A Search for Sphalerons at the Large Hadron Collider

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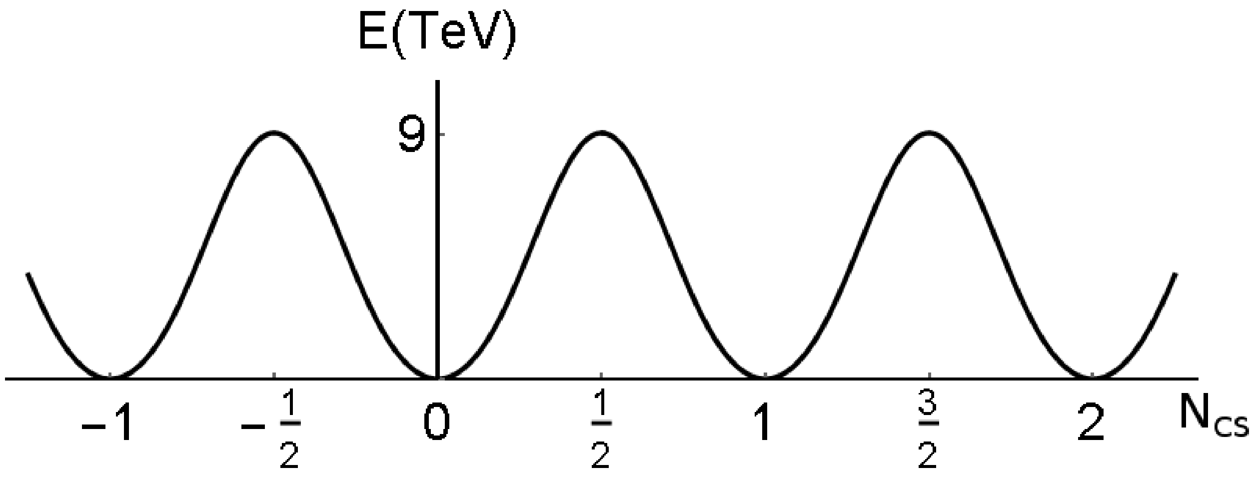
What is a Sphaleron?

- Non-abelian gauge field configuration
  - First proposed by 't Hooft in 1976
  - Sister to instantons
  - Potential in Chern-Simons number (N_{CS}) of gauge field
- Not yet discovered, now know SM energy: **~9 TeV**
  - Higgs mass was the last piece needed to calculate
  - “Fireball” final states: around twelve 0.8 TeV particles
- **Violates B+L**
  - B-L is conserved
  - Potential piece of universal matter antimatter asymmetry
- **First dedicated EW sphaleron search**
  - Using full 2016 CMS dataset
  - QCD sphalerons violate chirality and searched for by ALICE (https://indico.cern.ch/event/656773/)

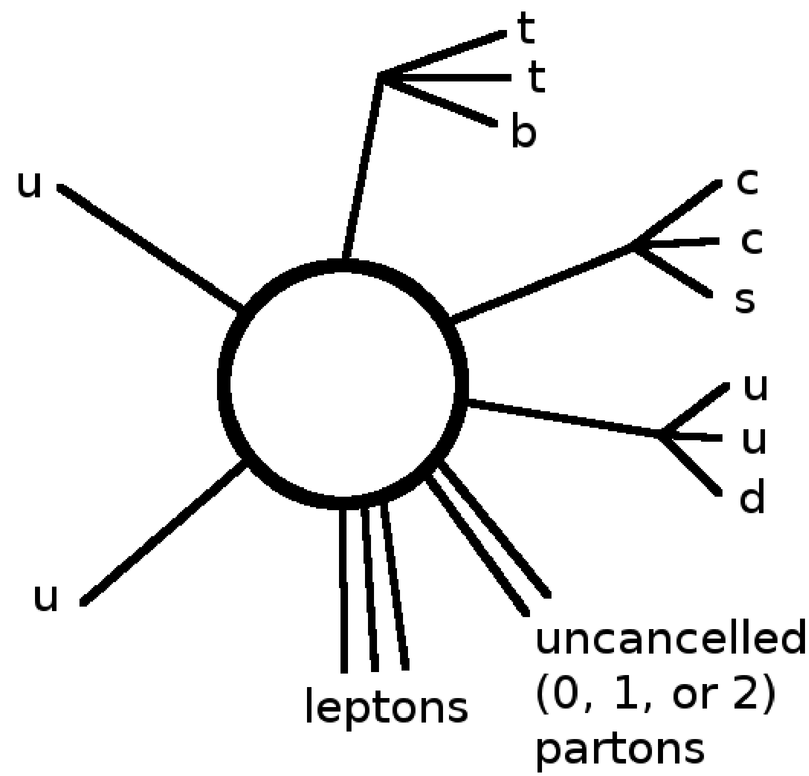


Where to Begin?

- Phenomenology of B+L violating part of transitions has never been fully studied
- Only public generator makes complicated assumptions which include the generation of an additional O(30) electroweak gauge bosons
  - Theorists have a lot of disagreement
- What would a “minimal” model look like?
  - Want model focused on B+L violation
  - Distill complex parameter space into salient experimental signatures

How to Build Final States?

- There are 12 different SM fermion doublets
  - One lepton doublet for each generation
  - Three quark doublets for each generation
  - All fermions of a given configuration are exclusively matter or anti-matter, corresponding to $\Delta N_{CS} = 1$ or -1
- Pair doublets and choose opposite SU(2) indices for each pair, this guarantees all relevant charges are conserved
  - 1,330,560 quantum mechanically unique fermionic configurations
- Cancel partons if any quark-antiquark pairs exist

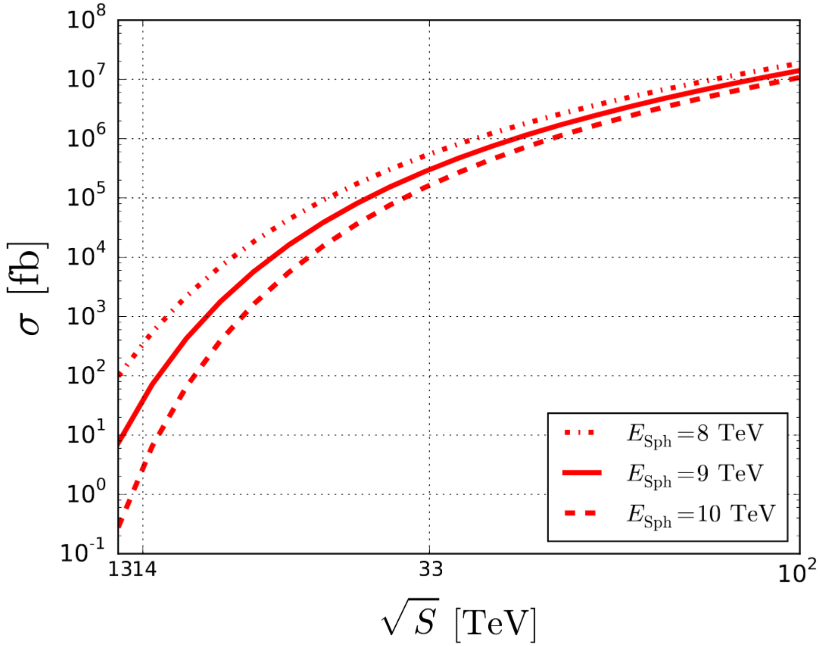


Phenomenological Final States

- Many of the 1,330,560 different final states are phenomenologically identical in a collider experiment
  - e uud μ ccs τ ttb
  - e udu μ csc τ tbt these are different in QM (color charge)
- At CMS u, d, c, and s are difficult to distinguish from each other. There are 8 lepton configurations and 4 configurations of 3 3rd generation quarks, making **32** phenomenological final states
  - 1/8 have 3 neutrinos (before W decays)
  - ttt, ttb, tbb, and bbb 3rd generation quark configurations each characterize 1/8, 3/8, 3/8, 1/8 of the final states respectively

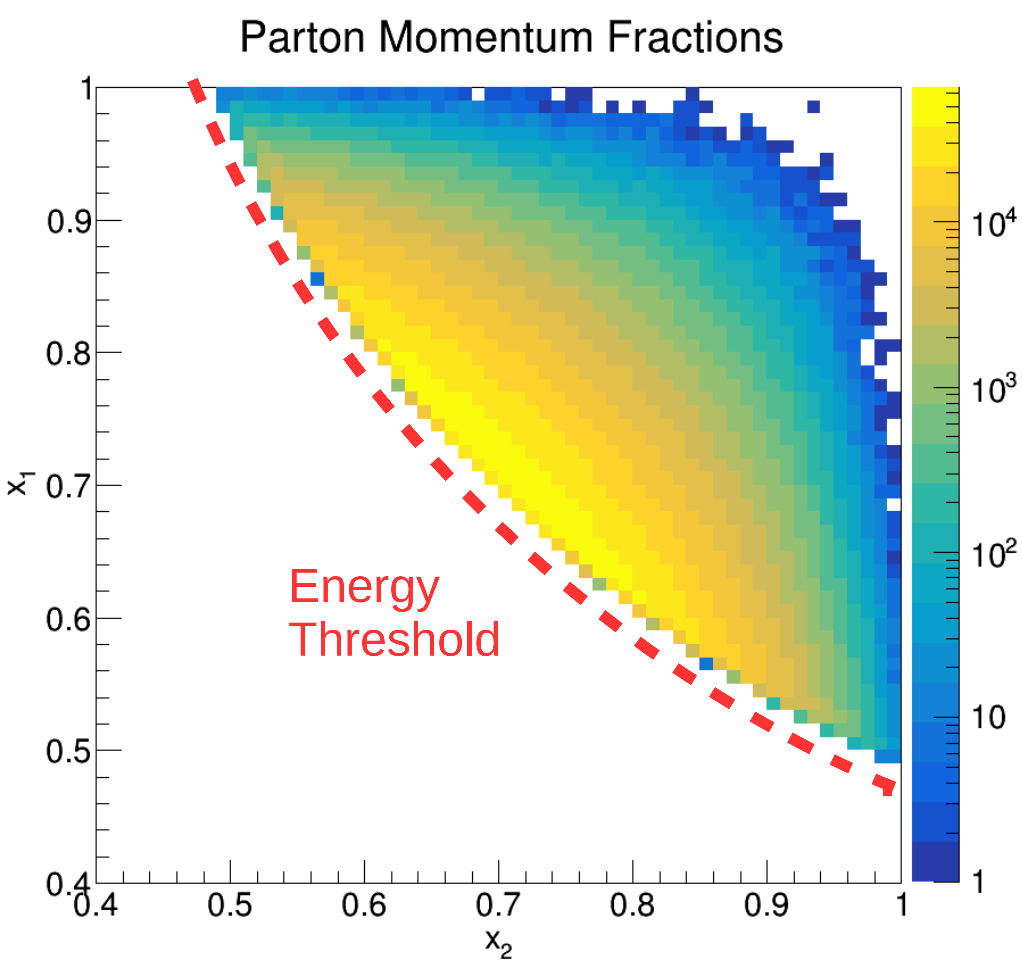
Sphaleron Phenomenology

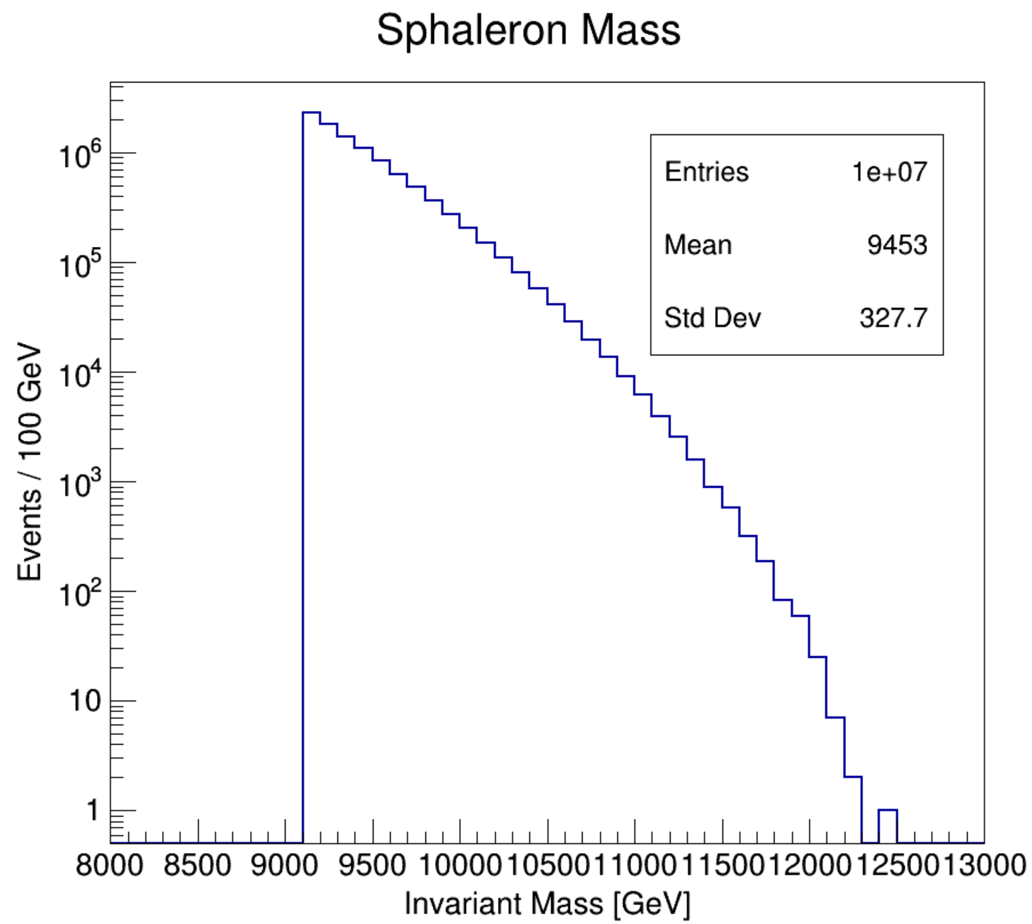
- 10/12/14 particles sharing 9 TeV so each has on average about 760 GeV
  - 4/6/8 light quark jets
  - There are always 3 b's, including b's from tops
  - ≤ 3 W's all the same sign
  - 0 or 1 of each e, μ, and τ, which will all be the same sign
  - ≤ 3 ν's
  - Example: e uud μ ccs τ ttb uu



- $S_T = H_T$ + Lepton E_T + Photon E_T + *MET* is ~7 TeV on average
- σ = *PEF**10 fb, *PEF* = [0,1] is the pre-exponential factor for a threshold of 9 TeV at sqrt(s) = 13 TeV [Ellis and Sakurai, arXiv:1601.03654]
  - The cross-section for PEF = 1 corresponds to all quark-quark interactions over the energy threshold and comes from the parton distribution functions (PDF)

BaryoGEN, a New MC Generator

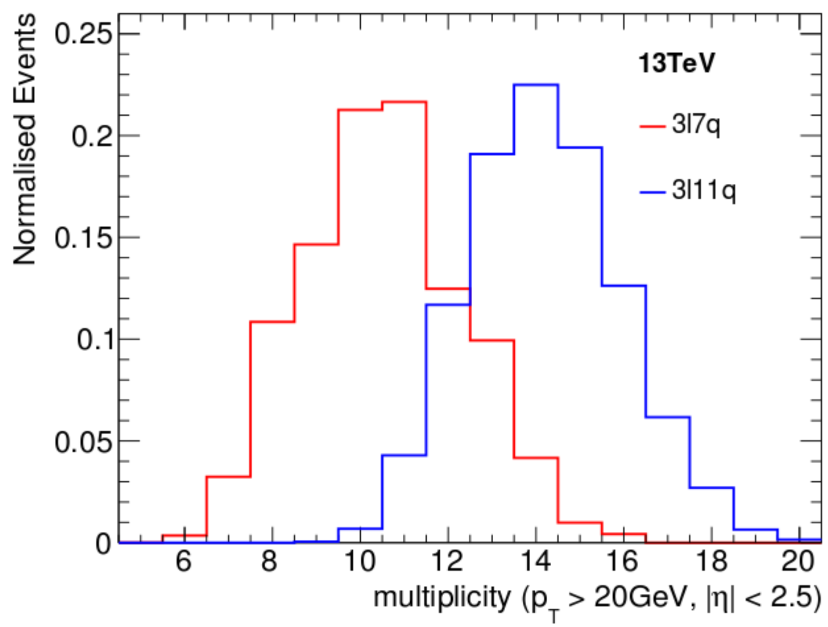




- Available on github: https://github.com/cbravo135/BaryoGEN
- Paper recently accepted at JHEP (C. Bravo and J. Hauser, arXiv:1805.02786)

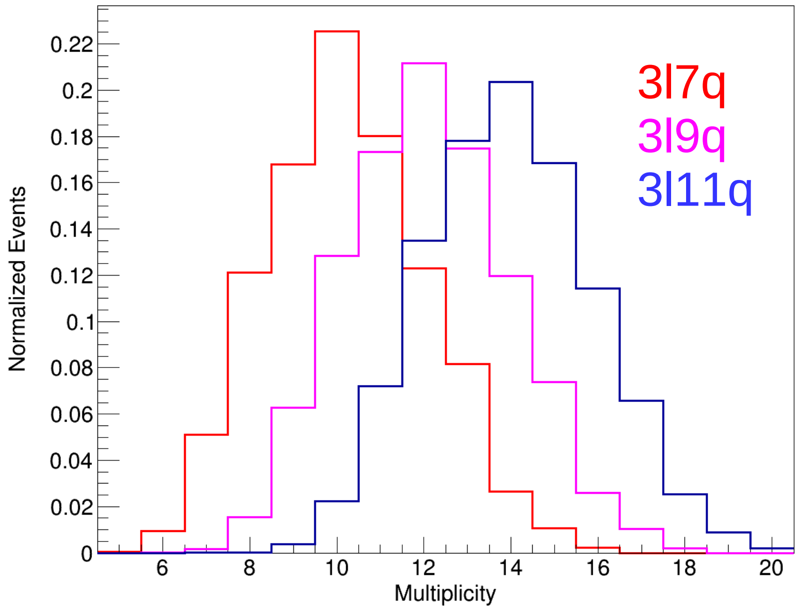
Comparison with Ellis and Sakurai

3l7q, 3l9q, and 3l11q are different outgoing parton multiplicities due to cancellation with incoming states



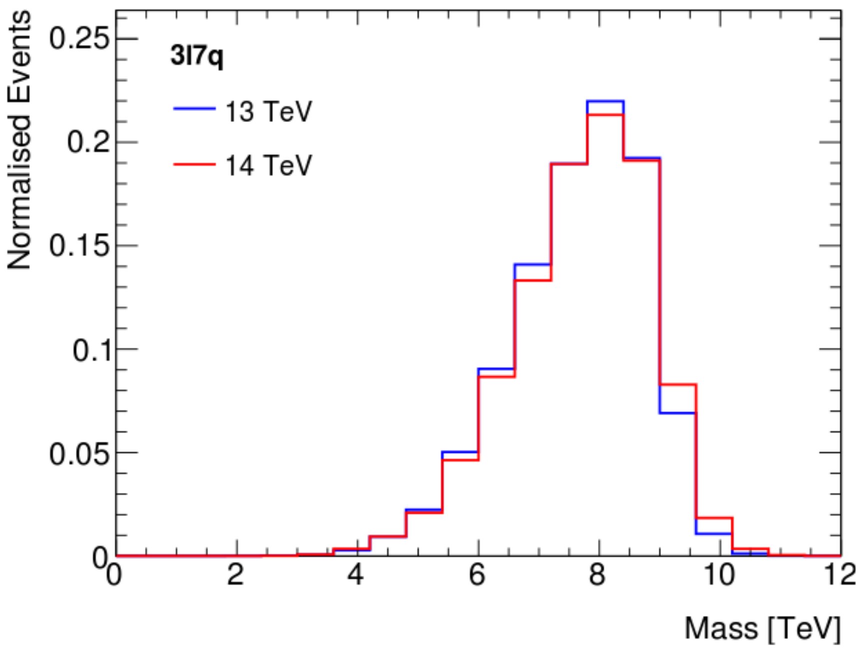
Ellis and Sakurai

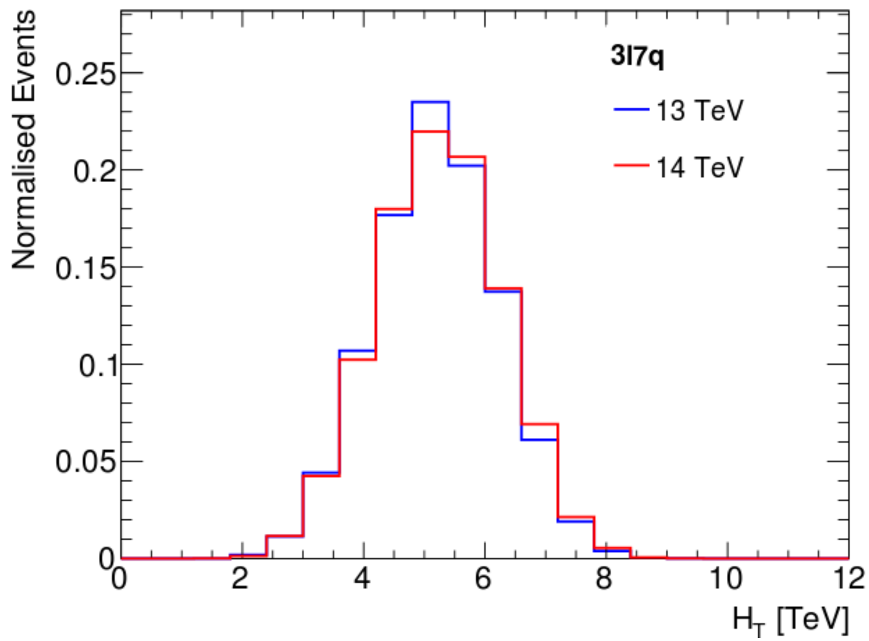
w.r.t. Ellis and Sakurai I am adding 3l9q and additional multiplicity category, which is the case of only one parton cancellation



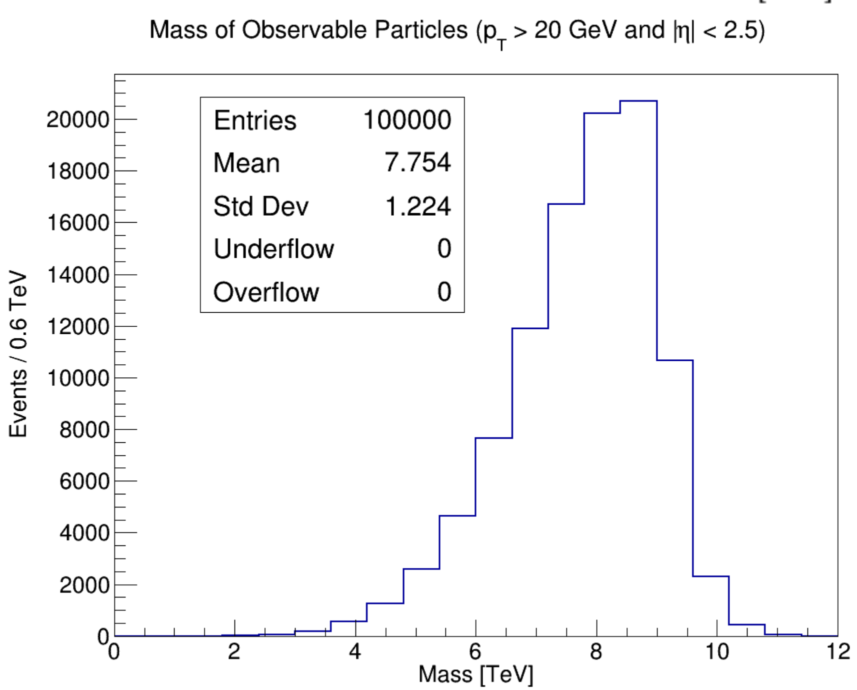
BaryoGEN 13 TeV

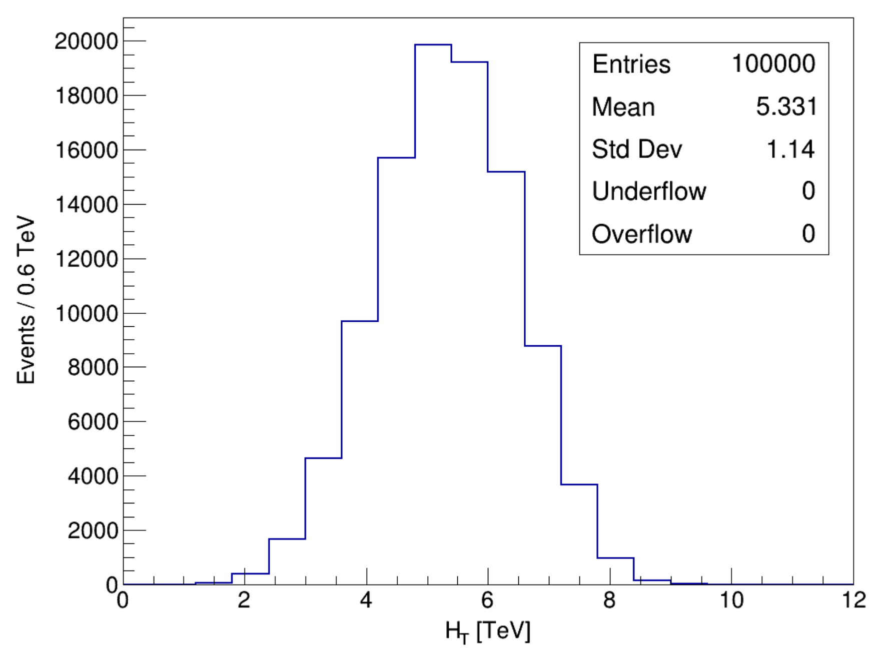
Energy Comparison





Ellis and Sakurai

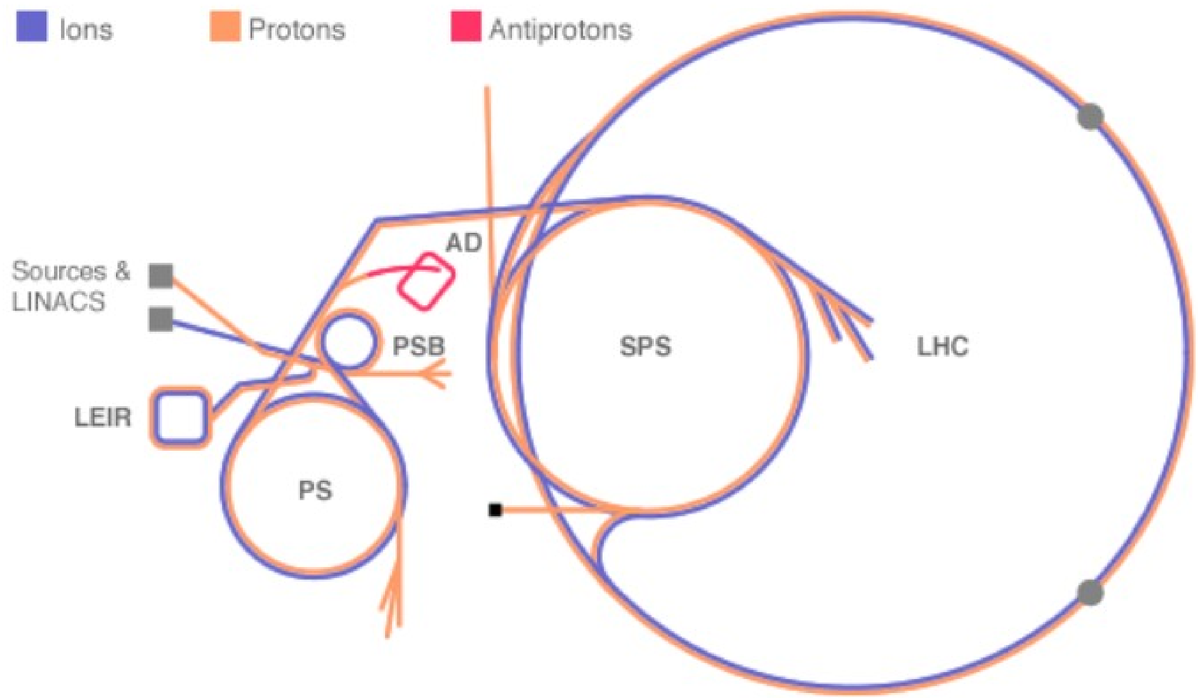




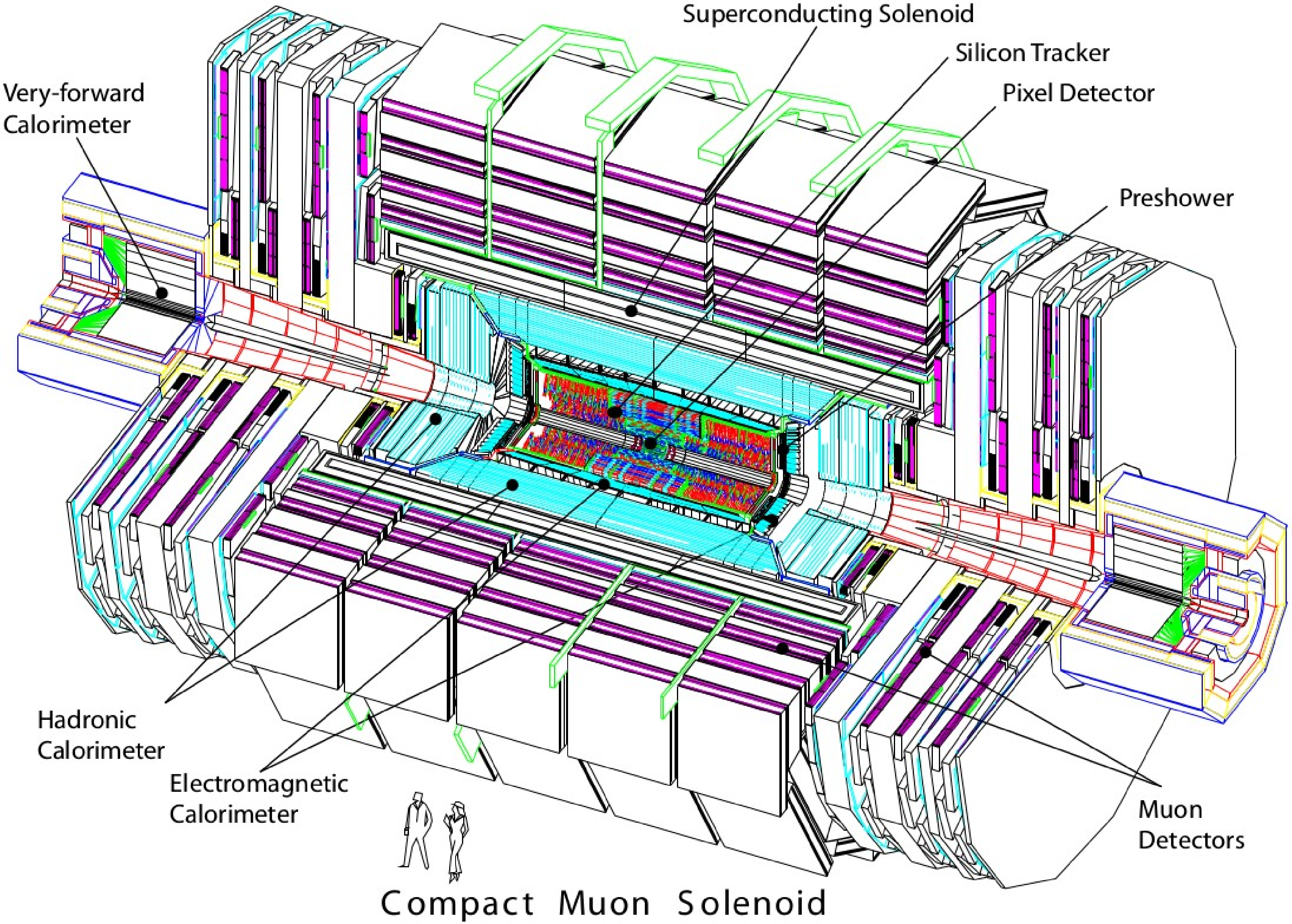
BaryoGEN
13 TeV

How do We Look for It?

- Need the worlds largest particle accelerator: LHC
  - Run 2 with sqrt(s) = 13 TeV is just at the production threshold
  - We can finally start making sphalerons
- Full 2016 CMS dataset
  - Integrated Luminosity: 35.9 fb^{-1}

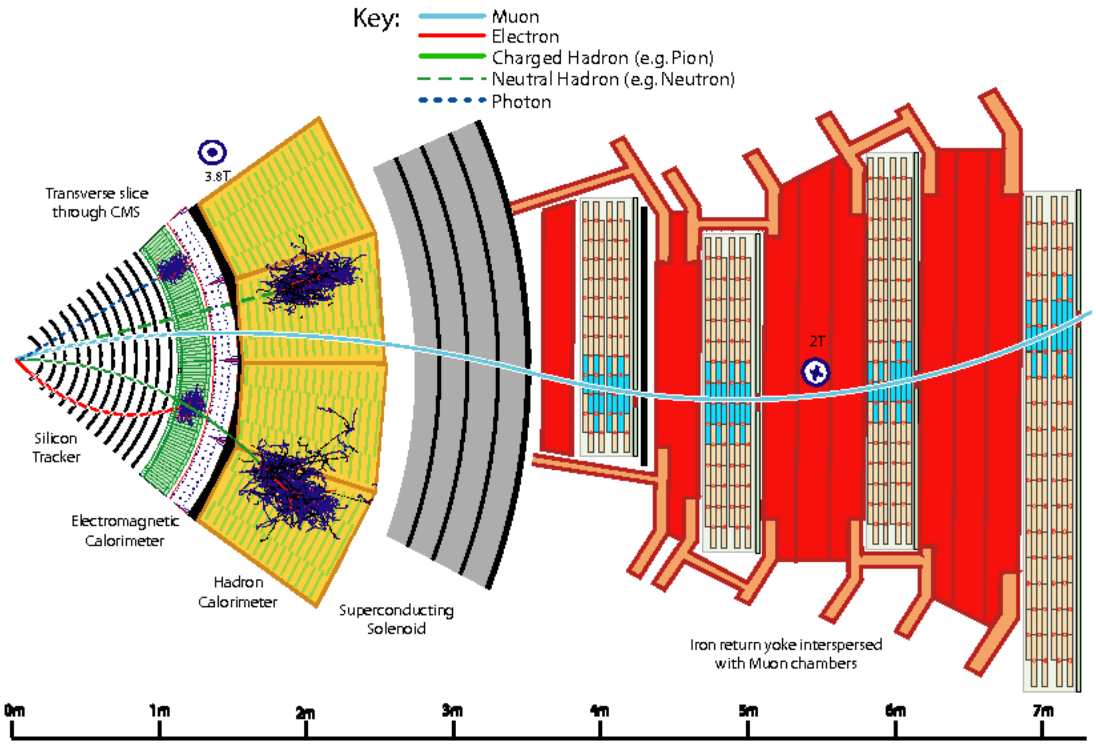


The CMS Detector



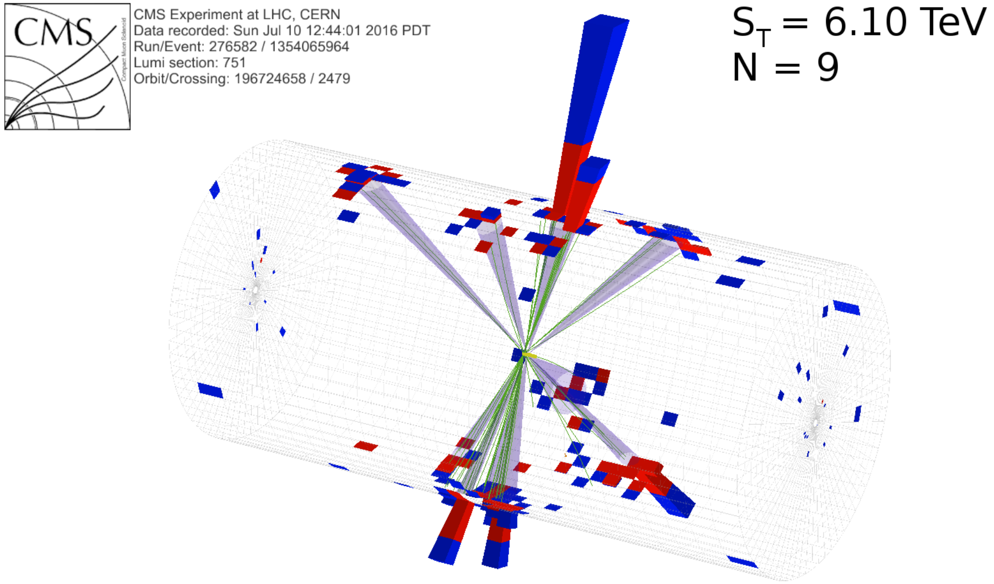
Event Reconstruction

- Build *physics objects* from digital signals: Particle Flow
- Jets
  - Hadrons and photons
  - Calorimeters
- Electrons and Photons
  - ECAL
  - Tracking and Isolation
- Muons
  - Gas detectors
  - Tracking



Introduction to CMS Search

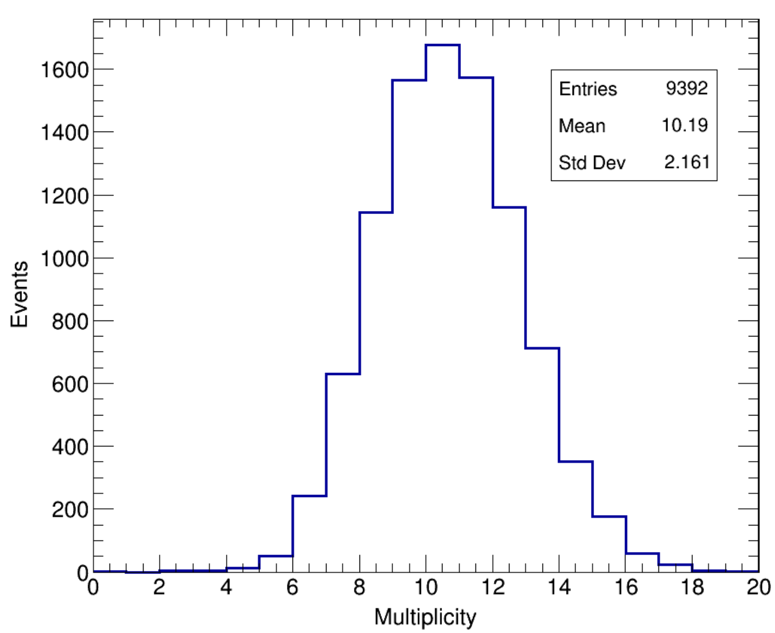
- High energy and high multiplicity search for new physics
- LHC could produce new physics with high (~TeV) mass and decaying into a high multiplicity of physics objects
  - Events with such objects would have high transverse energy, and possibly high MET
- Flagship analysis searching for microscopic black holes is a great fit
  - BH/Sphaleron search is born
- Multijet QCD is the dominant background
- Main results of analysis are model independent limits in case no significant excess is observed

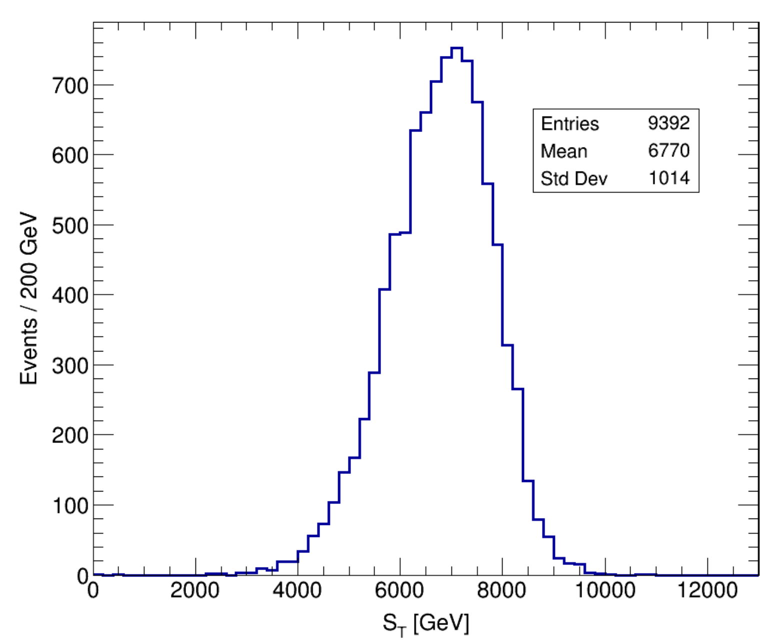


The Data

- Collect data with online high H_T triggers
- Inclusive search: two search variables
  - Multiplicity (*N*) is defined as total number of physics objects over 70 GeV
  - $S_T = \left(\sum_{i=1}^{N} E_{T,i} \right) + E_T^{miss}$ summed over jets, photons, electrons, and muons
- Sensitive to a broad range of high-energy signatures

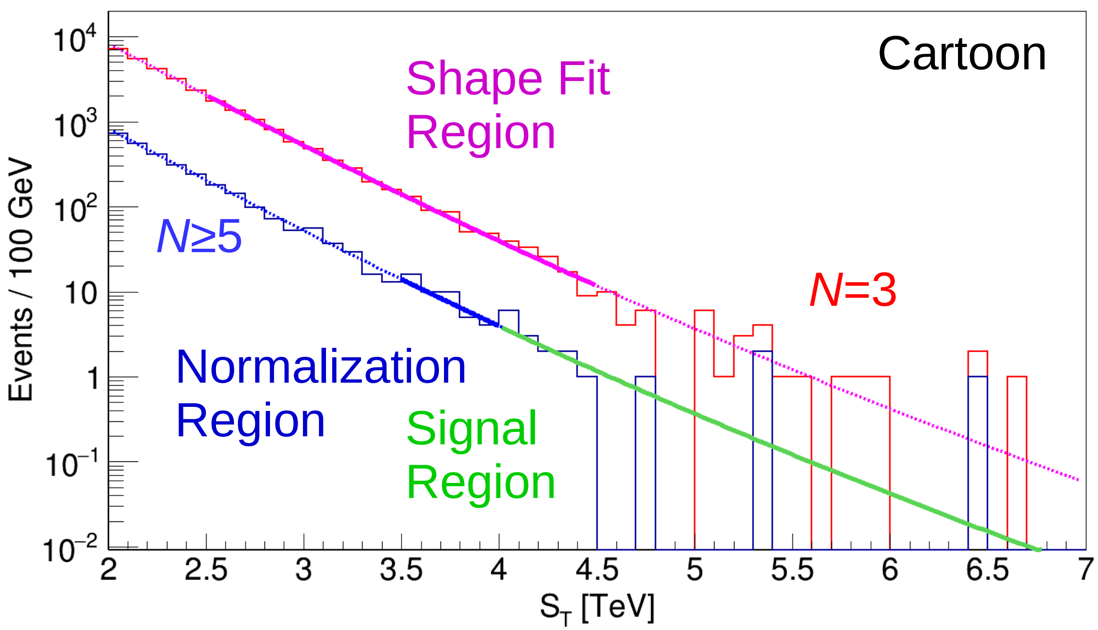
Sphaleron Signal

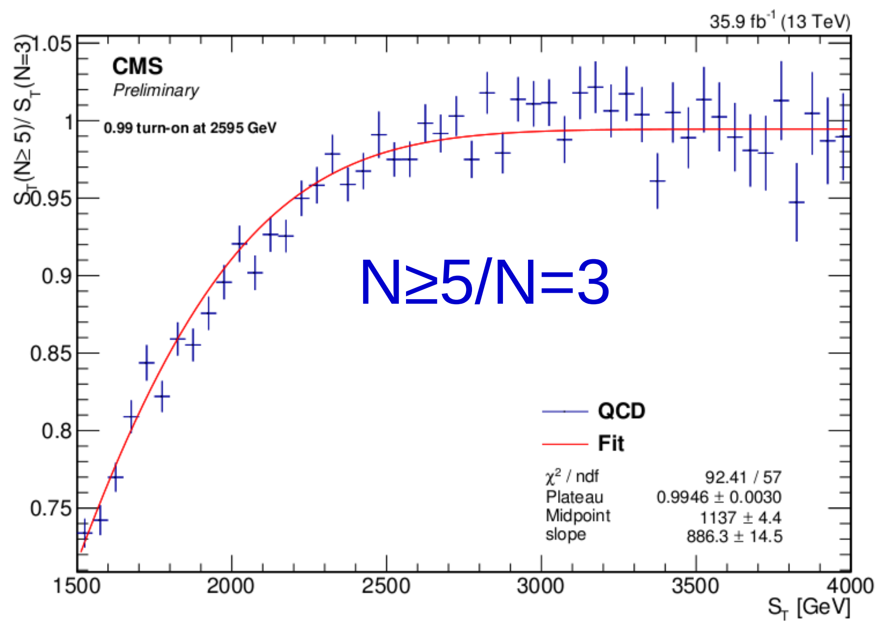




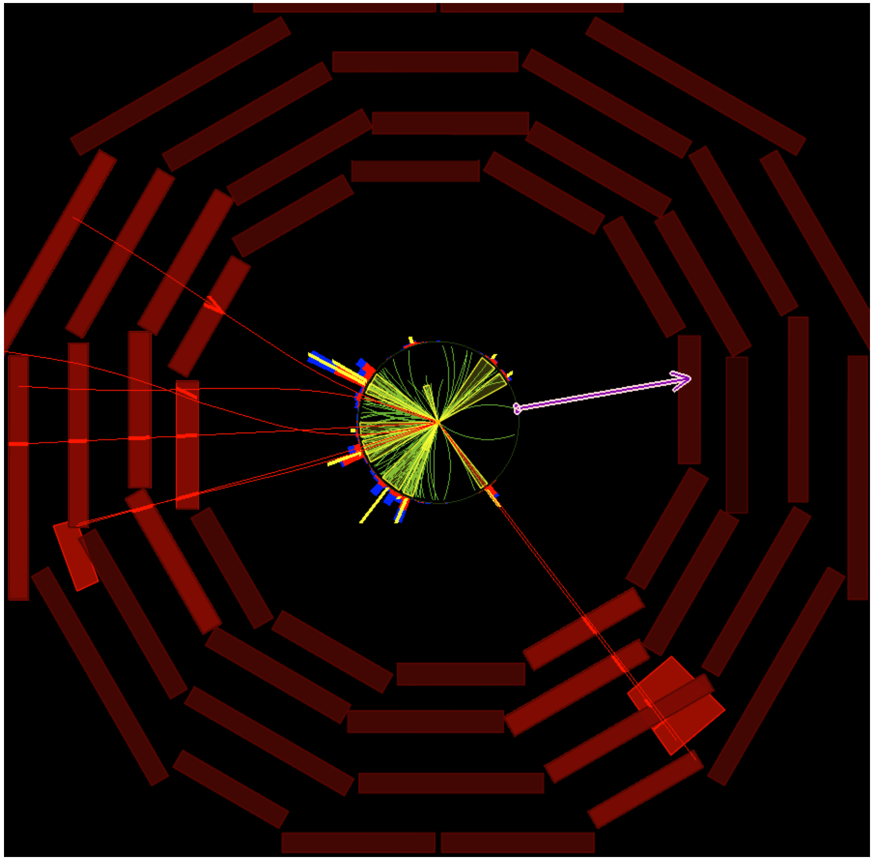
Analysis Strategy

- Data driven background estimation takes advantage of the shape of the S_T spectrum being independent of N
  - Fit shapes to data at low S_T for N=3 and N=4
  - For each N (≥ 3,4,5,6,...,11) scale shape using signal-free normalization region
  - Procedure developed and validated on MC and then applied independently to data





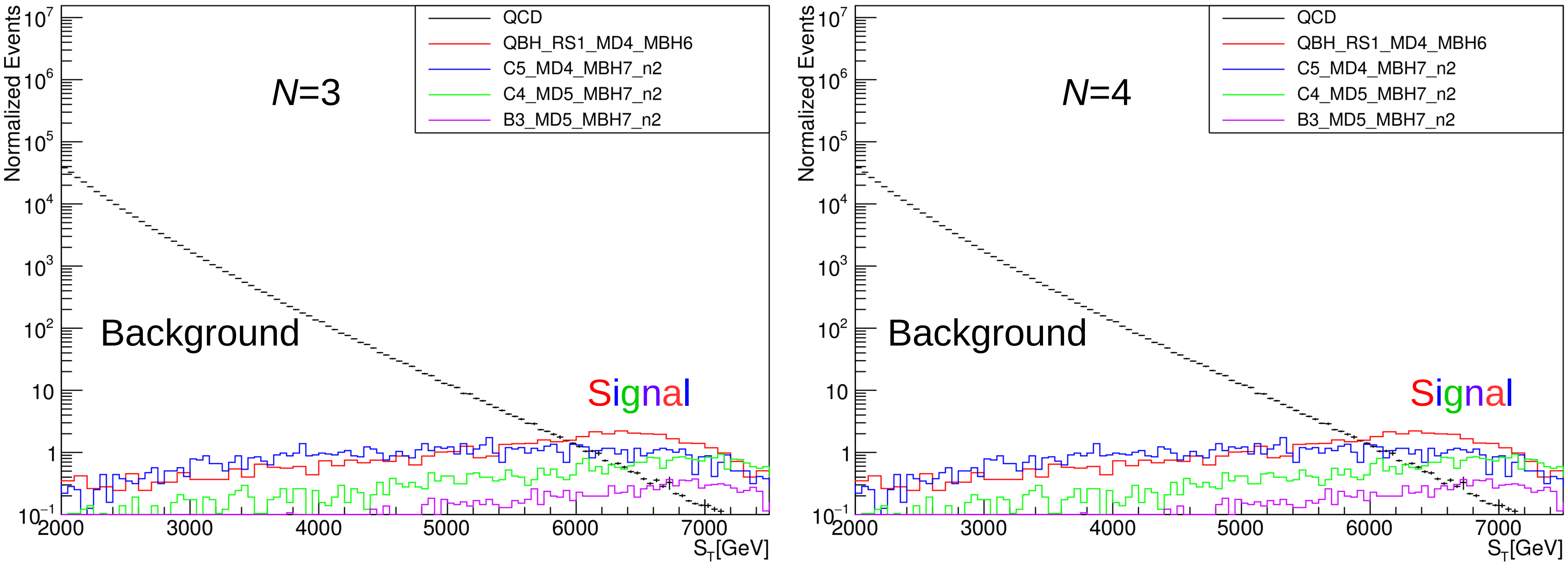
Background Estimation Procedure



Sphaleron MC Event Display

1) Choose fit region
2) Choose fit functions
3) Fit background shape
4) Normalization

Step 1: Choose Fit Region



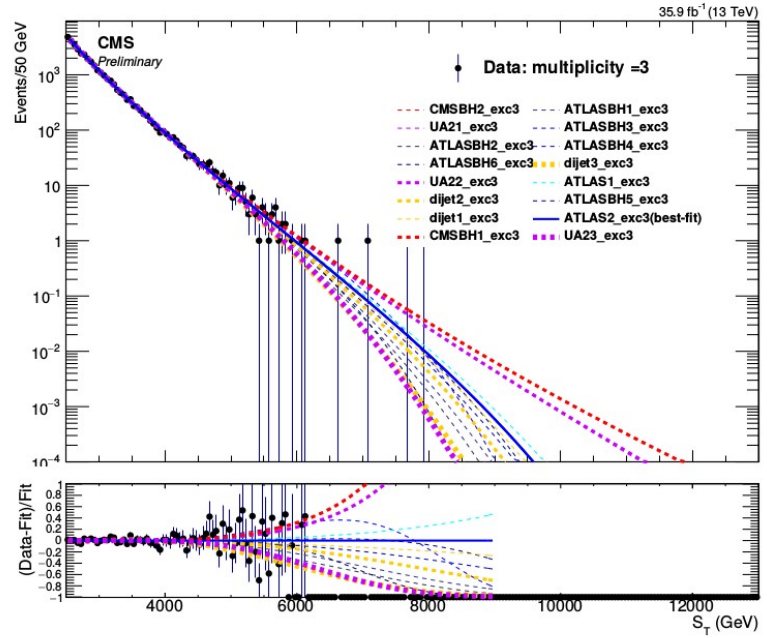
- Look at lowest unexcluded mass for each class of models from 2015
- Choose fit range 2.5 TeV < S_T < 4.3 TeV
- Less than 2% signal contamination in both *N*=3 and *N*=4 in any bin
- No signal contamination at these multiplicities from sphalerons

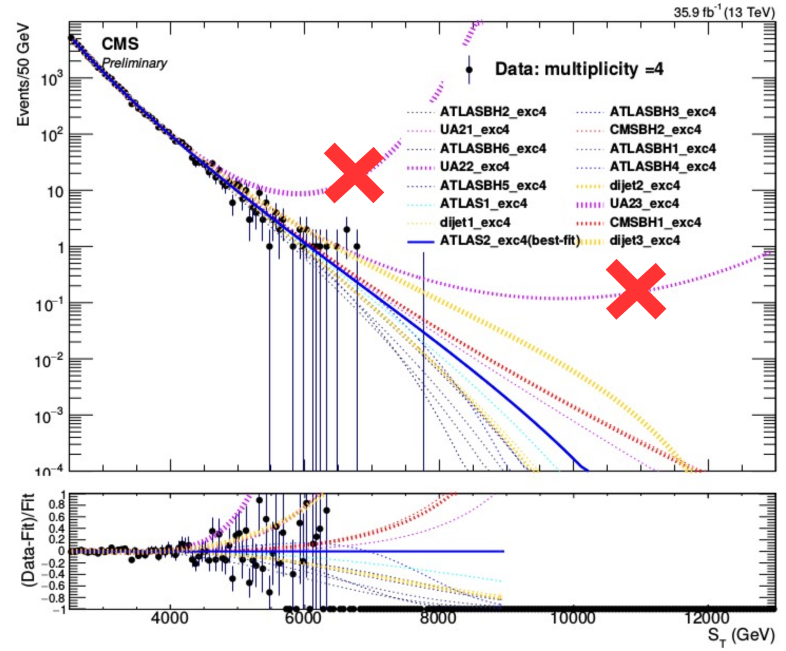
Step 2: Choose Fit Functions

- Goal is to find steeply falling functions over a wide range
- Search literature for functions used in a reasonably similar setting
  - CMS and ATLAS BH searches
  - Dijet searches
  - All functions used are in backup

Step 3: Background Shape

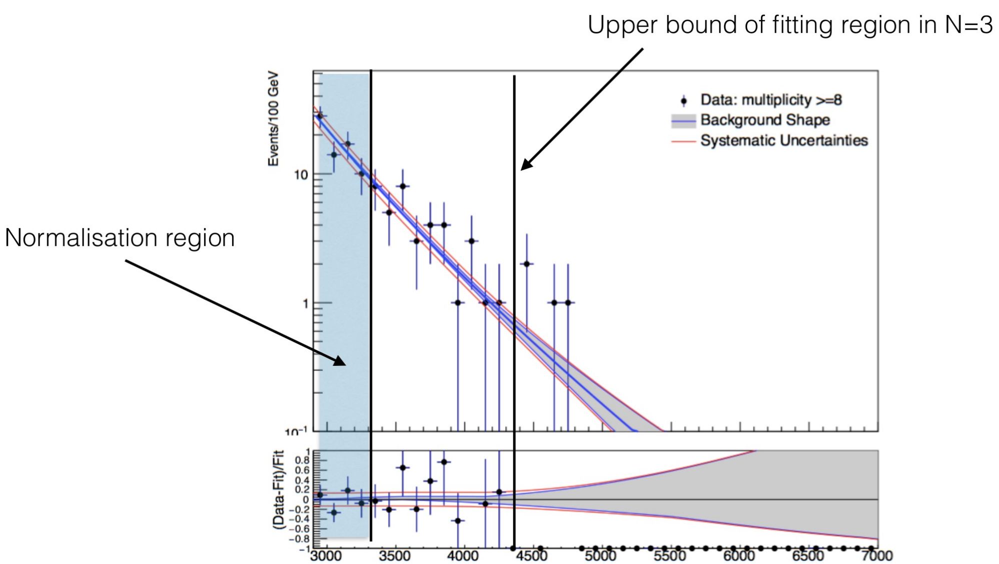
- Higher order functions can often diverge at high S_T
  - Require functions to be monotonically decreasing up to 13 TeV
  - Remaining functions generally describe data well
  - Use collective results to build background prediction
- Choose central fit from ensemble of N = 3 fits
- Shape systematic is taken as the maximum and minimum values at each S_T point
  - This step includes N=4 fits

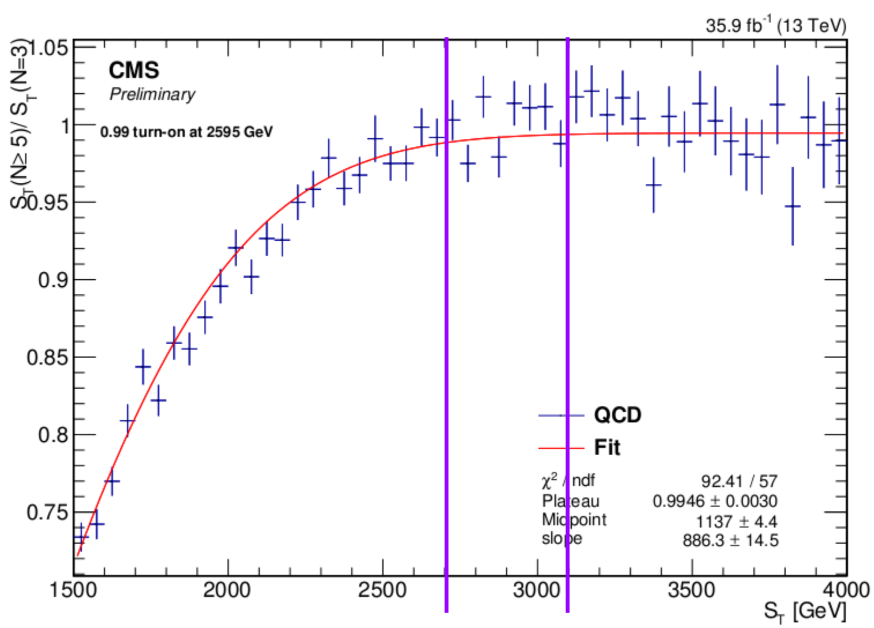




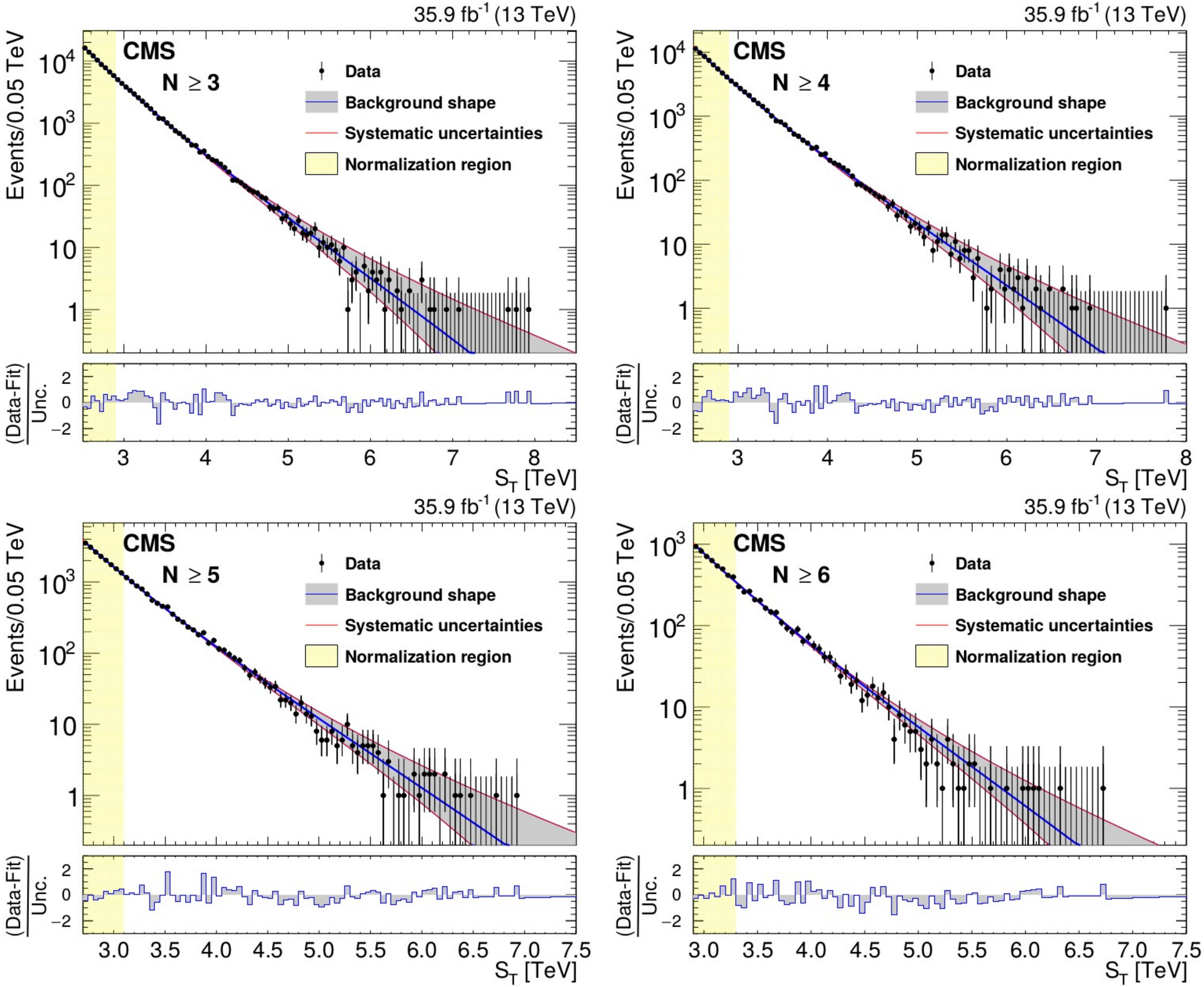
Step 4: Background Normalization

- Study ratio of inclusive spectra to exclusive 3 spectrum
  - Determine the lower bound of normalization region
- All normalization regions are 400 GeV wide
- $s_{N\geq i}$ = (#Events)$_{N\geq i}$/(#Events)$_{N=3}$
- At low S_T (inside fit region) the uncertainty is dominated by the uncertainty of $s_{N\geq i}$

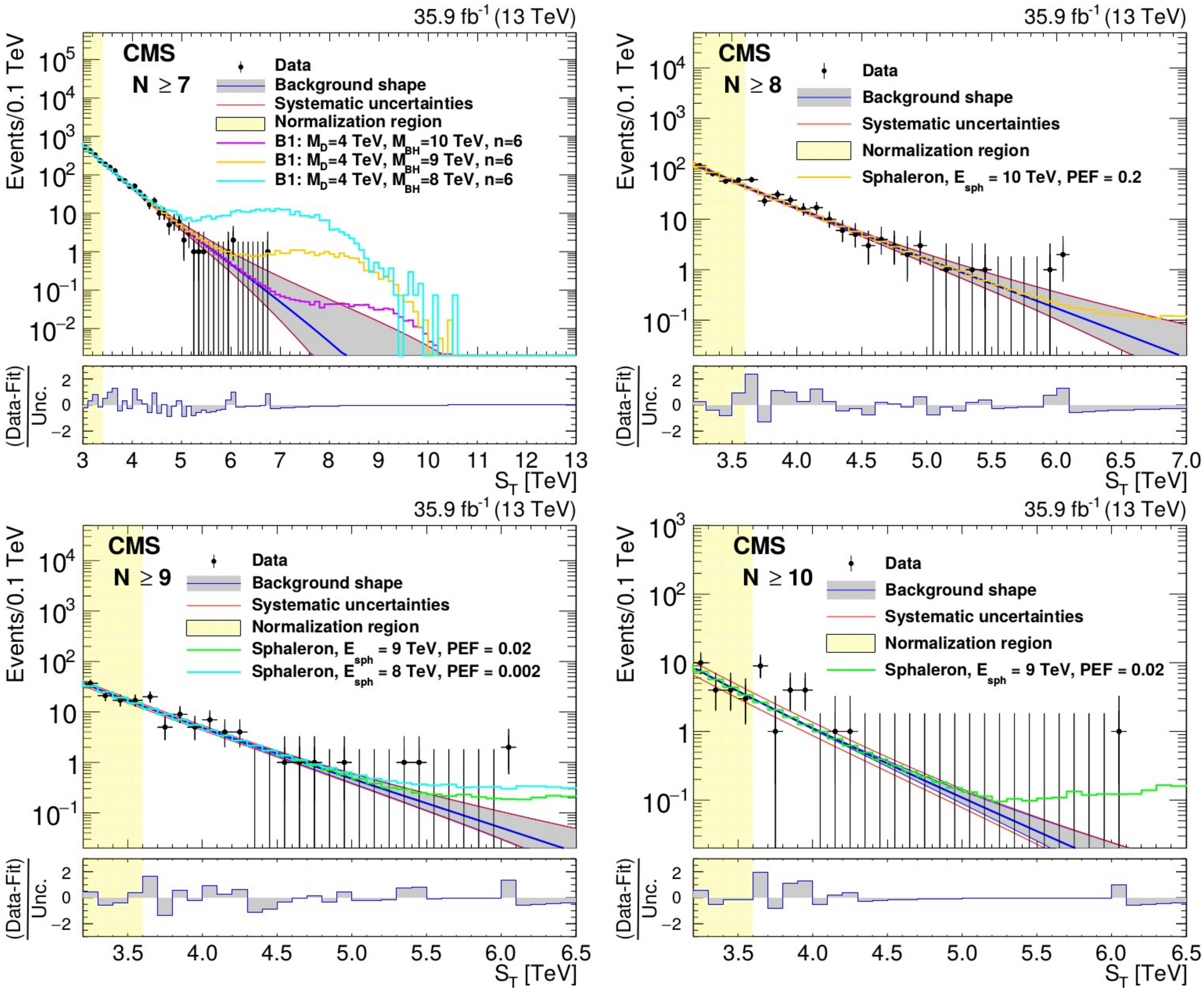




Take a Look at the Data

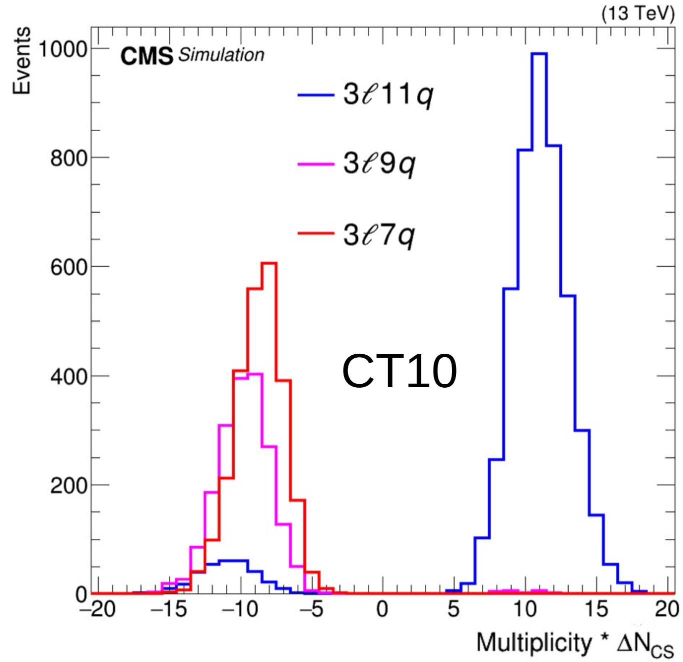


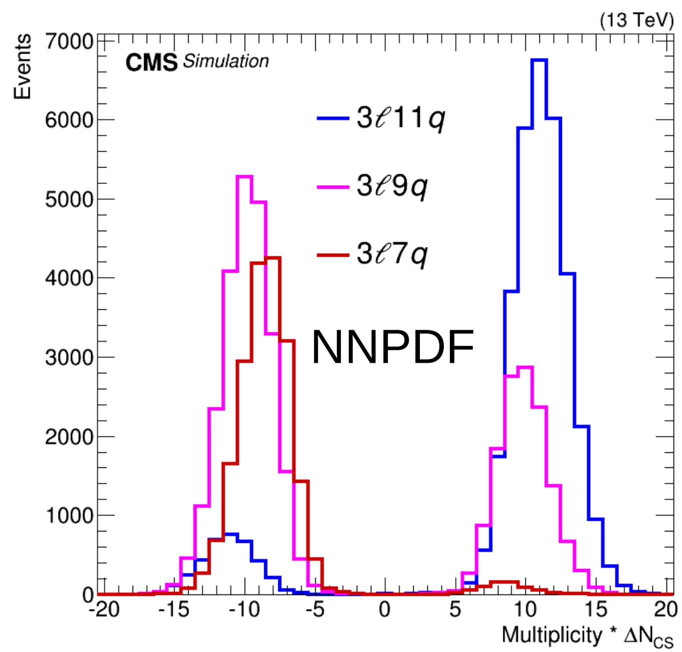
No Excess Observed



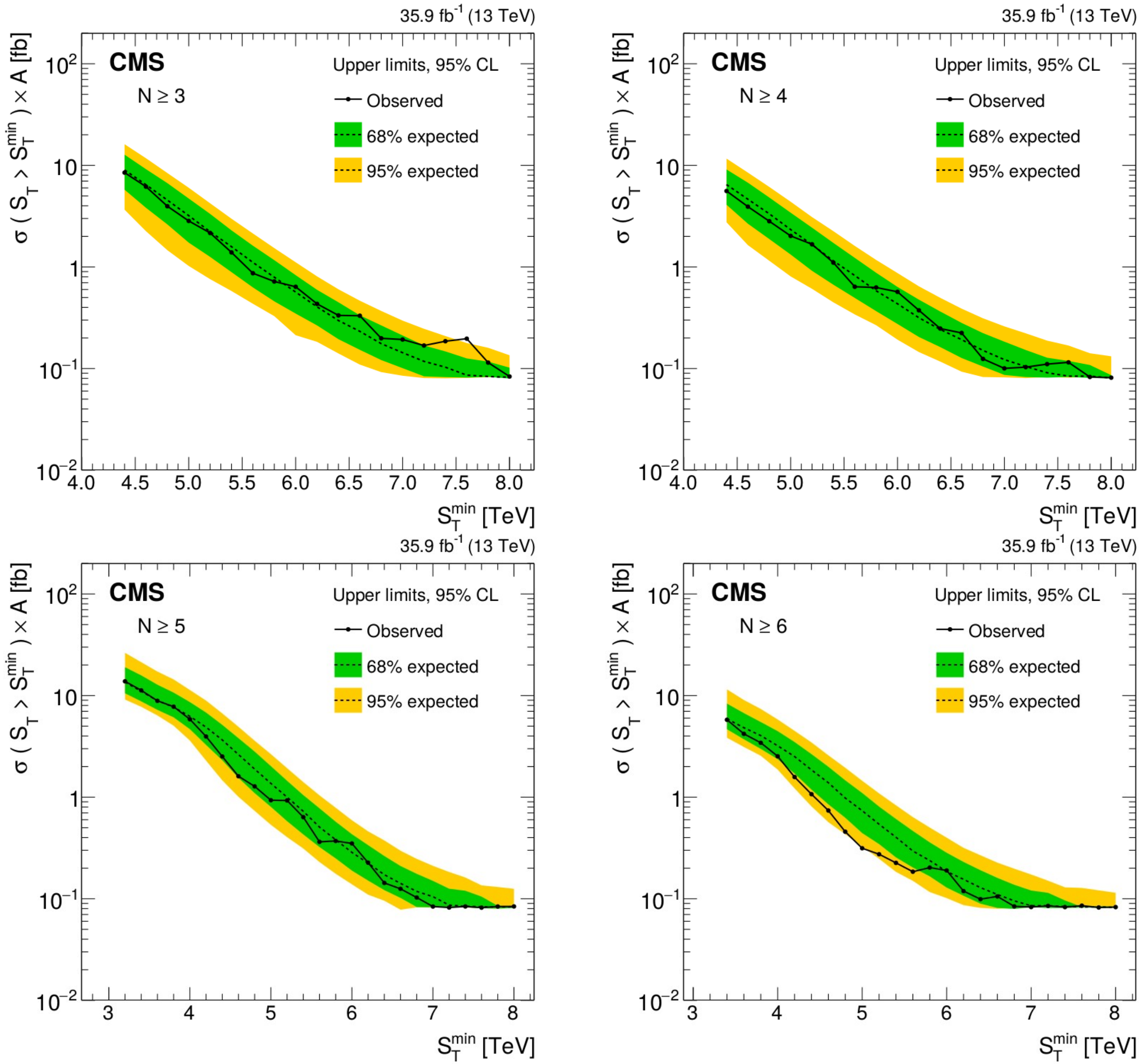
No Excess, Set Limits

- Data shows no significant deviation from background prediction, proceed settting upper limits
- Full CL_s criterion to set 95% confidence level upper limit for each inclusive multiplicity for varying S_T cuts
- Systematics
  - Signal
    - Jet Energy Scale: 5%
    - Jet Energy Resolution: 4%
    - Parton Distribution Functions: 6%
    - Luminosity: 2.5%
  - Background
    - Shape: 1-1000%
    - Normalization: 4-23%

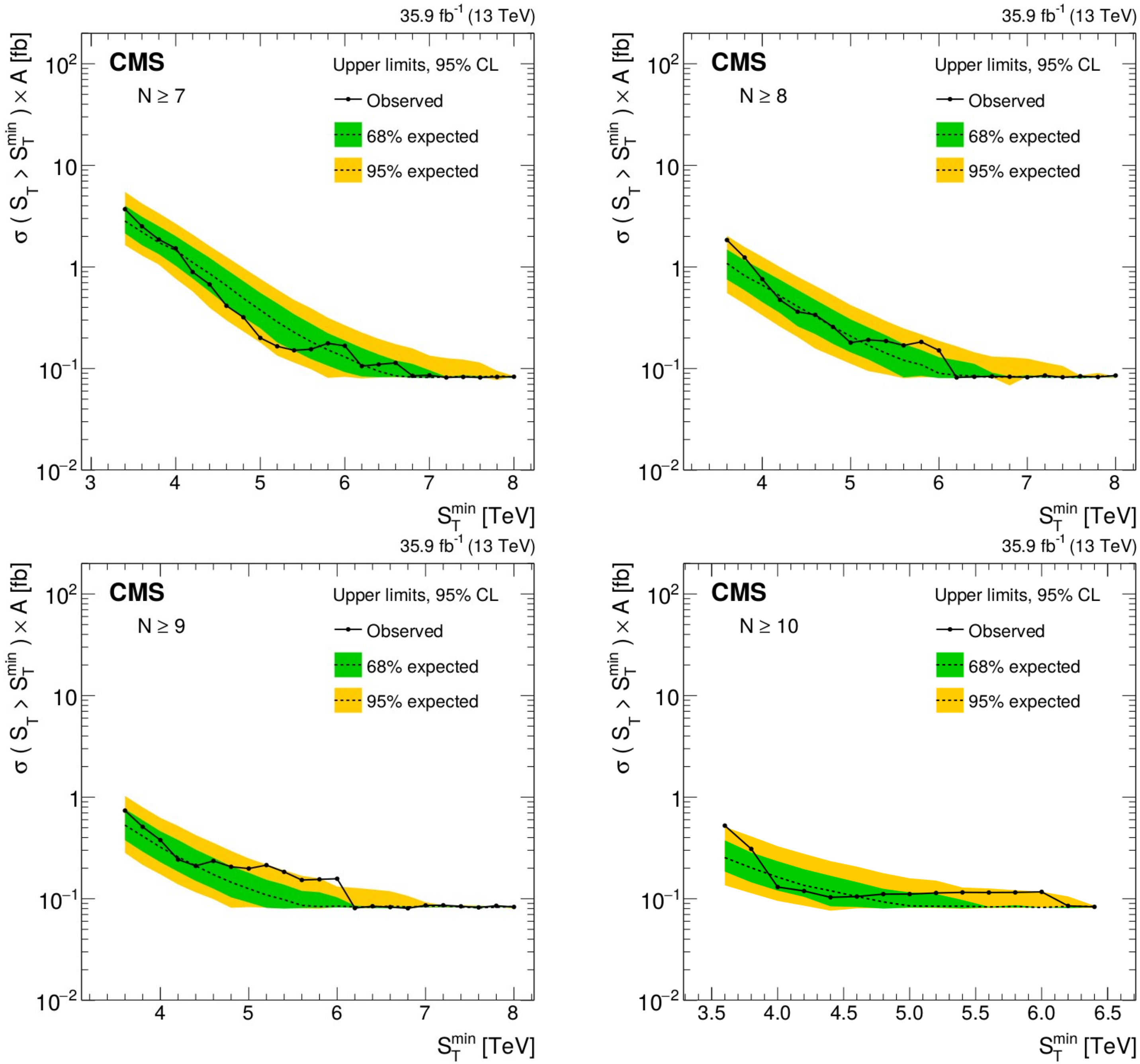




Model Independent Limits

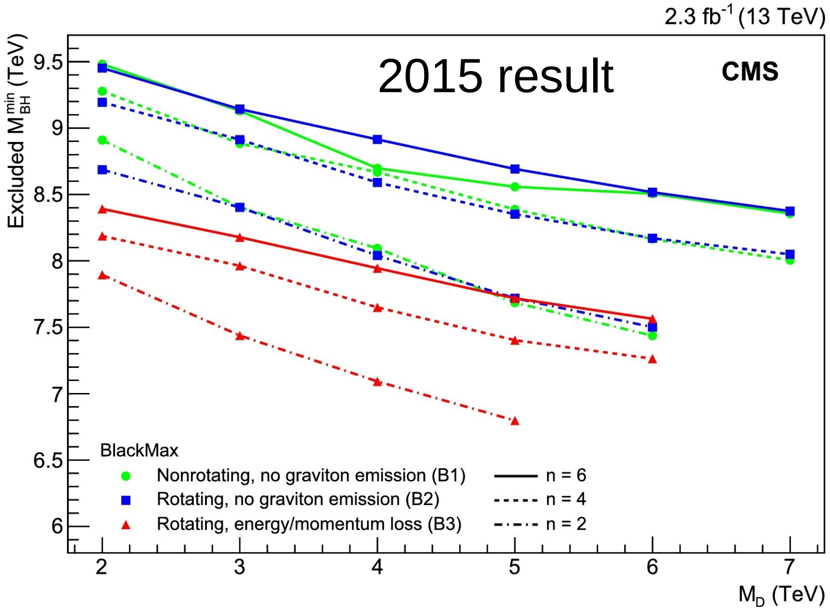


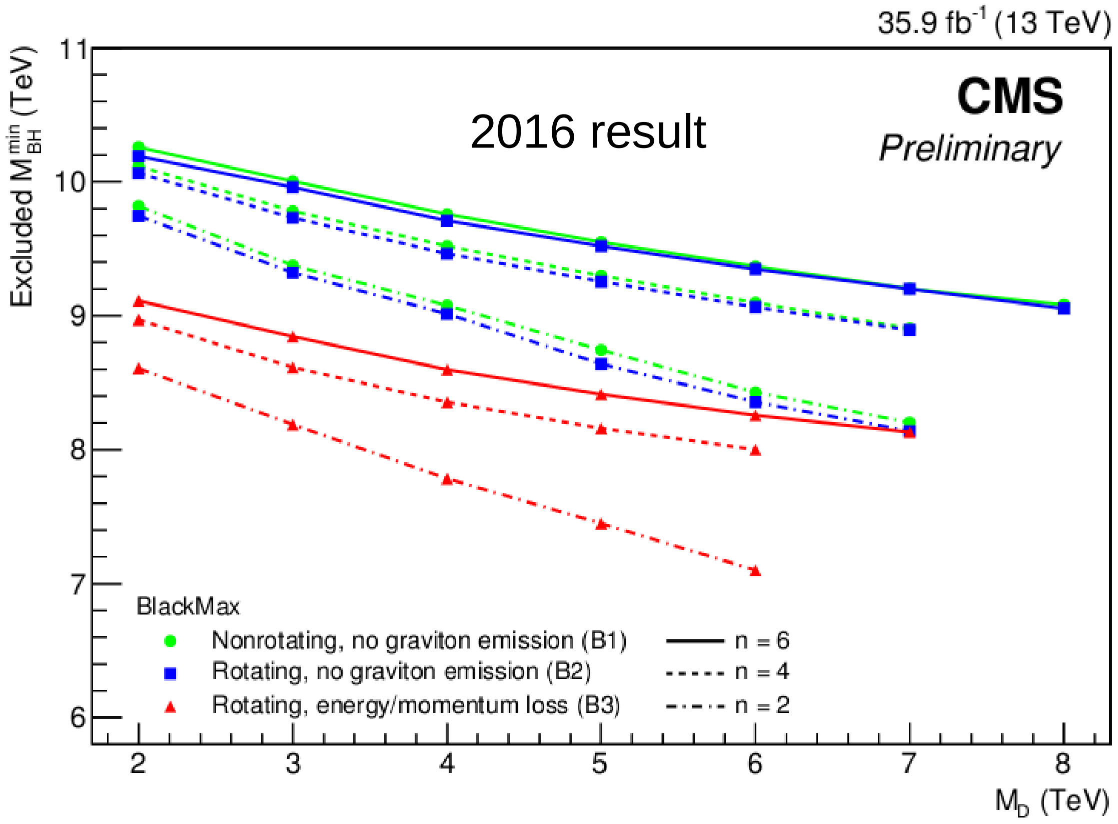
Model Independent Limits



Model Specific BH Interpretations

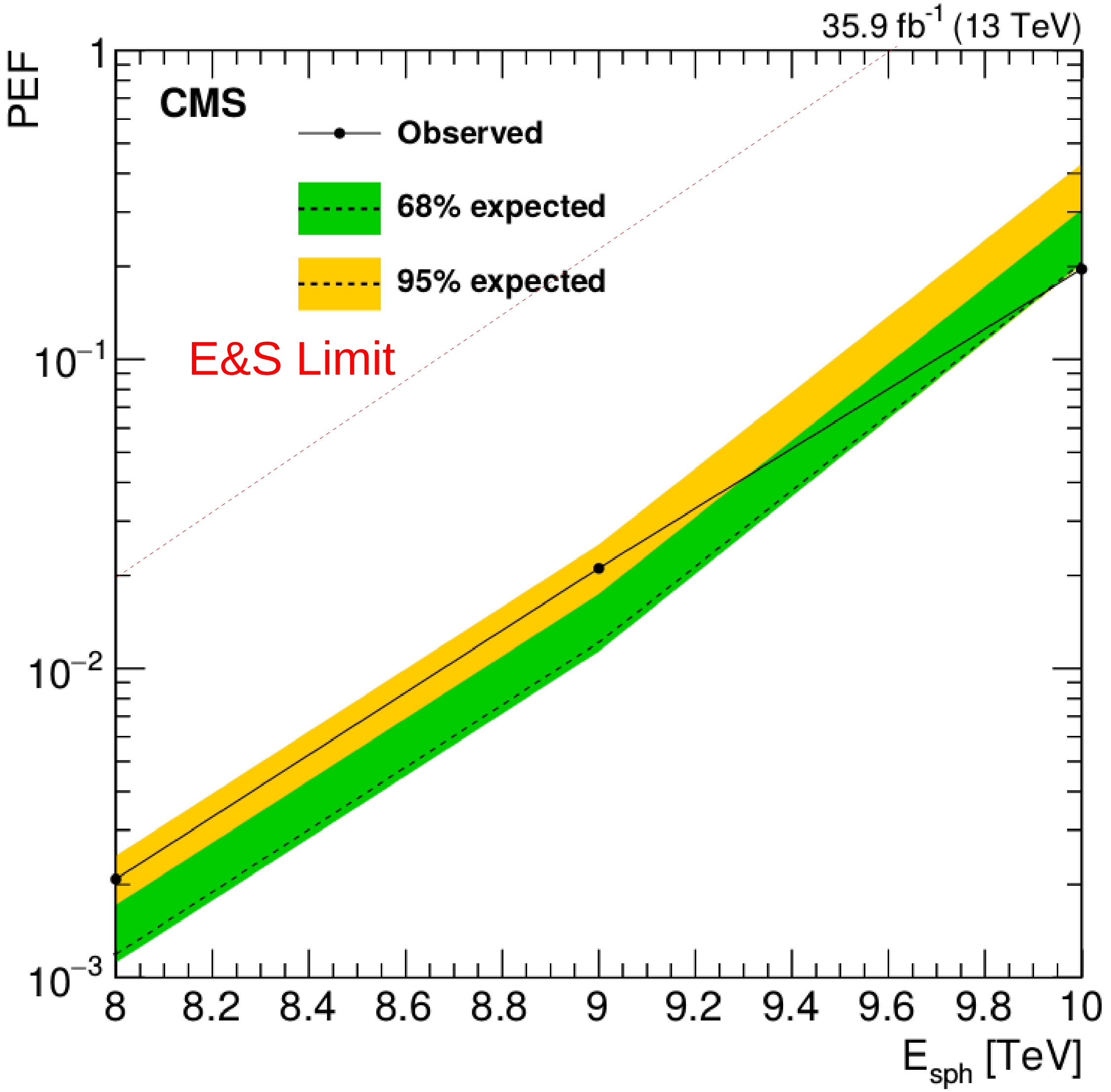
- Black Hole limits are pushed about 1 TeV beyond 2015 analysis
- Now including boiling remnant model limits which are nearly the same as the YR model limits





Sphaleron Limit

- Limit improved by a factor of 10
- Previous limit is a phenomenological study
- First dedicated experimental limit



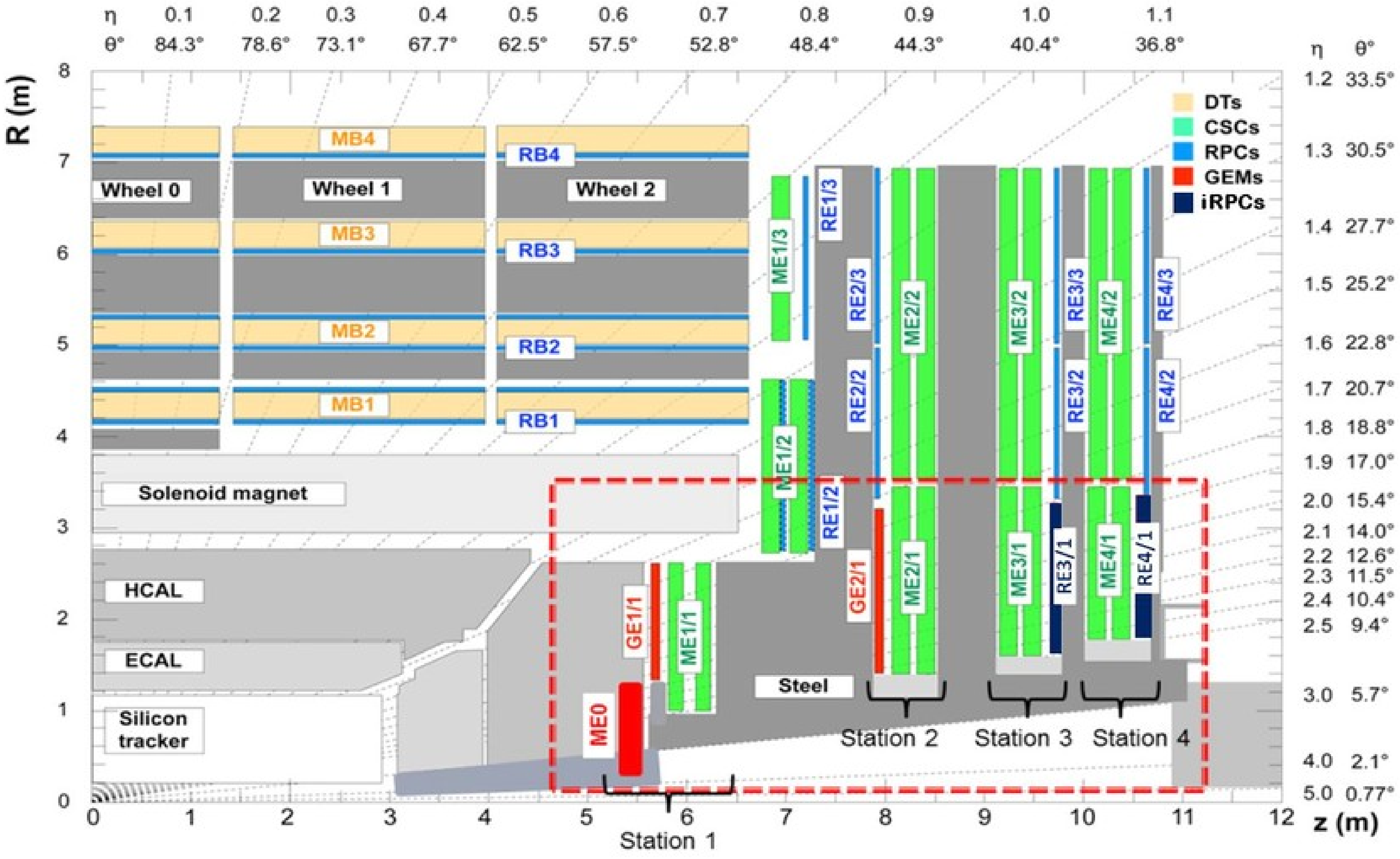
Possibilities for Future

- Upgrade generator
  - Parameterize relative rates of different fermionic configurations in some reasonable manner
  - Include more specific models which have been proposed
- Build new dedicated analysis for sphalerons
  - Include larger scan of transition energies to also take into account possible BSM physics (arXiv:1611.05466)
  - Build set of more targeted analyses which each target one of the 32 phenomenological final states
    - Lower transition energies will have more background
    - More independent of which fermionic configurations sphaleron transitions “choose” in nature
- Increase beam energy
  - 13 TeV → 14 TeV gives 5x the cross section
  - 14 TeV → 28 TeV gives 2200x the cross section
- Add more integrated luminosity to analysis...

HL-LHC

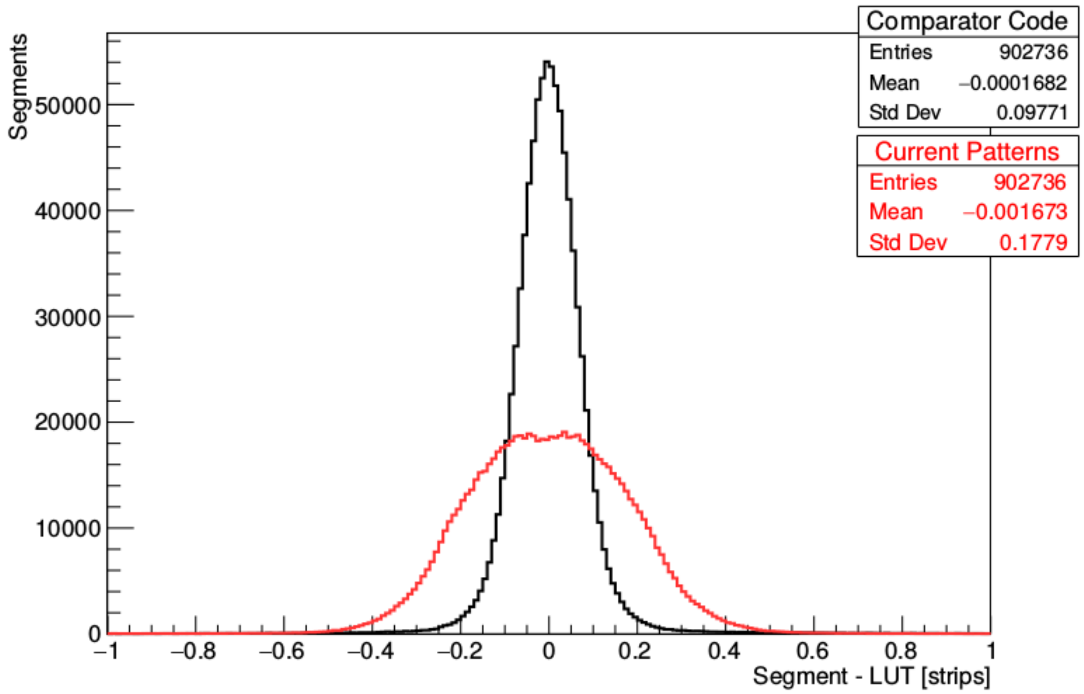
- Upgrade to LHC expected to be finished by 2026
- Expected to increase luminosity up to 10^{35} $cm^{-2}s^{-1}$
- Great for sphalerons but there are challenges
  - More proton-proton interactions per bunch crossing
  - Longer trigger latency
  - Higher trigger frequency: 100 kHz → 1 MHz
  - Must upgrade electronics and trigger to keep up with higher demand
  - Detectors must be robust against higher backgrounds

Muon System Upgrade



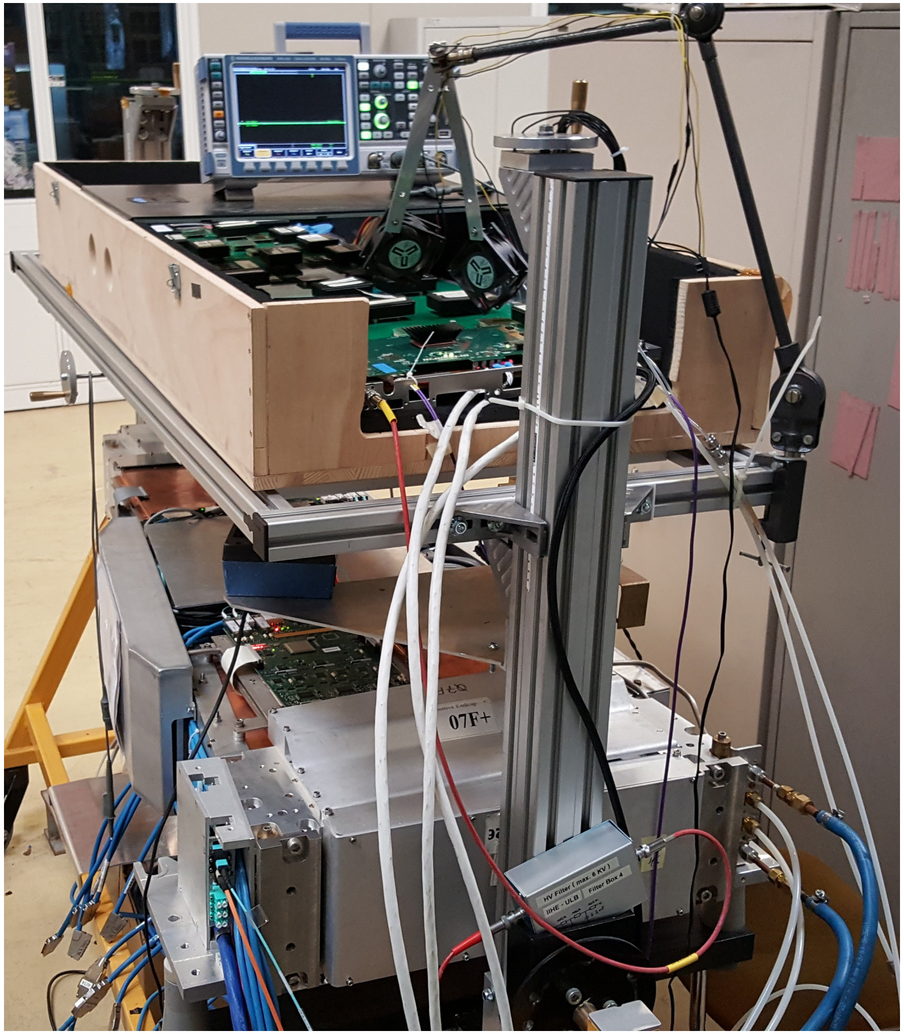
CMS Cathode Strip Chambers

- Upgrade on-chamber electronics to increase bandwidth
- Studied performance of trigger primitives
- My focus has been upgrading local pattern recognition
  - Still a work in progress
  - We expect a factor of 2 better position resolution



CMS Gas Electron Multipliers

- We installed demonstrator system onto CMS in 2017
  - A lot of effort in getting first generation operational
- My focus: DAQ Electronics
  - Prototype integration
  - DAQ SW/FW development
  - Calibration/Characterization analysis
  - ENC reduced to about 0.5 fC from up to 10 fC



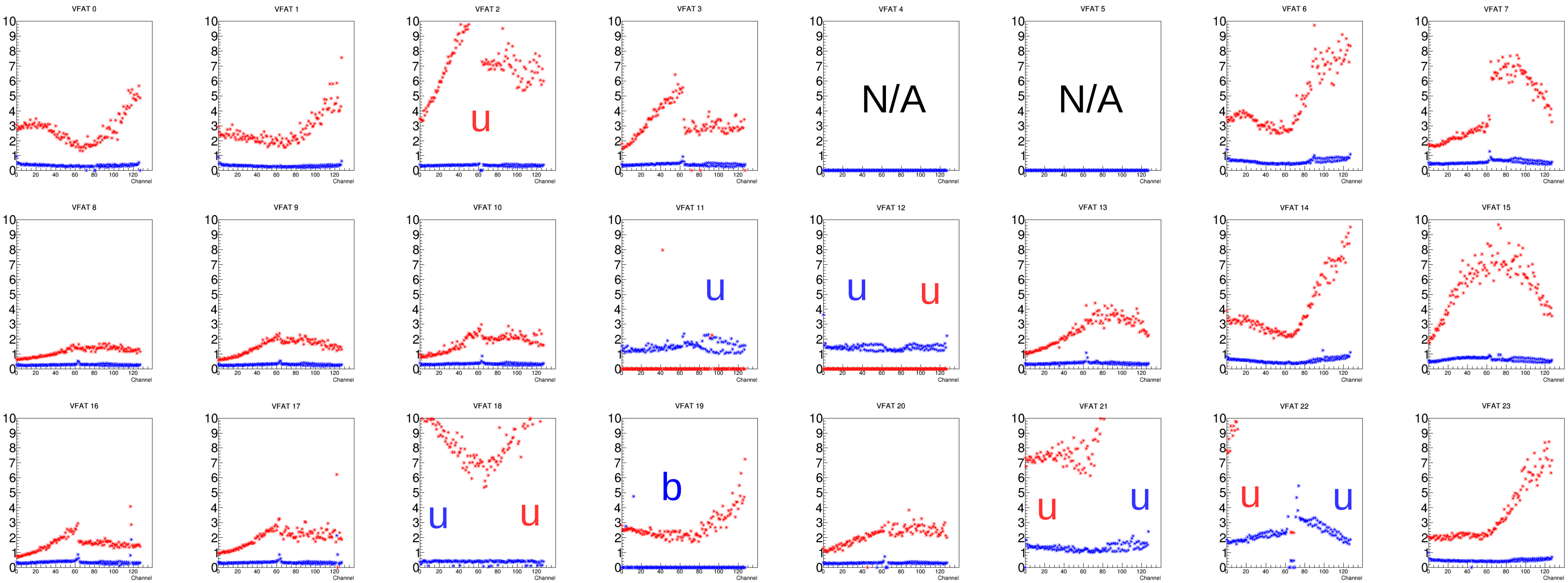
Summary

- **First** dedicated result on Sphaleron production
  - PEF < 0.021 for E_{sph} = 9 TeV
    - Factor of 10 better than previous theorist reinterpretation
  - "Search for black holes and sphalerons in high-multiplicity final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV" (CMS Collaboration, arXiv:1805.06013) has been approved by CMS and submitted to JHEP
- Built "BaryoGEN, a Monte Carlo Generator for Sphaleron-Like Transitions in Proton-Proton Collisions" (C. Bravo and J. Hauser, arXiv:1805.02786)
  - Establishes a minimal phenomenological model
  - First to include a complete set of fermion configurations in final-state
  - Paper recently accepted for publication in JHEP
- This is just the beginning of sphalerons at the LHC
  - Stay tuned for more extensive searches
  - Just wait until HL-LHC
- Thanks to Jay Hauser, David Saltzberg, Graciela Gelmini, Doojin Kim, John Ellis, Kazuki Sakurai, and Steve Mrenna

Thank you for your attention

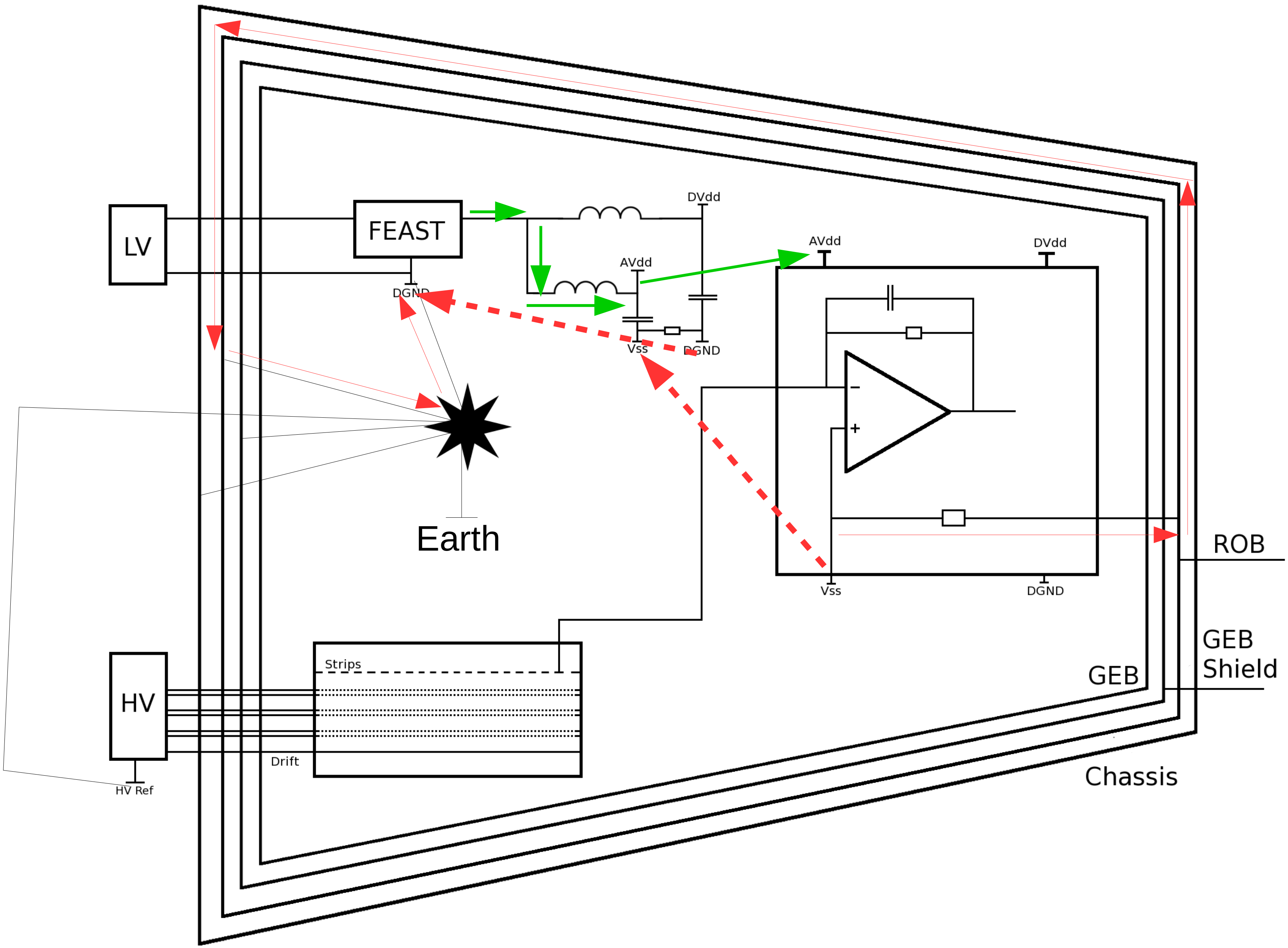
Backup

Killing GEM Noise

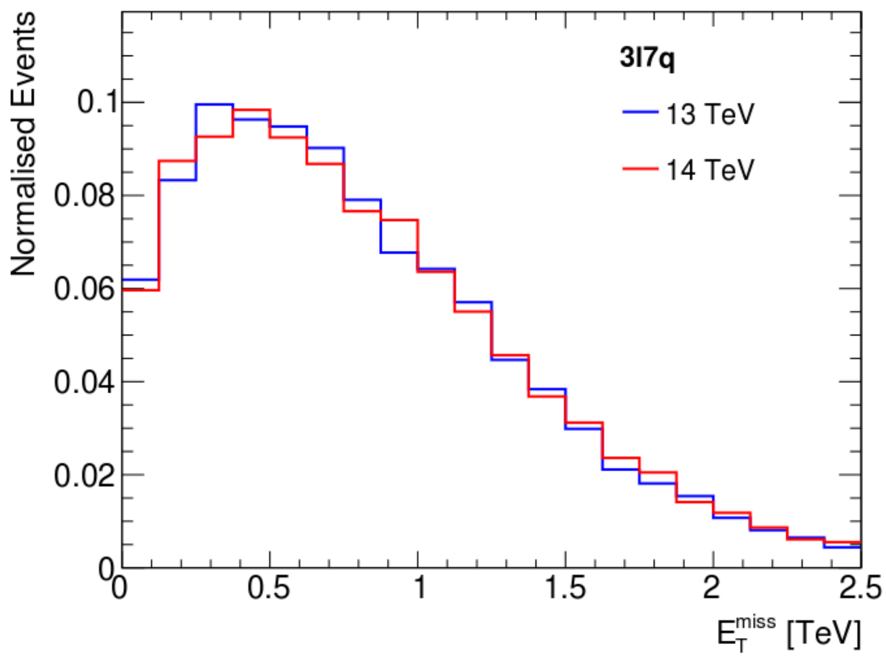


u = uncalibrated b = broken VFAT

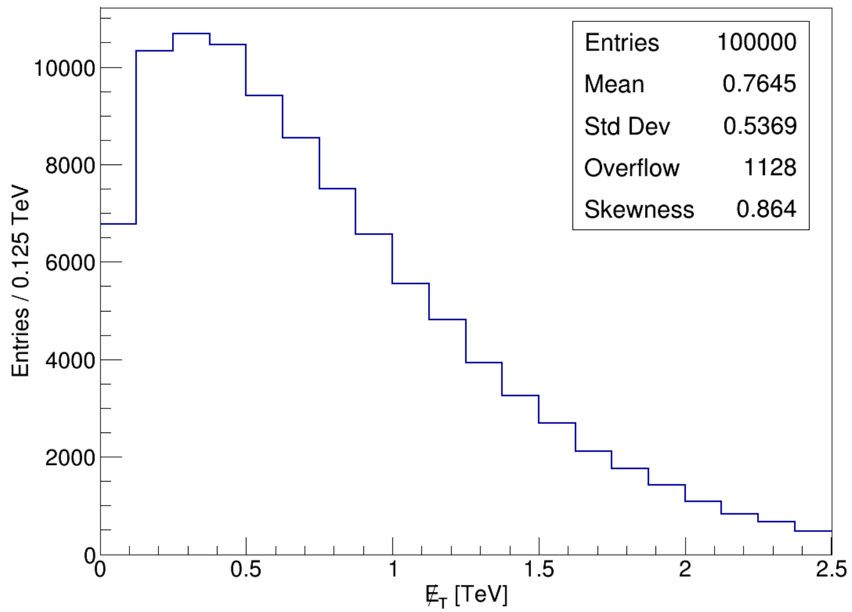
Analog LV Current Paths



Comparing MET



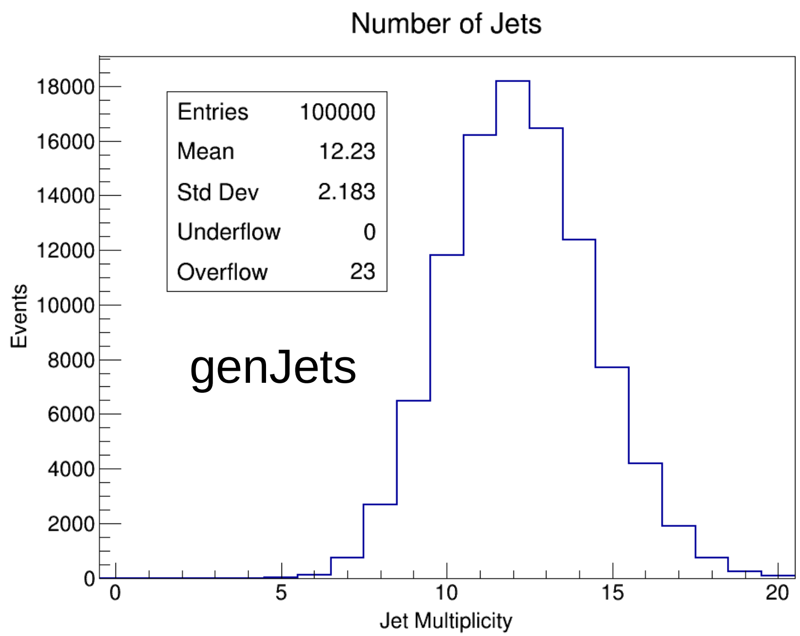
Ellis and Sakurai

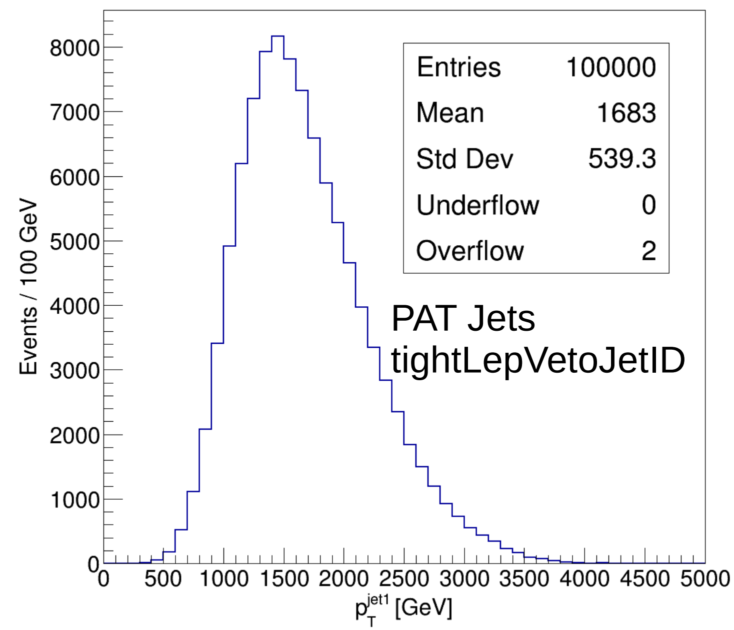


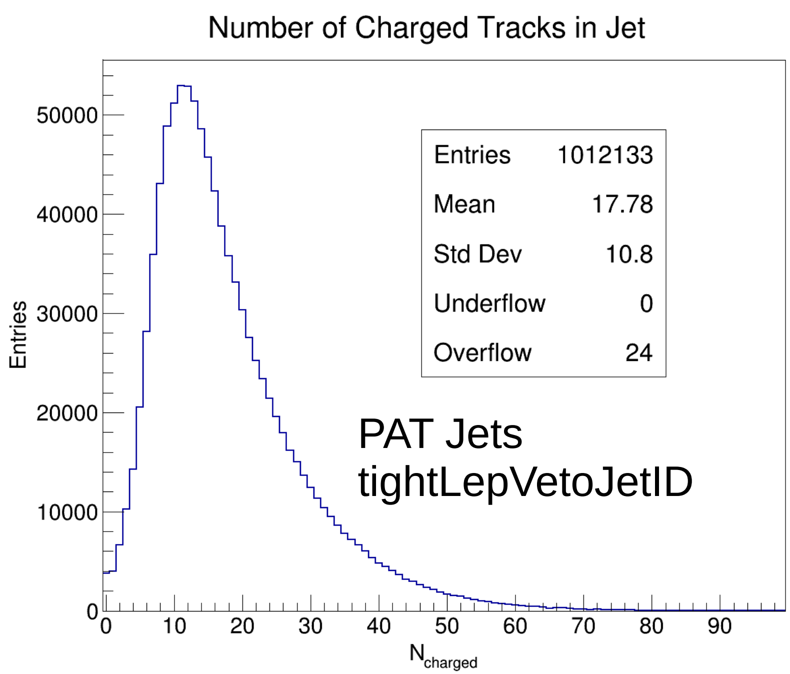
Mine GEN-SIM genMET

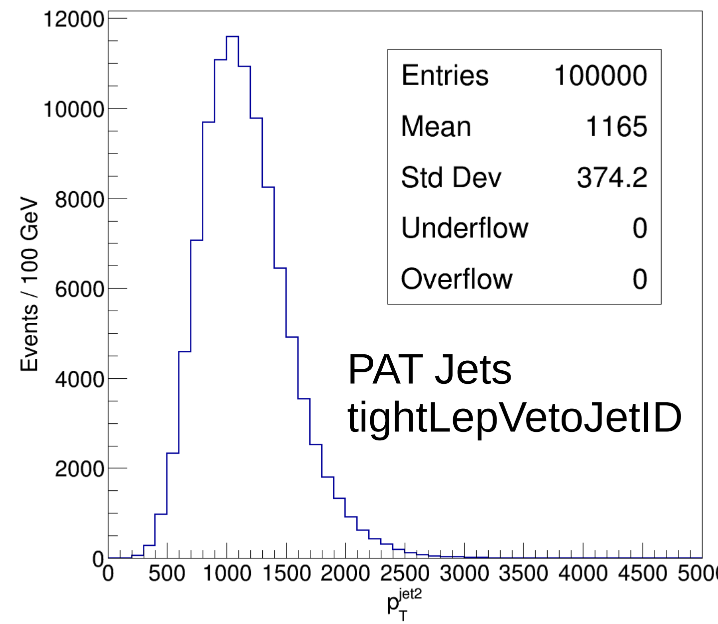
Hadronic Quantities

p_T > 50 and |η| < 5.2 everywhere



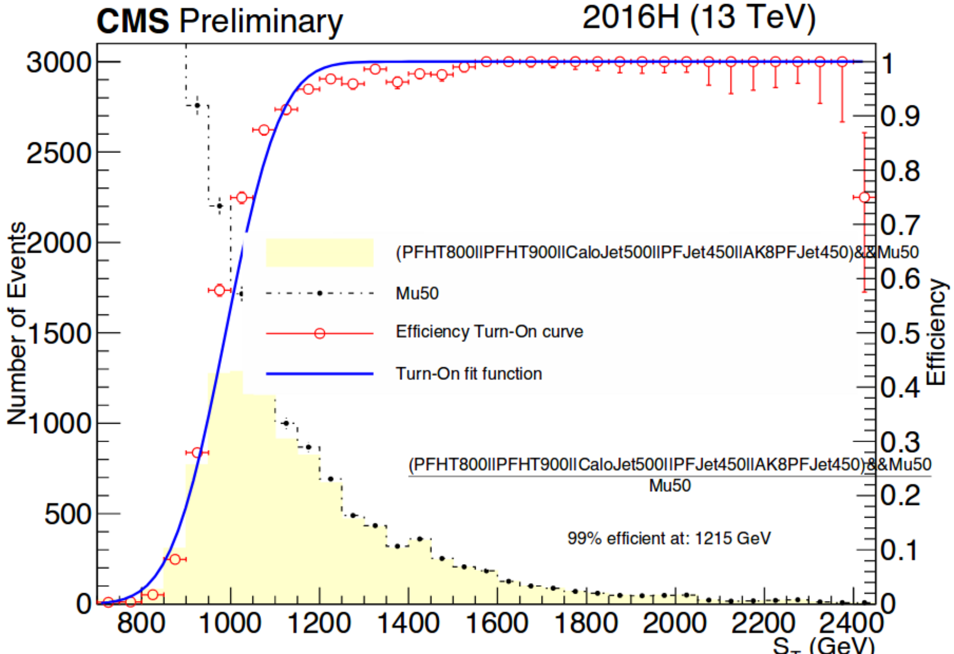






Datasets and Triggers

- Primary dataset: JetHT, 03Feb2017 Re-MiniAOD, corresponding to 35.9/fb
  - /JetHT/Run2016B-03Feb2017_ver2-v2/MINIAOD
  - /JetHT/Run2016C-03Feb2017-v1/MINIAOD
  - /JetHT/Run2016D-03Feb2017-v1/MINIAOD
  - /JetHT/Run2016E-03Feb2017-v1/MINIAOD
  - /JetHT/Run2016F-03Feb2017-v1/MINIAOD
  - /JetHT/Run2016G-03Feb2017-v1/MINIAOD
  - /JetHT/Run2016H-03Feb2017_ver2-v1/MINIAOD
  - /JetHT/Run2016H-03Feb2017_ver3-v1/MINIAOD
- Used the lowest un-prescaled HT trigger: HT800 (Except 2016H)
- “OR” of 4 triggers used for 2016H
  - HLT_PFJET450, HLT_AK8PFJET450, HLT_CaloJet500_NoJetID, HT900
- Full efficiency for S_T > 1.6 TeV, measured w.r.t. Mu50



Step 2: Choose Fit Functions

- Considered 5 classes of functions commonly used to fit high mass/S_T/H_T spectra
- Used multiple orders of each class of function
- x = S_T / 13 TeV for all functions

CMSBH (from previous CMS BH searches) [link]

$$f_{cmsBH1}(x) = \frac{p_0(1+x)^{p_1}}{x^{p_2 \log x}}$$

$$f_{cmsBH2}(x) = \frac{p_0(1+x)^{p_1}}{x^{p_3 + p_2 \log x}}$$

Standard dijet [link]

$$f_{dijet1}(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2}}$$

$$f_{dijet2}(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2 + p_3 \log(x)}}$$

$$f_{dijet3}(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2 + p_3 \log(x) + p_4 \log^2(x)}}$$

"ATLAS" (from Zgamma search) [link]

$$f_{ATLAS1}(x) = \frac{p_0(1-x^{1/3})^{p_1}}{x^{p_2}}$$

$$f_{ATLAS2}(x) = \frac{p_0(1-x^{1/3})^{p_1}}{x^{p_2 + p_3 \log^2(x)}}$$

ATLAS BH (3 parameters variants of dijet2) [link]

$$f_{ATLASBH1}(x) = p_0(1-x)^{p_1} x^{p_2 \log(x)}$$

$$f_{ATLASBH2}(x) = p_0(1-x)^{p_1} (1+x)^{p_2 \log(x)}$$

$$f_{ATLASBH3}(x) = p_0(1-x)^{p_1} e^{p_2 \log(x)}$$

$$f_{ATLASBH4}(x) = p_0(1-x^{1/3})^{p_1} x^{p_2 \log(x)}$$

$$f_{ATLASBH5}(x) = p_0(1-x)^{p_1} x^{p_2 x}$$

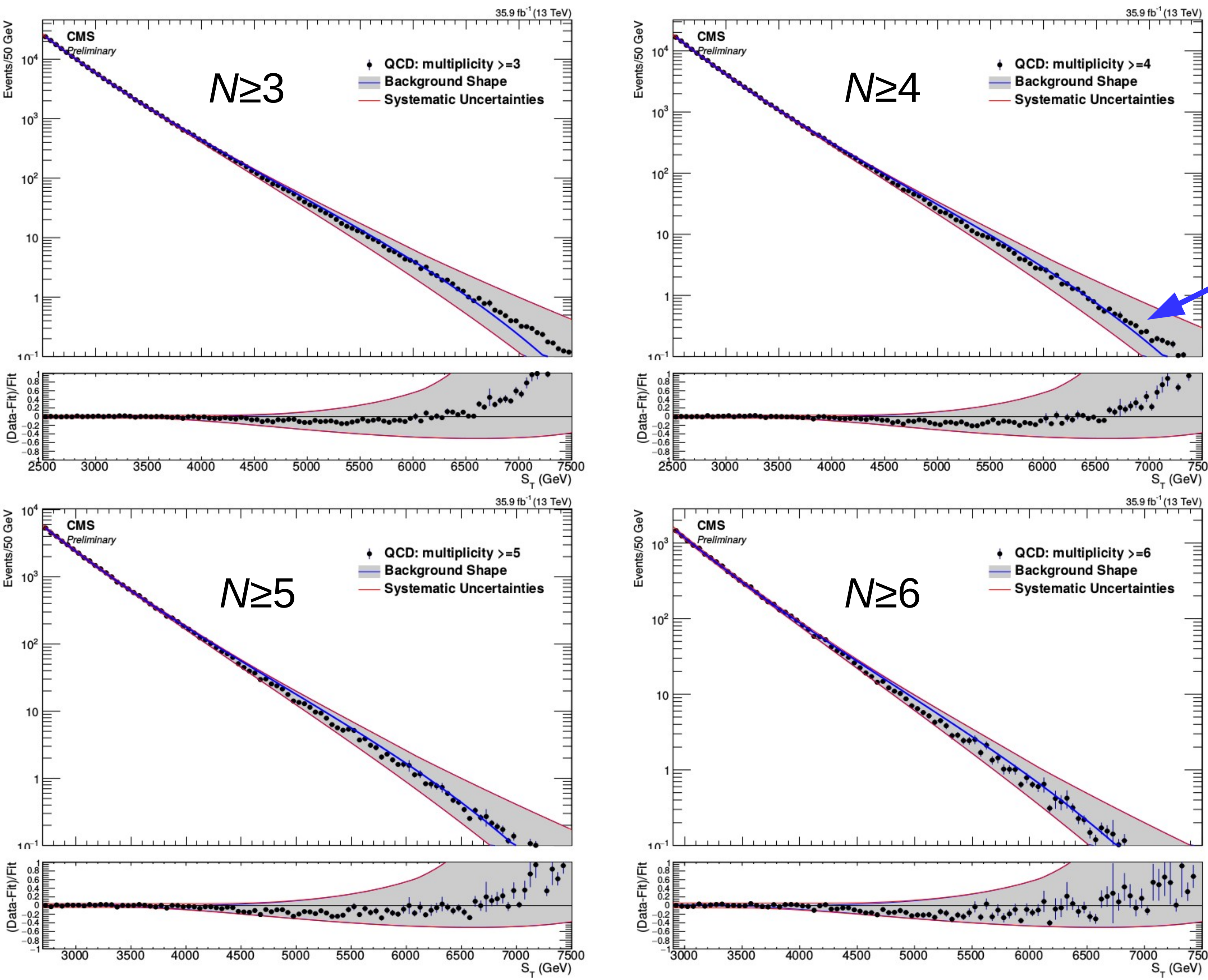
$$f_{ATLASBH6}(x) = p_0(1-x)^{p_1} (1+x)^{p_2 x}$$

"UA2" (from UA2 dijet search) [link]

$$f_{UA2_1}(x) = p_0 x^{p_1} e^{p_2 x}$$

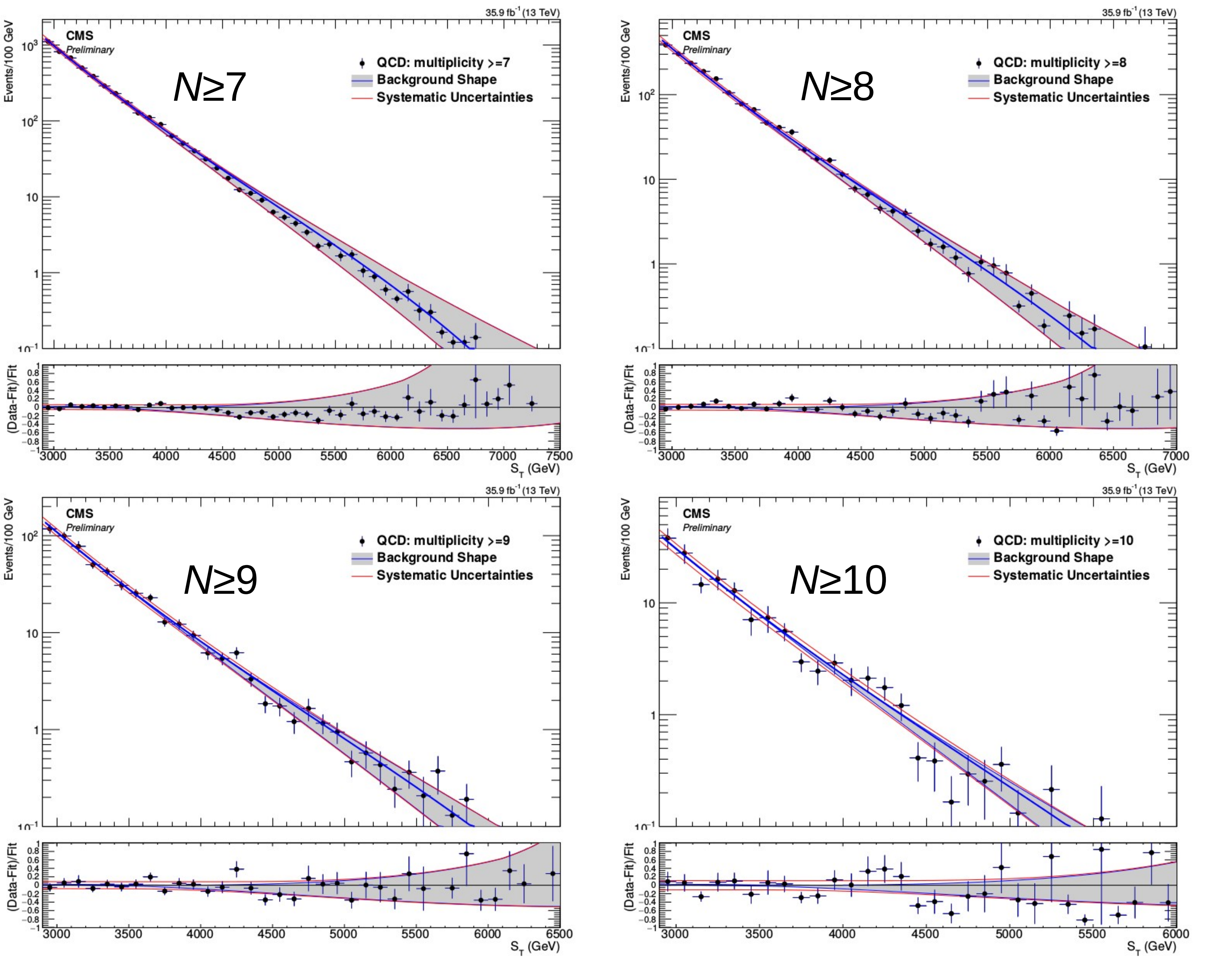
$$f_{UA2_2}(x) = p_0 x^{p_1} e^{p_2 x + p_3 x^2}$$

Closure of Background Estimate using QCD MC



Shape systematics large compared to central prediction bias

Closure of Background Estimate using QCD MC



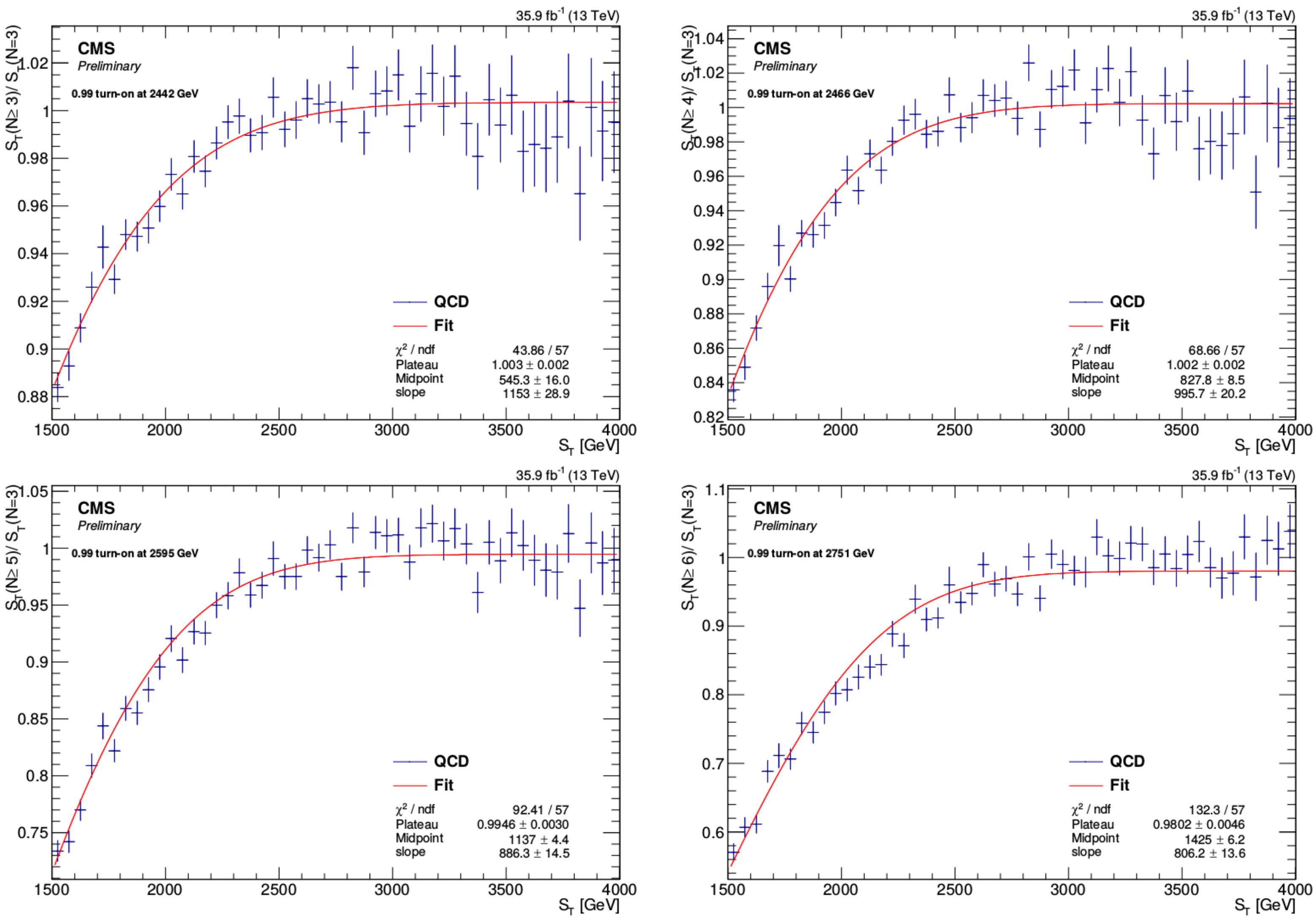
Phenomenological Final States

- Choose an ordering of the doublets for labeling
  - I personally like l1 q1 q1 q1 l2 q2 q2 q2 l3 q3 q3 q3
- Many of the 1,330,560 different final states are phenomenologically identical
  - e uud μ ccs τ ttb
  - e udu μ csc τ tbt these are different in QM (color charge)
- At CMS u, d, c, and s are difficult to distinguish from each other. There are 8 lepton configurations and 4 configurations of 3 3rd generation quarks, making **32** phenomenological final states
  - 1/8 have 3 neutrinos (before W decays)
  - ttt, ttb, tbb, and bbb 3rd generation quark configurations each characterize 1/8, 3/8, 3/8, 1/8 of the final states respectively

Background MC Samples

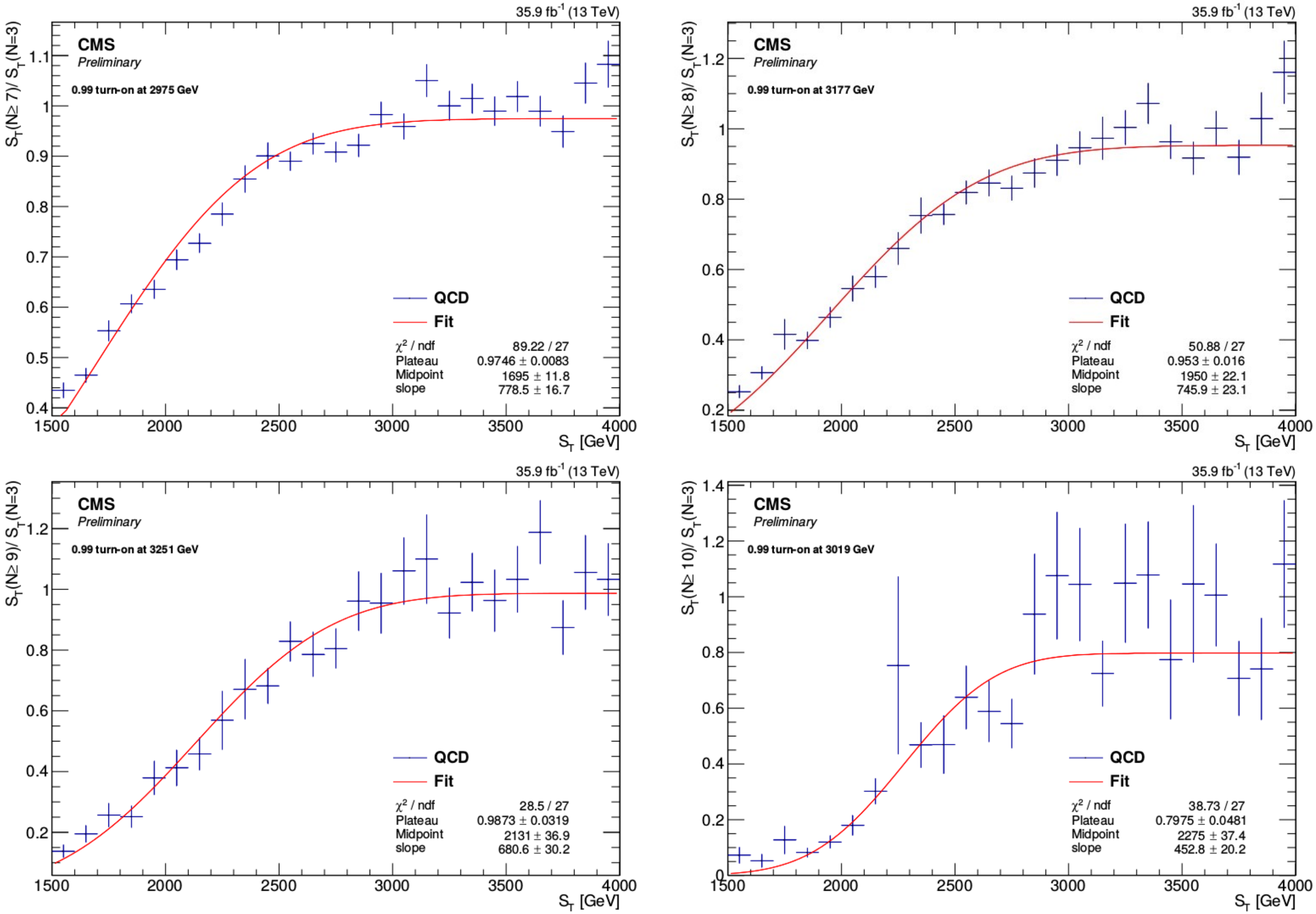
Sample	/*/RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-v1/MINIAODSIM	Number of Events	Cross-section [pb]
--------	--	------------------	--------------------
γ+jets	GJets_HT-600ToInf_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	2463946	93.38
	GJets_HT-400To600_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	2529729	277.4
	GJets_HT-200To400_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	10036487	2300
Drell-Yan	DYJetsToNuNu_PtZ-650ToInf_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	1022595	0.02639
+ Jets	DYJetsToNuNu_PtZ-400To650_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	1050705	0.2816
	DYJetsToNuNu_PtZ-250To400_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	1052985	2.082
	DYJetsToNuNu_PtZ-100To250_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	5353639	55.03
	DYJetsToNuNu_PtZ-50To100_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	21953584	593.9
	DYJetsToNuNu_Zpt-0To50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	47728607	3483
	DYJetsToQQ_HT180_13TeV-madgraphMLM-pythia8	12055100	1187
W+Jets	WJetsToLNu_HT-2500ToInf_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	253561	0.03216
	WJetsToLNu_HT-1200To2500_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	244532	1.329
	WJetsToLNu_HT-800To1200_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	1544513	5.501
	WJetsToLNu_HT-600To800_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	3779141	12.05
	WJetsToLNu_HT-400To600_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	1963464	48.91
	WJetsToQQ_HT180_13TeV-madgraphMLM-pythia8	22402469	2788
QCD	QCD_Pt_3200toInf_TuneCUETP8M1_13TeV_pythia8	391735	0.000165445
	QCD_Pt_2400to3200_TuneCUETP8M1_13TeV_pythia8	399226	0.00682981
	QCD_Pt_1800to2400_TuneCUETP8M1_13TeV_pythia8	397660	0.114943
	QCD_Pt_1400to1800_TuneCUETP8M1_13TeV_pythia8	396409	0.84265
	QCD_Pt_1000to1400_TuneCUETP8M1_13TeV_pythia8	2999069	9.4183
	QCD_Pt_800to1000_TuneCUETP8M1_13TeV_pythia8	3992112	32.293
	QCD_Pt_600to800_TuneCUETP8M1_13TeV_pythia8	3896412	186.9
	QCD_Pt_470to600_TuneCUETP8M1_13TeV_pythia8	3959986	648.2
	QCD_Pt_300to470_TuneCUETP8M1_13TeV_pythia8	4150588	7823
	QCD_Pt_170to300_TuneCUETP8M1_13TeV_pythia8	6958708	117276
	QCD_Pt_120to170_TuneCUETP8M1_13TeV_pythia8	6708572	471100
	QCD_Pt_80to120_TuneCUETP8M1_13TeV_pythia8	6986740	2.76253e+06
	QCD_Pt_50to80_TuneCUETP8M1_13TeV_pythia8	9954370	1.92043e+07
	QCD_Pt_300to470_TuneCUETP8M1_13TeV_pythia8	4150588	7823
ttbar	TTJets_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	10139950	502.2

MC S_T Shape Invariance Turn-On



- Fit ratio of inclusive spectra to N=3 spectrum and fit to error function to decide where normalization regions are for each multiplicity individually
- Normalization regions are determined based on MC

MC S_T Shape Invariance Turn-On



- Fit ratio of inclusive spectra to N=3 spectrum and fit to error function to decide where normalization regions are for each multiplicity individually
- Normalization regions are determined based on MC

Counting Final States

- There are $$\frac{\prod_{n=1}^{6} \binom{2n}{2}}{6!} = 10395$$ doublet pairings
- There are also 7 factors of 2 , one for each pair (2 possible SU(2) index choices) and the 7th for the sign of the Chern-Simons Number, giving a total of 1,330,560 quantum mechanically unique final states

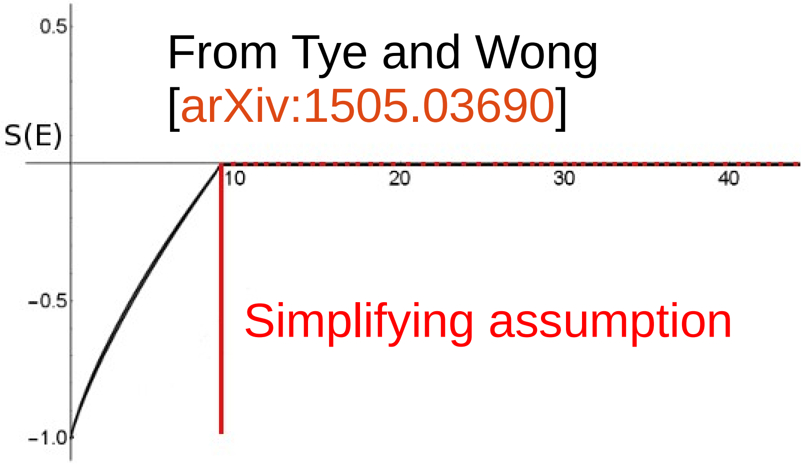
Monte Carlo Integration

- I am approximating integrals I found in Ellis and Sakurai

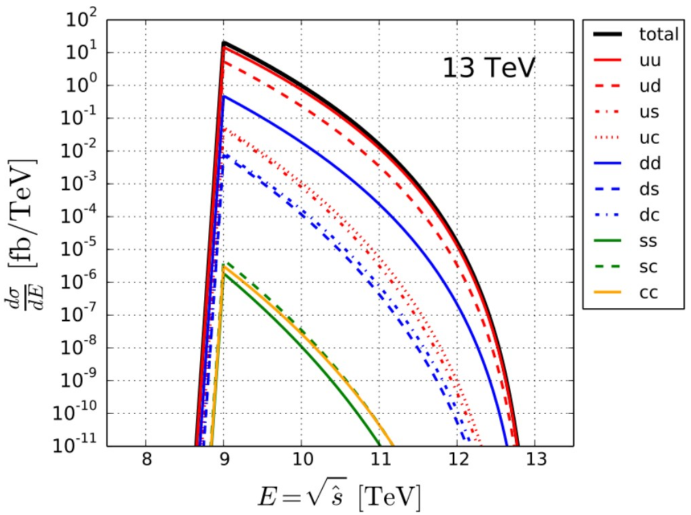
$$\sigma(\Delta n = \pm 1) = \frac{1}{m_W^2} \sum_{ab} \int dE \frac{d\mathcal{L}_{ab}}{dE}\, p\, \exp\left(c \frac{4\pi}{\alpha_W} S(E)\right)$$

$$\frac{d\mathcal{L}_{ab}}{dE} = \frac{2E}{E_{\rm CM}^2} \int_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} dy f_a(\sqrt{\tau}e^{y}) f_b(\sqrt{\tau}e^{-y})$$

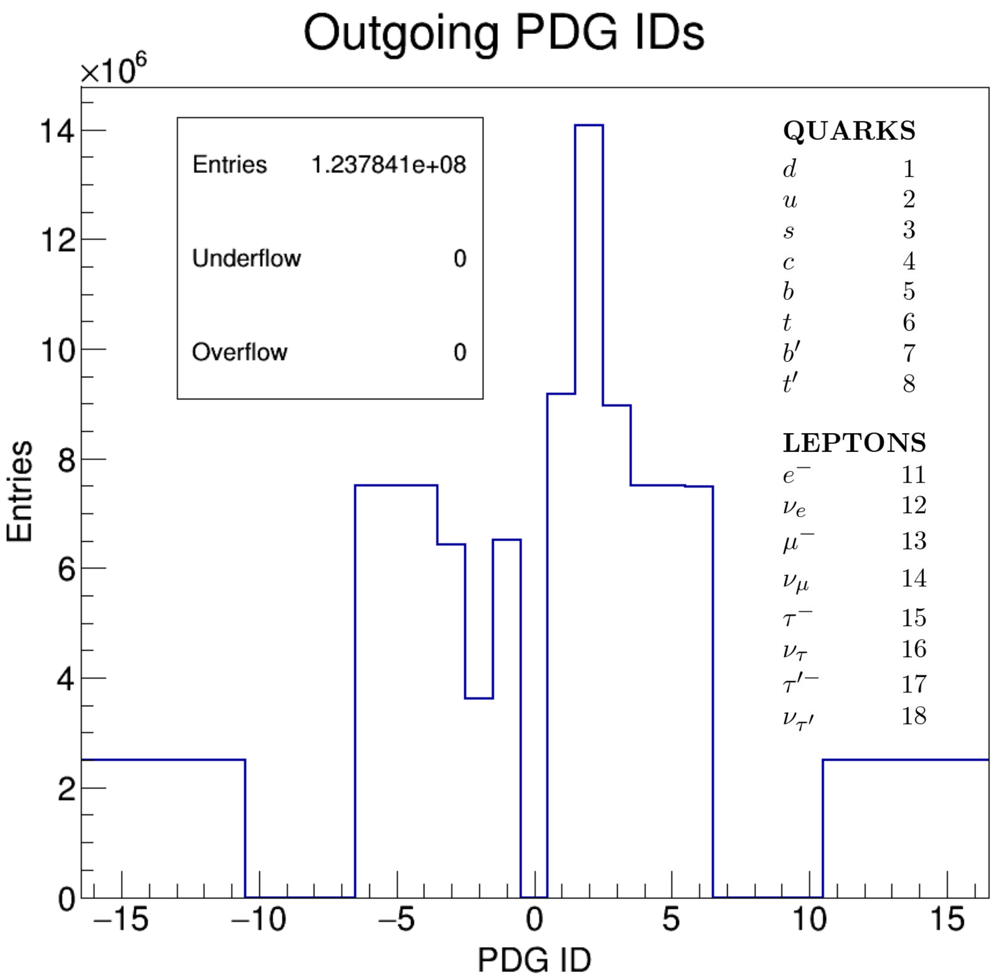
From Tye and Wong [arXiv:1505.03690]

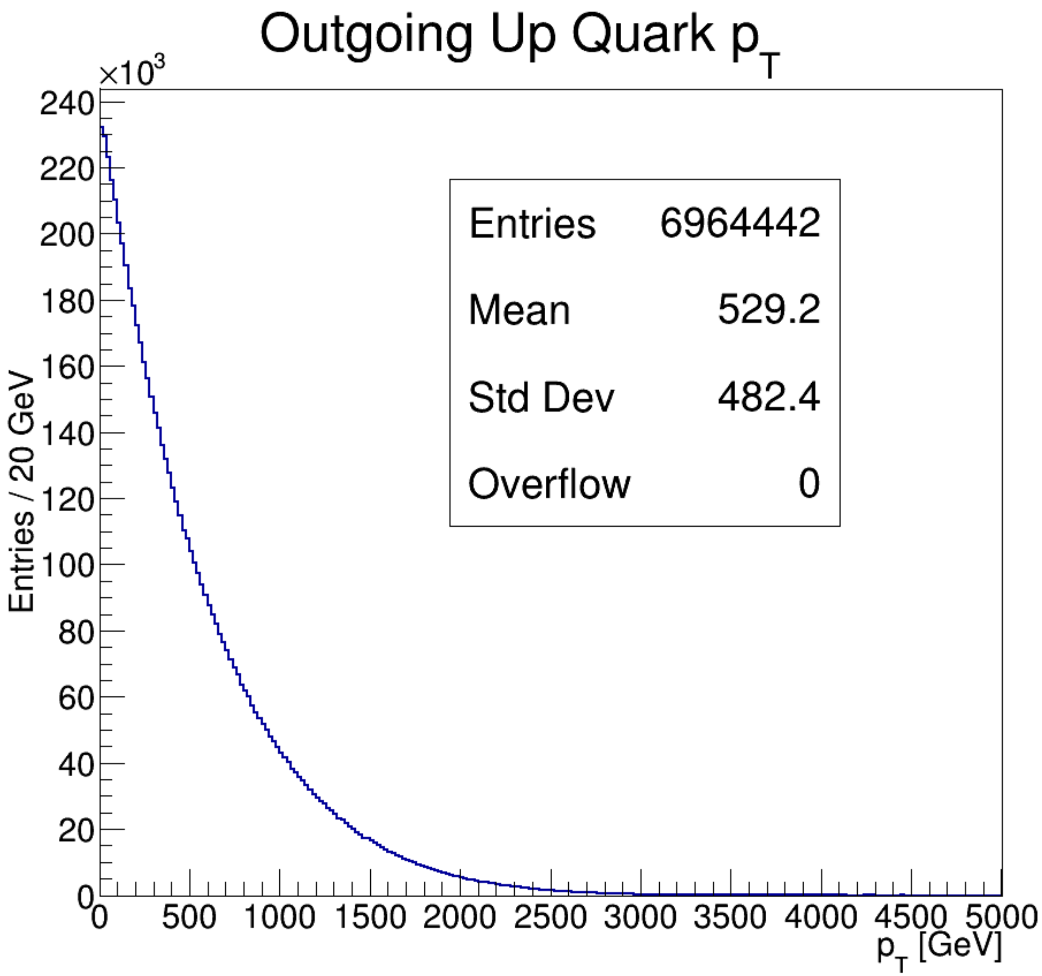


- Made a simplifying assumption to make the MC more efficient



Outgoing Particles

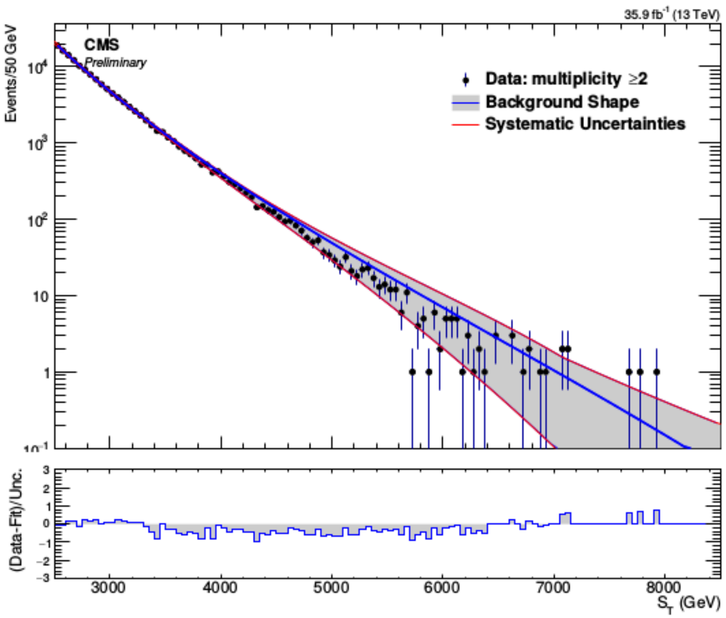




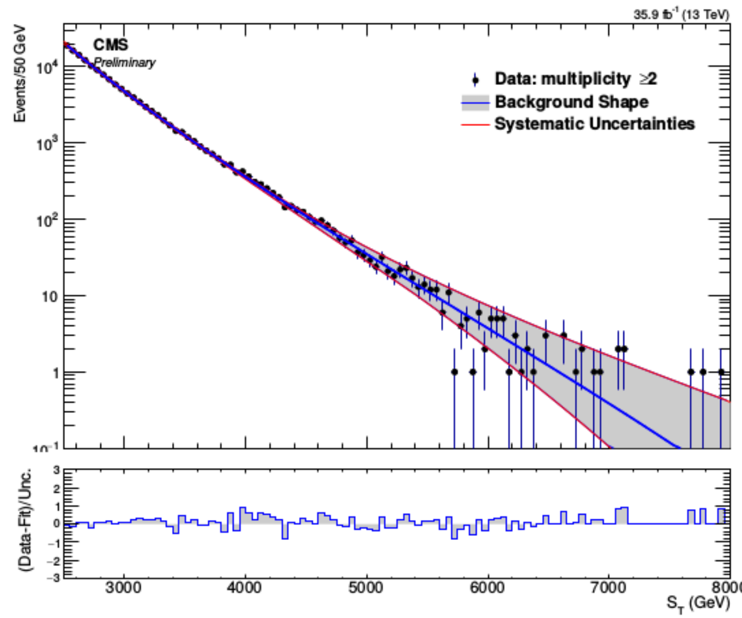
- Peak at two and dip at minus two makes sense because u quarks are most probable incoming type so anti-ups get canceled most often
- Have looked at kinematics of all outgoing particles and they all look reasonable

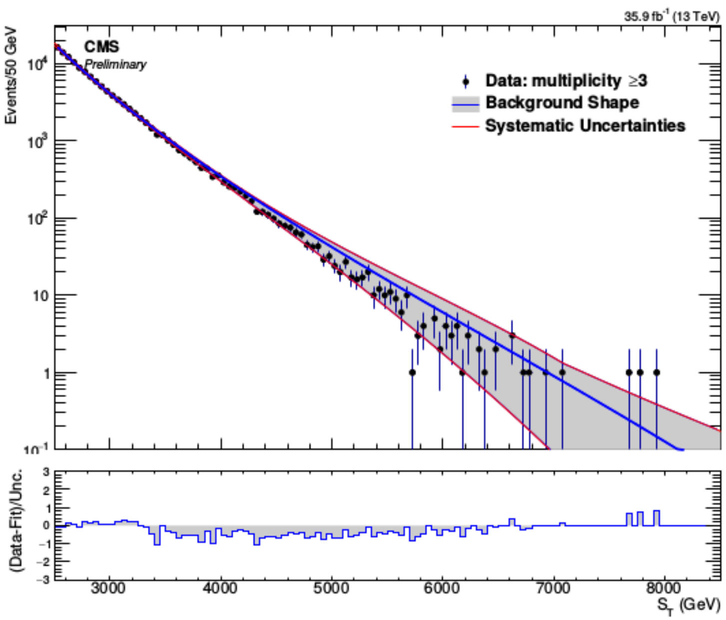
Crosscheck with Fit to N=2

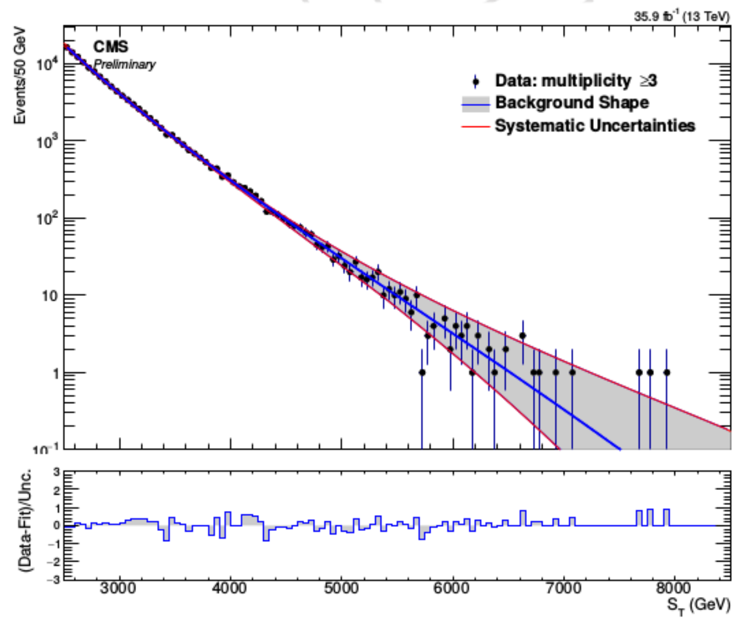
Fit to N=2



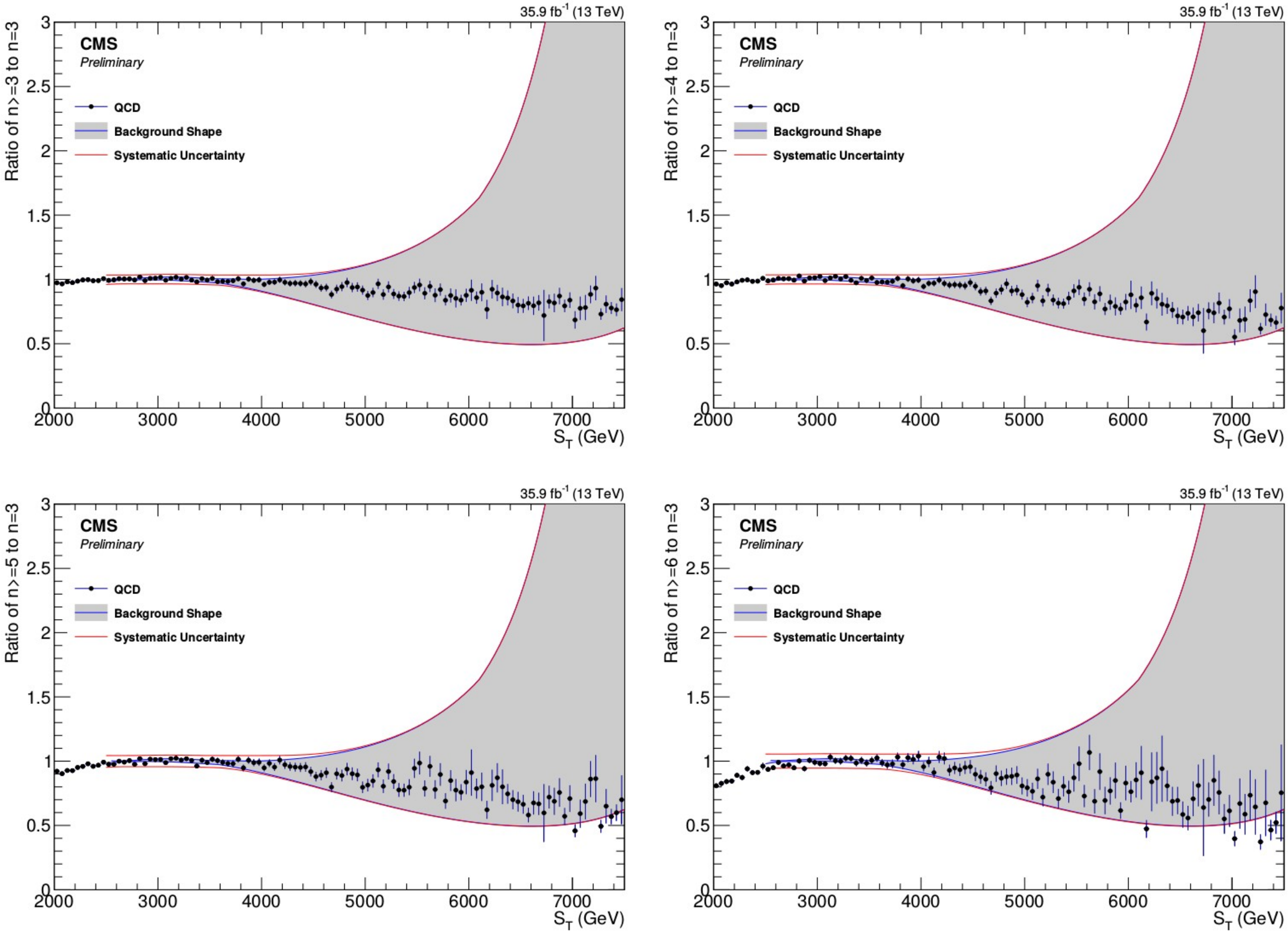
Fit to N=3



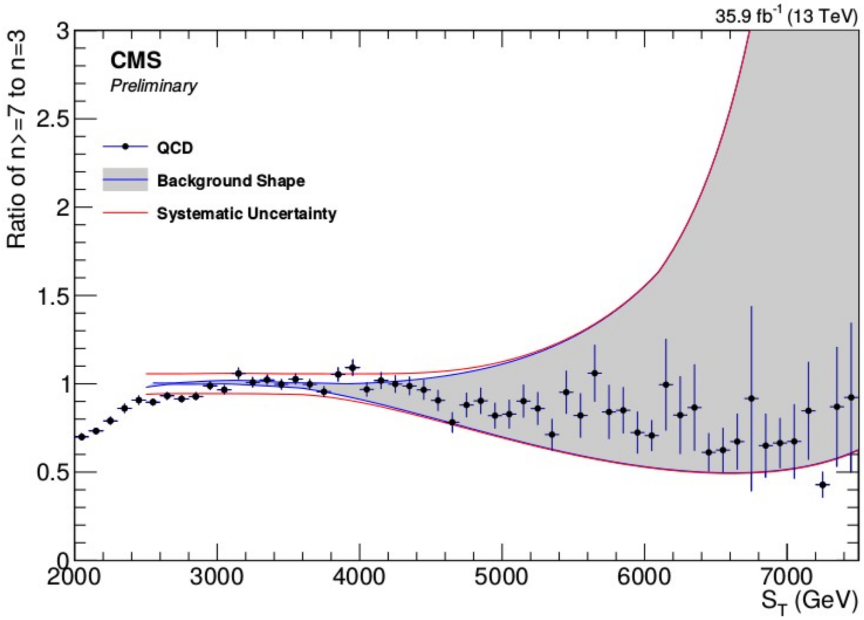


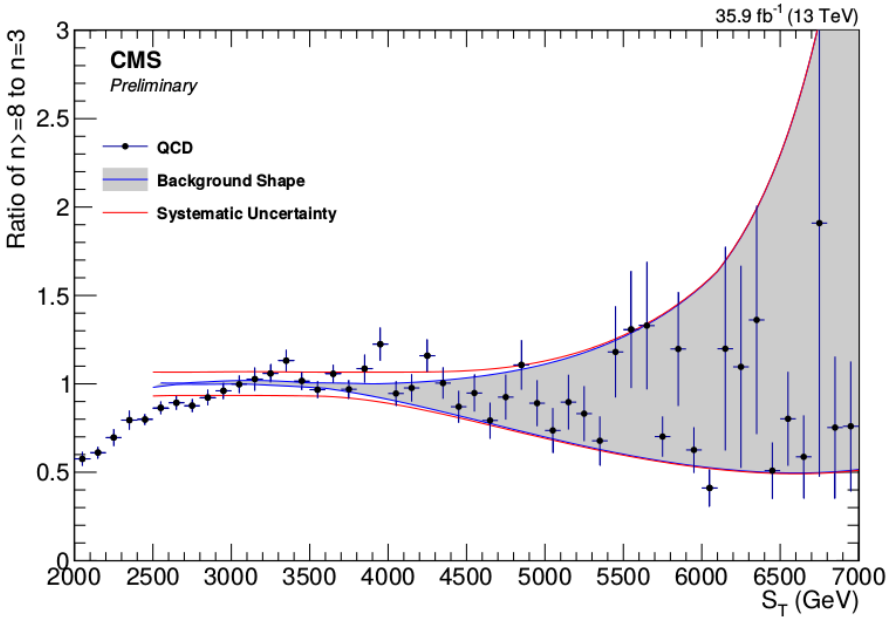


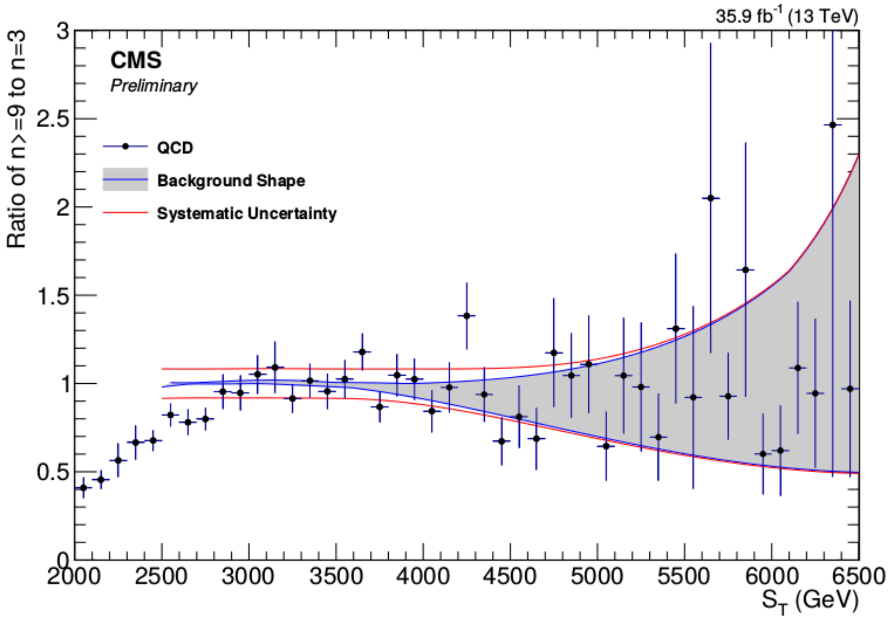
MC S_T Shape Invariance

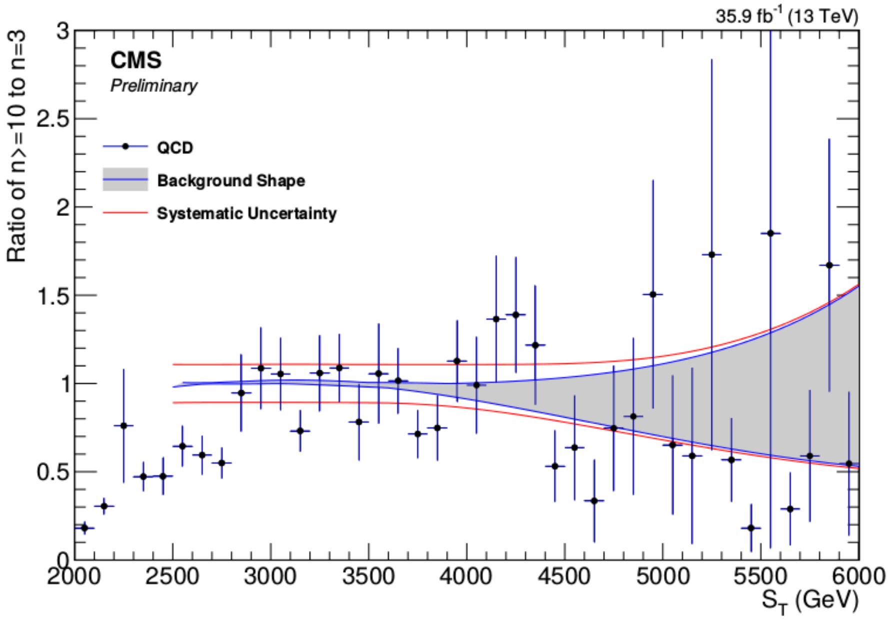


MC S_T Shape Invariance

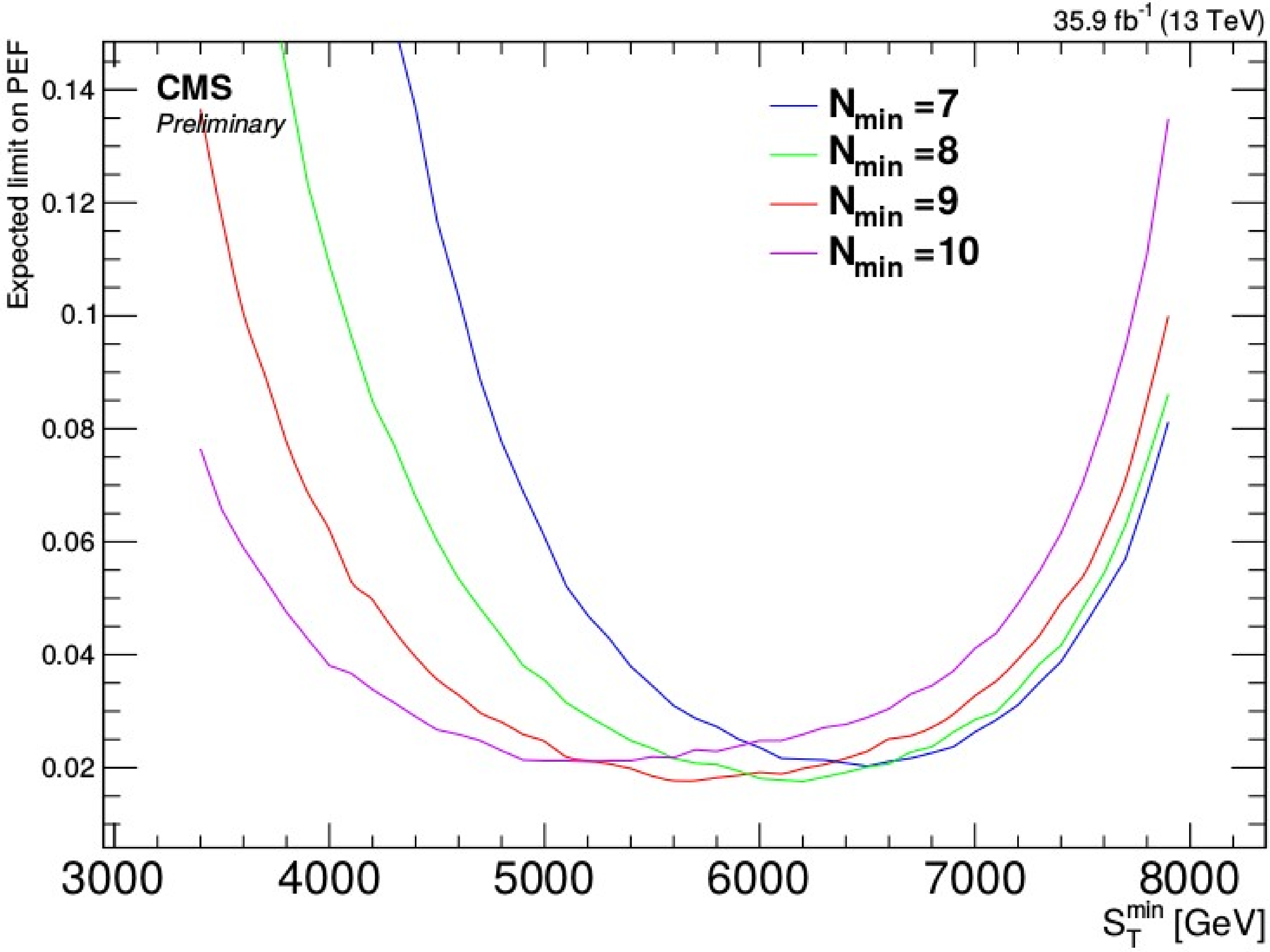








Sphaleron Limit



Normalization Details

Multiplity	Normalization Region [GeV]	Normalization Scaling
≥ 3	2500 – 2900	3.437 ± 0.129
≥ 4	2500 – 2900	2.437 ± 0.094
≥ 5	2700 – 3100	1.379 ± 0.066
≥ 6	2900 – 3300	0.653 ± 0.039
≥ 7	3000 – 3400	0.516 ± 0.034
≥ 8	3200 – 3600	0.186 ± 0.017
≥ 9	3200 – 3600	0.055 ± 0.006
≥ 10	3200 – 3600	0.012 ± 0.002
≥ 11	3200 – 3600	0.0024 ± 0.0005