ATLAS EXPERIMENT + CMS Compact Muon Solenoid

Physics Highlights

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on behalf of the ATLAS and CMS Collaborations

MEPhI

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ICPPA

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Discovery ⇒ Precision ⇒ Discovery

- Hadron colliders: "discovery machines"
- Electron-positron colliders: "precision machines"

However recent developments in computing and technology allow the experiments at the LHC compete with the precision of electron-positron colliders.

Among the recent developments:

- Wide use of Machine Learning (ML) techniques:
  - Event selection
  - Tagging
  - Jet substructure
  - Discrimination
  - Anomaly detection
  - Event simulation
- Search for new event signatures
- Techniques allowing to process and store more data

Nobel physics prize 2024 won by Artificial Intelligence (AI) pioneers

John J. Hopfield and Geoffrey E. Hinton

“for foundational discoveries and inventions that enable machine learning with artificial neural networks”

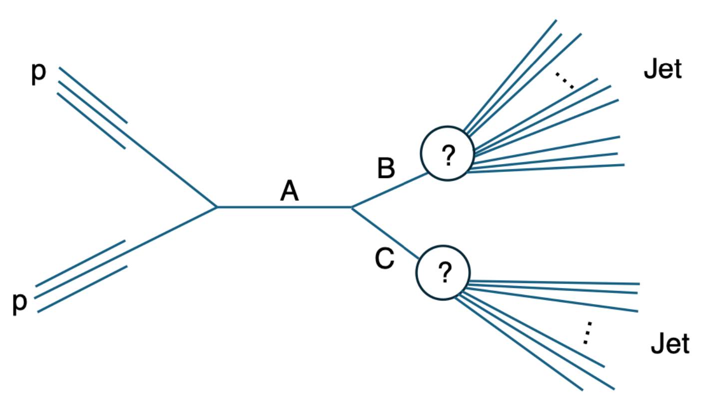
Can ML find particles on its own?

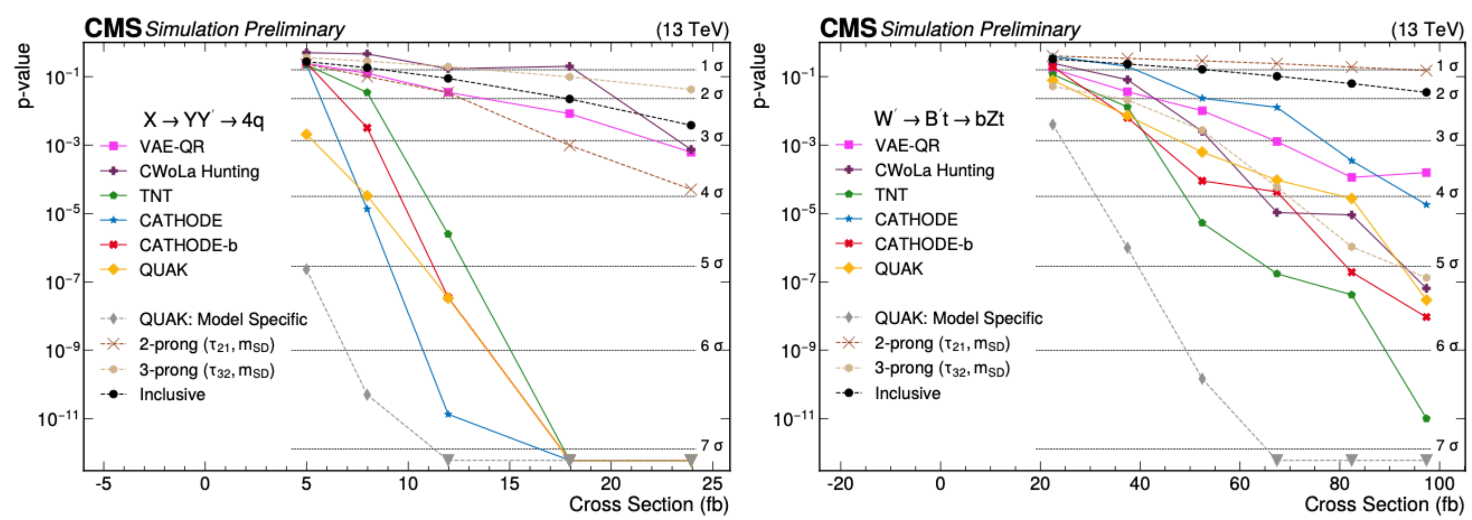
13 TeV: CMS [CMS-PAS-EXO-22-026]

Usually analyses look for one specific type of new particle or event signature at a time

What if we aren't seeing new particles because we haven't thought of the right ones to look for?

[CMS-PAS-EXO-22-026] employed what is known in ML as Anomaly Detection



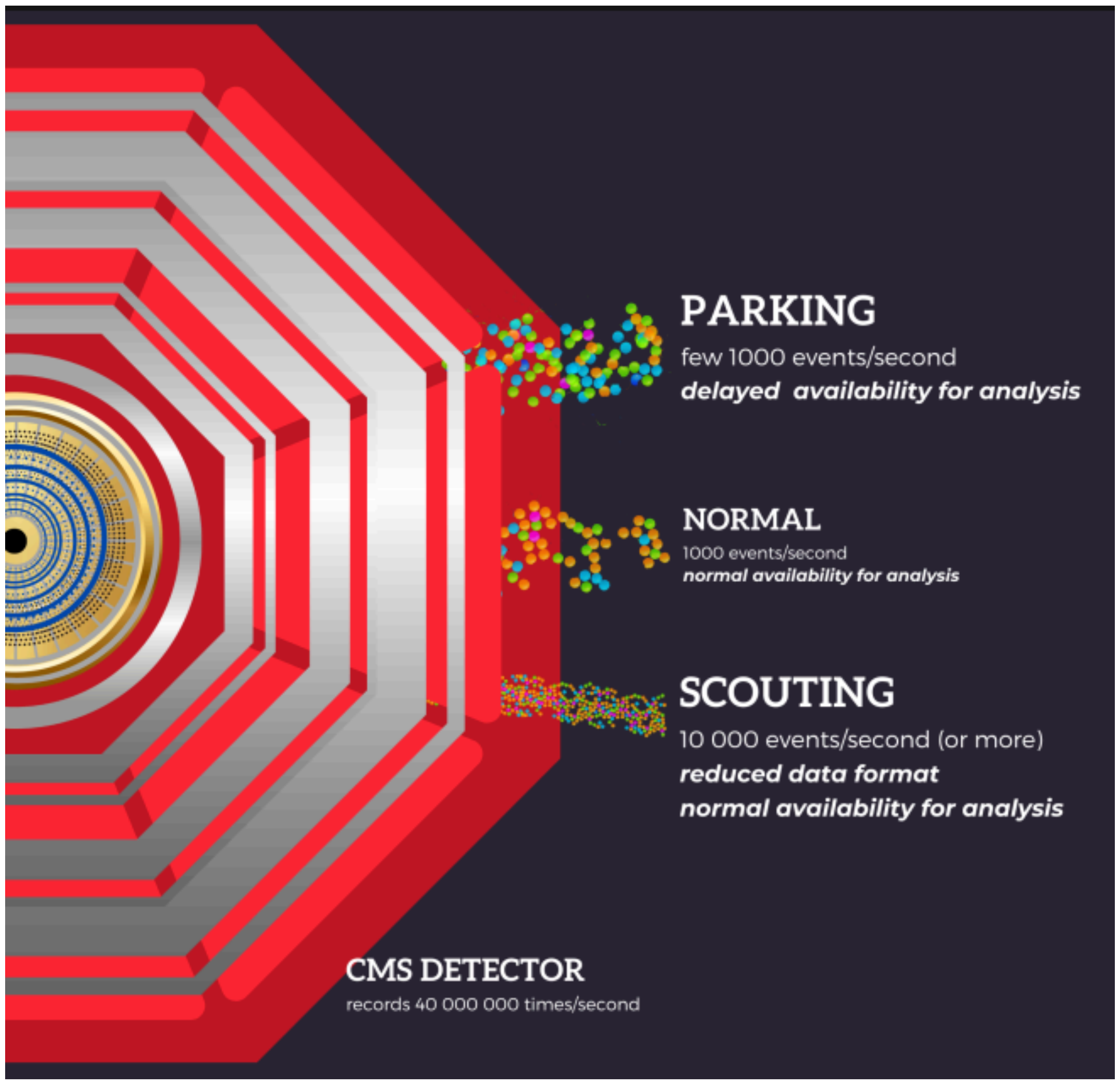


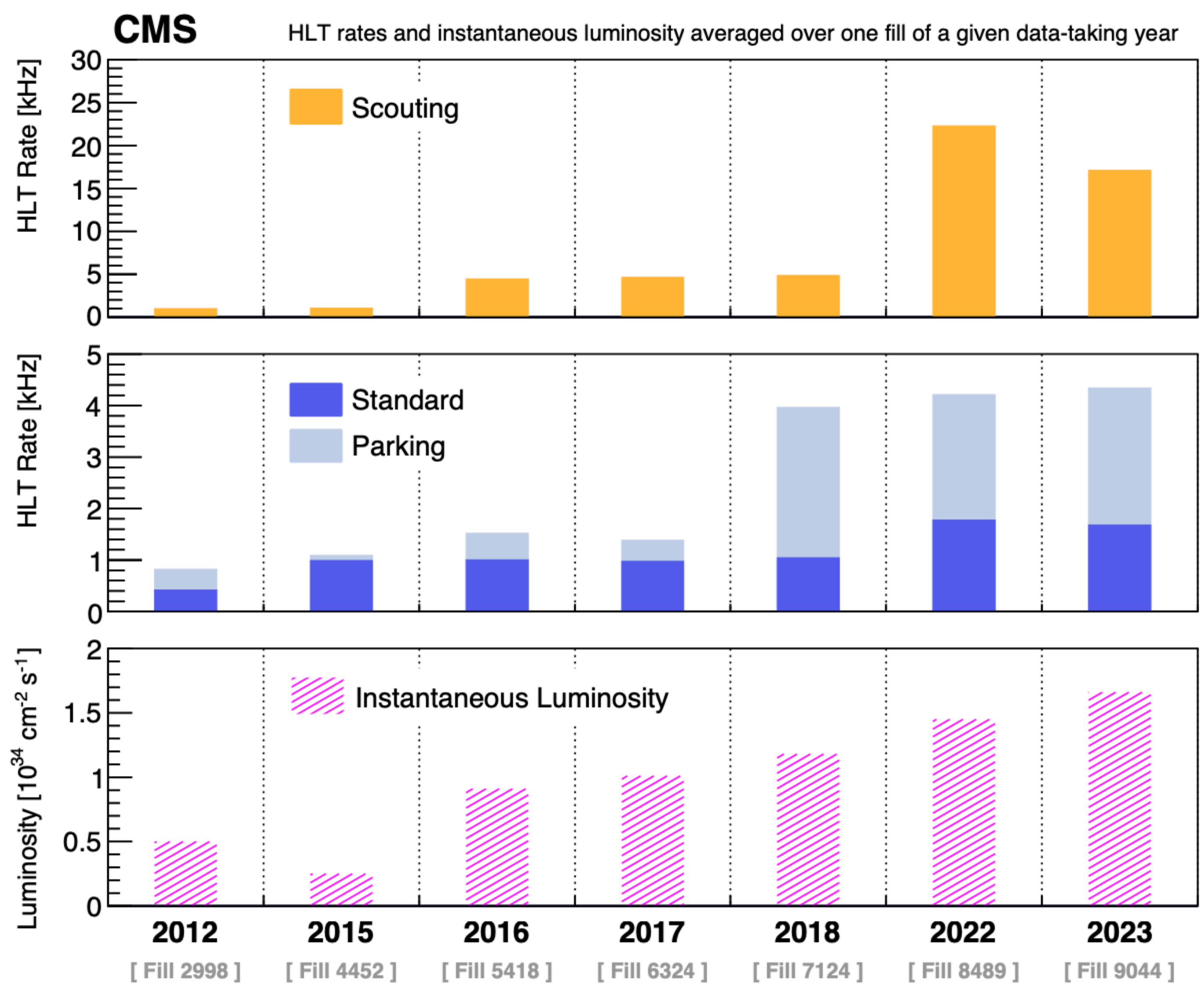
No signals of new resonances found at the moment

But
Anomaly Detection methods showed improved discovery sensitivity to a broad range of possible signals, although it is less sensitive than dedicated model-specific search

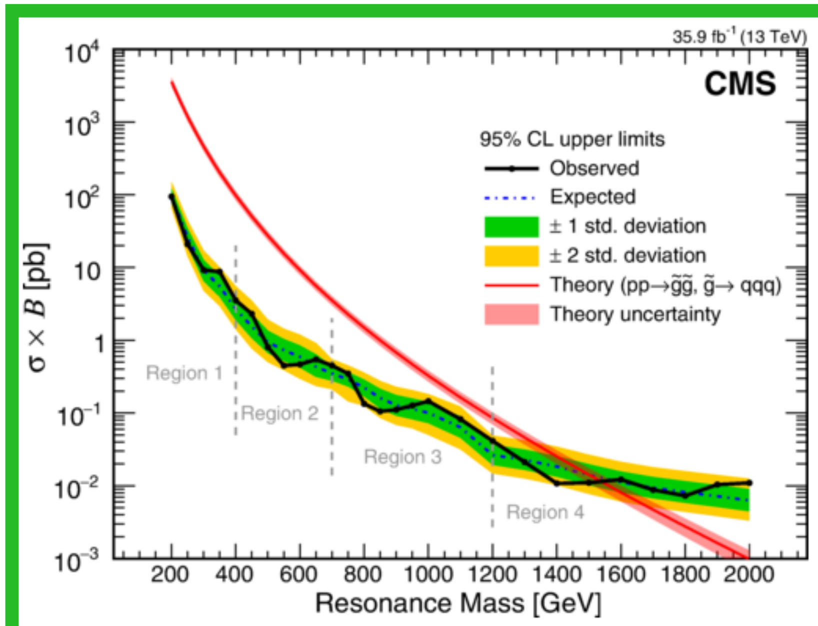
Data: Parking/Delayed stream and Scouting (1)

CMS [arXiv:2403.16134] , [arXiv:2404.02992],[JHEP06(2024)183]





Data: Parking/Delayed stream and Scouting (2)

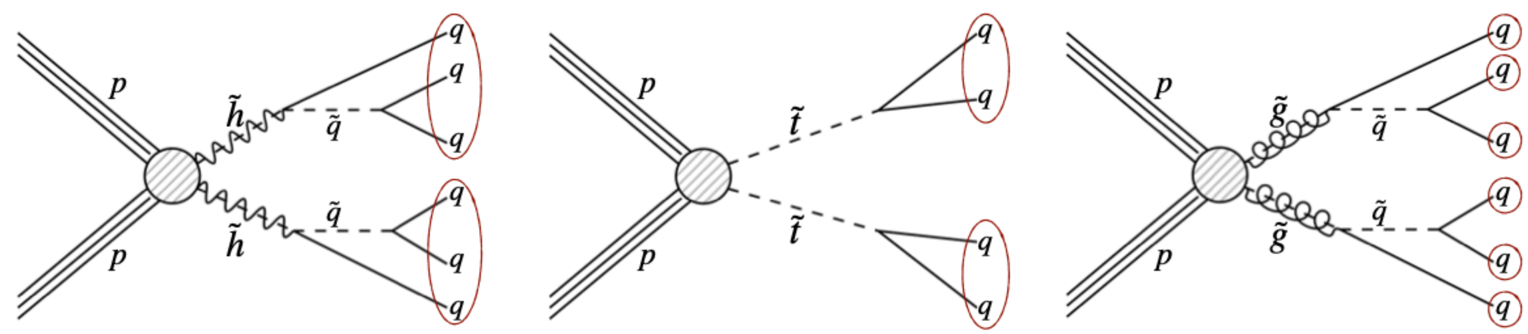


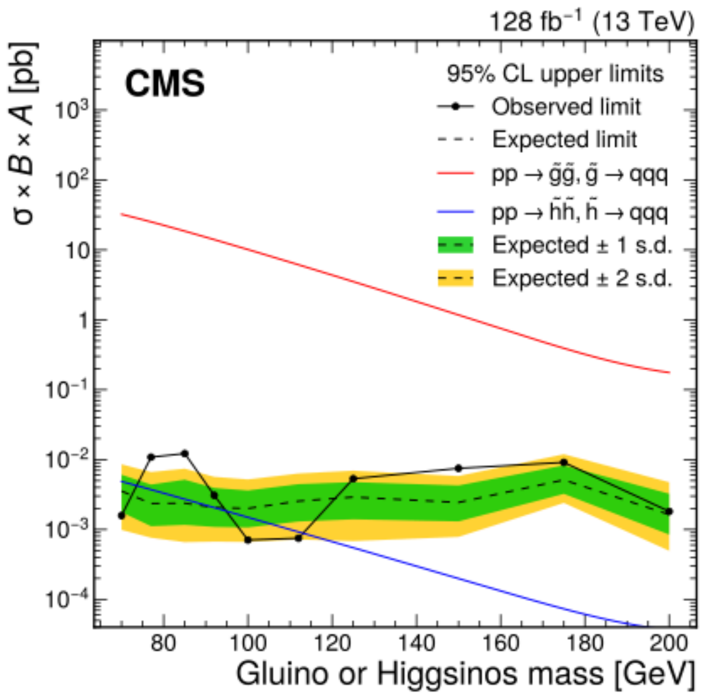
Previous result 13 TeV CMS [PhysRevD.99.012010]

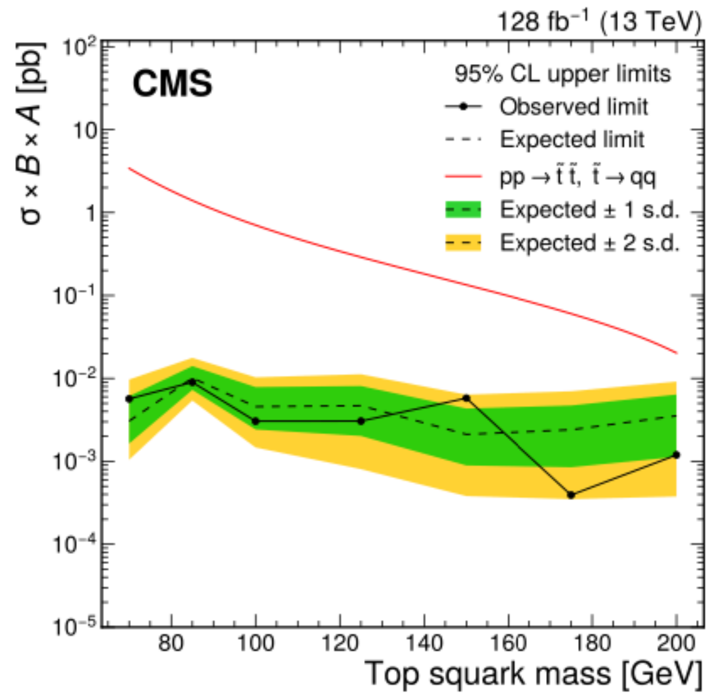
13 TeV: CMS [arXiv:2404.02992]

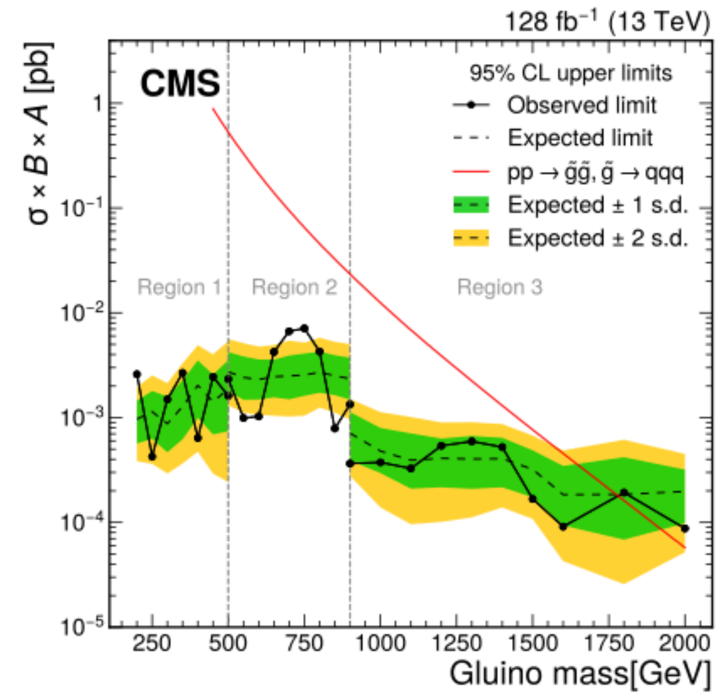
Search for R-parity violating (RPV) supersymmetric (SUSY) particles with Scouting sample.

$$P_R = (-1)^{3B+L+2s}$$



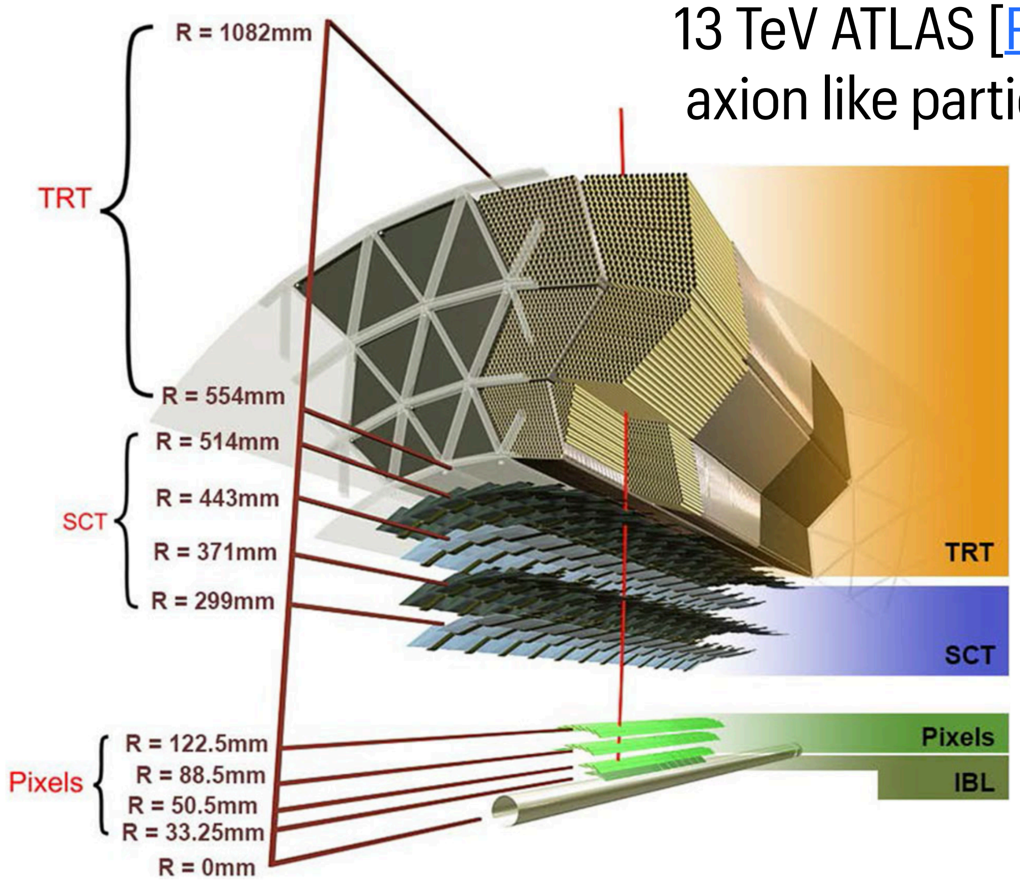




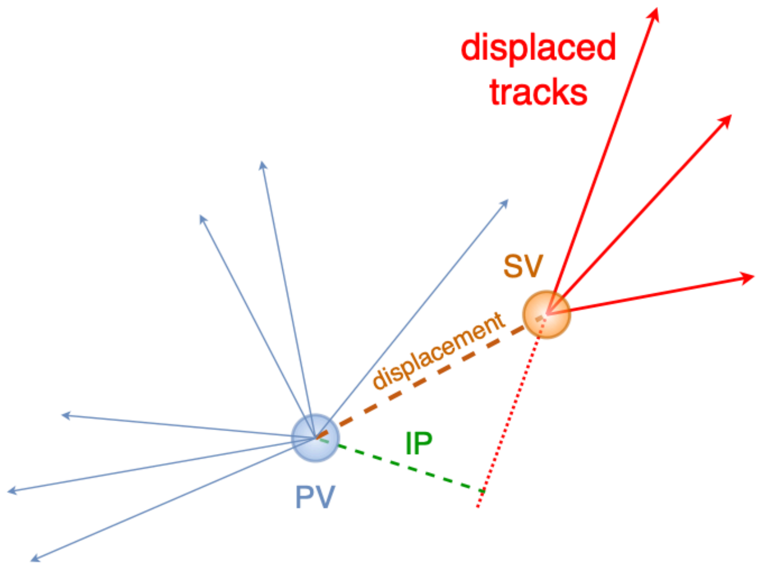


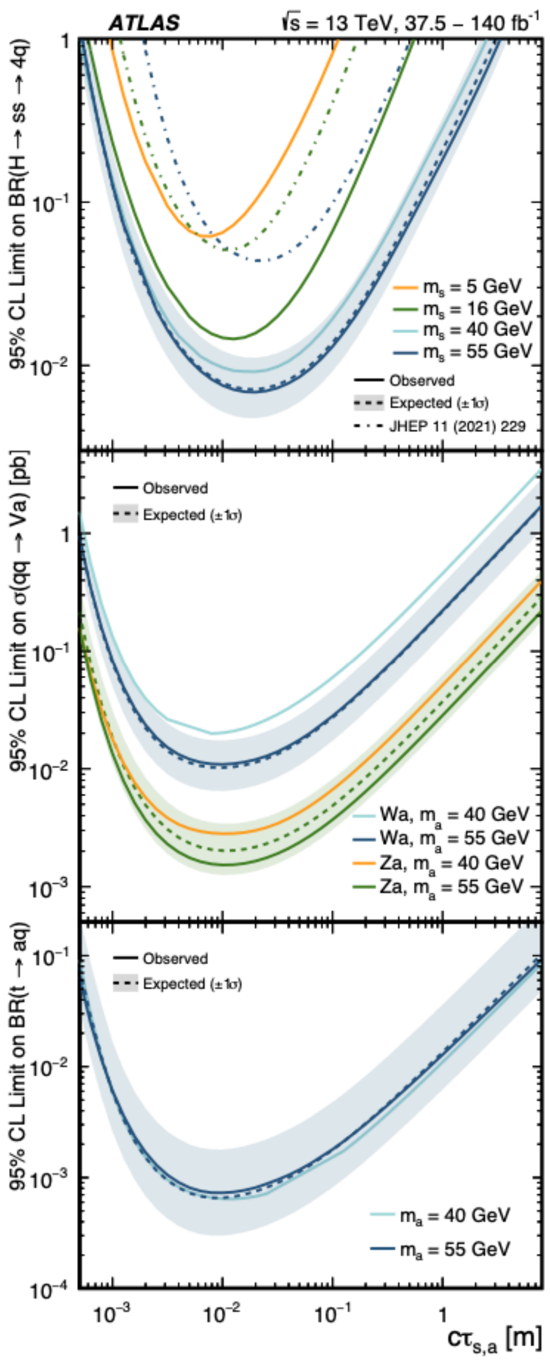
New event signatures: Long-lived particles (LLP) (1)

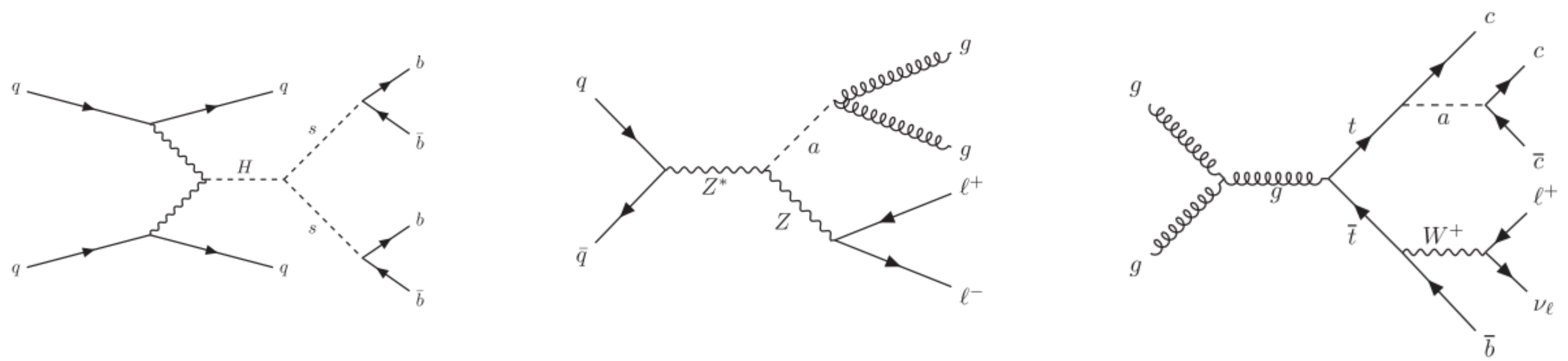
ATLAS [Eur. Phys. J. C 83 (2023) 1081] Large radius tracking (LRT) algorithm for displaced vertices



13 TeV ATLAS [PRL 133 (2024) 161803] search for Higgs "portal" and axion like particles (ALP)

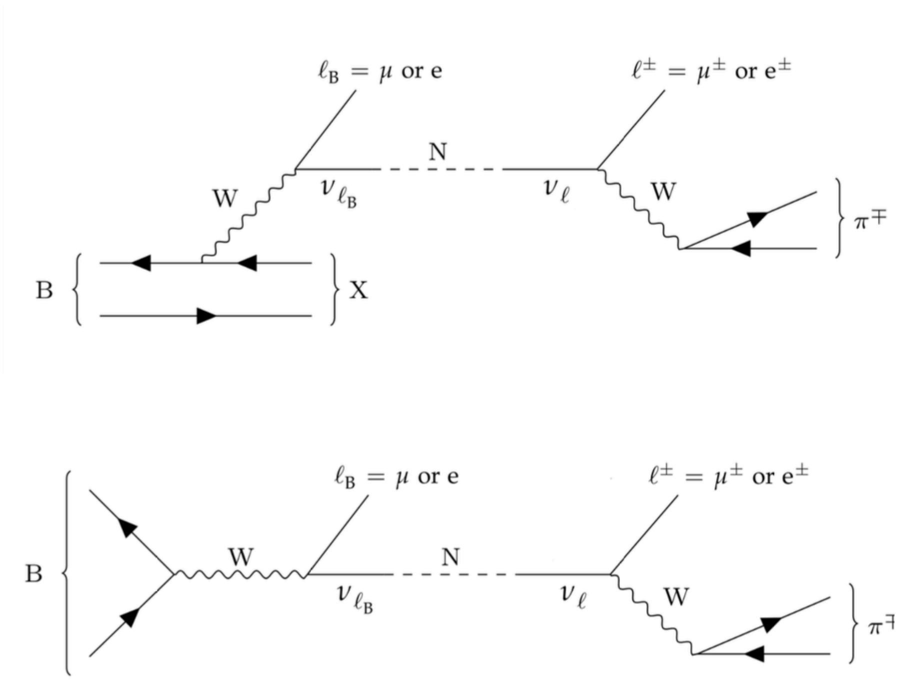


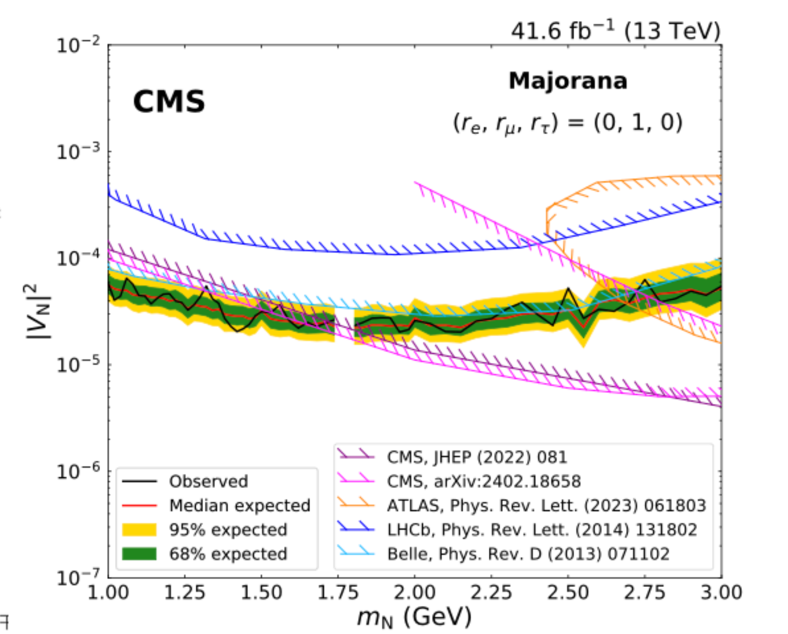


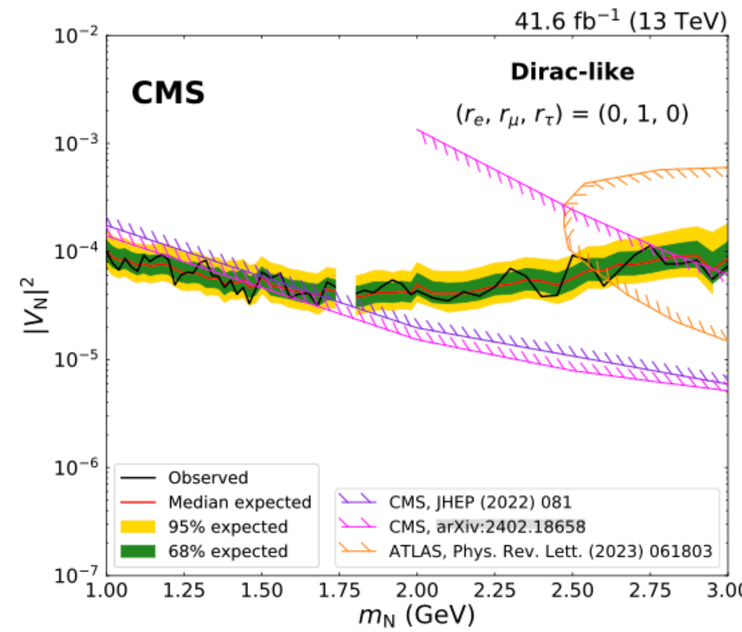


New event signatures: Long-lived particles (LLP) (2)

13 TeV: CMS [JHEP06(2024)183] Search for long-lived heavy neutrinos using B-parking data sample

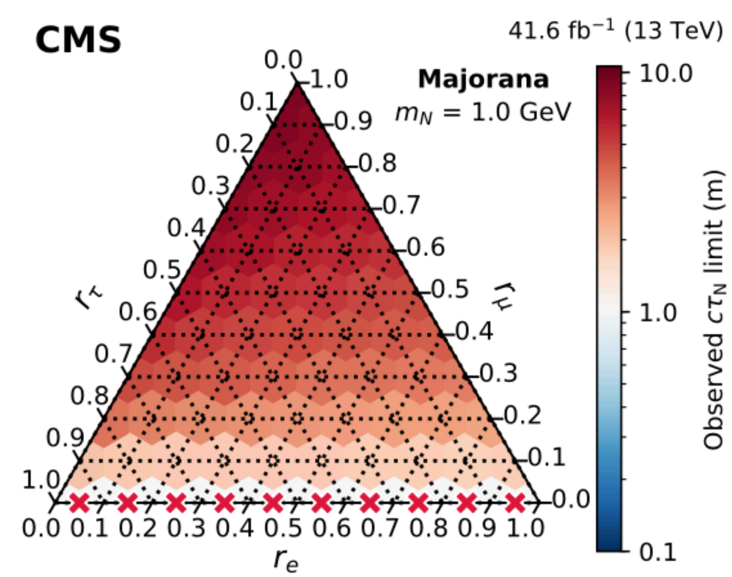


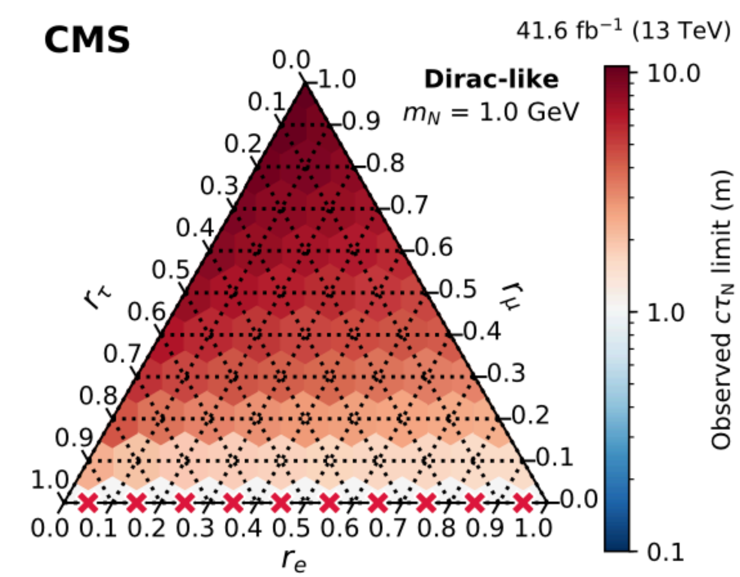




$$|V_N|^2 \equiv |V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$$

$$r_\ell \equiv |V_{\ell N}|^2 / |V_N|^2 \qquad \ell = (e, \mu, \tau)$$



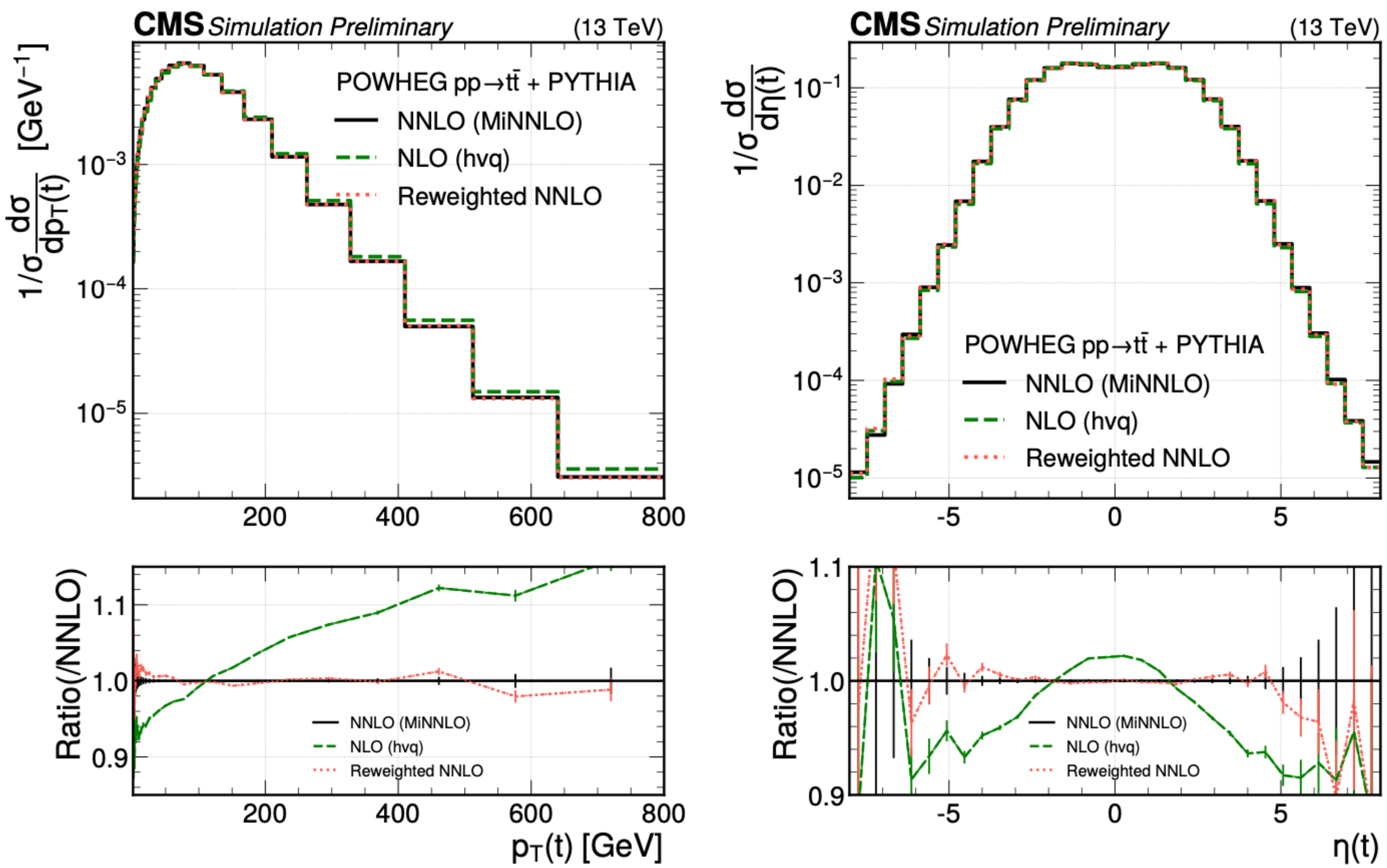


The limits on $|V_N|^2$ for masses $1 < m_N < 1.7$ GeV are the most stringent from a collider experiment to date.

Machine Learning (ML): simulations speed up

CMS [CMS-PAS-MLG-24-001] Deep neural network using classification for tuning and reweighting (DCTR)

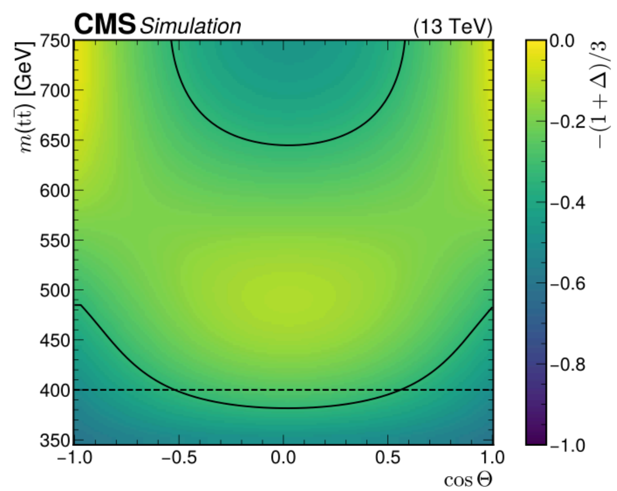
- Current estimates: We need 150 billion simulated events per year after the HL-LHC begins operation in 2029.
- Shortfall between our needs and future resources will be a factor of 4 in CPU and a factor of 7 in disk storage.
- 75% of computing time is Detector Simulation and Reconstruction

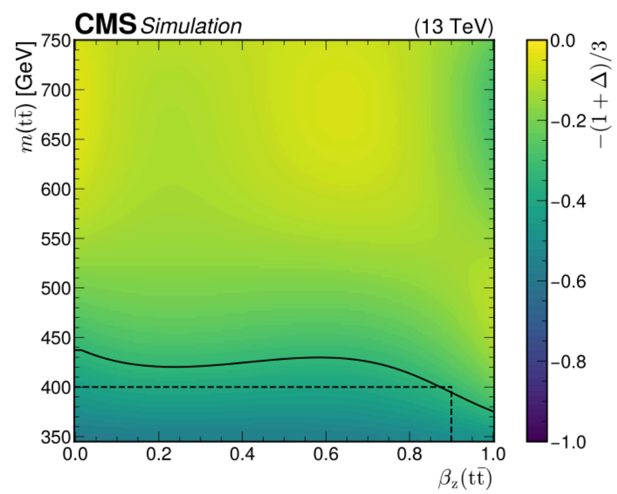


- The approach allow to produce one single simulated sample (with detector simulation and reconstruction)
- Use ML-based reweighting to produce samples with required properties

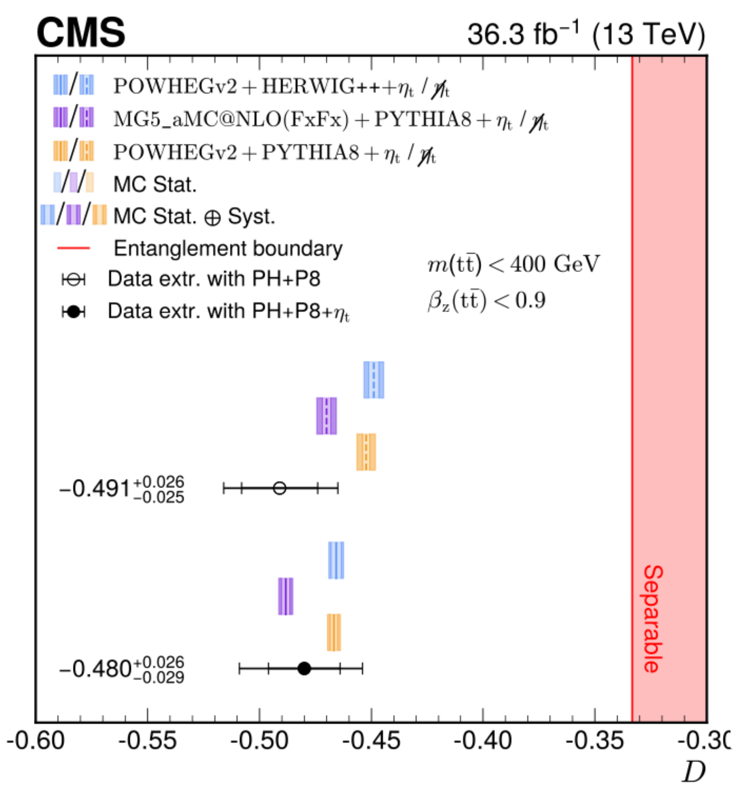
Quantum entanglement of tt

13 TeV: CMS [arXiv:2406.03976] ,[arXiv:2409.11067]; 13 TeV: ATLAS [Nature 633 (2024) 542]



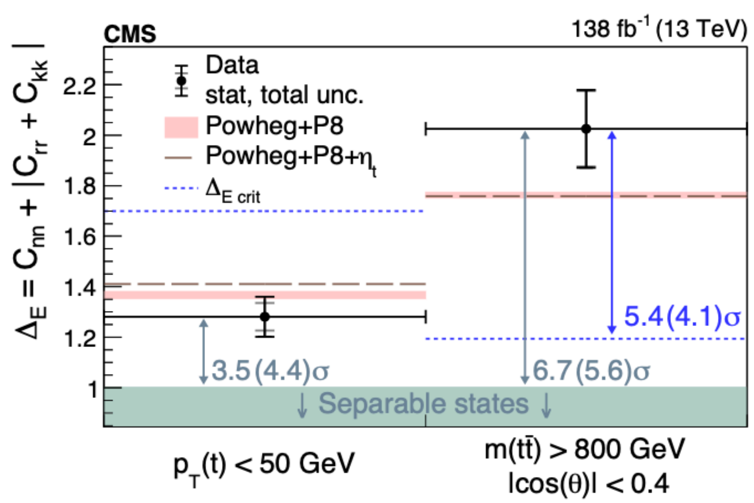


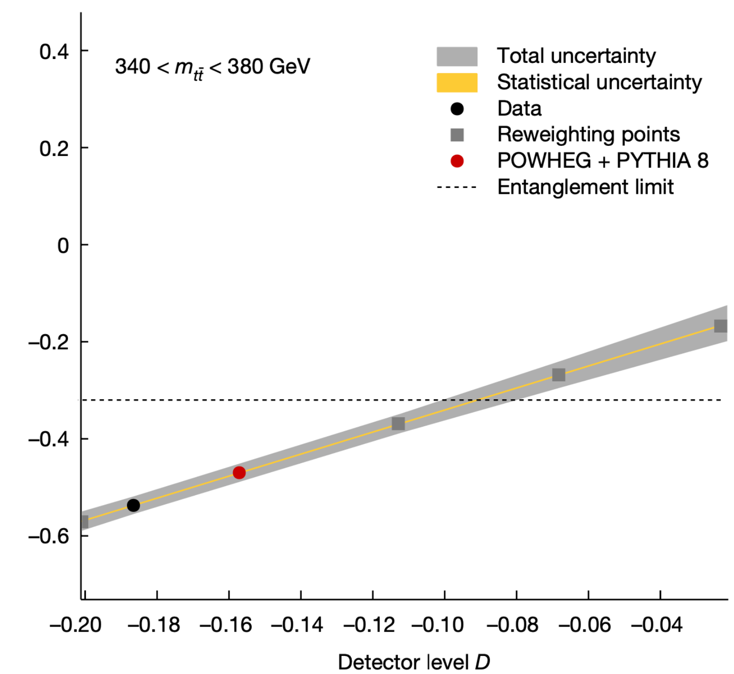
$$345 < m(t\bar{t}) < 400\,\mathrm{GeV} \text{ and } \beta_z(t\bar{t}) < 0.9$$

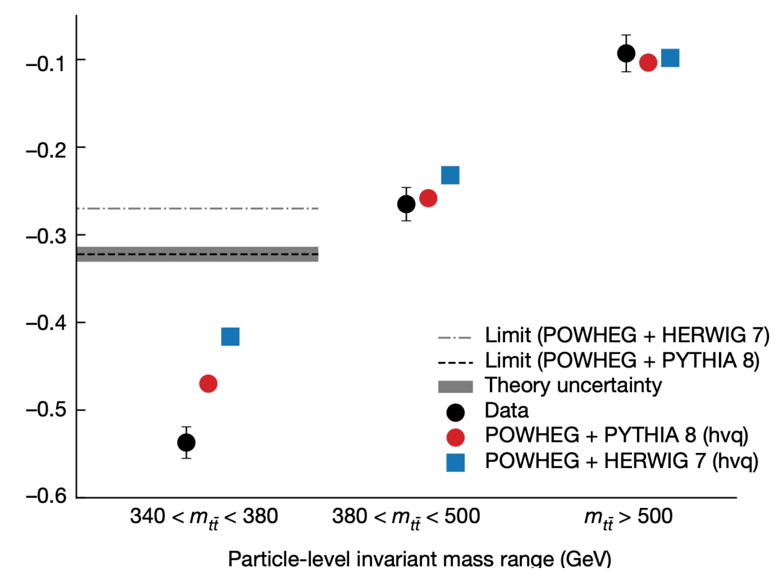


$$-0.480^{+0.026}_{-0.029}\ (-0.467^{+0.026}_{-0.029})$$

Significance 5.1 σ

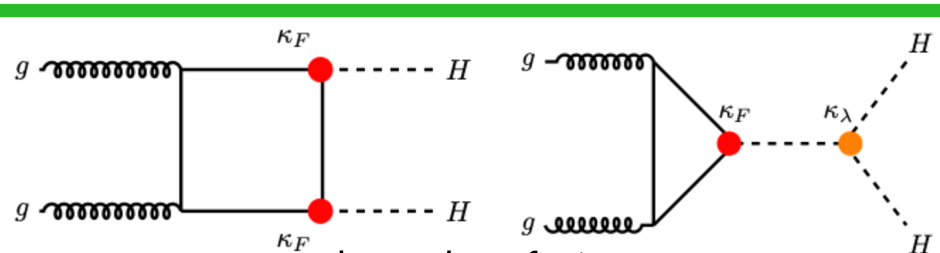




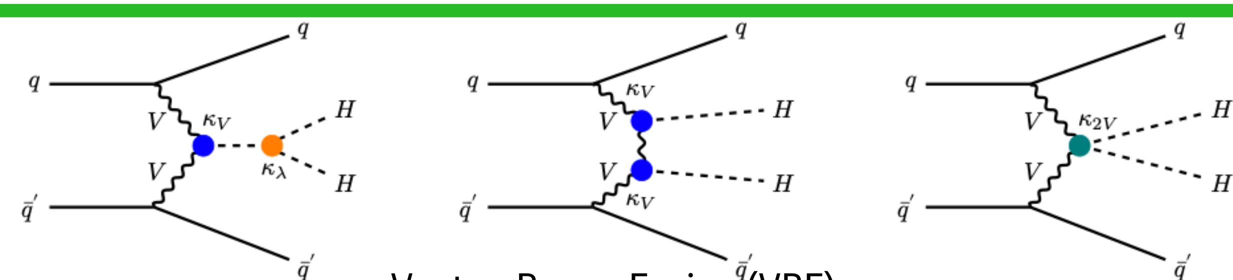


Higgs boson self coupling

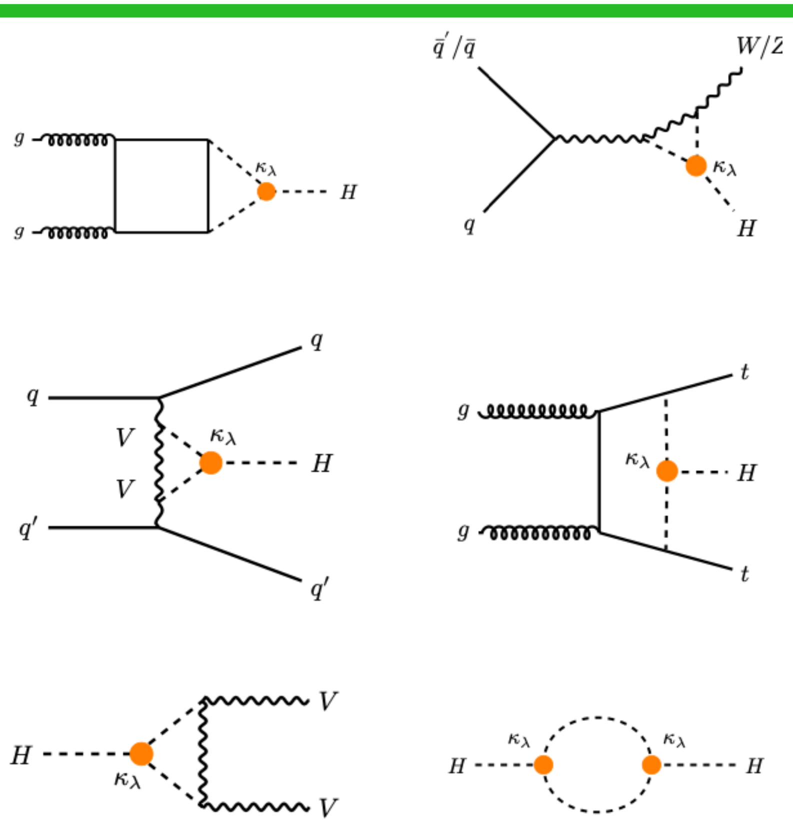
13 TeV: CMS [arXiv:2407.13554] Higgs self coupling



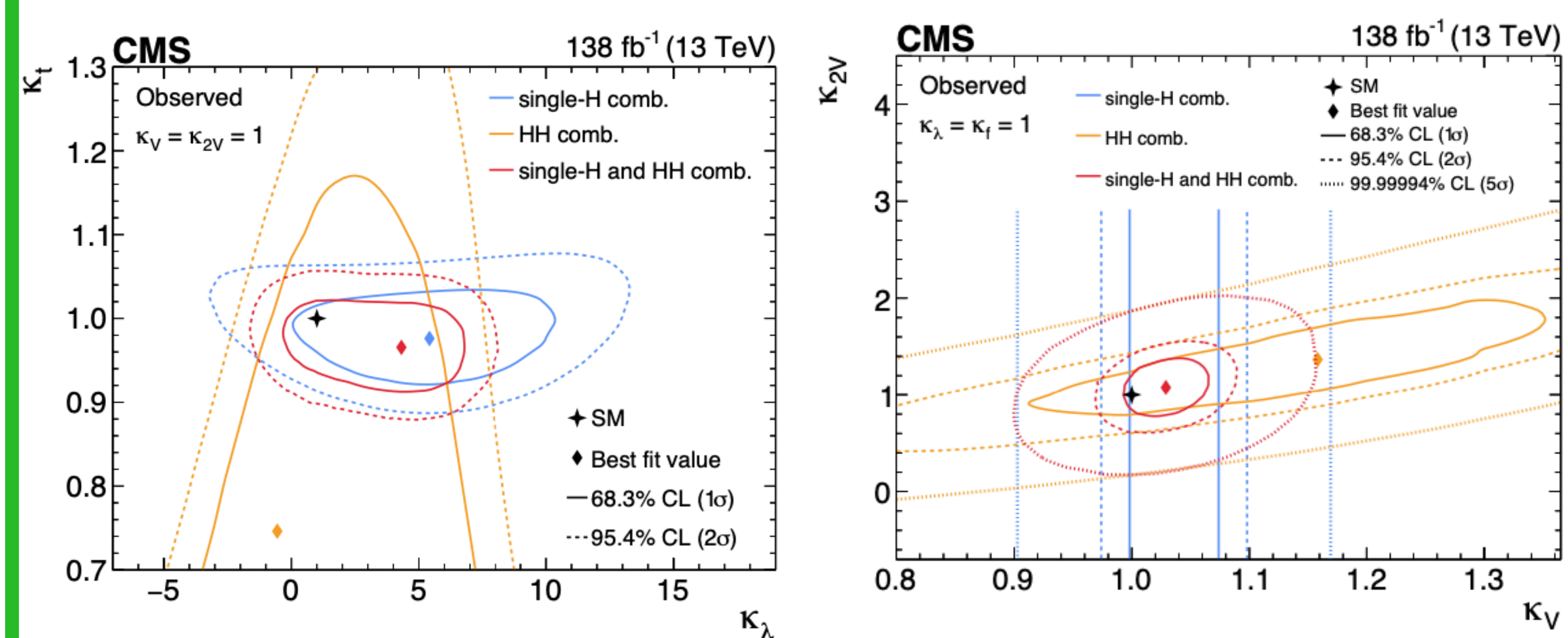
gluon-gluon fusion



Vector Boson Fusion (VBF)



NLO corrections depending on Higgs self coupling



Additional Higgs bosons: ATLAS

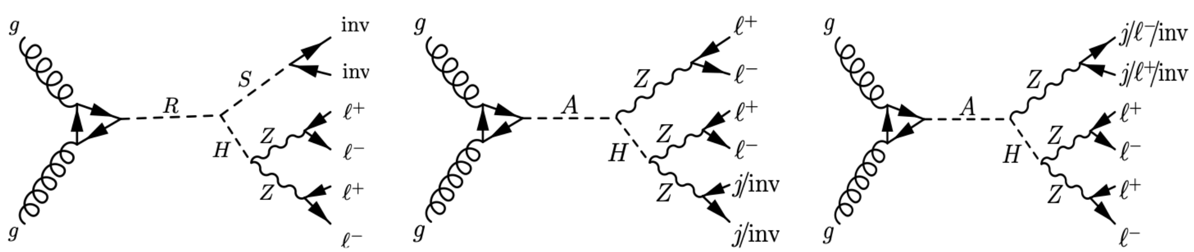
13 TeV: ATLAS [arXiv:2401.04742], [arXiv:2404.12915]

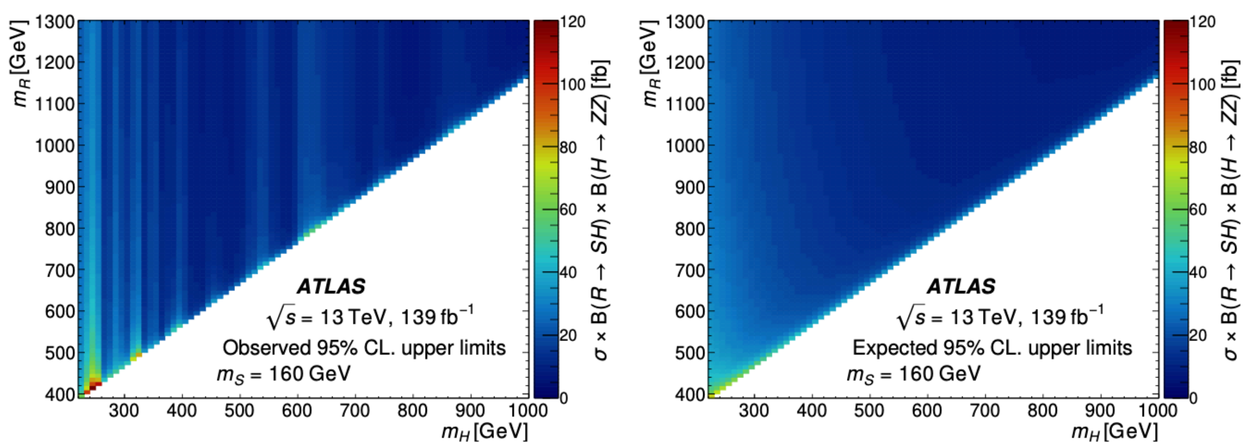
Two-Higgs-Doublet Models (2HDMs) introduce a second Higgs doublet: $H^{\pm}$, (h, H) and pseudoscalar A

another extension 2HDM+S introduce:

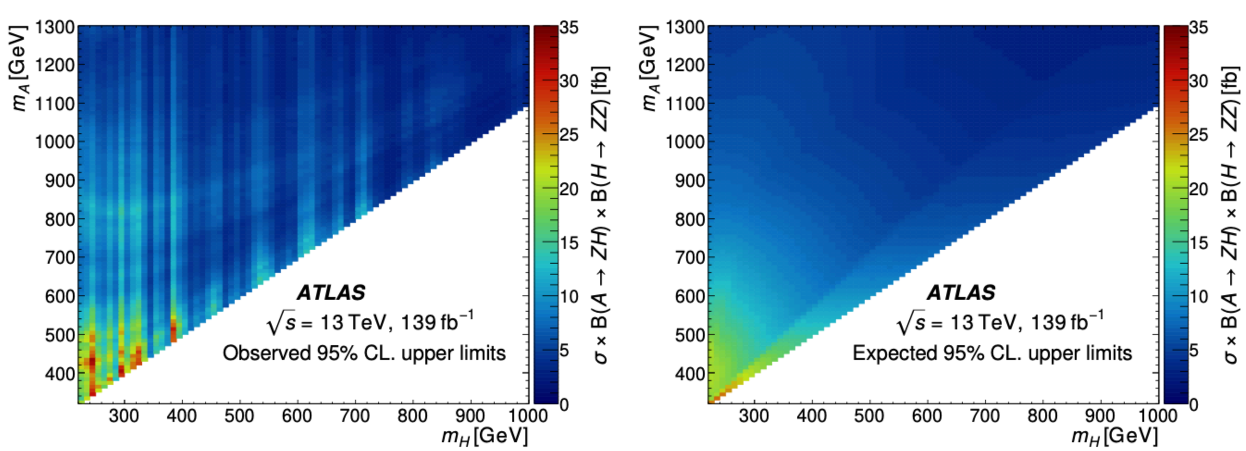
Scalar boson S (dark matter "portal")

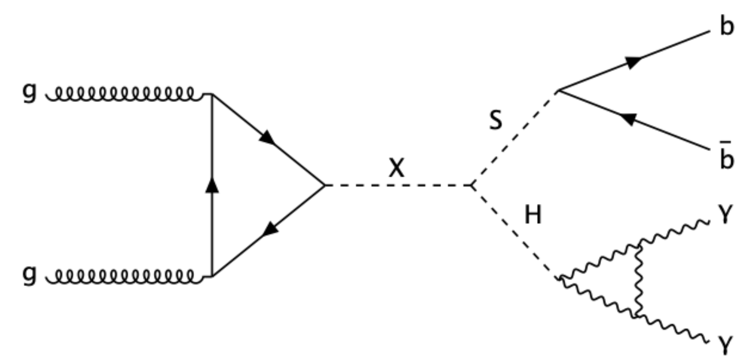
Heavy scalar R decaying to H and S

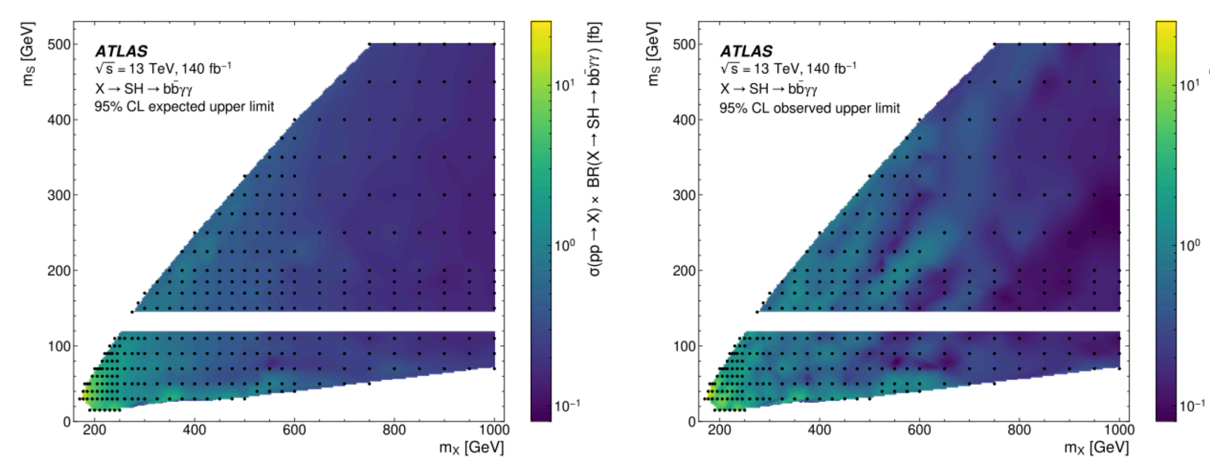




(a) (b)

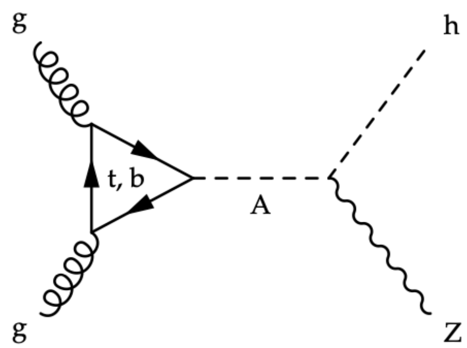


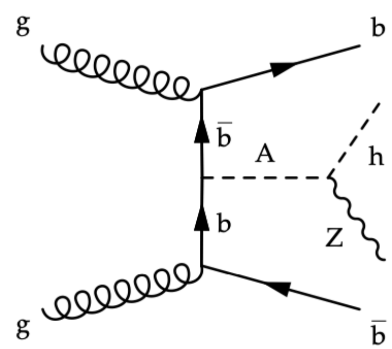




Additional Higgs bosons: CMS

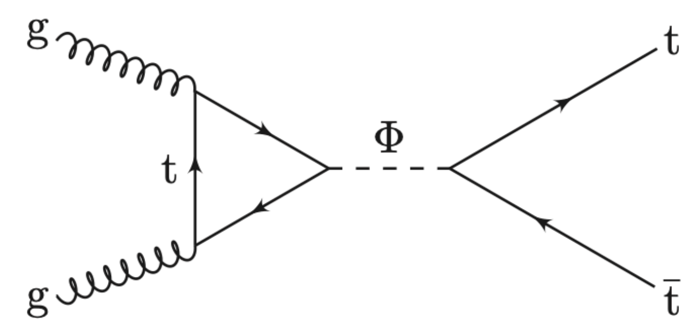
13 TeV: CMS [CMS-PAS-HIG-22-004], [CMS-PAS-B2G-23-006], [CMS-PAS-HIG-22-013]

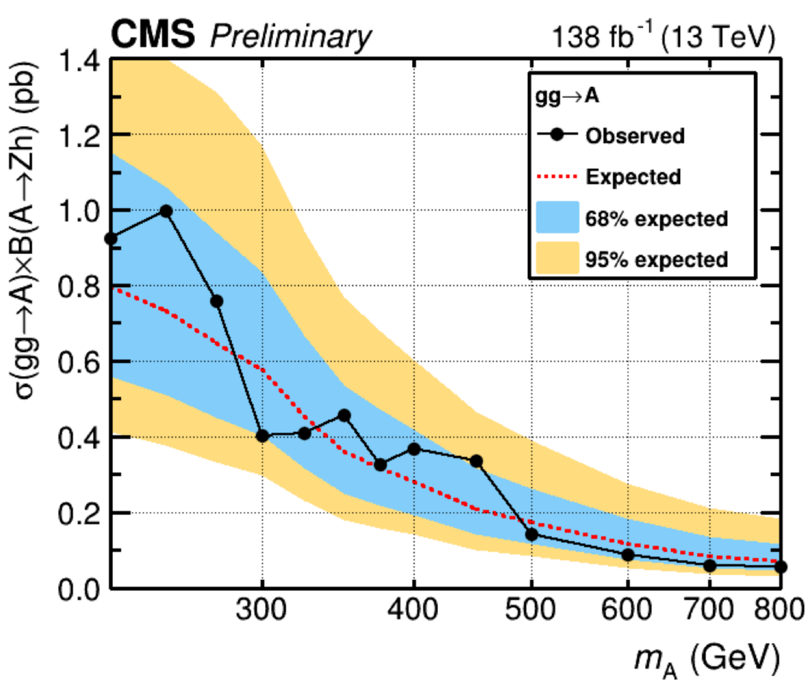


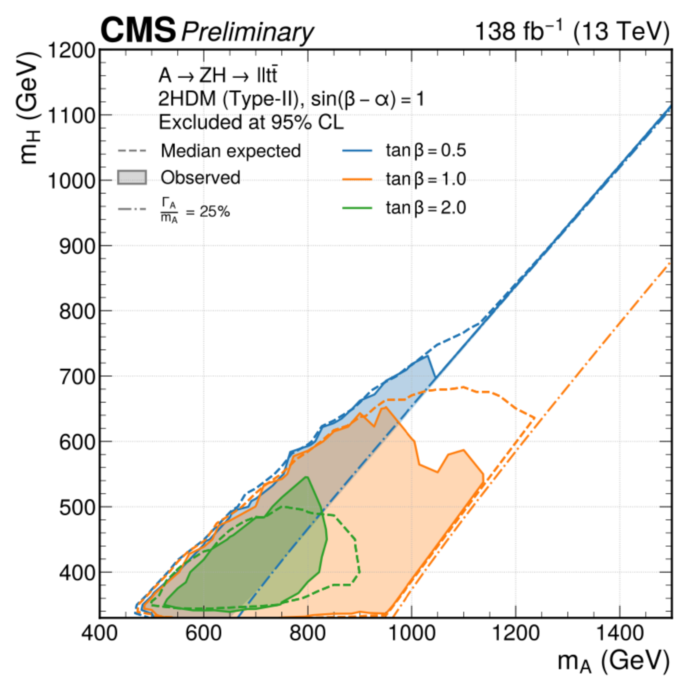


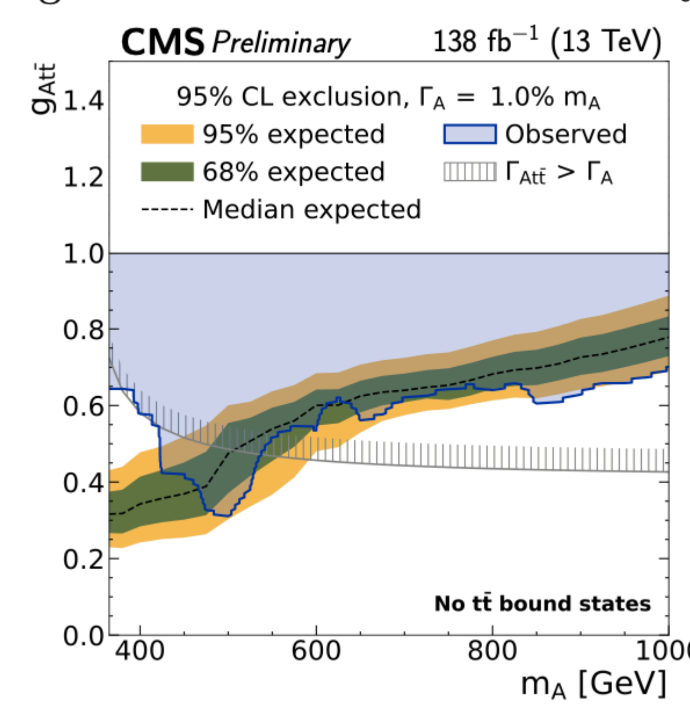
Two-Higgs-Doublet Models (2HDMs) introduce a second Higgs doublet: $H^{\pm}$, (h, H) and pseudoscalar A

the ratio of the vacuum expectation values of the two doublets ($\tan\beta$)







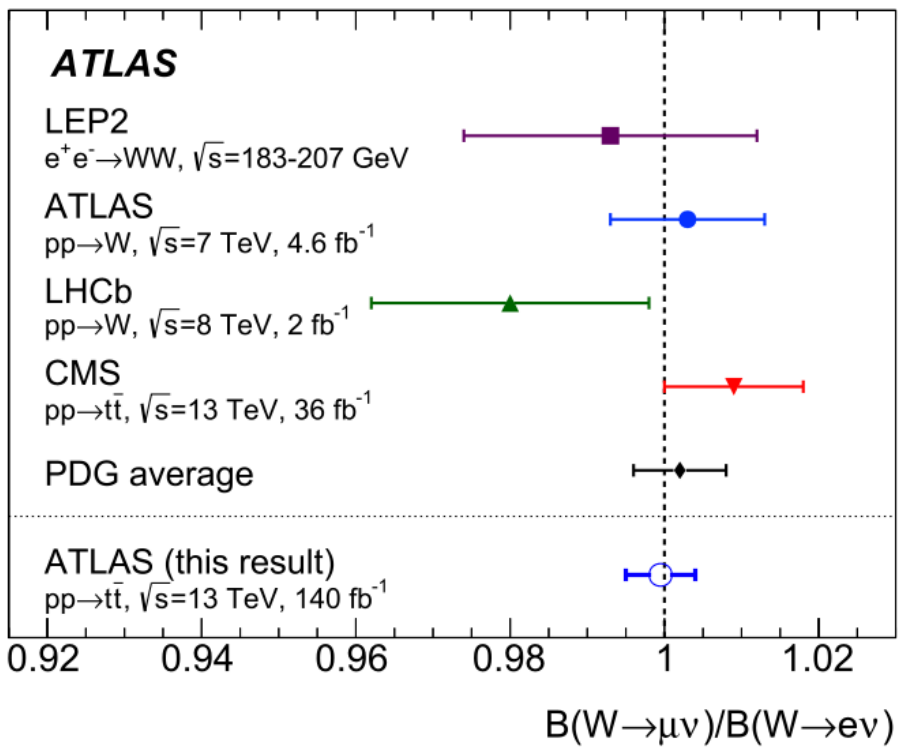


$^1S_0^{[1]}$ $t\bar{t}$ bound state (η_t)

Lepton Flavor Universality (LFU)

13 TeV ATLAS [Eur. Phys. J. C 84 (2024) 993] LFU in W decays

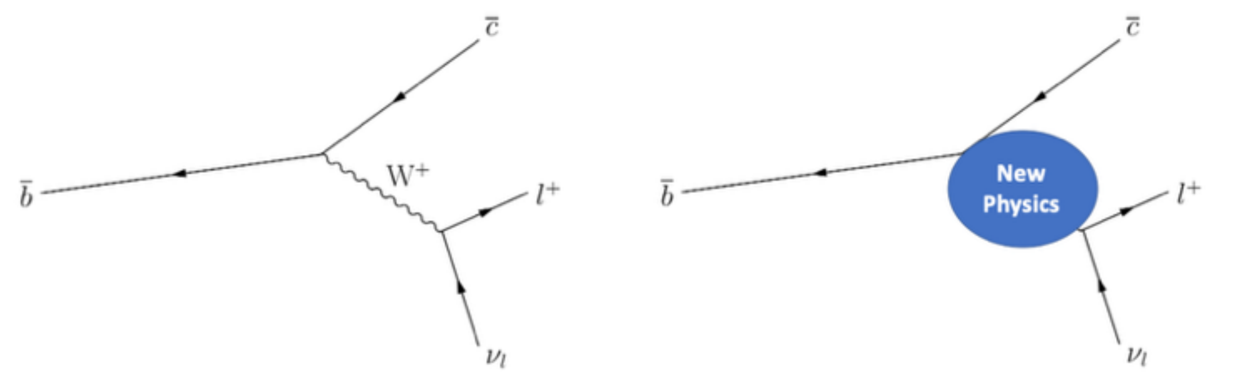
$$R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} = \frac{\overline{W}(1+\Delta_W)}{\overline{W}(1-\Delta_W)}$$



$$R_W^{\mu/e} = 0.9995 \pm 0.0022\,(\text{stat}) \pm 0.0036\,(\text{syst}) \pm 0.0014\,(\text{ext}).$$

CMS [arXiv:2408.00678] LFU in B_c^+ decays

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}.$$

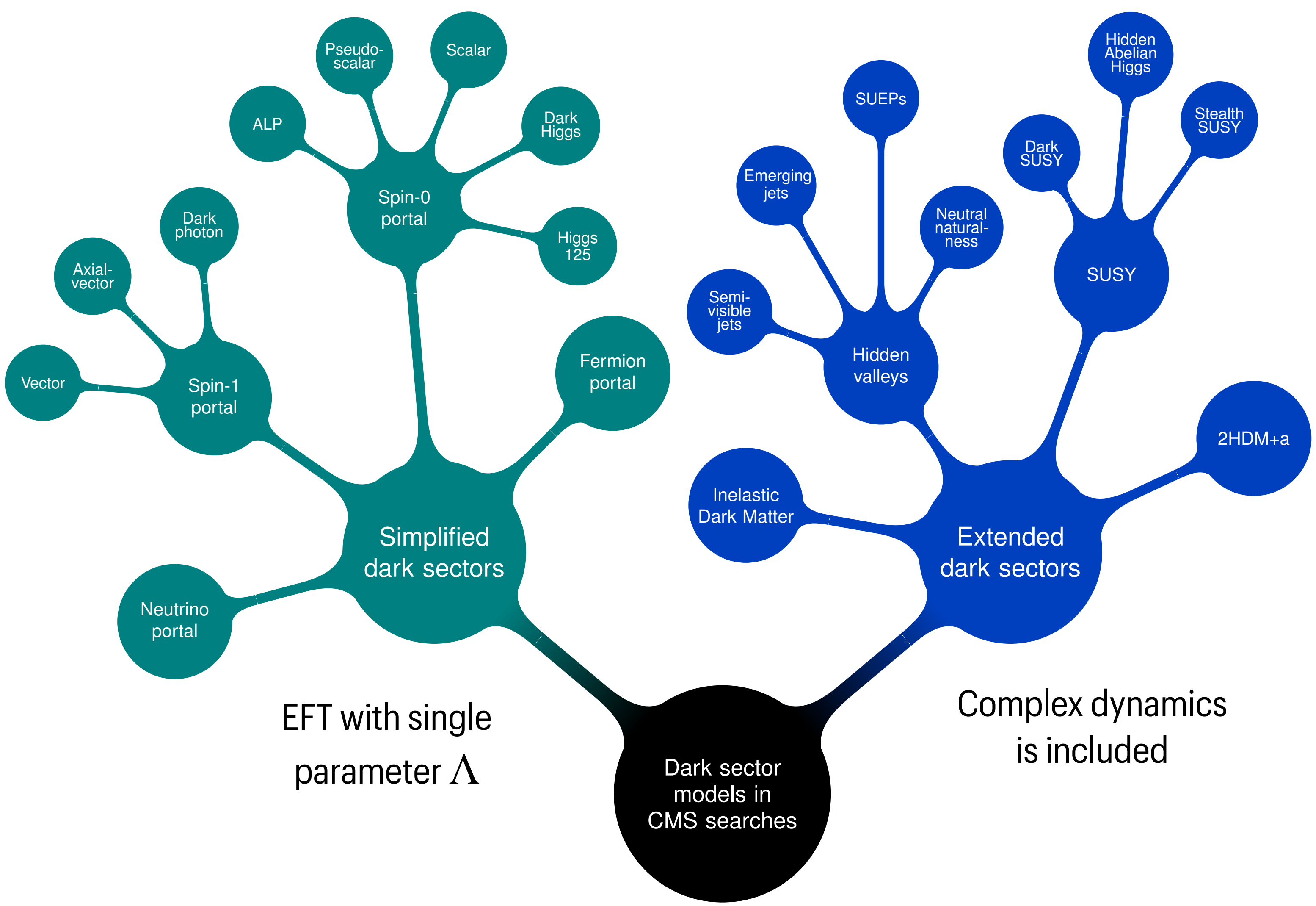


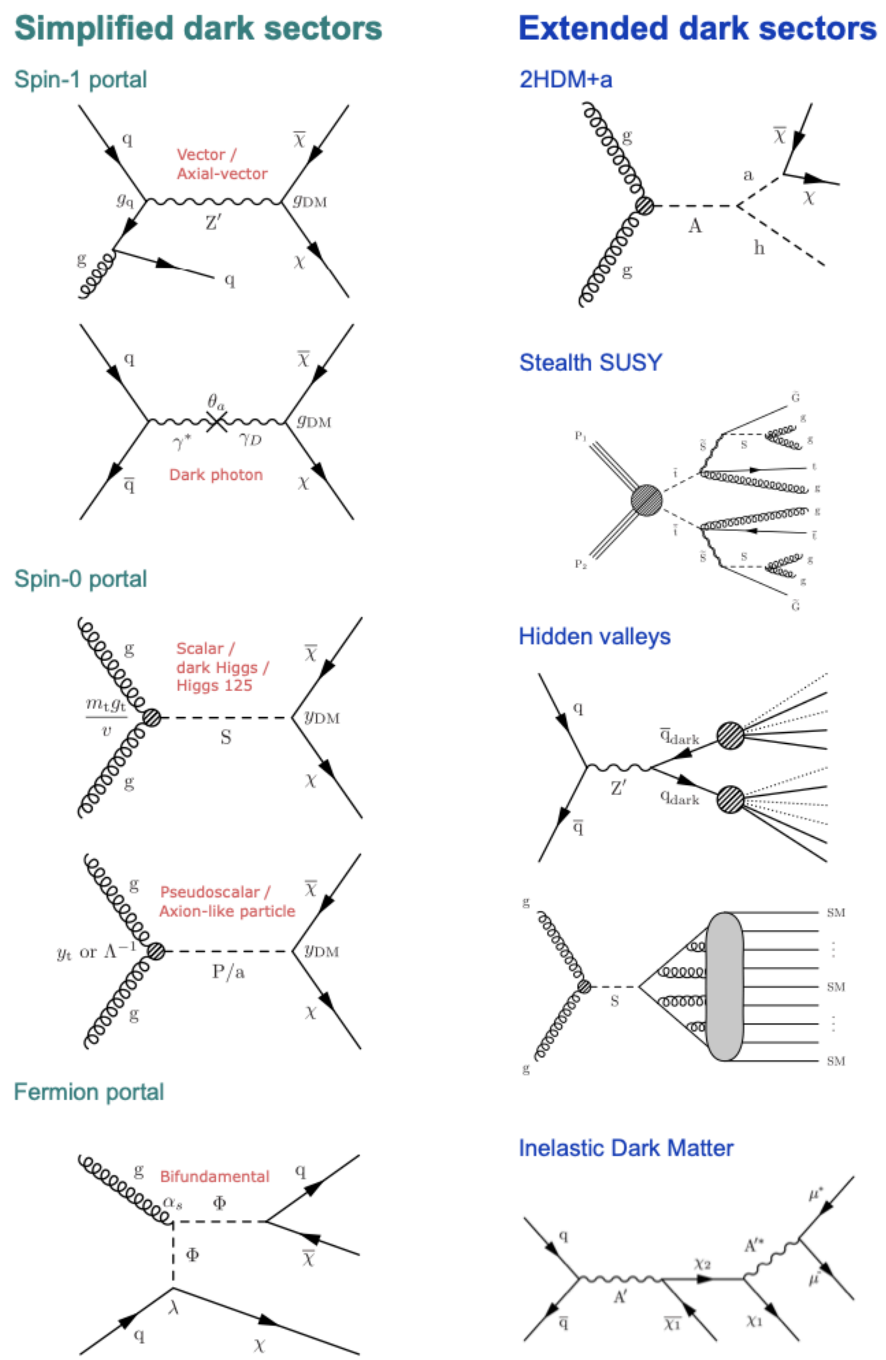
$$R(J/\psi) = 0.17^{+0.18}_{-0.17}\,(\text{stat})^{+0.21}_{-0.22}\,(\text{syst})^{+0.19}_{-0.18}\,(\text{theo}) = 0.17 \pm 0.33$$

This is consistent with Standard Model

Dark sector and hidden valleys (1)

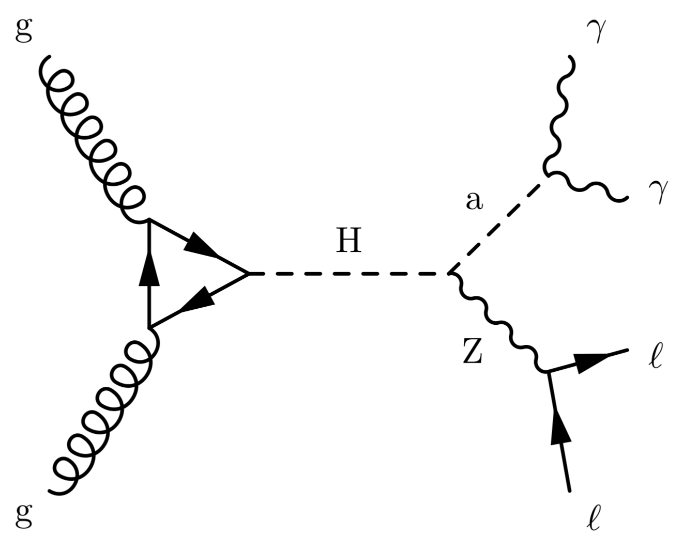
CMS large review [arXiv:2405.13778], CMS [Phys. Lett. B 852 (2024) 138582]

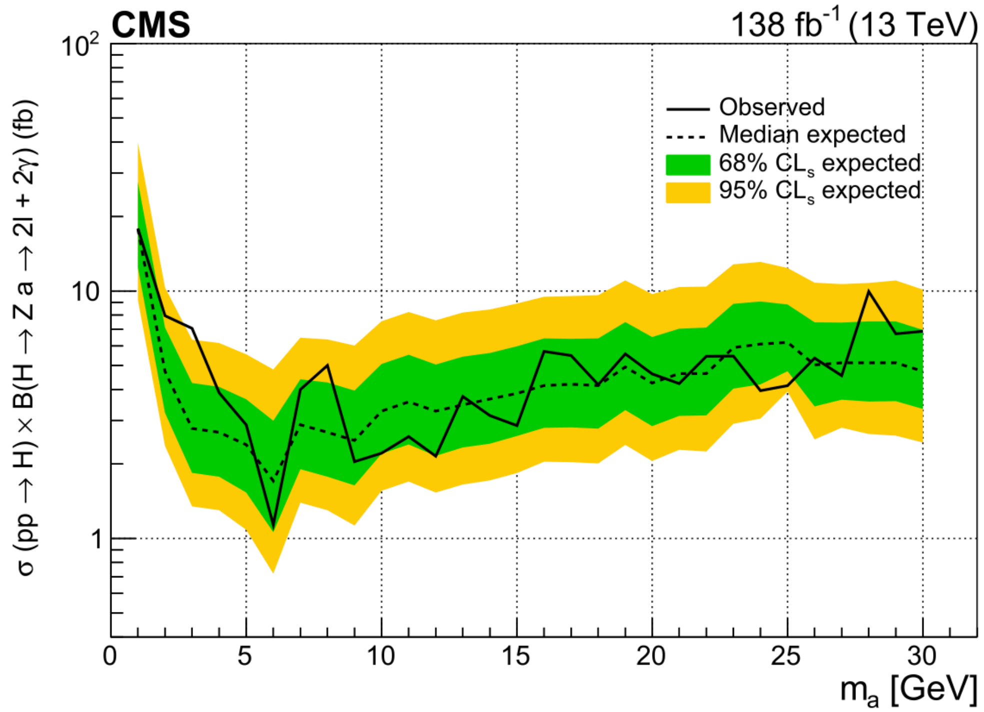


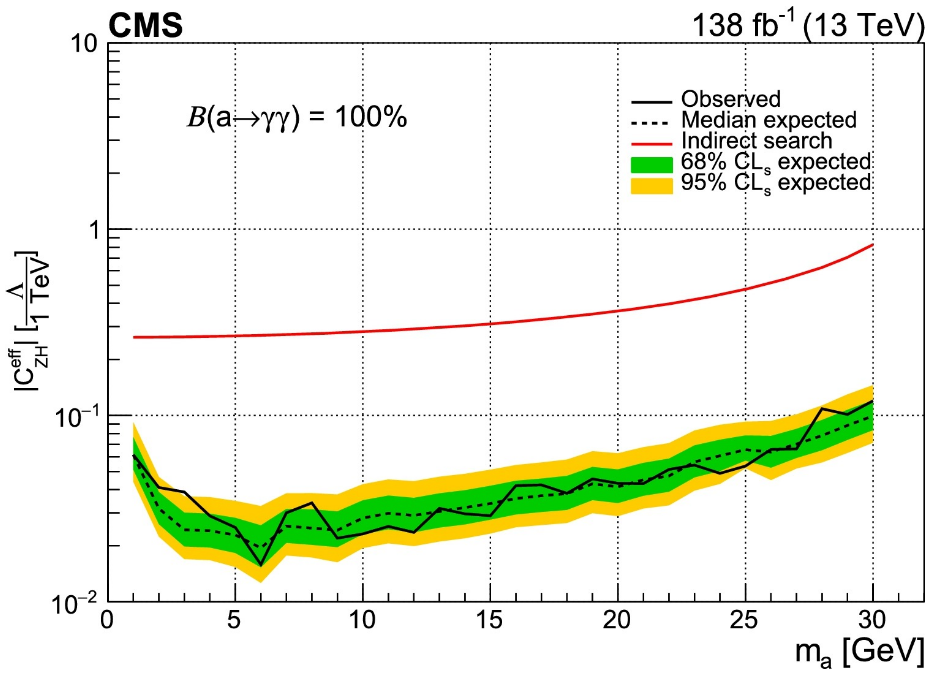


Dark sector and hidden valleys (2): ALP

13 TeV: CMS [Phys. Lett. B 852 (2024) 138582] Search for ALP



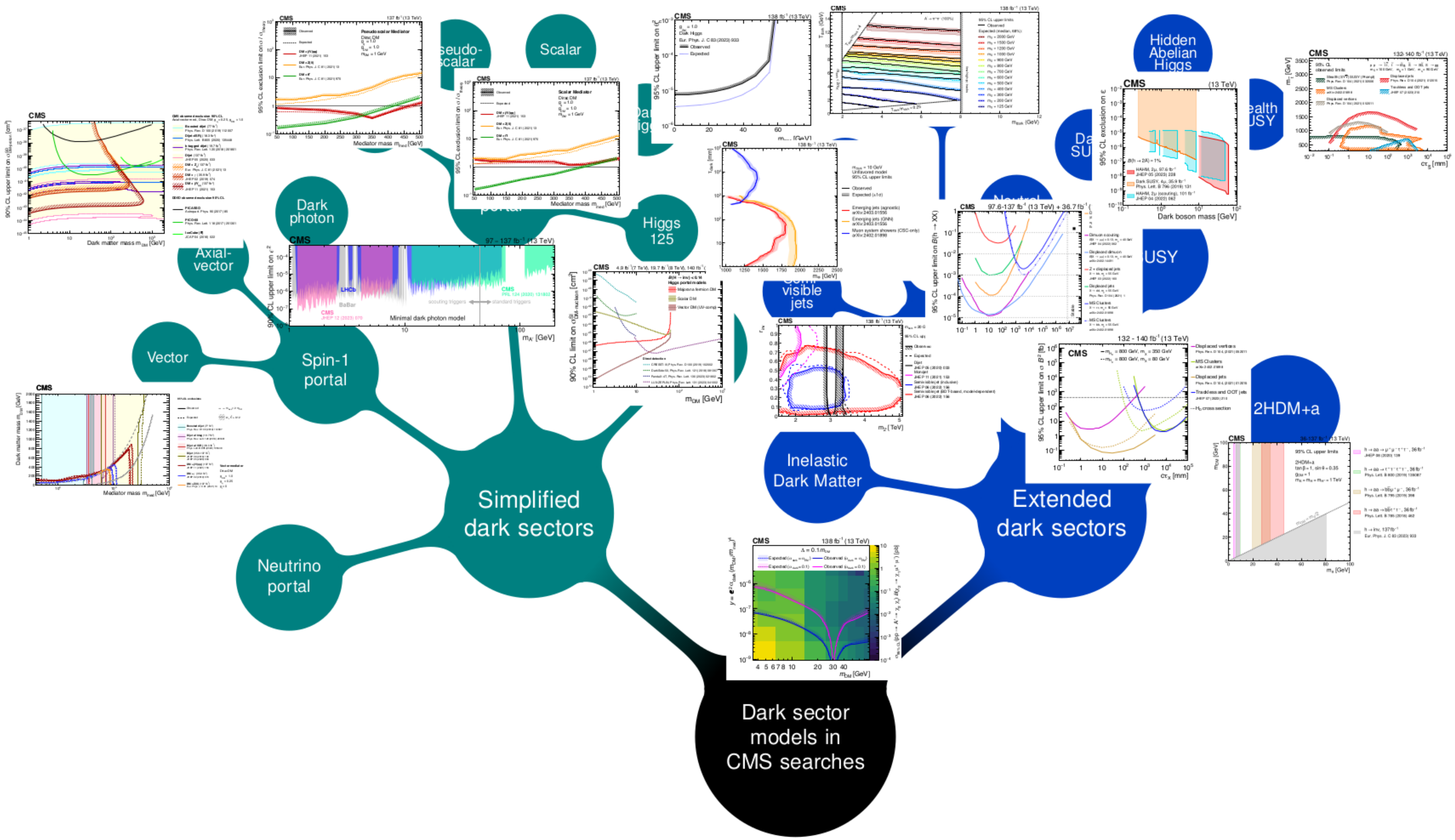




Red line is indirect invisible decay search by CMS [Eur. Phys. J. C 83 (2023) 933]

Dark sector and hidden valleys (3)

13 TeV: CMS large review [arXiv:2405.13778], CMS [Phys. Lett. B 852 (2024) 138582]

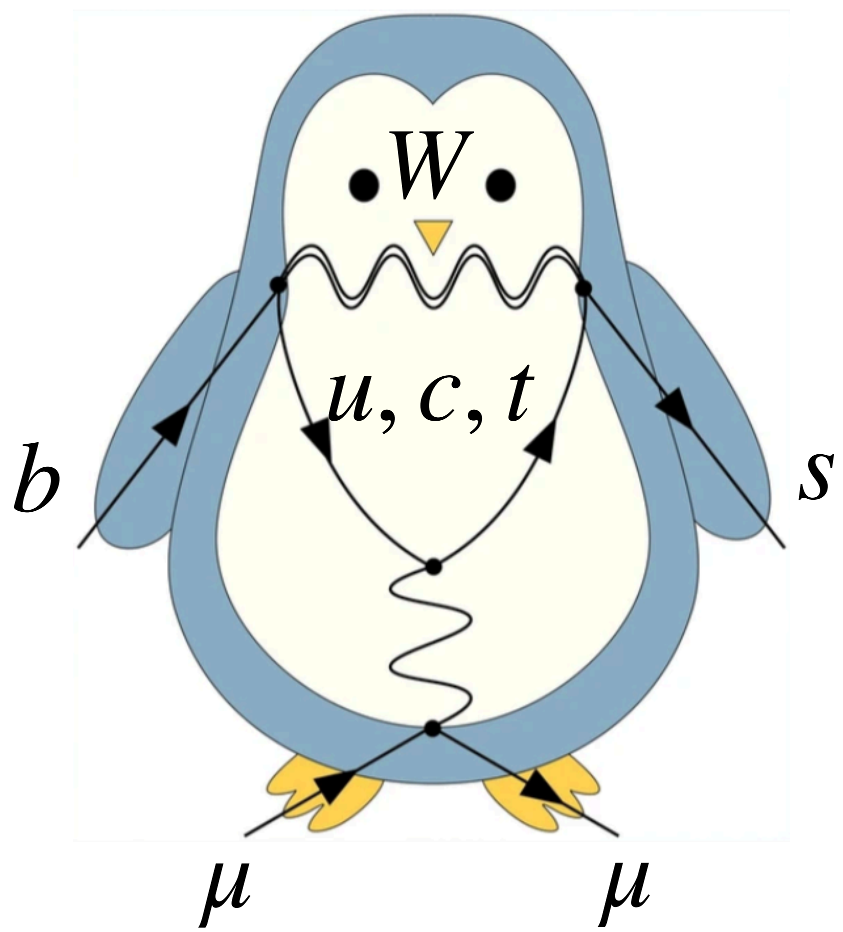


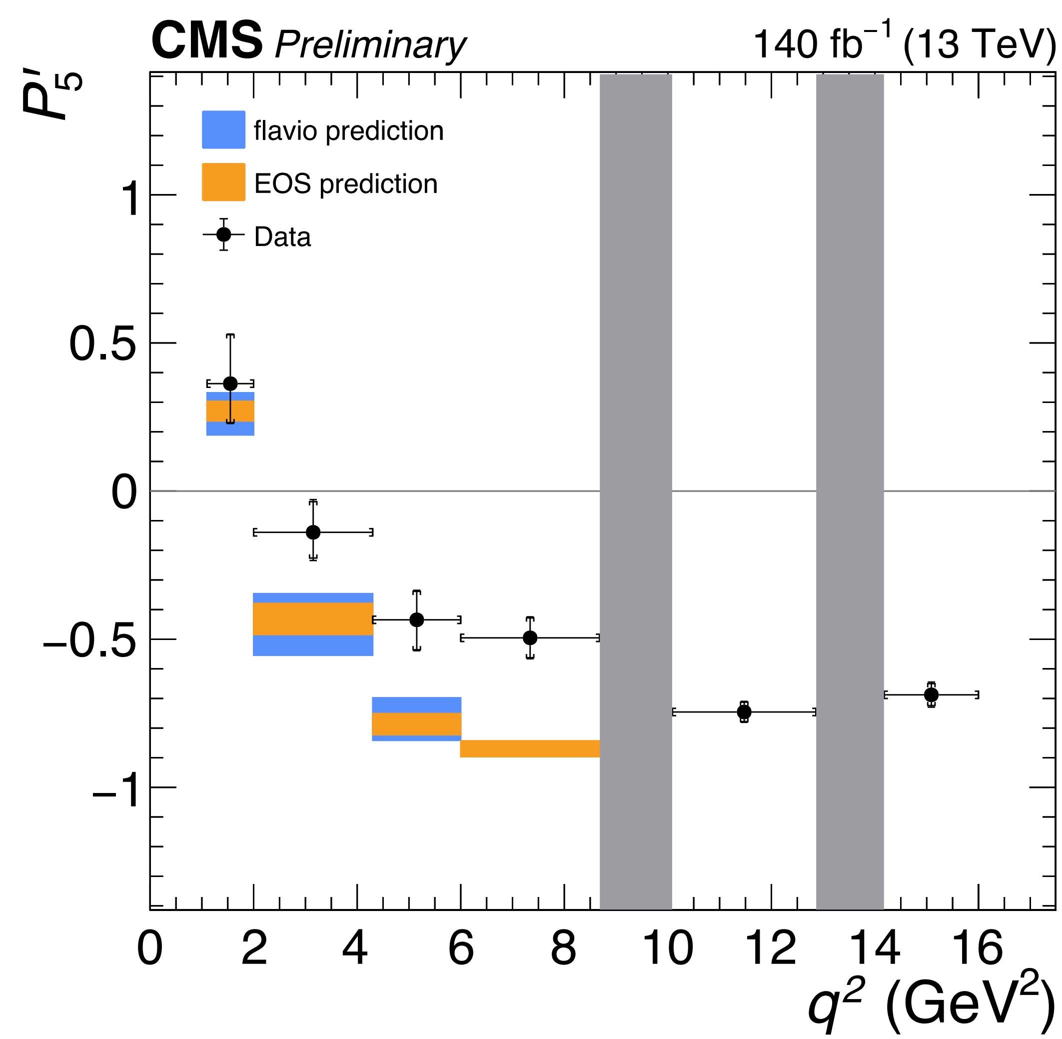
No sign of Dark Matter up to now

Rare Penguin $B^0 \to K^*\mu\mu$: indirect new physics

13 TeV: CMS [CMS-PAS-BPH-21-002]

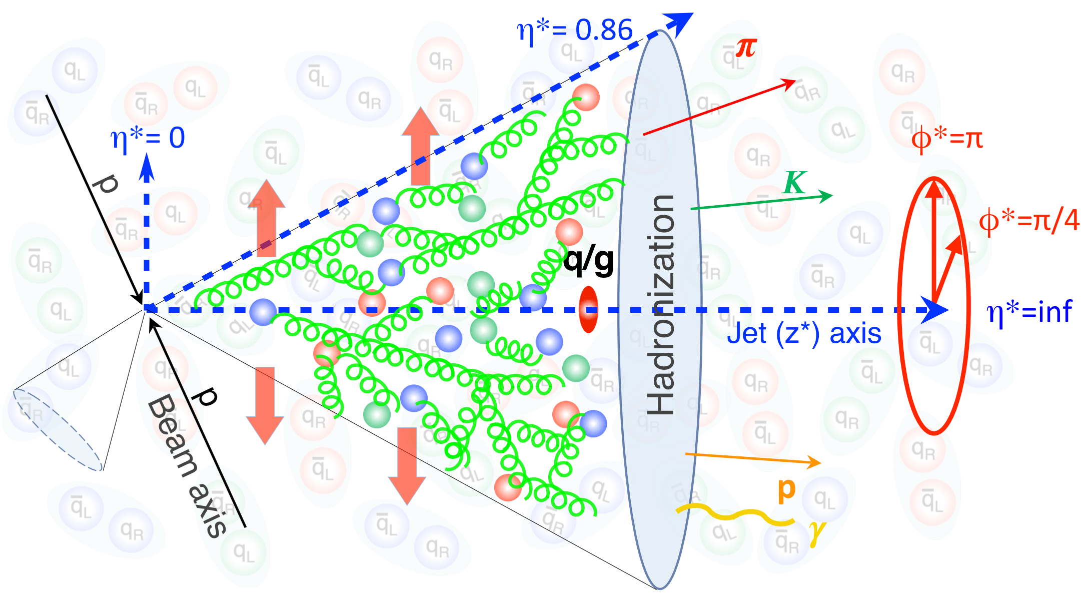
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+ (\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l$$
$$+ \frac{1}{2}P_1(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+ \sqrt{(1-F_L)F_L}(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi)$$
$$- \sqrt{(1-F_L)F_L}(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi)$$
$$+2P_2(1-F_L)\sin^2\theta_K\cos\theta_l - P_3(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi)\Big] \quad (1)$$

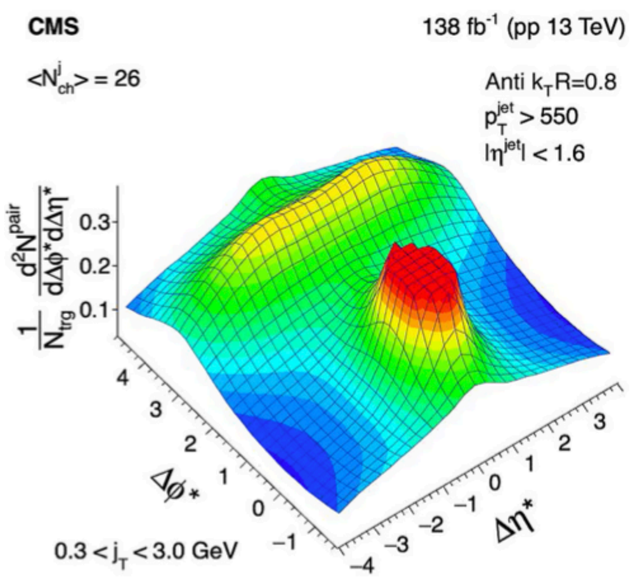


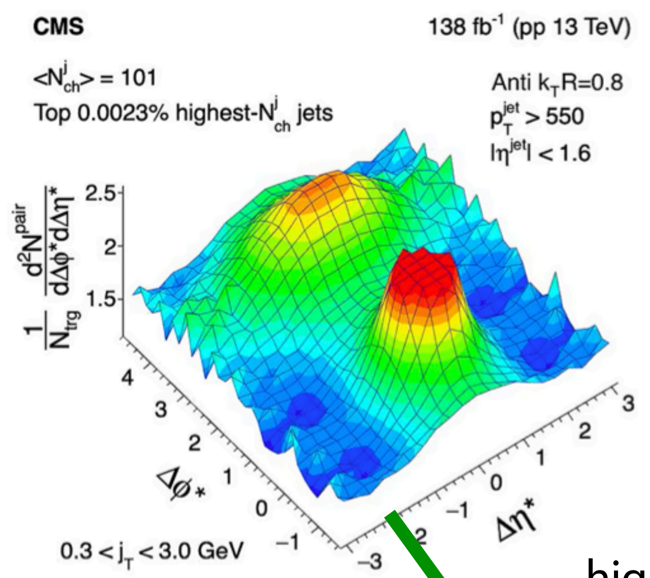


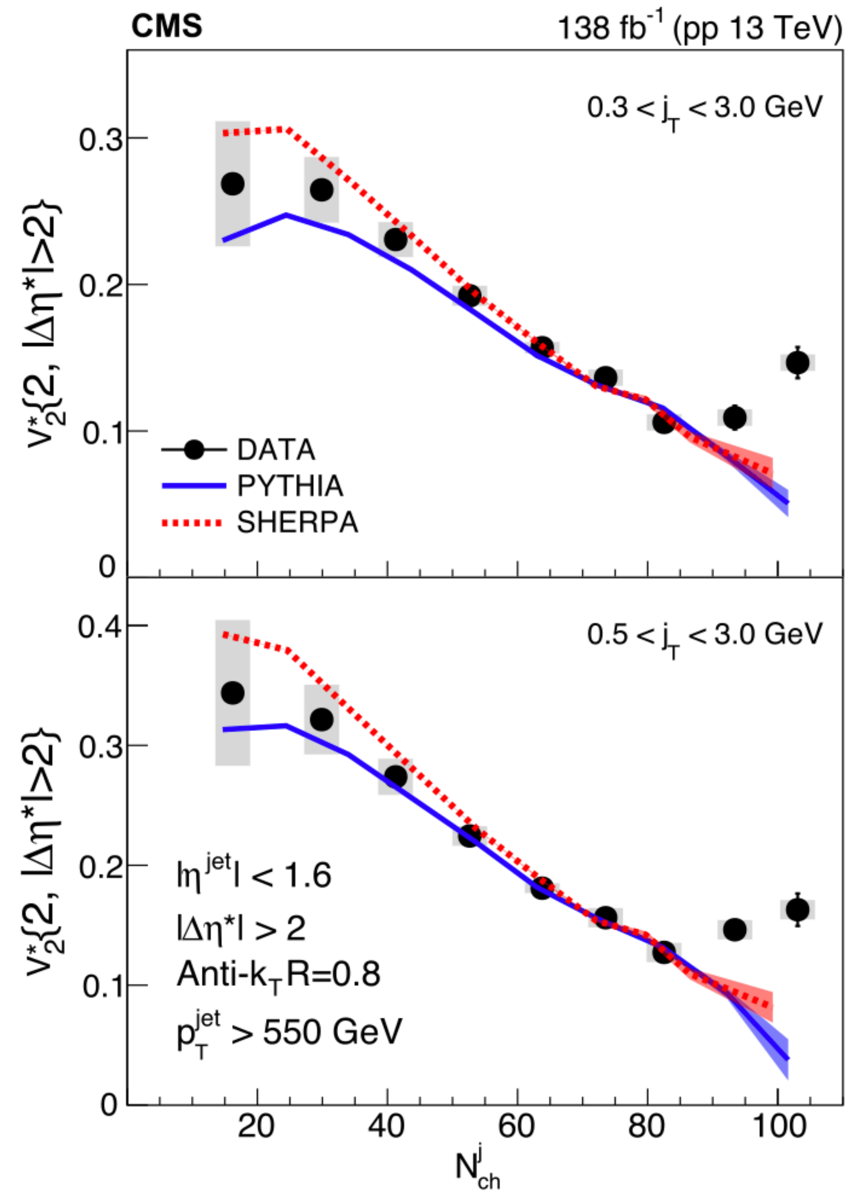
Collective effects in high multiplicity jets

13 TeV: CMS [Phys. Rev. Lett. 133 (2024) 142301]







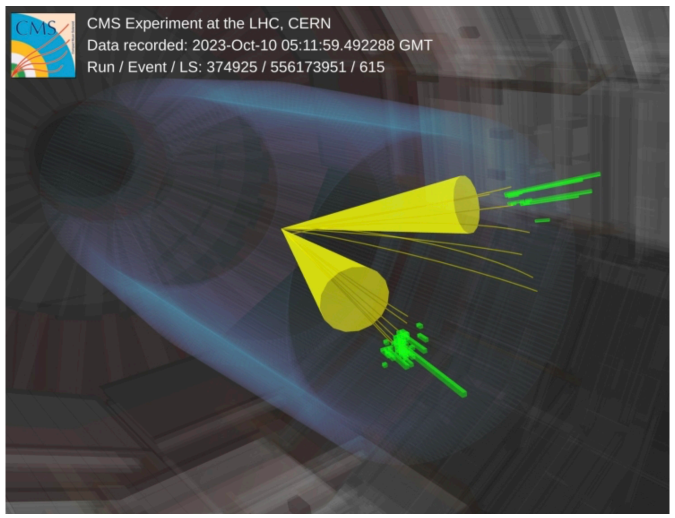


high multiplicity produced particles create similar ridge structure in:

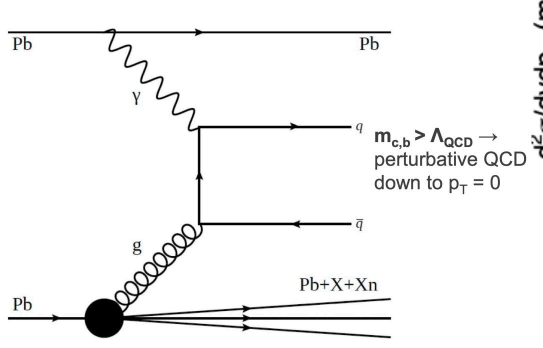
- heavy ion collisions
- pp collisions
- inside jet

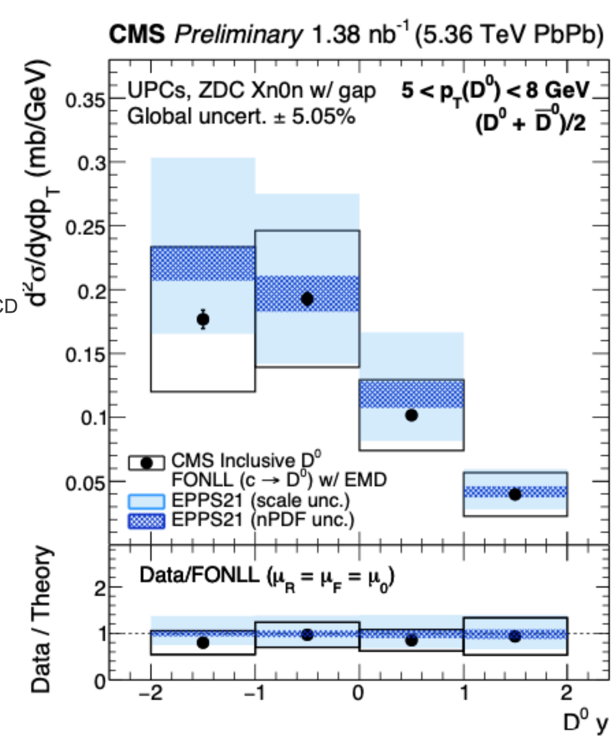
Ultra-Peripheral collisions (UPCs) of nuclei

5.36 TeV PbPb CMS [CMS-PAS-HIN-24-003],



Small-x
gluon nuclear PDF

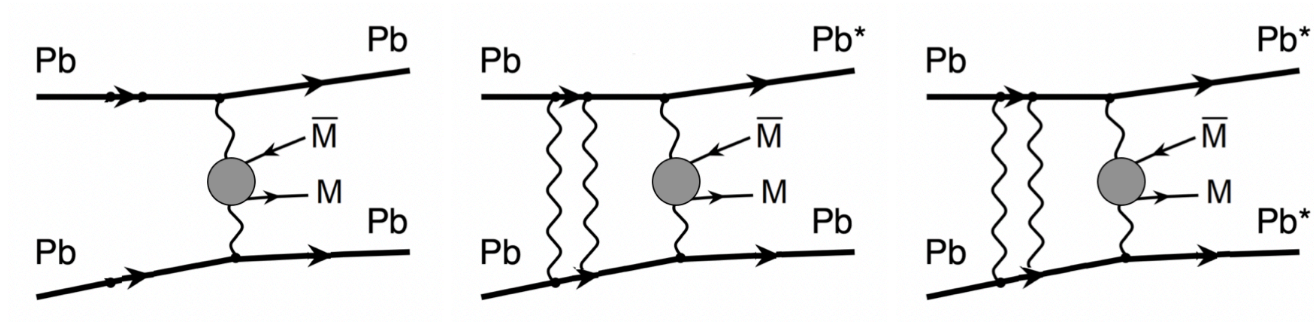


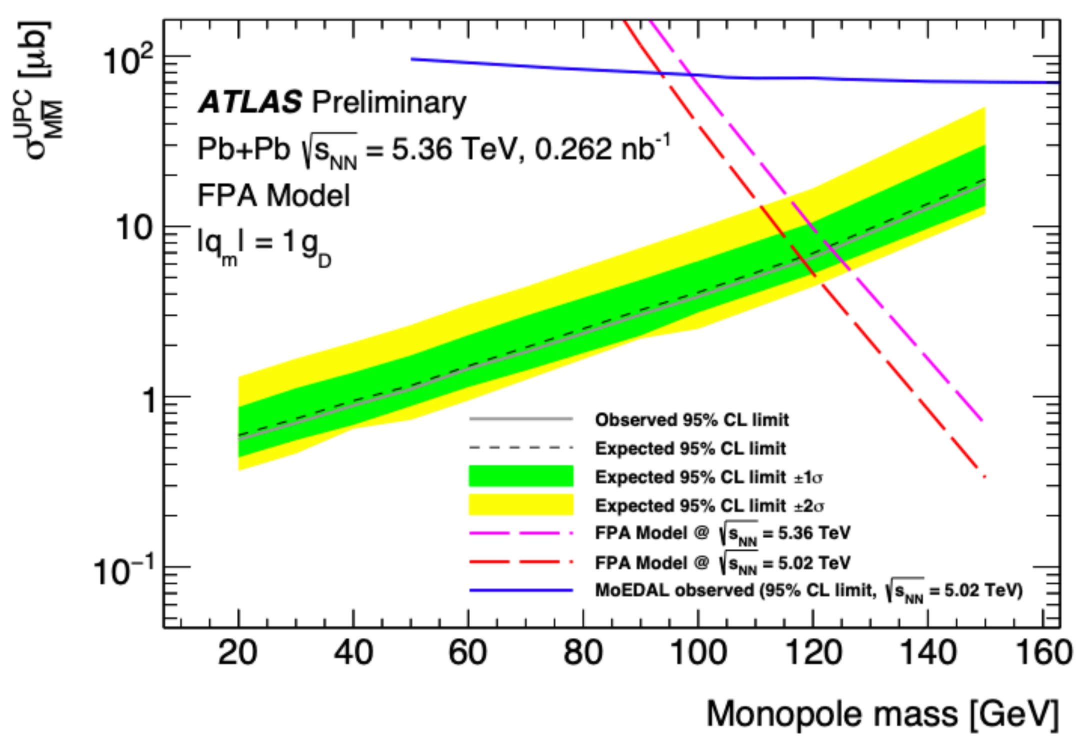


ATLAS [ATLAS-CONF-2024-009] (Monopole search)

These interactions can produce the largest magnetic fields in the Universe, with strength up to 10^{16} Tesla.

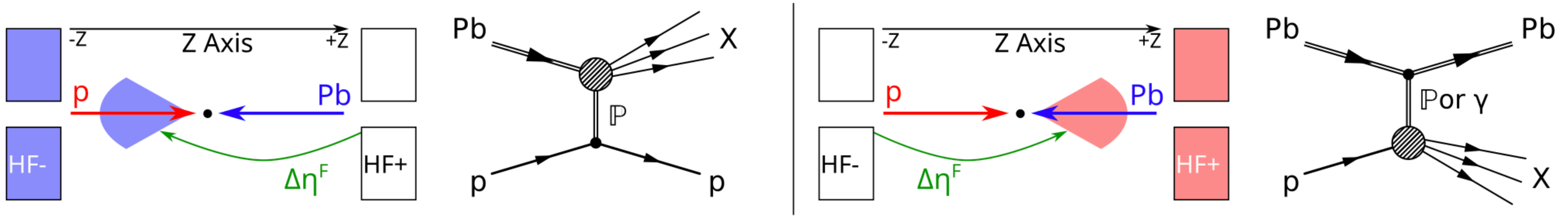
$$|q_m| = 1 g_D \qquad g_D = e/(2\alpha) \approx 68.5e$$



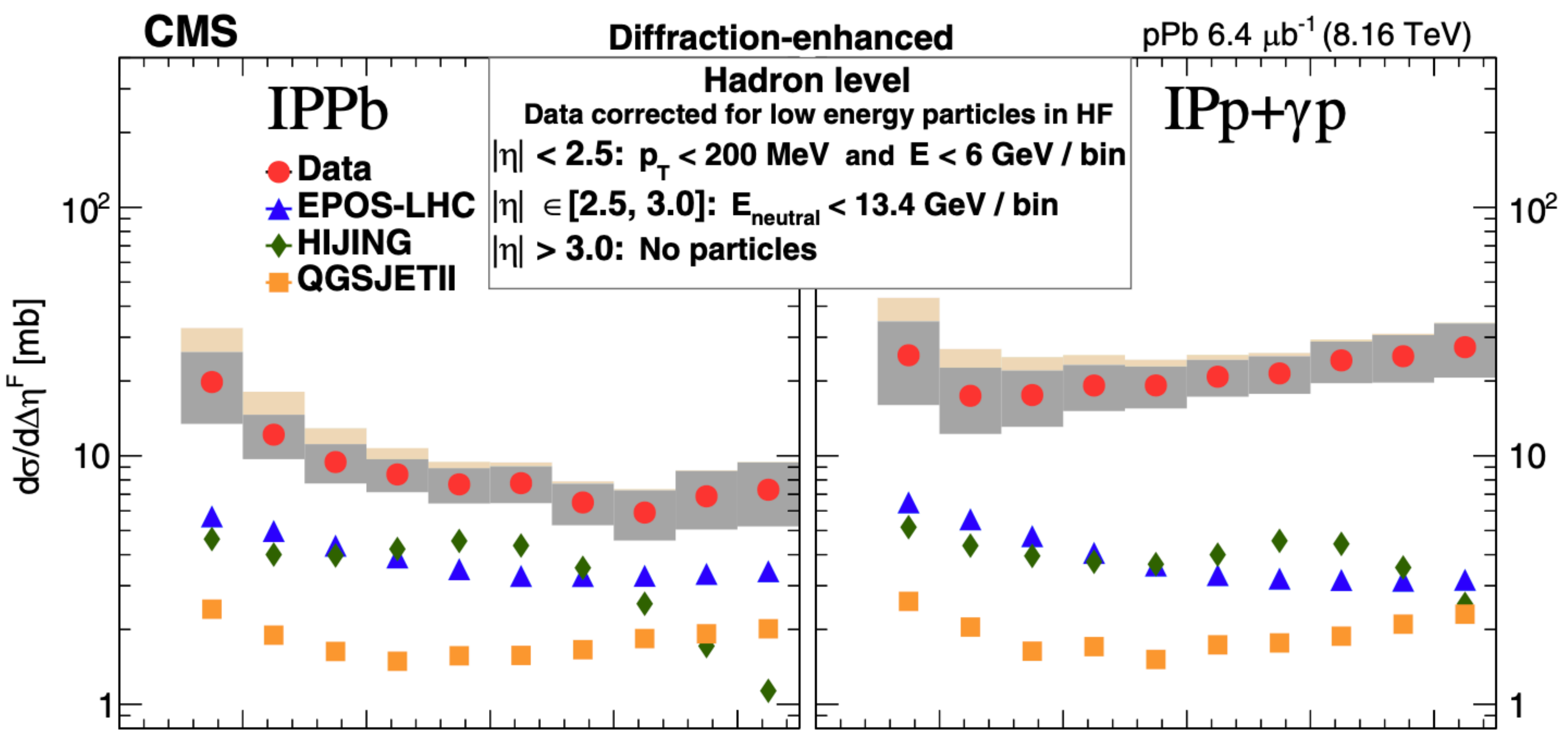


Forward rapidity gaps in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

pPb 8.16 TeV: CMS [Phys. Rev. D 108 (2023)092004] - the first measurement of forward rapidity gaps in pPb processes at LHC (previous measurement was done at 300 times less energy)



Rapidity gap observable in p-A:
- electromagnetic contribution exceeds strong interaction diffraction

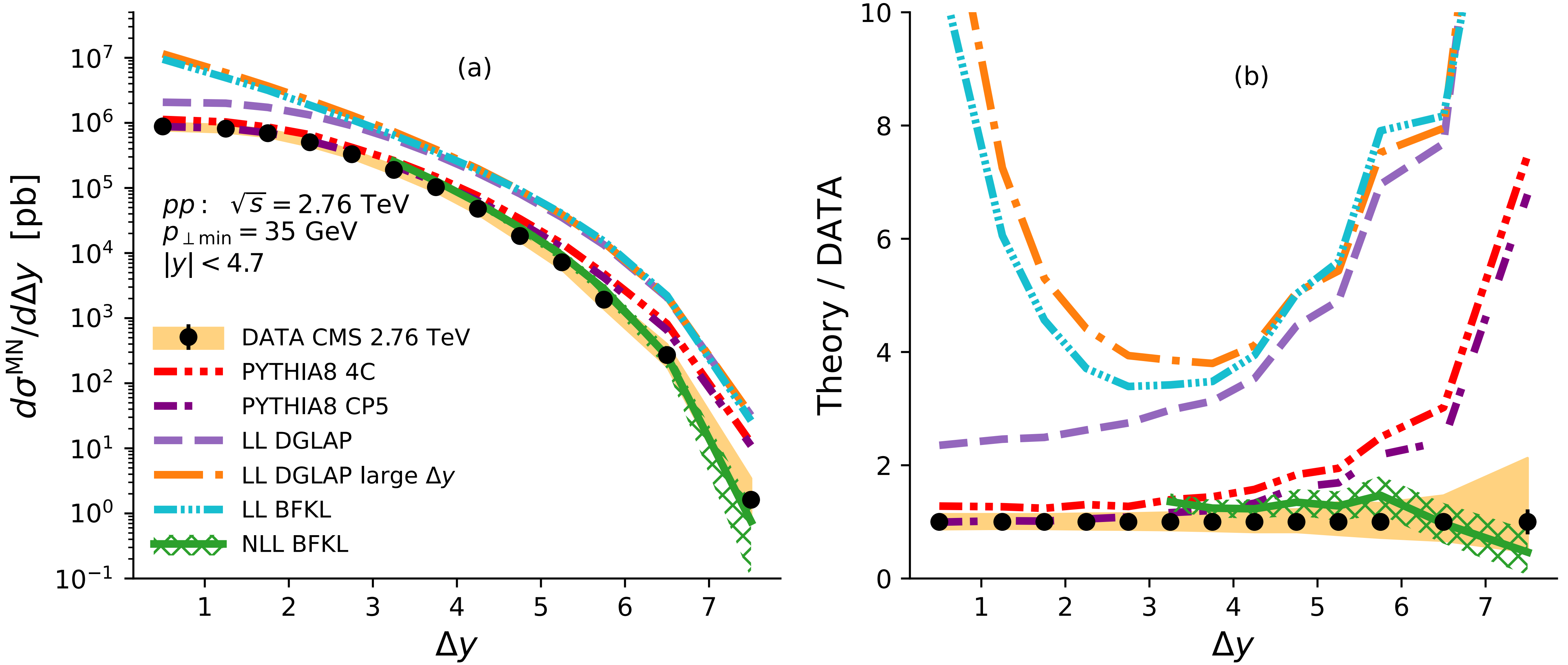


New hints on BFKL at LHC

Balitsky-Fadin-Kuraev-Lipatov (BFKL) QCD evolution is expected to become dominant in high-energy regime Q is finite $\ll \sqrt{s} \to \infty$.

2.76 TeV: CMS [JHEP03(2022)189]

A.Iu.Egorov. & V.T.Kim. [Phys. Rev. D 108 (2023) 014010] - NLL BFKL calculations



Conclusions

- Many Standard Model (SM) processes are measured by ATLAS and CMS in the "precision regime"
- No hints of the physics beyond the SM (BSM) are obtained up to now
- New ML-based achievements allow to push analyses to the new precision level enhancing discovery potential of the LHC
- The developed techniques (ML, Parking/Scouting) allow to observe interesting complex effects and dynamics within the SM (Quantum entanglement, Rare processes, Collective multiparticle effects, BFKL evolution)
- Techniques under development are crucial for HL-LHC and FCC, as well as all other collider based future experiments

THANK YOU !