Highlights of the CMS Experiment

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On-behalf of the CMS collaboration

Outline

CMS Detector performance

Recent CMS Analyses

- Top sector: Entanglement in top quark pairs
- Higgs sector: Higgs produced in association with *b*-quarks
- Standard Model measurements
  - Event Shapes in Minimum Bias Events
  - Effective weak mixing angle
- Beyond SM searches
  - $Z' \rightarrow \tau\tau$ searches
  - Excited tau lepton in the $\tau\tau\gamma$ final state
  - Search for Kaluza–Klein (KK) gluon resonances g_{KK}
- SUSY searches: Stealth/R-parity violation (RPV) Stop Search

Summary

Outline

CMS Detector performance

Recent CMS A

- Top sector: Ent
- Higgs sector: I
- Standard Mod
  - Event Shape
  - Effective wea
- Beyond SM se
  - Z′ → ττ searc
  - Excited tau le
  - Search for Ka
- SUSY searches
- B hadron phys

Summary

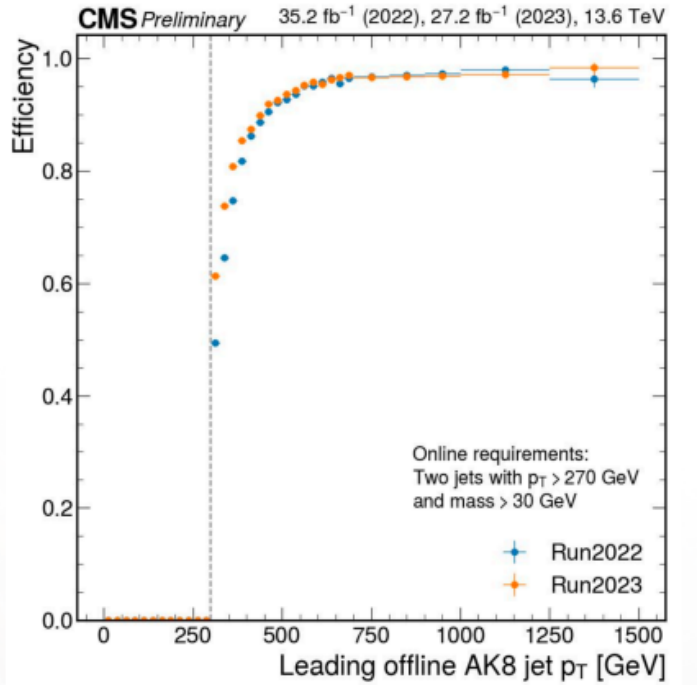
Disclaimer

A lot of interesting analyses are not covered

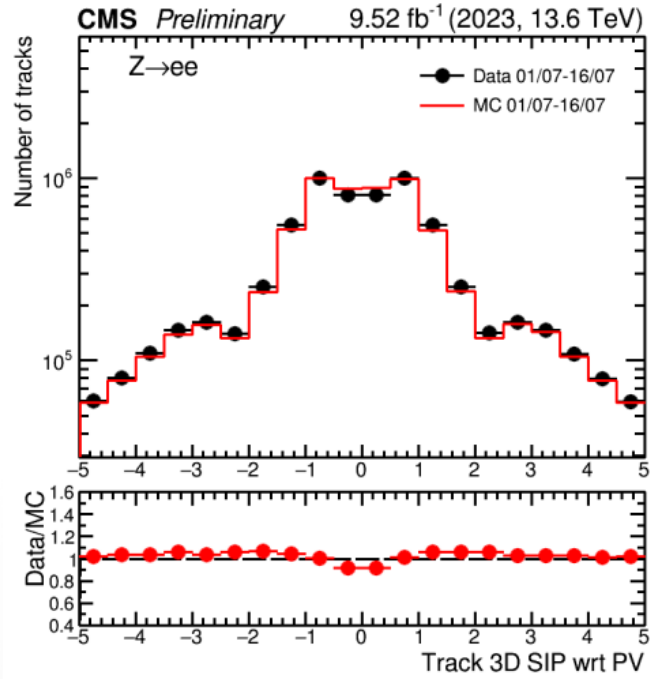
- (X→)HY/HH→γγττ CMS-PAS-HIG-22-012
- γγ→ττ in pp and limits on τ *g-2* CMS-PAS-SMP-23-005
- New structures in the J/ψJ/ψ spectrum CMS-PAS-BPH-21-003, see the talk from Kai
- Run3 measurements
  - WW cross section measurement CMS-PAS-SMP-24-001
  - tW cross section measurement CMS-PAS-TOP-23-008
- Heavy ion studies
  - Double-J/ψ meson production in pPb CMS-PAS-HIN-23-013
  - Azimuthal dependence of hyperon polarization CMS-PAS-HIN-24-002
  - Multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in pPb CMS-PAS-HIN-24-001
- Nice review papers
  - Physics of Dark Sectors in CMS CMS-EXO-23-005
  - Review of HY searches CMS-B2G-23-002, see the talks from Elise, Chu
- …

Detector performance in Run 3

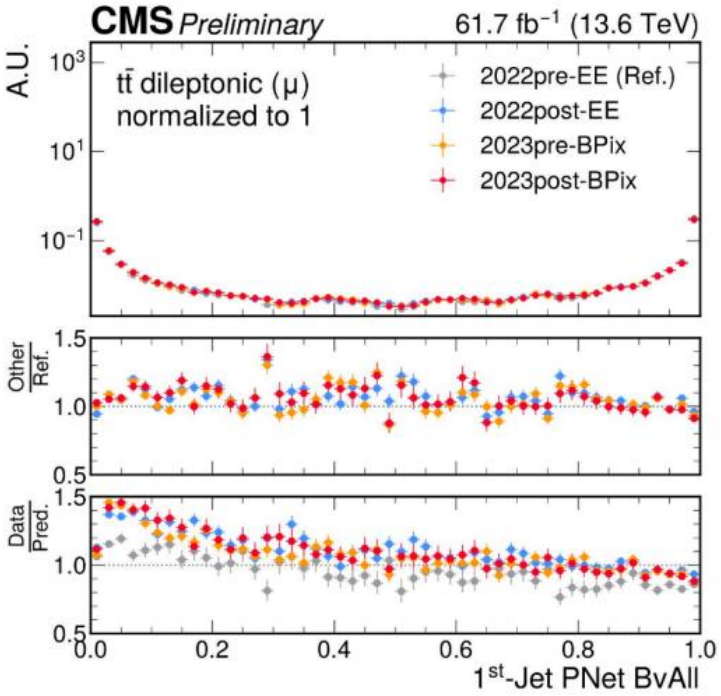
Stable and excellent performance



CMS-DP-2023-094
Stability of HLT jet mass selection in Run 3



CMS-DP-2023-090
Excellent performance of impact parameter significance in 3D for electron tracks in data and simulation

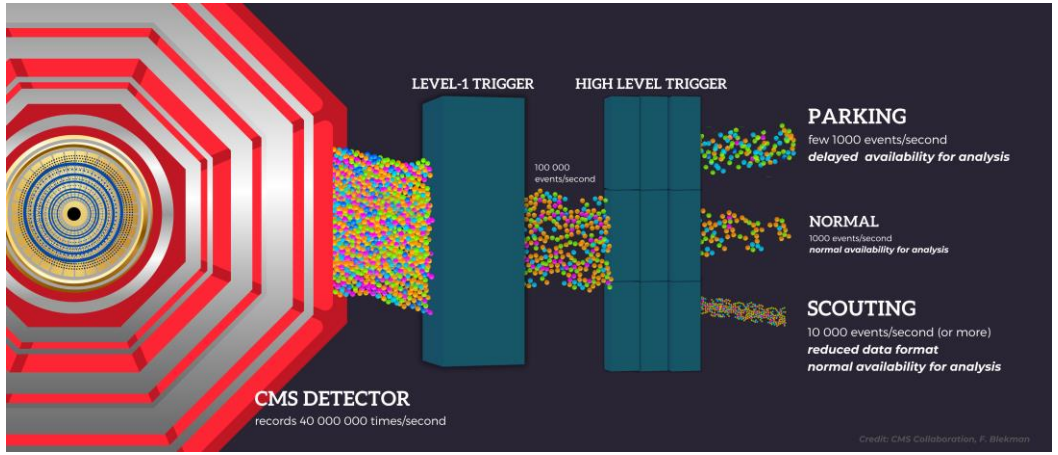


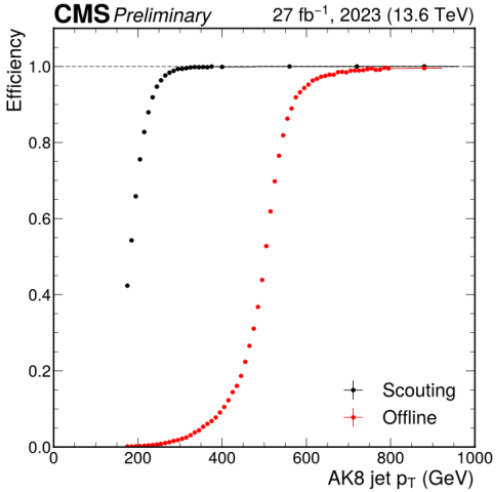
CMS-DP-2024-024
Stable ParticleNet b-tag scores w.r.t. years and data taking periods

From detector performance to physics potential

Trigger strategies for Run3

- Complementary approaches to support all physics cases within available resources
- Continuous development: new systems at L1 and improved GPU use at the HLT

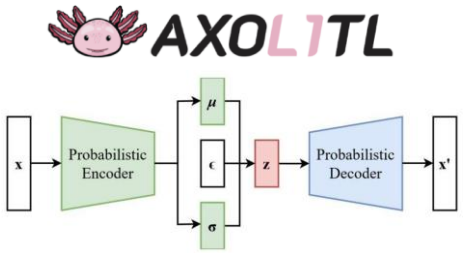




CMS-DP-2023-076
Lower threshold for largeradius jets with scouting

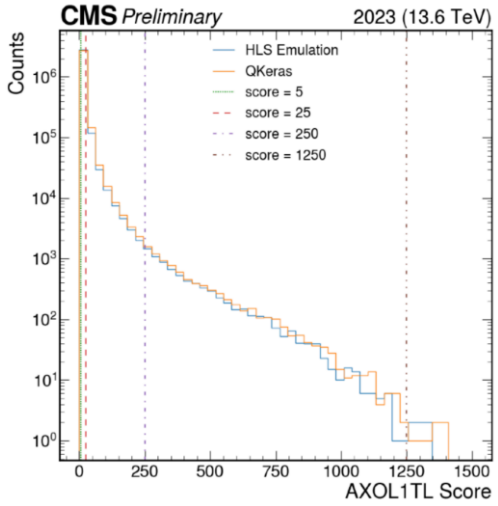
Anomaly detection at L1

- E.g., **AXOL1TL**: variational auto encoder using input objects to global L1



CMS-DP-2023-079
AXOL1TL scores and efficiency gains vs standard L1 menu.
Signal: H→XX(15GeV)→bbbb

AXOL1TL Rate	1 kHz	5 kHz	10 kHz
Signal Efficiency Gain	46%	100%	133%



Observation of top quark entanglement

Measure entanglement of top quark pairs in **dilepton** events using spin correlations

What does it mean to be entangled? Non-separable!

- To probe entanglement: Peres-Horodecki Criterion [PRL.77.1413, PLA232 (1997) 333]
  - Hard to show it is separable but "easily" to show it is non-separable

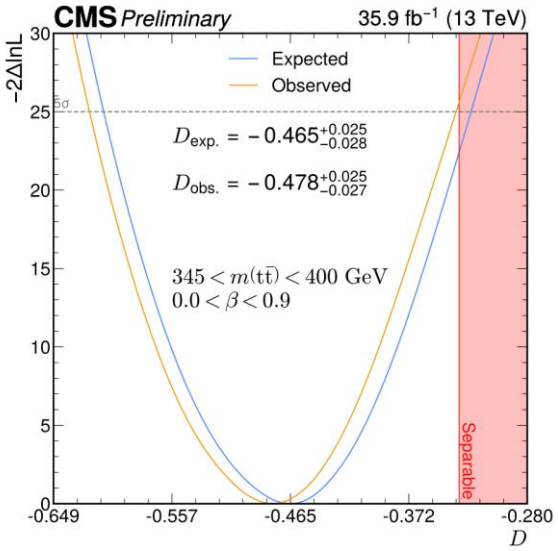
After some messy algebra a sufficient condition for entanglement is reached [EPJP (2021) 136:907]:

- Using diagonal elements: $\Delta_E = -C_{33} + |C_{11} + C_{22}| > 1$
- Entanglement proxy $D = Tr[C]/3$ (for small m_{tt}) can be extracted from angle between decay products

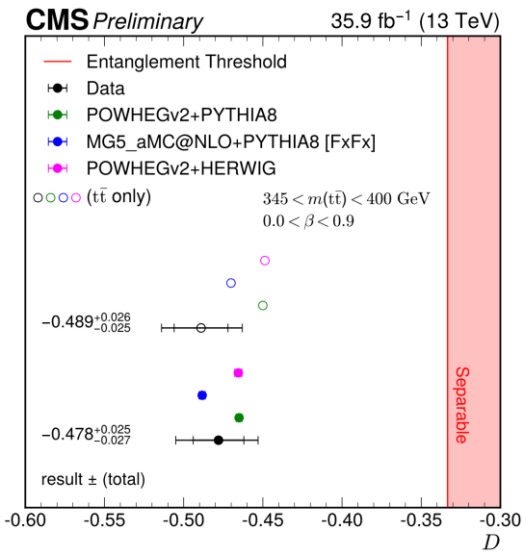
Measure D to access entanglement information!

$$\Delta \equiv -C_{33} + |C_{11} + C_{22}| - 1 > 0 \longrightarrow -\mathrm{tr}[\mathbf{C}] > 1 \longrightarrow D < -1/3$$

- **D < -⅓ → Entangled!**



D<-⅓ established at the 5σ level



Higher sensitivity in the low m_{tt} region

CMS-PAS-TOP-23-001

* Atlas also observed the ttbar entanglement TOPQ-2021-24

Entanglement of top quark pairs via lepton+jets

Measuring the correlation matrix in **single-leptonic** tt events

- All coefficients of polarization vectors and correlation matrix from fit to the angles of two decay products
  - Using NN to reconstruct the tt system in each event
- Test variables:
  - Δ_E from the full matrix: $\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$
  - Two proxies D (for low m_{tt}) , $\widetilde{D}$ (for high m_{tt})

D measurement

Criterion for entanglement: D < -1/3

$$D = \frac{1}{3}(C_{nn} + C_{rr} + C_{kk})$$

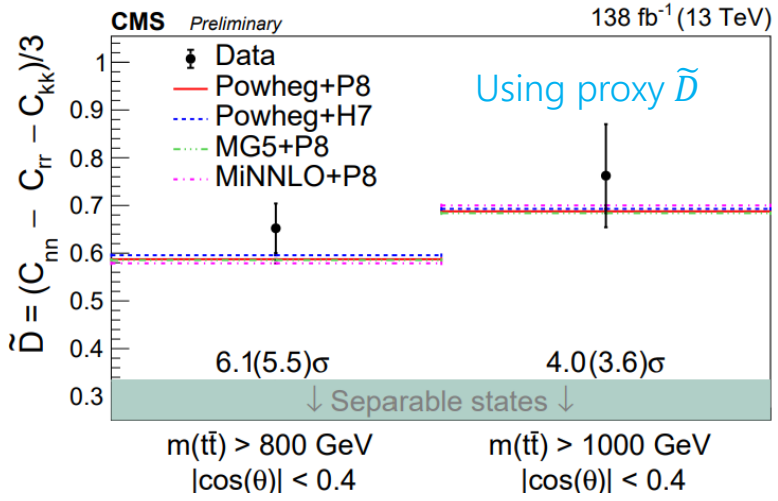
Spin-singlet state

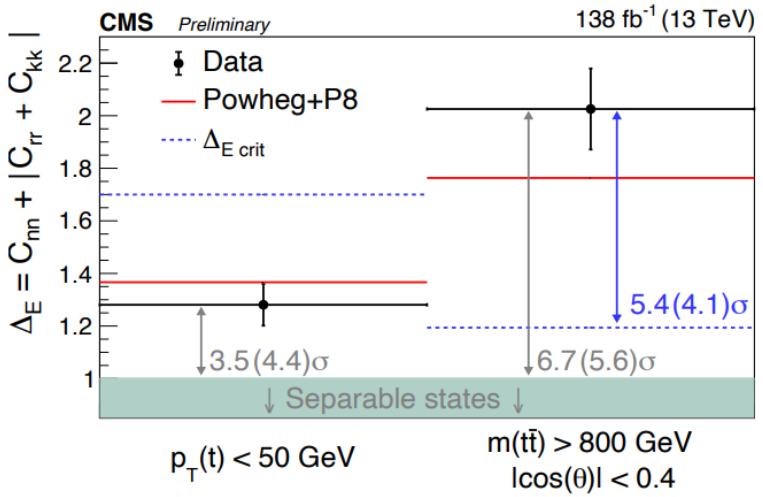
$\widetilde{D}$ measurement

Criterion for entanglement: $\widetilde{D}$ > 1/3

$$\widetilde{D} = \frac{1}{3}(C_{nn} - C_{rr} - C_{kk})$$

Spin-singlet state





Separation from entanglement limit reaches 6.7σ obs (5.6σ exp) using Δ_E

CMS-PAS-TOP-23-007

Higher m_{tt} allows to search exceeding maximum entanglement achievable by classical exchange of information

- Fraction of events with space-like separation increases with m_{tt}
  - >90% for m_{tt} >800GeV

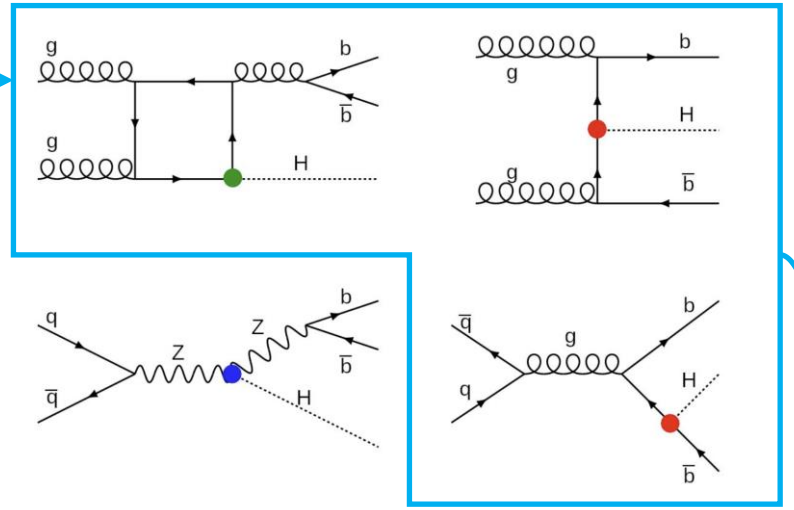
Higgs produced in association with *b*-quarks

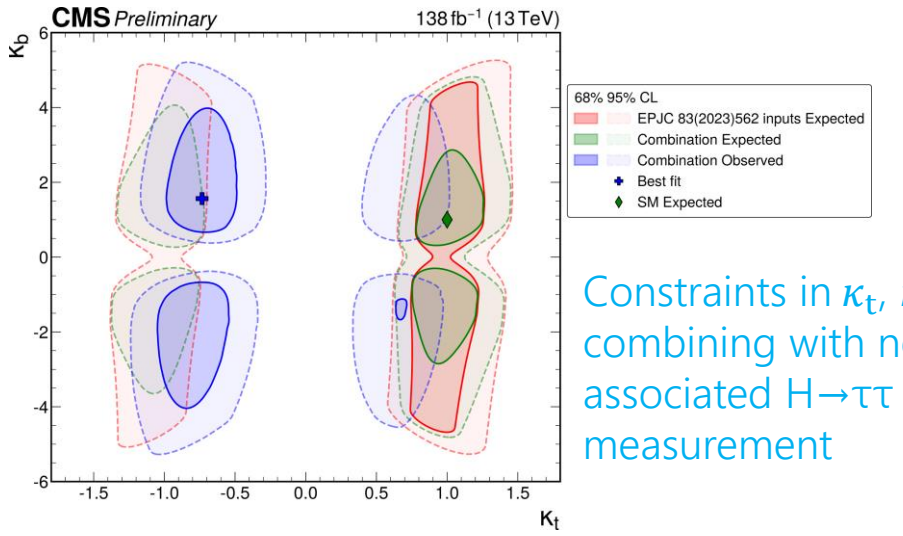
Higgs production with associated b-quarks via

- b-fusion
- gluon fusion with gluon→bb splitting

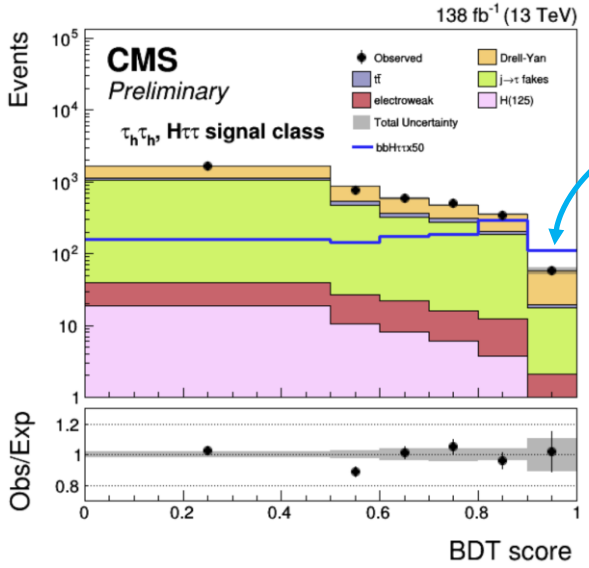
Study the final states with leptons (WW, ττ)

Obs (exp) upper limit: 3.7 (6.1) x SM





Constraints in κ_t, κ_b plane, combining with non b-associated H→ττ measurement

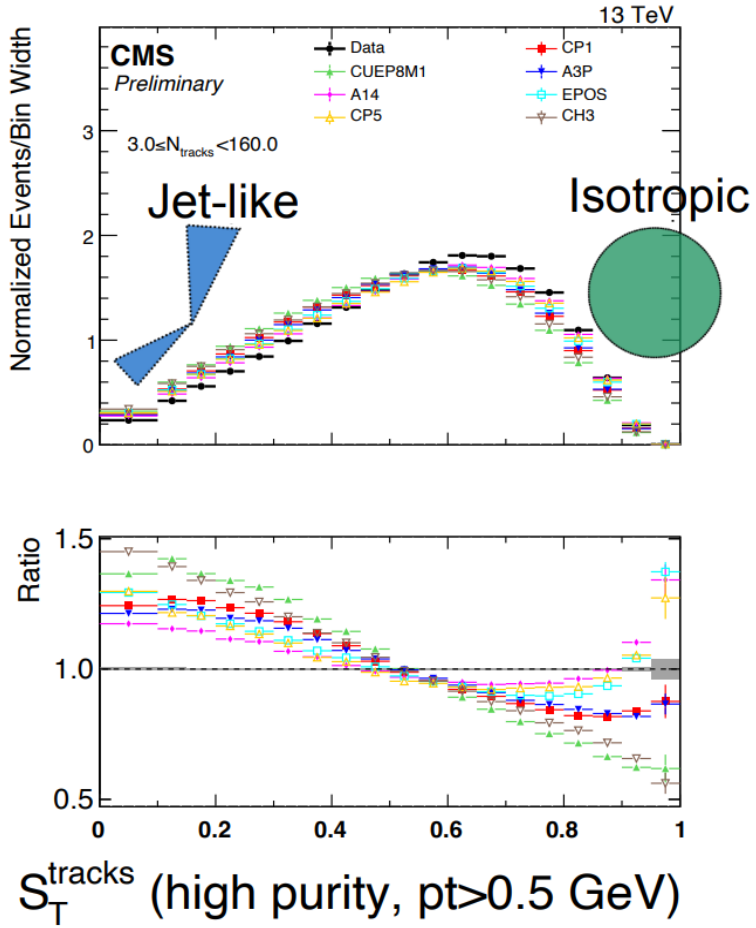


CMS-PAS-HIG-23-003

Event Shapes in Minimum Bias Events

Event shape observables

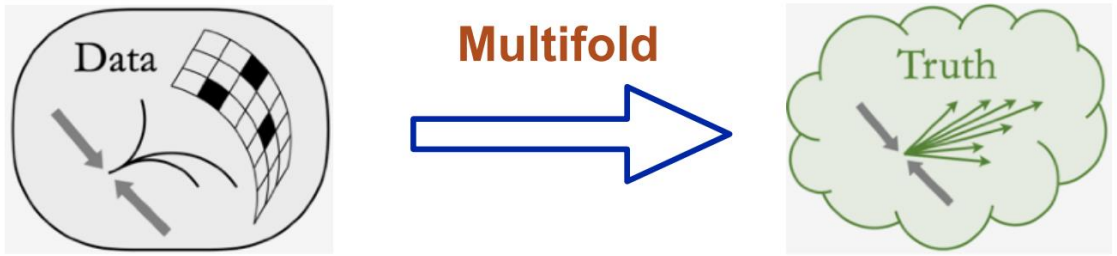
- Describing the "shapes" of the events
  → Functions of the momentum of the final state particles
- An example: **transverse sphericity**
- Others: (transverse) thrust, broadening, isotropy etc.



CMS-PAS-SMP-23-008

Unfold with a machine-learning-based algorithm

- Multifold* PRL.124.182001, arXiv.2105.04448



Event shapes of detector-level objects

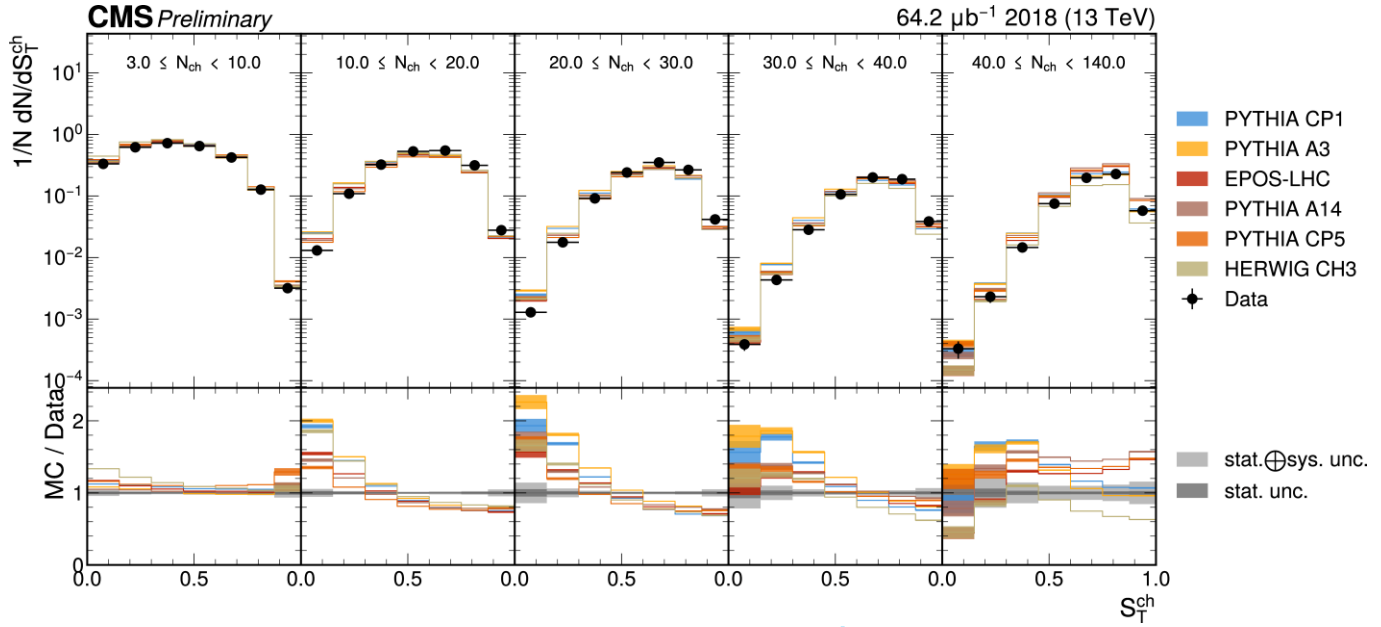
Event shapes of particles

Event Shapes in Minimum Bias Events

Simultaneously unfold all the variables for ML-based weighting

Add a variable to the unfolding:

- Methods based on binned histograms
  - Add another dimension in binning
  - Require higher statistics
  - More computations in simulation and unfolding
- ML-based method
  - Add a feature in the ML training and evaluation
  - Much easier to scale up the dimensions



2D visualization of **transverse sphericity** in charged particle multiplicity slices

CMS-PAS-SMP-23-008

More isotropic data than MC

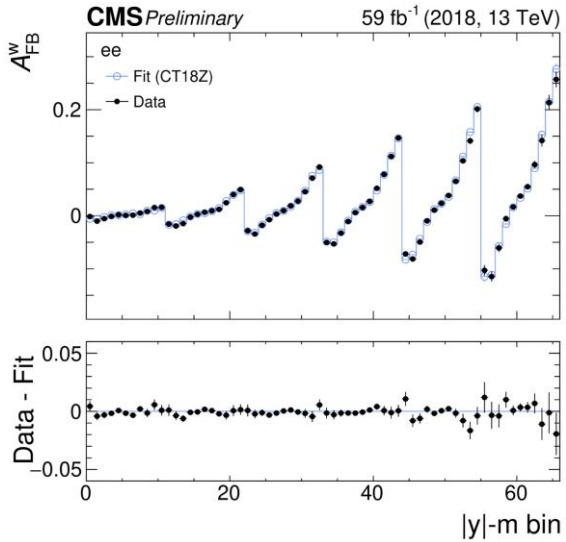
- multi-parton-interaction model?
- collective effects?
- instantons?

Provide the unfolded results for theoretical interpretation

Effective weak mixing angle

Precision measurement of EWK key quantity at a hadron collider

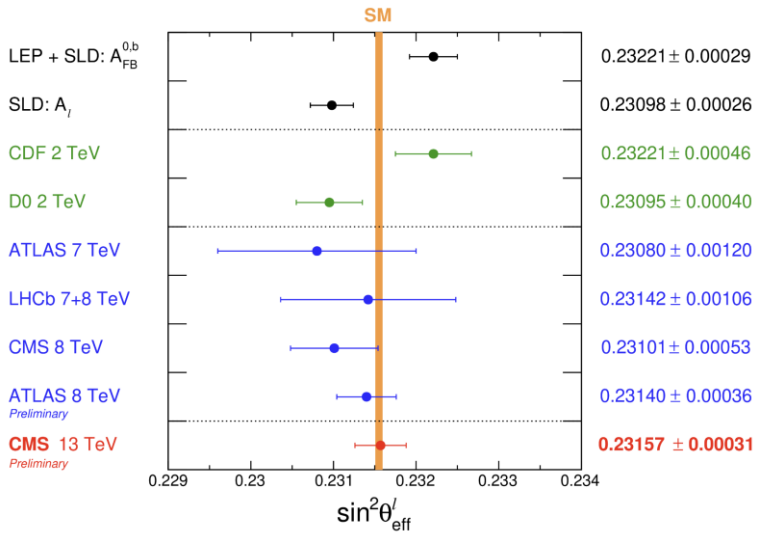
- $\sin^2\theta^l_{\text{eff}}$ is extracted from simultaneous χ^2 fit of $A_{FB}(y,m)$ in all di−muon or di−electron channels



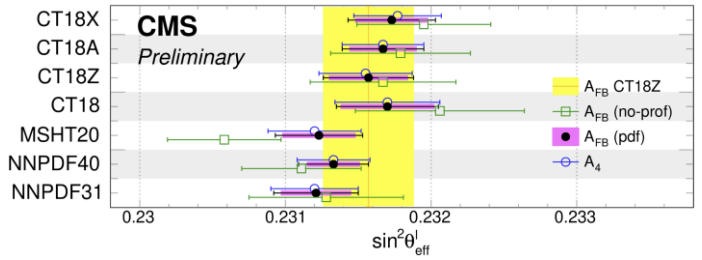
Acceptance and sensitivity enhanced with extended acceptance for forward electrons

- Result (**CT18Z**)

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00010(\text{stat}) \pm 0.00015(\text{syst}) \pm 0.00009(\text{theo}) \pm 0.00027(\text{PDF})$$

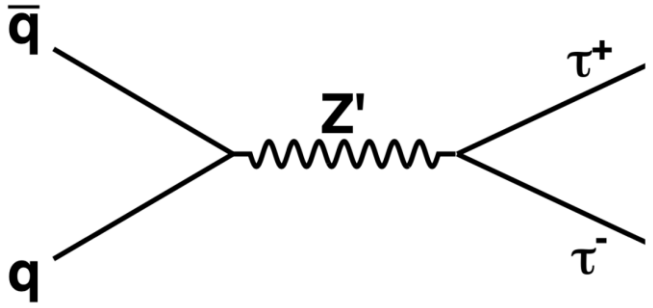


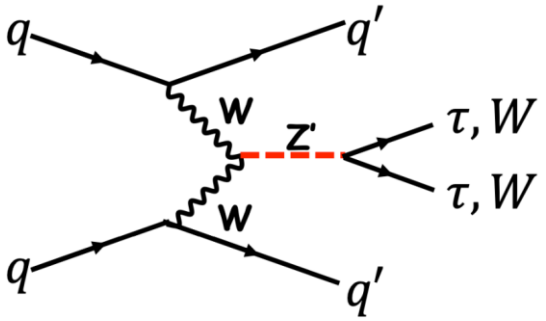
- Matches LEP/SLD precision
- Compatible with the SM prediction
- Adds to understanding of a long-standing tension between previous measurements



CMS-PAS-SMP-22-010

Search for Z′ in ττ decay





CMS-PAS-EXO-21-016

Search in the eτ$_h$, μτ$_h$, and τ$_h$τ$_h$ final states

- Z′ not boosted -> high m$_{Z'}$ two back-to-back τ

$$m_{Z'}^{reco} = \sqrt{(E_1^{\tau vis} + E_2^{\tau vis} + |p^{Z'miss}|)^2 - |p_1^{\tau vis} + p_2^{\tau vis} + p^{Z'miss}|^2}$$

$$p^{Z'miss} = (-(\vec{p}_{1T}^{\,\tau vis} + \vec{p}_{2T}^{\,\tau vis}), 0)$$

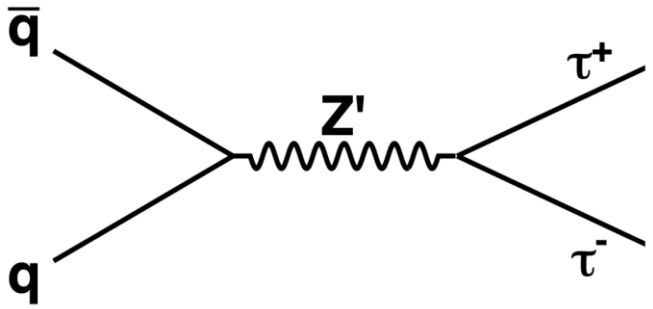
CMS-PAS-EXO-21-015

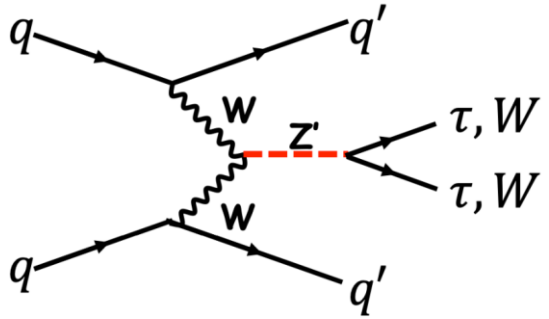
Study the ττ (the eμ, eτ$_h$, μτ$_h$, and τ$_h$τ$_h$ final states) and WW decays

- VBF topology requires a pair of well separated & in the opposite jets with high mass :
  - $|\Delta\eta_{jj}| > 4.2$ & $|\eta_{j1}\eta_{j2}| < 0$
  - $m_{jj} > 500$ GeV
- Boost to the Z′ → p$_T^{miss}$ from τ decay is collinear with Z′

$$m_{Z'}^{reco} = \sqrt{(E_{\ell 1} + E_{\ell 2} + p_T^{miss})^2 - (\vec{p}_{\ell 1} + \vec{p}_{\ell 2} + \vec{p}_T^{\,miss})^2}$$

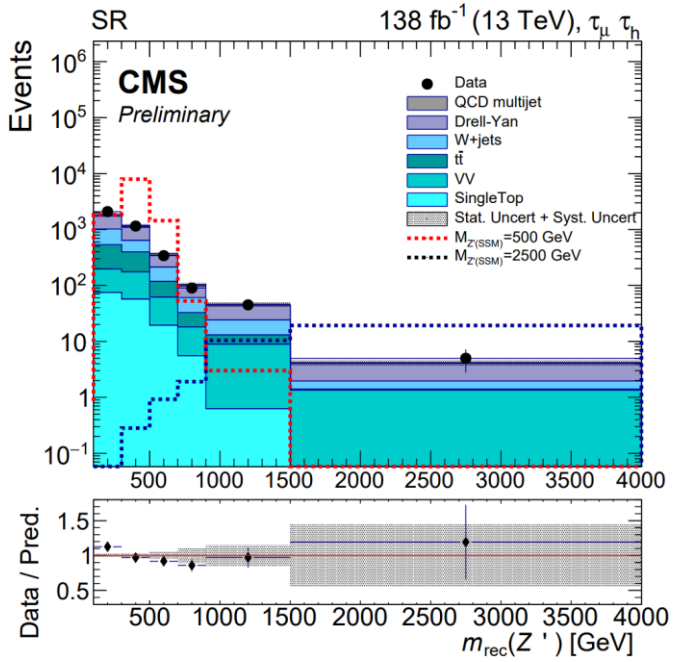
Search for Z’ in ττ decay – backgrounds



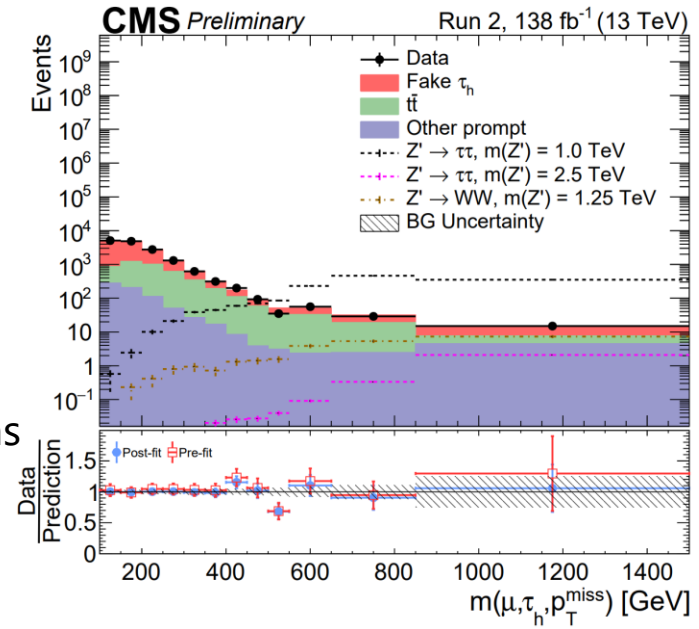


CMS-PAS-EXO-21-016

- QCD estimated with **ABCD** method
- Background estimation: DY, W, tt estimated by MC and normalizations from data



- Non-prompt: **loose-tight** method from sidebands
- Prompt bkgs: estimated by MC and normalizations from data

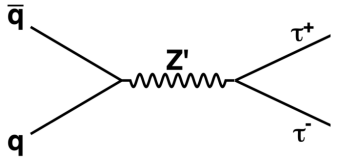


CMS-PAS-EXO-21-015

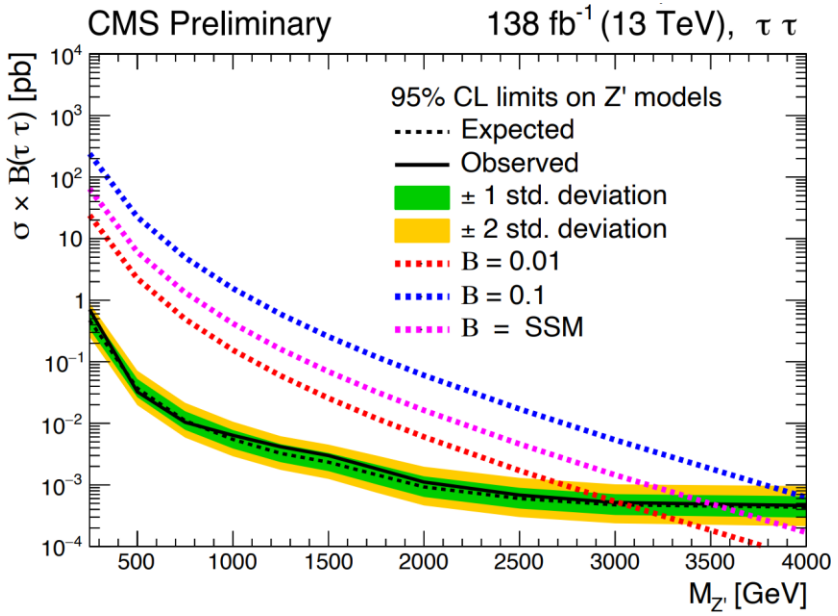
Search for Z′ in ττ decay – results

Interpretation relies on Sequential Standard Model (SSM)

- Limits in mass range from **400 GeV to 4 TeV**
- **Most stringent limits for Z′->ττ**

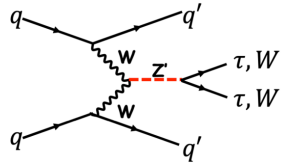


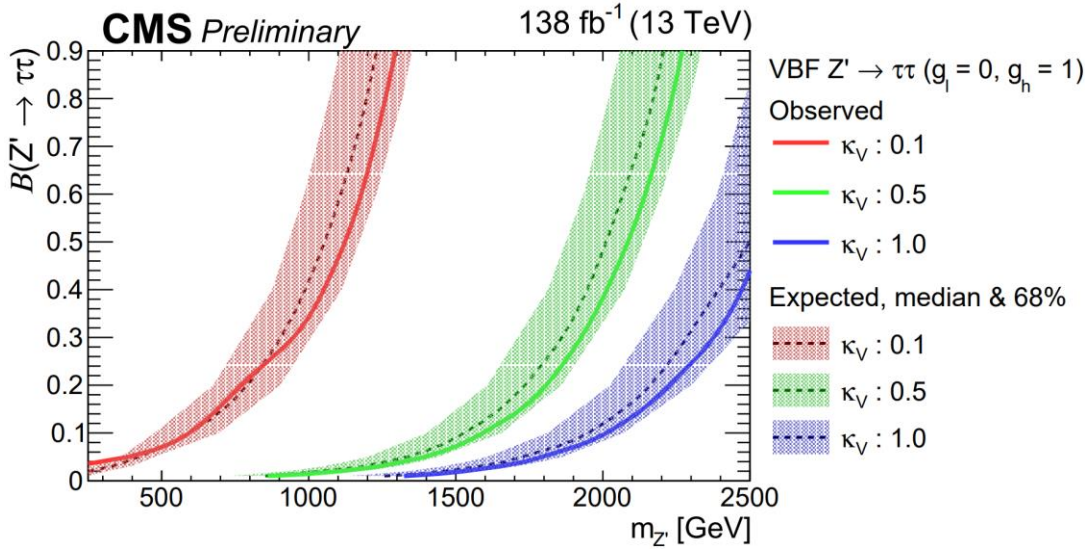
CMS-PAS-EXO-21-016



Interpretation relies on the SSM

- Four independent parameters:
  - Z′ couplings to 1st+2nd (g_l) and 3rd (g_h) generations
  - Coupling to W(k_V)
  - Z′ mass ($m_{Z'}$)
- **First interpretations of VBF produced Z′ at the LHC**





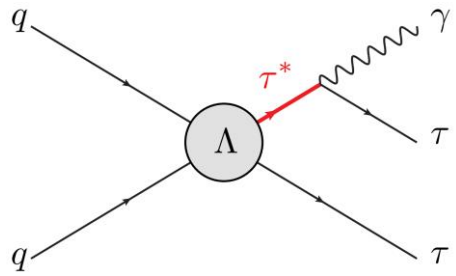
CMS-PAS-EXO-21-015

Excited tau lepton (τ*) in the ττγ final state

Excited states of the τ would give evidence of compositeness

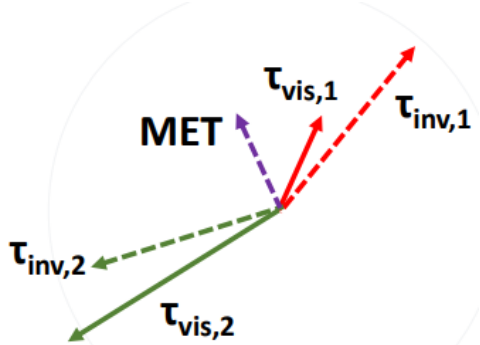
Contact interaction (CI) model predicts a ττ + high-p_T γ final state

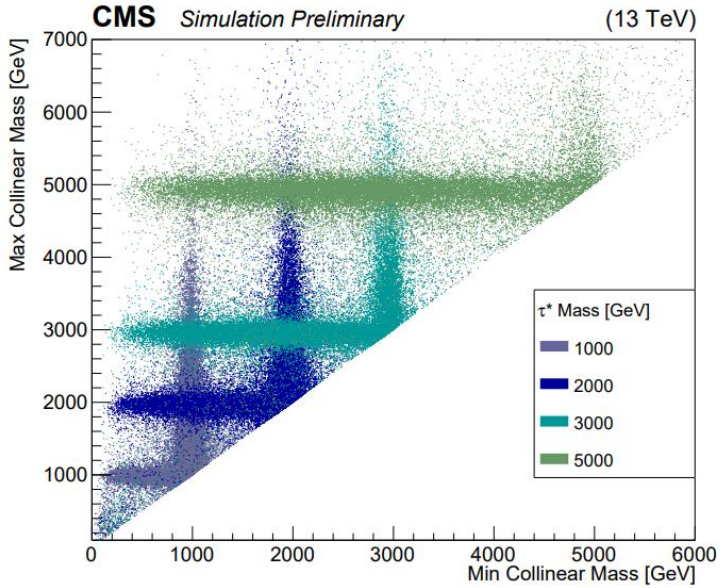
- Single excited τ lepton (τ*) is produced via a contact interaction (CI)
  - CI production → $\mathcal{L}_{CI} = \frac{g^{*2}}{2\Lambda^2} j^\mu j_\mu$
- τ* decays via emission of a SM photon
  - SU(2) like decay → $\mathcal{L}_{GM} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left[g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] f_L + h.c.$



Several steps to reconstruct the mass of the τ* in $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$

- Collinear approximation:
  - Assume that ν_τ is collinear with the visible part of the τ decay (either of τ_h, e, μ)
- Split p_T^{miss} into components from each τ





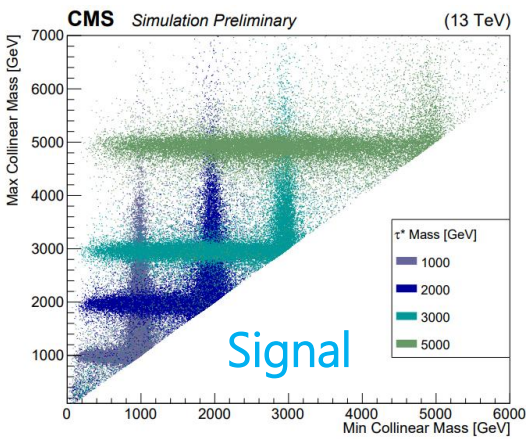
Signal populates a region in which either mass is compatible with m_{τ^*}

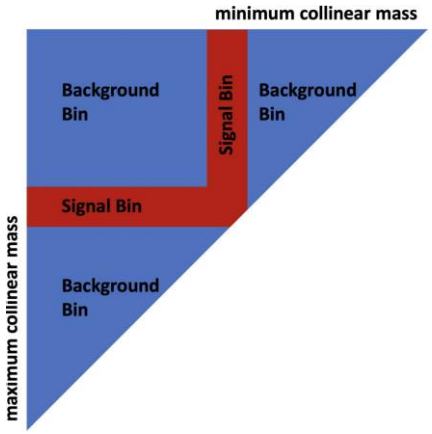
CMS-PAS-EXO-22-007

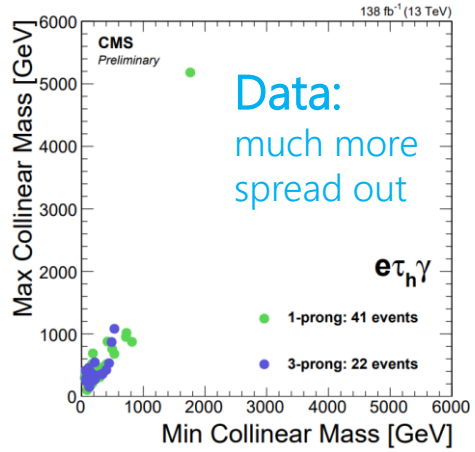
Excited tau lepton (τ*) in the ττγ final state

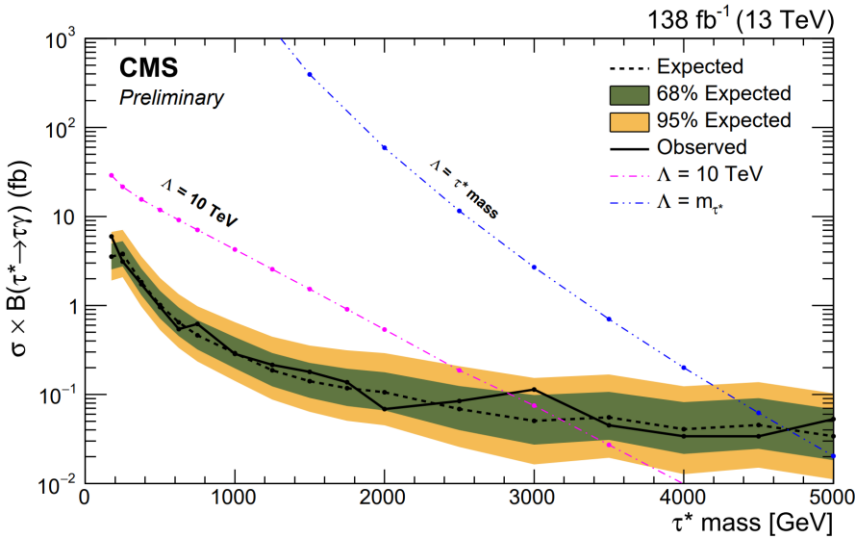
The peculiarity of the L shape is used to define a parametric SR selection:

- Same data is used for all signal interpretations, but binning depends on the m_{τ^*} hypothesis being tested









Depending on the assumptions on the CI energy scale:

Λ = 10 TeV (m_{τ^*}) → **excluding m_{τ^*} > 2.8 (4.7) TeV**

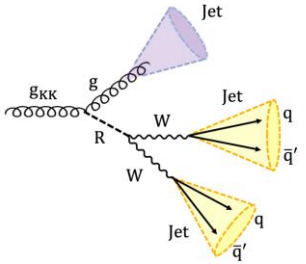
- Similar performance to the results obtained by ATLAS with a different strategy based on ττjj JHEP 06 (2023) 199

CMS-PAS-EXO-22-007

Search for Kaluza–Klein (KK) gluon resonances g_{KK}

Cascade decay of g_{KK} into two W bosons and a gluon via a scalar radion R

- $g_{KK} \rightarrow gR \rightarrow gW(qq)W(qq)$: final state with three large-radius jets

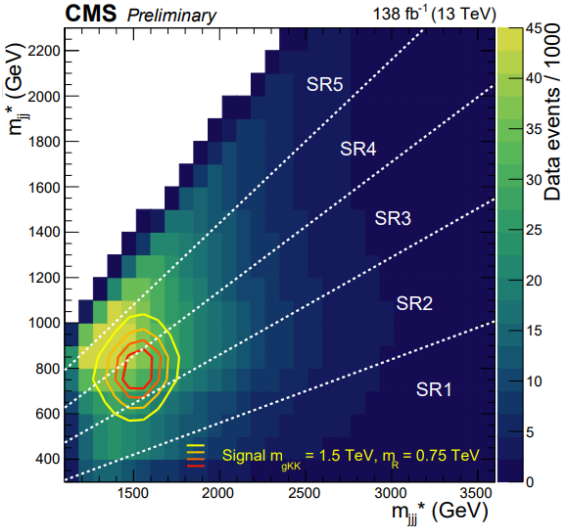


Probing extended warped-extra-dimensional (WED) model

- With suppressed direct g_{KK} decay to SM particles

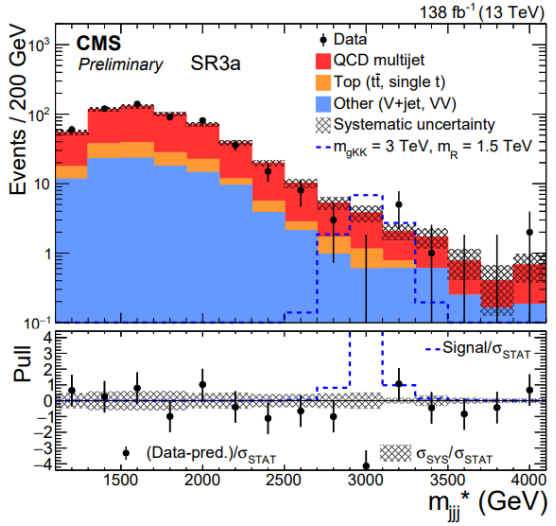
5 SRs defined in $m(g_{KK})/m(R)$ plane

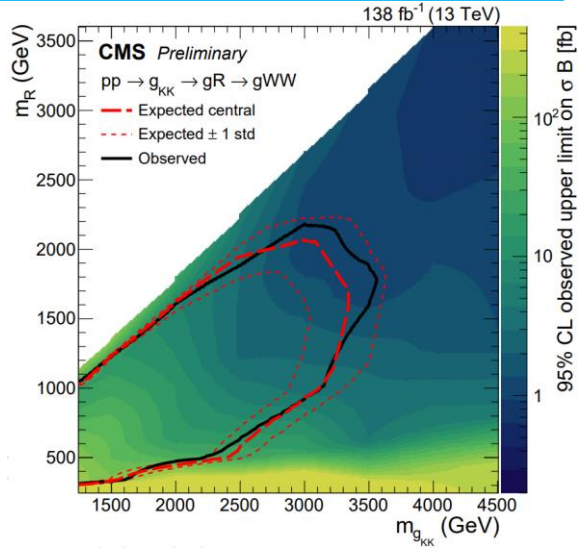
- Split further in two according to sub-leading W jet ParticleNet score



Limits on σ×BR as a function of m(R) and $m(g_{KK})$

- Excluding $m(g_{KK})$ up to 3 TeV and m(R) up to 2.05 TeV for $m(R) / m(g_{KK})$ in the range of 0.30–0.72
- Downward fluctuation of data at ~3-3.5 TeV
  Yield tight observed limits w.r.t. expectation





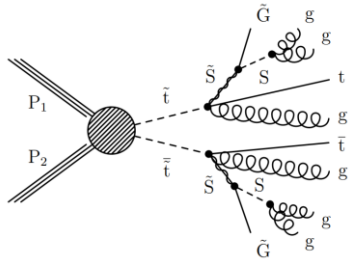
CMS-PAS-B2G-23-004

Stealth/R-parity violation (RPV) Stop Search

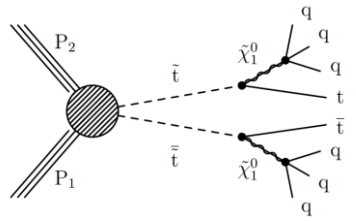
Looking for both an R-parity violating (RPV) and a Stealth SUSY Signature

- Final state: **ttbar+jets** with **little to no p_T^{miss}**
- Primary observable is N_{jets}
- Three channels: zero lepton (0l), one lepton (1l), and two lepton (2l)

Stealth $SY\overline{Y}$ SUSY



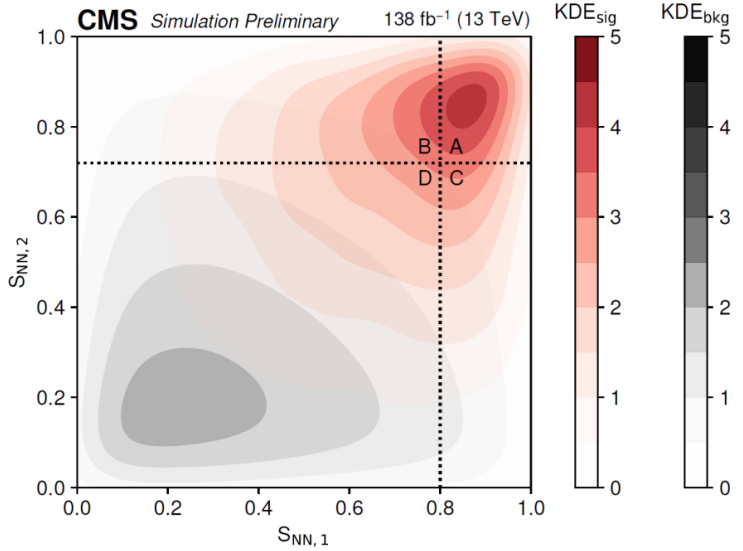
R-Parity Violating SUSY



CMS-PAS-SUS-23-001

Signal and ttbar+jets estimated separately in each N_{jets} bin with simultaneous fit to data in four 'ABCD' bins of $S_{NN,1}$ vs. $S_{NN,2}$ plane

- $S_{NN,1}$ and $S_{NN,2}$: independent variables that discriminate signal from ttbar+jets generated using ABCDisCoTEC neural network (ML-based ABCD)
- Floating parameters of fit are ttbar+jets event yields in each ABCD bin and signal strength
- Fit relies on key 'ABCD' constraint: $N_A = \kappa \frac{N_B N_C}{N_D}$
  - Appropriate given independence of $S_{NN,1}$ and $S_{NN,2}$

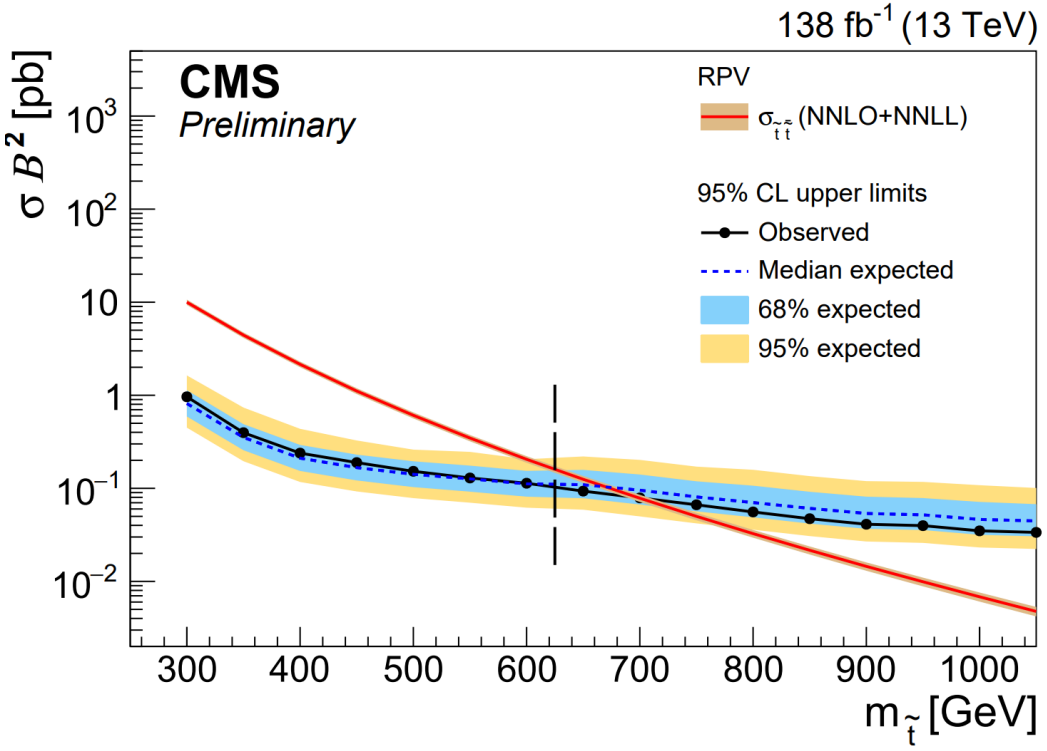


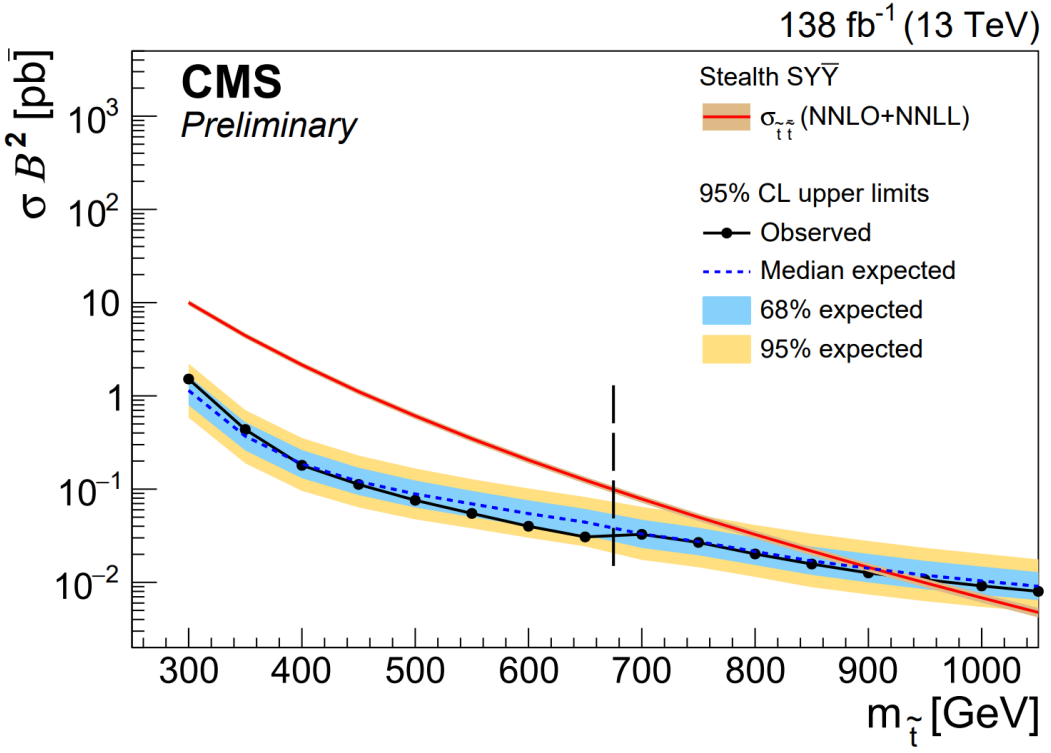
Stealth/R-parity violation (RPV) Stop Search

Three channel combination limits shown for the RPV (left) and Stealth $S\bar{Y}\bar{Y}$ (right) signal models

- No significant excess observed above expected background for either model

Mass exclusion limits set at 700 GeV (RPV) and 920 GeV (Stealth $S\bar{Y}\bar{Y}$)





CMS-PAS-SUS-23-001

Summary

Run 3 operations

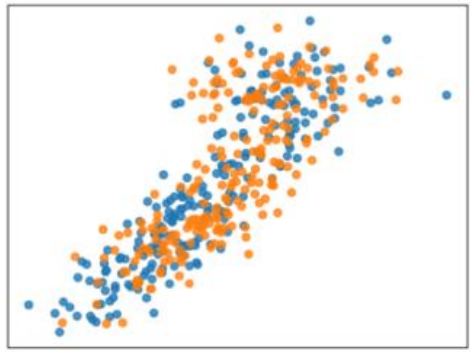
- Stable and efficient data taking
- High quality of promptly reconstructed objects
- Trigger, data taking and reconstruction strategies open new possibilities for analysis

Physics analysis: many new results since the winter conferences

- Entering the era of precision measurements
  - Some results on EWK physics now competitive with those from e^+e^-
  - Investigating subtle effects as in ttbar spin correlations
- Study of Higgs, BSM particles with multiple objects of
  - Tau leptons, top quarks, large radius jets, …

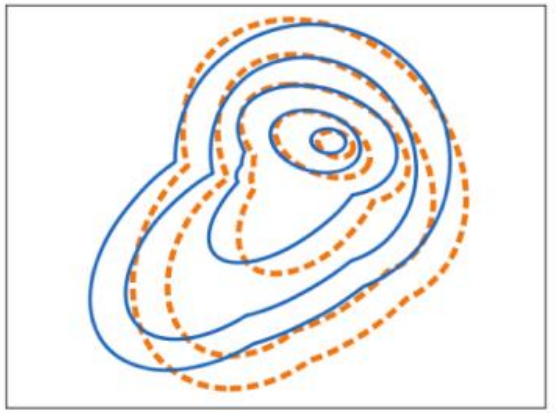
Backup

Unbinned unfolding and uncertainty estimation

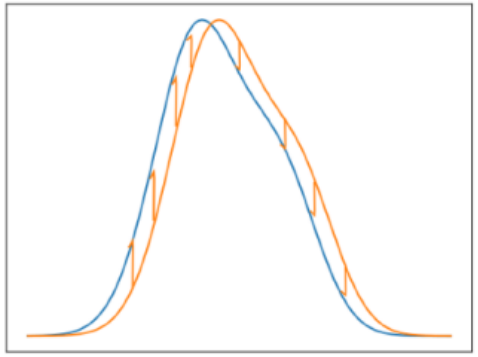


← A typical binary classifier to distinguish two sets

What it actually did: learn the differences in the distributions →



CMS-PAS-SMP-23-008



← Could use the classification scores to weight **MC** to **data**, and **nominal sample** to **systematic variations**

Event-wise unfolding → the result independent of binning

- ❖ Step 1: weight MC to data, at detector level
- ❖ Step 2: pull back the weights to particle(truth) level

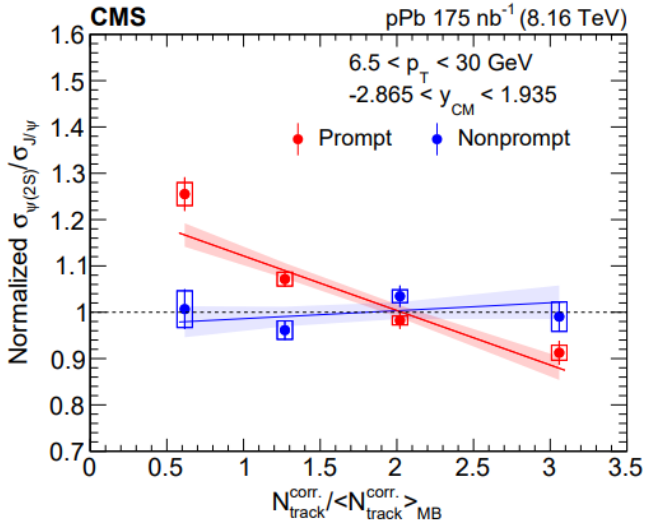
Multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in pPb

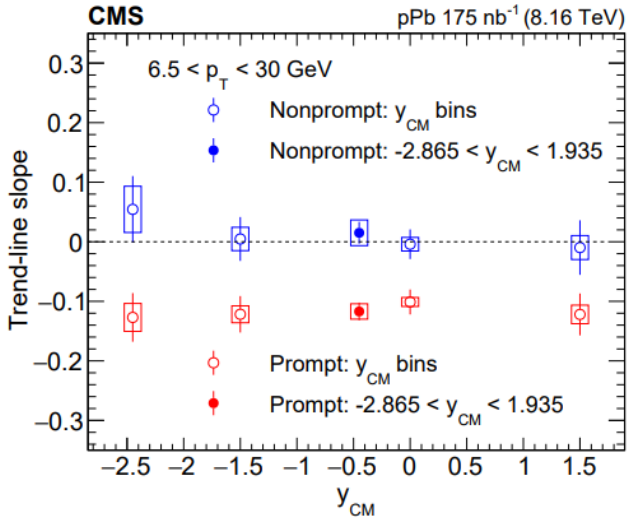
Ratio of ψ(2S) and J/ψ production cross sections in pPb collisions at $\sqrt{s_{NN}}$ = 8.16TeV

- Motivated by growing interest for quarkonium suppression in small systems
- Ratios measured for prompt and non-prompt mesons in the dimuon channel

Multiplicity-dependent modification of the ratio observed for prompt mesons

- Stable for non-prompt mesons
- Co-moving particles could dissociate excited states more easily than the ground state



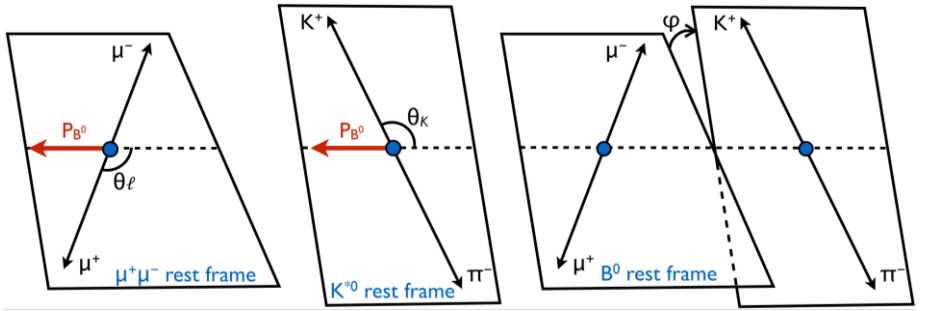


CMS-PAS-HIN-24-001

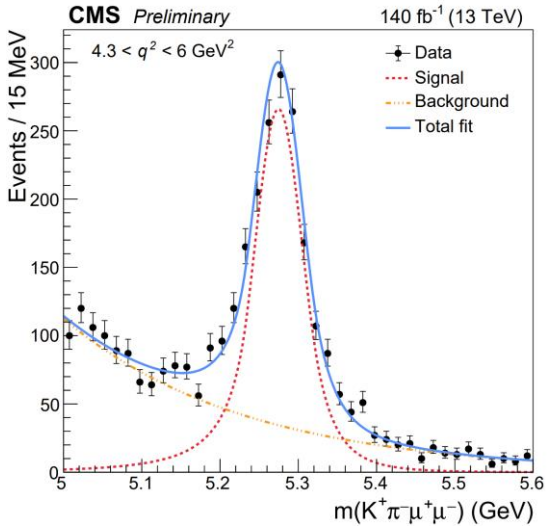
Angular analysis of $B^0 \to K^{*0}(892)\mu^+\mu^-$

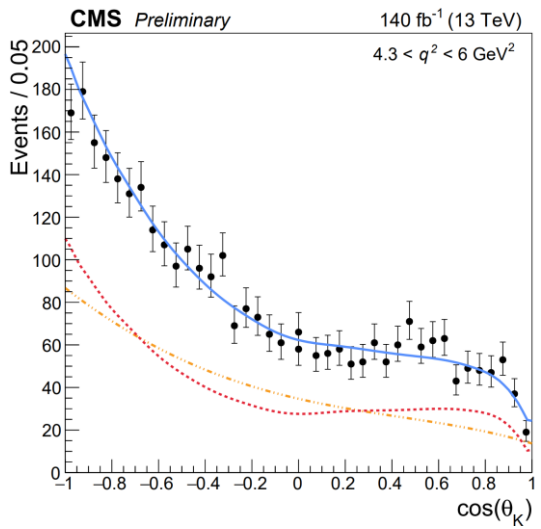
Measurement of the complete set of CP averaged variables

- Long history of searches for hints of new physics in this process
  - Limited impact of theoretical uncertainties in angular distributions
- Background rejection optimized with a BDT
- Angular parameters extracted from fit to m_B and 3 angles as f(q^2)
  - F_L, P_1, P_2, P_3, P'_4, P'_5, P'_6, P'_8



CMS-PAS-BPH-21-002





Post-fit mass and $\cos(\theta_K)$ distributions

Results among the most precise measurements of these parameters