Searches for SUSY in Hadronic Final States at CMS

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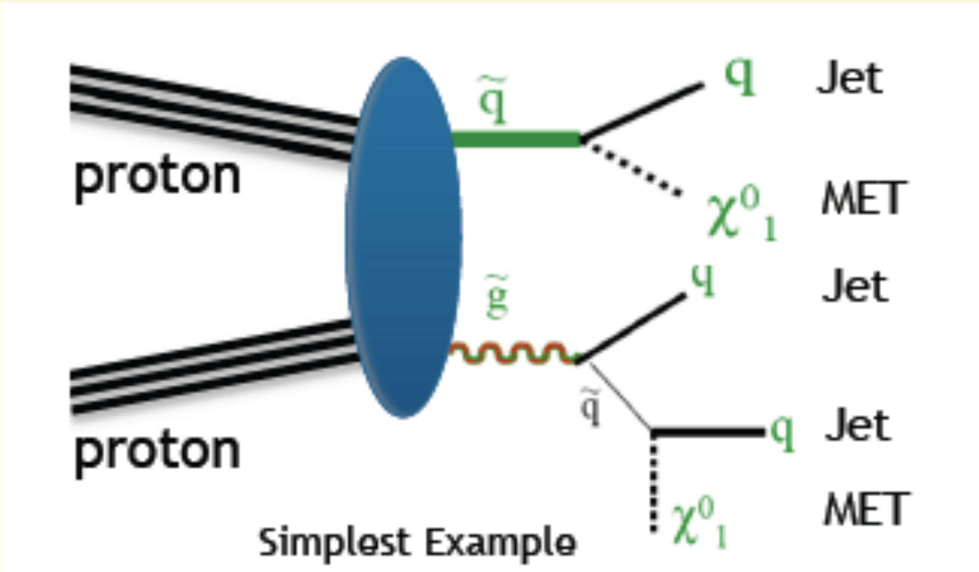
Jets+Missing Transverse Momentum

- A generic search for large missing transverse momentum in multijet events is motivated by R-parity conserving SUSY
  - strong production of pairs $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$

SUSY particles eventually decay to **L**ightest **S**upersymmetric **P**article (stable, neutral, massive) which results in missing transverse momentum (χ^0_1 in this example)



Experimental signature:
Jets + Missing Transverse Momentum

The SM processes which can give similar signature are
- Z(ν ν) +Jets
- W/Top+Jets with W(e/μ/τ ν)
- QCD multijet production (heavy flavor, mis-measured jets)

Key point is to understand the backgrounds.

All Hadronic Analysis @ CMS

- CMS has four analyses in all hadronic channel looking for excess of events in the tail of distributions of sensitive variables used. Events with an isolated electron or muon are vetoed in these analyses.
  - Jets + MHT ; 5 fb^{-1} @ 7 TeV (SUS-12-011)
  - M_{T2} Analysis ; 5 fb^{-1} @ 7 TeV (SUS-12-002)
  - α_T analysis; 4 fb^{-1} @ 8 TeV (SUS-12-016)
    - α_T analysis (5 fb^{-1} @ 7 TeV) : SUS-11-022
  - SUS-12-005 : RAZOR (Talk [659] by Will Reece @ 12:30 today)

Results can be interpreted in terms of any theory model which results in the same final state : a number of quarks and gluons and undetected particles.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Jets + MHT Search

Sensitive variables used for this search

HT : Transverse Hadronic Energy

$$H_T = \sum_i^{jets} \left| \vec{p}_{T,i} \right|$$

Characterizes visible energy of the event

MHT : Missing Transverse Hadronic Energy (equivalent to MET)

$$\not{H}_T = \left| -\sum_i^{jets} \vec{p}_{T,i} \right|$$

Characterizes momentum carried by undetected particle in the event

HT using jets with p_T>50 GeV, $\lvert\eta\rvert < 2.5$
No. of jets ≥ 3
MHT using jets with p_T>30 GeV, $\lvert\eta\rvert < 5.0$
$\Delta\Phi(\text{MHT}, \text{Jets}^{\{1,2,3\}}) > (0.5, 0.5, 0.3)$
Veto events with isolated electrons/muons

MHT→ HT↓	200-350	350-500	500-600	>600
500-800	bin 1	bin 2	bin 3	bin 4
800-1000	bin 5	bin 6	bin 7	bin 8
1000-1200	bin 9	bin 10	bin 11	
1200-1400	bin 12	bin 13		
>1400	bin 14			

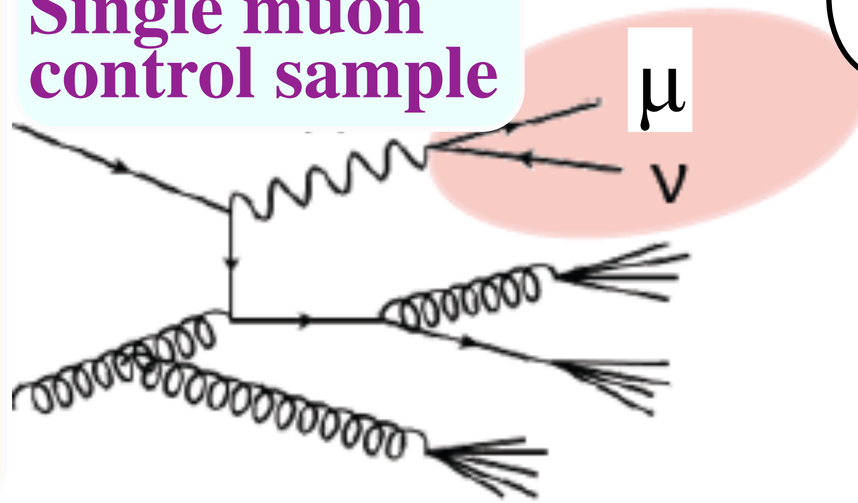
“Classical” approach : multiple search bins in HT and MHT

Jets + MHT : Background Estimation

Backgrounds are estimated using control samples from data (signal depleted selection)

1. **W / Top (→ lost lepton + ν) + Jets** : rescale event yield in search region with lepton inefficiencies measured from data

Single muon control sample

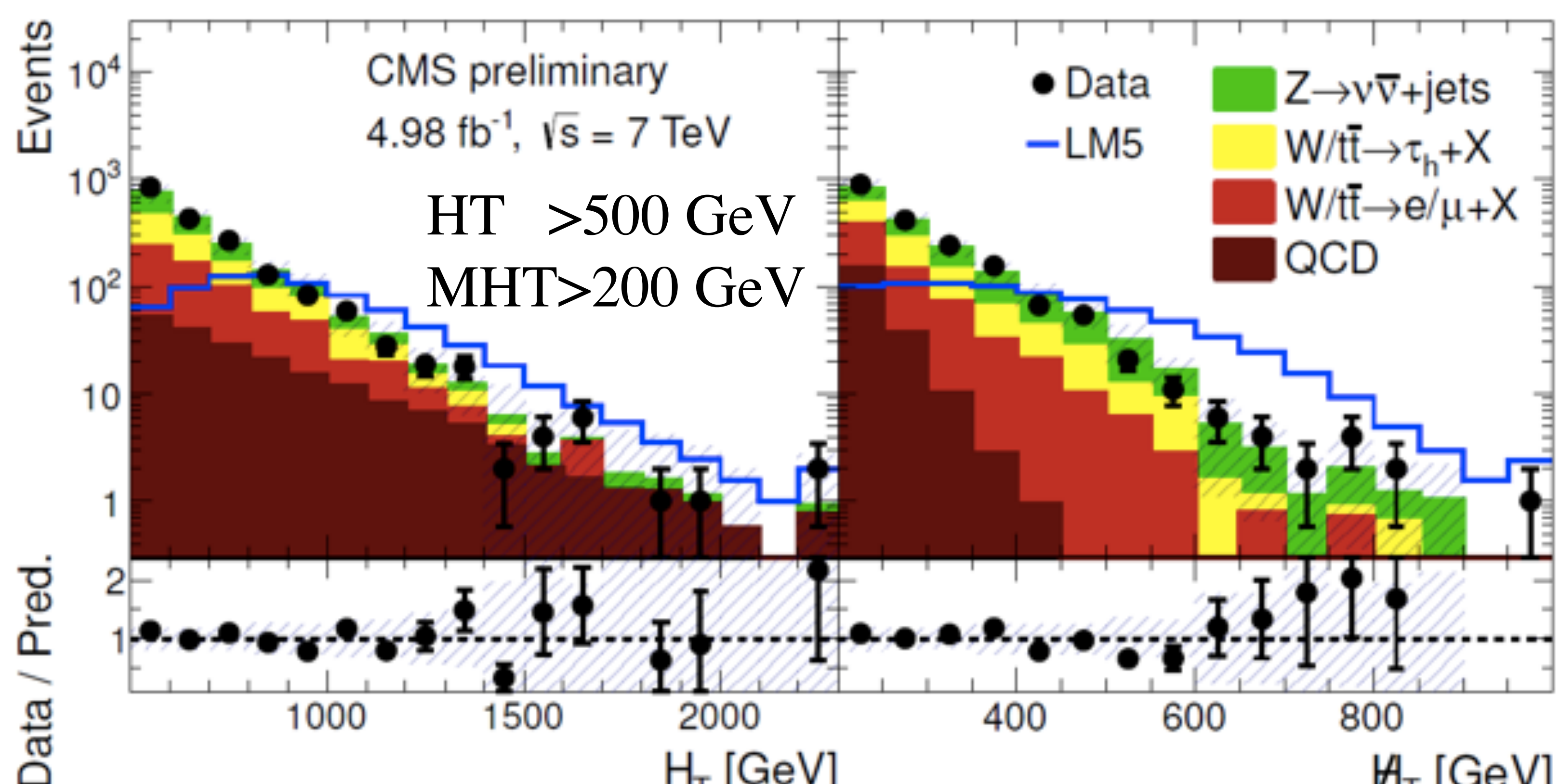


2. **W / Top (→ hadronic τ + ν) + Jets** : replace muon with a tau jet and recalculate kinematic variables used in the analysis (HT/MHT/M_{T2})

3. **Z(νν)+Jets using γ+jets events** : exclude γ in HT and MHT calculation

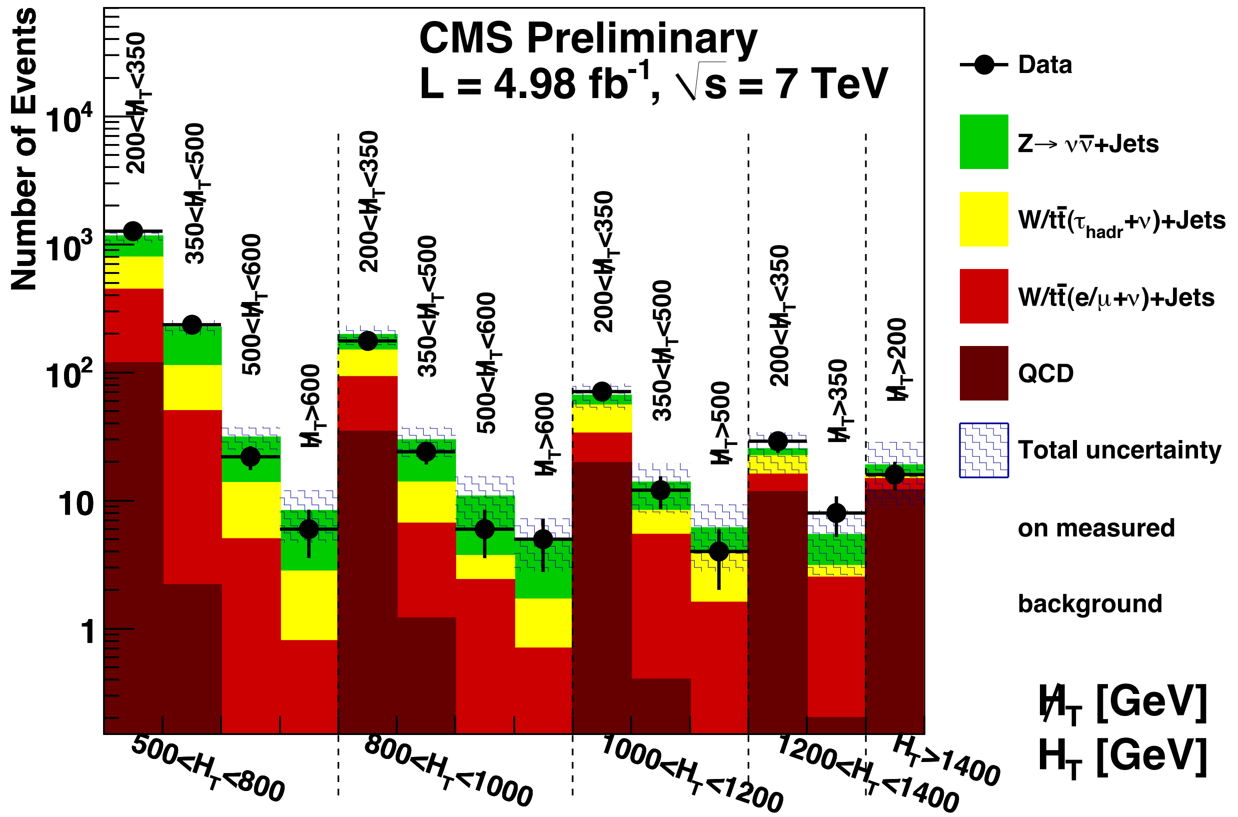
4. **QCD multijet background** : using rebalance and smear technique on multijet data events

- Methods are validated using simulated events.
- Full kinematics of the events in the signal region can be predicted using these methods on data.

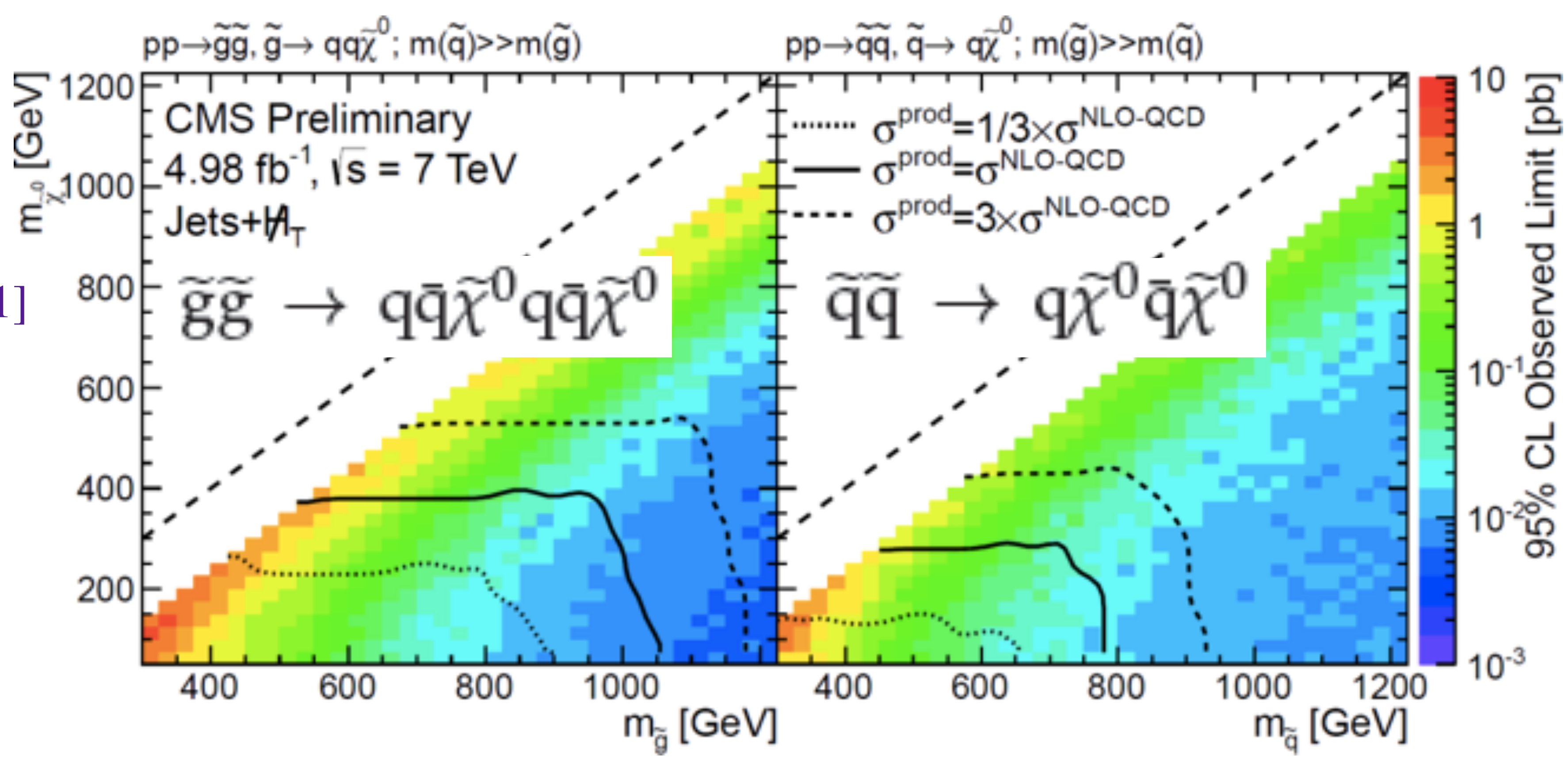


Jets + MHT : Results and Interpretation

Observed events are consistent with expected standard model backgrounds in all 14 search regions in HT & MHT.



- Results are used to :
  - constrain CMSSM parameters
  - derive cross-section upper limits for Simplified topologies (SMS) defined by production mode and decay channel
  - More details in interpretation talk[661] by Christopher Rogan @ 14:00 today
- Exclusions in parameter space is derived using production cross-sections (NLO+NLL calculations).



M_{T2} (STransverse Mass)

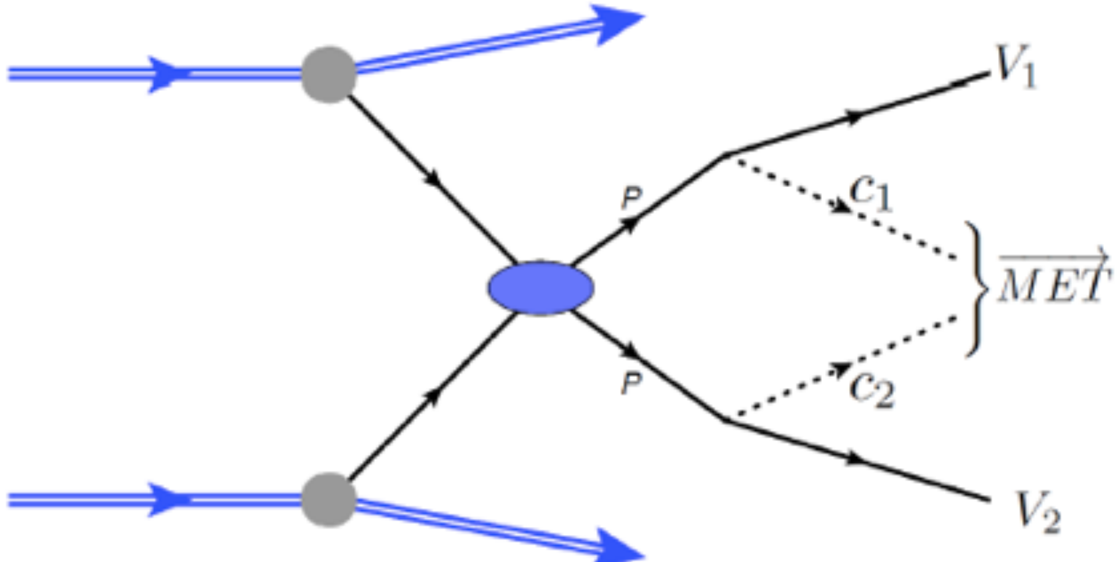
Sensitive variables used in this analysis : STransverse Mass or M_{T2}

Extension of transverse mass in presence of two decay chains with missing particles.

$$M_{T2} = \min_{p_T^{c1}+p_T^{c2}=\not{p}_T} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$

Multijet events are divided into two pseudojets using hemisphere algorithm.

- $M_{T2} \sim$ MET for symmetric topologies : SUSY
- M_{T2} is a QCD killer :
  - $M_{T2} \sim 0$ for nearly balanced systems
  - M_{T2} < MET for imbalanced and asymmetric systems : still highly suppressed for nearly back-to-back QCD mismeasurements



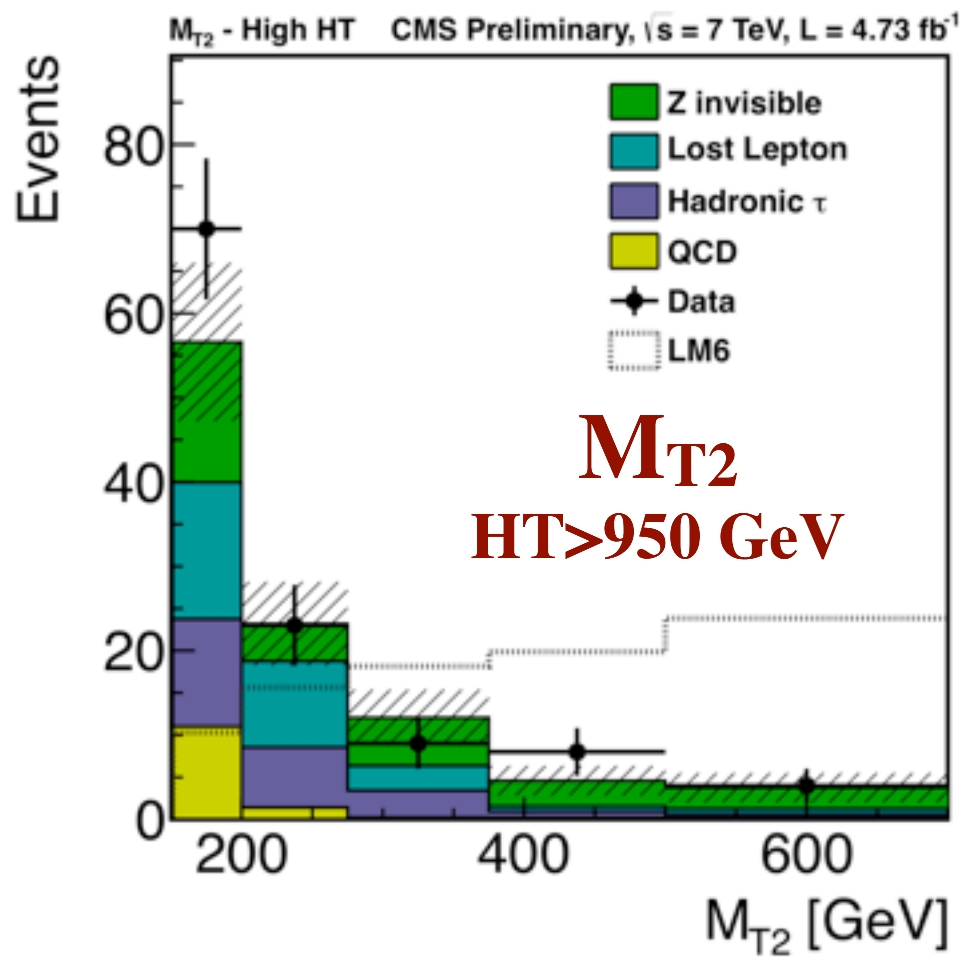
Multibinned analysis :

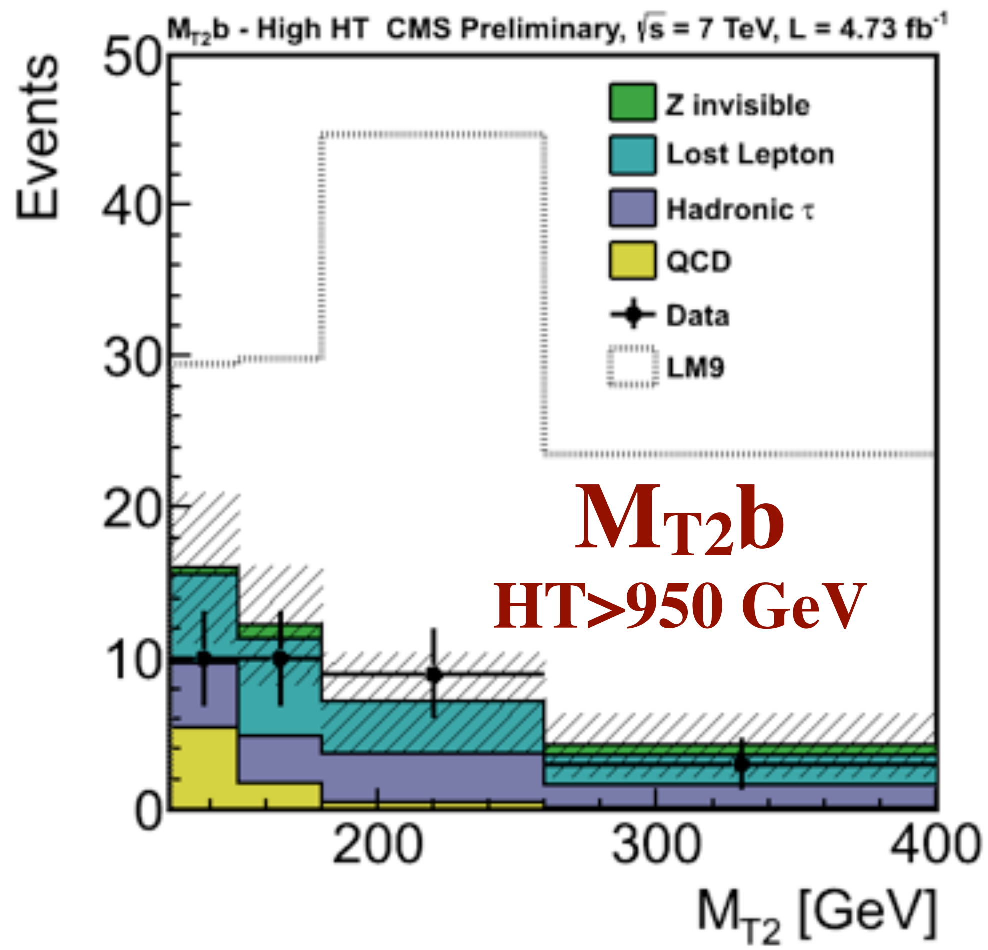
- excess in tails on M_{T2} in inclusive search
- and search requiring a b-jet in the event

No. of jets ≥ 3 (≥ 4 for M_{T2}b)
2 HT bins : (750-950), (>950) GeV
5 M_{T2} bins (150-200-275-375-500-∞) GeV)
$\Delta\Phi^{min}$(MET, Jets) > 0.3

M_{T2} : Background Estimation

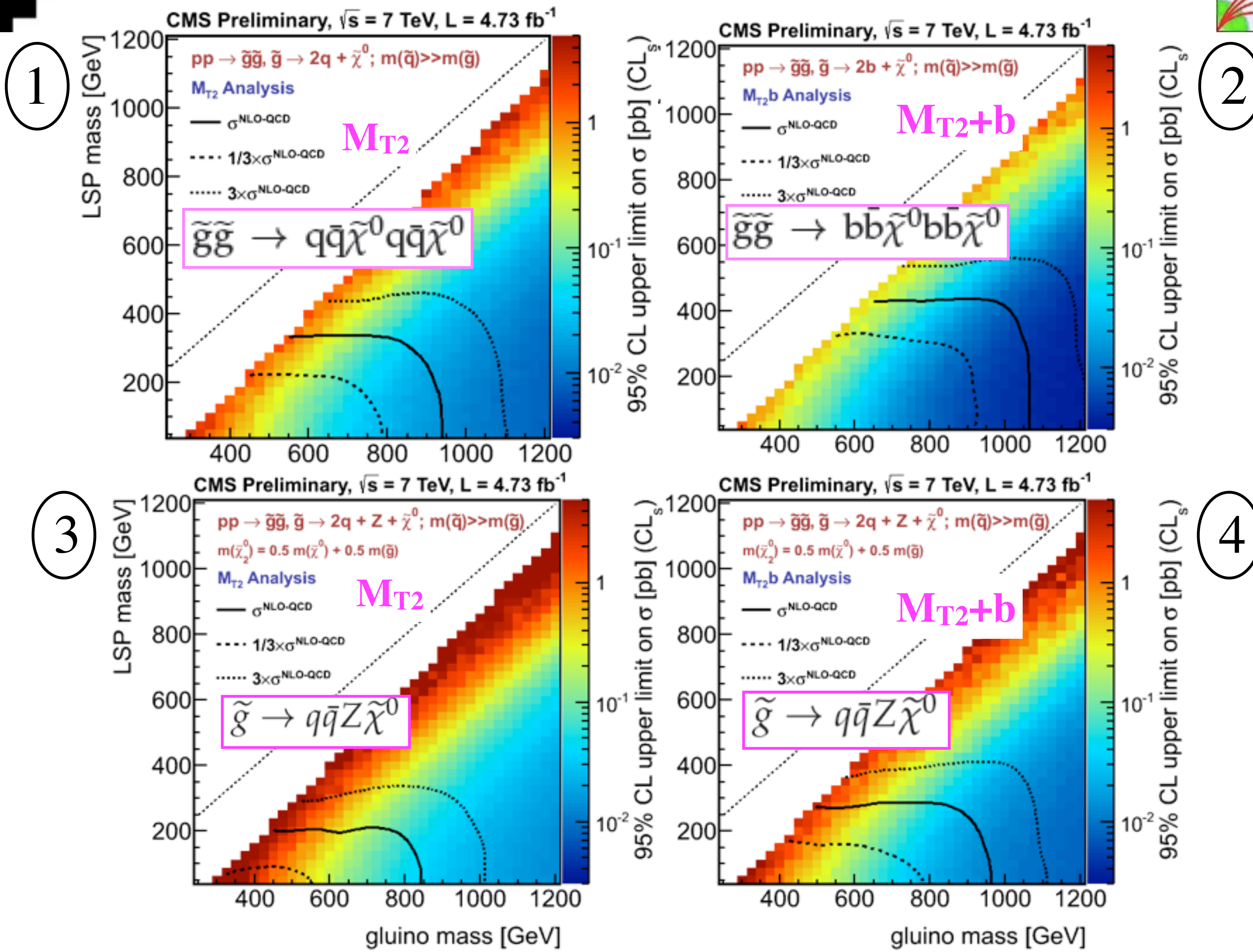
- Electroweak backgrounds are estimated using similar methods discussed in previous search :
  - Z(νν)+Jets : using γ+jets event and μ+jets events
  - W / Top (→ lost lepton + ν) + Jets : using μ(e)+jets events
  - W / Top (→ hadronic τ + ν) + Jets : based on simulation, validated for tau jet reconstruction using data events
- QCD multijet background : factorization method based on functional form, fitted in QCD dominated region (negligible QCD background in signal region)





No excess in observed data over expected backgrounds

M_{T2} : Cross-section limits in Simple Topologies



Search using α_T Variable

Key feature : Strong suppression of QCD multijet events

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

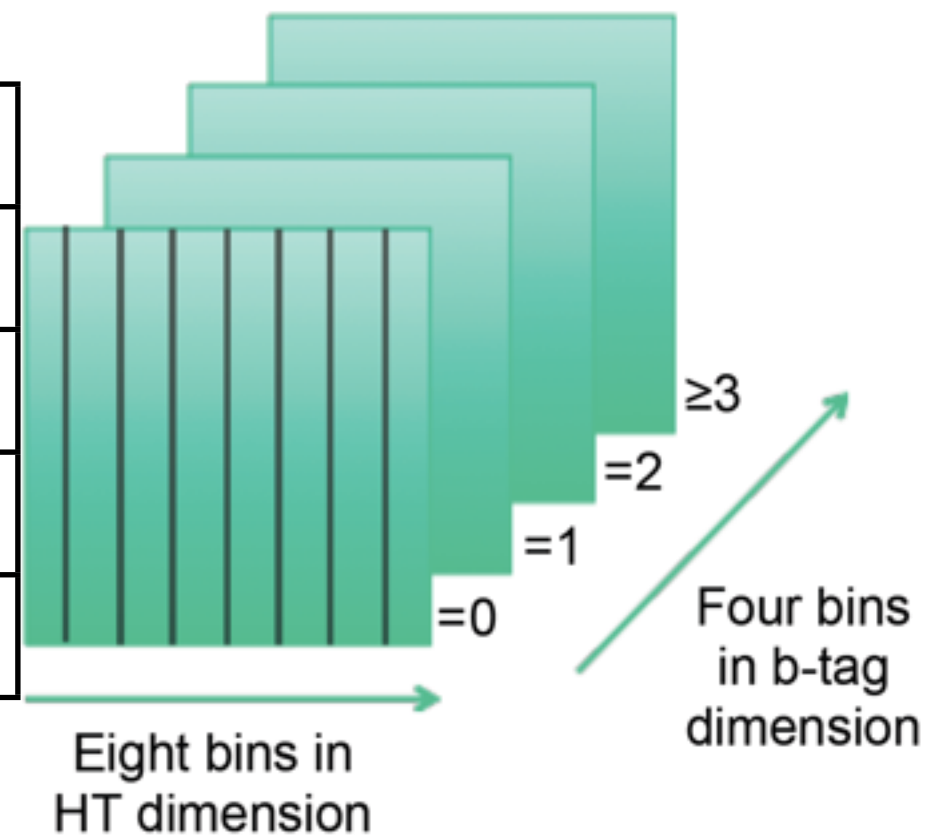
For well balanced dijet systems, $\alpha_T = 0.5$

For an multi-jet system, jets are merged to make an equivalent dijet system such that difference in E_T of two systems (ΔH_T) is minimum.

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

Jets with p_T>50 GeV, $\lvert\eta\rvert < 3$
No. of jets ≥ 2
$\alpha_T > 0.55$
lepton/photon veto
Protection against mis-measurement of jets due to insensitive detector component

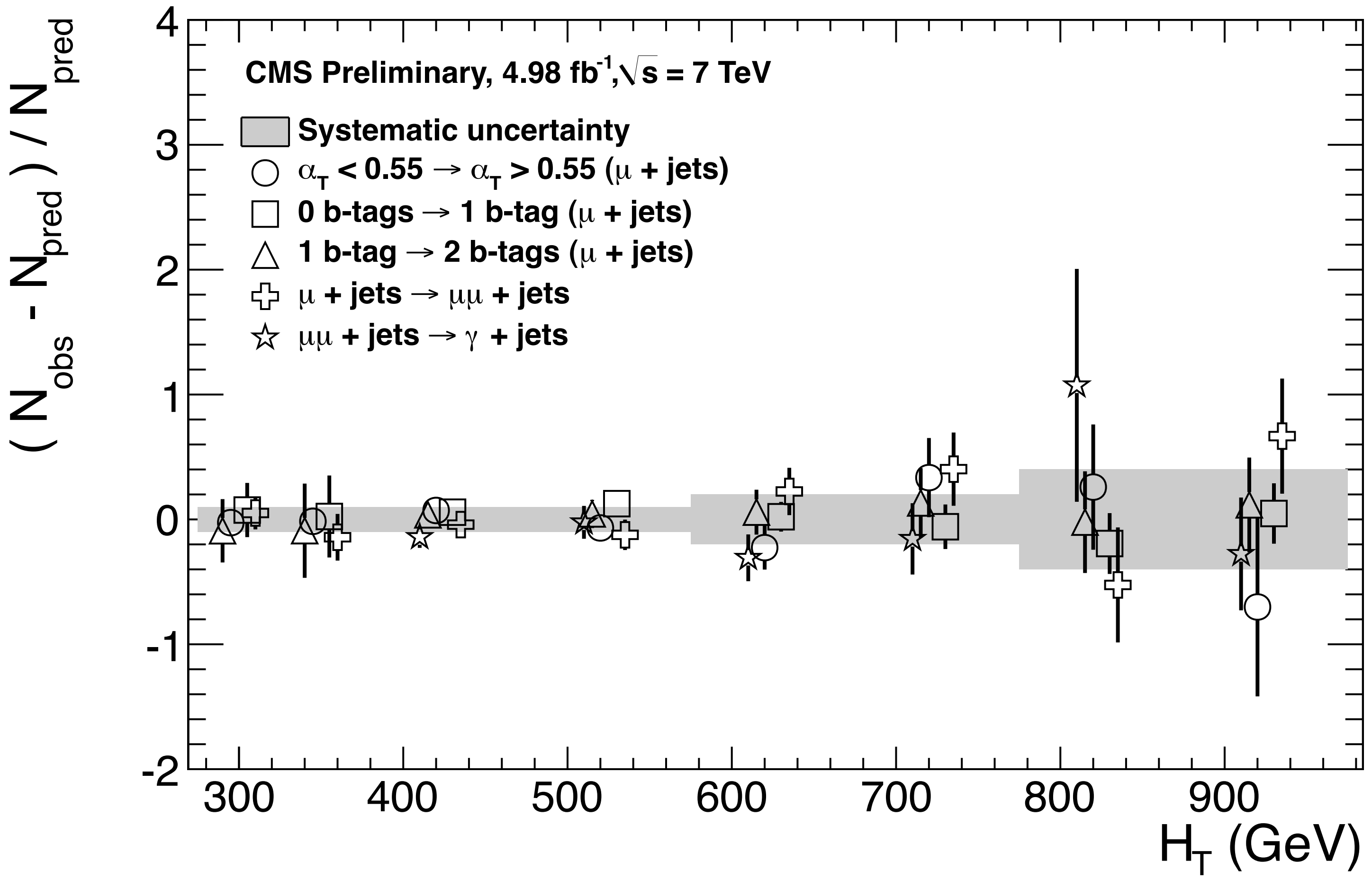
HT bins (GeV)	
275-325	275-375
375-475	475-575
575-675	675-775
775-875	> 875



α_T : Background Estimation

- Backgrounds are estimated using single muon, dimuon and photon + jets control samples from data.

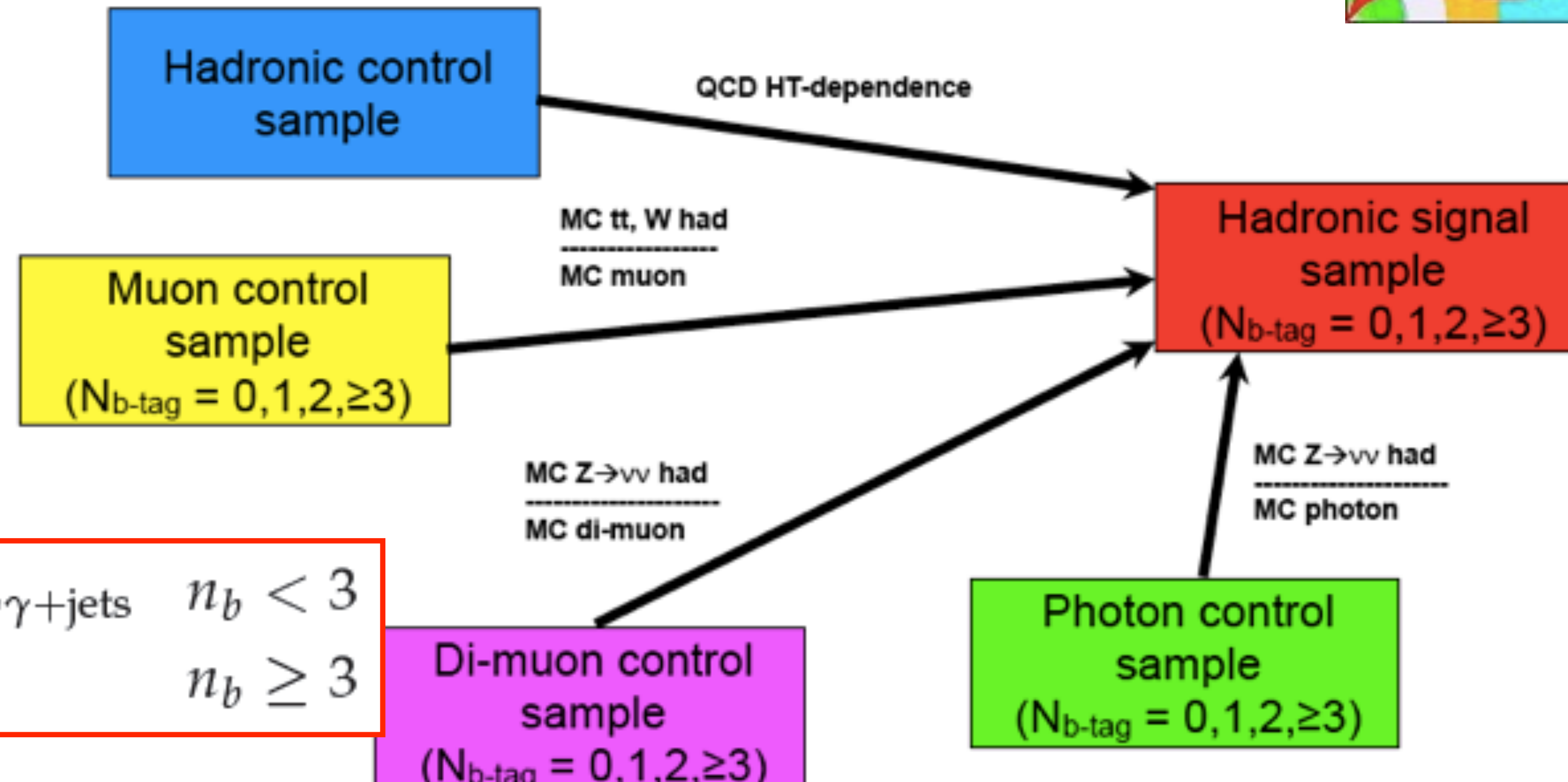
$$N^{\text{signal}}_{\text{pred}}(H_T, n_b) = N^{\text{control}}_{\text{obs}}(H_T, n_b) \times \frac{N^{\text{signal}}_{\text{MC}}}{N^{\text{control}}_{\text{MC}}}(H_T, n_b)$$



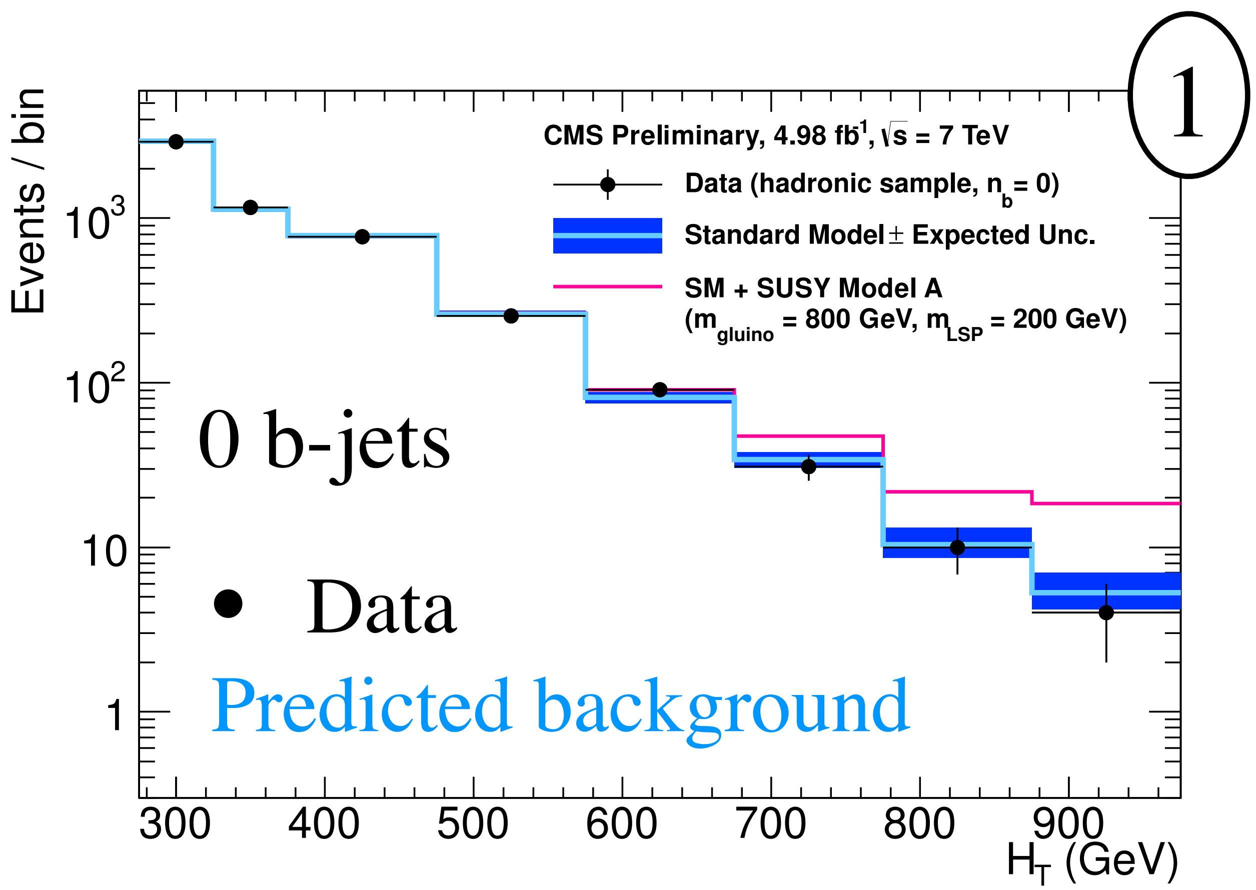
- Systematic uncertainties on MC ratios are determined from detailed closure tests using various control samples from data to validate relative contribution of various backgrounds, kinematic properties & b-jet reconstruction.

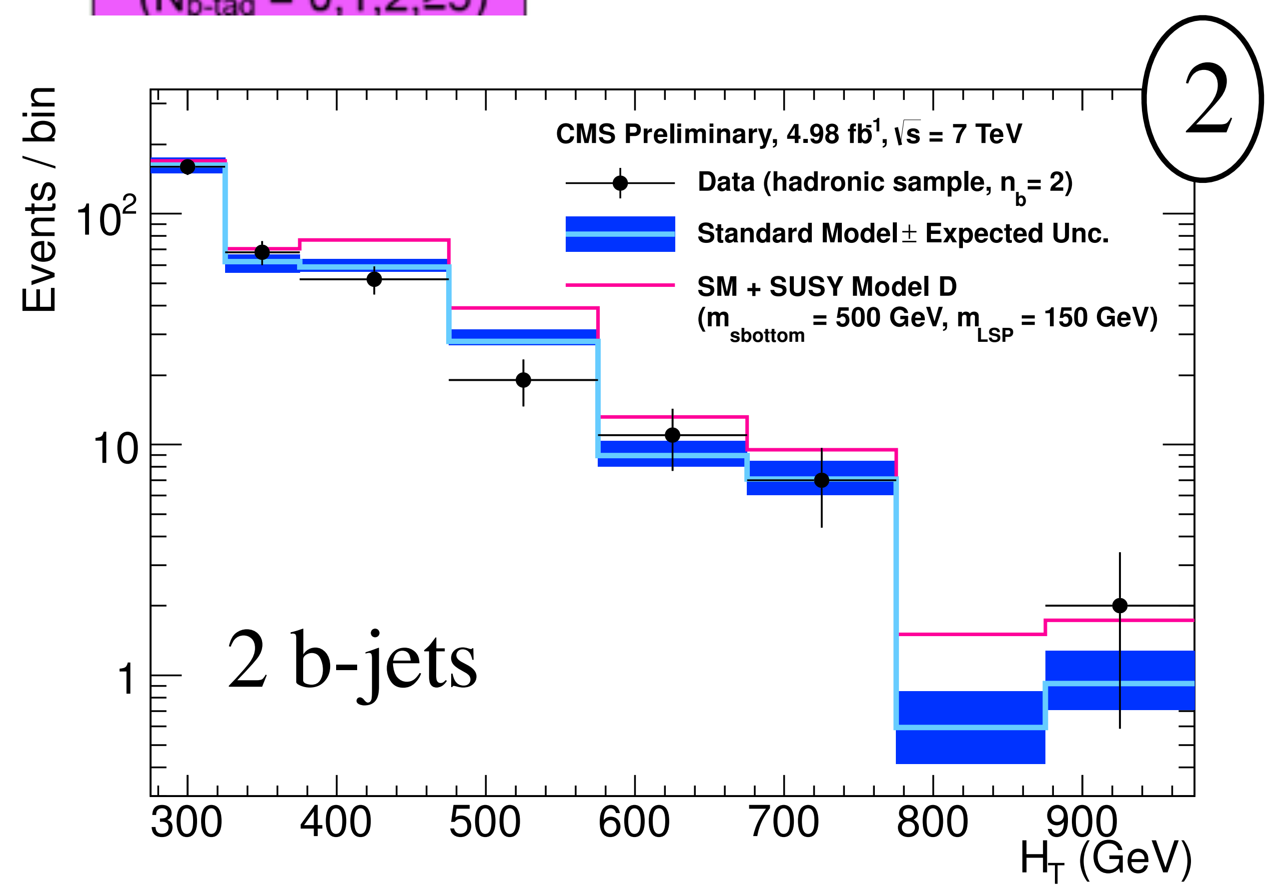
α_T : Shape Analysis

- To predict SM backgrounds in each search bin, a binned likelihood fit using all control samples is carried out to maximize the total likelihood :



$$L_{\text{total}} = L_{\text{hadronic}} \times L_{\mu+\text{jets}} \times L_{\mu\mu+\text{jets}} \times L_{\gamma+\text{jets}} \quad n_b < 3$$
$$L_{\text{total}} = L_{\text{hadronic}} \times L_{\mu+\text{jets}} \quad n_b \geq 3$$

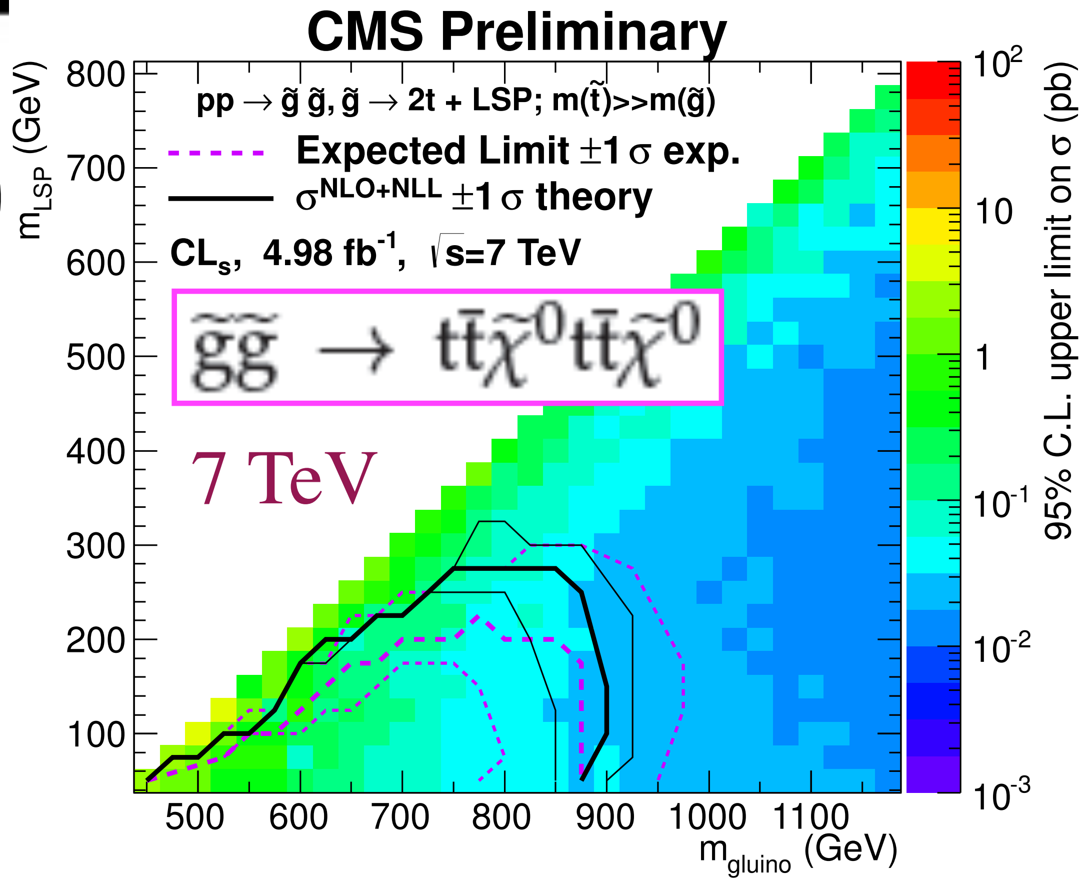




Data is consistent with predicted standard model backgrounds.

α_T : Cross-section limits in Simple Topologies

1



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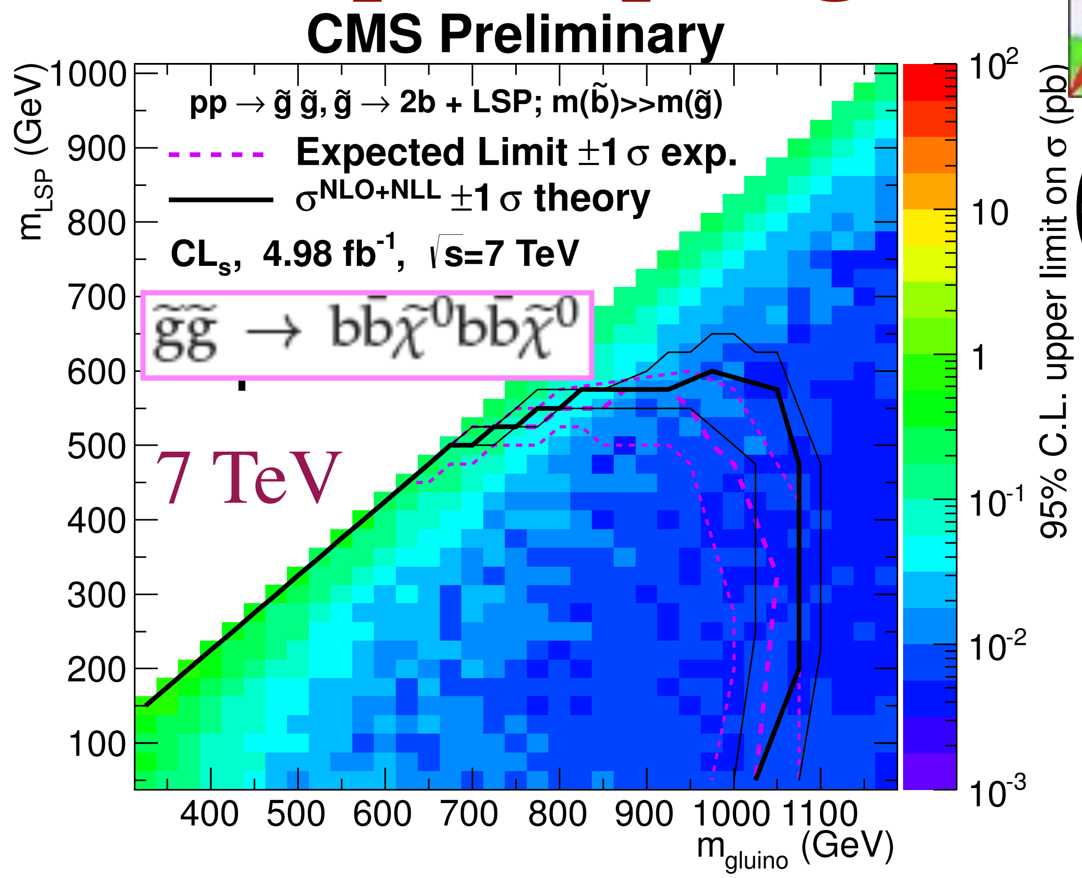

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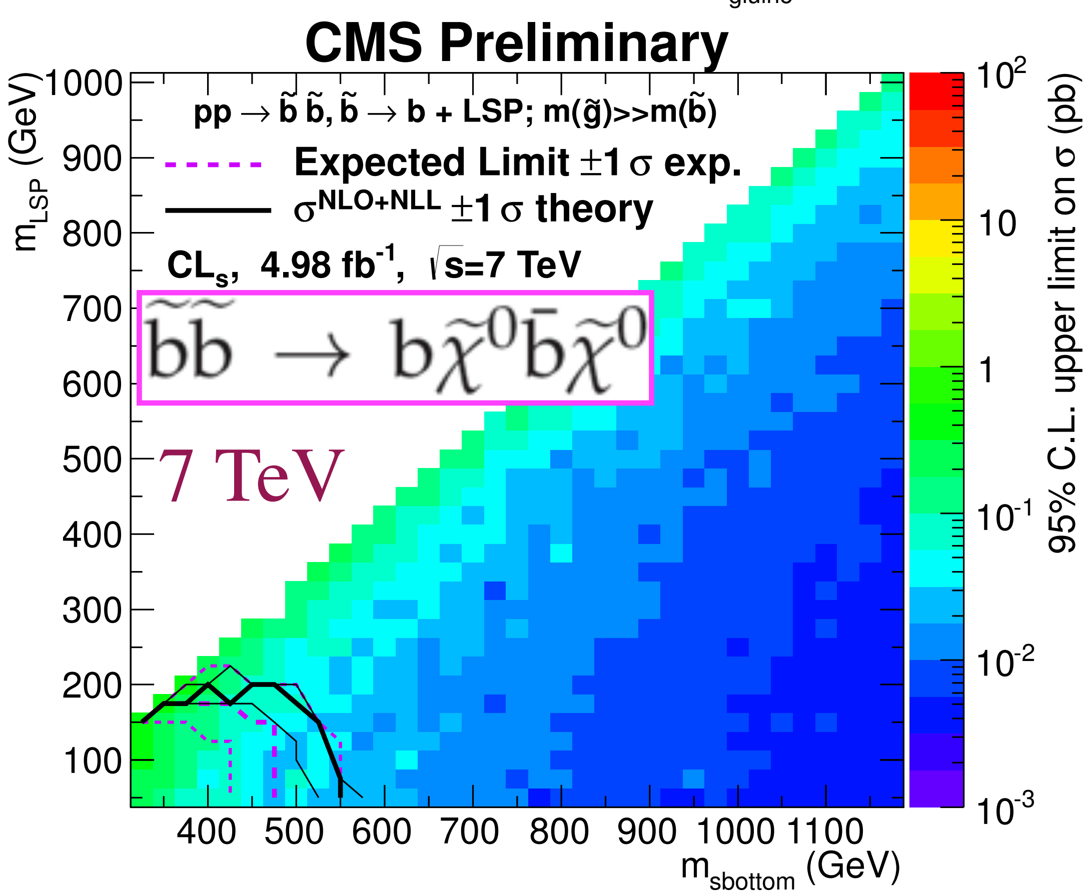

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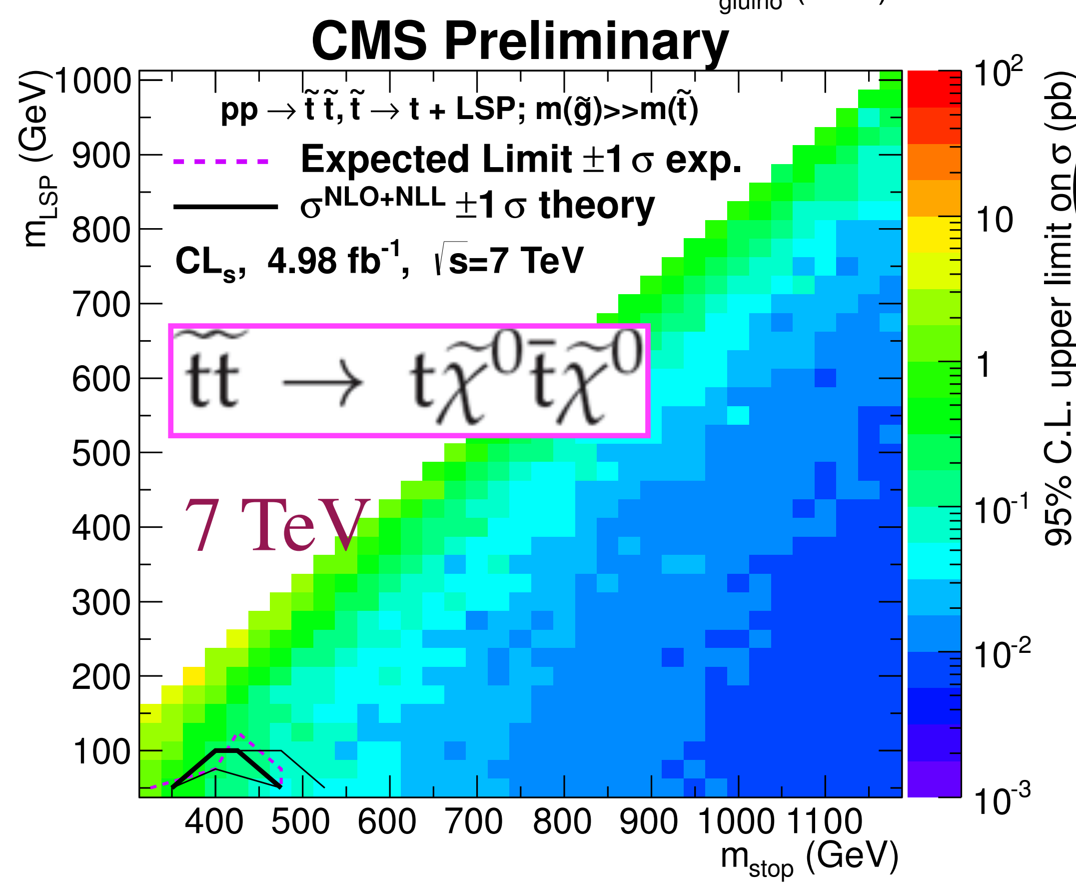
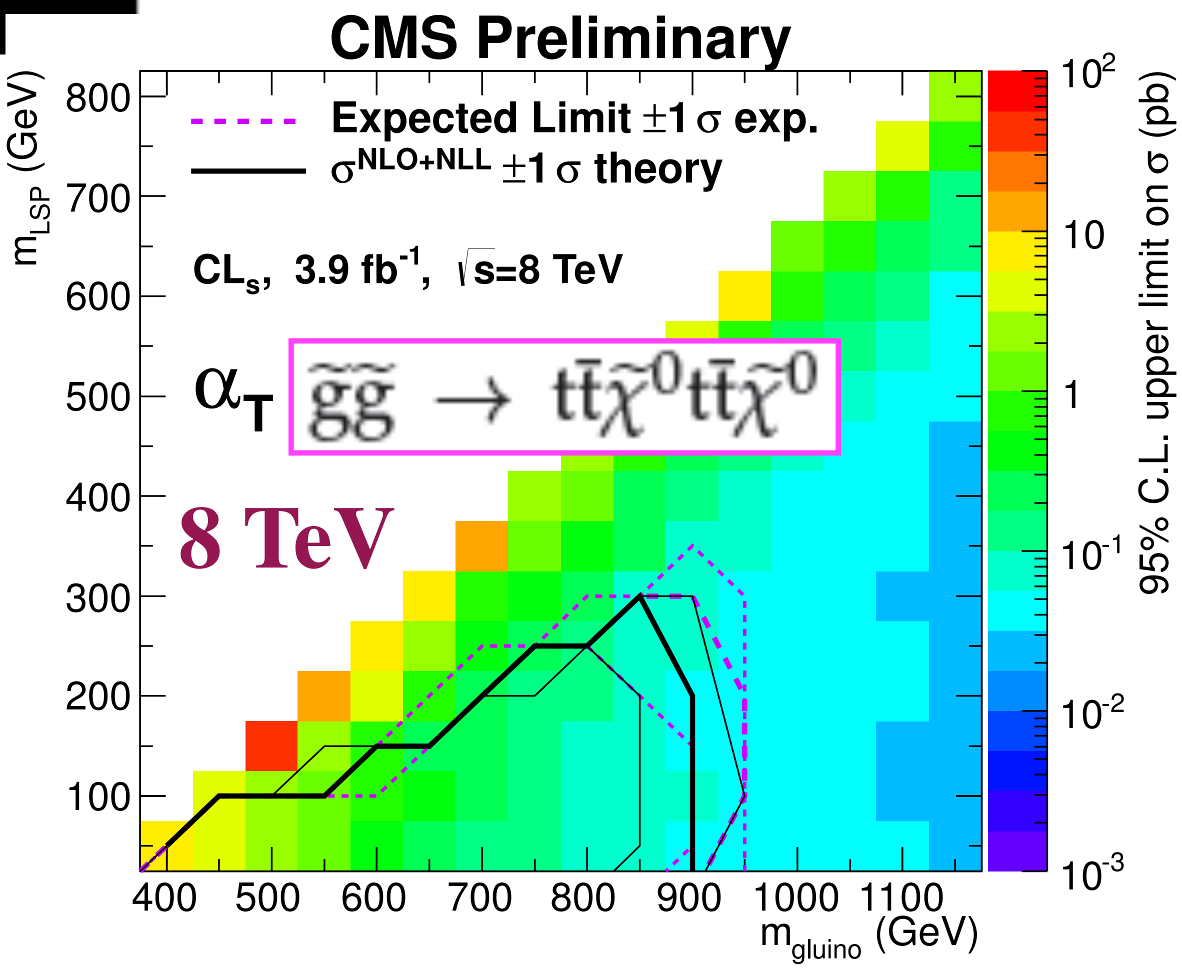
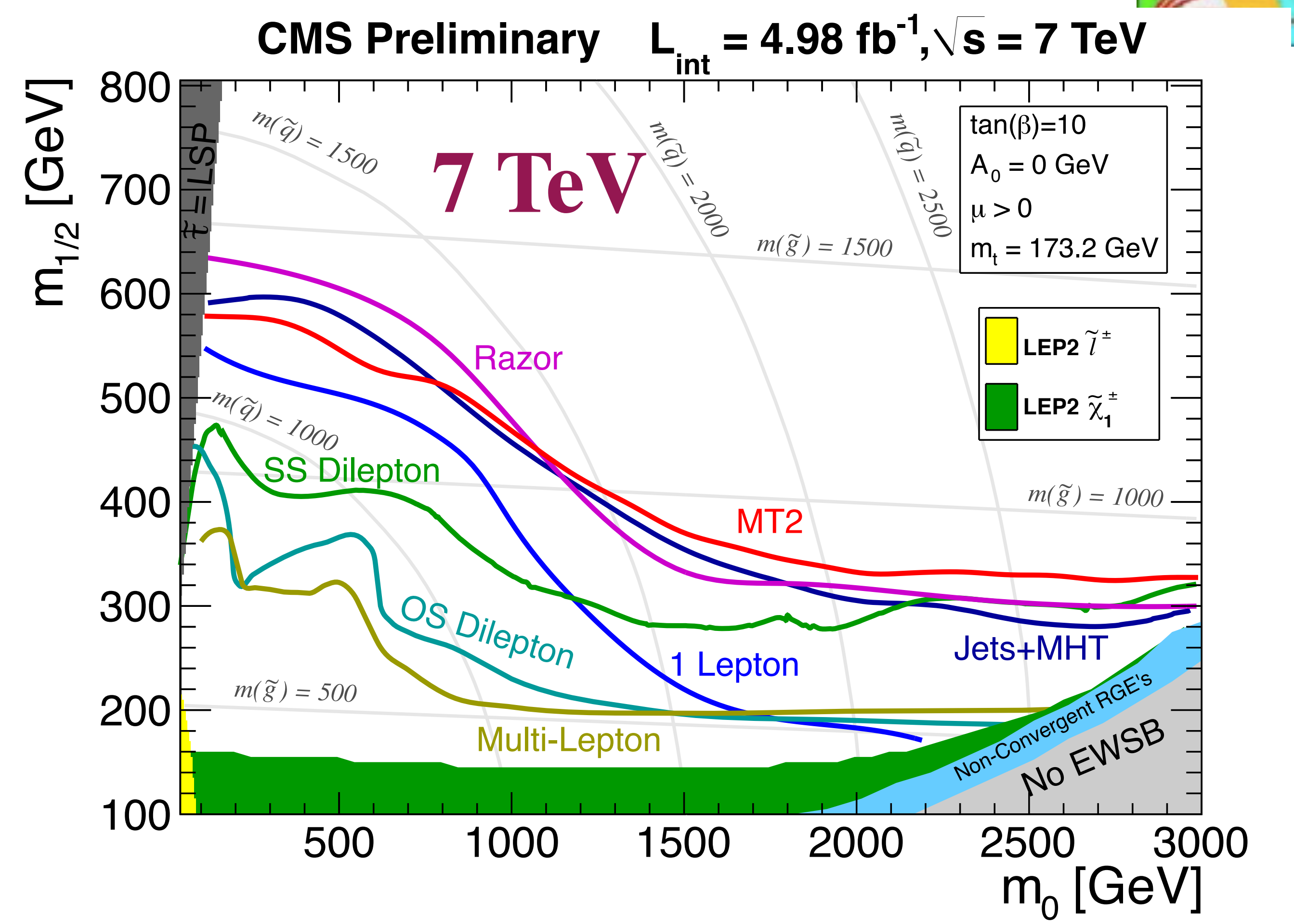


Also see talk[620] on 3rd generation searches by Altan Cakir @ 11:30 today

Summary





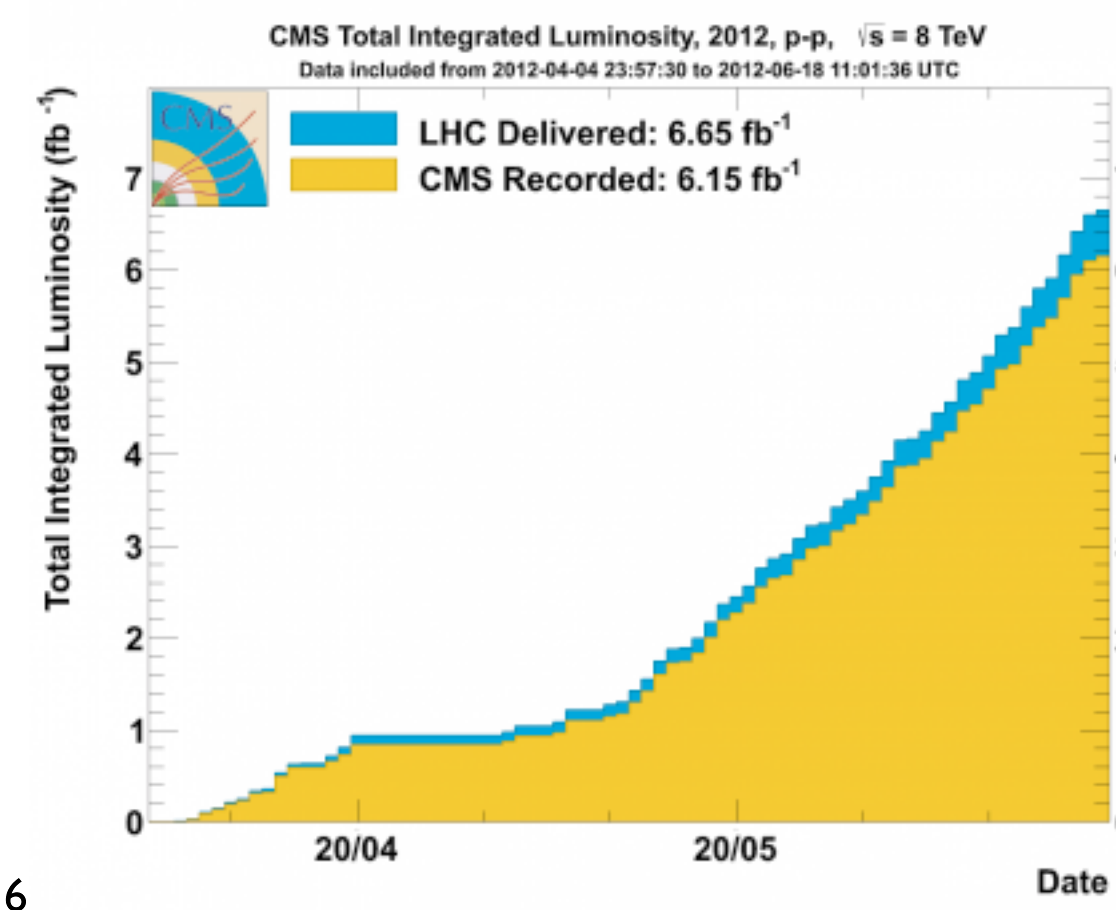
- CMS has performed SUSY searches in all hadronic channel with different kinematic variables using 5 fb^{-1} pp collision data collected @ 7 TeV.
- Results from first search (**α_T** variable), using 4 fb^{-1} data collected @ 8 TeV.
- In the context of simplified models, gluino masses are excluded in the range 0.8-1 TeV depending on details of decay modes for low LSP masses.

More results using 8 TeV data are expected soon !!

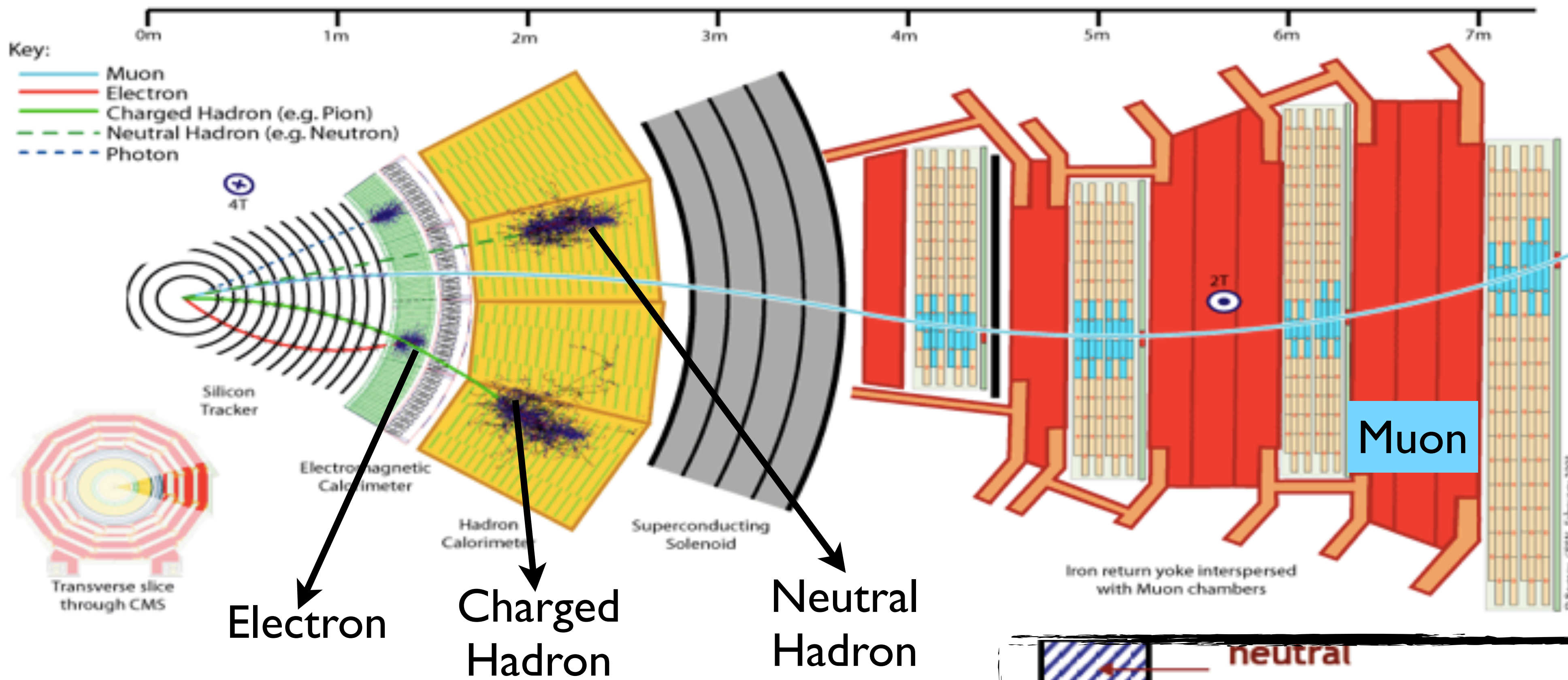
Backup

Large Hadron Collider

The LHC has already delivered more than 6 fb^{-1} of proton-proton collision data at centre of mass energy of 8 TeV.

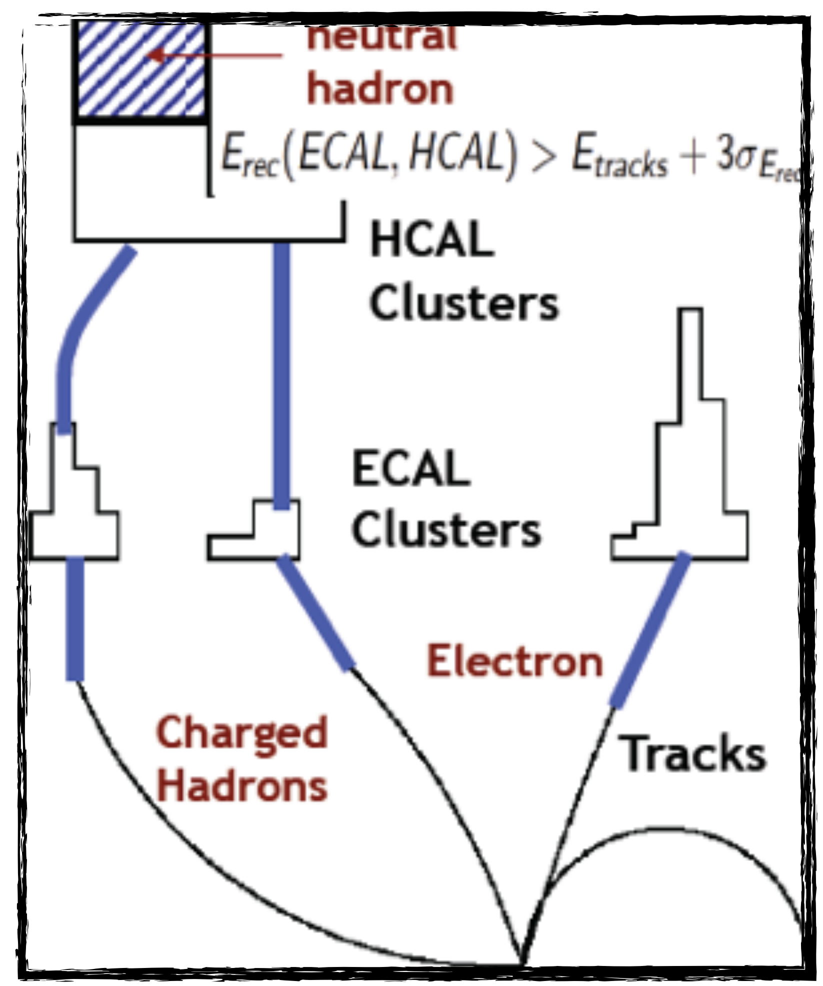


CMS Detector & Event Reconstruction



Events are reconstructed using Particle Flow algorithm which combines information from the tracker, EM calorimeter, Hadron Calorimeter and Muon detectors in an optimized way to get the best estimate of energy, direction and identity of particles.

The various physics objects used in this analysis are jets (antiKT 0.5), photons, electrons & muons.

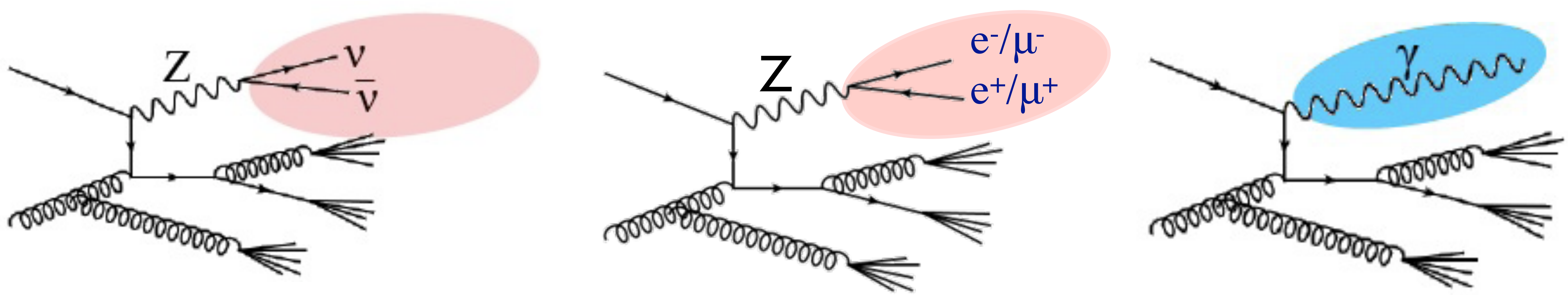


Background Prediction using Data Events

- Data driven methods are used for the background prediction from the collision data for this analysis
- A control data sample is a set of events which is signal depleted
    - This sample can be used to infer the backgrounds in the signal enriched phase space using event properties, physics laws, our theoretical knowledge of various physics processes ...
- A search region is the area of phase space where the signal is enhanced (good signal to background distinction)
- A signal depleted data sample which can be used to infer the backgrounds in the signal enriched phase space using event properties, physics laws, our theoretical knowledge of various physics processes ...

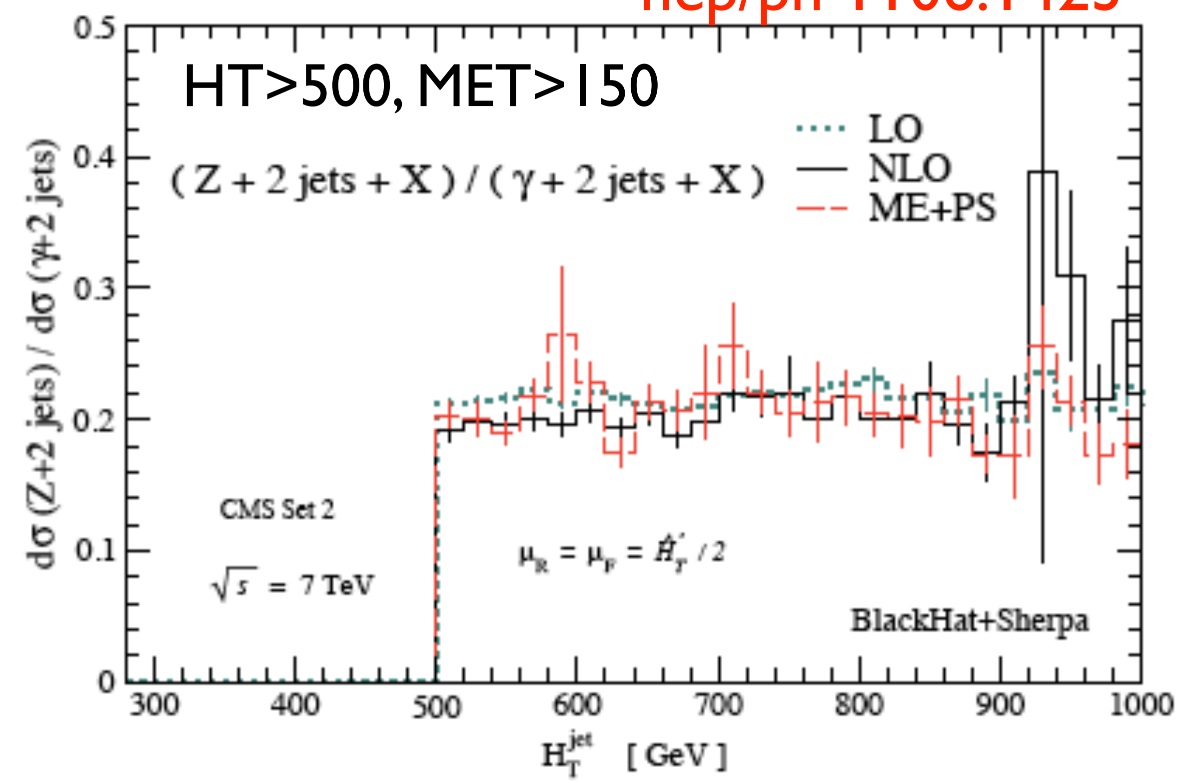
Z (ν ν) + Jets using γ + Jets

- A straightforward method is to use Z (→ e^+e^- or $\mu^+\mu^-$) +Jets events as the topology of events is identical if one ignores leptons in the event
  - suffers from lack of statistics in tighter search regions and is used only to cross-check the background prediction using γ + Jets



- At sufficiently high pT, the ratio of Z+jets to γ +jets production cross-section depends mainly on the electroweak characteristics of the event.
- Hadronic part of the event is independent of whether boson is Z or γ (figure on right)
- Theoretical uncertainty (provided by BlackHat collaboration) :
  - EWK corrections at higher orders of production
  - large QCD logarithm terms

hep/ph 1106.1423

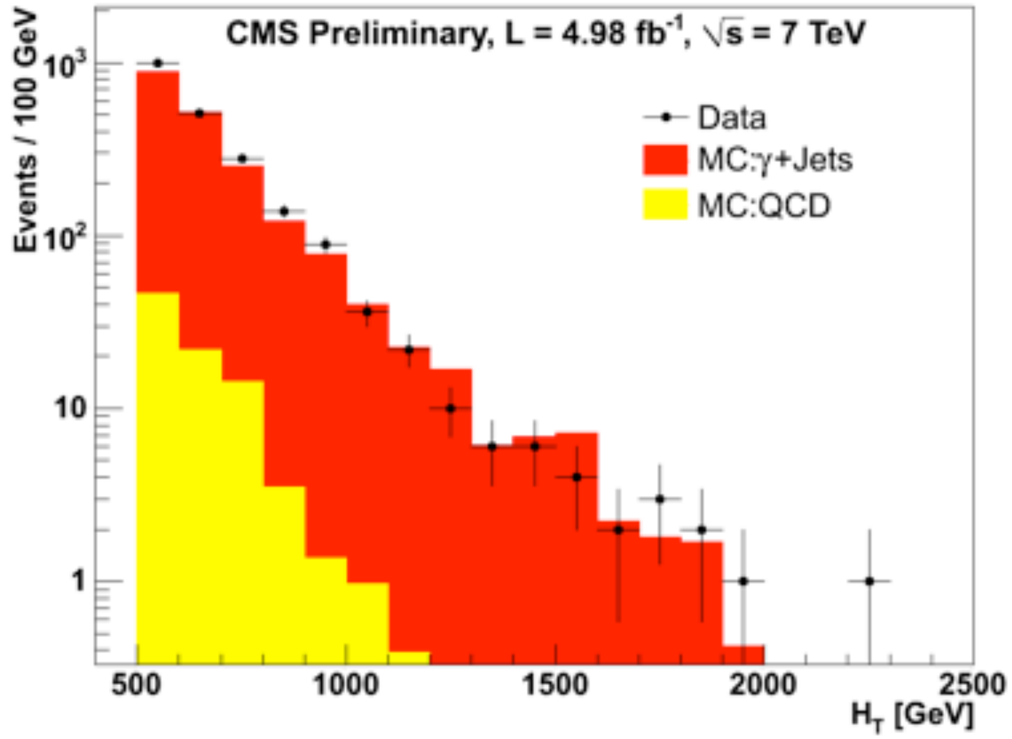


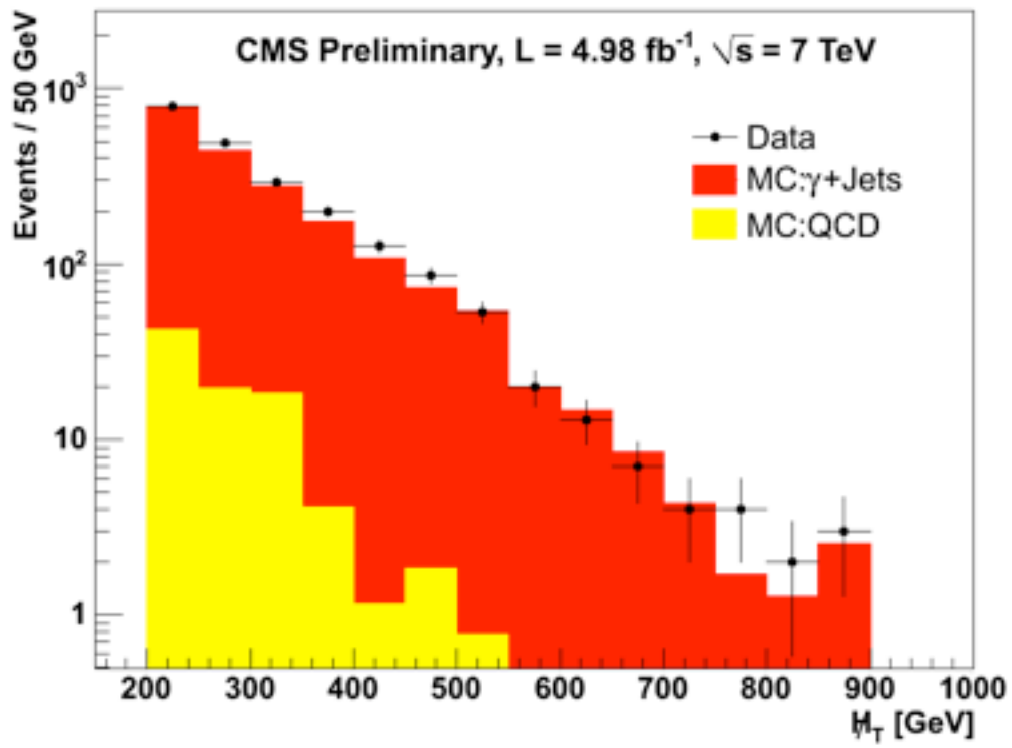
Z (ν ν) + Jets using γ + Jets

Start with a γ+jets control sample : pT(γ)>100 GeV

$N^{Z(\nu\nu)+Jets}$ (data) = (Z(νν)+Jets/γ+Jets) * Purity * $N^{\gamma+jets}$ (data)

- Subtract the contribution from secondary photons
  - Purity is 98-99% as measured from data using isolation template technique
- Subtract photons radiated from final state partons.
  - JETPHOX : (5±5)% contribution
- Correct for photon reconstruction & isolation efficiencies measured from data.
- Scale with Z(ν ν)+Jets/γ + Jets production ratio taken from theory.

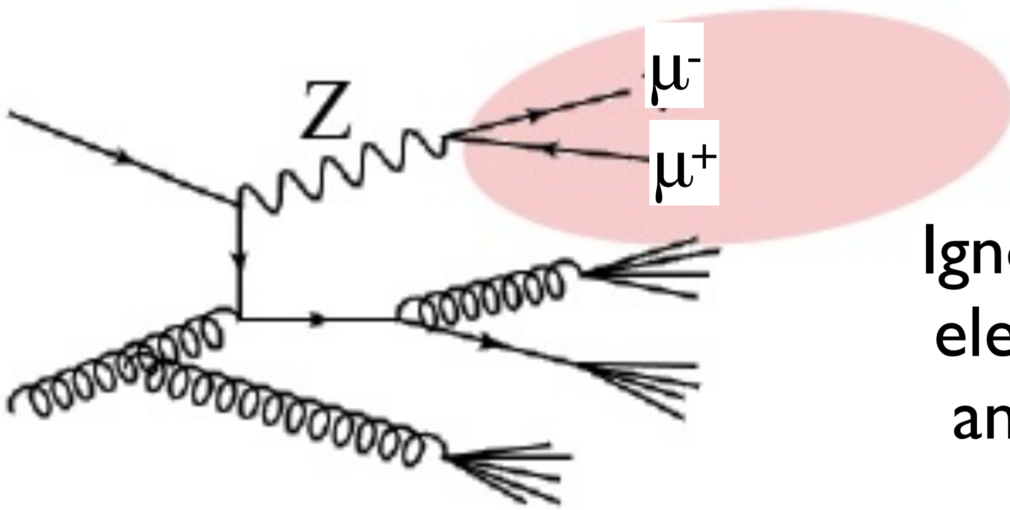




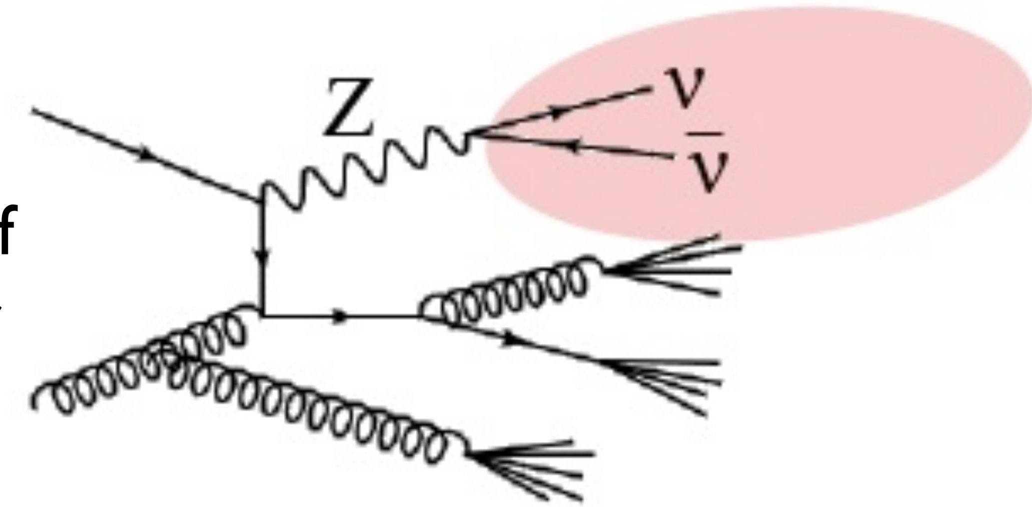
Z Invisible : (Z → ν ν) + Jets

Using Z → μ⁻μ⁺ Events from Data

$Z \rightarrow \ell^+\ell^-$ + Jets (limited by statistics but straightforward prediction)



Ignore the momenta of electron or muon pair and recalculate MET (or MHT)



$$N(Z \rightarrow \nu\nu) = \frac{N_Z^{obs} - N_Z^{bkg}}{A_Z \cdot \varepsilon_Z \cdot L} \cdot R\left(\frac{Z \rightarrow \nu\nu}{Z \rightarrow ll}\right)$$

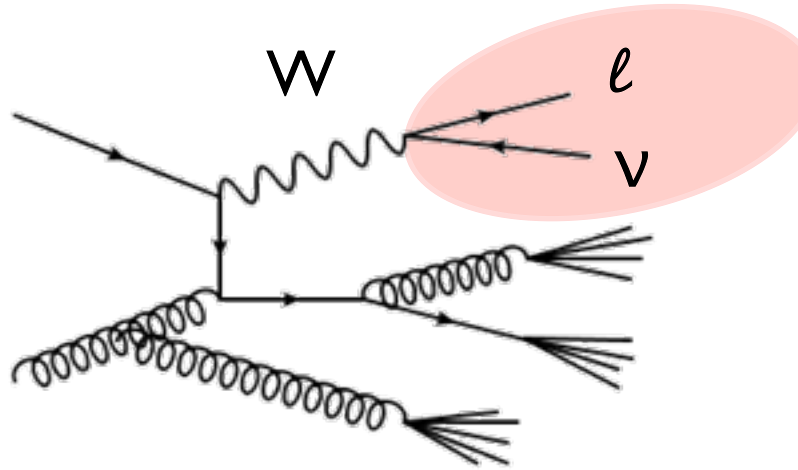
$$R\left(\frac{Z \rightarrow \nu\nu}{Z \rightarrow ll}\right) = 5.95 \pm 0.02$$

- Need to subtract background contamination from QCD, ttbar & dibosons
  - small contribution, derived from simulation except QCD
- Correct for detector acceptance (due to kinematical cuts in PT and Eta of leptons)
- Correct for inefficiency of lepton identification (measured from data using Tag & Probe)
  - depends on NJets, separation of leptons from jets, lepton pT etc ...
- Theoretical correspondence

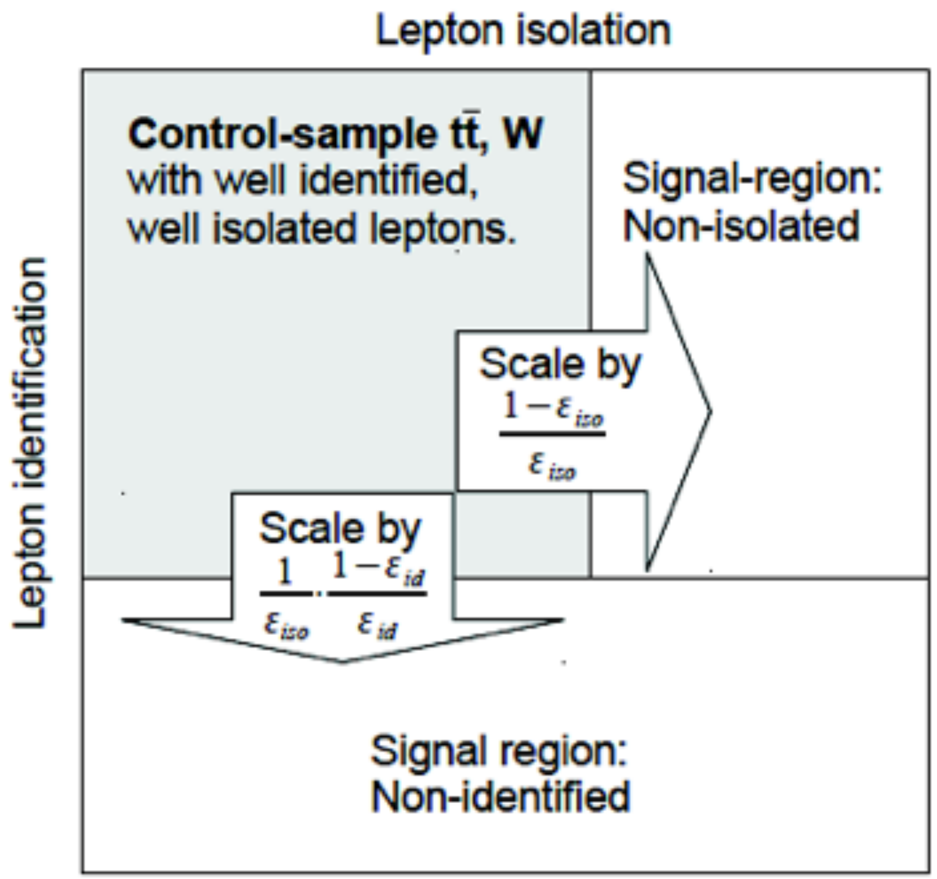
Lack of statistics for events in high HT or high MHT regions

W/top (lost lepton + ν) + Jets

- Lepton (e/μ) failing veto criteria contribute to background
- There can be three reasons a lepton is lost
  - if it is not reconstructed
  - not isolated
  - out of detector acceptance



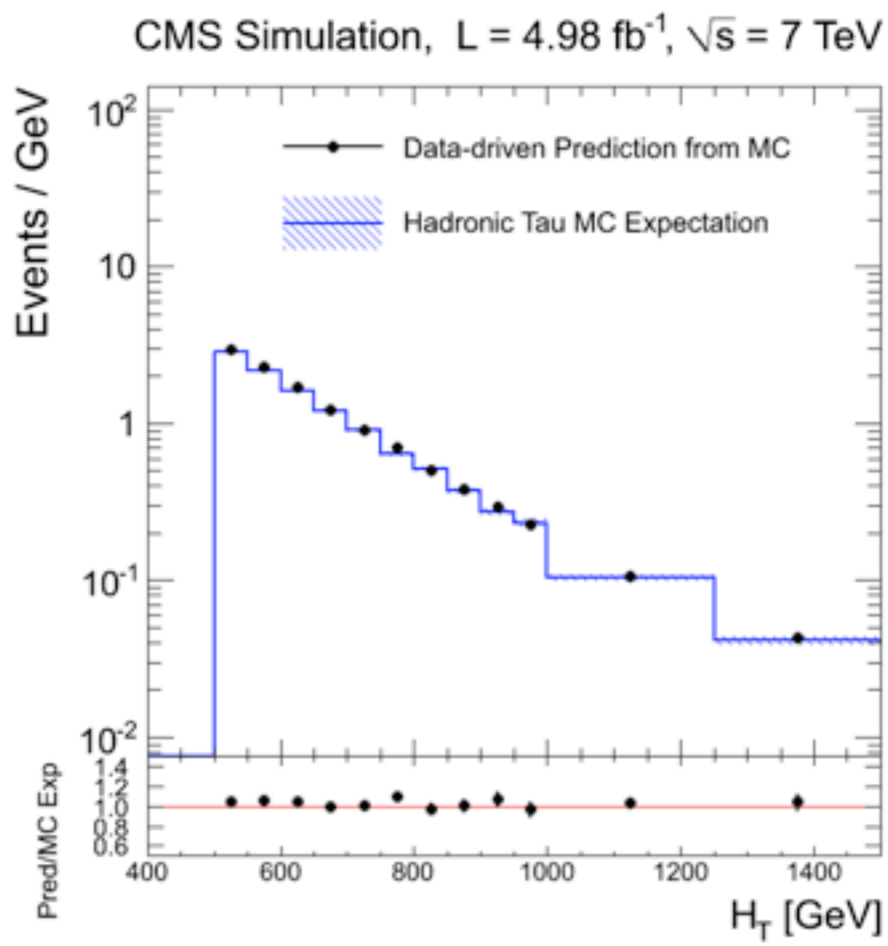
- Start with a control sample of μ+jets events (invert the lepton veto)
- Measure the muon reconstruction and isolation (in)efficiencies from data
  - scale the control sample with measured (in)efficiencies from data
  - Correct for detector acceptance

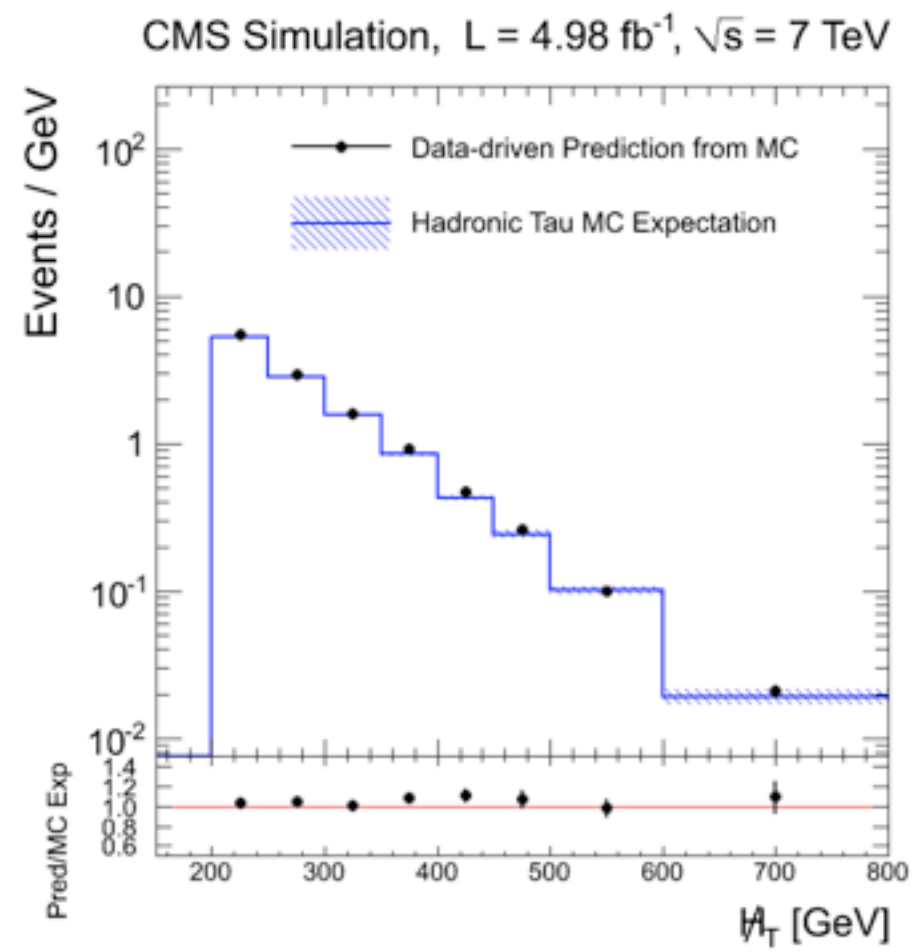


Top / W → hadronic τ + ν + Jets

- Use a control sample of events with :
  - exactly one identified & isolated muon in the event with pT>20 GeV & |eta|<2.1
  - ≥ 2 jets with pT>50 GeV & |eta|<2.5

Test method in MC : compare data driven method applied to MC with the expectation from MC.





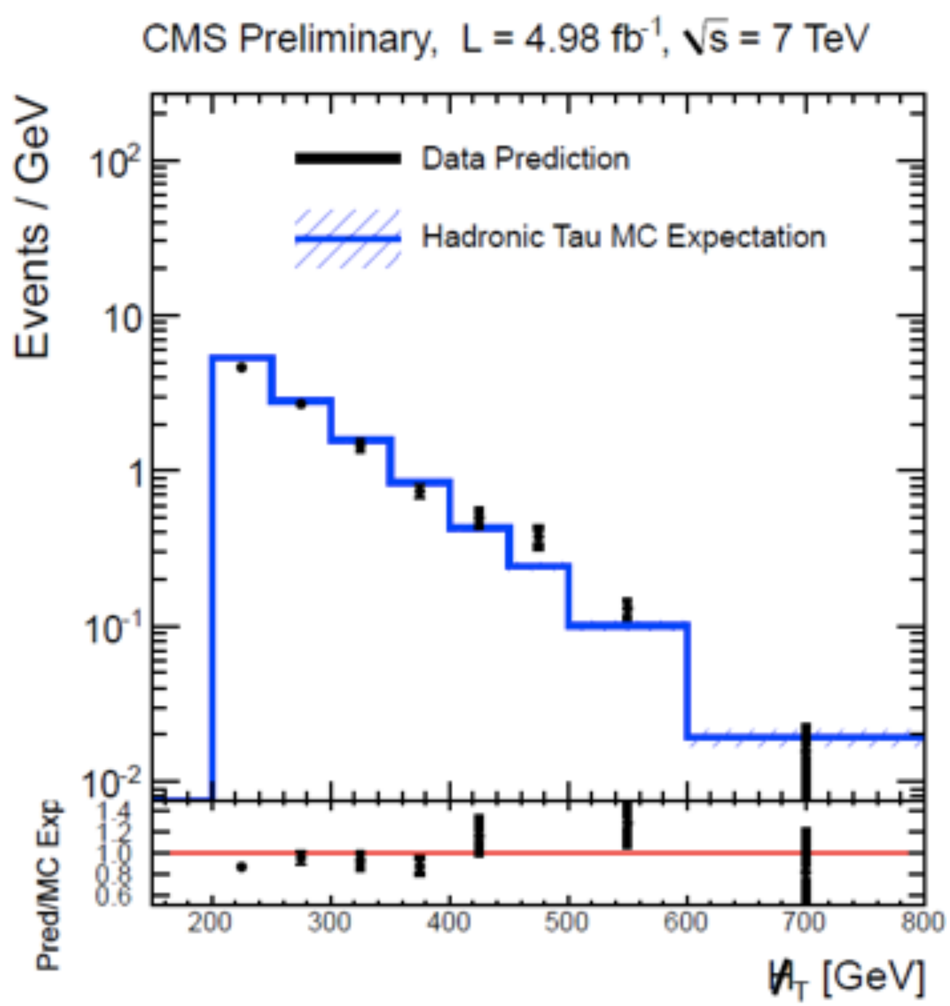
- Smear the muon Pt using a tau response template derived from MC sample
  - recalculate search variables HT and MHT including the energy of tau jet

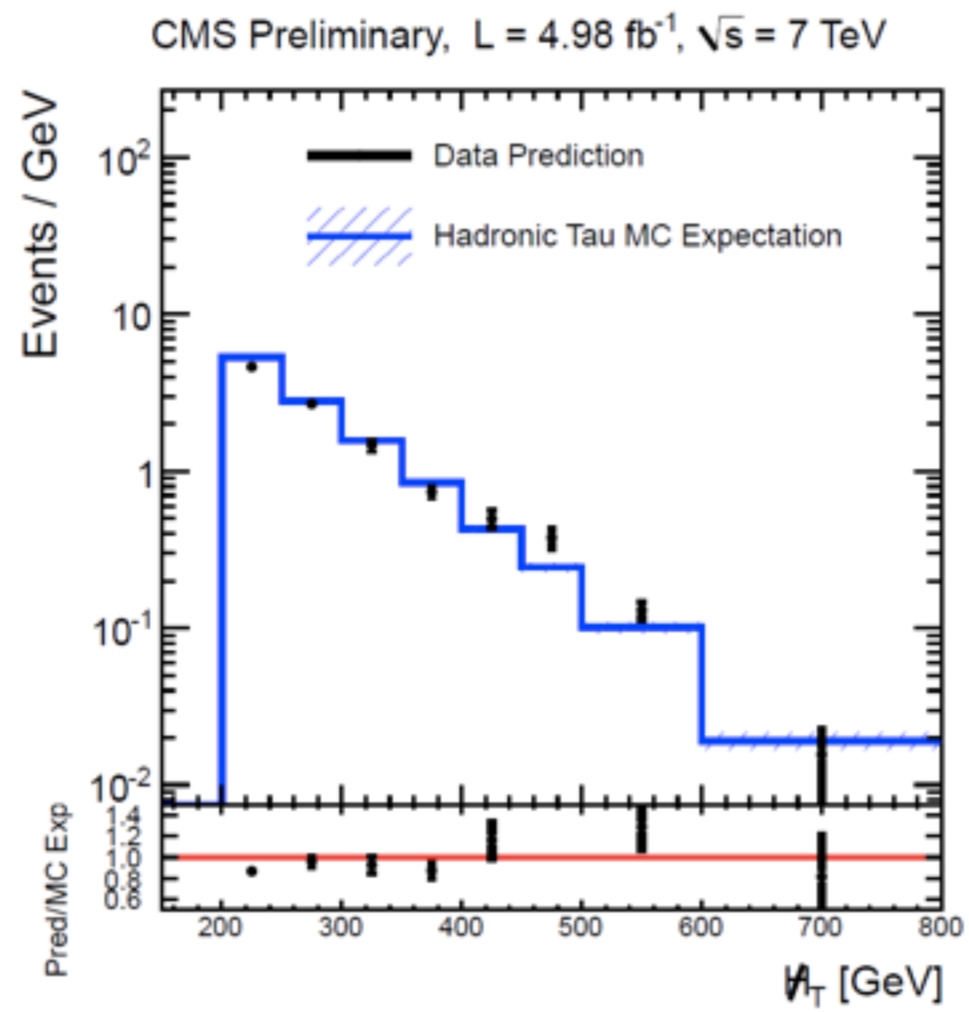
- To get the background prediction, correct for :
  - detector acceptance from muons
  - muon reconstruction efficiencies
  - BR(W→τ)/BR(W →μ) * BR(τ->Hadrons)

Hadronic Taus - Results

(Top / W → hadronic τ + ν + Jets)

Data driven estimation is compared with prediction from MC.





Systematic uncertainties :

-tau energy scale (2-20%),

-acceptance (5-12%),

-closure of the method in MC sample (6-12%),

Systematic uncertainties :

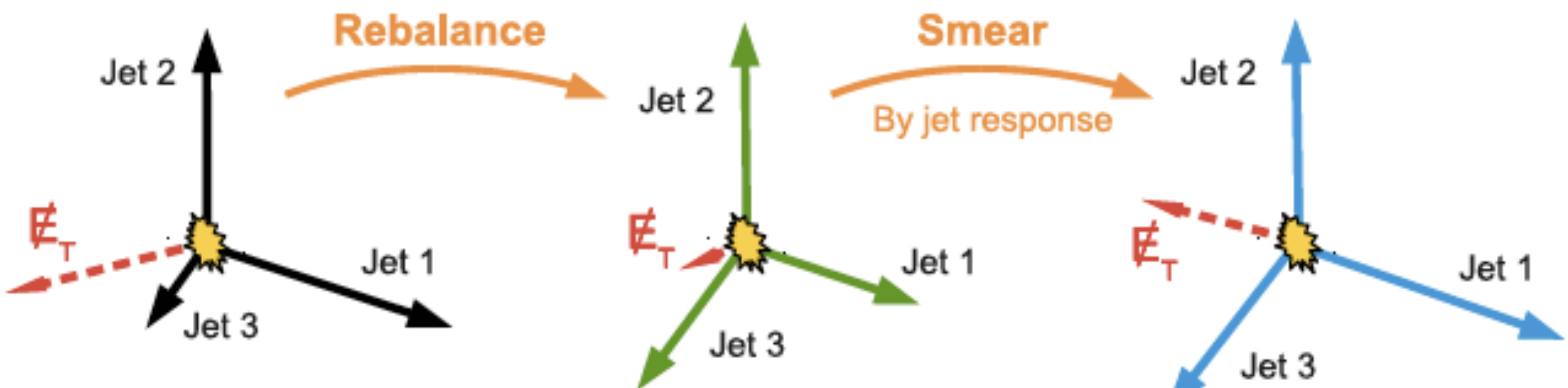
-background subtraction (1-2%),

-muon identification and isolation efficiencies (1-2%),

-trigger efficiency (~1%).

Introduction : Jets+Missing Transverse Momentum

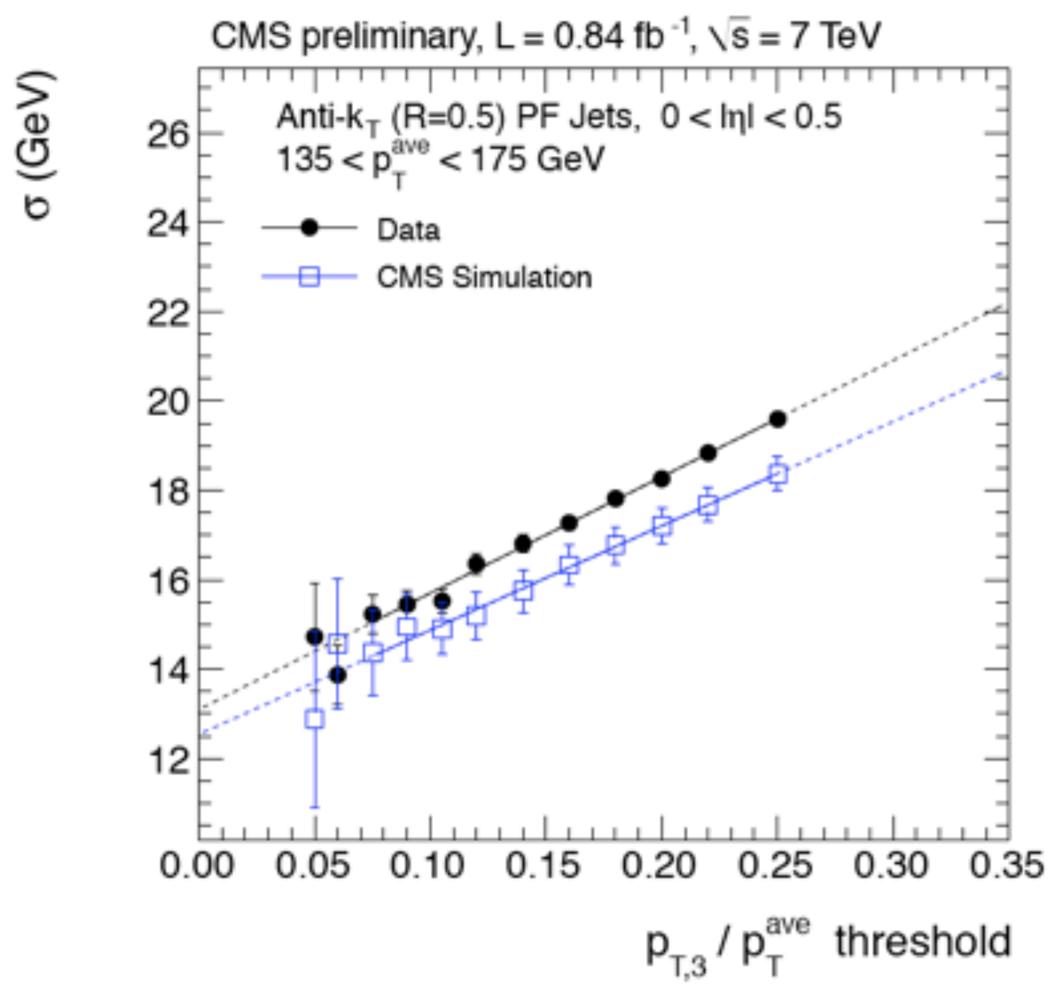
- QCD multijet events are balanced at the parton level
- An imbalance is introduced by the mis-measurement of jets due to fluctuations in response of detector, non-functional detector channels or a small fraction of events with b or c quarks decaying semileptonically

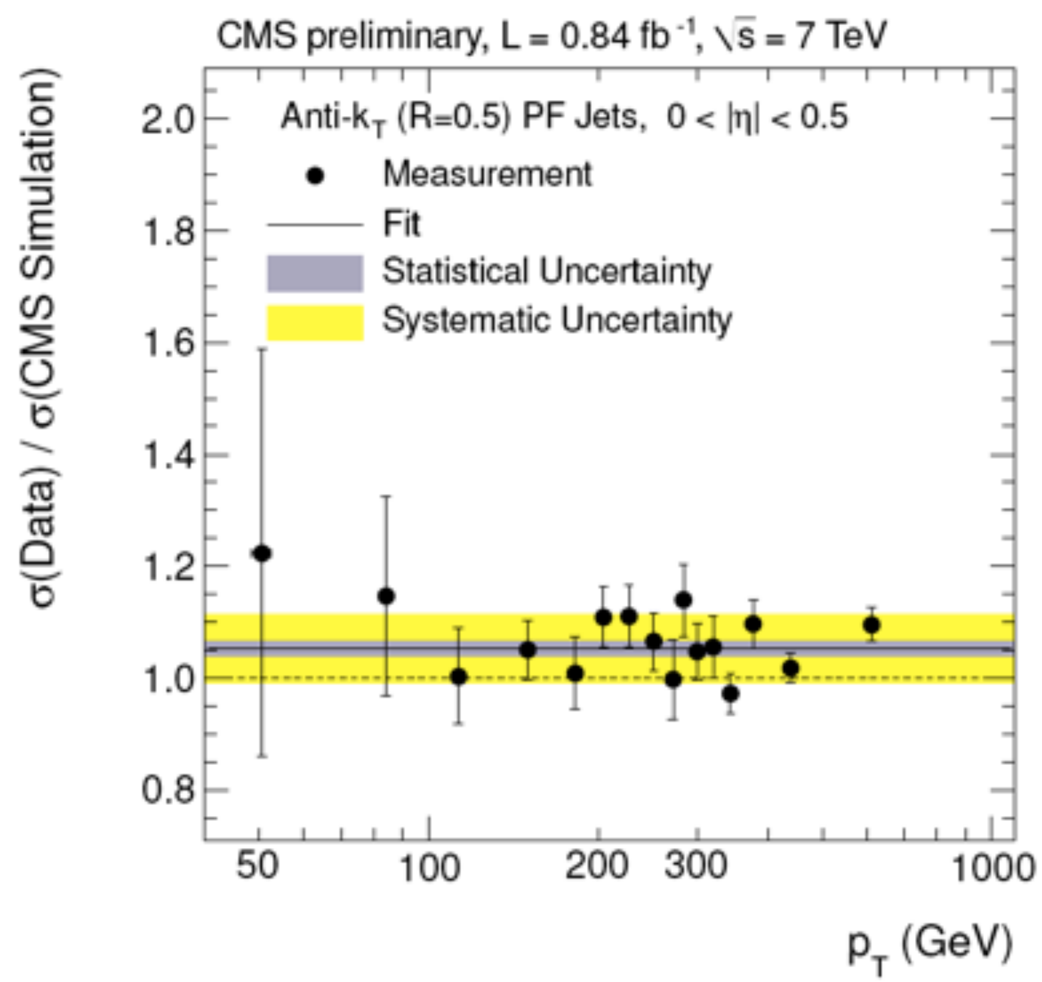


- Rebalance : Particle level jet pT is restored from detector level inclusive multijet data using a kinematic fit subject to constraint MHT=0 (using jet resolution functions derived from MC but corrected to match data)
- Smear : "Rebalanced" events are smeared using the measured jet resolution functions including the tails
- Obtain a data driven estimation of full kinematics of QCD multijet events
  - predict HT, MHT, angles between jets and MHT and apply kinematic selection of the analysis to predict the background from QCD multijet events from data

Jet pT Response Function - Gaussian Core

- Measurement using maximum likelihood fit of measured pt imbalance in dijet events
- Strategy :
  - Extrapolate the measured resolution to zero 3rd jet pT
  - Measure the ratio σ(Data)/σ(MC)   (common biases cancel)
  - Correct MC truth response functions with the measured ratio

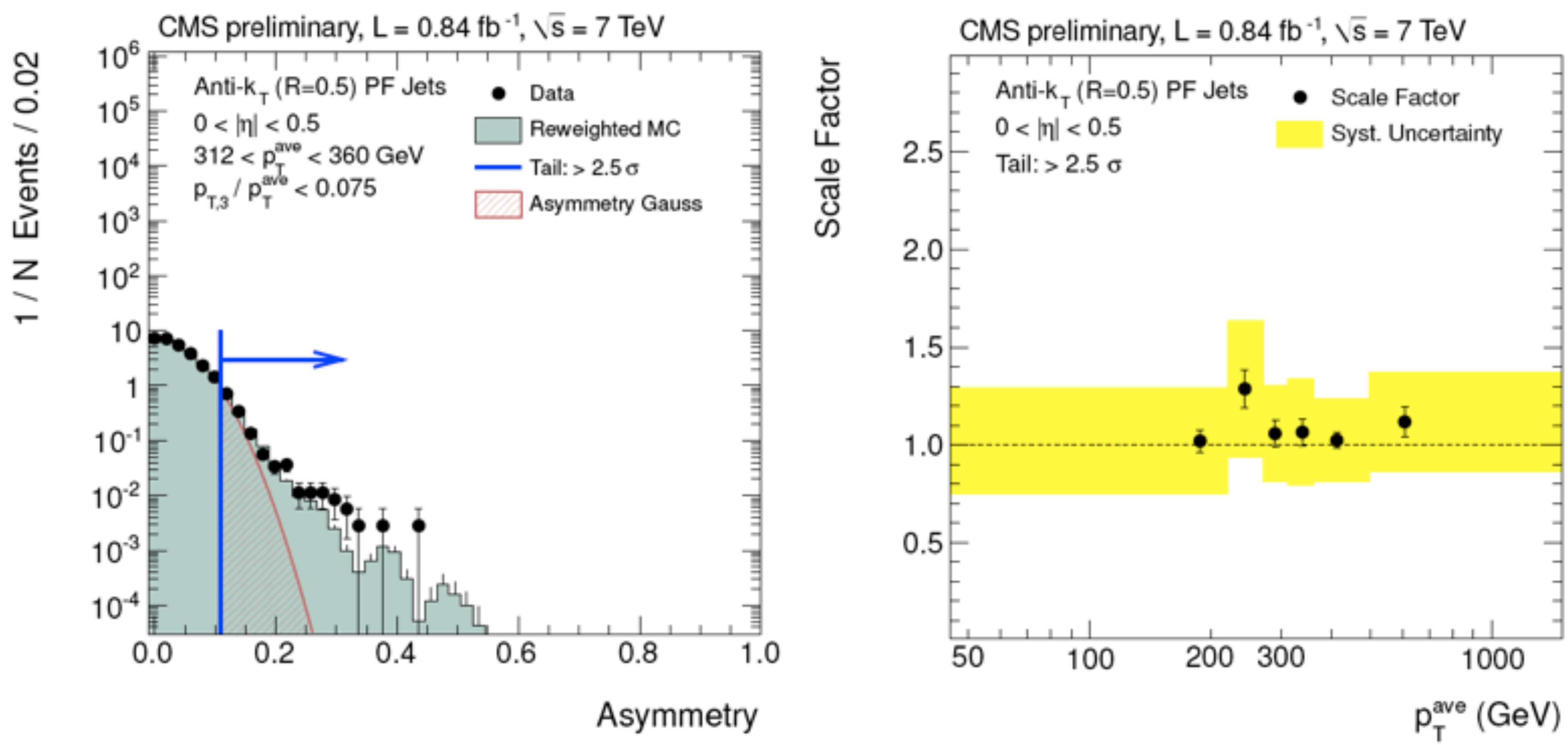




- Correction is ~5% in central regions and 25% in very forward region
- Dominant uncertainties : jet energy scale, extrapolation procedure (5-25%)

Jet pT Response Function : Non-Gaussian Tail

- Strategy : compare dijet asymmetry distributions in Data and MC
  - MC dijet asymmetry is corrected for larger core resolution in Data
  - Extrapolate the number of events in tail region to zero 3rd Jet pT
  - Scale the tails in MC truth response functions with Data/MC ratio



- Data/MC ratio of number of events in non-Gaussian component of response function is ~1 - simulation describes the data reasonably well.
- Dominant uncertainties : Core resolutions (others : pile-up, non-closure)

MT2 : Z (ν ν) + Jets using W/top-> Mu+Jets

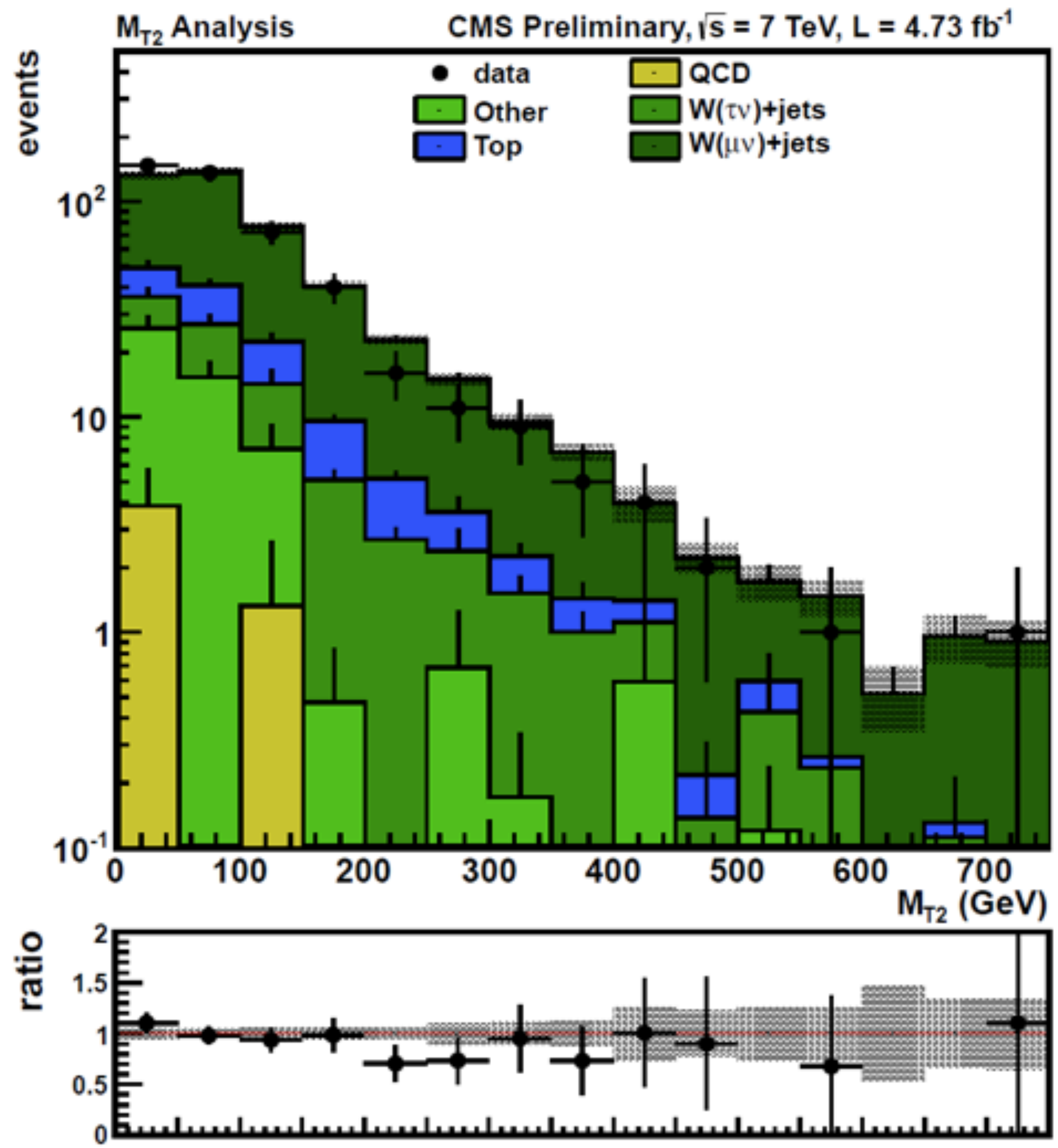
- Predict Z(νν)+jets from photon+jets and W(lν)+jets events

Z(νν)+jets from W(lν)+jets

- W(→lν)+jets enriched sample obtained by using all selection cuts and:
  - One μ with p_T>10 GeV
  - B-tag veto to suppress ttbar
  - $m_T(W)$<100 GeV to reduce signal contamination
- Z(→νν)+jets estimated as

$$N_{Z(\to\nu\nu)} = N_{W(\to l\nu)}\ 1/(\varepsilon_{acc}\varepsilon_{reco/iso})\ R_{MC}$$

  - Muon acceptance from MC
  - Muon reco/iso efficiencies obtained from Tag&Probe in data
  - R_{MC} corrects for: kinematic differences, cross-sections, M_T&b-tag veto efficiencies
  - Backgrounds subtraction by MC, except ttbar, which is estimated using ttbar enriched data by requesting 1 b-tag



Consistent with the estimation from photon+jets

Weighted average to give the final Z→νν estimation

MT2/MT2b : Search Results