Imperial College London

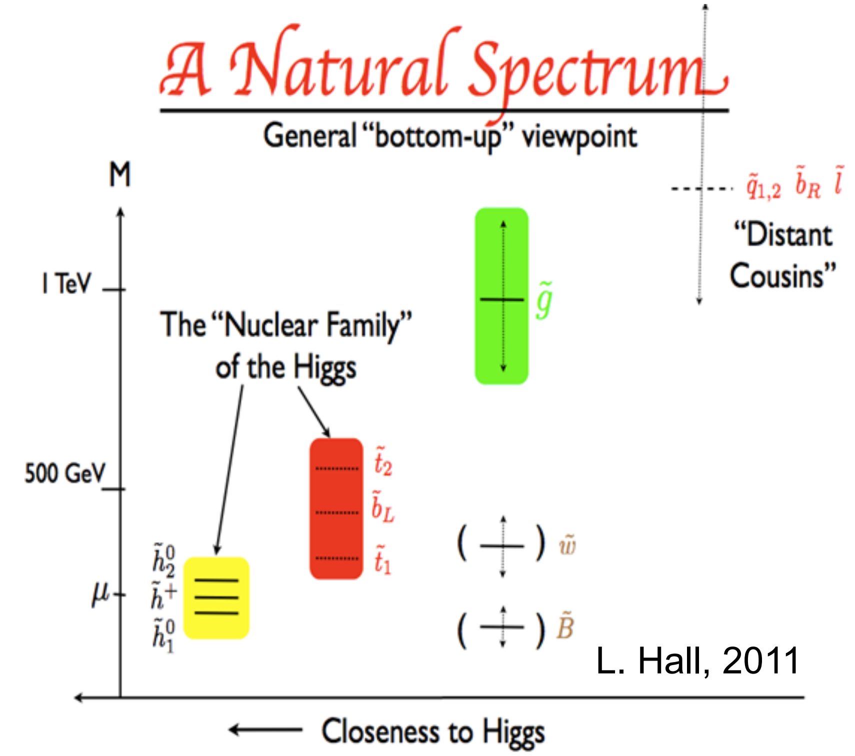
CMS Compact Muon Solenoid

All-hadronic α_T search for SUSY with 2.2/fb of 13TeV data at CMS

IOP Conference, University of Sussex
23/03/16

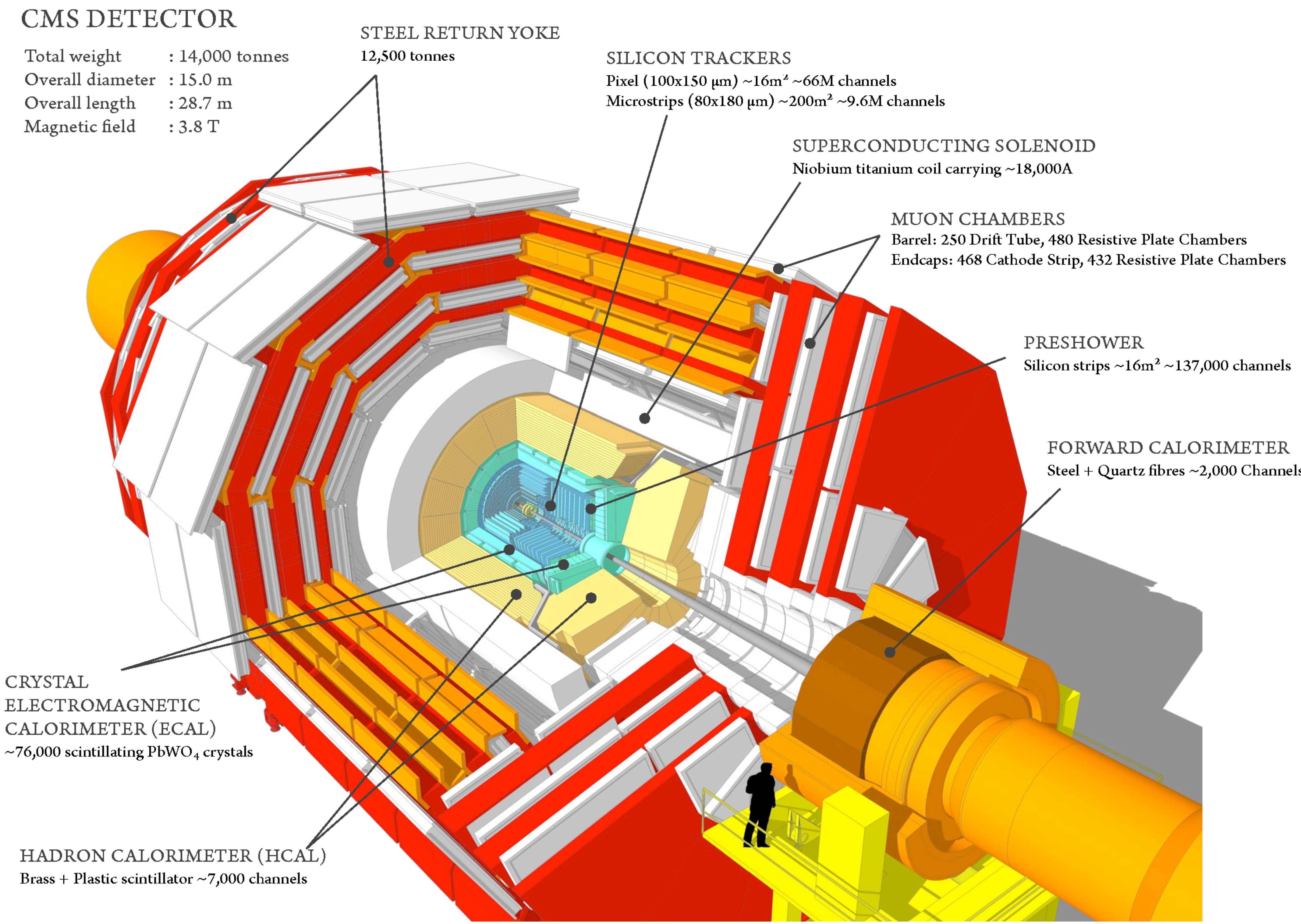
Matthew Citron
for the CMS collaboration

Introduction



- SUSY solves many limitations of the SM
  - Hierarchy problem → TeV-scale superpartners
  - Dark Matter → neutralino LSP is a possible candidate (assuming R parity)
  - Grand unification → modified running of gauge couplings
- LHC @ 13 TeV provides perfect conditions for natural SUSY discovery!
- Present **CMS α_T search**: all-hadronic jets + MET search
- Stringent new limits with 2.2/fb of data at 13 TeV on wide range of SUSY (+DM) models
- Show interpretations for two gluino simplified models

The CMS detector

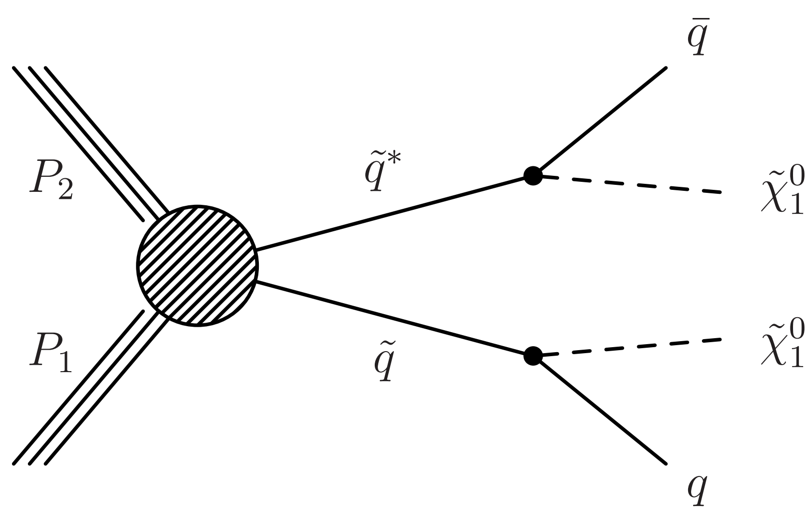


Hadronic SUSY signatures

H_T = total jet energy

MH_T = 'missing' momentum from jets

Uncompressed (large mass splittings)



H_T :

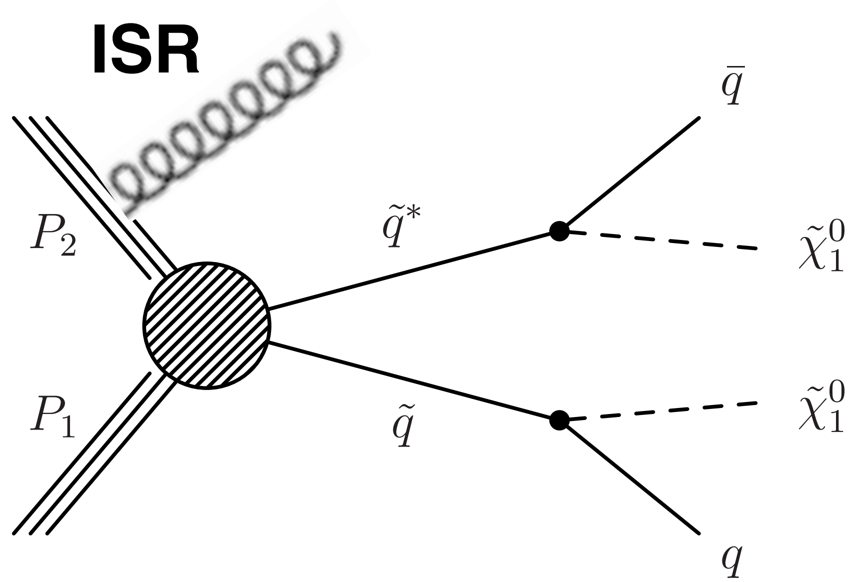
$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$

MH_T :

$p_{T_{\tilde{\chi}_1^0}}$

+ jets

Compressed (small mass splittings)



H_T :

$p_T(ISR)$ → softer

MH_T :

$p_{T_{\tilde{\chi}_1^0}}$

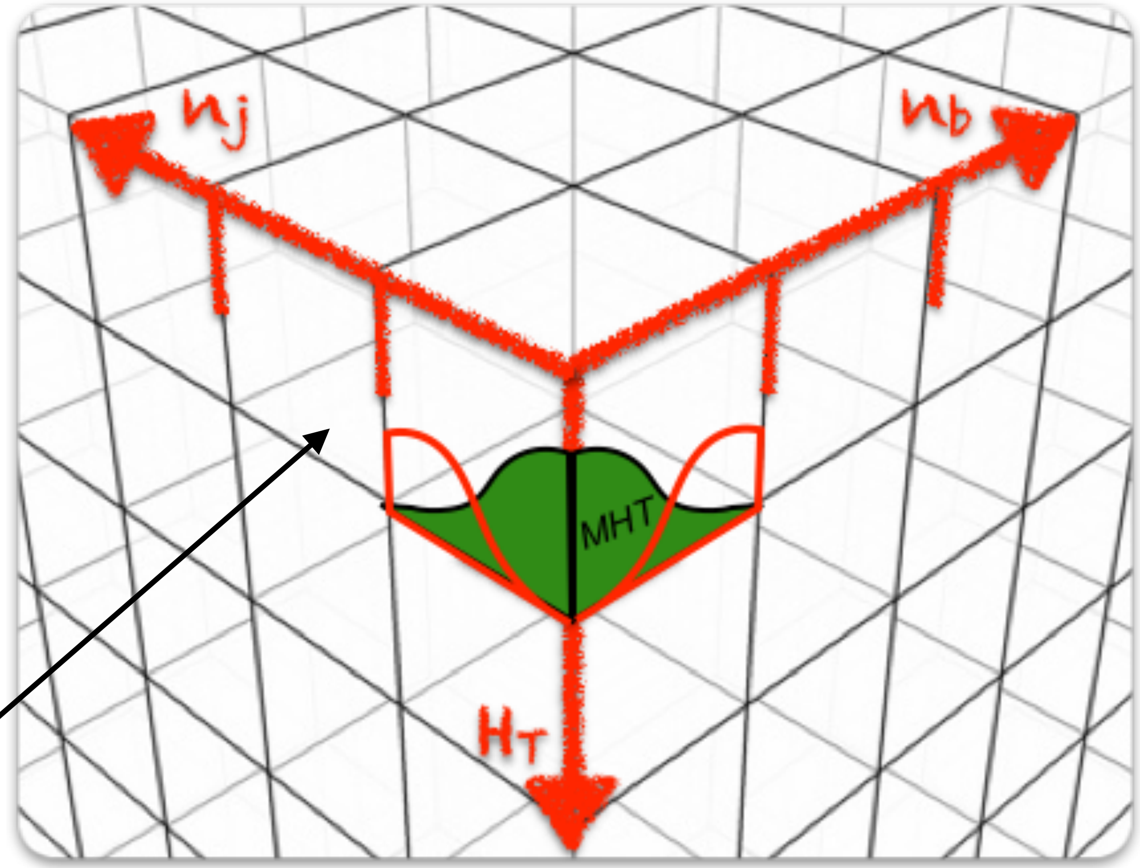
+ jets

+ b jets from 3rd generation decays (lightest squarks for natural SUSY)

Analysis strategy

- Reject electroweak backgrounds with lepton/photon veto - all hadronic jets + ME_T final state
- Maximise sensitivity by binning in n_{jet},n_b,$H_{T,}$ MH_T
- Two key variables: α_T and $\Delta\phi^*$ used to reduce dominant QCD background to negligible level
  - Additional cleaning cuts applied (e.g. $MH_T/ME_T < 1.25$) - see backup for full selection
  - Residual QCD measured in data (see backup and added in likelihood)
- Data driven estimates of remaining ewk backgrounds in signal region from several control samples

Control region prediction



+ Split into symmetric, asymmetric and monojet topologies based on second jet p_T
(> 100, 40 -100, < 40 GeV)

Boost sensitivity for softer signal models

Control region binned identically in H_T,n_{jet},n_b for prediction of ewk backgrounds: $Z \rightarrow \nu\nu$ (+jets),tt (+jets) +W (+jets) + residual

$$N^{\mathrm{signal}}_{\mathrm{pred}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}}) = \frac{N^{\mathrm{signal}}_{\mathrm{MC}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}})}{N^{\mathrm{control}}_{\mathrm{MC}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}})} \times N^{\mathrm{control}}_{\mathrm{obs}}(n_{\mathrm{jet}}, n_{\mathrm{b}}, H_{\mathrm{T}})$$

transfer factor

X systematic terms

Transfer factor systematic summary

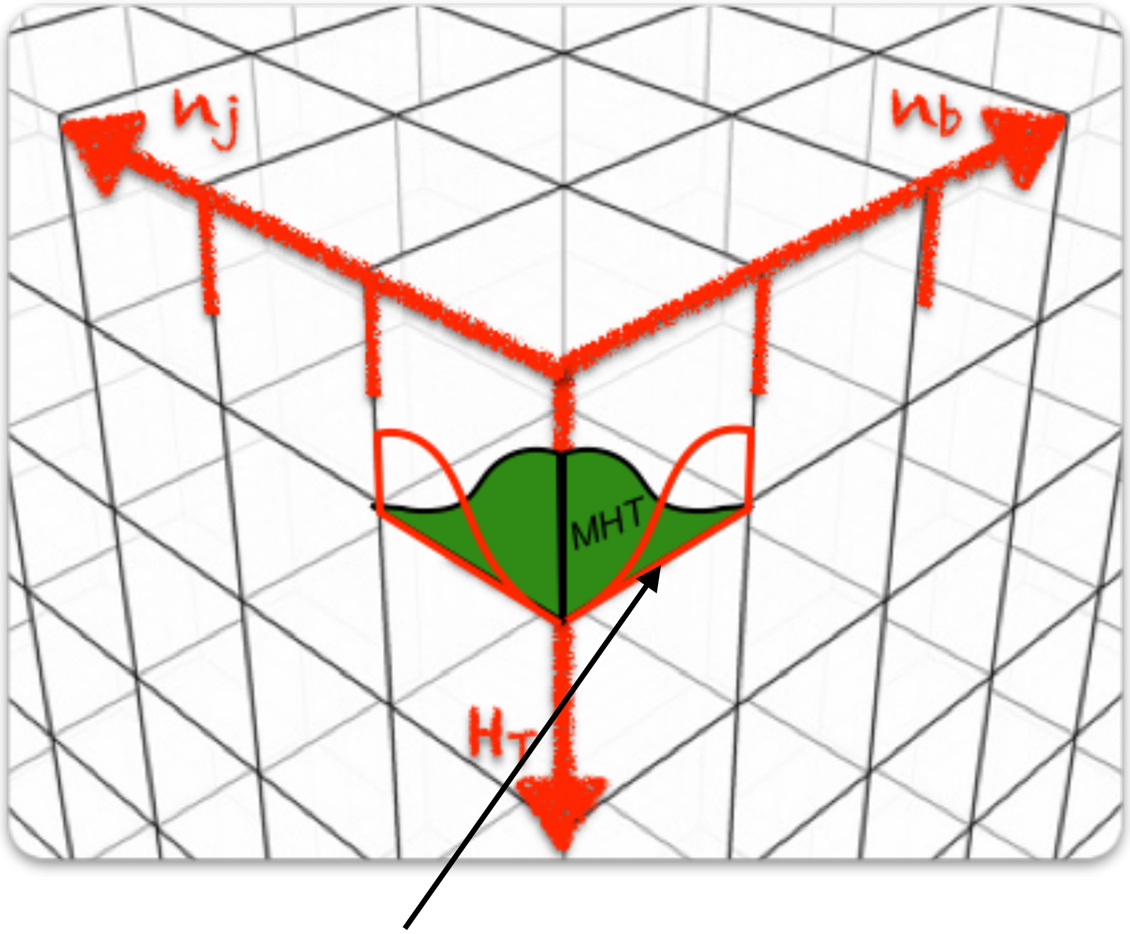
Source	Method	Uncertainty on transfer factor			
		μ -> Zinv	μμ->Zinv	γ -> Zinv	μ -> tt+W
JEC	variation of JECs	< 15%	< 10%	< 15%	< 15%
b-tag	variation of b-tag SFs	< 5%	< 2%	< 2%	< 5%
PU	variation of min. bias xs	< 6%	< 4%	< 3%	< 10%
Top p_T	variation of top pT weights	< 20%	< 4%	-	< 5%
Lepton ID/iso/ trigger	variation of lepton SFs	-	-	-	~3%
W polarisation	μ+→μ- closure test	5-10%	-	-	5-50%
α_T/Δϕ* extrapolation	α_T closure test	5-80%	50-80%	-	5-80%
W/Z ratio	μ→μμ closure test	10-30%	-	-	-
Z/g ratio	g→μμ closure test	-	-	10-30%	-
tt/W admixture	0→1 b-tag closure test	-	-	-	10-100%

Fully correlated (JEC, b-tag, PU, Top p_T, Lepton ID/iso/trigger)

Uncorrelated across H_T/jet top. (sym/asym) (W polarisation, α_T/Δϕ* extrapolation, W/Z ratio, Z/g ratio, tt/W admixture)

MH_T dimension

MH_T binning provides additional separation between SUSY and Ewk backgrounds for a range of models



Use MH_T dimension **binned** in H_T (+n_j) → **negates the effect of missing higher order corrections** that otherwise bias Data/MC agreement

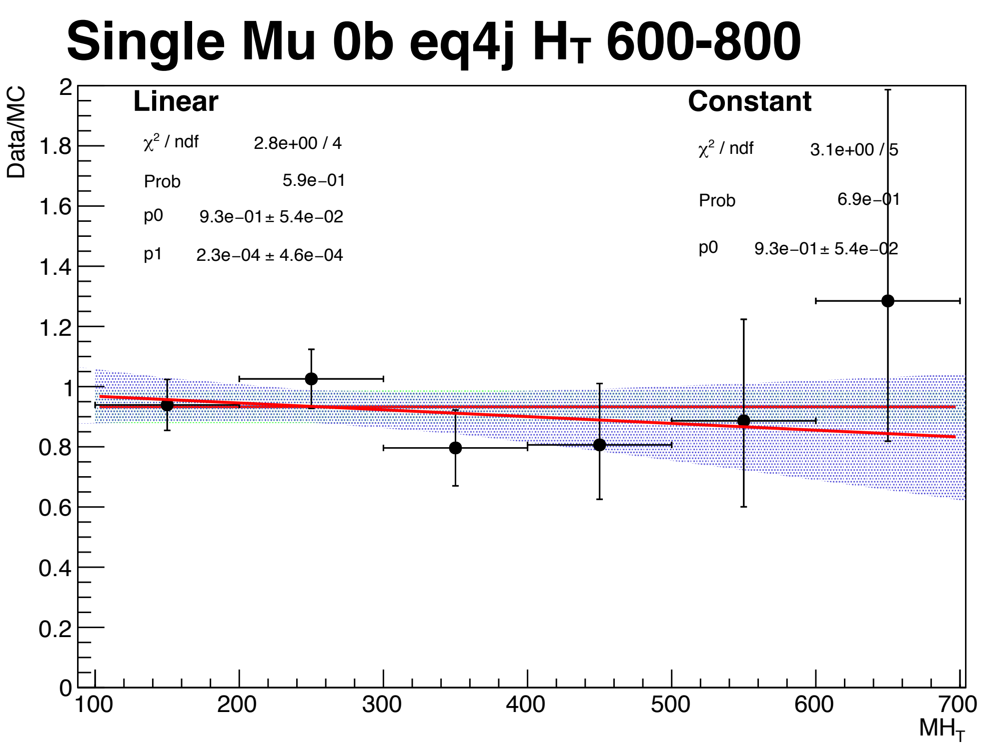
MH_T dimension probes only the **kinematics** of events fixed at a certain scale - predict MH_T distribution with MC (normalisation set in data)

Fully validated using control regions (next slide)

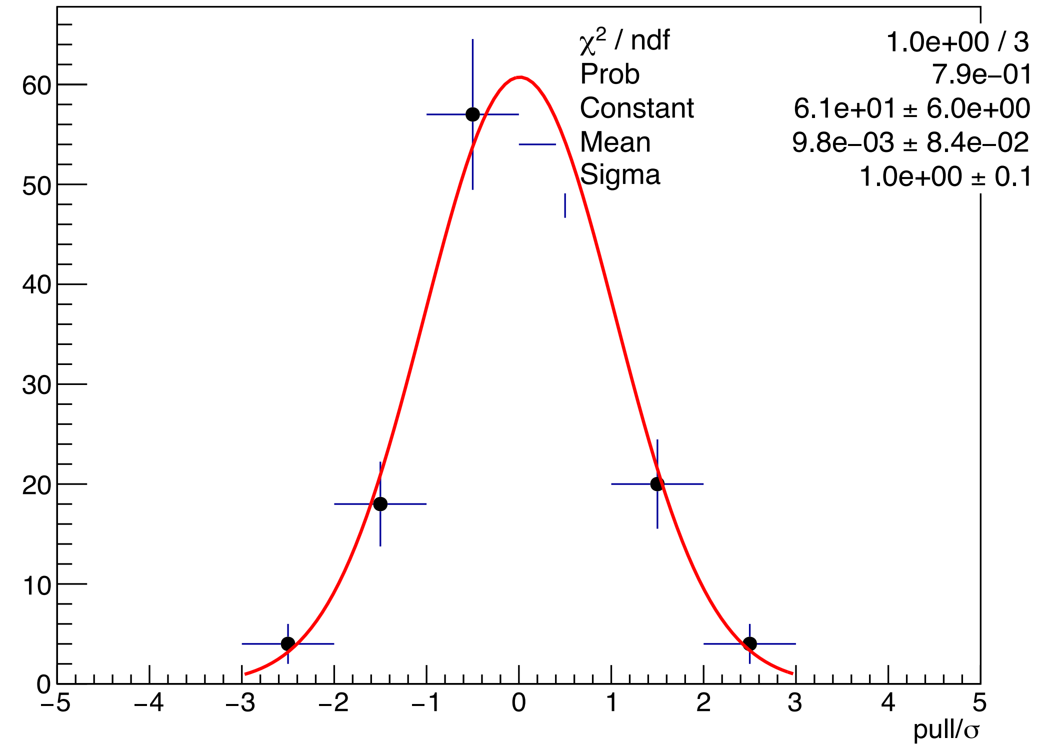
MH_T dimension

$$f(x) = p_0 + (x - <x>) \times p_1$$

- Nominal templates taken directly from MC (normalisation from control regions)
- In each (n_{jet},n_b,H_T) bin, the data/MC ratio is validated in multiple control regions and used to derive uncertainties in templates
- Fit linear orthogonal polynomial and check linear term is compatible with 0 over all bins
  - Linear function with intersect (p_0 - norm changing) and slope (p_1 - shape changing) components decorrelated
  - p_1 uncertainty and best fit value are propagated to derive alternative templates for systematics
- Validated with full 13 TeV and 8 TeV datasets

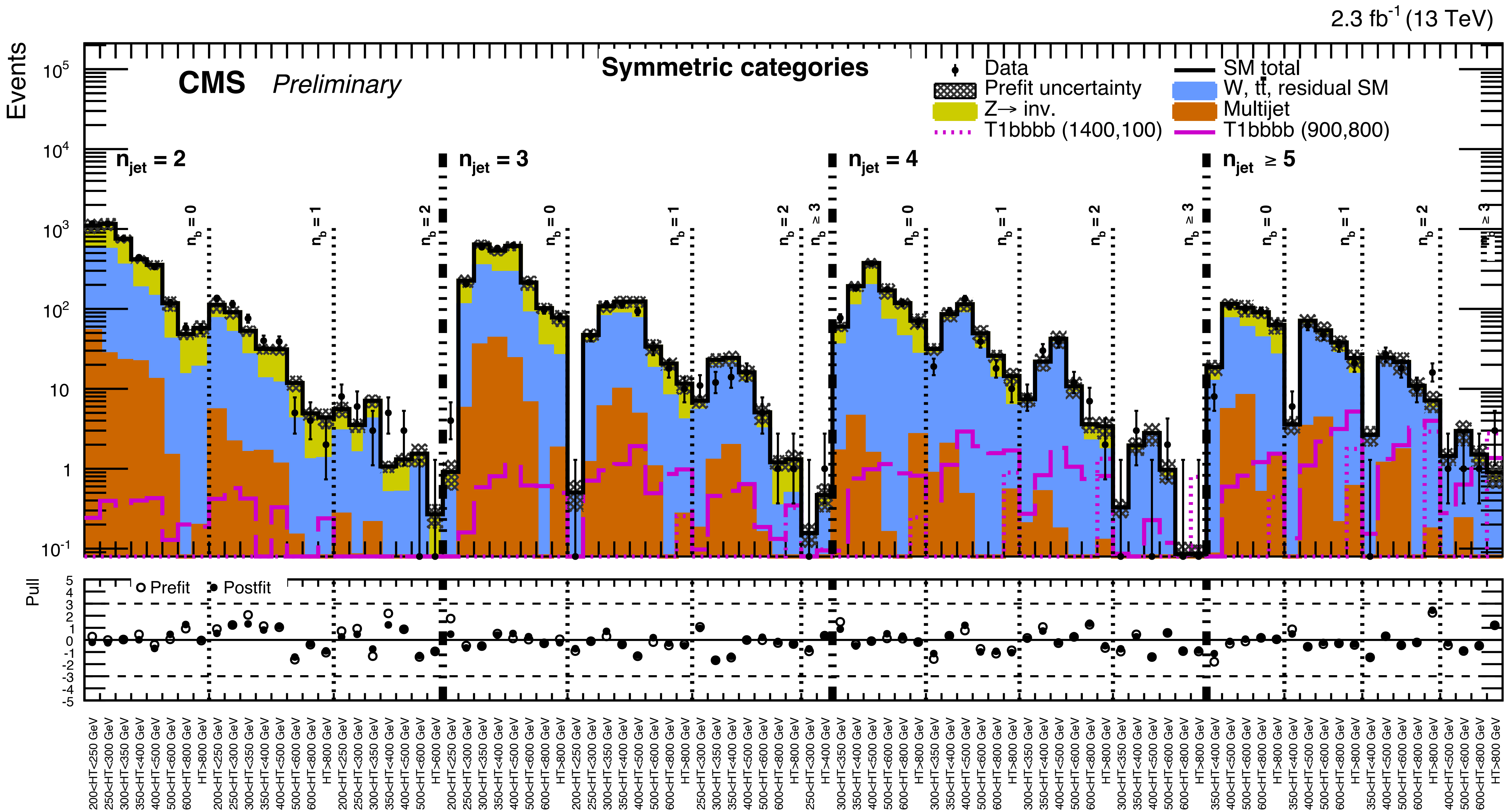


Example validation in control region



Pull distribution ($p1/p1_{Err}$) showing linear parameter consistent with 0

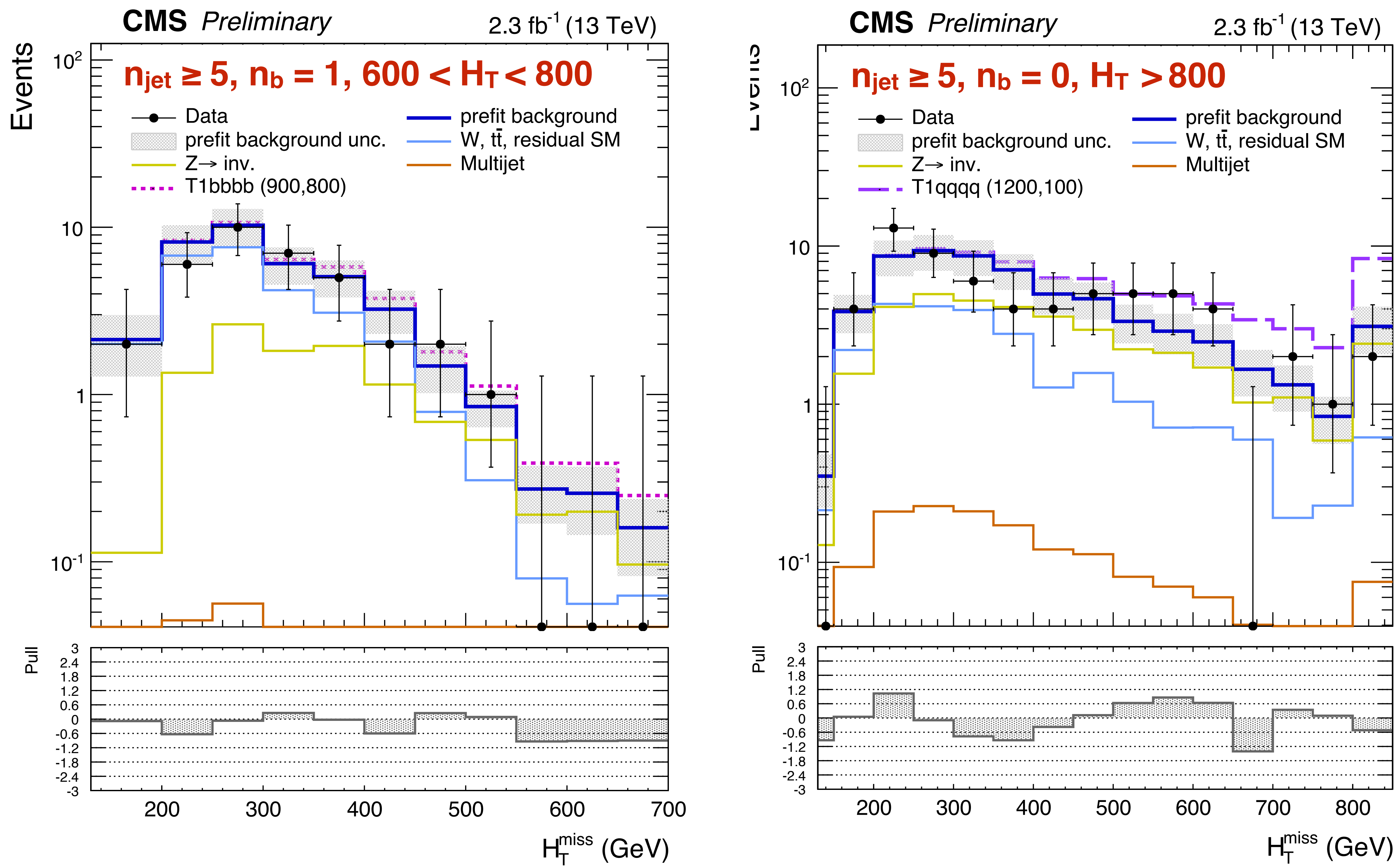
Symmetric category predictions



Predictions agree well with data across the signal region

M. Citron mc3909@ic.ac.uk

Prefit MH_T distribution examples



Example **sensitive** categories show pre-fit MH_T distributions agree well with data

M. Citron mc3909@ic.ac.uk

Likelihood model

i = $H_T/n_{jet}/n_b$ bin

signal strength

$$L(\mu, \underline{\theta}(\mu)) = \prod_i (L^i_{had}(\mu, \underline{\theta}(\mu)) \times \prod_{control} L^i_{control}(\mu, \underline{\theta}(\mu)))$$

nuisances

- **Binned analysis** - L is a product of **poisson terms** of the likelihood of the observation in each bin given the expected counts from background and signal processes (+ systematics)

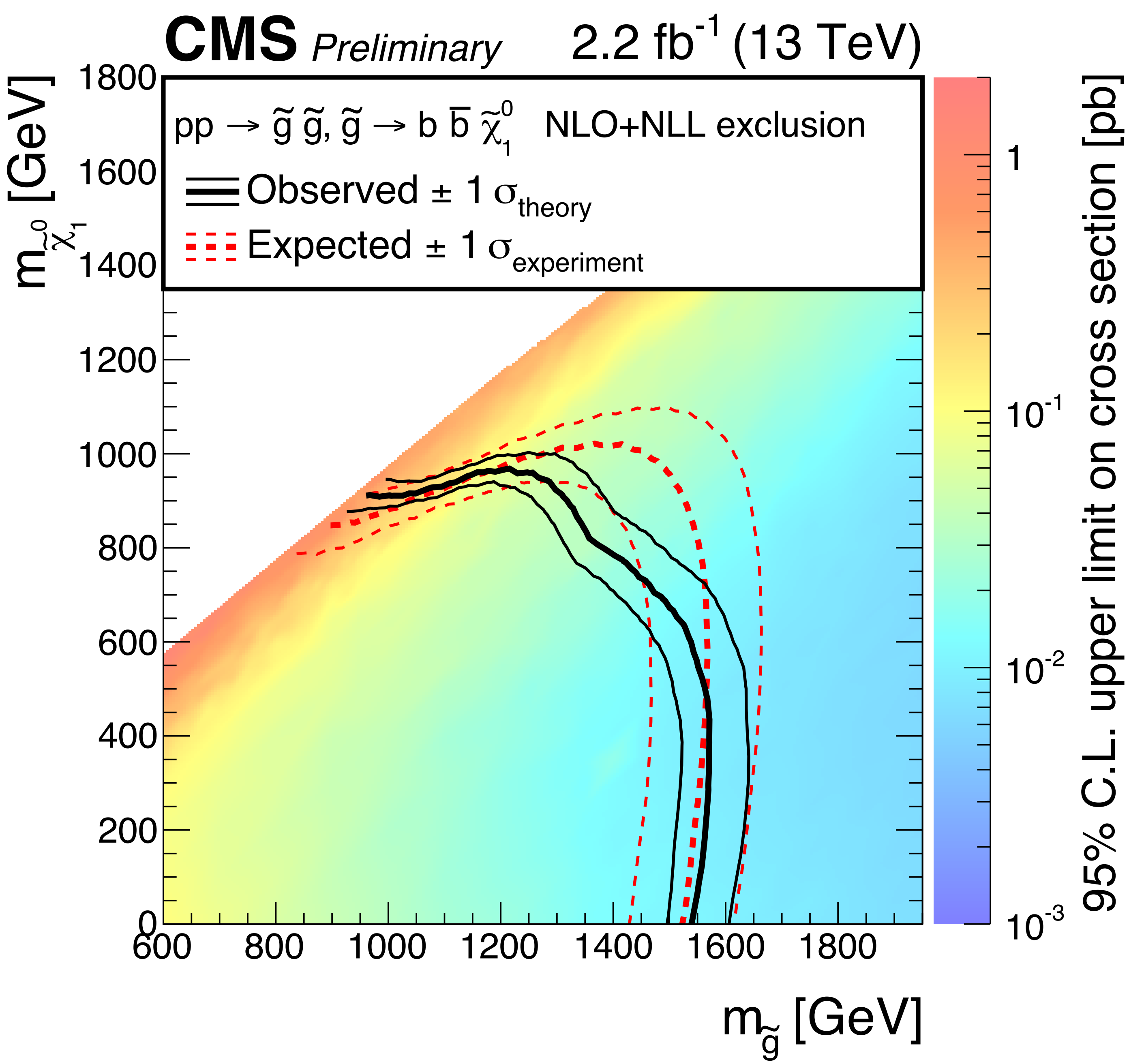
- Likelihood broken into two parts per $H_T/n_j/n_b$ - had (signal region) and control
  - L^i_{had} contains the signal and background yields per MH_T bin and relevant (shape) systematics on the MH_T distribution within the signal bin
  - $L^i_{control}$ contains the prediction of the dominant background yields by the control regions inclusive in MH_T including the relevant (log normal) systematics

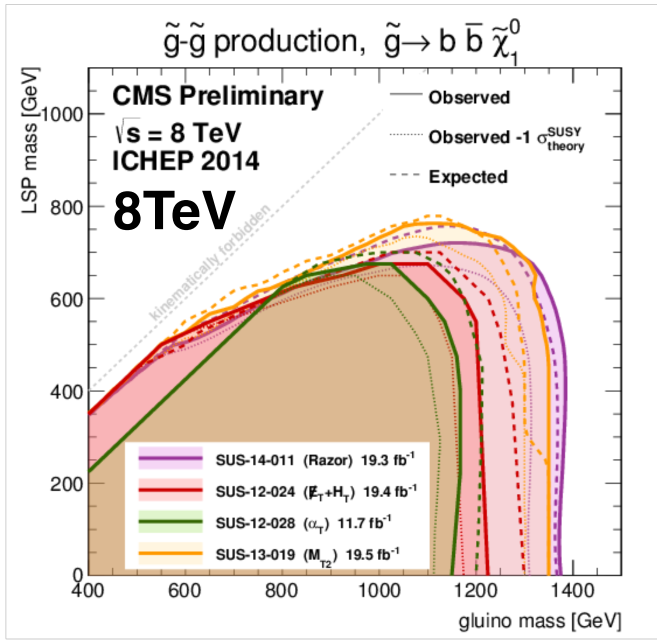
- Signal contribution in signal and control regions (with relevant systematics) included

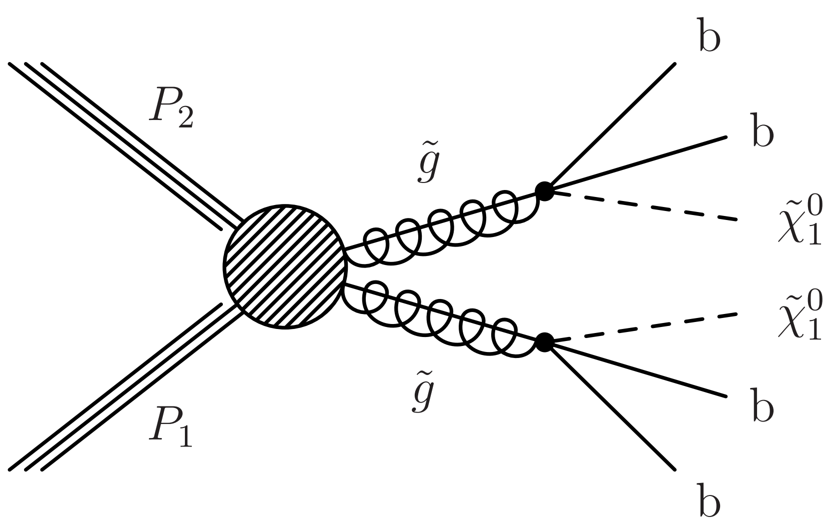
- Set limits based on value of μ excluded with CLs > 95% derived using LHC test statistic*

*ATL-PHYS-PUB-2011-11

Interpretation - T1bbbb

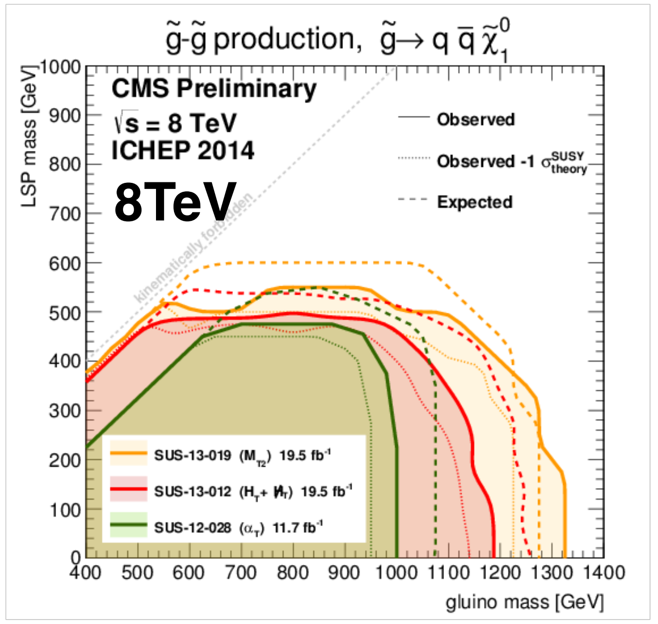


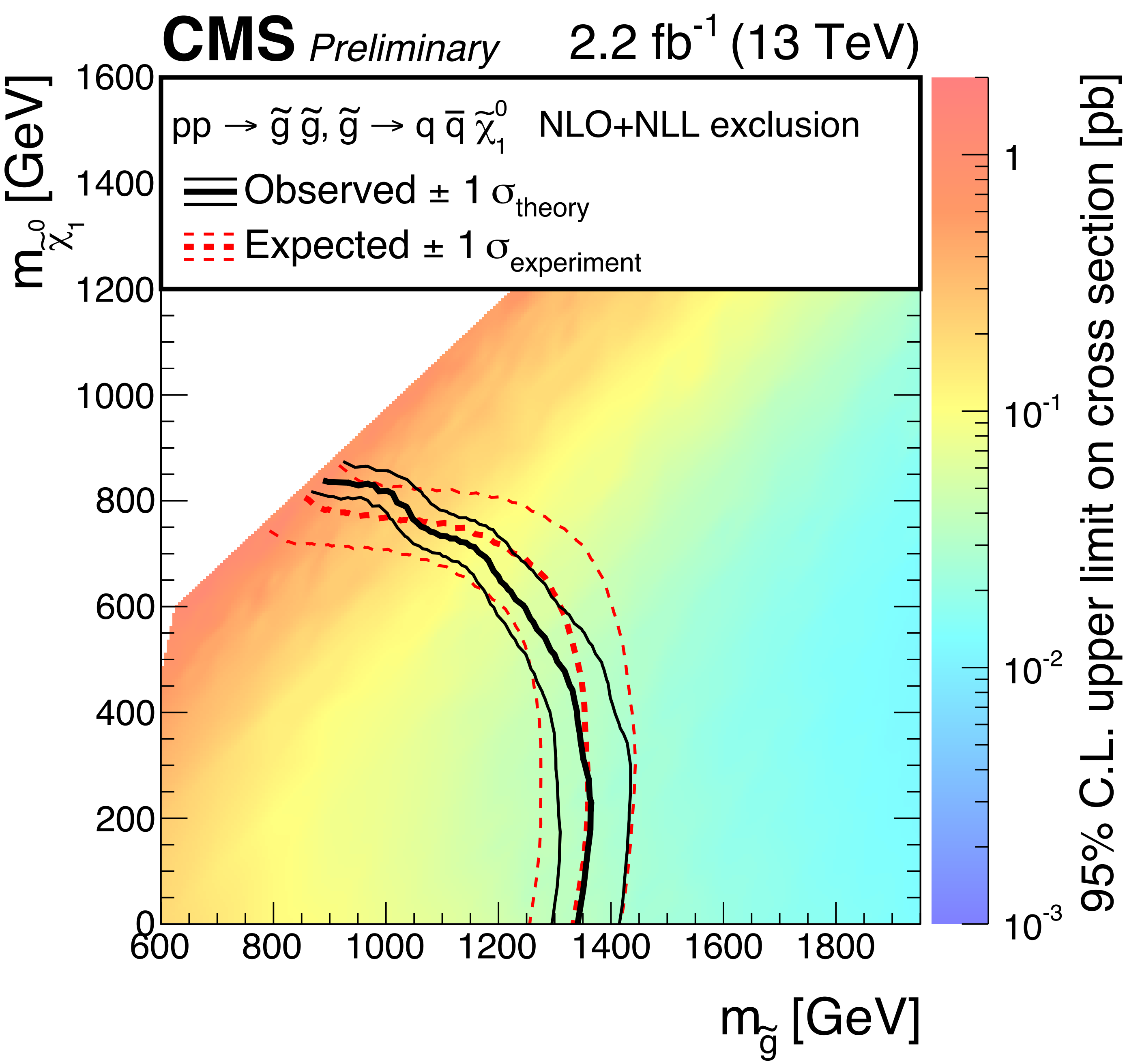


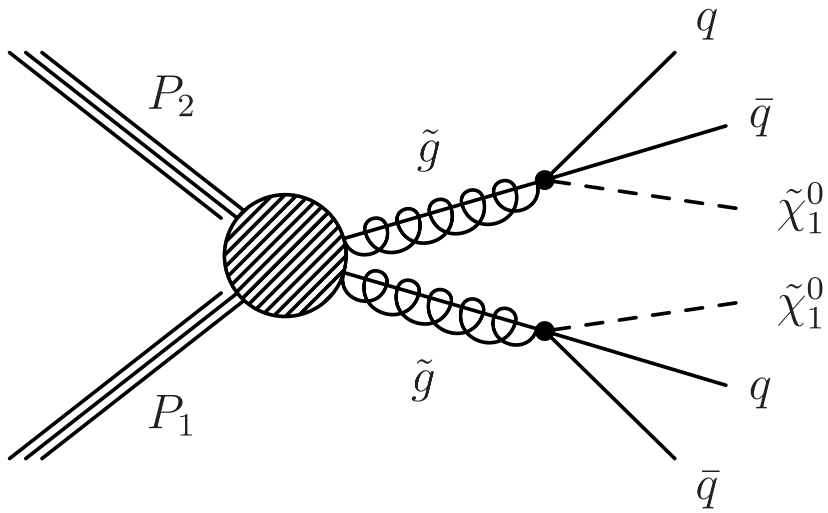


- Exclude up to a maximum of m_{gluino} ~1550 GeV and m_{LSP} ~950 GeV

Interpretation - T1qqqq







- Exclude up to a maximum of m_{gluino} ~1350 GeV and m_{LSP} ~800 GeV

Conclusions

- Inclusive and robust α_T search provides good sensitivity to a range of SUSY models
- Sensitivity optimised through binning in $H_T/n_j/n_b$ and the MH_T dimension
- Limits extend reach beyond 8TeV
- With additional data (~O(10)/fb) coming this year primed for discovery of natural SUSY

Backup

Transfer factor systematics

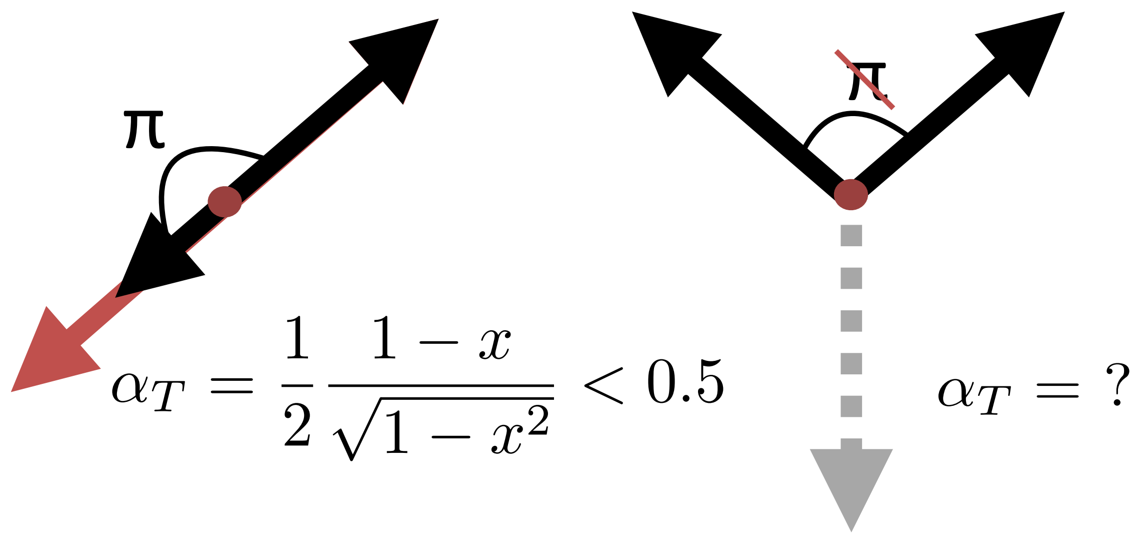
- Systematics from known experimental / theoretical uncertainties
  - Consider variations for: JEC, lepton ID/ISO/Trigger, PU weight, top pT reweighting, B-tag SF, signal trigger
  - Use ±1 σ variations of known effects to define correlation and magnitude of systematics on transfer factors and encode in likelihood
- Data driven systematics from 'closure tests'
  - Derive systematic per H_T / jet topology **per effect**
  - Systematic applied on relevant transfer factor(s) from control to signal region in likelihood

summary in backup

The α_T variable

$$\alpha_T = \frac{1}{2}\frac{1-(\Delta H_T/H_T)}{\sqrt{1-(\not{H}_T/H_T)^2}}$$

- Mis-measured jets from QCD events cause ‘fake’ MH_T
  - Very high cross section means dominant background source
- α_T is designed to reduce this ‘fake’ MH_T to sub-percent level



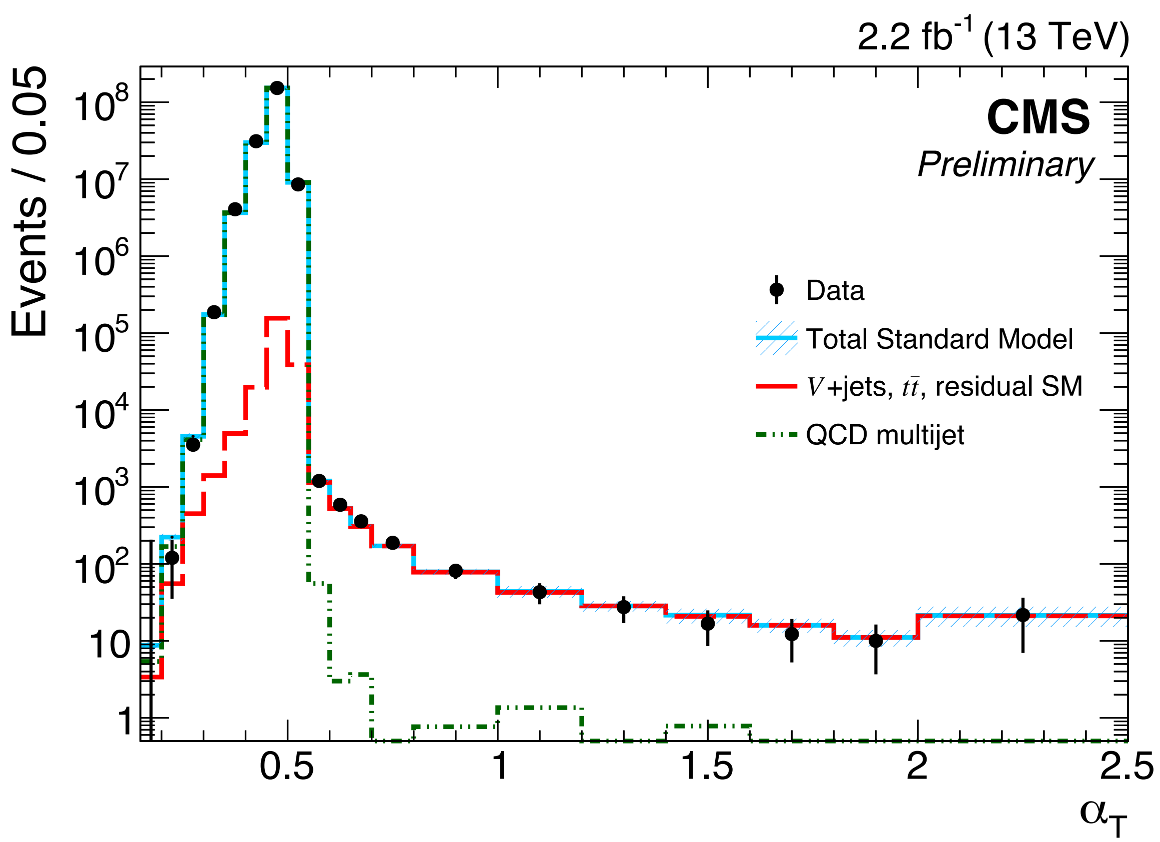
Scale independent!

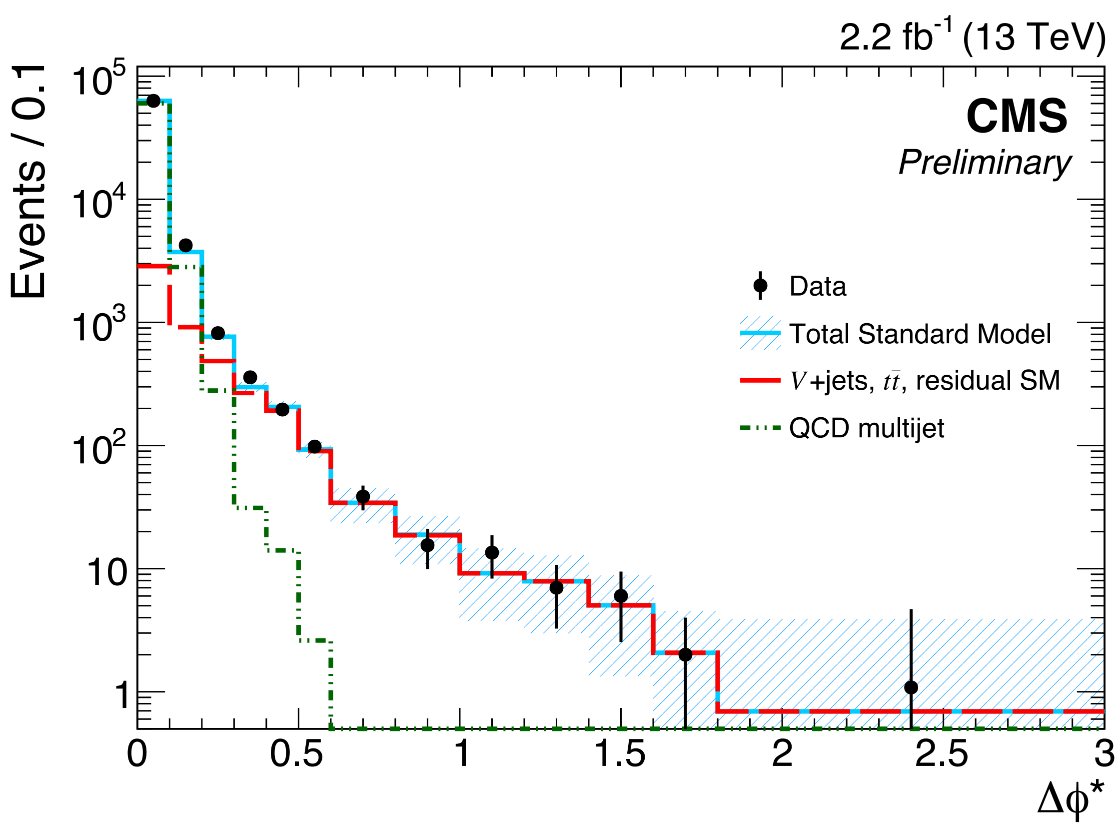
- Back to back jets must have $\alpha_T < 0.5$ but unconstrained for true MH_T
  - Balanced (no MH_T) events have $\alpha_T = 0.5$
- For N-jets define pseudo dijet system as one which minimises energy difference between the jets (ΔH_T) - aggressively kills QCD

Key variables - α_T and $\Delta\phi^*$

$$\alpha_T = \frac{1}{2} \times \frac{H_T - \Delta H_T}{\sqrt{{H_T}^2 - {\not{H}_T}^2}}$$

- Effective in rejecting QCD multijet events (and keeping low trigger thresholds)
  - Back-to-back events ⇒ $\alpha_T = 0.5$
  - "mismeasured" balanced events ⇒ $\alpha_T < 0.5$
  - genuine MET events ⇒ $\alpha_T > 0.5$





$\Delta\phi^*$

- Minimum $\Delta\phi$ between jet and the MH_T vector computed without that jet ("biased MH_T")
- Compute minimum $\Delta\phi^*$ with ALL jets in the event - very robust even against even severe under/over measurement (but at the expense of signal)
- Mis-reconstructed jets and jets with significant neutrino component peak at low min $\Delta\phi^*$

Full selections in backup

Baseline Selection

Selection

- $n_{jet} \geq 1$
  - $p_{T,j1} > 100$ GeV, $|\eta_{j1}| < 2.5$
  - $p_{T,j2} > 40$ GeV, $|\eta_{j2}| < 3$
- $H_T > 200$ (bins up to 800-Inf) GeV
- MHT > 130 GeV
- Forward jet veto
  - $p_{T,j} > 40$ GeV, $|\eta_j| > 3$ (regardless of ID)
- Isolated track veto
  - $p_{T,t} > 10$ GeV, $|\eta_t| < 2.5$
- MHT/MET < 1.25
- Recommended MET filters

Categorisation

Based on 2nd jet

- **Symmetric**
  - $p_{T,j2} > 100$ GeV
- **Monojet** **NEW**
  - $p_{T,j2} < 40$ GeV
- **Asymmetric** **NEW**
  - $40 < p_{T,j2} < 100$ GeV
- Compressed SUSY and Generic DM
  ⇒ Monojet + Asymmetric
- Un-compressed SUSY
  ⇒ Symmetric

Selection - Single Lepton

- Single Electron + Single Muon control region selections
- Baseline selection +
  - Exactly one muon/electron with $p_T > 30$ GeV, $|\eta| < 2.1$ (1.479 for electron)
  - Relative isolation requirement
  - 30 GeV < $M_T(\mu/e, ME_T)$ < 125 GeV
  - dR(lepton,jet) > 0.5
  - Muon/electron ignored when computing ME_T, MH_T, α_T

Selection - Double Lepton

- Double Electron + Double Muon control region selections
- Baseline selection +
  - exactly two muon/electrons with pT > 30 GeV, $|\eta| < 2.1$ (1.479 for electron) and opposite charge
  - relative isolation requirement
  - $|M_{ll} – M_Z| < 25$ GeV
  - dR(lepton,jet) > 0.5
  - Muons/electrons ignored when computing ME_T, MH_T, α_T

Selection - Single Photon

- Single Photon control region selections
- Baseline selection +
  - Exactly one photon with p_T > 200 GeV, $|\eta| < 1.479$
  - Relative isolation requirement
  - dR(photon,jet) > 0.5
  - Photon ignored when computing ME_T, MH_T, α_T

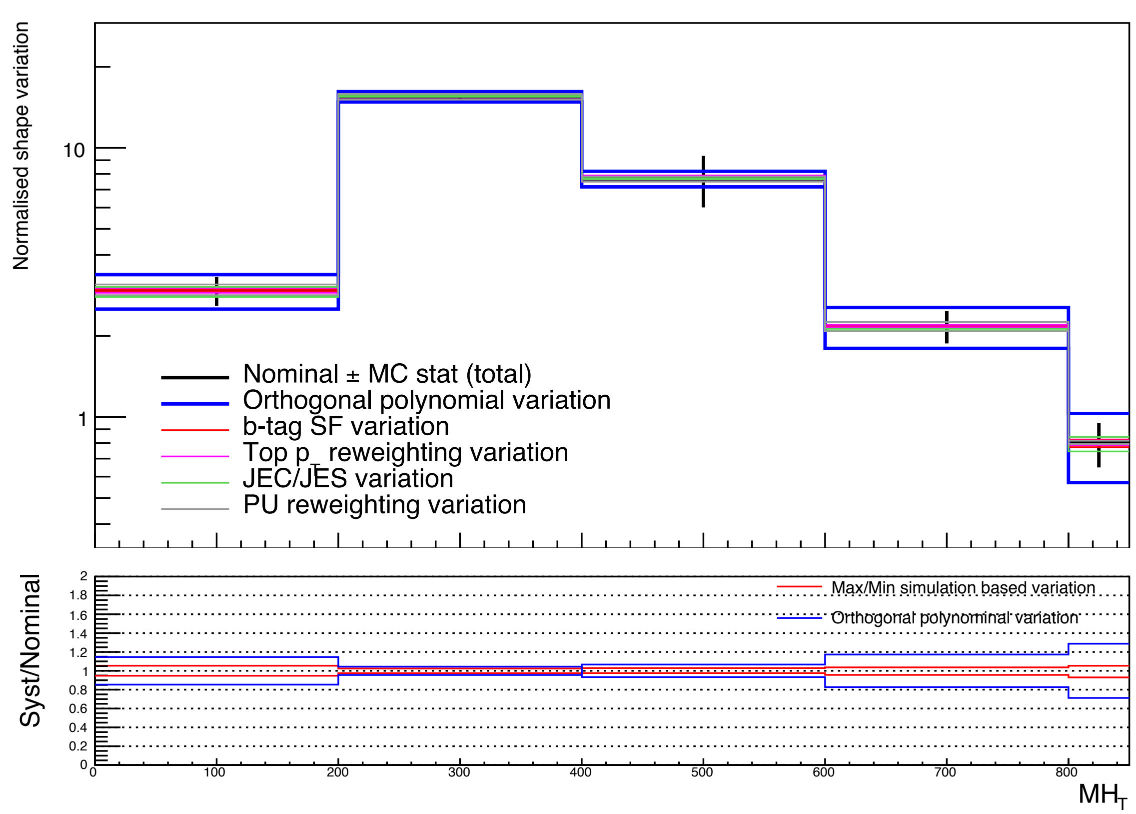
Signal

- Baseline selection +
- Signal selection
    - MHT/MET < 1.25
    - $\Delta\phi^* > 0.5$
    - HT-dependent αT cut (see next slide) for HT < 800 GeV
    - MHT > 130 GeV for HT > 800 GeV

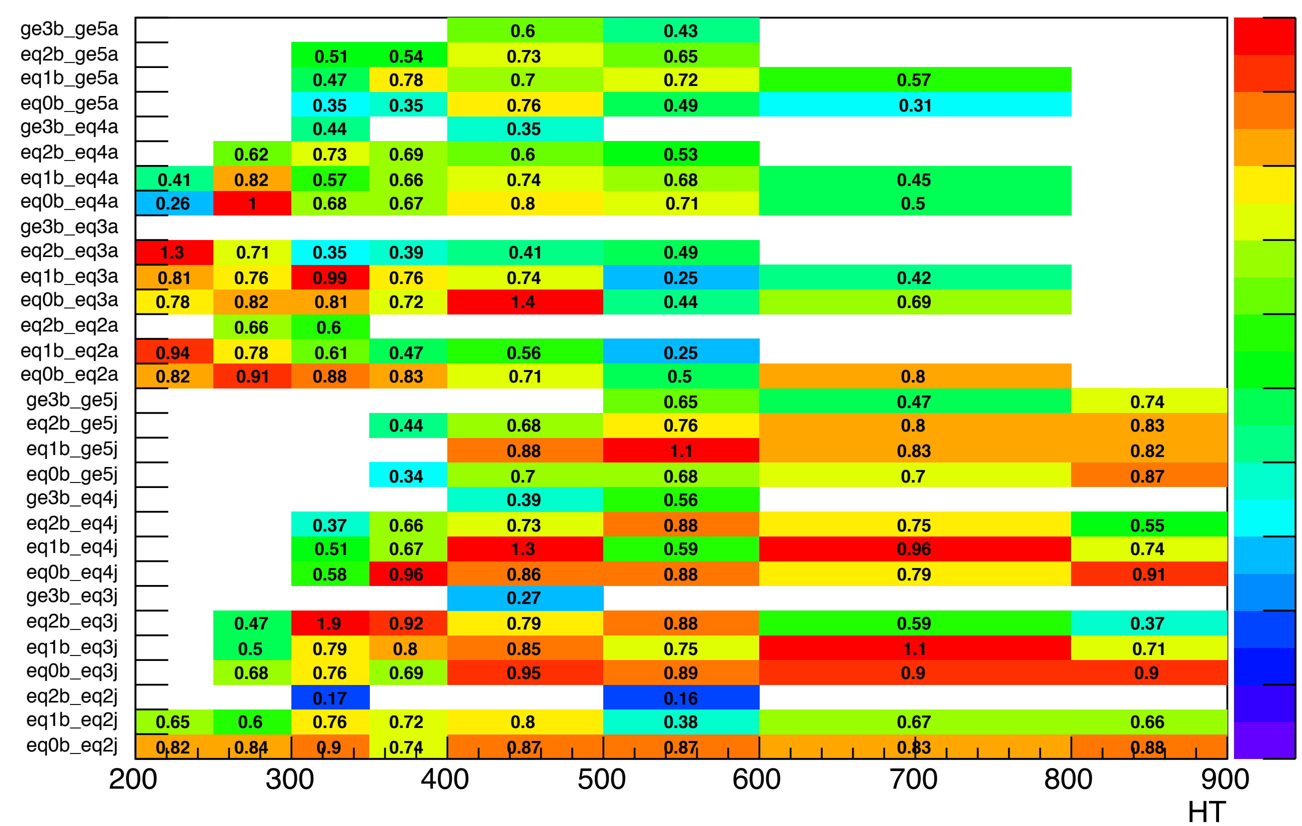
MH$_T$ dimension systematic (MC comparison)

- Compare data-driven MH$_T$ dimension systematic for one category and across whole plane
    - Normalise MH$_T$ distribution and compare MC based variations to data driven systematic
- MC based variations are **subdominant** compared to data driven (orthogonal polynlomial) systematic

eq1b, ge5j



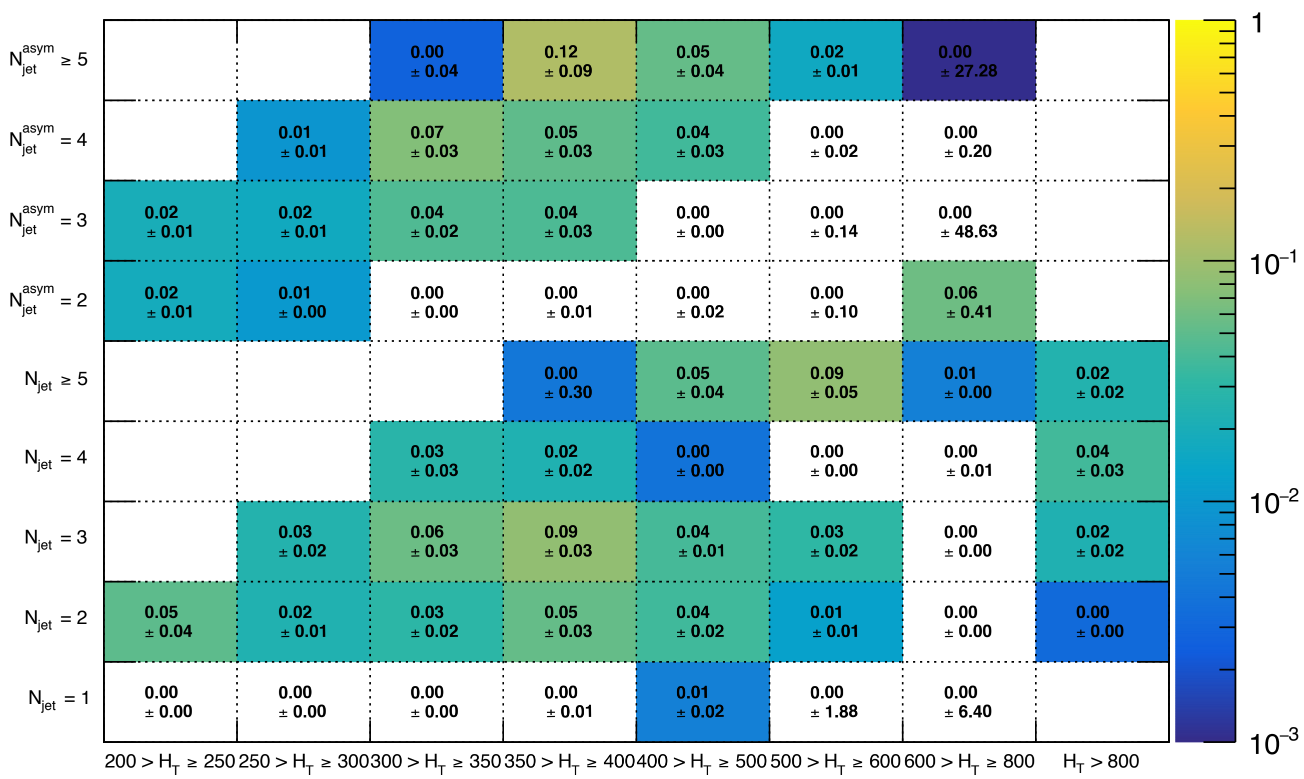
Last MH$_T$ bin max MC variation/ortho. poly



QCD Prediction

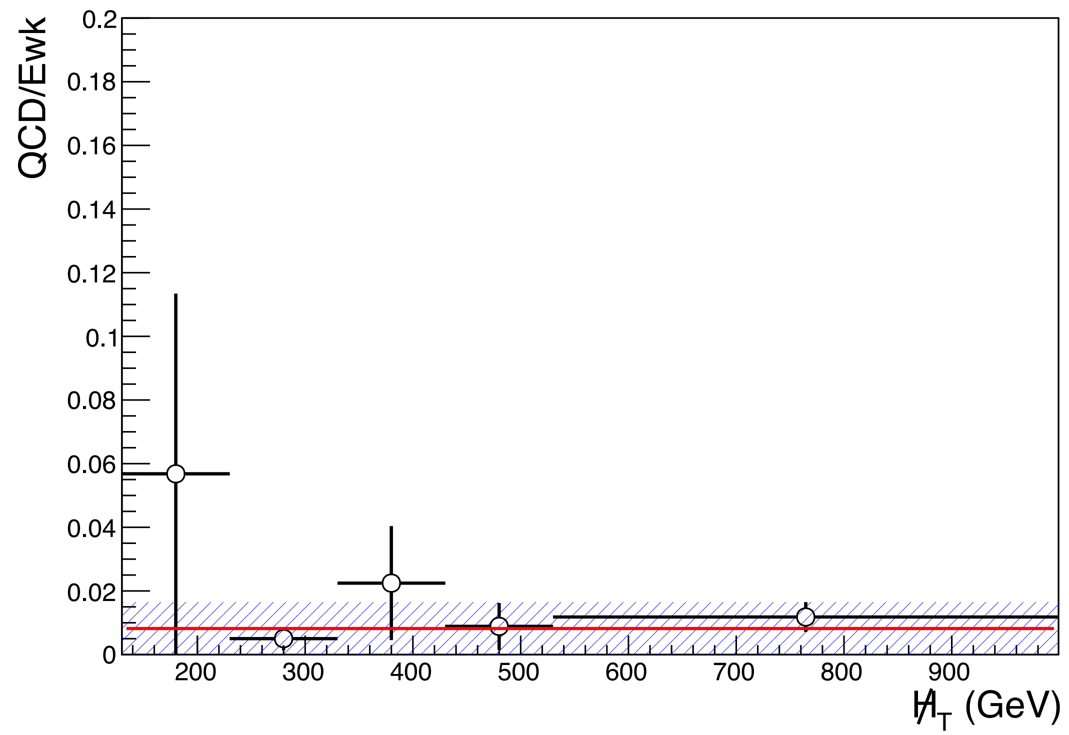
- The residual QCD contamination is measured and included in likelihood
- Extrapolate yields in n_{jet},H_T bins from $MH_T/ME_T > 1.25$ data sideband using ratio taken from MC.
- MC ratio validated with data control regions (see backup)
- MC studies demonstrate no enrichment of QCD w.r.t non-QCD vs MHT nor Nb, within assumed uncertainties (statistical up to ~100%, systematic 100%)

QCD/Ewk relative contamination

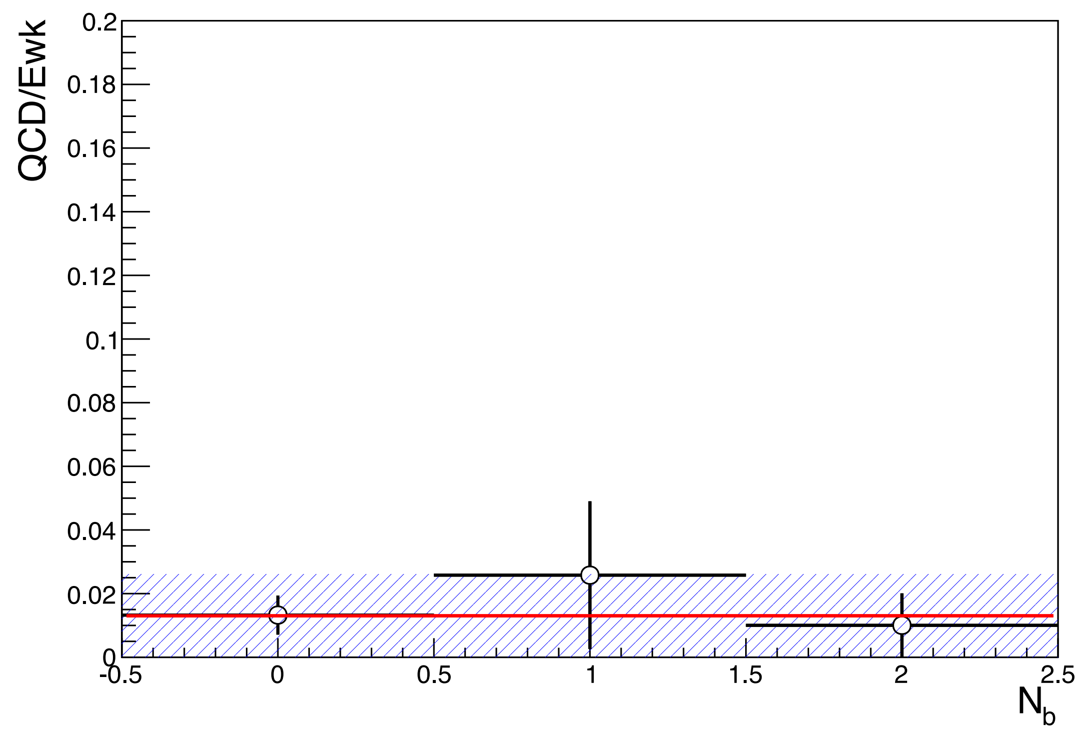


QCD/Ewk relative contamination at percent level

QCD Validation e.g. HT > 800



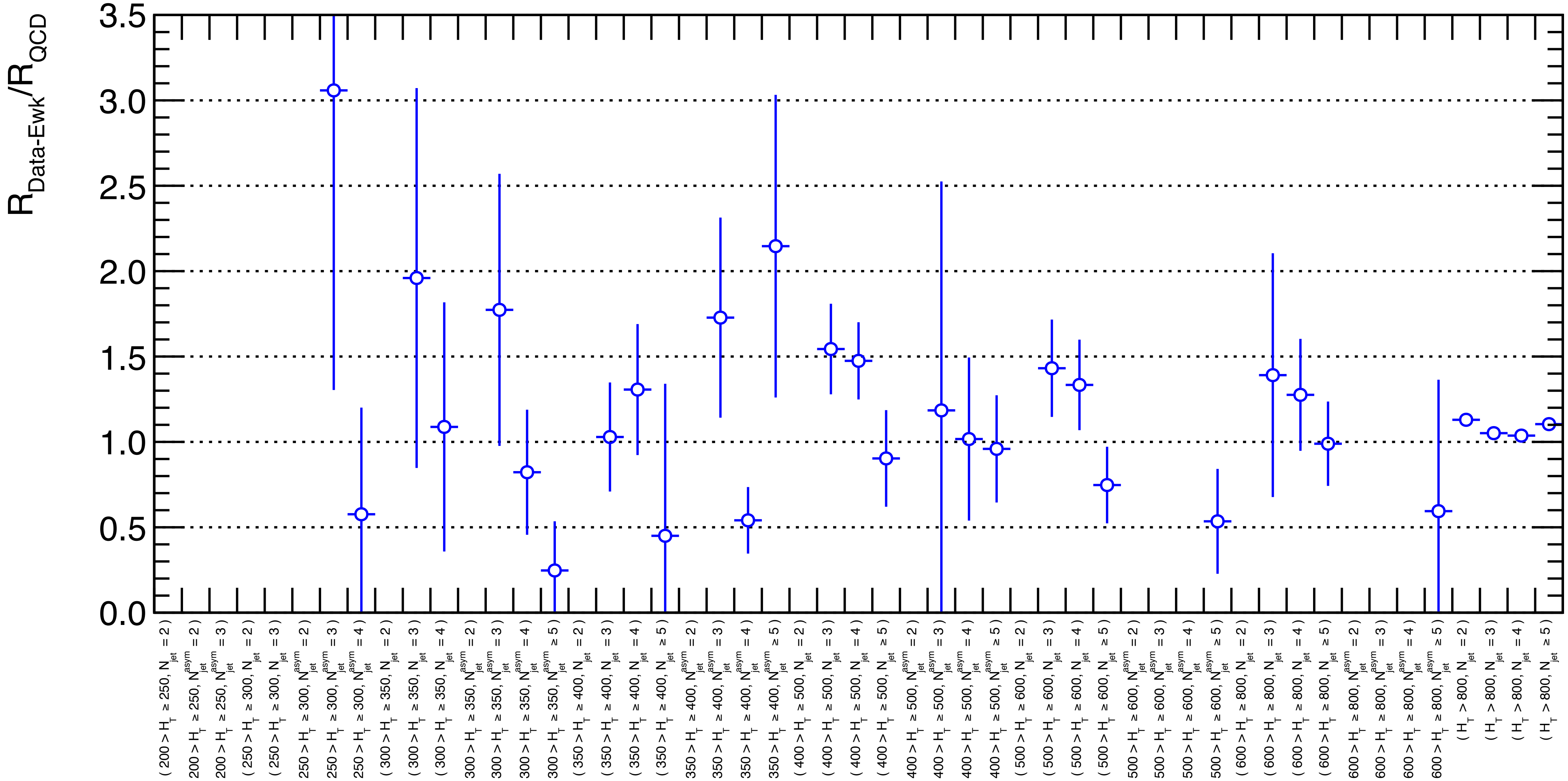
QCD relative contamination is flat in MH_T (within uncertainties)



QCD relative contamination is flat in nB (within uncertainties)

M. Citron mc3909@ic.ac.uk

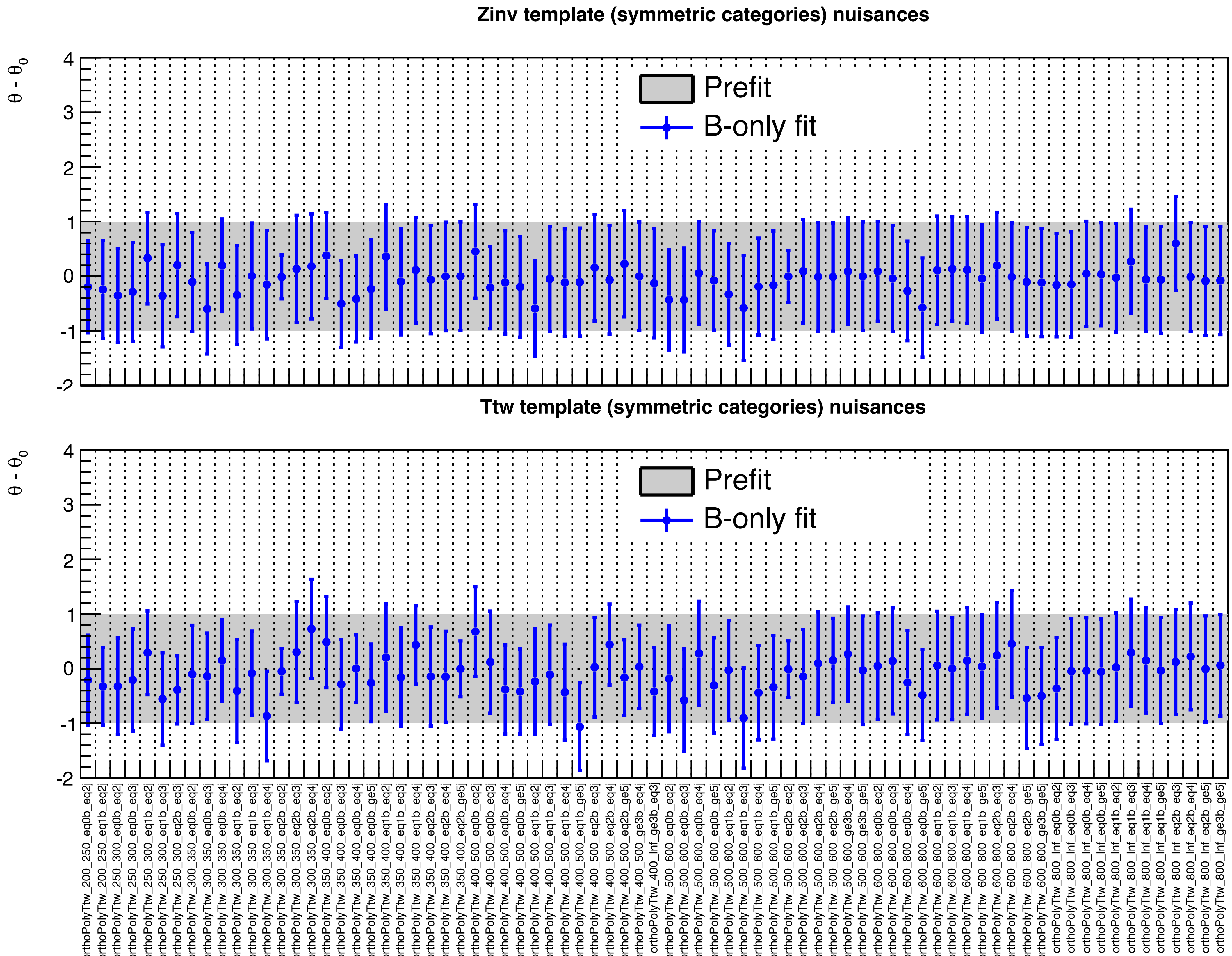
QCD Ratio validation in data sideband



Ratio of pass/fail ratio of MHT/MET < 1.25 cut measured in data and MC in Δϕ* sideband

M. Citron mc3909@ic.ac.uk

Template nuisances post-fit not significantly pulled/ constrained



High nJet/nB predictions for HT 600-800 and HT > 800

		HT 600-800	HT >800
nJet = 4, nB = 2	Data	7	2
	SM	3.6 ± 0.8	3.4 ± 1.1
	Ttw	2.2 ± 0.6	1.6 ± 0.6
	Zinv	1.4 ± 0.3	1.7 ± 0.6
	QCD	0.0 ± 0.0	0.1 ± 0.1
nJet = 4, nB >= 3	Data	0	0
	SM	0.1 ± 0.0	0.1 ± 0.0
	Ttw	0.0 ± 0.0	0.1 ± 0.0
	Zinv	0.0 ± 0.0	0.0 ± 0.0
	QCD	0.0 ± 0.0	0.0 ± 0.0
nJet >= 5, nB = 2	Data	10	16
	SM	10.9 ± 2.9	7.2 ± 2.2
	Ttw	8.9 ± 2.7	5.3 ± 1.8
	Zinv	1.9 ± 0.4	1.7 ± 0.5
	QCD	0.1 ± 0.1	0.2 ± 0.2
nJet >= 5, nB >= 3	Data	1	3
	SM	1.5 ± 0.4	0.9 ± 0.3
	Ttw	1.1 ± 0.4	0.6 ± 0.3
	Zinv	0.3 ± 0.1	0.2 ± 0.1
	QCD	0.0 ± 0.0	0.0 ± 0.0

In region around bins with excess the data agrees well with prediction

Signal systematics

The following sources of uncertainties are considered (following SUS PAG recommendations)

Systematic	Benchmark model			
	T1bbbb		T1qqqq	
	compressed	uncompressed	compressed	uncompressed
Luminosity	4.6%	4.6%	4.6%	4.6%
Trigger	0-15%	3-5%	0-15%	3-5%
MC statistics	0-50%	0-50%	0-50%	0-50%
PU reweighting	1-5%	1-5%	1-5%	1-5%
B-tag efficiency	0-10%	0-20%	0-10%	0-10%
Lepton efficiency	10%	10%	10%	10%
Jet energy scale	5-20%	0-10%	5-20%	0-10%
Initial state radiation	0-15%	1-2%	0-15%	1-2%

Data driven systematics

$$\delta TF_i = \sqrt{r_i^2 + \delta r_i^2},\ r_i = (N_i^{obs} - N_i^{pred})/N_i^{pred} \qquad [1]$$

- Each source of systematic considered separately
- Look at closure (r_i) in using one sample to predict another within the control regions - e.g. $\alpha_T < \alpha^{cut}_T$ -> $\alpha_T > \alpha^{cut}_T$ (see next slide)
  - Inspect trend of r_i vs H_T (integrated in n_b) per n_{jet} and inclusively in topology
  - In absence of bias, collapse n_{jet} dimension and calculate systematic per H_T for symmetric and asymmetric topologies (Eq. [1])
  - For tests involving μμ+jets pairs of H_T bins merged to gain statistics
- Systematic is correlated in n_{jet}/n_b, decorrelated in H_T and jet topology

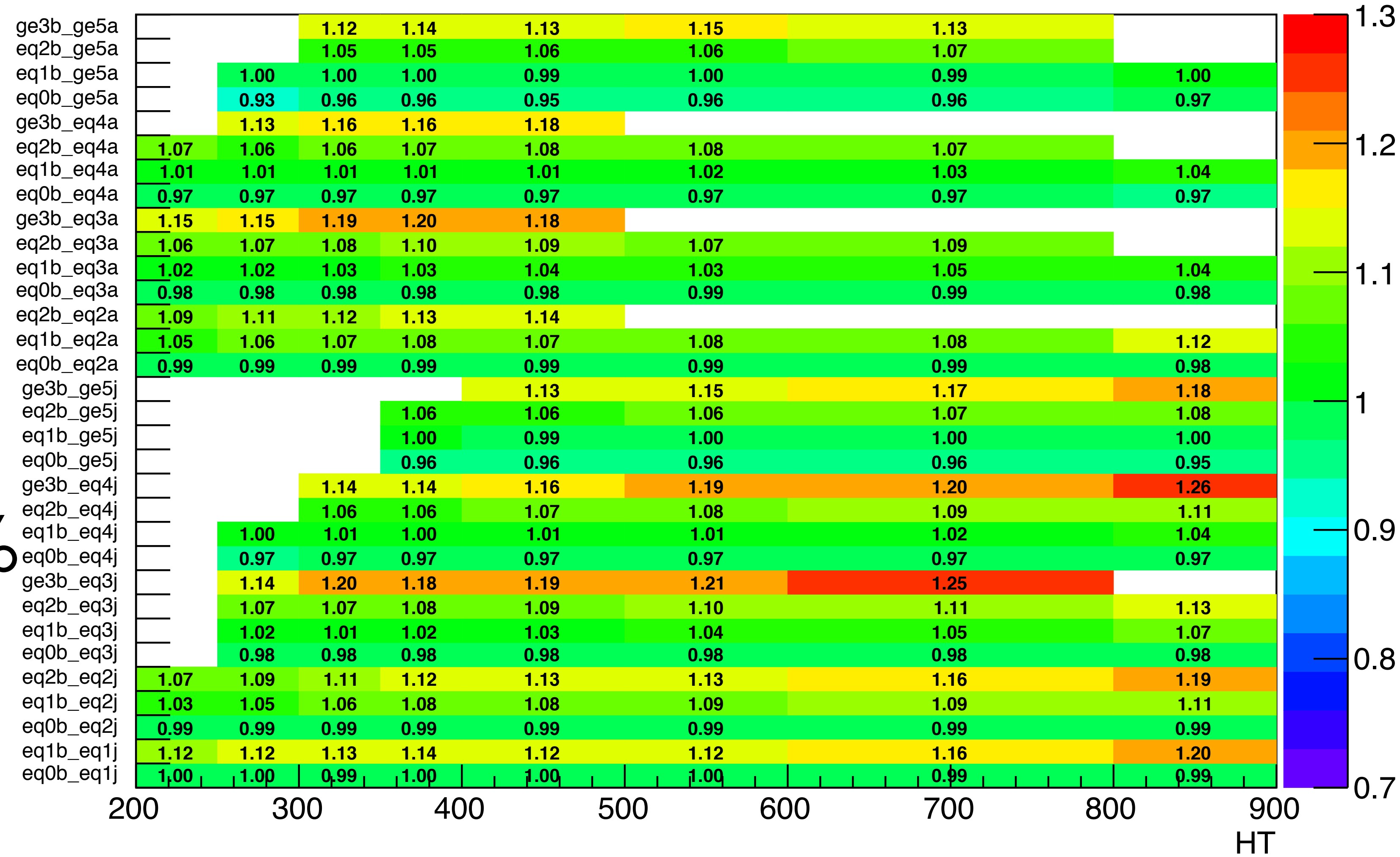
Example TF variation (B-tag weight)

- Eg. Change in μ -> tt+W TF under variation of btag SF weight
- Effect on **all** transfer factors encoded in likelihood for each systematic variation

Btag variation up

Systematic size ~5-30%

TF = $MC_{signal}/MC_{control}$



Likelihood model - MH_T

j = MH_T bin

i = HT/njet/nb bin

observation **background yield** **signal yield**

$$L^i_{had} = \prod_j Pois(n^{ji}|\rho^j b^{ji} + \mu \prod_n \eta^{jin}_{had} s^{ji})$$

MH_T shape nuisance **signal strength** **signal nuisances**

- For $H_T/n_j/n_b$ bin there is an uncorrelated nuisance on the MH_T distribution for the background
- Signal nuisances affect the signal shape in all binning dimensions
- Shape variations implemented by providing alternative templates for ±1 σ variations (interpolation by 'vertical morphing')*
- In full likelihood have term per dominant background + QCD

*CERN-2011-006

Likelihood model - $H_T/n_j/n_b$

j = MH_T bin

i = HT/njet/nb bin

observation — background in signal region — transfer factor — signal yield

$$B^i \equiv \sum_j b^{ij}$$

$$TF^i \equiv \frac{N_{MC}^{had}(n_{jet}, n_b, H_T)}{N_{MC}^{control}(n_{jet}, n_b, H_T)}$$

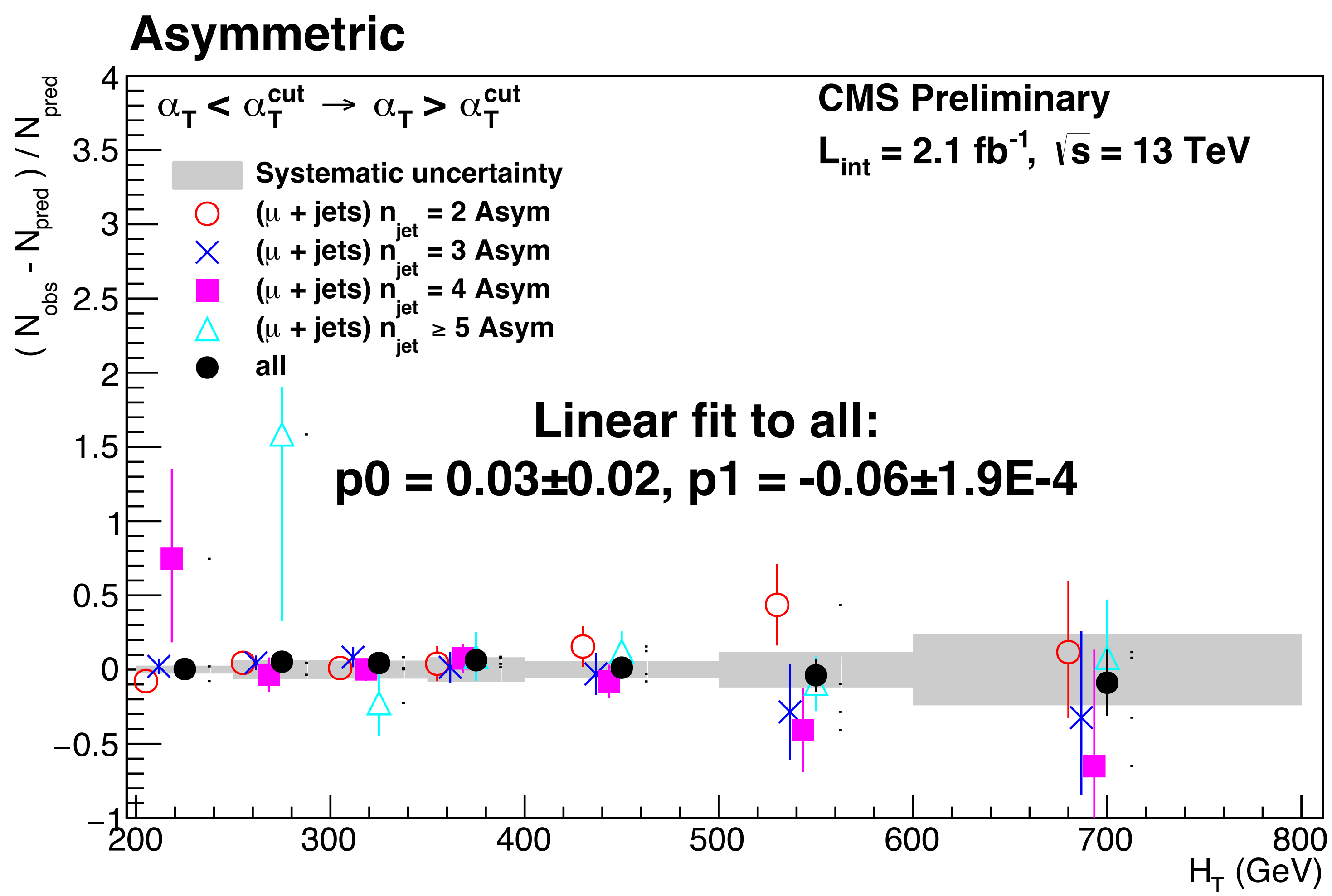
$$L^i_{control} = Pois(n^i_{control} | \prod_m \rho^{im}_{TF} B^i / TF^i + \mu \eta^i_{control} s^i_{control})$$

TF nuisances — signal strength — signal nuisances

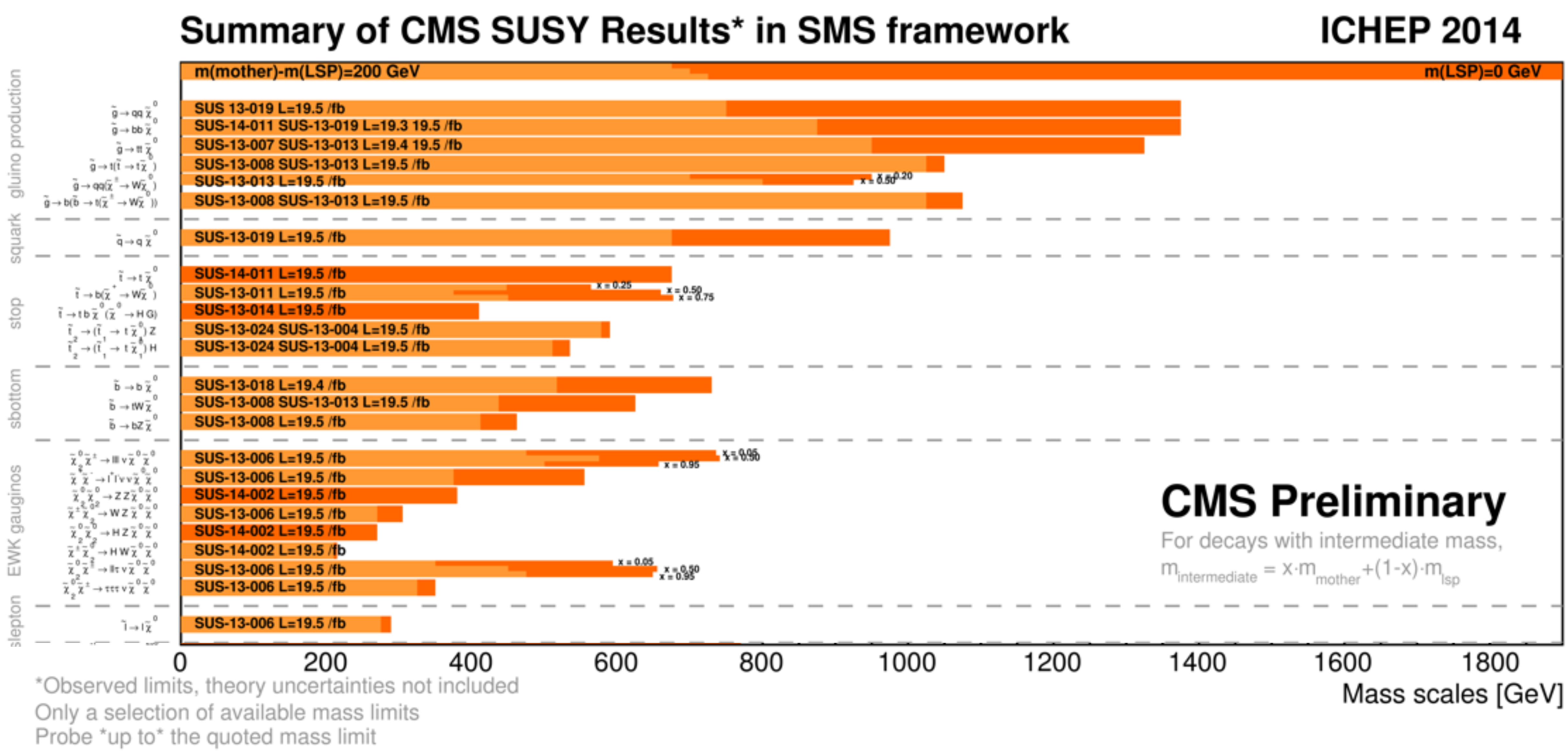
- Control yields connected to signal region yields via transfer factors
- Have correlated and uncorrelated nuisances on TF between signal and control regions per $H_T/n_j/n_b$ bin
- Account for signal contamination in control region

Example closure test - $\alpha_T/\Delta\phi^*$ extrapolation

- This test probes the prediction from muon CRs with no $\alpha_T/\Delta\phi^*$ cut to SR containing this cut
- Use μ + jets for this test due to highest statistics
- Systematics (grey bands) taken **per H_T** based on difference in prediction and observation for symmetric and asymmetric topologies separately
- All closure tests fully documented in AN



Run 1 legacy


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-013 L=19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-019 L=19.5 /fb
SUS-14-011 L=19.5 /fb
SUS-13-011 L=19.5 /fb
SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
gluino production
squark
stop
sbottom
EWK gauginos
slepton
x = 0.25
x = 0.05
x = 0.95
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother + (1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit