Search for New Physics in All-hadronic Events with AlphaT in 8 TeV Data with CMS

Y. Eshaq

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Outline

- The Standard Model (SM), Supersymmetry (SUSY)

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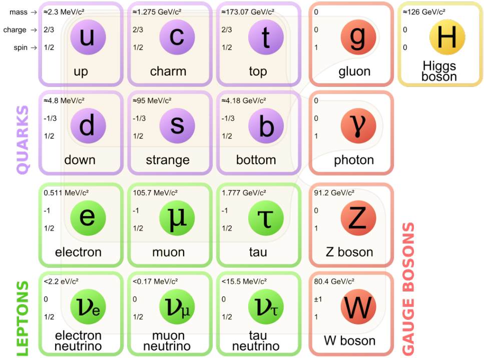
- Results

The Standard Model

- Very succesful model:
  - Predicts all known particles and interaction
  - Muon Anomalous Magnetic Moment
  - Z Boson → cross section, branching fraction
- The Standard Model doesn't explain everything



Shortcomings of the SM

- Dark Matter: 96% of matter remains unexplained
- Gravity: The SM becomes invalid above $M_{plank} > 10^{19}\ GeV$ where gravity can't be ignored
- Massless Neurinos
- Does not allow for unification of forces
- Divergent corrections to the Higgs mass - "Hiearchy problem"

$$\underbrace{\mathrm{m}^2_{\mathrm{physical}}}_{\text{what we measure}} = \underbrace{\mathrm{m}^2_{\mathrm{h}}}_{\text{tree level}} + \underbrace{\frac{3\lambda}{8\pi}\Lambda^2}_{\text{1-loop}} - \underbrace{\frac{3\lambda}{8\pi}\mathrm{m}^2_{\mathrm{h}}\log\left(\frac{\Lambda^2 + \mathrm{m}^2_{\mathrm{h}}}{\mathrm{m}^2_{\mathrm{h}}}\right)}_{\text{much smaller than}\Lambda^2}$$

Any extension of th SM should attempt to solve these shortcomings...

Supersymmetry

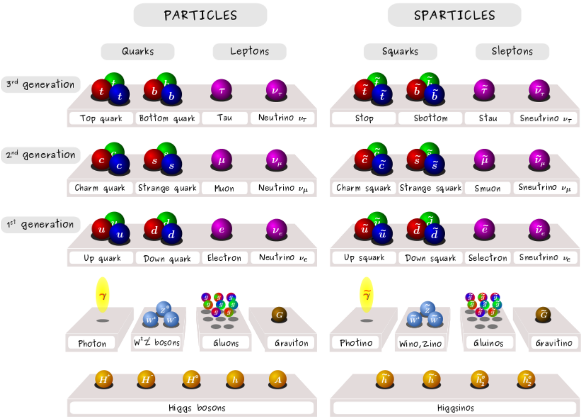
A proposed symmetry of spin

spin 1/2

spin 0

spin 1

spin 1/2



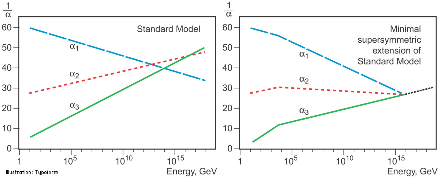
$$\text{Higgsino} \Longleftrightarrow \text{Bino/Wino} = 4 \text{ Neutralino } (\tilde{\chi}^0_{1-4})$$

$$\text{Higgsino} \Longleftrightarrow \text{Wino} = 2 \text{ Charginos } (\tilde{\chi}^+_{1-2})$$

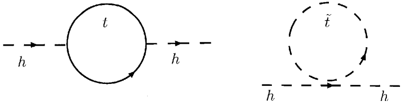
Supersymmetry

Supersymmetry is theoretically well motivated:

- It provides a solution to the hierarchy problem
- Unifies the gauge couplings
- Provides a candidate for Dark Matter

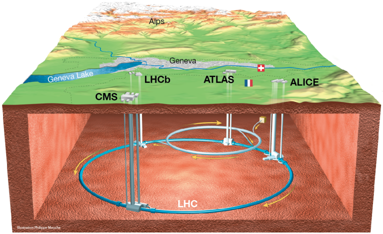


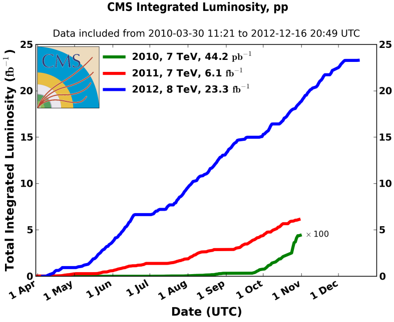
- Provides additional loop corrections ot the Higgs mass which cancel the qudratic divergence!

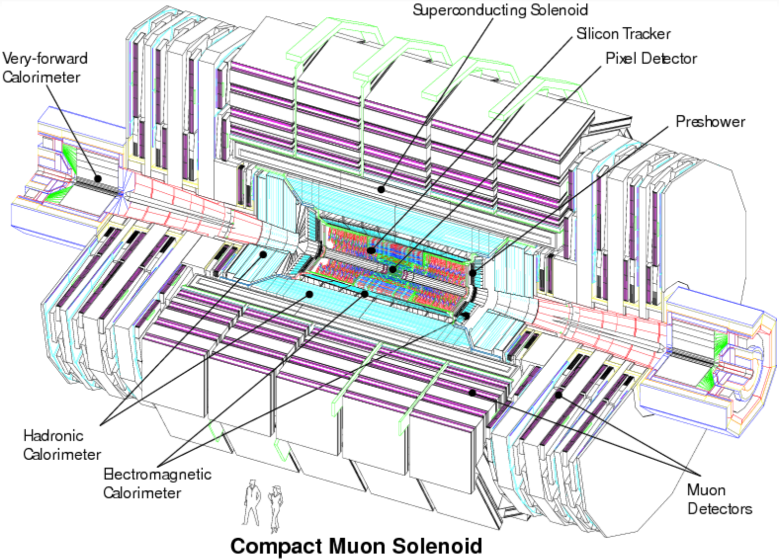


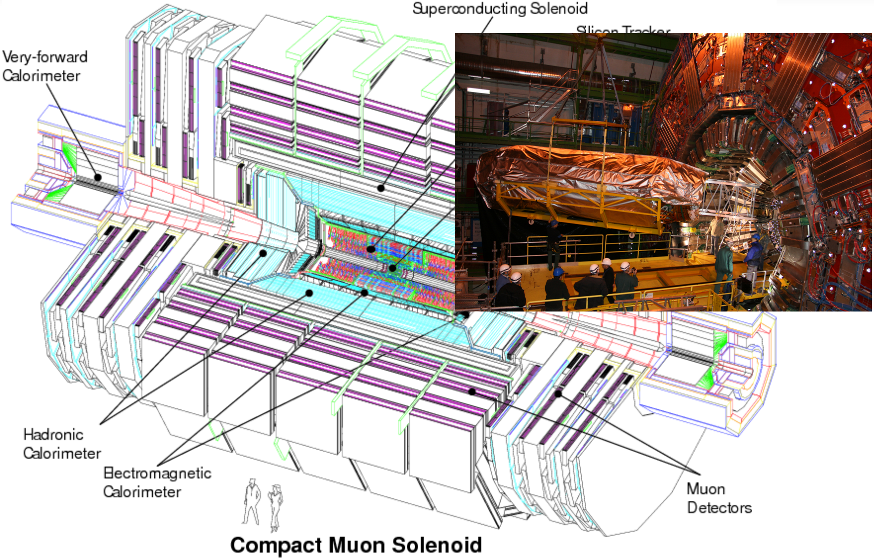
The Large Hadron Collider

- proton-proton (pp) collider housed 100m underground in a 27km circular tunnel
- 2808 “bunches” of protons measuring 16 μm transversely and $\sim$ 30 cm long orbit 7 m apart
- 10^{11} protons per bunch lead to around 20 collsions per beam crossing.






Superconducting Solenoid
Silicon Tracker
Pixel Detector
Very-forward Calorimeter
Preshower
Hadronic Calorimeter
Electromagnetic Calorimeter
Muon Detectors
Compact Muon Solenoid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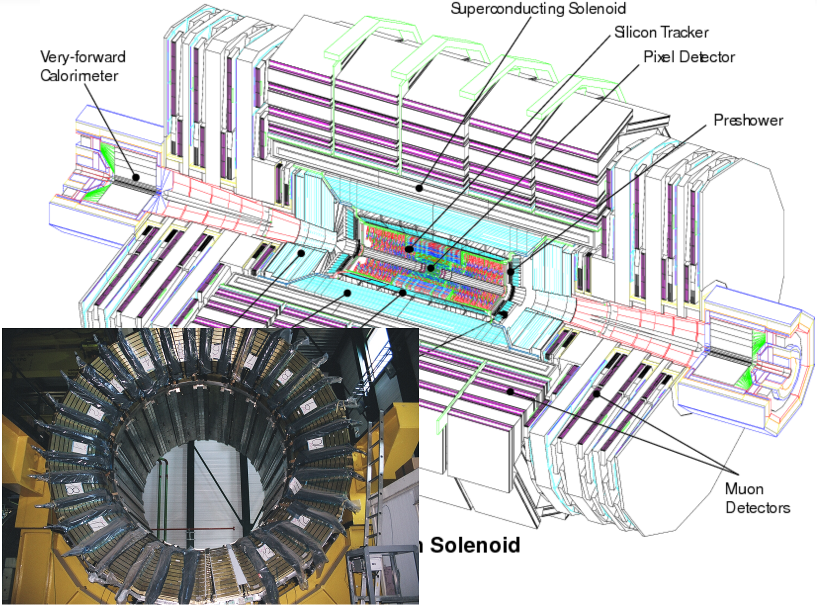
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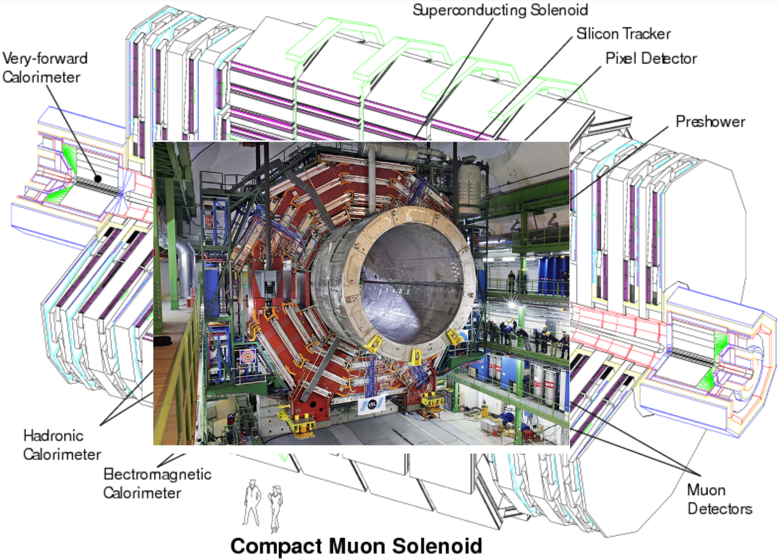
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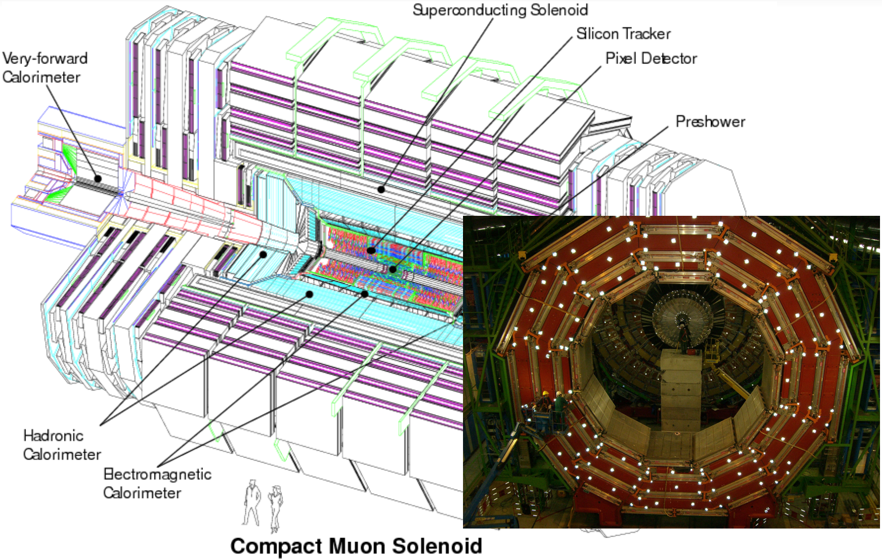
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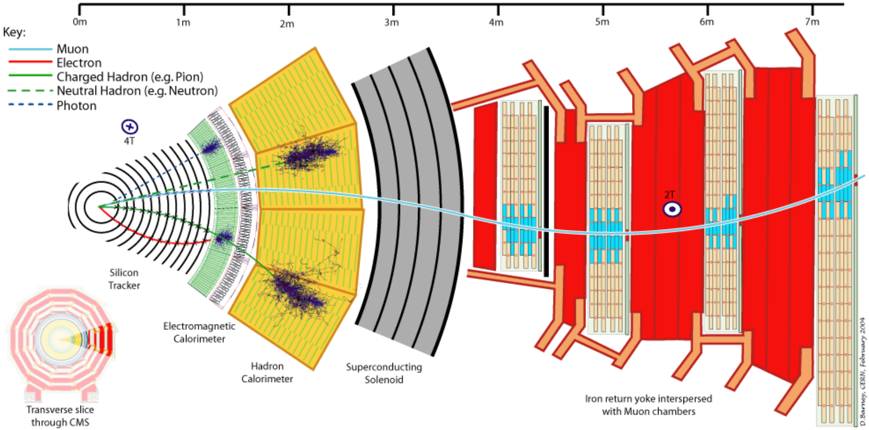
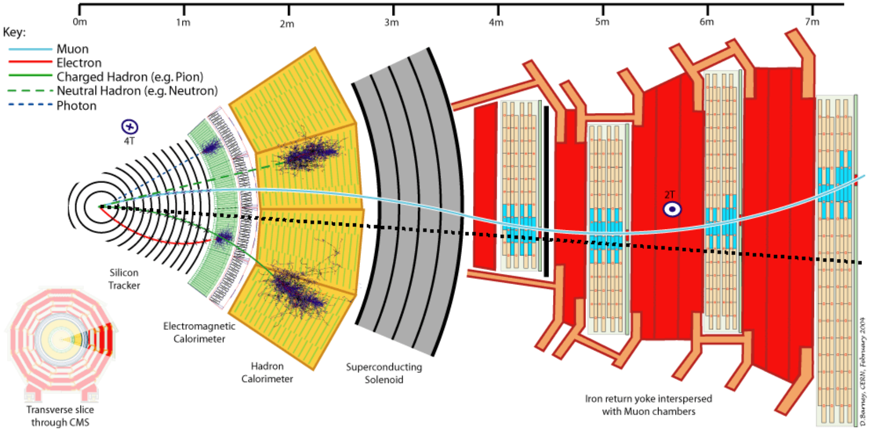
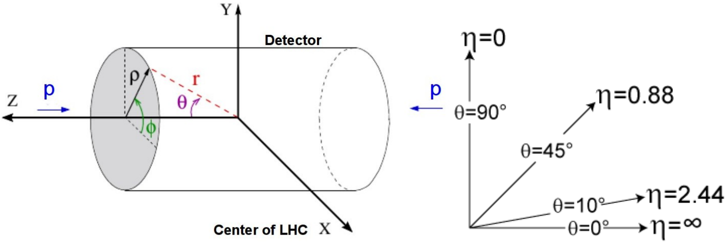
A Slice of CMS



A Slice of CMS



The Coordinate System



- Azymuthal (ϕ): 2π angle around beam line
- polar (θ): $0 \leq \theta \leq \pi$ from the beam-line

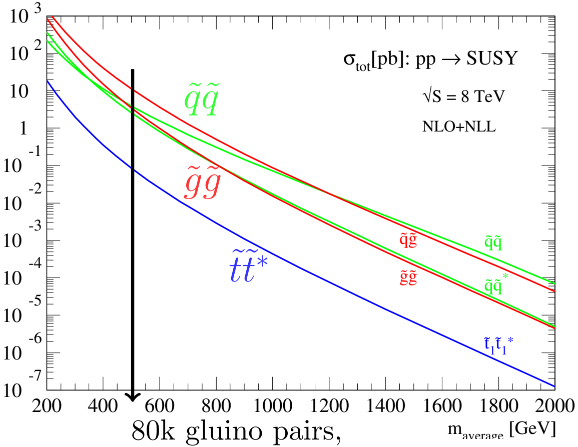
Known and conserved quantities:

- transverse momentum, $p_{\mathrm{T}} \equiv P \sin\theta$
- transverse energy, $E_T \equiv E \sin\theta$
- pseudo-rapidity:

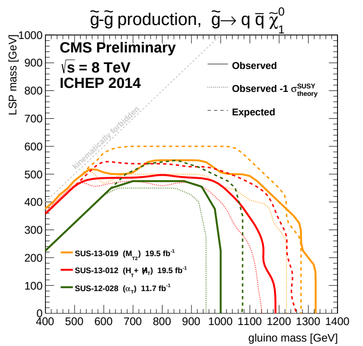
$$\eta \equiv \ln\left(\tan\left(\theta/2\right)\right)$$

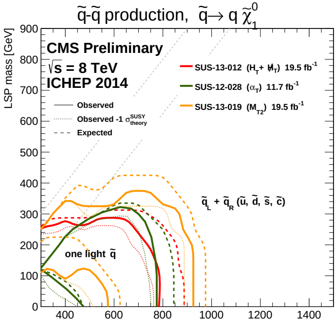
Search Stategy

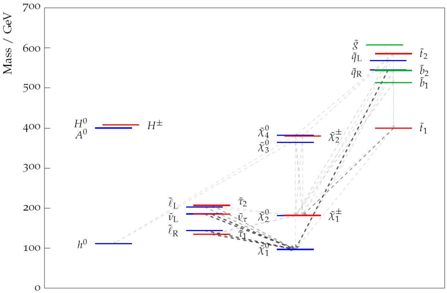
Early searches at LHC focused on high cross section production models $\rightarrow \frac{\sigma(\tilde{g}\tilde{g})}{\sigma(\tilde{t}\tilde{t})} \sim 100$.



80k gluino pairs,
2000 stops in $20fb^{-1}$







current exclusions:

- gluinos masses $< 1.1\ TeV$
- 1^{st}- and 2^{nd}-gen. squarks masses$<\ 800\ $ GeV

One expects relatively light top, $< 1\ TeV$, if SUSY is to be the natural solution to the hierarchy problem

Search Strategy

Conserved quantity, R-parity:

$$R = (-1)^{3B+L+2s}$$

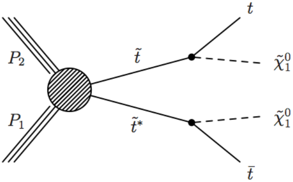
SM: R = +1, SUSY: R = -1.

R-parity conserving SUSY theory implies:

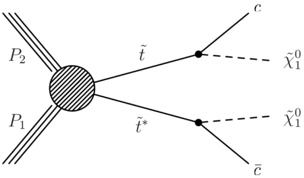
- SUSY particles are pair-produced
- a stable "light" supersymmetric particle (LSP).

In this analysis: LSP is assumed to be the neuralino: $\tilde{\chi}_1^0$

"T2tt"



"T2cc"



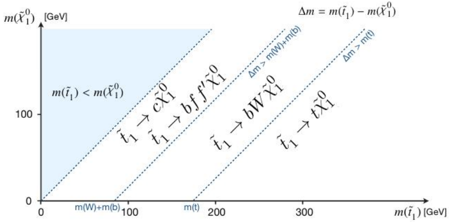
Search strategy

"T2tt": $\tilde{t} \to t\tilde{\chi}_1^0$

- highest reach for $m_{\tilde{t}}$

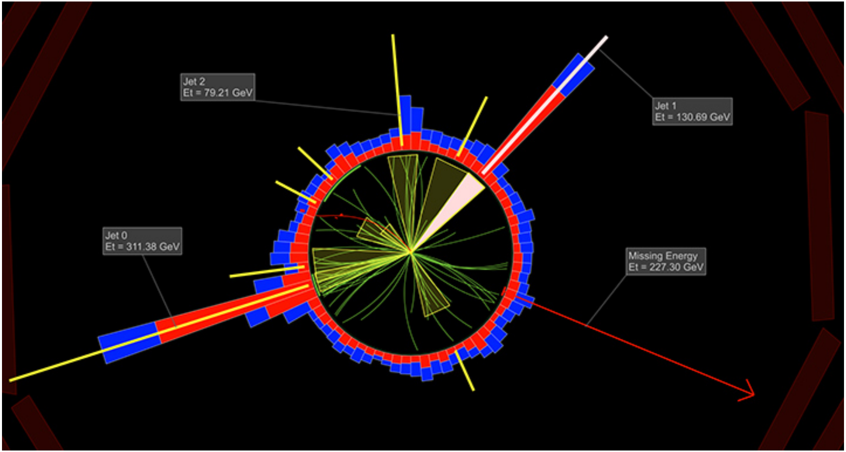
"T2cc": $\tilde{t} \to c\tilde{\chi}_1^0$

- i.e. $\Delta M \equiv m_{\tilde{t}} - m_{\tilde{\chi}_1^0} < 80\ GeV$, (mass of W)
- top squark can only decay to a charm quark and neutralino.
- dependent on initial state radiation



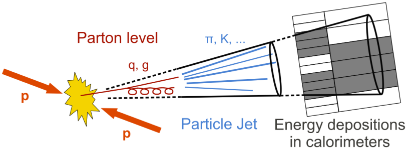
final state: "Jets" + undetected energy

An Event Display



Calorimeter Jets

- “Traditional” jet reconstruction
- Calorimeter towers
  - 1 HCAL cell ~ 0.1 $(\Delta\phi \times \Delta\eta)$
  - 25 ECAL crystals ~ 0.01 $(\Delta\phi \times \Delta\eta)$

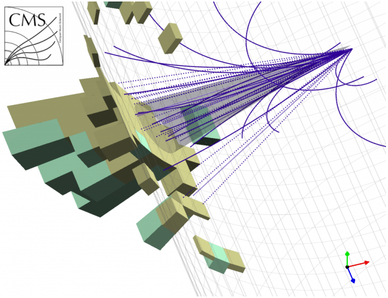


- Does not make use of ECAL granularity
- Jet resolution driven by HCAL:
  - HCAL resolution $\sim 100\%/\sqrt{E}$
  - non-compensating → non-linear response
- Low p_T charged hadrons bent outside jet

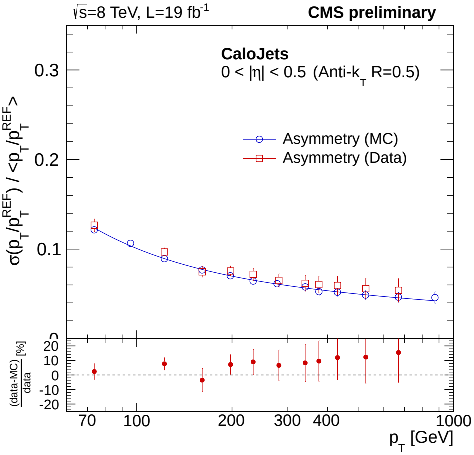
Particle Flow Jets

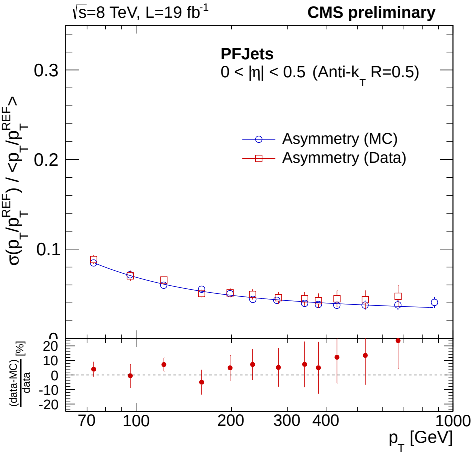
Particle Flow (PF) reconstructs all stable particle in the event: $h^{\pm}$, γ, h^0, e, μ

- On average jets are:
- $\sim$ 65% charged hadrons, $\sim$ 25% photons, $\sim$ 10% neutral hadrons
- Using the silicon tracker (vs. HCAL) to measure charged hadrons
  - Improves resolution, avoids non-linearity
  - Decreases sensitivity to the fragmentation pattern of jets



Jet Resolution





Summary of Signal Characteritics

- Signficant hadronic content:

$$H_{\mathrm{T}} = \sum_j E_{\mathrm{T}}{}^j$$

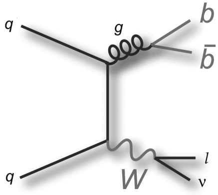
- missing transverse energy:

$$\not{H}_{\mathrm{T}} = \sum_j -\vec{E}_{\mathrm{T}}{}^j, \quad \not{E}_{\mathrm{T}} = \sum_{\texttt{all objects}} -\vec{E}_{\mathrm{T}}{}^j$$

- no leptons

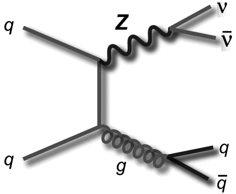
Backgrounds

W + jets; $W \rightarrow l\nu$

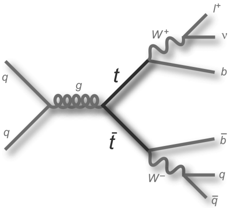


- Largest background: multi-jet (QCD)
- Electroweak backrounds with genuine $\not{E}_T$
  - W + jets
  - $t\bar{t}$ + jets
  - $Z \rightarrow \nu\bar{\nu}$
  - $Z/\gamma^* \rightarrow l^+l^-$, Single Top, WW, ZZ, WZ

Z + jets; $Z \rightarrow \nu\bar{\nu}$



$t\bar{t}$ + jets



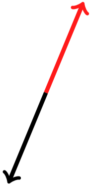
Overview of the Search Strategy

- Seek all-hadronic signature $\rightarrow$ veto isolated e, μ
- Reduce QCD to a negligible level via α_{T}.
- Produce data-driven estimates of remaining SM rates from $Z \rightarrow \nu\bar{\nu}$ or $(t \rightarrow)W \rightarrow l\nu$ using control stamples with jet systems, containing also isoalted μ or γ.
- Two search channels (optimized on expected sensitivity)
  - T2cc: 2–3 jets, 0 b-tags, and ≥ 4 jets, 0, 1 b-tag.
  - T2tt: ≥ 4 jets, 1, 2 b-tag.
  - Look simultaneously in 8 H_{T} bins from 375–1075 GeV.

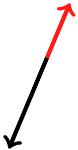
α_{T}

$$\alpha_{\mathrm{T}} = \frac{E_{\mathrm{T}}^{\mathrm{j_2}}}{M_{\mathrm{T}}} = \frac{1}{2} \times \frac{1 - (\Delta H_{\mathrm{T}}/H_{\mathrm{T}})}{\sqrt{1 - (\not{H}_{\mathrm{T}}/H_{\mathrm{T}})^2}}$$

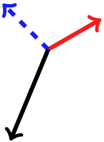
Mulit-jet (QCD)	Mis-measured Mulit-jet (QCD)	Genuine $\not{E}_{\mathrm{T}}$



$\alpha_{\mathrm{T}} = \frac{1}{2}$

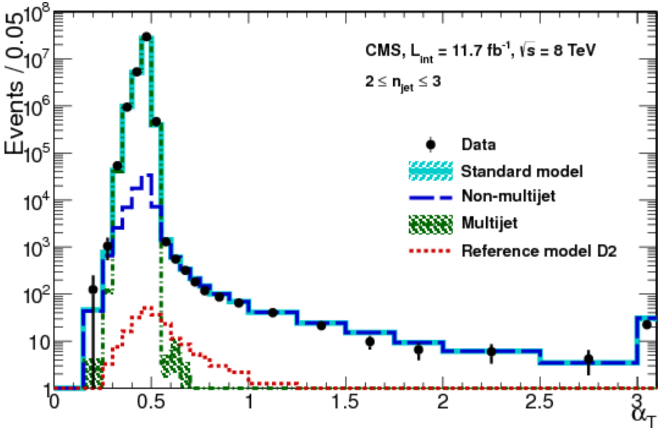


$\alpha_{\mathrm{T}} < \frac{1}{2}$



$\alpha_{\mathrm{T}} > \frac{1}{2}$

$$2 \leq n_{\text{jet}} \leq 3$$



Event Selection

Hadronic:

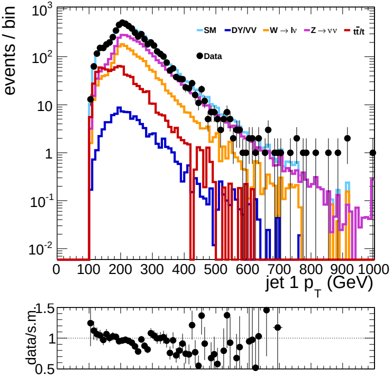
- $H_{\mathrm{T}} > 375$ GeV
  - all jets: $p_T > 50$ GeV
  - ≥ 2 jets with $p_T > 100$ GeV
- No isolated μ or e with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$
- $\alpha_{\mathrm{T}} > 0.55$
- $\not{H}_{\mathrm{T}}/\not{E}_{\mathrm{T}} < 1.25$
- HBHE Noise and $\not{E}_{\mathrm{T}}$ filters

Control: req's above +

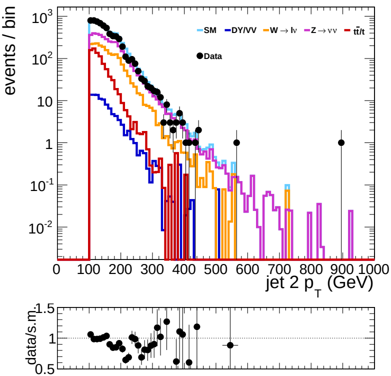
- photon $p_{\mathrm{T}} > 165$ GeV, $|\eta| < 1.4442$
- one isolated muon $p_{\mathrm{T}} > 25$ GeV
  - no α_{T} cut for muon samples
    $\Longrightarrow$ higher statistics
    $\Longrightarrow$ reduced S/B from signal contamination

Example data-MC comparison plots 1

Hadronic



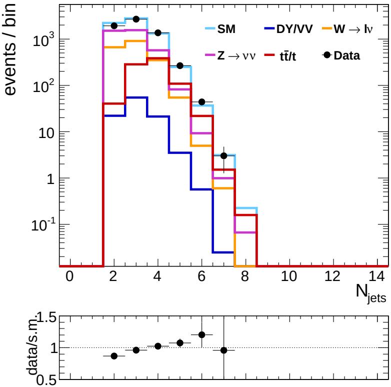
(a) $n_{\text{jet}} \geq 2$, $n_{\text{b}} \geq 0$



(b) $n_{\text{jet}} \geq 2$, $n_{\text{b}} \geq 0$

Example data-MC comparison plots 2

Hadronic



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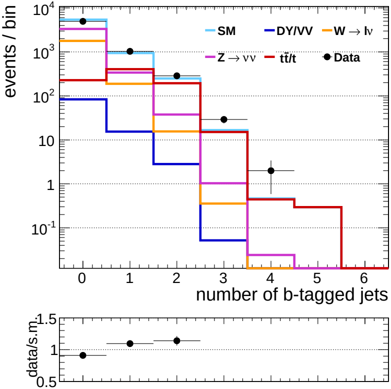
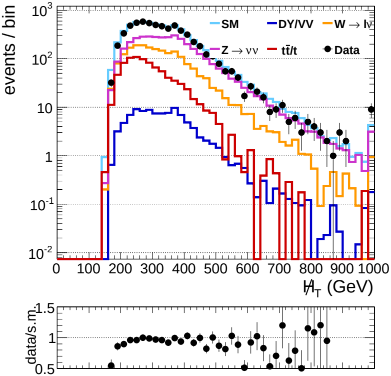


(b) $n_{\mathrm{jet}} \geq 2$, $n_{\mathrm{b}} \geq 0$

Example data-MC comparison plots 3

Hadronic



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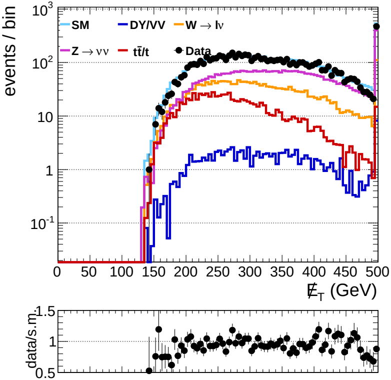
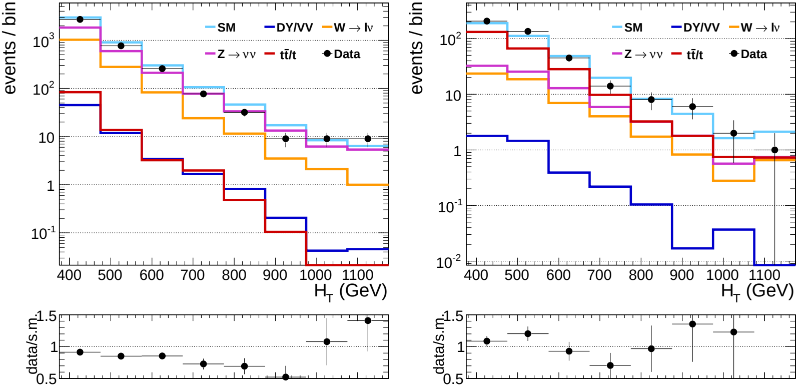


(b) $n_{\mathrm{jet}} \geq 2$, $n_{\mathrm{b}} \geq 0$

Example data-MC comparison plots 4

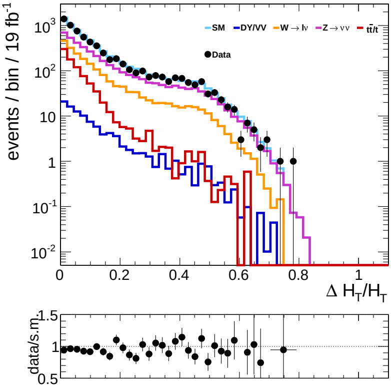
Hadronic



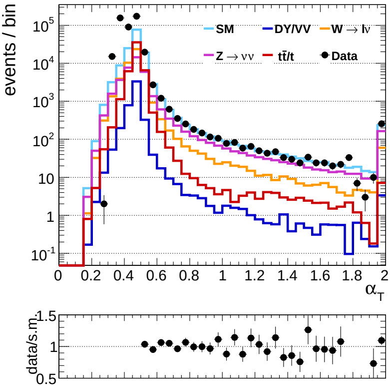
(a) $2 \leq n_{\text{jet}} \leq 3$, $n_{\text{b}} = 0$ (b) $n_{\text{jet}} \geq 4$, $n_{\text{b}} = 1$

Example data-MC comparison plots 5

Hadronic



(a) $n_{\text{jet}} \geq 2$, $n_{\text{b}} \geq 0$



(b) $n_{\text{jet}} \geq 2$, $n_{\text{b}} \geq 0$

Translation Factors

Translation factors = ratio of MC yields

$$N^{\text{had}}_{\text{pred}} = \underbrace{\frac{N^{\text{had}}_{\text{MC}}}{N^{\text{control}}_{\text{MC}}}}_{\text{translation factor}} \times N^{\text{control}}_{\text{obs}},$$

Benefits:

- reduced dependence on accuracy of MC modelling
- control and hadronic regions:
  - binned identically
  - kinematically similar,
  - similar admixtures of SM bkgds

Checks for biases provided by, and systematics derived from, closure tests

Closure Tests

$$N_{\text{pred}} = \frac{N_{\text{MC}}^{\mu+\text{jets}}(H_{\text{T}}, n_{\text{jet}} \geq 4, n_{\text{b}} = 1)}{N_{\text{MC}}^{\mu+\text{jets}}(H_{\text{T}}, n_{\text{jet}} \geq 4, n_{\text{b}} = 0)} \times N_{\text{Data}}^{\mu+\text{jets}}(H_{\text{T}}, n_{\text{jet}} \geq 4, n_{\text{b}} = 0)$$

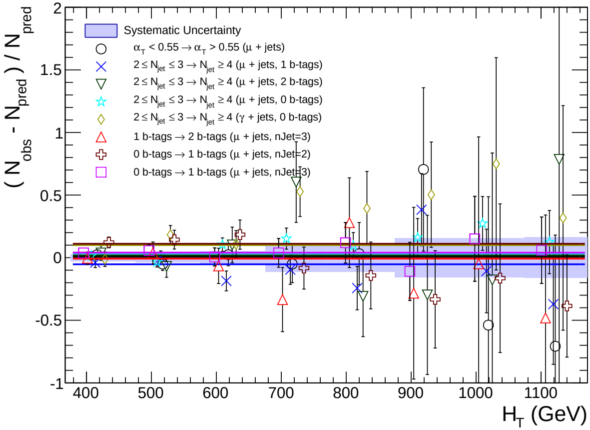
Compare N_{pred} with N_{obs} (i.e. $N_{\text{Data}}^{\mu+\text{jets}}(H_{\text{T}}, n_{\text{jet}} \geq 4, n_{\text{b}} = 1)$)

- statistically independent
- uncover biases
- determine background

Tests:

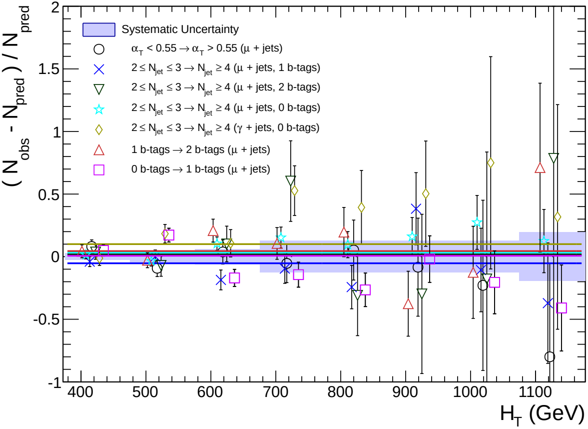
- $\alpha_{\text{T}} < 0.55 \rightarrow \alpha_{\text{T}} > 0.55$: check μ + jets
- between b-tag multiplicities: check bkg ad-mixture
- between n_{jet} multiplicities: check jes, kinetmatics

Closure Tests



(a) $2 \leq n_{\text{jet}} \leq 3$

Closure Tests



(a) $n_{\text{jet}} \geq 4$

Background Uncertainty

In addition:

- trigger: 5%

Table: A summary of the magnitude of the total systematic uncertainties (%) assigned to the translation factors, according to n_{jet} and H_{T} bin.

	H_{T} bin (GeV)							
n_{jet}	375	475	525	675	775	875	975	> 1075
2–3	6	6	7	12	12	17	17	17
$\geq$4	6	6	8	14	14	14	14	21

Likelihood Model Overview

Setup:

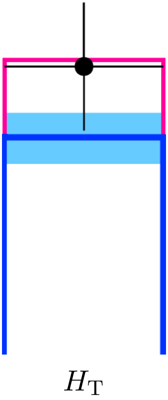
- Each observation is modeled as Poisson
- Hadronic SM EWK expectations are related to μ, γ expectations via “translation factors” from MC

Pick a signal model, a given value of signal cross section (e.g. 0=SM or 1=nominal), and a particular category of n_{b}. The parameters oated are:

- the yields of SM EWK events in each hadronic bin
- those determining the relative contributions from ($t \rightarrow$) W and Z
- those accommodating systematic uncertainty on the background translations and on the signal eciency

The Likelihood

$$L^k = L^k_{hadronic} \times L^k_{\mu} \times L^k_{\gamma} \times L^k_{\mathrm{EWK\,syst.}}$$



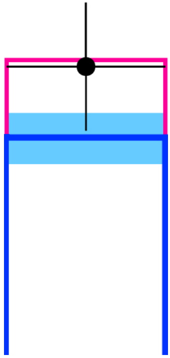
The Likelihood

$$L^k = L^k_{hadronic} \times L^k_{\mu} \times L^k_{\gamma} \times L^k_{\mathrm{EWK\,syst.}}$$

For a given an analysis category,

$$L_{hadronic} = \prod_i \mathrm{Pois}(n^i |\, b^i + s^i)$$

for H_{T} bin i.



The Likelihood

$$L^k = L^k_{hadronic} \times L^k_{\mu} \times L^k_{\gamma} \times L^k_{\mathrm{EWK\,syst.}}$$

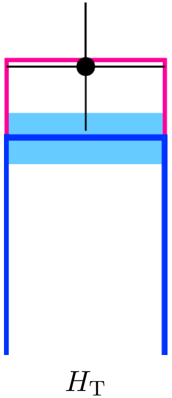
For a given an analysis category,

$$L_{hadronic} = \prod_i \mathrm{Pois}(n^i | \, b^i + s^i)$$

for H_{T} bin i.

$$L_{\gamma} = \prod_i \mathrm{Pois}(n^i_{\gamma} | \, \rho^i_{\gamma Z} \cdot r^i_{\gamma} \cdot Z^i_{\mathrm{inv}})$$

$$L_{\mu} = \prod_i \mathrm{Pois}(n^i_{\mu} | \, \rho^i_{\mu W} \cdot r^i_{\mu} \cdot ttW^i)$$



The Likelihood

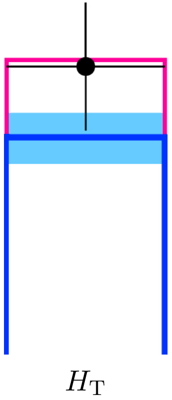
$$L^k = L^k_{hadronic} \times L^k_{\mu} \times L^k_{\gamma} \times L^k_{\mathrm{EWK\,syst.}}$$

For a given an analysis category,

$$L_{hadronic} = \prod_i \mathrm{Pois}(n^i | \, b^i + s^i)$$

for H_{T} bin i.

$$L_{\gamma} = \prod_i \mathrm{Pois}(n^i_{\gamma} | \, \rho^i_{\gamma Z} \cdot r^i_{\gamma} \cdot Z^i_{\mathrm{inv}})$$



$$L_{\mu} = \prod_i \mathrm{Pois}(n^i_{\mu} | \, \rho^i_{\mu W} \cdot r^i_{\mu} \cdot ttW^i)$$

$$r^i_{\gamma} = \frac{MC^i_{\gamma}}{MC^i_{Z_{\mathrm{inv}}}}; \; r^i_{\mu} = \frac{MC^i_{\mu}}{MC^i_{t\bar{t}+W}}$$

The Likelihood

$$L^k = L^k_{hadronic} \times L^k_{\mu} \times L^k_{\gamma} \times L^k_{\mathrm{EWK\,syst.}}$$

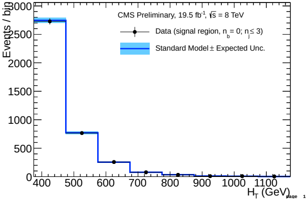
$$L_{\mathrm{EWK\,syst.}} = \prod_i \mathrm{Logn}(1.0|\, \rho^i_{\mu W}, \sigma^i_{\mu W}) \times \mathrm{Logn}(1.0|\, \rho^i_{\gamma Z}, \sigma^i_{\gamma Z})$$

where Logn is the log-normal distribution [2]:

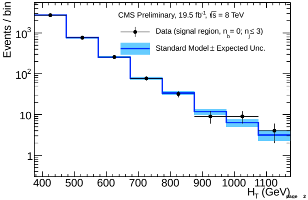
$$\mathrm{Logn}(x|\, \mu, \sigma_{\mathrm{rel.}}) = \frac{1}{x\sqrt{2\pi}\ln k} \exp\left(-\frac{\ln^2\left(\frac{x}{\mu}\right)}{2\ln^2 k} \right); \quad k = 1 + \sigma_{rel.} \quad .$$

- non-negative
- relative uncertainty

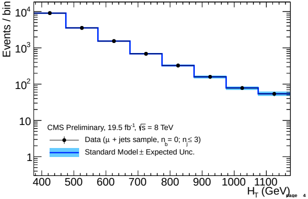
$2 \leq n_{\text{jet}} \leq 3$, 0b



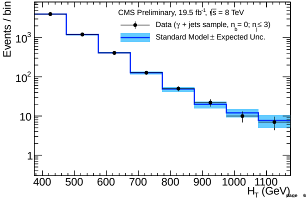
(a) Hadronic sample (lin. scale)



(b) Hadronic sample (log. scale)

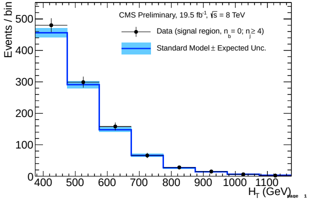


(c) μ + jets sample

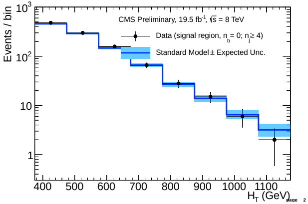


(d) γ + jets sample

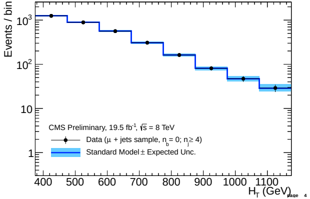
$n_{\text{jet}} \geq 4$, 0b



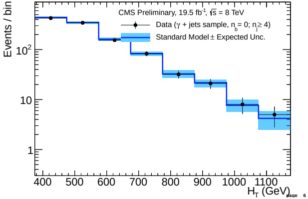
(a) Hadronic sample (lin. scale)



(b) Hadronic sample (log. scale)

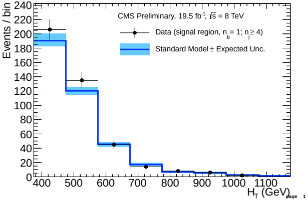


(c) μ + jets sample

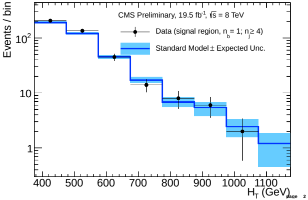


(d) γ + jets sample

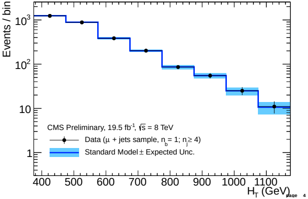
$n_{\text{jet}} \geq 4$, 1b



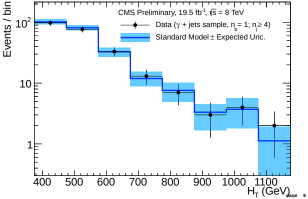
(a) Hadronic sample (lin. scale)



(b) Hadronic sample (log. scale)

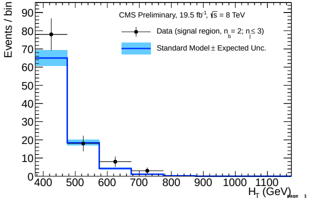


(c) μ + jets sample

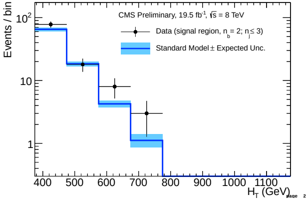


(d) γ + jets sample

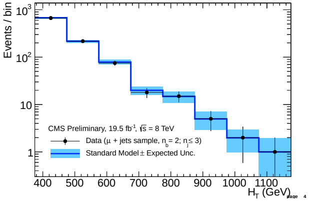
$2 \leq n_{\text{jet}} \leq 3$, 2b



(a) Hadronic sample (lin. scale)

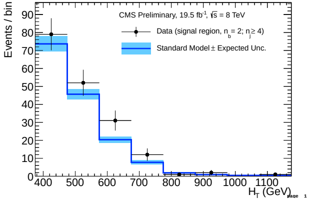


(b) Hadronic sample (log. scale)

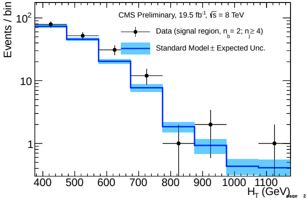


(c) μ + jets sample

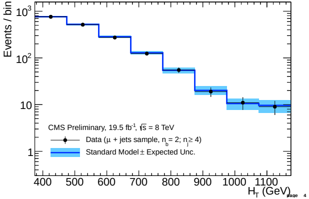
$n_{\text{jet}} \geq 4$, 2b



(a) Hadronic sample (lin. scale)

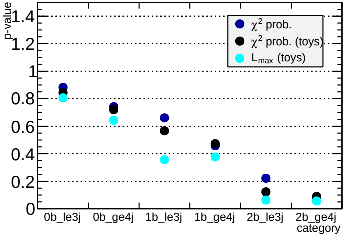


(b) Hadronic sample (log. scale)

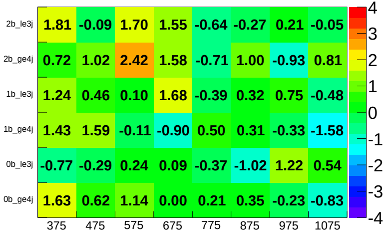


(c) μ + jets sample

p-values and pulls



(a) p-values per event category.



(b) Pull versus signal region bin.

Including the Signal Models

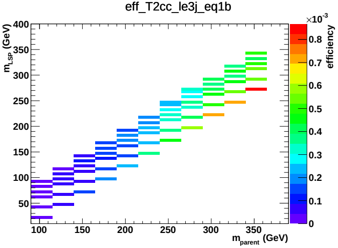
$$L = L^k_{sig.\,syst} \times \prod_k L^k_{hadronic} \times L^k_{\mu} \times L^k_{ph} \times L^k_{\mathrm{EWK\,syst.}} \quad .$$

$$L_{hadronic} = \prod_i \mathrm{Pois}(n^i |\, b^i + s^i)$$

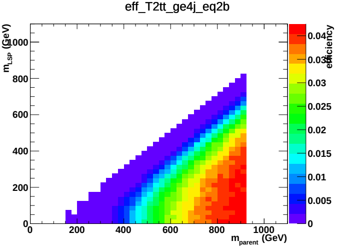
$$s^i \equiv f \rho_{sig} x l \epsilon^i_{had}$$

$$L_{sig.\,syst} = \mathrm{Logn}(1.0|\, \rho_{sig}, \delta) \quad .$$

example signal efficiencies



(a) T2cc, Hadronic Selection Efficiency, (2–3,1)



(b) Hadronic Selection Efficiency, ($\geq$ 4,2)

Uncertainty on Signal Efficiency

- PDF - Parton Distribution Function
- JES - Jet Energy Scale
- ISR - Initial State Radiation

T2cc

Category	(2–3,0)		($\geq$ 4,0)		($\geq$ 4,1)	
Range	Min.	Max.	Min.	Max.	Min.	Max.
PDF	0.00	0.05	0.00	0.05	0.00	0.10
JES	0.00	0.10	0.00	0.10	0.00	0.15
ISR	0.15	0.25	0.10	0.15	0.15	0.30
b-tag SF	0.00	0.08	0.00	0.10	0.00	0.15
Luminosity	0.026					
Trigger	0.05					
Dead Ecal	0.03					
Total syst	0.18	0.25	0.19	0.30	0.20	0.38

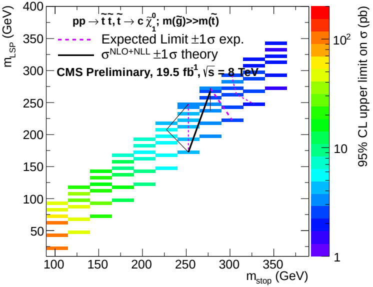
Uncertainty on Signal Efficiency

- PDF - Parton Distribution Function
- JES - Jet Energy Scale
- ISR - Initial State Radiation

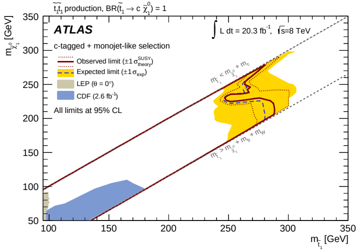
T2tt

Category	($\geq$ 4,1)		($\geq$ 4,2)	
Range	Min.	Max.	Min.	Max.
PDF	0.00	0.10	0.00	0.10
JES	0.00	0.10	0.00	0.05
ISR	0.00	0.20	0.00	0.22
b-tag SF	0.00	0.05	0.00	0.10
Luminosity	0.026			
Trigger	0.05			
Dead Ecal	0.03			
Total syst	0.05	0.25	0.05	0.30

T2cc: Limits on Upper Cross Sections

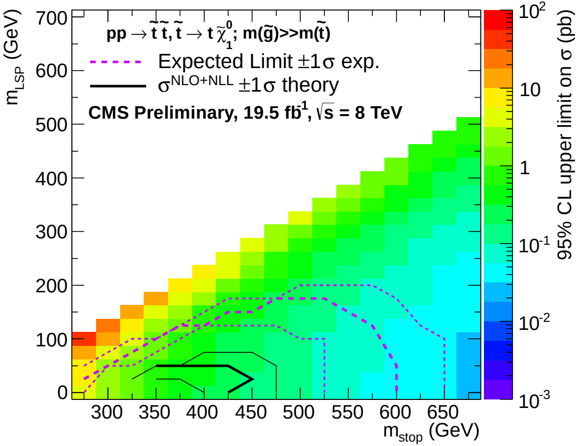


(a) Analysis T2cc Limits



(b) ATLAS T2cc Limits

T2tt: Limits on Upper Cross Sections



pulls

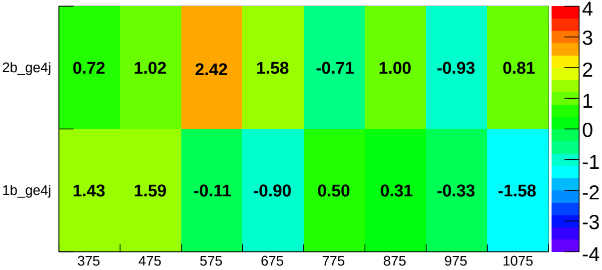
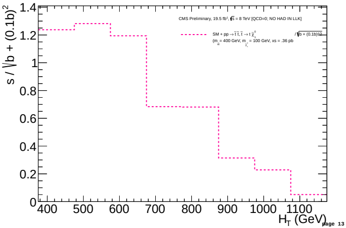


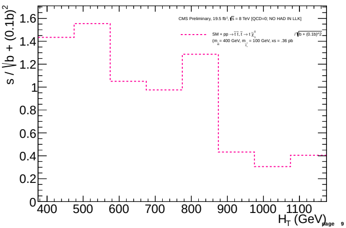
Figure: Pulls in categories used in T2tt interpretation.

Signal Significance

$$\frac{s}{\sqrt{b+(0.1b)^2}}$$



(a) $n_{\text{jet}} \geq 4$, $n_{\text{b}} = 1$, simultaneous fit

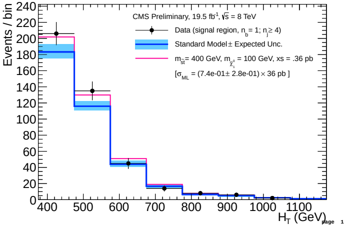


(b) $n_{\text{jet}} \geq 4$, $n_{\text{b}} = 2$, simultaneous fit

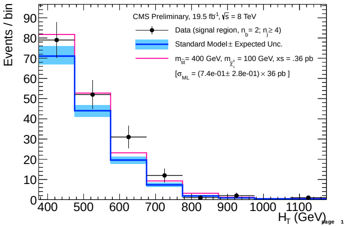
Fit with Signal

Example mass point ($m_{\tilde{t}} = 400\,\mathrm{GeV}, m_{LSP} = 100\,\mathrm{GeV}$)

- fluctuations consistant signal



(a) $n_{\mathrm{jet}} \geq 4$, $n_{\mathrm{b}} = 1$, simultaneous fit



(b) $n_{\mathrm{jet}} \geq 4$, $n_{\mathrm{b}} = 2$, simultaneous fit

Calo and PF Upper Limit Comparison

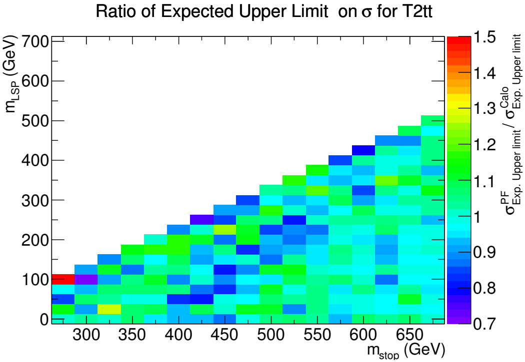


Figure: The ratio of the expected upper limit on the signal cross section for the signal model T2tt between PF-jets and calo-jets. See text for details.

Summary

- Limits with calo & PF comparable → inneficency in trigger

References

S. Chatrchyan et al.
Search for supersymmetry in hadronic final states with missing transverse energy using the variables α_{T} and b-quark multiplicity in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$.
EPJC, 01:077, 2013.

Robert Cousins.
Probability Density Functions for Positive Nuisance Parameters.
`http://www.physics.ucla.edu/~cousins/stats/cousins_lognormal_prior.pdf`.

Backup

Closure Tests

Closure test	Constant fit: Best fit value	χ^2	d.o.f.	p-value
$\alpha_{\mathrm{T}} < 0.55 \rightarrow \alpha_{\mathrm{T}} > 0.55$ (μ + jets)	0.007 ± 0.02	3.91	7	0.79
1 b-tags $\rightarrow$2 b-tags (μ + jets, n_{jet} =3)	-0.008 ± 0.04	3.20	7	0.87
0 b-tags $\rightarrow$1 b-tags (μ + jets, n_{jet} =2)	0.111 ± 0.03	5.87	7	0.55
0 b-tags $\rightarrow$1 b-tags (μ + jets, n_{jet} =3)	0.040 ± 0.02	1.12	7	0.99

Closure test	Constant fit: Best fit value	χ^2	d.o.f.	p-value
$\alpha_{\mathrm{T}} < 0.55 \rightarrow \alpha_{\mathrm{T}} > 0.55$ (μ + jets)	0.011 ± 0.04	5.81	7	0.56
1 b-tags $\rightarrow$2 b-tags (μ + jets)	0.045 ± 0.03	9.36	7	0.23
0 b-tags $\rightarrow$1 b-tags (μ + jets)	0.007 ± 0.03	25.30	7	7.6×10^{-4}
0 b-tags $\rightarrow$1 b-tags (μ + jets)†	0.009 ± 0.03	10.12	6	0.12

Closure test	Constant fit: Best fit value	χ^2	d.o.f.	p-value
$2 \leq n_{\text{jet}} \leq 3 \rightarrow n_{\text{jet}} \geq 4$ (μ + jets, 1 b-tags)	-0.053 ± 0.03	8.02	7	0.33
$2 \leq n_{\text{jet}} \leq 3 \rightarrow n_{\text{jet}} \geq 4$ (μ + jets, 1 b-tags)	0.018 ± 0.04	6.23	7	0.51
$2 \leq n_{\text{jet}} \leq 3 \rightarrow n_{\text{jet}} \geq 4$ (μ + jets, 0 b-tags)	0.034 ± 0.02	9.24	7	0.24
$2 \leq n_{\text{jet}} \leq 3 \rightarrow n_{\text{jet}} \geq 4$ (γ + jets, 0 b-tags)	0.100 ± 0.04	12.20	7	0.09

HT $\times$ α_{T} Trigger

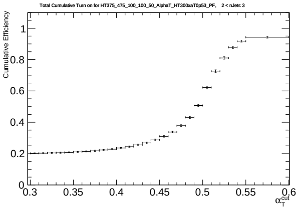
innefficiency in trigger:

- Online: calo jets $\rightarrow$ Offline: PF jets

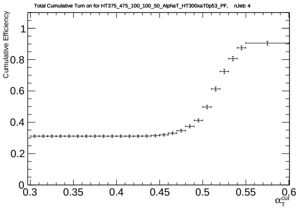
Offline H_{T} bin (GeV)	Offline α_{T} threshold	Trigger (HLT)	Efficiency (%) $2 \leq n_{\mathrm{jet}} \leq 3$	Efficiency (%) $n_{\mathrm{jet}} \geq 4$
$375 < H_{\mathrm{T}} < 475$	0.55	HT300_AlphaT0p53	$94.2^{+0.5}_{-0.6}$	$90.5^{+1.2}_{-1.3}$
$475 < H_{\mathrm{T}} < 575$	0.55	HT350_AlphaT0p52	$96.2^{+0.8}_{-0.9}$	$94.6^{+1.2}_{-1.4}$
$575 < H_{\mathrm{T}} < 675$	0.55	HT400_AlphaT0p51	$95.4^{+1.4}_{-1.8}$	$98.7^{+0.7}_{-1.12}$
$H_{\mathrm{T}} > 675$	0.55	HT400_AlphaT0p51	$100^{+0.0}_{-2.0}$	$100^{+0.0}_{-2.0}$

Muon control samples: IsoMu24_eta2p1 88%
Photon control sample: Photon150 100% for $p_T > 165$ GeV

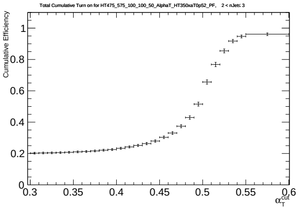
HT $\times$ α_{T} Trigger



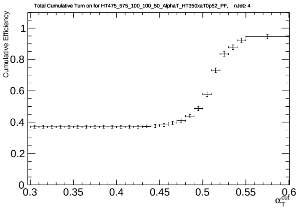
$2 \leq n_{\mathrm{jet}} \leq 3$, $375 < H_{\mathrm{T}} < 475\,\mathrm{GeV}$



$n_{\mathrm{jet}} \geq 4$, $375 < H_{\mathrm{T}} < 475\,\mathrm{GeV}$



$2 \leq n_{\mathrm{jet}} \leq 3$, $475 < H_{\mathrm{T}} < 525\,\mathrm{GeV}$



$n_{\mathrm{jet}} \geq 4$, $475 < H_{\mathrm{T}} < 525\,\mathrm{GeV}$