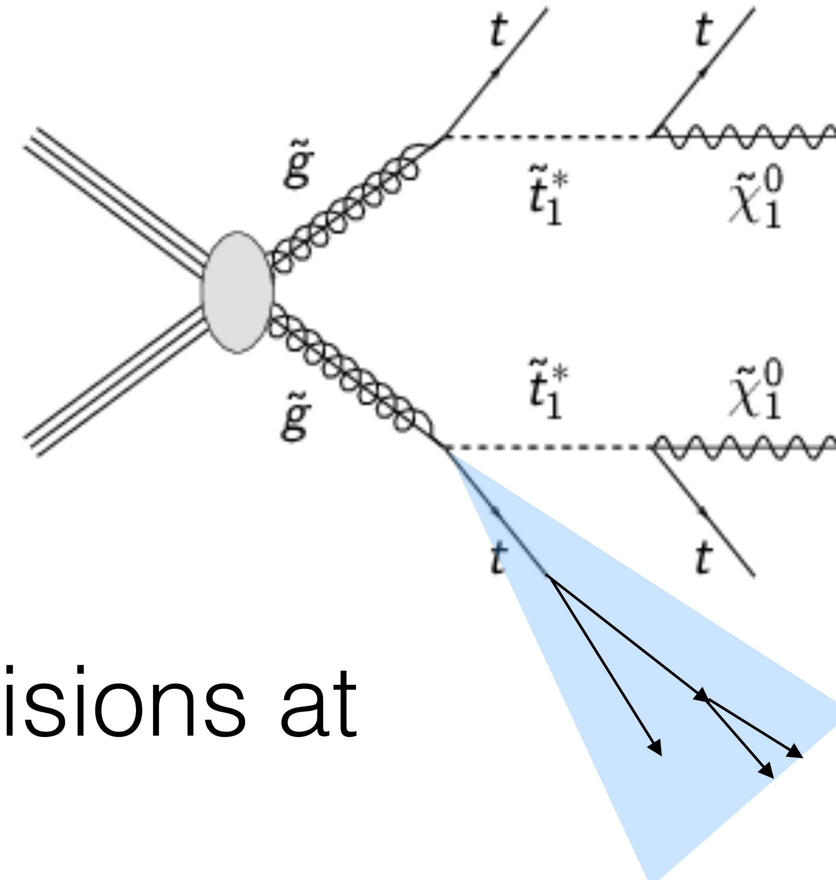

Search for supersymmetry in pp collisions at CMS at $\sqrt{s} = 13$ TeV

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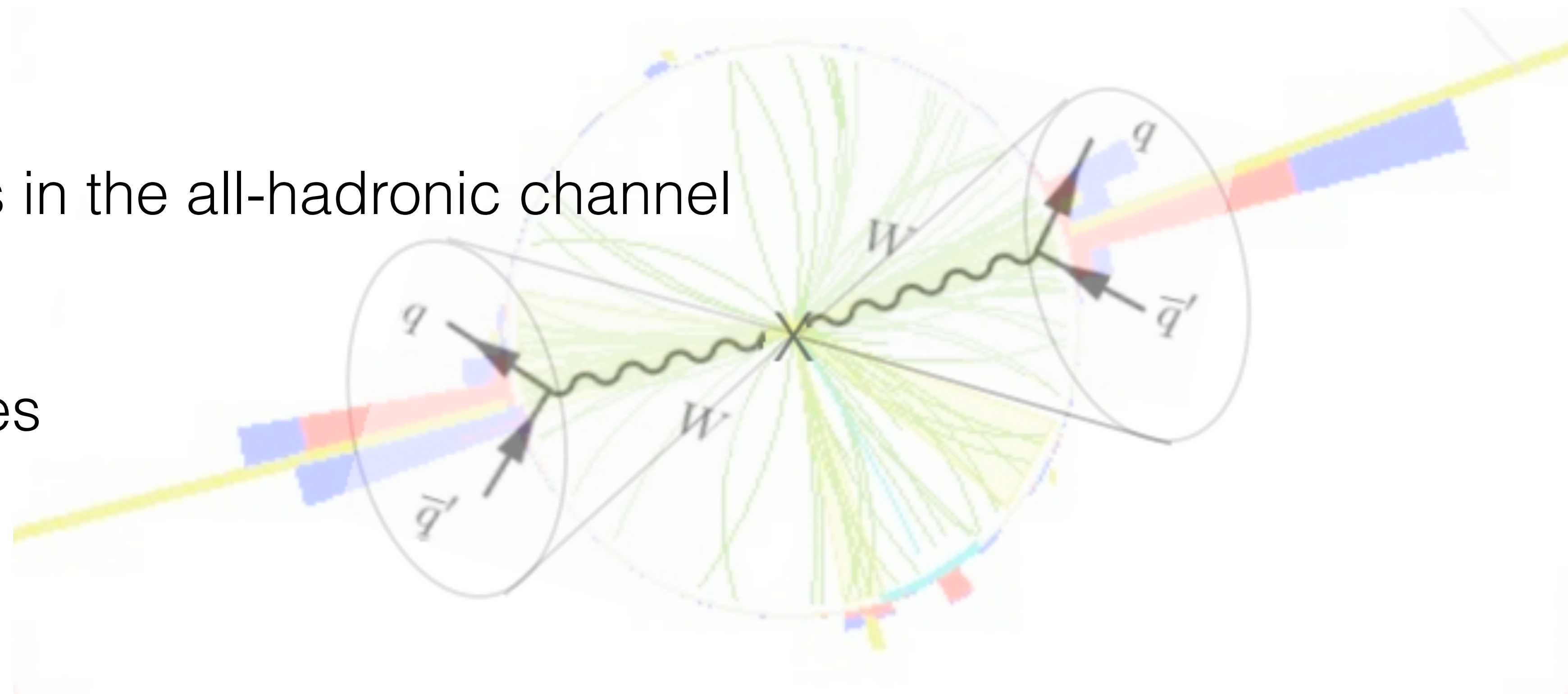
On behalf of the CMS collaboration

22nd March 2016
Joint annual HEPP and APP conference
University of Sussex

Outline

- Introduction
    - Motivation for supersymmetry
- Analysis
    - Search for new physics in the all-hadronic channel

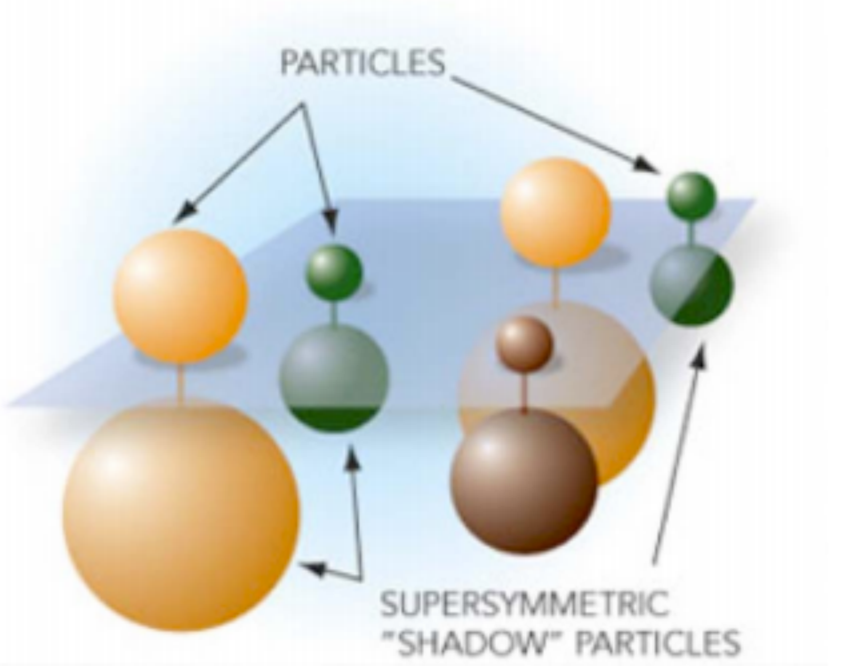


- Jet substructure techniques
- Application to the analysis
    - Search for gluino mediated top squarks using jet substructure techniques

Supersymmetry

A continuous symmetry that relates fermions and bosons.

- Supersymmetry (SUSY) is an extension to the SM
- Aims to address current short-comings:
  - The Higgs hierarchy problem
  - At high enough energies, no unification of the couplings of the three forces
  - Lack of a dark matter candidate

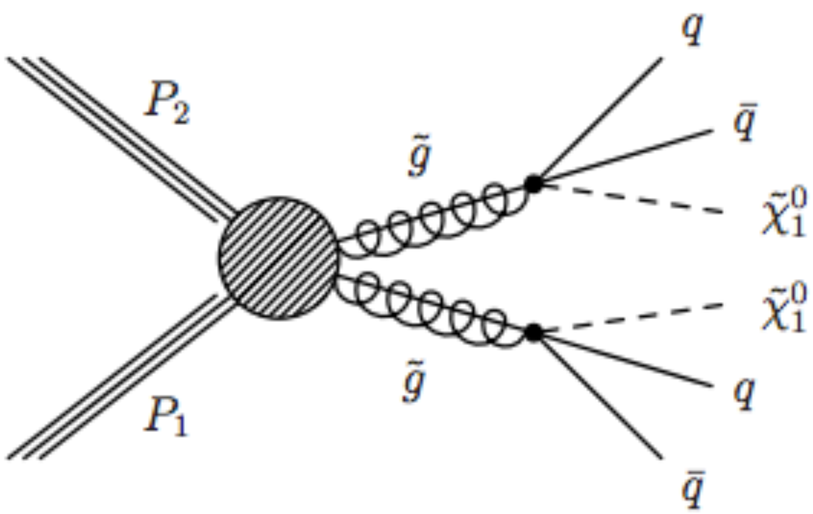


- Direct searches for SUSY have two classical signatures
  - Multileptons and missing energy
  - Jets and missing energy
- R-parity conserving supersymmetry requires sparticles be pair produced
- Two SUSY decay chains per event

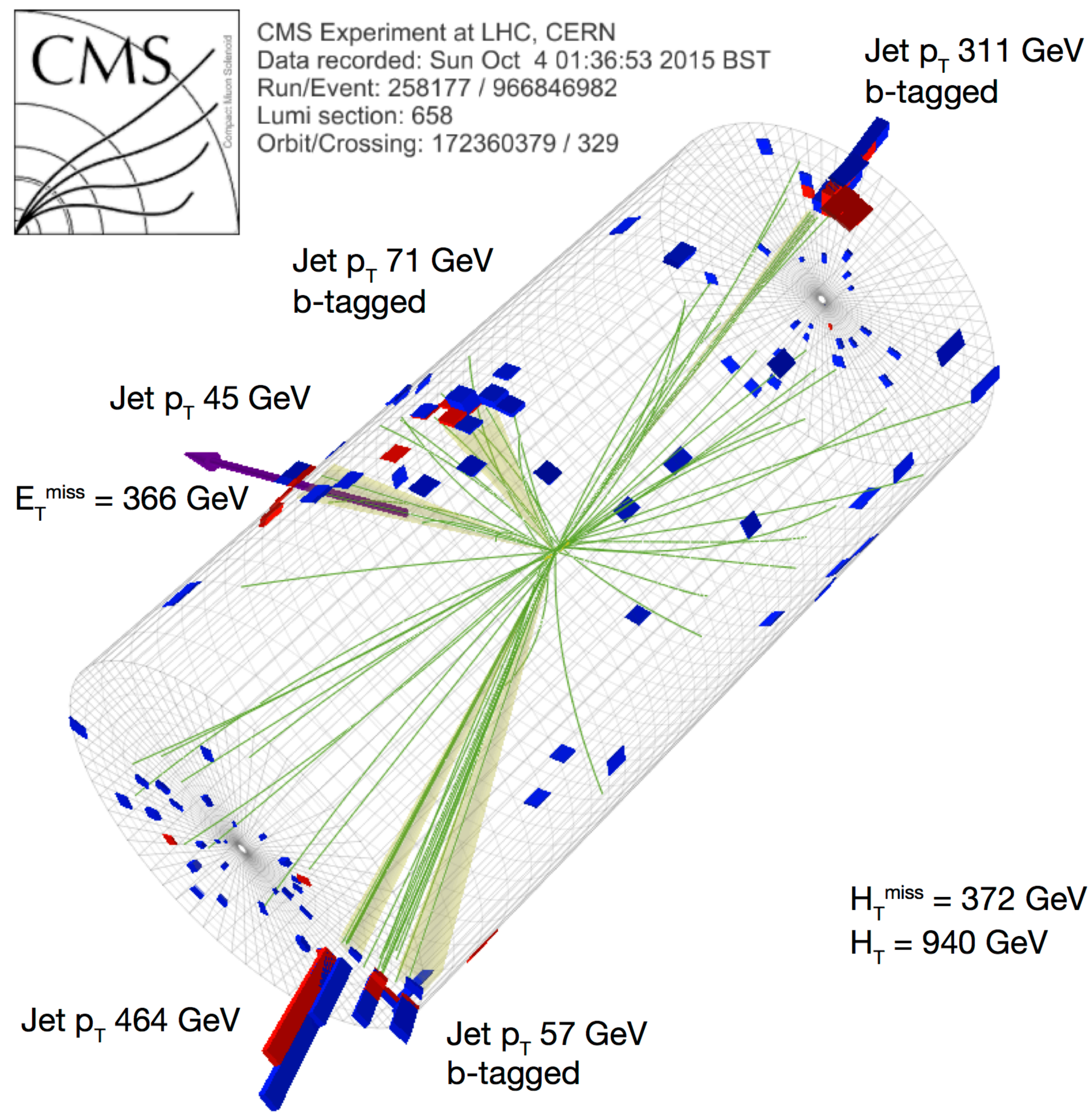
Analysis Introduction

Search for new physics with the α_T variable

- **Fully hadronic analysis**
  - Final state rich in **jets** and **missing transverse momentum**



http://inspirehep.net/record/1410157



- QCD multijet background strongly suppressed with α_T and $\Delta\phi^*$
- Data-driven estimations of backgrounds
- Events categorised according to
  - Hadronic observables: N_{jet}, N_b, H_T, MH_T
  - Topology

Selections

Description of the key variables

α_T

Di-Jet

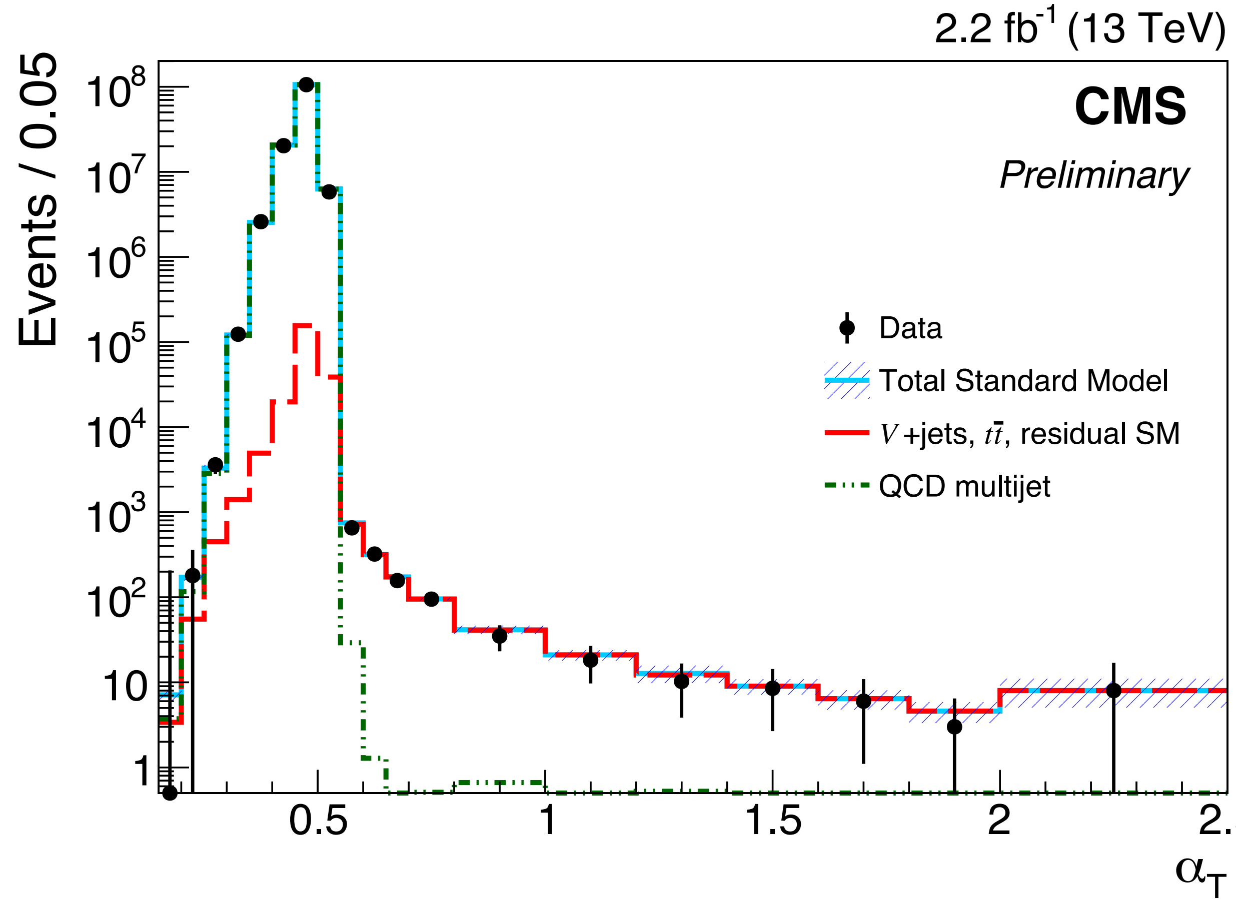
$$\alpha_T = \frac{E_T^{j_2}}{M_T}$$

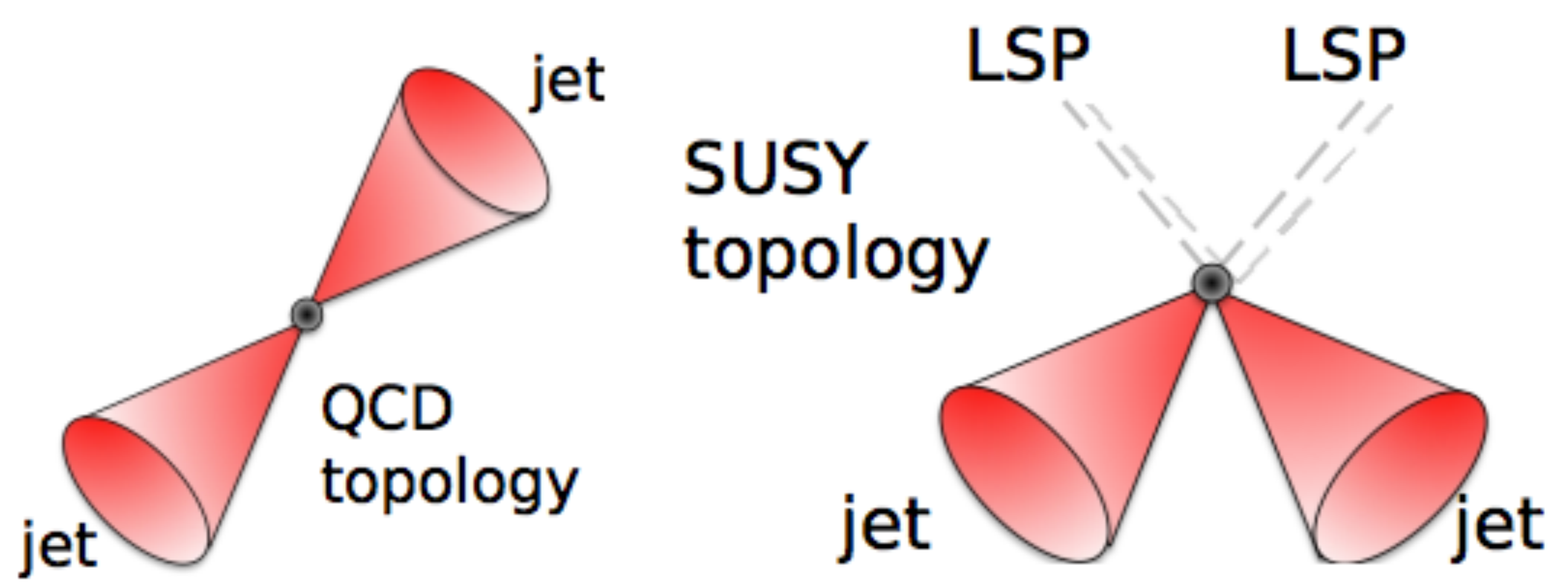
j2, sub-leading jet

Multi-Jet

$$\alpha_T = \frac{1}{2} \times \frac{H_T - \Delta H_T}{\sqrt{{H_T}^2 - {H_T^{miss}}^2}}$$

- back-to-back events: 0.5
- "unbalanced" events: < 0.5
- genuine MET events: > 0.5





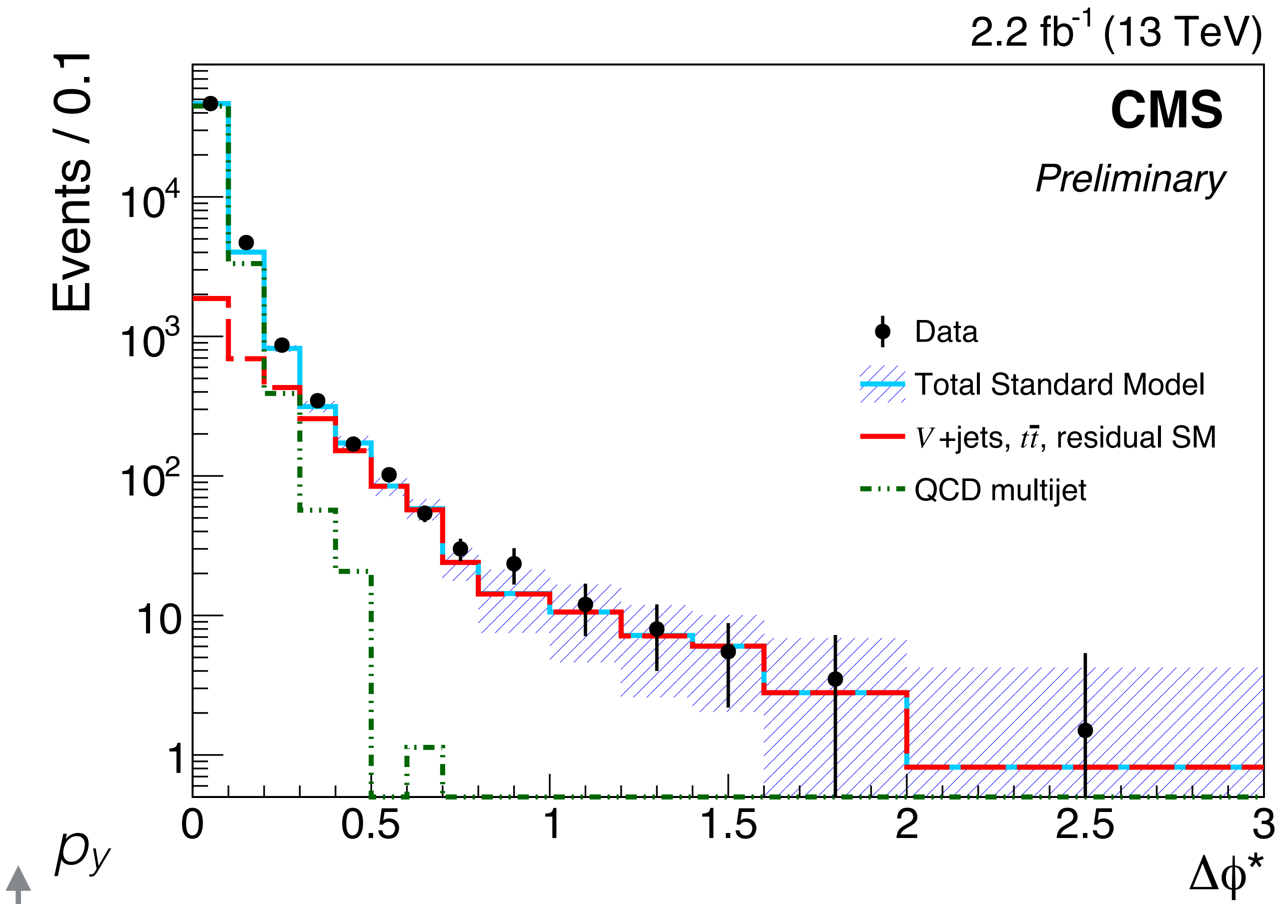
Selections

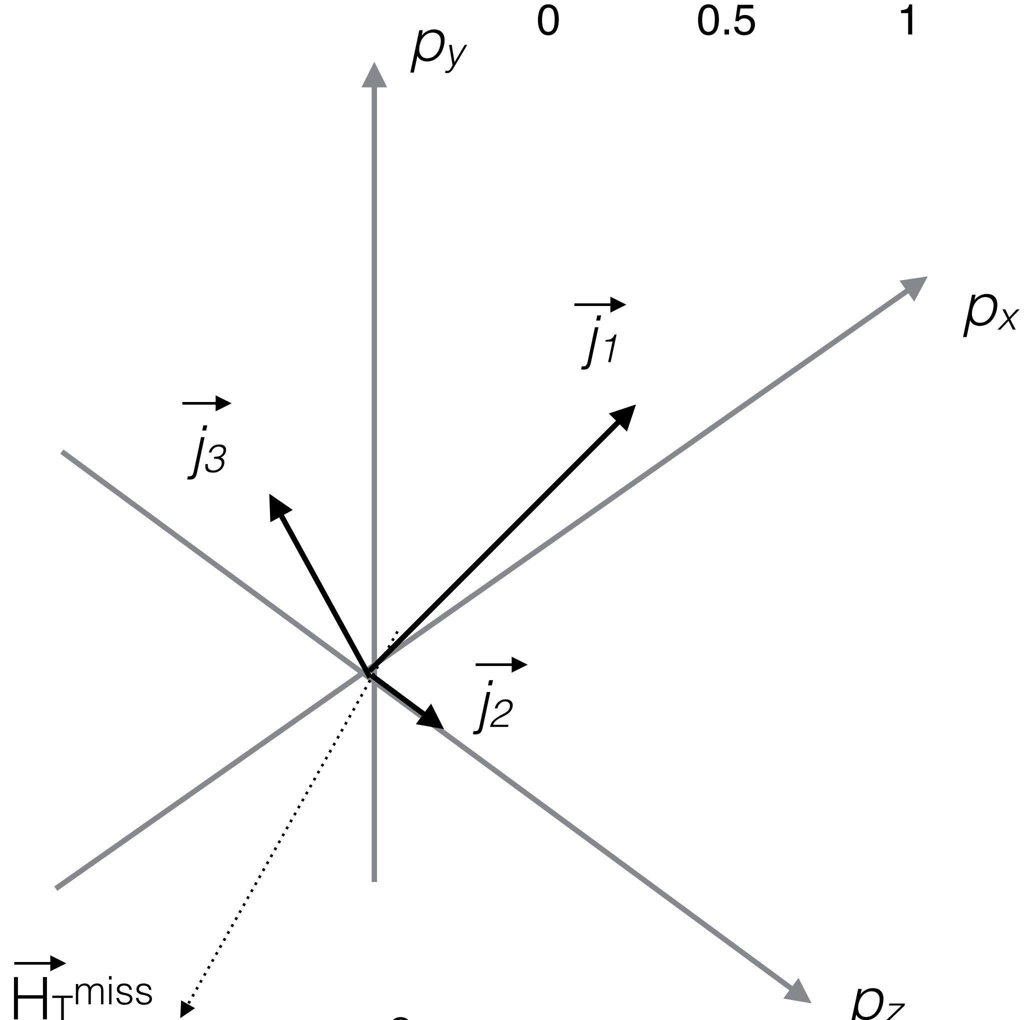
Description of the key variables

$\Delta\phi^*$

$$\Delta\phi^* = \min_{i \in \text{jets}} \Delta\phi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\text{miss}} + \vec{p}_{\mathrm{T}i})$$

- Aim to find events where MHT in same direction as mis-measured jet
- Mis-measured jets and jets with significant missing energy components peak at low values



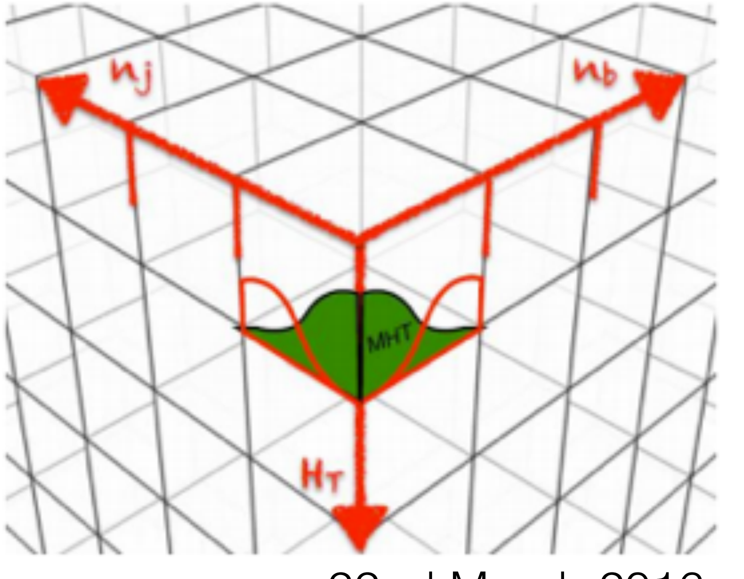


$H_T = \sum p_T(j_i)$

Analysis strategy

Signal and Control regions

- Baseline selection
    - $N_{jet} \geq 1$ ($p_T > 40$ GeV), $H_T > 200$ GeV, $MH_T > 130$ GeV
    - Employ a forward jet veto and MHT/MET < 1.25 cut
- Signal region
    - Lepton and photon **veto**
    - H_T dependent α_T cuts from 0.65 to 0.52 for $H_T < 800$ GeV
    - $\Delta\phi^* > 0.5$ requirement
- Control regions
    - Backgrounds from data-driven estimates from control regions
- Events categorised according to
    - Hadronic observables: N_{jet}, N_b, H_T, MH_T
    - Topology



Results

Interpreted in the context of simplified model spectra (SMS)

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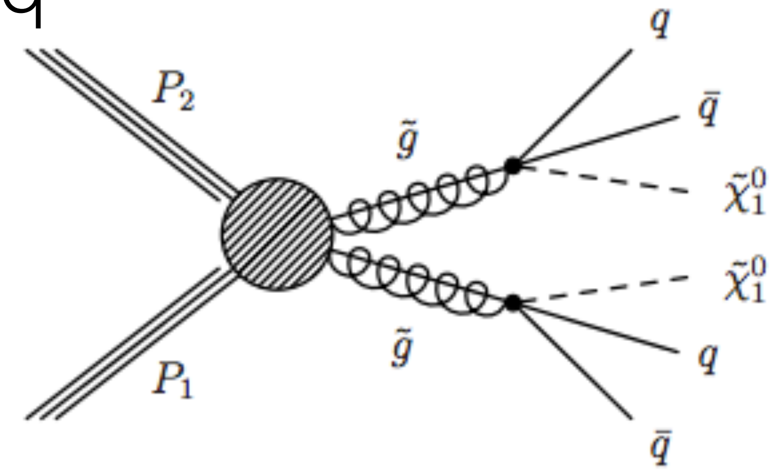

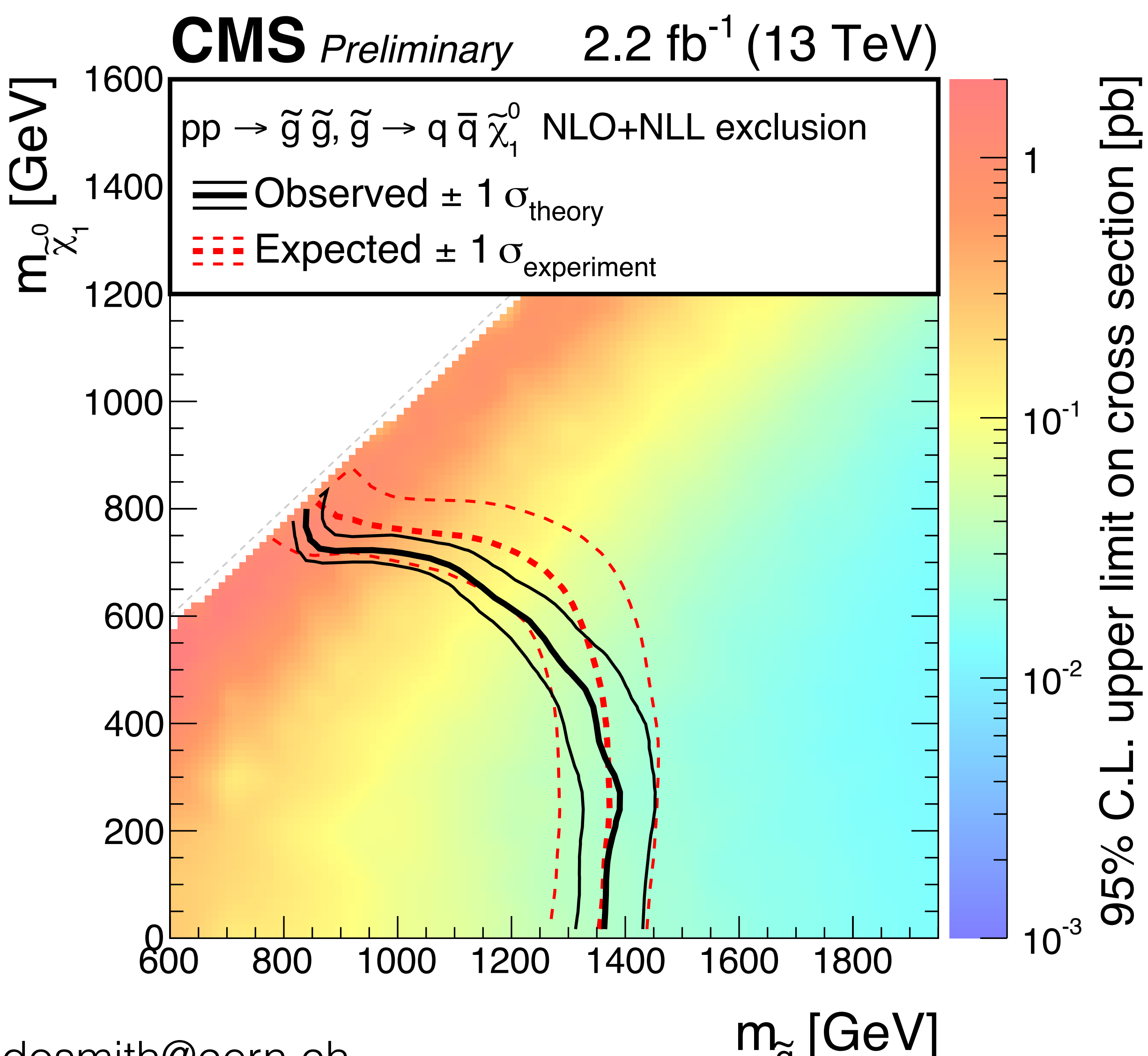

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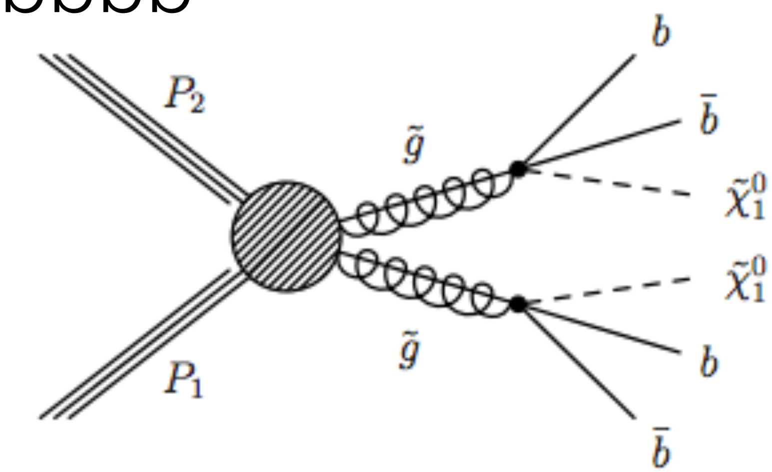
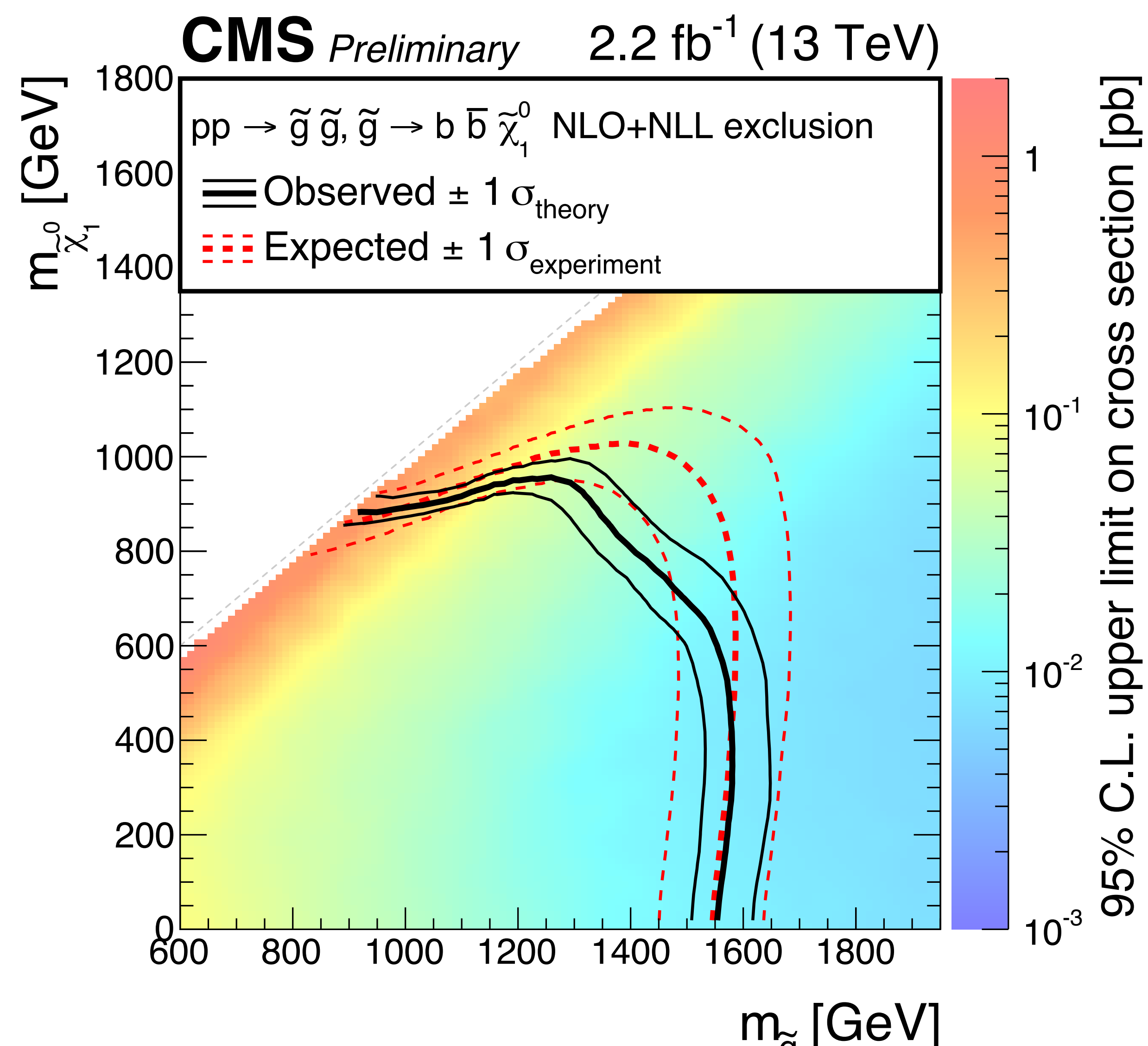


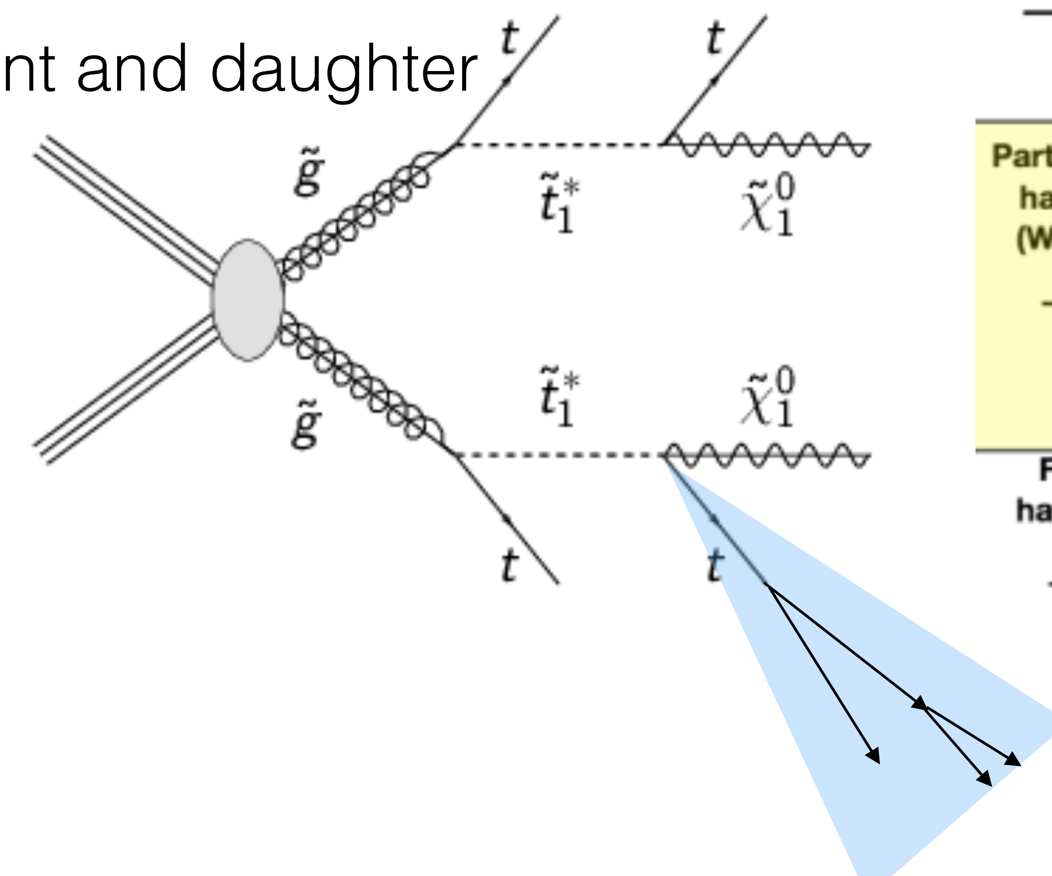


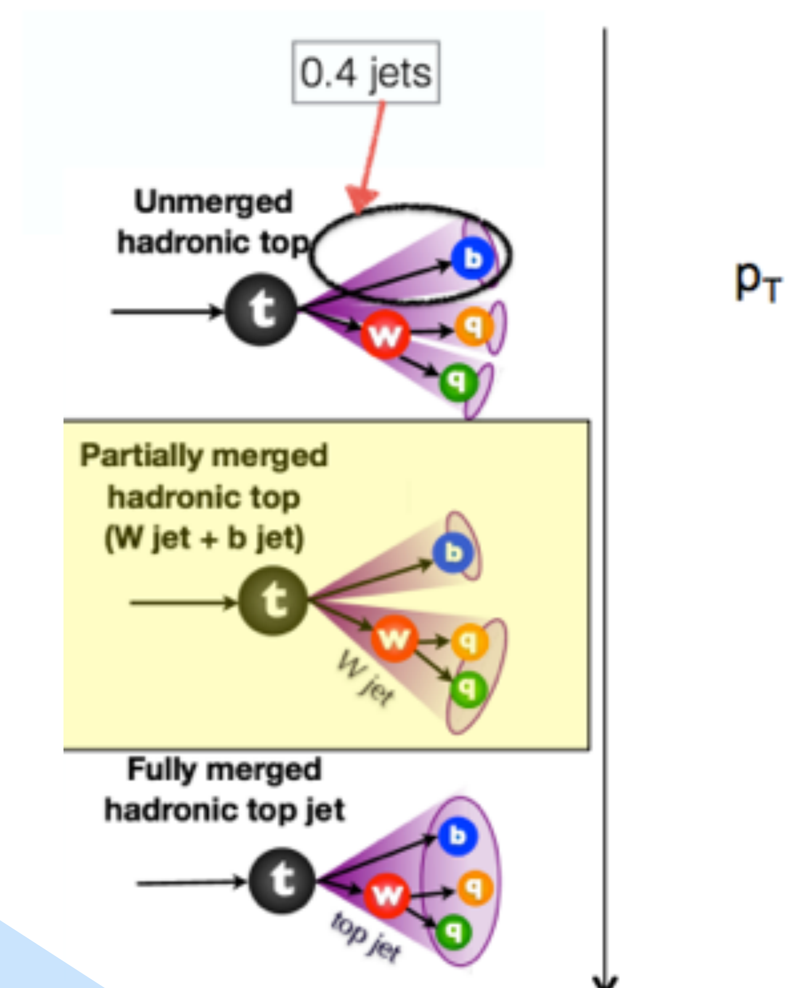
Results

Further SMS considerations

- A simplified model is defined by new particles and their production and decay
  - Sparticles are produced in pairs
  - Each sparticle undergoes a decay chain
  - Decay chain ends with lightest supersymmetric particle
- Several SMS models with top/ b quarks in final states

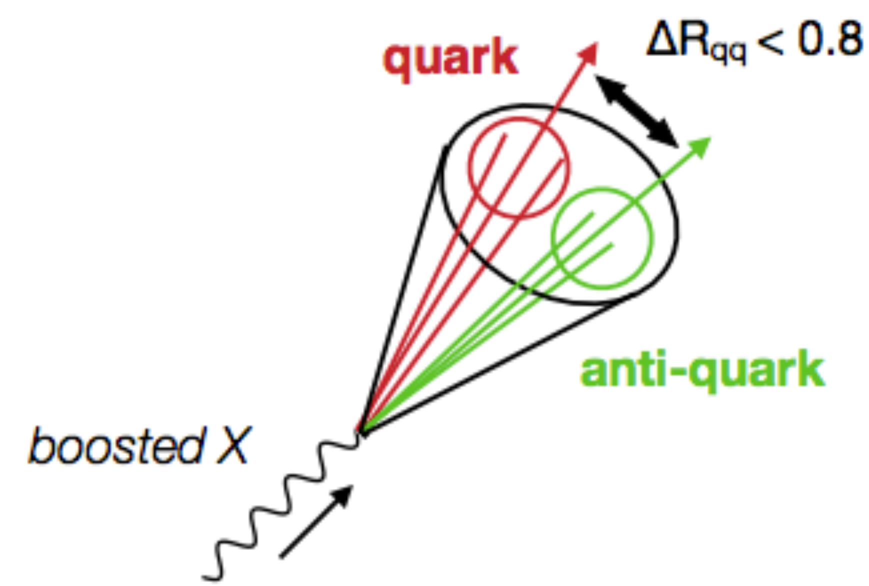
- If mass splitting between parent and daughter sparticle large enough
  - Tops acquire boost
    - Decay products merge



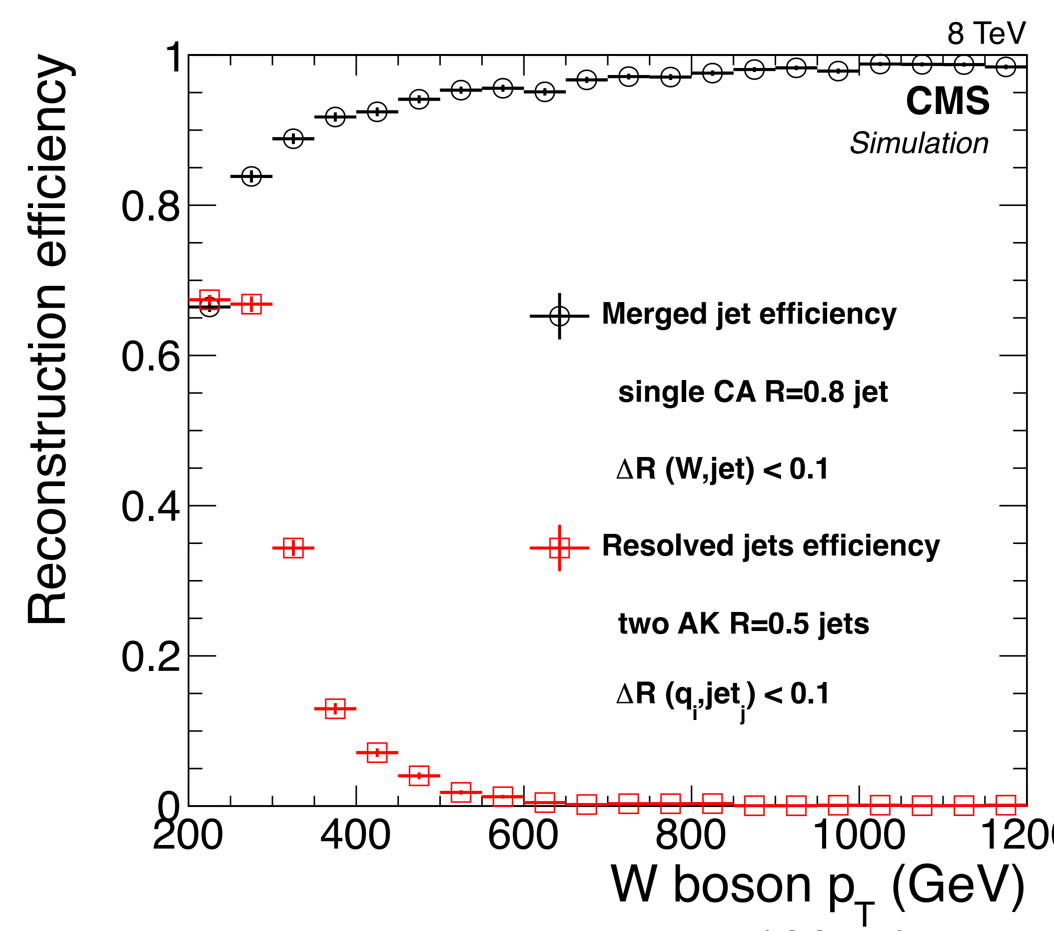


Jet Substructure Techniques

- For high p_T objects, object X is boosted
  - Decay products collimated
  - $\Delta R \sim 2M/p_T$



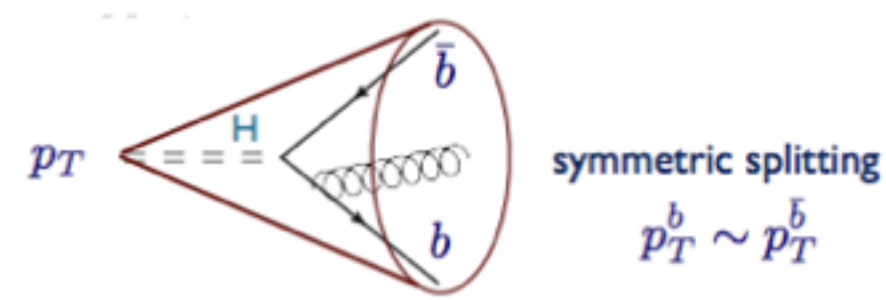
- Example, W/Z boson originating from resonance decay
  - For p_T (W/Z) > 200 GeV, decay products merged into single jet
  - Higher W/Z tagging efficiency with large jet, than resolved jets at high p_T.



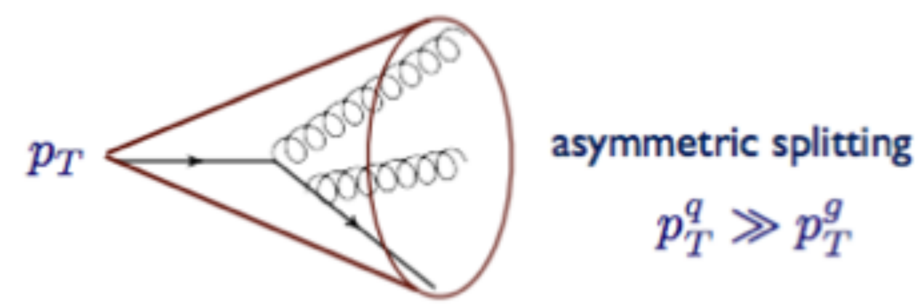
Jet Substructure Techniques

Procedure

- Key aim is to partially reverse jet clustering process
  - 'Groom' to improve signal mass resolution
  - Identify smaller structures within jet

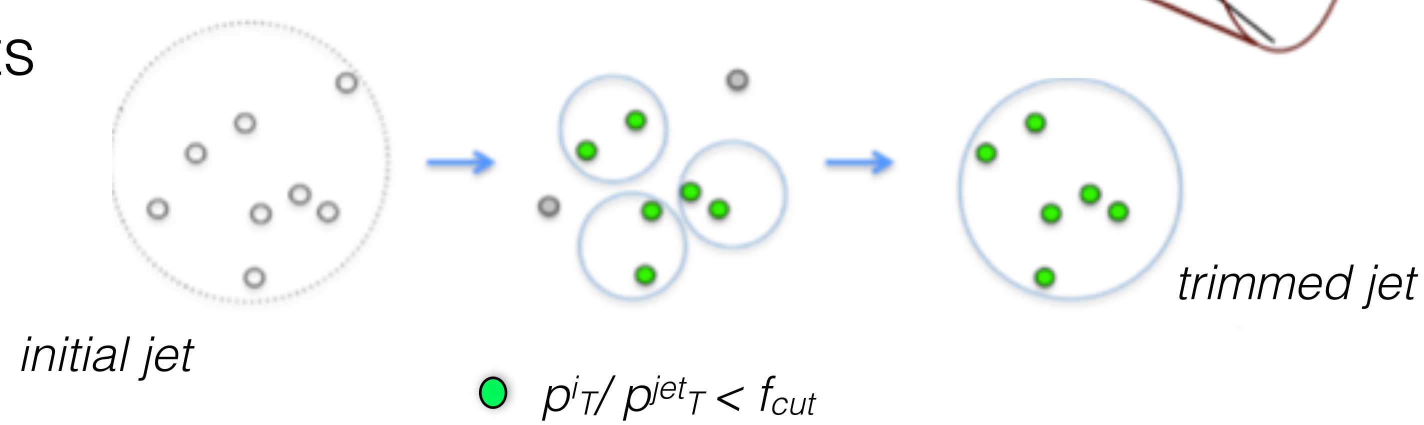


- Heavy object decays have symmetric splittings, QCD splittings asymmetric



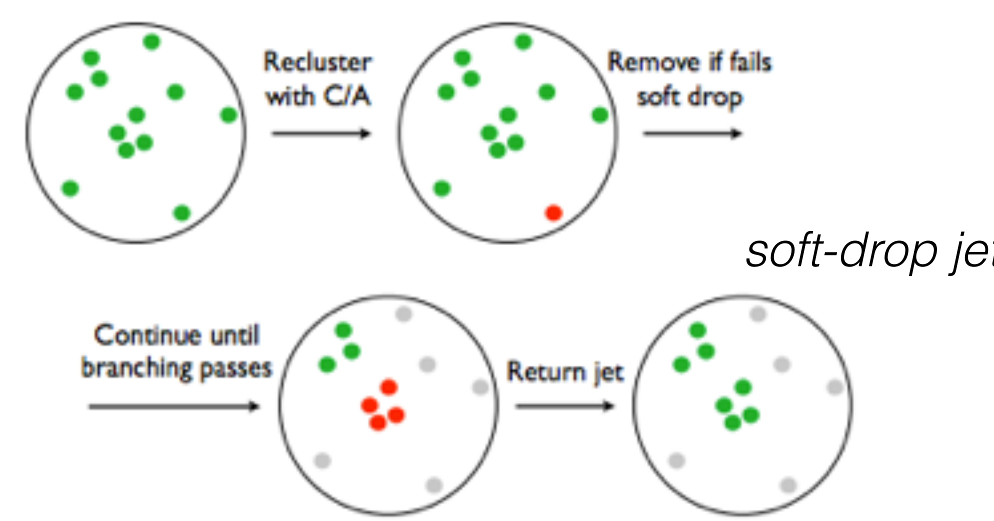
- Jet grooming algorithms:
  - Remove soft constituents

trimming



  - Remove wide angle then/ and soft constituents

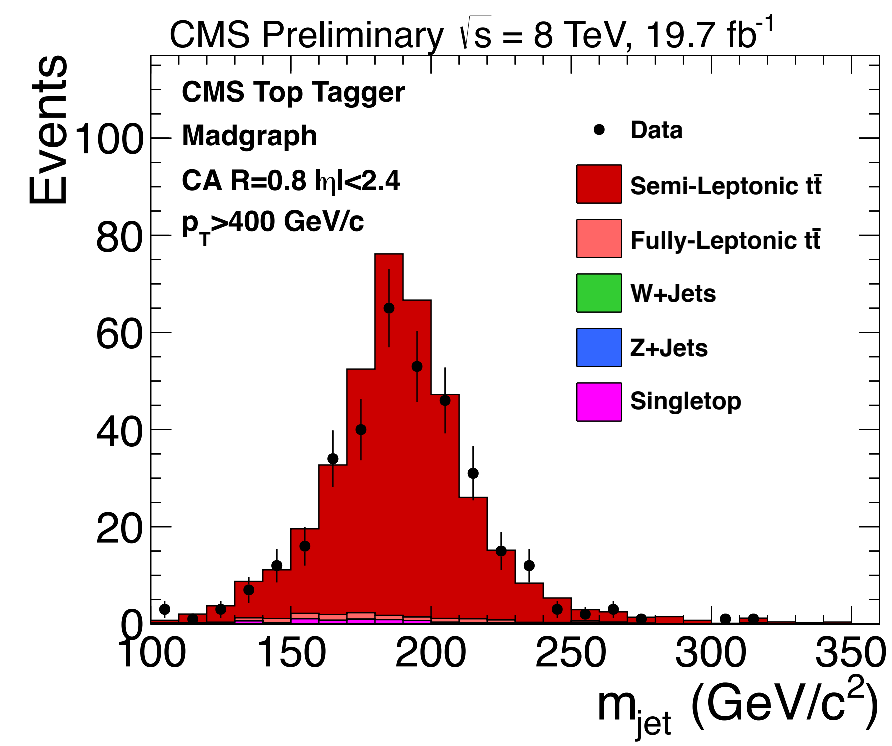
pruning *soft-drop*

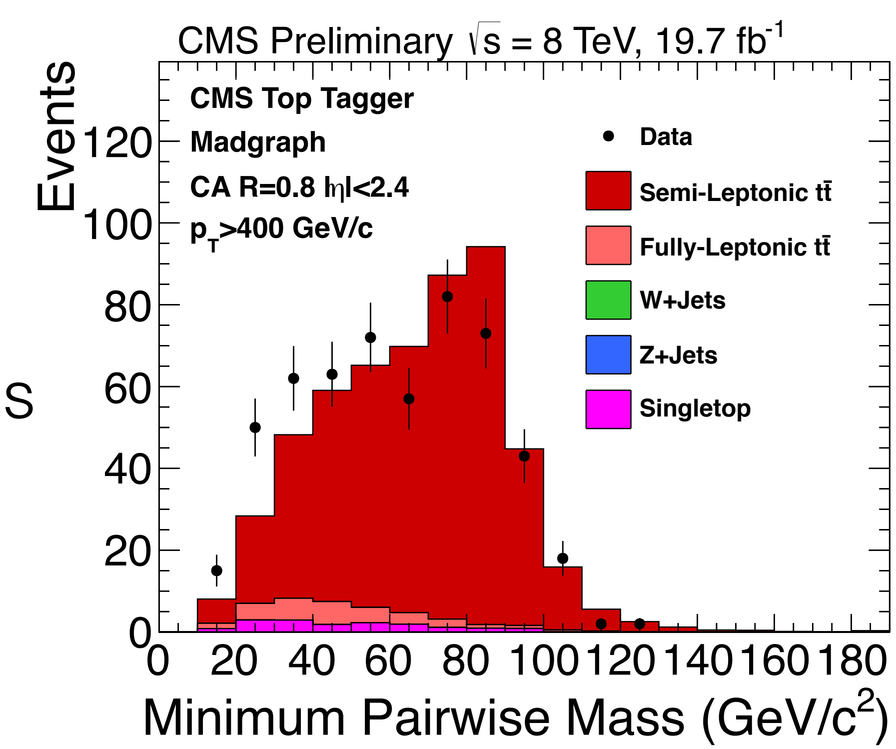


Jet Substructure Techniques

t-tagging

- Start with fat-jets
- Construct variables per fat-jet
  - Invariant mass of the fat-jet
  - Minimum invariant mass of every combination of di-subjets per jet
    - Should resemble the W mass
  - Likelihood of fat-jet consisting on N subjets
- **CMSTopTagger (CTT)**:
  - Jet mass in top mass range
  - 3 or more subjets per fat-jets
  - W mass: approximated by minimum di-subjet mass
  - High degree of likelihood jet contains 3 subjets
  - subjet to originate from b quark





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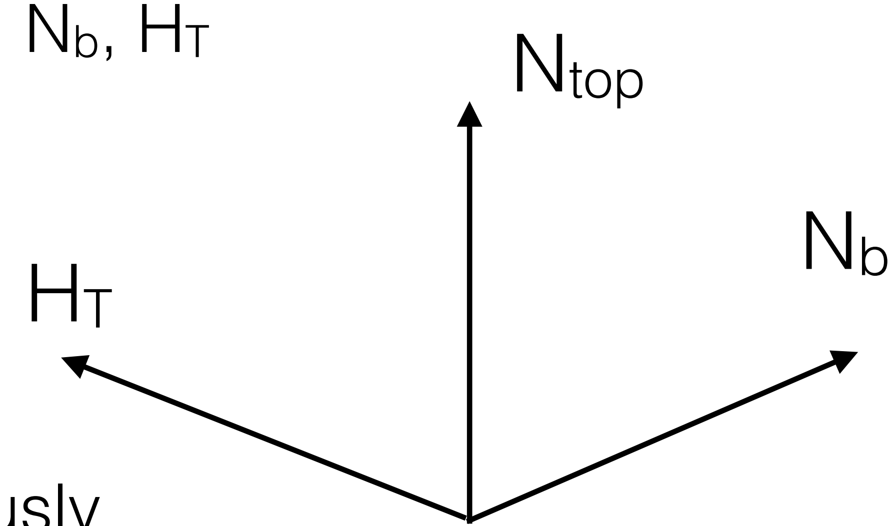
Application to the analysis

Control regions & Additional binning

- High background rejection with **CTT** ≥ 1
- Can exploit **CTT** to append binning categorisation N_{top}, N_b, H_T
  - For H_T, N_b and N_{jet} events



- Potential to include W tagging in parallel or simultaneously
  - Identical grooming techniques as before

- Can redefine control regions to enrich with more tagging ‘friendly’ backgrounds
  - Add N_b ≥1 in SingleMu to enrich with ttbar
  - Invert tagging requirements to predict background contamination

Conclusions

- We have searched for SUSY in the all hadronic channel using the α_T variable
  - No sign of any excess in data
  - Several other SMS models to explore
- Jet substructure techniques could greatly improve sensitivity
  - Provide coverage for boosted topologies
  - Explore regions of phase space previously unreachable
- At CMS, boosted object tagging is already proving itself
  - Run II proving to be very fertile ground
- Hope to incorporate t-tagging in the next generation of α_T analyses

Backup

Supersymmetry

A continuous symmetry that relates fermions and bosons.

- *Minimal Supersymmetric Standard Model (MSSM) includes:*
  - Unification of gauge couplings
  - Dark matter
  - Stability of the vacuum
  - Radiative Elecrtoweak Symmetry Breaking

Hierarchy problem

through a Renormalisable Toy Model

Complex Scalar field: φ

Weyl fermion: ψ

$$\begin{aligned}\mathcal{L} \;=\; & \partial^\mu \phi^* \partial_\mu \phi \;+\; i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi \\ & -\; \frac{1}{2} M_F\, \psi\psi \;-\; \frac{1}{2} M_F\, \psi^\dagger \psi^\dagger \;-\; \lambda_F\, \phi\psi\psi \;-\; \lambda_F^*\, \phi^* \psi^\dagger \psi^\dagger \\ & -\; M_B^2\, \phi^* \phi \;-\; \lambda_B\, (\phi^* \phi)^2 \qquad (1)\end{aligned}$$

Supersymmetry

A continuous symmetry that relates fermions and bosons.

$$\mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi + i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi$$
$$- \frac{1}{2} M_F \, \psi\psi - \frac{1}{2} M_F \, \psi^\dagger \psi^\dagger - \lambda_F \, \phi\psi\psi - \lambda_F^* \, \phi^* \psi^\dagger \psi^\dagger$$
$$- M_B^2 \, \phi^* \phi - \lambda_B \, (\phi^* \phi)^2 \qquad (1)$$

Chiral global $U(1)$ symmetry when $M_F = 0$

$$\phi \to e^{-2i\alpha}\phi \, , \qquad \psi \to e^{i\alpha}\psi$$

1-loop Fermion mass corrections

They must contain at least M_F insertion e.g.

M_F is protected by U(1) symmetry

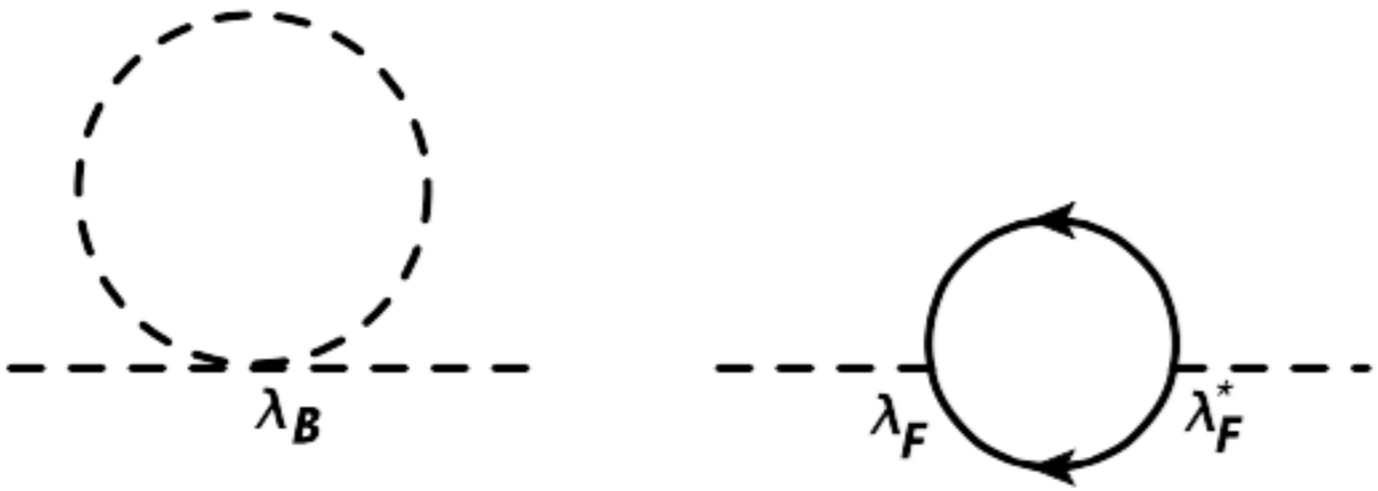
$$\delta M_F \simeq \frac{\lambda_F^2}{16\pi^2} M_F$$

Supersymmetry

A continuous symmetry that relates fermions and bosons.

1-loop Boson mass corrections

The boson mass is not protected by the chiral symmetry



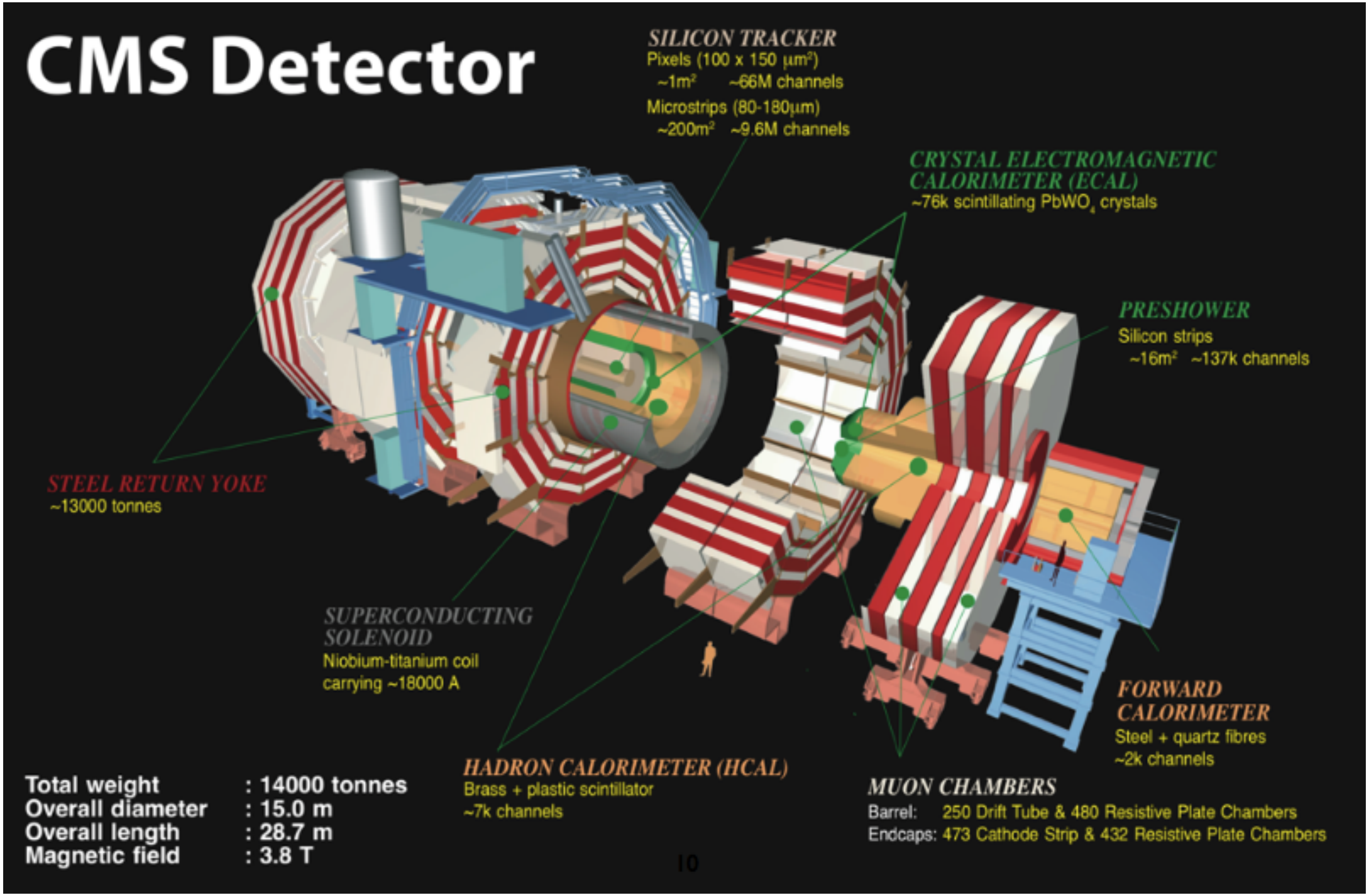
$$\delta M_B^2 \simeq \frac{\lambda_B}{16\pi^2}\Lambda^2 - \frac{\lambda_F^* \lambda_F}{16\pi^2}\Lambda^2$$

Light boson masses are not natural: they are not stable under radiative corrections

M_B receives large, quadratically divergent, radiative corrections, and so does the Higgs boson in the SM

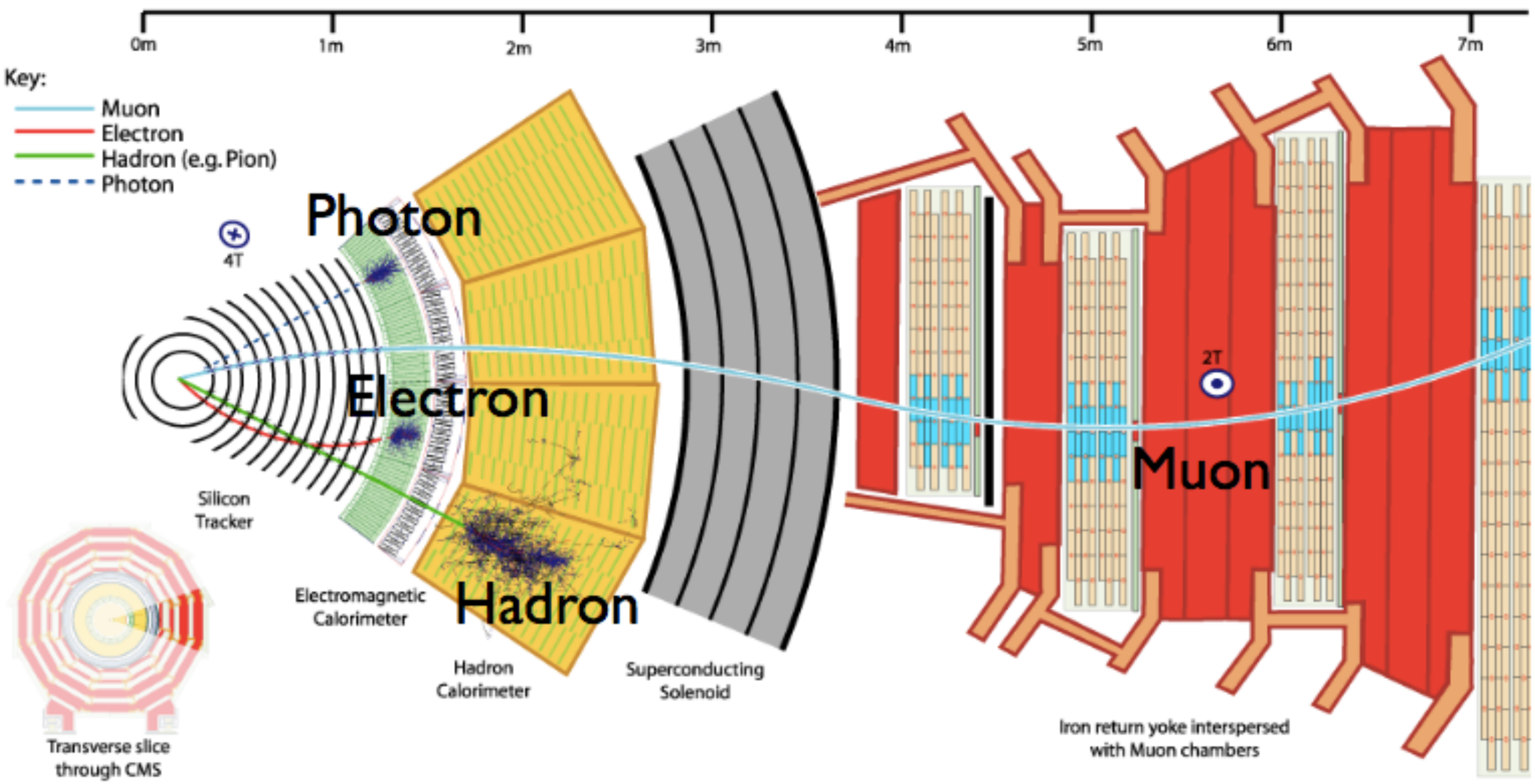
CMS

Compact Muon Solenoid



CMS

Particle interactions at CMS

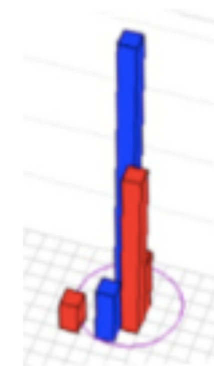


CMS

Jet reconstruction at CMS

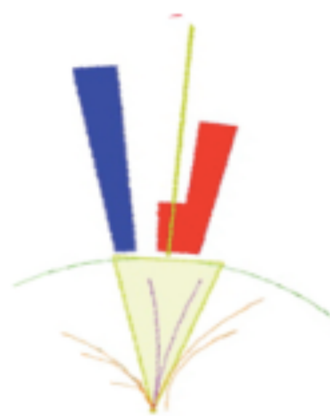
Calorimeter Jets

Jets clustered from ECal and HCal deposits



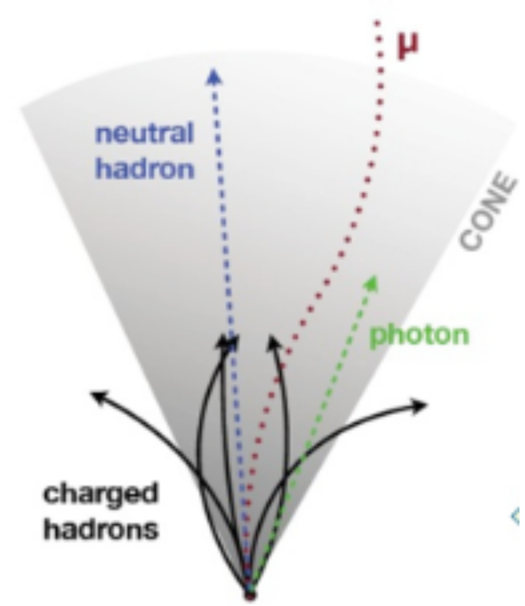
Jet-Plus-Track Jets (JPT)

Subtract average calorimeter response from CaloJet and replace it with the track measurement



Particle Flow

Construct particle flow (PF) objects linking the information from various sub-detectors and interpret them as a unique list of calibrated particles



Event variables at CMS

- **H_T**
  - A measure of how energetic the event was

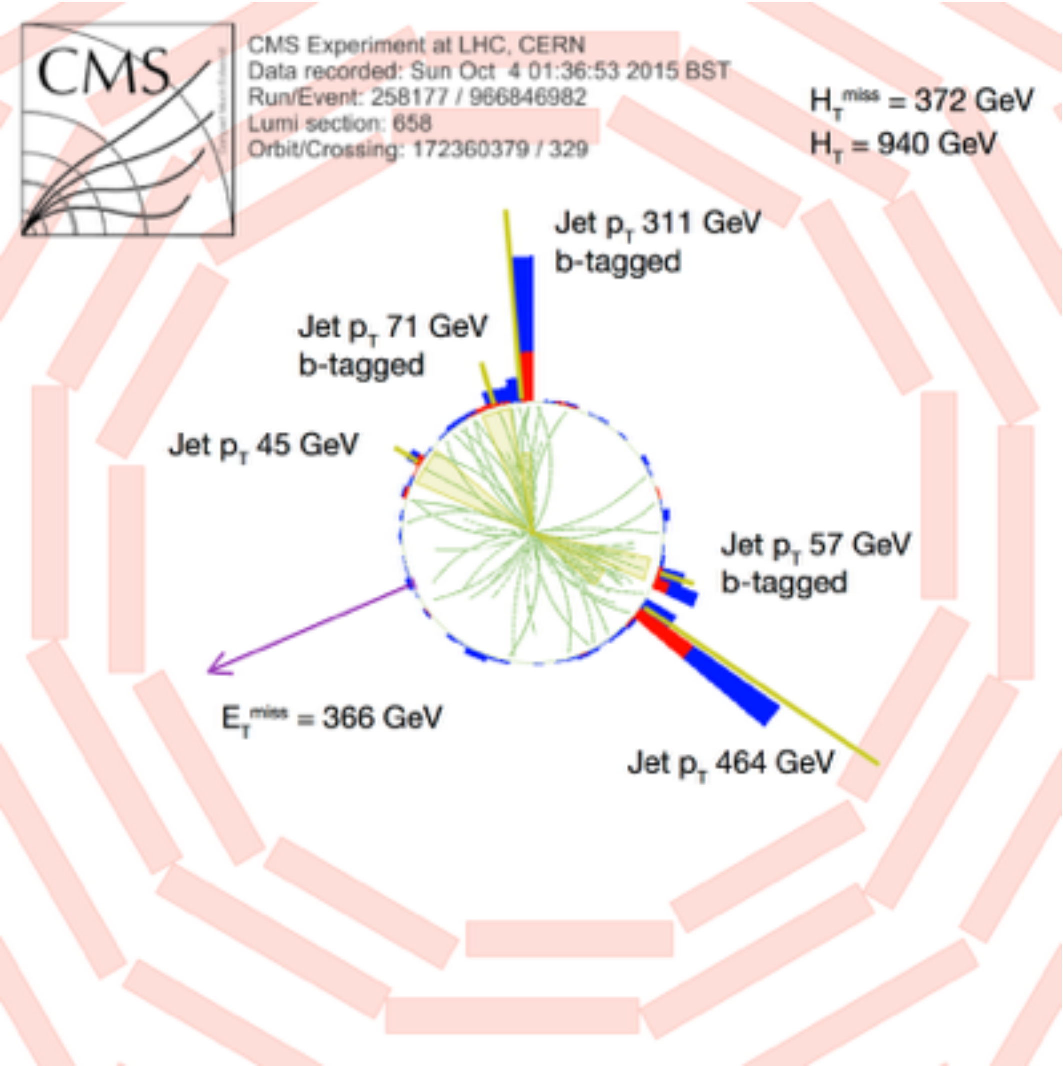
$$H_{\mathrm{T}} = \sum_{i \in \text{jets}} \left| \vec{p}_{\mathrm{T}i} \right|$$

- **MET**
  - Missing energy- ideally due to invisible particles

$$\vec{E}_{\mathrm{T}}^{\text{miss}} = \vec{\not{E}}_{\mathrm{T}} = -\sum_{i \in \text{particles}} \vec{p}_{\mathrm{T}i}$$

- **MHT**
  - Alternative to MET- constructed with jets only

$$\vec{H}_{\mathrm{T}}^{\text{miss}} = \vec{\not{H}}_{\mathrm{T}} = -\sum_{i \in \text{jets}} \vec{p}_{\mathrm{T}i}$$



Analysis strategy

Control regions

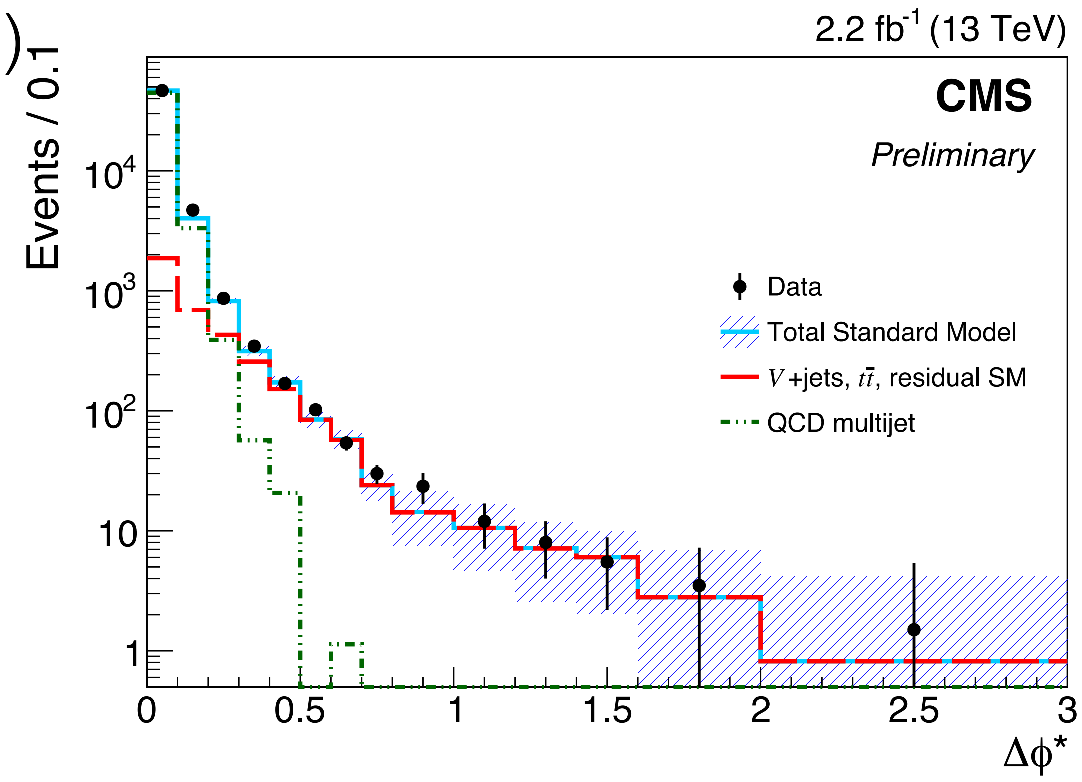
- Baseline selection
  - $N_{jet} \geq 1$ ($p_T > 40$ GeV), $H_T > 200$ GeV, $MH_T > 130$ GeV
  - Employ a forward jet veto and MHT/MET < 1.25 cut
- Signal region
  - Lepton and photon **veto**
  - H_T dependent α_T cuts from 0.65 to 0.52 for $H_T < 800$ GeV
  - $\Delta\phi^* > 0.5$ requirement
- Single (double) muon and photon control region
  - 1(2) muon(s) with $p_T > 30$ GeV, |eta| < 2.1 or one photon with $p_T > 200$ GeV
  - Relative isolation requirement
  - For leptons, M_T (M_{ll}) to be compatible with W (Z) mass
  - Lepton/ photon ignored for variables

Background Estimation

QCD multijet and non-multijet backgrounds

- QCD multijet production strongly suppressed with α_T, $\Delta\phi^*$, MHT/MET cuts
    - Remainder estimated with QCD-enriched sideband in data
        - Invert MHT/MET (> 1.25) cut
        - Obtain data counts with non QCD contribution removed
        - Take pass-fail ratio R_{QCD} of QCD MC on MHT/MET cut
        - Product of above yields estimate for QCD contamination

- Validation of R_{QCD} in $\Delta\phi^*$ data sideband ($\Delta\phi^* < 0.5$)
    - Ratio R_{QCD}(data) / R_{QCD}(mc) should be 1



Background Estimation

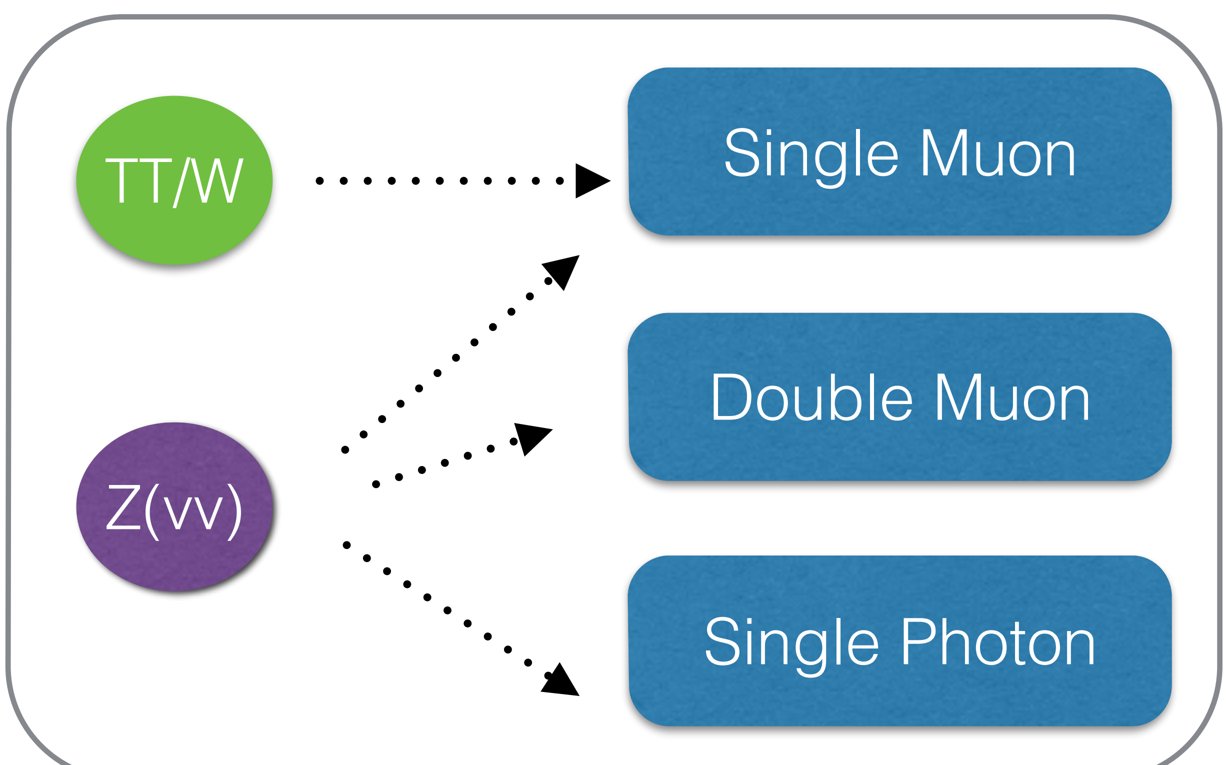
QCD multijet and non-multijet backgrounds

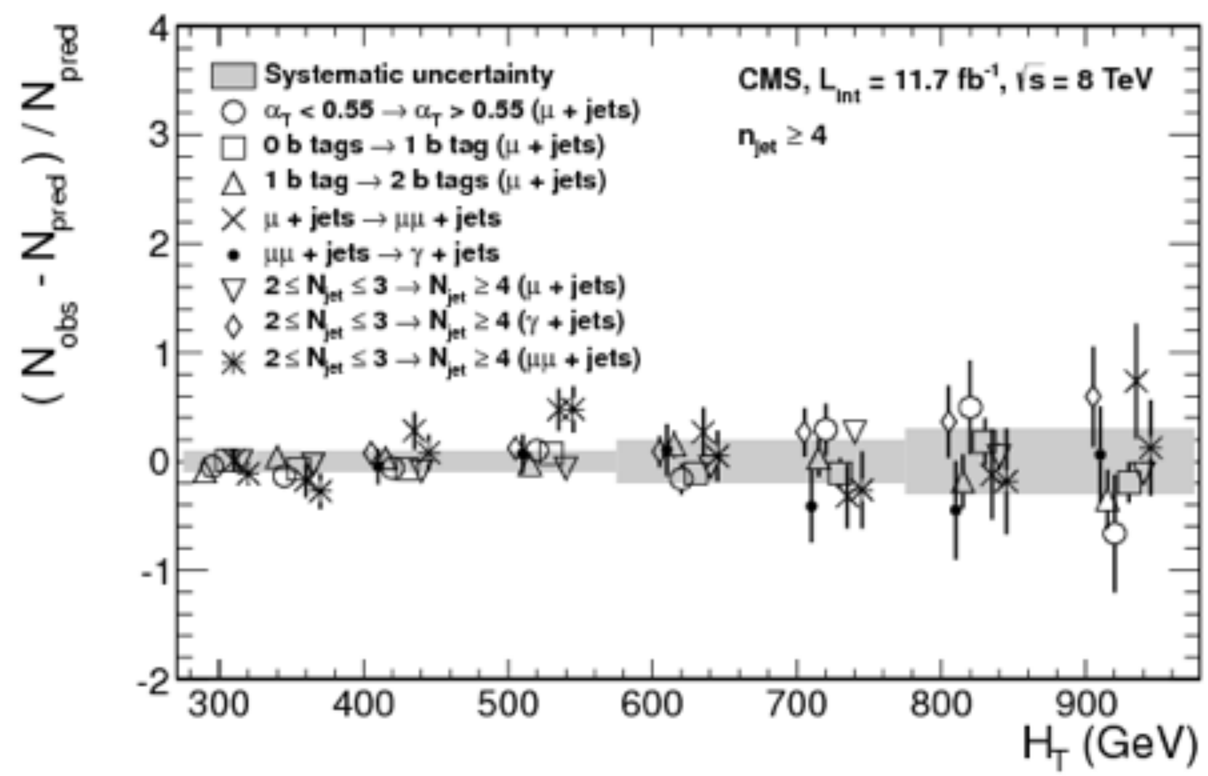
- For non-multijet backgrounds, transfer factors used to predict backgrounds
  - Extrapolation of observed counts in control regions to predicted counts in signal

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

- Potential biases in TFs are assessed in data with closure tests between several control (sub-)samples

http://arxiv.org/abs/1303.2985





Tagging at CMS

- N-subjettiness
  - Describes a jet shape
  - Effective measure for identifying how the jet energy is divided into subjets
  - Try to obtain 'lobes' of energy in a jet by clustering *k* constituent jet particles around N candidate subjet axes

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\} .$$

  - where $d_0 = \sum_k p_{T,k} R_0$

- Minimum pair wise mass
  - Minimum invariant mass of every combination of di-subjets per jet
  - Should resemble the W boson

V-tagging

- AK8 jets (recluster CA8)
  - Reverse clustering sequence based of 'groomer'
- For Run II use soft drop mass variable (instead of pruned mass):
  - Jet mass in range [70, 100] GeV
  - 2 or more subjets per AK8 jet
  - N-subjetiness τ_{21} in range [0.5, 0.75]
  - N-subjetiness $\tau_{21} < 0.5$ → **tight working point**

Previous results

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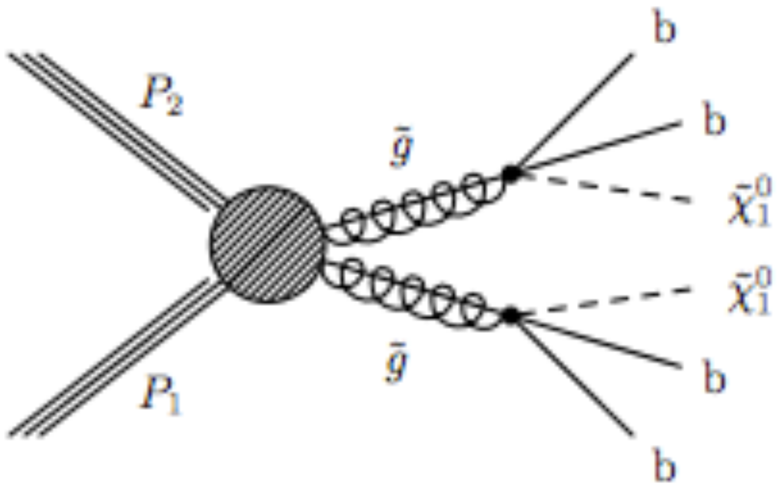
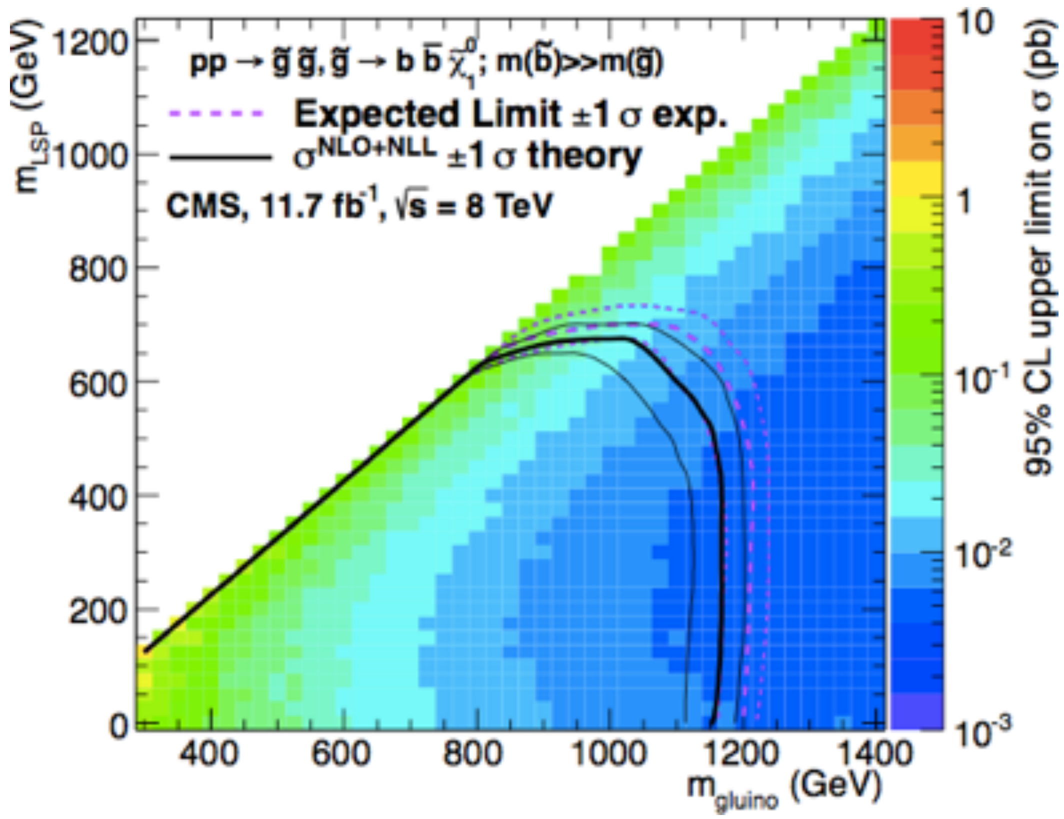
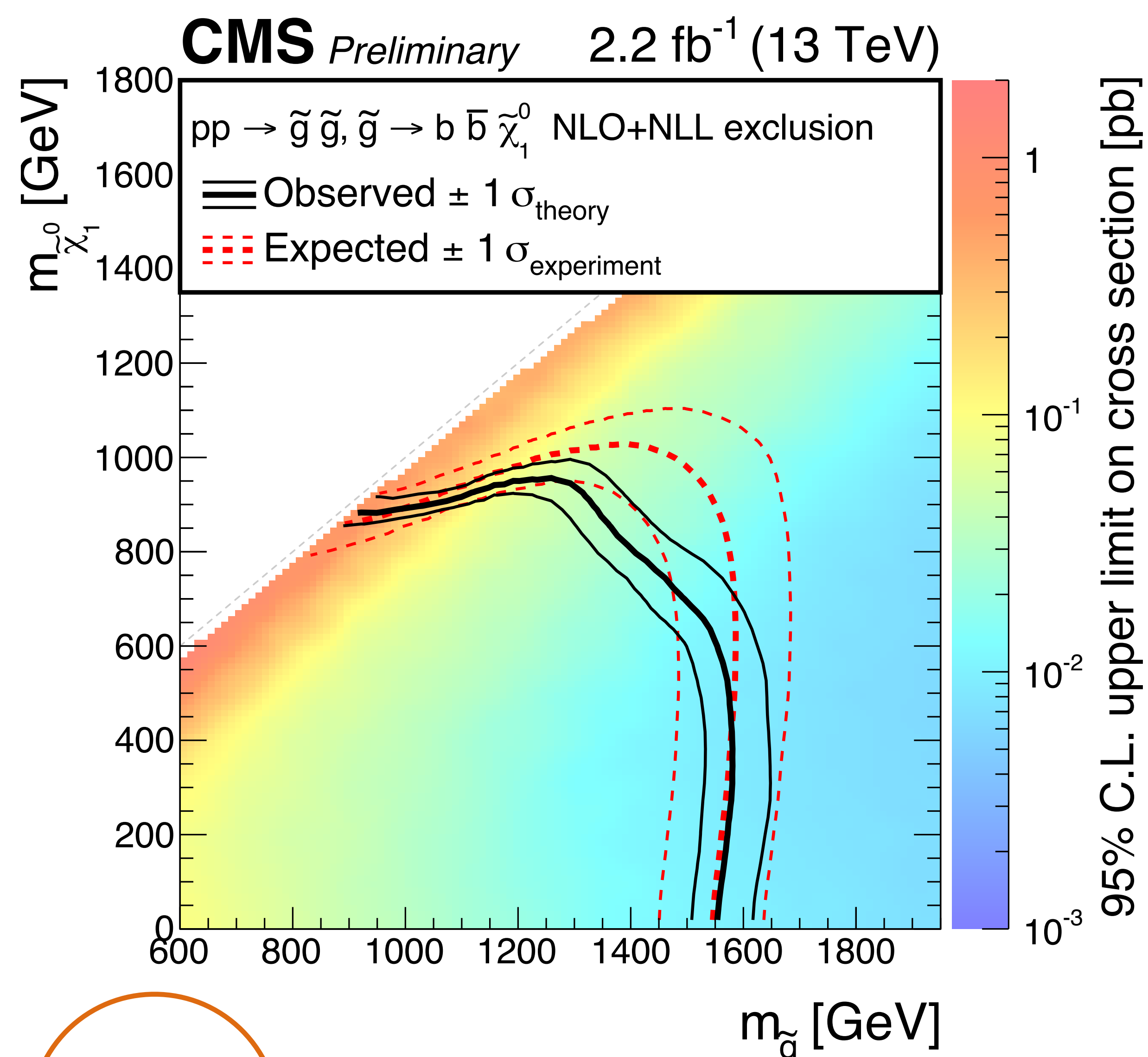




8 TeV



13 TeV

Incorporation

Pre-Selection

- Objects become boosted at high p_T
- Apply a harsher baseline selection
  - N_{jet} (ak4) ≥ 5, Nb (ak4) ≥ 2, H_T (ak4) ≥ 800 GeV, MH_T (ak4) ≥ 130 GeV
  - Apply a forward jet veto and MH_T / MET < 1.25

  - N_{jet} (ak8) ≥ 2
  - p_T (ak8) ≥ 170 GeV
  - $N_{subjets}$ (per at least 1 ak8 jet) ≥ 3

  } t-tagging baseline

- **CTT**:
  - Jet mass in [140, 250] GeV range
  - m_{min} > 50 GeV
  - τ_{32} < 0.6
  - subjet b-disc > 0.79

Substructure at Trigger Level