PURDUE UNIVERSITY

Towards quantum measurements at CMS

AJ Wildridge

on behalf of the CMS Collaboration

Foundational Tests of Quantum Mechanics at the LHC

March 20th – 22nd , Oxford

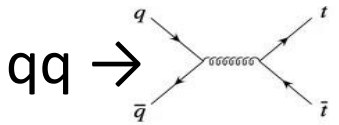
Overview

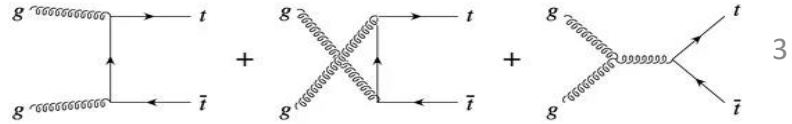
- Overview of top quark physics & spin correlations
- 2016 measurement of spin density matrix
- Machine Learning top reconstruction
- Extrapolation to High Luminosity Large Hadron Collider (HL-LHC) & Beyond

Top Quark Physics

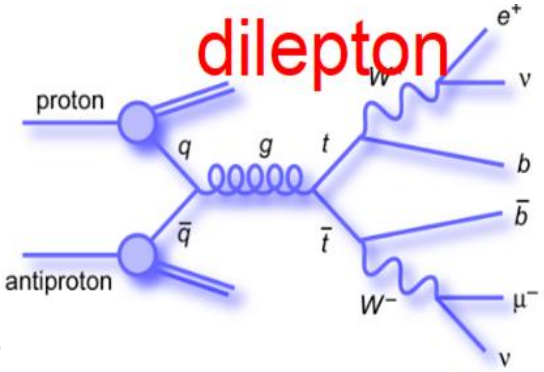
- Top quark is the heaviest fundamental particle discovered thus far: m_t = 173.34 +/- 0.76 GeV [arxiv:1403.4427]
- Unique:

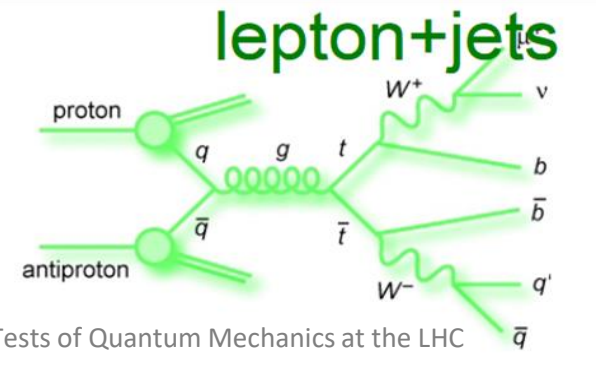
$$\underbrace{\frac{1}{m_t}}_{\text{production}\ 10^{-27}\ \text{s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime}\ 10^{-25}\ \text{s}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\text{hadronization}\ 10^{-24}\ \text{s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip}\ 10^{-21}\ \text{s}}$$

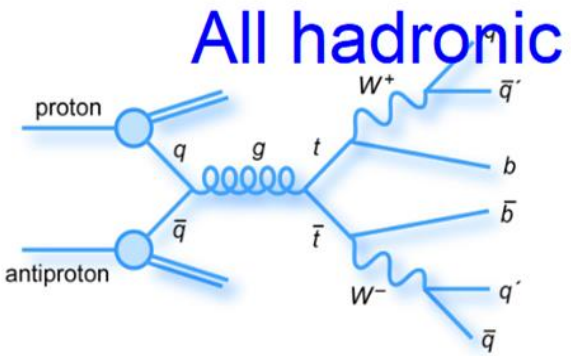
qq → 

gg → 

- Allows for probing of bare-quark physics
  - Inaccessible realm of physics except for asymptotic freedom!
- LHC is a top quark factory (100m+ thus far)
- Spin information is accessed "best" in leptonic decays of W



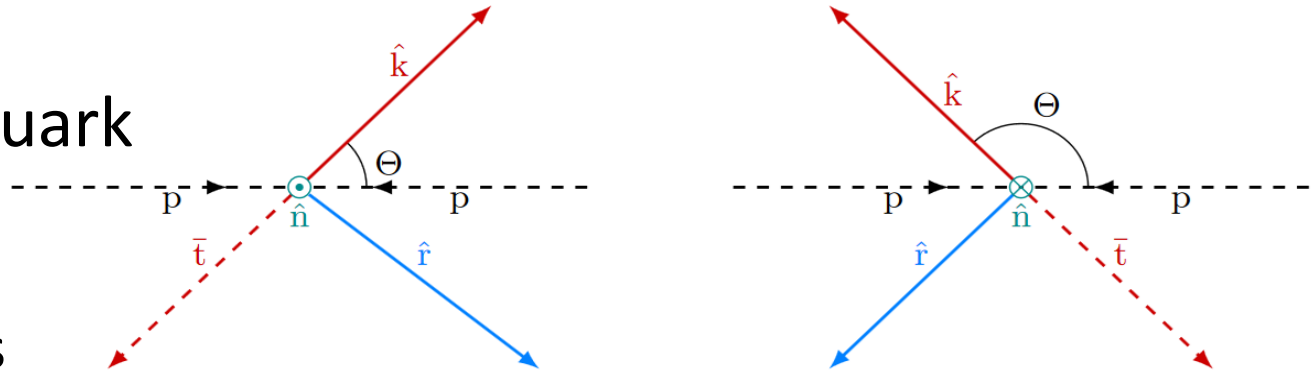




Top Quark Spin Correlations

Phys. Rev. D 100, 072002

- Measuring spin directly on top quark is inaccessible
  - Preserved in decay products → measure angle between spin axis and lepton in parent top quark rest frame
  - Measured in the helicity basis for symmetry reasons → sensitive to BSM phenomenon!
- Dependent on:
  - production mode
  - scattering angle of the top quark
  - Invariant mass of the top quark and antiquark system

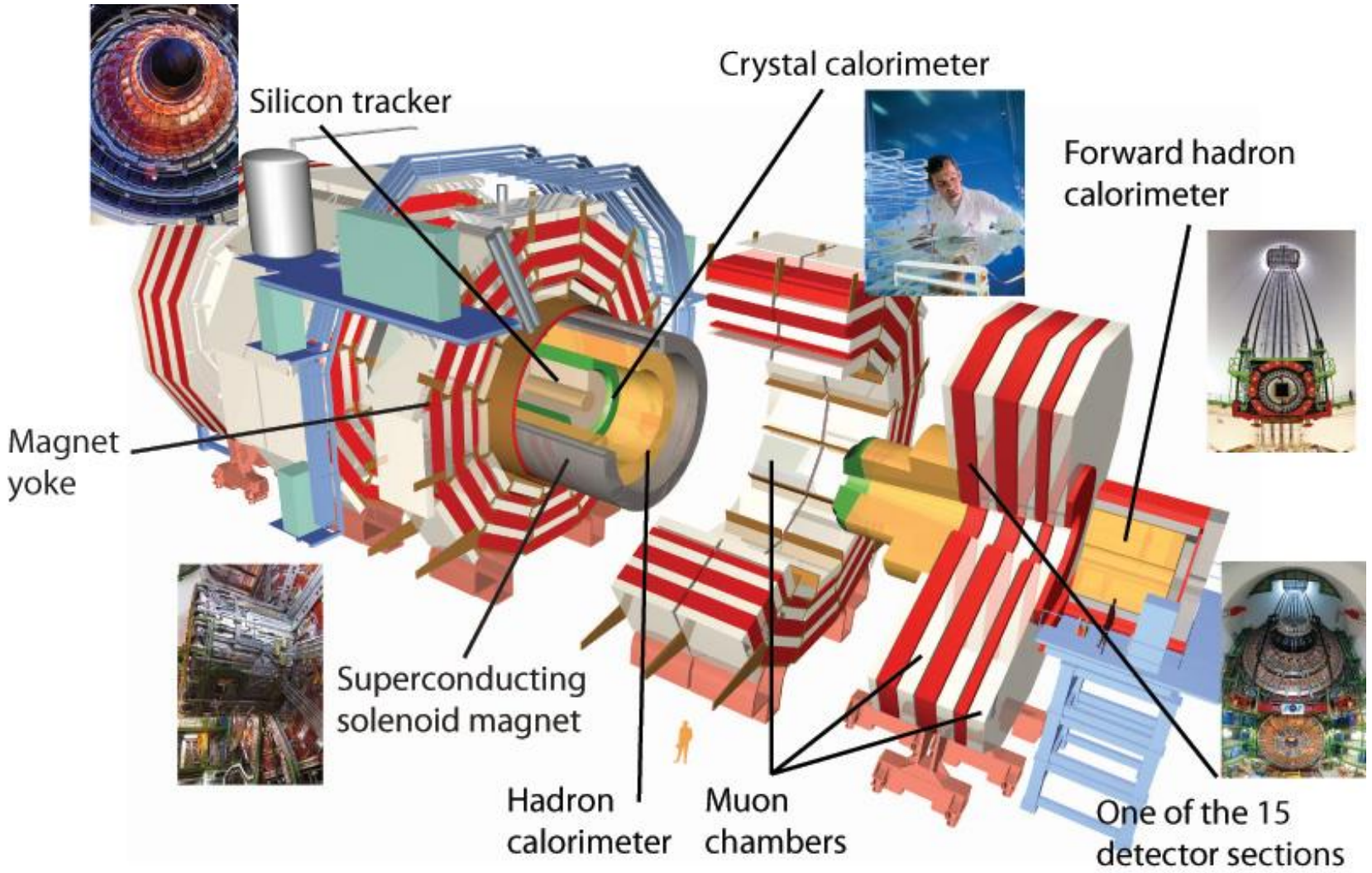


$$R \propto \tilde{A}\mathbb{1} \otimes \mathbb{1} + \tilde{B}_i^+ \sigma^i \otimes \mathbb{1} + \tilde{B}_i^- \mathbb{1} \otimes \sigma^i + \tilde{C}_{ij} \sigma^i \otimes \sigma^j$$

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\chi_a} = \frac{1}{2}\left(1 + \kappa_a \cos\chi_a\right)$$

$$\frac{1}{\sigma}\frac{\mathrm{d}^4\sigma}{\mathrm{d}\Omega_1\,\mathrm{d}\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1 \cdot \mathrm{C} \cdot \hat{\ell}_2\right)$$

The CMS Detector

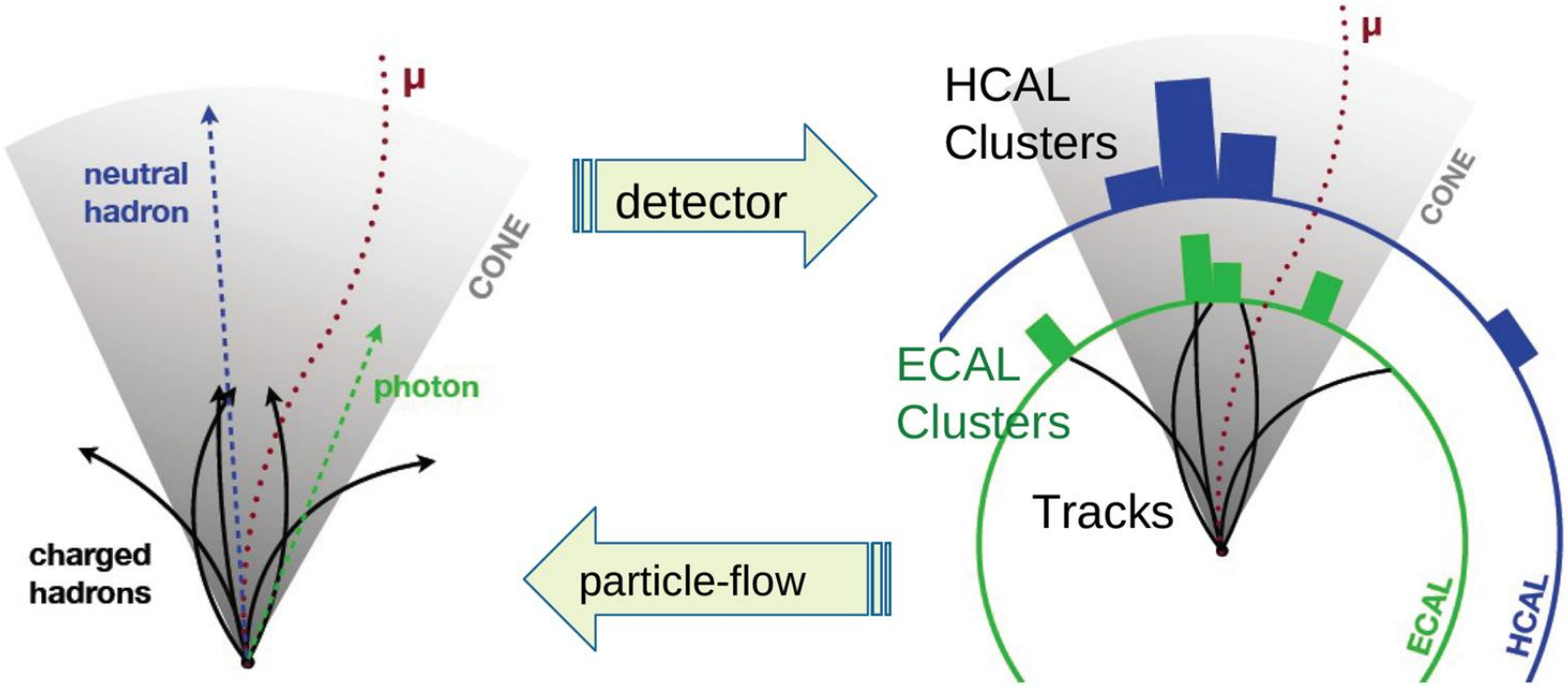


Weight: 14000t

Particle Flow in CMS

- Isolated leptons
  - Dilepton resonances (Z, upsilon, J/psi)
- b-tagging of jets
- Jets & missing E_T
  - Gamma & Z-jet balance
  - Pile-up subtraction

CMS-JME-13001



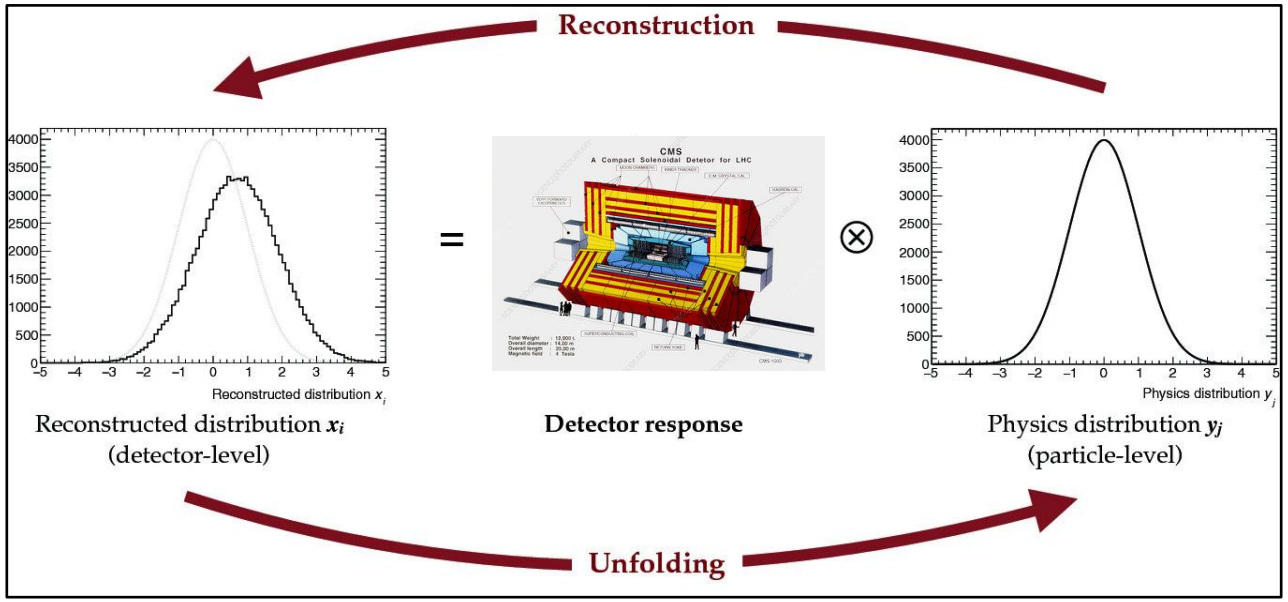
CMS Measurement using 2016 Data

$\mathbf{L_{int}} = 35.9\ fb^{-1}$

Phys. Rev. D 100, 072002

Analysis Strategy

- Unfold to parton level for 10 polarizations, 9 correlations, D, and lab frame observables
  - Polarizations measured along helicity basis and k^*, r^* axes
  - Measured diagonal of spin correlation matrix and off-diagonal sums and differences
  - Measured trace of spin correlation matrix, D, via $\cos\phi$
  - Measure $|\Delta\phi_{l\bar{l}}|$ and $\cos\phi$ in the lab frame – indirectly related to spin correlations



Analysis Strategy

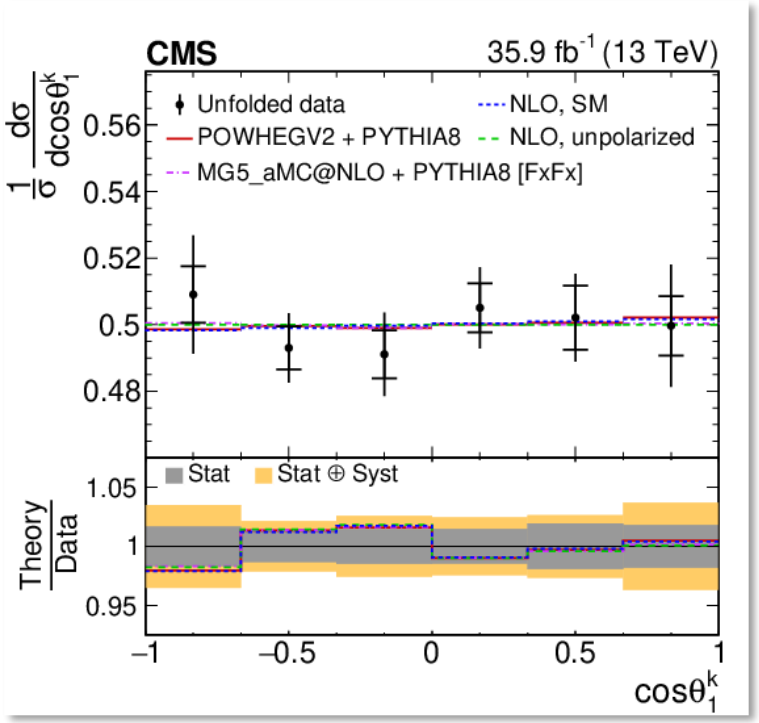
- Compute statistical and systematic correlation matrices between all bins of unfolded distributions
  - Unfolding introduces correlations between bins of the same observable
  - Correlations between observables may exist, e.g., C_{kk}, C_{rr}, C_{nn} and D
  - Bootstrap method is used for computing correlations

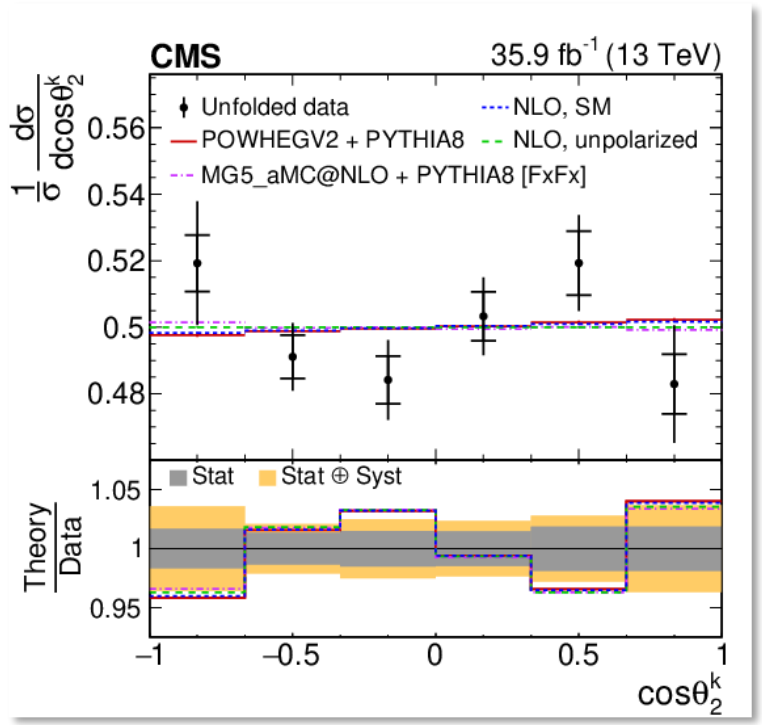
- Correlations are very important when performing a fit/interpretation
  - Uncorrelated is a very poor assumption

Spin Density Matrix Polarizations - 2016 Results

Phys. Rev. D 100, 072002

- All consistent with expectation of SM ≈ 0

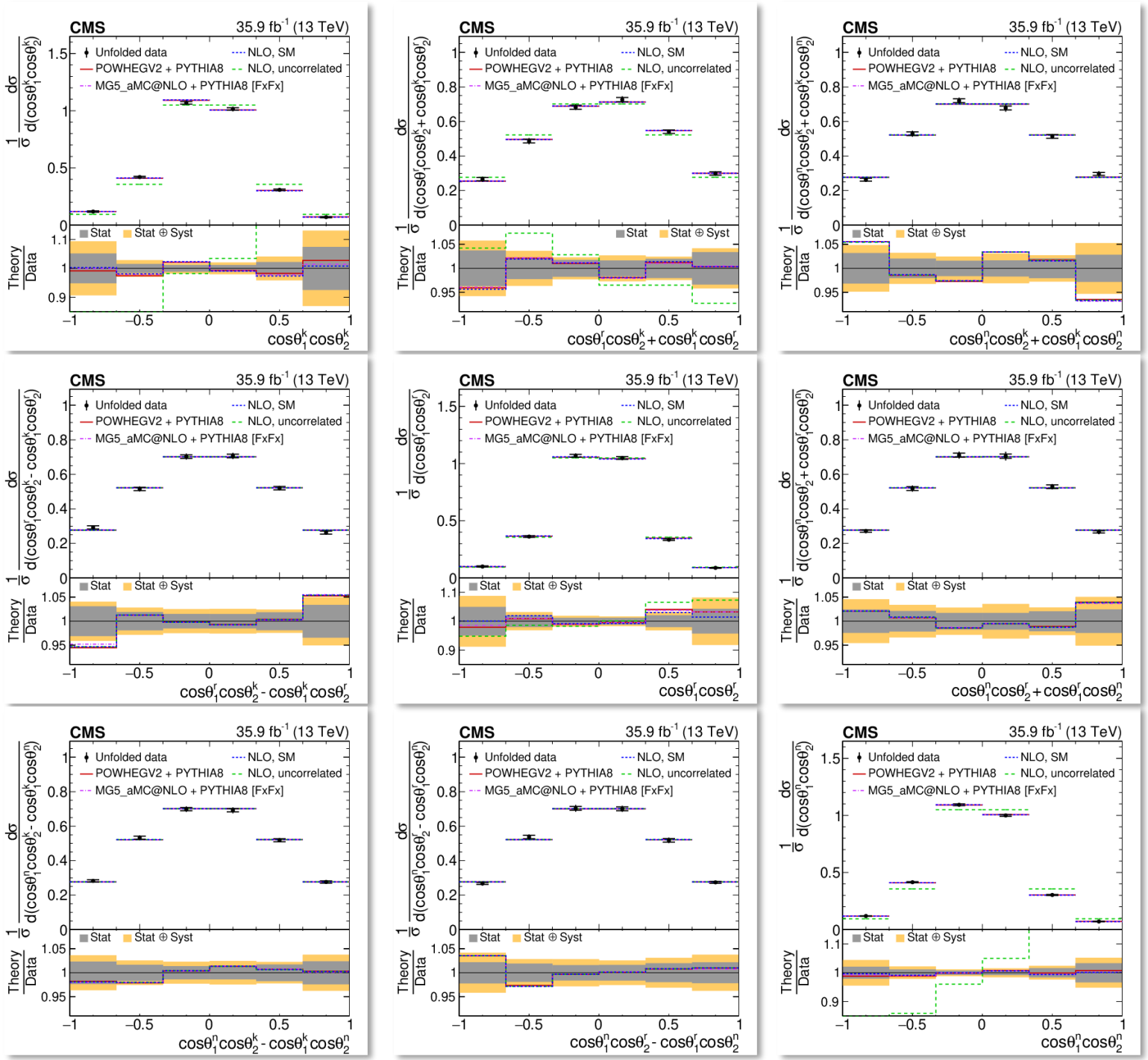




Spin Density Matrix Correlations

[Phys. Rev. D 100, 072002]

2016 Results



Spin Correlation Matrix Trace & Lab Observables

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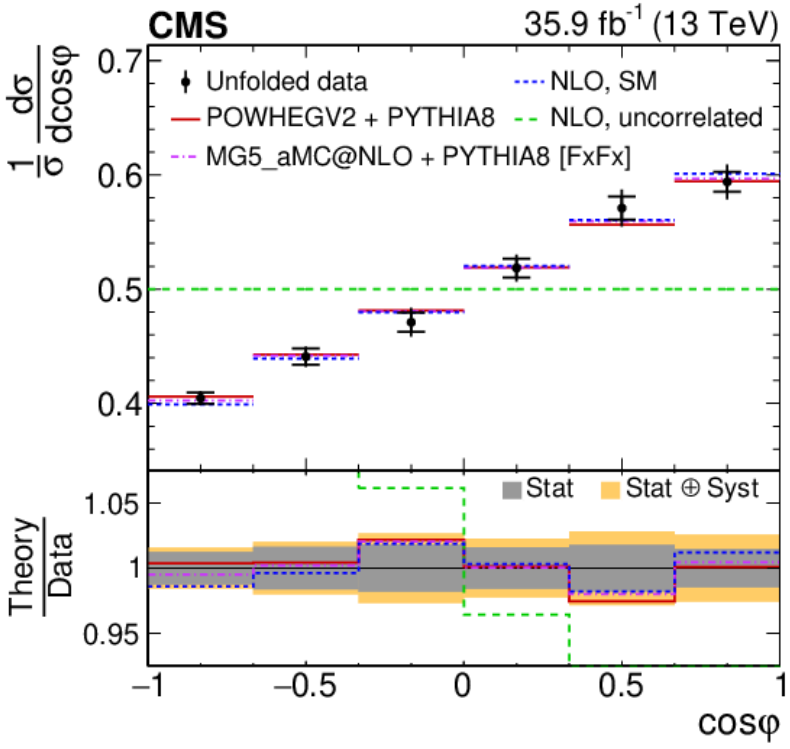
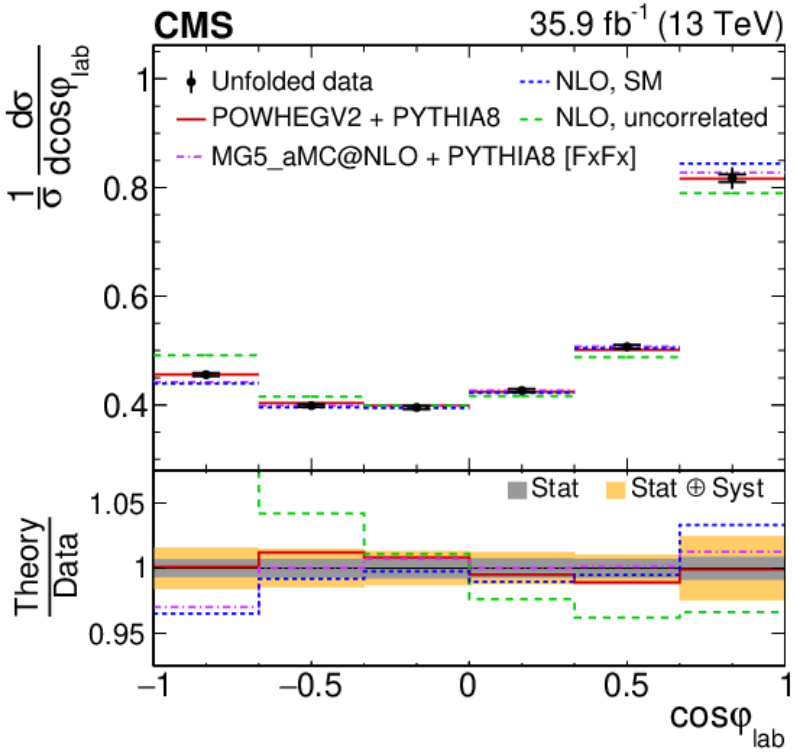
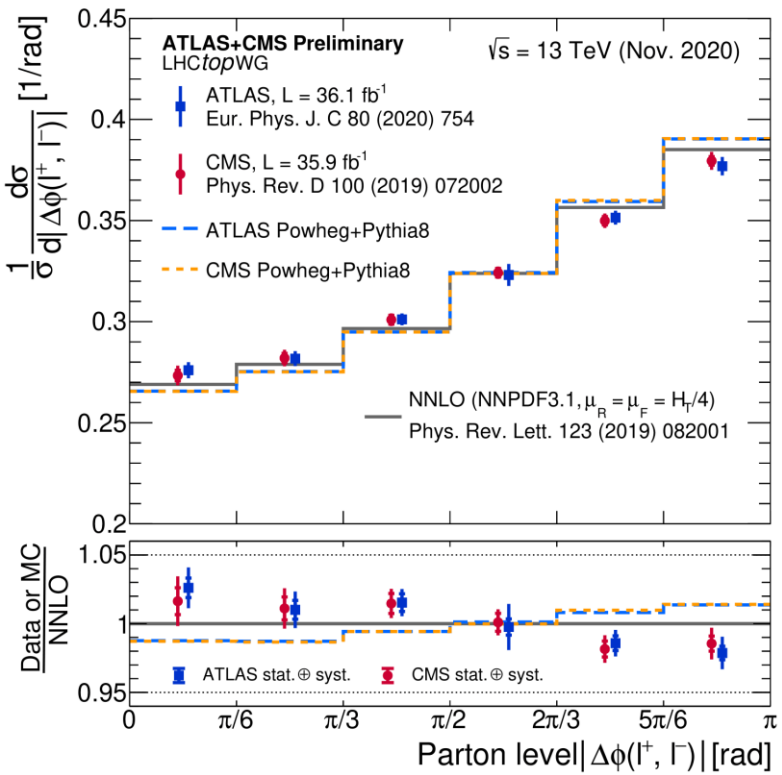
2016 Results



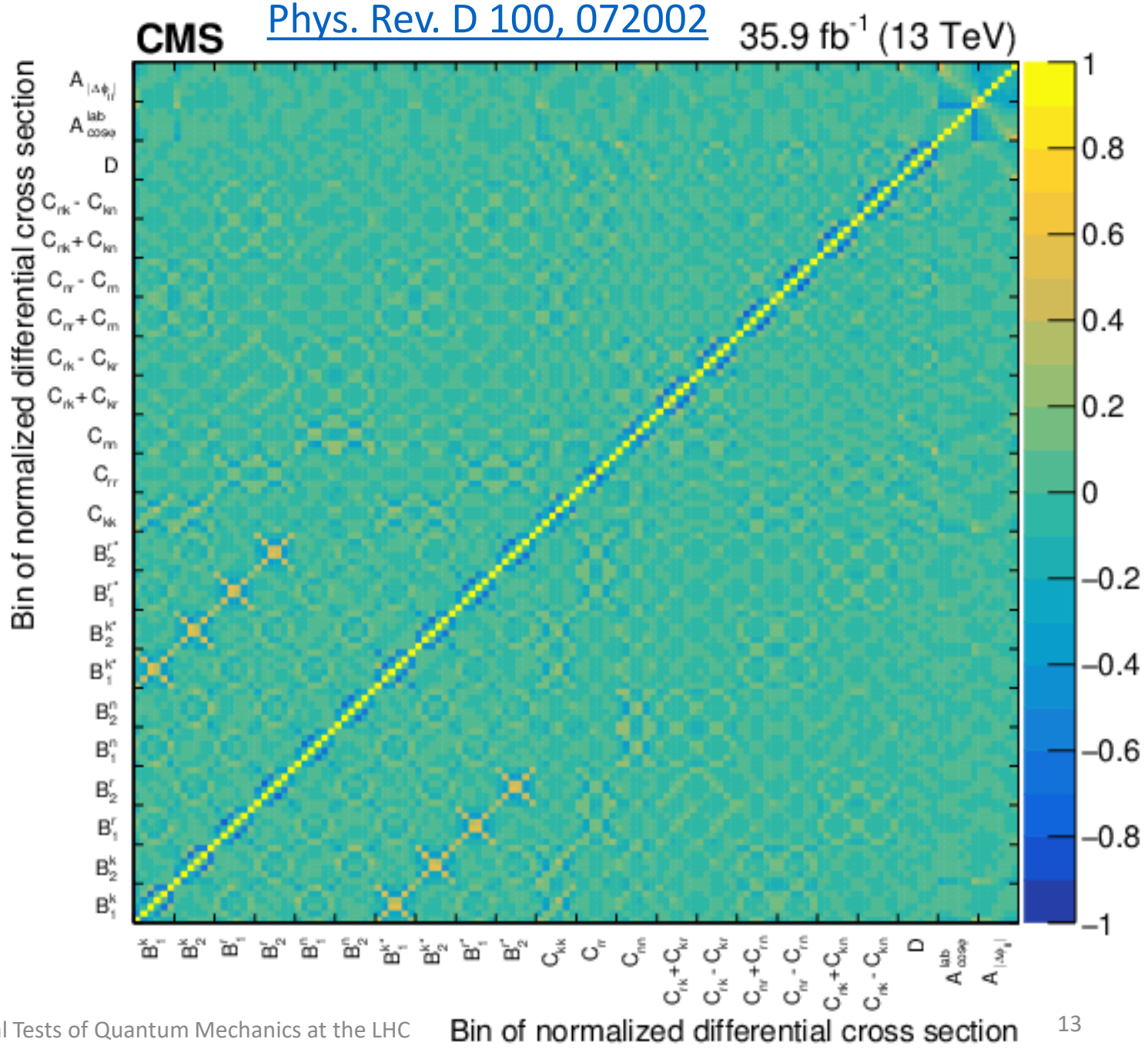


LHC Top Working Group



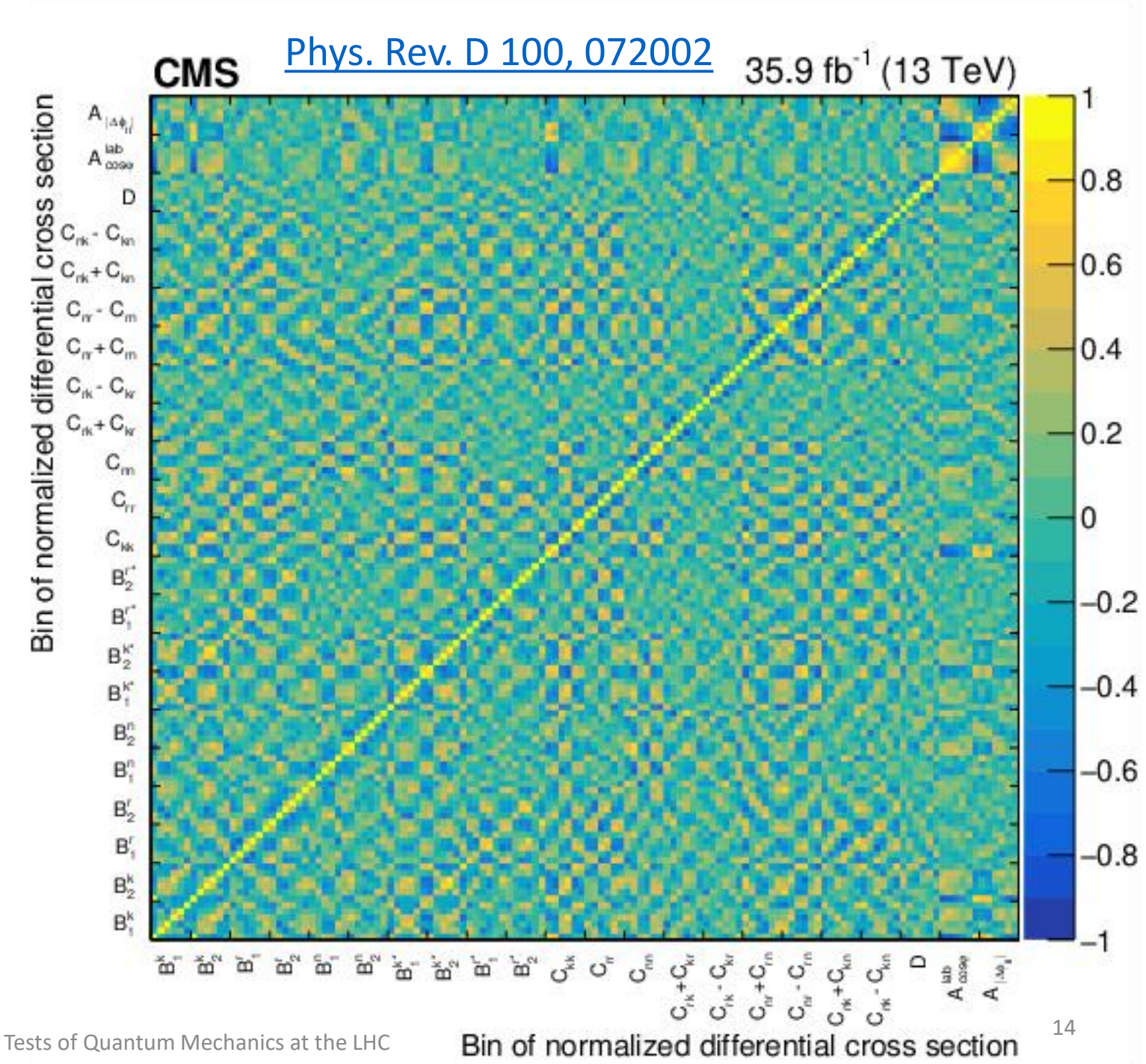
Correlations Between All Observables

- Statistical correlations between bins of normalized distributions
- Mostly 0 between distributions
- Within distribution can be highly correlated due to unfolding



Correlations Between All Observables

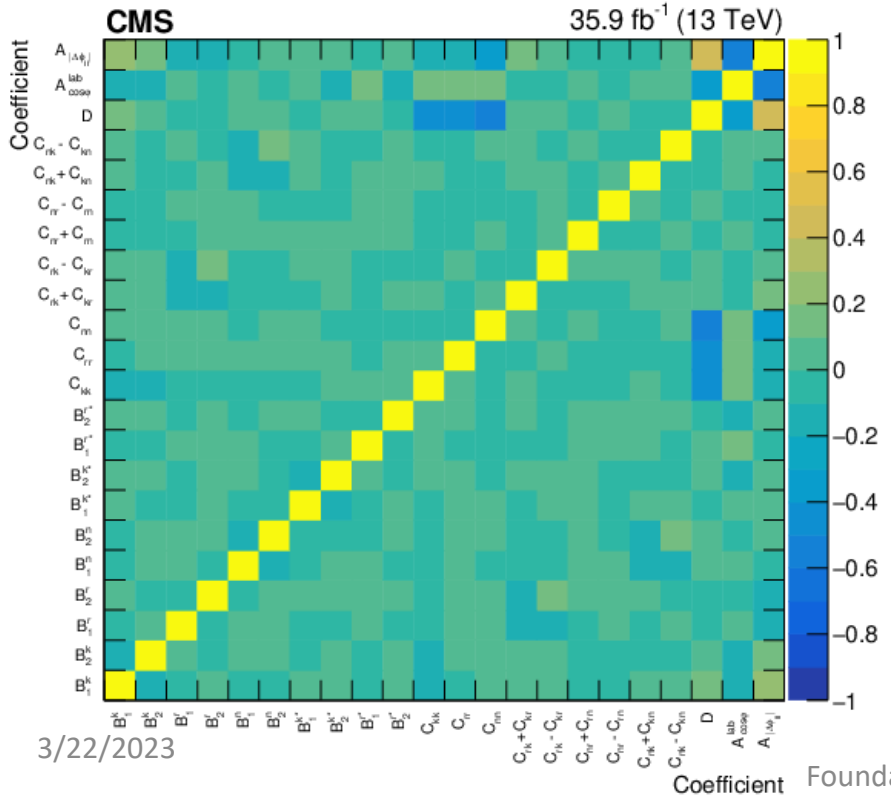
- Systematic correlations between bins of normalized distributions
- Clearly uncorrelated is a poor assumption

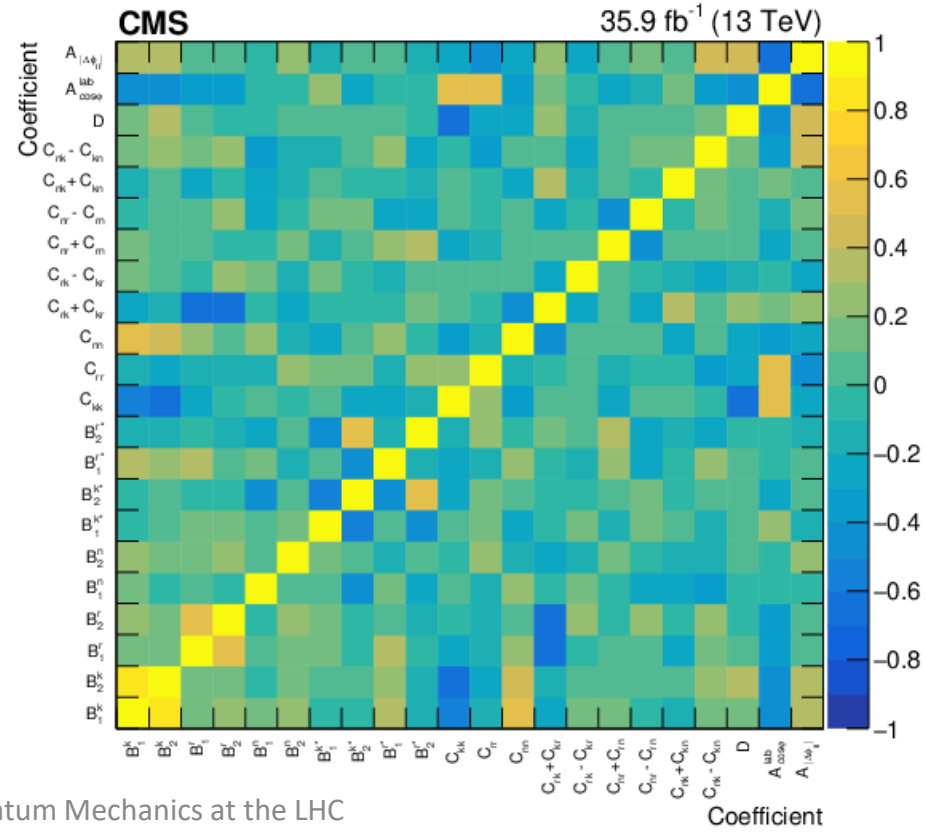


Correlations between all observables

Phys. Rev. D 100, 072002

- Statistical (left) and Systematic (right) correlations between spin coefficients
- Note statistical correlations between diagonal elements of spin correlation matrix and D





Quantum Tomography

- Spin correlations are highly phase-space dependent
- Higher dimensional operators are sensitive to this phase-space dependence

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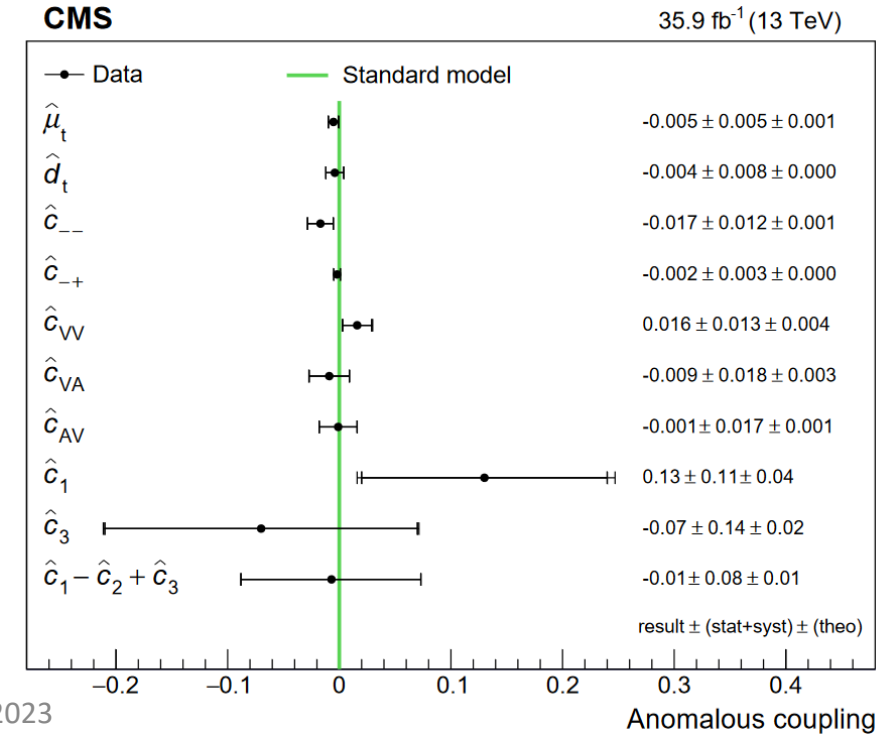
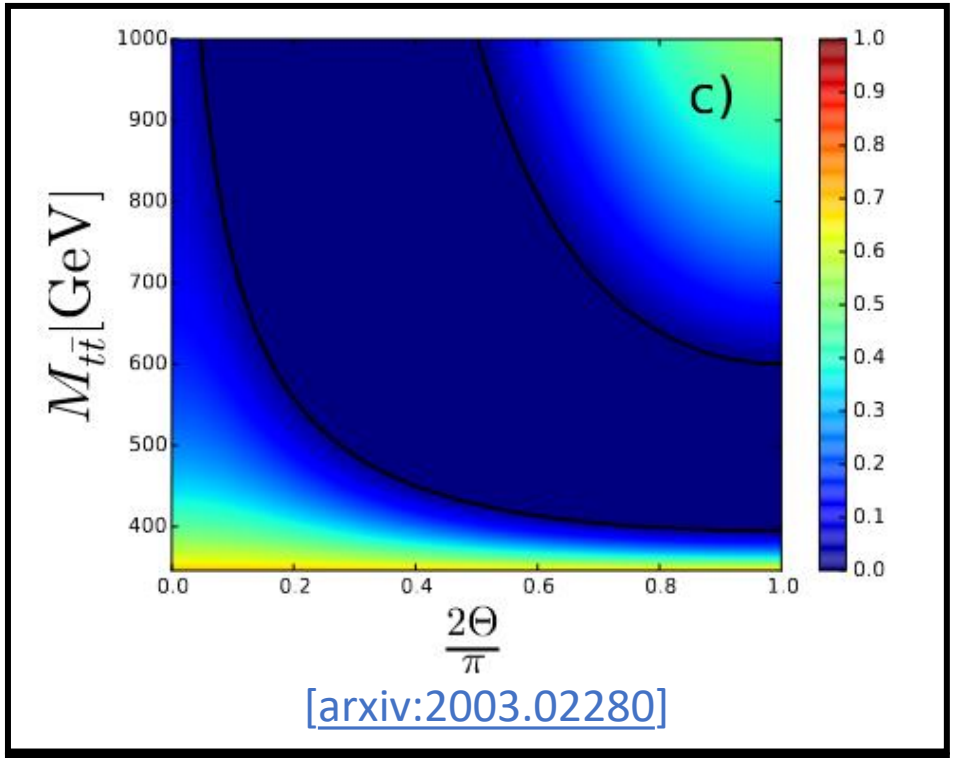
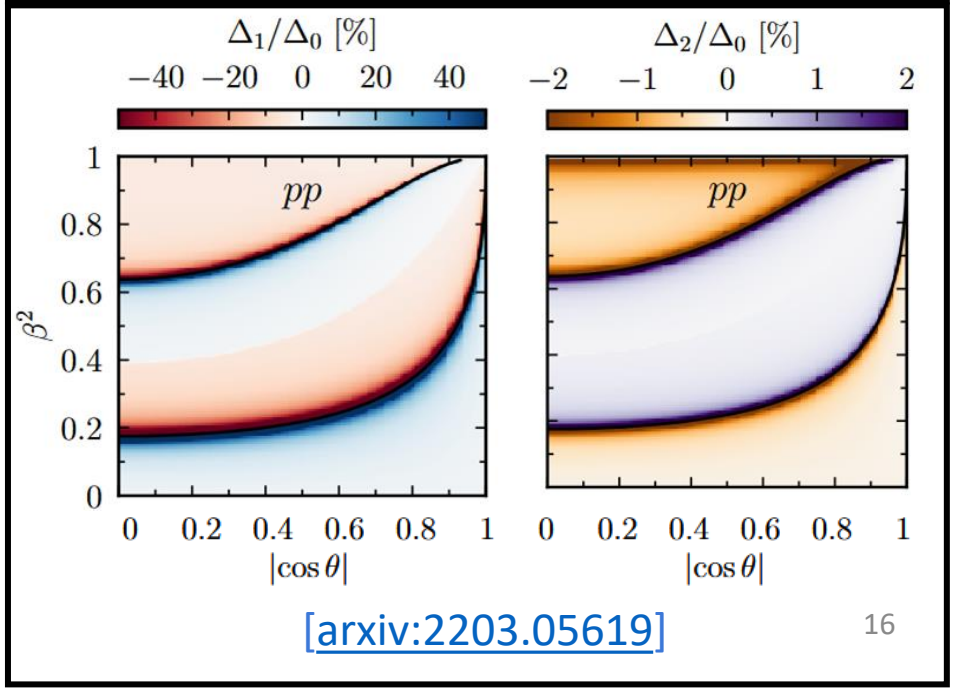




[arxiv:2003.02280]



[arxiv:2203.05619]

Machine Learning (ML) Enhanced Neutrino Reconstruction

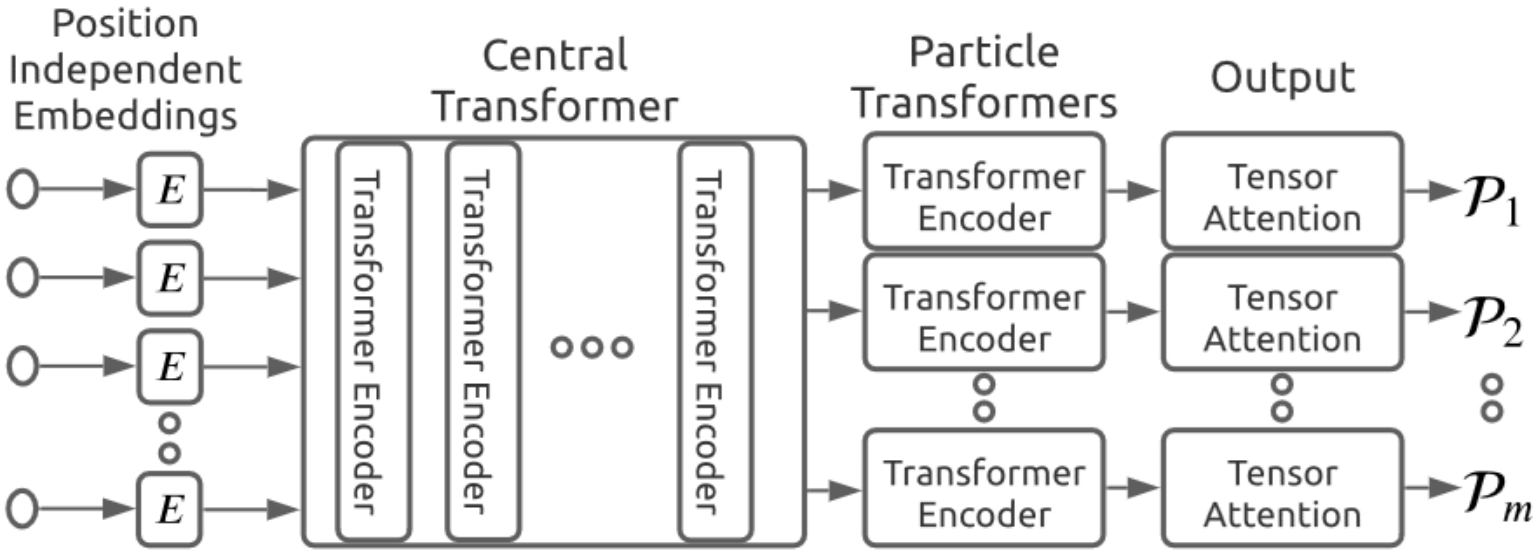
Machine Learning (ML) Neutrino Reconstruction

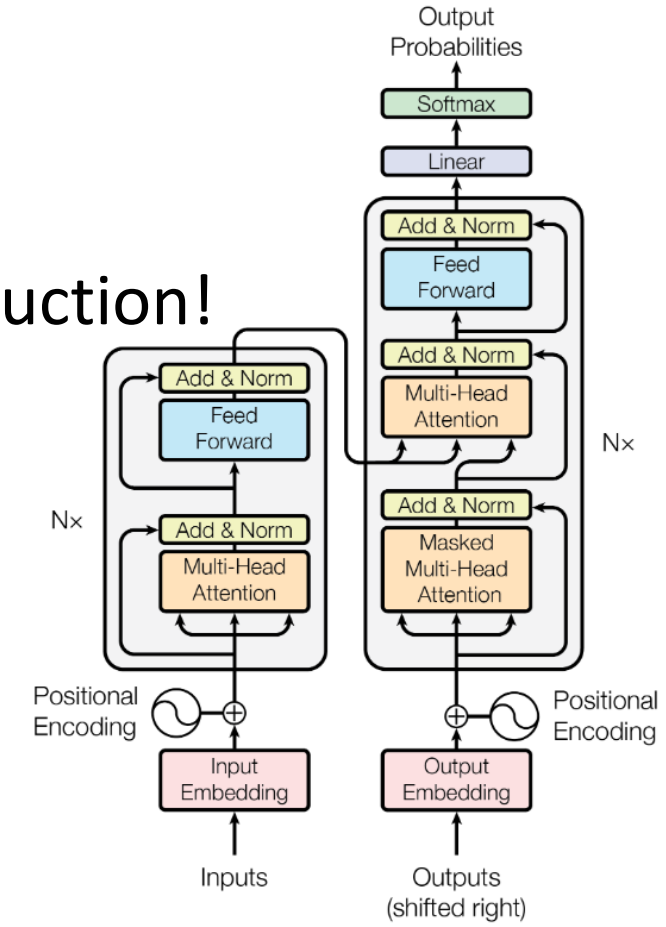
- Can use classical techniques to perform neutrino reconstruction
  - Roots of quartic polynomial
  - Ellipse reconstruction [arxiv:1305.1878]
- Both suffer from either
  - No solution
  - Many solutions
- Can use ML to perform regression directly on neutrino kinematics
  - What architecture to use?

Hadronic Reconstruction with Transformers (SPANet) [arxiv:2106.03898]

- Achieved state-of-the-art reconstruction on 3 full hadronic decays:
  - ttbar - 58.6% vs. 38.7% reconstruction efficiency
  - ttbarH - 33.0% vs 4.5% reconstruction efficiency
  - tttt - 23.1% vs 0.00% reconstruction efficiency
- Maybe we can see similar gains in neutrino reconstruction!

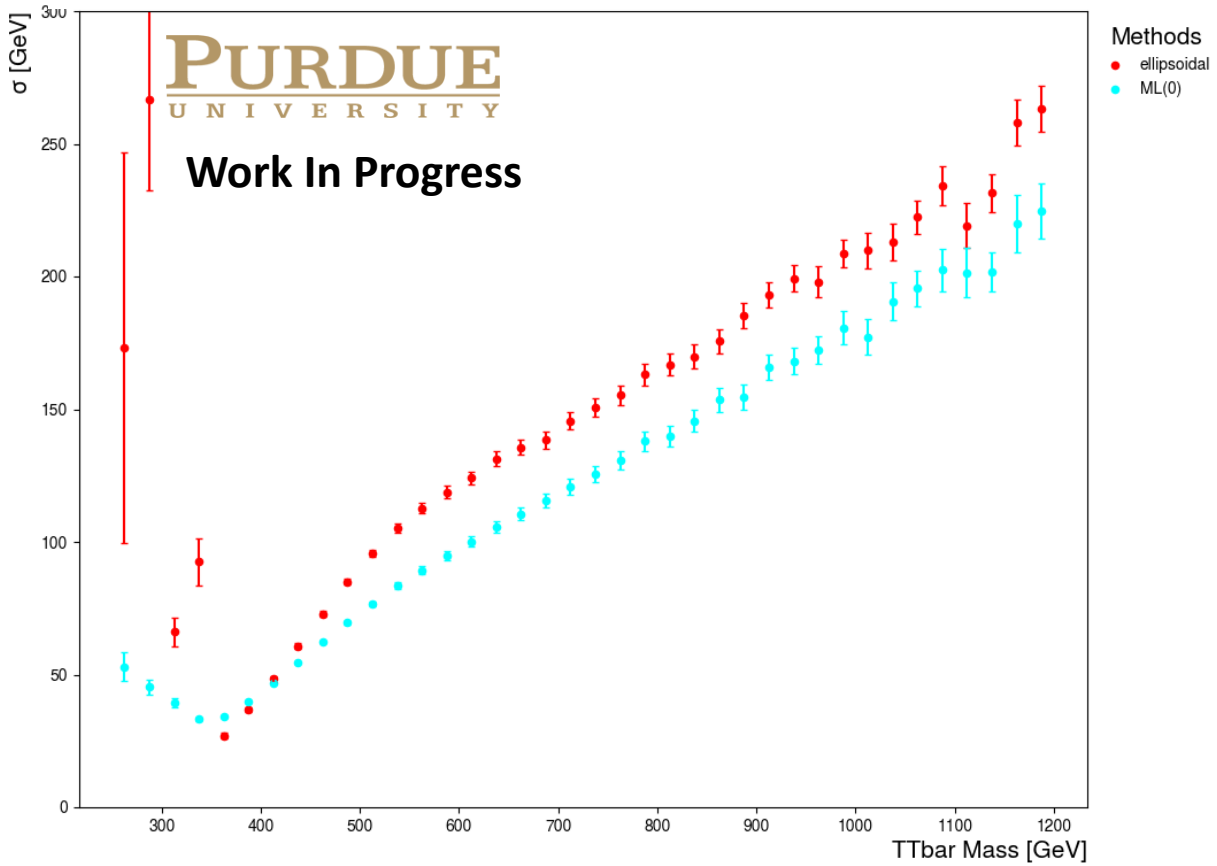
[arxiv:1706.03762]





ML Results on Neutrino Reconstruction

- Used on private Delphes dataset
- Adding benchmarks and investigating impacts on spin correlation and polarization observables
  - Ellipse-based reconstruction [arxiv:1305.1878]
  - Neutrino reweighing
  - Other ML algorithms/models

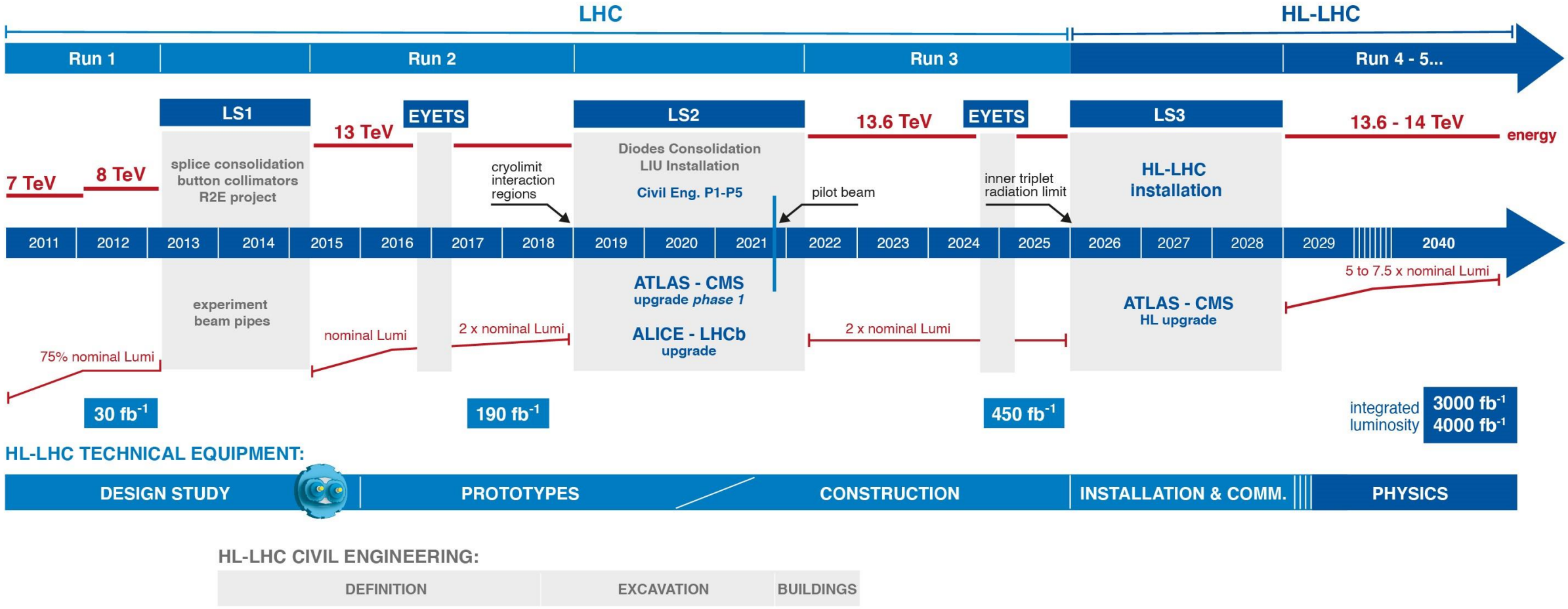


High Luminosity LHC (HL-LHC)

$L_{\text{int}} \cong 3000\ fb^{-1}$

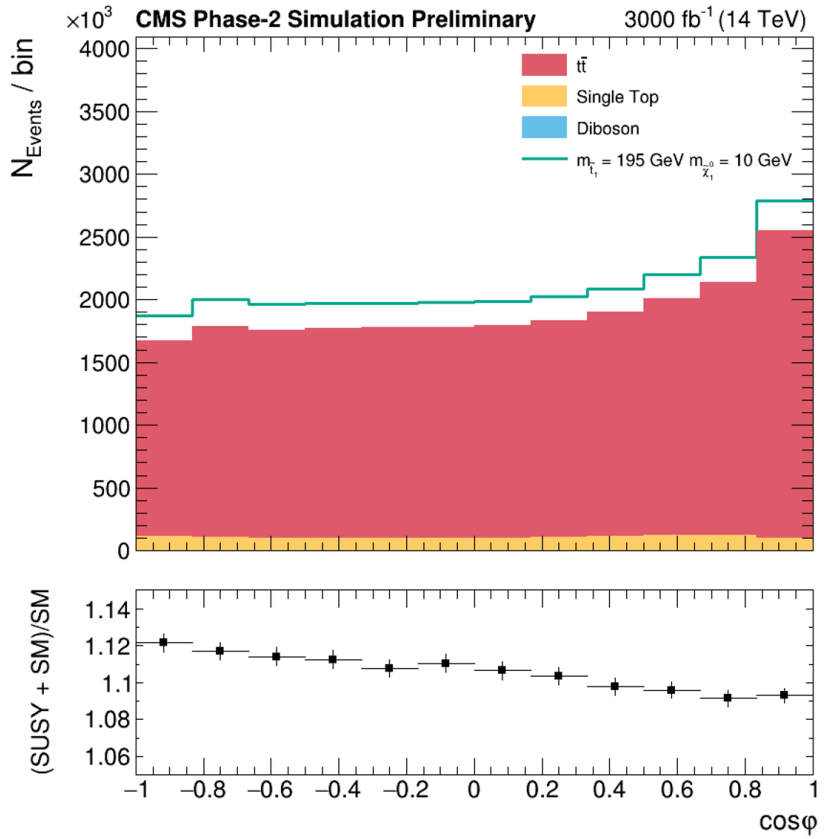
CMS-FTR-18-034

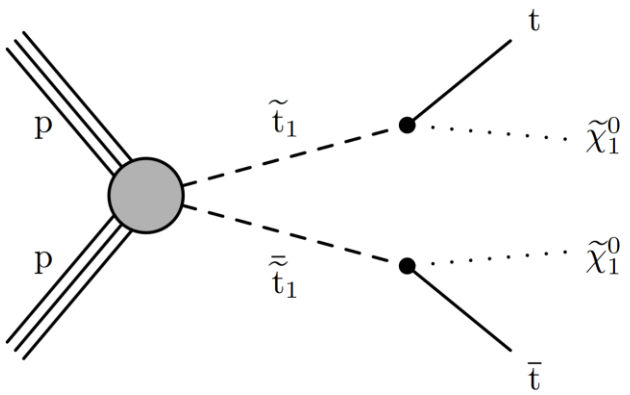
LHC / HL-LHC Plan

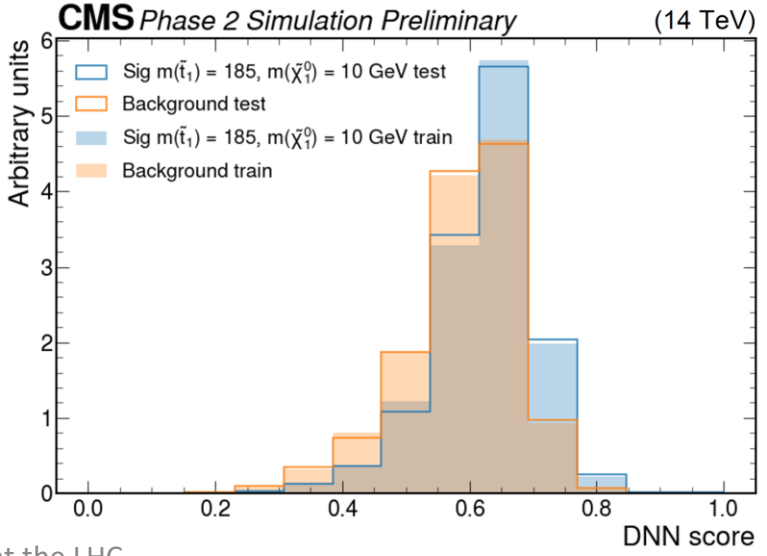


Projection Study [CMS-FTR-18-034]

- Project impact of HL-LHC on spin correlations and limits on stop (supersymmetric top quarks) production
- Uses ellipse reconstruction algorithm [arxiv:1305.1878]
- 14 TeV, 3 ab^{-1}
- DNN trained on spin correlation variables

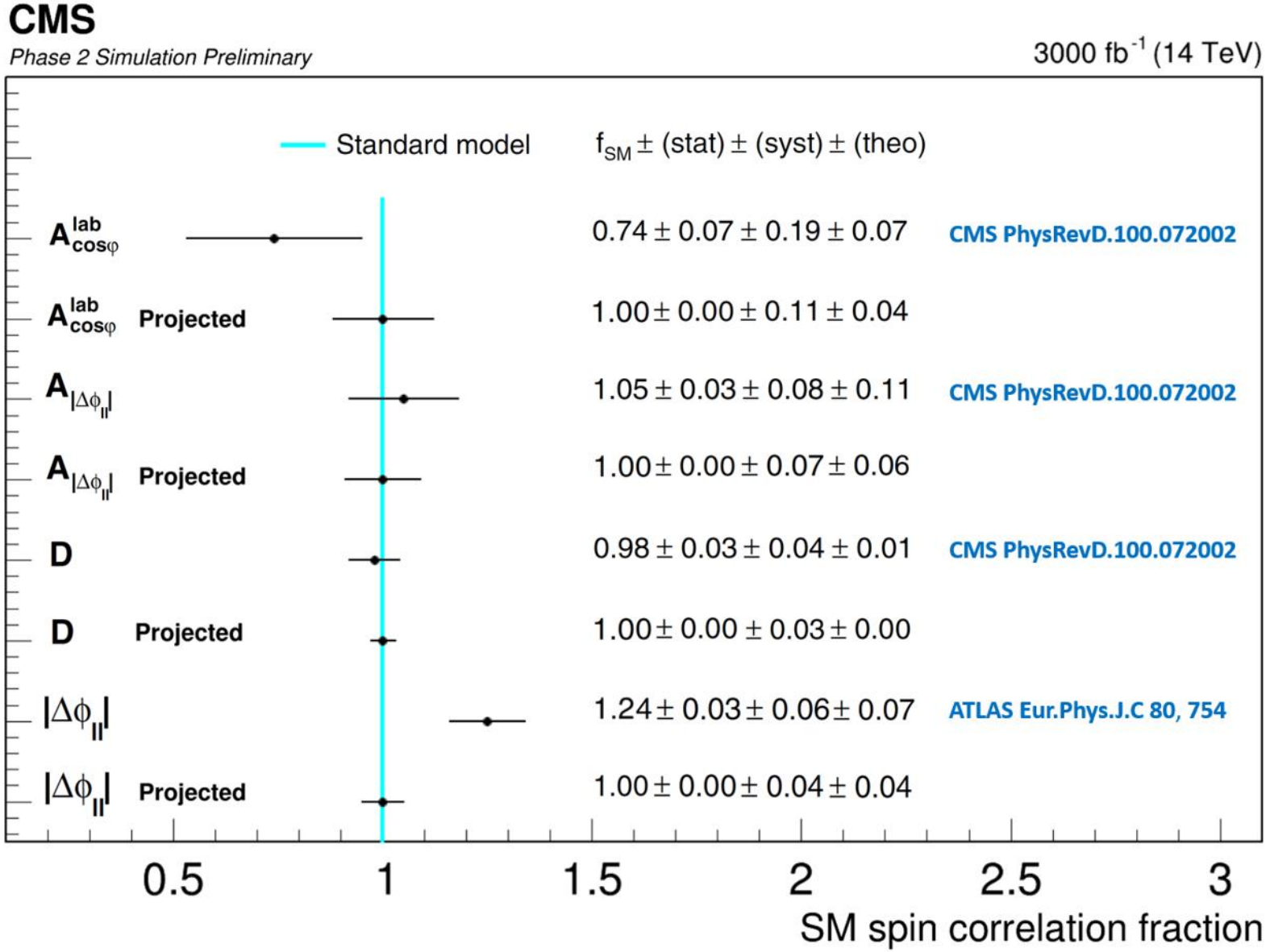






Full LHC Extrapolation [CMS-FTR-18-034]

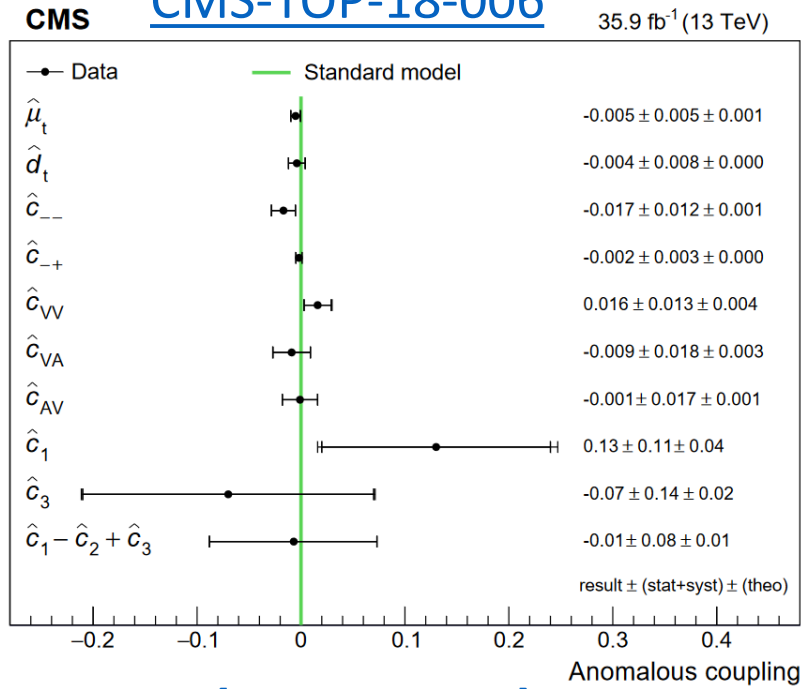
- Statistical uncertainty becomes negligible
- Systematics are reduced based on yellow paper suggestions
- Improve precision on D by ~60%



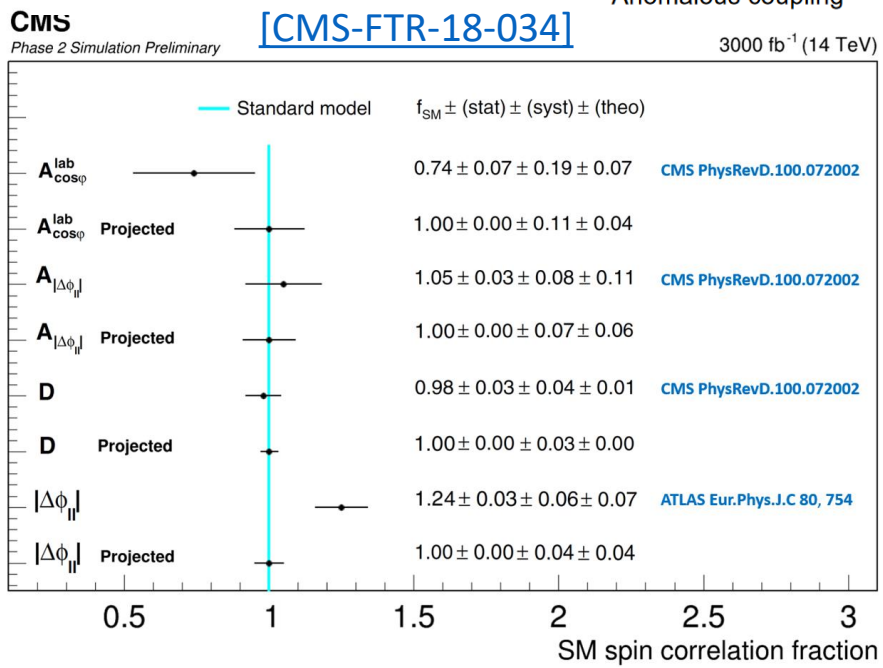
Summary

- Full spin density matrix measurement has been performed
- Agrees thus far with SM expectation
- Spin correlation/information is very useful
  - Constrain EFT operators [Phys. Rev. D 100, 072002]
  - Exclusion limits on stop production [CMS-FTR-18-034]
  - And more…
- Plenty of new exciting ideas
  - Quantum tomography [arxiv:2003.02280]
  - Discord [arxiv:2209.03969], Bell's Inequality[arxiv:2102.11883, arxiv:2110.10112], Entanglement [arxiv:2003.02280, arxiv:2110.10112], etc

CMS-TOP-18-006



[CMS-FTR-18-034]



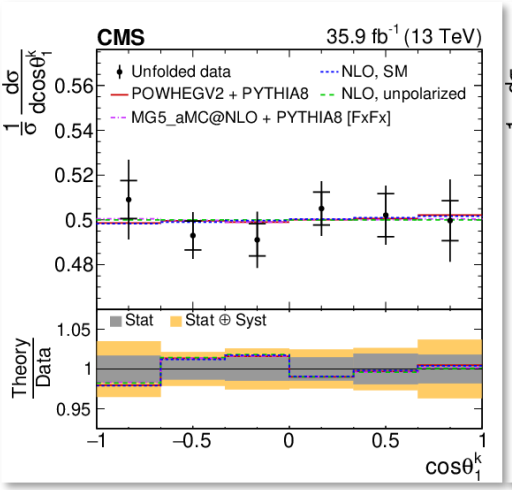
Top Quark Precision Frontier & Quantum Tomography

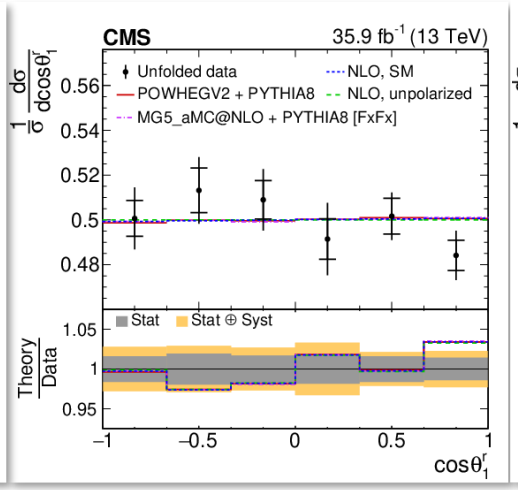
- Workshop on latest results at precision frontier of top quark physics, Oct. 2-3rd 2023.
- New probes to top quark physics
  - Entanglement, Quantum tomography
  - Latest developments on AI + ML
- 2-day satellite event to TOP23
  - Venue: Purdue University
  - Registration Fee's likely around 100$ / person
  - Discount for students & TOP23 participants
  - All plenaries, agenda in preparation
- Contact: Dr. Andy Jung at anjung@purdue.edu for details

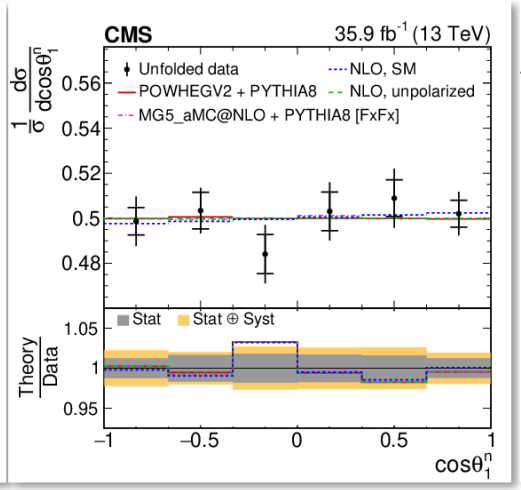
Backup

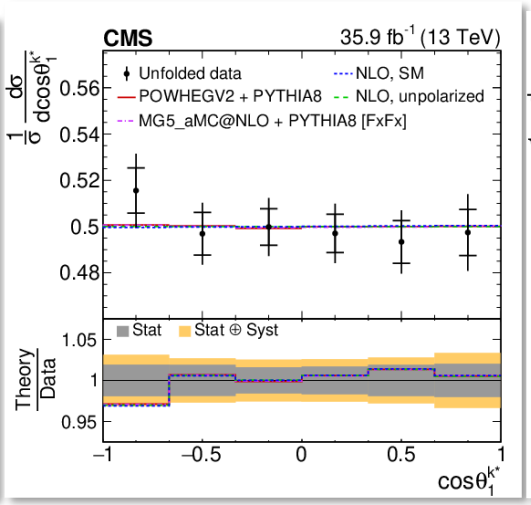
Spin Density Matrix Polarizations - 2016 Results

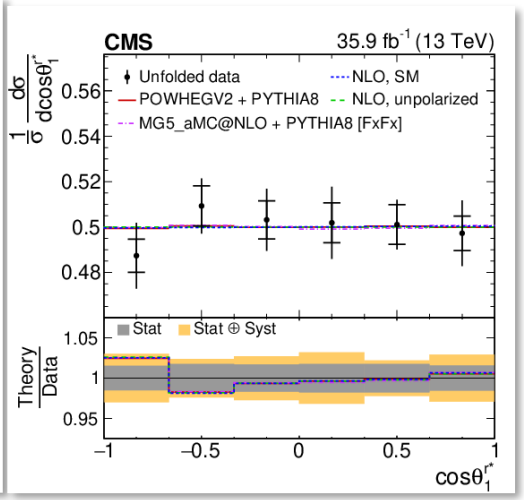
Phys. Rev. D 100, 072002

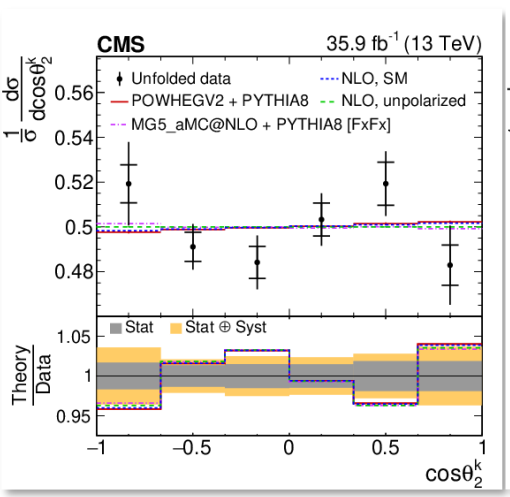


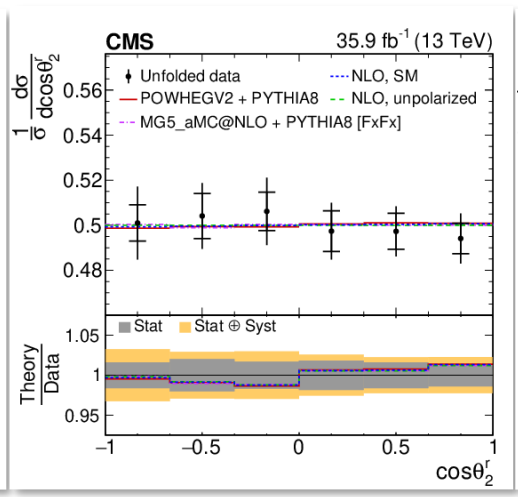


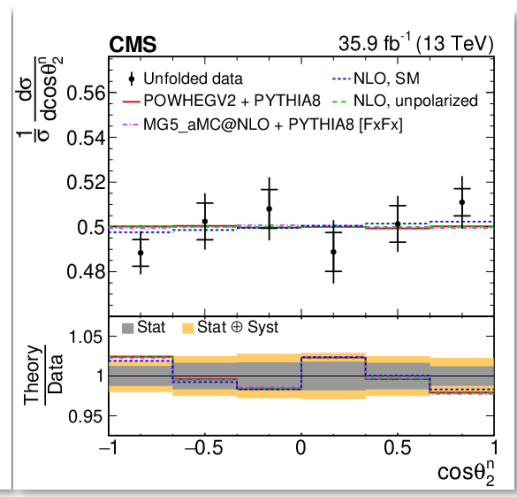


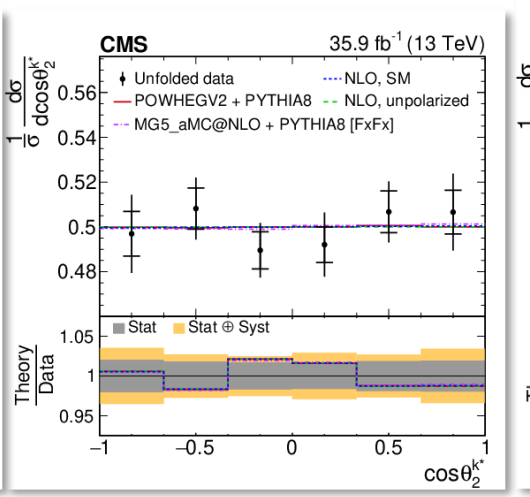


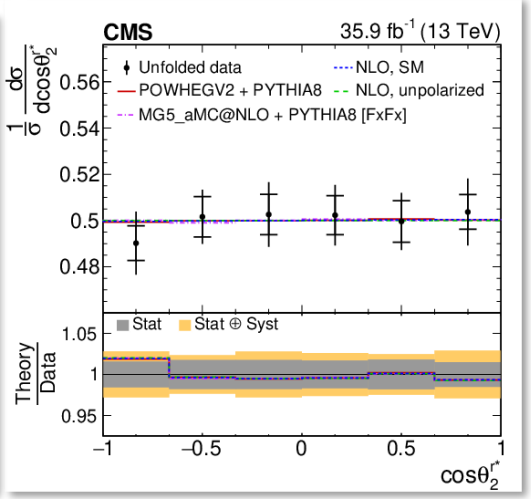






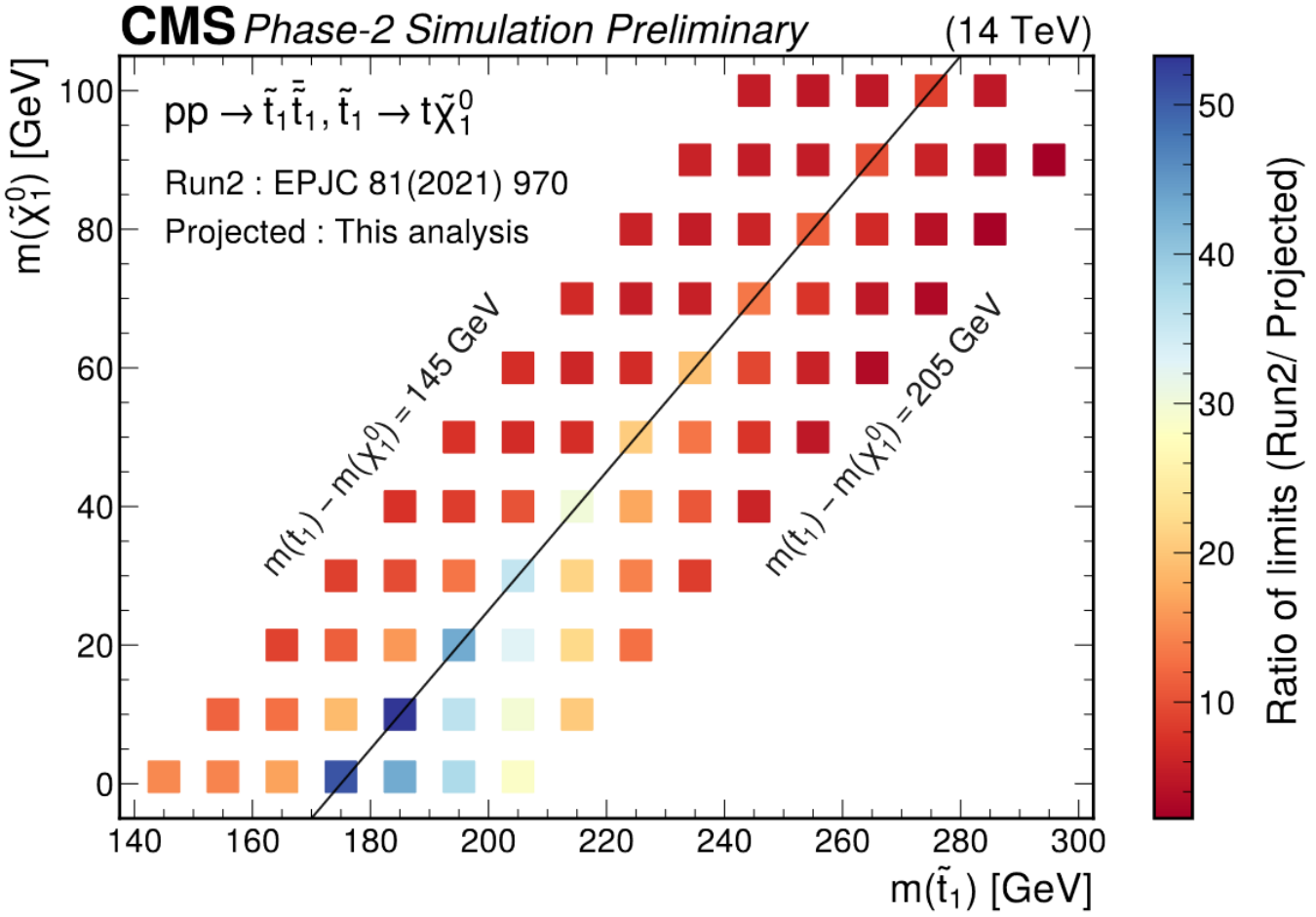






SUSY top Production Limit Improvement

- ~4x improvement comes from statistics
- Maybe another ~5x comes from systematic uncertainty reduction
- **Improvements > 10x come from using spin correlations in deep neural network**



ML Reconstruction on Scattering Angle

- No real improvement over ellipse reconstruction