Massachusetts Institute of Technology

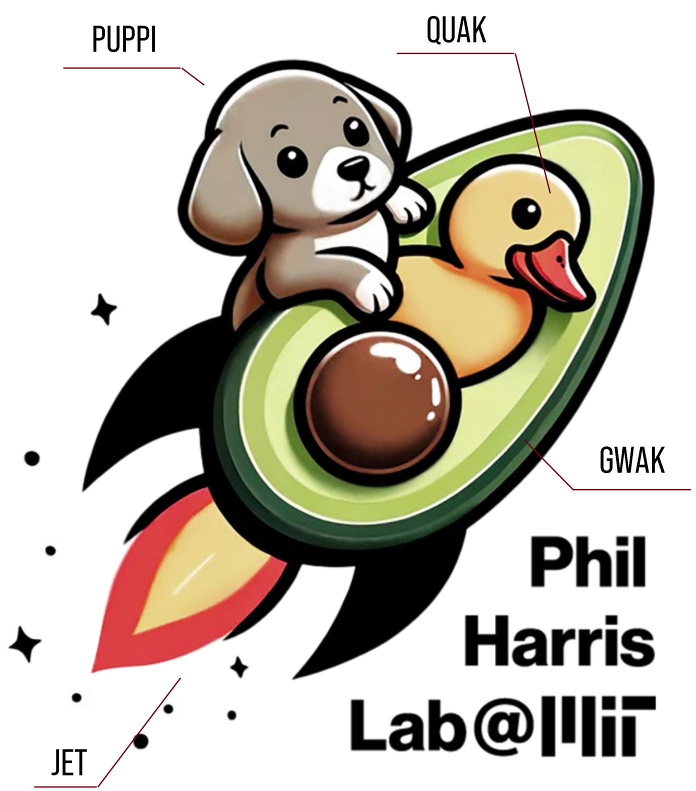
High p_T Higgs Probes of New Physics

Overview of recent searches at CMS

Andrzej Novak

8 Oct 2024

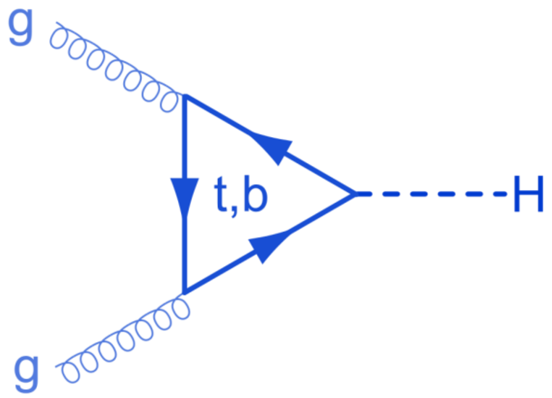
DOE HEP Review



Higgs Boson Production at the LHC

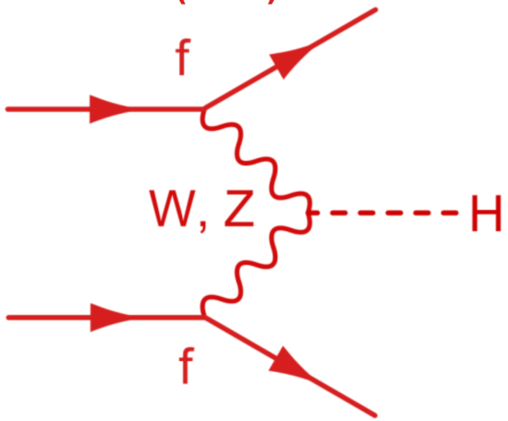
- Higgs boson production initiated by different proton constituents
  - Different modes probe different couplings
- Gluon fusion is the statistically dominant channel…

Gluon fusion (ggF)



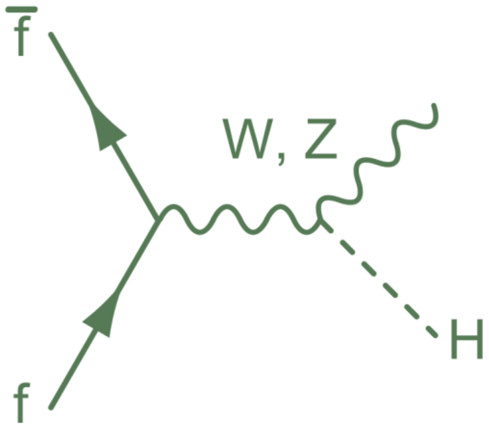
σ(13 TeV) = 48.5 pb

Vector boson fusion (VBF)



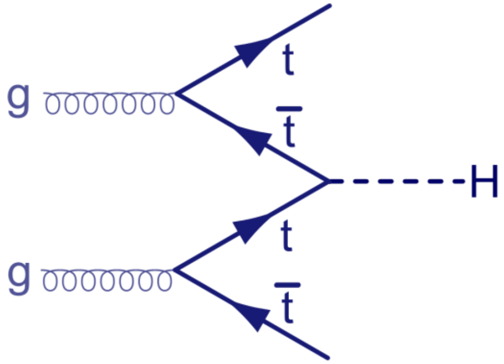
σ(13 TeV) = 3.8 pb

VH



σ(13 TeV) = 2.3 pb

ttH



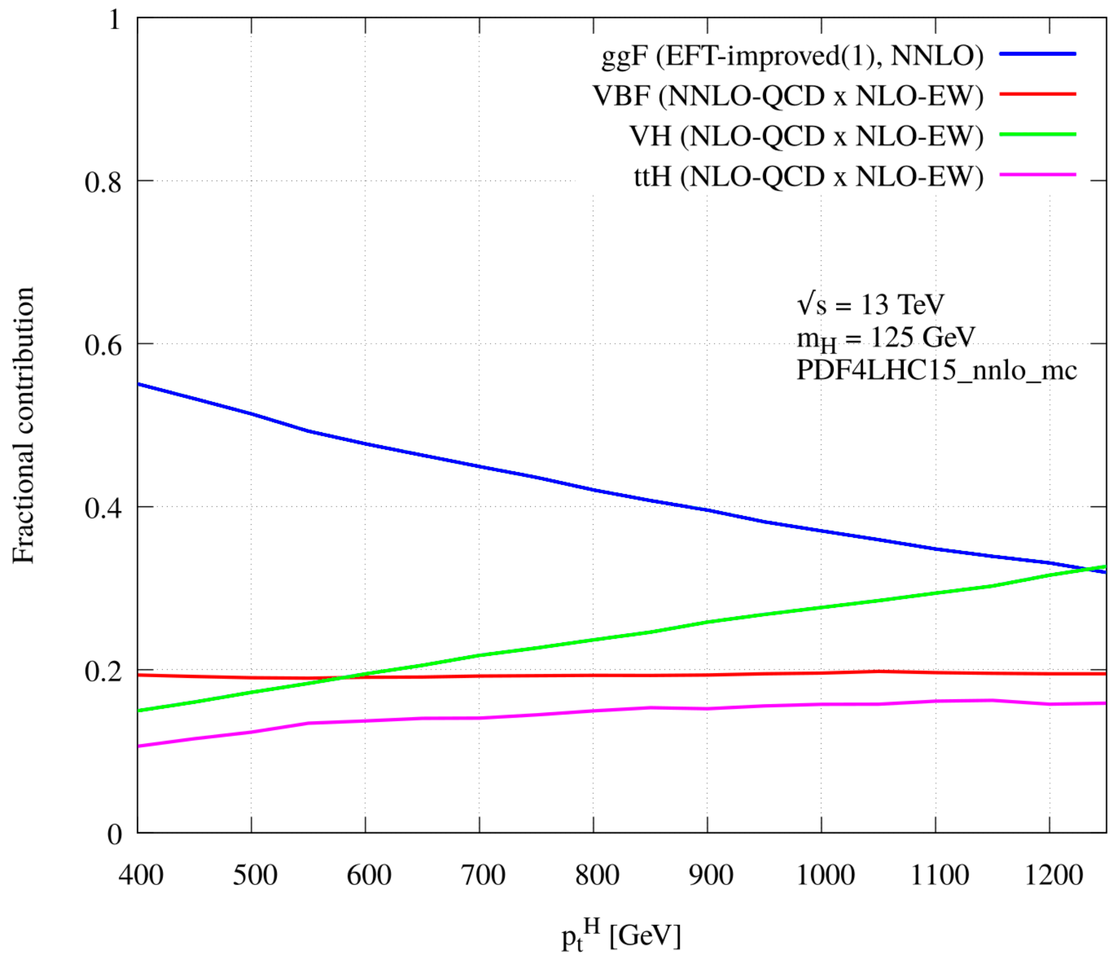
σ(13 TeV) = 0.5 pb

Higgs Boson Production at High p_T

- ~~Gluon fusion is the dominant channel~~… **Or is it?**

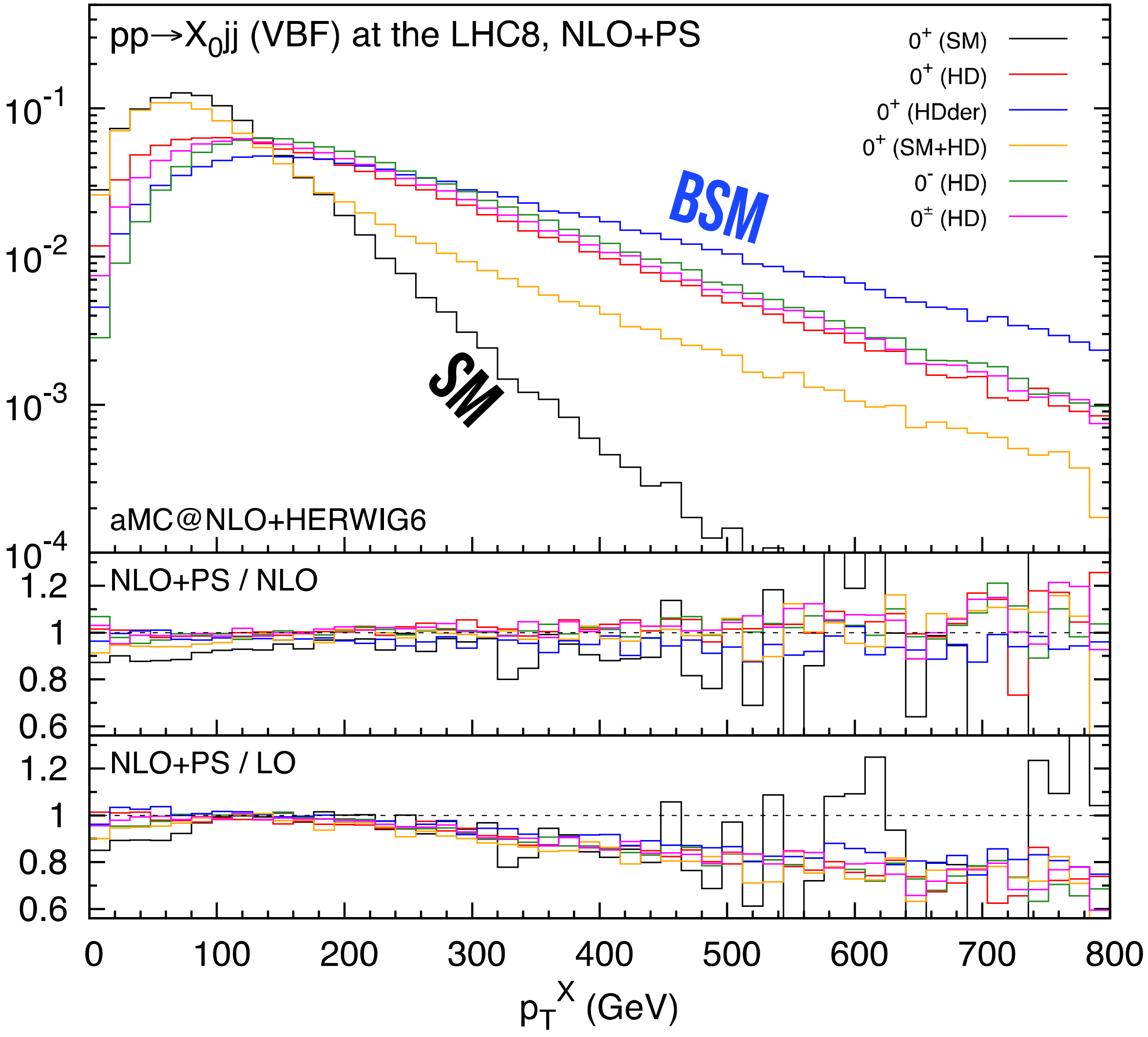
- p_T spectra differ between production modes
- Inclusively:
  - ggF = 88%, VBF = 6.9%, VH = 4.2%, ttH= 0.9%

- At p_T = 800 GeV:
  - ggF = 42%, **VBF = 19%, VH = 26%,** ttH= 13%
  - Gluon fusion accounts for less than half



Higgs Boson Production at High pT … is Interesting

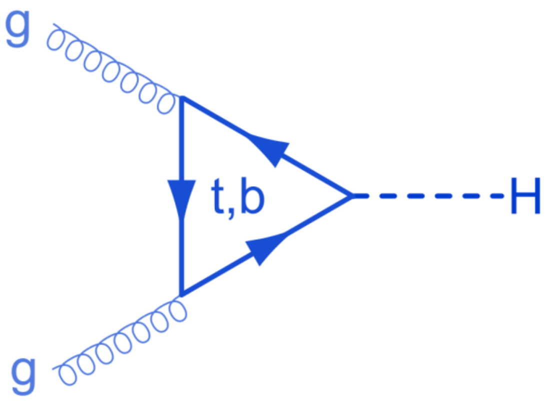
arXiv 1311.1829



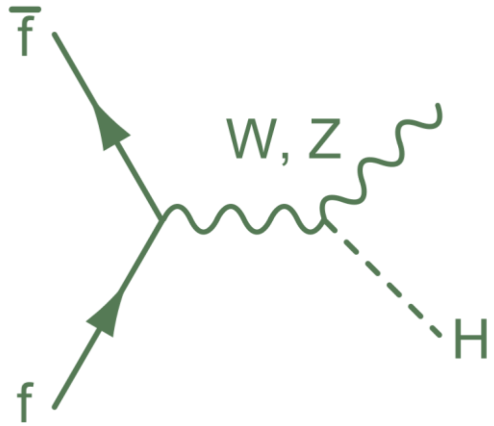
- Not yet well measured
  - Difficult due to decreasing statistics.
- New physics can modify the pT distribution
  - Is the Higgs a fundamental particle?
  - Best visible in the tails
- Does the Standard Model still describe Higgs interactions in this regime well?

Detecting Higgs –Statistical Power vs Purity

Gluon Fusion



Higgs Strahlung



x 20

Premise:

- Largest Higgs production cross-section
  - $\sigma(pp \rightarrow H)$@13 TeV = **48.6 pb**
- Very large QCD contamination: $g \rightarrow qq$
  - $\sigma(pp \rightarrow qq)$@13 TeV $\sim$ **360 000 pb** (HT > 300 GeV)

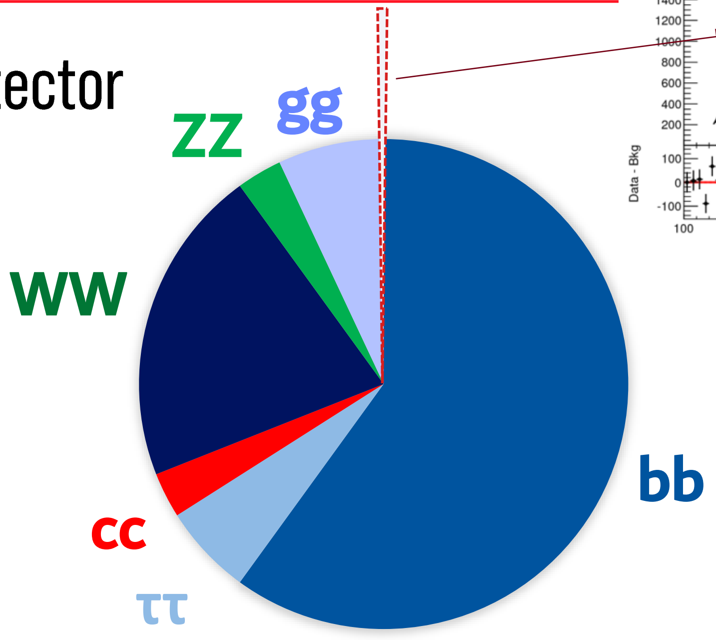
Premise:

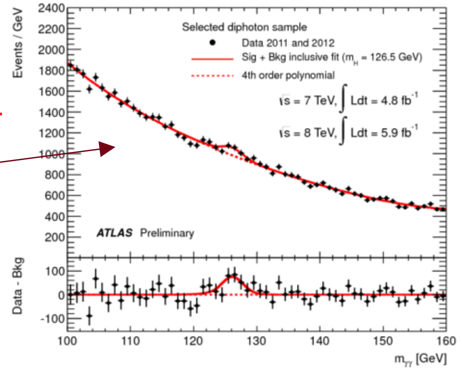
- Low cross-section
  - $\sigma(pp \rightarrow VH)$@13TeV = **2.25 pb**
- Clean signature: trigger on leptons from Z,W
- Mostly V+jets background
  - $\sigma(pp \rightarrow V+qq)$@13TeV $\sim$ **600 pb** (HT > 400 GeV)

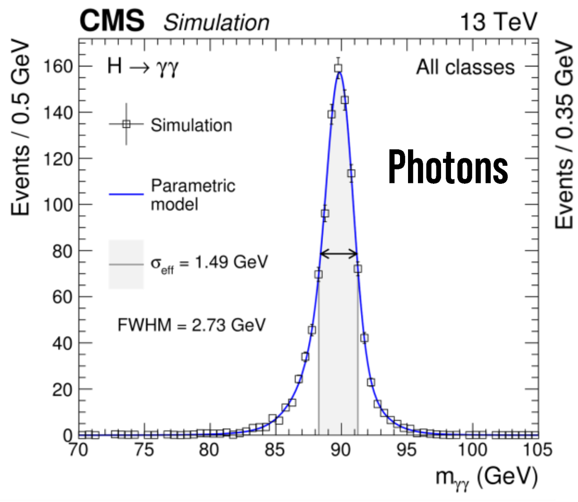
x 600

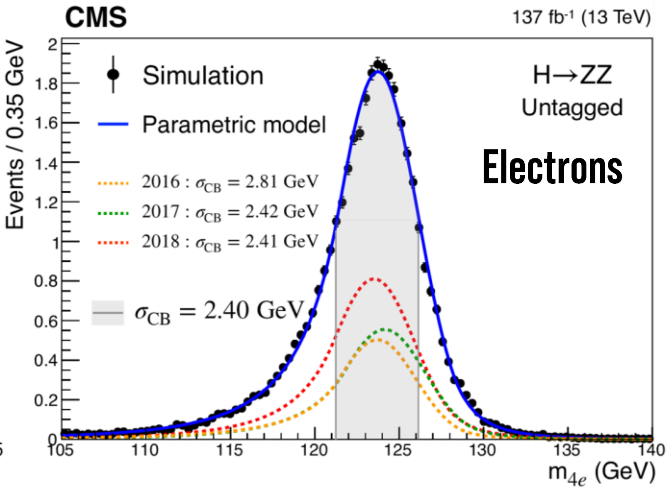
Detecting Higgs –Statistical Power vs Purity in Decays

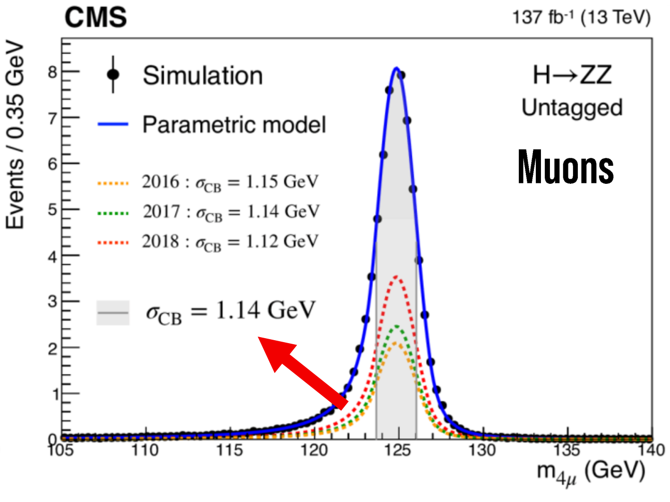
- Bulk of Higgs decays are hadronic – forming **jets** in the detector
- But… jets are *everywhere*
  - ~10^9 fb vs ~10^7 fb for photons @ 7 TeV
- Jet resolution and identification is very *poor

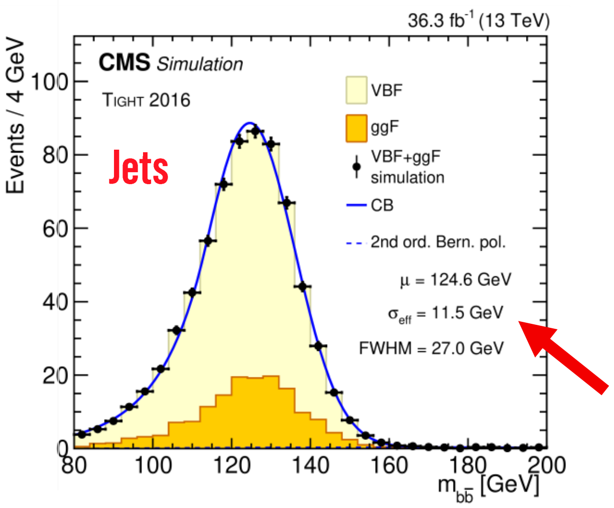






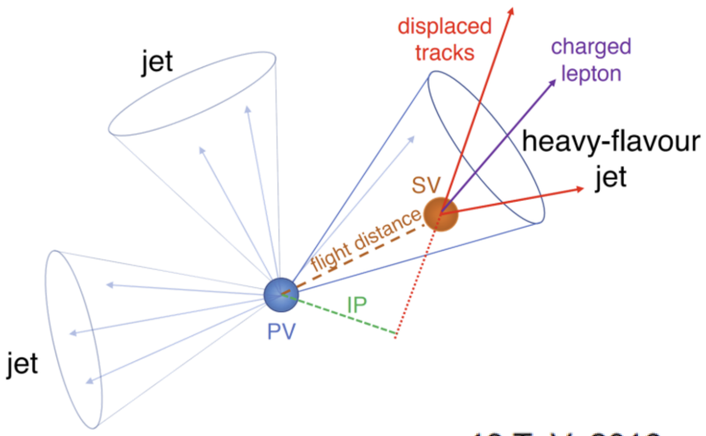


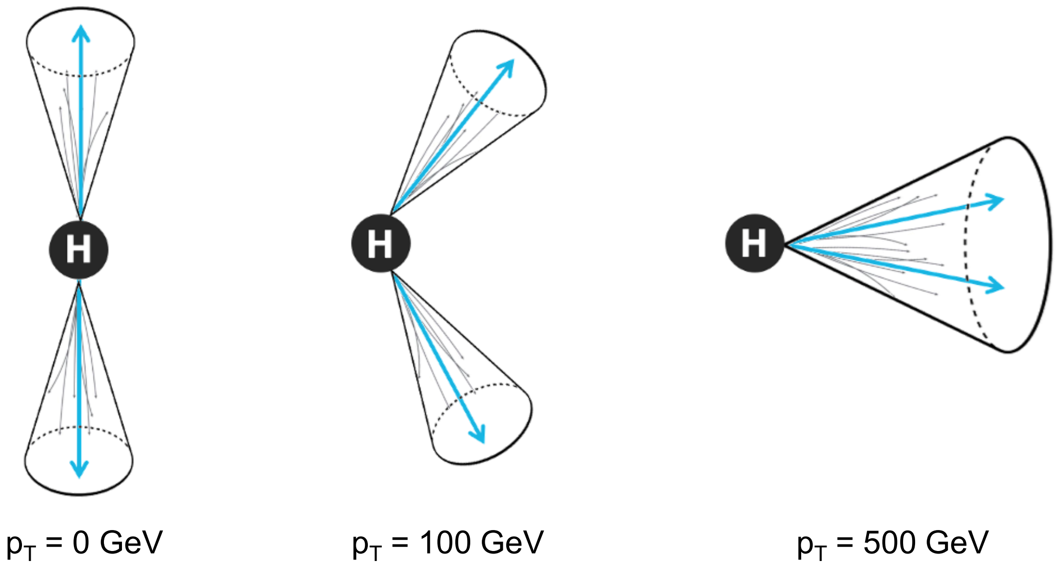


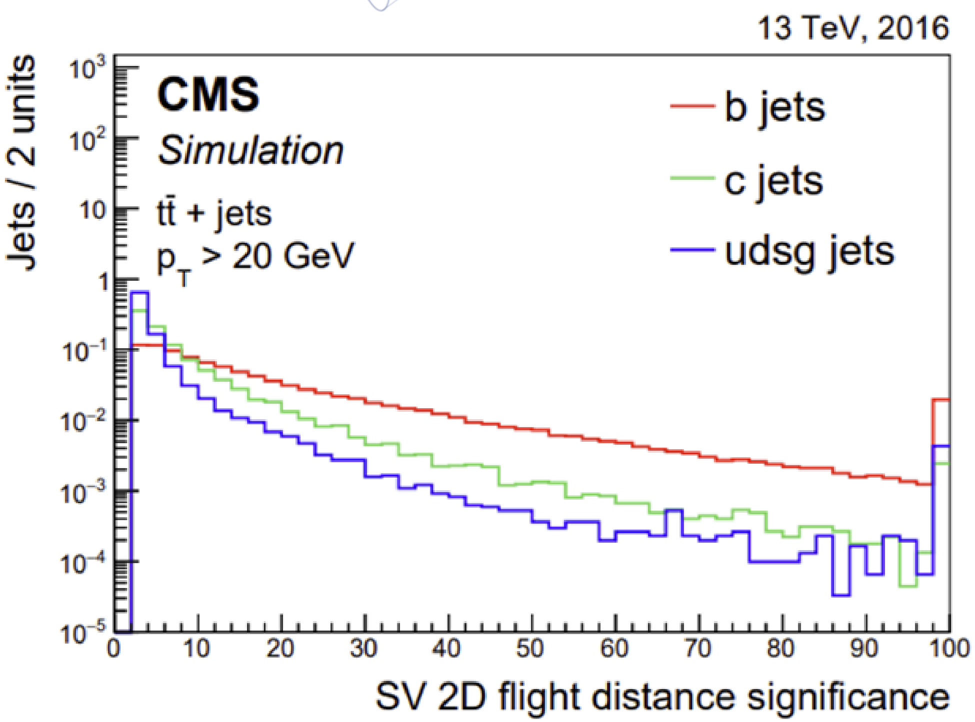


Detecting Higgs – Making Lemonade out of Lemons

- At high p_T, Higgs boson decays products become **collimated**
  - This generates an inherent **jet substructure** that can be used for identification
- Together with **flavor information** provides a strong tagging handle
  - Secondary vertex and displaced track information

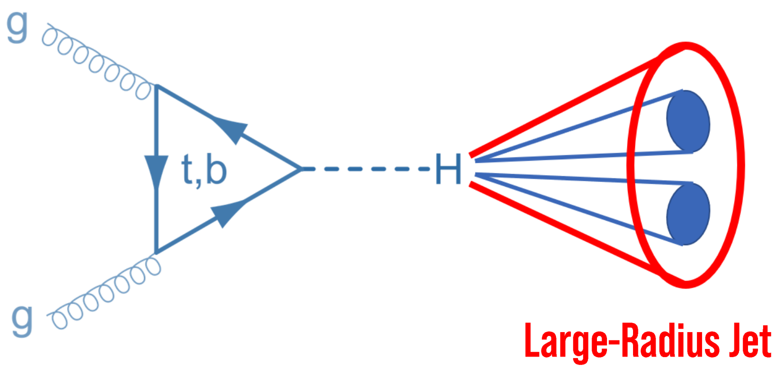




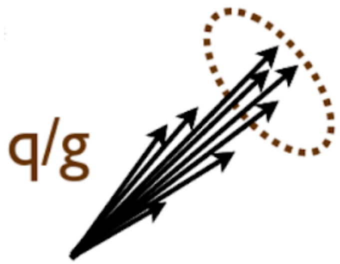


Typical Analysis Strategy

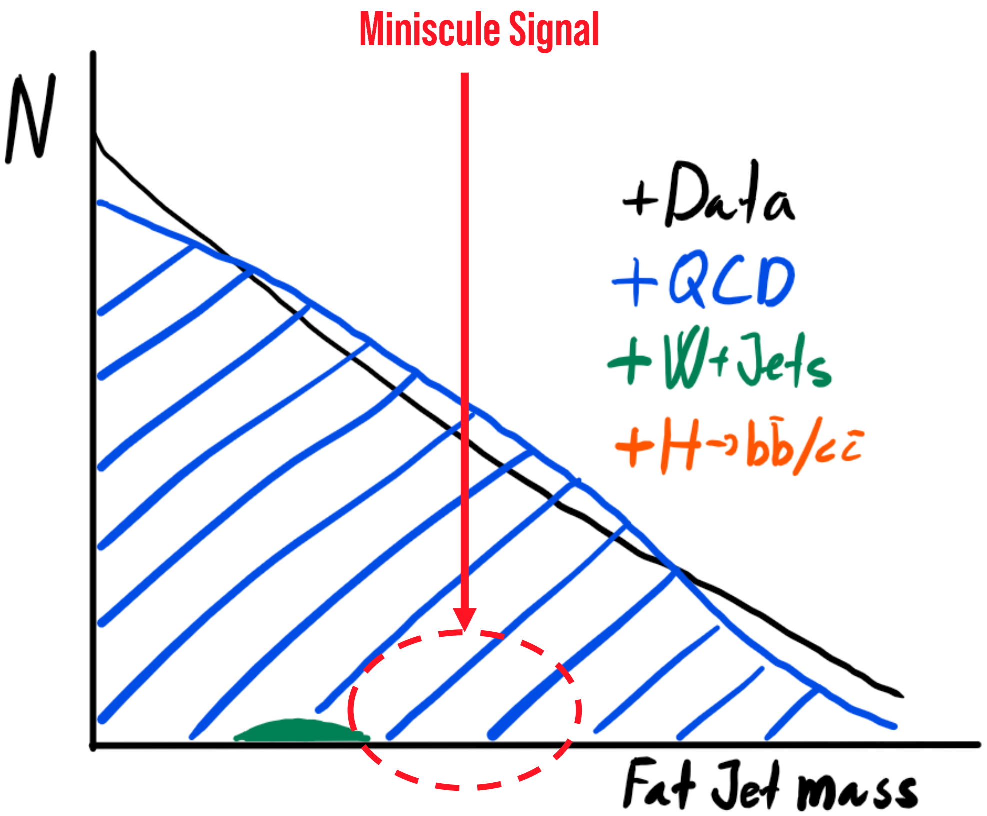
Reconstruction



Jet Identification / Flavour Tagging

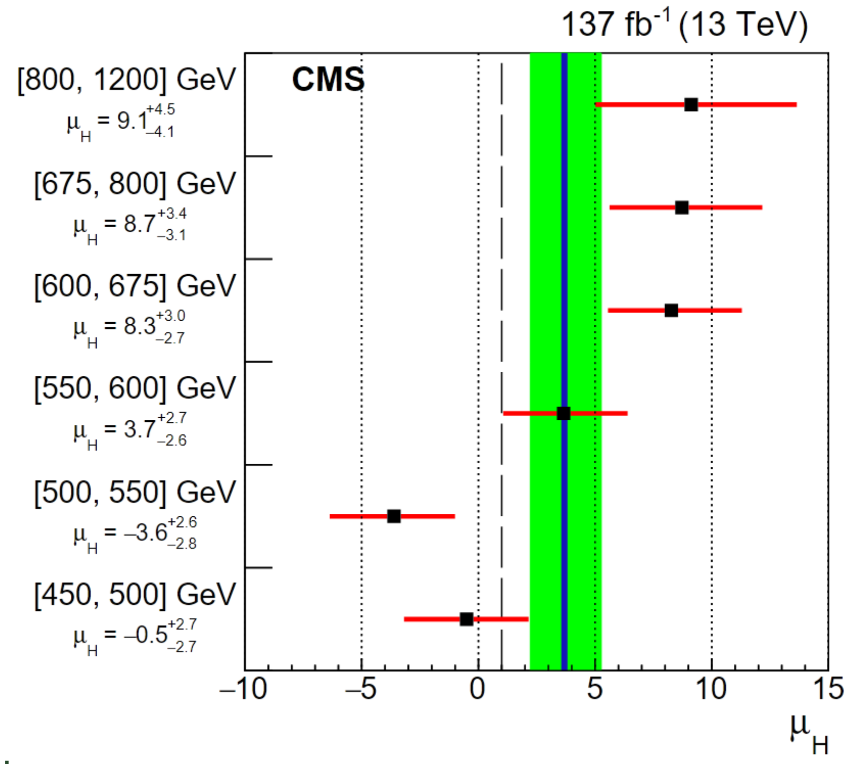


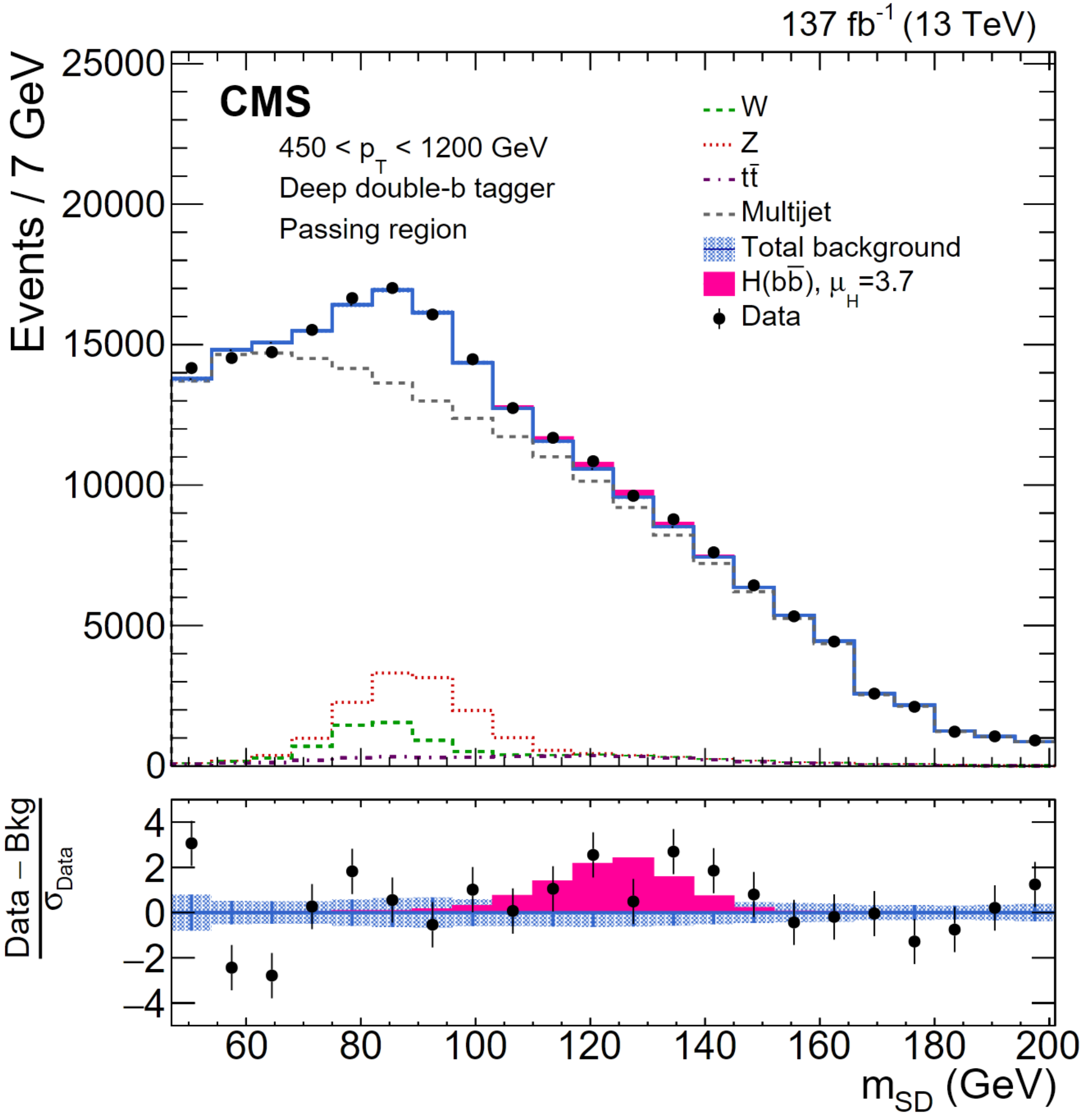
Data-driven Fit



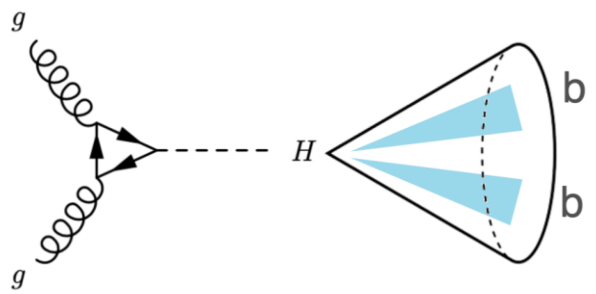
Inclusive High p_T Search ($H \rightarrow bb$)

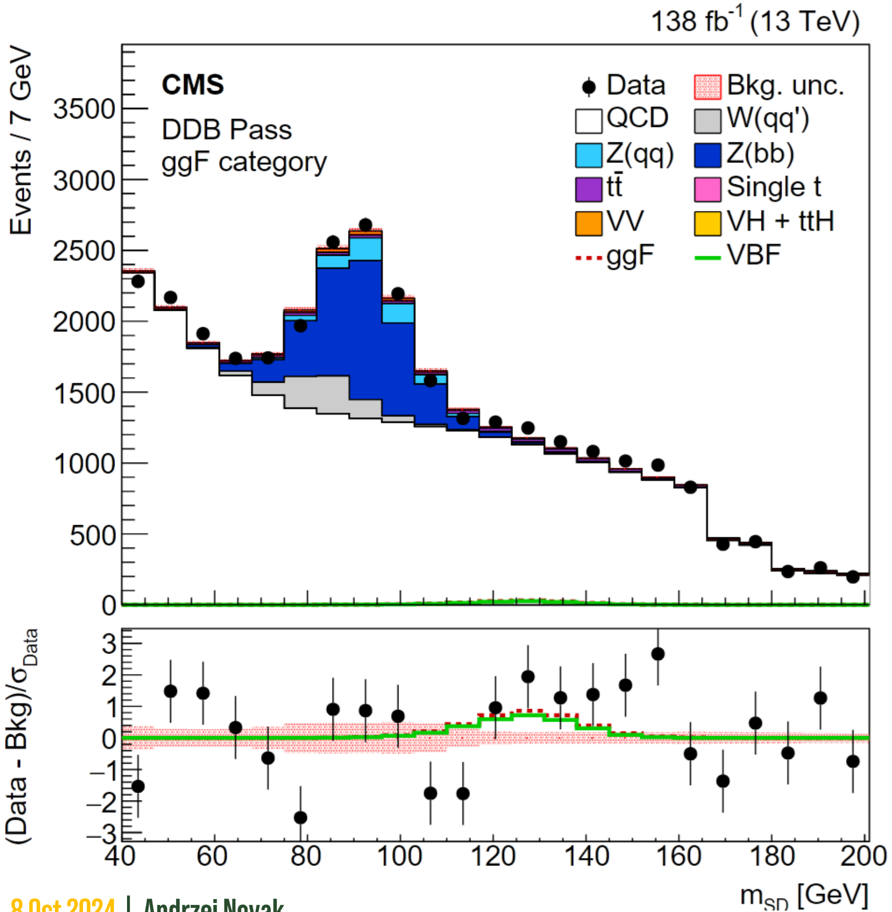
- First full Run2 analysis in this phase space
- Observed a moderate excess – 3.7x SM expectation
  - 2.5 (0.7) σ observed (expected) local significance
- A good first hint to test this space further

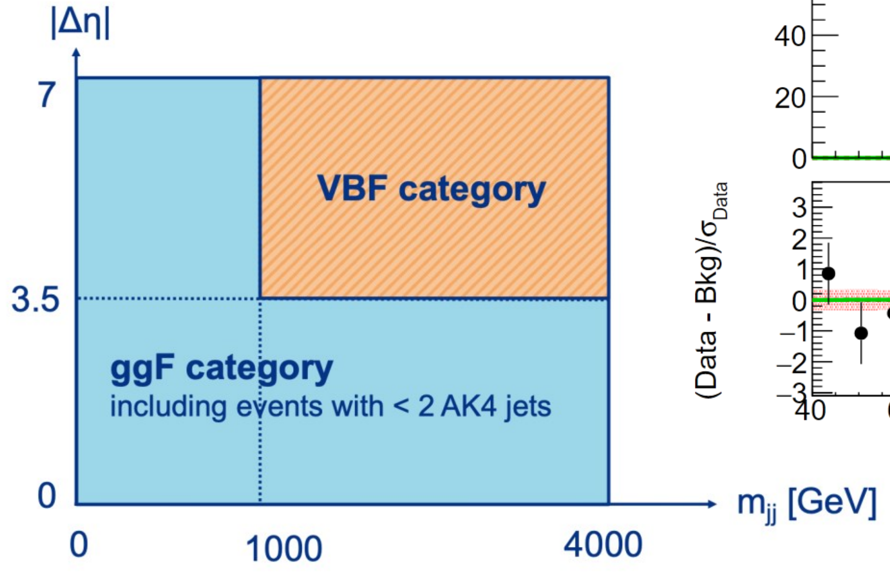


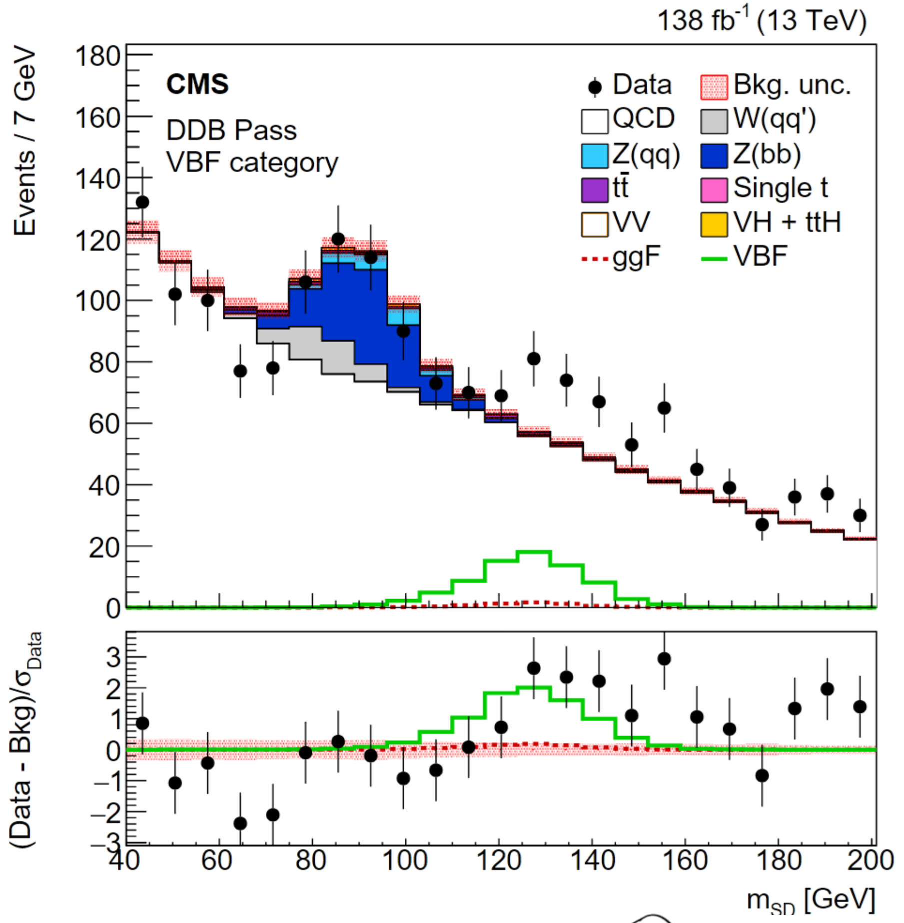


Splitting the Phase Space – ggF vs VBF

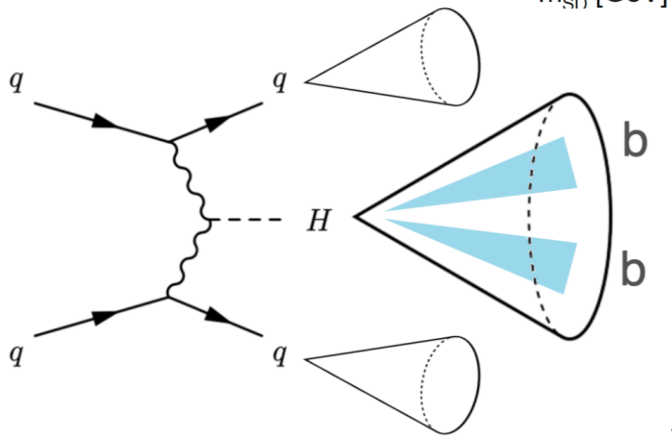






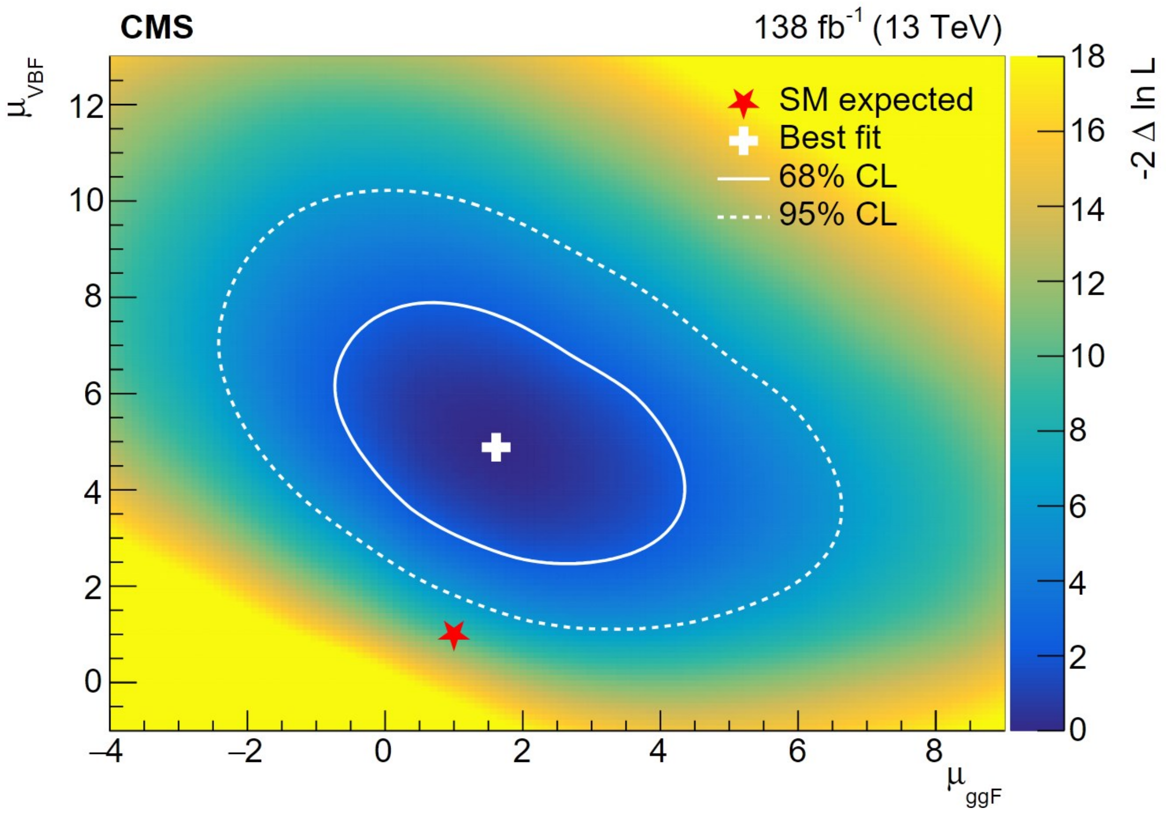


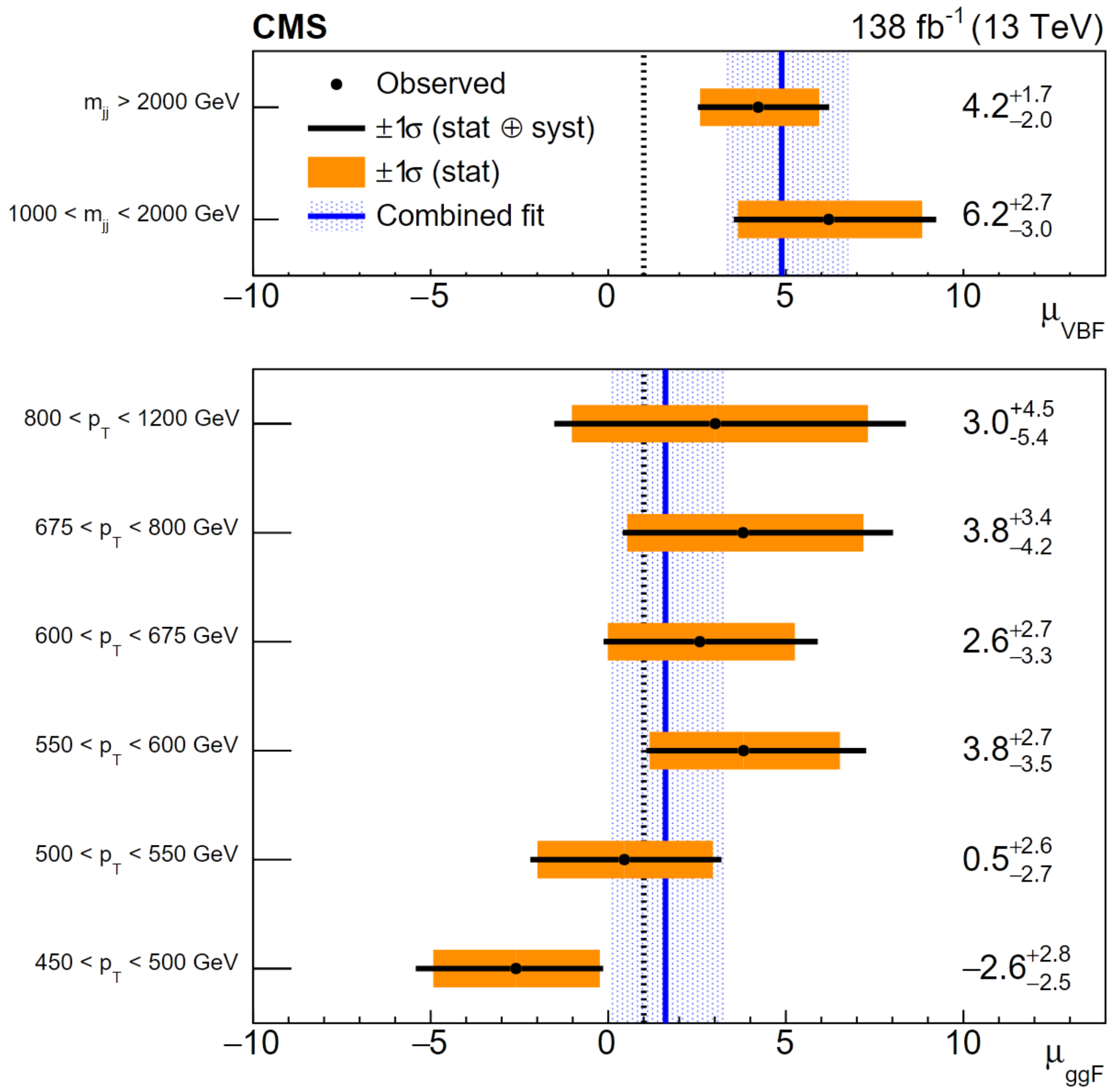
- Reanalysis of the same events



Splitting the Phase Space – ggF vs VBF

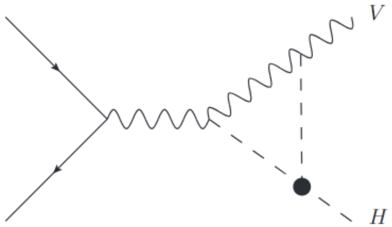
- Excess confirmed
  - Localized in the VBF production mode
  - 3.0 (0.9) σ observed (expected) local significance (VBF)

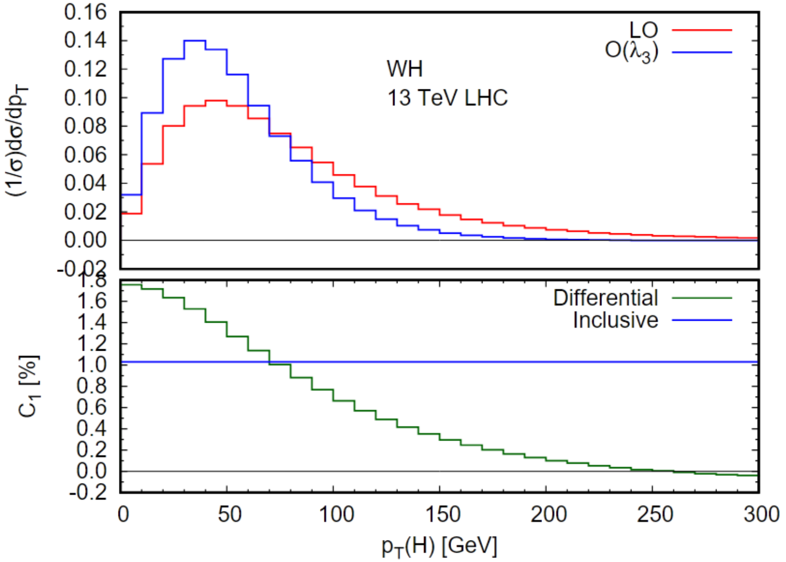


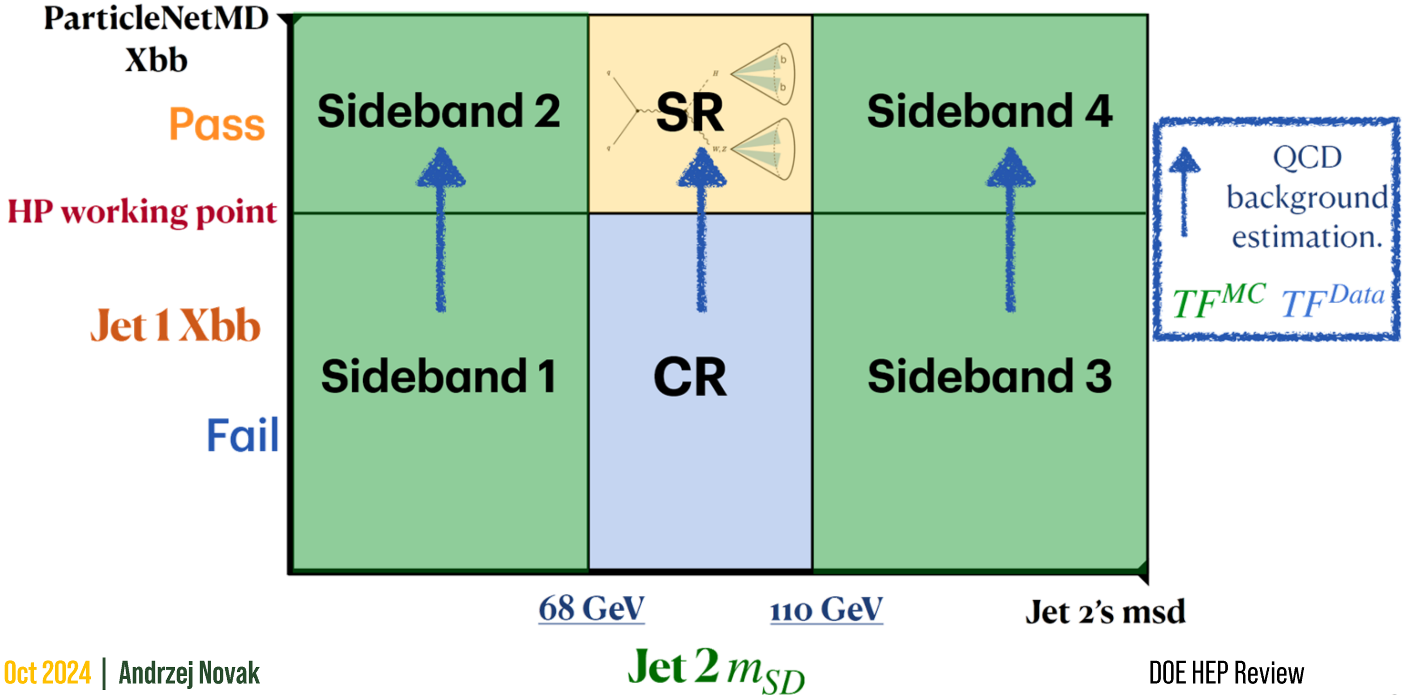


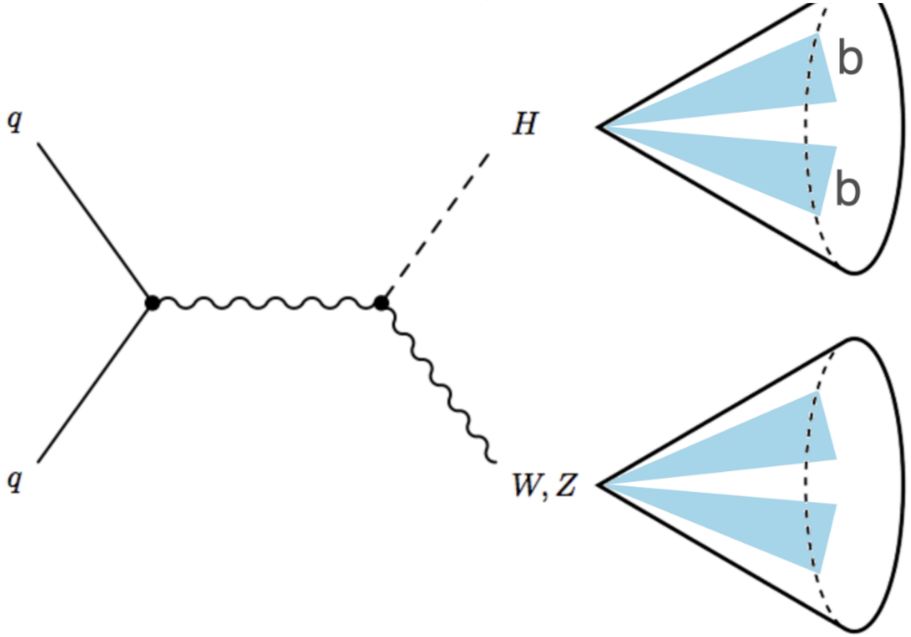
Closer look at Coupling to Vector Bosons – VH

- Higgs coupling is the same in VH and VBF production modes
  - Independent test of the VBF excess (events largely not overlapping)
- An indirect probe of Higgs self-coupling [1]
  - Modification of VH p_T spectrum
- Not yet measured at CMS



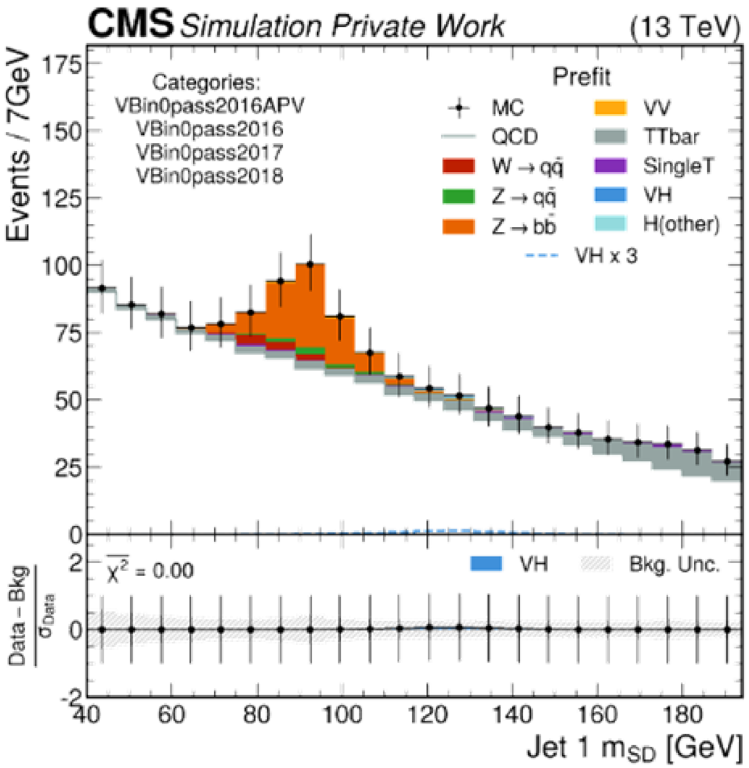


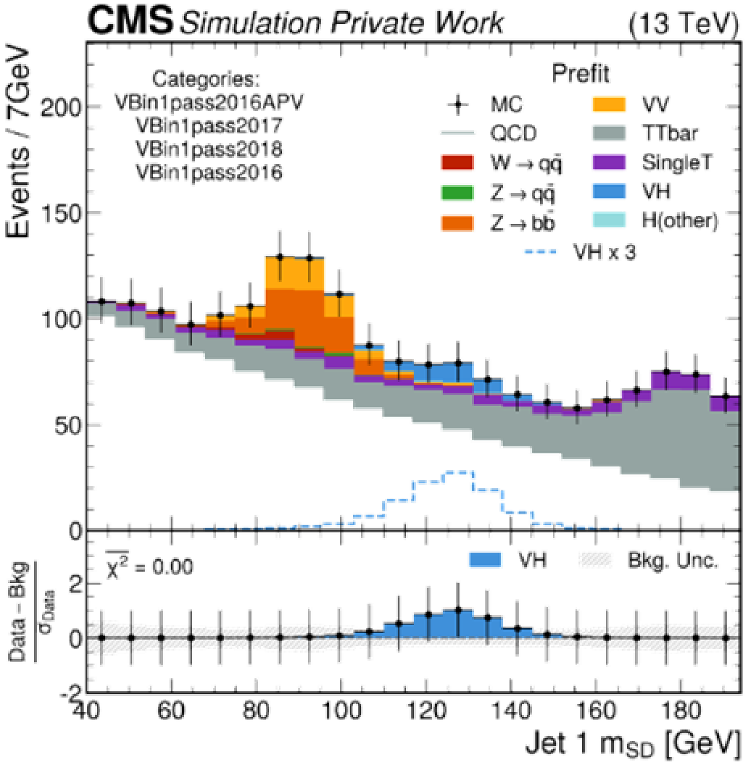


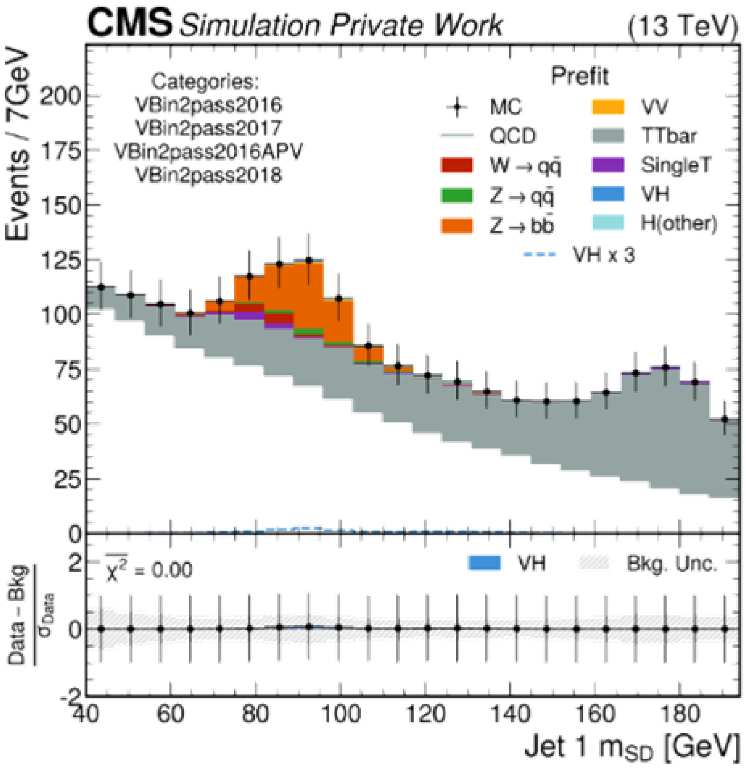


Closer look at Coupling to Vector Bosons – VH

- Jet 2 mass sidebands allow us to disentangle VV from V+jets processes
- Pre-approval talk today in the morning!

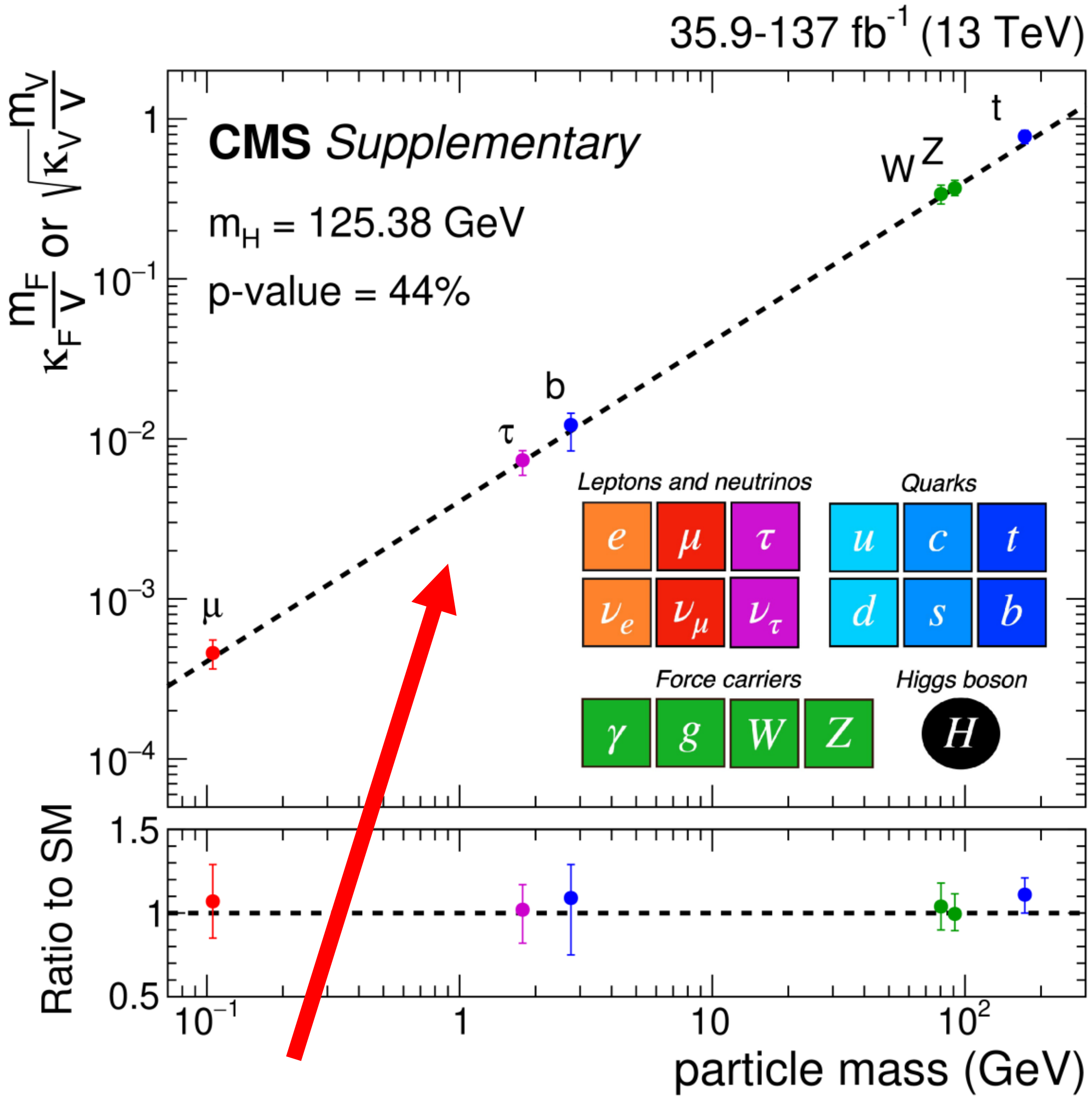






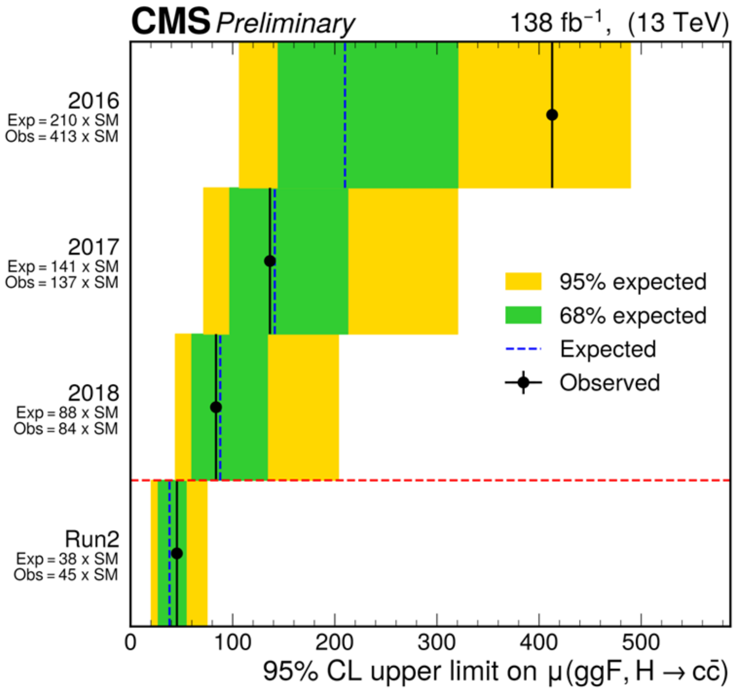
Charm Coupling – Well-Motivated Completionism?

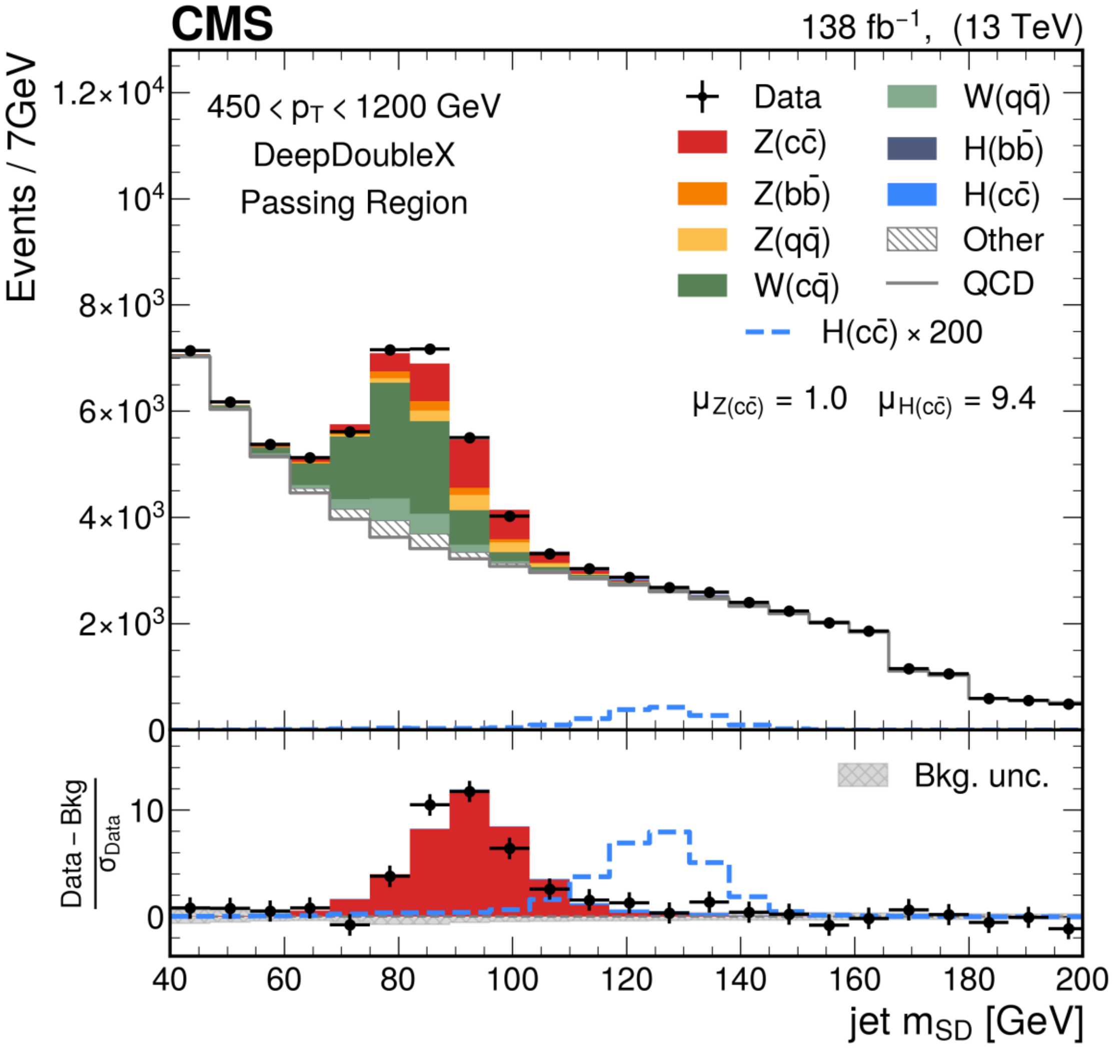
- Complete description of the Higgs boson
  - Observed couplings (~90% of BR)
    - Vector bosons (WW, ZZ)
    - 3rd generation fermions (ttH, bb, ττ)
  - Evidence for 2nd generation couplings
    - H ⟶ μμ
- Next target – **H ⟶ cc**
  - Largest missing fraction of BR
  - Establishing couplings to 2nd gen. quarks
  - Enhancements to couplings would hint at BSM



Inclusive High p_T Search ($H \to cc$)

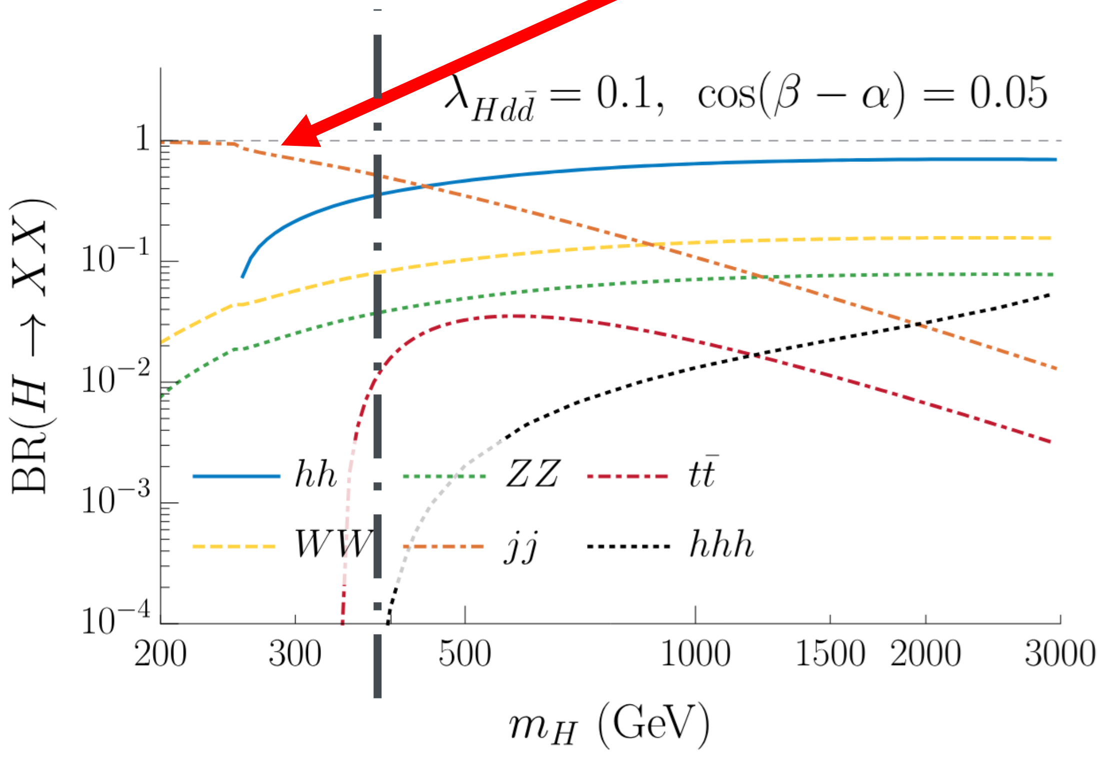
- **First Z → cc observation** at hadron collider
  - Significance >> **5** σ, validation of the analysis method
- H → cc limit **47** (39) x SM@95%
  - First new channel for H → cc since VH searches
  - Statistically limited

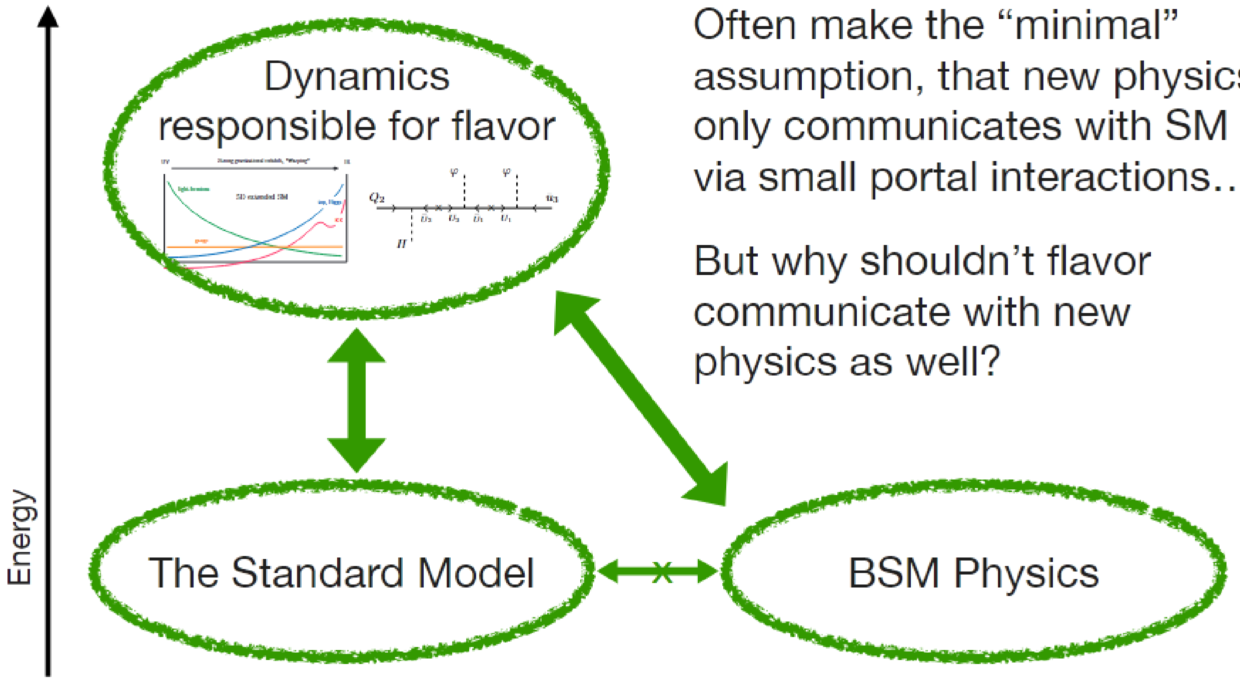




Charm Physics and Low-mass Resonances

- Enhancements up to 3 x κ_c^{SM} not yet excluded by other fits
- Correlated with resonant signatures of new physics
  - For m_H < 400 preferentially decays to di-jets
- Also connects to **Dark Sector**





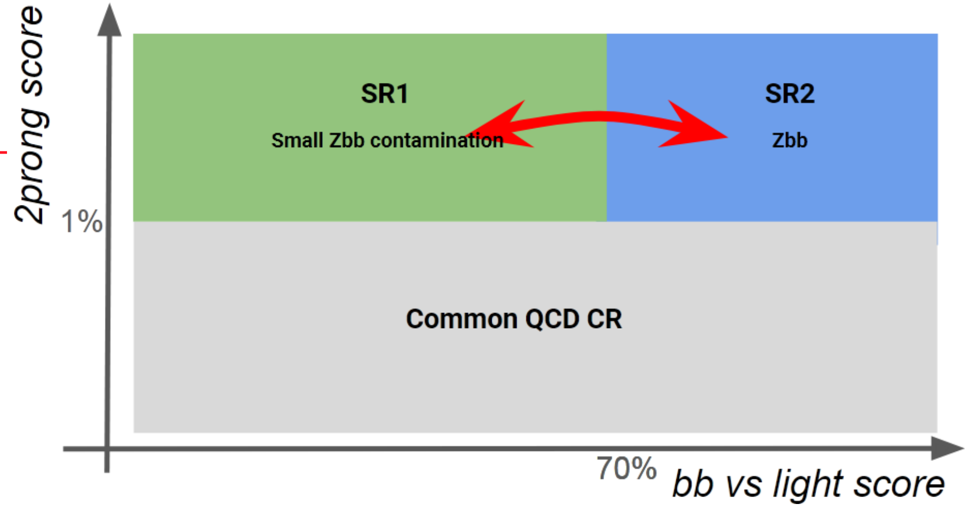
Often make the "minimal" assumption, that new physics only communicates with SM via small portal interactions…

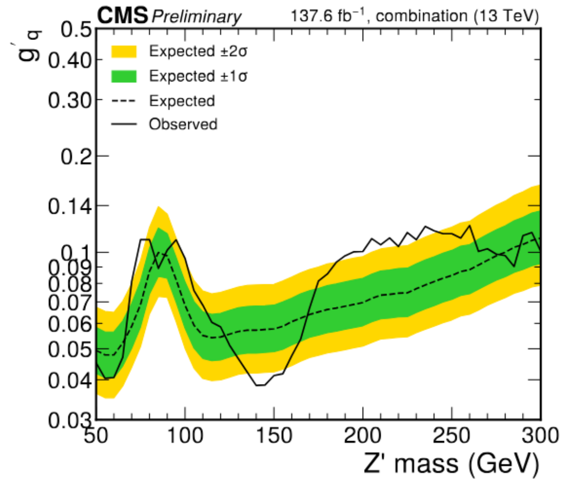
But why shouldn't flavor communicate with new physics as well?

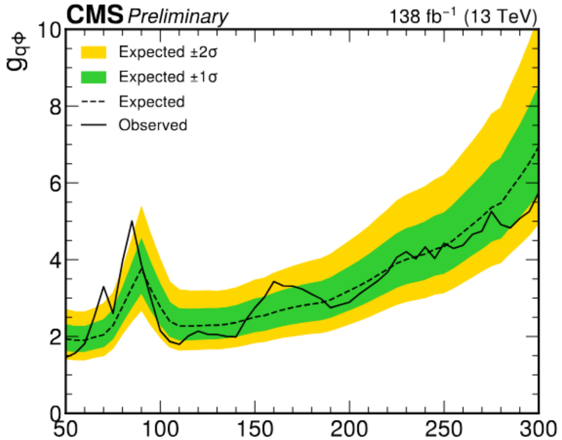
Low-mass Resonances

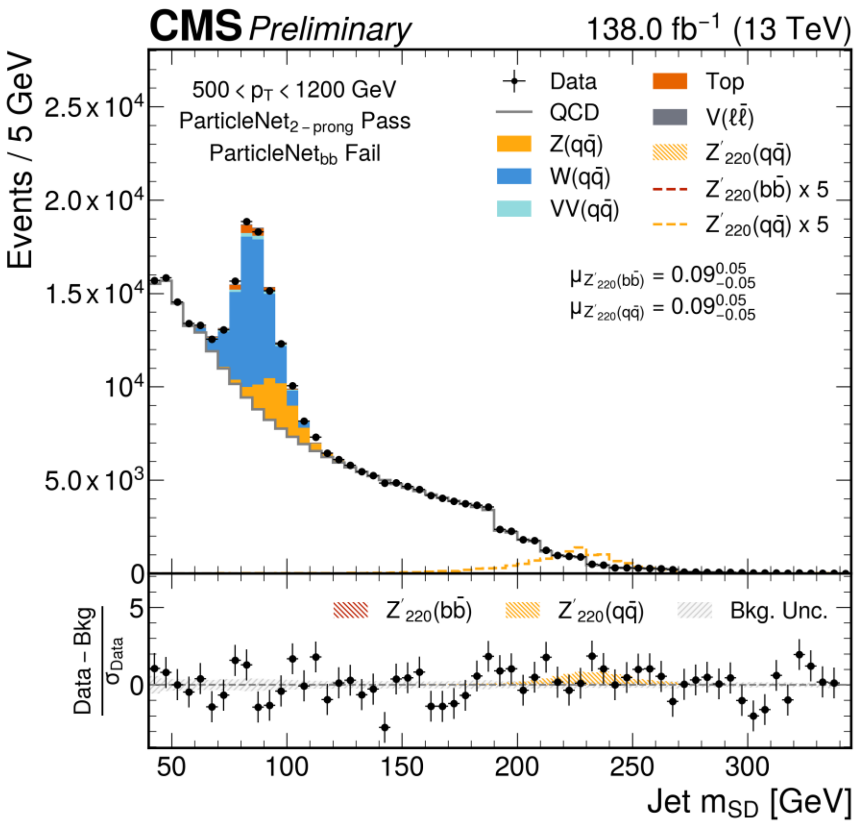
[EXO-24-007](EXO-24-007)

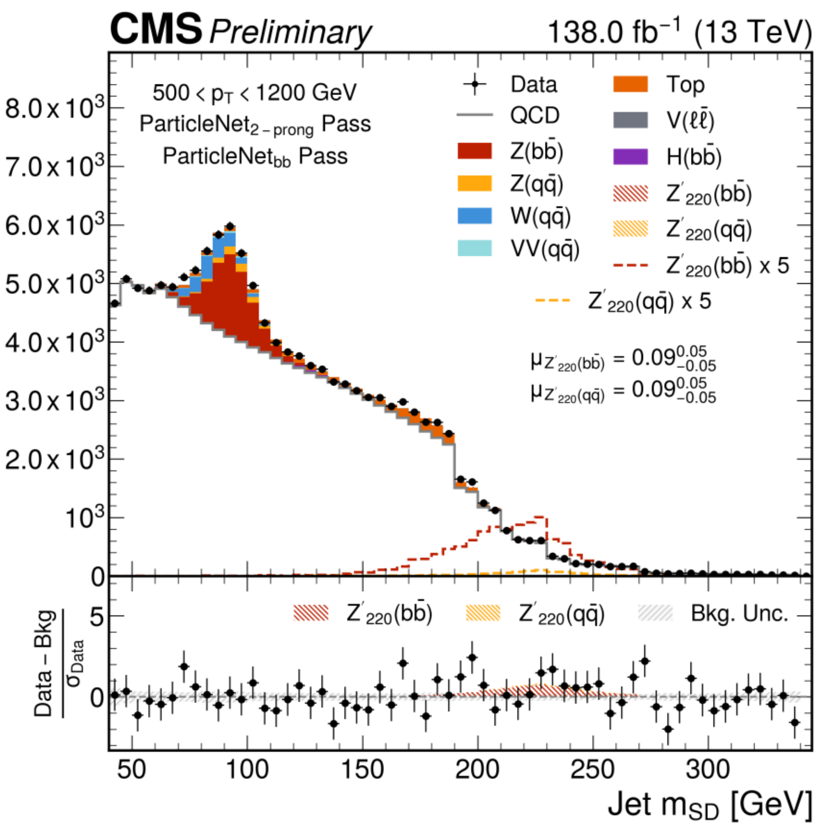
- Same analysis techniques can be applied
- Newly split SR into bb-enriched/depleted



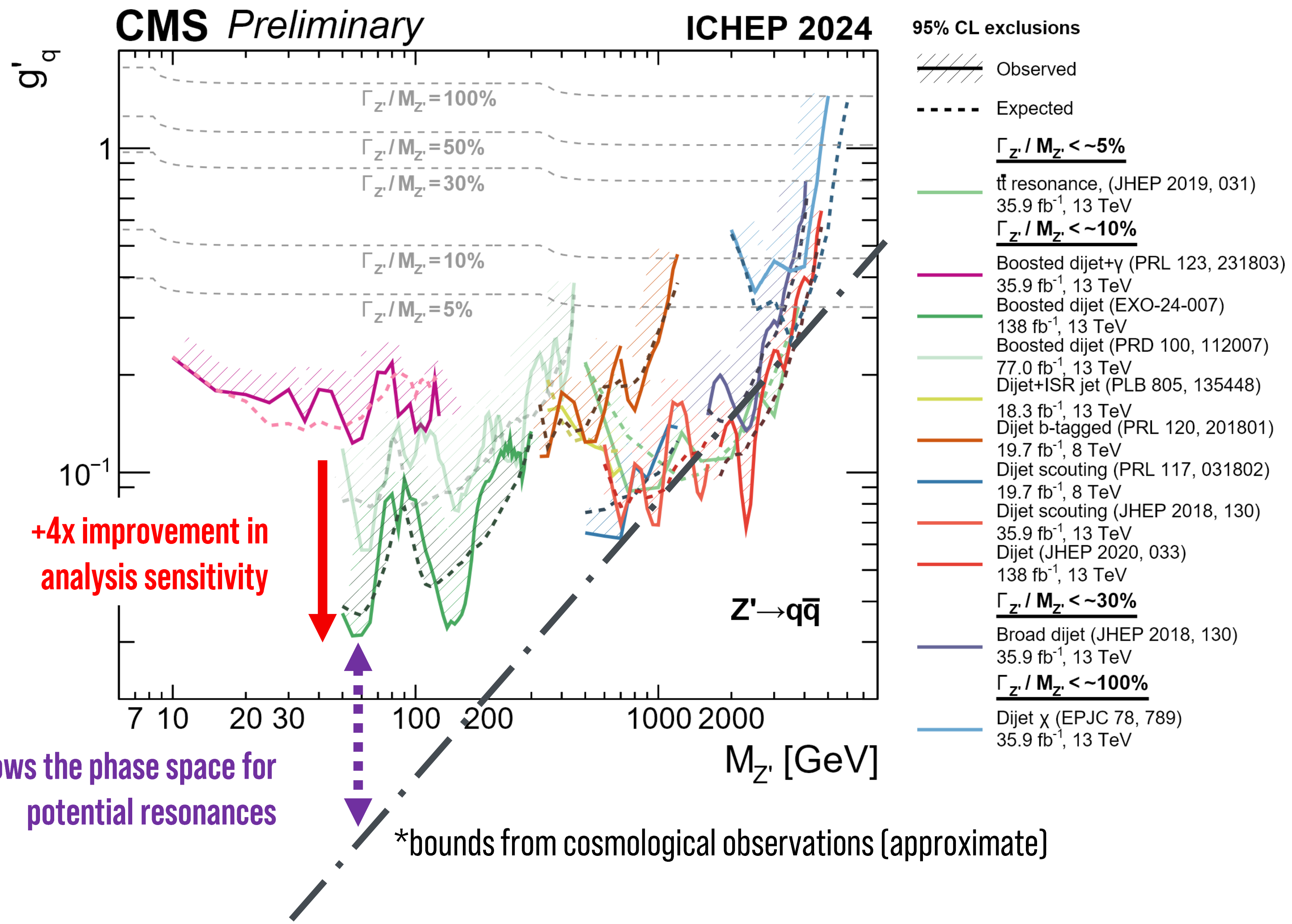








Low-mass Resonances



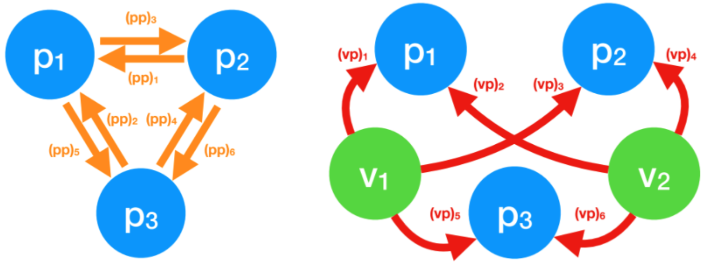
+4x improvement in analysis sensitivity

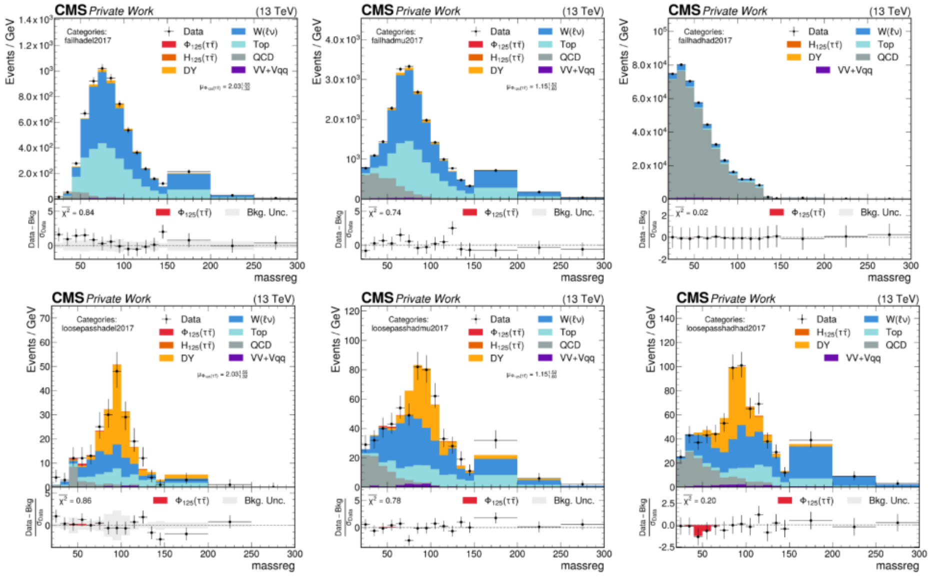
Substantially narrows the phase space for potential resonances

*bounds from cosmological observations (approximate)

What About Other Decay Modes ($H \rightarrow \tau\tau$)

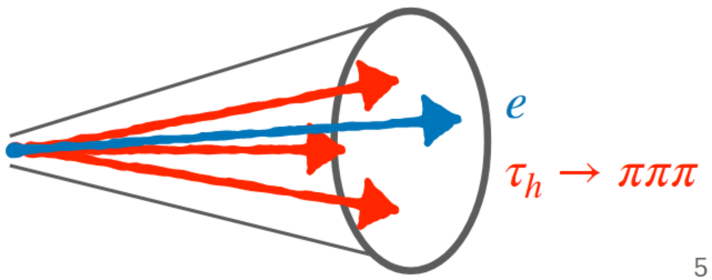
- Same scalars could decay to tau leptons
- Similar analysis approach can be used
  - However, custom di-tau jet tagging algorithm is needed – Interaction Networks
  - Train both discriminator and mass regression
- 3 channels x 3 sensitivity regions x (1 SR + 2 CRs)
  - Enables data-driven background predictions (tt, W)



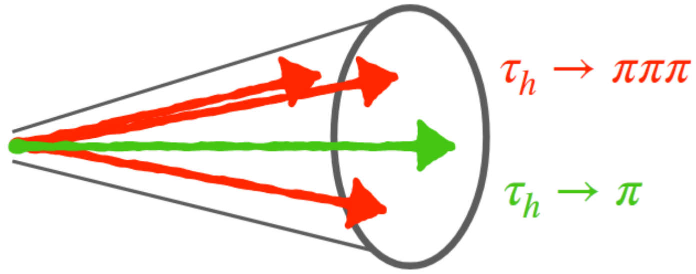


+ 2 CRs

e.g. boosted $e\tau_h$

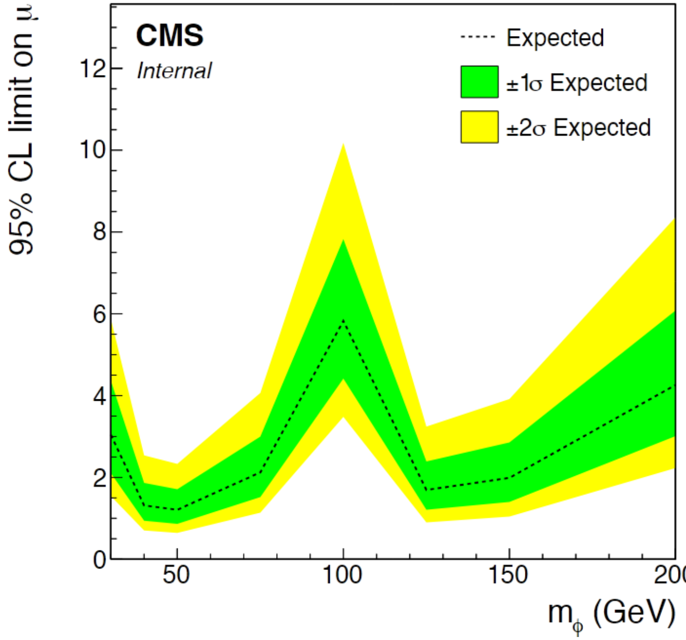


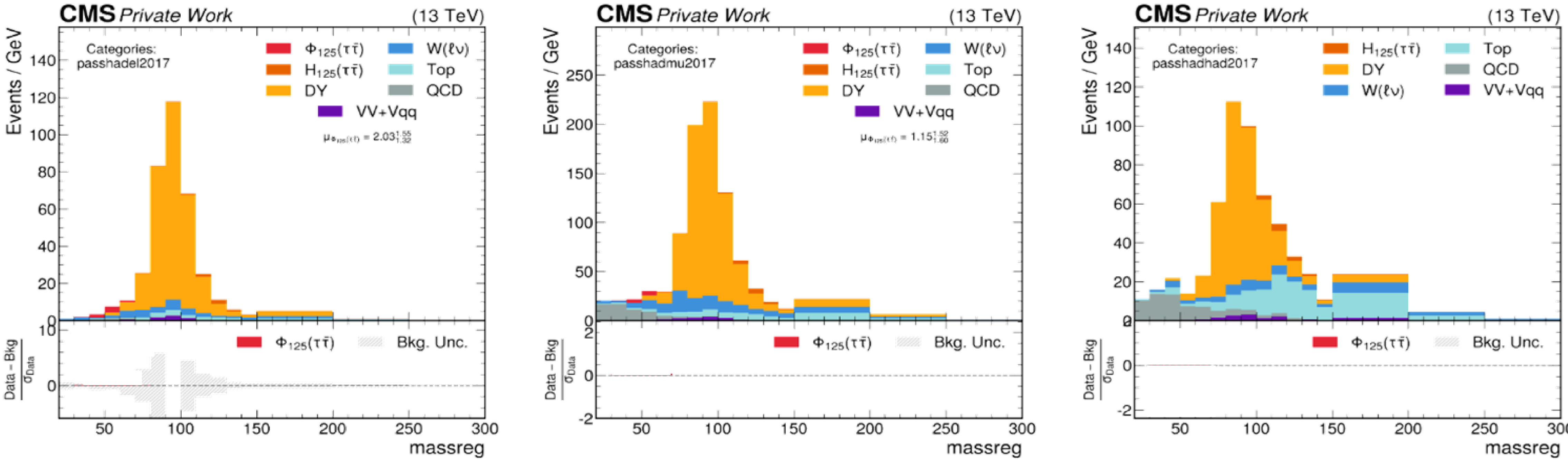
e.g. boosted $\tau_h\tau_h$



What About Other Decay Modes (H → ττ)

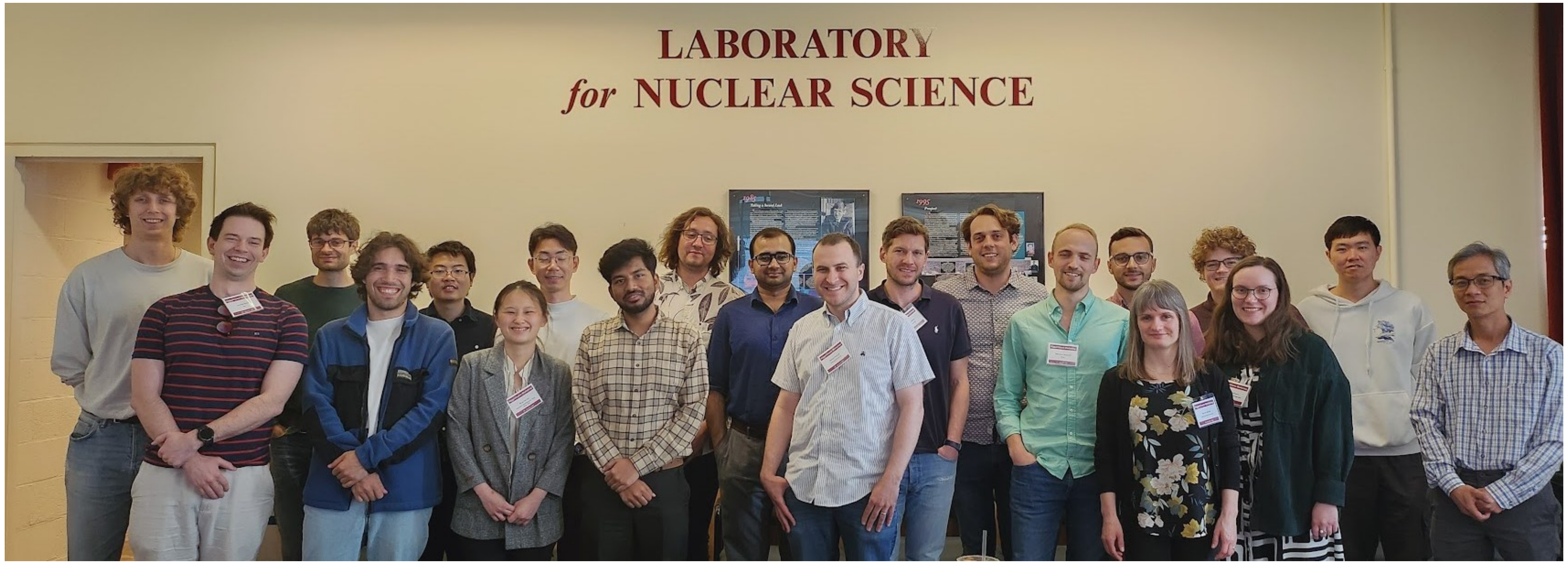
- Currently in internal review
  - Unblinding before the end of the year
- Substantial expected sensitivity from leveraging GNNs
- Tau leptons offer a good balance of background rejection and BR%





Group Engaged in Ongoing Efforts in CMS

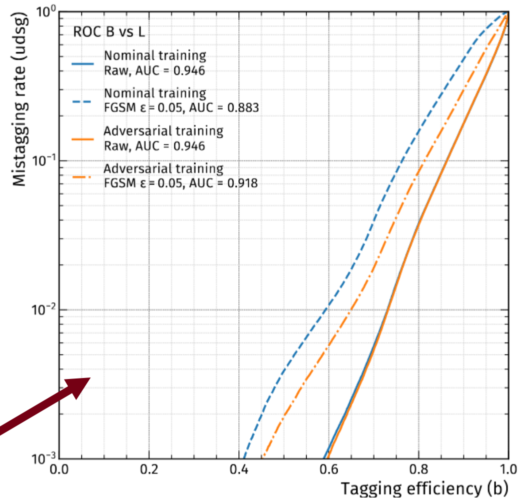
- Robust effort in boosted Higgs and BSM searches
- Three analyses completed* in 2024 (PAS, PreApp scheduled, L3 review)
- Leadership role in CMS – L3 Hbb/cc convenership
- Organized a successful Higgs/Charm workshop at MIT in May 2024



Future Work

- Expertise with b-jet, c-jet, and tau leptons identification and analysis

- Continue to build out boosted Higgs physics program
  - Important test of the Standard Model
  - Organizing work towards Run3 analyses - statistically limited
    - **Direct improvement with more data!**
  - Rich collaboration with other institutes (FNAL, UCSD, Cornell, Brown, JHU...)



- Strongly intertwined with new ML/AI developments
  - Controlling **robustness** and systematic uncertainties of classifiers becomes crucial with more data
  - Self-supervised and contrastive learning can be used for **anomaly detection**
    - Leverage existing analysis frameworks and strategies

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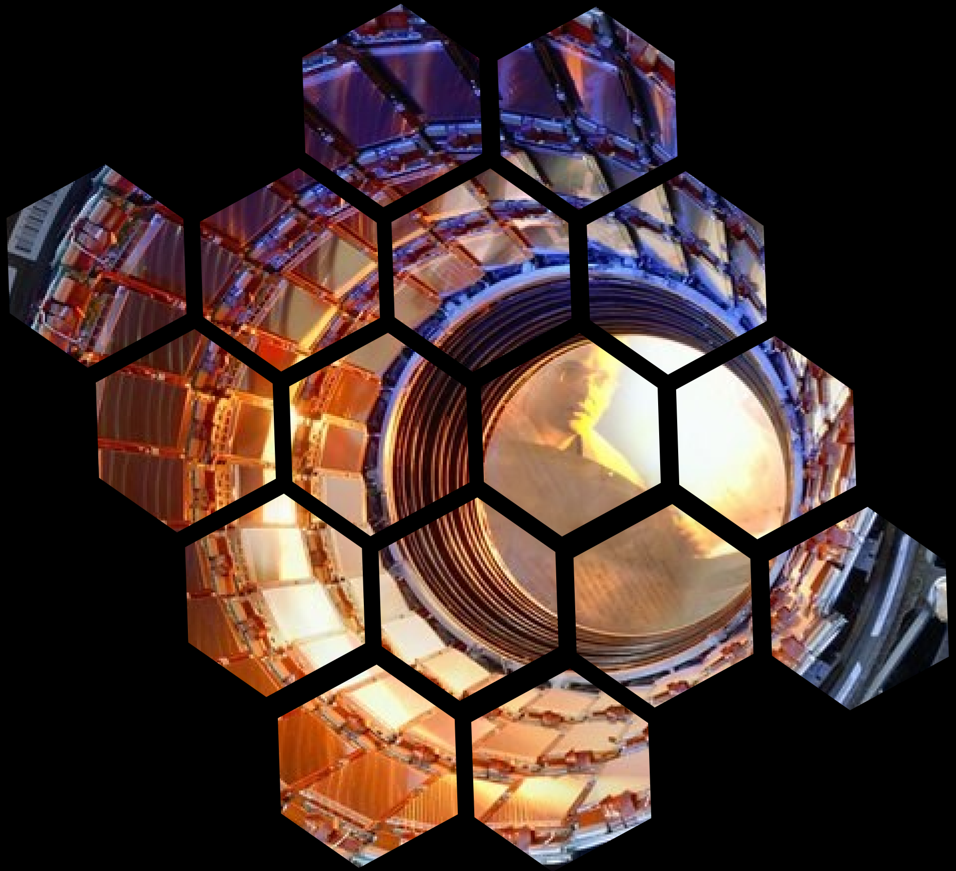
CMS

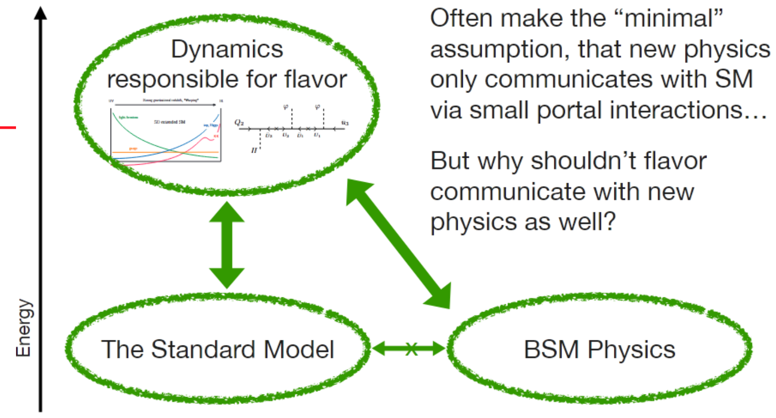
CERN

Thank You



Andrzej Novak

Charm Physics and Low-mass Resonances



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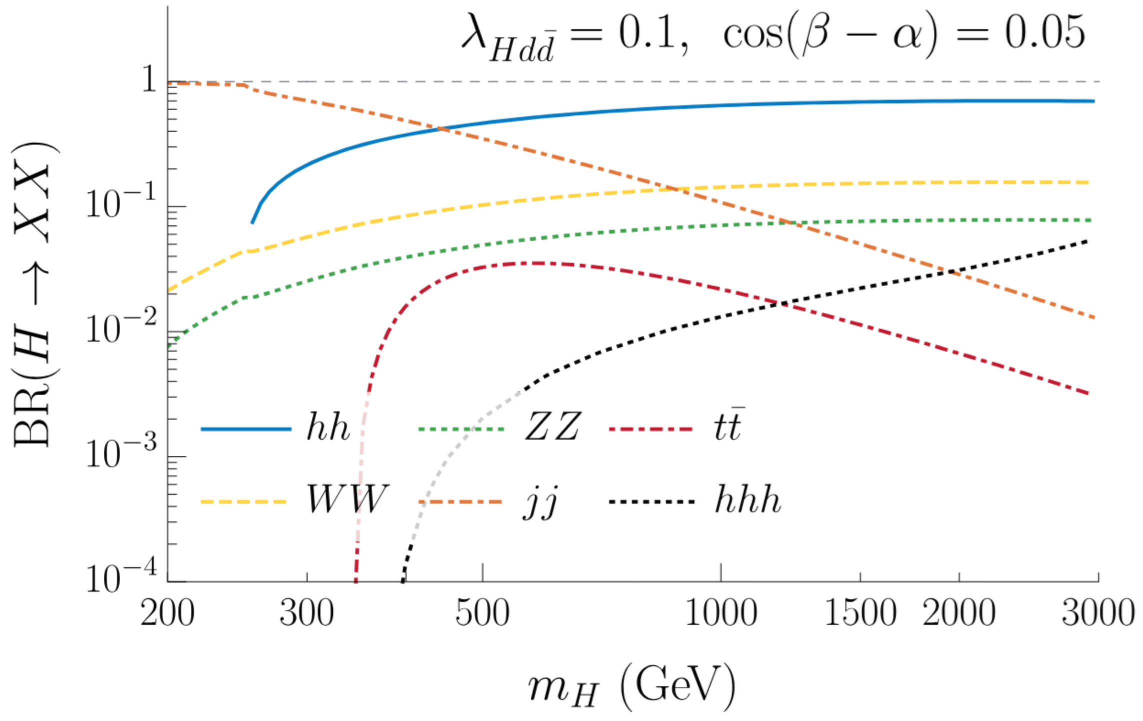
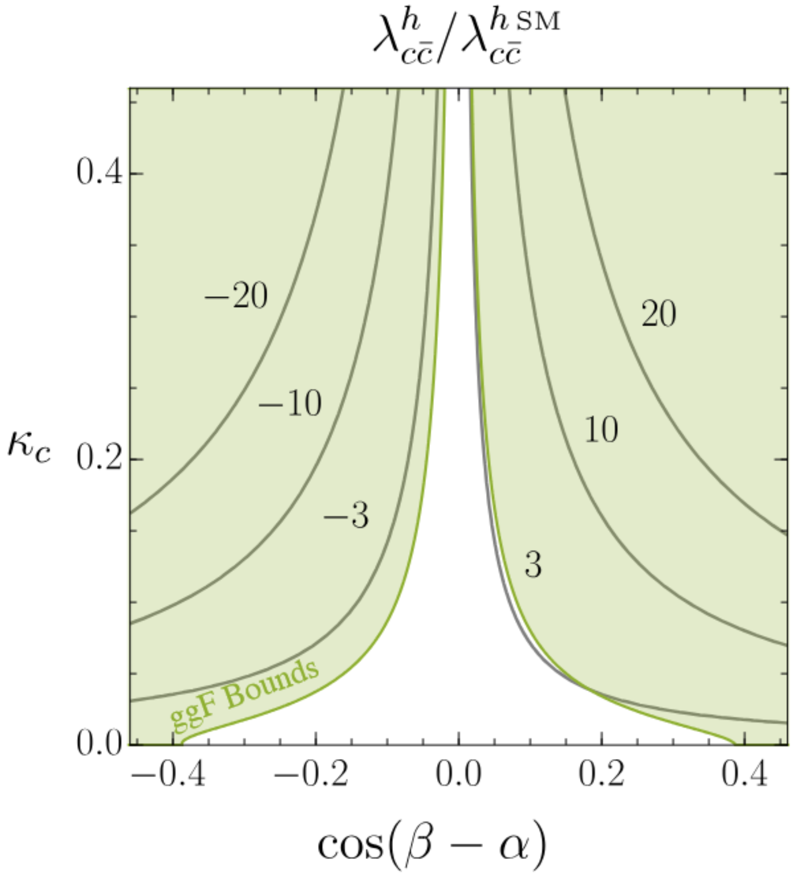
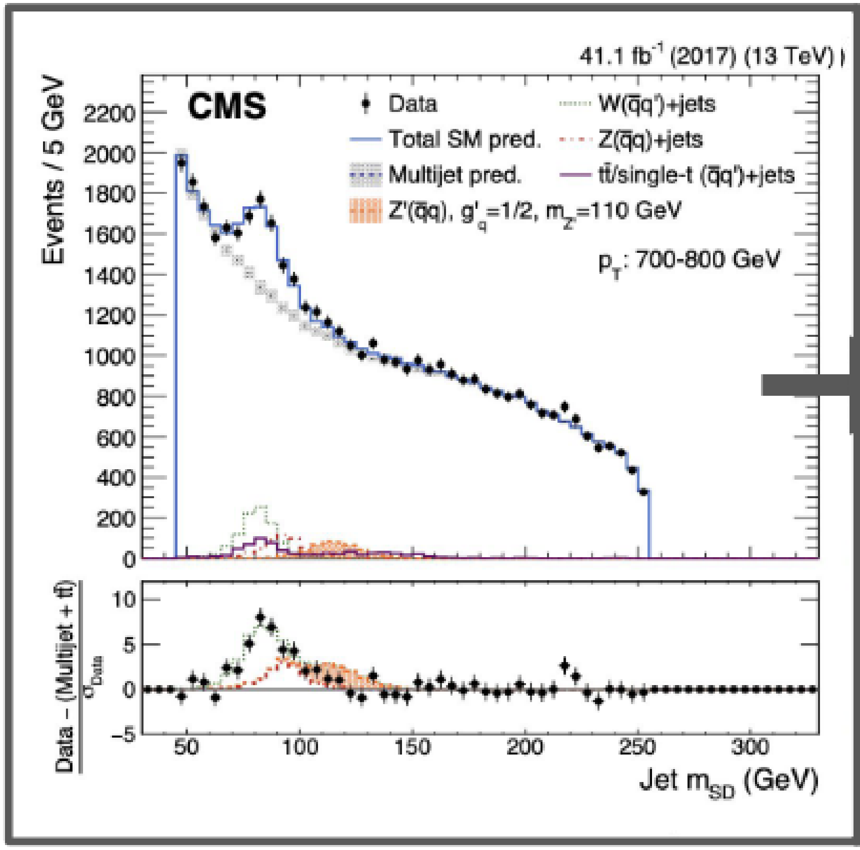
- Also compatible with DM models



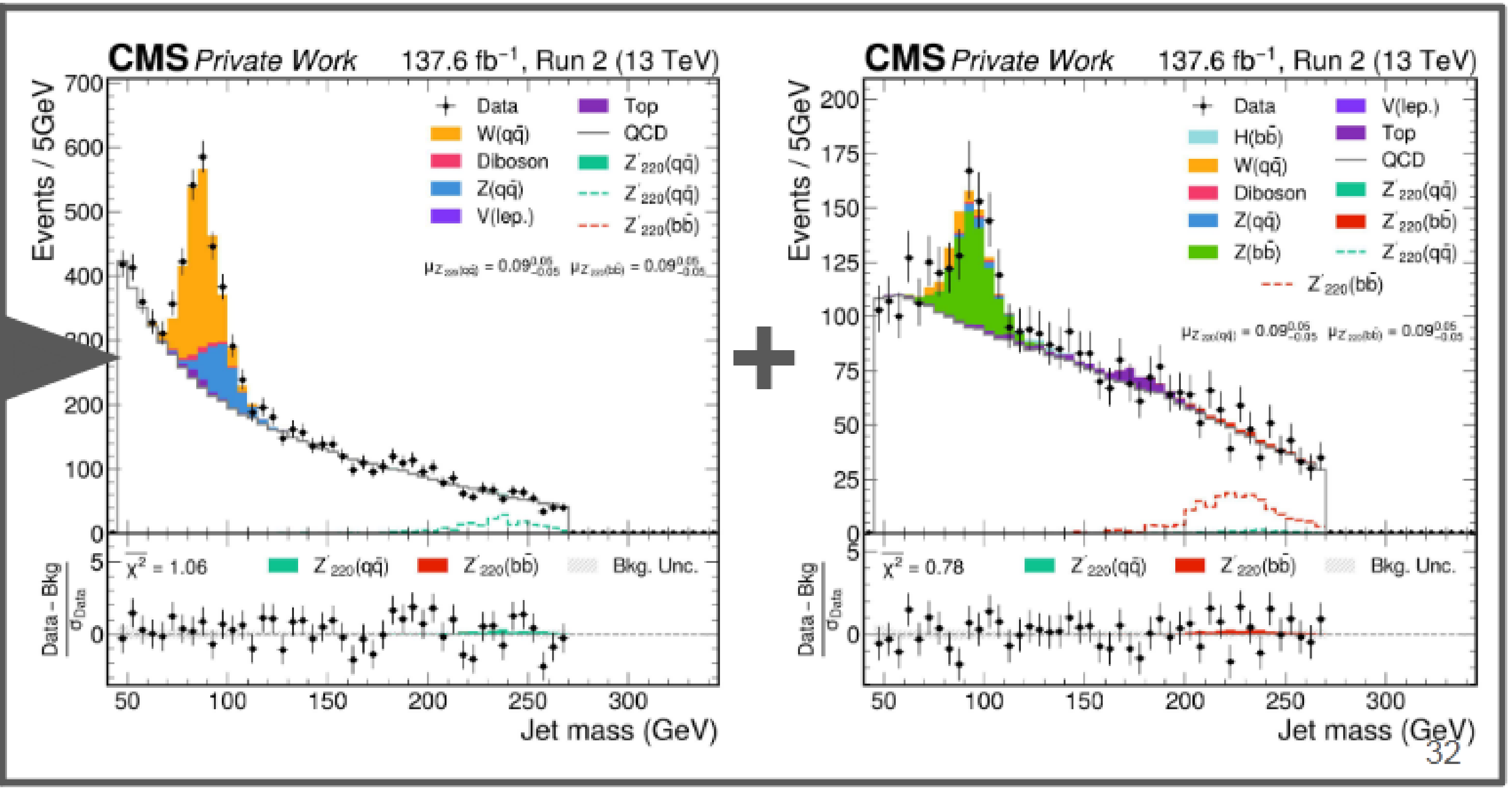


Low-mass Resonances

EXO-18-012 (old)



EXO-24-007 (new)



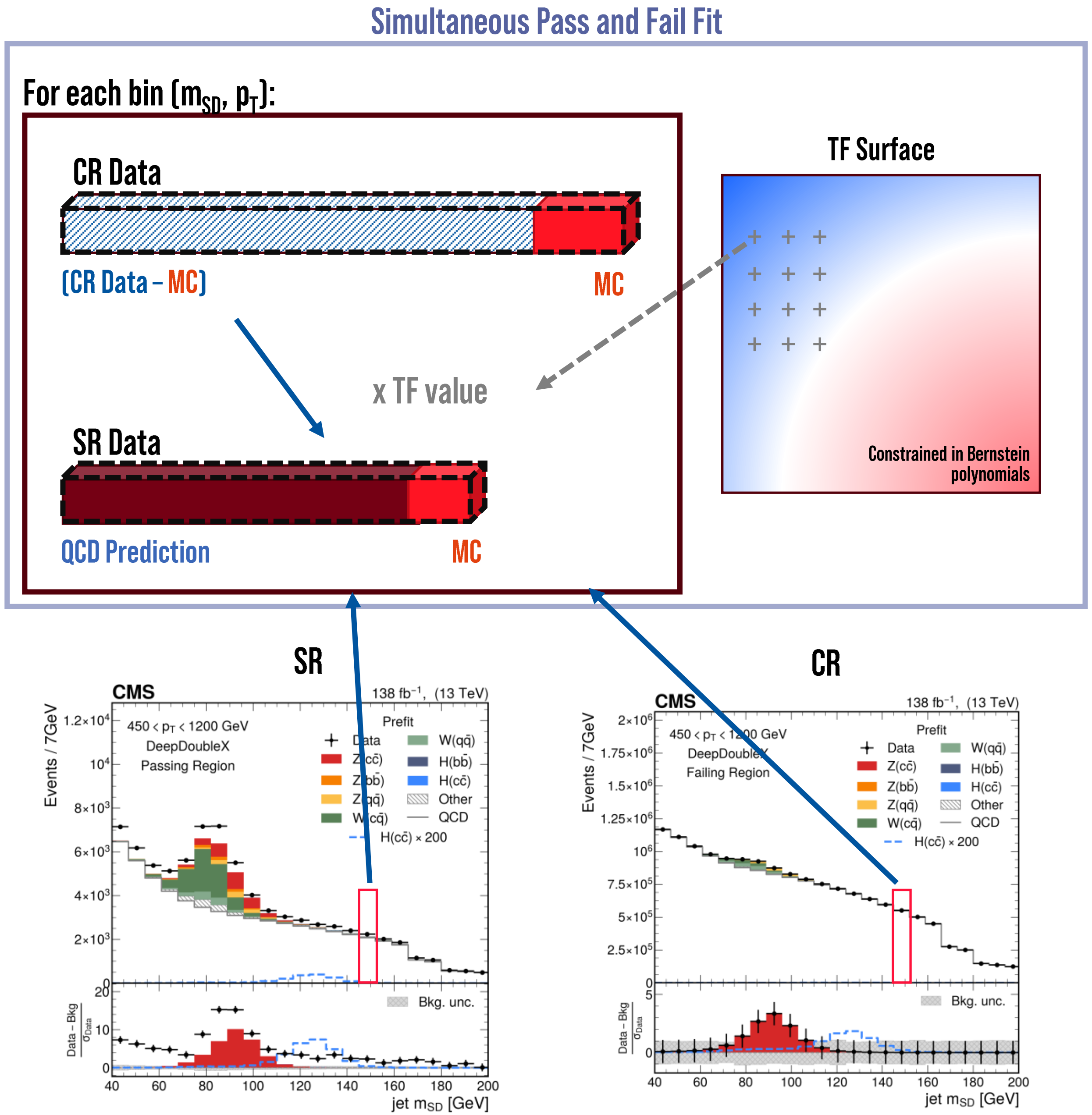
Transfer Factor Fit

- ***Rhalphabet***
  - Differential **Alphabz` et** (ABCD)
- **Transfer Factor – residual correction**
  - Accounting for different tagger response
  - Flat TF ➔ **Regular ABCD method**
- TF defined (constrained) bin **barycenters**
  - 6 pT x 23 ρ (mass) bins
  - Surface parametrized in **Bernstein basis**

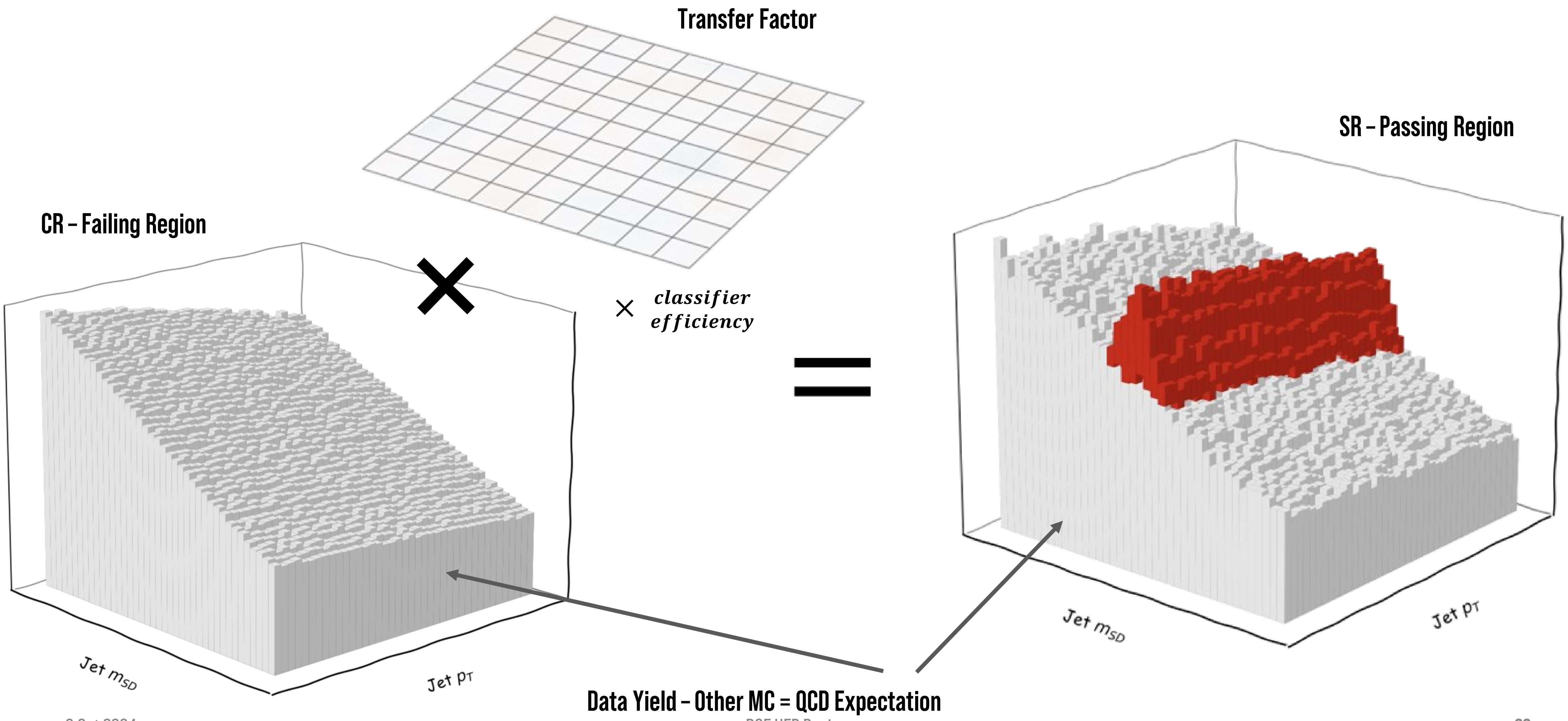
$$R(\rho, p_T) = \sum_{k=0}^{n_\rho} \sum_{\ell=0}^{n_{p_T}} a_{k,\ell} b_{k,n_\rho}(\rho) b_{\ell,n_{p_T}}(p_T) \epsilon^{\mathrm{QCD}}(\rho, p_T)$$

$$b_{\nu,n}(x) = \binom{n}{\nu} x^\nu (1-x)^{n-\nu}$$

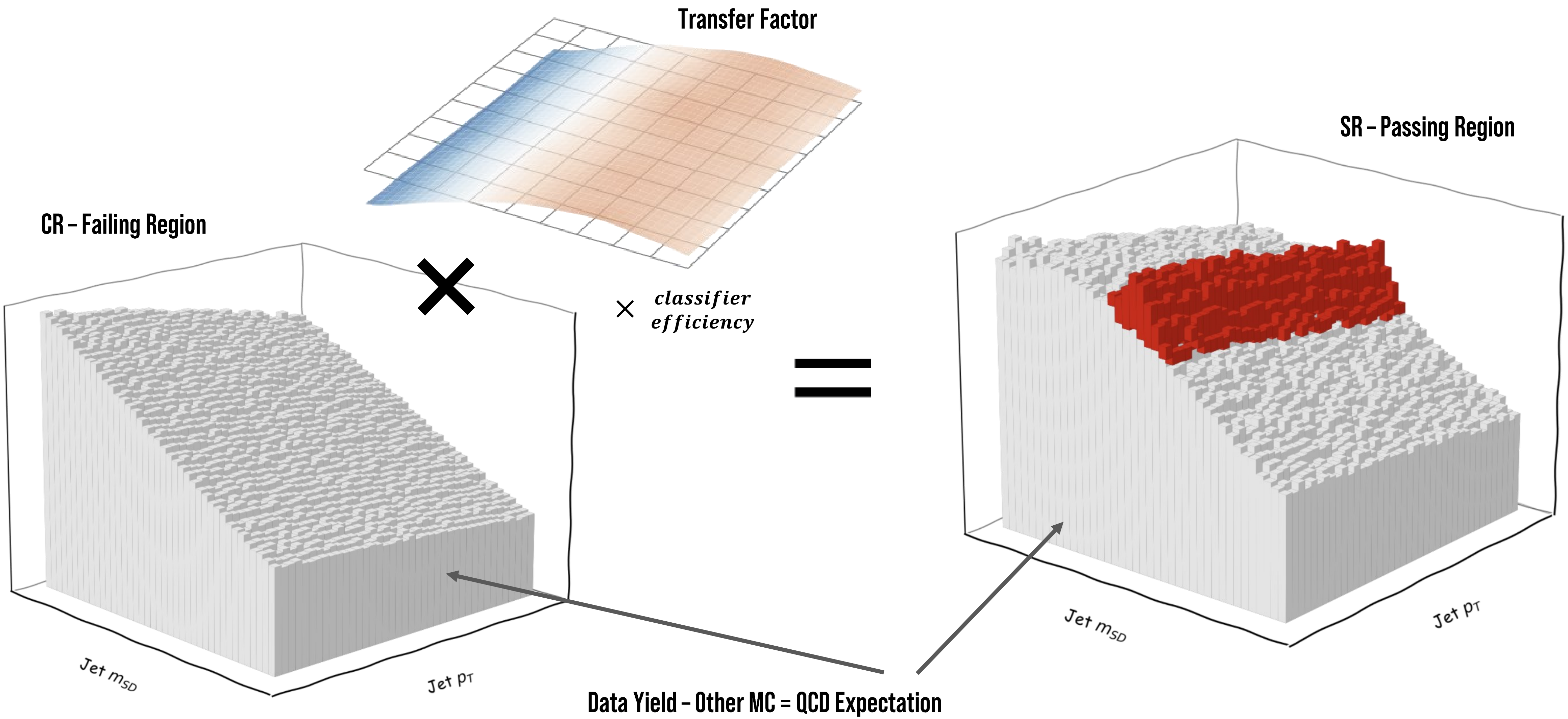
- **Order of polynomials is arbitrary**
  - **Determine optimal configuration based from goodness of fit (F-test)**



Transfer Factor Fit – Optimal Case (ABCD)

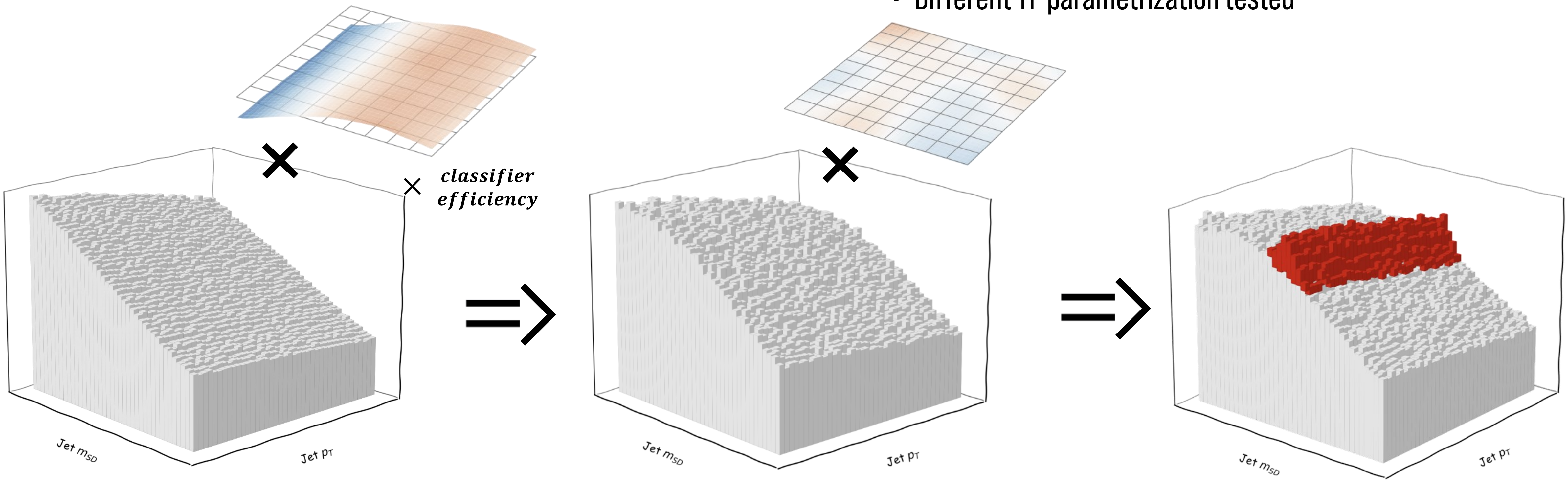


Transfer Factor Fit – Realistic Example

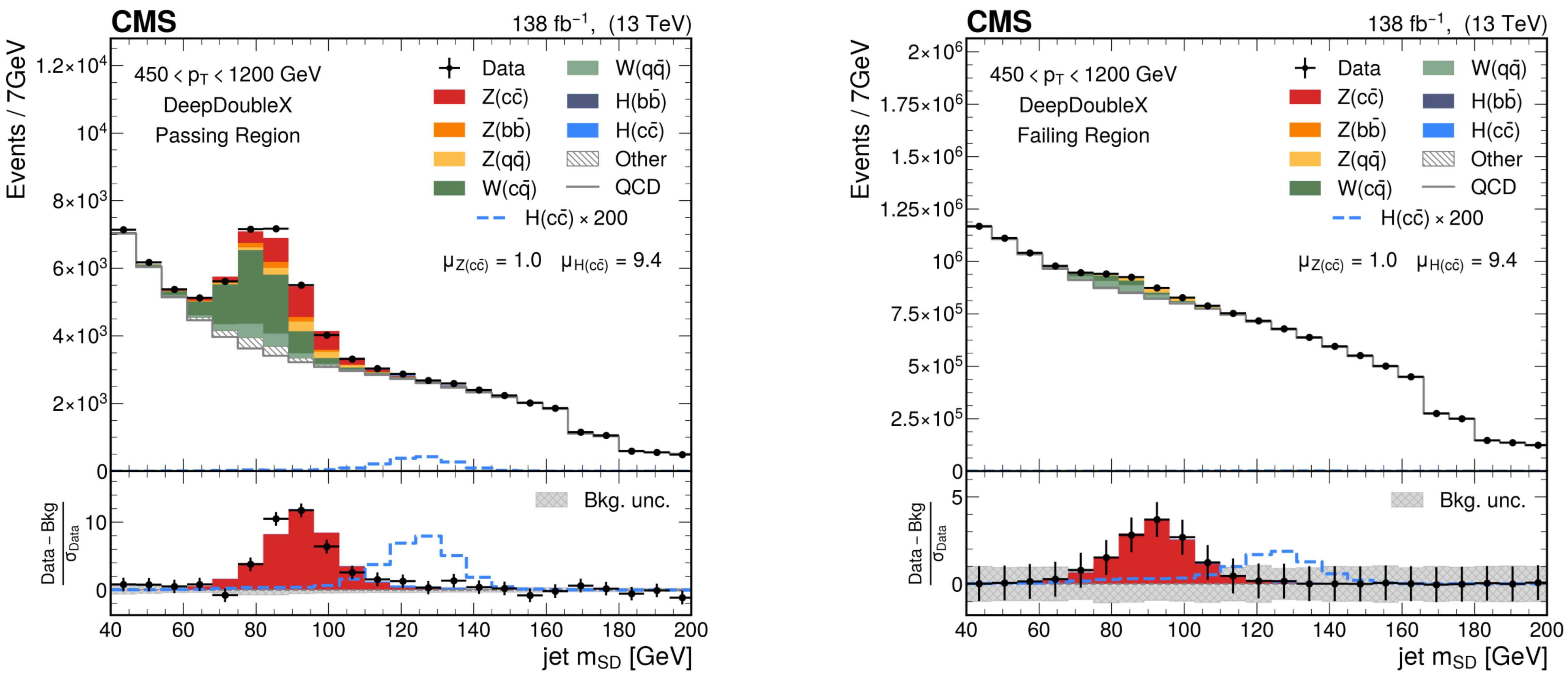


Transfer Factor Fit – In Practice

- **2 effects** to parametrize
  - Classifier **Mass Sculpting** (MC only fit)
  - **Discrepancies** due to **Data/MC** mismodelling
- Both independently parametrized
- Method tested against bias
  - Spurious ‘’peaky” signal
  - Different TF parametrization tested



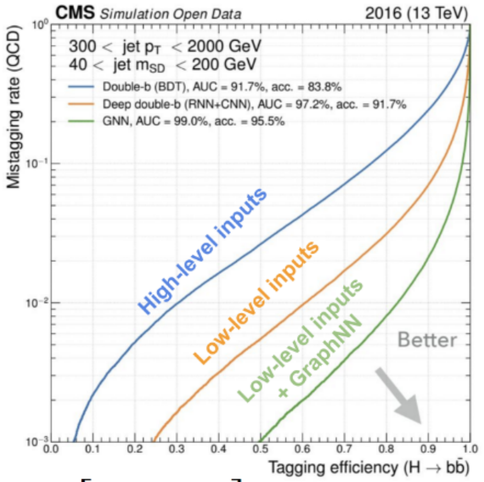
Inclusive High p_T Search ($H \rightarrow cc$)



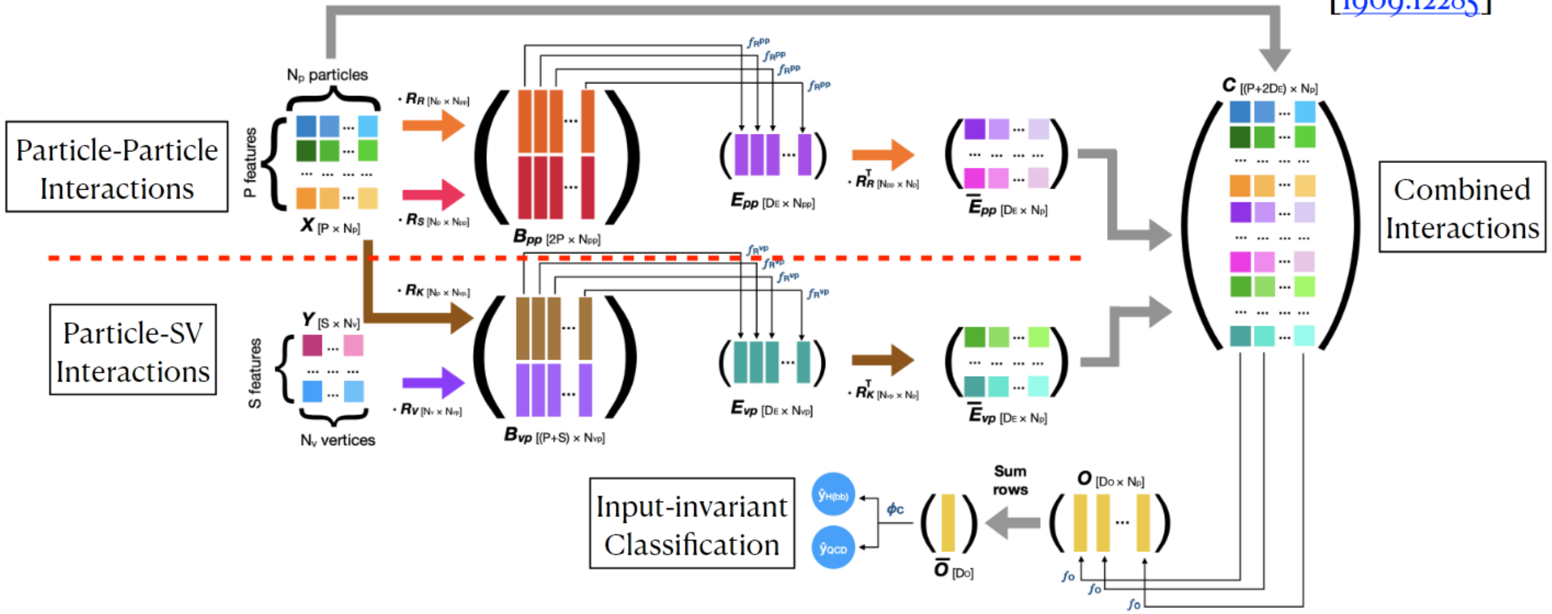
What About Other Decay Modes (H → ττ)

Neural Network Taggers

- Both Z-taggers and $\tau\tau$-taggers use similar inputs into graph-based Interaction Network:
  - Top 30 p_T particles in jet
  - Top 5 p_T SVs in jet
  - Top 3 p_T boosted taus in jet
  - Top 2 p_T electrons/muons in jet (for $e\tau/\mu\tau$)
  - Multiplicities and energy fractions for {charged hadrons, neutral hadrons, e, γ, μ}



[1909.12285]



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