Search for New Physics in Multijet Final States

28th January 2015

High Energy Physics Seminar
University of Virginia

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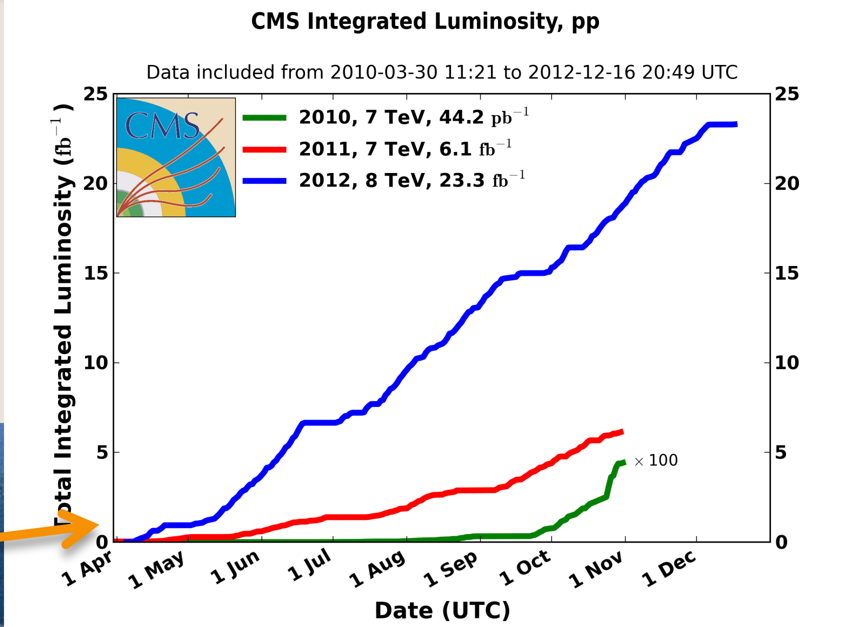
Outline

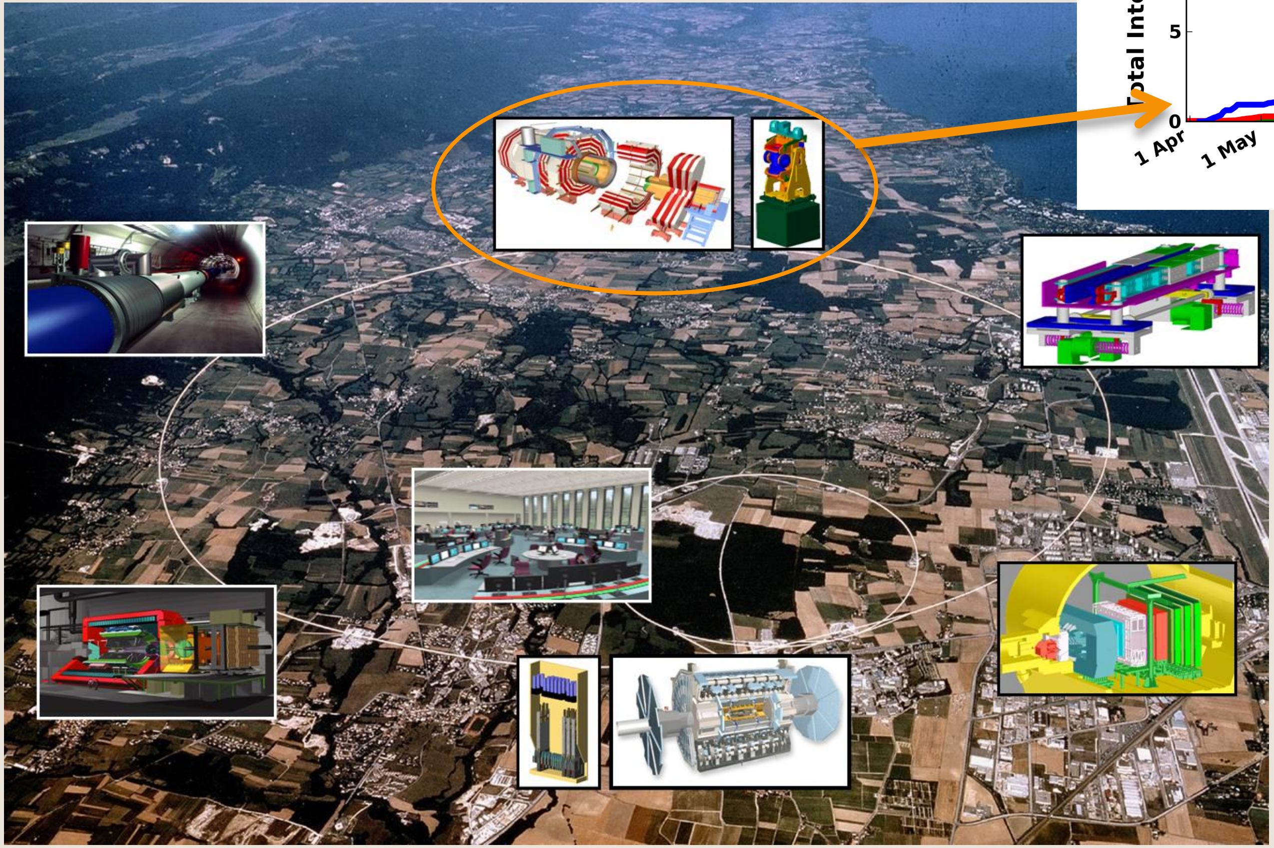
- The Large Hadron Collider
- The Compact Muon Solenoid experiment
- Physics Analyses (high Pt physics with multijet final states)
  - New physics in 8-jet final state (7 TeV, PAS pub)
  - Microscopic black hole at CMS (8 TeV, JHEP 07 (2013) 178)
  - New physics in 8- and 10-jet final states (8 TeV, publication anticipated)
    - Motivation
    - Data and MC samples
    - Search strategies
    - Results
- BSM with multijet in the LHC Run 2 (perspective and sensitivity reach)

The Large Hadron Collider

Proton-proton collider: 7 Experiments

ATLAS, CMS, LHCb, ALICE, ToTEM, LHCf, and MoEDAL





2010-2011: 7 TeV, ~5 fb^{-1}

2012: 8 TeV, ~20 fb^{-1} (PU ~21 events)

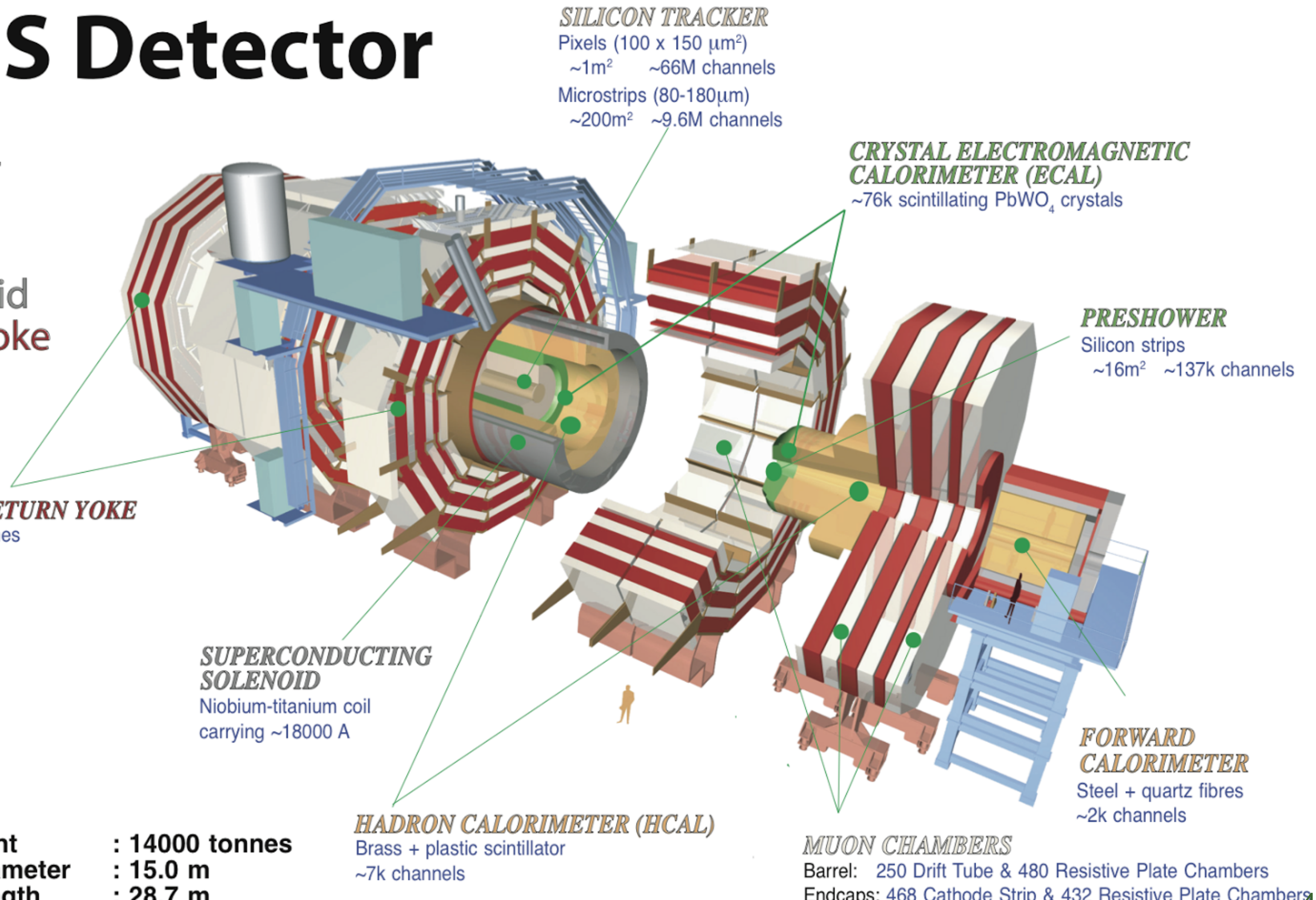
2015: 13 TeV, ~100 fb^{-1}, Pileup of ~40 events per bunch crossing (by the end of 2015)

The CMS Experiment

The Compact Muon Solenoid

CMS Detector

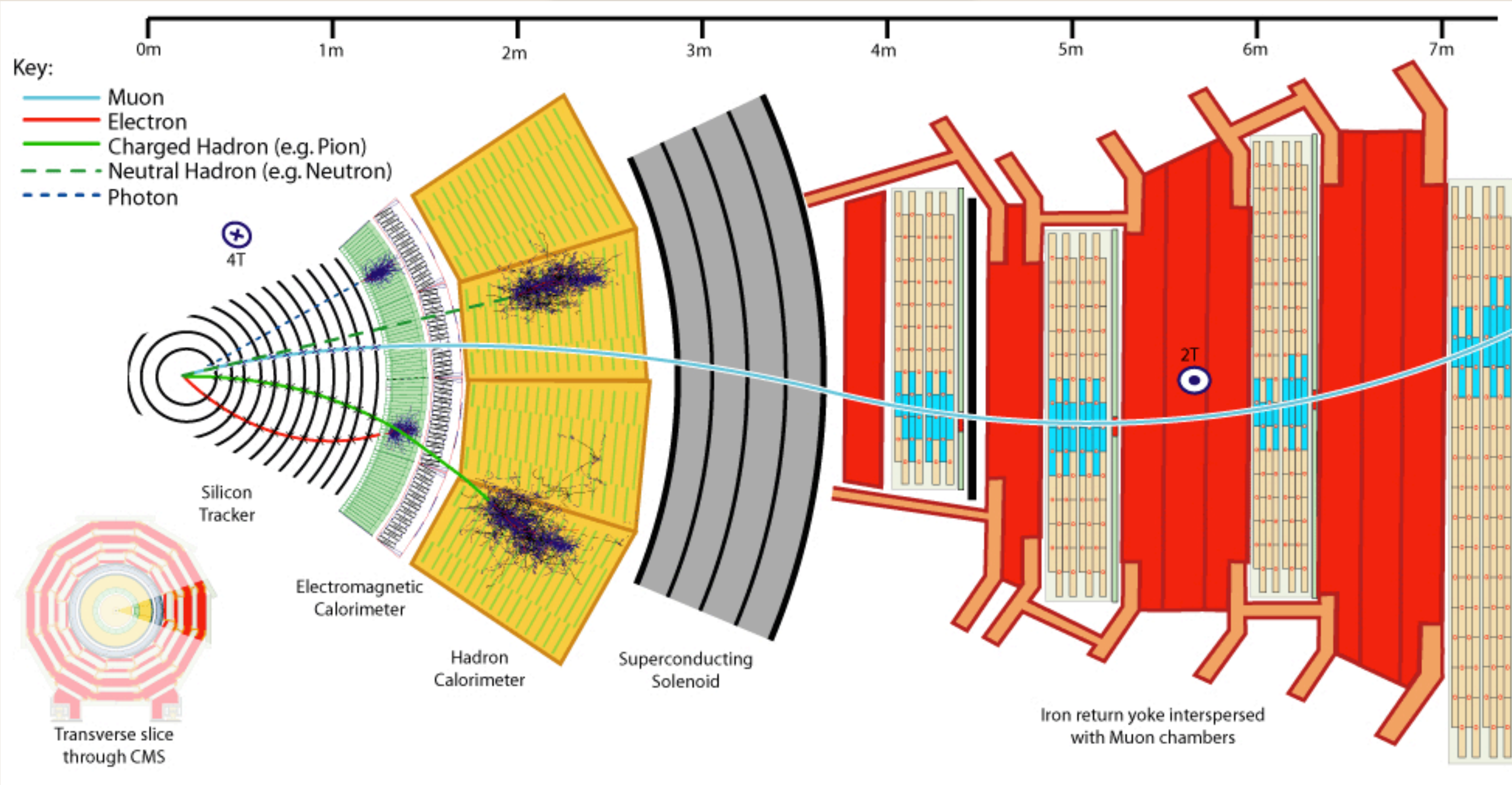
- Pixels
- Tracker
- ECAL
- HCAL
- Solenoid
- Steel Yoke
- Muons



Total weight : **14000 tonnes**
Overall diameter : **15.0 m**
Overall length : **28.7 m**
Magnetic field : **3.8 T**

The CMS Experiment

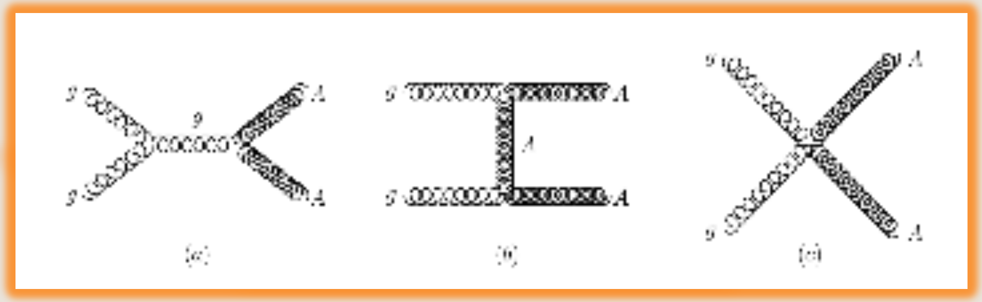
Particle detection at CMS

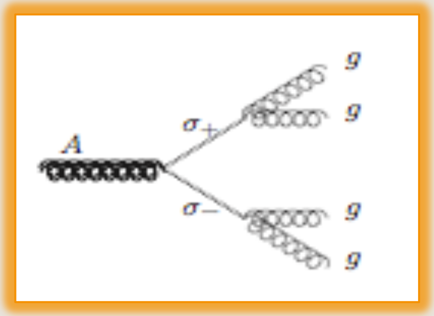


Particle Flow (PF) is an event reconstruction algorithm used to identify and reconstruct the particle. It combines the information from all the subdetectors.

Motivation

- Pair-produced Axigluon/Colorons in 8-jet final state
- Pair-produced Gluinos in 10-jet final state
- The first time to search for new physics in 8-or 10-jet events (continuation of 2011 analysis)
- Pair-produced Axigluon
  - http://arxiv.org/abs/arXiv:1209.6375v1 (M. Schmaltz, et al)





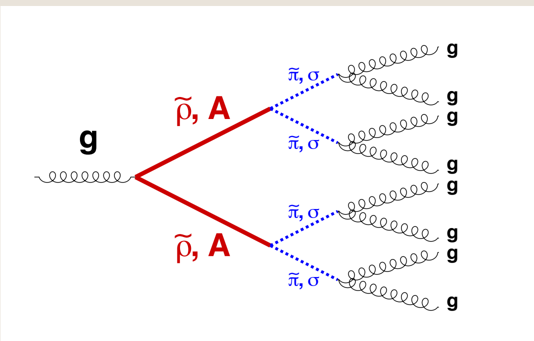
- Pair-produced Color-Vector Boson (coloron/hyper-pion)
  - http://arxiv.org/abs/arXiv:1012.5694 (S. Nandi, et al)

$$\tilde{\rho}\tilde{\rho} \to \tilde{\pi}\tilde{\pi}\tilde{\pi}\tilde{\pi} \to 8g$$

- Pair-produced Gluinos in R-parity Violation Supersymmetric Model
  - http://arxiv.org/abs/arXiv:1310.5758v1 (J. Evans, M. Strassler et al)

Signal Simulation (1)

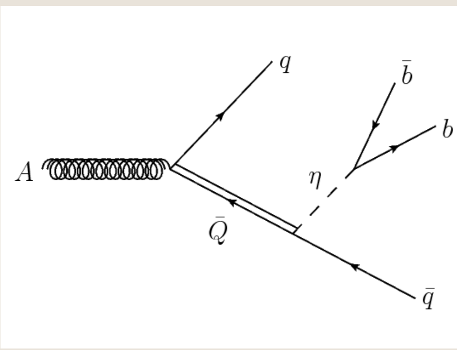
- Signal characteristics (8-jet final state) define the kinematics properties
  - Pair-produced massive vector bosons (Axigluon/Coloron)
  - Each vector boson decays to a pair of massive scalars/hyperpion
  - Each scalar decays to a pair of gluons



Signal Simulation

- Pythia 6 + Fastsim , gluinos → techni-η → gluons
- 3 parameter set named as XX_YY_ZZ in 4 scenarios
  - XX is vector boson mass
  - YY is scalar mass
  - ZZ is vector boson width

Stephen Mrenna



4 Scenarios

- YY = 1/3 or 1/4*XX
- ZZ = 10% or 20/15% of XX
- [400-1500] mass points with 100 GeV interval

Signal Simulation — **Schmaltz**

- First topology: MG5+ Pythia 6 + Fullsim , axigluon→ scalar → gluons
- 3 parameter set named as XX_YY_ZZ in 4 scenarios
  - XX is vector boson mass
  - YY is scalar mass
  - ZZ is vector boson width
- Second topology: MG5+Pythia 6 +Fullsim, axigluon→Qq→ηqq→bbqq

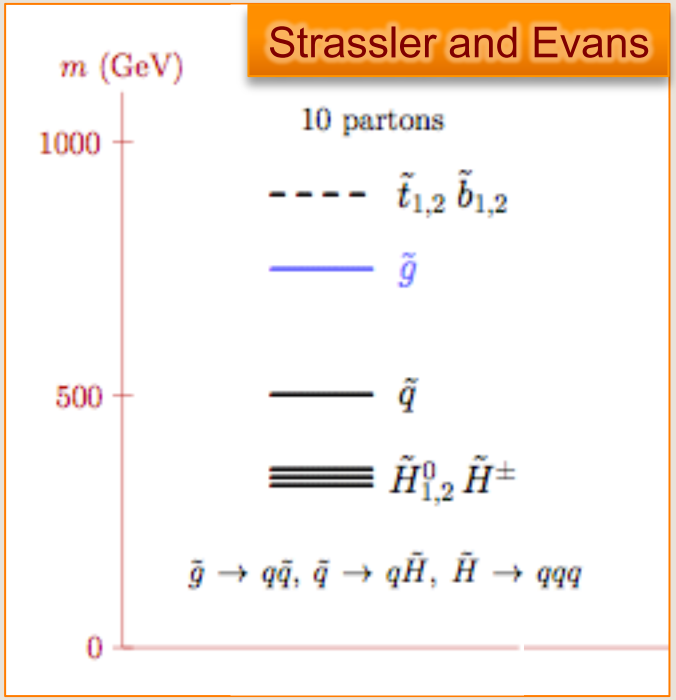
Signal Simulation (2)

- RPV SUSY Gluino
  - Pair-produced RPV SUSY gluino
  - Each gluino decays to quark and squark
  - Each squark decays higgsino and quark
  - Each higgsino decays to three quarks

4 Scenarios

- 10 jets
- 10 jets (8 light quarks, 2 b-quarks)
- 10 jets (6 light quarks, 4 b-quarks)
- 10 jets (4 light quarks, 6 b-quarks)
- 2D grid M_G = [500-1500] GeV
- M_{Sq} = [100-900] GeV
- 100 GeV interval

Strassler and Evans



Signal Simulation

- MG5+ Pythia 6 + Fastsim
- $M_{H0} = 3/4M_{sq}$ (rounded to the nearest 10 GeV)
- tan(β) = 10

M_{Sq} = 500 GeV
$M_H = 3/4M_{sq}$

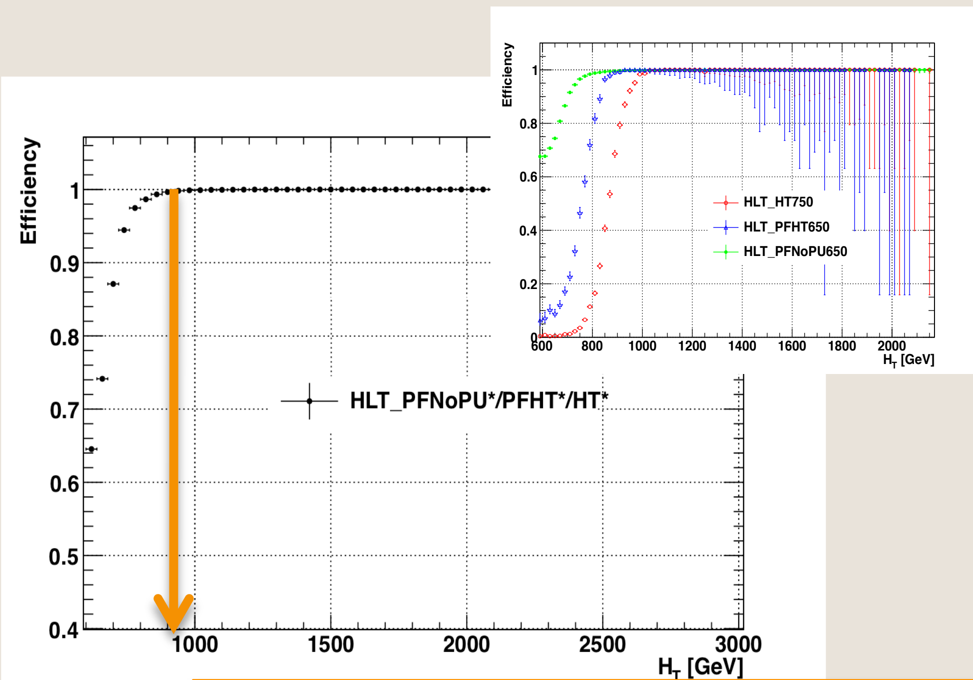
Data and Monte Carlo Samples

Data sample (total integrated luminosity of 19.7 fb^{-1})

Dataset	Integrated Luminosity (pb^{-1})
/HT/Run2012A-22Jan2013-v1/AOD	876
/JetHT/Run2012B-22Jan2013-v1/AOD	4412
/JetHT/Run2012C-22Jan2013-v1/AOD	7051
/JetHT/Run2012D-22Jan2013-v1/AOD	7369

QCD MC Sample

- /QCD_HT-XXX_TuneZ2star_8TeV-madgraph-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM



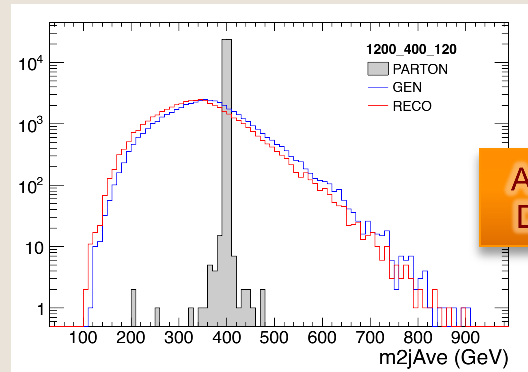
Preselection

- Good primary vertex
  - $|PV_Z| < 24$ cm, $|PV\rho| < 2$ cm, $N_{dof} > 4$
- At least 8 or 10 Anti-KT5 PF Jets
- Standard tight PF Jets ID recommended by EXO group
- $H_T > 900$ GeV (trigger is fully efficient), $P_T > 30$ GeV, and $|\eta| < 2.4$

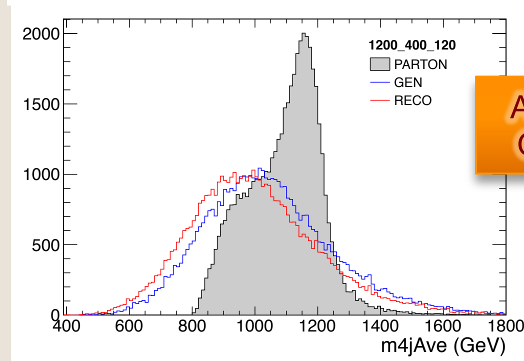
$H_T > 900$ GeV, $P_{T,8} > 30$ GeV and $|\eta| < 2.4$

Search Strategies (1)

- Traditional "Bump Hunt"
  - 8 gluon-jets final states with axigluon and coloron models have "broad" resonance due to strong color coupling
  - The situation is worsened due to "large" combinatorial background (2520 combinations!!) and "radiation effect"
- 8- and 10-jet final state
  - With many available sources of information, this allows us to exploit the correlations in order to suppress the background and preserve the signal efficiency
- Multivariate Approach
  - Ideal for our situation and is increasingly used in CMS in order to boost the sensitivity
- Artificial Neural Network (ANN)
  - Powerful instruments for optimal background and signal separation with TMVA packages interface to ROOT



Averaged Doublets



Averaged Quartets

Shape Based MVA Strategy

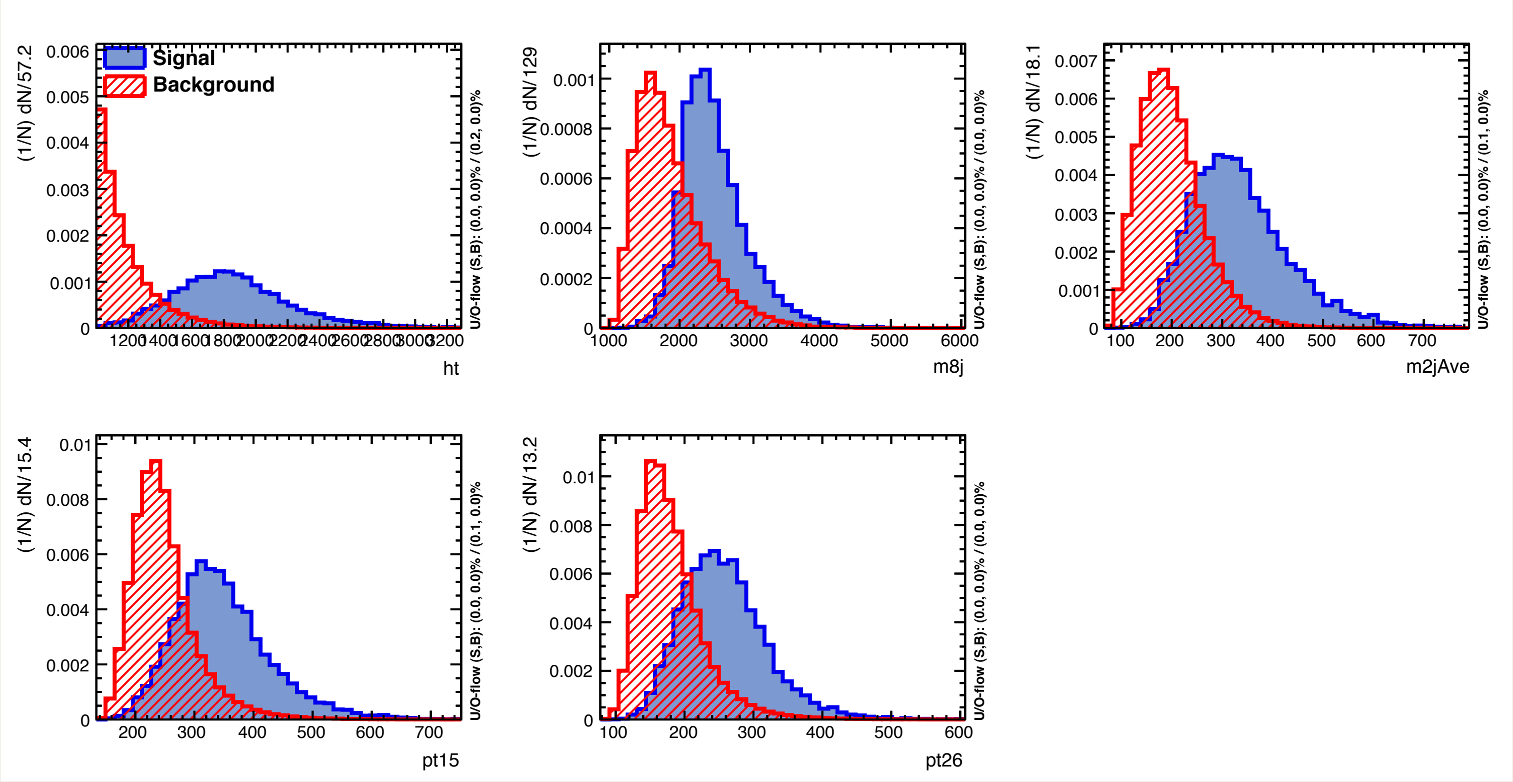
MVA Shape-based Analysis

- Artificial Neural Network (ANN)
  - utilizes a set of high discriminating-power variables as inputs to a system of interconnected artificial neural nodes with modifying weights that are tuned by a learning algorithm
  - separates the signal from the multijet (QCD) background
- Input variables in Artificial Neural Network (ANN)
  - $\langle P_{t,1} + P_{t,5} \rangle$ and $\langle P_{t,2} + P_{t,6} \rangle$
  - Invariant mass of 8 jets M_{8j}, $\langle M_{2j} \rangle$, H_T
- Systematic Uncertainties:
  - QCD MC Alpgen (up to 6 partons) and Madgraph (up to 4 partons)
  - Jet Energy Scale (JES) and Jet Energy Resolution (JER)
  - Limited MC statistics
  - Initial and Final State Radiation (ISR/FSR)
  - Parton Distribution Functions (PDF)
  - Luminosity Calculation

Discriminating Variables

5 Discriminating Variables as Inputs to ANN

- $<P_{t,1} + P_{t,5}>$ and $<P_{t,2} + P_{t,6}>$
- Invariant mass of 8 jets M_{8j}, $<M_{2j}>$, H_T

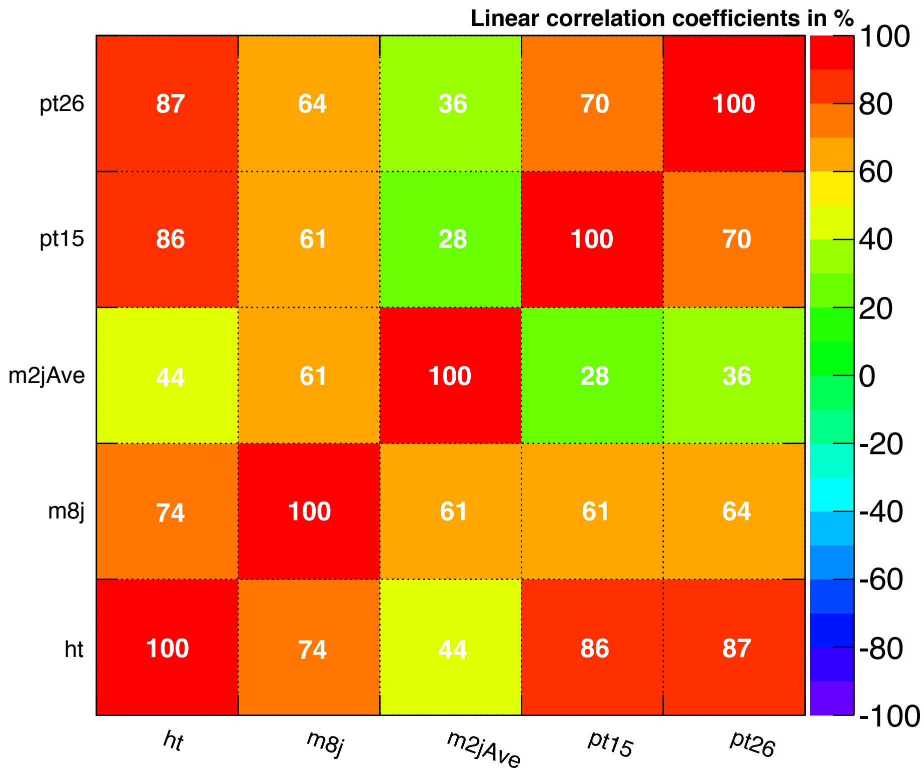


1000_333_100

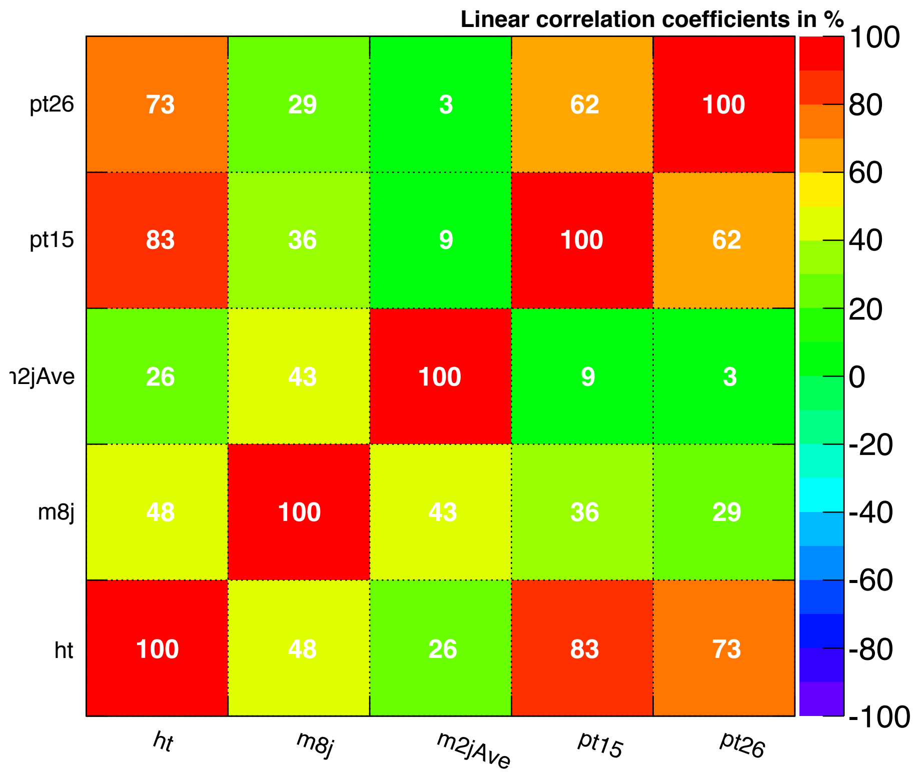
$(M_A\_M_\sigma\_W_A)$

Correlation Matrices

- Correlation Matrices



Signal

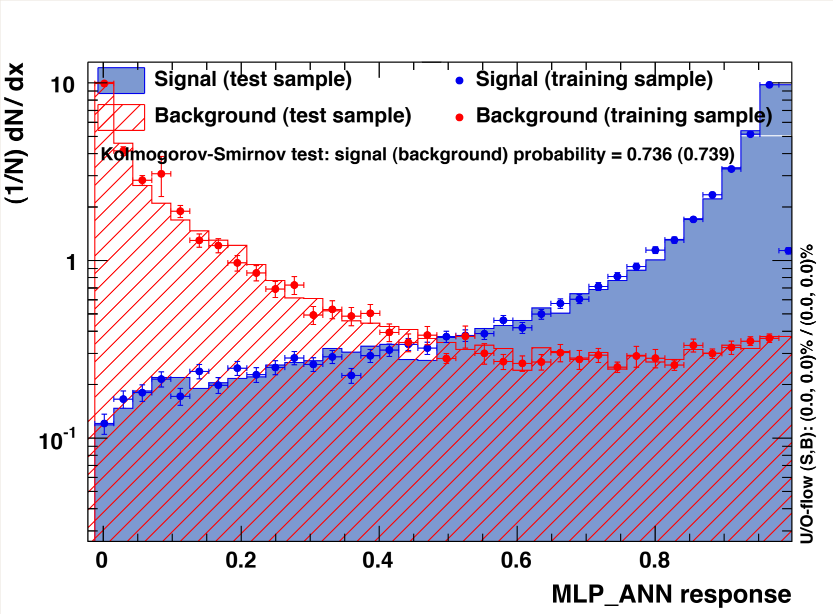


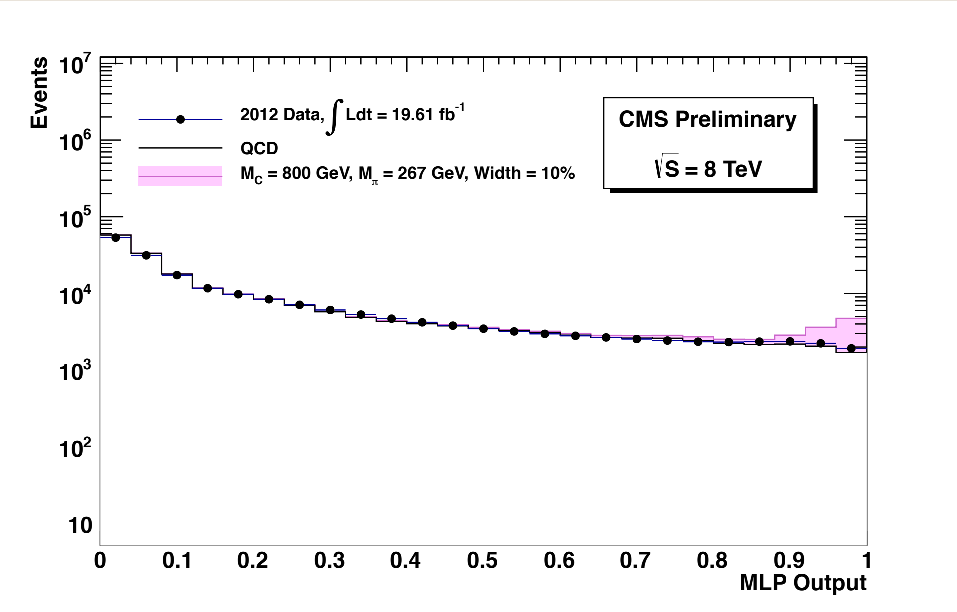
Background

1000_333_100

(M_A_M_σ_W_A)

ANN Response: Data VS MC





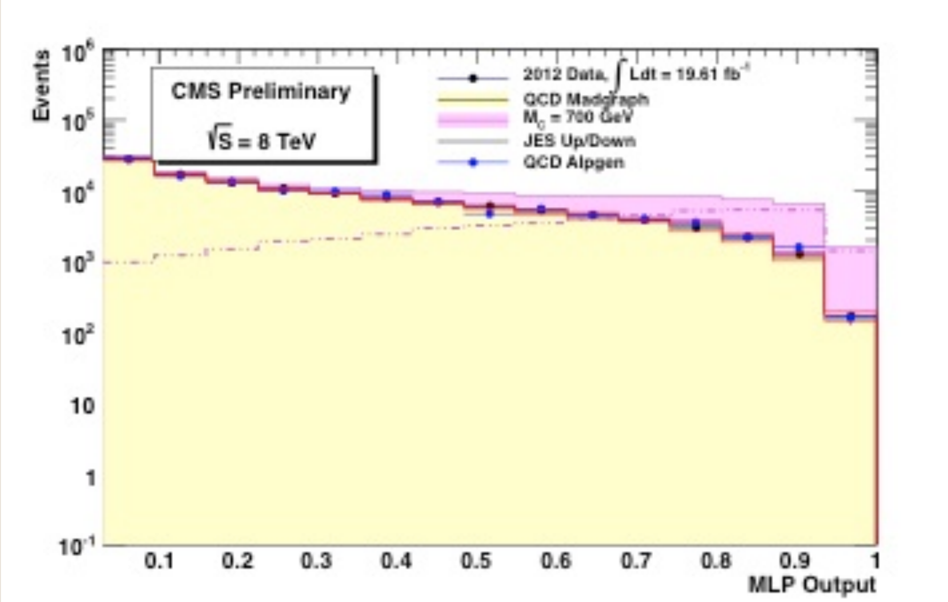
- Weights from training ANN (TMVA package)
- Apply to data, background, and signal

Good agreement between ANN Output of the Data and QCD Background

Higgs Combination Tool
- MVA shape analysis
- Find best fit of QCD/signal templates to the data
- Compute CL_s limits

Systematic Uncertainties

- Systematic Uncertainties:
  - QCD MC Alpgen (up to 6 partons) and Madgraph (up to 4 partons)
  - Jet Energy Scale (JES) and Jet Energy Resolution (JER)
  - Limited MC statistics
  - Luminosity calculation
  - Initial and Final State Radiation (ISR/FSR)
  - Parton Distribution Functions (PDF)
  - Multiple interactions per bunch crossing (PU)
  - Fast and Full Simulation



Main systematic effects on shape are:

JES (shape)

Limited MC (shape)

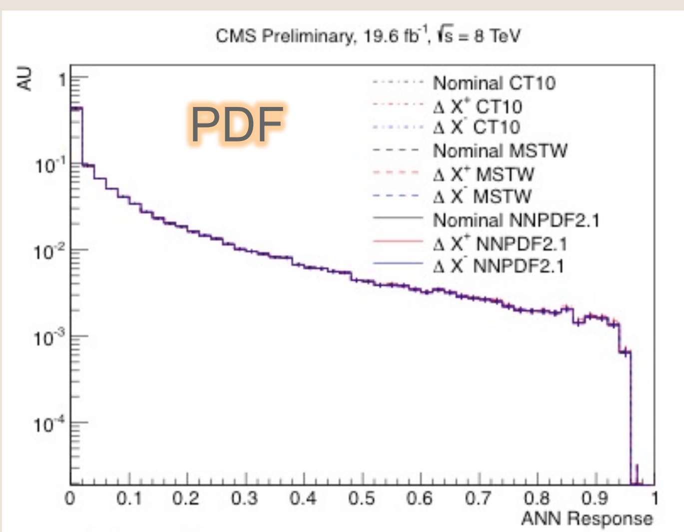
Retrain the QCD MC samples accounting for JES/JER/MC and apply weight to the signal/ background and data

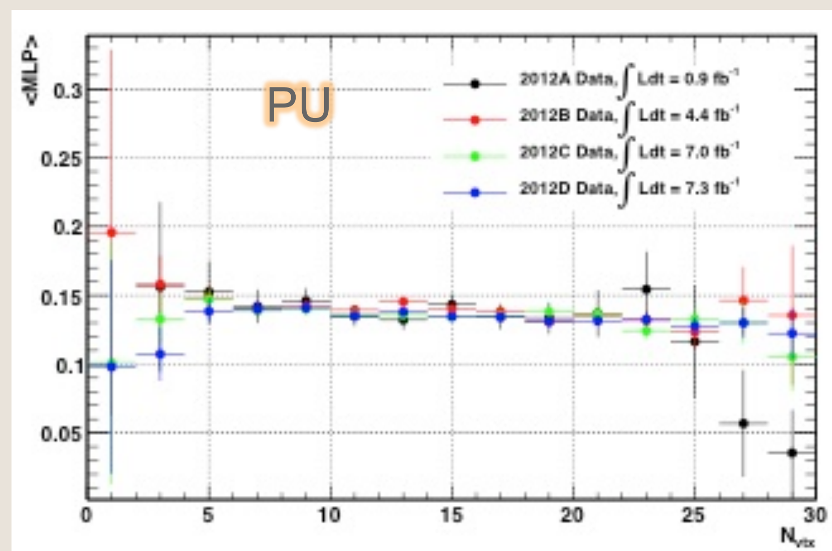
Systematic Uncertainties

- Systematic Uncertainties:
  - QCD MC Alpgen (up to 6 partons) and Madgraph (up to 4 partons)
  - Jet Energy Scale (JES) and Jet Energy Resolution (JER)
  - Limited MC statistics
  - Luminosity calculation
  - Initial and Final State Radiation (ISR/FSR)
  - Parton Distribution Functions (PDF)
  - Multiple interactions per bunch crossing (PU)
  - Fast and Full Simulation

Negligible effects on the final limit

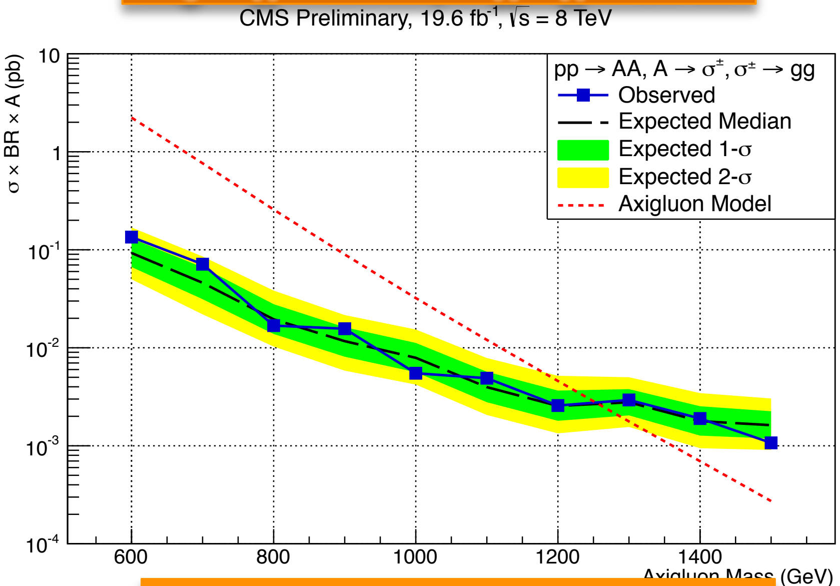
CT10, MSTW and NNPDF2.1



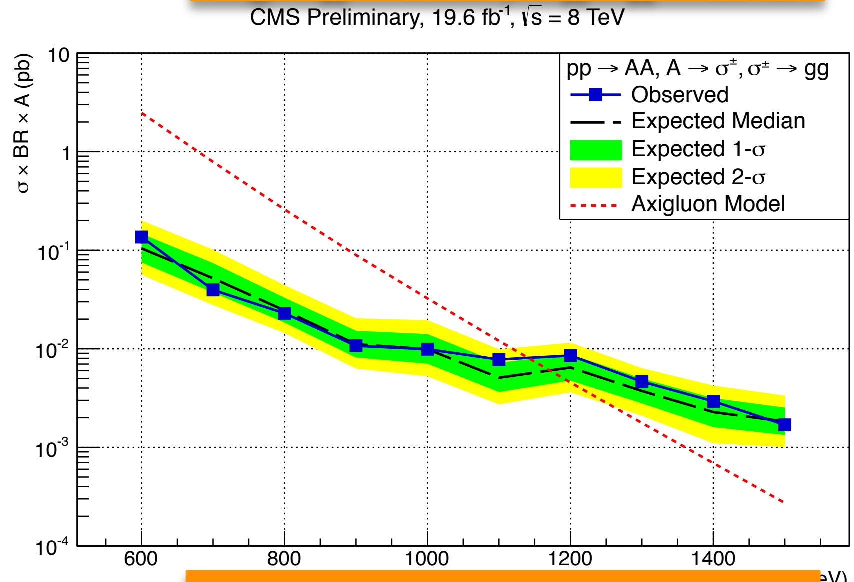


Limits Setting (Axigluon Model)

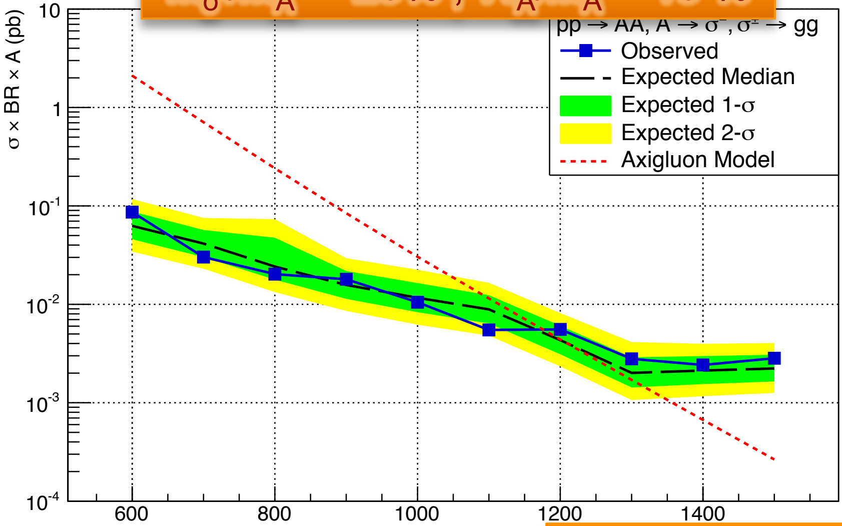
M_σ/M_A = 33% , W_A/M_A = 10 %



M_σ/M_A = 33% , W_A/M_A = 15 %



M_σ/M_A = 25% , W_A/M_A = 10 %



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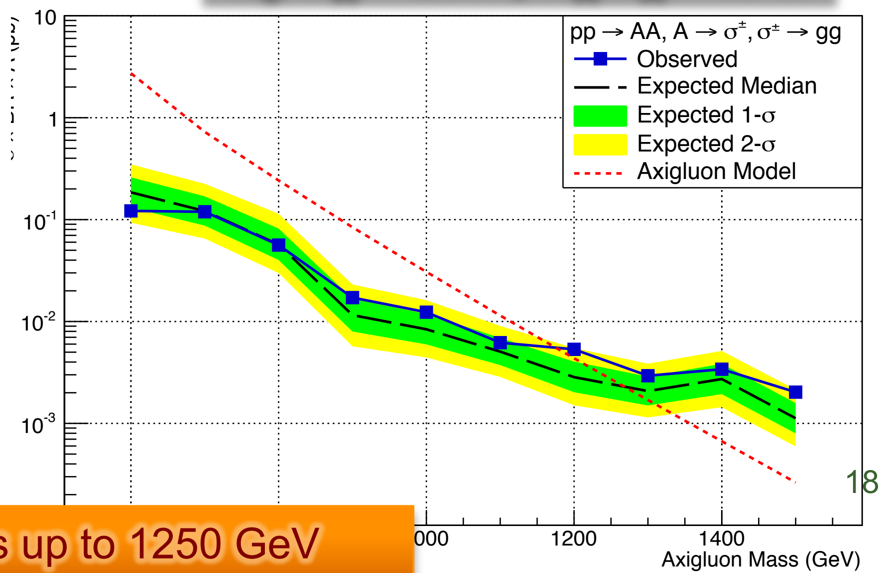


Exclusion limits up to 1250 GeV

Search Strategies (2)

- Rely on background MC
  - Systematic uncertainty from theoretical prediction of the QCD 8 jets process
  - Very difficult to gauge how large the systematic uncertainty is
  - Require expertise on QCD generation
  - Involve re-generation of QCD samples

Other different strategies?

- Simple counting experiment
  - Straightforward method relative to NN
  - Easy to estimate background from data directly
  - "S_T multiplicity invariance method" (microscopic blackhole search)
  - Sensitivity boost with global shape variables

Our main search strategy

Cut and Count Strategy (1)

- Data driven background estimation (H_T multiplicity invariance)
- Boost sensitivity with additional offline cuts on
  - Simple global shape variable, such as sphericity
  - b-tagged jets requirements
  - As long as these cuts do not affect H_T shape
- Study systematic uncertainty
- Set limits on different models

Signal Models	Final State		Additional Requirement
	Light quarks jets	bottom quarks jets	
Axigluon	8	-	Sphericity > 0.1
	4	4	b-tagged jets ≥ 1
Colorons	8 (gluon jets)	-	Sphericity > 0.1
Gluinos	10	-	Sphericity > 0.1
	8	2	b-tagged jets ≥ 1
	6	4	b-tagged jets ≥ 1
	4	6	b-tagged jets ≥ 1

7 different final states are reduced to 4 categories based on:

- Number of jets in the final states
- whether the final state contains bottom quarks

Categories	Total Number of Jets	b-tagged jets	Global Variables Cuts
1	8	-	Sphericity > 0.1
2	8	b-tagged jets ≥ 1	-
3	10	-	Sphericity > 0.1
4	10	b-tagged jets ≥ 1	-

Cut and Count Strategy (2)

Data-driven Background Estimation: H_T multiplicity invariance method

QCD MC

Choose the background template where there is negligible signal contamination

↓

H_T shape invariance ?
(jet multiplicities, b-tagged requirement, global shape cuts)

↓

Background shape parameterizations

↓

Normalize background template to data in signal depleted region

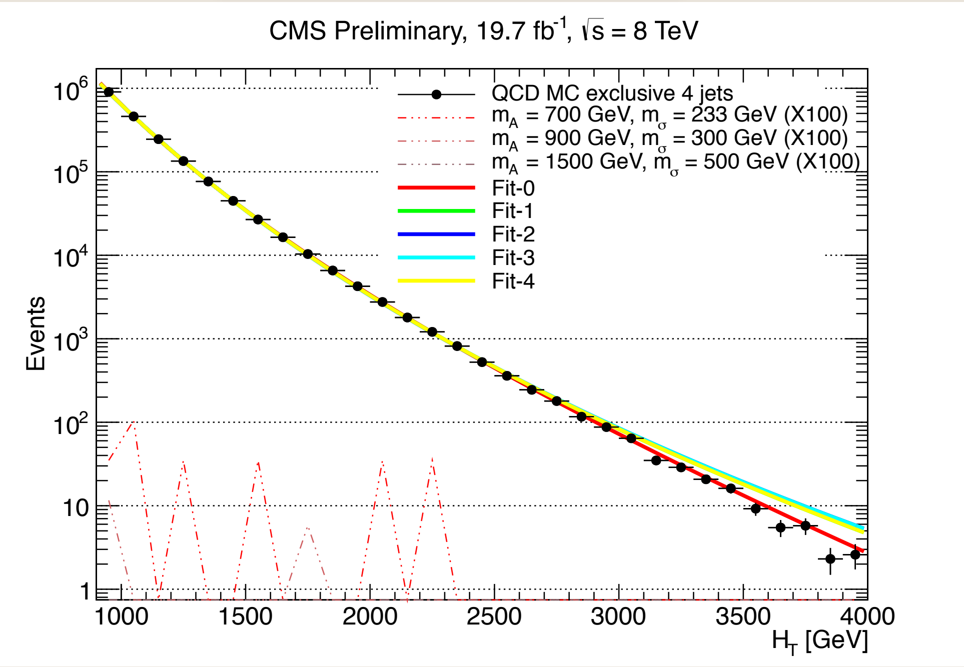
Note:

- Additional checks on H_T shape invariance are performed if b-tagged jets or global variables cuts are required

Signal Contamination and H_T Shape Invariance

Find phase space where signal is depleted in the H_T distribution in the MC samples

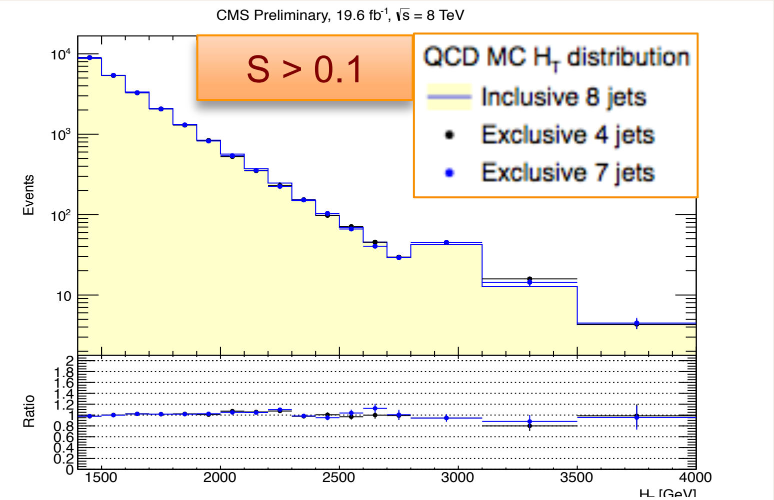
Model with 8-jet final state

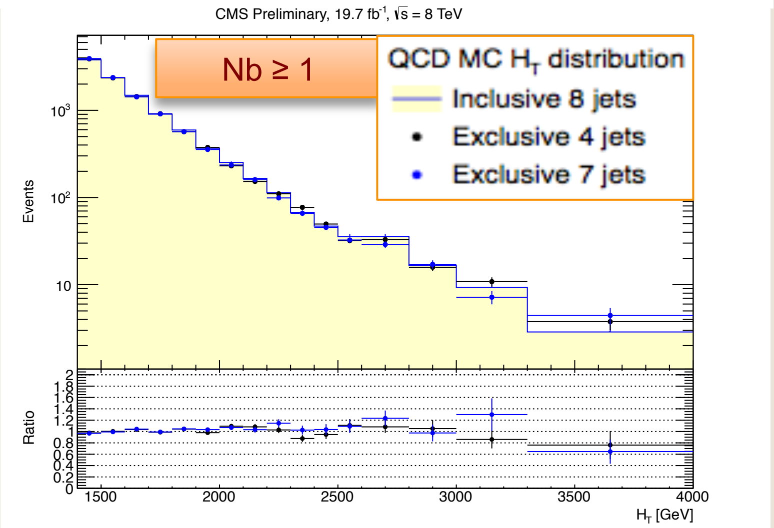


Njets = 4

Negligible signal contamination for all models in jet multiplicity = 4

H_T Shape Invarance under sphericity (s) cut and b-tagged jet requirement

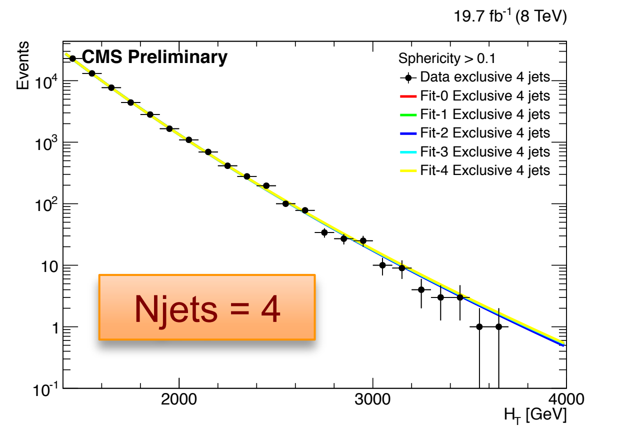


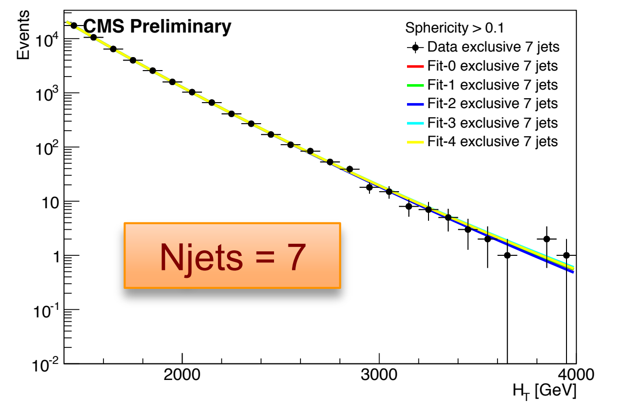


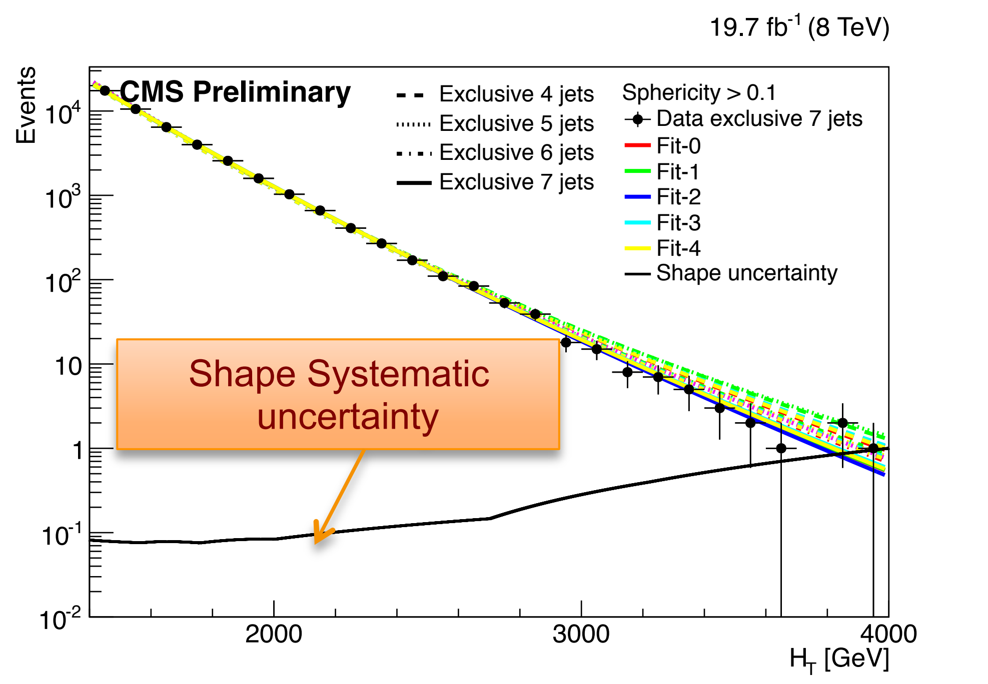
Estimate Background Uncertainty

Njets ≥ 8

S > 0.1







Fitting Functions from blackhole search

$$\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

$$\frac{P_0}{(P_1+P_2x+x^2)^{P_3}}$$

$$\frac{P_0}{(P_1+x)^{P_2}}$$

$$\frac{P_0(1+x)^{P_1}}{x^{P_2}\log(x)}$$

Dijet

$$\frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

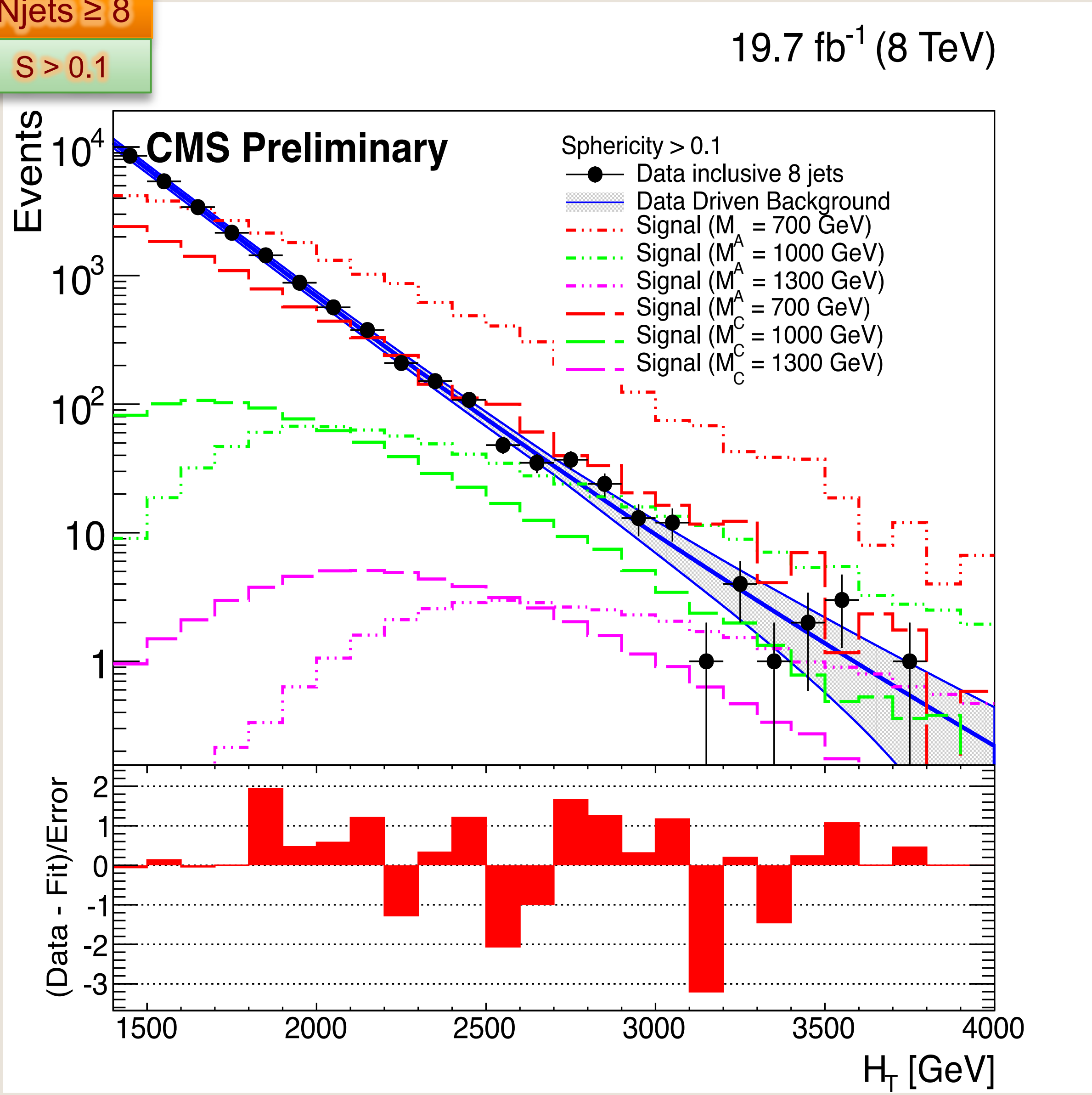
Background Uncertainty

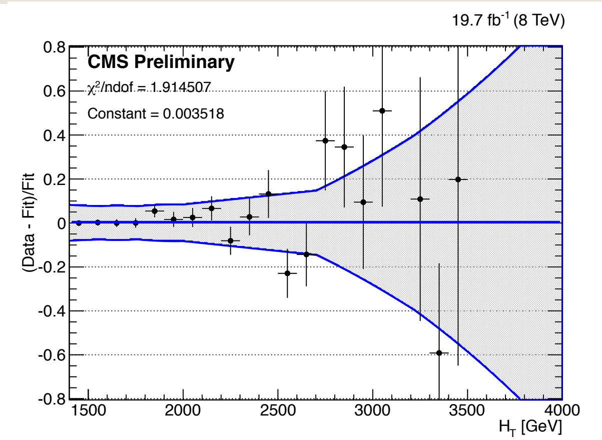
- Fitting data for Njets = 4, 7 with 5 functions [1500-2500 GeV]
- Normalize the fitting functions from Njets = 4 to Njets = 7 [1400-1700 GeV]
- Greatest difference between the two outliers is taken as our uncertainty

H_T Distribution with Data-Driven Background

Njets ≥ 8

S > 0.1





- (Data-Fit)/Fit are consistent within statistical uncertainty and mostly covered by background shape systematic uncertainty

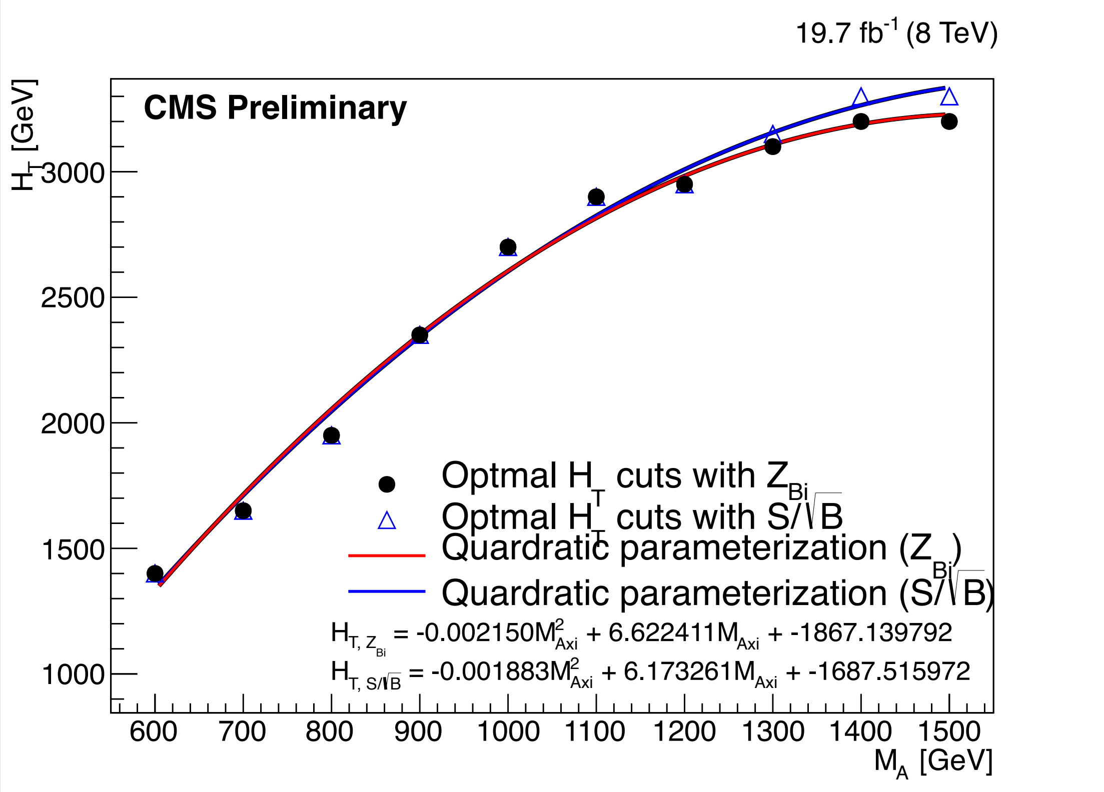
- Pull distribution as a function of H_T is within 1 sigma statistical and sytematic uncertainties combined.

- No deviation from data-driven background prediction

Parameterization of H_T Optimal Cuts

Njets ≥ 8

S > 0.1



- Final optimization is performed on H_T cuts (parameterized as a function of axigluon/ coloron masses)
- Z_{bi} [1] test statistic is used when the number of background events is less than 20

Uncertainty	Effect on Signal Acceptance	Effect on Background
Integrated Luminosity	±2.6%	-
Jet Energy Scale	±5%	-
PDF	±3%	-
Rescaling	-	±(2-100)%
Shape Modeling	-	±(3-140)%, depends on the H_T value.

Using official Higgs combination tool to set limit (with JES, PDF, lumi and background uncertainties)

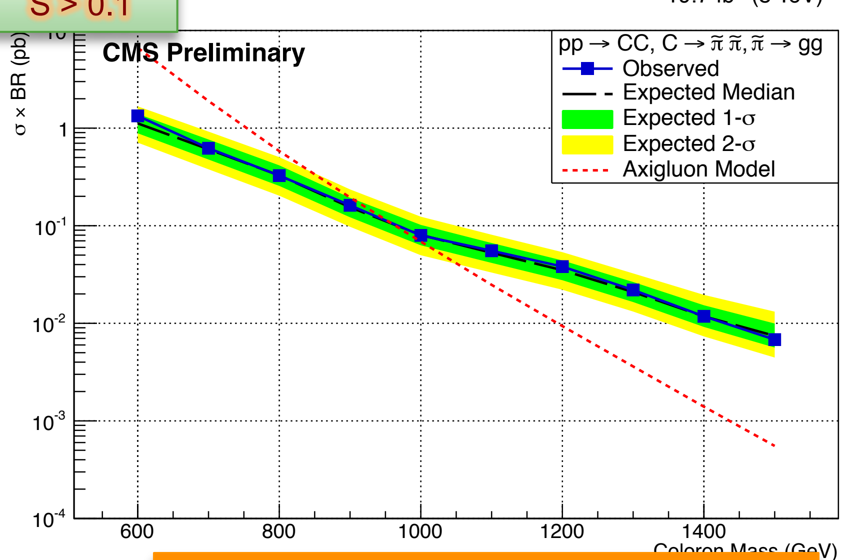
[1] Z_{bi} test statistics: http://arxiv.org/abs/physics/0702156

Limits (Coloron Model)

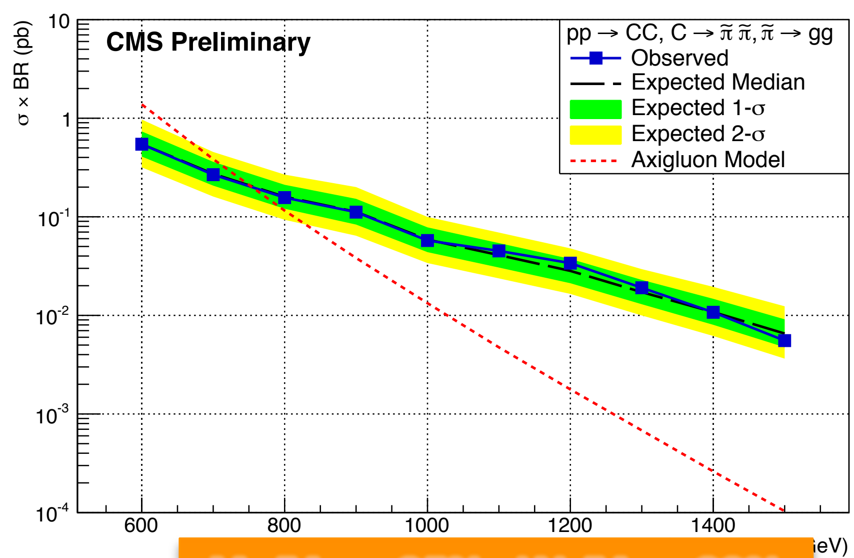
Njets ≥ 8

S > 0.1

$M_\sigma/M_A = 33\%$, $W_A/M_A = 10\ \%$



$M_\sigma/M_A = 33\%$, $W_A/M_A = 20\%$



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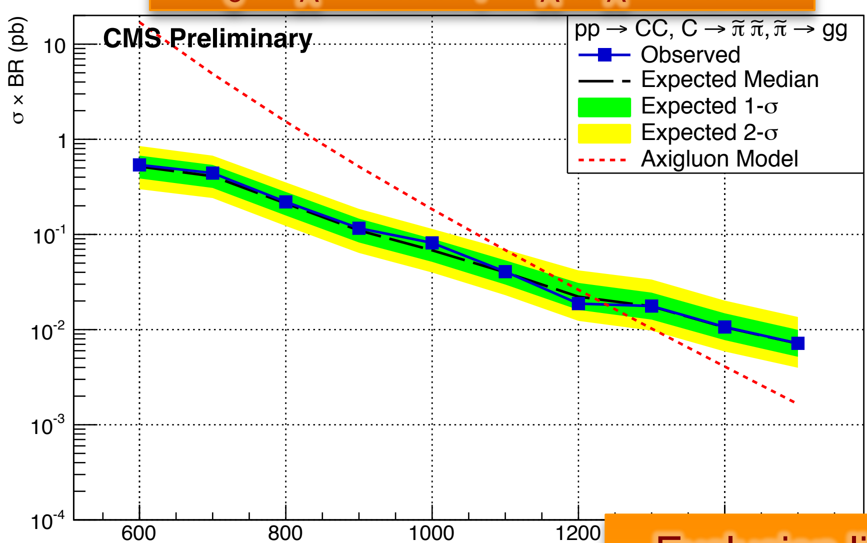

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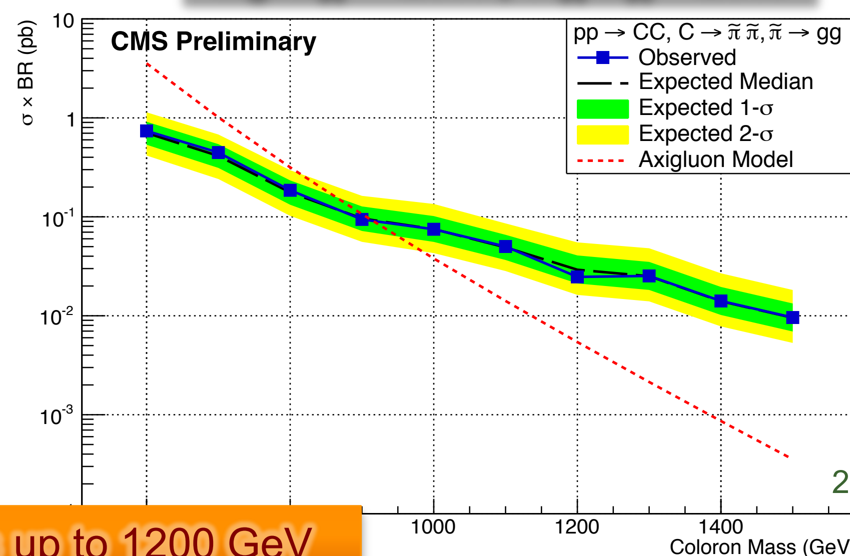
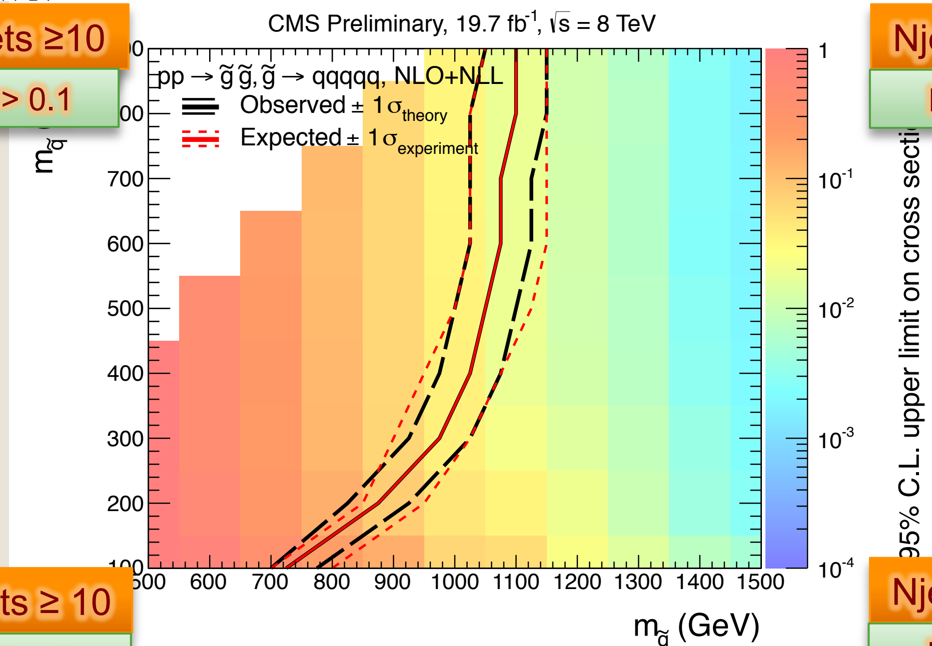


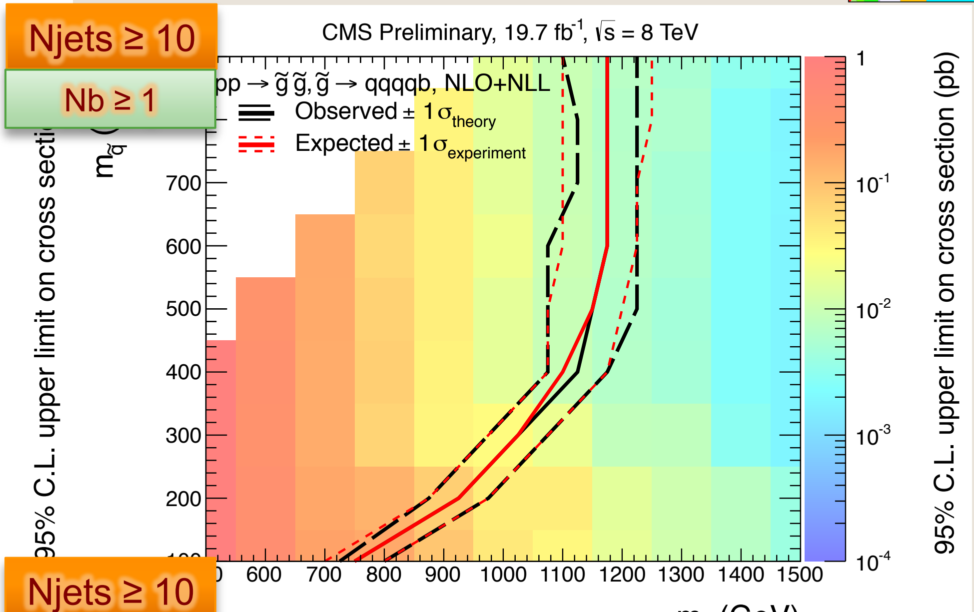
Exclusion limits up to 1200 GeV

Limits (RPV SUSY Gluino Model)

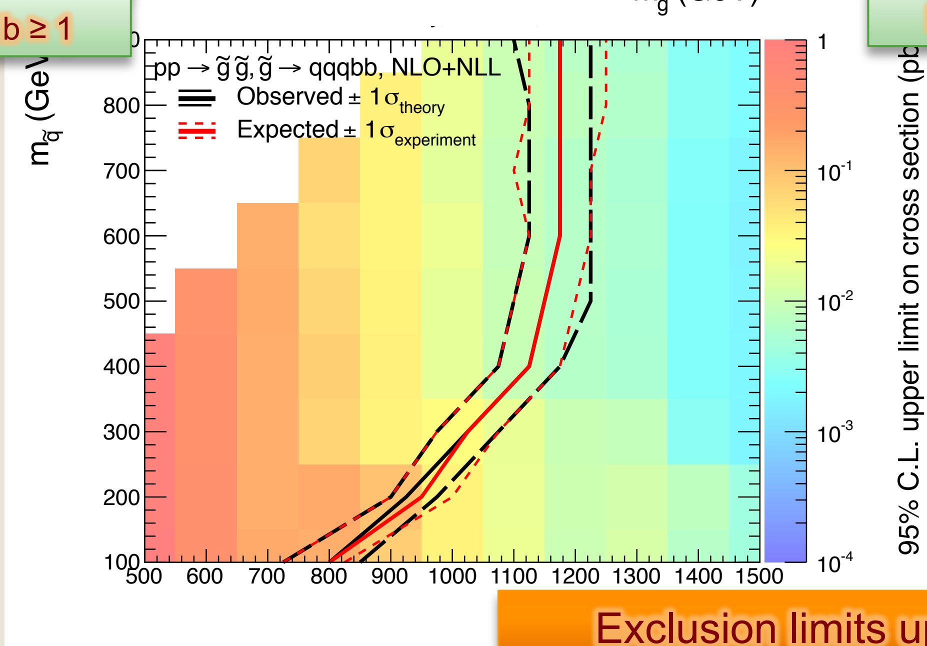
Njets ≥10
S > 0.1



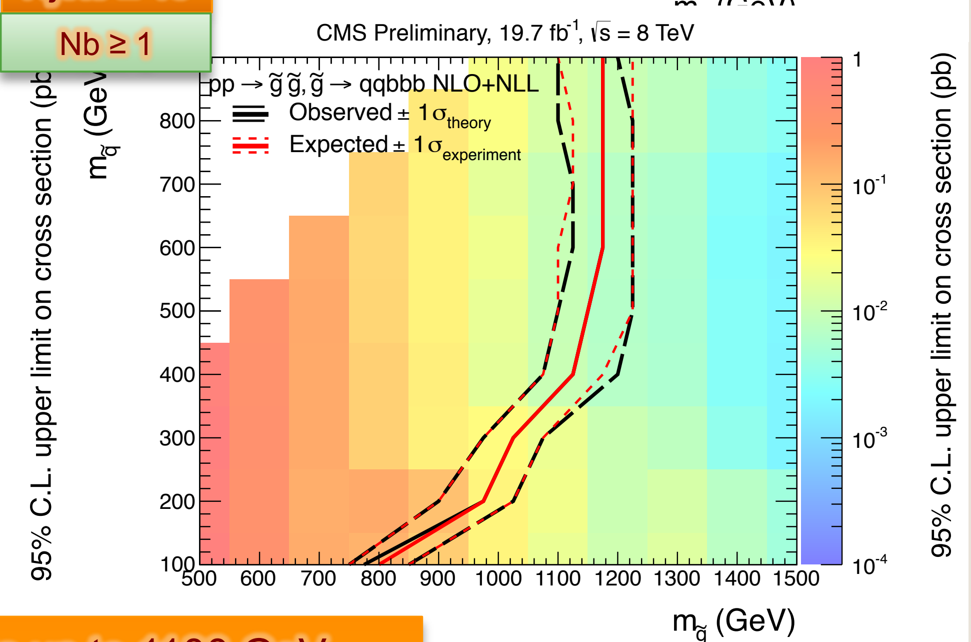
Njets ≥ 10
Nb ≥ 1



Njets ≥ 10
Nb ≥ 1



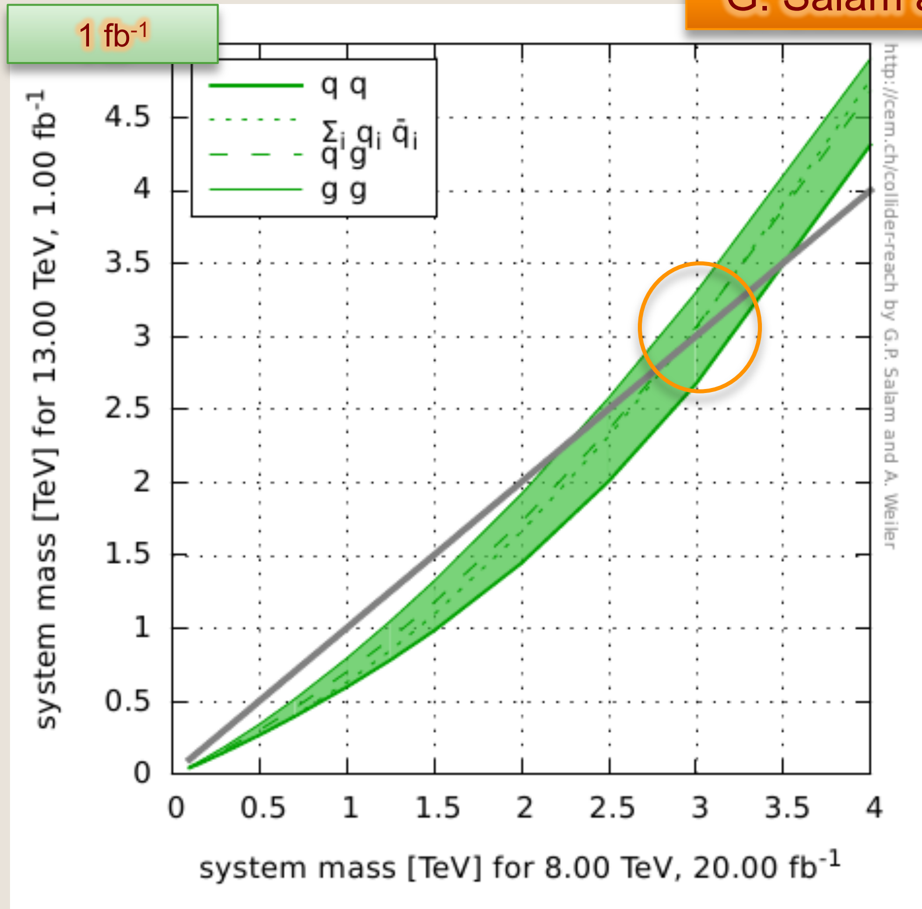
Njets ≥ 10
Nb ≥ 1

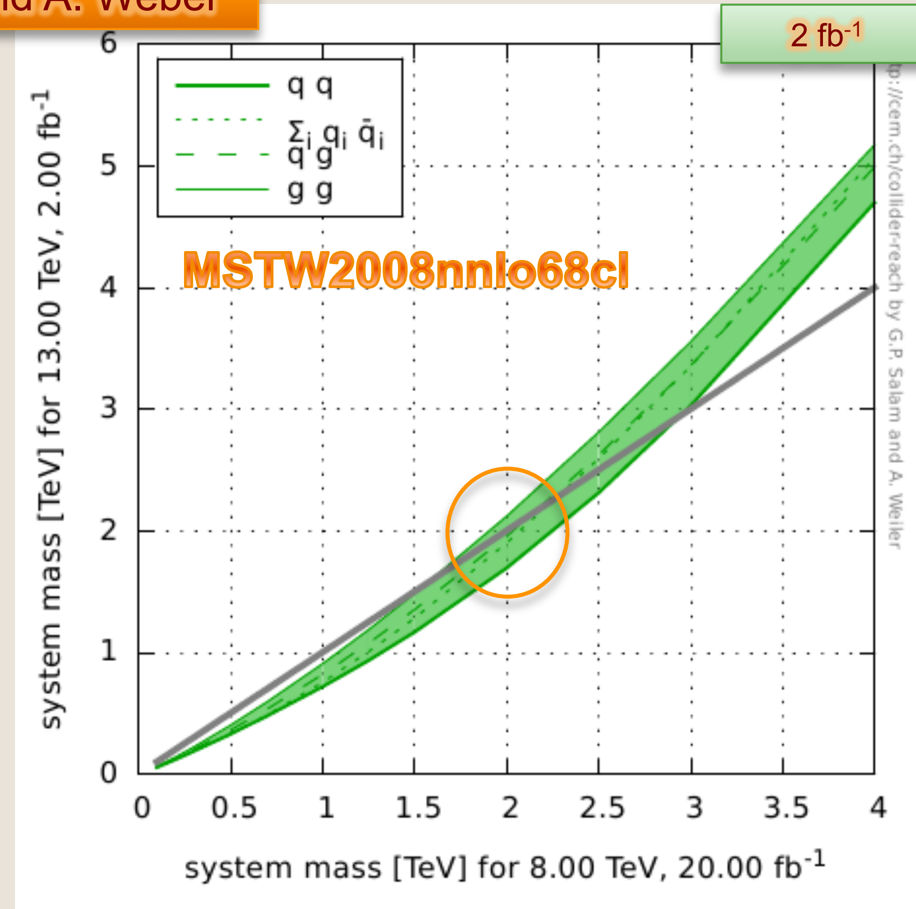


Exclusion limits up to 1100 GeV

BSM Reach at the LHC Run 2

G. Salam and A. Weber





Calculation under assumptions of:

1. cross sections scale with the inverse squared system mass and with partonic luminosities
2. reconstruction efficiencies, background rejection rates, etc., all stay reasonably constant as the collider setup changes

Assuming current gluino (pair production) limit at 1 TeV, the LHC run 2 will already have higher sensitivity at 2 fb^{-1} data at 13 TeV.

Strategy for BSM Search in Mulijet Final State

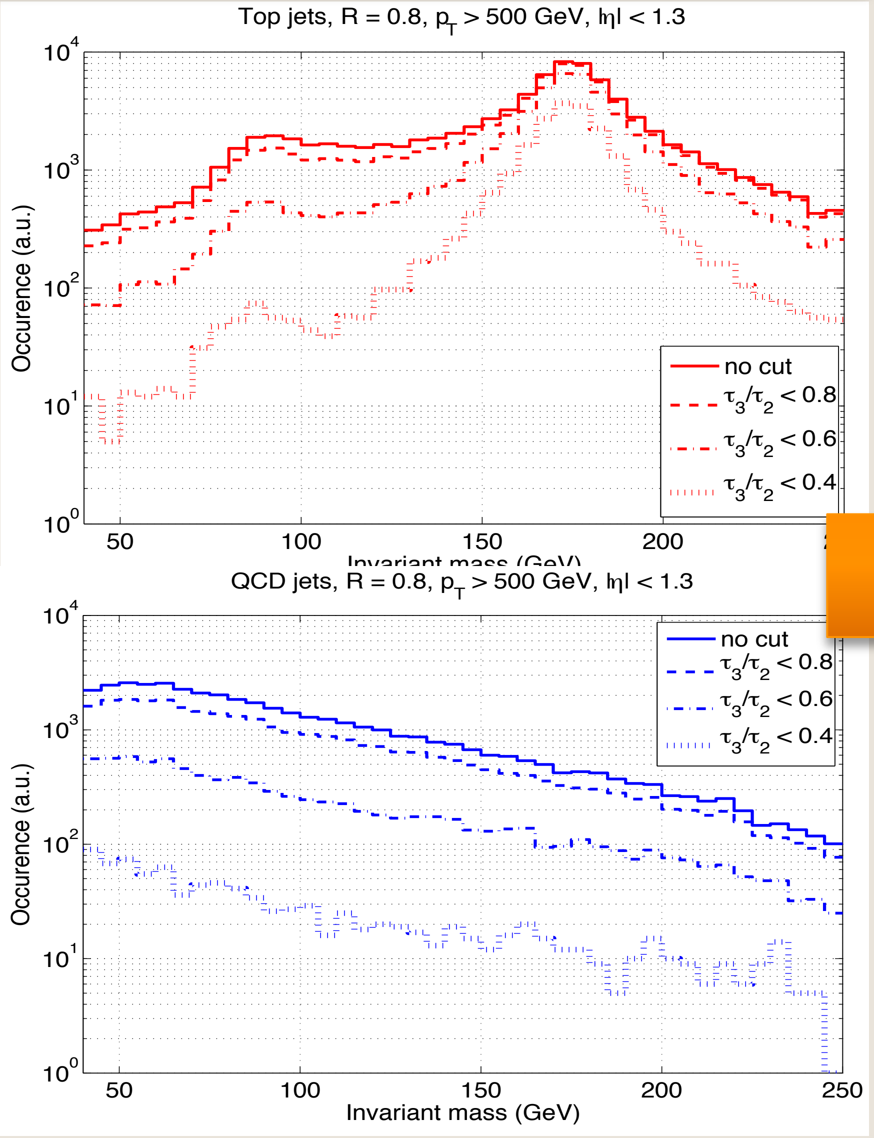
Balance between reach and robustness in the search for BSM Physics

- Accidental Subtructure in multijet events
- Innovative variables:
- N-subjettiness (τ)
- Total jet mass (M)

$$\tau_N^{\text{gen}} = \frac{1}{d_0} \sum_k \min_J \{d(p_J, p_k)\}$$

$$d^{\alpha,\beta}(p_J, p_k) = p_{T,k} \left(p_{T,J}\right)^{\alpha} \left(\Delta R_{J,k}\right)^{\beta}$$

$$d_0 = \max_J \{(p_{T,J})^{\alpha}\} (R_0)^{\beta} \sum_k p_{T,k}$$



Multi-top topologies

J. Thaler and K.V. Tilburg

Strategy for BSM Search in Mulijet Final State

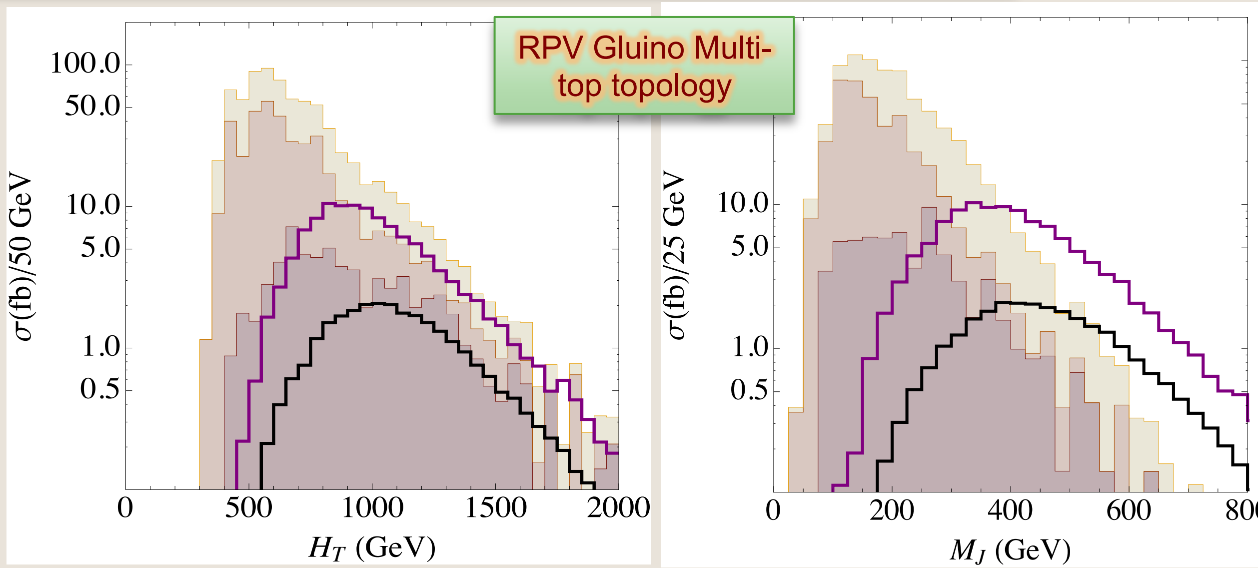
Balance between reach and robustness in the search for BSM Physics

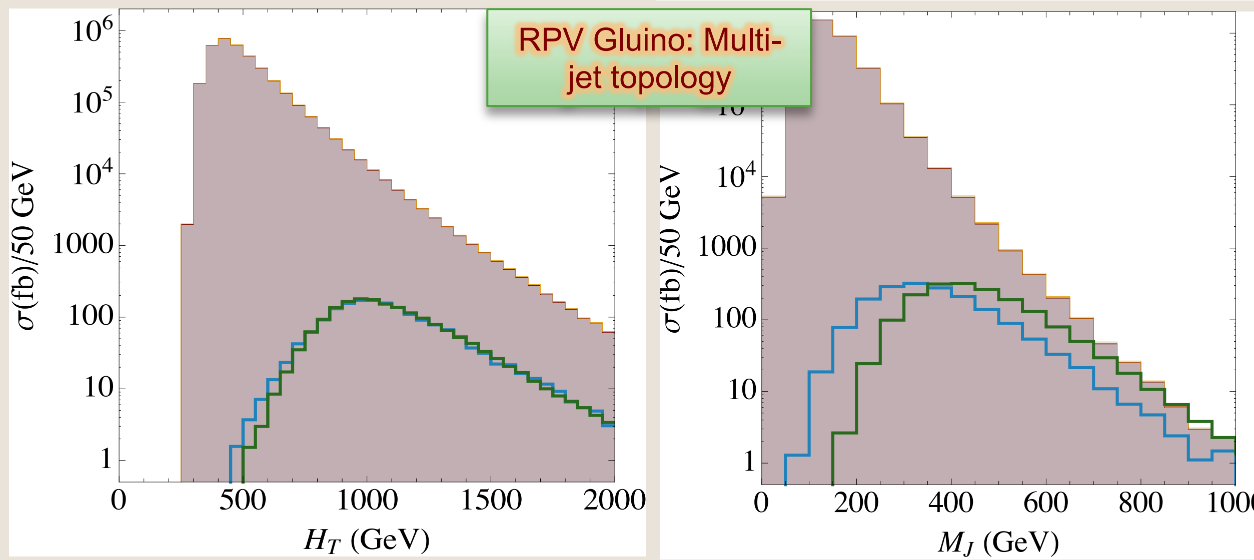
- Accidental Subtructure in multijet events
- Innovative variables:
- N-subjettiness (τ)
- Total jet mass (M)

$$H_T = \sum_{i=1}^{n_J} (p_{T,i}^2 + m_{j_i}^2)^{\frac{1}{2}}$$

$$\propto \sum_{i=1}^{n_J} \sqrt{\langle m_{j_i}^2 \rangle ((\kappa R)^{-2} + 1)}$$

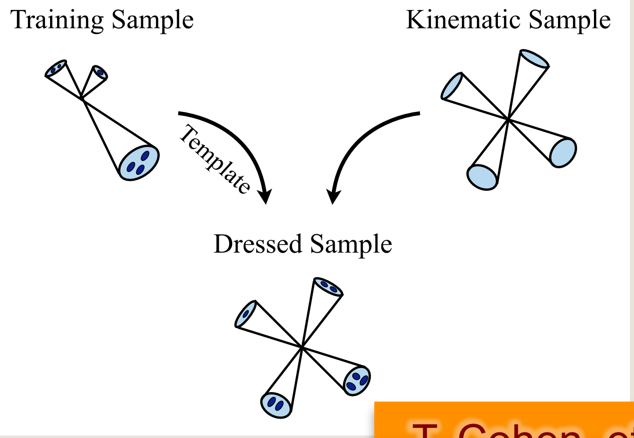
$$\simeq M_J \frac{\sqrt{1 + (\kappa R)^2}}{\kappa R}$$





New Technique for Background Estimation

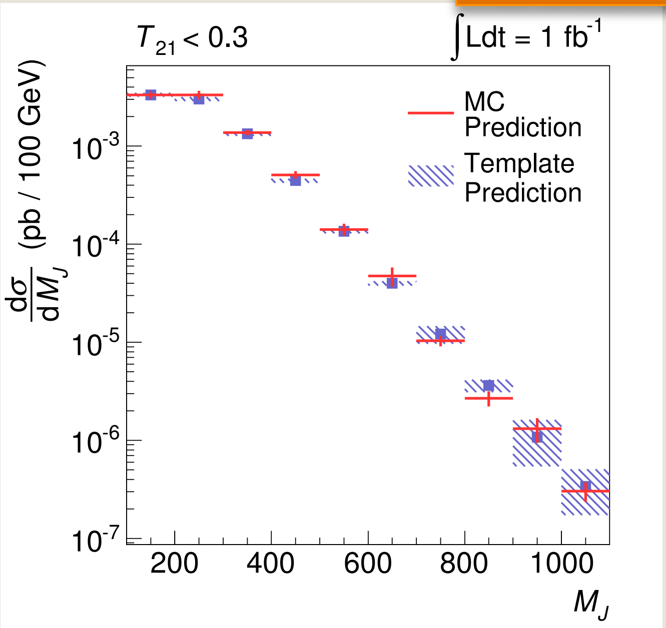
Jet Substructure Template

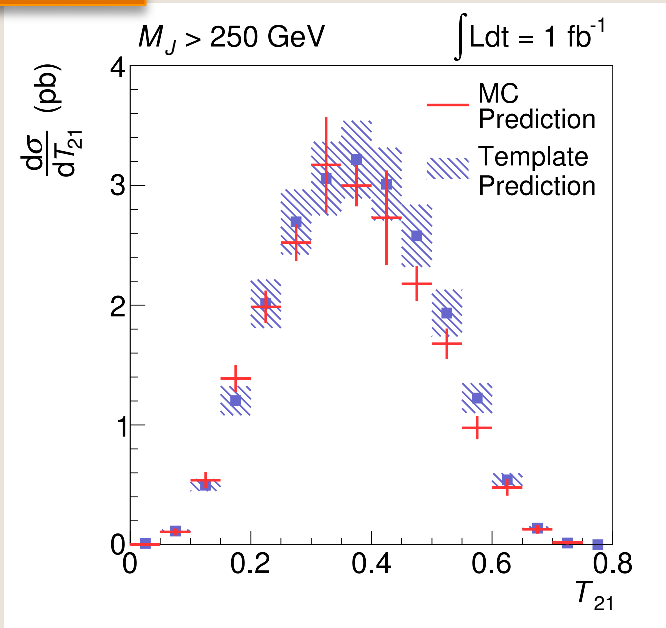


T. Cohen, et al.

Substructure template

1. Identify control region
2. Map out the template using data in the control region
3. Generate the MC sample in the signal region
4. Convolve the template derived from the control sample with the MC sample
5. Apply to cut on the data/MC hybrid to obtain the data-driven background estimation





The preliminary "Jet Substructure Template" background prediction demonstrated good consistency between MC simulation and substructure template prediction

Summary

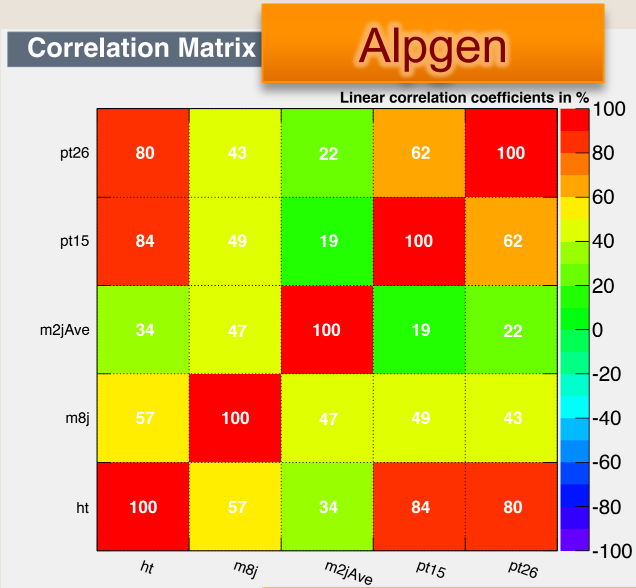
- Counting experiment is performed on 2012 dataset for 8/10-jet analysis, for the first time at hadron collider
  - 4 scenarios for Colorons model
  - 4+2 scenarios for Axigluons model
  - 4 scenarios for RPV SUSY Gluino

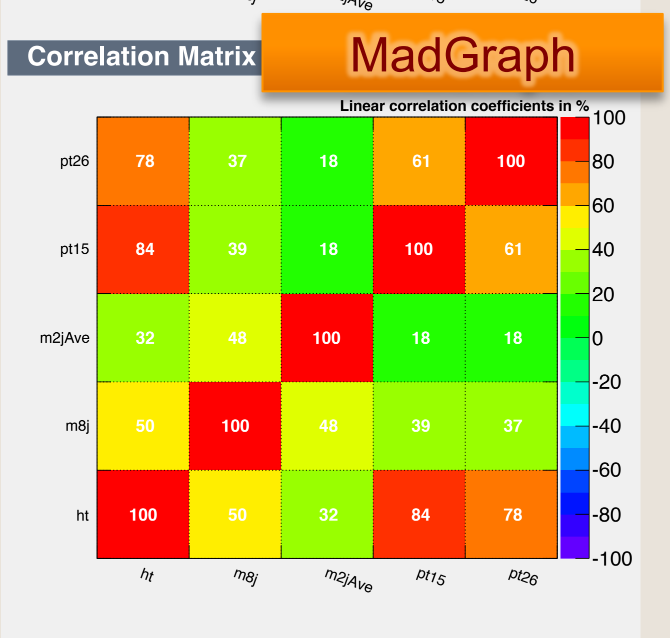
No significant excess of the data was observed, hence the upper limits are reported on the signal cross section at 95% confidence level.

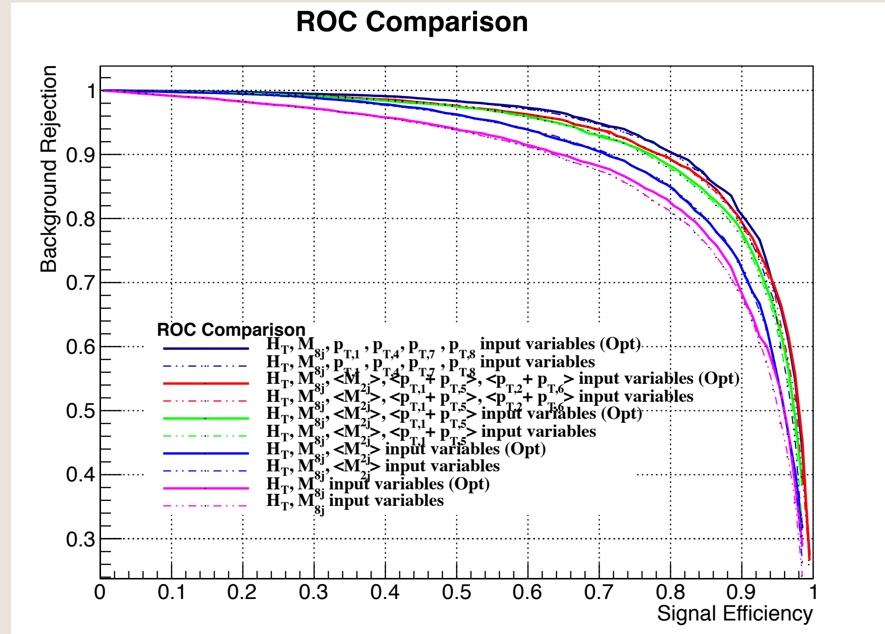
- The quest for new physics (BSM) is just about to begin with the LHC run 2.
- Stay tuned and keep an open mind about where the new physics could be

Back up

Monte Carlo Background (3)

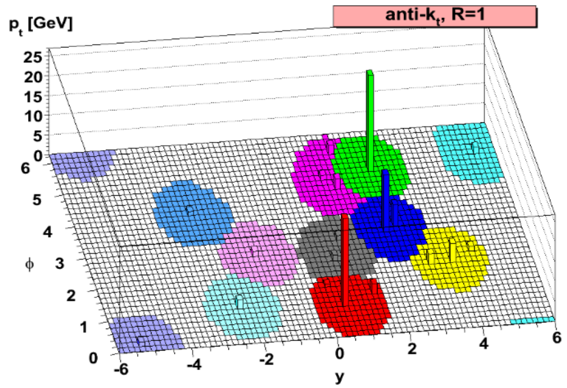






- Background rejection VS signal efficiency are approximately the same between old set and new set of input variables.
- Correlation matrices show that for new set of input variables, these variable's correlations are well consistent between Madgraph and Alpgen QCD

Anti-KT Algorithm and JEC Unc



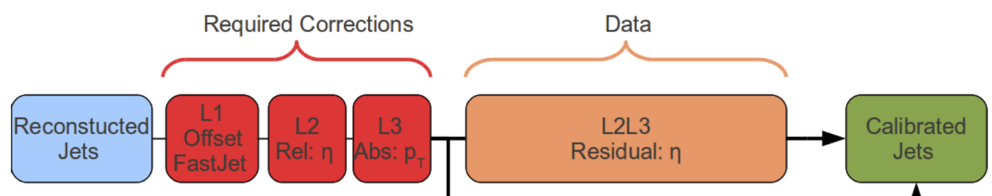
arXiv:0802.1189

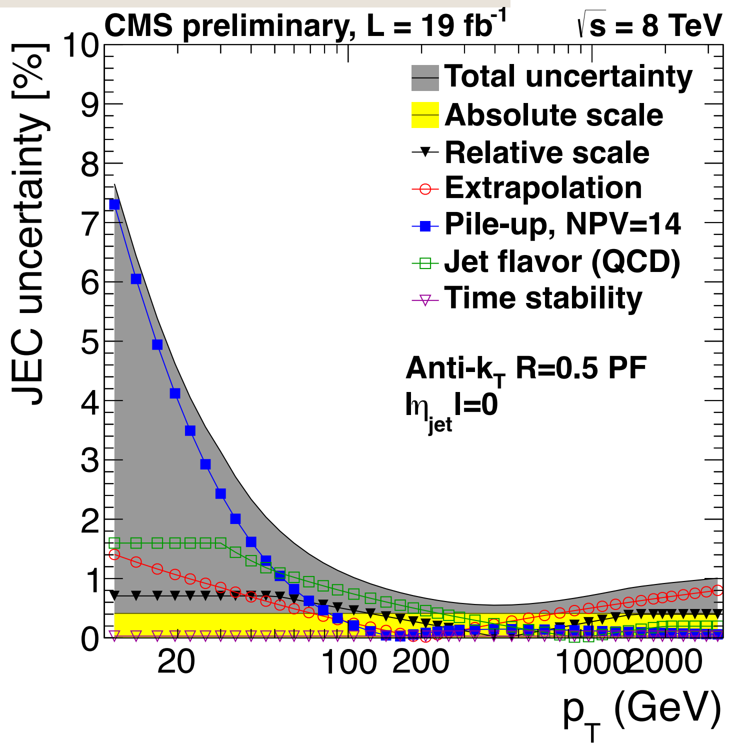
$$d_{ij} = min(k_{ti}^{2p}, k_{ti}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

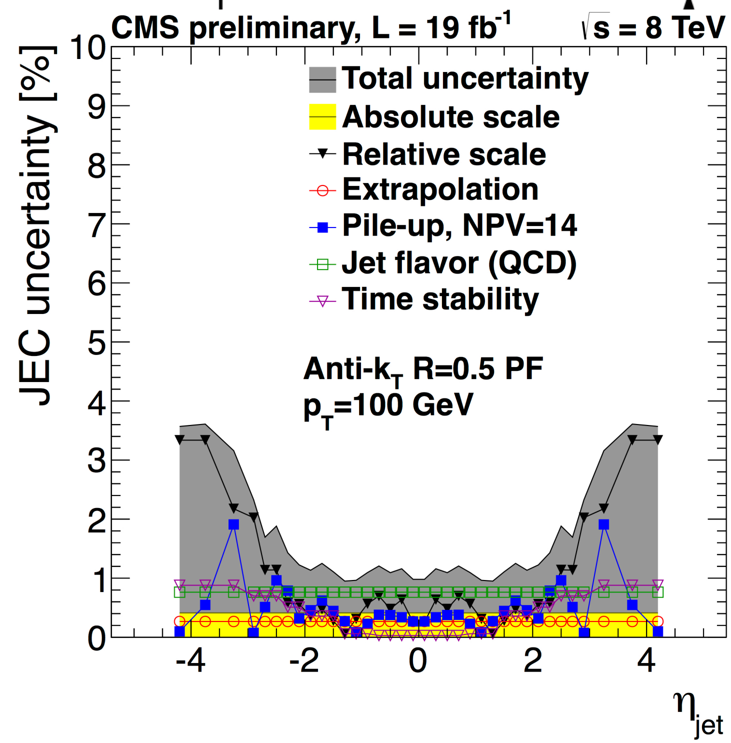
$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{ib} = k_{ti}^{2p}$$

P= -1 is Anti-KT algorithm:
soft particles tend to cluster
with hard ones before
cluster among themselves





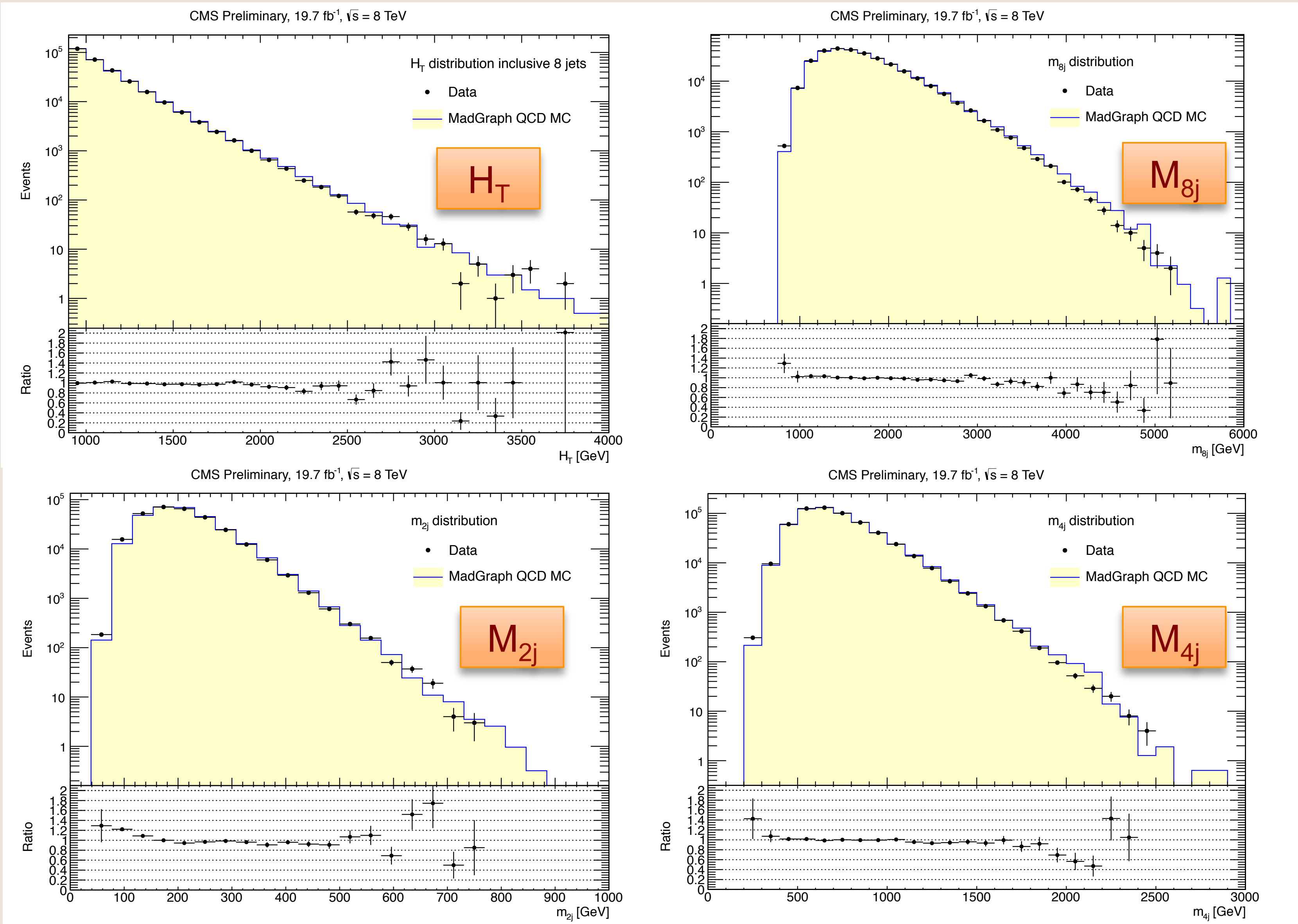


Jet Identification

PF Jet ID	Loose (Recommended)	Medium	Tight
Neutral Hadron Fraction	<0.99	<0.95	< 0.90
Neutral EM Fraction	<0.99	<0.95	< 0.90
Number of Constituents	>1	>1	> 1
And for η<2.4 , η>-2.4 in addition apply			
Charged Hadron Fraction	>0	>0	>0
Charged Multiplicity	>0	>0	>0
Charged EM Fraction	<0.99	<0.99	<0.99

Using tight ID Jets with 99.9% Jet ID efficiency

Data and Background Comparison



Choose Background Template (1)

Inclusive 8 jets

Sphericity> 0.1

At least 1-btagged jets

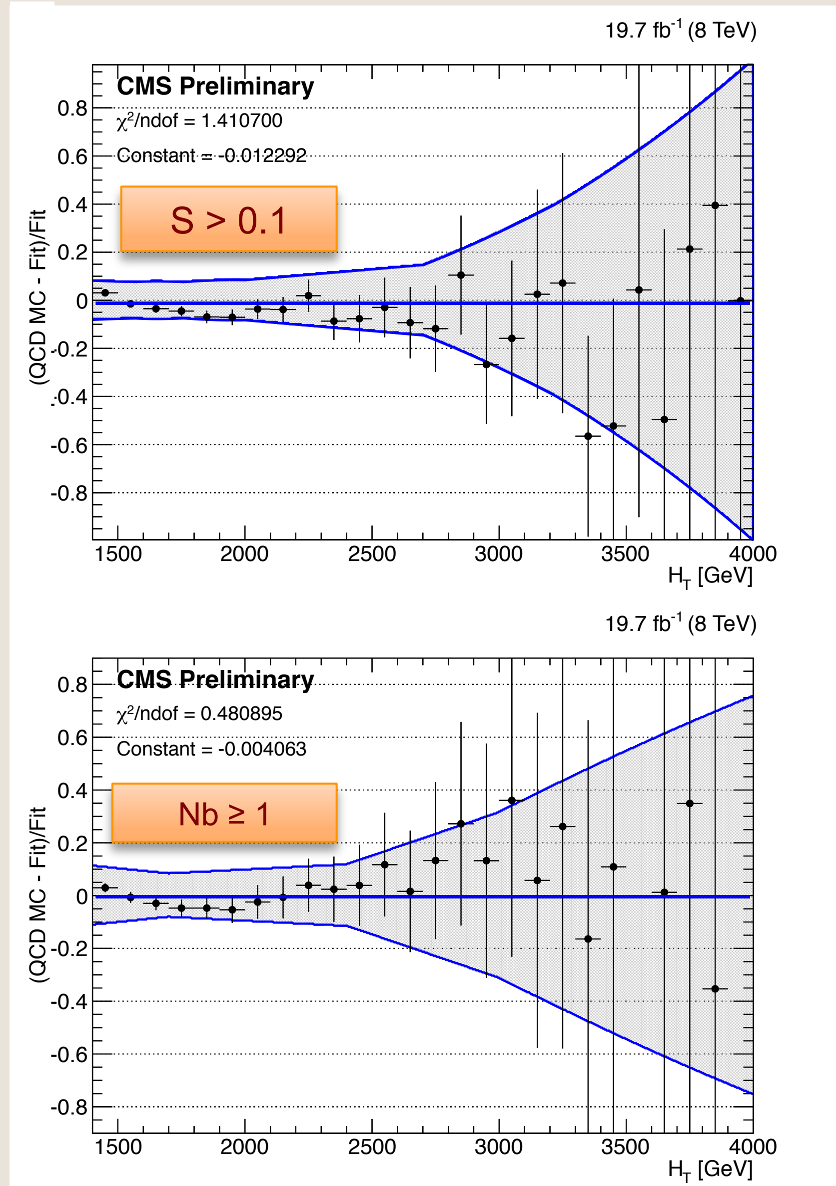
•Perform QCD MC background parameterizations from jet multiplicities of 4, 5, 6

•Normalize the background template to jet multiplicity of at least 8

•Calculate (QCD-Fit)/Fit and fit to a constant

•Choose the jet multiplicity at which Chi2/Ndof are small in comparison to other multiplicities and constants are close to 1

- Choose 4 jets as template background template



Choose Background Template (2)

Inclusive 10 jets

Sphericity> 0.1

At least 1-btagged jets

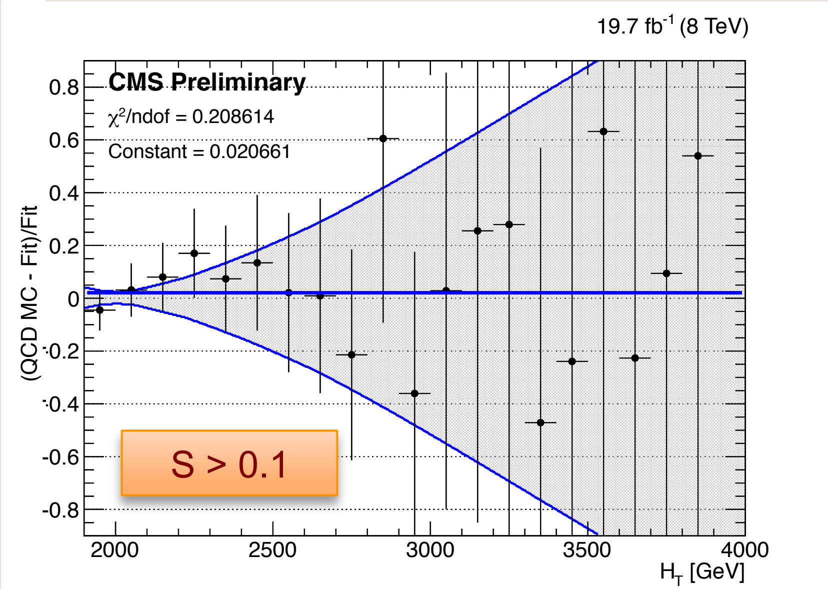
•Perform QCD MC background parameterizations from jet multiplicities of 4, 5, 6, 7, 8, 9

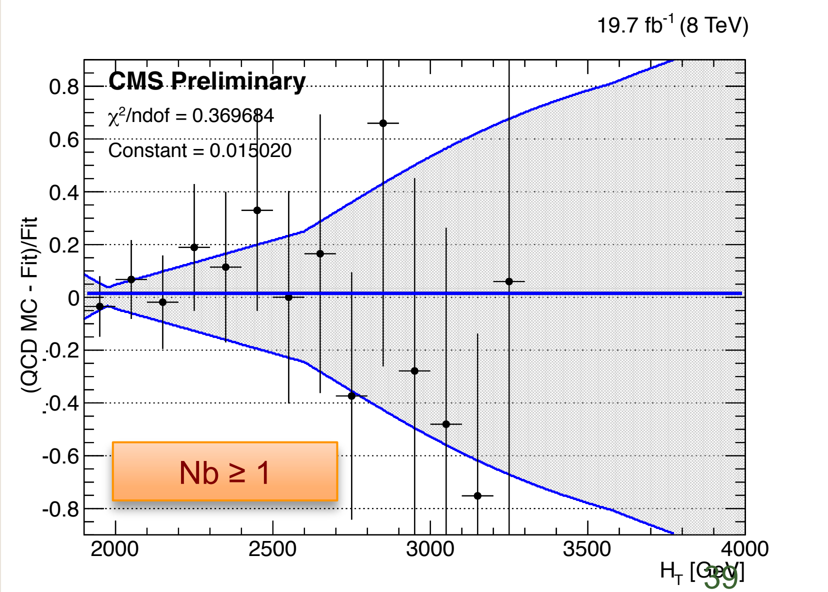
•Normalize the background template to jet multiplicity of at least 8

•Calculate (QCD-Fit)/Fit and fit to a constant

•Choose the jet multiplicity at which Chi2/Ndof are small in comparison to other multiplicities and constants are close to 1

- Choose 4 jets as template background template



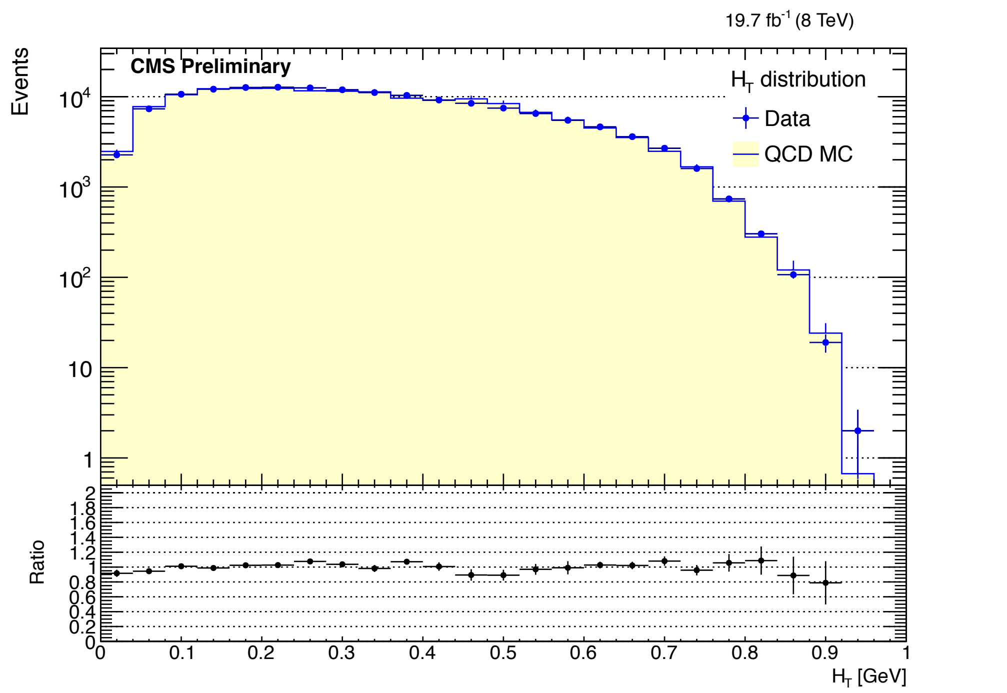


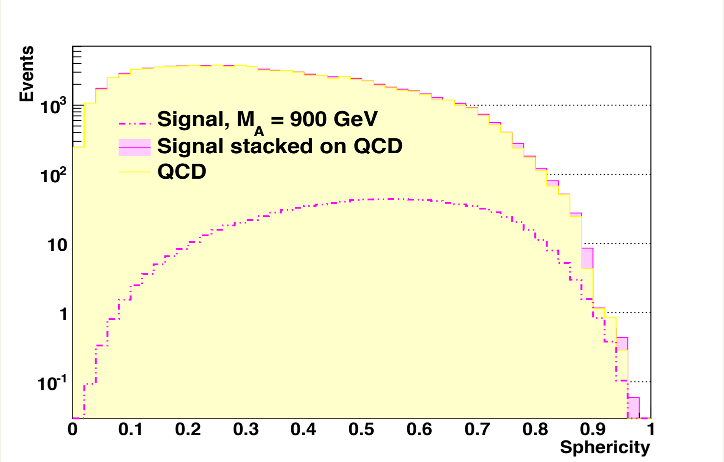
Additional Cuts (Global Shape)

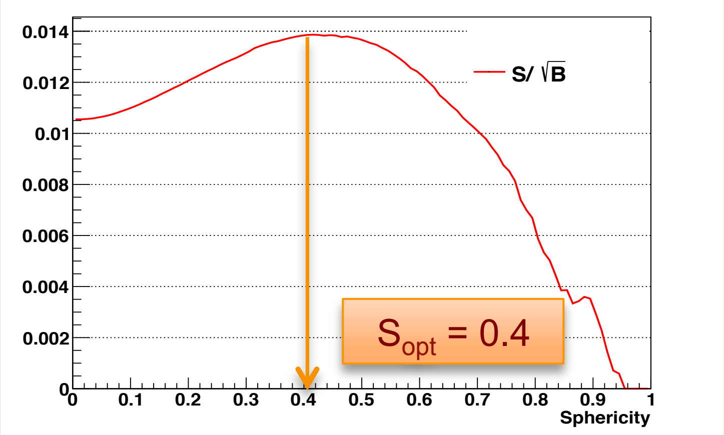
- Sphericity (S) $S = \frac{3}{2}(\lambda_2 + \lambda_3)$, $S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\mathbf{p}_i|^2}$,

Sphericity to boost signal sensitivity

- How spherical the event shape is
- Signal tends to be more spherical (close to 1)
- Background is less spherical (close to 0)





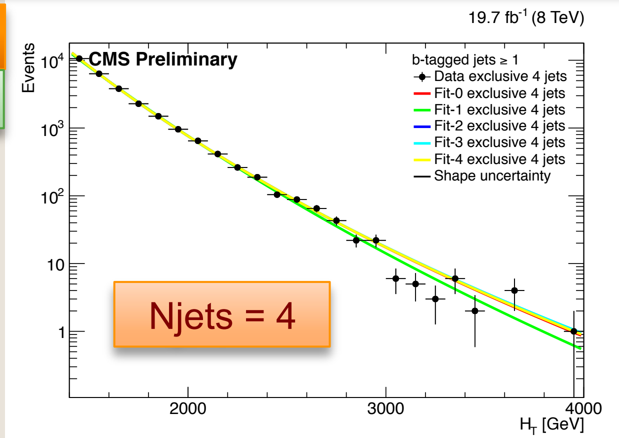


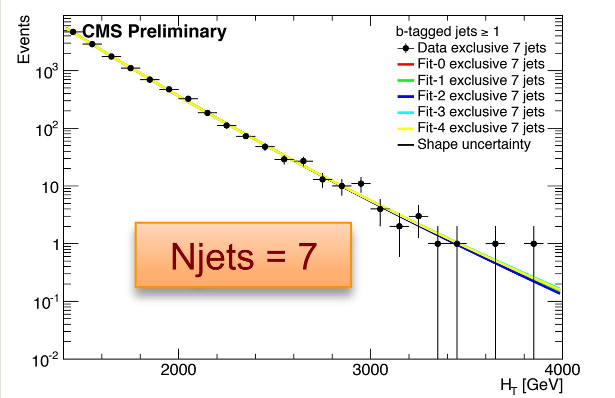
See good agreement of between Data and QCD MC

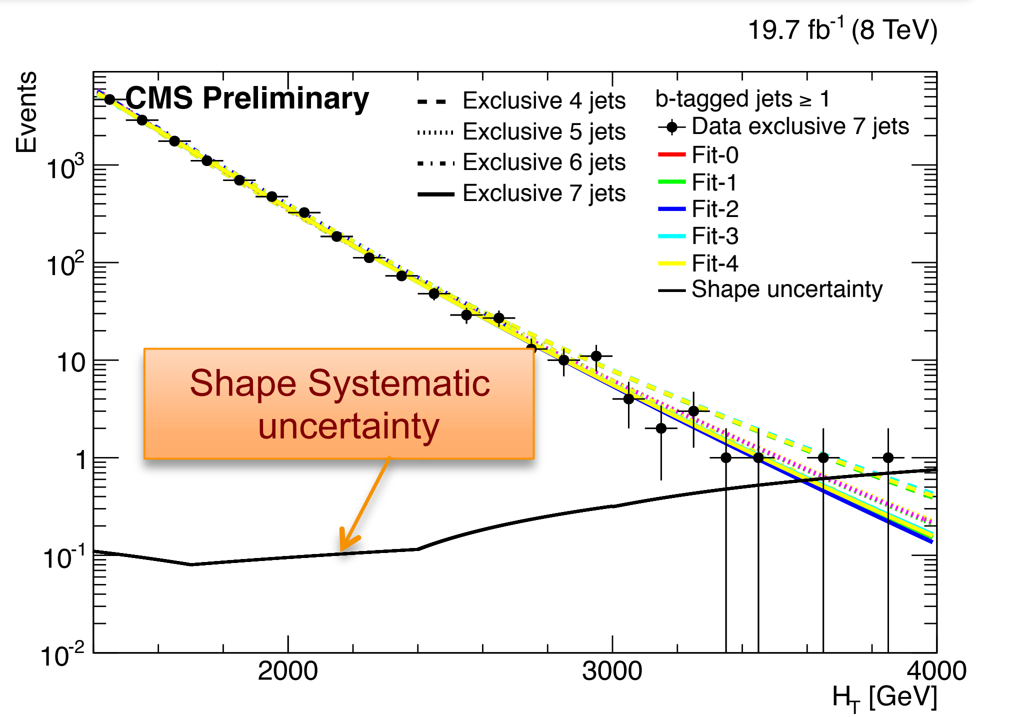
Estimate Background Uncertainty

Njets ≥ 8

Nb ≥ 1







Fitting Functions from blackhole search

$$\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

$$\frac{P_0}{(P_1+P_2x+x^2)^{P_3}}$$

$$\frac{P_0}{(P_1+x)^{P_2}}$$

$$\frac{P_0(1+x)^{P_1}}{x^{P_2}\log(x)}$$

Dijet

$$\frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

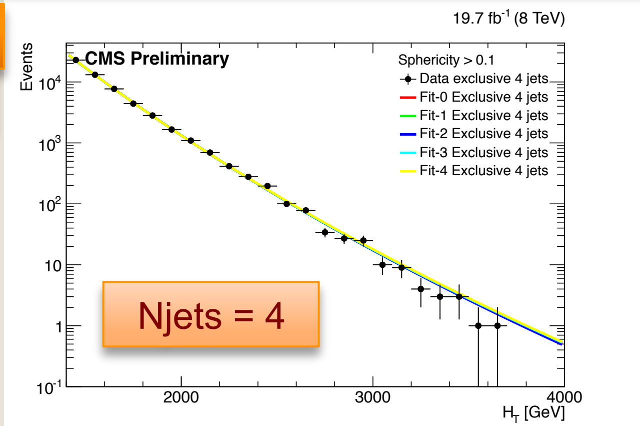
Background Uncertainty

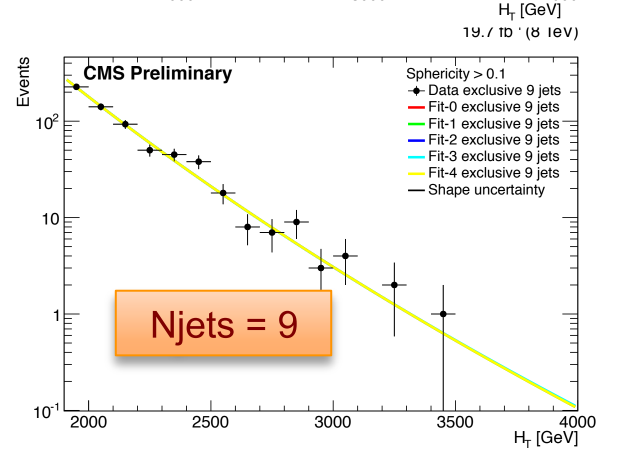
- Fitting data for Njets = 4, 7 with 5 functions [1500-2500 GeV]
- Normalize the fitting functions from Njets = 4 to Njets = 7 [1400-1700 GeV]
- Greatest difference between the two outliers is taken as our uncertainty

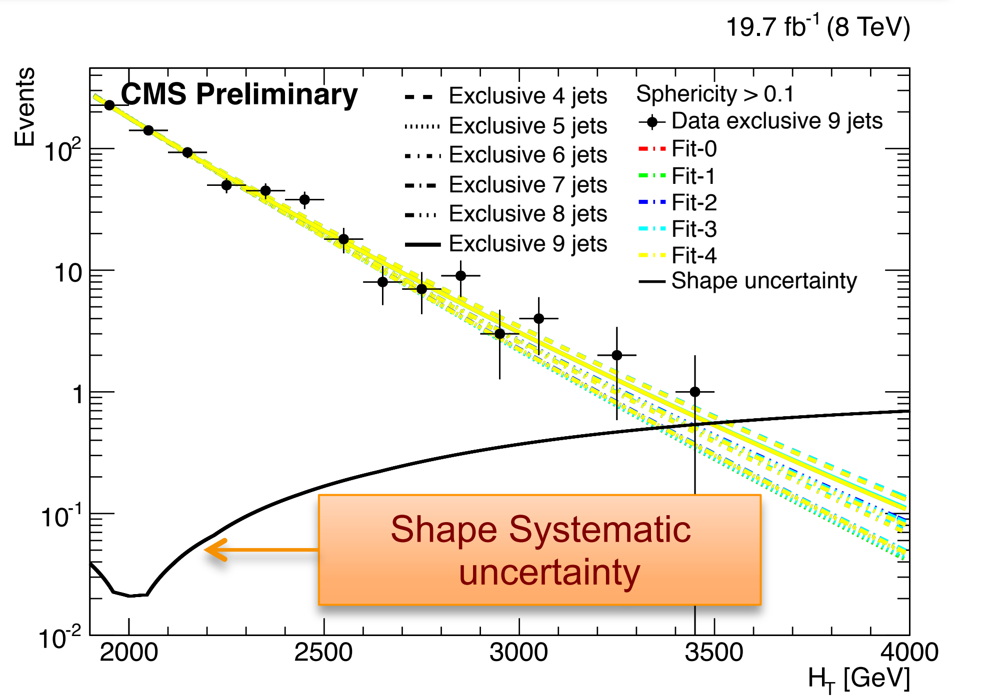
Estimate Background Uncertainty

Njets ≥10

S > 0.1







Fitting Functions from blackhole search

$$\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}} \qquad \frac{P_0}{(P_1+P_2x+x^2)^{P_3}} \qquad \frac{P_0}{(P_1+x)^{P_2}}$$

$$\frac{P_0(1+x)^{P_1}}{x^{P_2}\log(x)}$$

Dijet

$$\frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

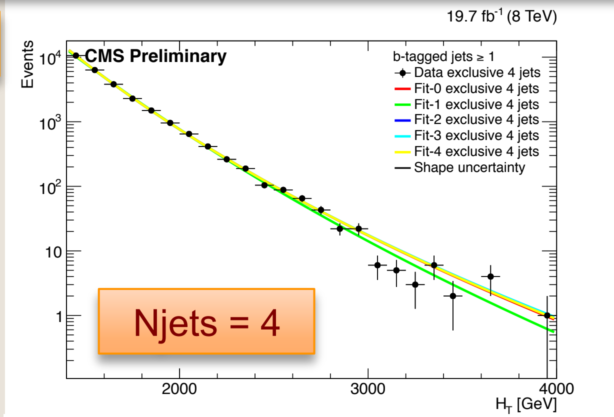
Background Uncertainty

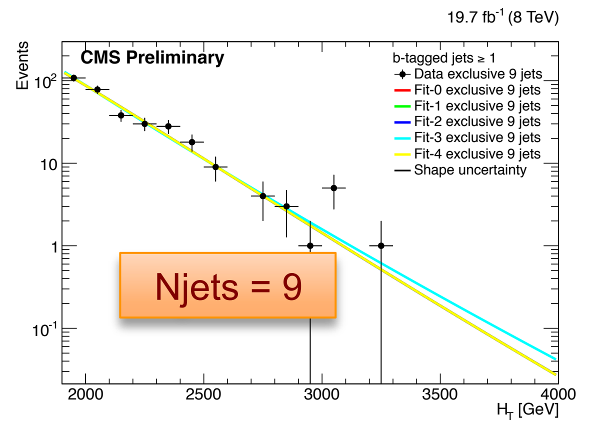
- Fitting data for Njets = 4, 9 with 5 functions [2000-3000 GeV]
- Normalize the fitting functions from Njets = 4 to Njets = 9 [1900-2100 GeV]
- Greatest difference between the two outliers is taken as our uncertainty

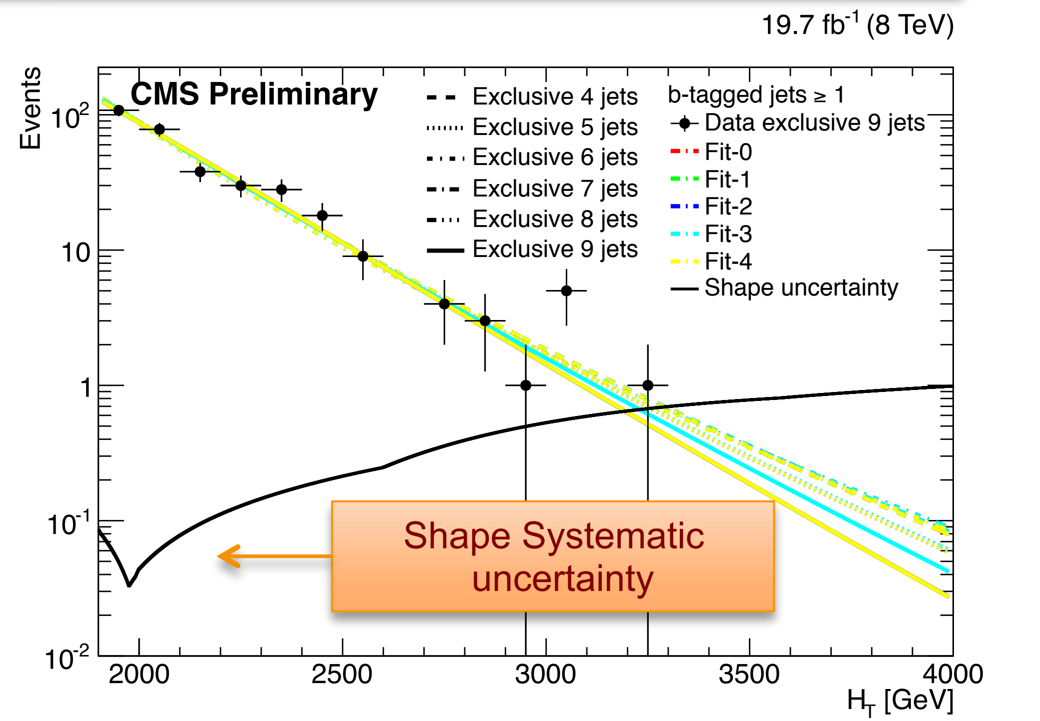
Estimate Background Uncertainty

Njets ≥10

Nb ≥ 1







Fitting Functions from blackhole search

$$\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

$$\frac{P_0}{(P_1+P_2x+x^2)^{P_3}}$$

$$\frac{P_0}{(P_1+x)^{P_2}}$$

$$\frac{P_0(1+x)^{P_1}}{x^{P_2}\log(x)}$$

Dijet

$$\frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

Background Uncertainty

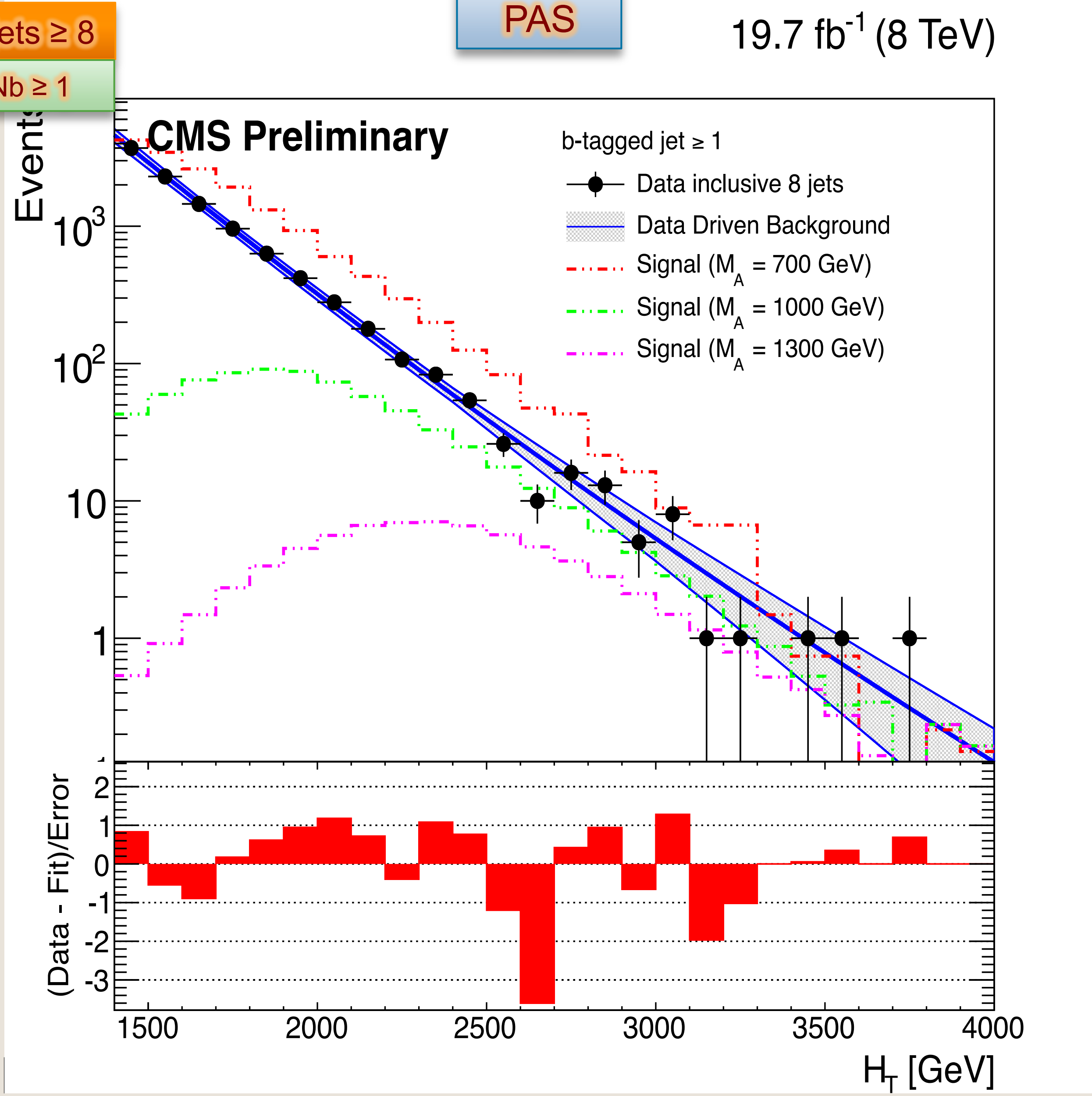
- Fitting data for Njets = 4, 9 with 5 functions [2000-3000 GeV]
- Normalize the fitting functions from Njets = 4 to Njets = 9 [1900-2100 GeV]
- Greatest difference between the two outliers is taken as our uncertainty

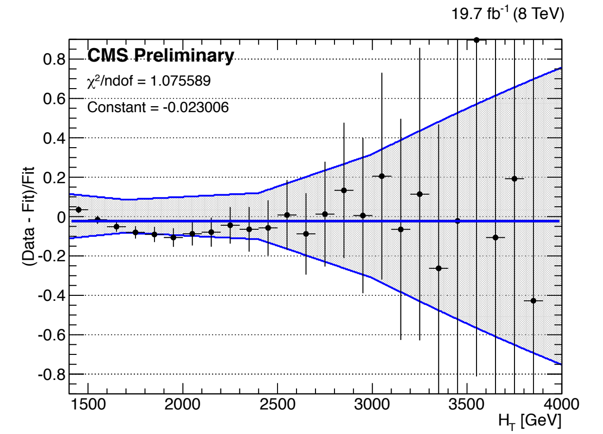
H_T Distribution with Data-Driven Background

PAS

Njets ≥ 8

Nb ≥ 1





- (Data-Fit)/Fit are consistent within statistical uncertainty and mostly covered by background shape systematic uncertainty

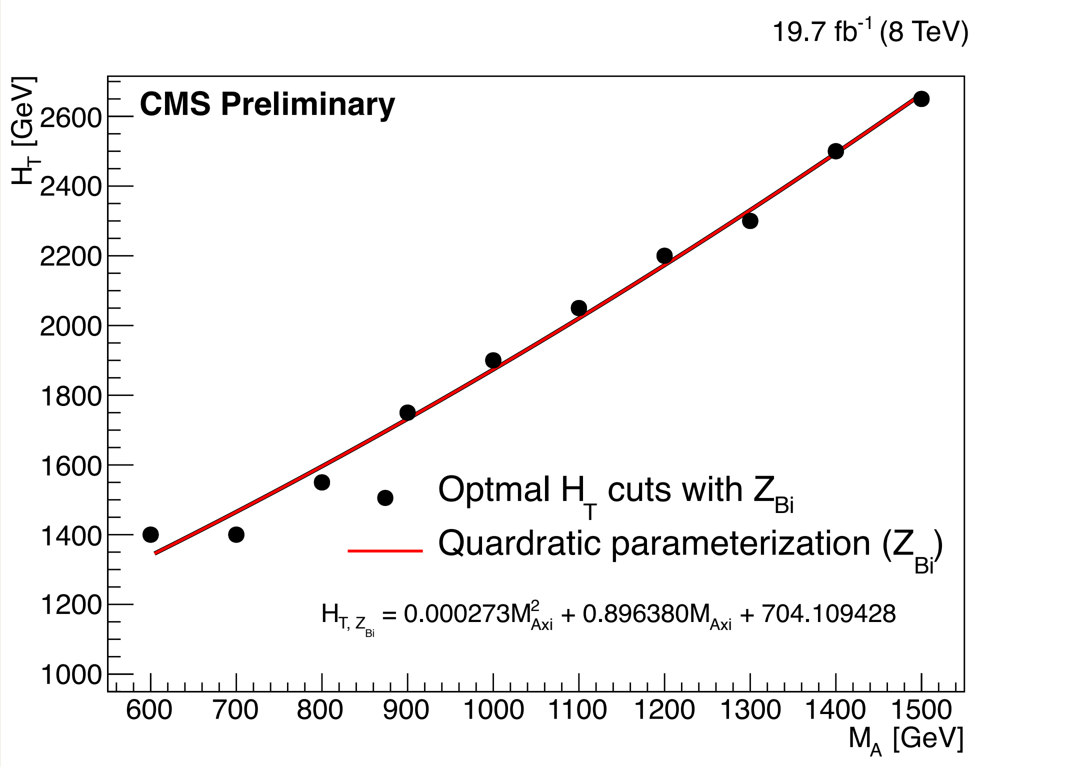
- Pull distribution as a function of H_T is within ~1 sigma statistical and sytematic uncertainties combined.

- No deviation from data-driven background prediction

Parameterization of H_T Optimal Cuts

Njets ≥ 8

Nb ≥ 1



- Final optimization is performed on H_T cuts (parameterized as a function of axigluon/ coloron masses)
- Z_{bi} test statistic is used when number of background events is less than 20

Uncertainty	Effect on Signal Acceptance	Effect on Background
Integrated Luminosity	±2.6%	-
Jet Energy Scale	±5%	-
PDF	±3%	-
B-tagging Scale Factor	±(2-5)%	-
Rescaling	-	±(2-100)%
Shape Modeling	-	±(3-140)%, depends on the H_T value.

Using official Higgs combination tool to set limit (with JES, PDF, lumi and background uncertainties)

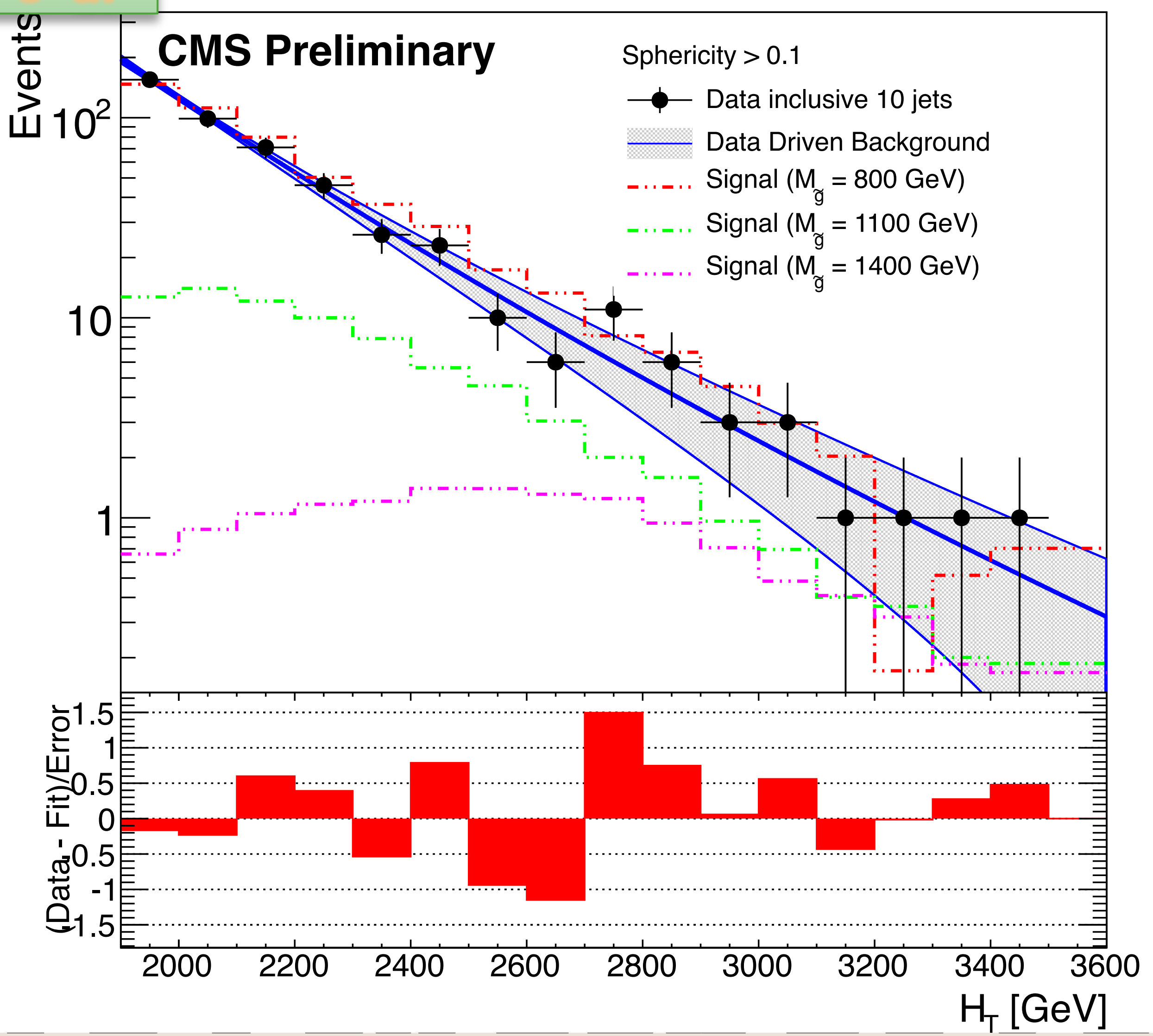
H_T Distribution with Data-Driven Background

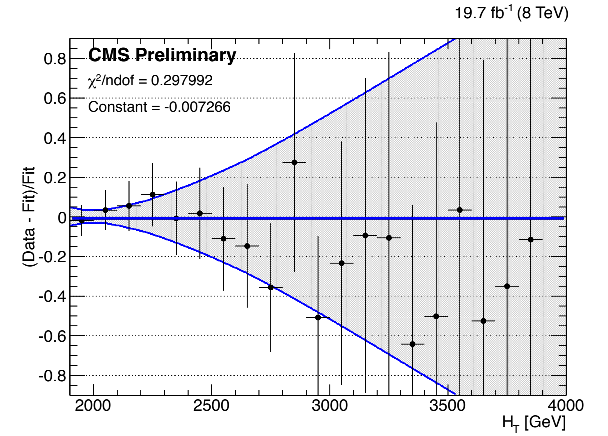
Njets ≥10

S > 0.1

PAS

19.7 fb^{-1} (8 TeV)





- (Data-Fit)/Fit are consistent within statistical uncertainty and mostly covered by background shape systematic uncertainty

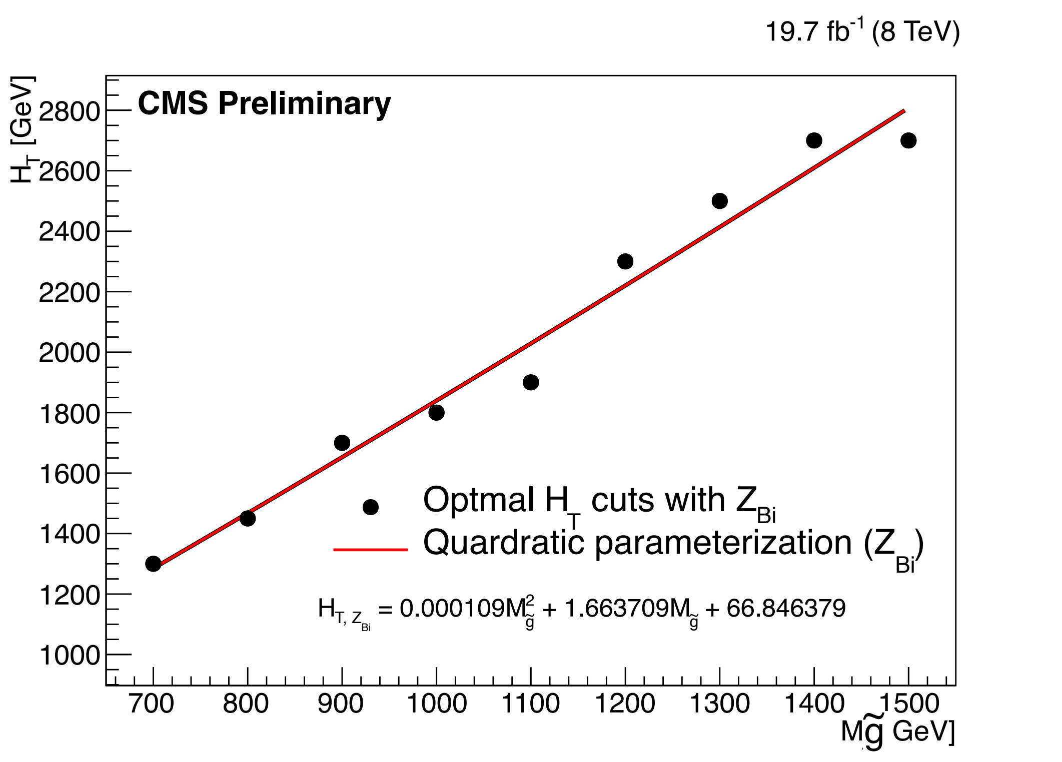
- Pull distribution as a function of H_T is within 1 sigma statistical and sytematic uncertainties combined.

- No deviation from data-driven background prediction

Parameterization of H_T Optimal Cuts

Njets ≥10

S > 0.1



- Final optimization is performed on H_T cuts (parameterized as a function of gluino mass for each fixed squark mass)
- Z_{bi} test statistic is used when the number of background events is less than 20

Uncertainty	Effect on Signal Acceptance	Effect on Background
Integrated Luminosity	±2.6%	-
Jet Energy Scale	±5%	-
PDF	±3%	-
Rescaling	-	±(2-100)%
Shape Modeling	-	±(3-140)%, depends on the H_T value.

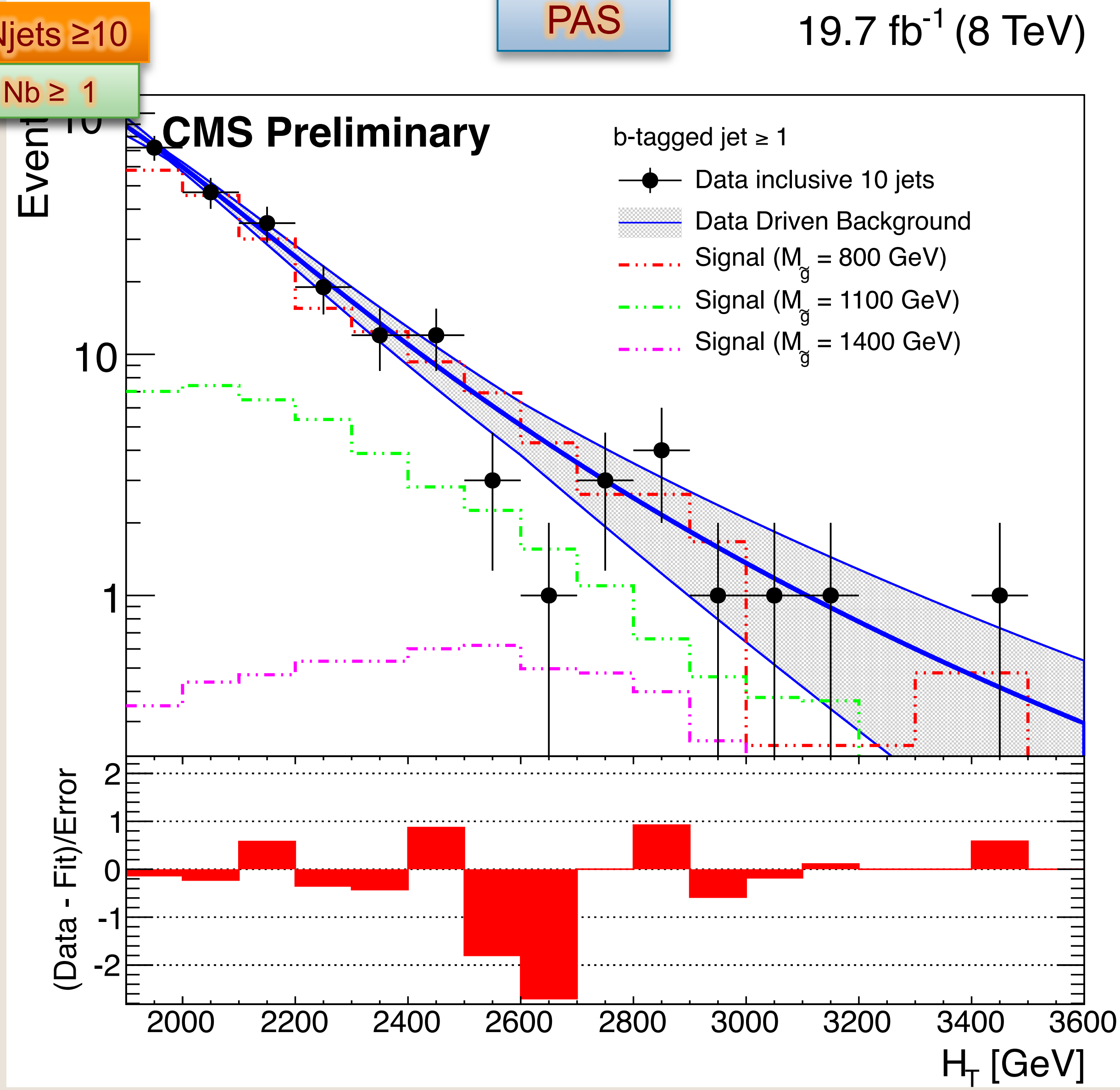
Using official Higgs combination tool to set limit (with JES, PDF, lumi and background uncertainties)

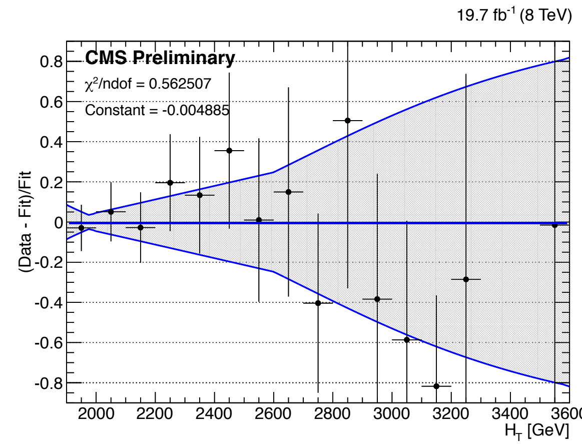
H_T Distribution with Data-Driven Background

Njets ≥10

Nb ≥ 1

PAS





- (Data-Fit)/Fit are consistent within statistical uncertainty and mostly covered by background shape systematic uncertainty

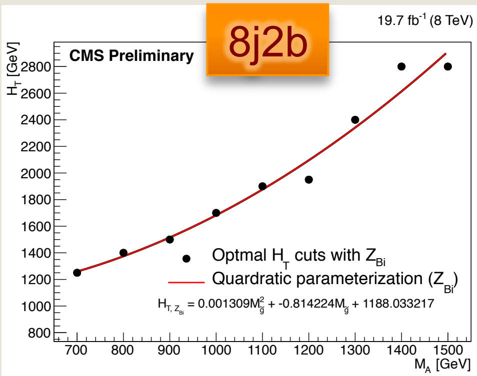
- Pull distribution as a function of H_T is within ~1 sigma statistical and sytematic uncertainties combined.

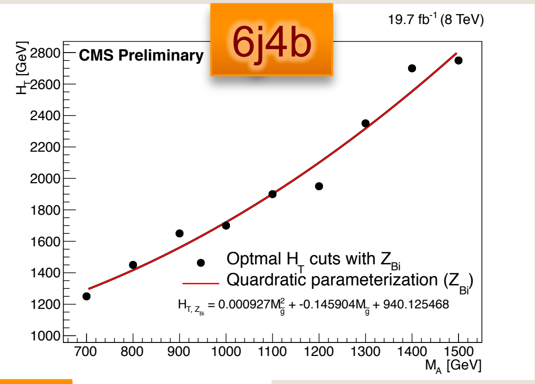
- No deviation from data-driven background prediction

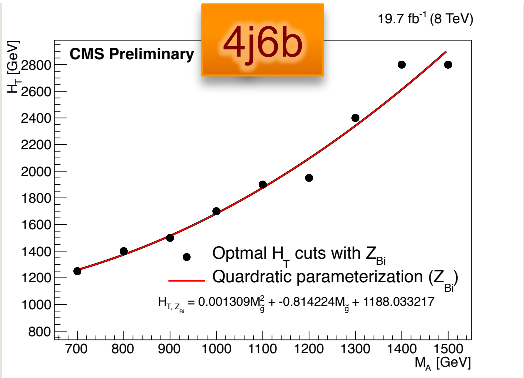
Parameterization of H_T Optimal Cuts

Njets ≥10

Nb ≥ 1







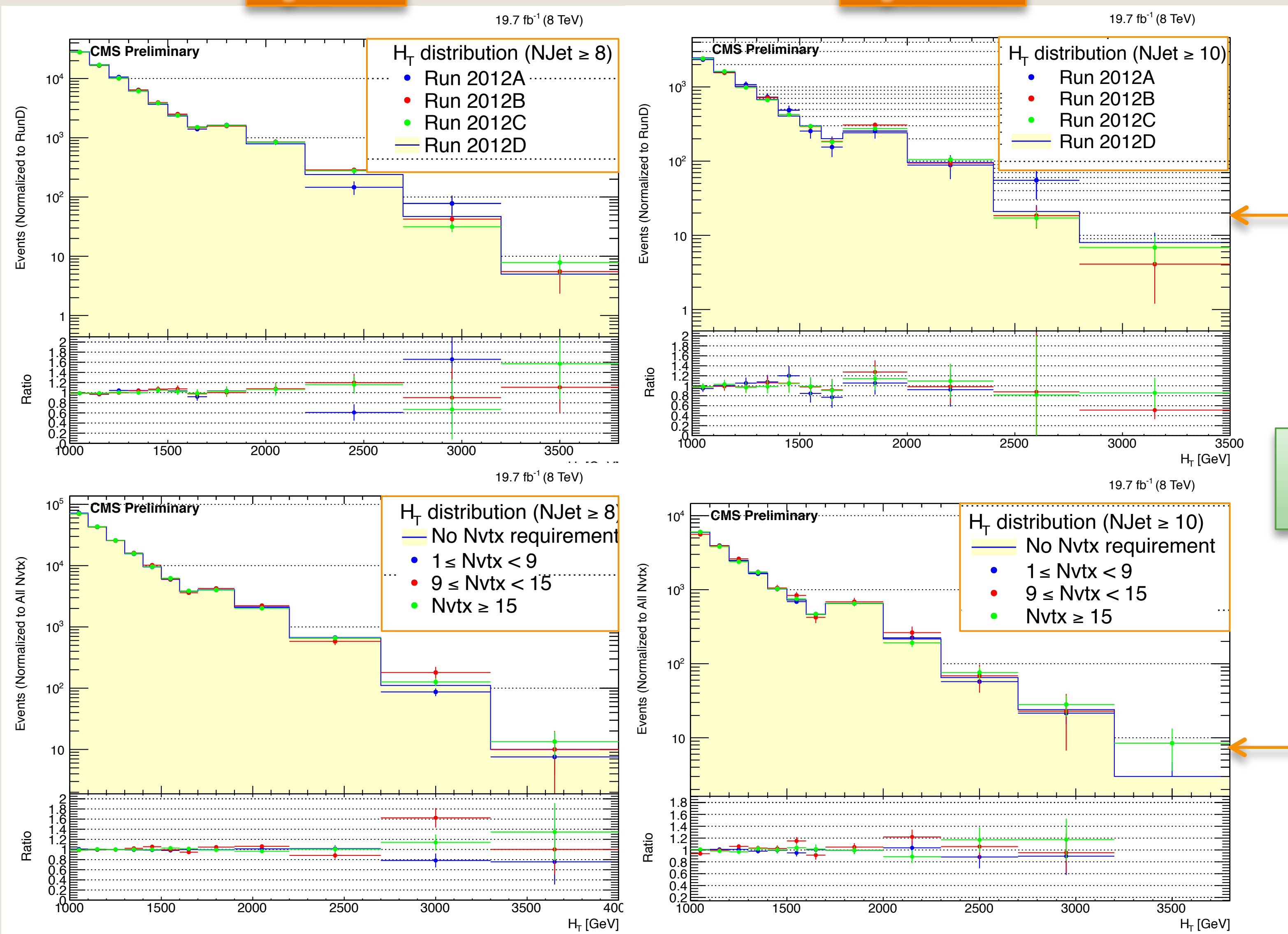
- Final optimization is performed on H_T cuts (parameterized as a function of gluino mass for each fixed squark mass). The average $H_{T,opt}$ is used for all three models.
- Z_{bi} test statistic is used when number of background events is less than 20

Uncertainty	Effect on Signal Acceptance	Effect on Background
Integrated Luminosity	±2.6%	-
Jet Energy Scale	±5%	-
PDF	±3%	-
B-tagging Scale Factor	±(2-5)%	-
Rescaling	-	±(2-100)%
Shape Modeling	-	±(3-140)%, depends on the H_T value.

Using official Higgs combination tool to set limit (with JES, PDF, lumi and background uncertainties)

Sensitivity to Pile Up

Njets ≥ 8 | Njets ≥ 10



Diffferent Runs

Not sensitive to PU effect

Diffferent Nvtx Ranges

Limits (Axigluon Model)

BROWN

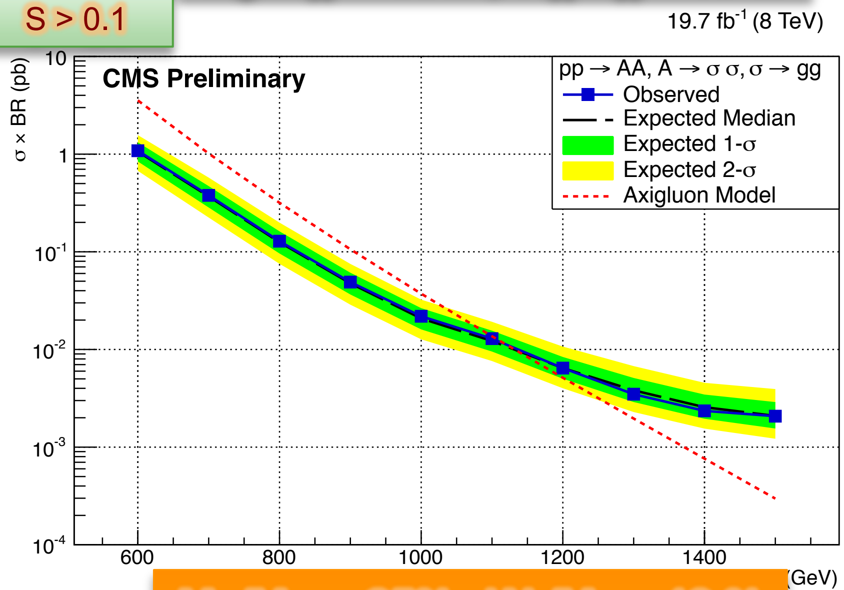
CMS

Njets ≥ 8

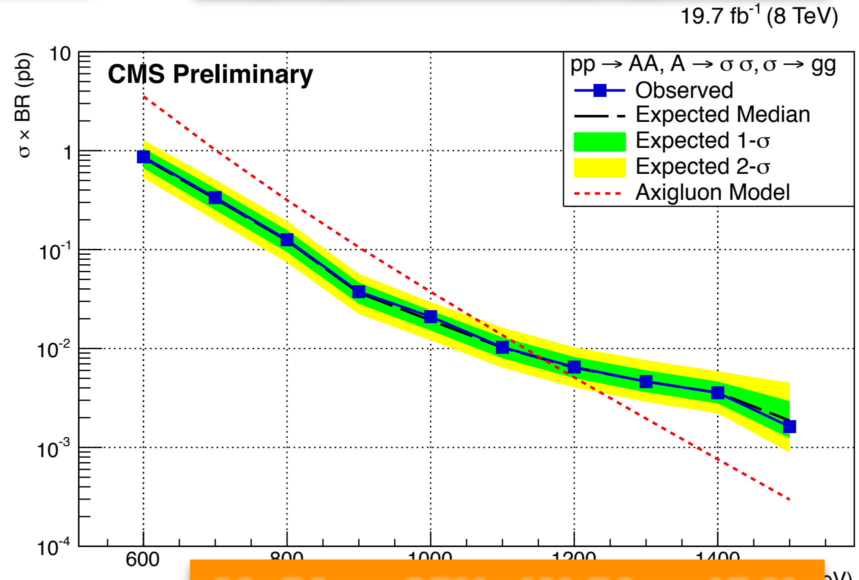
S > 0.1

PAS

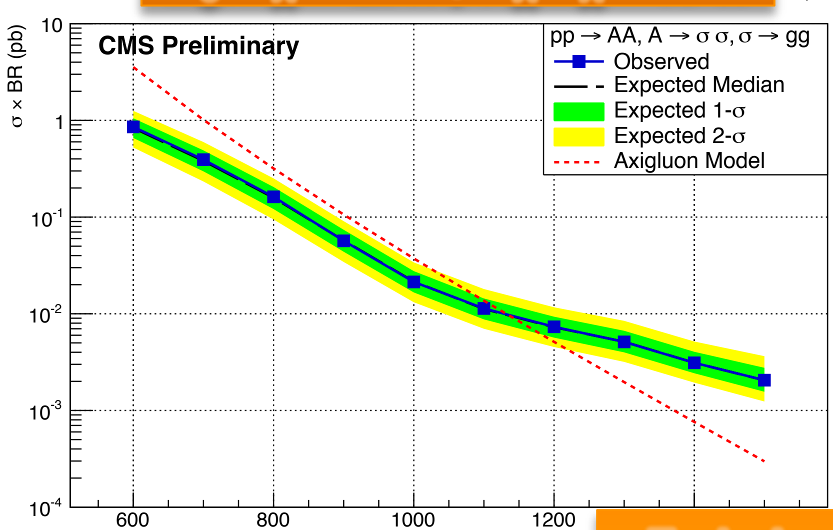
M_σ / M_A = 33% , W_A/M_A = 10 %



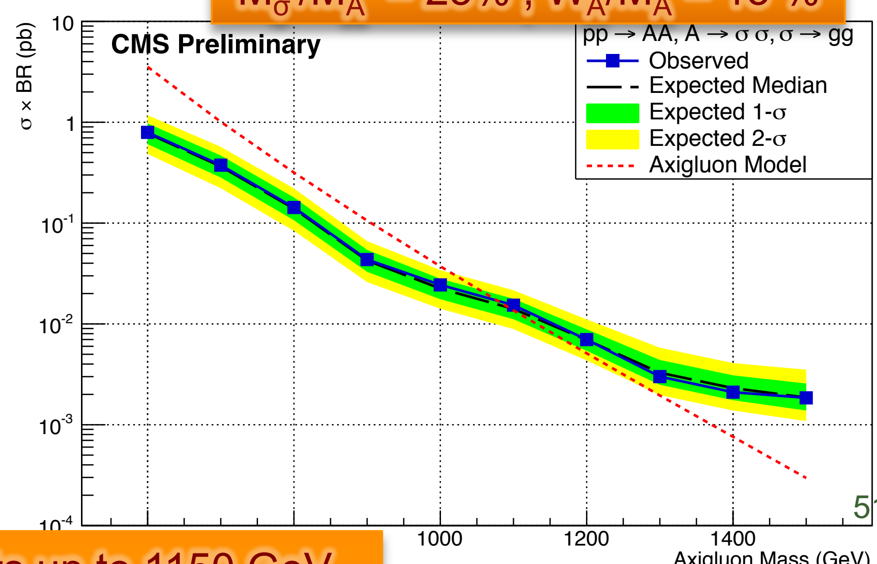
M_σ / M_A = 33% , W_A/M_A = 15 %



M_σ / M_A = 25% , W_A/M_A = 10 %



M_σ / M_A = 25% , W_A/M_A = 15 %



Exclusion limits up to 1150 GeV

Limits (Axigluon Model with 4bs)

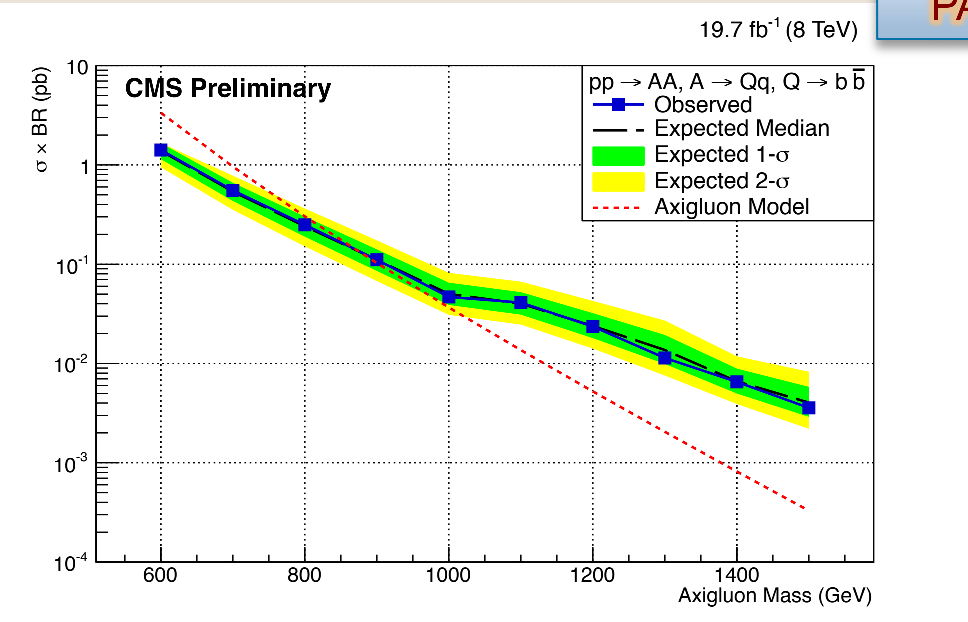
Njets ≥ 8

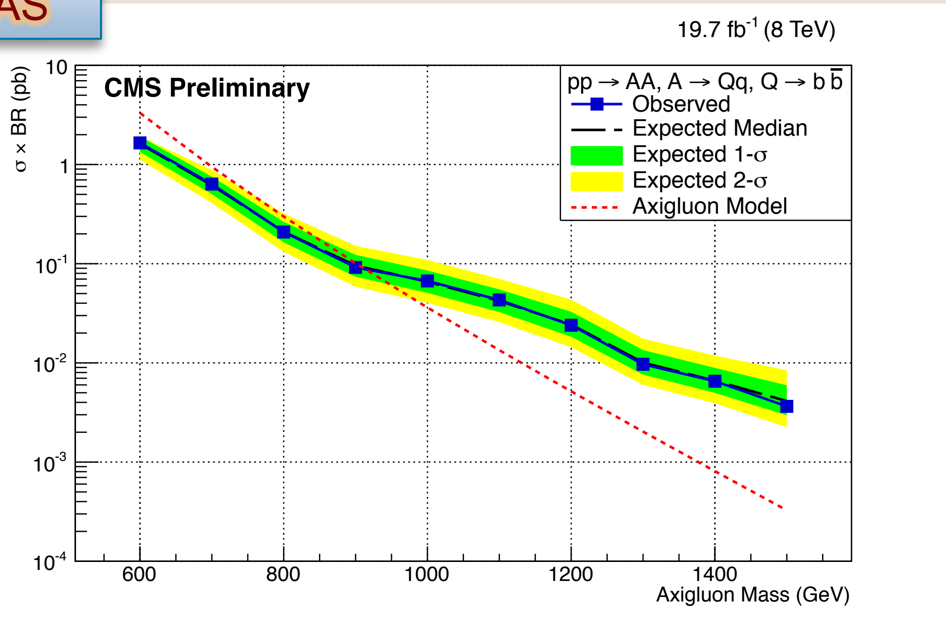
Nb ≥ 1

W_A:M_A = 3.5%

W_A:M_A = 10%

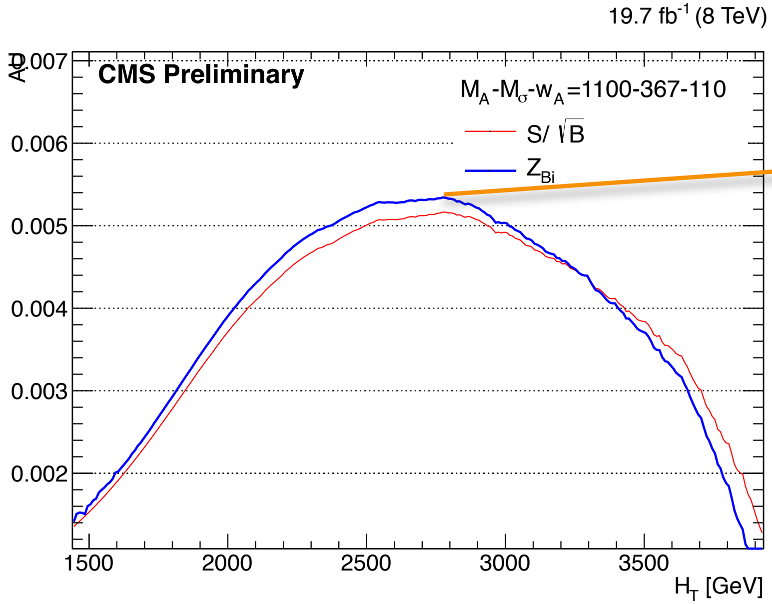
PAS

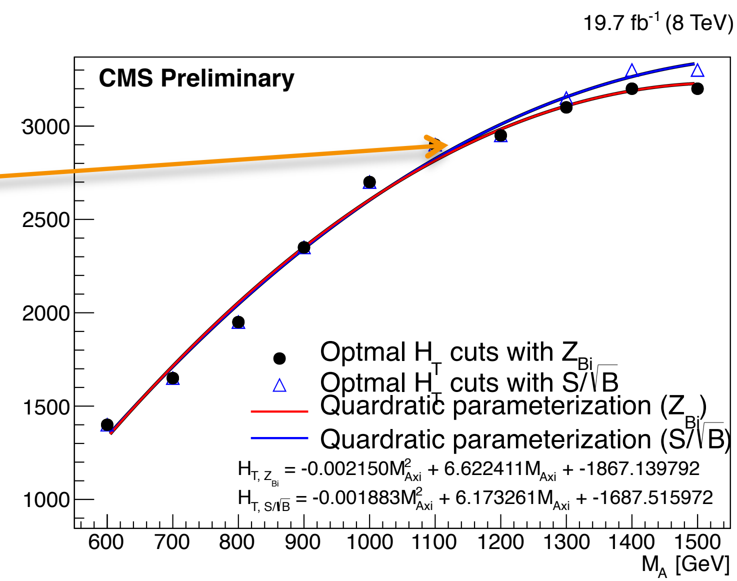


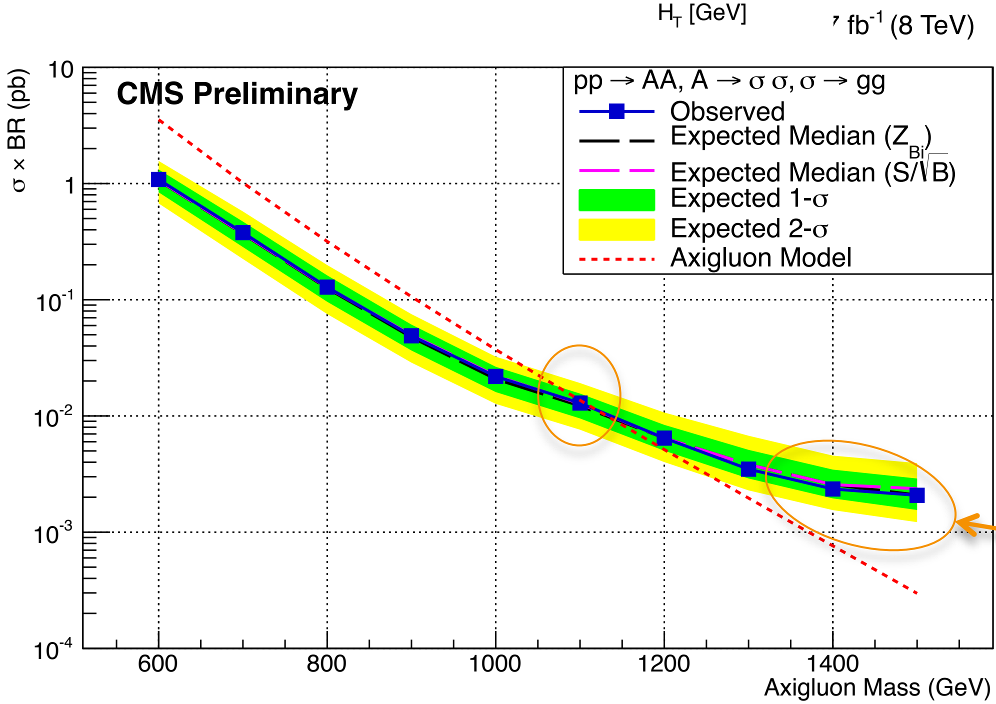


Exclusion limits up to 900 GeV

Different Test Statistics



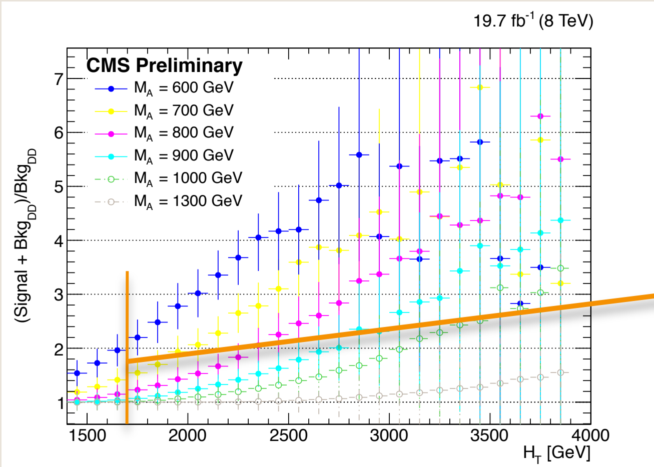




- By taking into account of low background events in higher H_T optimal cut, i.e., using Z_{bi} test statistic, this does not change the result.

- Negligible effect in higher mass

Signal Contamination



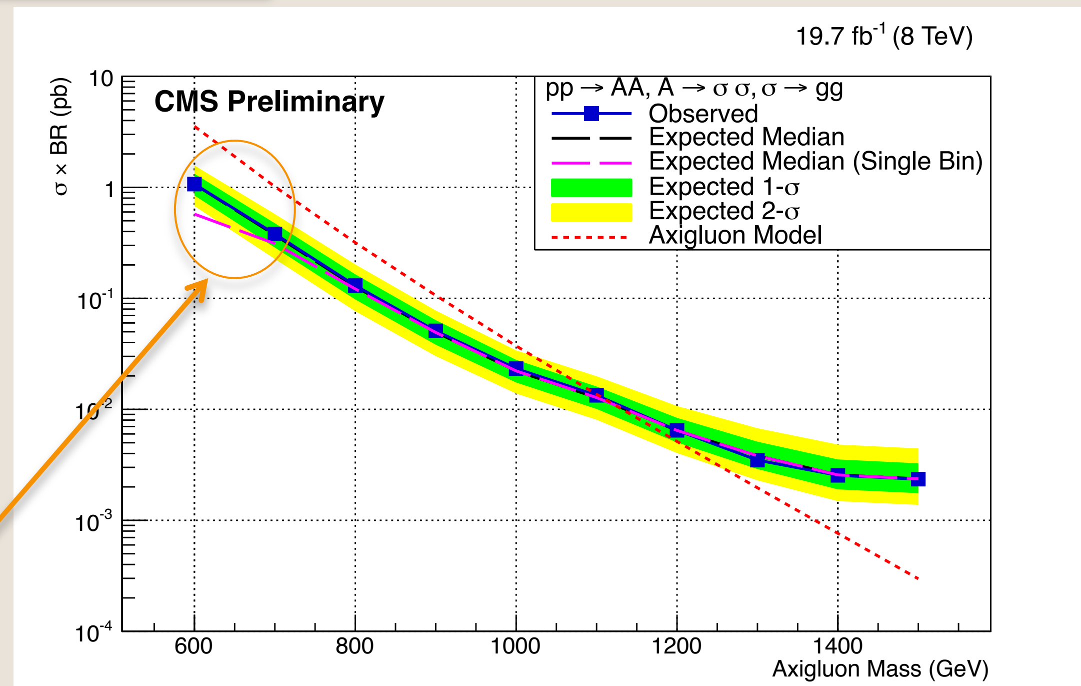
Data card for Higgs Combination Tools

Could be up to 65% signal contamination in lower mass

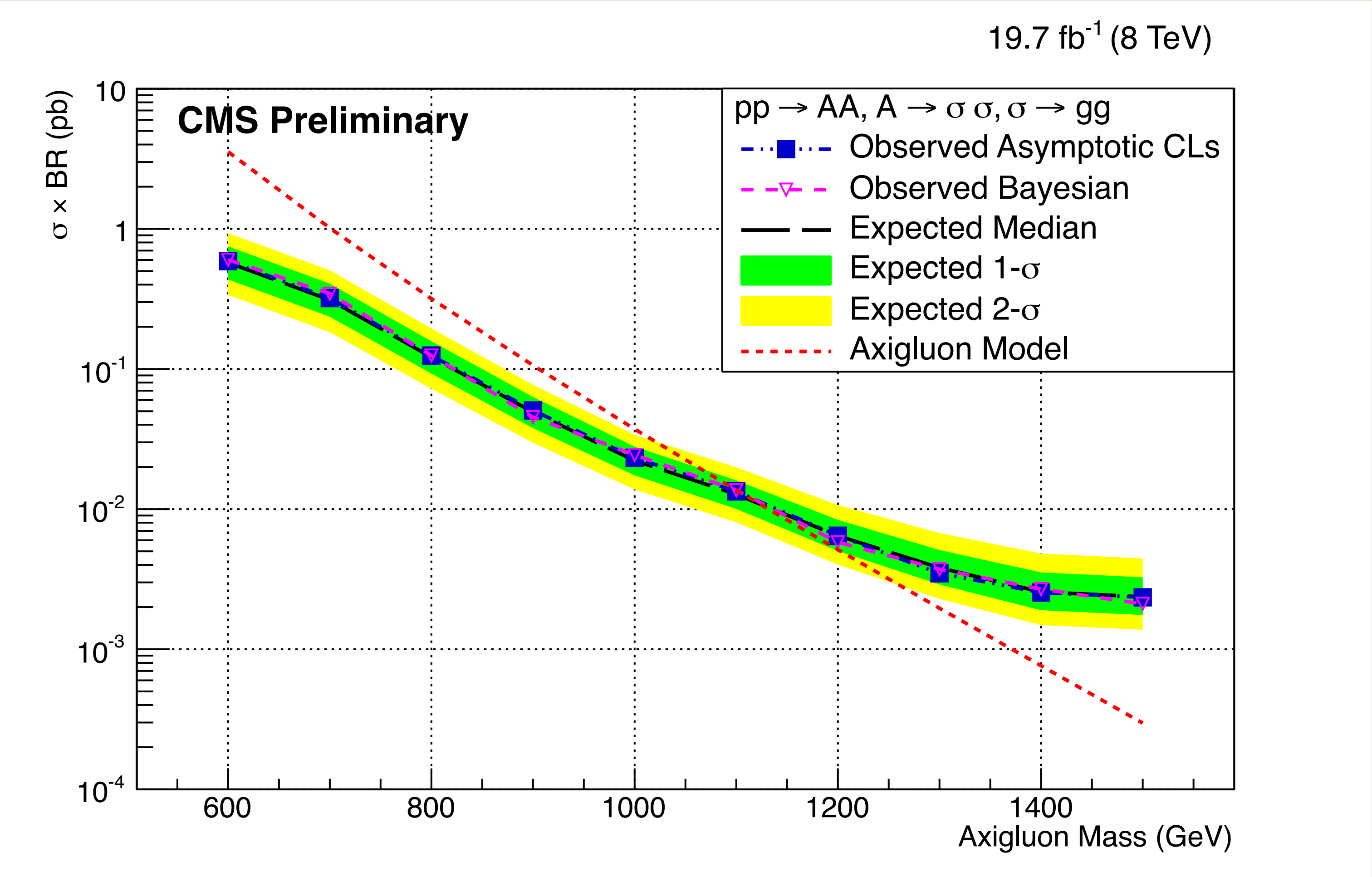
```
imax 2
jmax 1
kmax 5
----------------
bin          1            2
observation  17350        440
----------------
bin          1        1           2         2
process      signal   background  signal    background
process      0        1           0         1
rate         215.687  17347.3     436.078   426.293
----------------
lumi         lnN      1.026       1         1.026      1
jes          lnN      1.04        1         1.05       1
pdf          lnN      1.015       1         1.02       1
ddm          lnN      1           1         1          1.32532
norm         lnN      1           2         1          2
```

- Exaggerate systematic uncertainty on the scaling to 100% in the mass point where signal contamination is > 10%
- Explicitly account for this contamination in the limit calculation (essentially reduce signal efficiency)

• Lower mass exclusion stays the same
•Upper limits cross section on lower masses are higher as a result of signal contamination



Asymptotic CLs VS Bayesian

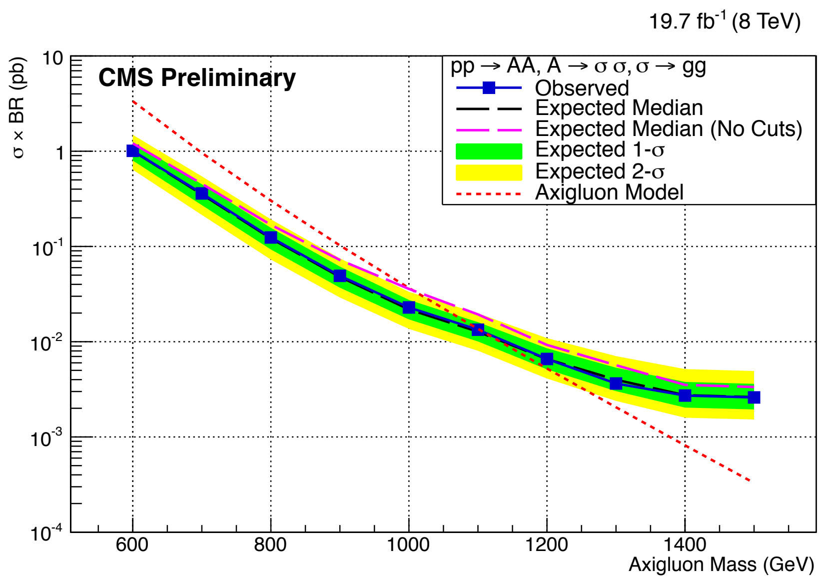


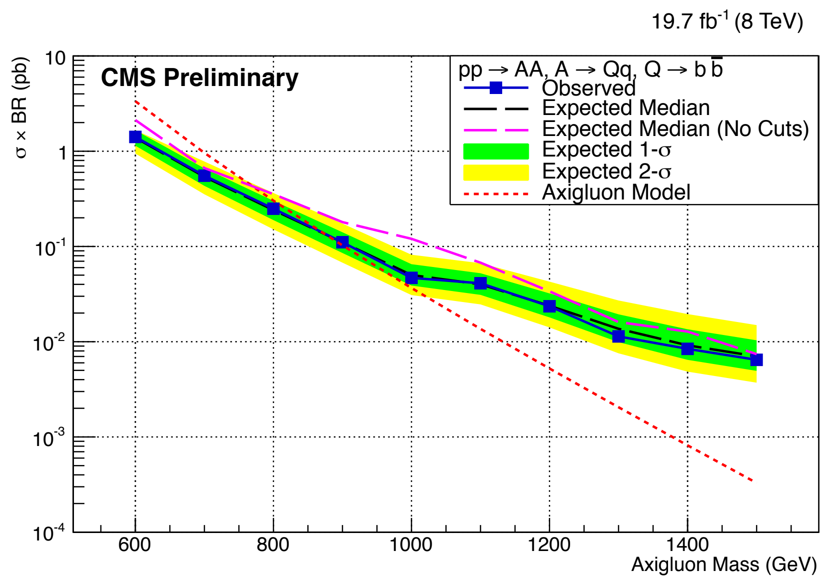
Consistent between Asymptotic CLs and Bayesian Calculator

What if no additional cuts?

With and without sphericity requirement

With and without b-tagged jets requirement



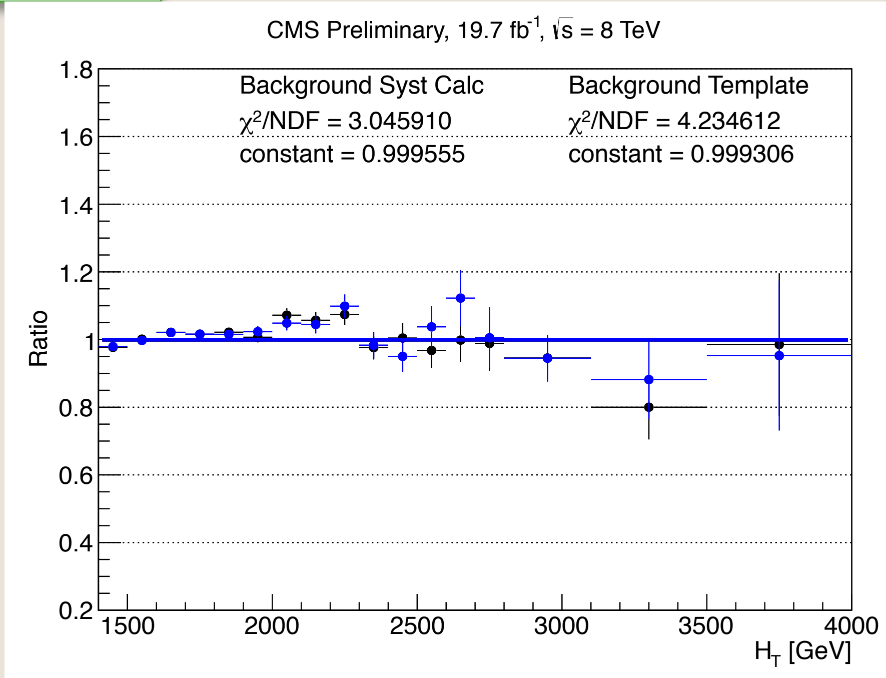


With additional cuts, we gain ~75 – 150 GeV in lower mass exclusion limits

H_T Invariance (with Sphericity)

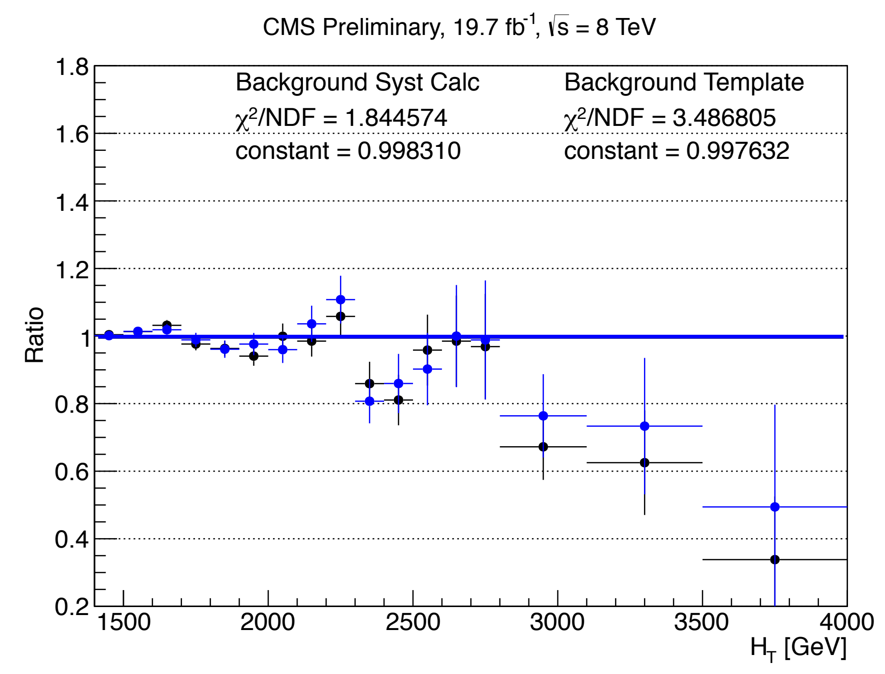
Njets ≥8

S > 0.1



Njets ≥ 8

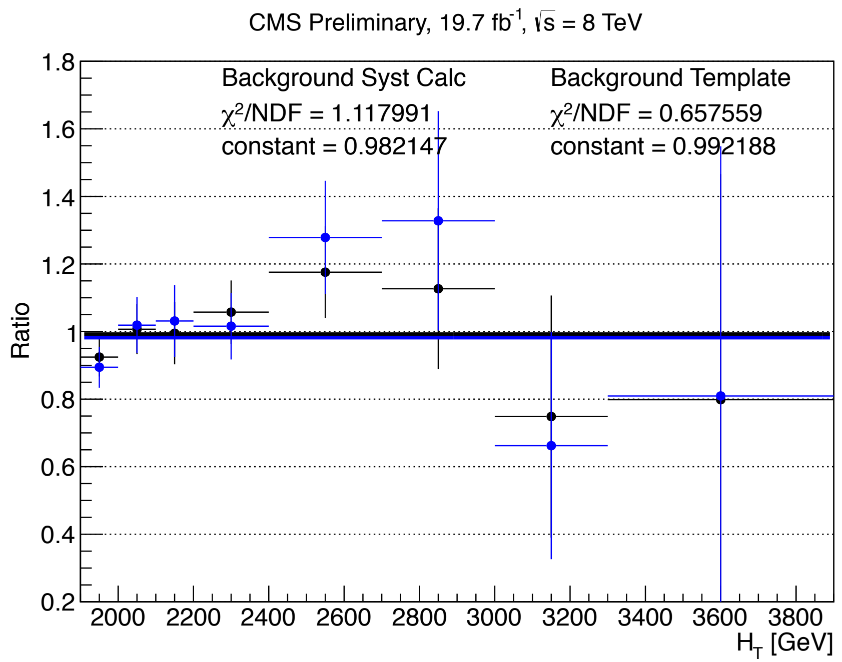
S > 0.4



H_T Invariance (with Sphericity)

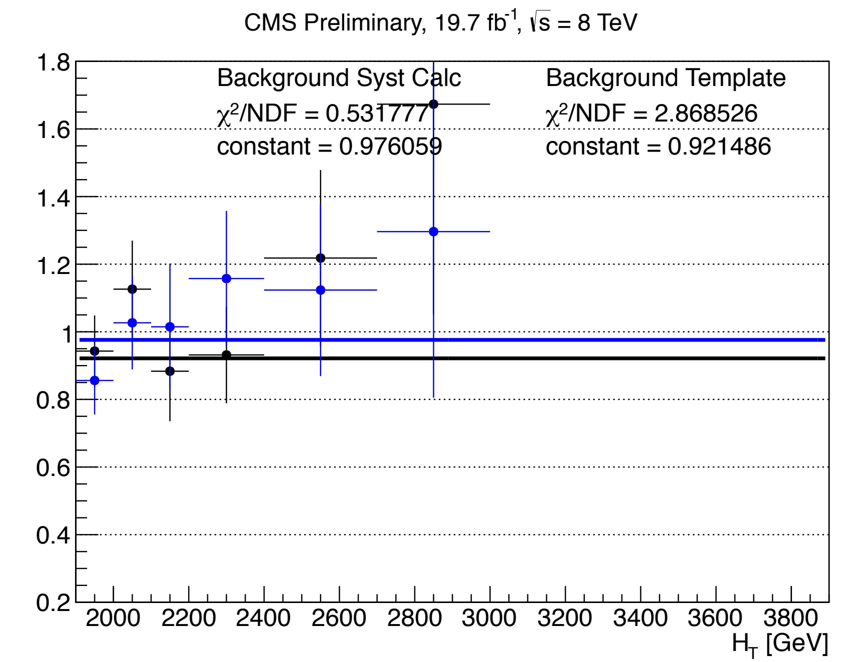
Njets ≥10

S > 0.1



Njets ≥ 10

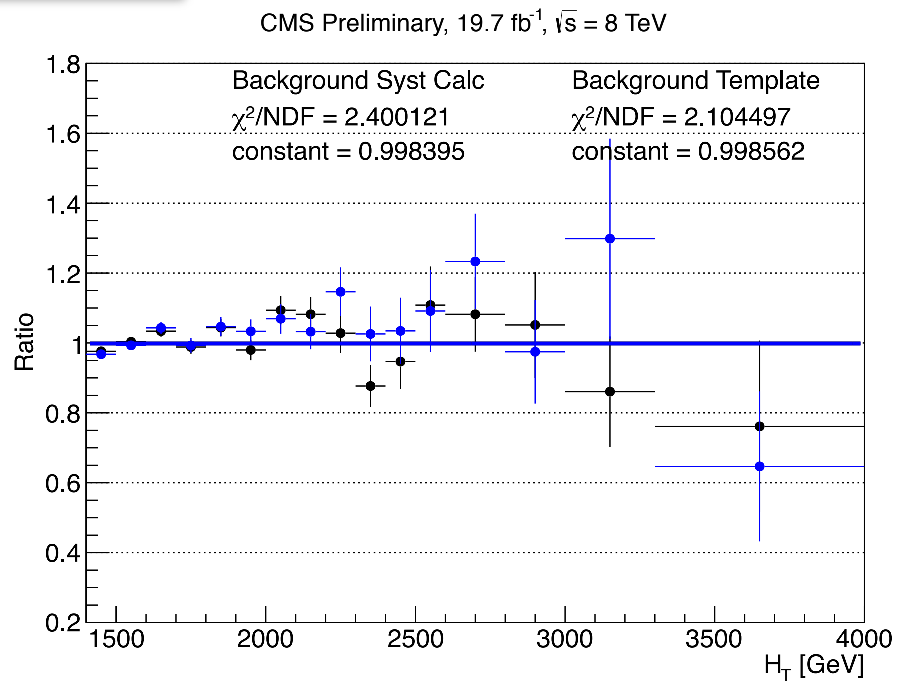
S > 0.4



H_T Invariance (b-tagged Jets)

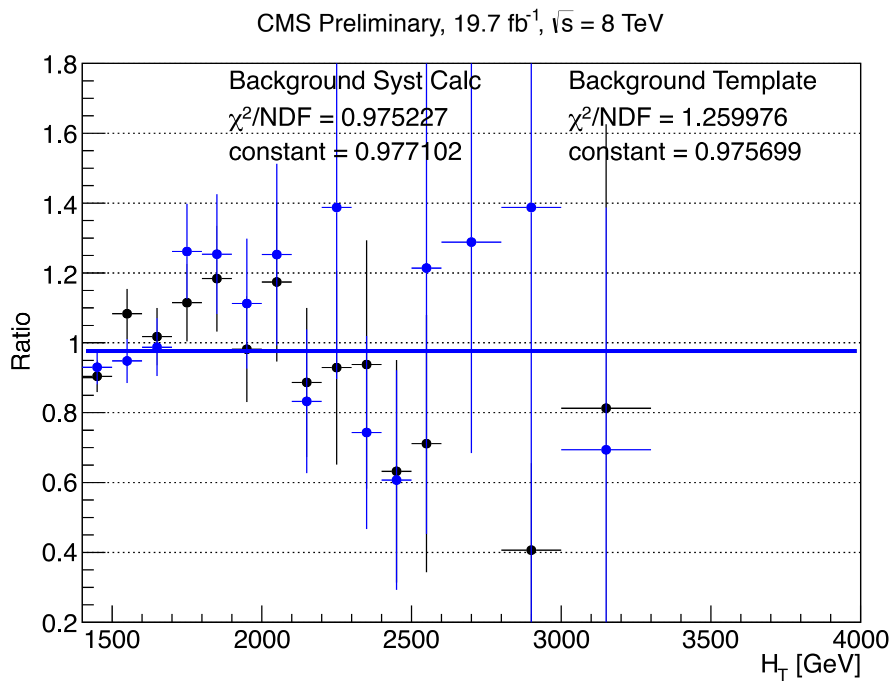
Njets ≥ 8

Nb ≥ 1



Njets ≥ 8

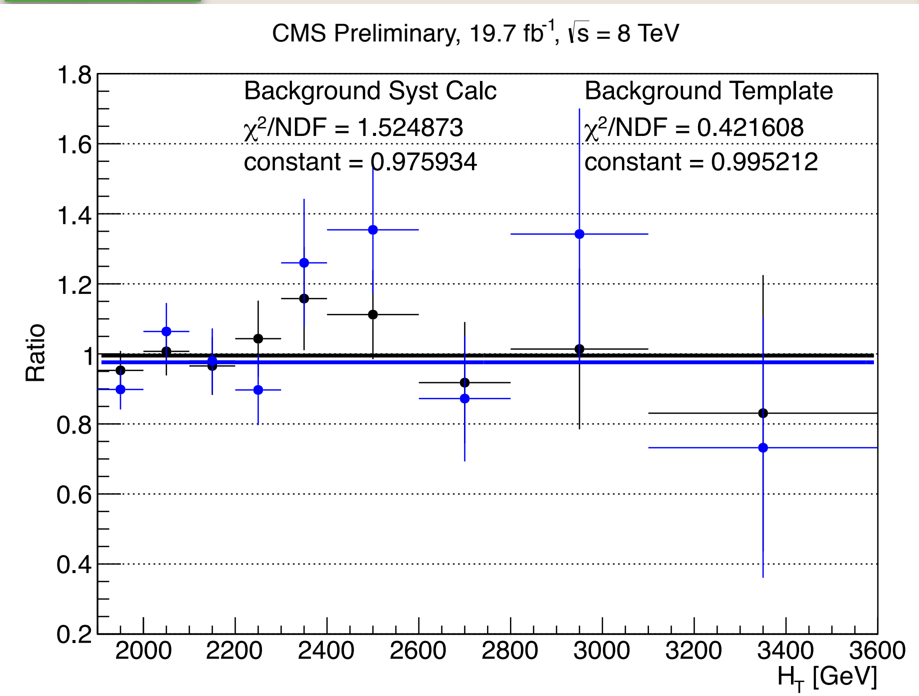
Nb ≥ 3



H_T Invariance (b-tagged Jets)

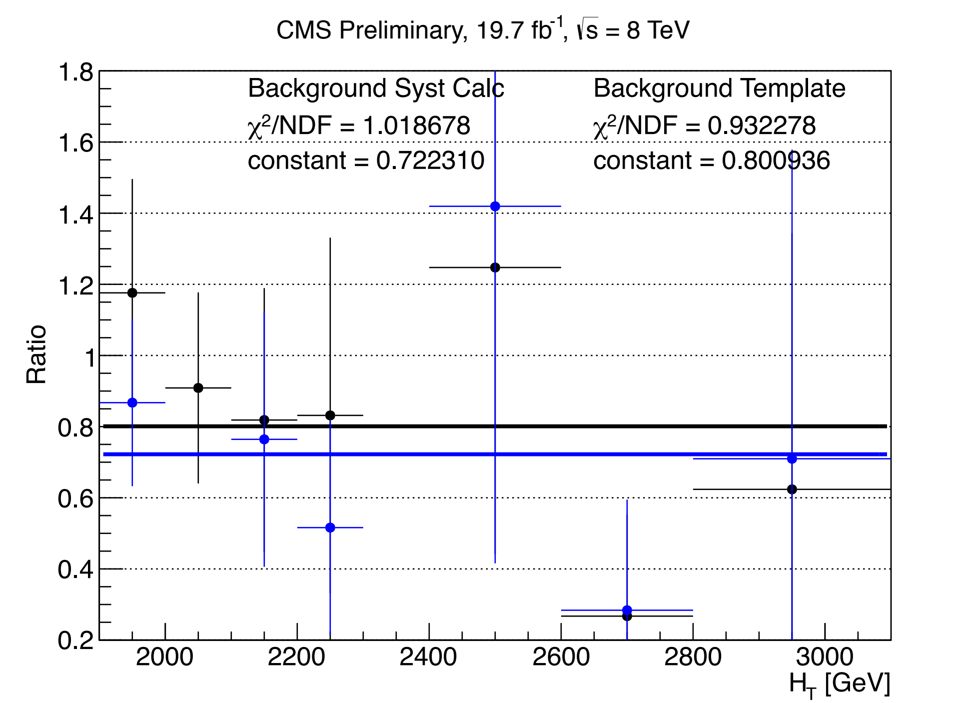
Njets ≥10

Nb ≥ 1



Njets ≥10

Nb ≥ 3

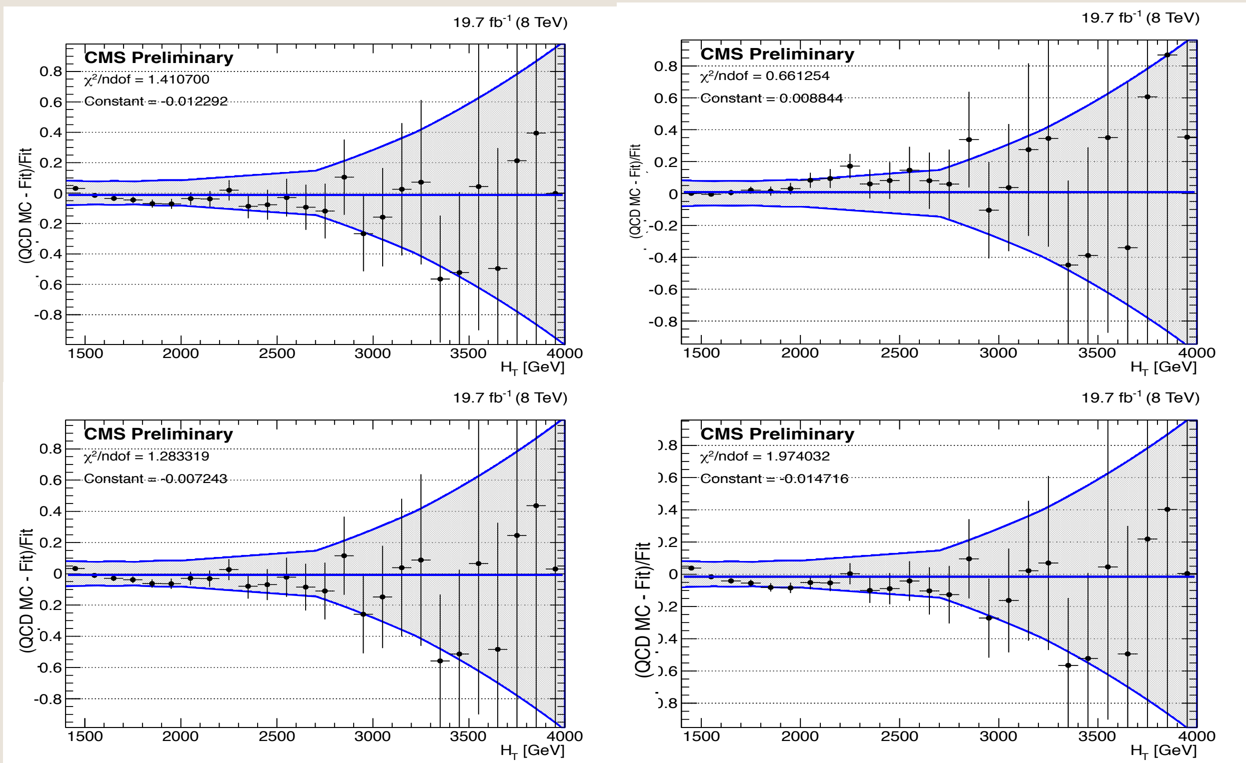


What functions to use?

Example

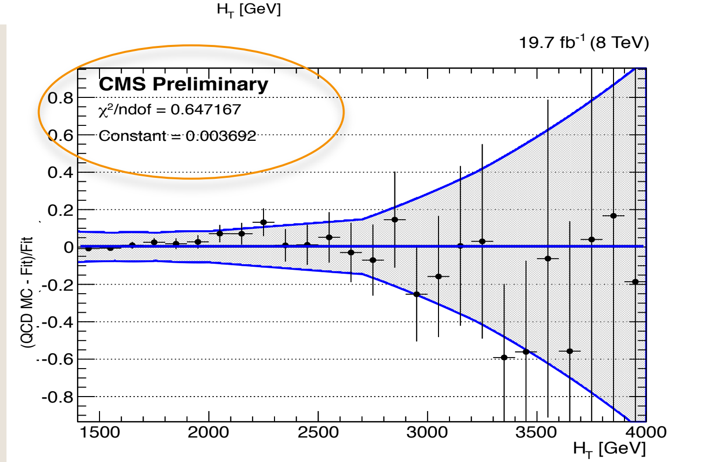
$$\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

$$\frac{P_0}{(P_1+P_2x+x^2)^{P_3}}$$



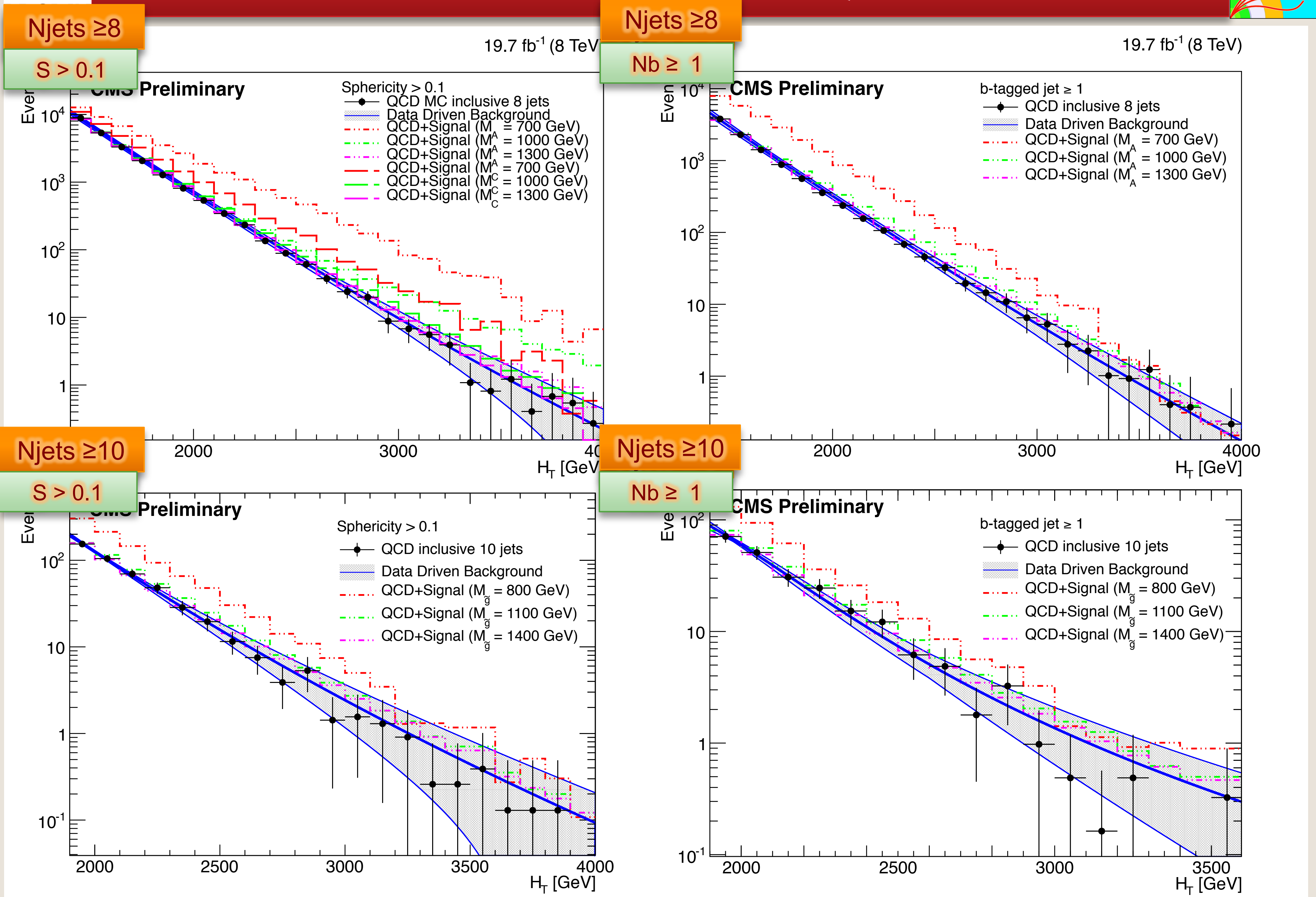
$$\frac{P_0}{(P_1+x)^{P_2}}$$

$$\frac{P_0(1+x)^{P_1}}{x^{P_2\log(x)}}$$



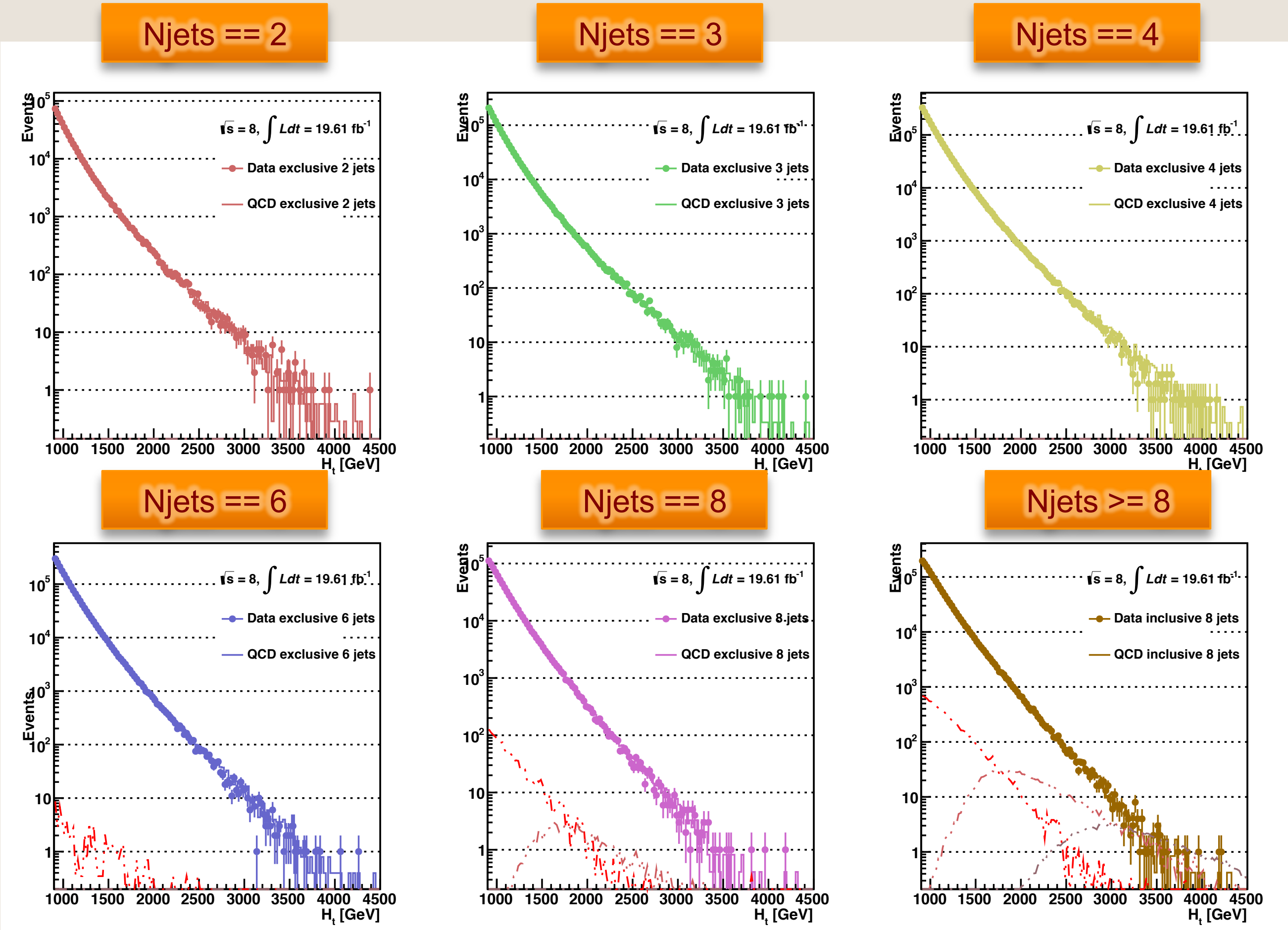
$$\frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\log(x)}}$$

Closure Test with QCD MC



Signal Contamination

- Find phase space where signal is depleted in the H_T distribution

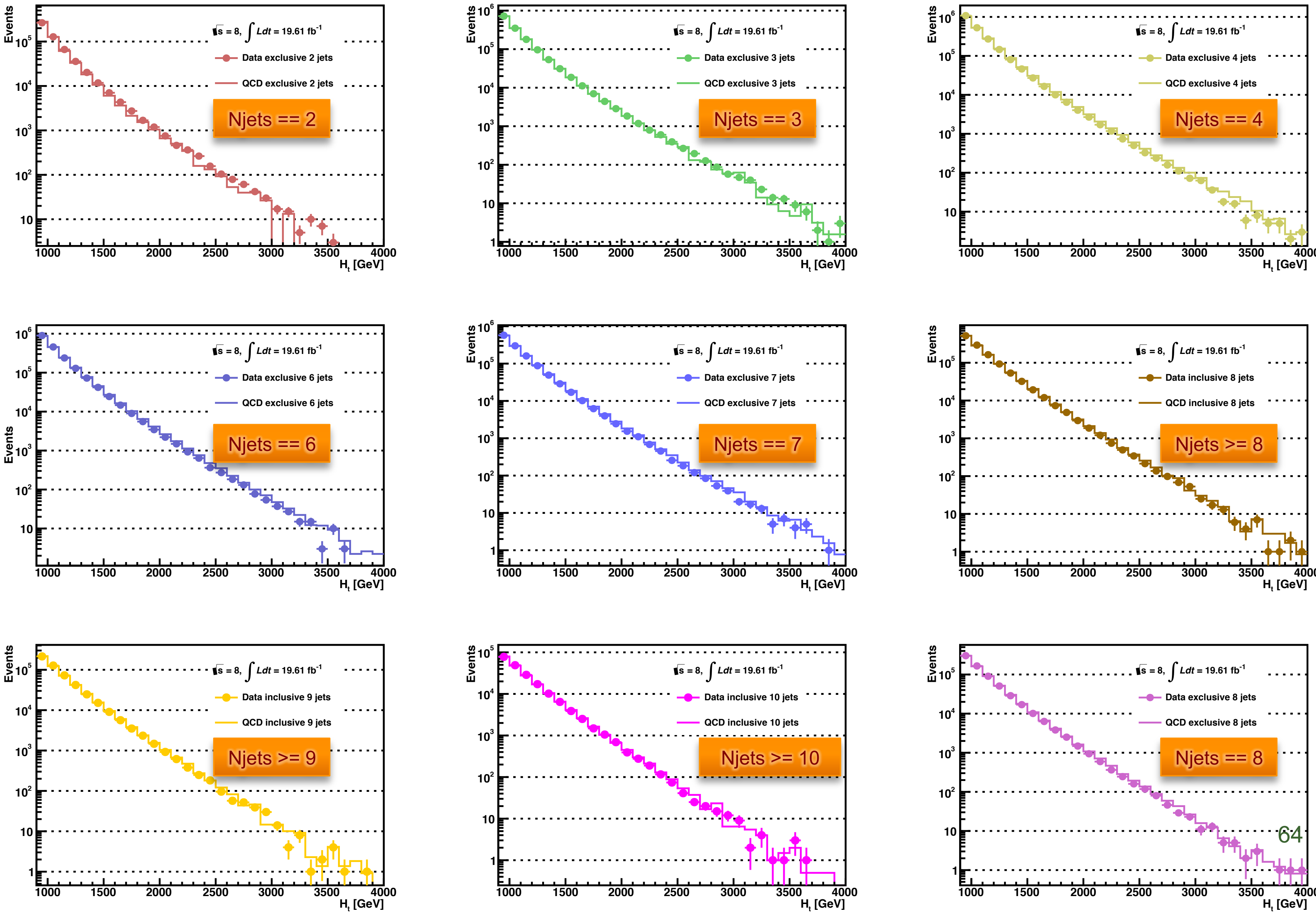


✓ Very small signal contamination in H_T distribution for lower multiplicity jet for Njets < 8

- Use fitting functions to estimate background at Njets < 8 and extrapolate to Njets >=8

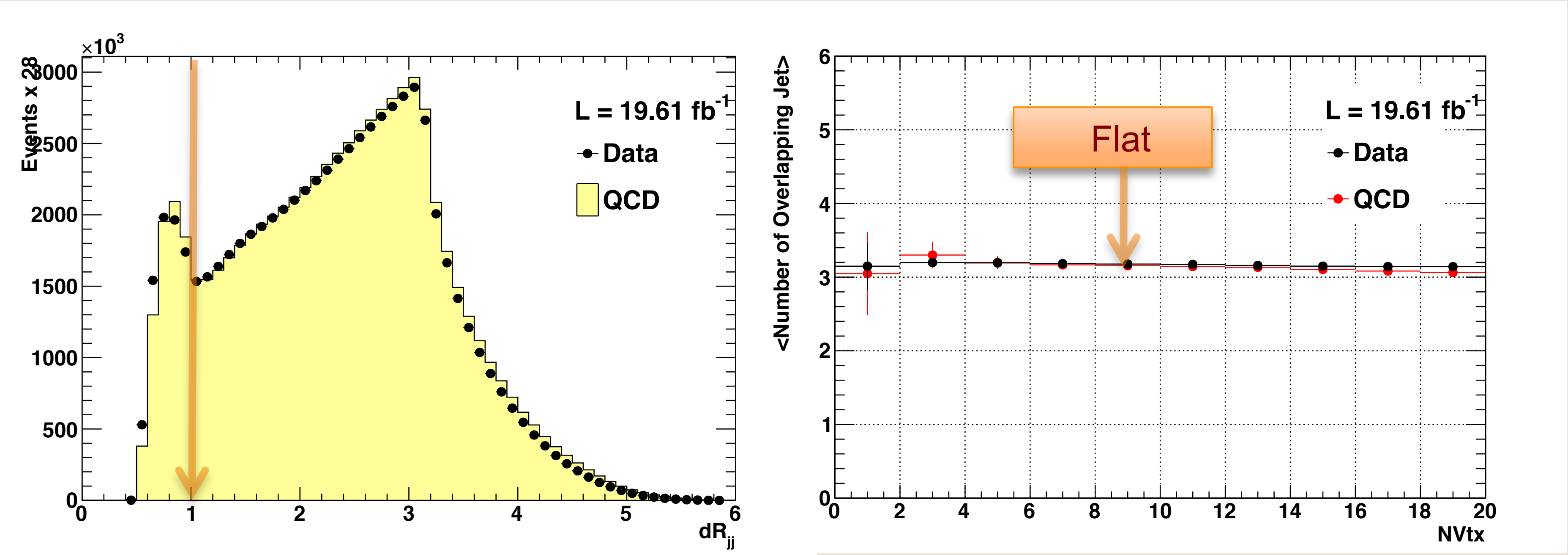
Negligible signal contamination for jet multiplicity = 2, 3, 4, 6

Data VS Background Consistency



Additional PU Sensitivity

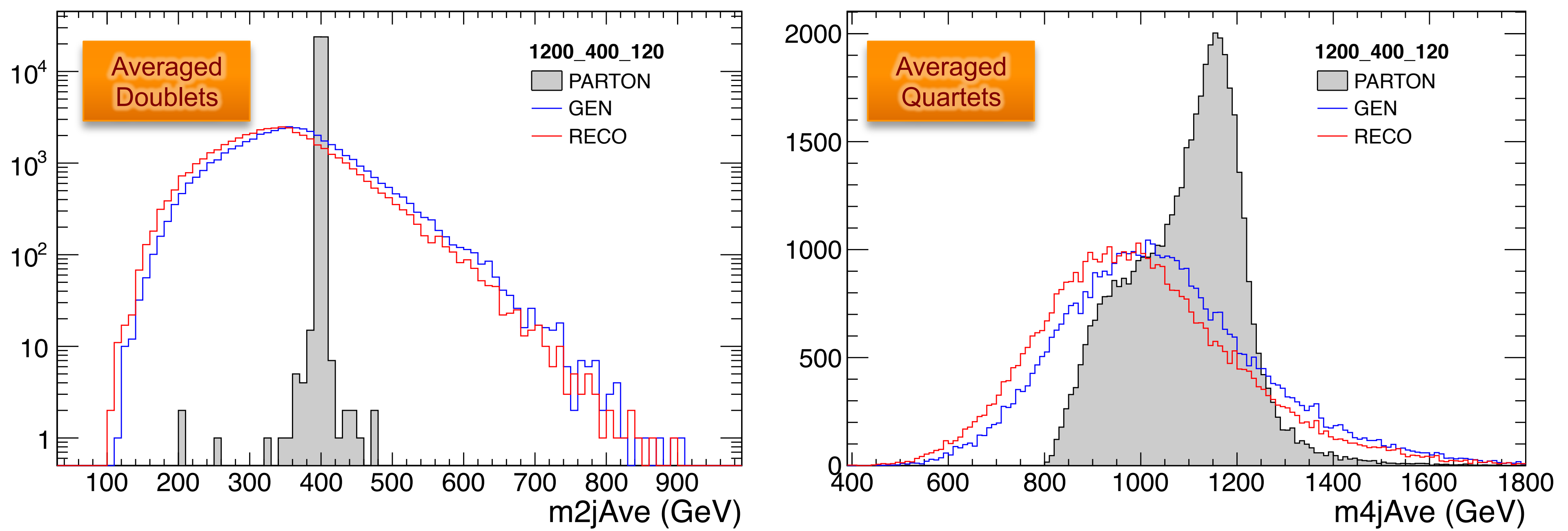
- Sensitivity to PU is negligible



- Plot the distribution of dR_{jj} for all combination of the dijets in 8 jets ensemble
- Average the number of overlapping jets in events
- Insensitive to number of vertices

Signal Reconstruction

The average of 4 doublets and 2 quartets are used to represent the invariant mass of the (pseudo)scalar/hyper-pion and Axigluon/Colorons



- At parton level
  - The optimal configuration gives us delta function for the averaged doublets
  - The quartet mass distribution has the tail which comes from the "wrong" combinatorial background with our optimal configuration
- At generator and reco level
  - Loss of resolution due to particle radiation

Signal Reconstruction

- How to reconstruct 8-jet for the pair-produced Colorons?
  - To select 4 doublets out of 8 jet, we reconstruct 2520 possible combinations
    - Choose the combination which has minimum mass spread (standard deviation) between the doublets
    - Identify the quartets with the minimum mass difference from the selected doublets (3 combinations)