AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

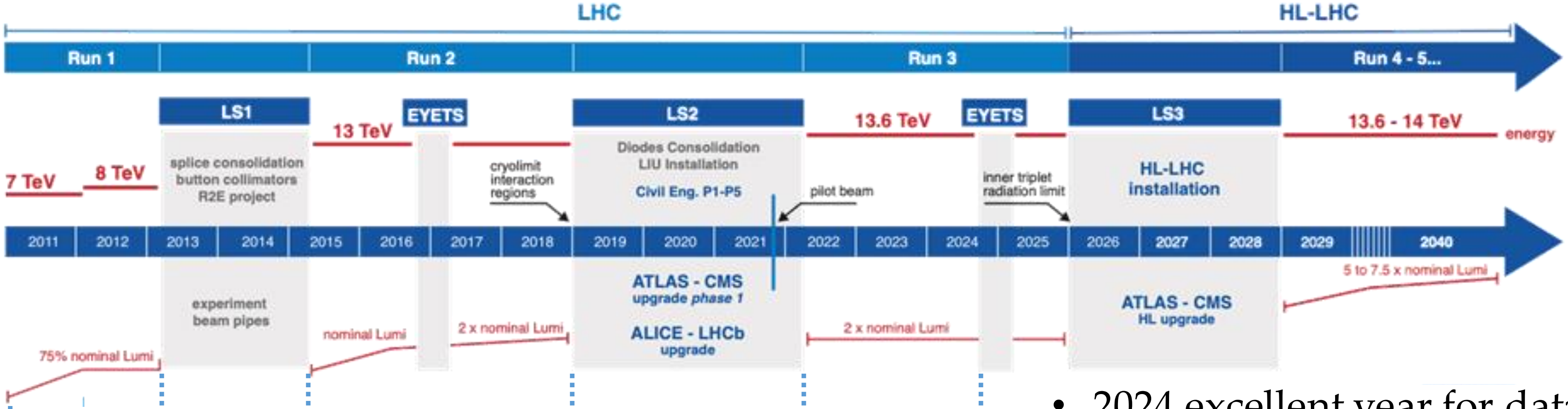
Highlights from the CMS Experiment

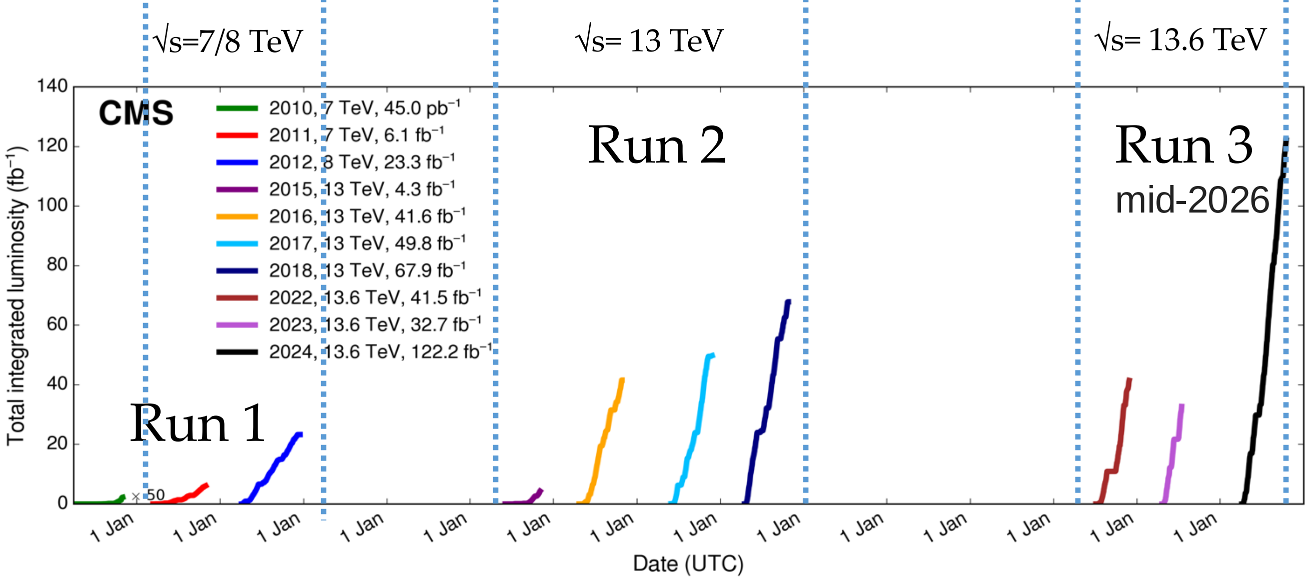
(& the CMS data analysis group at HEPHY)

R. Schöfbeck (HEPHY Wien)

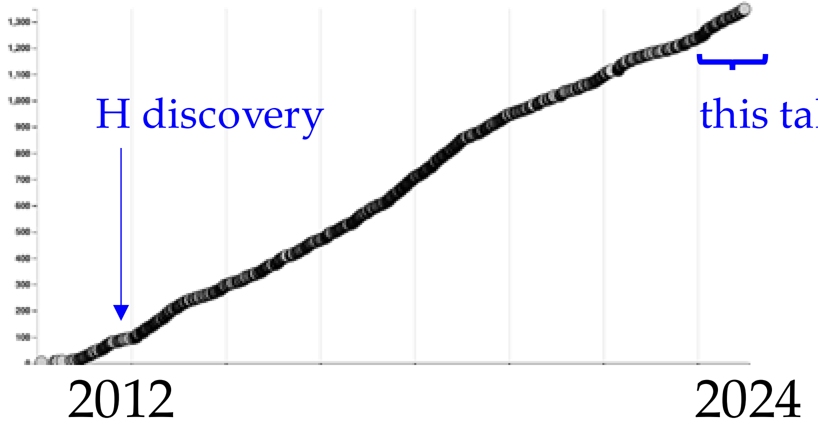
recent HEPHY results
https://hephyanalysissw.github.io/

LHC data taking

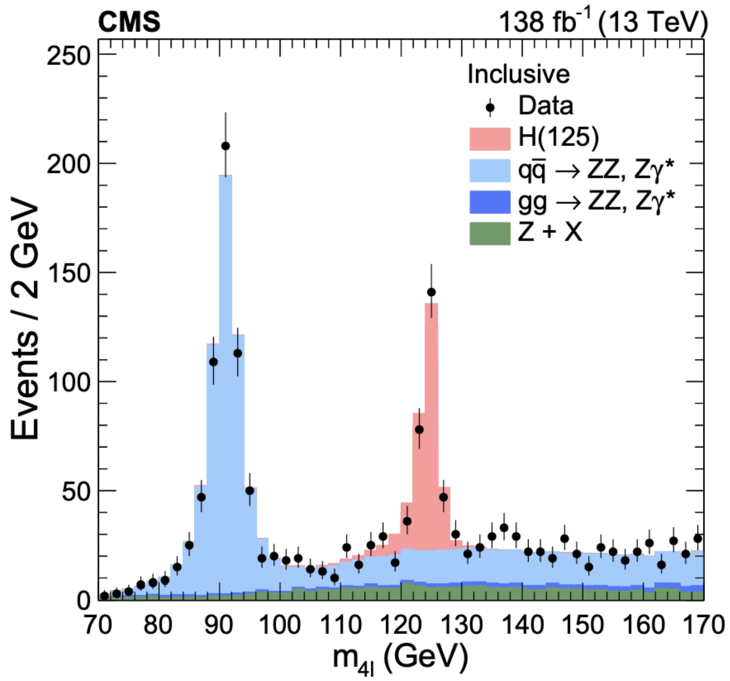


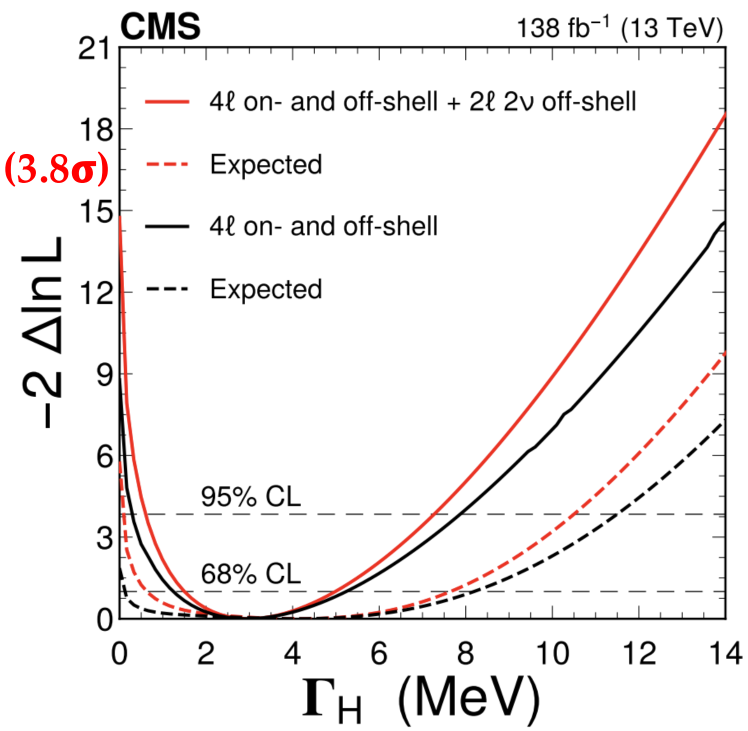


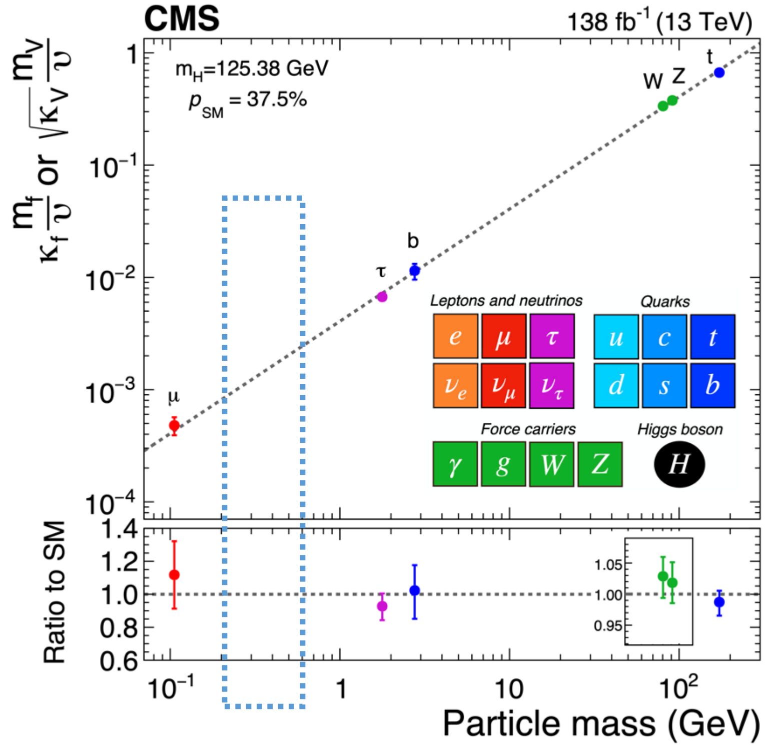
- 2024 excellent year for data taking
  - pp-operations: L(2024)=122/fb, tot. 331/fb (√s ≥13 TeV)
- Run III until mid 2026; HL-LHC until 2041
- 1347 collider-data papers



Higgs boson mass, widths & couplings







M_H is a free parameter

- Ingredient to couplings, BR, width, EWPO, M_W, $\sin^2\theta_W$
- Best single-channel measurement in 4ℓ [2409.13663]

125 040 ± 120 MeV (0.09%)
Fully driven by statistics
HL-LHC: go below 30 MeV!

Γ_H = 3.0 MeV + 2.0 -1.7 MeV **(exp. 4.1 MeV)**
from ratio of on/off-shell production (3.8**σ**)

H⟶cc ?!

- ML improvements in charm tagging (gNN)
- Obs. (Exp.) 95% CL $1.1<\varkappa_c<5.5$ ($\varkappa_c<3.5$)
- Searched for in VH

Interference resurrection

- VH is a weak-sector BSM probe
  - Use the SMEFT as a "model-independent" model
  - Include all symmetry preserving field monomials

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

$$\frac{C_{\phi W}}{\Lambda^2} \left(\phi^\dagger \phi\right) W_I^{\mu\nu} W_{\mu\nu}^I$$

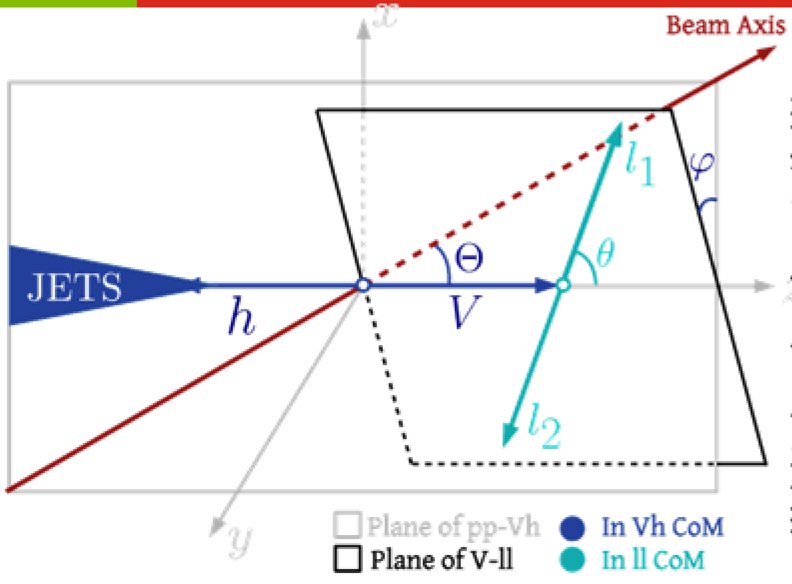
$$\frac{C_{qq}^{(8)}}{\Lambda^2} (\bar{q}\, \gamma^\mu T^A\, q)\, (\bar{q}\, \gamma_\mu T^A\, q)$$

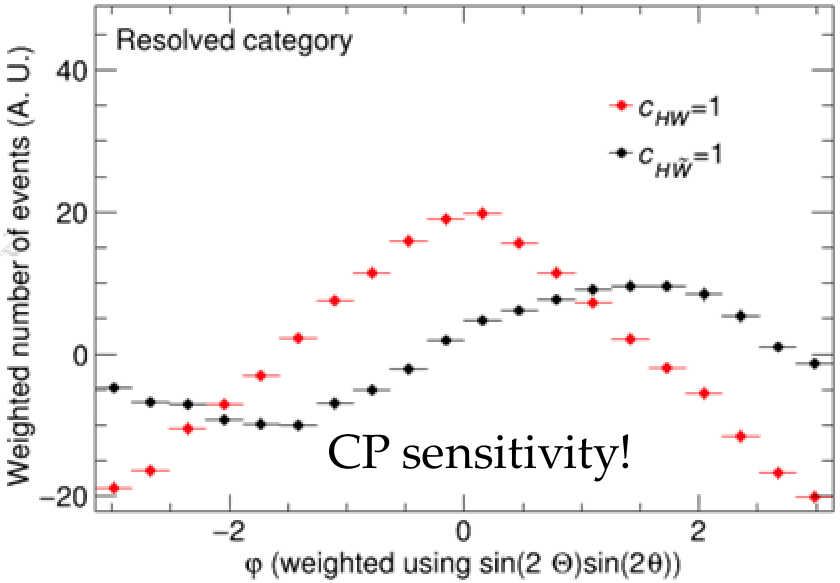
$$\frac{C_{qq}^{(3)}}{\Lambda^2} (\bar{q}\, \gamma^\mu \tau^I\, q)\, (\bar{q}\, \gamma_\mu \tau^I\, q)$$

unknown coefficients

known SM particles

known SM symmetries





- SMEFT = $|M_{SM} + \theta\, M_{BSM}|^2$ = SM + θ linear + θ^2 quadratic
  - Linear term: Interference! Boost into rest frame; 9 helicity functions

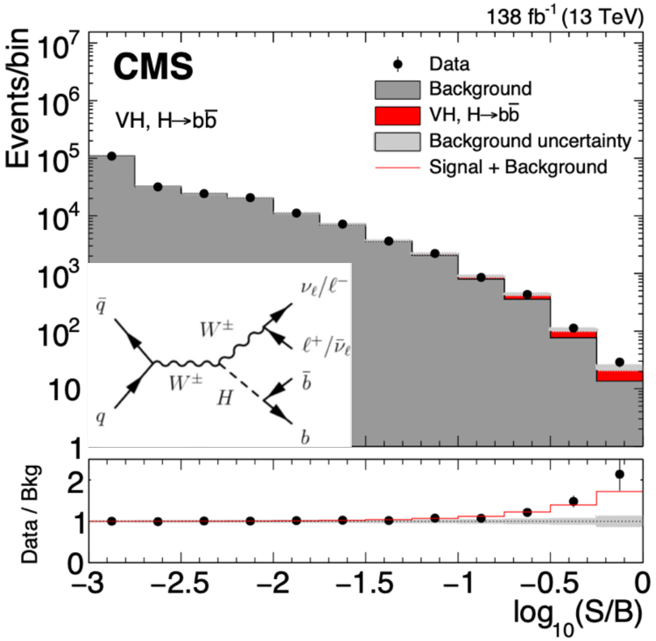
$$f_1 = f_{LL} = \sin^2\Theta \sin^2\theta, \qquad f_4 = f_{LT}^1 = \cos\varphi \sin\Theta \sin\theta,$$

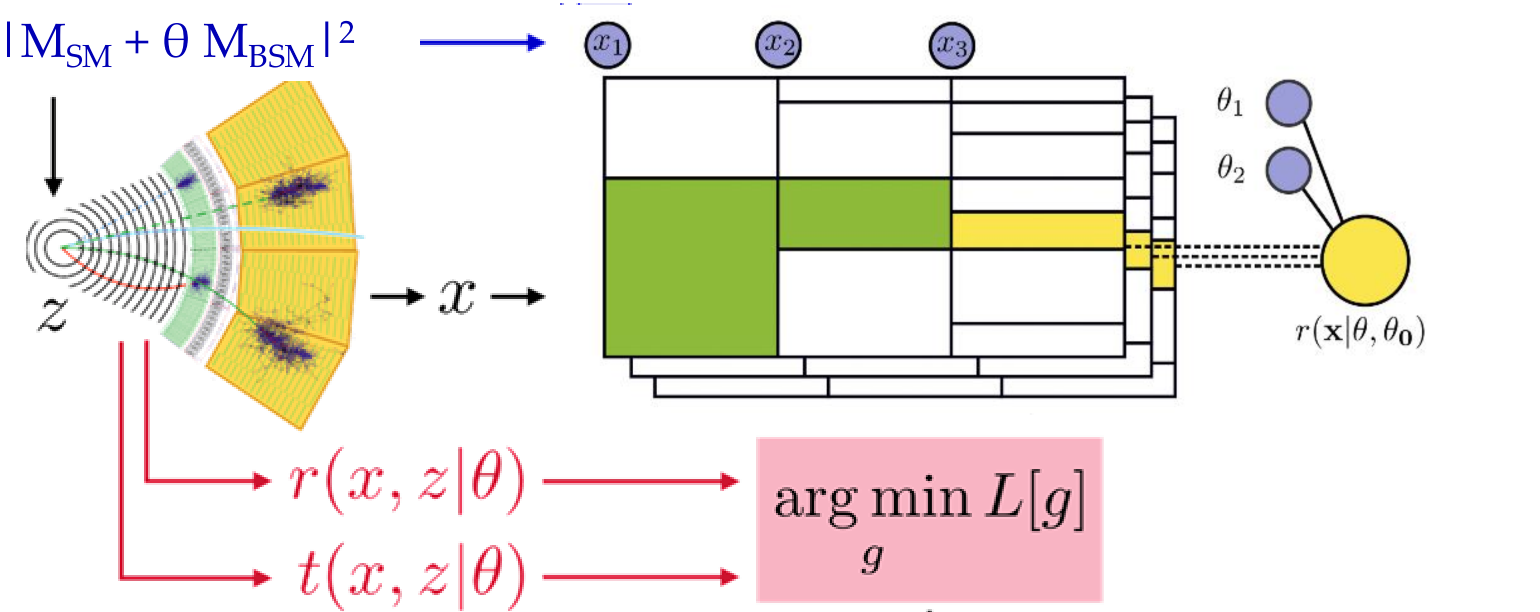
$$f_2 = f_{TT}^1 = \cos\Theta \cos\theta, \qquad f_5 = f_{LT}^2 = \cos\varphi \sin\Theta \sin\theta \cos\Theta \cos\theta$$

$$f_3 = f_{TT}^2 = (1+\cos^2\Theta)(1+\cos^2\theta),$$ +4 more

- Triple angular observables integrate out *unless*…
  (Ingredient #1) we keep suitable products → CP sensitivity

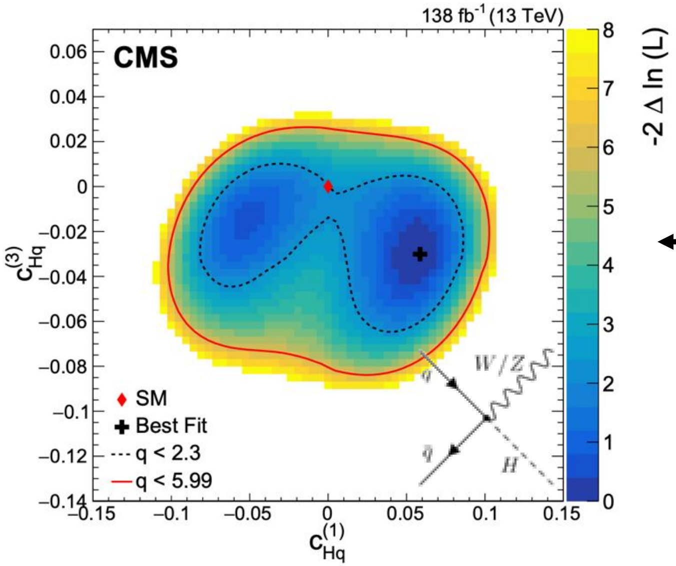
H+W/Z interpretation with ML

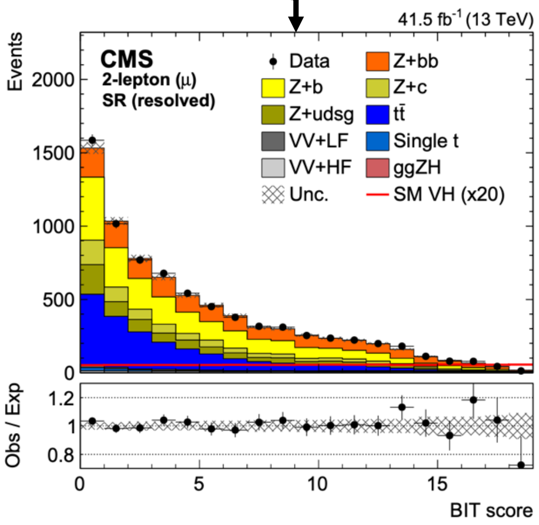




H unitarizes SM at high energy

- cancellations over many orders of magnitude ⟶ BSM probes
- Ingredient #2: Energetic observables ~θ^2 ⟶ combine?
- Developed ML algorithm fully aware of $|M_{SM} + \theta M_{BSM}|^2$ [MLST 2025, 2205.12976, CPC 2022]



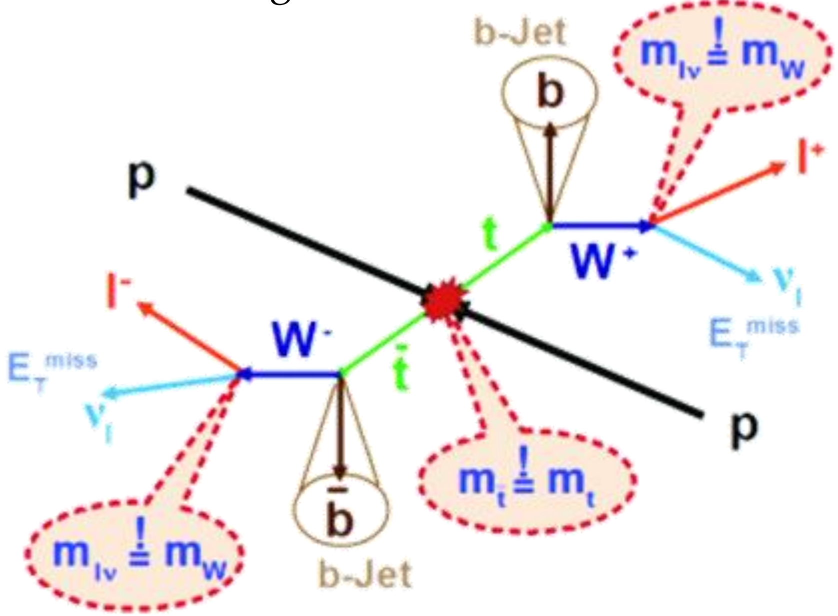


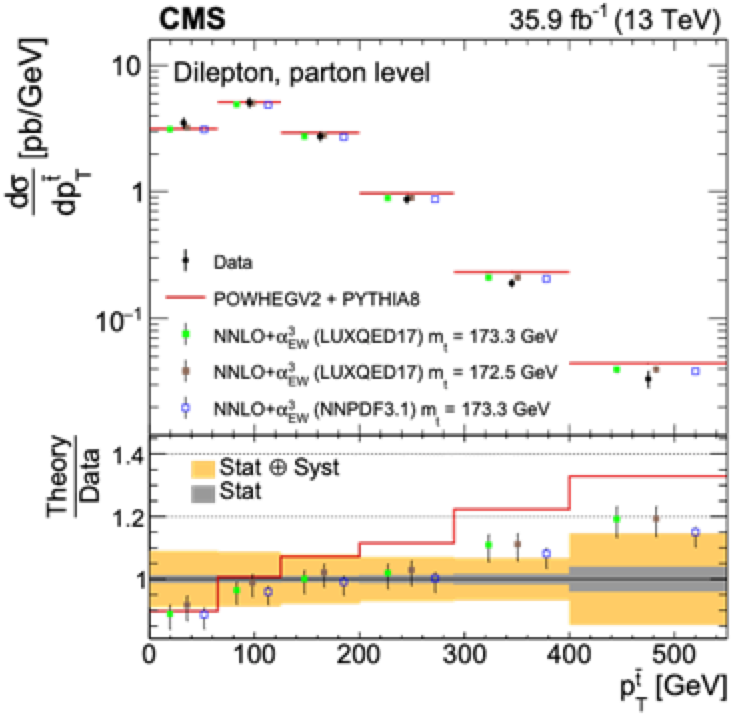
- "ML optimal obsevable"
  $0\ell/1\ell/2\ell$
  high dim!
  - 48 features
  - 6 BSM effects

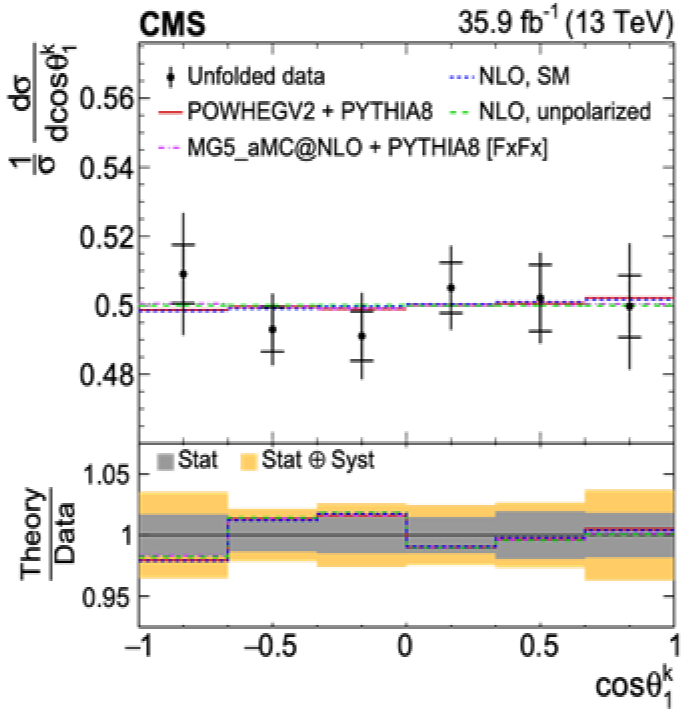
  up to x8 sensitivity [2411.16907]
  Systematic optimality?

Steps to precision: Top quark pairs

- Success = Theory+Exp
  - Consider kin. Reco in 2ℓ-channel
  - Clean signature







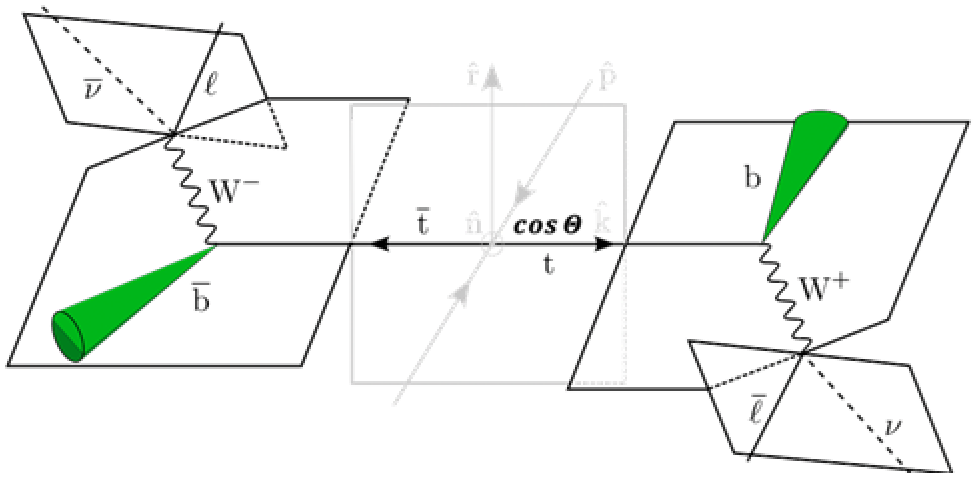
$$(p_{\ell_1} + p_{\nu_1})^2 = m_W^2, \quad (p_{\ell_2} + p_{\nu_2})^2 = m_W^2$$

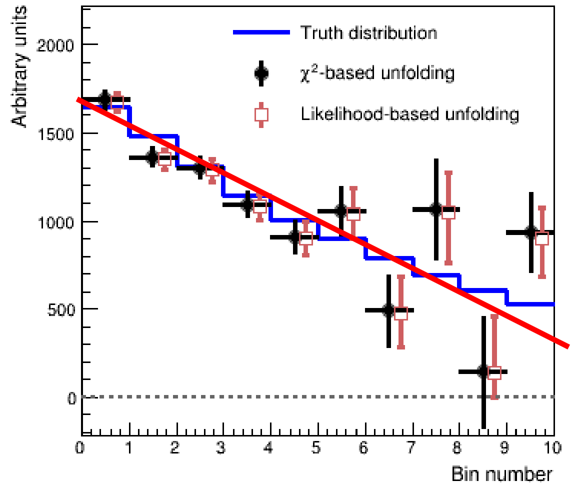
$$(p_{b_1} + p_{\ell_1} + p_{\nu_1})^2 = m_t^2, \quad (p_{b_2} + p_{\ell_2} + p_{\nu_2})^2 = m_t^2 \qquad \vec{p}_T^{\,\nu_1} + \vec{p}_T^{\,\nu_2} = \vec{E}_T^{\text{miss}}$$

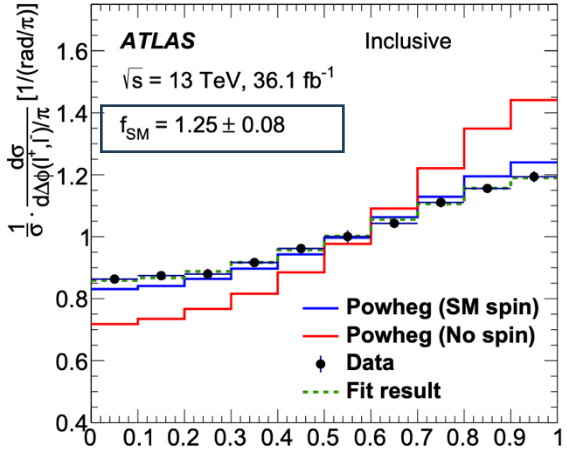
- 6 unknowns; 6 constraints
- Solve kinematic equations
- 4 solutions - 100x smearing and Likelihood-weighted average
  [JHEP 02 (2019) 149]
  [Phys. Rev. D 100, 072002 (2019)]

- Exquisite precision → All purpose tool
- 10% systematics on energetic quantities & diff. x-sec
- <5% on angles & in ratios
- What's good theory directions to best exploit this precision?

Top quark pair – steps to precision





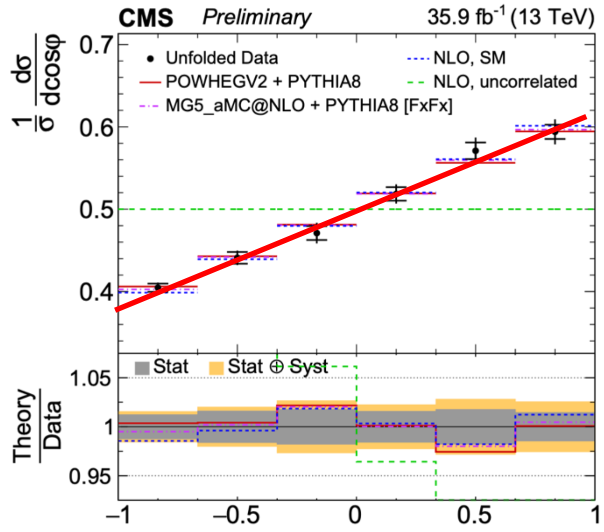


$$\cos\varphi_{\mathrm{lab}} = \hat{\ell}_1^{lab}\cdot\hat{\ell}_2^{lab}$$

- Example: spin-correlation matrix in the tt rest-frame [Bernreuther et al., 1508.05271]
  - Transform observables so that dependence is *linear* (or simple *known*.)

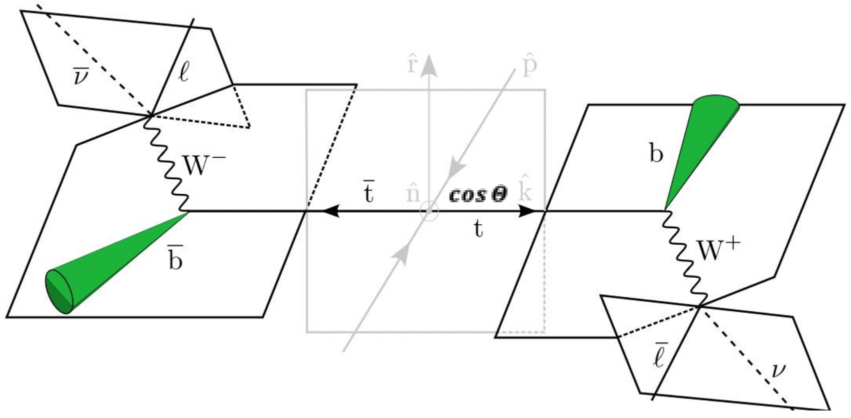
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi) \qquad D = -1/3\mathrm{Tr}[C] = -(C_{nn}+C_{rr}+C_{kk})/3$$

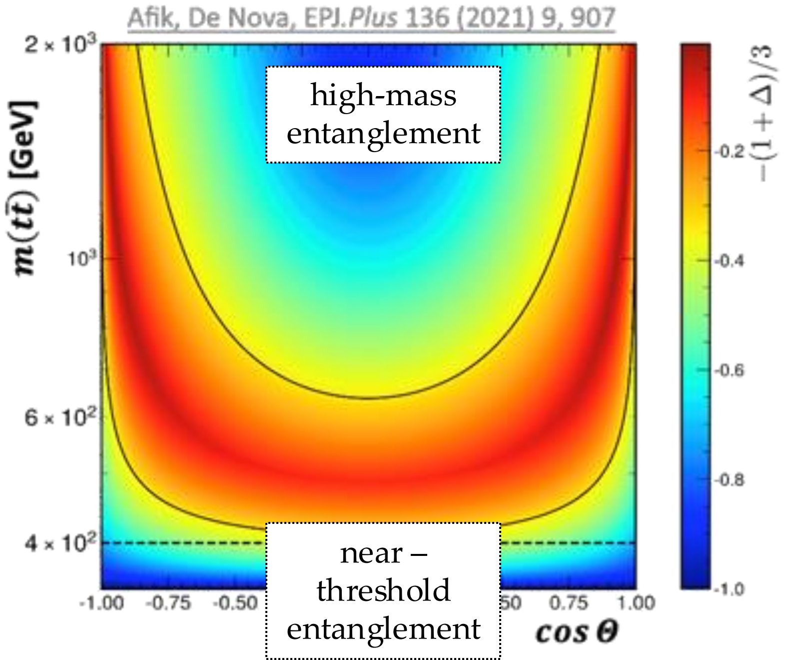
  - Experimentally, need determine a slope in the unfolded distribution
  - Curvature regularization constrains the 2nd derivative; regulator → ∞ → χ^2 fit
- ATLAS lab-frame SC meas. later understood via scale unc.
- Much smaller theory/modeling uncertainties in the rest frame

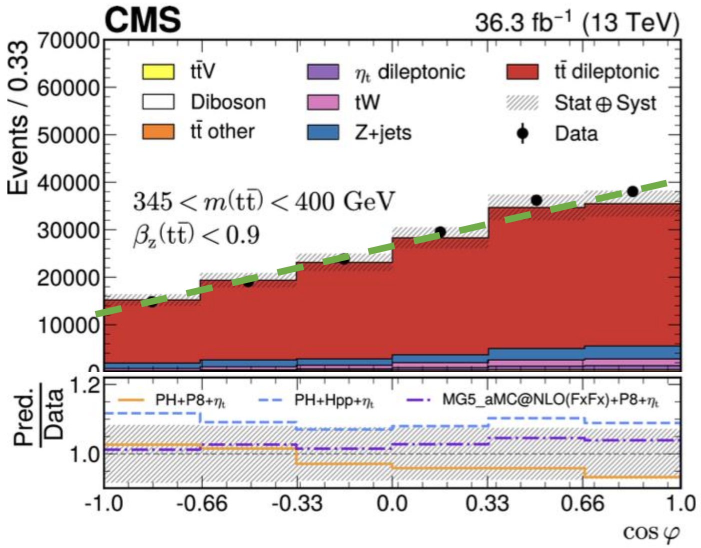


Rest-frame $\cos\varphi$

Entanglement of top quark pairs (2ℓ)







- Now that we've measured the spin-correlation matrix, what's next?

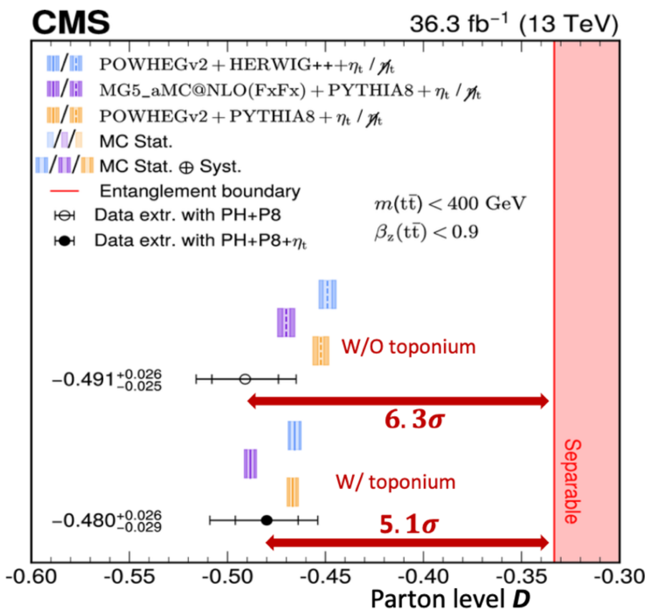
- Peres–Horodecki criterion

$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

→ Entanglement!

(C_{nn} etc. are diagonal entries)

- Entanglement at low & high m(tt)
- low m(tt) region [Rept.Prog.Phys. 87 (2024) 117801]
  - "Entanglement witness": Steepness of cos **φ**(ℓ^+,ℓ^-) spectrum
  - > 5.1 **σ** at low m(tt)
  - Main uncertainties: Toponium(!)



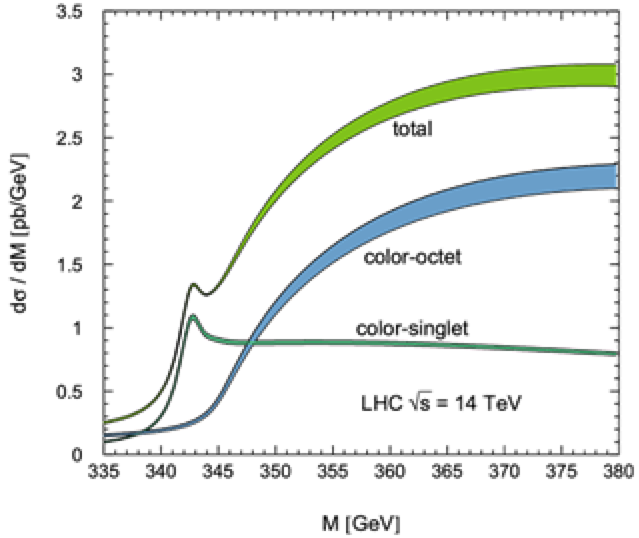
A near-threshold pseudo-scalar structure

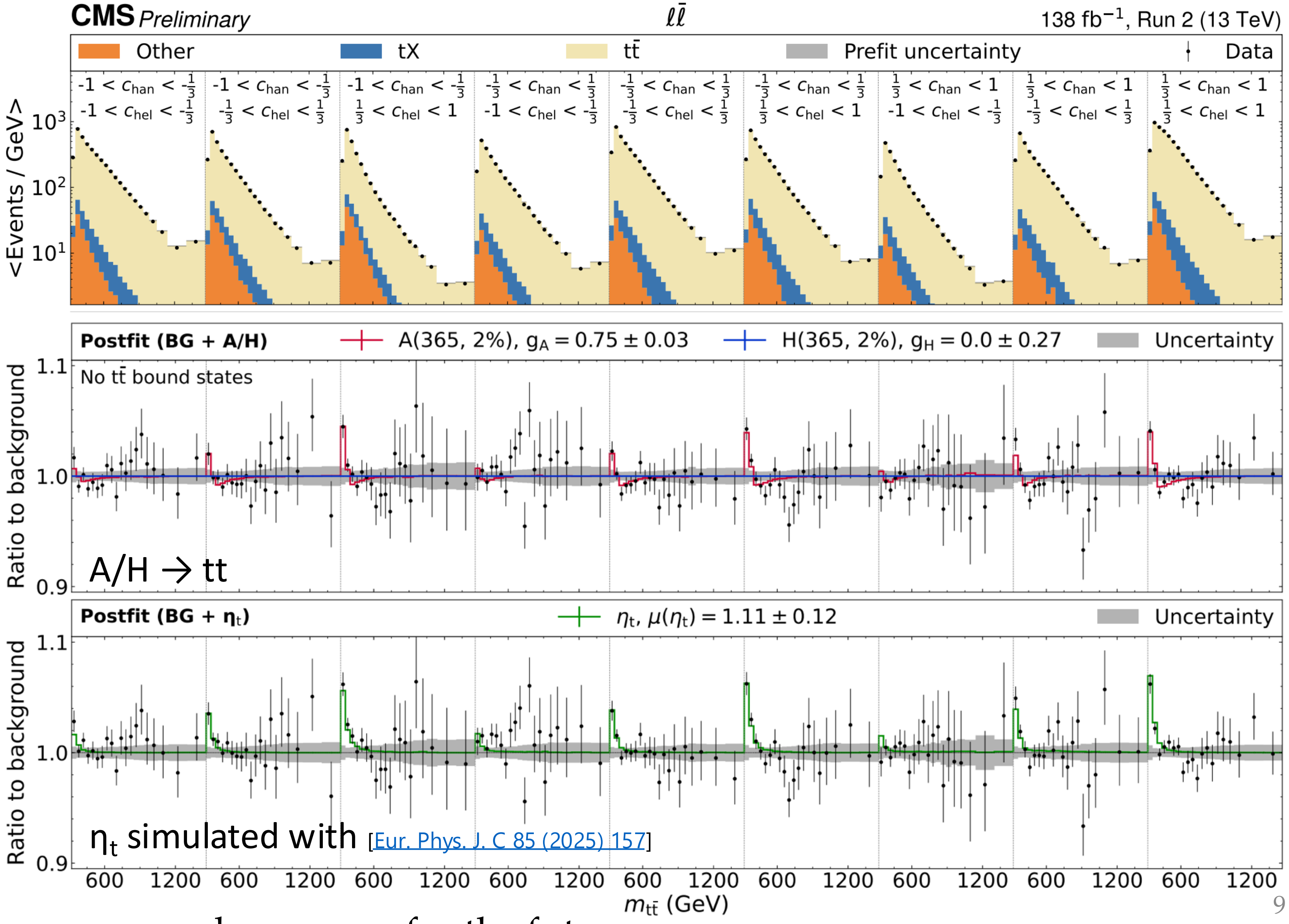
Deficit *in simulation* at low mass

- Measure in bins of spin-correlation observables
- Consistent with low-M pseudo-scalar ($^1S_0^{[1]}$) state [HIG-22-013] at ~340 GeV

Color-singlet bound state?

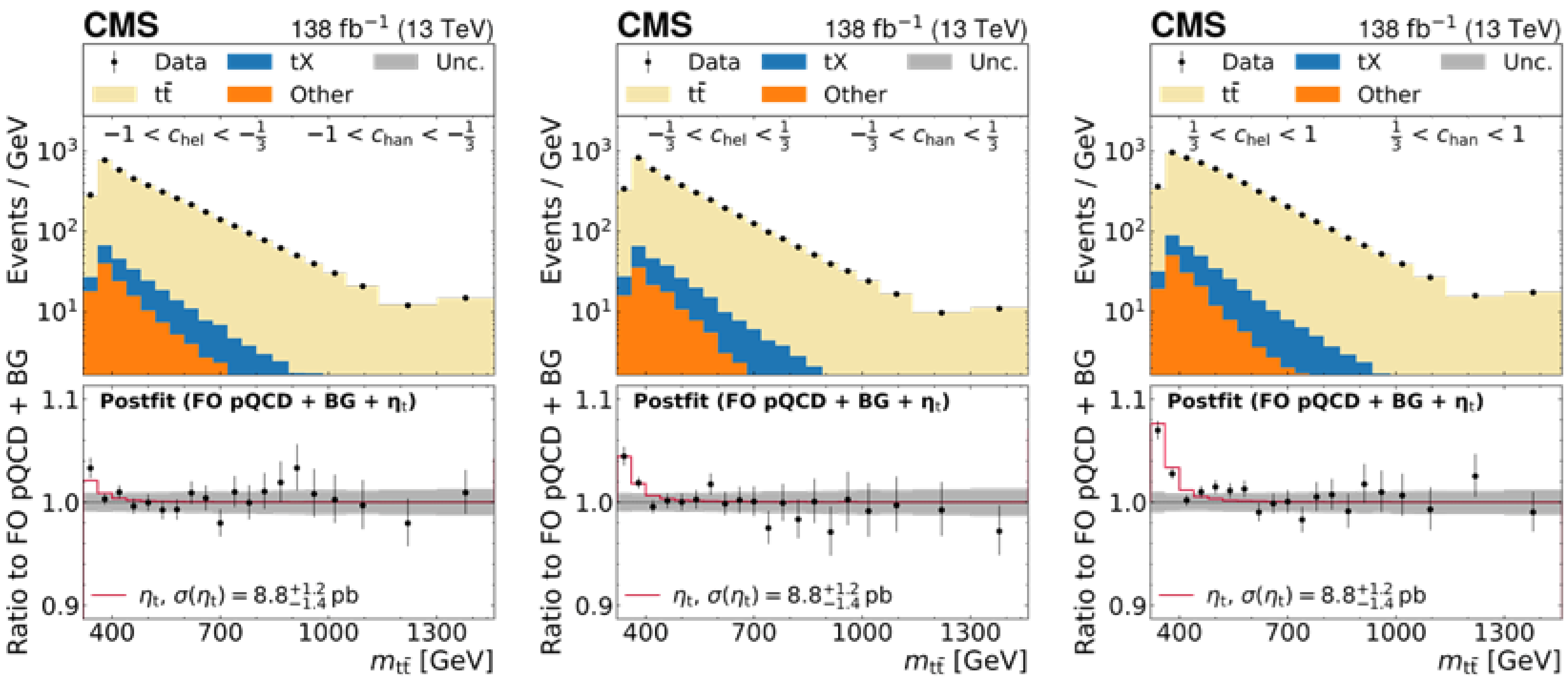
- Meas.: $\sigma(\eta_t) = 7.1 \pm 0.8$ pb
- NRQCD 6.43 pb [PRD 104, 034023 (2021)]

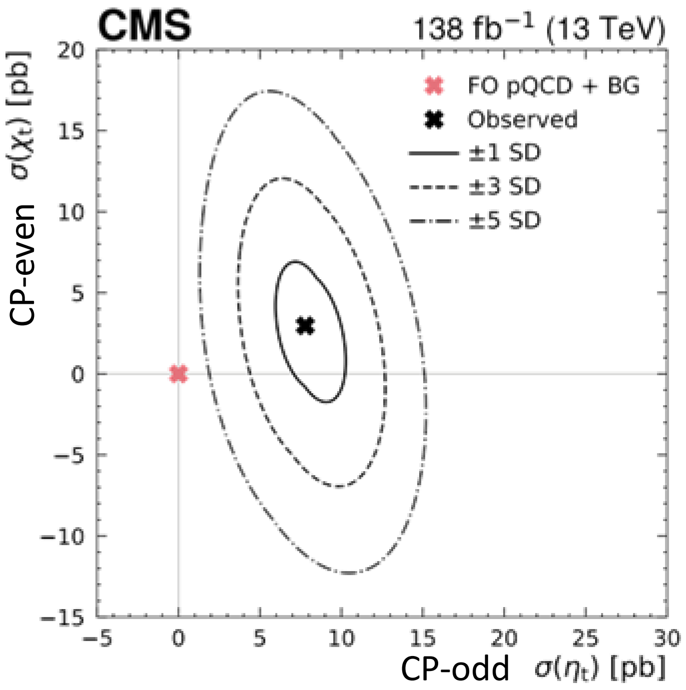




Interpret with caution! Nevertheless: a new research program for the future.

A near-threshold pseudo-scalar structure





– Interpretation in CP-odd η_t vs. χ_t CP-even scalar [TOP-24-007]

– Removing generator mass cut, refined modeling systematics

$$\sigma(\eta_t) = 8.8 \pm 0.5\,(\text{stat})\,^{+1.1}_{-1.3}\,(\text{syst})\,\text{pb} = 8.8\,^{+1.2}_{-1.4}\,\text{pb}.$$

observation with >5**σ**

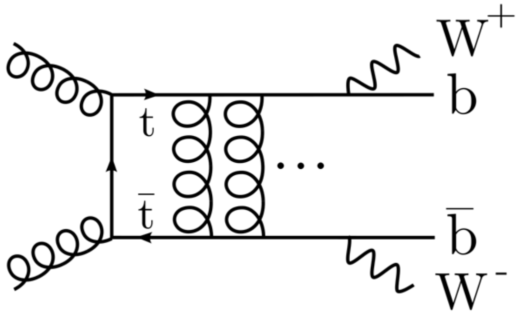
FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
MADGRAPH5_aMC@NLO FxFx + PYTHIA	9.8 ± 1.3
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8^{+1.2}_{-1.4}$

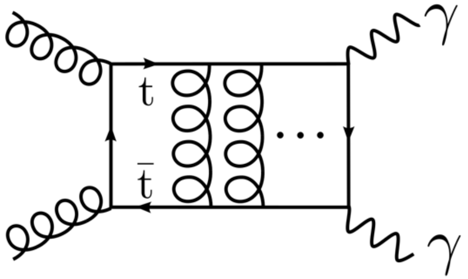
Where to go with this?

- The low-mass signal is an experimental feat
- "Operationally defined": QCD enhancement over fixed-order predictions
- Theory is actively developed
  - BR($\eta_t \to \gamma\gamma$) ~ 2×10^{-5} [2412.18527]
    ~50 evts in Run II+III ?!
  - ZZ (stat limited), hX (?), WW (?), gg (.. not)
  - ${}^3S_1^{[1]}$ ψ_t

$n^{2S+1}L_J$	M
$1^1S_0(^3S_1)$	343.62
$2^1S_0(^3S_1)$	344.59
$3^1S_0(^3S_1)$	344.93

[2411.17955]





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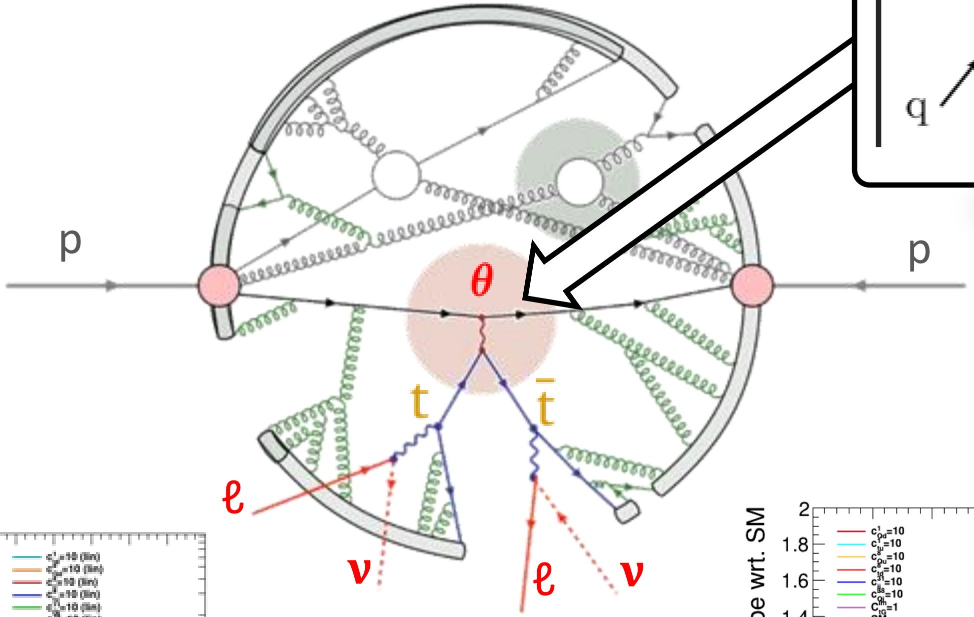
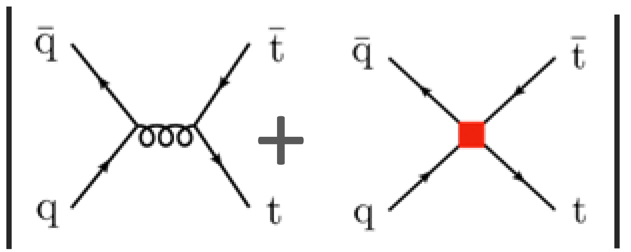
Simulation with [Eur. Phys. J. C 85 (2025) 157]

- Quality of the predictions & modeling will improve
  - "no theory consensus" [ref]
  - NLO, interference, matching, …
- New techniques needed for the experimental challenge
- I think a rich subfield will develop, to be explored together

High-mass top quark pairs (2ℓ)

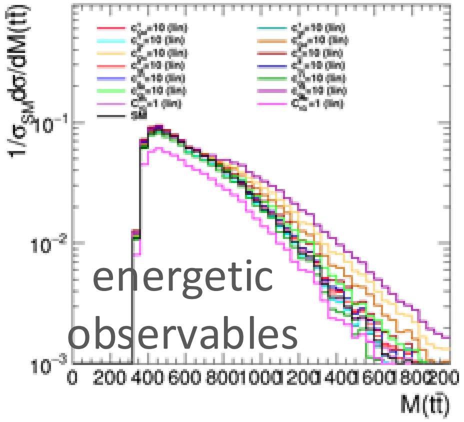
- What about the tails of tt(2ℓ)?

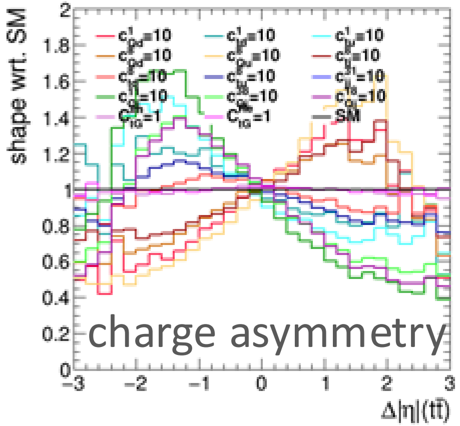


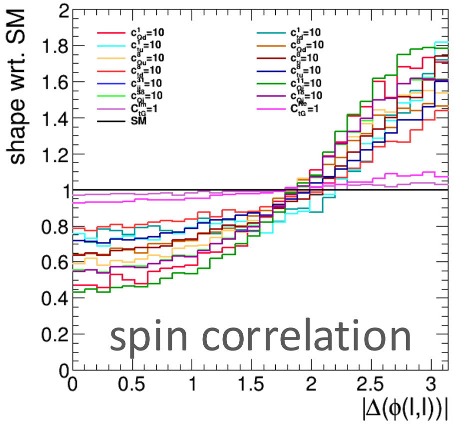


Standard Model Effective Theory

$$\left| \cdots + \cdots \right|^2 = d\sigma(\boldsymbol{x}) + \frac{\boldsymbol{\theta}}{\Lambda^2} d\sigma_{\mathrm{int}}(\boldsymbol{x}) + \frac{\boldsymbol{\theta}^2}{\Lambda^4} d\sigma_{\mathrm{quad}}(\boldsymbol{x})$$

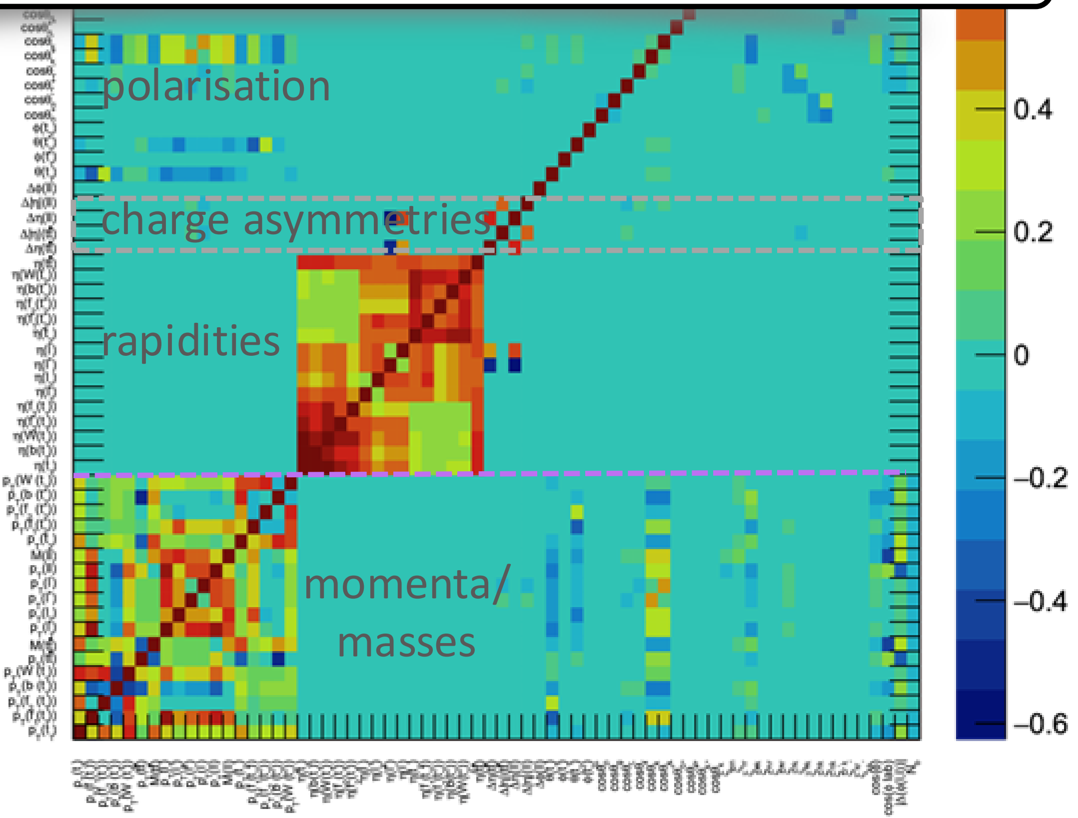






≳ 72 features

≳ 15 SMEFT POIs



linear feature correlation in tt(2ℓ)

Typically use only 1 or 2 features!

Unbinned modeling in 3-steps

1. Let's write an unbinned *additive* model

$$d\Sigma(\boldsymbol{x}|\boldsymbol{\theta},\boldsymbol{\nu}) = \sum_{p=1}^{N_p} \underbrace{R_p(\boldsymbol{x}|\boldsymbol{\theta})}_{\text{SMEFT}}\, \underbrace{\alpha_p^{\nu_p}}_{\text{normalisation ("k-factors")}} \underbrace{\exp\{\boldsymbol{\nu}^{\mathsf{T}}\Delta_{n,p,1}(\boldsymbol{x}) + \boldsymbol{\nu}^{\mathsf{T}}\Delta_{n,p,2}(\boldsymbol{x})\boldsymbol{\nu} + \ldots\}}_{\text{systematics } S_p(\boldsymbol{x}|\boldsymbol{\nu})}\, d\sigma_p(\boldsymbol{x}|\text{SM})$$

2. The experimentalist/theorist (not the framework) decides on specification

TT(2ℓ) has 90% purity: A single EFT process and a number of small backgrounds (DY, NP,…)

$$d\Sigma(\boldsymbol{x}|\boldsymbol{\theta},\boldsymbol{\nu}) = R_{\text{EFT}}(\boldsymbol{x}|\boldsymbol{\theta})\,S_{\text{EFT}}(\boldsymbol{x}|\boldsymbol{\nu})\,d\sigma_{\text{EFT}}(\boldsymbol{x}|\text{SM}) + \sum_{p=1}^{N_{\text{bkgs}}} \alpha_p^{\nu_p} S_p(\boldsymbol{x}|\boldsymbol{\nu})\,d\sigma_p(\boldsymbol{x}|\text{SM})$$

3. Form the ratio & learn the factors!

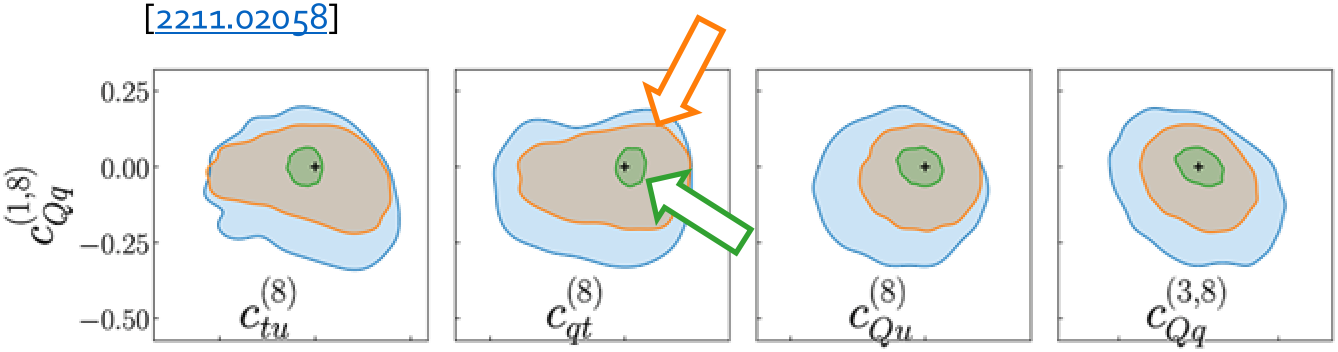
$$\frac{d\Sigma(\boldsymbol{x}|\boldsymbol{\theta},\boldsymbol{\nu})}{d\Sigma(\boldsymbol{x}|\text{SM})} = \frac{R_{\text{EFT}}(\boldsymbol{x}|\boldsymbol{\theta})S_{\text{EFT}}(\boldsymbol{x}|\boldsymbol{\nu}) + \sum_{p=1}^{N_{\text{bkgs}}} \alpha_p^{\nu_p} S_p(\boldsymbol{x}|\boldsymbol{\nu}) \frac{d\sigma_p(\boldsymbol{x}|\text{SM})}{d\sigma_{\text{EFT}}(\boldsymbol{x}|\text{SM})}}{1+\sum_{p=1}^{N_{\text{bkgs}}} \frac{d\sigma_p(\boldsymbol{x}|\text{SM})}{d\sigma_{\text{EFT}}(\boldsymbol{x}|\text{SM})}} \approx \frac{\hat{R}_{\text{EFT}}(\boldsymbol{x}|\boldsymbol{\theta})\hat{S}_{\text{EFT}}(\boldsymbol{x}|\boldsymbol{\nu}) + \sum_{p=1}^{N_{\text{bkgs}}} \alpha_p^{\nu_p} \hat{S}_p(\boldsymbol{x}|\boldsymbol{\nu})\hat{g}_p(\boldsymbol{x})}{1+\sum_{p=1}^{N_{\text{bkgs}}} \hat{g}_p(\boldsymbol{x})}$$

1) SMEFT learning — 2) systematics learning — 3) classifiers

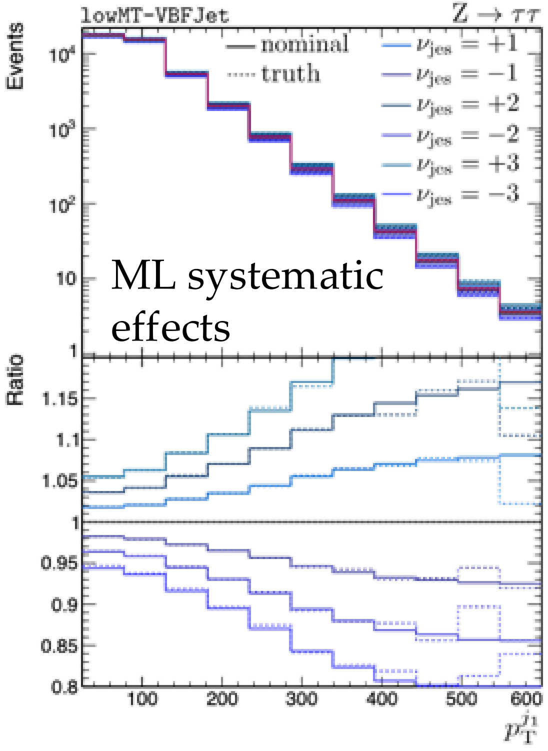
Likelihood ratio → optimal test statistic! Adding systematics or processes *doesn't invalidate* partial training!

What are the gains?

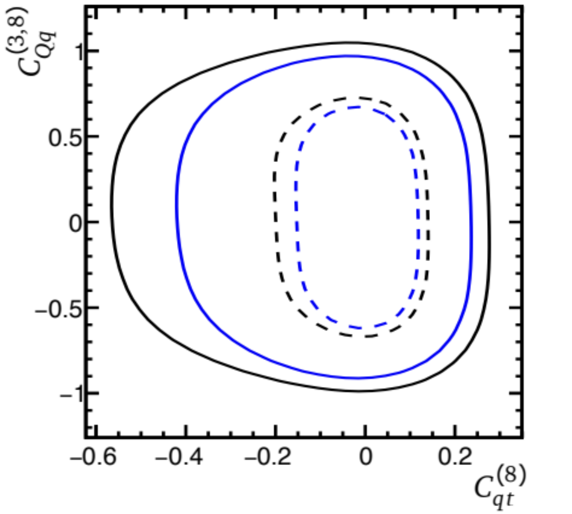
- Systematics-free analysis of 8 WC with 18 features shows ~x5 sensitivity gain
  ML4EFT R. Ambrosio, J. Hoeve, M. Madigan, J. Rojo, V. Sanz [2211.02058]



- Developed techniques to learn systematics
  [RS, Mach. Learn. Sci. Technol. 6 015007 (2025)]
- New project starting soon @ HEPHY on tt(2ℓ)
  [PAT7453824]
- Tested technology on H→$\tau\tau$ cross section
  - FAIR Universe Higgs Uncertainty Challenge [2410.02867]
  - Very steep learning curve!
  - Currently at the top of the leader board



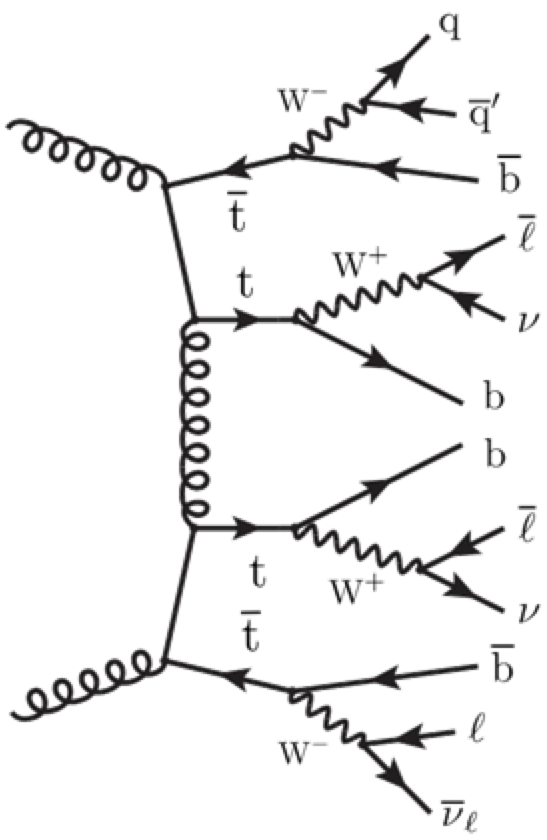
Effects on limits

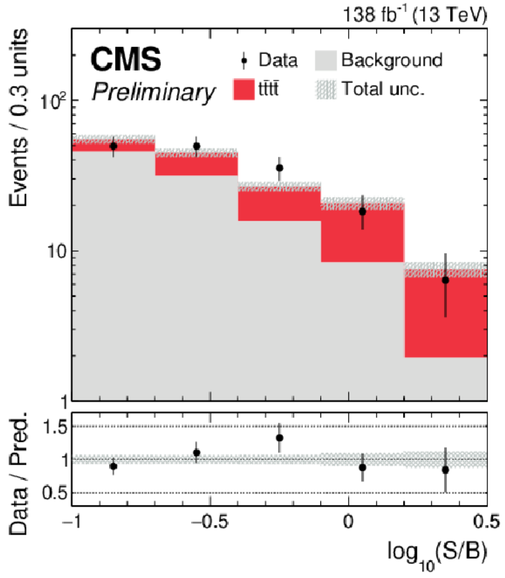


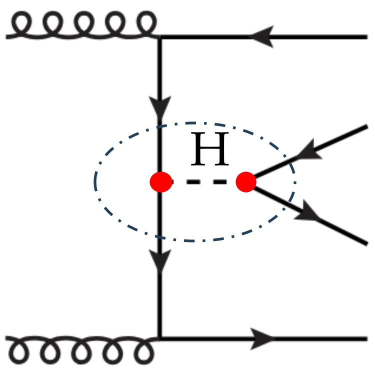
1	HEPHY	1	2025-03-12 18:26	244525	GOLLUM_calib-v5_v2-8	0.878
2	HEPHY	1	2025-03-10 20:20	243324	GOLLUM_v10-3	0.833
3	ibrahime	1	2025-03-12 14:47	244411	AdvnF-2j-4nf-edge	0.823

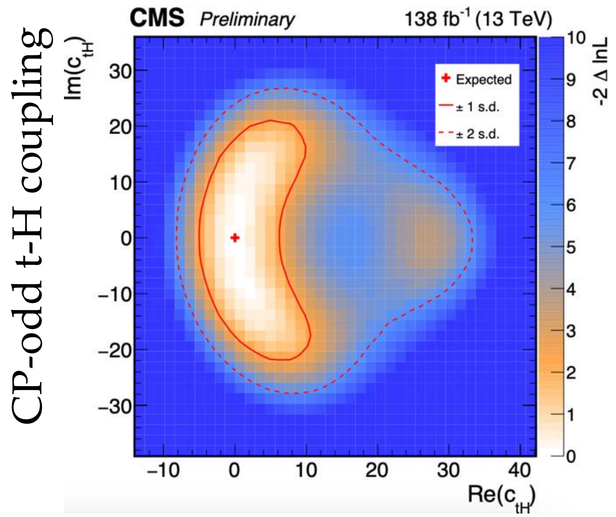
(preliminary)

Four top quark production

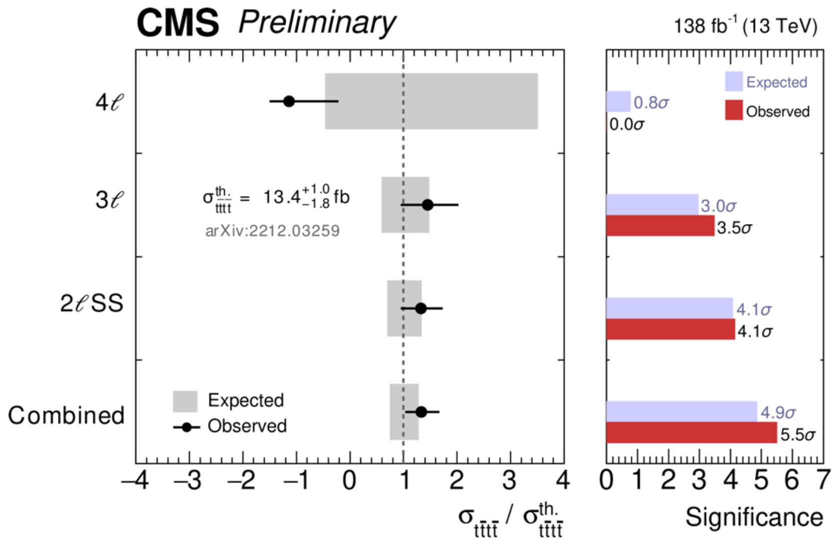








CP-even t-H coupling



- Complex final state 2ℓSS/3ℓ/4ℓ
- Observation in 2023
  $\sigma_{tttt} = 13.4 + 1.0 - 1.8$ fb
  [Phys. Lett. B 847 (2023) 138290]

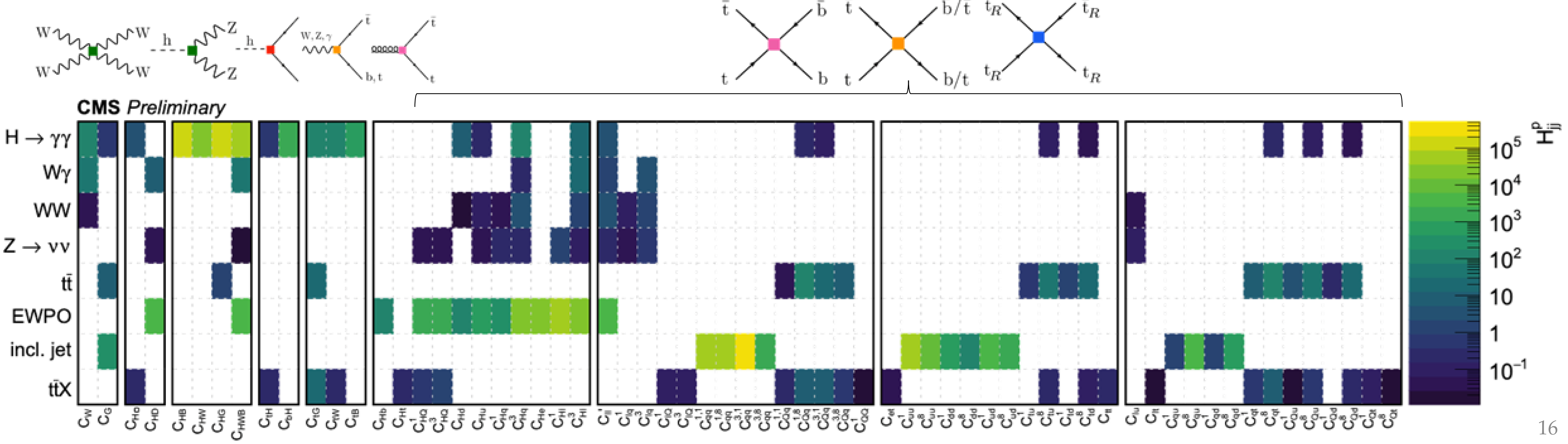
- Process observed ≥ 5**σ** in 2023
- Probe forces among top quarks
  - Color singlet/octet, different chiralities, CP-even and odd
  - (Pseudo-/) Scalar & vector mediator resonances
  - Yukawa-coupling modifications probe indirect effects from H
- Equal BSM footing with EFT

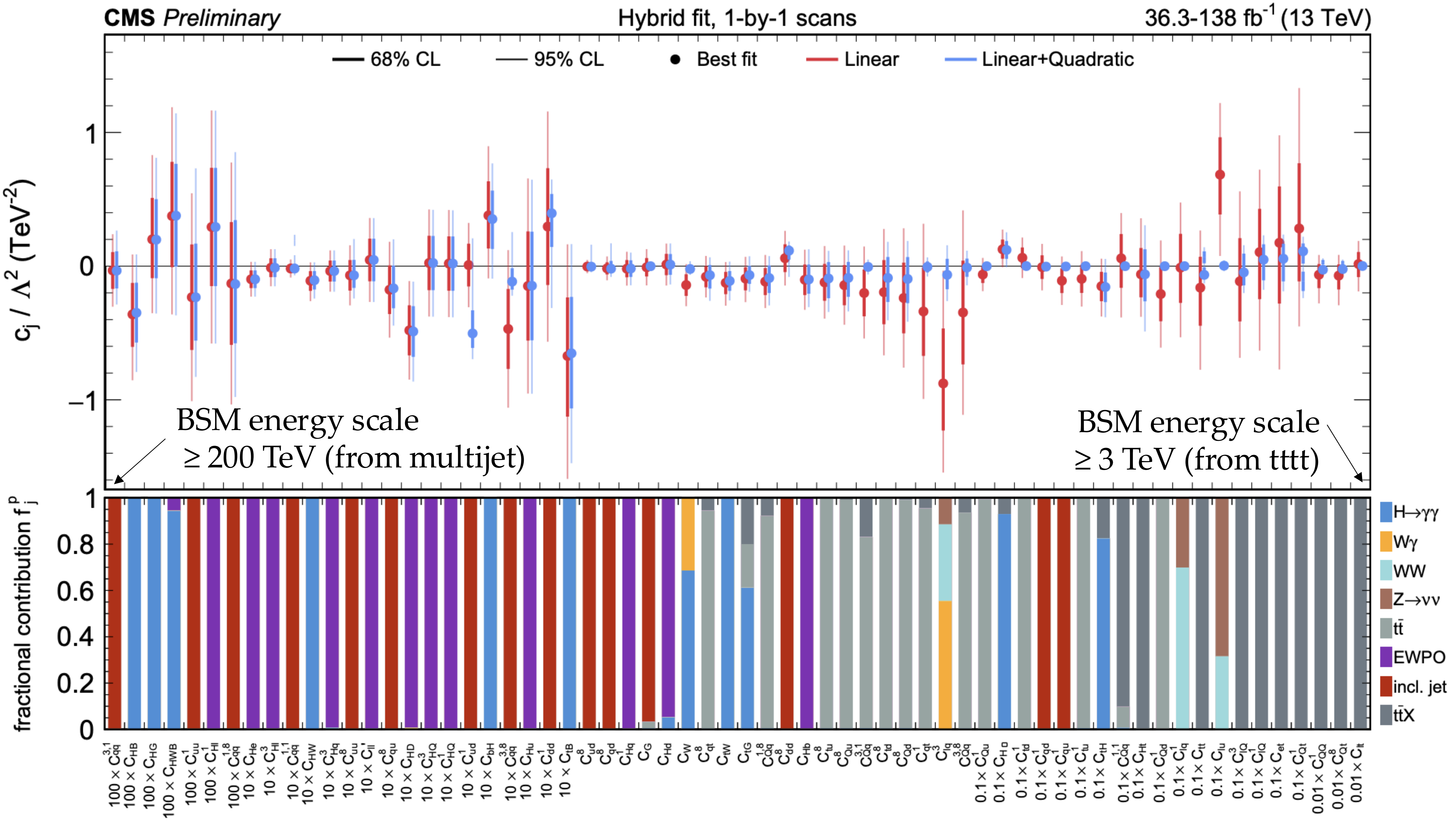
CMS global EFT fit

$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]
$W\gamma$	Fid. diff. cross sections	$p_T^{\gamma} \times \lvert\phi_f\rvert$
WW	Fid. diff. cross sections	$m_{\ell\ell}$
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^{Z}
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$
EWPO	Pseudo-observables	$\Gamma_Z,\ \sigma^0_{had},\ R_\ell,\ R_c,\ R_b,\ A^{0,\ell}_{FB},\ A^{0,c}_{FB},\ A^{0,b}_{FB}$
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$
$t\bar{t}X$	Direct EFT	Yields in regions of interest

Combination of Higgs, EW, Top, QCD, EWPO to globally constrain non-resonant BSM: SMEFT [SMP-24-003]

- 64 individual measurements, 42 eigenvectors constrained simultaneously
- $h \to \gamma\gamma$ STXS, leading sensitivity to 11 coefficients





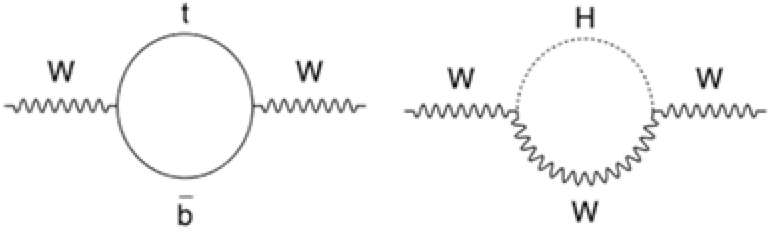
CMS Preliminary
Hybrid fit, 1-by-1 scans
36.3-138 fb^{-1} (13 TeV)
68% CL
95% CL
Best fit
Linear
Linear+Quadratic
c_j / Λ^2 (TeV^{-2})
BSM energy scale ≥ 200 TeV (from multijet)
BSM energy scale ≥ 3 TeV (from tttt)
fractional contribution f_j^p
H→γγ
Wγ
WW
Z→νν
$t\bar{t}$
EWPO
incl. jet
$t\bar{t}X$

The mass of the W boson

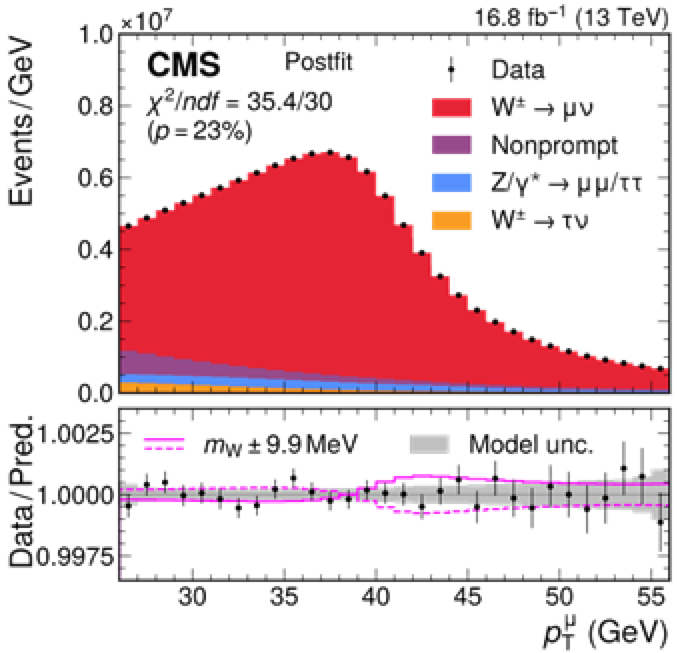
- With M_H and M_t known, the SM is over-constrained

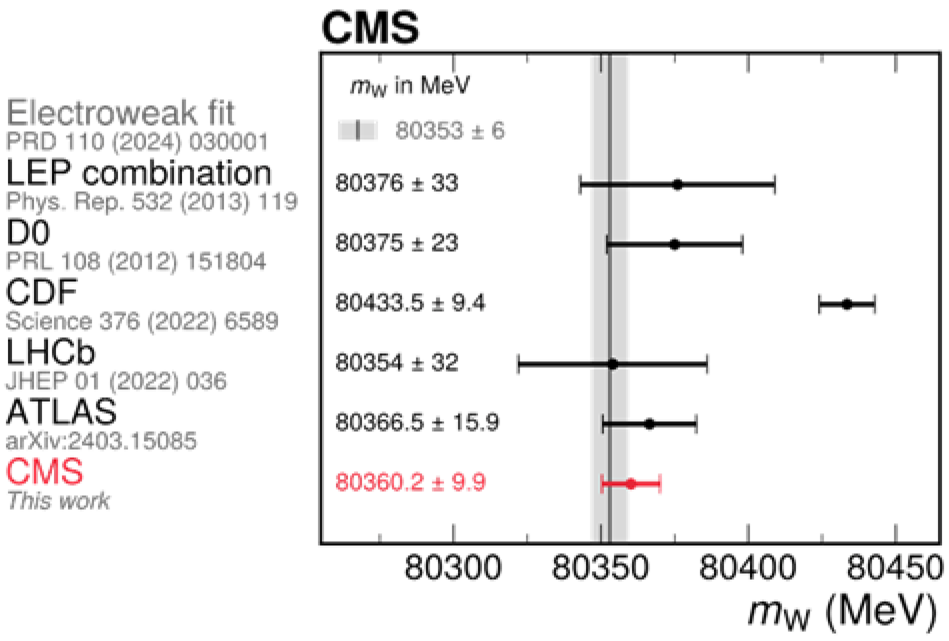
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{QED}}{\sqrt{2}G_F}\times\frac{1}{1-\Delta r}$$

- Δr is mostly affected by M_t and M_H



- Lack of consistency would be a sign of BSM





- Data set 16.8/fb at 13 TeV with ~25 PU
- Highly binned measurement in $p_T(\boldsymbol{\mu})$, $\eta(\boldsymbol{\mu})$, q
- Difficulty: In-situ constraint of PDFs, $p_T(\ell)$ calibration J/**Ψ**, validation Z, modeling (helicity fractions, scales, non-pert.)

M_W = 80 360.2 ± 9.9 MeV [Nature sub.] [press release]

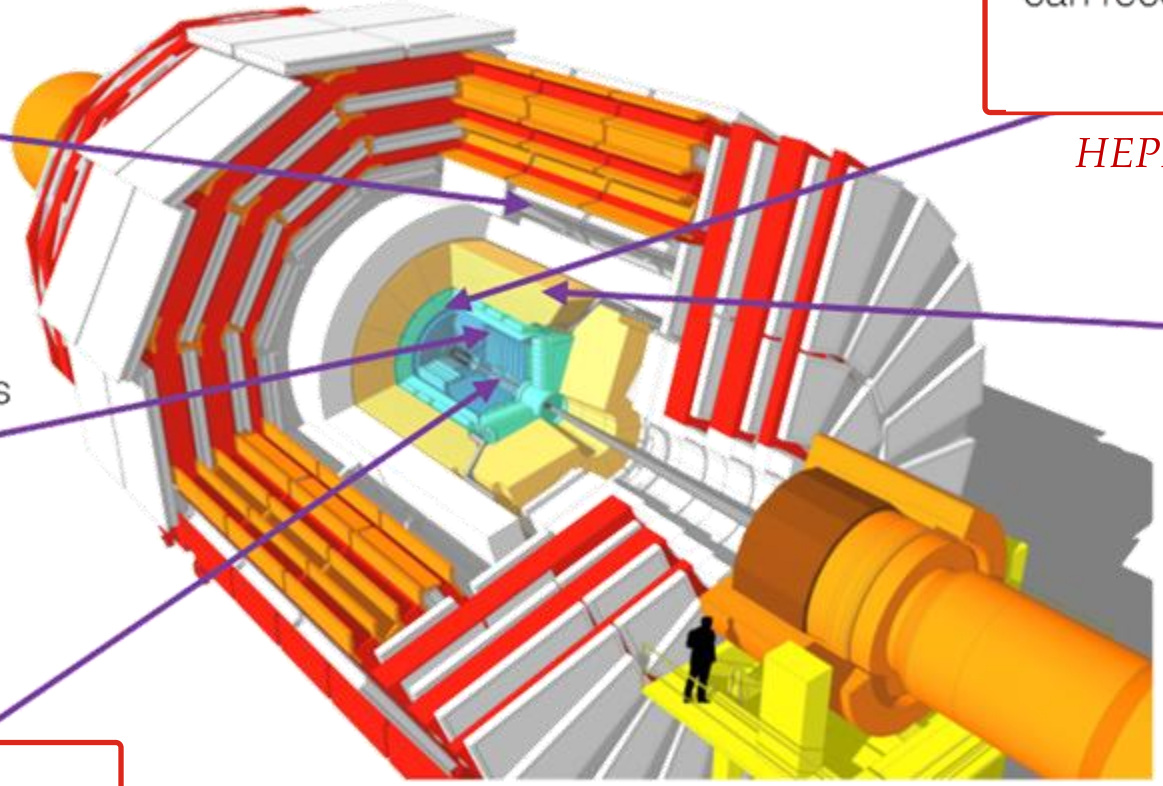
- Important uncertainties:
  Scale of p_T (4.8MeV), PDF (4.4 MeV)

CMS upgrades for HL-LHC

Improved muon coverage and trigger
increased RPC coverage (1.5 < |η| < 2.4)
new electronics
[CMS-TDR-016]

New endcap calorimeters
high granularity
can reconstruct showers in 3D
CMS-TDR-019

HEPHY Tracker/HGCal group



Updates to calorimeter and trigger
higher granularity
electronics for trigger

New precision timing detector
Timing resolution of 30-40 ps for MIPs
full coverage of |η| < 3.0
[CMS-TDR-020]

HEPHY Tracker/HGCal group

New inner tracker
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to |η| < 4 [CMS-TDR-014]

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1
[L1: CMS-TDR-021]
[DAQ/HLT: CMS-TDR-022]

M_t from track-based energy correlators

- In traditional analyses, we
  - a) predict S-matrix elements $S_{fi} = \langle f_{\text{out}} | i_{\text{in}} \rangle = \delta_{fi} + i\,(2\pi)^4 \delta^{(4)}(p_f - p_i)\,\mathcal{M}_{fi}$
  - b) sample from |M|^2 c) compute observables (e.g. peak position) d) compare with data
- New paradigm: Energy correlators (EEEC) [2201.08393]
  - Define "calorimeter" cells at spatial infinity

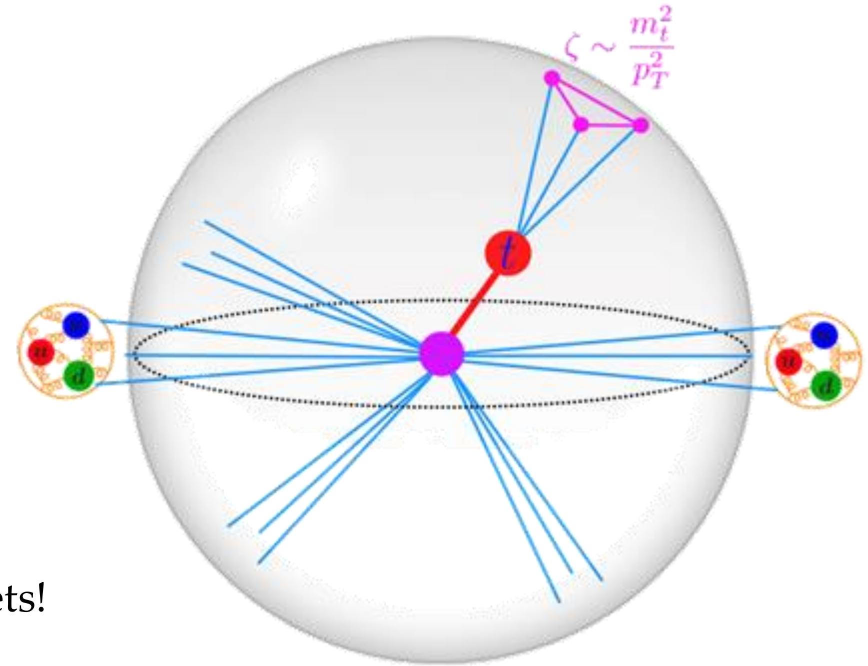
$$\mathcal{E}(\hat{n}) = \lim_{r\to\infty} r^2 \int_{-\infty}^{\infty} dt\, n^i\, T_{0i}(t, r\,\hat{n})$$

  - Compute the expectation of the operator product

$$\text{EEEC}^{(3)}(\vec{n}_1, \vec{n}_2, \vec{n}_3) = \langle \Psi | \mathcal{E}(\hat{n}_1)\, \mathcal{E}(\hat{n}_2)\, \mathcal{E}(\hat{n}_3) | \Psi \rangle$$

$$= \sum_{\sigma \in S_3} \prod_{j=1}^{3} \left[E(p_{\sigma(j)})\, \delta^{(2)}\left(\hat{p}_{\sigma(j)} - \vec{n}_j \right) \right]$$

  - This is an experimentally trivial representation of the data: triplets!

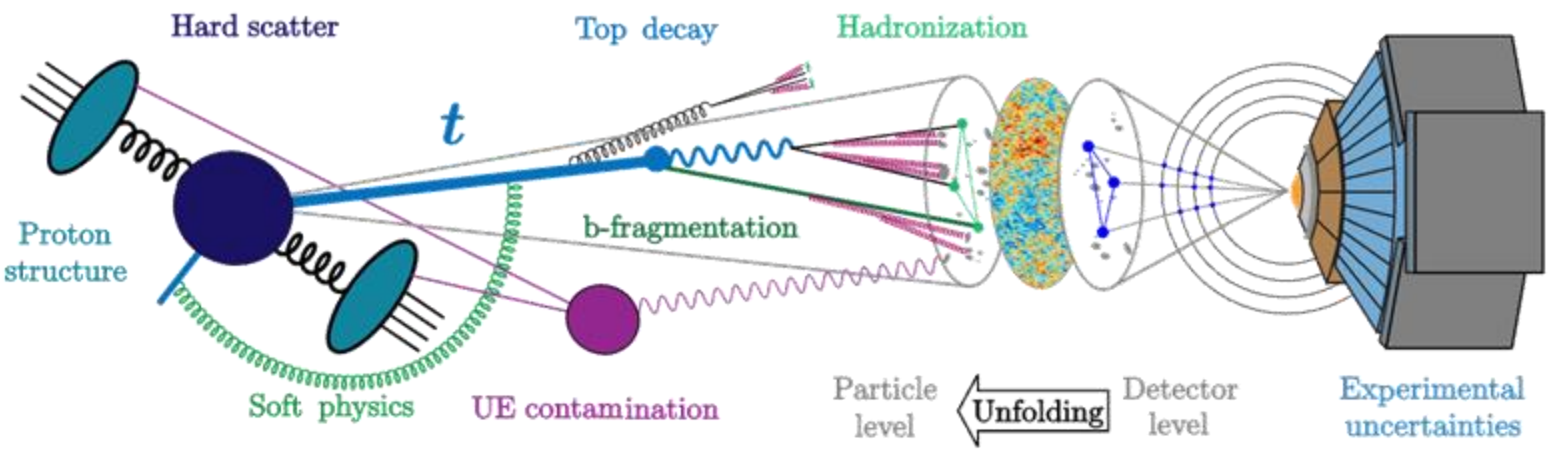


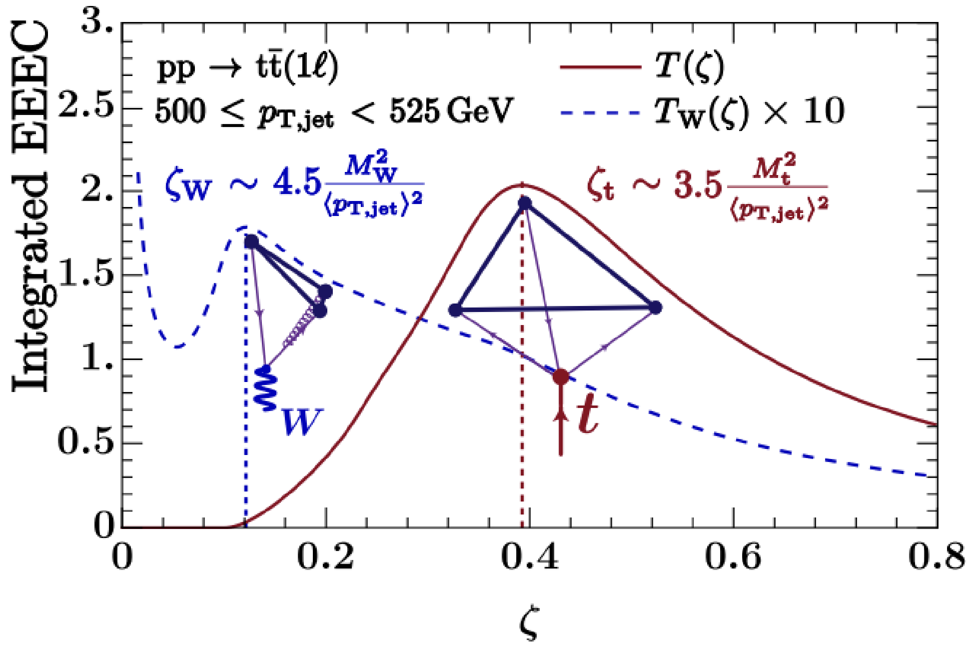
- The energy correlator is parametric in the directions!
  For example, can compute an arbitrary Lorentz-invariant substructure observable

$$\int d\Omega_1 \ldots d\Omega_m \text{EEEC}(\underbrace{\vec{n}_1, \ldots, \vec{n}_1}_{k_1 \text{ times}}, \underbrace{\vec{n}_2, \ldots, \vec{n}_2}_{k_2 \text{ times}}, \ldots \underbrace{\vec{n}_m, \ldots \vec{n}_m}_{k_m \text{ times}})\, n_1^{\mu_{1,1}} \ldots n_1^{\mu_{1,k_1}} \ldots n_m^{\mu_{m,k_1}} \ldots n_m^{\mu_{m,k_m}} \longrightarrow S^{\mu\nu} = \frac{\sum_{i<j} p_i \cdot p_j \left[p_i^\mu p_j^\nu + p_j^\mu p_i^\nu \right]}{\sum_{i<j} (p_i \cdot p_j)^2}$$

M_t from track-based energy correlators

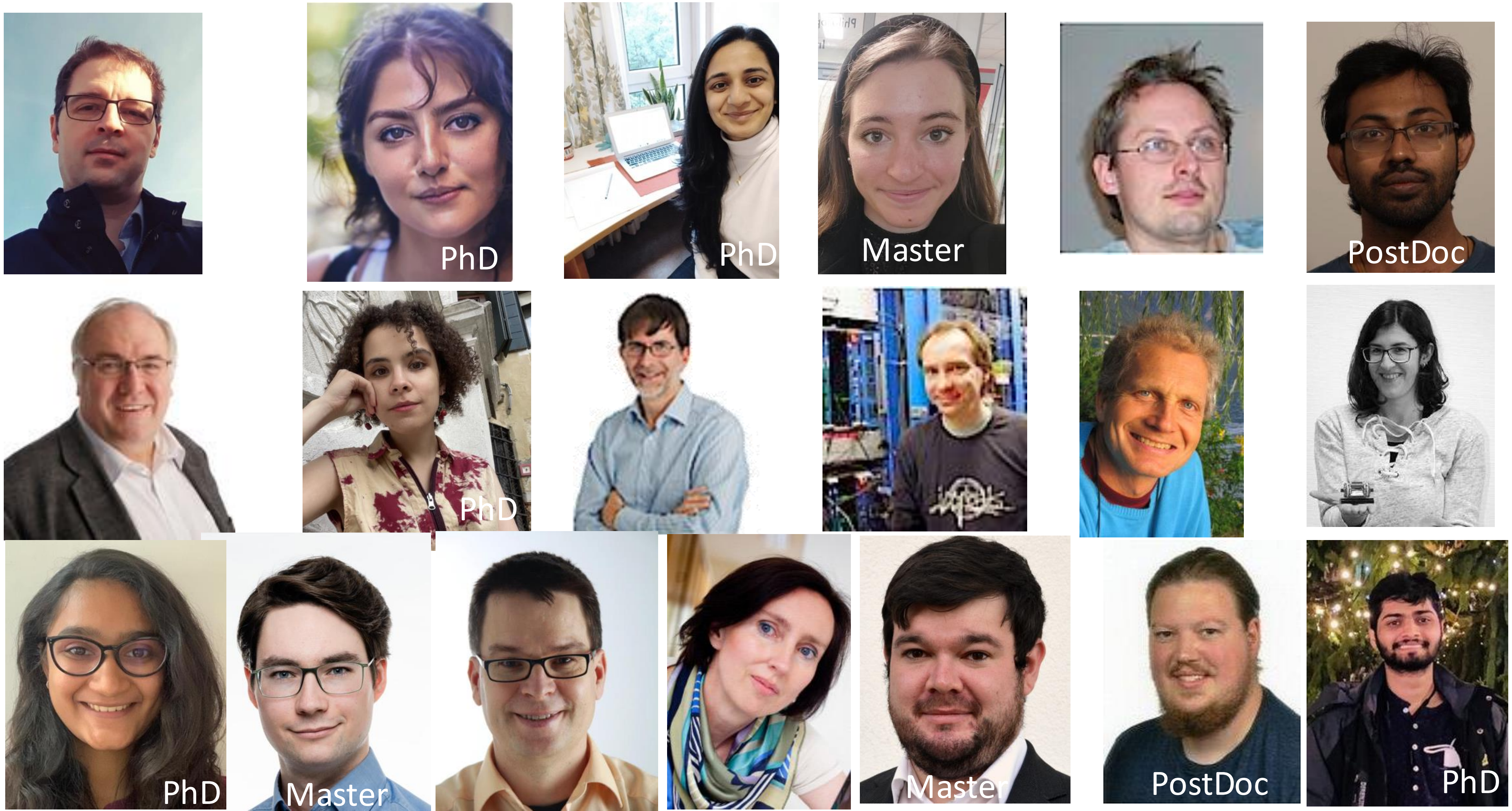
- Track-based M_t measurement with the double- and triple-energy correlator with
  - "in principle" theoretical control
  - FWF Project with UNIVIE & DESY [PAT2312224]
- Several aspects understood:
  - Which correlators to use, how & where to integrate
  - Calibration on M_W [2311.02157]
  - Feasibility study [2407.12900]
- Next steps:
  - Unfolding of triplet kinematics
    - 3D or 5D? Unbinned-ML?
  - Real-world demonstration
- Uncertainty projection
  - Run II+III: 500 MeV
  - HL-LHC: 300 MeV





ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS



Addons + Summary

– CMS has also a rich program also in
  – Flavor physics (Quarks & leptons), LVF, FCNC, …, HIN

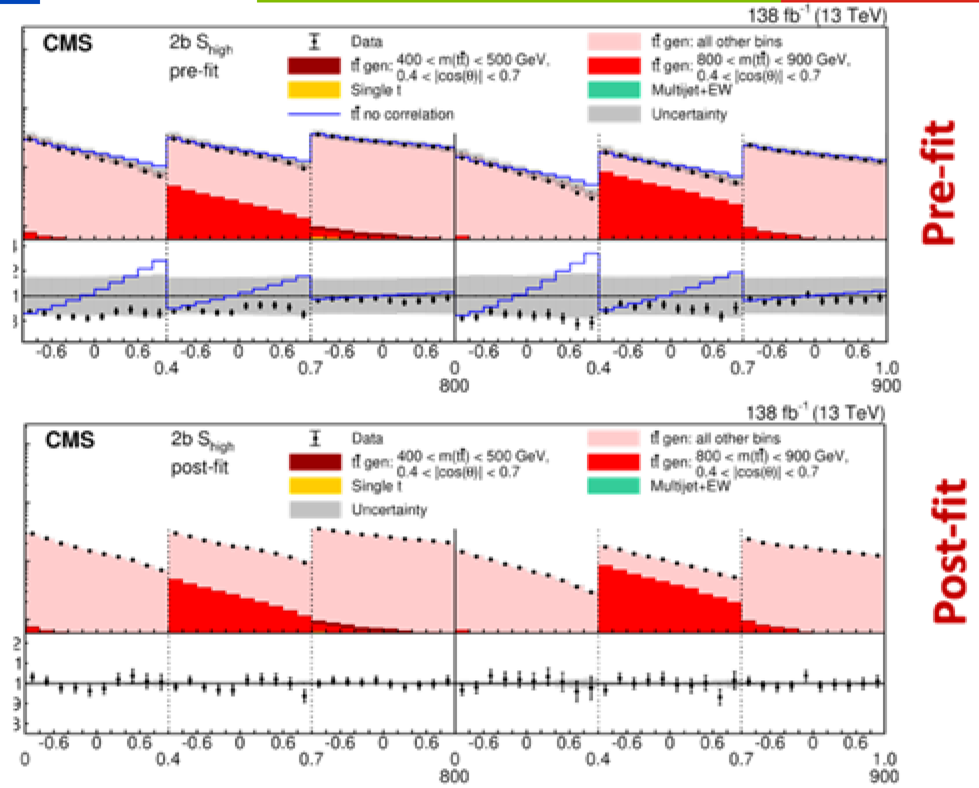
[B Physics and Quarkonia]
[Standard Model Physics]
[Top Physics] [Higgs Physics] [Supersymmetry]
[Exotica] [Beyond 2 Generations] [Heavy-Ion Physics]

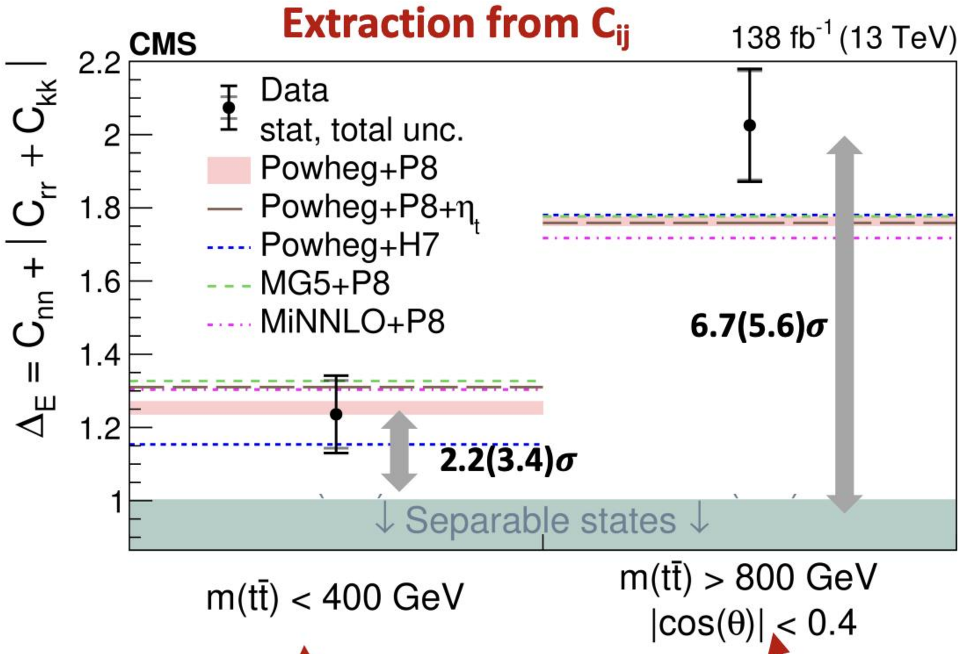
– Many collision data sets are [published] [CMS Open Data portal] including [code & instructions]

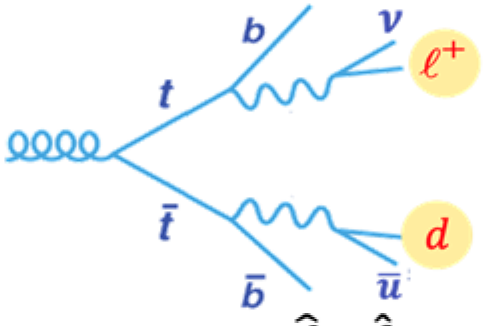
– Most recent results were NOT anticipated before data-taking
  – Planning is useful for the first steps
  – The CMS physics program is rich and also continously *en*riched

  – Upshot: That's best done if we're in exchange about problems, issues & ideas

Entanglement of top quark pairs (1ℓ)

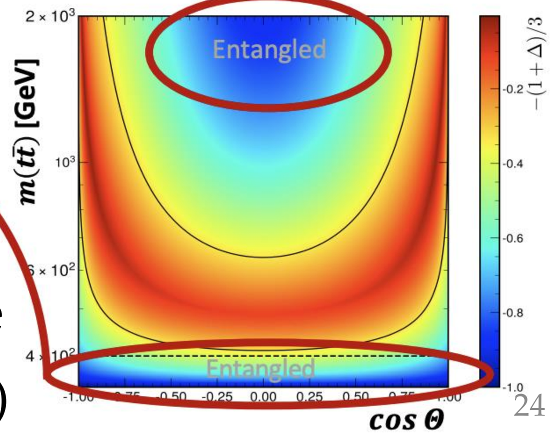






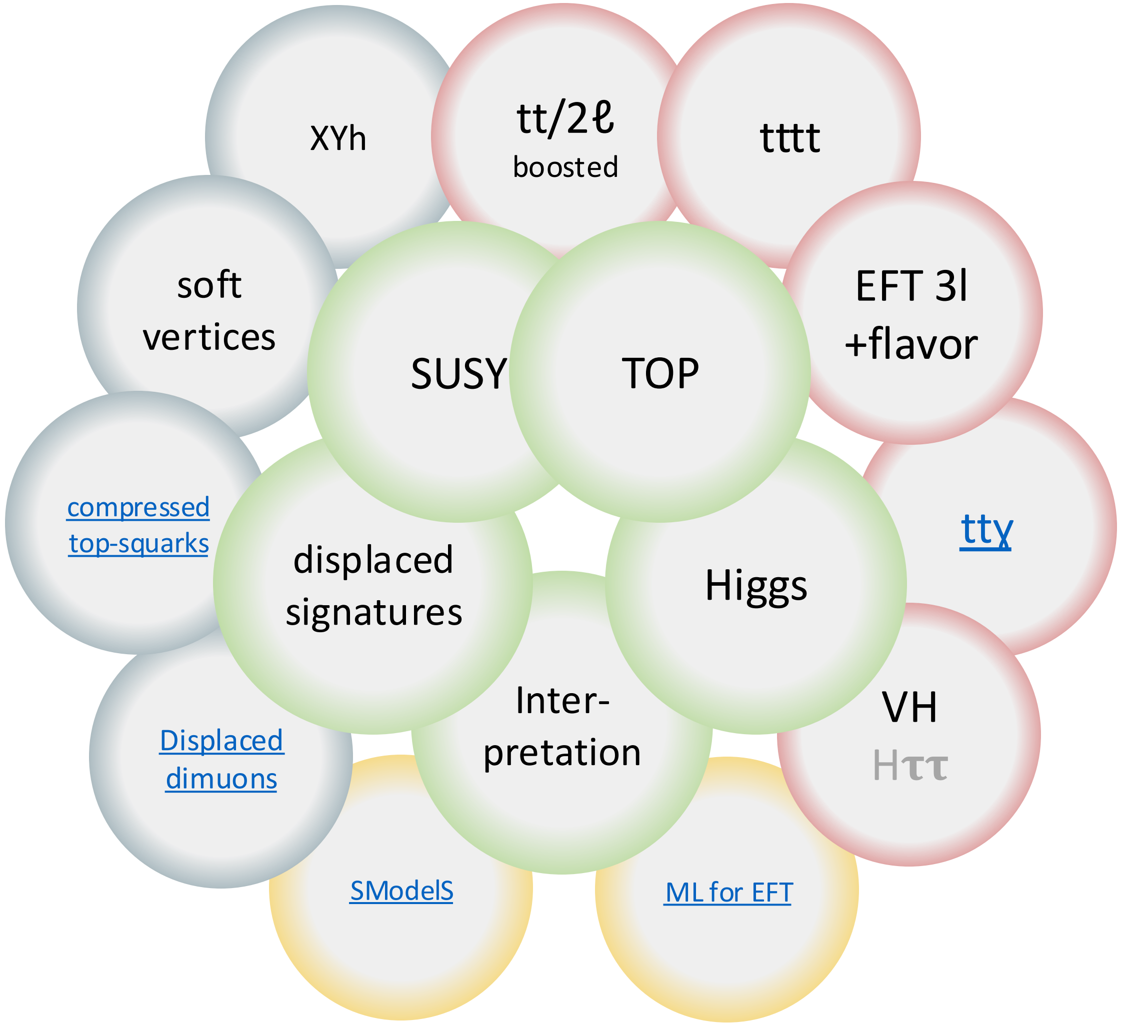
$\cos\varphi = \hat{\ell} \cdot \hat{d}$

- Need to identify the spin analyzer
  - down-type quark; no ID
  - Kinematical reco
- Events categorized according to e/m, N_{bjets}, and NN score
- Profile likelihood fits to cos(φ) in bins of m(tt) and cos(Θ)



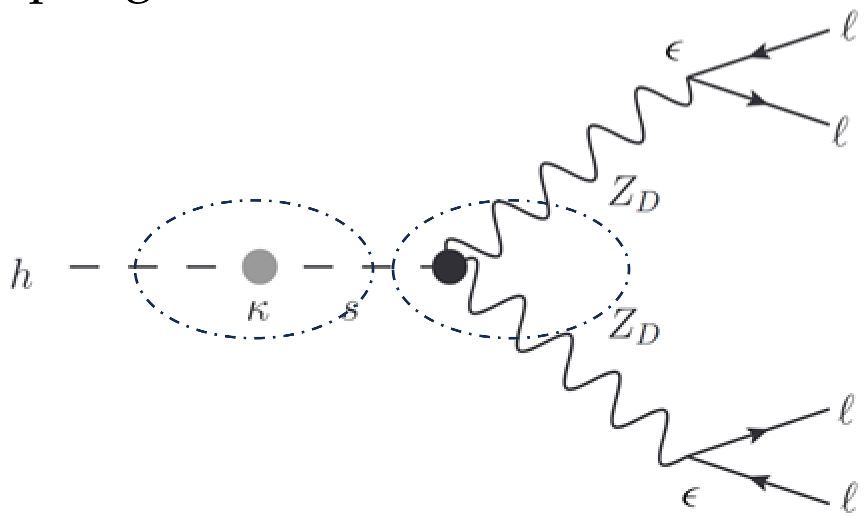
CMS Data Analysis at HEPHY

Searches, Measurements, Interpretation

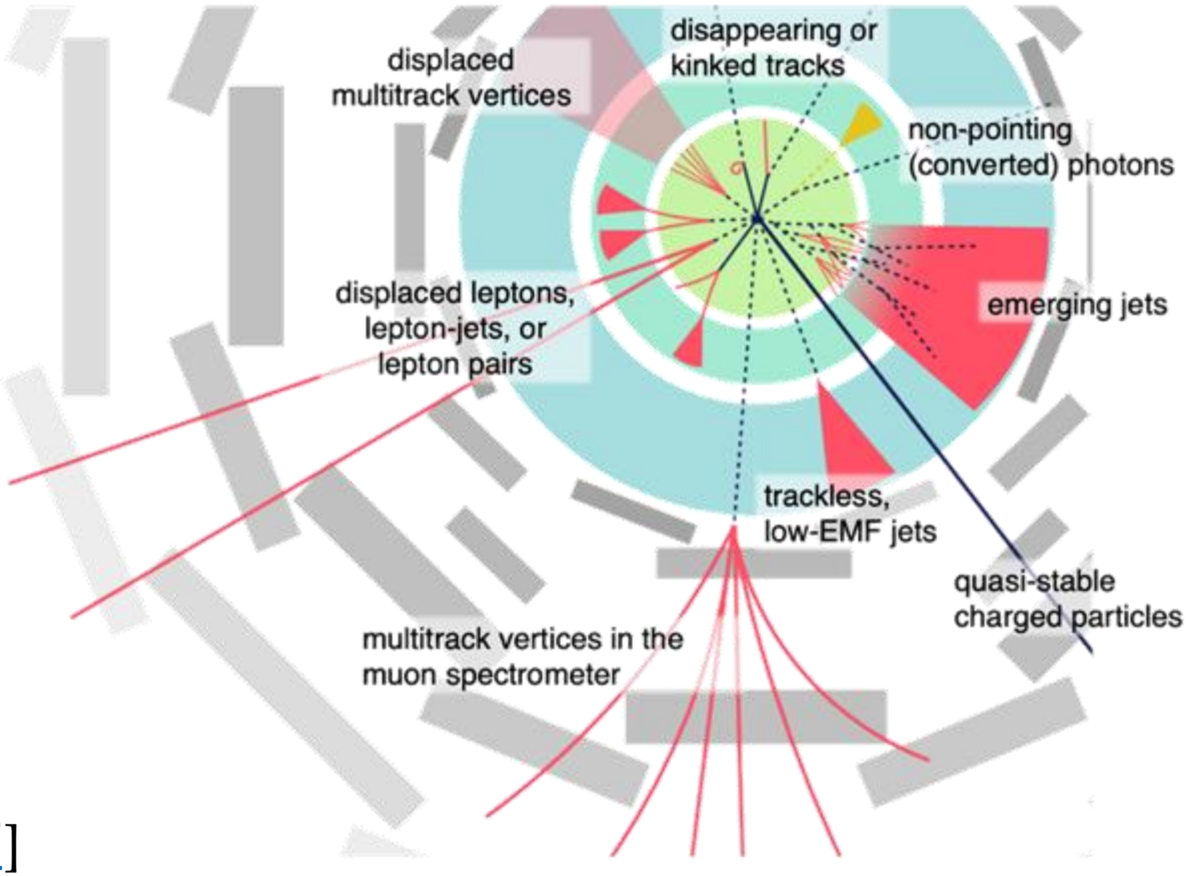


Long-Lived Particles

- Maybe BSM is in ``dark sectors`` with feeble couplings to the SM

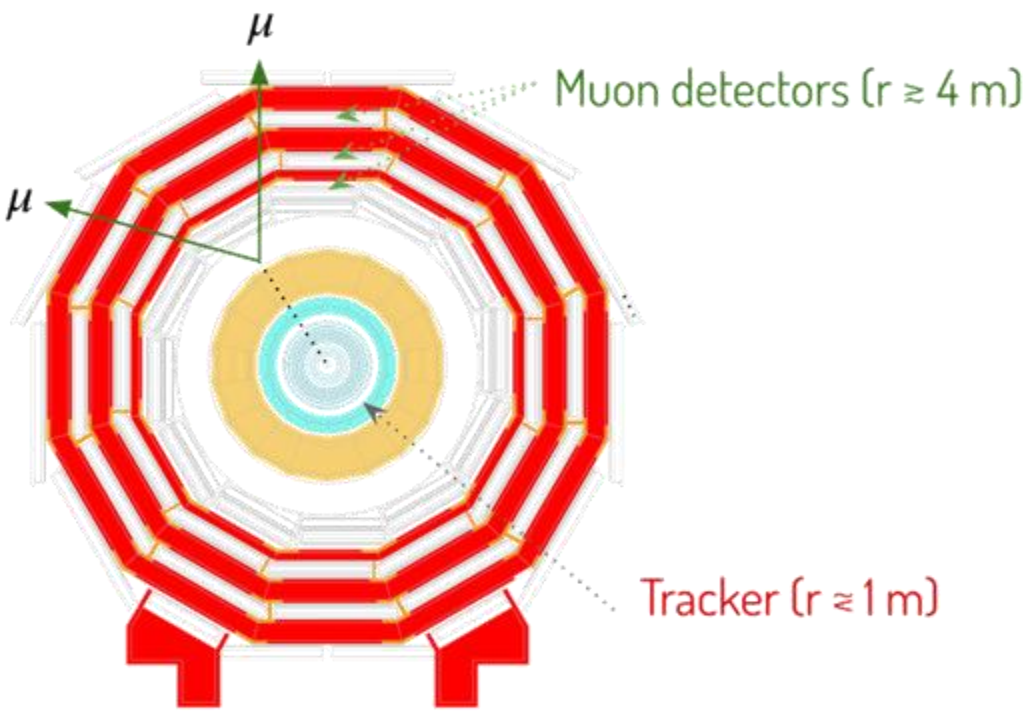


- Long-lived particles have versatile, often low-background, detector signatures
- LLPs are predicted in many BSM scenarios [ref]
  - Decays mediated by heavy neutral leptons (HNL)
  - Nearly mass degenerate states (e.g. compressed SUSY)
  - Small couplings to SM particles (e.g. dark mediators)

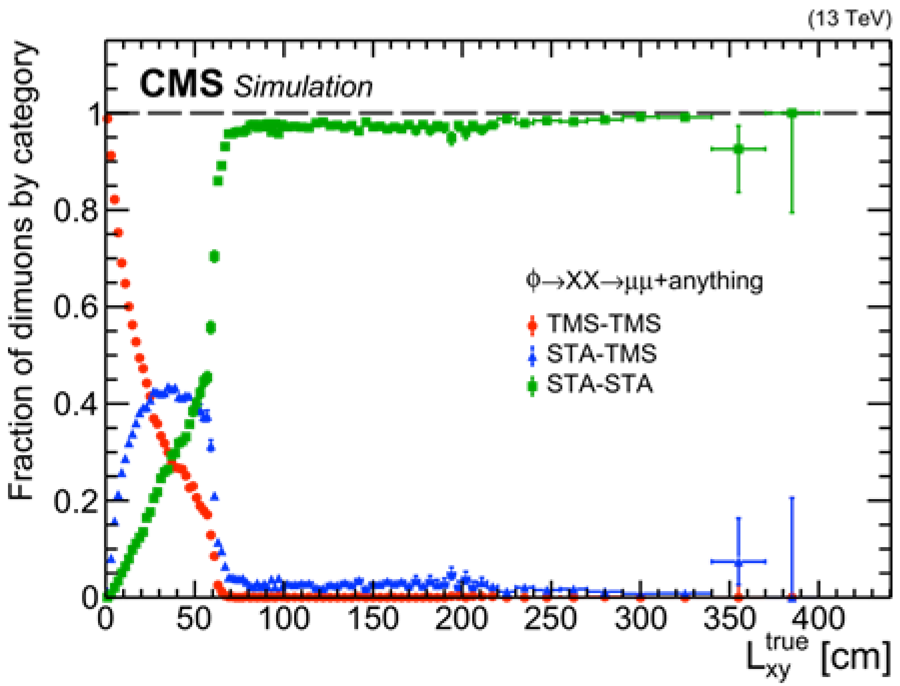


- Main difficulty: reconstruction

Long-Lived Particles: Displaced 2μ



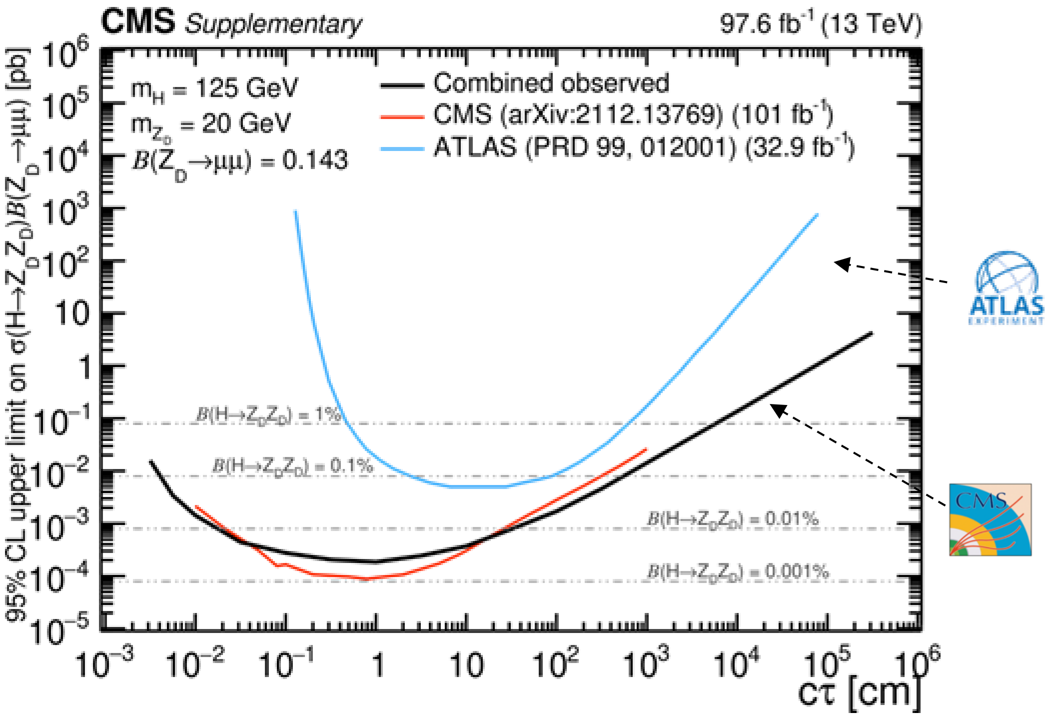
- **STA:** only use muon system
- **TMS:** STA + tracker information

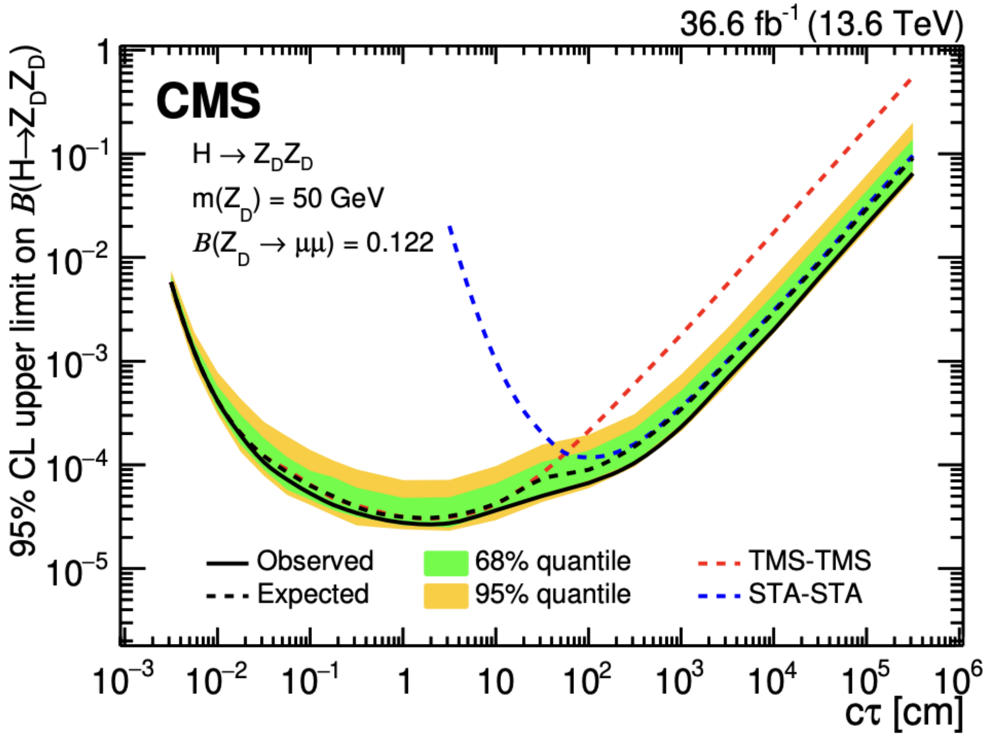


maximize decay length coverage

- Search is done in 3 categories **within and beyond the CMS tracker:** STA-STA, STA-TMS, TMS-TMS,
  - Double muon triggers relying on muon system information alone

Long-Lived Particles: Displaced 2μ



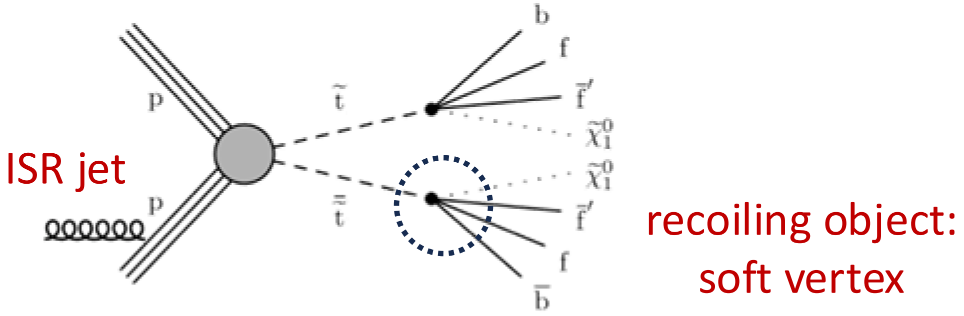


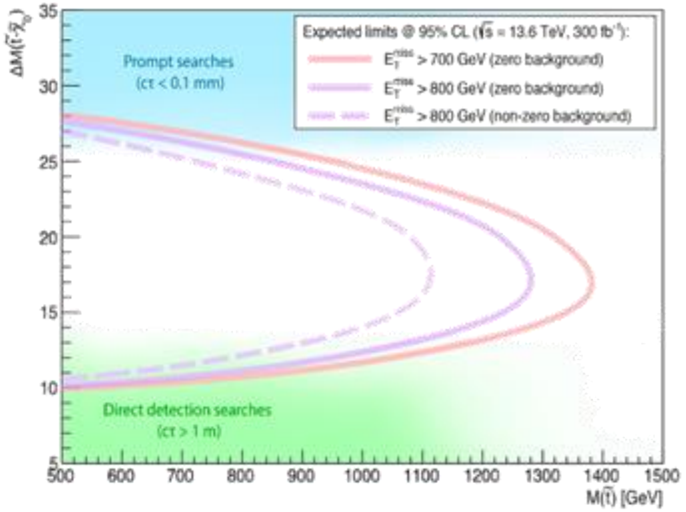
- Combination of categories → sensitivity to a wide range of life times ($c\tau$) from μm to km
- Excluded B(H→$Z_D Z_D$) >10^{-4}-10^{-5} as fkt of (M_{ZD}, $c\tau_{ZD}$) [JHEP 05 (2023) 228] [Physics briefing]
  EXO summary paper [EXO-23-005]

- Thanks to HEPHY's long-term trigger-involvement:
  ⟶ First search with Run-3 data (13.6 TeV)
  [Phys. Rev. D **110**, 032007]

New exotic directions

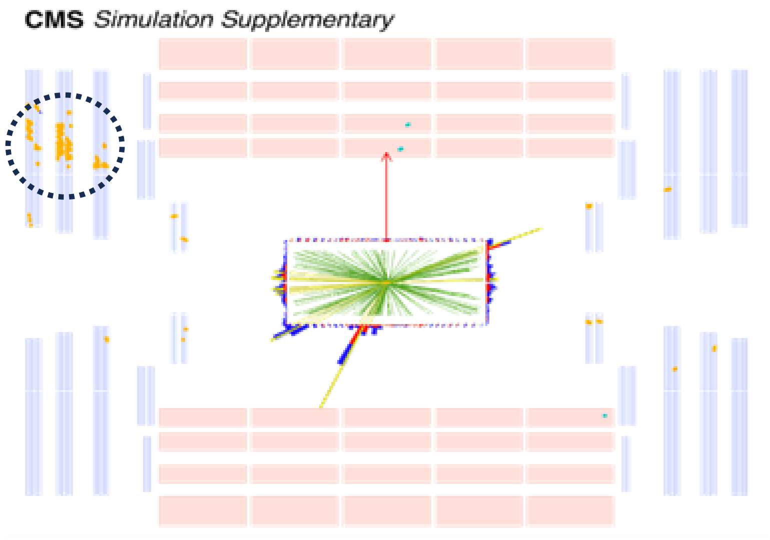
1. Explore small BSM mass gaps of 1 GeV < ΔM< 10 GeV with **soft vertices**



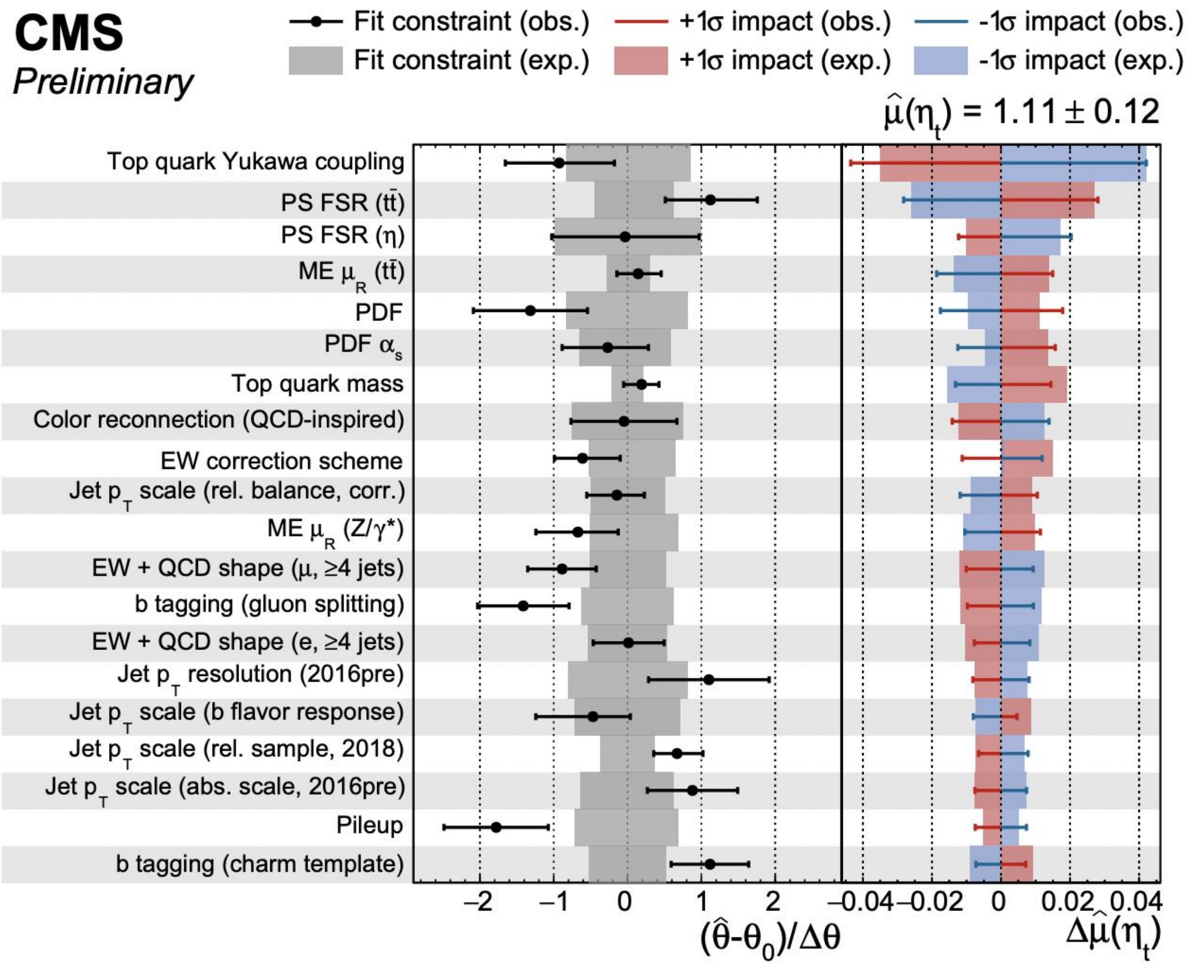


- Closes the sensitivity gap between “mono-jet” and prompt signals

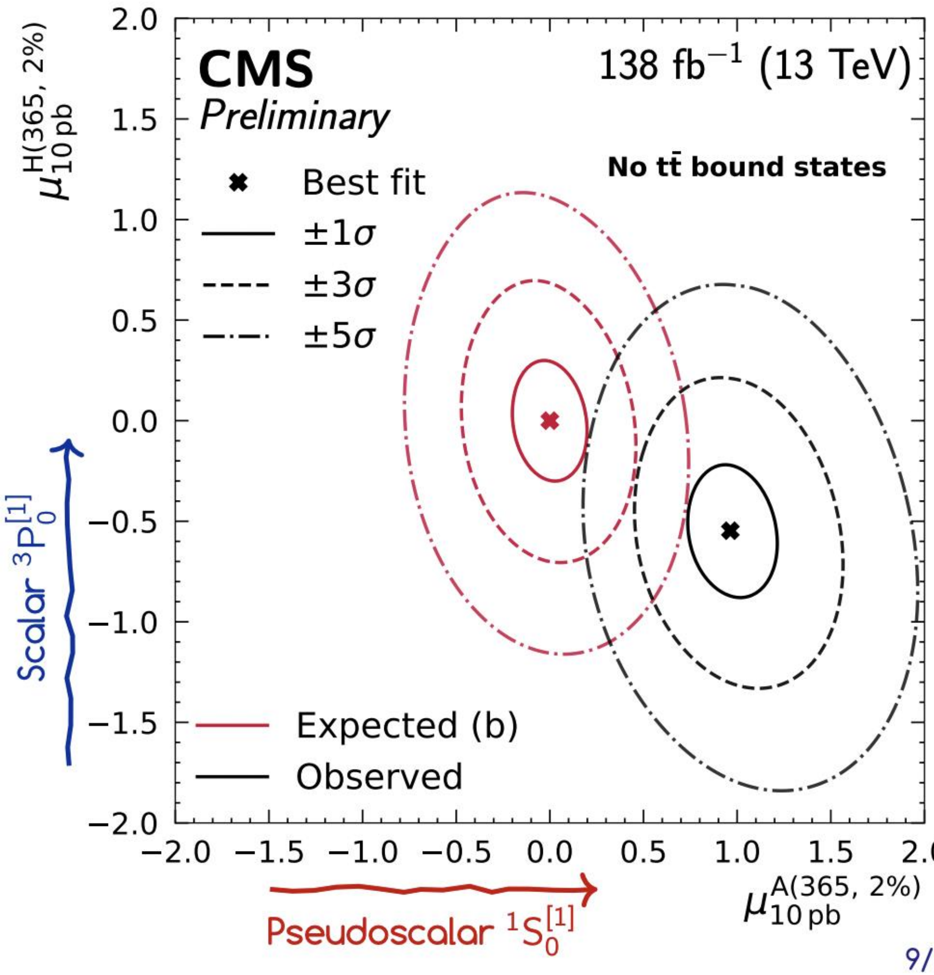
2. **CMS MUO system ⟶ calorimeter**
   - Together with KFU
   - Showers of decay products of LLP ionize gas in muon detectors → calorimeter
   - Probe QCD-like dark sectors (collimated dark showers) and “SUEPS”: Spherical Soft Unclustered Energy Patterns



- Example of a signal not anticipated at [TDR] times


CMS
Preliminary
Fit constraint (obs.)
Fit constraint (exp.)
+1σ impact (obs.)
+1σ impact (exp.)
-1σ impact (obs.)
-1σ impact (exp.)
μ̂(η_t) = 1.11 ± 0.12
Top quark Yukawa coupling
PS FSR (tt̄)
PS FSR (η)
ME μ_R (tt̄)
PDF
PDF α_s
Top quark mass
Color reconnection (QCD-inspired)
EW correction scheme
Jet p_T scale (rel. balance, corr.)
ME μ_R (Z/γ*)
EW + QCD shape (μ, ≥4 jets)
b tagging (gluon splitting)
EW + QCD shape (e, ≥4 jets)
Jet p_T resolution (2016pre)
Jet p_T scale (b flavor response)
Jet p_T scale (rel. sample, 2018)
Jet p_T scale (abs. scale, 2016pre)
Pileup
b tagging (charm template)
−2 −1 0 1 2
(θ̂-θ_0)/Δθ
−0.04 −0.02 0 0.02 0.04
Δμ̂(η_t)

Parity scan


CMS
Preliminary
138 fb^−1 (13 TeV)
No tt̄ bound states
Best fit
±1σ
±3σ
±5σ
Expected (b)
Observed
μ^H(365, 2%)_10 pb
μ^A(365, 2%)_10 pb
Scalar ^3P_0^[1]
Pseudoscalar ^1S_0^[1]
2.0 1.5 1.0 0.5 0.0 −0.5 −1.0 −1.5 −2.0
−2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0