Recent Physics Results from CMS

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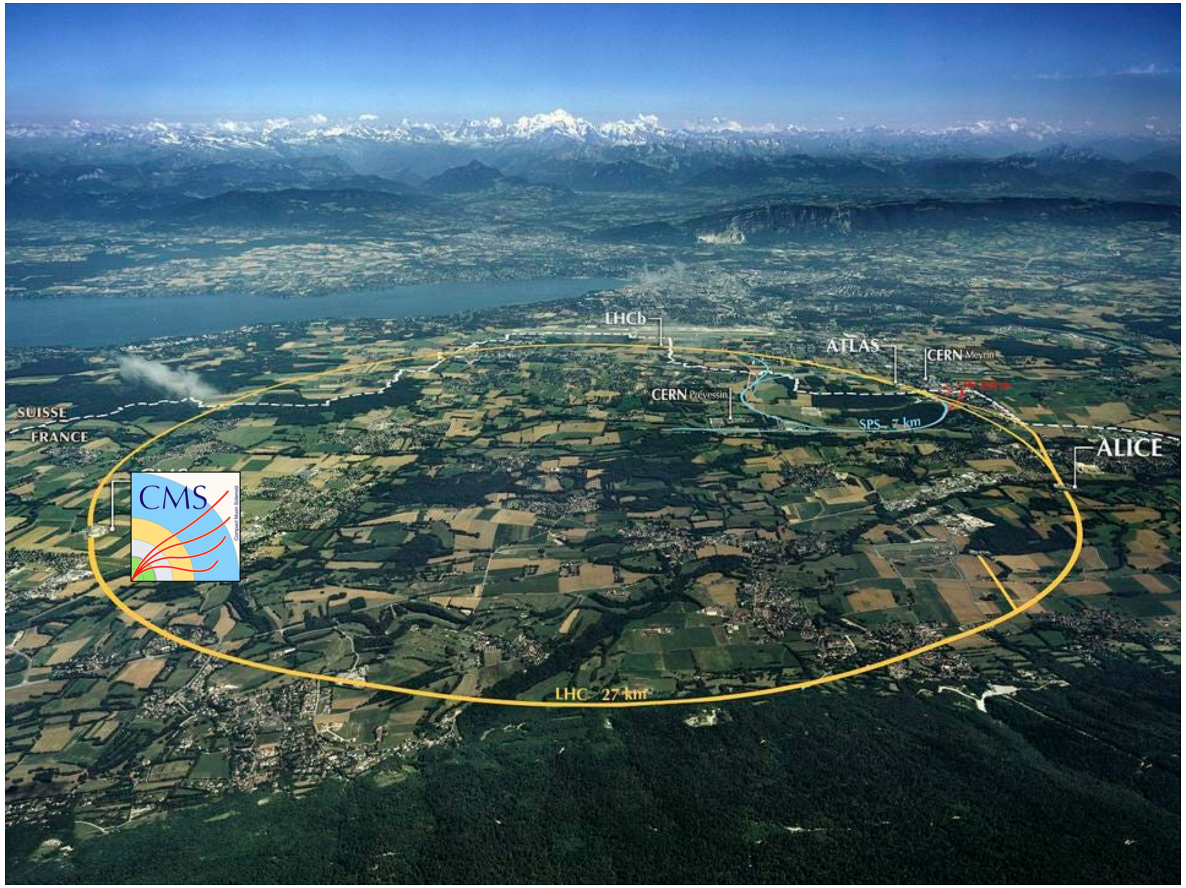
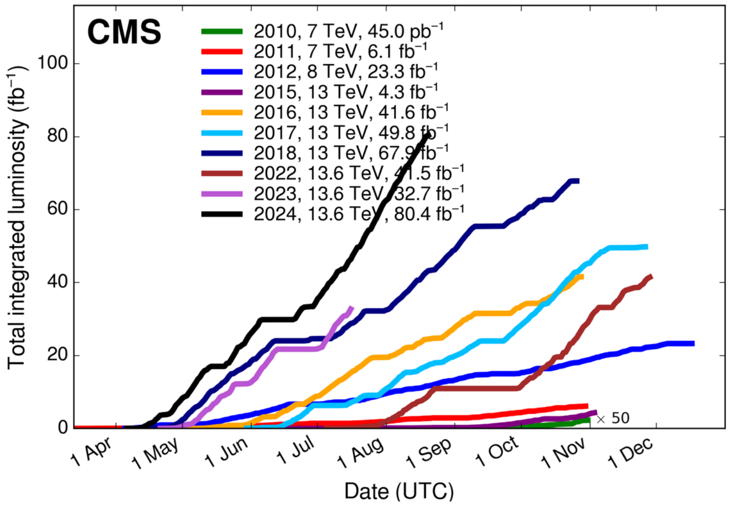
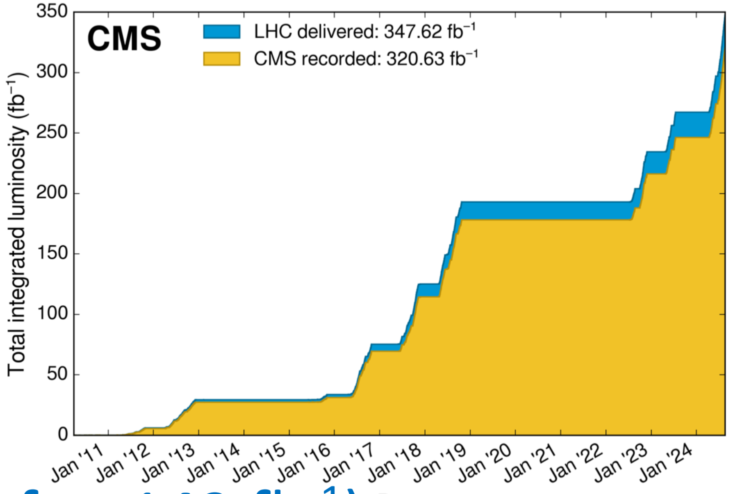
XIII International Conference on New Frontiers in Physics

Kolymbari, Aug 30, 2024

The LHC (with CMS)



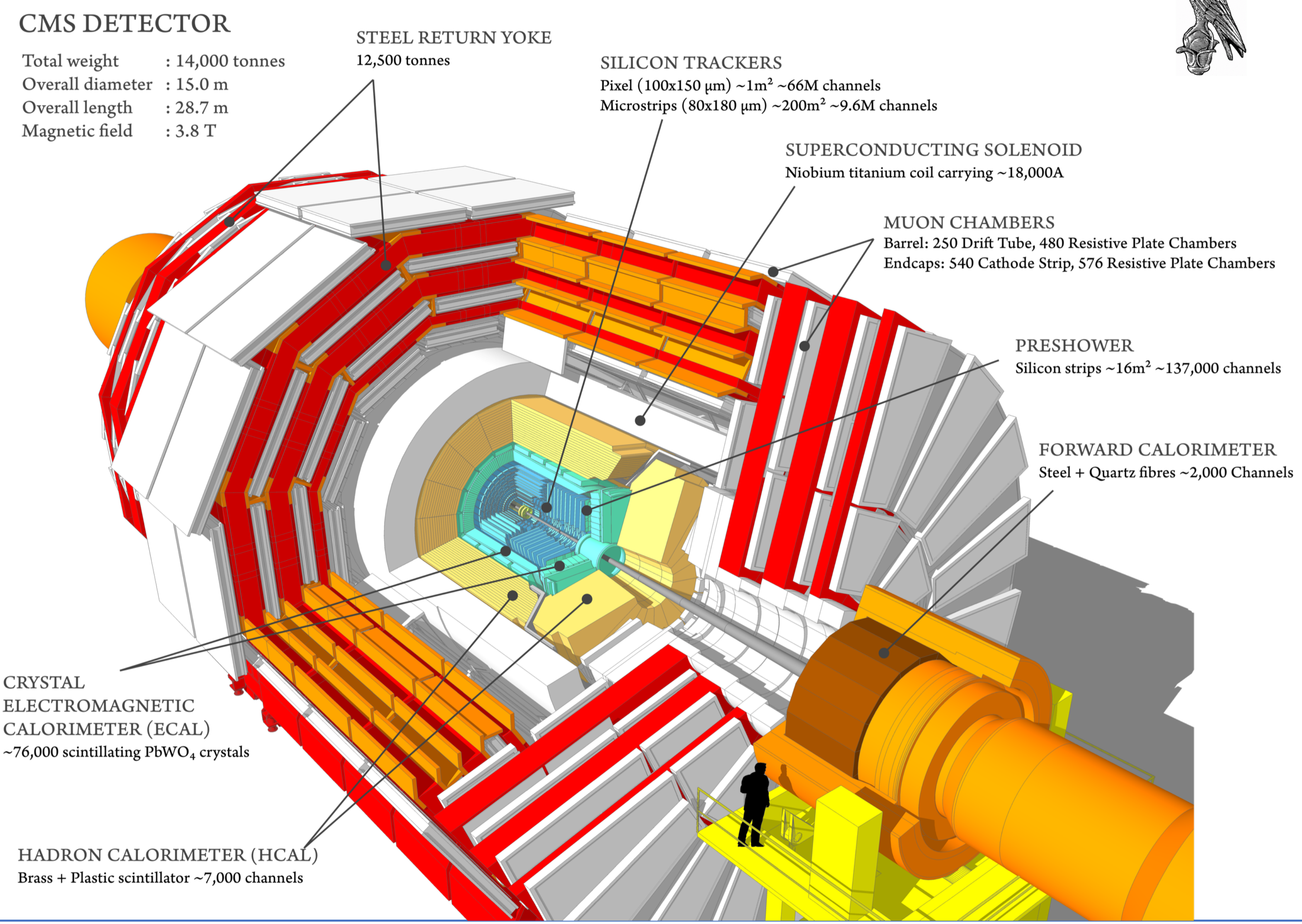




- Run2 total recorded luminosity: 138 fb^{-1} (Run3 so far: 142 fb^{-1})
- Unless otherwise noted, the presented analyses are Run2 with total recorded luminosity

The CMS detector

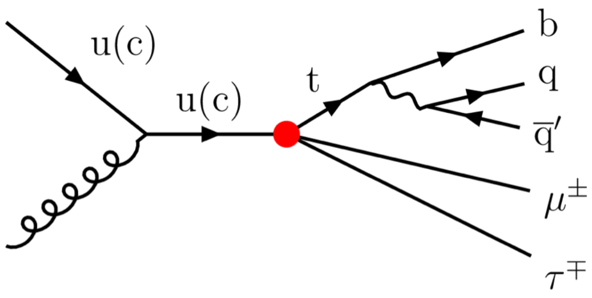
- 3.8 T magnet
- Silicon pixel + strip tracker
- Lead/Tungstate EM calorimeter
- Brass/Scintillator Had calorimeter
- Muon system embedded in return yoke
- Tungsten/quartz forward calorimeter

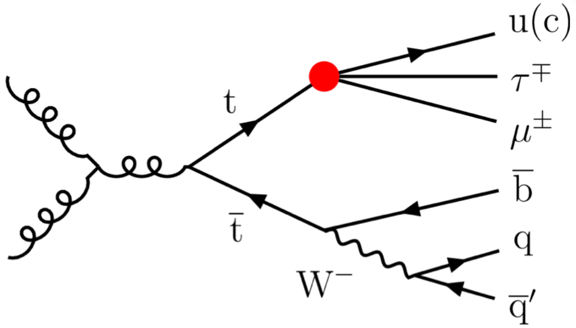


Outline of this talk

- We present all new post-ICHEP CMS results
  - They were all released last 30 days
- Covering a variety of physics
  - Lepton Flavor Violation
  - Dineutrino measurement in top pairs
  - SUSY searches in dileptons+MET
  - Phenomenological MSSM interpretation of CMS results
  - Search of Dark matter associated to Higgs to taus
  - Search for HHWW couplings in Vector-Boson Scattering WWH
  - Search for t-channel leptoquarks
  - Search for Rare Charm Decay into 2 muons
  - Study of Small-Angle Emissions in charm jets
  - Energy-Energy Correlations in PbPb and pp collisions

Charged-Lepton Flavor Violation in tuμτ interactions

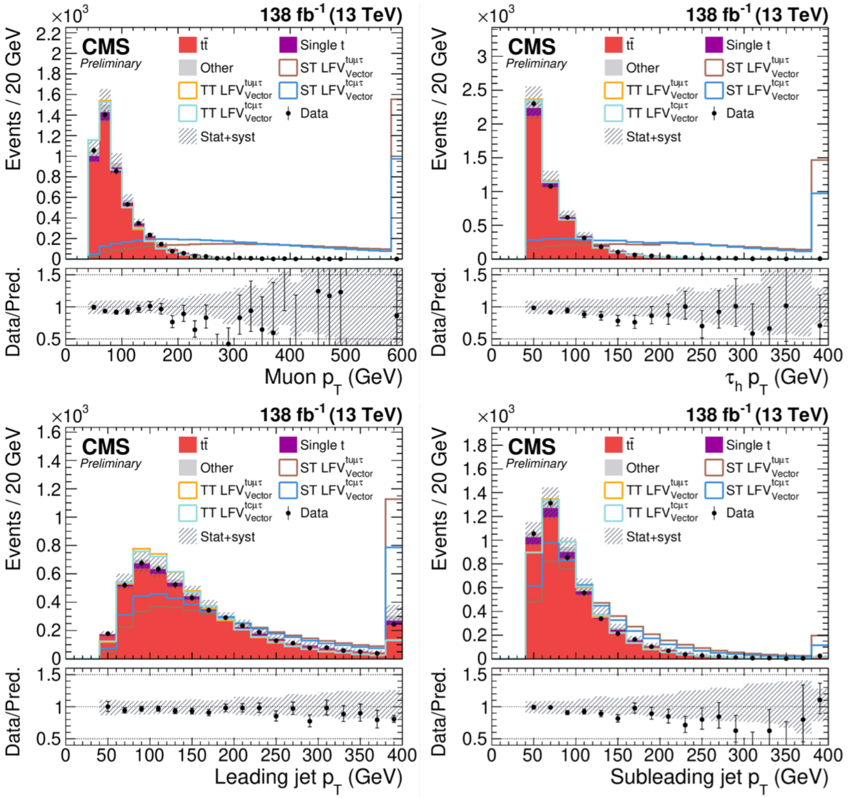




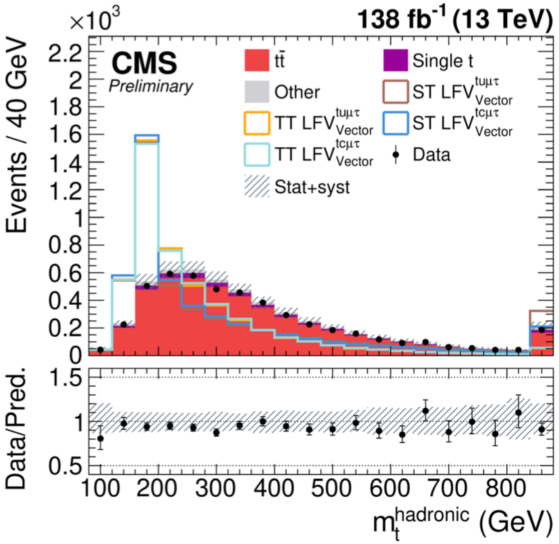
- 138 fb^{-1}, single-muon triggers, pt>24-27
- Exactly **1 isolated muon** p_T>50 GeV and exactly **1 hadronic tau** with pT>40 GeV with opposite charge and ΔR>0.4 away
  - VETO on additional leptons
- **≥3 jets, 1 b-tagged**
- Main backgrounds: t-tbar (to l+jets and dileptons) and single top (much lower)
- Jet → τ_h fake rates are determined with the ABCD method and applied on all MC
- **Top and hadronic W are reconstructed** from chi-squared constructed from bjj and jj masses
- Deep NN with score 10% P(ttbar CLFV) and 90% P(single-top SLFV) divided by P(background)
- **Data NN score is fitted to signal and background** scores and limits on Wilson coefficients for CLFV are set

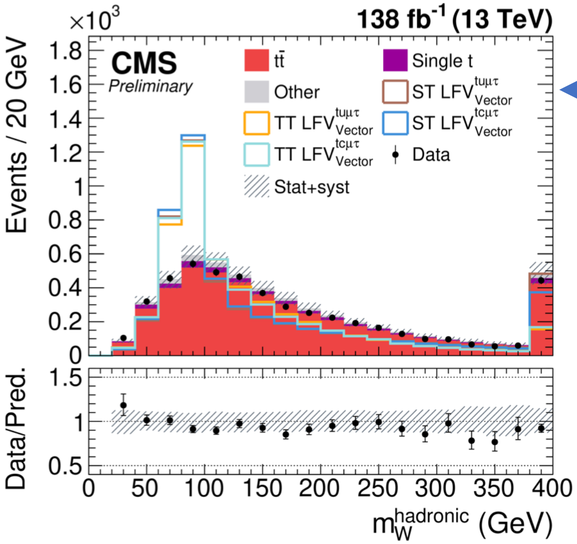
CMS-PAS-TOP-22-011

pT of muon, tau, leading and Subleading jet →

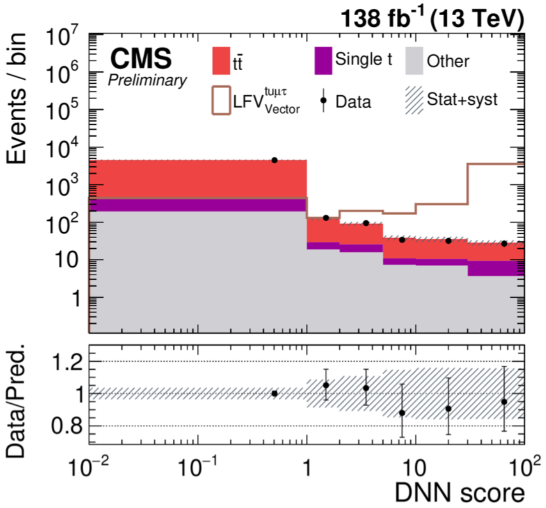


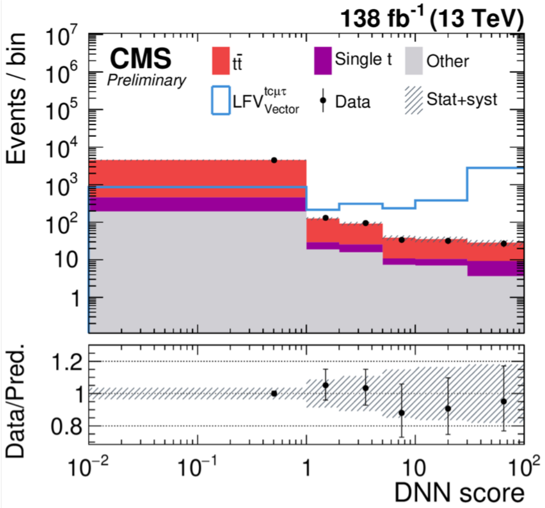
Charged-Lepton Flavor Violation in tuμτ interactions (2)





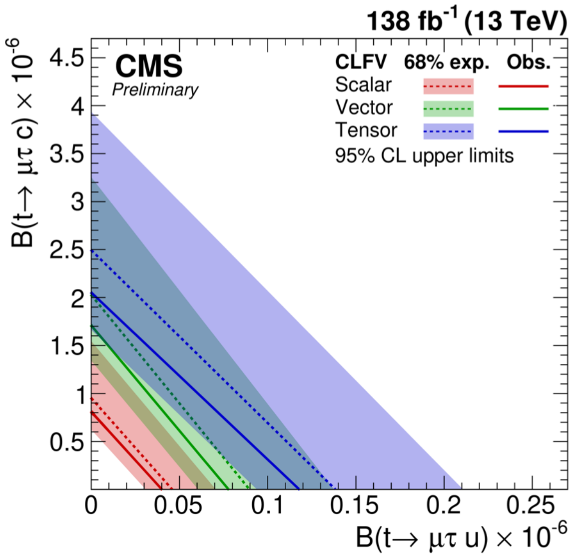
Top and W reconstruction



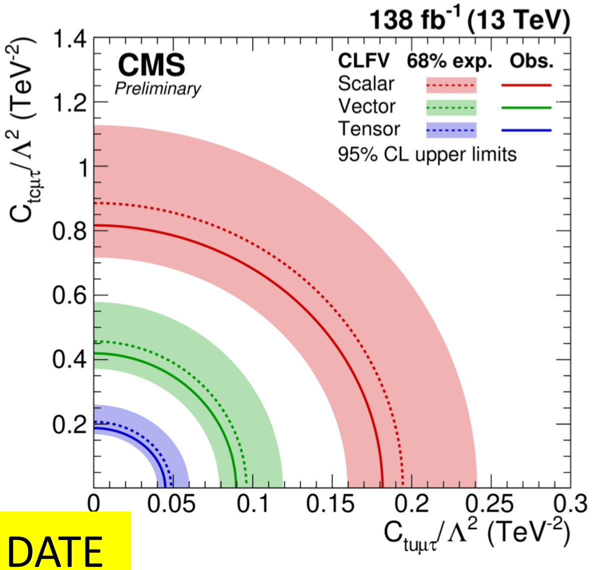


Fit of DNN score

BR limits for 3 kind of operators



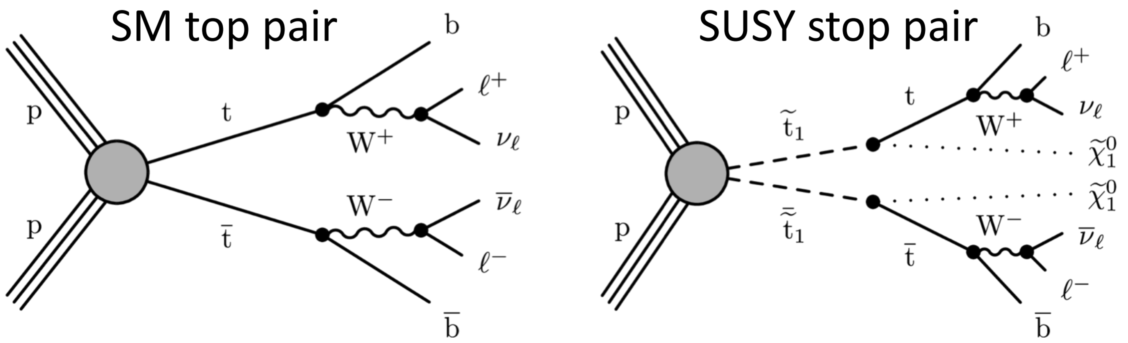
Wilson coefficient limits 3 kind of operators

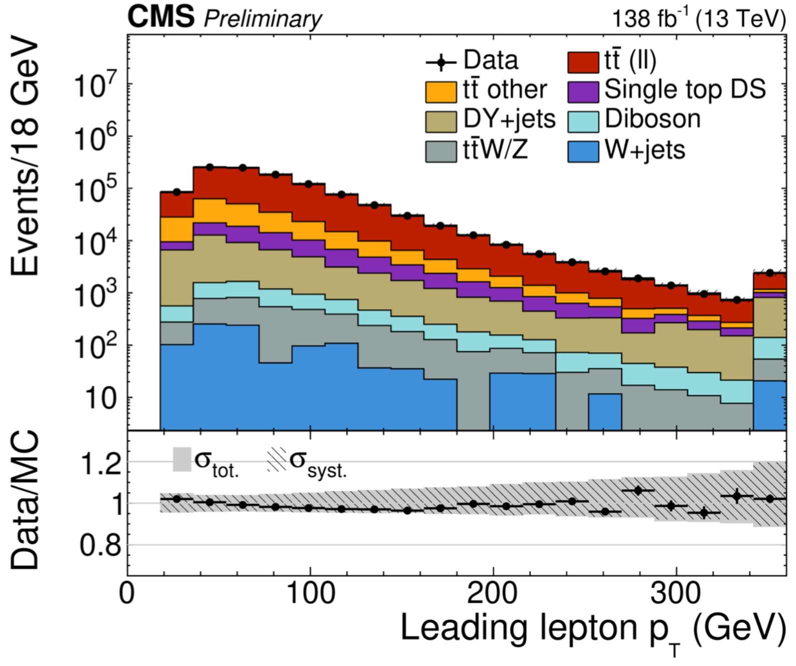


MOST STRIGENT RESULTS TO DATE

Measurement of dineutrino system in t-tbar production

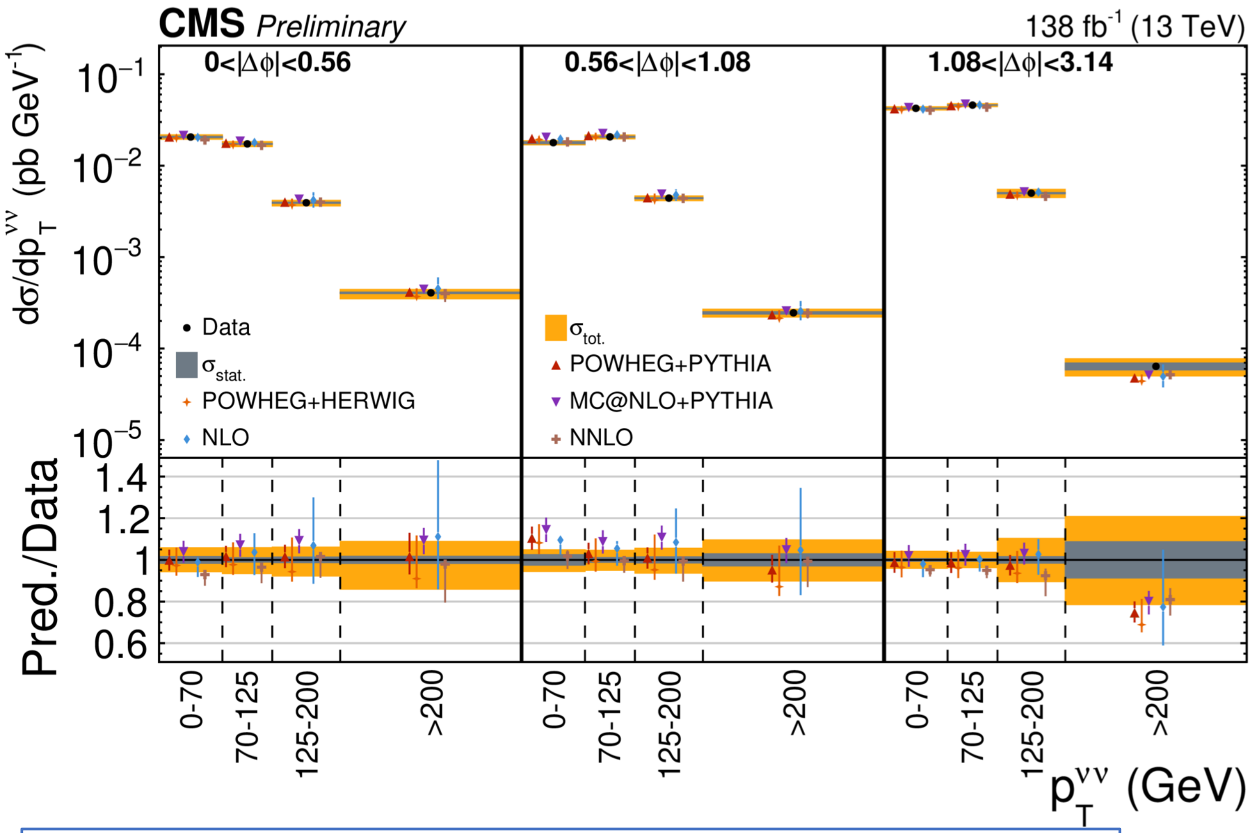
- 138 fb^{-1}, single-lepton and dilepton triggers
- **Signal: Top pairs to dileptons**
- Opposite charge ee, μμ, eμ pairs with p_T>25, 20 GeV and |η|<2.4
  - VETO on additional leptons with p_T>15 GeV
- **m_{ll}>20 GeV and 15 GeV away from Z boson mass**
- **≥2 jets (pT>30 GeV, |η|<2.4), 1 b-tagged**
- Main backgrounds: t-tbar to lepton+jets (or taus), single top, DY+jets, Diboson, t-tbar+W/Z, W+jets
- **Observables: p_T^{miss} and $\min[\Delta\Phi(p_T^{miss}, l)]$**
  - In one dimension but also 2-dimensional
- **Resolution of p_T^{miss} improved with a Deep Neural Network**
- Good agreement between observation and SM expectation
- **Extraction of differential cross sections as a function of p_T^{miss} and $min[\Delta\Phi(p_T^{miss}, l)]$ requiring at least 2 b-jets**
  - First, backgrounds are removed from data and then spectra are unfolded

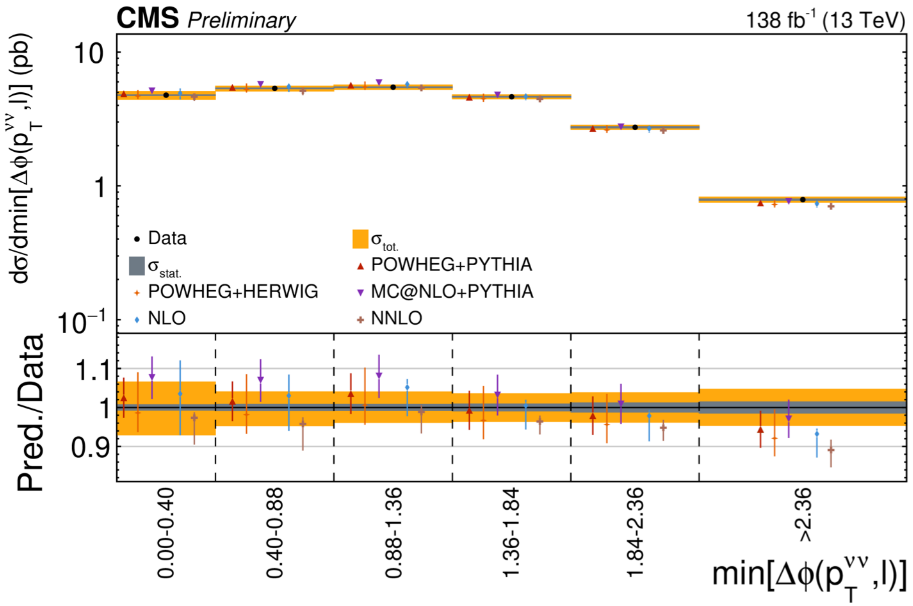


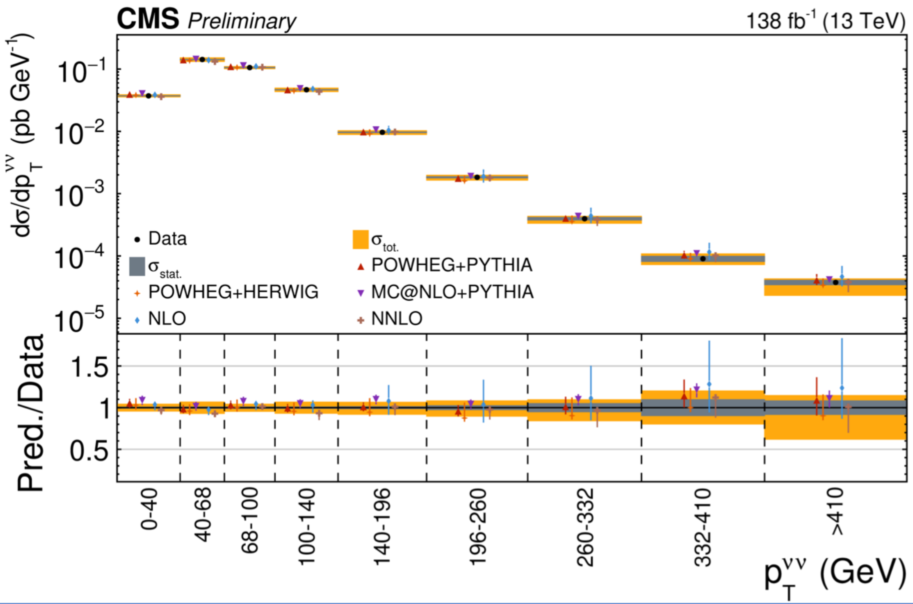


CMS-PAS-TOP-24-001

Measurement of dineutrino system in t-tbar production (2)

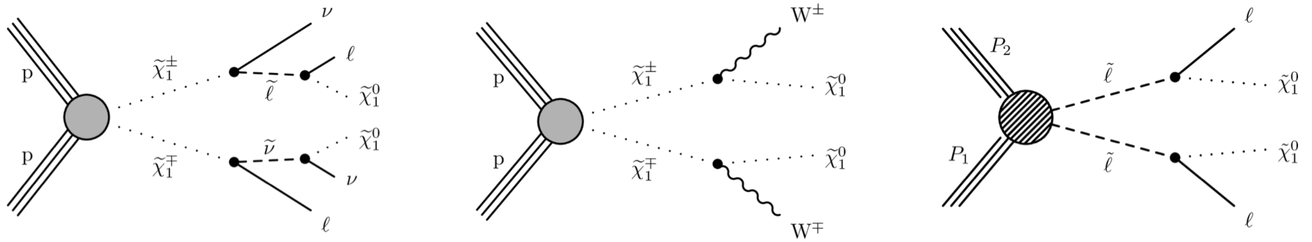






1D comparisons: Best prediction from Powheg+Pythia
2D comparisons: Best prediction from NNLO pQCD

SUSY searches in OS dilepton + p_T^{miss}

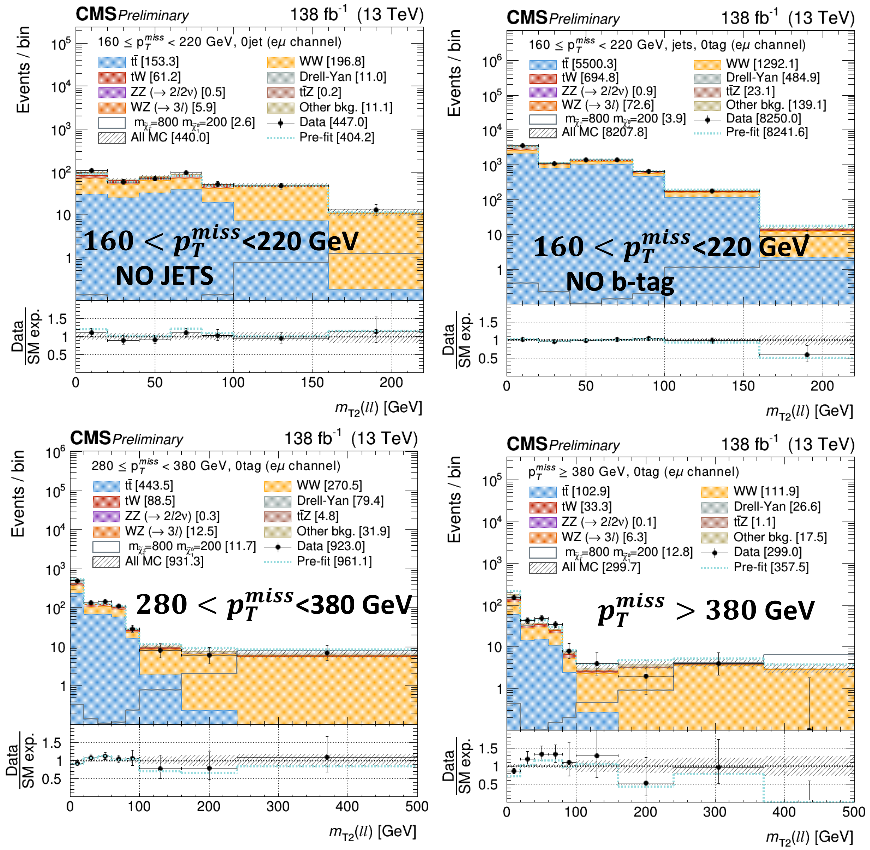


- 138 fb^{-1}, single-lepton and dilepton triggers
- BSM signal: chargino-neutrlino or slepton production
- **Opposite charge ee, μμ, eμ pairs with p_T>25, 20 GeV and |η|<2.4**
  - VETO on additional leptons with p_T>10 GeV
- **m_{ll}>20 GeV and 15 GeV away from Z boson mass**
- **p_T^{miss}>160 GeV**
- Main backgrounds: t-tbar, tW, WW
- **Observable:**

CMS-PAS-SUS-23-002

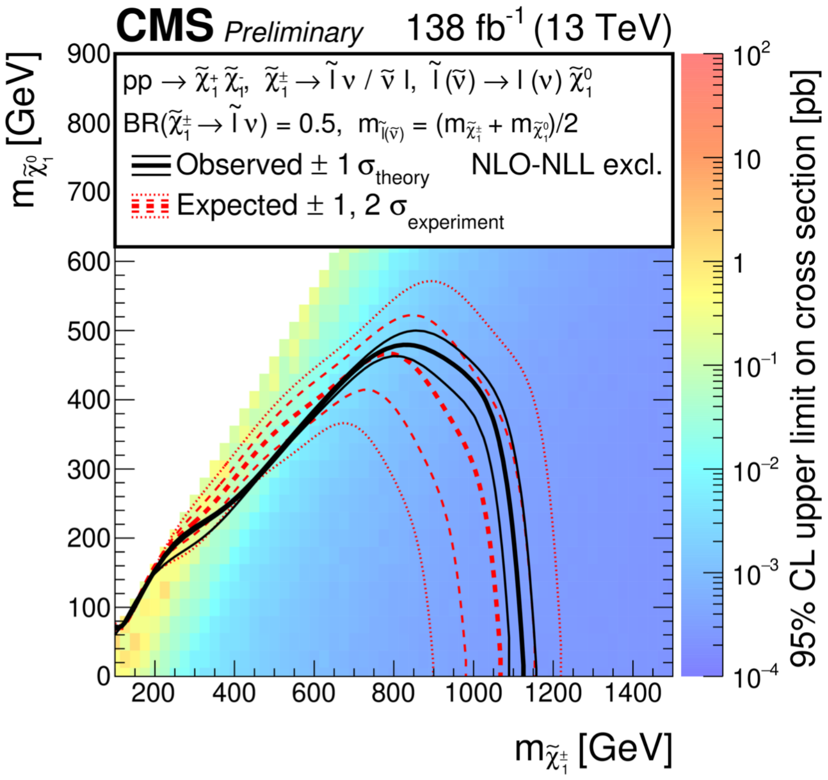
$$m_{T2}(\ell\ell) = \min_{\vec{p}_T^{\,miss1}+\vec{p}_T^{\,miss2}=\vec{p}_T^{\,miss}} \left(\max \left[m_T(\vec{p}_T^{\,lep1}, \vec{p}_T^{\,miss1}), m_T(\vec{p}_T^{\,lep2}, \vec{p}_T^{\,miss2}) \right] \right)$$

- **Further subdivisions of data based on bins of p_T^{miss}, Same-Flavor/Different-Flavor, b-veto or jet-veto**
- Good agreement between observation and SM backgrounds in Control Regions
- **Simultaneous fit of m_{T2} in Signal and Control Regions**

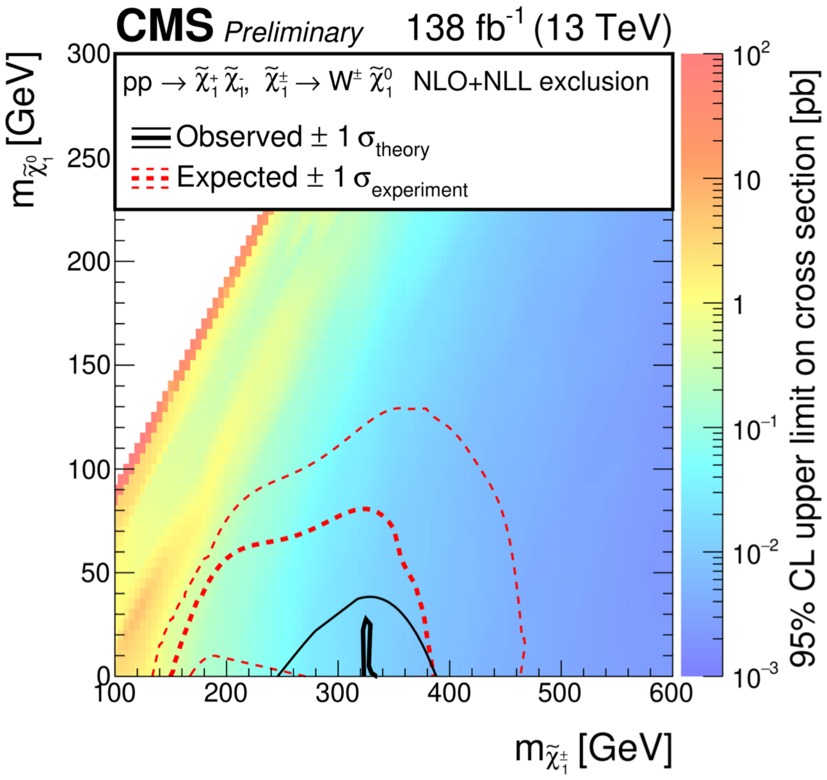


SUSY searches in OS dilepton + p_T^{miss} (2)

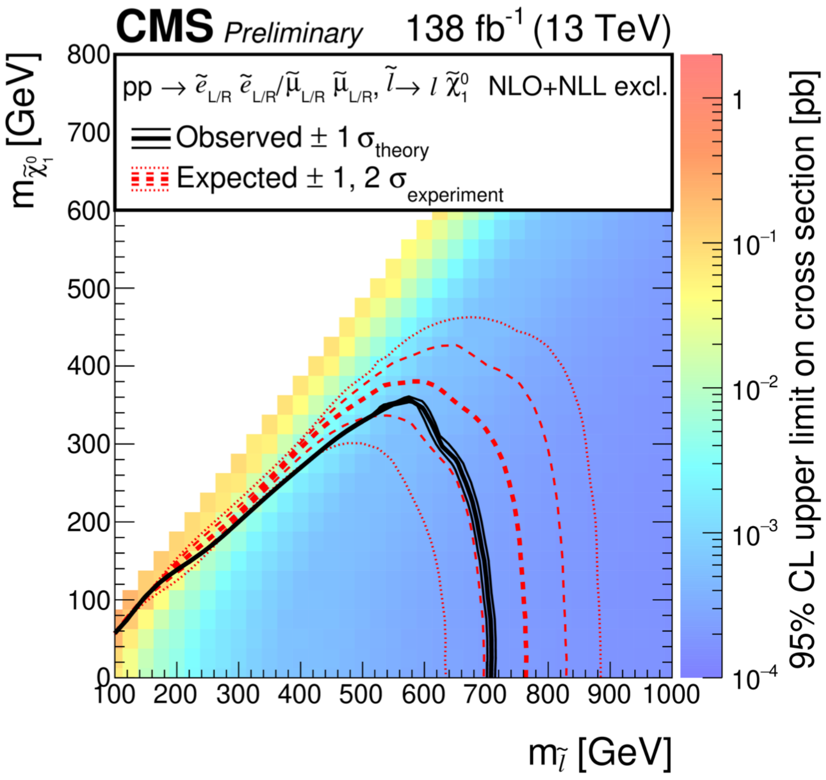
Chargino-pair limits
limits, chargino to slepton



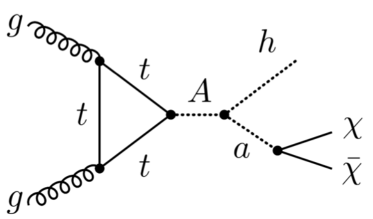
Chargino-pair limits
chargino to W+neutralino

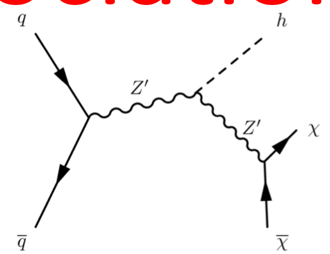


Slepton-pair limits



Search for Dark Matter in association with Higgs → τ+τ

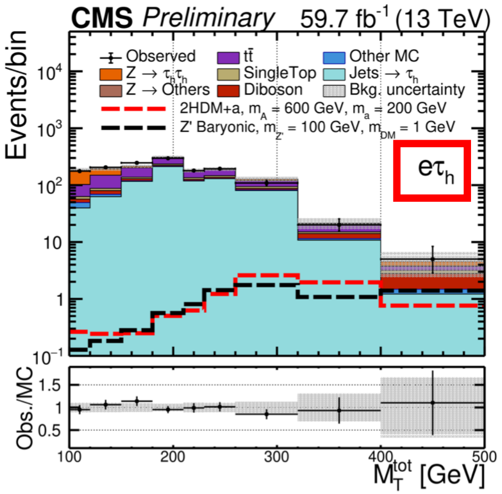


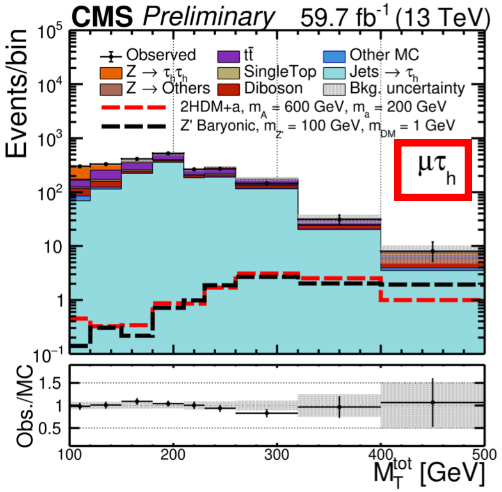


- 101 fb^{-1} (for the Z' study 138 fb^{-1})
- **Signature: Two taus (at least one hadronic) + p_T^{miss}**
- Single-electron and electron+tau triggers for $e\tau_h$, single-muon trigger for $\mu\tau_h$, and tau-tau trigger for $\tau_h\tau_h$
- Final objects have opposite charge and are ΔR>0.5 away
- e, μ (>25, 29 GeV) are isolated and their channel has τ_h above 30 GeV, b-jet veto and additional- lepton veto with $p_T > 10$ GeV
- In $\tau_\eta\tau_h$ channel the p_T are above 55 and 45 GeV and the p_T of they ditau system above 65 GeV
- All channels: p_T^{miss}>105 GeV, visible ditau p_T below 125 GeV, total transverse mass above 100 GeV and ΔR(τ,τ)<2
- Main backgrounds: faked taus in {W+jets, multijet, ttbar}
  - Fake factor determination, validated in control regions
- **Observable: Total Transverse mass (>100 GeV to reduce DY)**

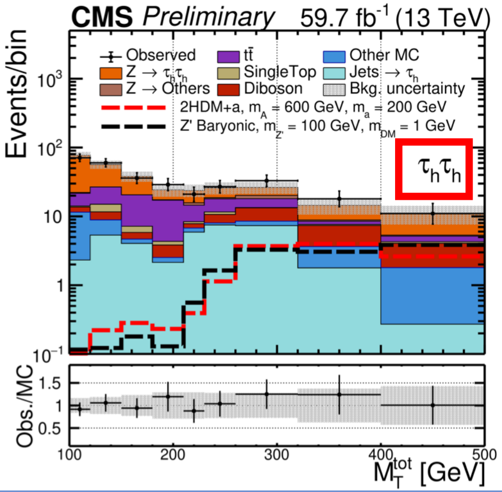
$$M_T^{tot} = \sqrt{(E_T^{\tau_1} + E_T^{\tau_2} + p_T^{miss})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{miss})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{miss})^2}$$

- Signal is extracted with simultaneous fits in all 3 signal regions

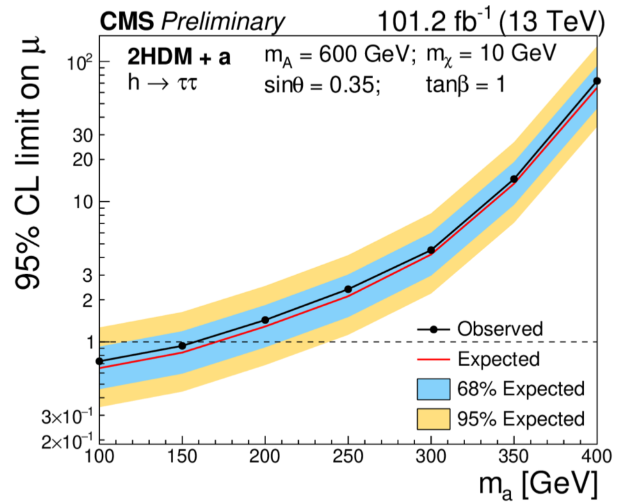


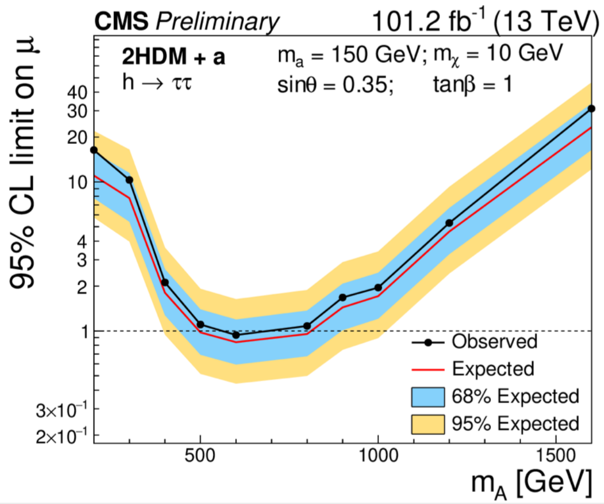


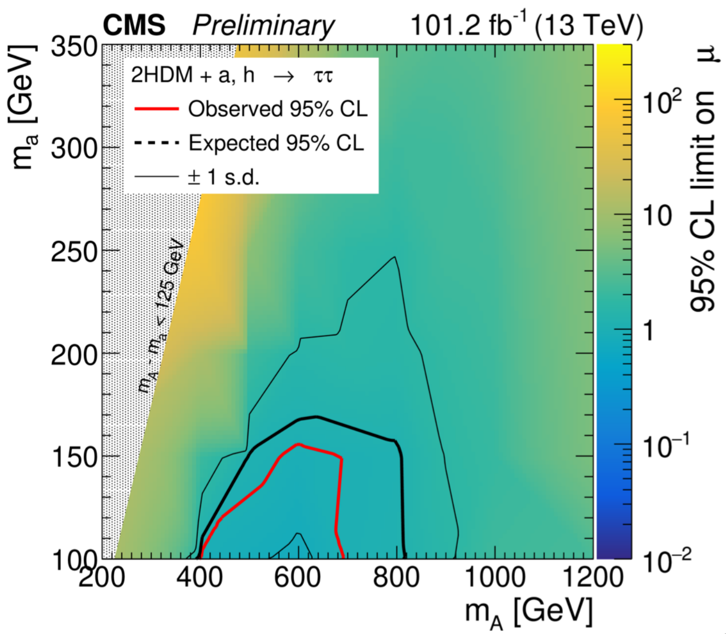
CMS-PAS-SUS-23-012

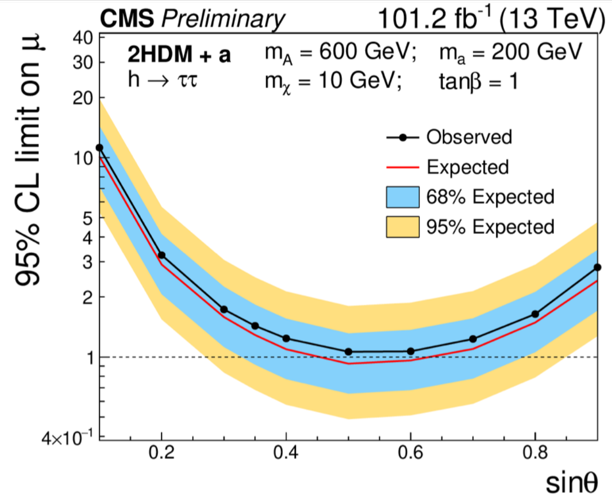


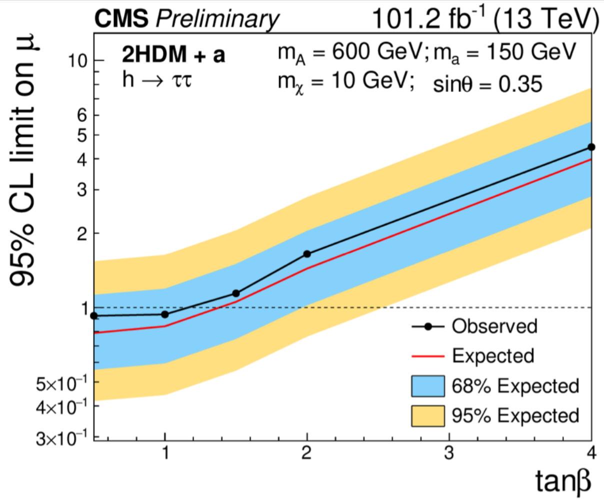
Search for Dark Matter in association with Higgs → τ+τ (2)



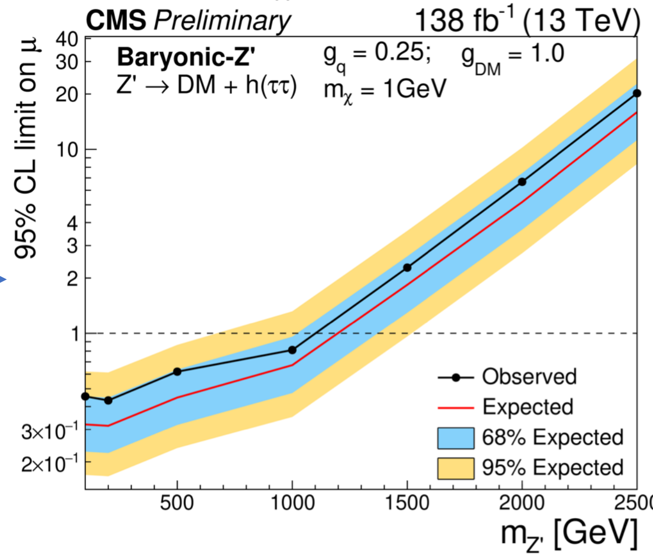








$m_{Z'}$ >1050 GeV at 95% CL
(1150 GeV expected)



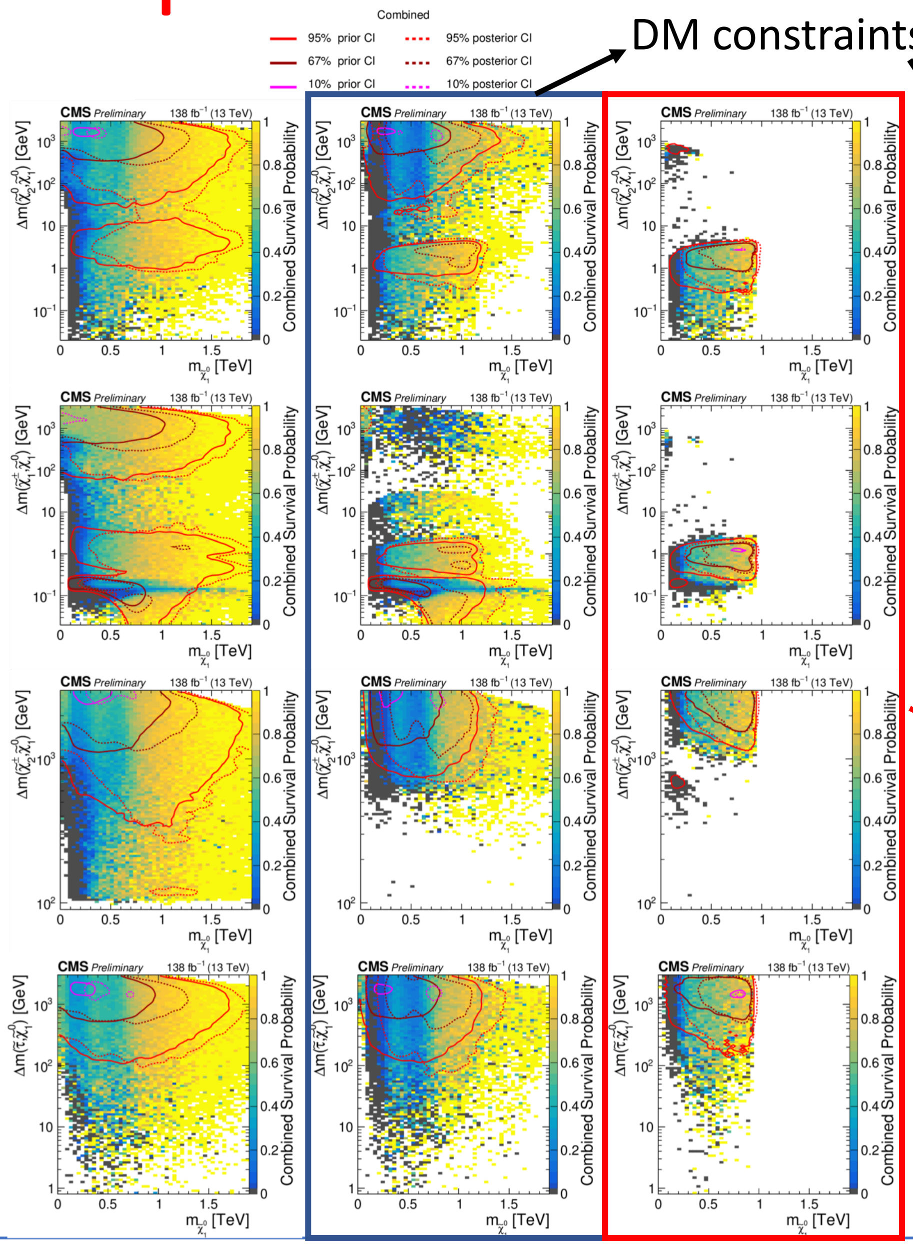
Phenomenological MSSM interpretation of CMS searches

CMS-PAS-SUS-24-004

- 138 fb^{-1}
- pMSMS with 19 parameters
- Scan of the parameter space with 600 Markov chains, about 40k pMSSM points each → 24 million pMSSM points
  - 500k points were randomly chosen for the studies

Analyses used:

- Soft Opposite Sign Λepton : low pT (<30 GeV), dileptons or trileptons, bins of p_T^{miss} and dilepton mass (**CMS-SUS-18-004**)
- p_T^{miss} + jets : 0 leptons, p_T^{miss}>300 Gev, bins of jet and b-tag multiplicity (**CMS-SUS-19-006**)
- Same-flavor opposite sign : two isolated SFOS leptons with p_T>30 GeV (**CMS-SUS-20-001**)
- Disappearing tracks : Search for SUSY with decay length of the size of the CMS detector (**CMS-SUS-21-006**)
- Single lepton ΔΦ: azimuthal angle difference between W and isolated lepton >30 GeV (**CMS-SUS-21-007**)
- Bayesian method to reject or accept a model : Survival probabilities: Fraction of models that survive CMS constraints
- Greater impact of CMS for more constraint priors (due to direct dark matter searches or due to naturaleness)



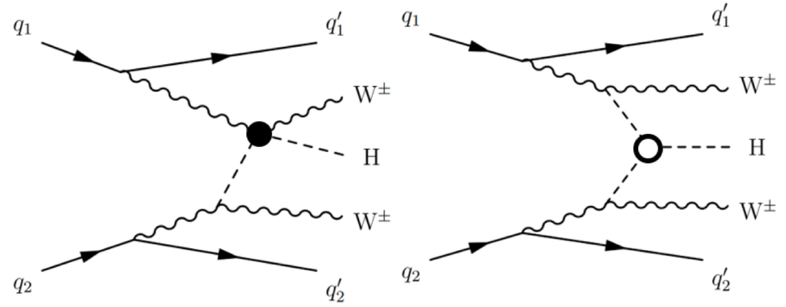
DM constraints

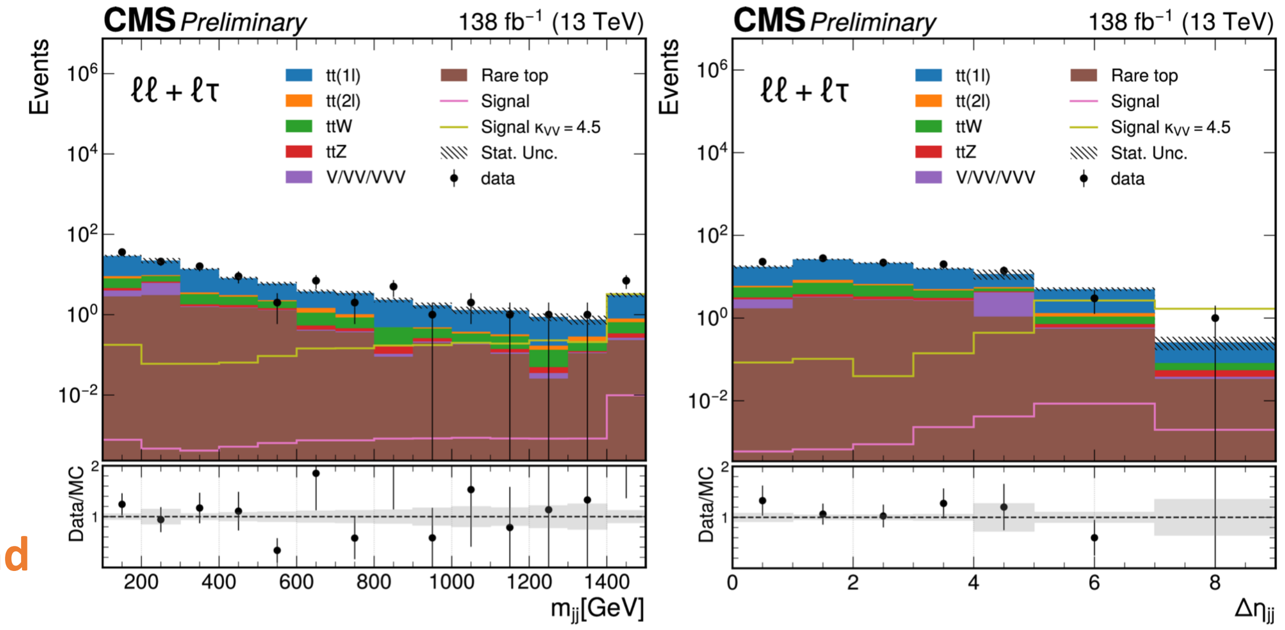
Relic density <1.1 of Planck measur. + limits from direct searches

Natural DM Subset (fine tuning less than 1/200)

Search for HHWW couplings in the VBS production of WWH, H→ bb

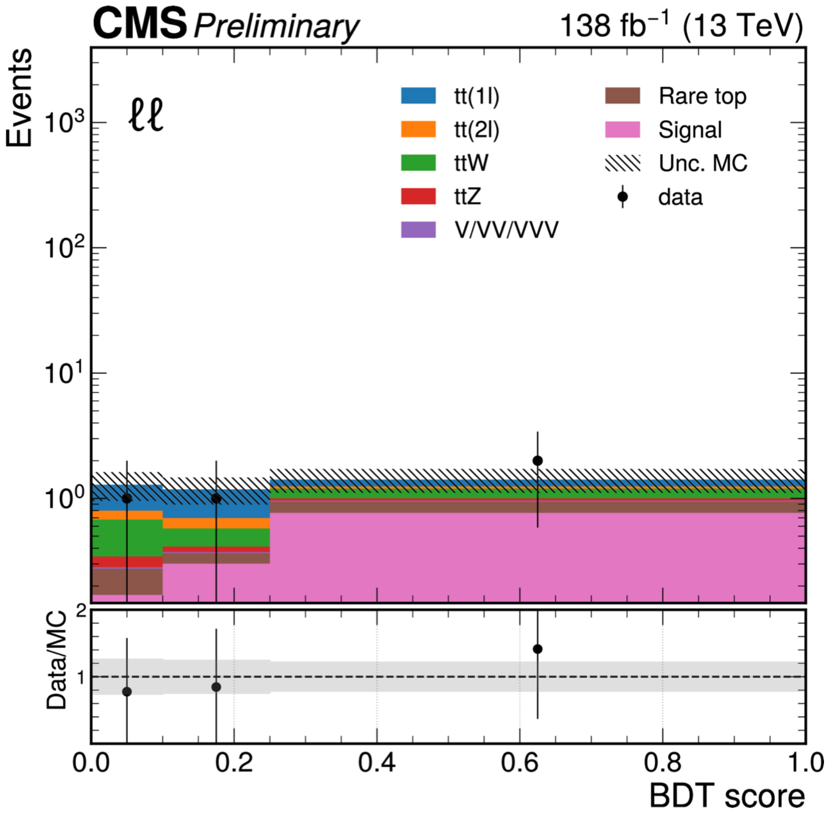
- 138 fb^{-1}, single-lepton and dilepton triggers
- **Signal: WWH+jj**
- Two **same-sign** leptons (ee, eμ, μμ, $e\tau_h$, $\mu\tau_h$) with pT>30 GeV and |η|<2.5.
    - VETO on additional leptons (suppresses HHZZ)
- Two forward anti-K_t jets with R=0.4, m_{jj}> 500 GeV, $|\Delta\eta_{jj}|$>3
- One fat jet with anti-K_t jets with R=0.8, ΔR=0.8 away from leptons (NN probability it originates from two b jets > 90%)
- Main backgrounds: t-tbar to lepton+jets or dileptons (minor ttbar+W/Z, single top, V/VV/VVV+jets)
- **Observables:** m_{jj} and $|\Delta\eta_{jj}|$
- **Boosted decision tree separates signal from background (output fitted in Signal and Control Regions**
- Good agreement between observation and SM expectation, limit on κ_{VV} coupling modifier

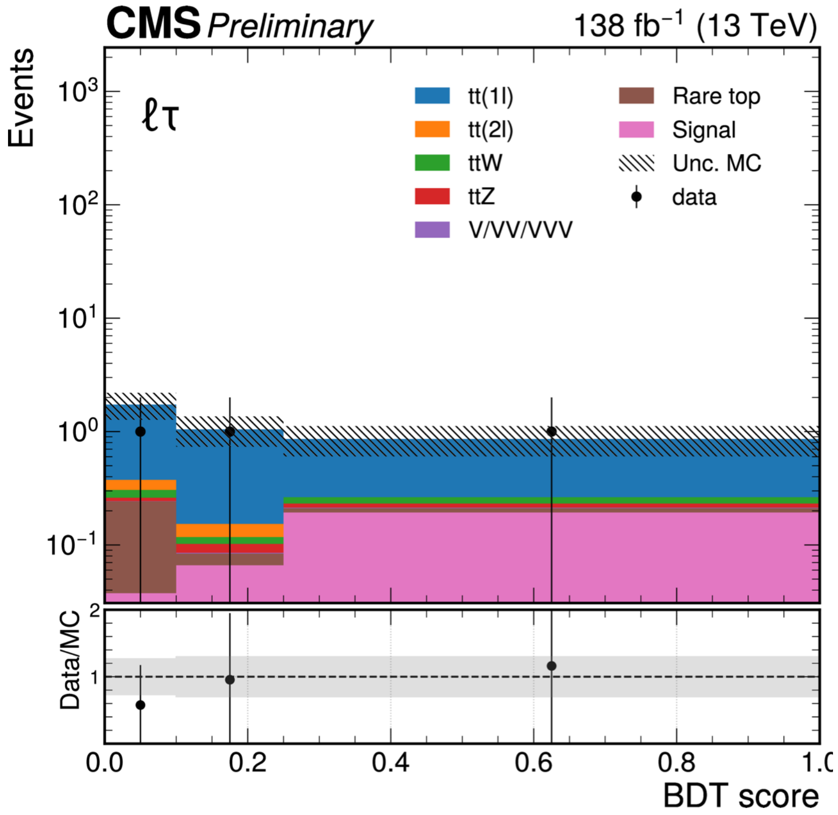


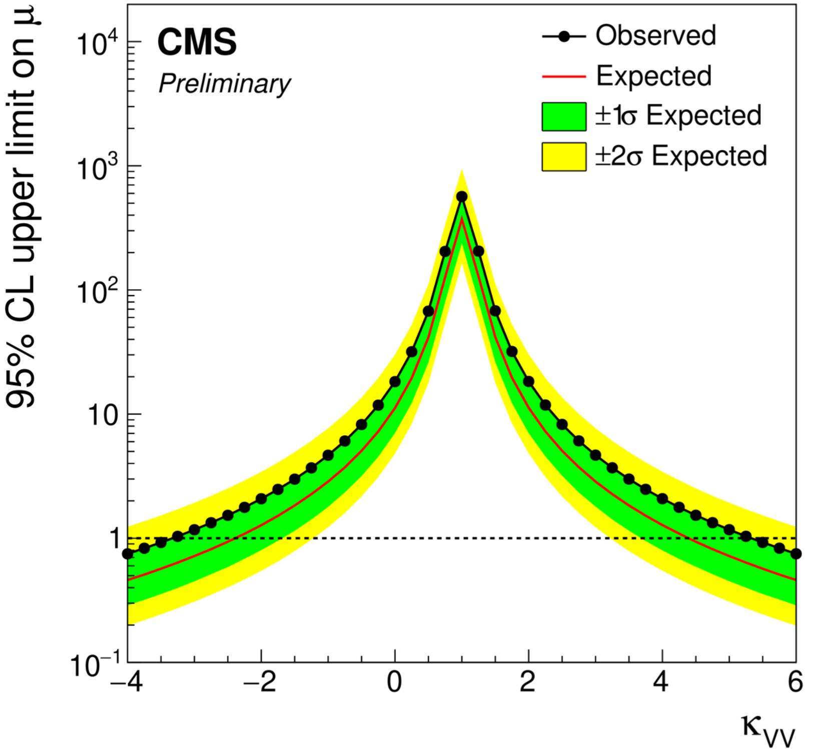


CMS-PAS-HIG-24-001

Search for HHWW couplings in the VBS production of WWH, H→ bb (2)



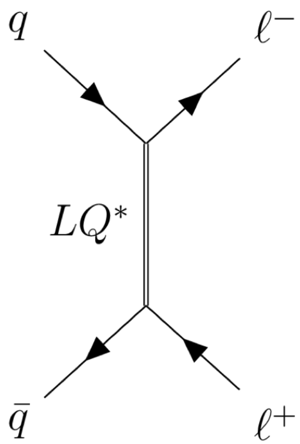


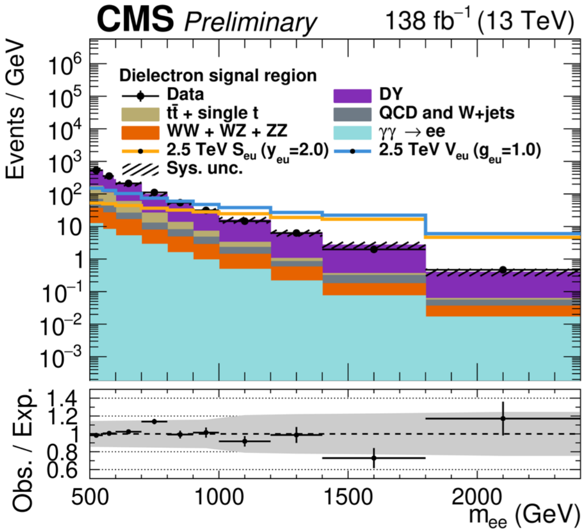


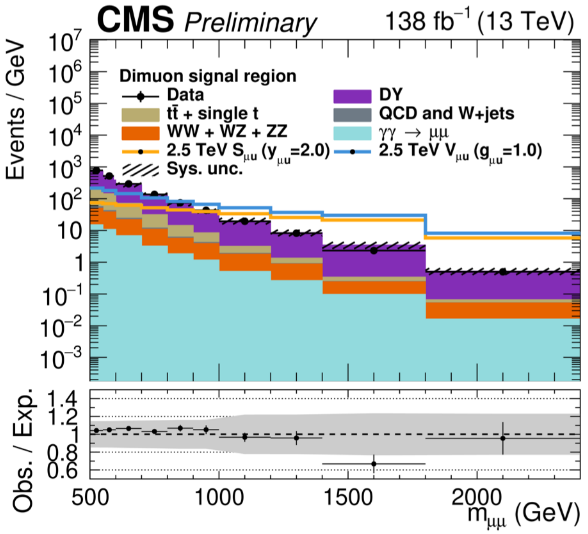
At 95% k_{WW} is in [-3.3, 5.3](expected [-2.4, 4.4])

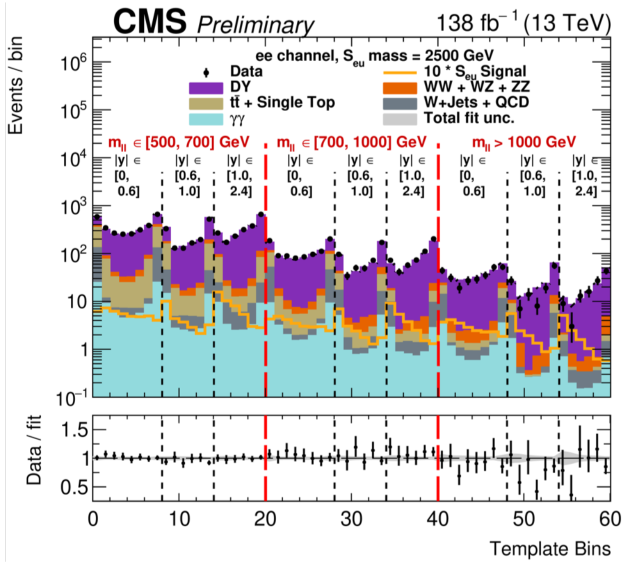
Search for t-channel scalar and vector leptoquarks in high-mass ee & μμ

- 138 fb^{-1}, single-electron and single-muon triggers
- Scalar and Vector leptoquarks are considered (t-channel is more sensitive to high masses and couplings) – lepton couplings to u and d
- Two **opposite-sign**, same flavor leptons (ee, μμ) with pT>40, 15 GeV and |η|<2.5 (2.4 for muons), m_{ll}>500 GeV
- **Observables:** m_{ll} , y_{ll}, cos(θ) [angle between incoming parton and lepton in Collins-Soper frame]
- Main backgrounds: DY (~85%), t-tbar to dileptons (~10%), diboson (~5%), fakes (~0.5%)
- LQ signal and DY background templates of the differential cross section are constructed from DY MC
  - Free parameters are two angular coefficients of SM Z and two couplings (pure and interference) for LQ (separately for scalar and vector)
- Good agreement between observation and SM expectation, limit on scalar/vector couplinds e/μ to u/d



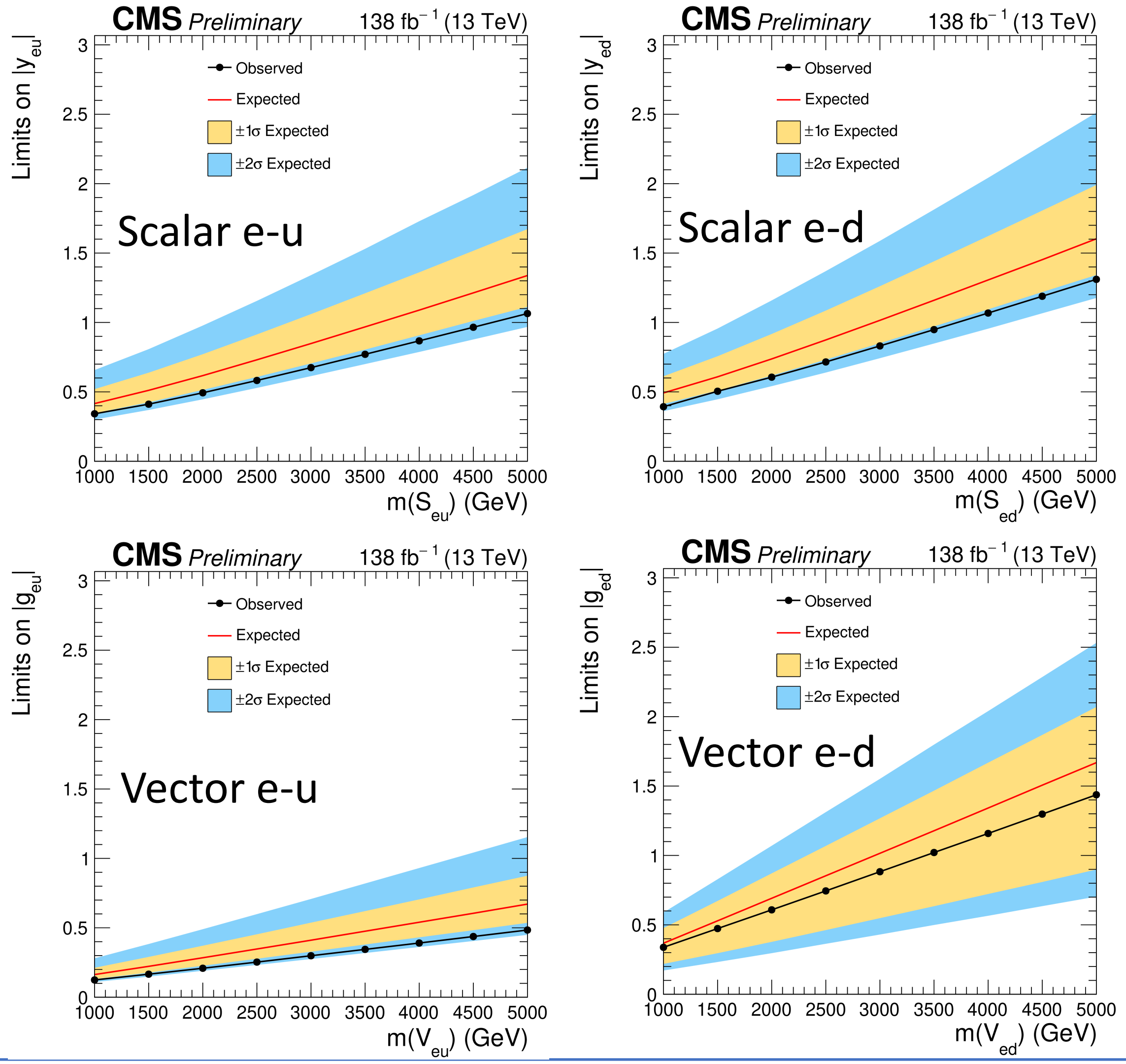






CMS-PAS-EXO-22-013

Search for t-channel scalar and vector leptoquarks in high-mass ee & μμ (2)



For equal coupling values, the **vector** LQ production cross section is higher thus limits better

Model	A_0	A_4	y^2_{LQ}
S_{eu}	0.07 ± 0.07	1.61 ± 0.08	$-0.10^{+0.15}_{-0.17}$ (stat) $^{+0.07}_{-0.11}$ (syst)
S_{ed}	0.07 ± 0.07	1.62 ± 0.08	$-0.09^{+0.20}_{-0.23}$ (stat) $^{+0.11}_{-0.13}$ (syst)
$S_{\mu u}$	0.02 ± 0.06	1.59 ± 0.07	$-0.13^{+0.14}_{-0.15}$ (stat) $^{+0.06}_{-0.11}$ (syst)
$S_{\mu d}$	0.02 ± 0.06	1.60 ± 0.07	$-0.11^{+0.18}_{-0.20}$ (stat) $^{+0.09}_{-0.13}$ (syst)

Model	A_0	A_4	g^2_{LQ}
V_{eu}	0.05 ± 0.07	1.66 ± 0.08	$-0.09^{+0.03}_{-0.03}$ (stat) $^{+0.04}_{-0.08}$ (syst)
V_{ed}	0.06 ± 0.07	1.64 ± 0.08	$0.13^{+0.06}_{-0.06}$ (stat) $^{+0.17}_{-0.09}$ (syst)
$V_{\mu u}$	0.01 ± 0.05	1.63 ± 0.06	$-0.10^{+0.02}_{-0.02}$ (stat) $^{+0.04}_{-0.08}$ (syst)
$V_{\mu d}$	0.01 ± 0.05	1.61 ± 0.06	$0.14^{+0.05}_{-0.05}$ (stat) $^{+0.14}_{-0.07}$ (syst)

Best limits for LQ masses up to 5 TeV and first limits on LQ couplings to 1st and 2nd generation fermions

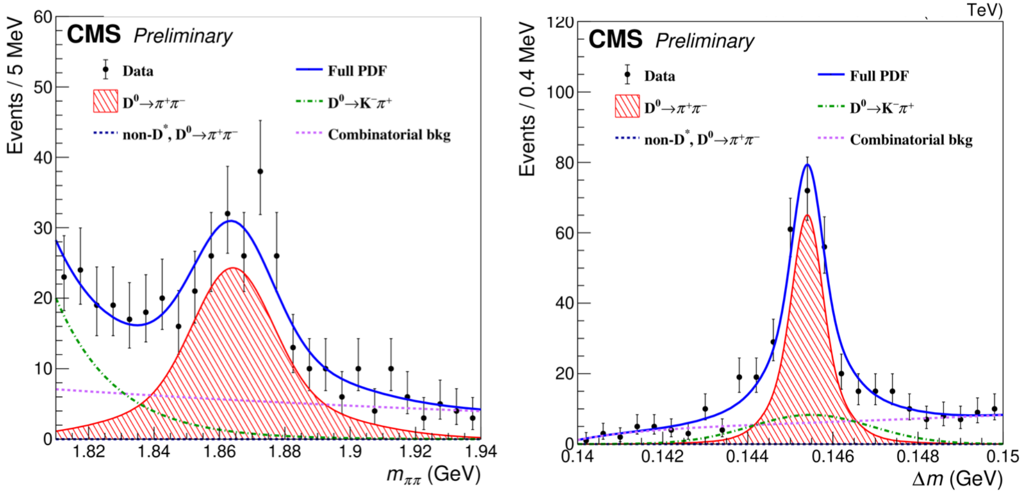
Search for rare Charm decays to μμ

- 64.5 fb^{-1}, **13.6 TeV**, new very low pT dimuon triggers
  - ≥ 2 and 3 GeV
- Most previous studies probed b → s and s→ d. Here we probe c → u
- **Signal: $D^{*+} \to D^0 \pi^+$, $D^0 \to \mu\,\mu$**
- **Observables: $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$**
- Measurement of branching ratio with respect to $D^0 \to \pi\,\pi$ to reduce uncertainties, Multivariate analysis
- Backgrounds on signal : ($D^{*+} \to D^0 \pi^+$, $D^0 \to \pi\,\pi \to \mu\,\mu$), ($D^*$, $D^0 \to \pi\mu\nu$), combinatorics
- Backgrounds on normalization sample : ($D^{*+} \to D^0 \pi^+$, $D^0 \to K\,\pi$), (non D^*, $D^0 \to \pi\pi$ or $K\pi$), combinatorics
- 2D fit is used to extract limit

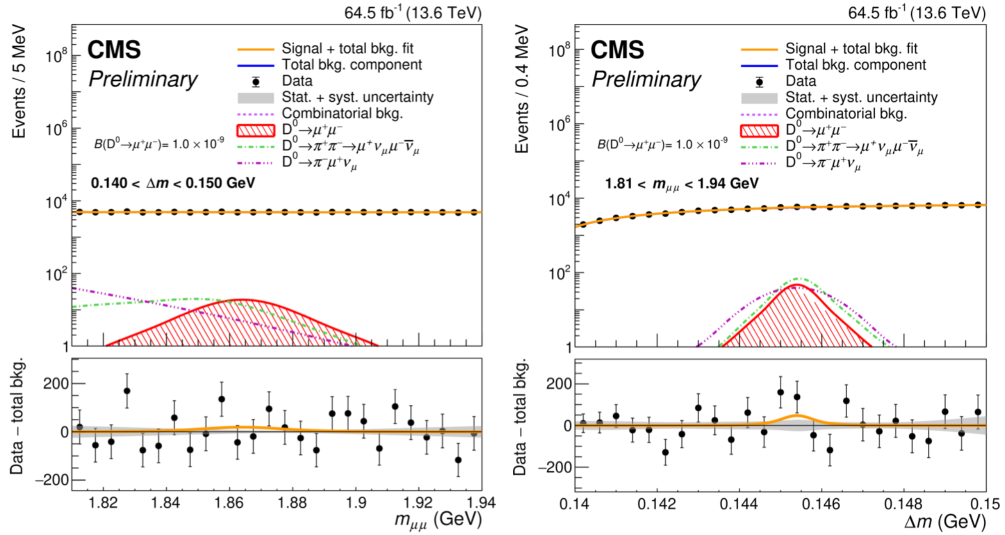
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

CMS-PAS-BPH-23-008

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \mathcal{B}(D^0 \to \pi^+\pi^-) \frac{N_{D^0\to\mu^+\mu^-}}{N_{D^0\to\pi^+\pi^-}} \frac{\varepsilon_{D^0\to\pi^+\pi^-}}{\varepsilon_{D^0\to\mu^+\mu^-}}$$



After MVA

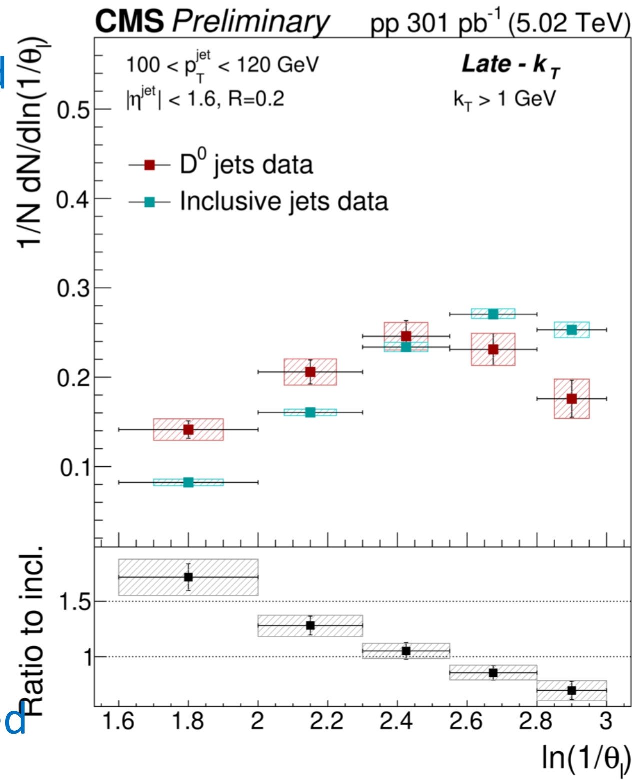


After fit

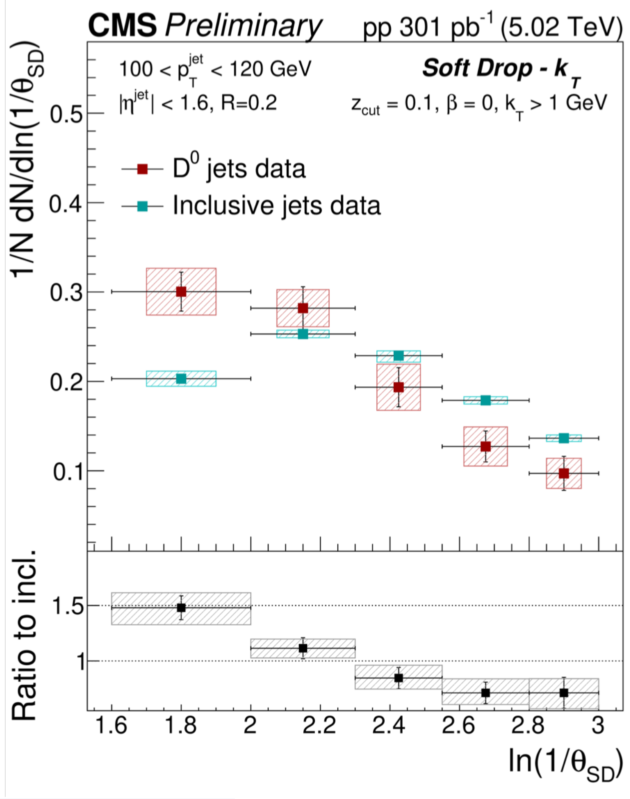
Small-angle emissions in prompt D^0 jets

- 301 pb^{-1}, **5.02 TeV**, single calorimetry jet triggers (>60 and >80 GeV)
- Study charm jet substructure and small-angle emission effects in parton showering
- Two grooming algorithms: "late-k_T" which is sensitive to hard charm. And modified soft-drop that is sensitive to charm from gluon splitting
- Jets are clustered with R=0.2 and have $100<p_{T<}120$ GeV
- D^0 is reconstructed from Kπ decays, ΔR<0.2 from jet radius, with p_T> 4 GeV to reduce combinatoric background
  - Out of 2M jets with $100<p_T<120$ GeV, about 25K have a D^0 in them
- Unfolding to particle level with Pythia, by matching particle-level jets with charm to detector-level jets with D^0
- Non-prompt D^0 is removed using distance of closest approach significance.
- The angle between the harder and softer subjets are reported using the two grooming algorithms
  - 2-D simultaneous unfolding of jet p_T and splitting angle

"late-k_T"



"modified softdrop"



CMS-PAS-HIN-24-007

Energy-energy correlations from PbPb and pp collisions at 5.02 TeV

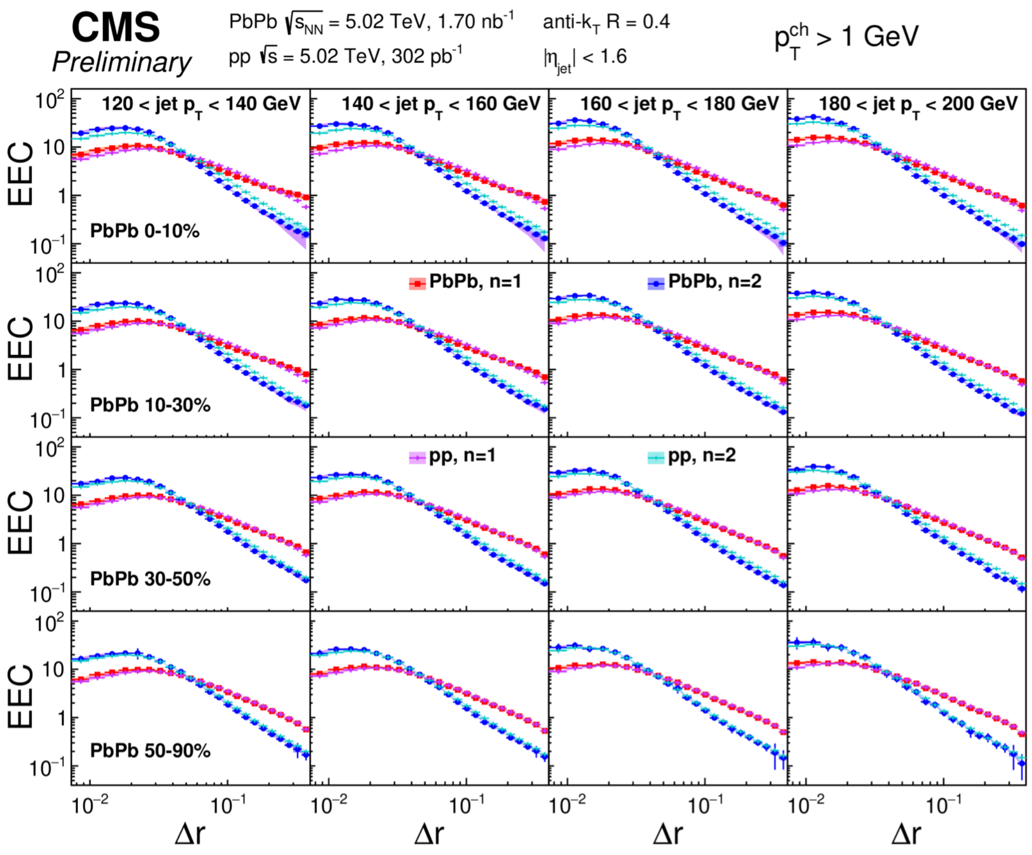
Red: n=1
Blue: n=2

- **5.02 TeV**, 1.70 nb_{-1} for PbPb and 302 pb^{-1} for pp, single calorimetry jet triggers (>60, >80 GeV and >100 GeV)
- Study 2-point energy-energy correlations in jets, in bins of centrality and p_T.
- Jets are reconstructed with R=0.4, |η|< 1.6
- Energy-Energy Correlations are defined as

$$\mathrm{EEC}(\Delta r) = \frac{1}{W_{\mathrm{pairs}}} \frac{1}{\delta r} \sum_{\mathrm{jets} \in [p_{\mathrm{T},1}, p_{\mathrm{T},2}]} \sum_{\mathrm{pairs} \in [\Delta r_a, \Delta r_b]} \left(p_{\mathrm{T},i}\, p_{\mathrm{T},j} \right)^n$$

(W_{pairs} is the weighted number of pairs of tracks in jet – Results presented for n=1,2 and for p_T^{ch}>1 or 2 GeV

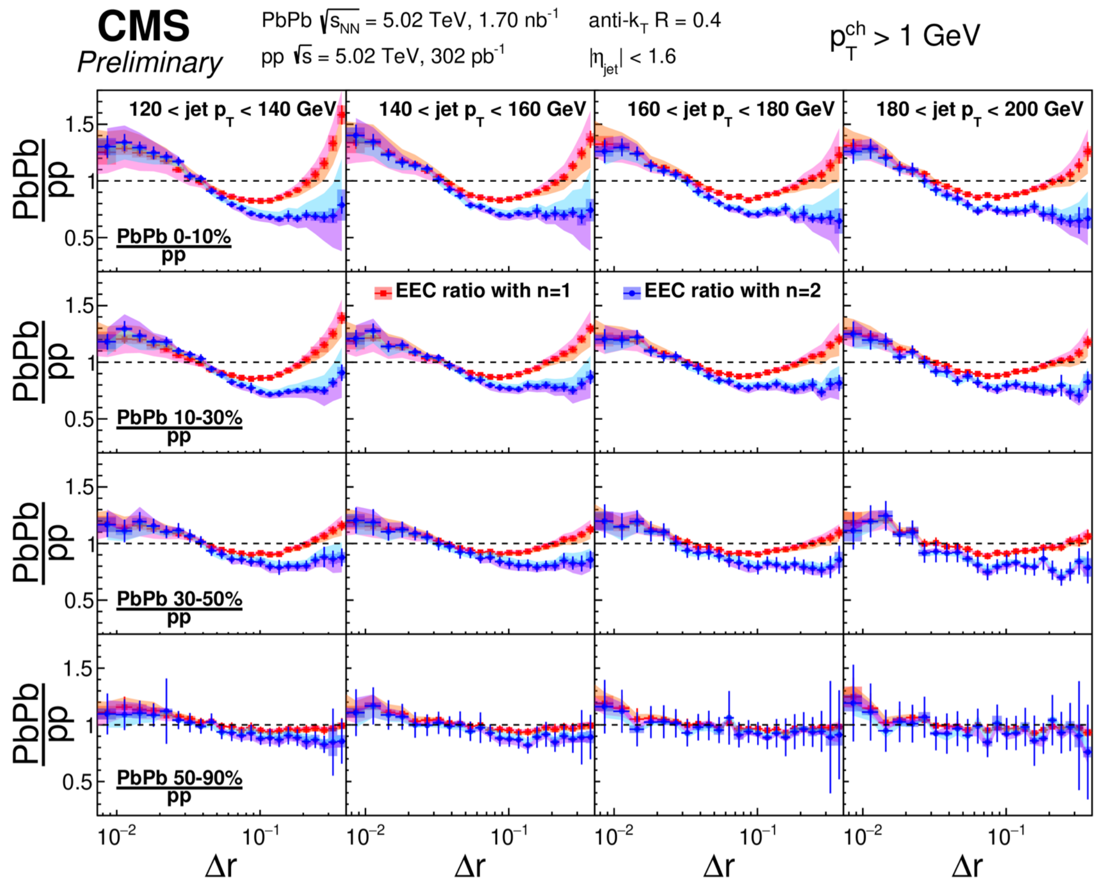
- Signal: tracks that come from fragmentation or jet-medium interactions. Background: other tracks, e.g., from underlying event
- Unfolding to particle level to remove jet p_T migrations. Background removed after the unfolding
- EEC results show clearly the free-hadron region, the transition region and the quark-gluon region
- Ratios between PbPb and pp results show the effect of quark –gluon plasma → The PbPb transition peak is shifted compared to pp collisions to lower values of Δr



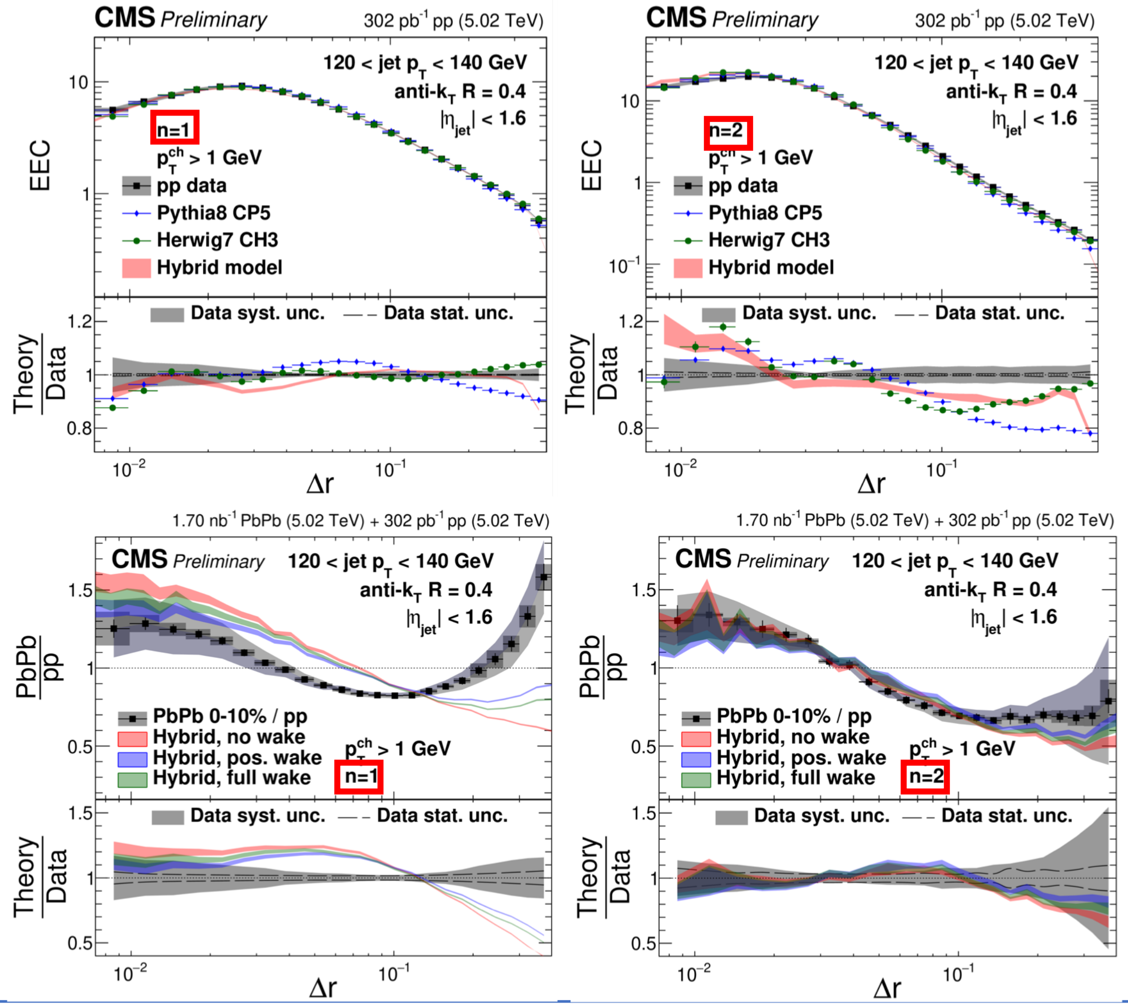
CMS-PAS-HIN-23-004

Energy-energy correlations from PbPb and pp collisions at 5.02 TeV (2)

PbPb/pp ratios reveal effect of interaction with nuclear medium



Comparisons with MC simulations



Conclusions

- We presented the most recent CMS Physics Results
  - All of them became public within about a month
- All results, including the recent publications can be found at the public physics results web page
  - https://cms.cern/org/cms-scientific-results
- We are excited about Run3 of the LHC !!!

BACK UP

Charged-Lepton Flavor Violation in tuμτ interactions

Group	Variables	Description
Muon (μ)	$p_{T\mu}$, η_μ	p_T and η of selected muon
Tau (τ_h)	$p_{T\tau_h}$, η_{τ_h}, m_{τ_h}	p_T, η, and mass of selected τ_h
Muon+Tau ($\mu\tau_h$)	$m_{\mu\tau_h}$, $\Delta\eta_{\mu\tau_h}$, $\Delta\phi_{\mu\tau_h}$, $\Delta R_{\mu\tau_h}$	Mass and angular differences of $\mu\tau_h$ system
Jets	p_{T1}, p_{T2}, p_{T3}	p_T of jets ordered in increasing p_T
	η_1, η_2, η_3	η of jets ordered in increasing p_T
	m_1, m_2, m_3	Mass of jets ordered in increasing p_T
	b_1, b_2, b_3	b tagging discriminant of jets ordered in increasing p_T
Event	p_T^{miss}	Missing transverse momentum
t and W reco.	χ^2, $m_{bjj'}$, $m_{jj'}$	*minimum*χ^2 and reconstructed t and W masses
	$\Delta\eta_{jj'}$, $\Delta\phi_{jj'}$, $\Delta R_{jj'}$	Angular differences of jets used in W reco.

Interaction	Type	σ [fb]	$C_{tq\mu\tau}/\Lambda^2$ [TeV^{-2}]	$\mathcal{B}(t \to \mu\tau q)[10^{-6}]$
tu$\mu\tau$	Scalar	2.039 (2.337) [1.574, 3.594]	0.182 (0.194) [0.16, 0.241]	0.040 (0.046) [0.031, 0.071]
	Vector	2.384 (2.746) [1.857, 4.213]	0.09 (0.096) [0.079, 0.119]	0.078 (0.09) [0.061, 0.138]
	Tensor	2.834 (3.326) [2.257, 5.063]	0.045 (0.049) [0.04, 0.06]	0.118 (0.138) [0.094, 0.211]
tc$\mu\tau$	Scalar	4.269 (5.02) [3.291, 8.142]	0.817 (0.886) [0.717, 1.128]	0.81 (0.953) [0.625, 1.545]
	Vector	7.213 (8.552) [5.663, 13.734]	0.419 (0.457) [0.372, 0.579]	1.71 (2.027) [1.342, 3.255]
	Tensor	7.927 (9.633) [6.427, 15.2]	0.188 (0.207) [0.169, 0.26]	2.052 (2.494) [1.664, 3.936]

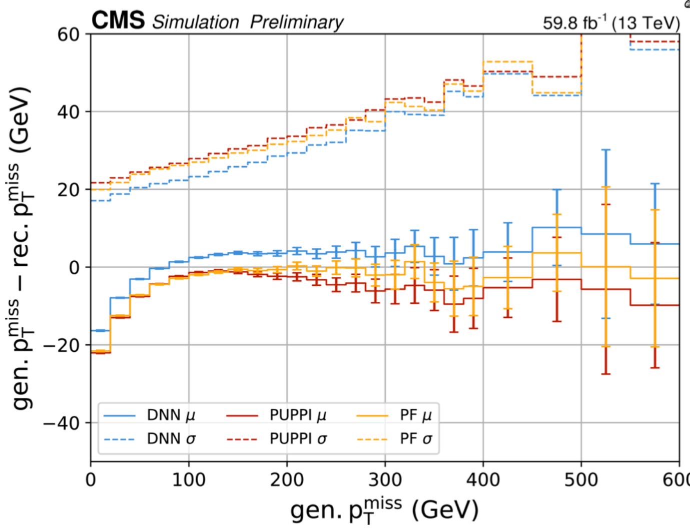
	OS μ, τ	SS μ, τ
τ tight	D	B
τ loose but not tight	C	A

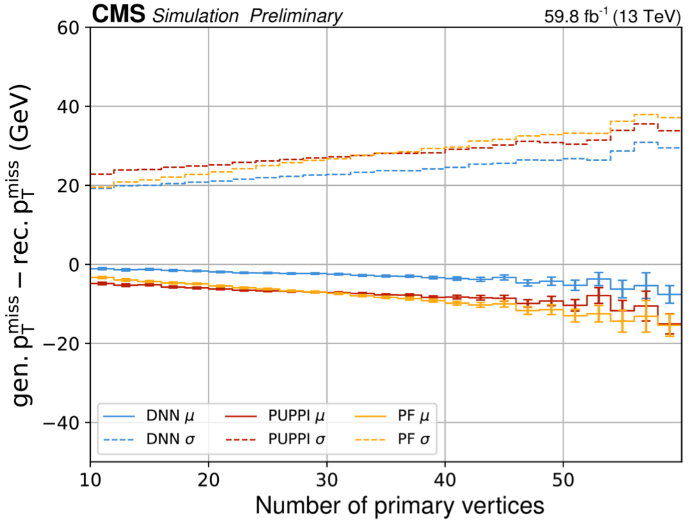
$$N_D^{misID} = \frac{N_C N_B}{N_A}$$

Measurement of dineutrino system in t-tbar production

Process	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	all
$t\bar{t}$ $(\ell\ell)$	1.16×10^5 (75.2)	2.21×10^5 (74.1)	5.31×10^5 (80.2)	8.67×10^5 (77.9)
$t\bar{t}$ other	1.82×10^4 (11.8)	3.86×10^4 (12.9)	9.05×10^4 (13.7)	1.47×10^5 (13.2)
Single top	6.15×10^3 (4.0)	1.17×10^4 (3.9)	2.84×10^4 (4.3)	4.63×10^4 (4.2)
DY+jets	1.26×10^4 (8.2)	2.48×10^4 (8.3)	6.87×10^3 (1.0)	4.42×10^4 (4.0)
Diboson	7.00×10^2 (0.5)	1.24×10^3 (0.4)	2.43×10^3 (0.4)	4.36×10^3 (0.4)
$t\bar{t}$W/Z	4.93×10^2 (0.3)	8.90×10^2 (0.3)	1.82×10^3 (0.3)	3.20×10^3 (0.3)
W+jets	7.54×10^1 (0.0)	7.51×10^1 (0.0)	8.82×10^2 (0.1)	1.03×10^3 (0.1)
Sum MC	$(1.54 \pm 0.10) \times 10^5$	$(2.98 \pm 0.14) \times 10^5$	$(6.62 \pm 0.27) \times 10^5$	$(1.11 \pm 0.05) \times 10^6$
Data	1.52×10^5	3.02×10^5	6.50×10^5	1.10×10^6

Improvement in p_T^{miss} resolution





SUSY searches in OS dilepton + p_T^{miss}

	$SR1^{0jet}_{0tag}$	$SR1^{jets}_{0tag}$	$CR1_{tags}$	$SR2^{0jet}_{0tag}$	$SR2^{jets}_{0tag}$	$CR2_{tags}$	$SR3_{0tag}$	$CR3_{tags}$	$SR4_{0tag}$	$CR4_{tags}$
p_T^{miss} [GeV]	160–220	160–220	160–220	220–280	220–280	220–280	280–380	380–380	$\geq$380	$\geq$380
$N_{b\ jets}$	0	0	$\geq$1	0	0	$\geq$1	0	$\geq$1	0	$\geq$1
N_{jets}	0	$\geq$1	$\geq$1	0	$\geq$1	$\geq$1	$\geq$0	$\geq$1	$\geq$0	$\geq$1
Channels	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF	SF, DF
$m_{T2}(\ell\ell)$	0–20, 20–40, 40–60, 60–80, 80–100, 100–160, 160–240, 240–370, $\geq$370 GeV									

$m_{T2}(\ell\ell)$ [GeV]		0-20	20-40	40-60	60-80	80-100	100-160	160-240	240-370	$\geq$ 370
DF events										
$SR1^{0jet}_{0tag}$	SM Processes	98.2 ± 8.7	65.5 ± 5.7	77.4 ± 6.4	88.0 ± 7.6	50.4 ± 4.5	49.3 ± 5.8	11.4 ± 1.8		
	Data	109	59	70	97	52	47	13		
$SR1^{jets}_{0tag}$	SM Processes	3467 ± 52	1149 ± 18	1388 ± 21	1379 ± 19	627 ± 14	181 ± 8	15.4 ± 2.2		
	Data	3545	1099	1368	1397	653	179	9		
$SR2^{0jet}_{0tag}$	SM Processes	19.6 ± 2.4	12.6 ± 1.8	13.6 ± 1.8	11.4 ± 1.6	4.5 ± 0.7	5.3 ± 1.0	6.8 ± 1.2	1.1 ± 0.4	
	Data	21	14	12	13	5	7	8	2	
$SR2^{jets}_{0tag}$	SM Processes	1036 ± 24	289 ± 7	311 ± 7	267 ± 7	87.9 ± 3.3	28.7 ± 2.2	9.5 ± 1.5	1.3 ± 0.4	
	Data	982	286	297	278	80	33	9	0	
$SR3_{0tag}$	SM Processes	524 ± 14	124 ± 4	126 ± 4	105 ± 4	27.3 ± 1.7	10.4 ± 1.2	7.7 ± 1.2	6.4 ± 1.4	
	Data	488	134	142	109	29	8	6	7	
$SR4_{0tag}$	SM Processes	180 ± 8	36.0 ± 2.2	36.7 ± 2.2	26.4 ± 1.7	7.3 ± 0.8	3.1 ± 0.5	3.7 ± 0.7	4.1 ± 1.0	3.1 ± 0.9
	Data	154	43	49	35	8	4	2	4	0
SF events										
$SR1^{0jet}_{0tag}$	SM Processes	119 ± 10	61.3 ± 5.1	73.4 ± 5.9	79.4 ± 6.7	42.4 ± 3.6	62.7 ± 5.3	26.3 ± 2.5		
	Data	118	73	79	82	40	70	31		
$SR1^{jets}_{0tag}$	SM Processes	3052 ± 49	999 ± 17	1186 ± 18	1153 ± 16	546 ± 14	215 ± 7	63.5 ± 3.8		
	Data	2992	1002	1142	1202	562	231	68		
$SR2^{0jet}_{0tag}$	SM Processes	19.2 ± 2.1	12.7 ± 1.6	13.1 ± 1.8	12.8 ± 1.7	4.0 ± 0.6	6.6 ± 1.0	11.6 ± 1.8	2.6 ± 0.5	
	Data	25	16	10	15	5	10	8	2	
$SR2^{jets}_{0tag}$	SM Processes	917 ± 22	248 ± 6	270 ± 7	236 ± 6	83.7 ± 4.3	35.4 ± 2.1	25.4 ± 2.1	9.7 ± 0.9	
	Data	947	230	303	243	82	46	28	11	
$SR3_{0tag}$	SM Processes	460 ± 13	108 ± 4	111 ± 4	86.9 ± 3.2	26.7 ± 1.7	15.3 ± 1.6	16.5 ± 1.7	15.7 ± 1.7	
	Data	454	119	118	82	30	15	20	13	
$SR4_{0tag}$	SM Processes	164 ± 7	32.4 ± 2.0	30.0 ± 1.9	24.5 ± 1.8	6.2 ± 0.7	5.3 ± 0.7	3.8 ± 0.6	8.1 ± 1.2	5.9 ± 1.0
	Data	159	34	31	25	7	6	4	10	8

Source of uncertainty	SM processes	
	Change in yields	Change in $m_{T2}(\ell\ell)$ shape
Integrated luminosity	1–3%	—
Trigger efficiency	2%	$<$ 1%
Pileup	$\leq$ 2%	2–20%
Jet energy scale	3–8%	2–10%
Jet energy resolution	1–2%	2–8%
Unclustered energy	1–2%	2–13%
Lepton ident./isolation	2–4%	$\leq$ 15%
b tagging	$\leq$ 5%	$\leq$ 6%
b tagging (light jets)	$<$ 1%	$\leq$ 3%
Simulated samples statistics	$\leq$ 3%	4–37%
Renorm./fact. scales	2–23%	1–15%
PDFs	$\leq$ 2%	$\leq$ 9%
Drell–Yan normalization	$\leq$ 7%	$\leq$ 26%
tW normalization	1–2%	$\leq$ 3%
Minor bkg. normalization	$\leq$ 3%	1–8%
$m_{T2}(\ell\ell)$ tails	1–2%	5–20%
Nonprompt leptons	$<$ 1%	$\leq$ 8%
$t\bar{t}$ p_T reweighting	1–6%	1–6%

Search for HHWW couplings in the VBS production of WWH, H→ bb

Process	$\ell\ell$ category	$\ell\tau$ category
Signal	0.25	0.06
$t\bar{t} \rightarrow 1\ell$	18.02	36.69
$t\bar{t} \rightarrow 2\ell$	1.51	1.33
$t\bar{t}W$	11.41	1.79
$t\bar{t}Z$	1.50	0.58
Rare top	4.54	4.79
V/VV/VVV	1.57	3.09
Total background	38.56 ± 5.14	48.26 ± 8.52
Data	39	49

Search for t-channel scalar and vector leptoquarks in high-mass ee & μμ

SCALAR LQ

$$\frac{d^2\sigma}{dm_{\ell\ell}dc_*} \propto \left[\frac{d^2\sigma}{dm_{\ell\ell}dc_*}\right]_{DY} + y^4_{LQ}N^S_{LQ(pure)}(m_{\ell\ell})\left(\frac{1-c_*}{1-c_*+\frac{2m^2_{LQ}}{m^2_{\ell\ell}}}\right)^2 + y^2_{LQ}N^S_{LQ(int)}(m_{\ell\ell})\left[\frac{(1-c_*)^2}{1-c_*+\frac{2m^2_{LQ}}{m^2_{\ell\ell}}}\right]$$

VECTOR LQ

$$\frac{d^2\sigma}{dm_{\ell\ell}dc_*} \propto \left[\frac{d^2\sigma}{dm_{\ell\ell}dc_*}\right]_{DY} + g^4_{LQ}N^V_{LQ(pure)}(m_{\ell\ell})\left(\frac{1+c_*}{1-c_*+\frac{2m^2_{LQ}}{m^2_{\ell\ell}}}\right)^2 + g^2_{LQ}N^V_{LQ(int)}(m_{\ell\ell})\left[\frac{(1+c_*)^2}{1-c_*+\frac{2m^2_{LQ}}{m^2_{\ell\ell}}}\right]$$