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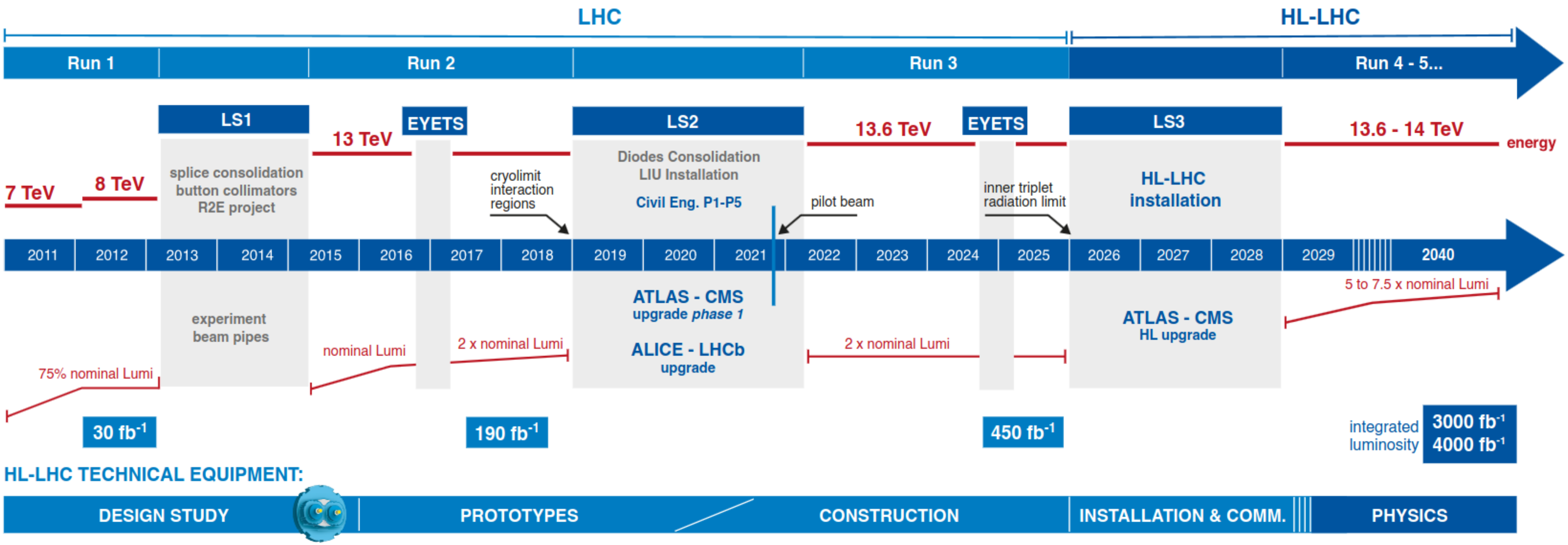
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

CMS data analysis & prospects for Fcc(-ee)

R. Schöfbeck for the HEPHY CMS Data Analysis group

LHC long term schedule



→ Precision Higgs factory

Higgs discovery!

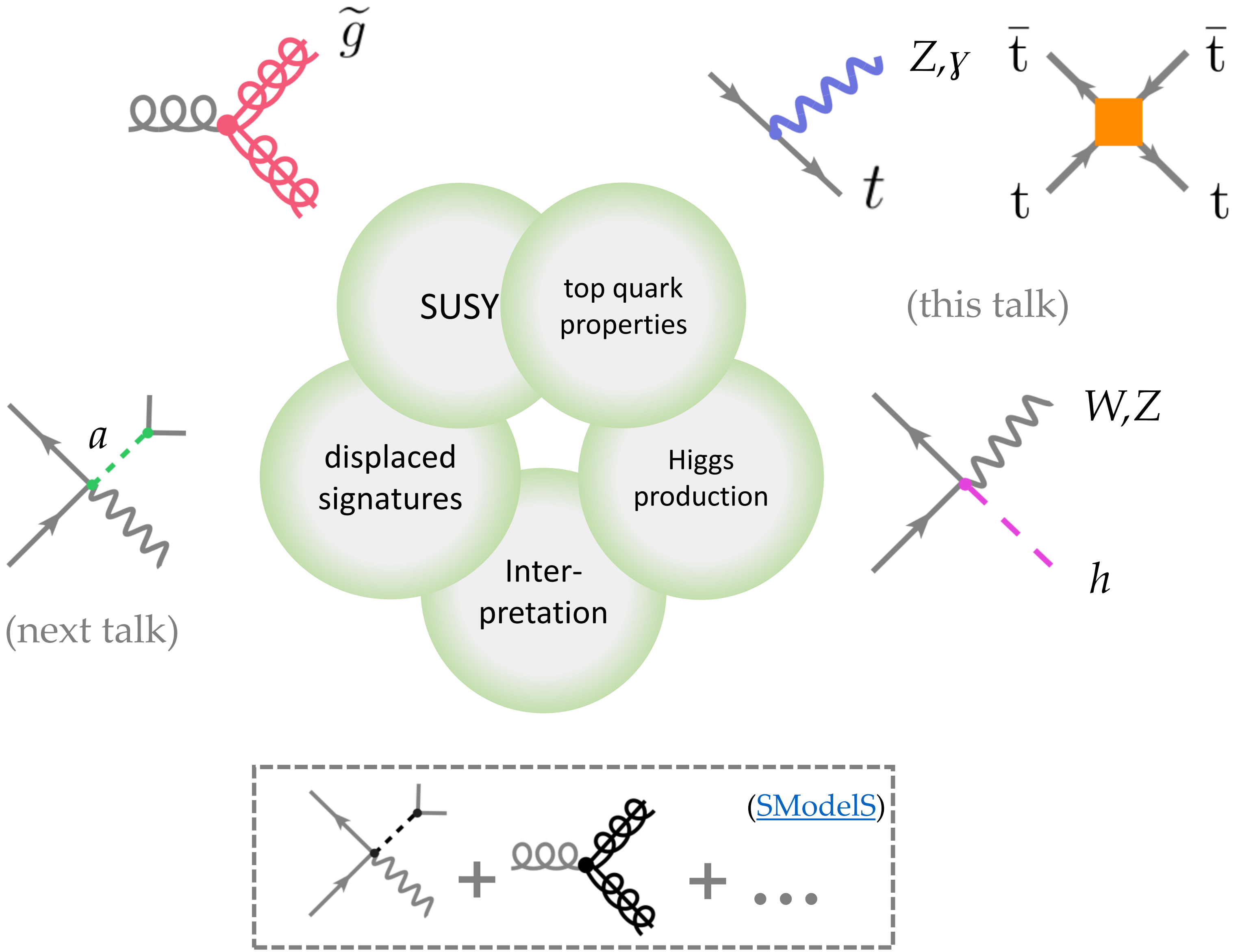
HL-LHC ~ factor 10 more data

substantial detector upgrades

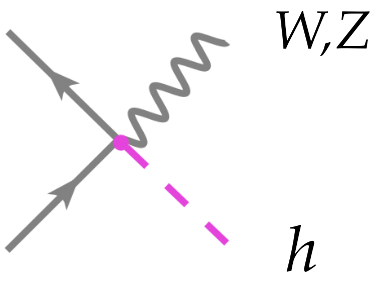
3 ab^{-1} (next talk)

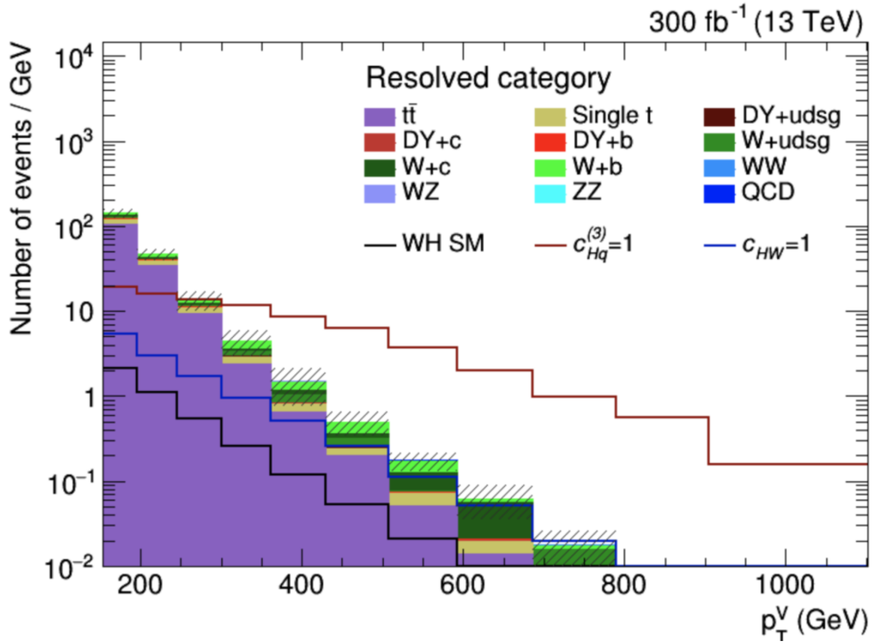
→ Run 3: double data set >300 fb^{-1}

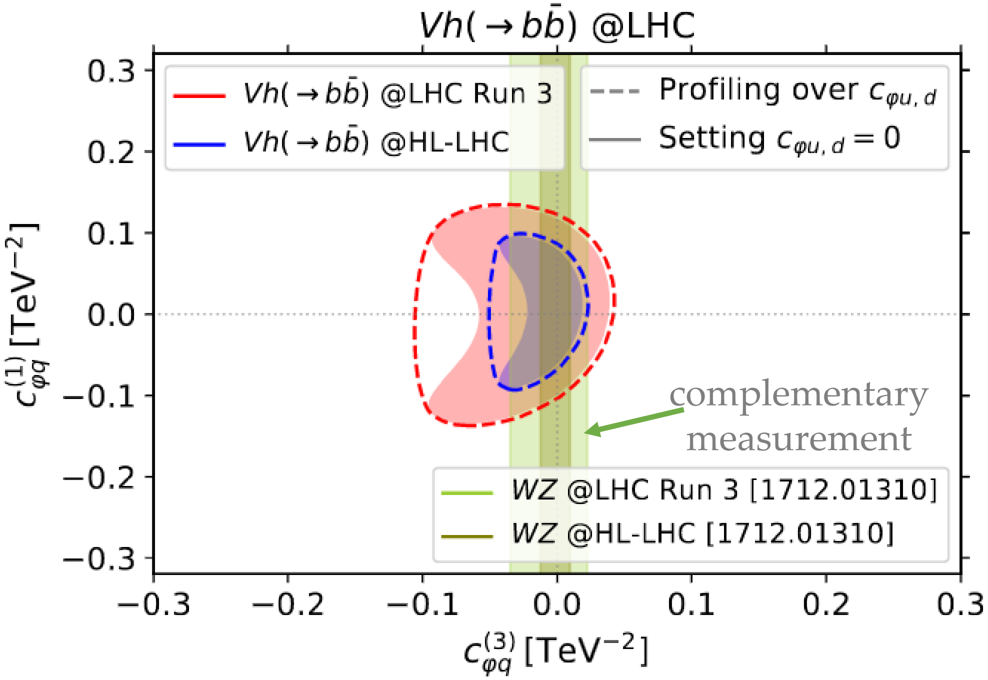
Ongoing analyses



Production of a H →bb with W/Z



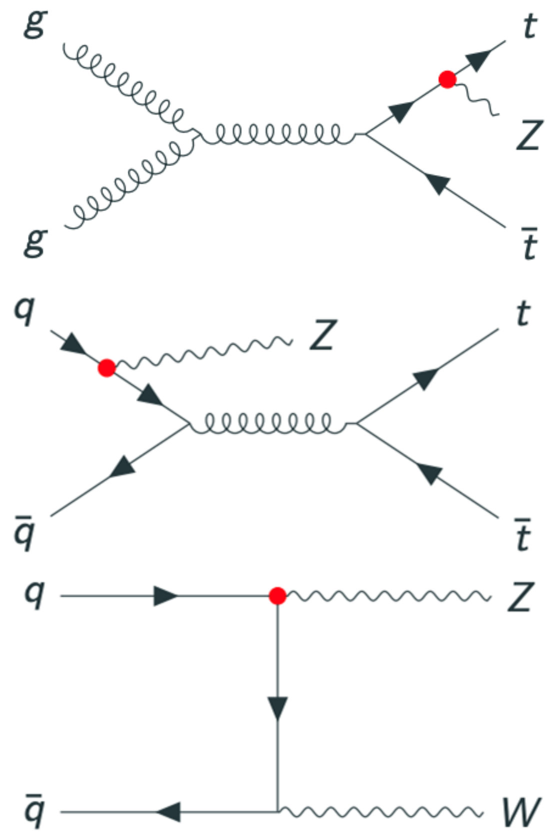


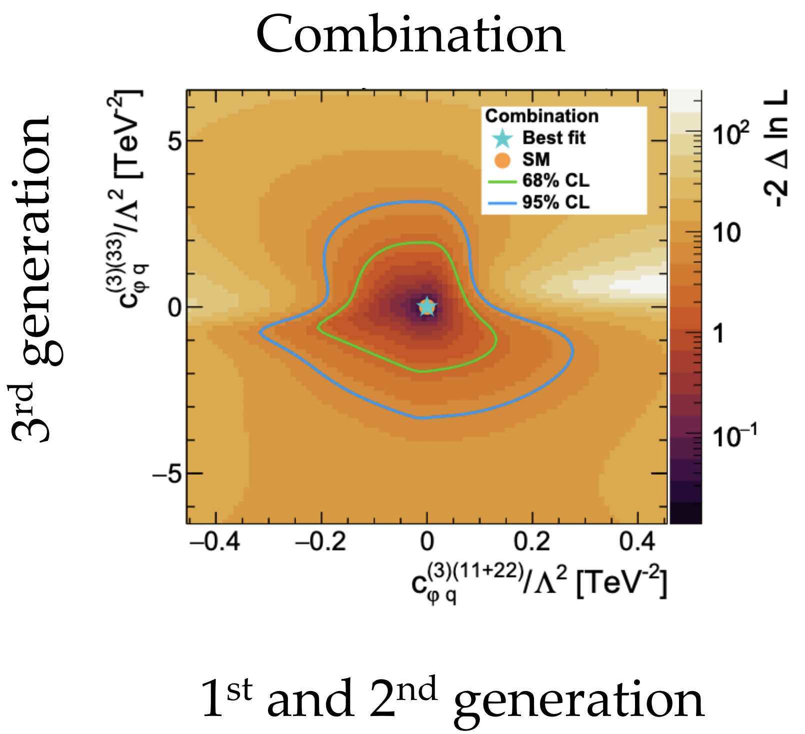


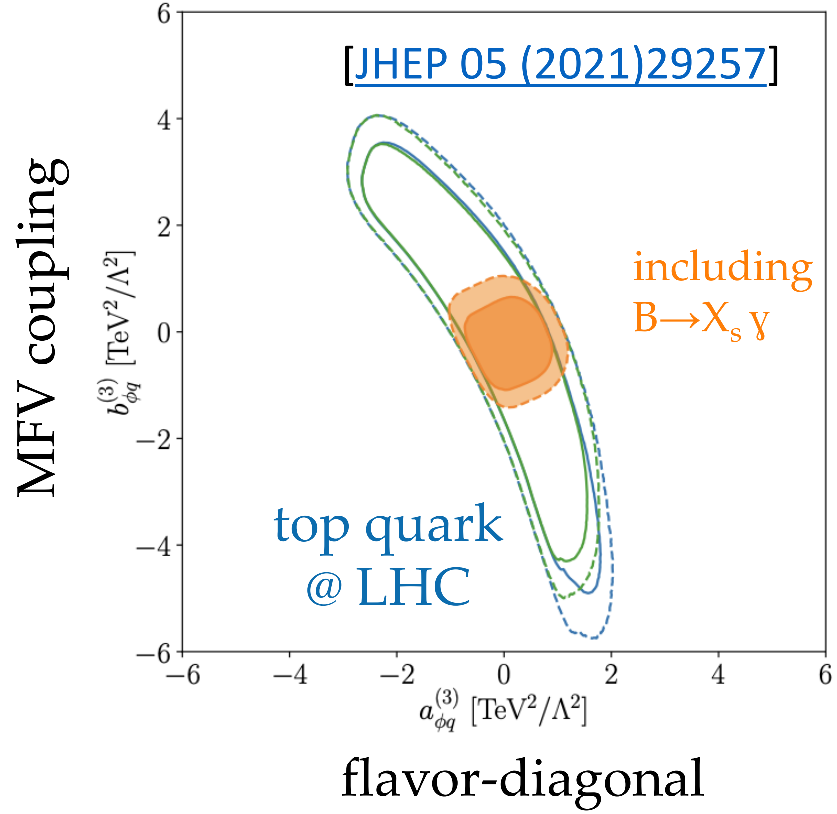
JHEP 06 (2023) 077

- Probes fundamental SM couplings in presence of large backgrounds
  - Combine H→bb channel in boosted and resolved reconstruction
- Tightly constrain the *anomalous* couplings of the Higgs boson to the SM fermions
  - Complementary measurements are needed! Within CMS: Take a global view with EFTs.
  - Also a resonant search in X →YH(bb) probing extended Higgs sectors

t-quark couplings and gauge bosons







- Combining different sectors results in tight constraints on deviations from the SM
  - top—Z coupling, top—light quark coupling, gauge-boson couplings
  - Resolve BSM flavor structure of the top quark-gauge boson couplings
  - Complementarity with B-physics precision observables

FCC-ee luminosity & energies

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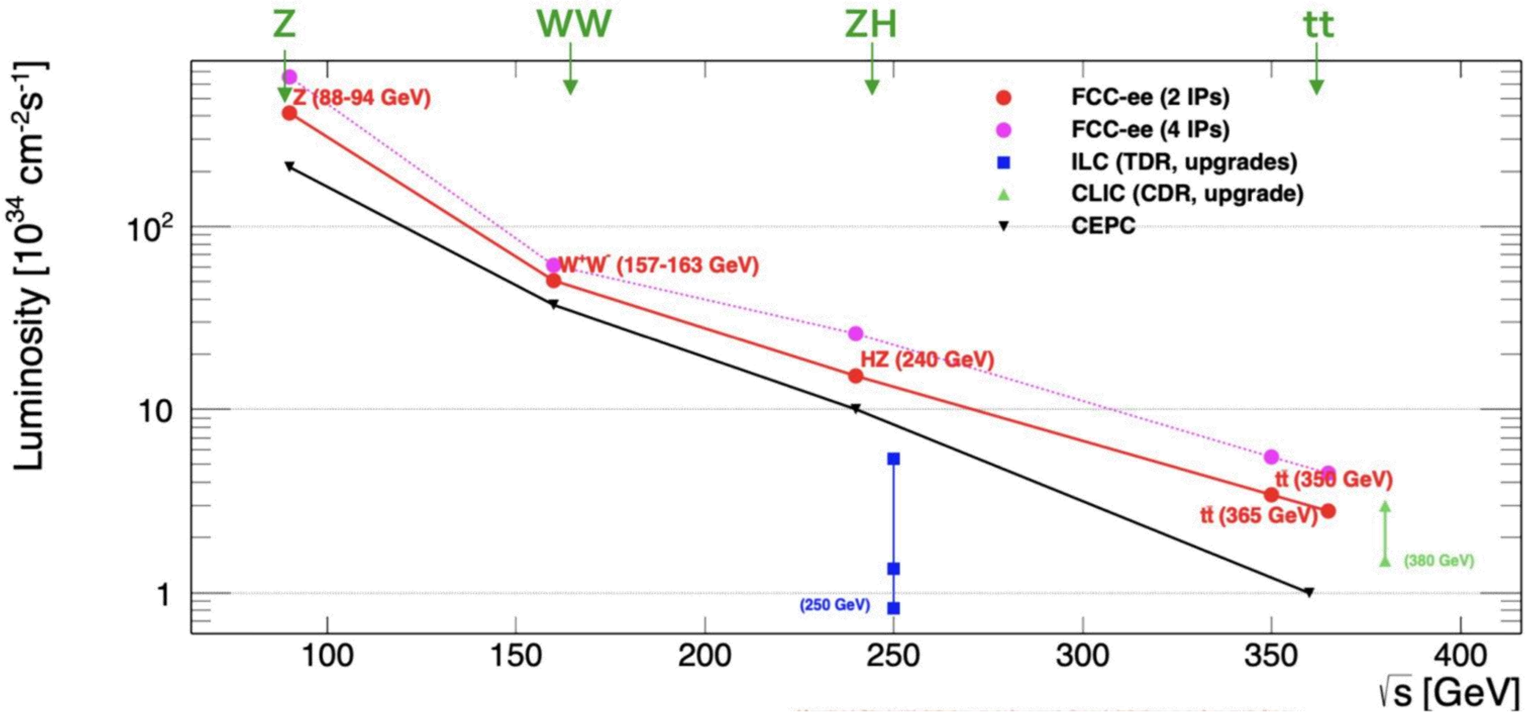
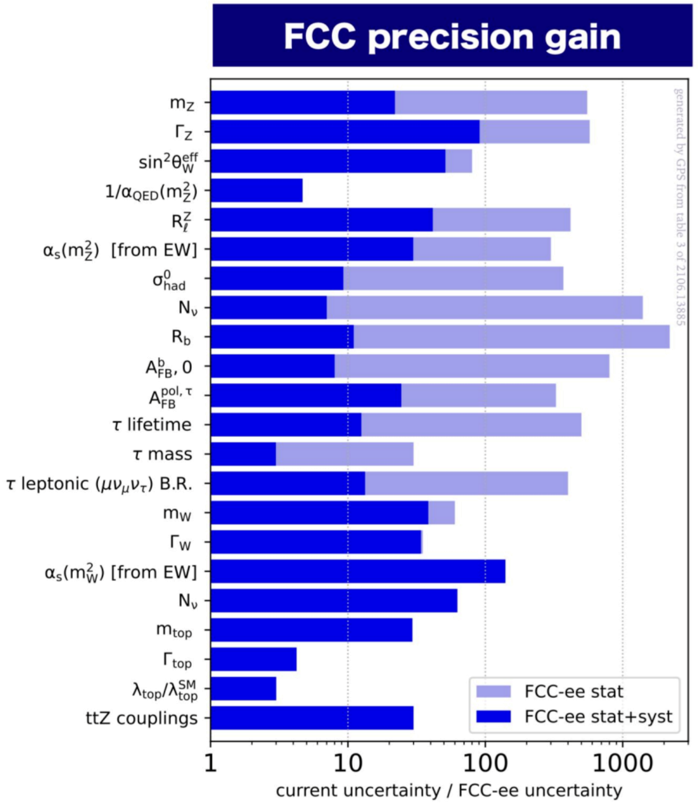




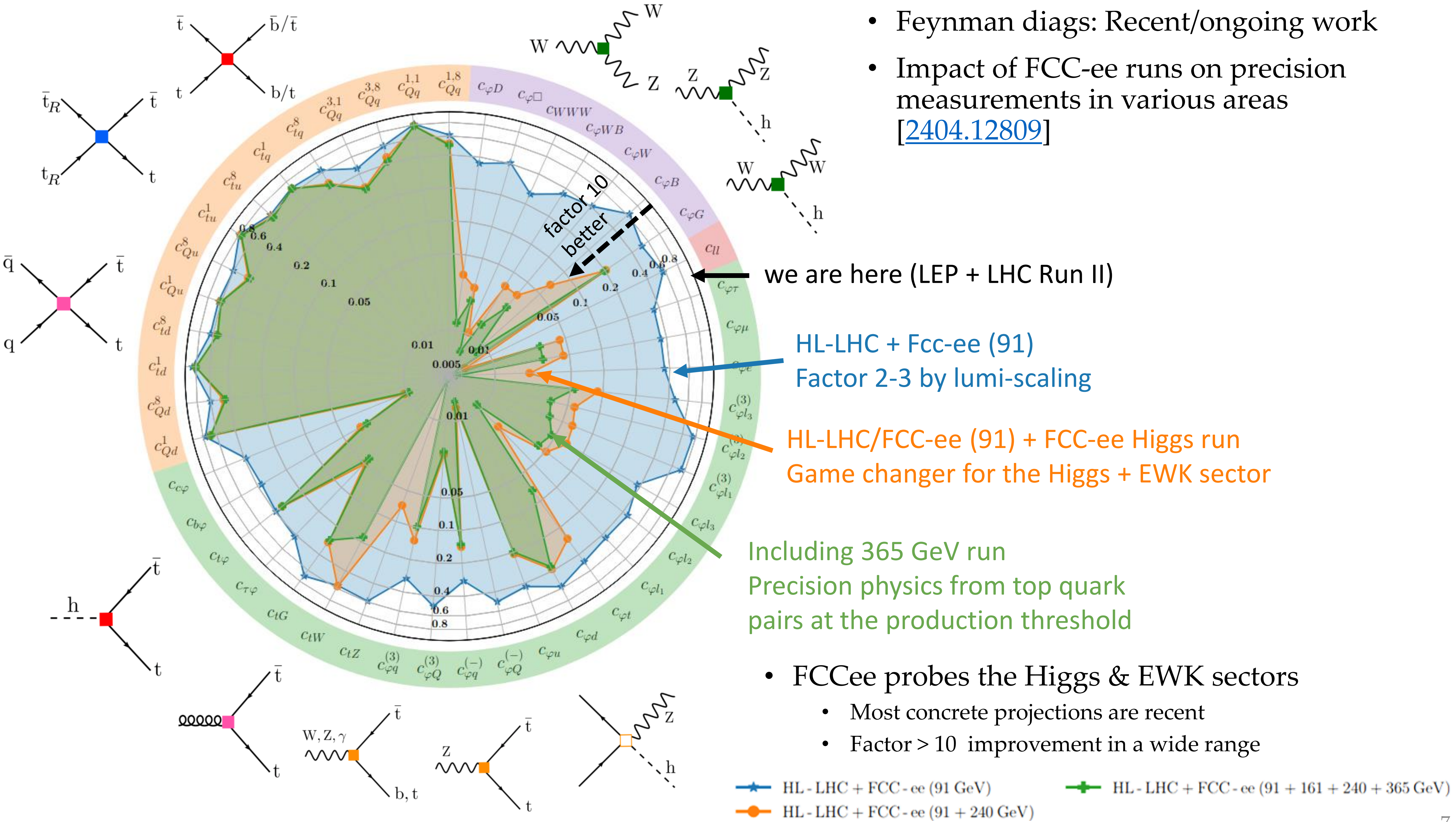
[Physics briefing book]
[2020 strategy update]
[P5 report]

14 year FCC-ee programme

150 ab^{-1} at Z pole
10 ab^{-1} at WW threshold
5 ab^{-1} at HZ threshold
0.2 ab^{-1} at top-antitop threshold
1.5 ab^{-1} at c.o.m of 365 GeV

EWPO observables:
x10 – x100
precision gain [link]
from Z-pole

- Feynman diags: Recent/ongoing work
- Impact of FCC-ee runs on precision measurements in various areas [2404.12809]

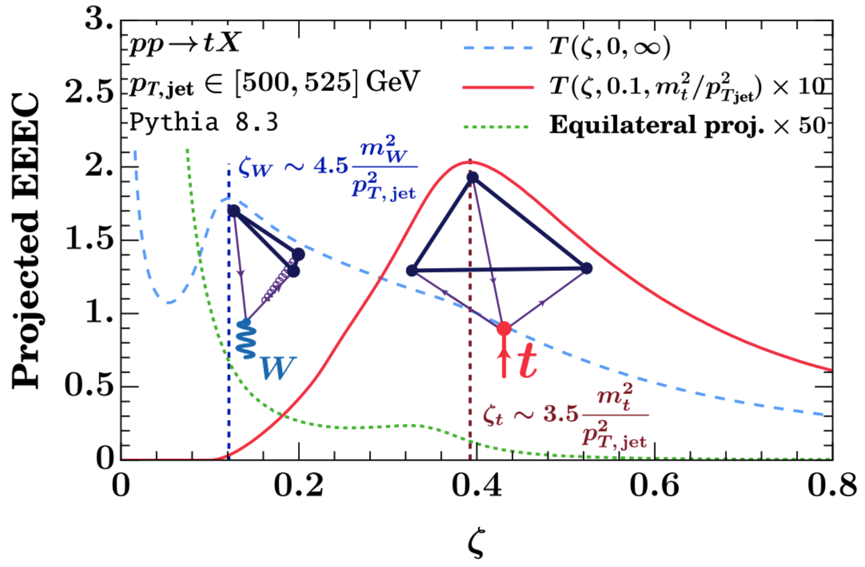


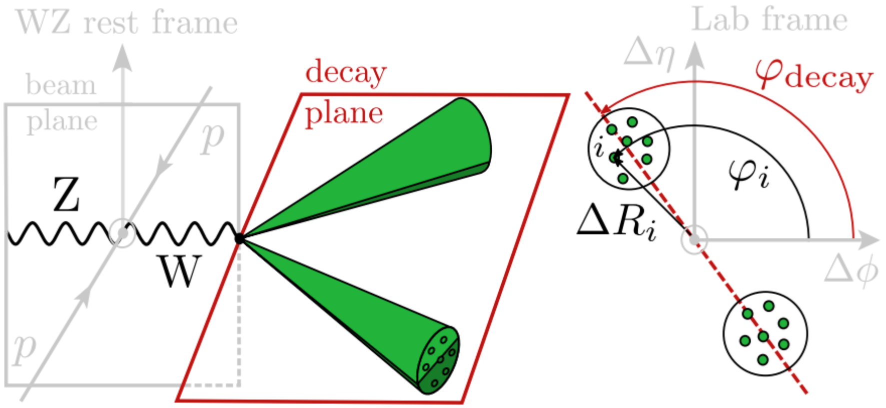
- FCCee probes the Higgs & EWK sectors
  - Most concrete projections are recent
  - Factor > 10 improvement in a wide range

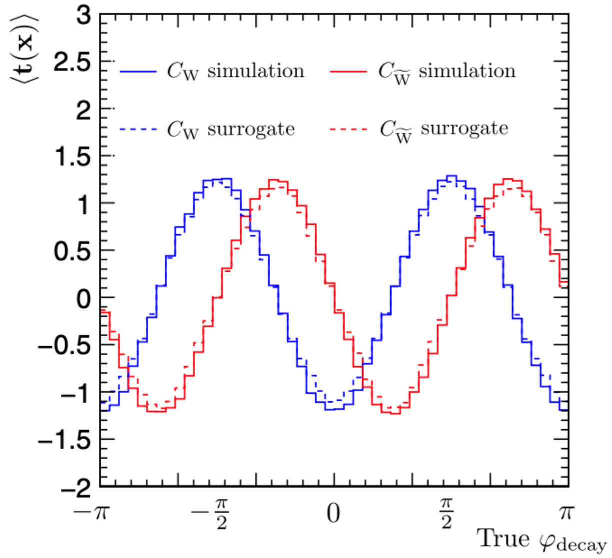
Group activities for HL-LHC

Recent developments much beyond incremental improvements

1. Precision top mass measurement using energy correlators [2311.02157]
   - Excellent theoretical control on (top)
   - Tracking based measurement at HL-LHC in boosted hadronic top
   - Collaboration with UNIVIE
2. Developing ML tools (gNNs) for measuring subtle decay patterns in hadronic final states [PRD (109) 076012]
   - Extract EFT coupling modifications
   - Candidate for FPGA/trigger dev. with HEPHY/ML-group







Summary

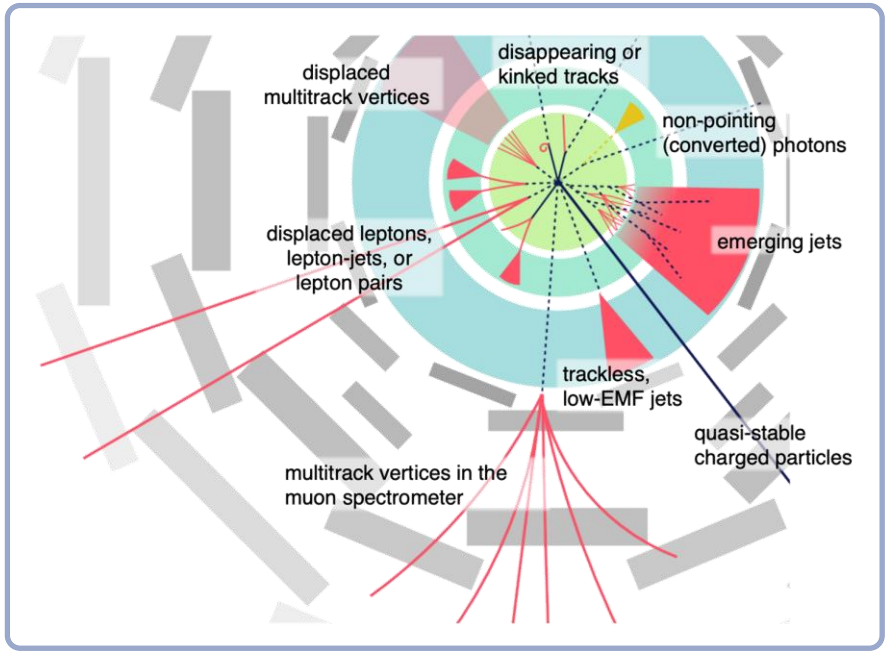
– There is a rich Higgs+EWK program at a future lepton collider
– Almost all ongoing activities relate strongly to future opportunities
– Many synergies among Th./Exp./Det./ML – input for Austrian contribution

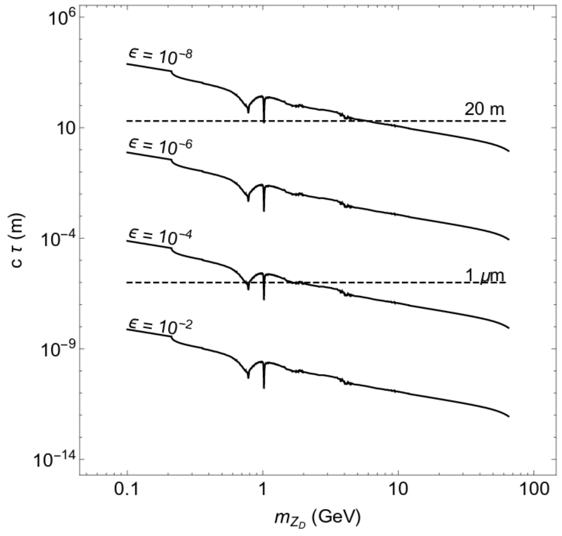
BACKUP

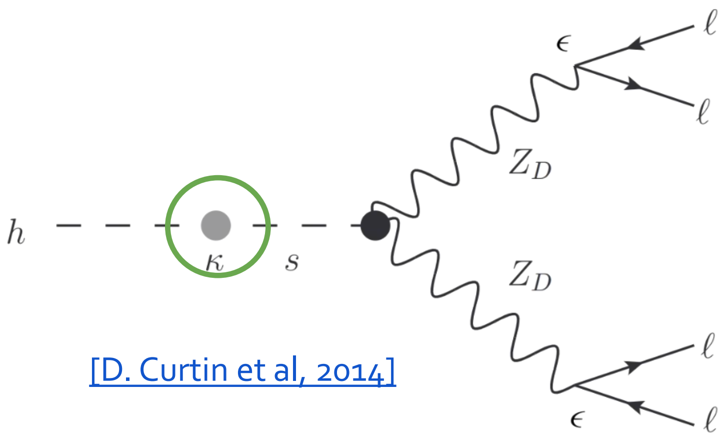
Searches

Long-Lived Particles

- Non-conventional signatures gained momentum in Run 2
- 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)
- Example: Dark sector portal predicting mixing of SM H, leading to displaced dimuon pairs





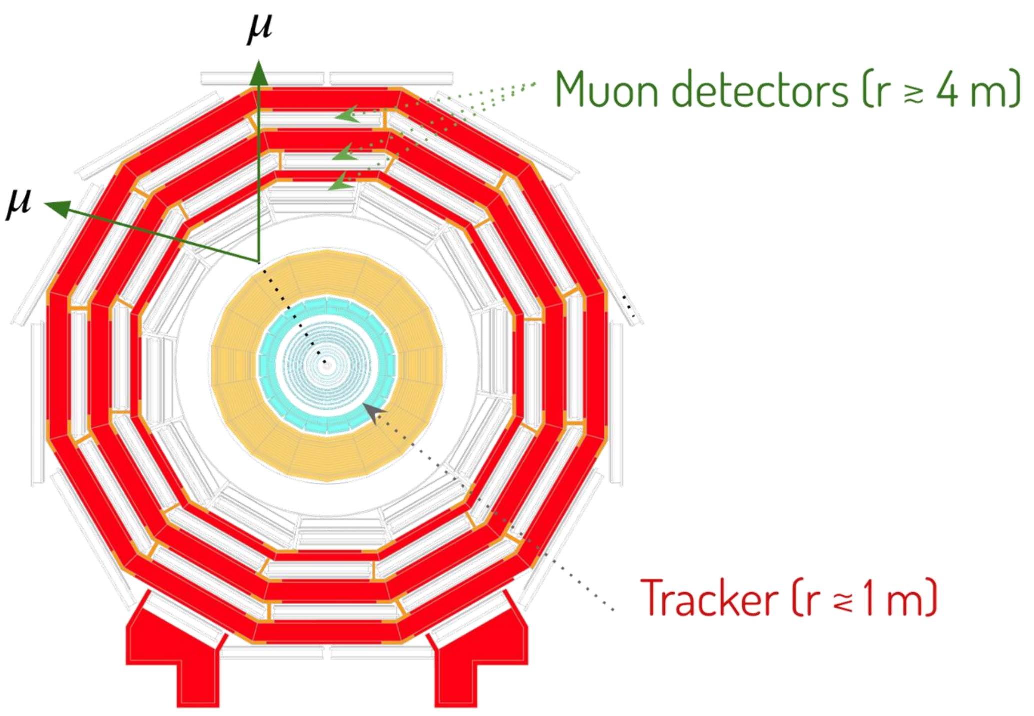


[D. Curtin et al, 2014]

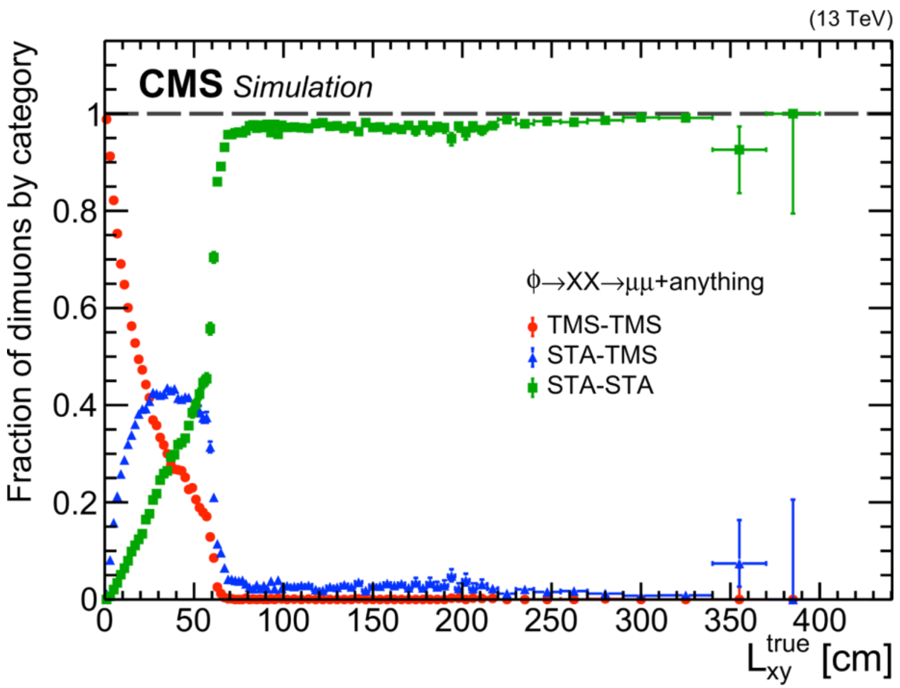
- We focuses on displaced dimuons
  - In collaboration with UCLA
- Branching ratio, $c\tau$, L_{xy} are all strongly model-dependent
  - A generic, mostly model-independent search strategy

Displaced dimuons

[EXO-21-006, accepted by JHEP](#)



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

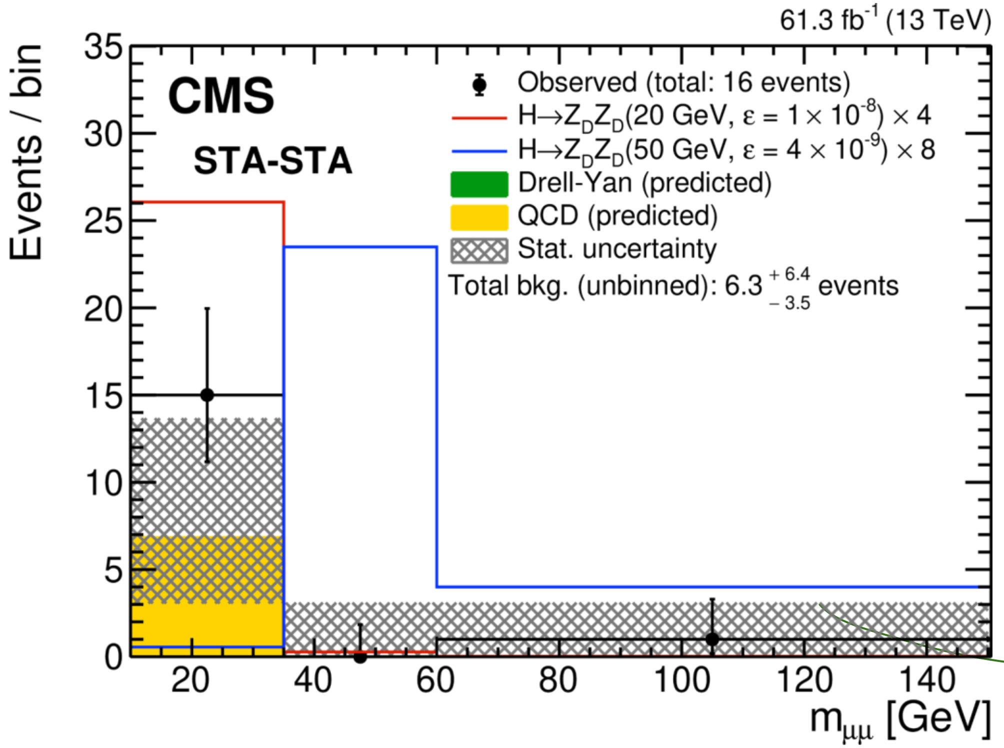


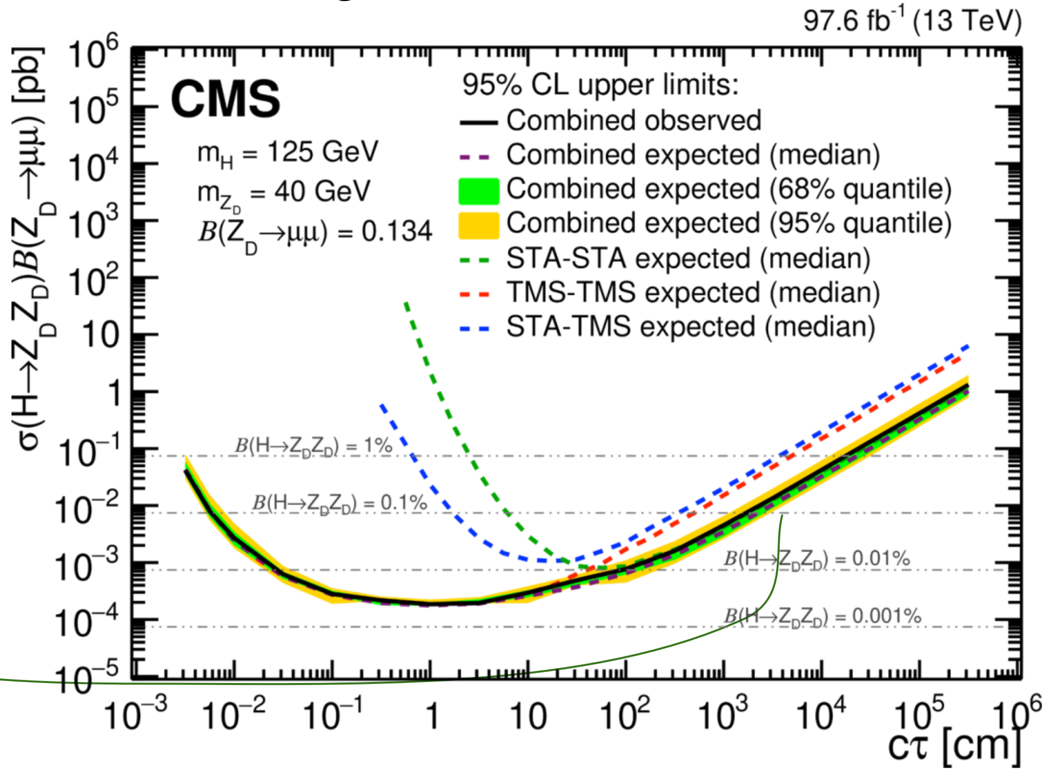
maximize decay length coverage

- 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

Displaced dimuons

- Signal: isolated muons with large d_0 and L_{xy} significance, clustered in $m_{\mu\mu}$
- Backgrounds evaluated using data in dedicated control regions





- Combination of categories → sensitivity to a wide range of $c\tau$ from μm to km
- Excluded $B(H \rightarrow Z_D Z_D) > 10^{-4}$-$10^{-5}$, depending on ($m_{ZD}$, $c\tau_{ZD}$)
- [Accepted by JHEP]

Displaced dimuons

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[PRD 99, 012001]

EXO-21-006, accepted by JHEP

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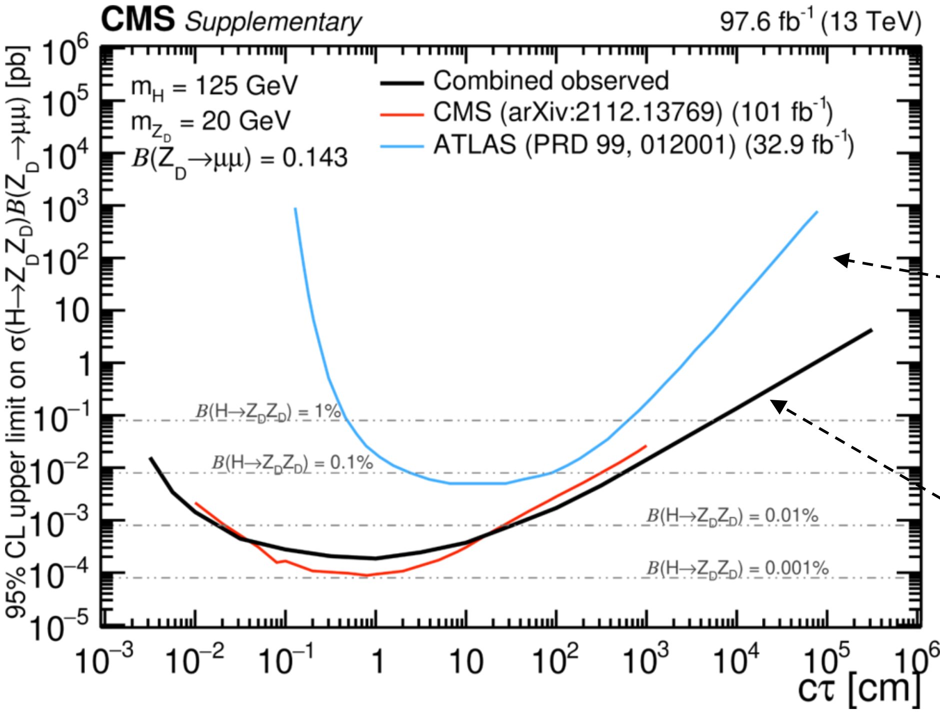
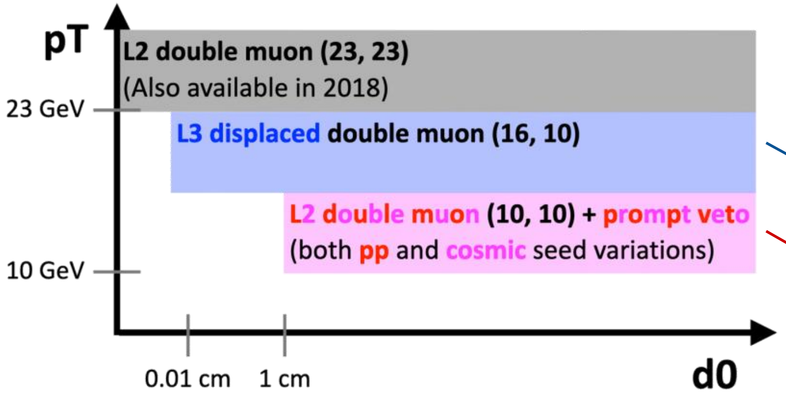
- Research initiated 'from scratch' in 2017, now a legacy result
- Today: State-of-the-art reference for displ. **μ**
  - pioneered triggering, lepton ID, and background suppression methods
  - World-leading constraints for long-lived dark photons in most $c\tau$ (superior wrt ATLAS)
- Early Run2 related efforts (IFCA, Oviedo) now joined
- PI Alberto will join CIEMAT on a tenure-track position "Atracción de Talento Investigador de la Comunidad de Madrid Modalidad-1"
  - Will continue to be involved [Physics briefing]

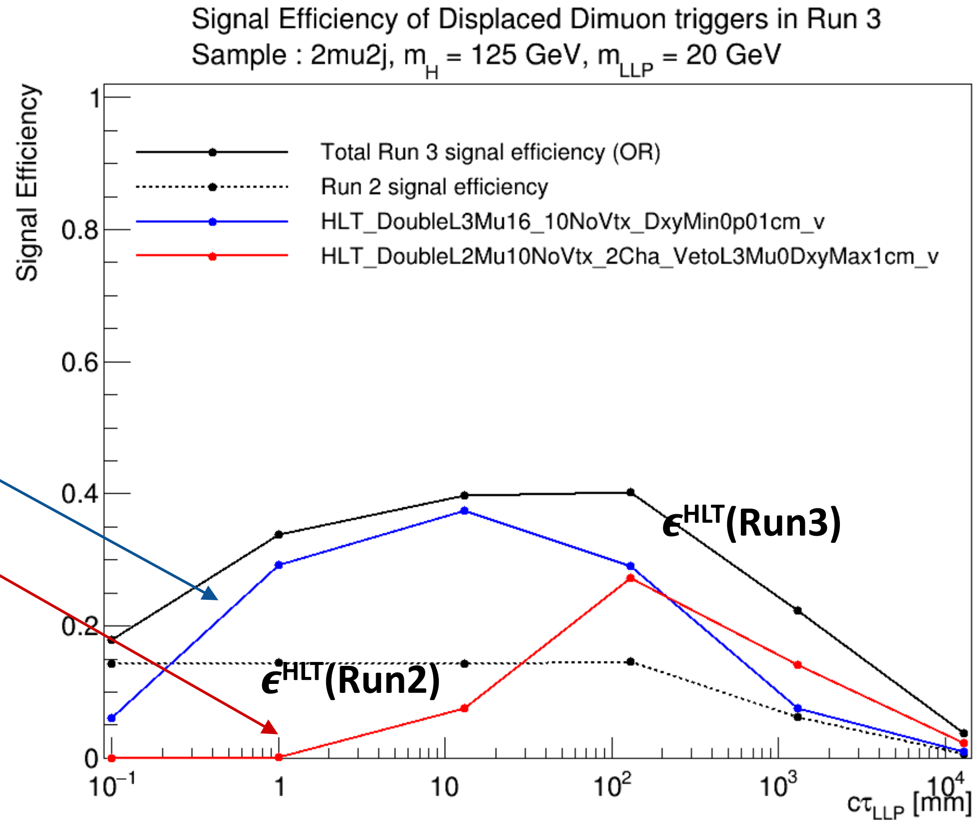


EXO-21-006

Displaced 2μ triggers in Run 3

- Used Run 2 experience for new HLT paths for Run 3
  1. Remove beamspot constraint in p_T measurement at L1 (with UCLA)
  2. Lower p_T thresholds at HLT (p_T> 23 GeV in Run 2)
  3. Prompt veto

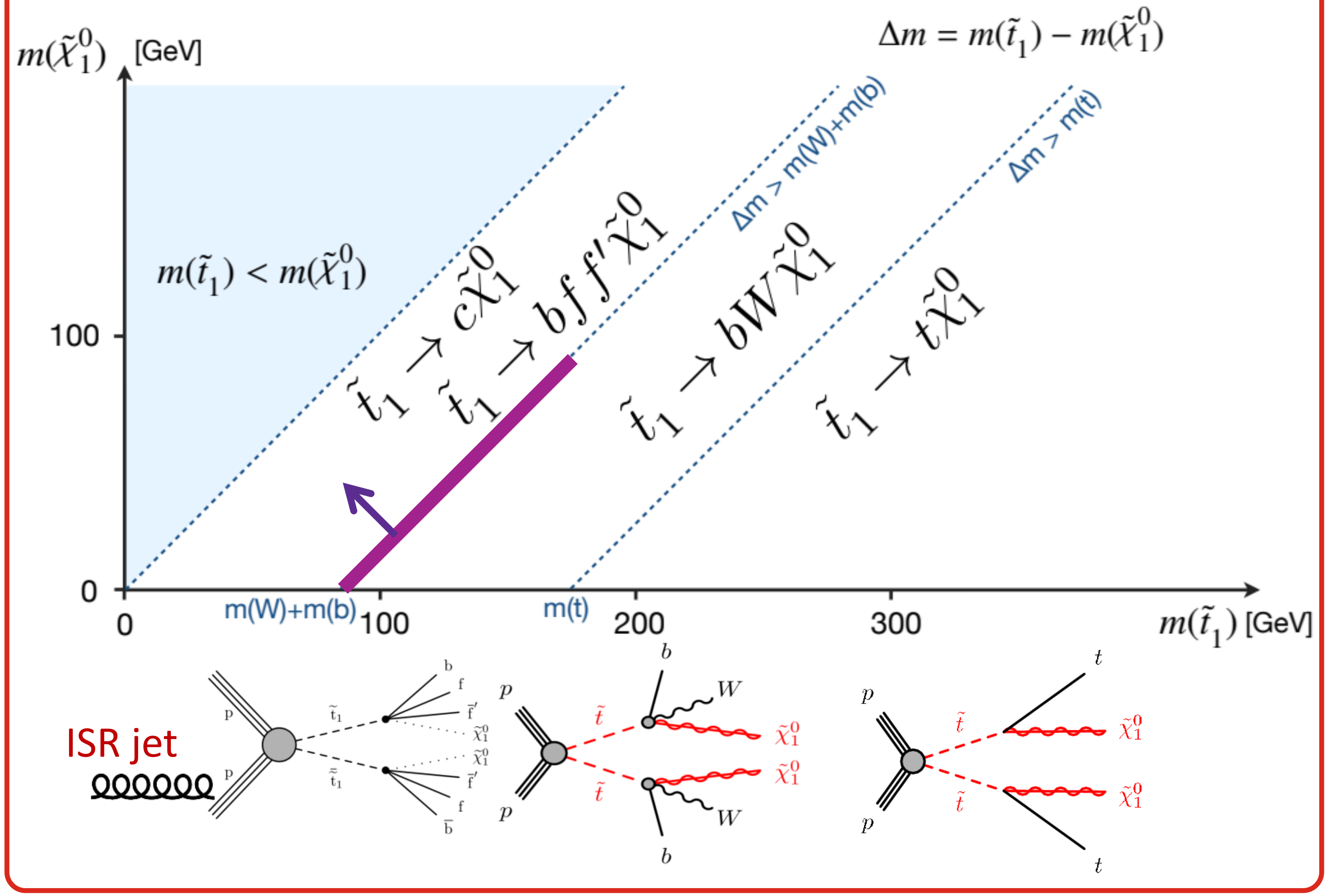




  - Displaced dimuons in inner tracker (d0 > 0.01 cm)
  - Displaced dimuons in muon system without prompt muons in tracker (d_0 > 1 cm)
- factor 2-4 gain in signal efficiency (depending on cτ)
  - Potential top-up with 2022 data (38 fb^{-1} recorded)

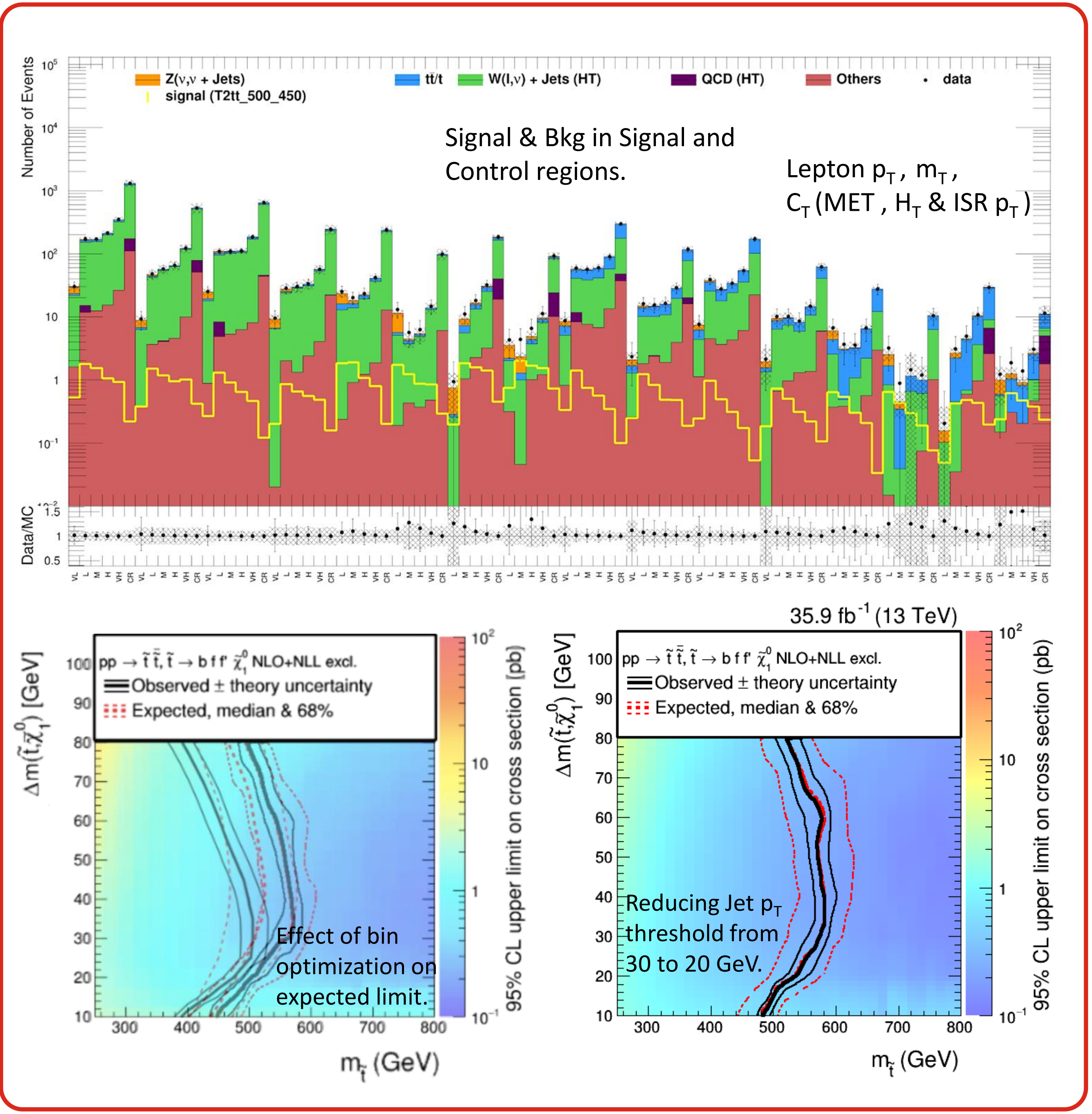
Supersymmetry

- Originally hoped to solve the hierarchy problem and provide a DM candidate
  - Involvement since Run I in final states with jets, leptons, and E_T^{miss}
- Remaining parameter regions are "compressed mass hierarchies"
  - DM coannihilation
  - Soft decay products from decays of top squarks with small mass gap
- Focus on 4-body top squark decay, 1ℓ
  - Boost sensitivity with high-p_T ISR jet
  - Target very compressed scenarios $\Delta m = m_{stop} - m_{LSP} < m_W$
- Collaboration with ELTE



Compressed stops

- Search regions, generically defined
  - lepton p_T, m_T, E_T^{miss}, H_T and ISR jet p_T
- Extend to long-lived scenario for Δm(stop, neutralino) ≤ 30 GeV
  - Higher lepton impact parameter ~10cm
  - Common strategy with prompt search
- Pushing the limit on various fronts
  1. Finer search region binning
  2. Reducing jet p_T threshold
  3. Improved QCD estimation
  4. Dedicated "soft" b-tagging
  5. New low p_T electron reconstruction down to 3 GeV (first SUSY search with $p_T(\ell) > 3$ GeV)
- Should conclude this year



New project: Soft vertex analysis

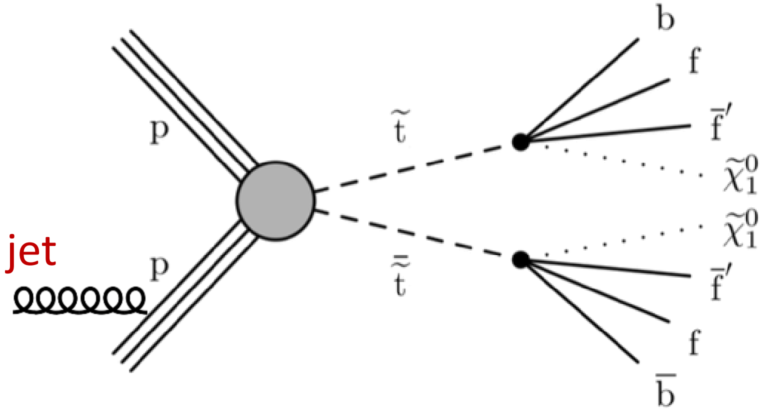
- Explore DM co-annihilation scenarios for ΔM from from few GeV to few tens of GeV
  - well below the compressed top squark search
  - Bino-stop [1408.4662], Bino-wino [1506.08206], Singlet-triplet Higgs portal [1812.04628], Extra-dimensions and composite models [1702.00750]

- Extend exp. signature to even softer decay products
  - E_T^{miss} + ISR jet with addition of soft displaced vertices

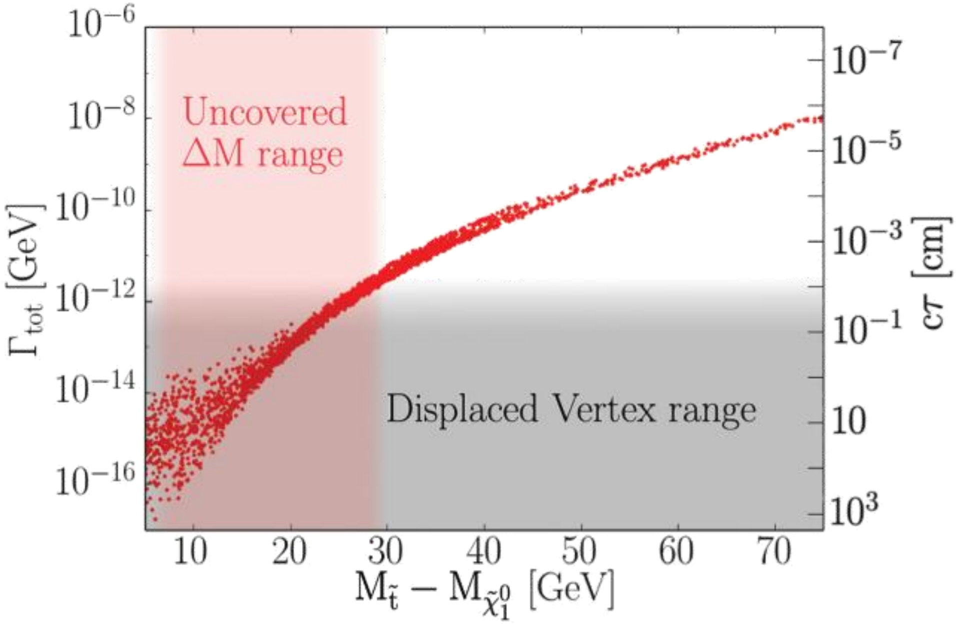
  - Make use of objects to their limit of detectability
  - Use displaced vertices up to a few cm's displacement
    - Tracks with p_T > ~0.5 GeV, DV with at least two selected tracks
    - Compressed top squarks can "only" go to 3 GeV

  - Unprecedented at LHC

Stop decay in bino-stop scenario

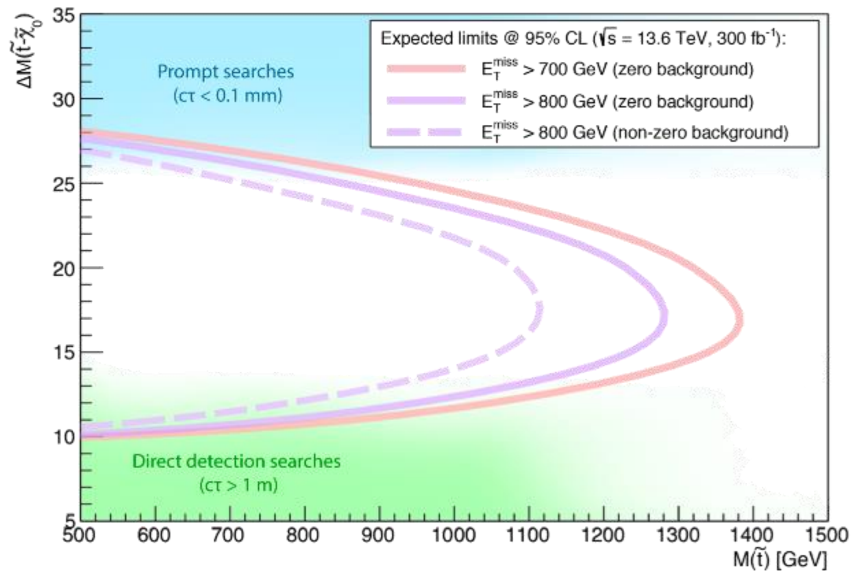


Decay width vs ΔM in bino-stop scenario



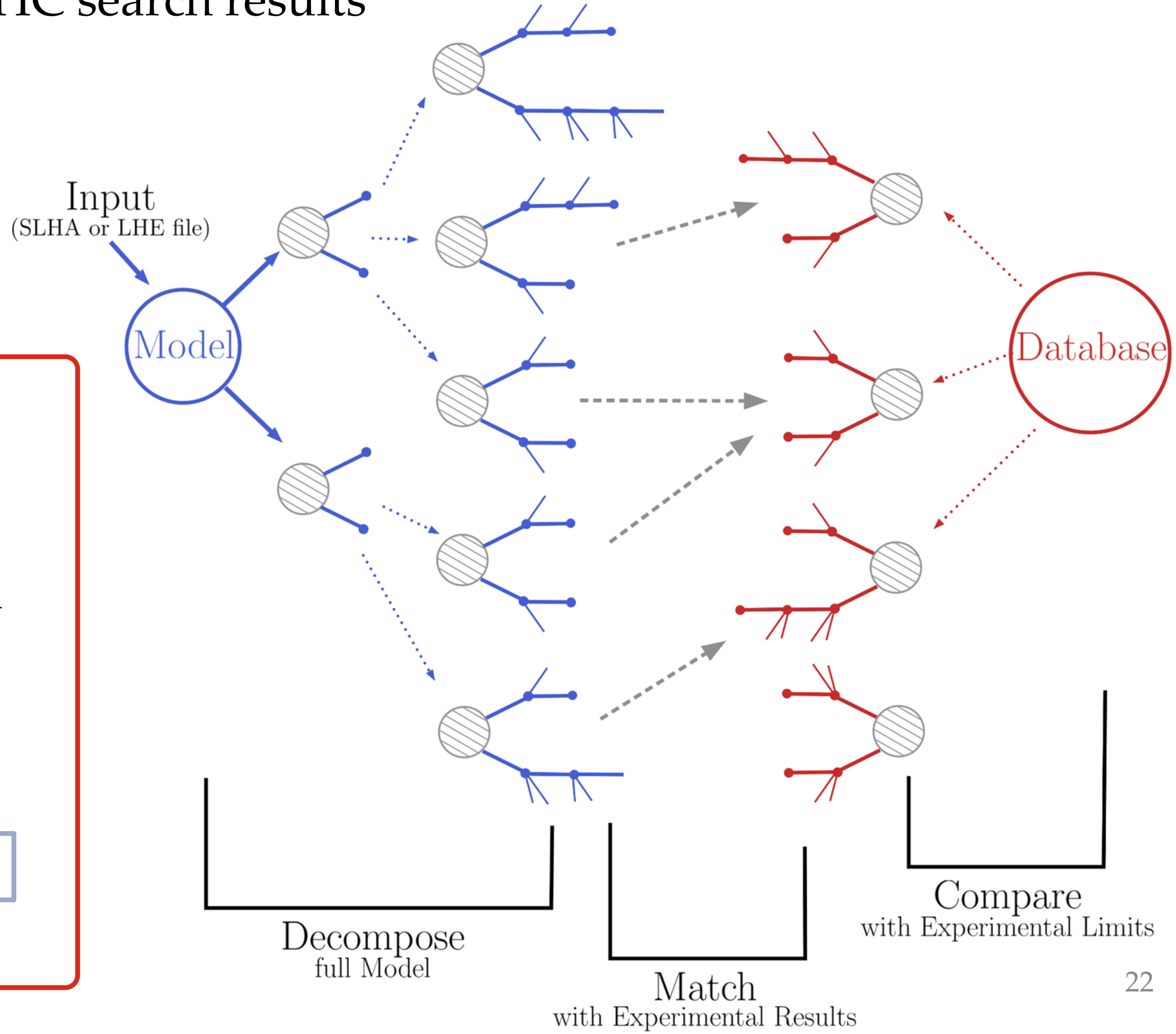
Soft vertex analysis: Status

- Feasibility study shows we can close sensitivity gap left by existing searches
- Experimental, closes the gap between "mono-jet" and E_T^{miss} +ISR+soft high-level object signatures
- Plan for the start of project
  - ML techniques for both track and DV selection
  - Use both Run 2 and Run 3 data
    - Use existing MET triggers
    - Make use of pixelless track reconstruction improvements in Run 3
- Hired Postdoc + PhD (FWF)



SModelS interpretation of LHC search results

- Framework to fully exploit the many new LHC search results
- A tool for quickly comparing a theory with a database of experimental results
- Decomposes theory automatically into simplified model spectrum
  - Matches against results, obtains new limits



GitHub | pypi package 2.2.1 | launch binder | docs main

18 Oct 2022: SModelS version 2.2.1 available (what's new)

10yrs onwards, database contains results from > 100 CMS and ATLAS publications

SModelS: a tool for interpreting simplified-model results from the LHC and its application to supersymmetry #1

Sabine Kraml (LPSC, Grenoble), Suchita Kulkarni (LPSC, Grenoble), Ursula Laa (Vienna, OAW), Andre Lessa (Sao Paulo U.), Wolfgang Magerl (Vienna, OAW) et al. (Dec 15, 2013)

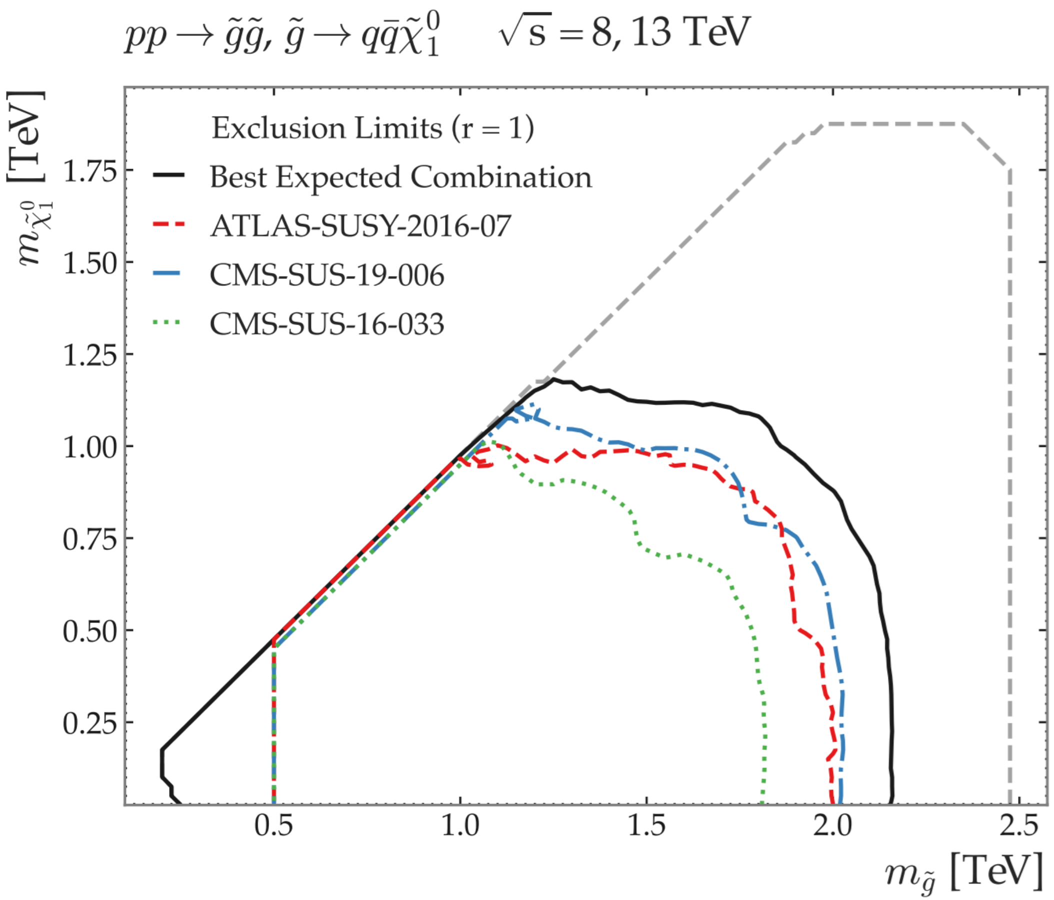
Published in: *Eur.Phys.J.C* 74 (2014) 2868 • e-Print: 1312.4175 [hep-ph]

pdf | DOI | cite | claim | reference search | 170 citations

https://smodels.github.io/

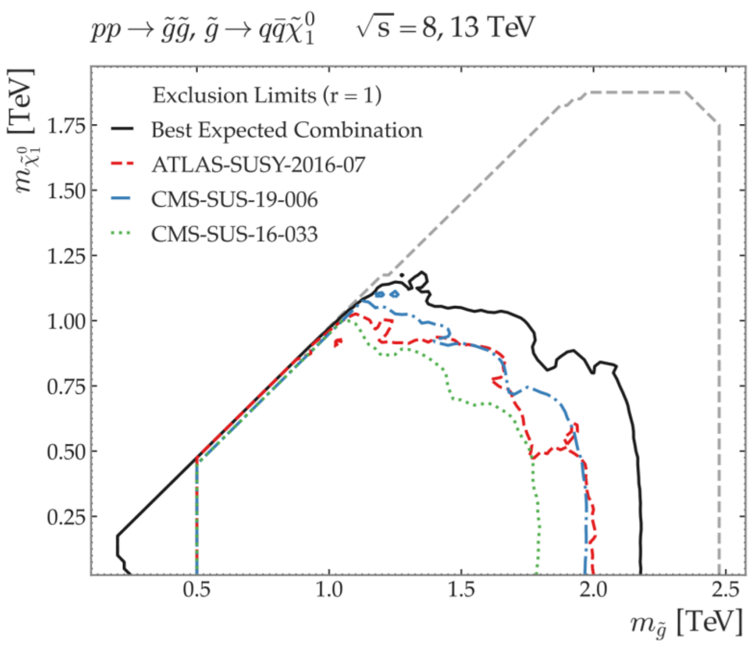
Combinations

- New feature: Can now **combine** several **results** to a single, more constraining result
  - often **results in ~ 200 GeV gain** in terms of exclusion
  - some **approximations** necessary



SModelS finds best combination based on *expected* exclusion reach

Observed exclusion (new result)

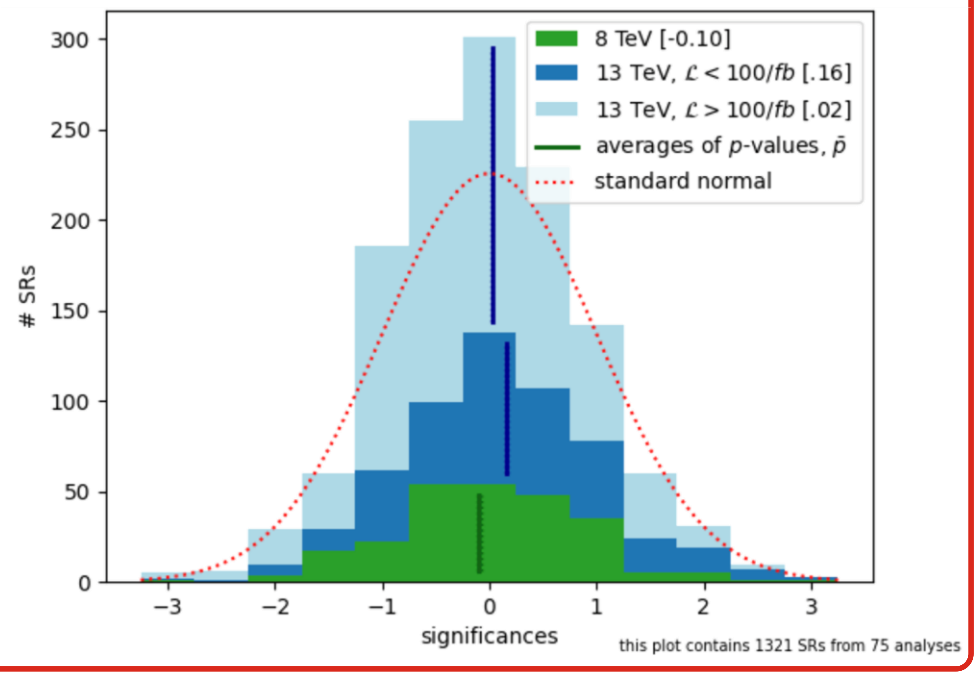


Meta-analysis & plans

- Meta-Analysis of 1321 SRs across all analyses
  - SM hypothesis: significances ~ N(0,1)
  - holds true to a remarkable degree
    - no reproducibility crisis in LHC physics!

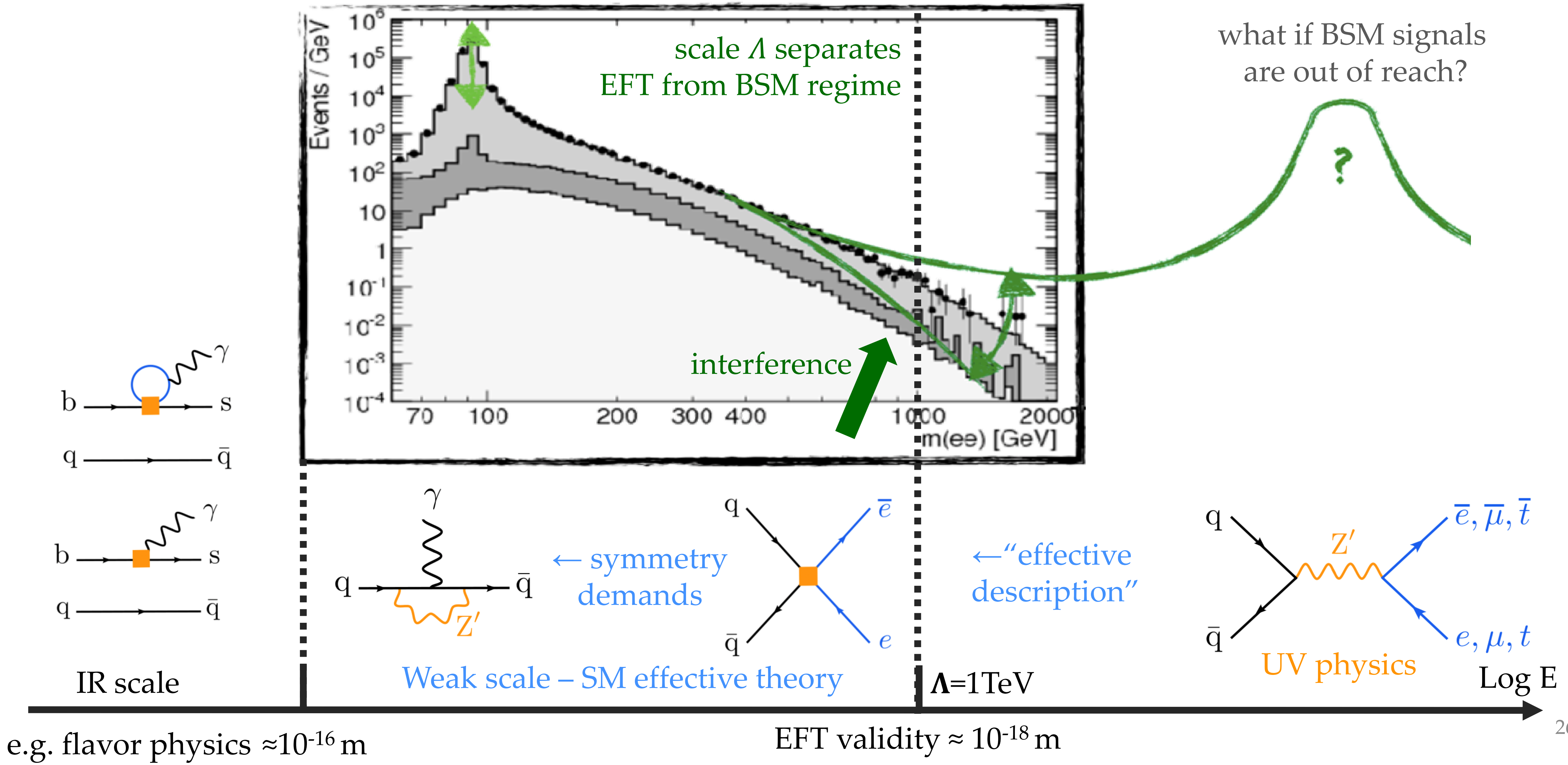
- next update: SModelS v3
  - > 1000 signal regions from > 100 publications
  - going beyond SUSY-like topologies
  - Cover more general, graph-like topologies
  - SModelS v3 will cover most of the amenable theory landscape

LHC posterior (meta analyses)



Measurements, EFT interpretations, and machine-learning

Catching new physics by the tail



The SM effective field theory

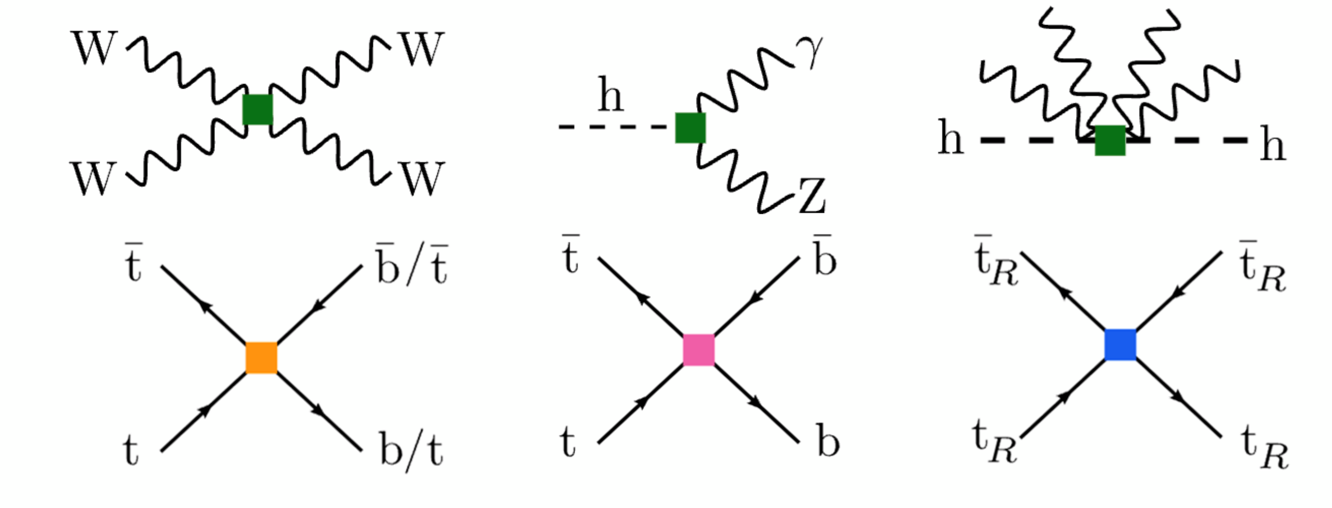
- SMEFT is long known, but in recent years gained strong momentum
  - Keep SM particle content
  - Add all possible modifications keeping SM symmetries intact

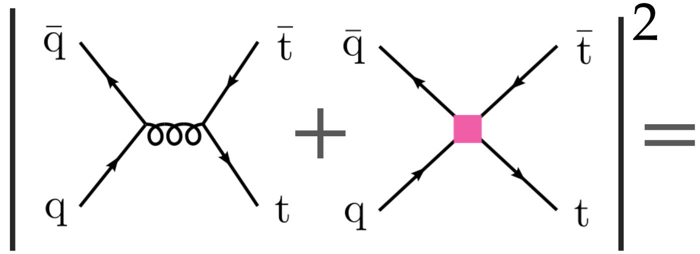
$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

  - $SU(3)_c \otimes SU(2)_L \otimes U(1)$
  - 59 operators at d=6 [JHEP10(2010)085]

- Important simplifications in the predictions: quadratic polynomials

Anomalous couplings & new interactions (tiny selection!)

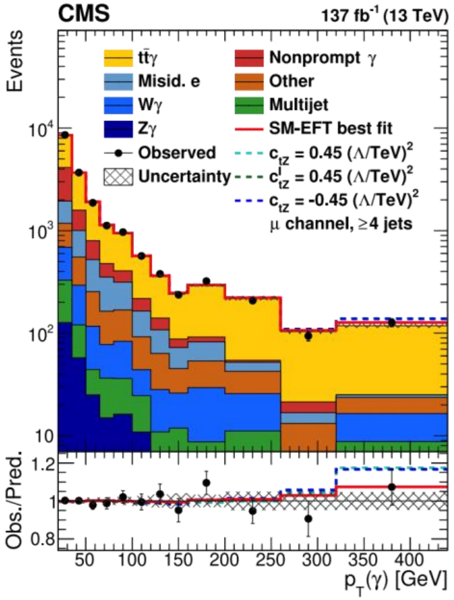


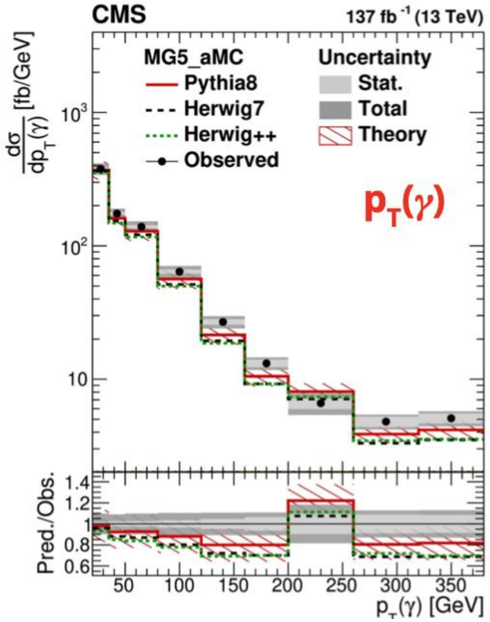


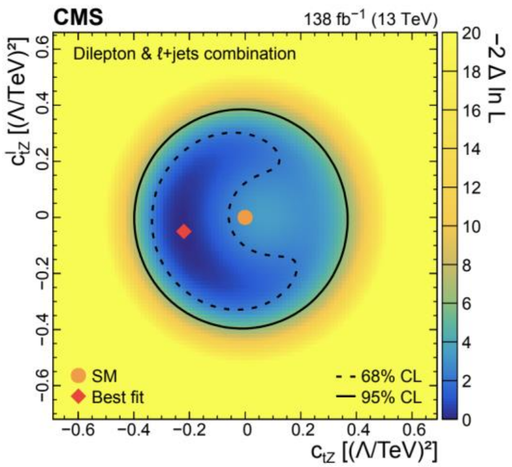
$$= \sigma^{SM} + \frac{C}{\Lambda^2}\sigma^{int} + \frac{C^2}{\Lambda^4}\sigma^{quad}$$

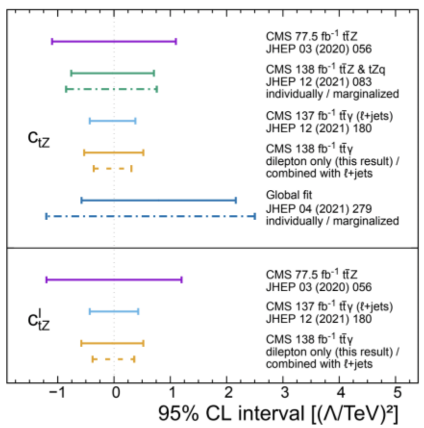
Measurements with top quarks

- Involvement in measurements of cross sections and top properties since 2017
  - Originally a SUSY background, we started SM measurements of the ttZ process [JHEP 03 (2020) 056]
- Latest result: ttγ differential cross section
  - SM measurement in the 1ℓ channel [JHEP 12 (2021) 180]
  - EFT effects appear in highly energetic $p_T(\gamma)$ tails
  - Sensitive to “electroweak dipole interactions”
    - Best current limits!
    - CMS [Physics Briefing]
- Combined with 2ℓ channel (UGhent) [JHEP 05 (2022) 091]
  - Run 2 legacy result
  - ttγ project finished in 2021



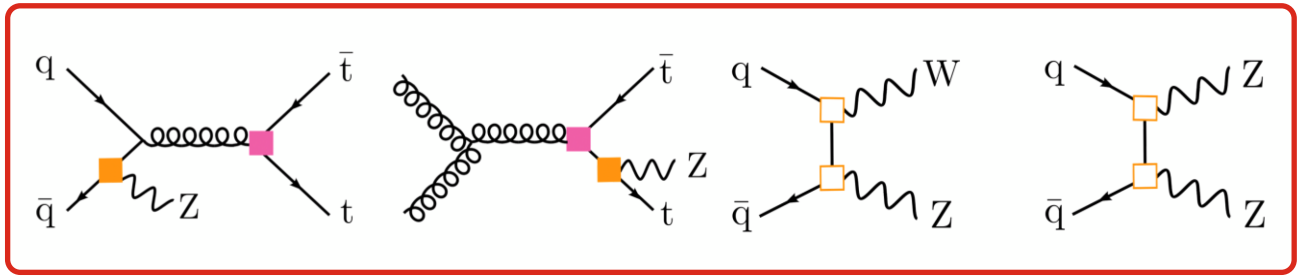




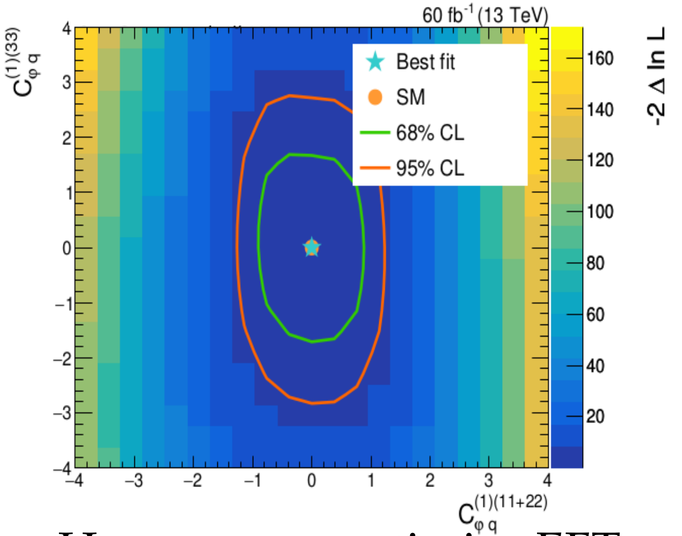


EFT Flavor structure of the Z coupling

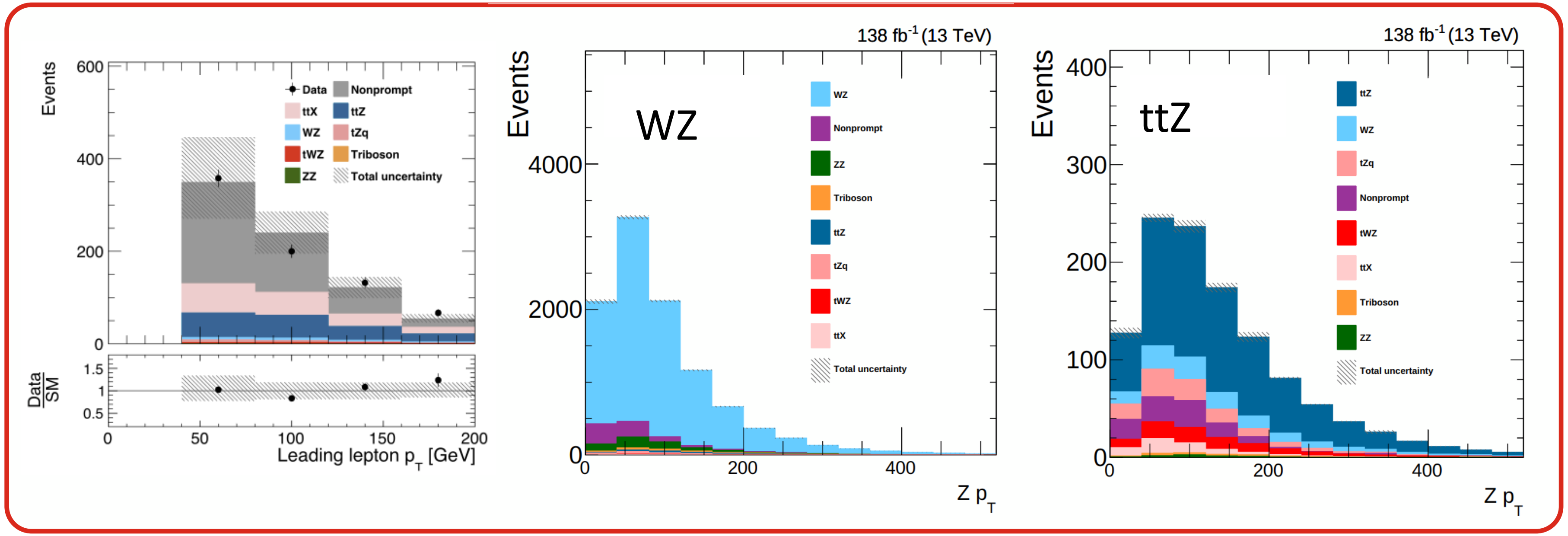
- New project on Z-(top/light quark) coupling in multilepton (3 or 4) final states
  - Resolve flavor structure of BSM effects in the top-Z couplings and the light-quark/Z couplings
  - WZ and ttZ are mutual backgrounds
  - Resolve ambiguity by simultaenous meas. in WZ/ ttZ / and ZZ selections
- Status: Signal regions, sensitivity, strategy done
  - Background estimation complete
  - Signal generation ongoing, expect first approval stage this year



Limit combination

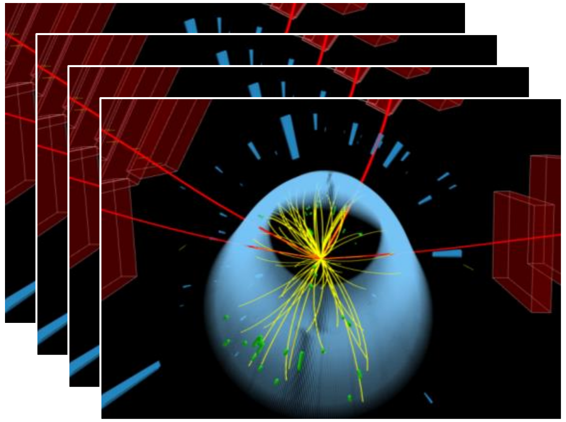


How can we optimize EFT limits with ML?

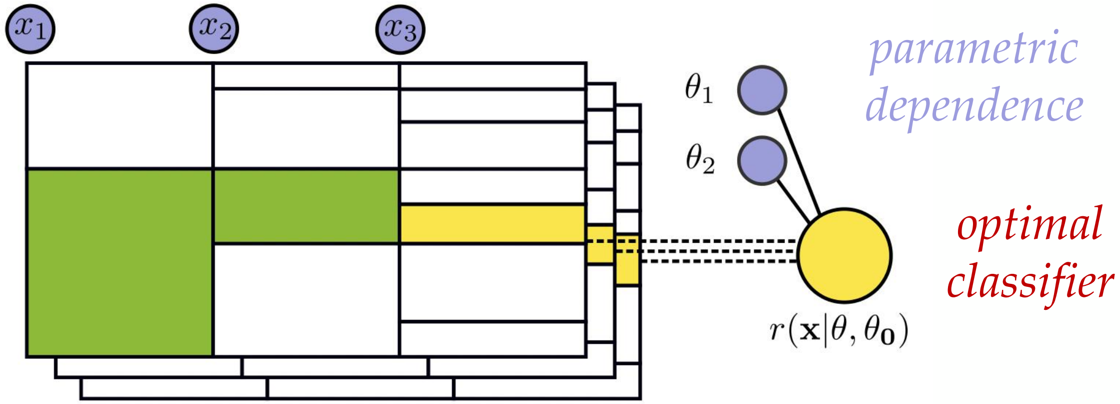


Boosted Information Tree

Q: How can we optimize EFT sensitivity with ML?



- Theory answer: Neyman-Pearson Lemma
  - *The likelihood ratio test statistic is optimal*
  - But SMEFT has 59 parameters → Can not train in this high dimensional space
- Exploit that EFT predictions are polynomial
  - learn the coefficient functions of EFT expansion
- New algorithm: "Boosted Information Tree" [2107.10859, 2205.12976]
  - Implements Likelihood-free inference (SMEFT) in trees
  - Provides a *parametrized* optimal observable



Fully exploits polynomial structure of EFT predictions $\hat{F}(\boldsymbol{x}, \boldsymbol{\theta}) = \sum_{j \in \mathcal{J}} \mathbb{1}_j(\boldsymbol{x}) F_j(\boldsymbol{\theta})$

Optimizes the Fisher information $L = -\sum_{\boldsymbol{\theta} \in \mathcal{B}} \sum_{j \in \mathcal{J}} \frac{w_j^2(\boldsymbol{\theta})}{w_j(\boldsymbol{\theta}_0)}$

Can solve for trainable parameters of the predictor → *Faster training than NNs*

- Used in ongoing CMS analysis
- Working on extending the methodology to graph neural networks

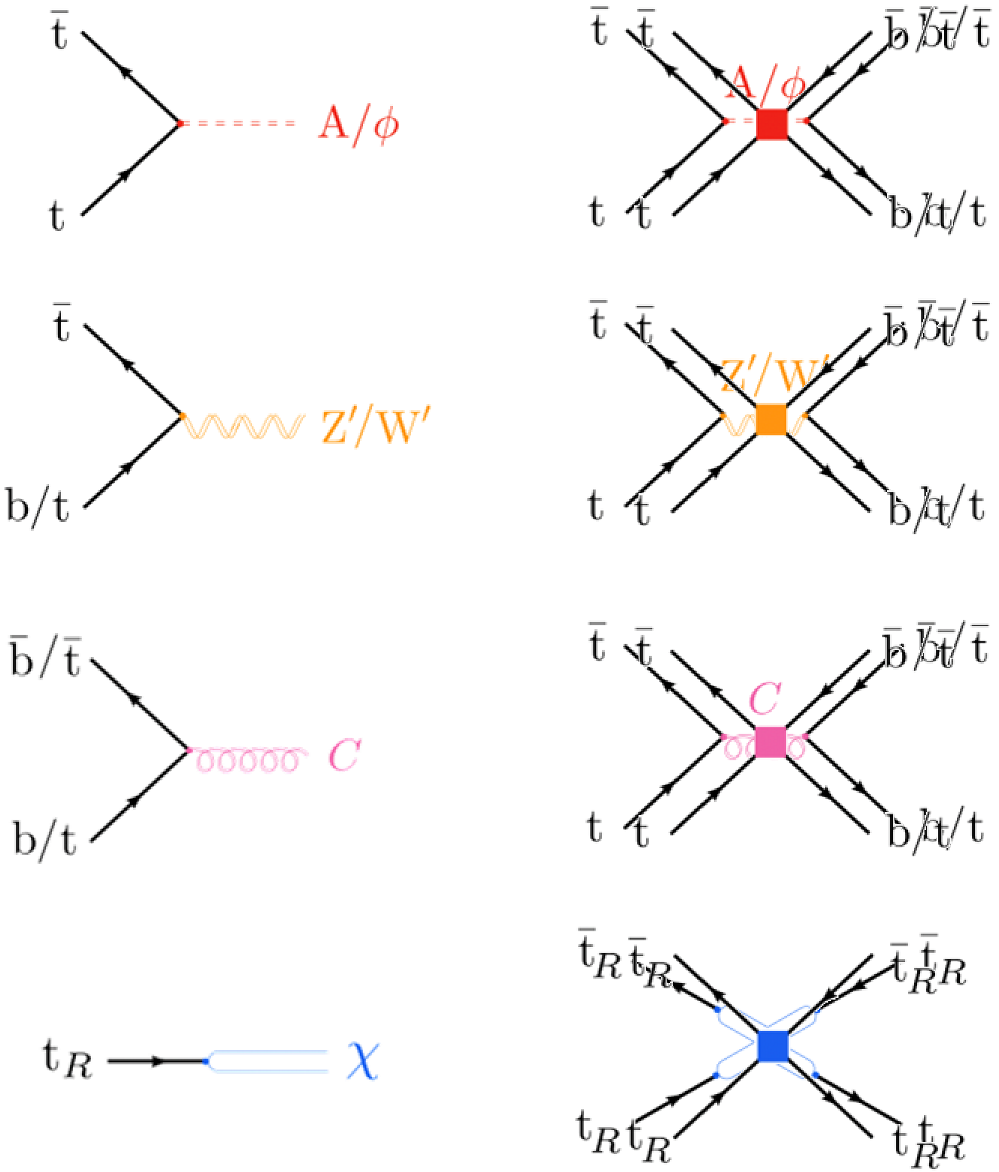
New Forces between heavy quarks?

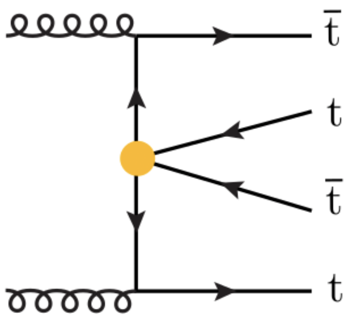
- Extended Higgs sectors "two Higgs doublet models" from SUSY or other BSM physics [review]

- High-mass force carriers similar to the W and Z bosons : Z′ and W′ bosons [review]

- Massive "chiral" colored force carriers, otherwise similar to the gluon: axigluons [Mimasu et.al.]

- Composite sector whose bound states mix with the SM particles: (right-handed) top-quark and/or Higgs compositness [review]





Test for EFT effects in a tttt and ttbb final states

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Four top quark production

[EPJC 80 (2020) 1085, arXiv:2211.01136]
[TOP-21-005, EPJC 80 (2020) 75]

HEPH INSTITUTE OF HIGH ENERGY PHYSICS

- Extremely rare process (SM: 12.2 ± 2.2 (scale) fb); Measurements exctract inclusive cross section

ATLAS

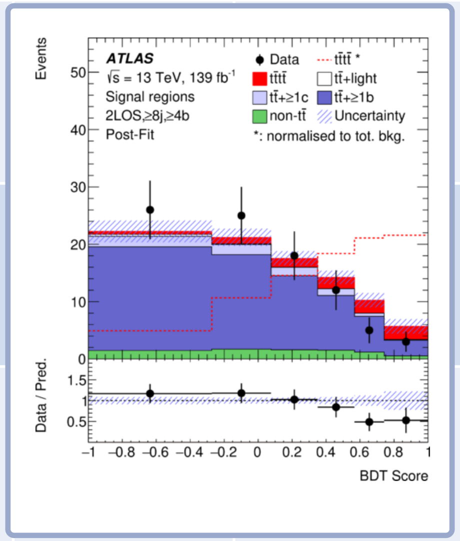
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\ ^{+4.6}_{-3.4}(\text{syst})\ \text{fb} = 22.5\ ^{+6.6}_{-5.5}\ \text{fb}$$

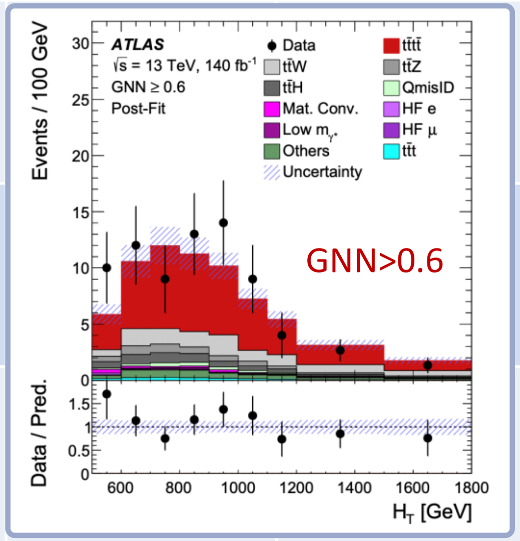
6.1σ (4.3σ) expected, consistent with SM at 1.8σ

CMS

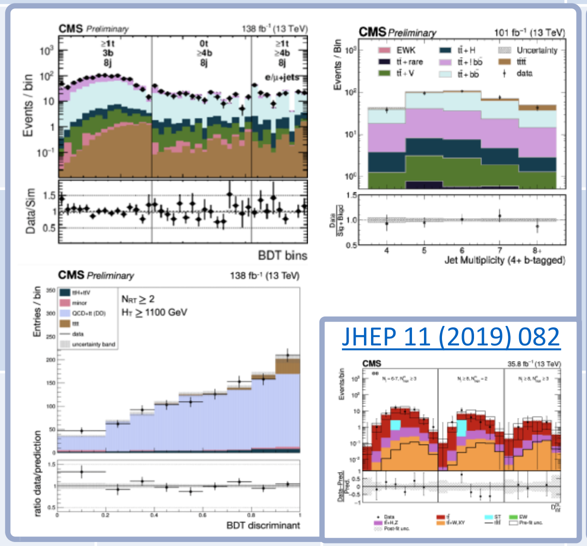
2ℓ	4.1 (4.1) s.d.	$17.6\ ^{+4.7}_{-4.3}$ (stat) $^{+2.8}_{-2.7}$ (syst) fb
3ℓ	3.5 (3.0) s.d.	$19.4\ ^{+7.1}_{-6.4}$ (stat) $^{+2.9}_{-2.3}$ (syst) fb
4ℓ	0.0 (0.8) s.d.	—
Combined	5.5 (4.9) s.d.	$17.9\ ^{+3.7}_{-3.5}$ (stat) $^{+2.4}_{-2.1}$ (syst) fb

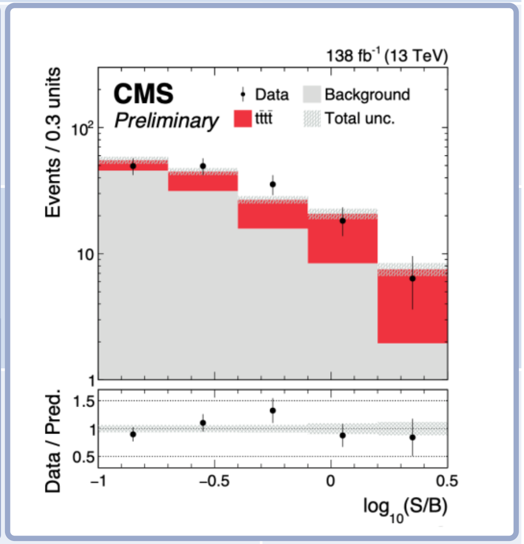
ATLAS	0ℓ	1ℓ	2ℓ(OS)	2ℓ(SS)	3ℓ+
		JHEP 11 (2021)118		[2303.13937]	
2018					
2017					
2016					





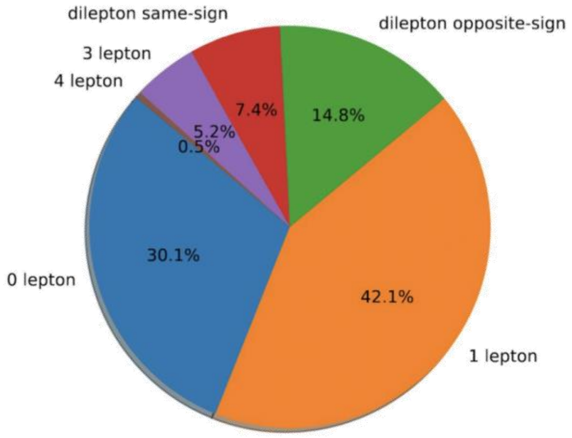
CMS	0ℓ	1ℓ	2ℓ(OS)	2ℓ(SS)	3ℓ+
		TOP-21-005		[TOP-22-006]	
2018					
2017					
2016					



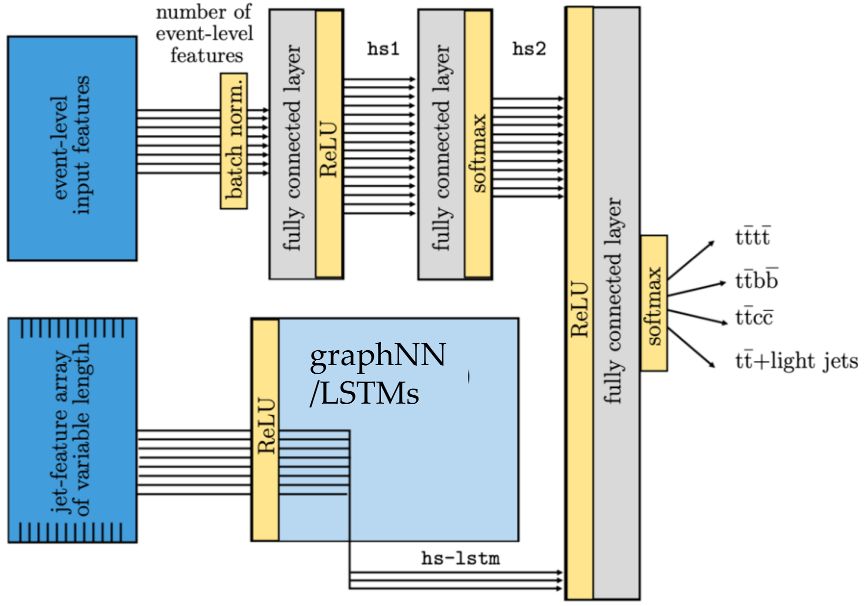


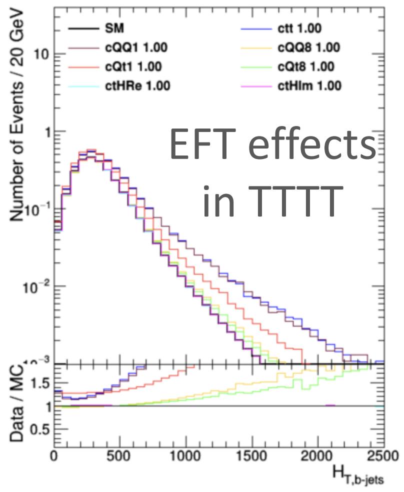
tttt: status

- New FWF project with UGhent + UNIGE (F. Riva)
  - CMS 4-top discovery part of the project (UGhent)
  - ML-assisted analysis strategy, combining 1ℓ, 2ℓOS, 2ℓSS, 3ℓ, 4ℓ
- 1ℓ, 2ℓOS are the pivotal regions for tttt/ttbb disambiguation & SMEFT interpretation
  - Large BR & large overlap with ttbb

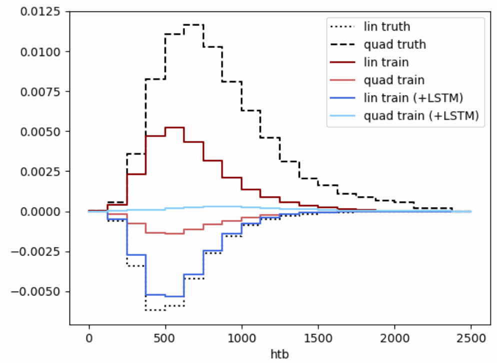


- Developed a LSTM/gNN based multi-classifier using the whole jet system (+20% efficiency)
- EFT sensitivity: Learn the SM-EFT effects





Coefficients of parametric "optimal observable" using gNNs & full jet vector

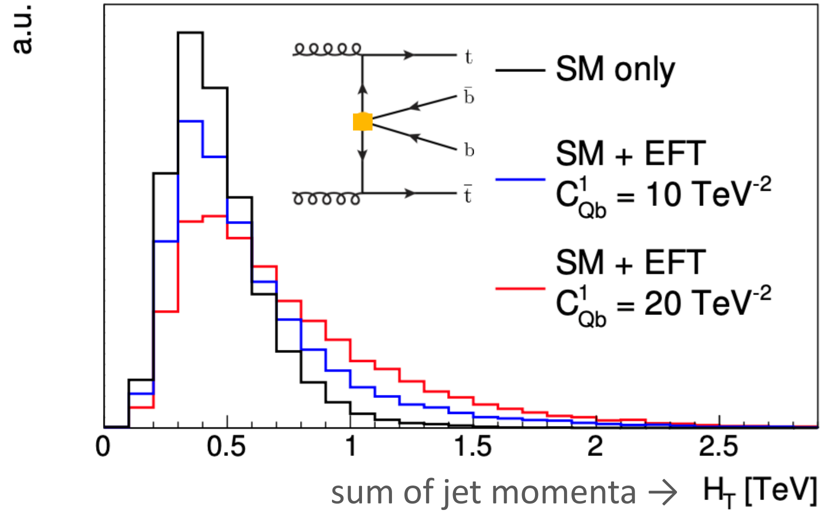


tt + bb

[JHEP 07 (2020) 125]
[PLB (2020) 135285]

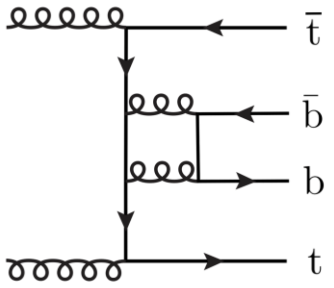
- EFT shapes interest
  - tt+bb studied mostly in "generator-tuning" context and as bkg

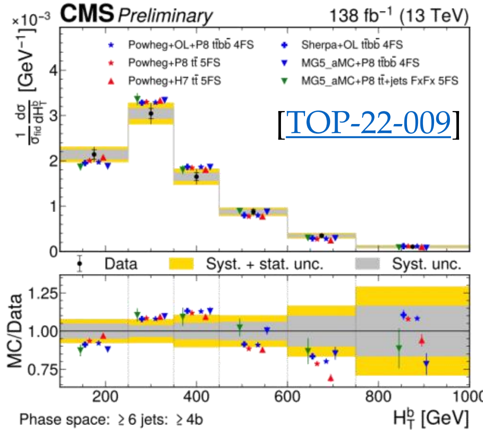
[Mimasu et.al. JHEP 11 (2018) 131]



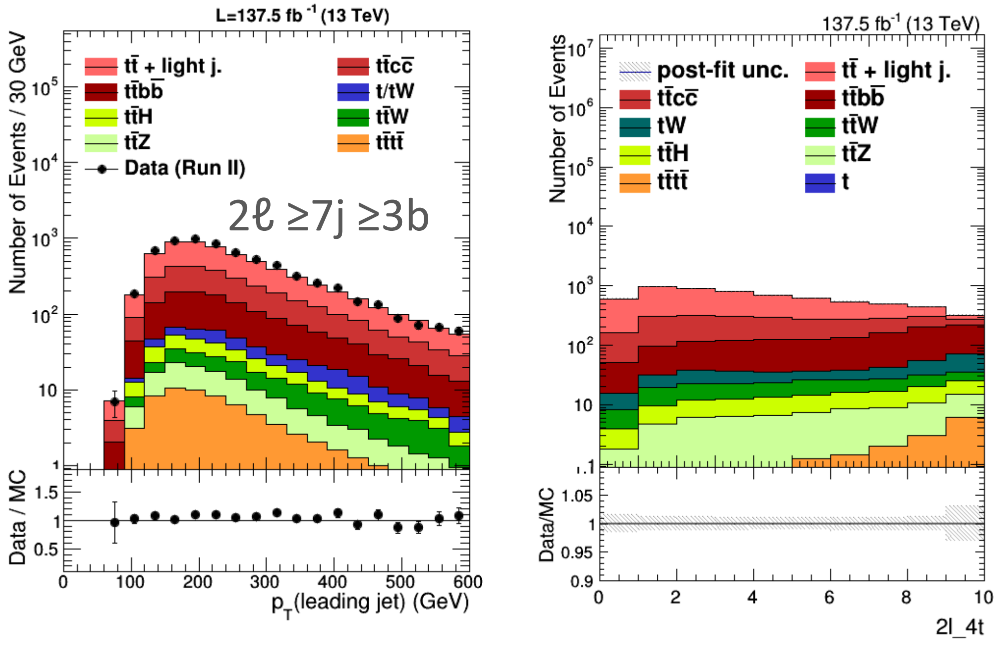
  - complementary EFT information to tttt

difficult modelling of SM bb production



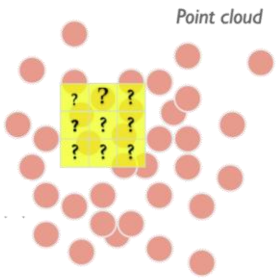


- Status
  - EFT search strategy & systematics done
  - collaborate with KIT (tt+bb)
  - signal generation is next

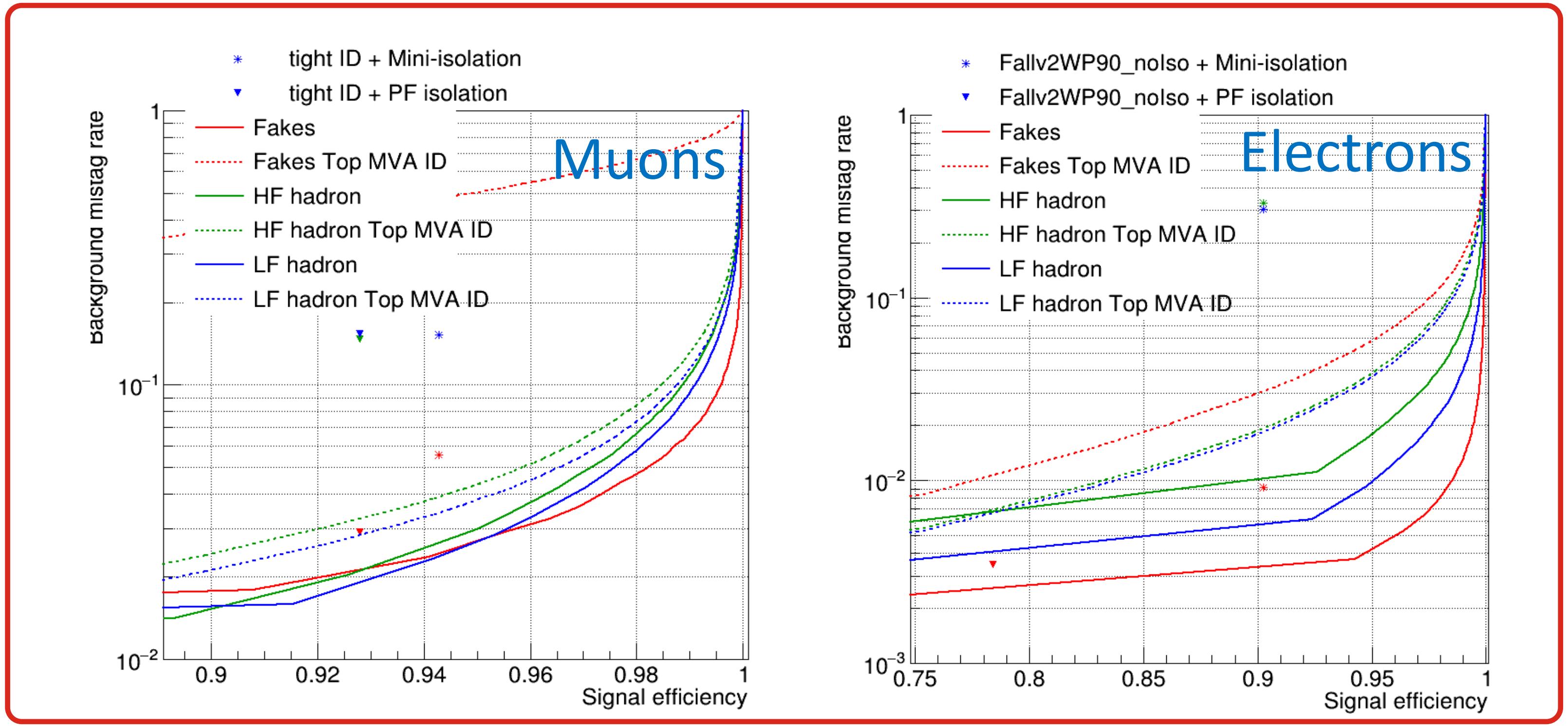


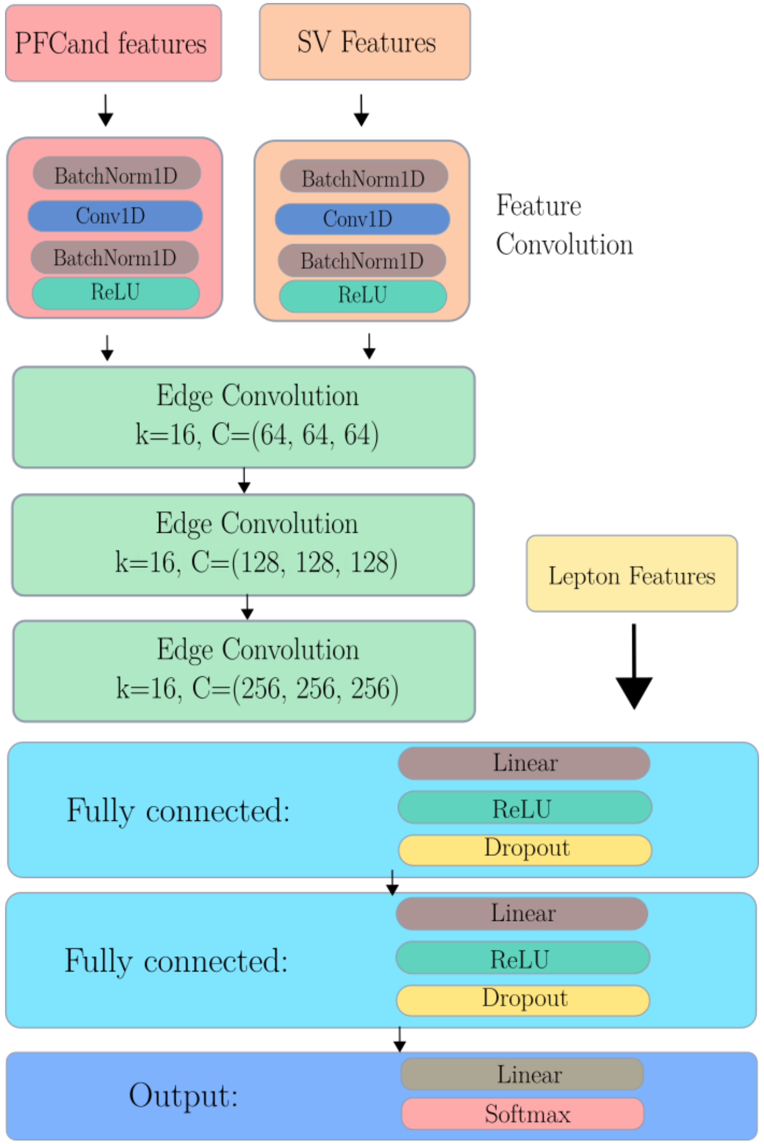
GraphNN for lepton ID

- Adaptation of ParticleNet algorithm used for jet tagging in CMS
  [Y. Wang et al. (2018) L. Gouskos, H. Qu (2019)]
  - Fully exploit data on activity around the lepton candidate
  - Treat particles around lepton as point cloud: unordered, permutation-invariant set of particles
  - Learn particle correlation with EdgeConv operation & DNN



– Prompt, heavy-flavor, light-flavor, fake categories

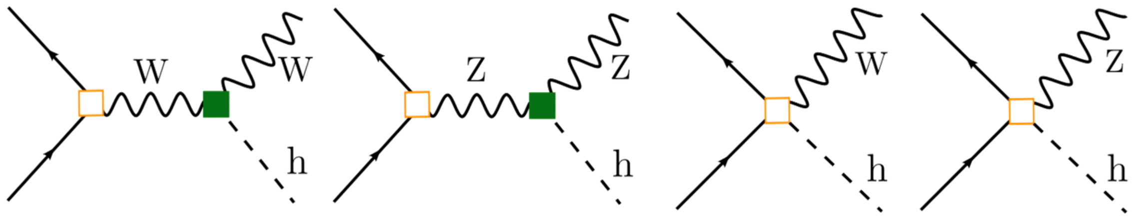




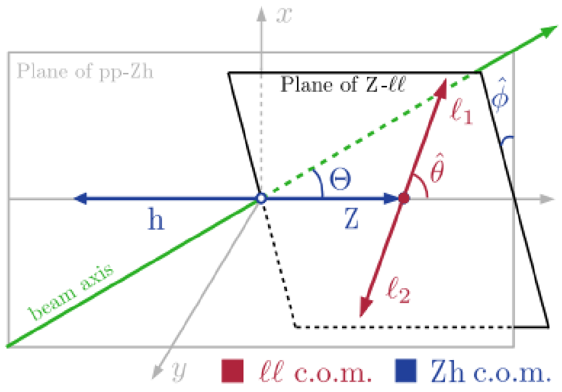
SMEFT analysis of Higgs-strahlung

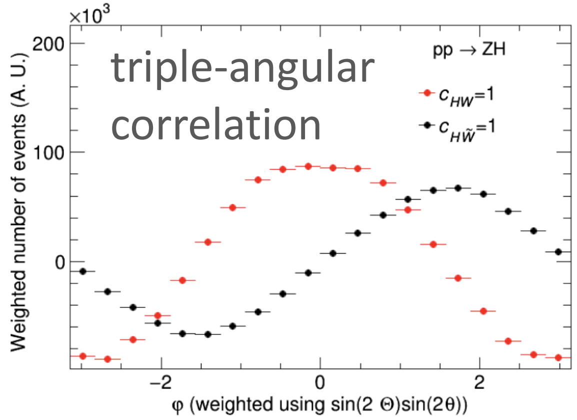
- Probing eight SMEFT operators in ZH and WH production
  - boosted & resolved H→bb
  - Higgs tagging: Mass-decorr. ParticleNet
- In collaboration with ETH team

1. Exploit E-growth of 4-point functions
   - Unique sensitivity to vector coupling modifications; better than tt+Z/γ
2. Interference resurrection
   [Spannowsky, JHEP 09 (2020)170]
   - Sensitivity from full angular analysis (Triple-variable correlations)
   - recover CP structure of BSM couplings



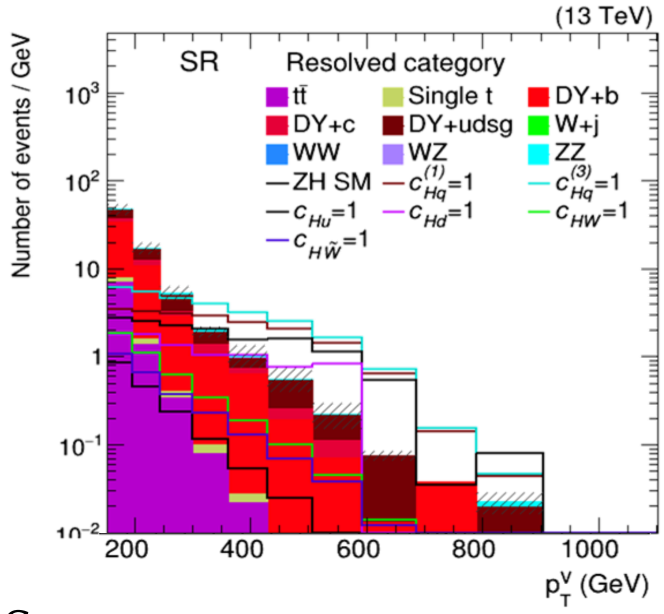
vector coupling modifications		aTGC/aQGC	
$\mathcal{O}_{Hq}^{(1)}$	$iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}\gamma^\mu q$	$\mathcal{O}_{HWB}$	$H^\dagger\sigma^a H W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{Hq}^{(3)}$	$iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}\sigma^a\gamma^\mu q$	$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\sigma^a H W^a_{\mu\nu} \widetilde{B}^{\mu\nu}$
$\mathcal{O}_{Hu}$	$iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R\gamma^\mu u_R$	$\mathcal{O}_{HW}$	$(H^\dagger H)\, W_{\mu\nu} W^{\mu\nu}$
$\mathcal{O}_{Hd}$	$iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R\gamma^\mu d_R$	$\mathcal{O}_{H\widetilde{W}}$	$(H^\dagger H)\, W^a_{\mu\nu} \widetilde{W}^{a\mu\nu}$

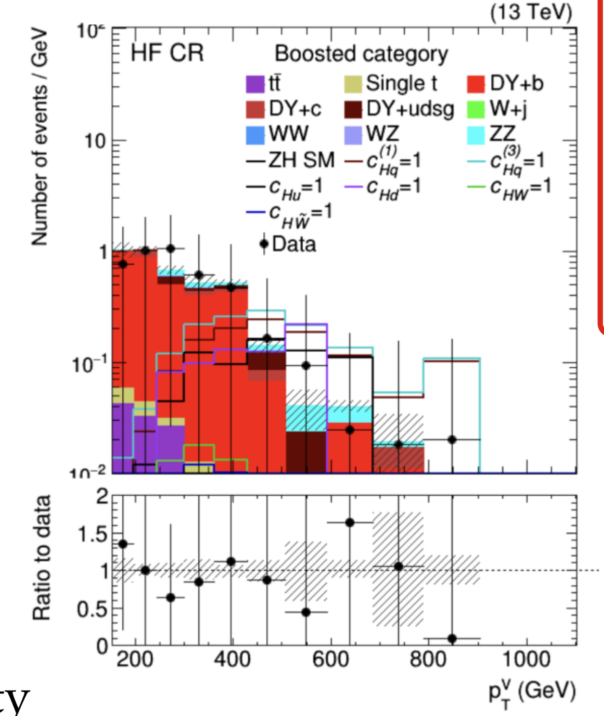


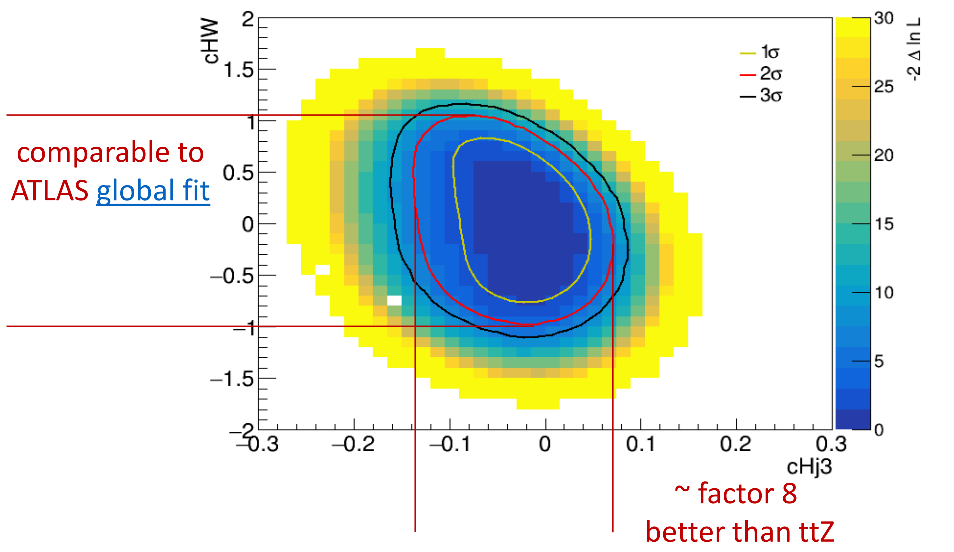


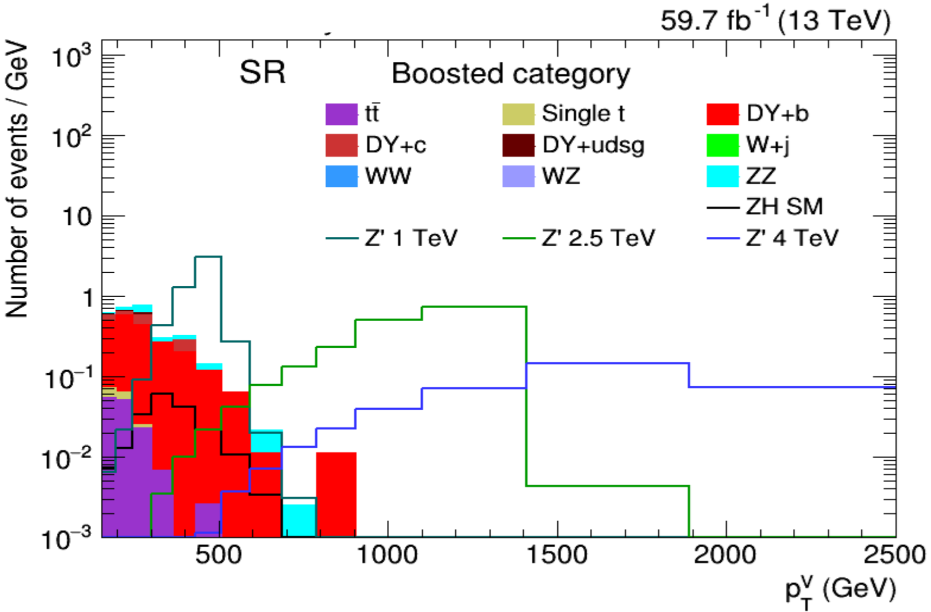
SMEFT analysis of Higgs-strahlung

- Extract BSM effects with Boosted Information Tree
- 1-D & 2-D constraints on ~8 SMEFT coefficients
  - learn separately the linear & quadratic terms





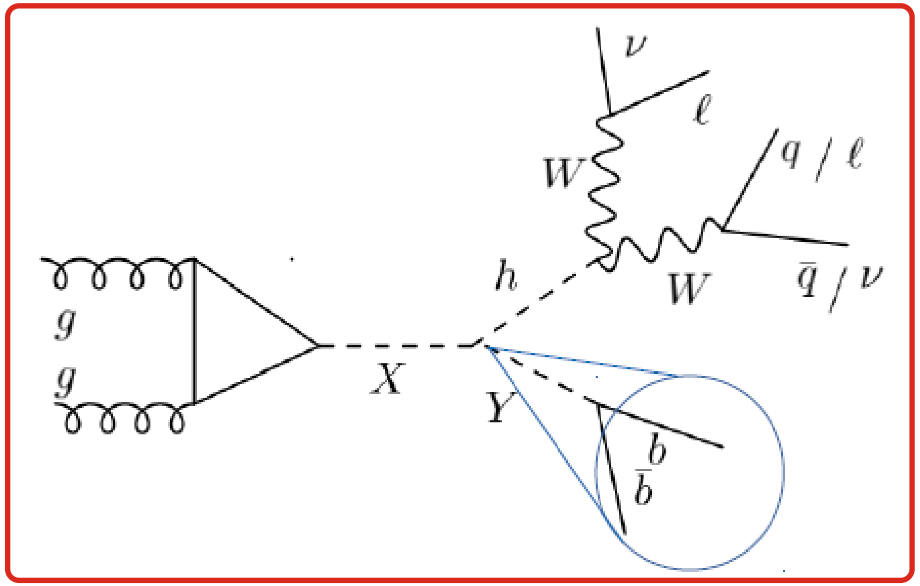




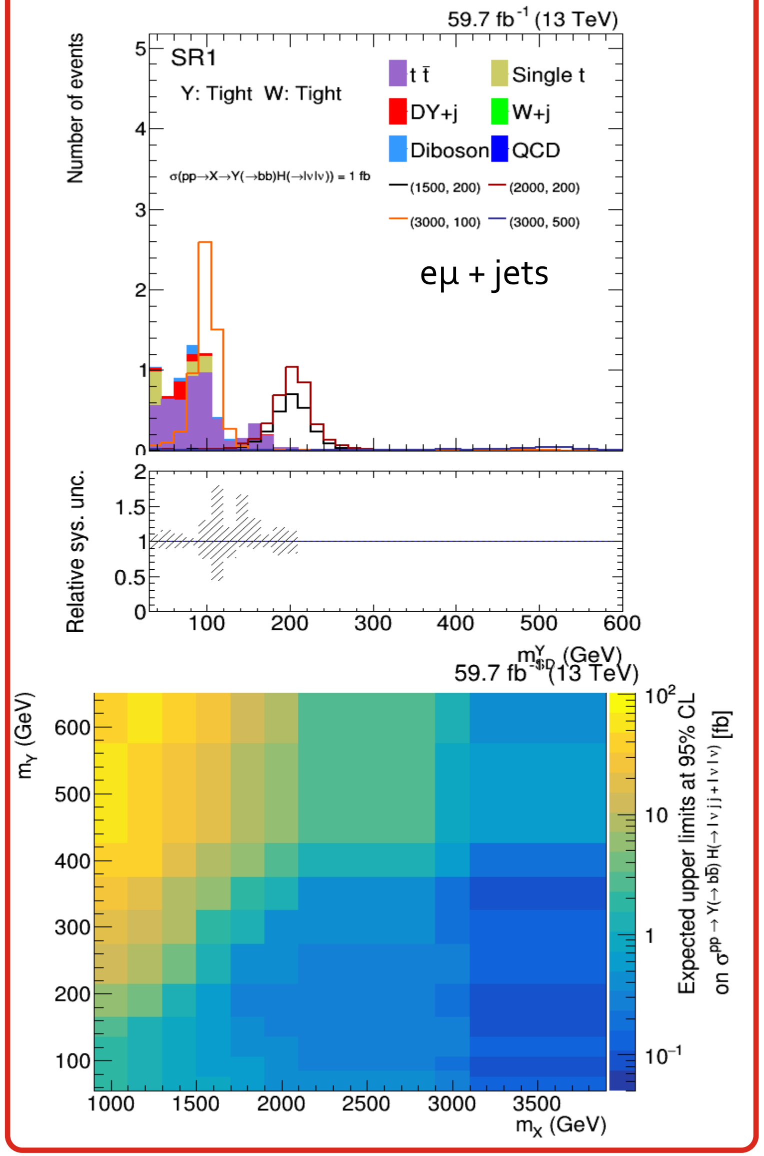
- Status
  - Finalize systematic uncertainty
  - Finalizing extracting of SMEFT constraints
  - FWF proposal: Two rounds with reviewers
- Also sensitive to UV model (Z′ production)

Search for X→ Y (→ bb) H (→ WW*)

- Resonant search for extended Higgs sectors
  - 3 CP-even Higgs bosons - X, Y & SM h
  - Motivation: NMSSM or 2-real-singlet-scalar SM extension (TRSM)



- 1ℓ+jets,2ℓ+jets ,
  with TFIR Mumbai
- Technology:
  mass-decorrelated ParticleNET tagger
- Status:
  - Sensitivity estimation with simulation & relevant systematics
- Work in progress: Background estimation using data



(Seeds for) future activities

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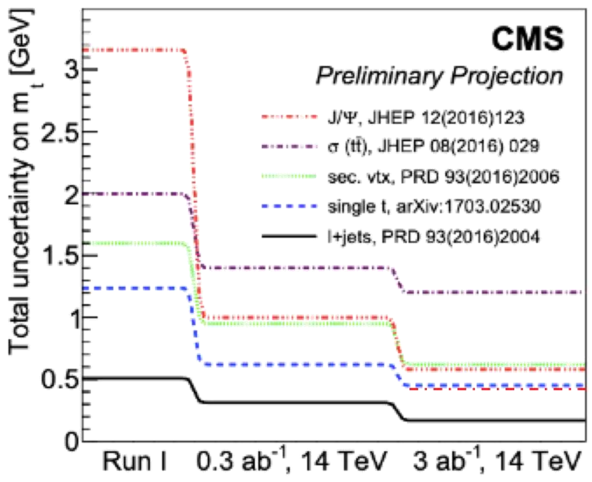
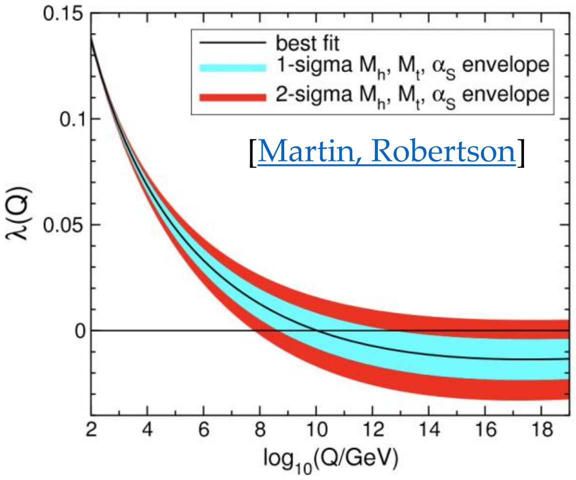
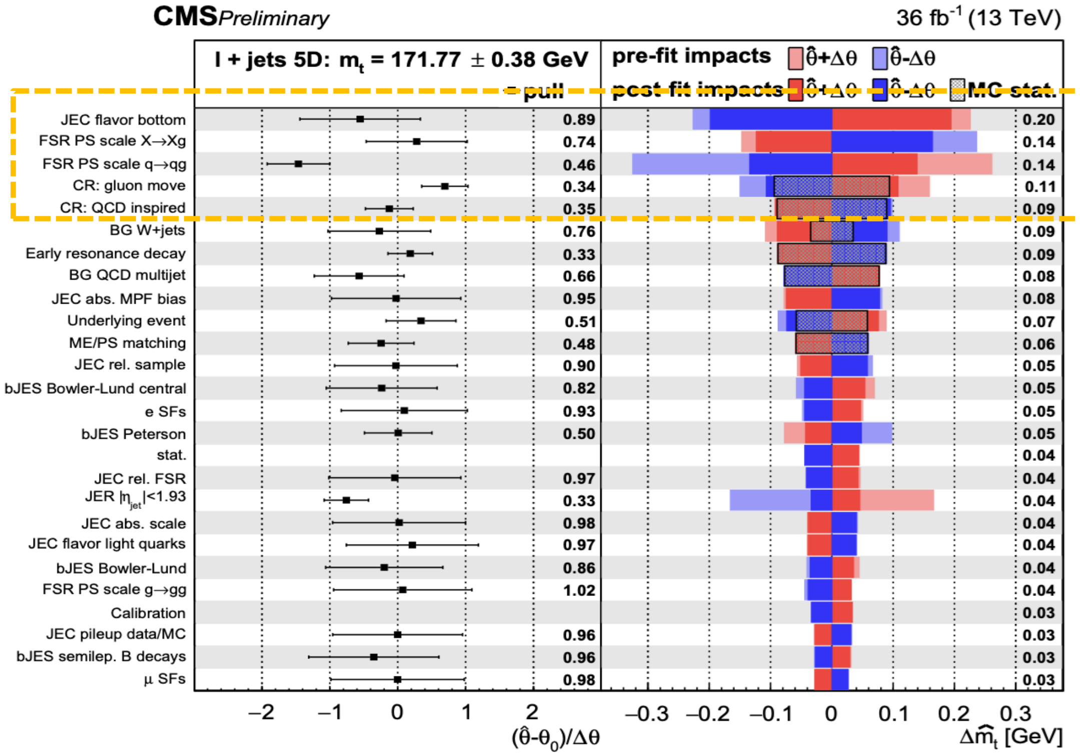
Top quark mass

- Precision M_t measurement is *HL-LHC target*
- HL-LHC projected uncertainty of 0.1%
  - with 1% of HL-LHC, only a factor of 2 away
  - Winning experimental strategy: resolved jets & in-situ JEC calibration on m_W
  - 380 MeV with 5D LL method [TOP-20-008, no involvement from HEPHY]
  - Exp: uncertainties:
    - response differs for light jets and b jets
    - modelling uncertainties
    - plateau for any m_W calibration strategy
  - NOT a pole mass measurement!
    - O(1GeV) non-perturbative uncertainties Review by A. Hoang (UNIVIE)
- Further improvements require *strategic change*, while building on what is known



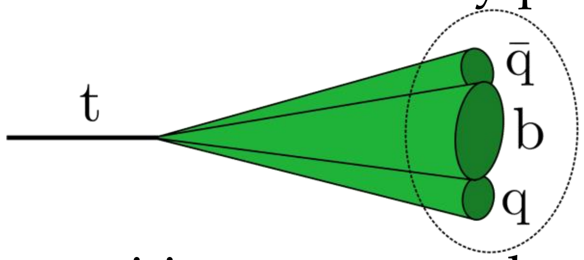




§

M_{jet} in boosted top quark decays

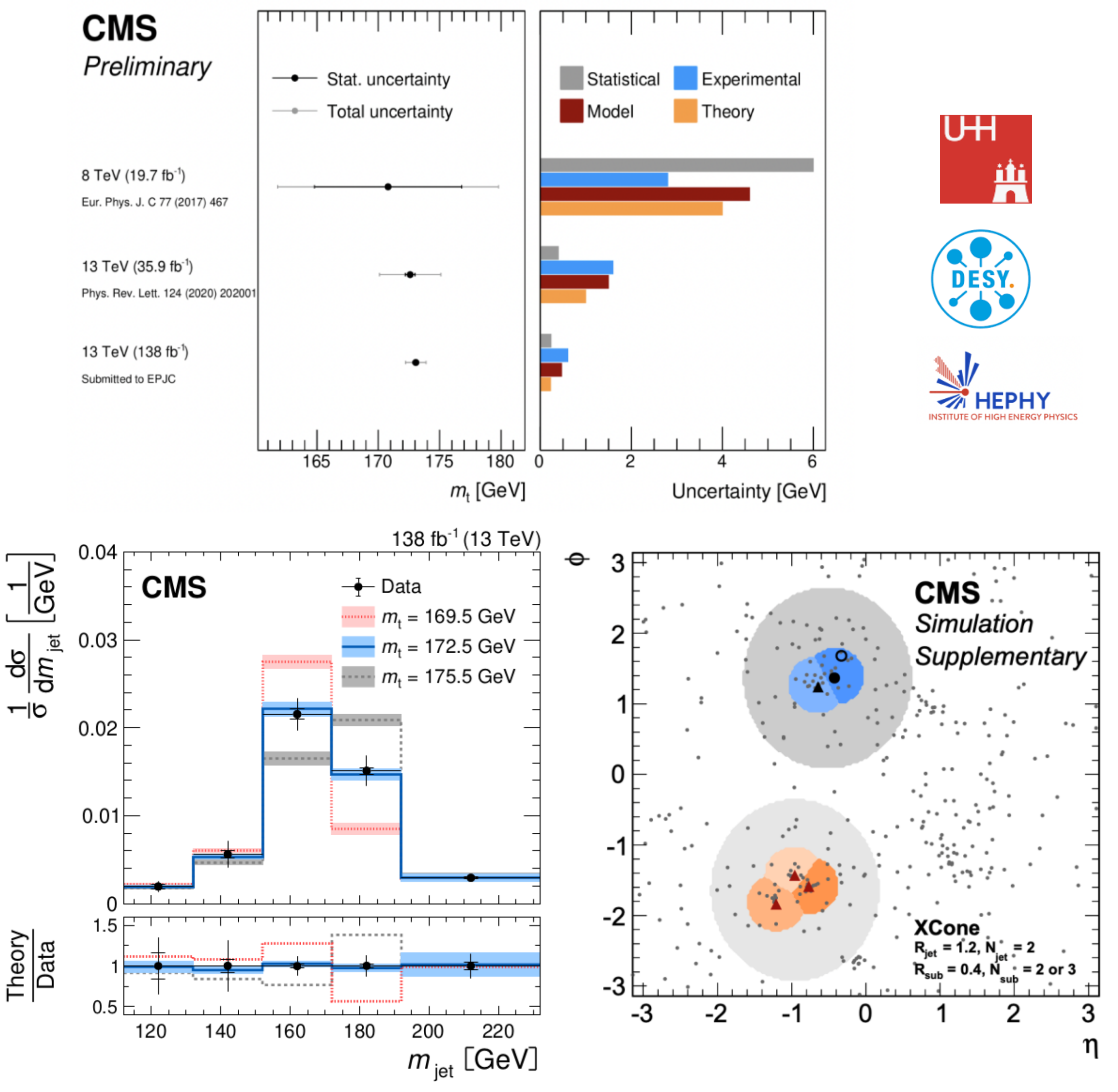
- Top quarks boosted → decay products merge



- Jet mass sensitive to top quark mass M_t
- Measurement thought impossible after Run I
  - Careful calibration of jet mass scale and FSR modelling improve sensitivity to 800 MeV

$m_t = 172.76 \pm 0.81$ GeV

  - [EPJC submitted], with Hamburg & DESY
- Jet mass (XCone) can be calculated *analytically* and allows an extraction of pole mass
  - Theory phase space (p_T>750) accessible at HL-LHC (at the moment p_T>400)
  - Can improve on strategy with *track-based* measurement



CMS upgrades for HL-LHC

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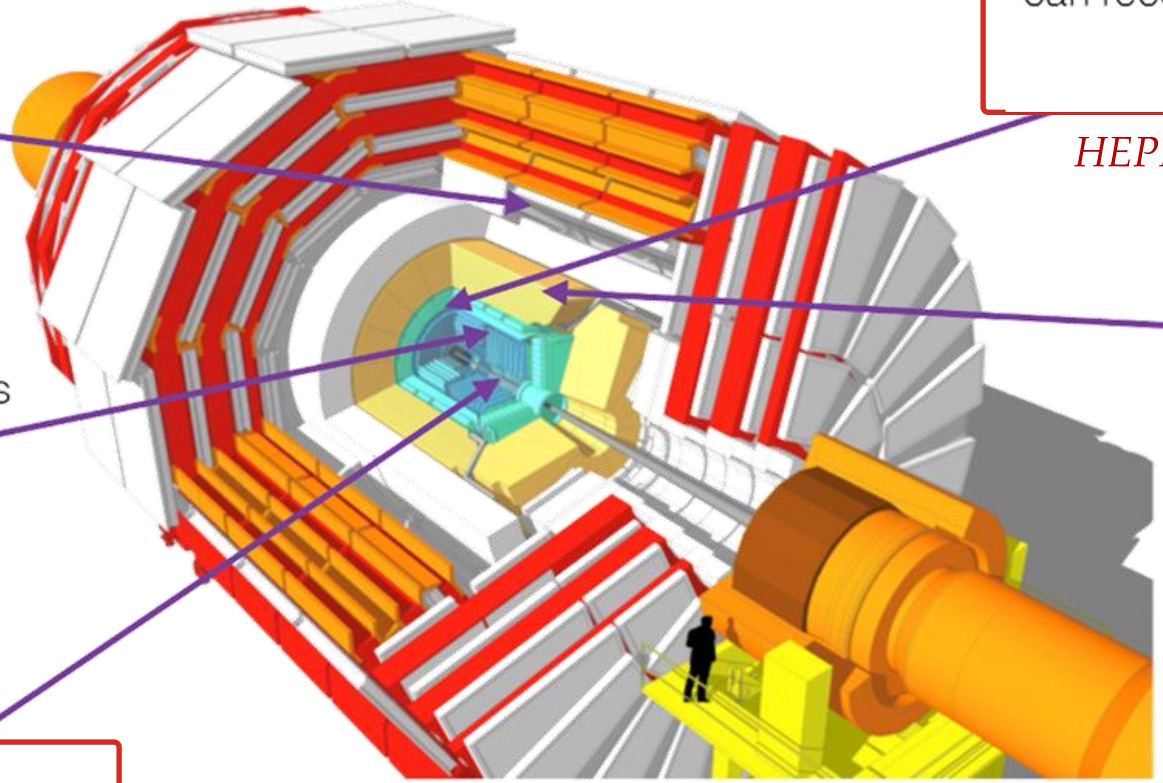
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

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]

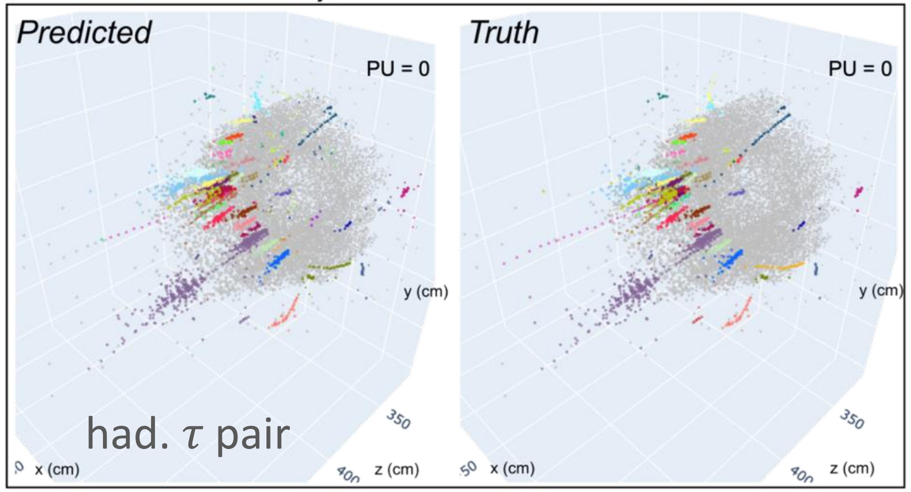
HEPHY Tracker/HGCal group

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]

New opportunities at HL-LHC

- HEP progress often tools-driven
- High-granularity calorimetry a major opportunity on the +10 years timescale
  - Resolve shower particles 200 PU



- Run-4 opportunities building on all the HEPHY strengths
  - Resolve hadronic BSM effects using state-of-the-art ML
    - Exploring VBS in 1ℓ with spatially oriented substructure
    - graphNNs learning SMEFT effects in hadronic final states
    - many more
  - Start early with building expertise on reconstruction and systematics
  - new PhD (CERN Austrian doctoral program) with E. Brondolin (CERN) on HL-LHC reco of τ leptons