σ exp)

ATLAS: https://arxiv.org/abs/2312.02394

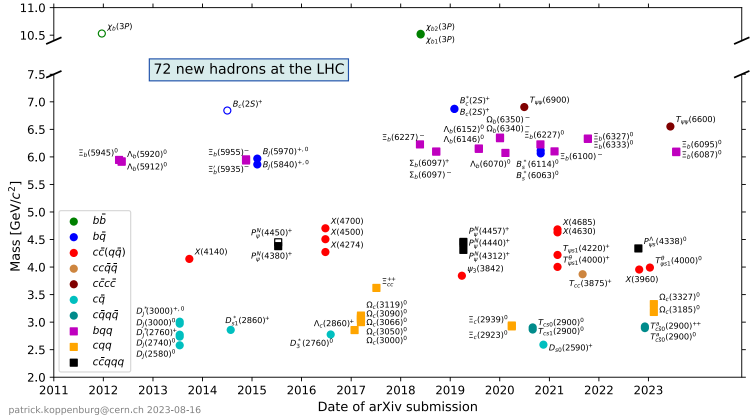


VH(cc): limits at 14.4x SM

CMS: Phys. Rev. Lett. 131 (2023) 061801



Hadron Spectroscopy



Many more results not highlighted here

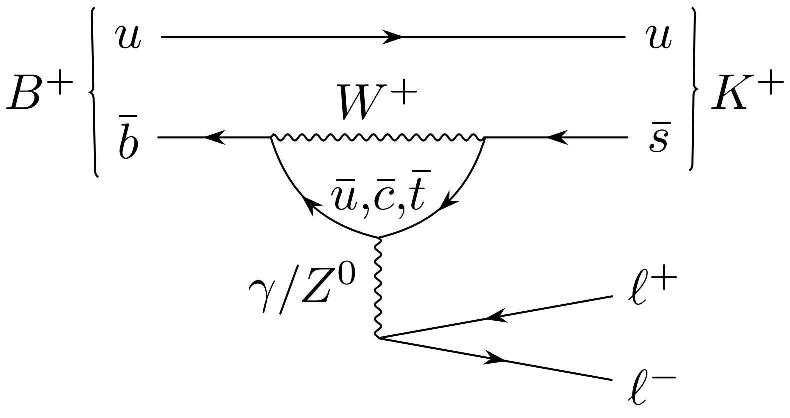
Precision Measurements: R_K

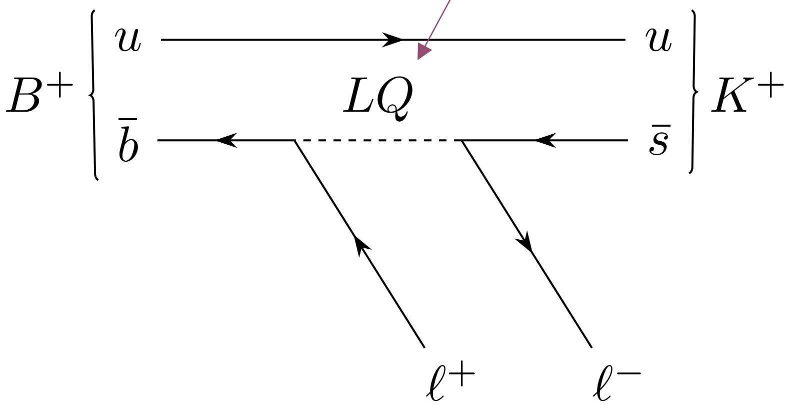
What is R_K?

New physics, such as leptoquarks could lead to imbalance in ratio of transitions producing a pair of muons vs. electrons

Probe of charged lepton flavour violation

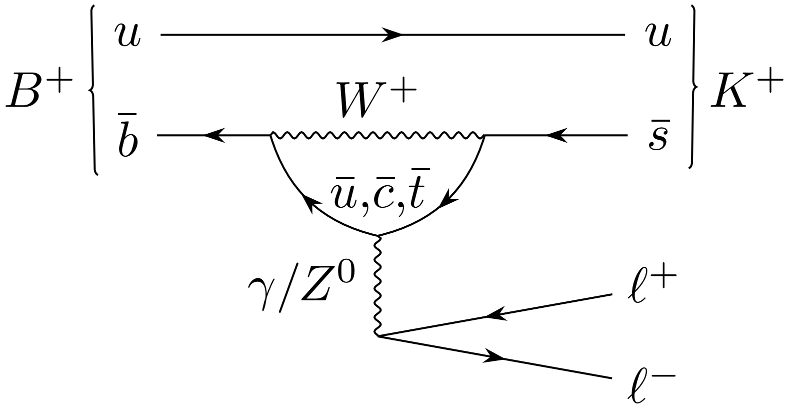
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

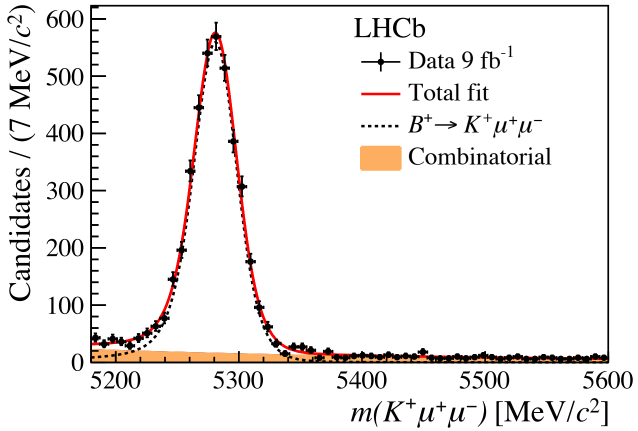


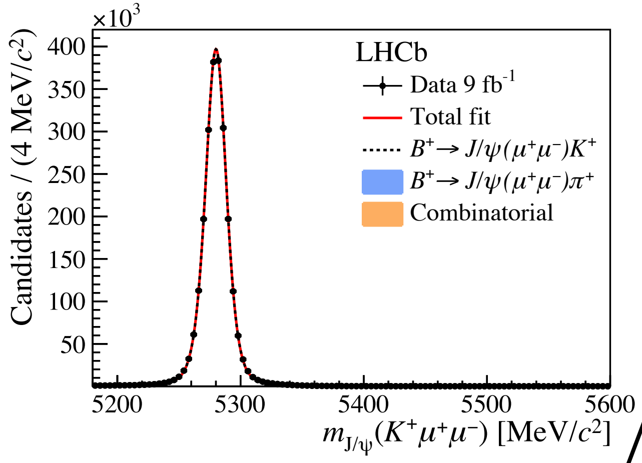


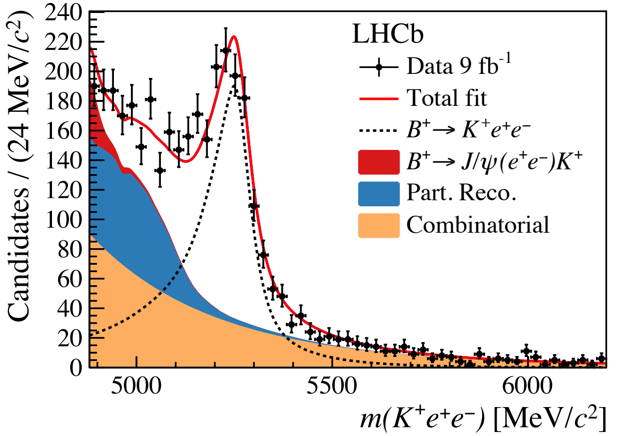
What is R_K?

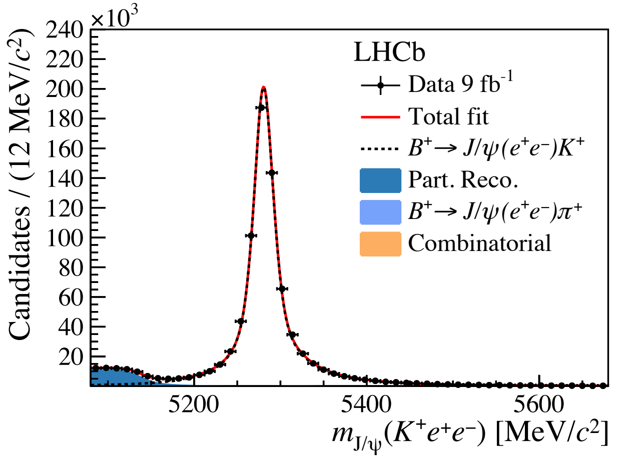
LHCb: Nature Physics 18, (2022) 277-282









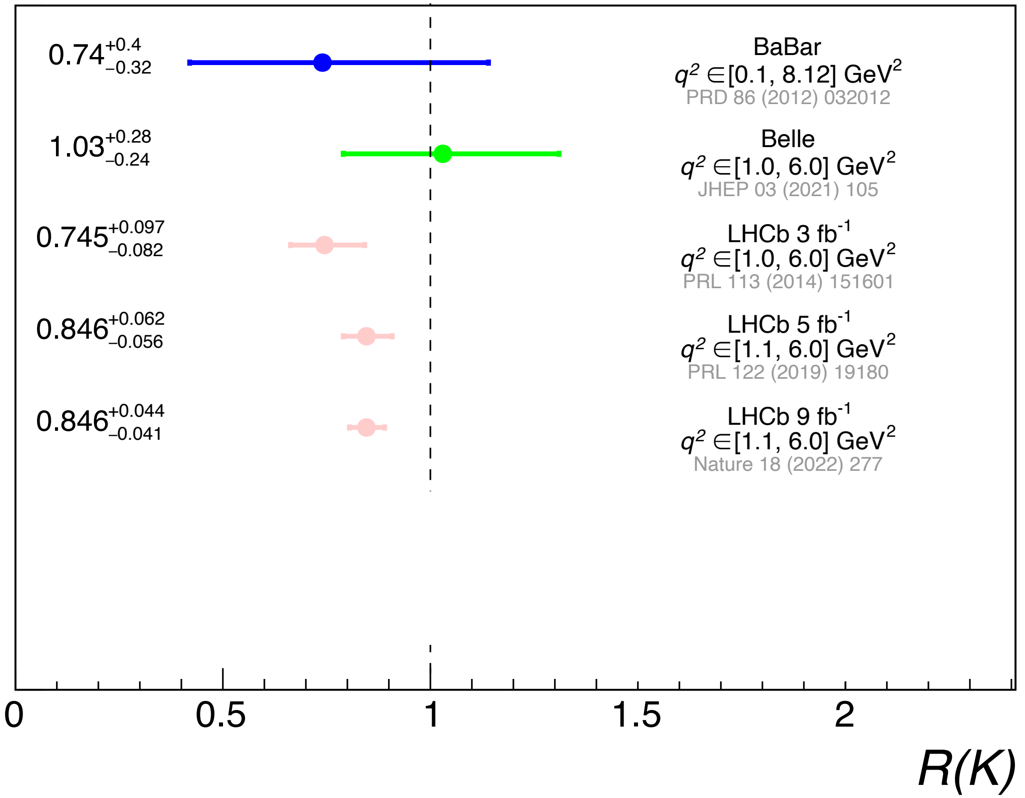


$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

R_K Measurements

LHCb: Nature Physics 18, (2022) 277-282
LHCb: Phys. Rev. D 108 (2023) 032002
CMS: CERN-EP-2023-297

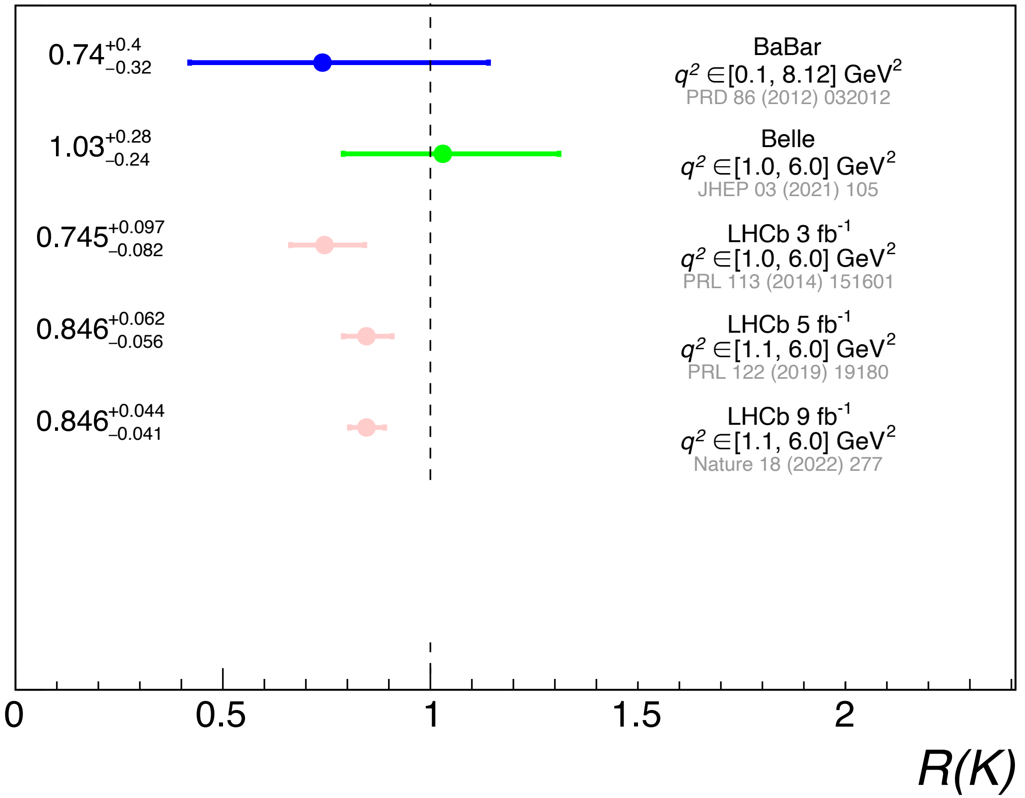
- Mounting evidence for lepton flavour violation in R_K from 2014-2022
- 3.1σ observed significance by LHCb in 2022



R_K Measurements

LHCb: Nature Physics 18, (2022) 277-282
LHCb: Phys. Rev. D 108 (2023) 032002
CMS: CERN-EP-2023-297

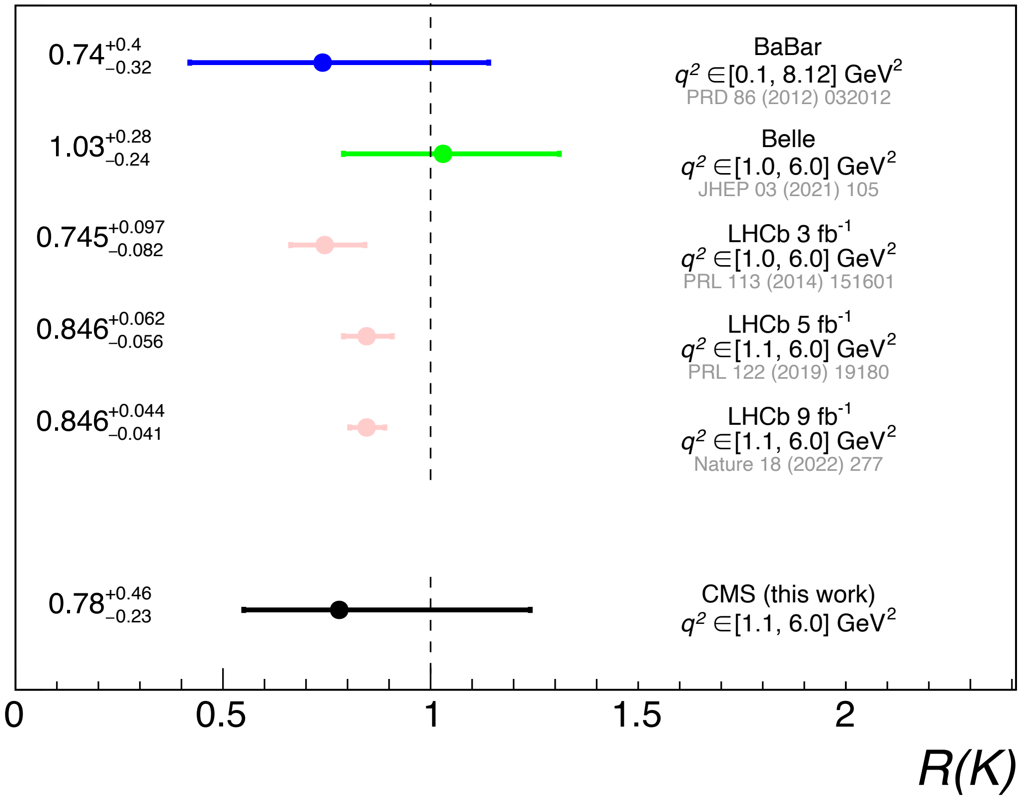
- Mounting evidence for lepton flavour violation in R_K from 2014-2022
- 3.1σ observed significance by LHCb in 2022
- CMS creates innovative "B-Parking" trigger strategy to trigger on low p_T muons and follow-up
- Allowed for collection of 10^{10} B-hadron decays that would not have been captured otherwise during 2018



R_K Measurements

LHCb: Nature Physics 18, (2022) 277-282
LHCb: Phys. Rev. D 108 (2023) 032002
CMS: CERN-EP-2023-297

- 2024 CMS produces their first measurement of R_K
- Consistent with SM, much larger uncertainties than LHCb
- Limited by statistics in electron channel
- B-Parking trigger strategy has collected large dataset for other B-Physics and low mass searches e.g. Observation of $J/\psi \rightarrow \mu\mu\mu\mu$ (CERN-EP-2024-058)



R_K Measurements

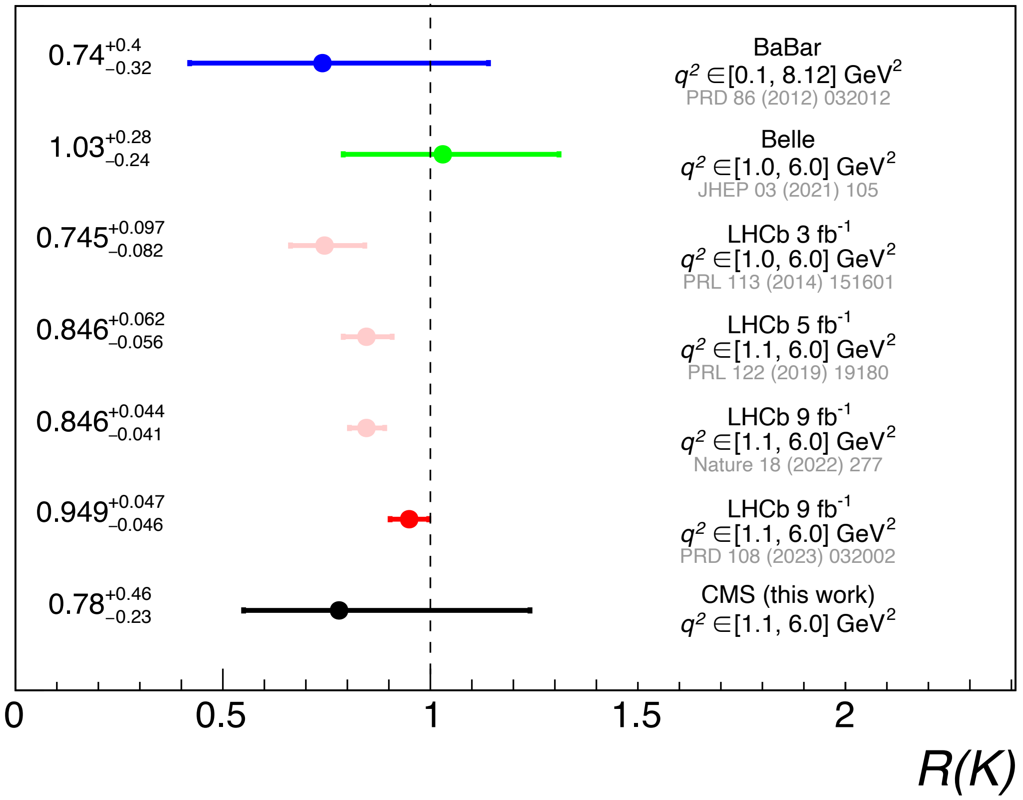
LHCb: Nature Physics 18, (2022) 277-282
LHCb: Phys. Rev. D 108 (2023) 032002
CMS: CERN-EP-2023-297

R_K low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.960 ± 0.097	0.971 ± 0.099	0.988 ± 0.102	0.997 ± 0.102	0.982 ± 0.100	0.973 ± 0.099	0.967 ± 0.099	0.967 ± 0.099	0.977 ± 0.102
DLL(e) > 5	0.961 ± 0.086	0.964 ± 0.086	0.969 ± 0.088	0.983 ± 0.090	0.973 ± 0.089	0.981 ± 0.091	0.979 ± 0.092	0.961 ± 0.090	0.985 ± 0.095
DLL(e) > 2	0.873 ± 0.073	0.904 ± 0.078	0.908 ± 0.079	0.958 ± 0.087	0.950 ± 0.086	0.954 ± 0.087	0.938 ± 0.086	0.940 ± 0.087	0.969 ± 0.093

ProbNN(e)

- Tighter electron identification criteria led to uncovering previously underestimated peaking backgrounds
- New result is compatible with SM



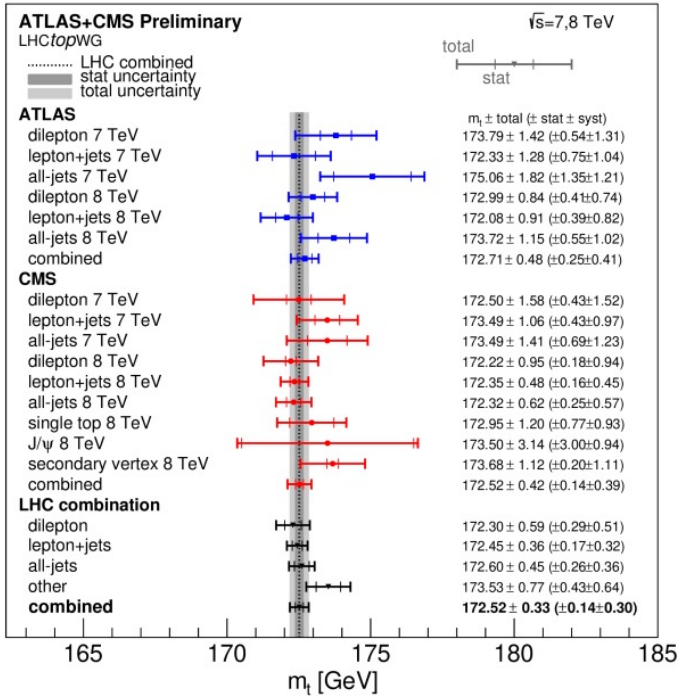
Precision Measurements

Top mass

m_t = 172.52 ± 0.14 (stat) ± 0.30 (syst) GeV

ATLAS+CMS:

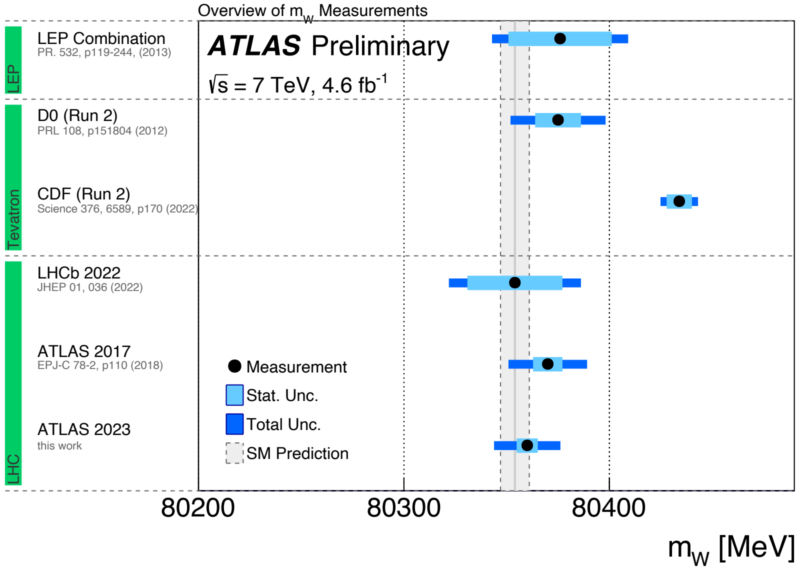
ATLAS-CONF-2023-066 / CMS-PAS-TOP-22-001/



W boson mass

ATLAS: ATLAS-CONF-2023-004

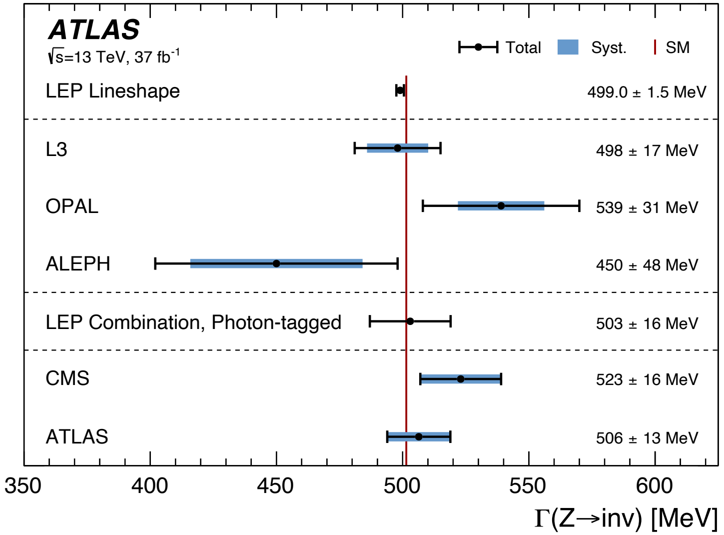
LHCb: JHEP 01 (2022) 036



Z boson invisible width

CMS: Phys. Lett. B 842 (2023) 137563

ATLAS: CERN-EP-2023-232



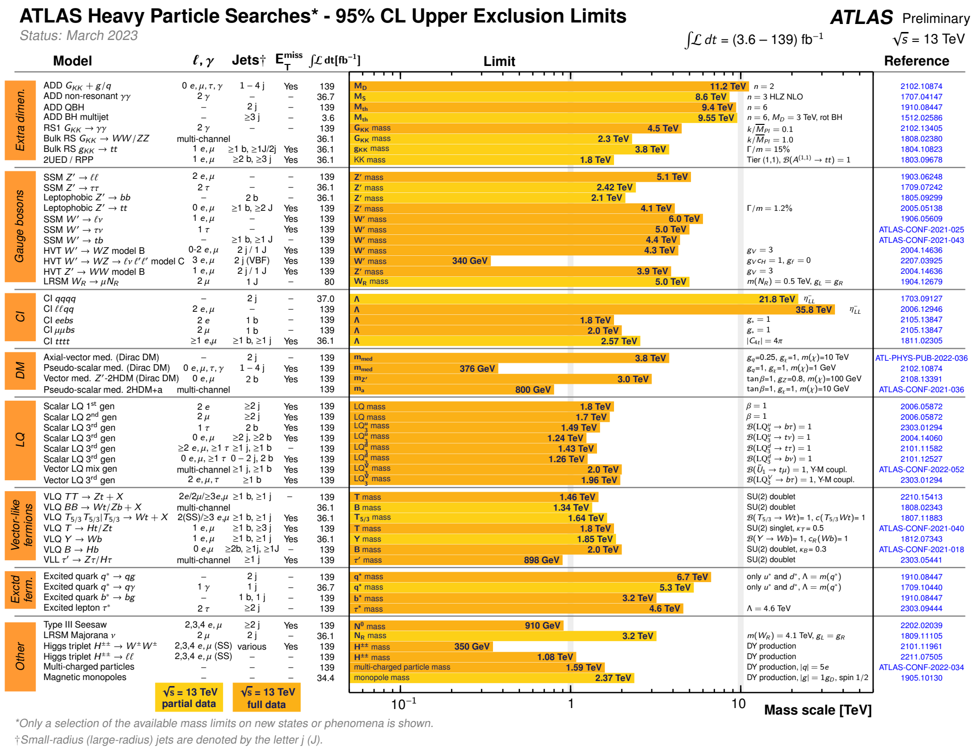
To name a few!

Direct Searches for New Physics

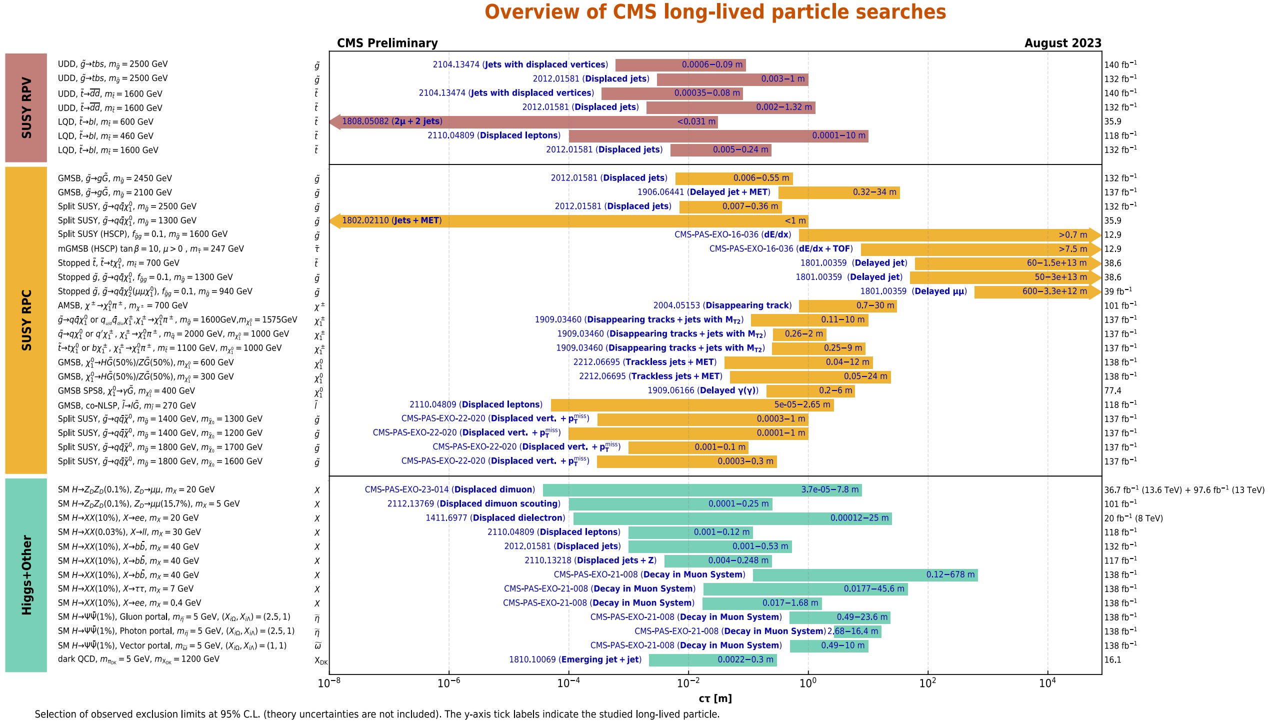
Getting creative with unconventional signatures

Searches for BSM Physics

Incredible range of models, masses and lifetimes studied to date.



ATL-PHYS-PUB-2023-008



CMS EXO Summary plots

Dark Showers

Searches for a QCD-like Dark Sector:

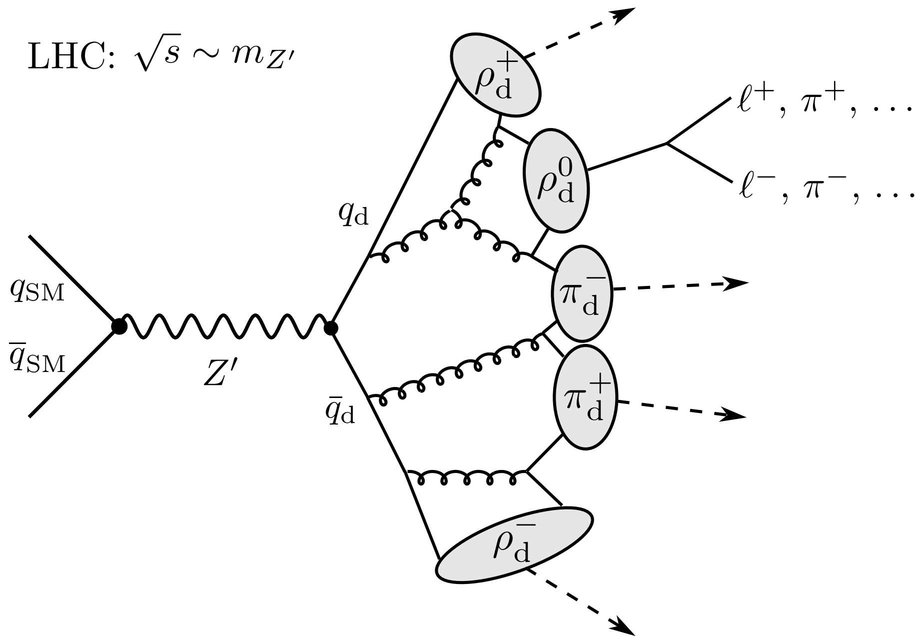


Image: arxiv:2203.08824

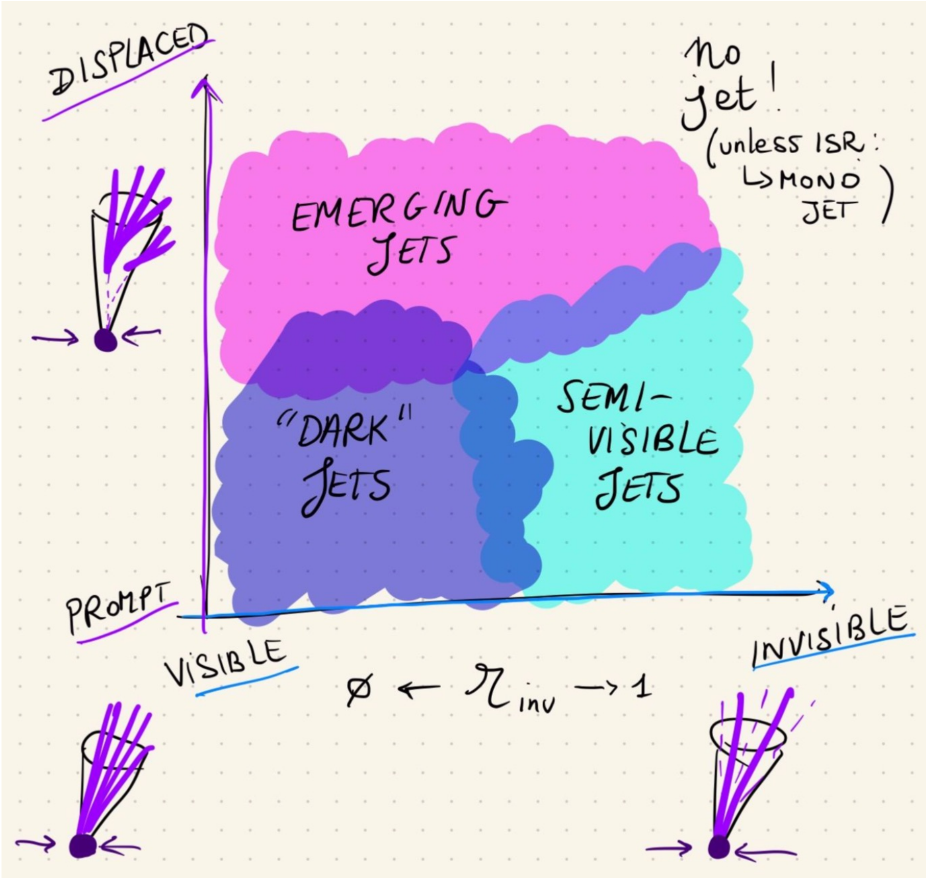
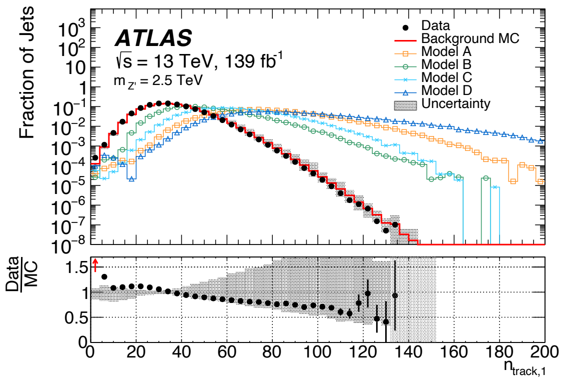


Image C. Doglioni

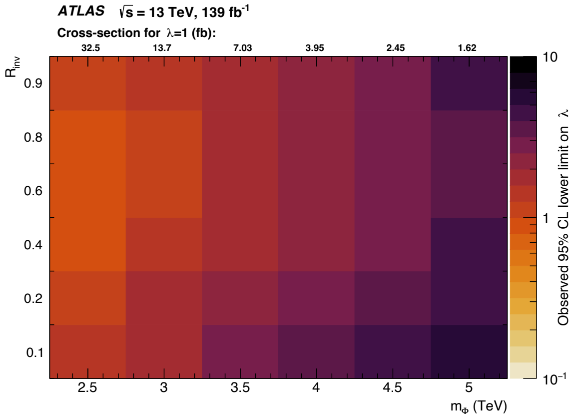
Dark Showers

Large number of new results out in the past year alone

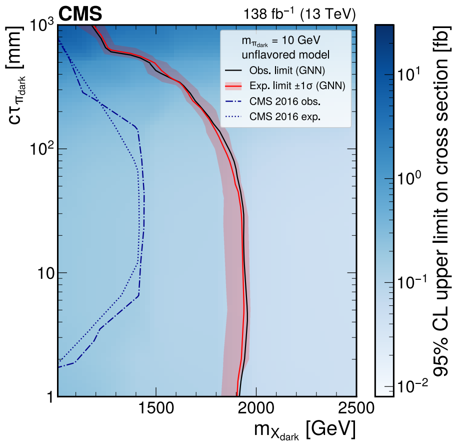
ATLAS Dark Jets (2023): [arXiv:2311.03944]



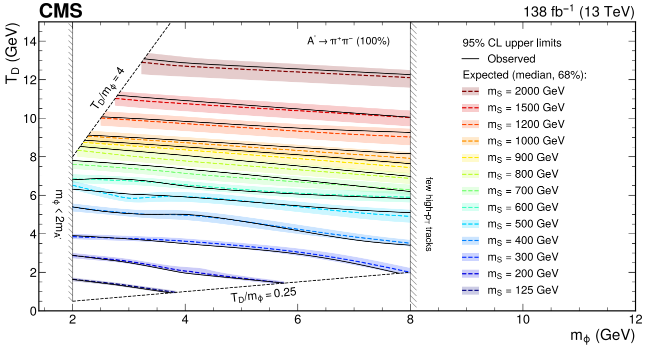
ATLAS Semi-visible jets (2024): [Phys. Lett. B 848 (2024) 138324]



CMS Emerging Jets (2024): [arXiv:2403.01556]



CMS SUEPs (2024): [arXiv:2403.05311]



Dedicated triggers for Run 3 promise of more to come!

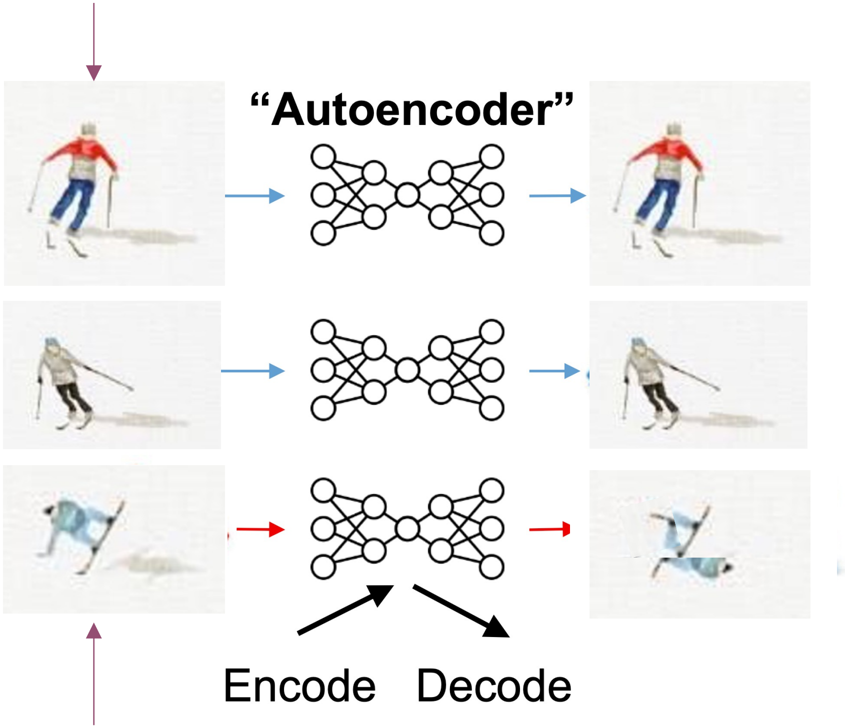
Anomaly Detection Searches with Unsupervised & Weakly Supervised Machine Learning

Doing analysis in an entirely new fashion

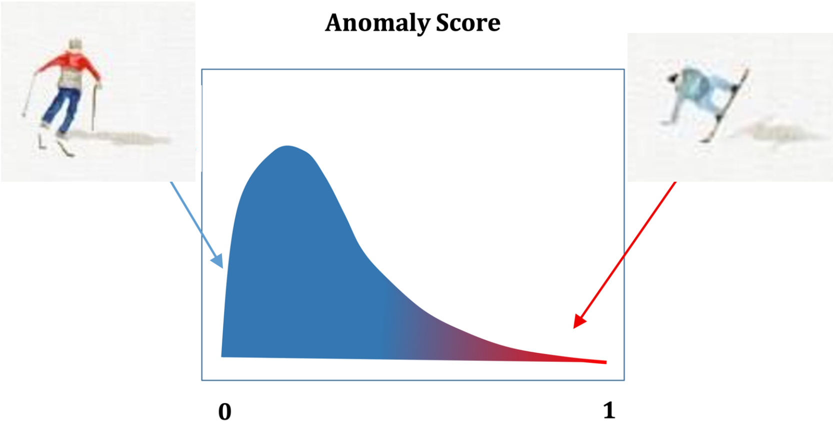
Anomaly Detection with with Unsupervised Machine Learning

Mostly SM training data

Common SM skier



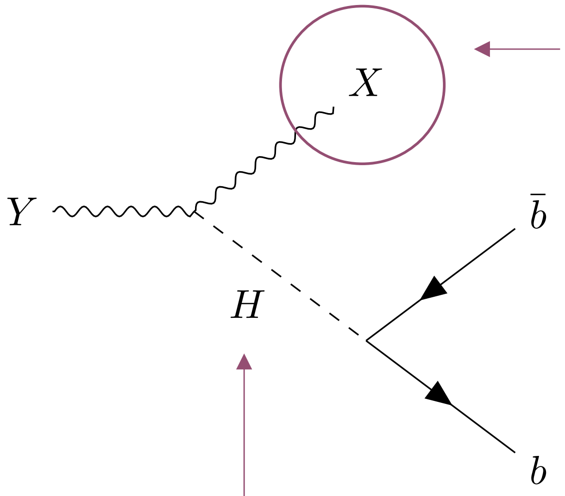
Rare BSM snowboarder



Images adapted from: A. Kahn & J. Aliga

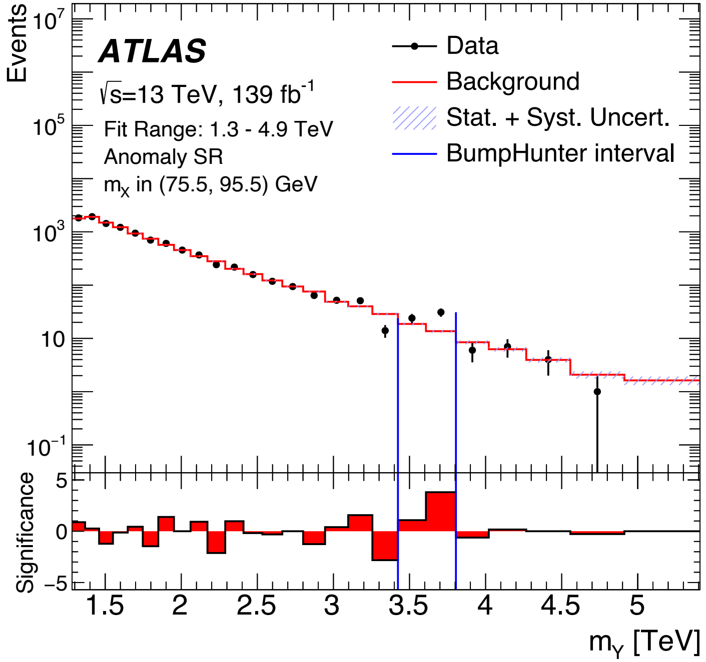
Anomaly Detection

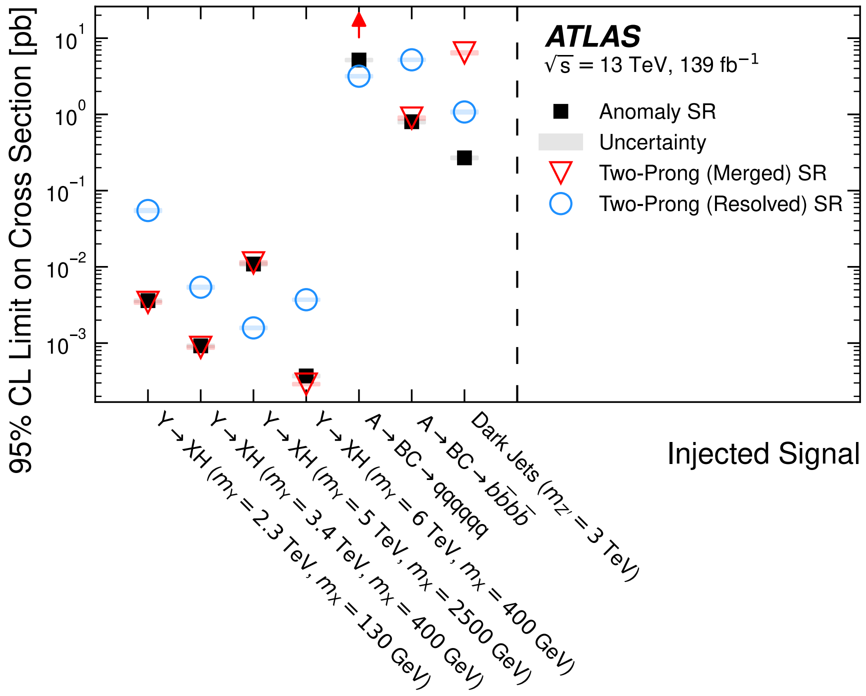
ATLAS: Phys. Rev. D 108 (2023) 052009



X selected based on anomaly score from VRNN, or two-pronged MVA scores

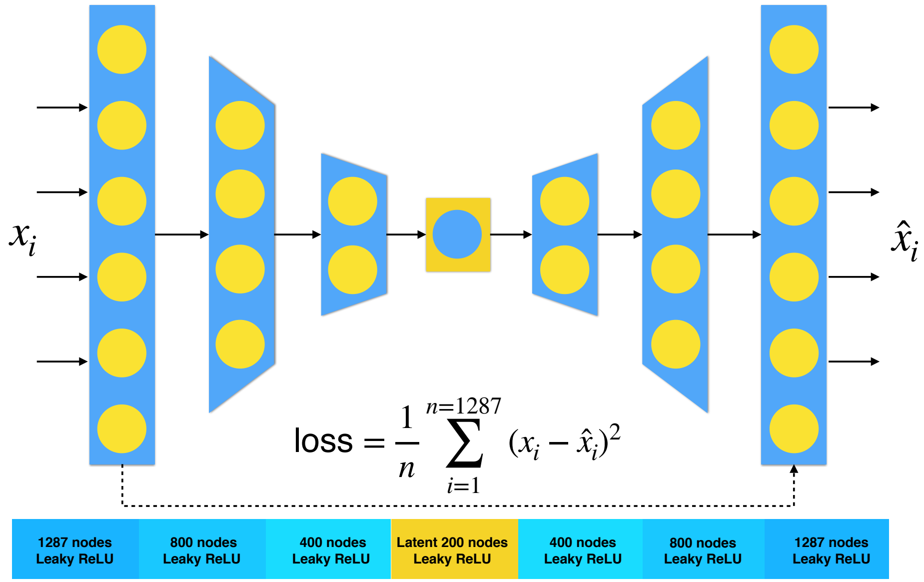
Higgs selected based on boosted H_{bb} tagger score

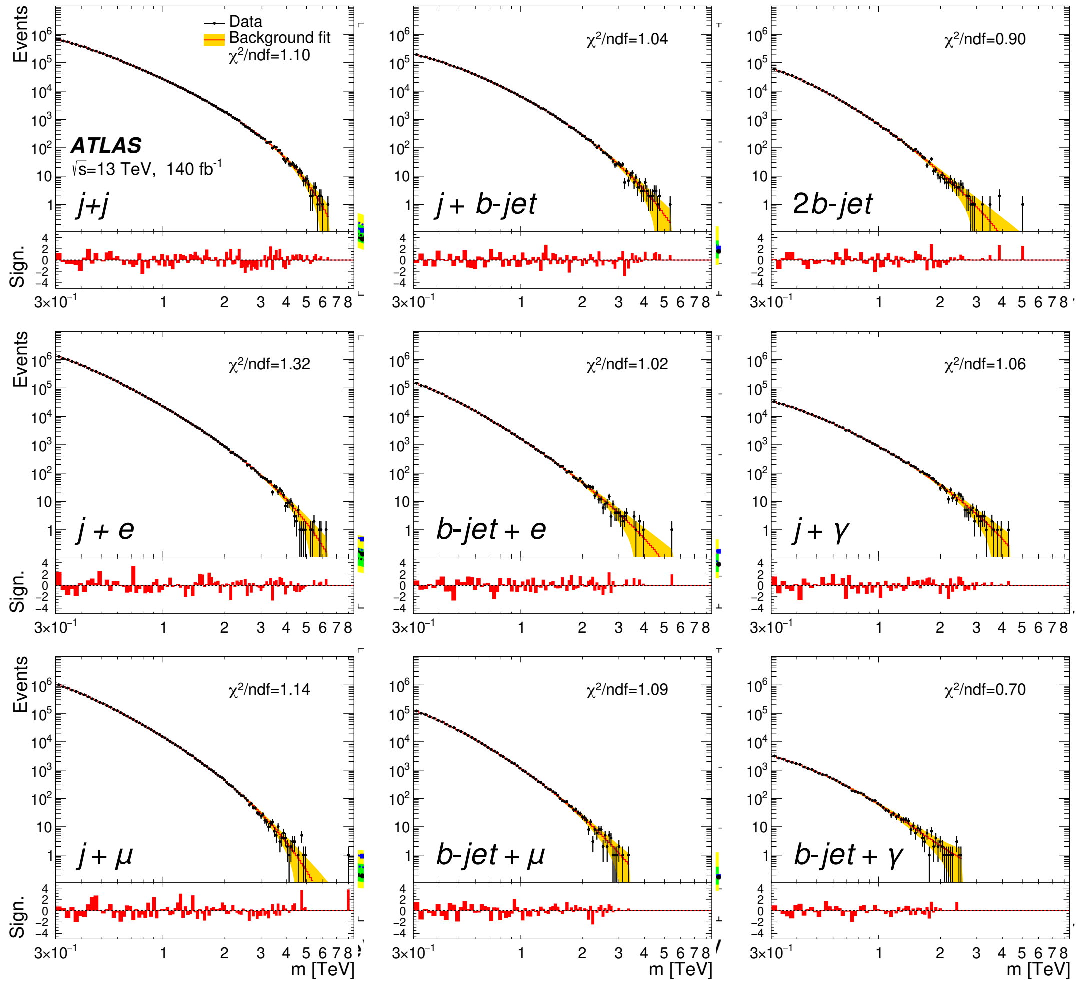




Anomaly Detection

ATLAS: [Phys. Rev. Lett. 132 (2024) 081801]

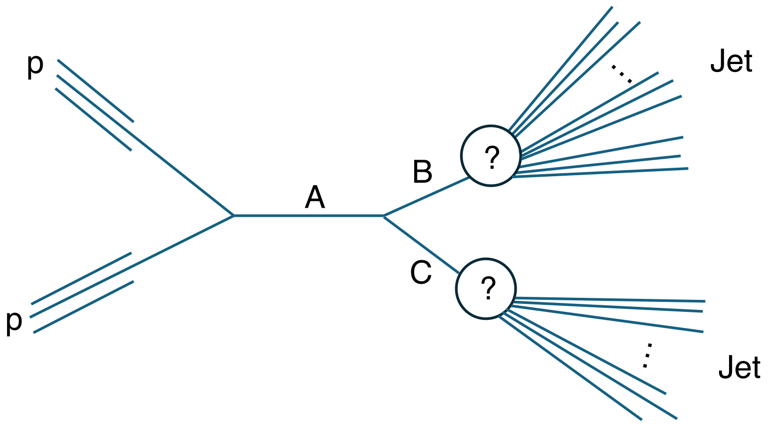


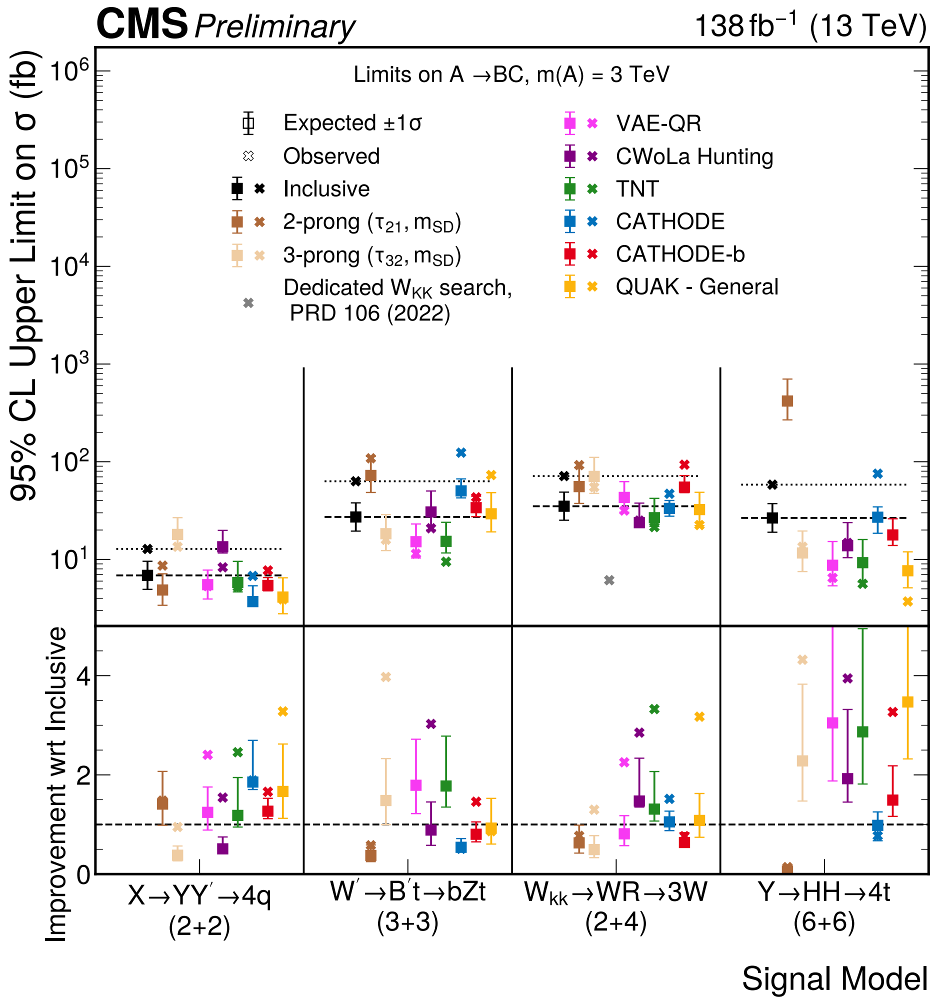


- Lepton triggered events
- Rapidity mass matrix used as input to autoencoder
- Highest local significances of 2.8σ and 2.9σ found for $m_{j\mu}$ = 1.2 and 4.8 TeV

Anomaly Detection

CMS: CMS-PAS-EXO-23-026





- Unsupervised (VAE-QR)
- Weakly supervised (CWoLa Hunting, TNT, CATHODE)
- Semi-supervised - multi-signal priors (QUAK)

- Anomaly detection improves sensitivity of standard methods up to ~3-7x

Summary

- Today's talk covered a very small selection of the incredibly productive LHC program
- Recent LHC results have focused on extracting as much as possible from the Full Run 2 dataset
- We are taking more **meticulous** and **creative** approaches to analyzing our data than ever before
- The technologies we are developing today will allow us to learn more about the SM and new physics in the future

Thank you!

References

Four top production:

- ATLAS: Eur. Phys. J. C 83 (2023)
- CMS: Phys. Lett. B 847 (2023)
- LHCTopWG Summary Plots

R_K:

- LHCb: Nature Physics 18, (2022) 277-282
- LHCb: Phys. Rev. D 108 (2023) 032002
- CMS: https://arxiv.org/abs/2401.07090

Dark Showers:

- ATLAS: arXiv:2311.03944
- ATLAS: Phys. Lett. B 848 (2024) 138324
- CMS: arXiv:2403.01556
- CMS: arXiv:2403.05311

Anomaly detection:

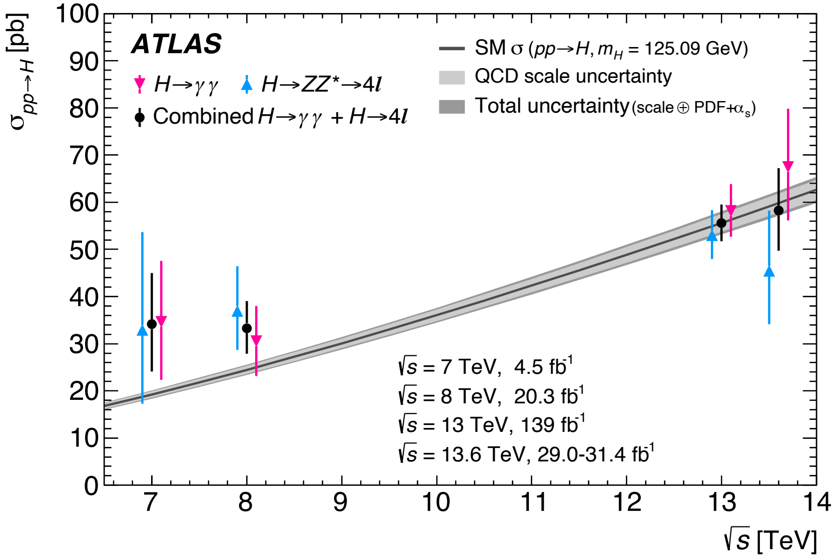
ATLAS: Phys. Rev. Lett. 132 (2024) 081801

ATLAS: Phys. Rev. D 108 (2023) 052009

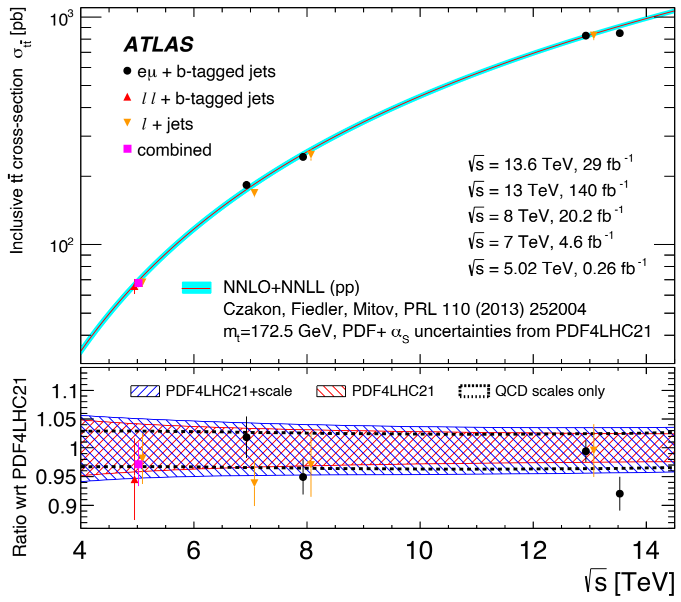
CMS: CMS-PAS-EXO-23-026

Some Early Run 3 Results:

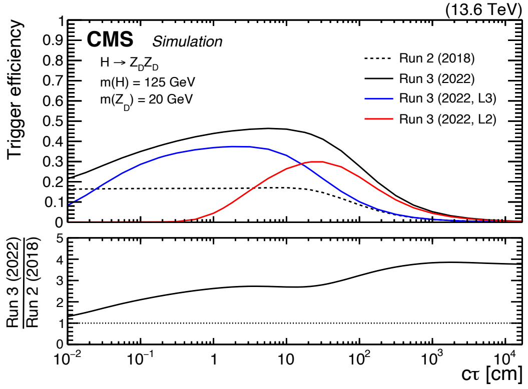
H→γγ and H→ZZ∗→4l cross-sections
ATLAS: Eur. Phys. J. C 84 (2024) 78

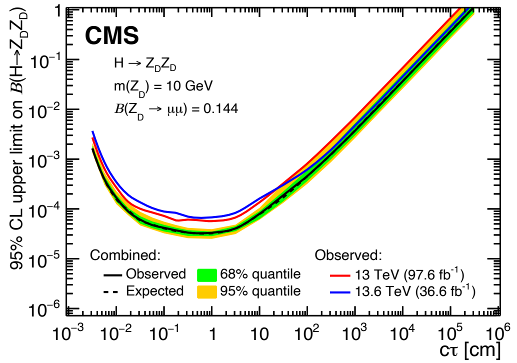


tt cross-section measurement
ATLAS: Phys. Let. B 848 (2024) 138376



CMS Displaced Muons:
CERN-EP-2024-025





Rate of Submitted Papers

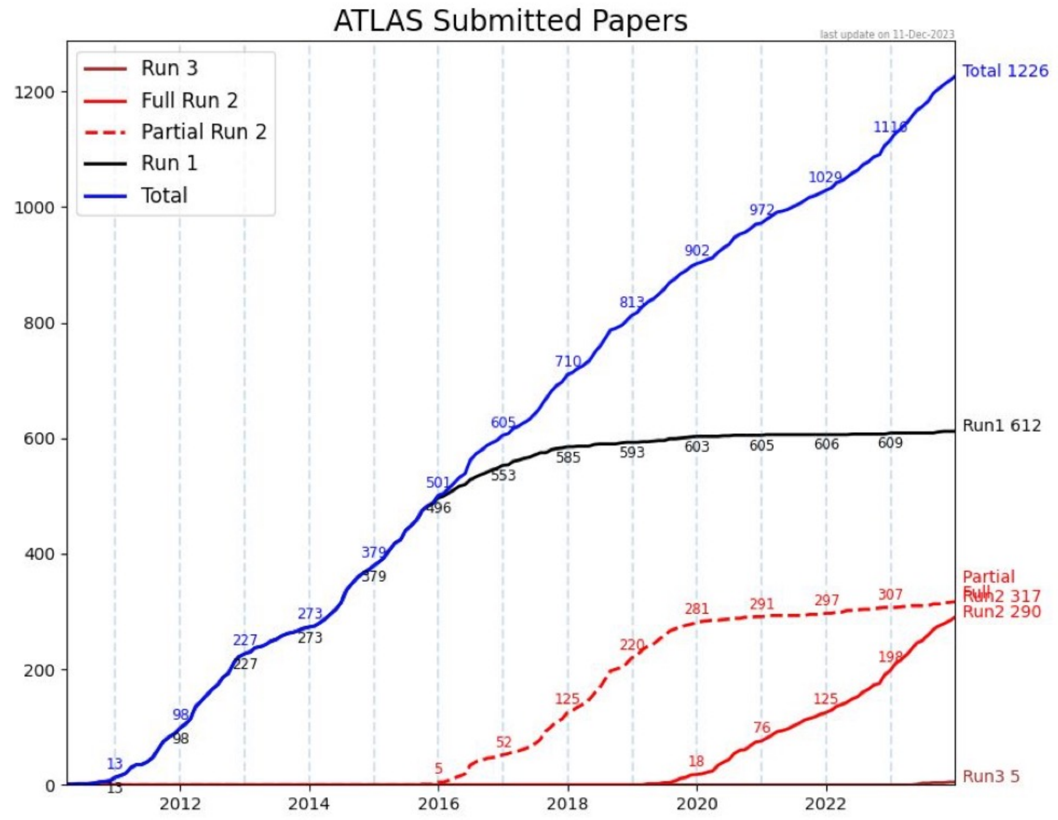
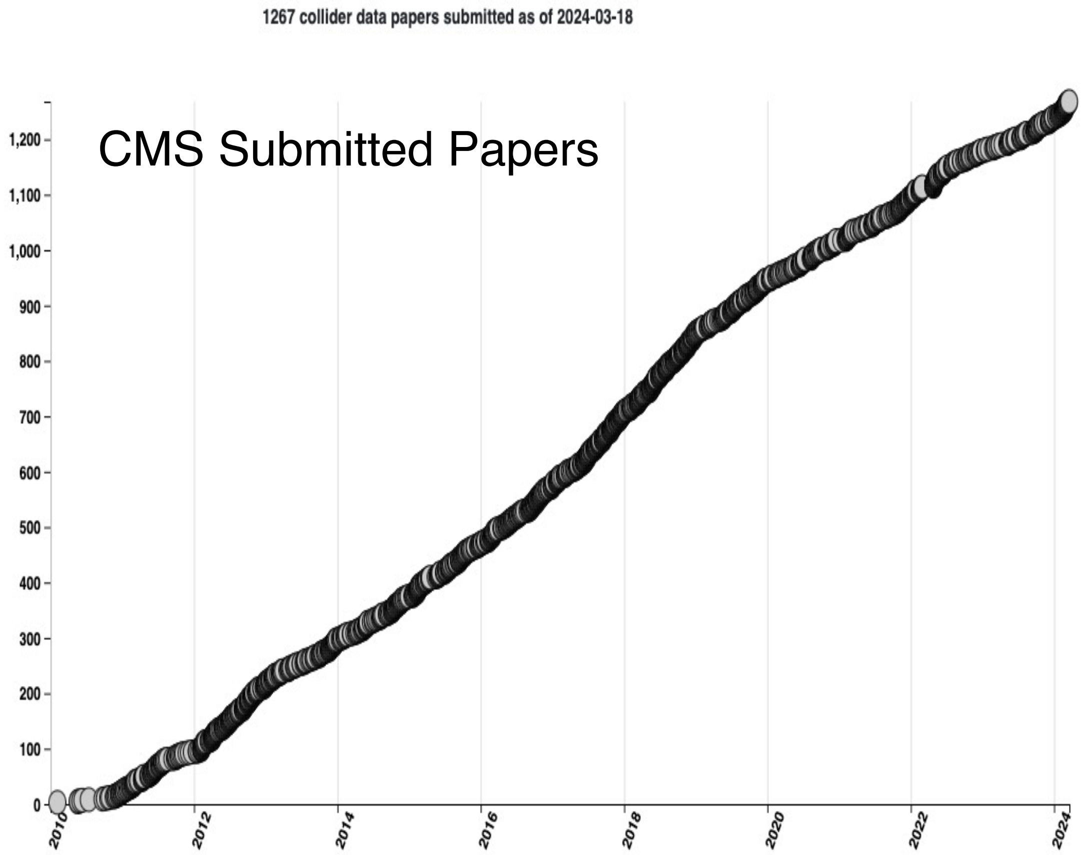
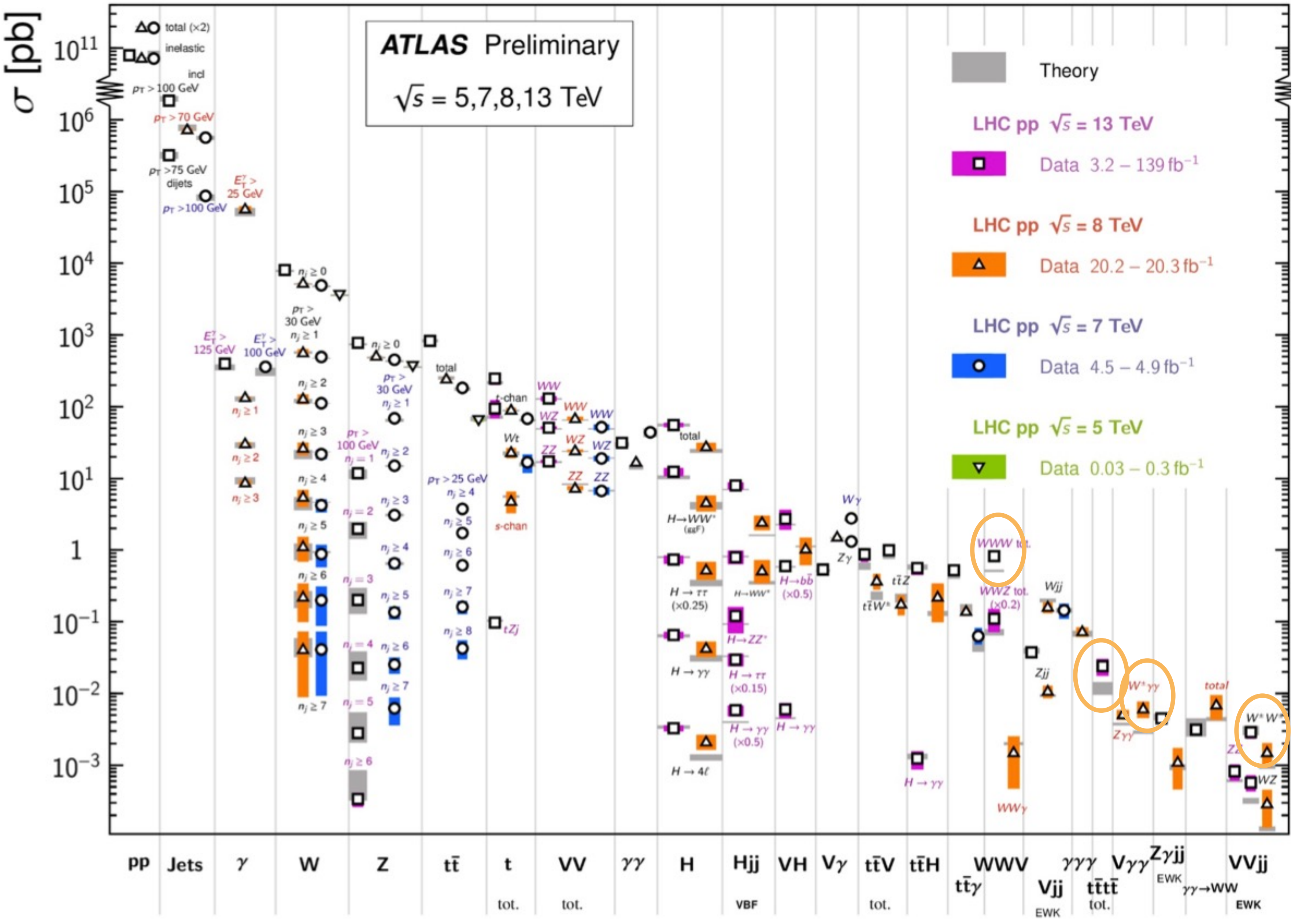


Image: J. Allison



https://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

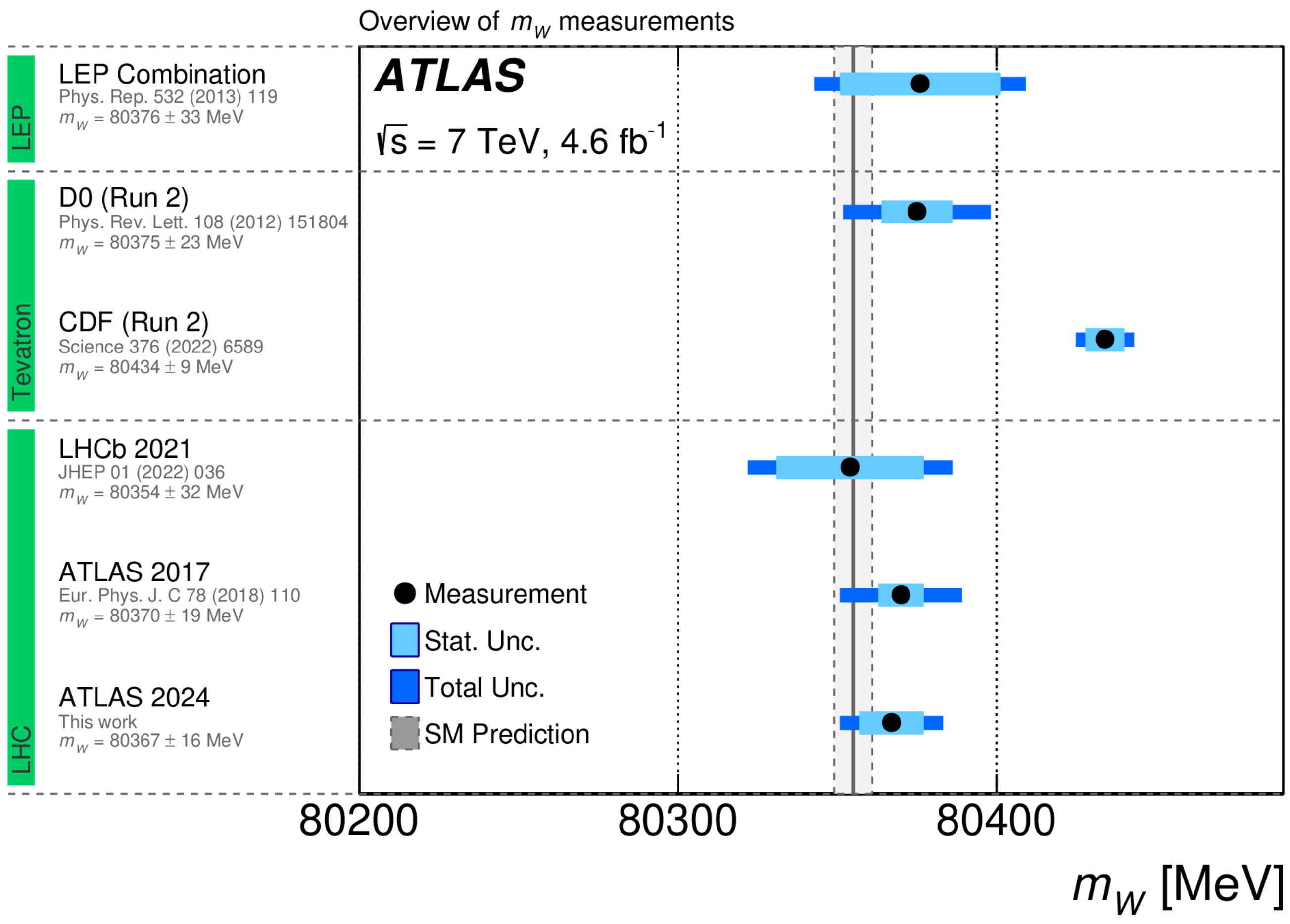
SM Cross Section Measurements



W-mass Measurement

Newest measurement:

m_W = 80360 ± 5(stat.) ± 15(syst.) MeV
(consistent with the SM)



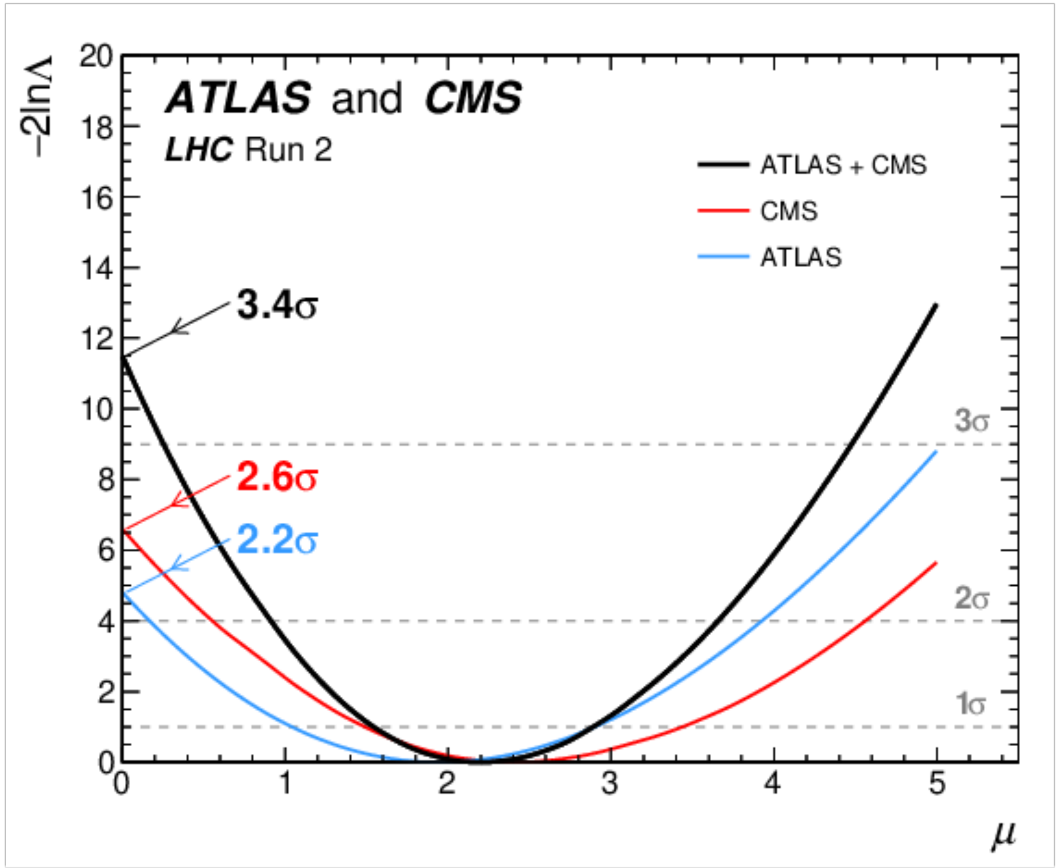
Higgs to $Z\gamma$ ATLAS+CMS Combination

First evidence of this decay process!

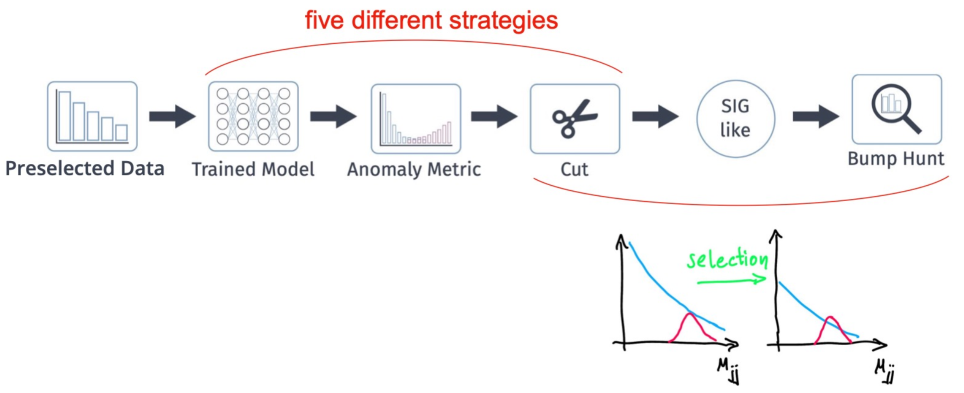
μ_{sig} = 2.2 ± 0.6(stat.)$^{+0.3}_{-0.2}$ (syst.) **3.4** σ
SM compatibility: 1.9 σ

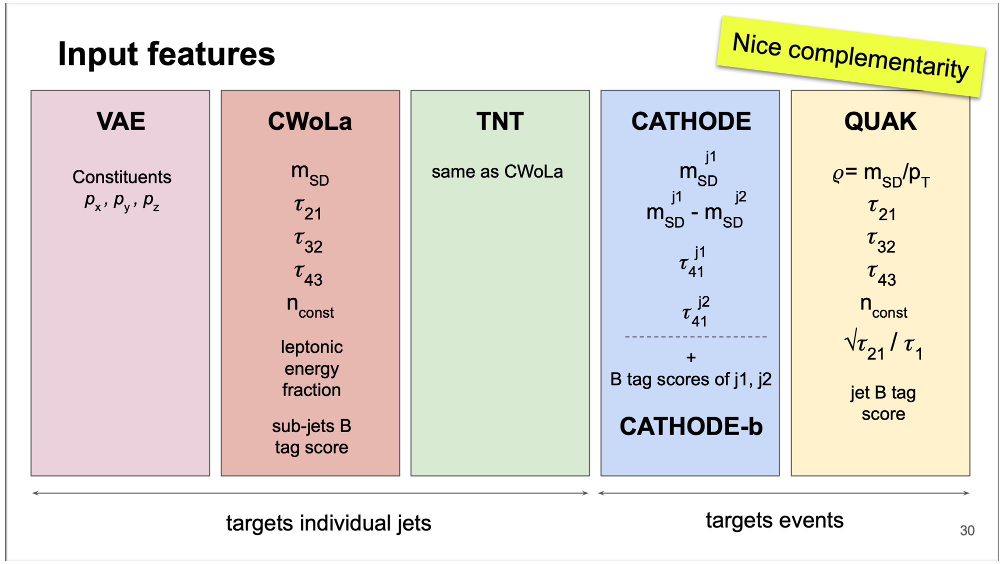
Uncertainty dominated by statistics.

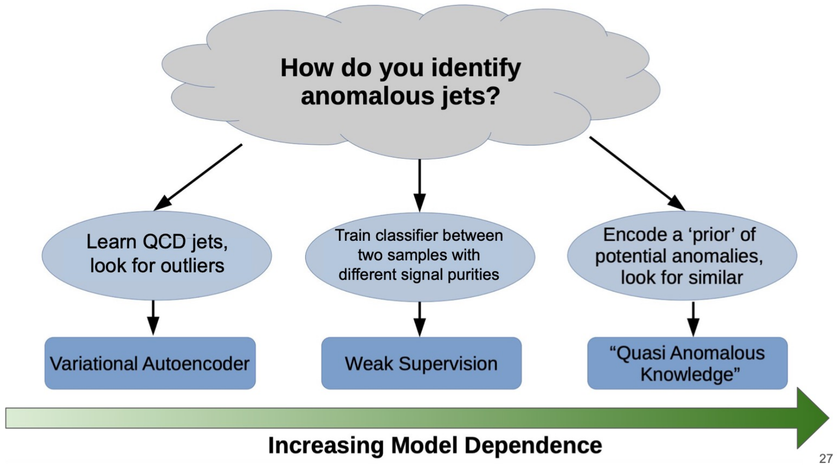
Strong contender for Run 3 observation



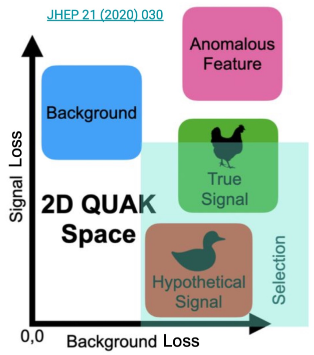
Analysis Strategy







Quasi Anomalous Knowledge (QUAK)



- **Hybrid** approach between model-independent and standard search
- Idea: **encode prior knowledge** of how a signal could look
- Train density estimator (normalizing flow) on colorful mix of simulated signals
- Train additional normalizing flow on background **simulation**
- Construct 2D space, select events with high background loss and low signal loss

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Slides: Benedikt Maier
CERN Data Science Seminar: https://indico.cern.ch/event/1392054/