Searches for direct production of stops and sbottoms at LHC

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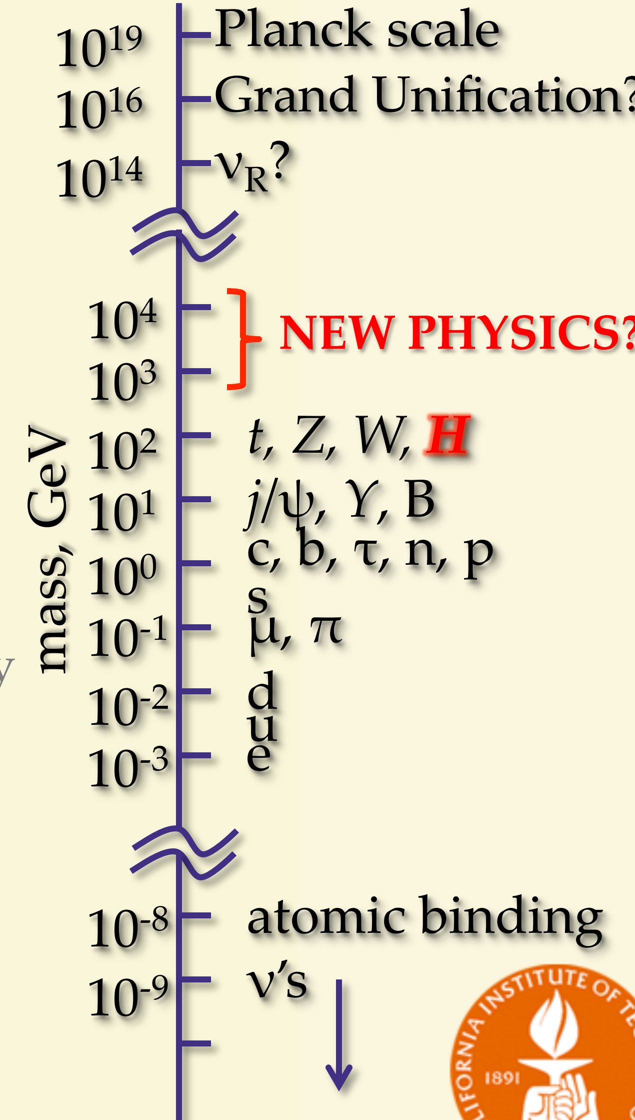
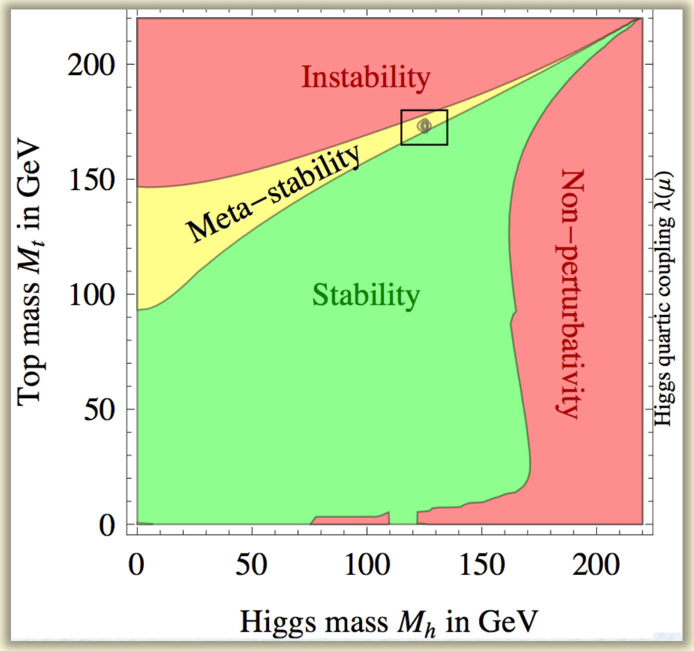
The Ultimate Question of Life, The Universe, and Everything

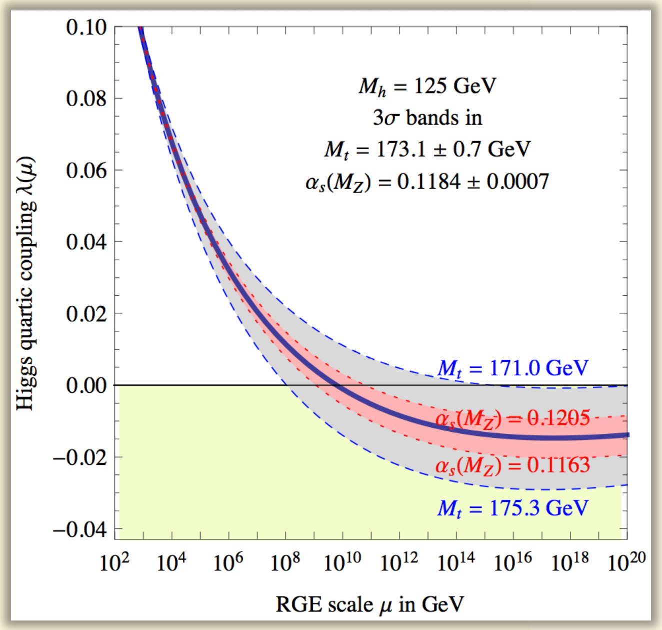
- THE theory describing all **fundamental particles** and their **interactions**
  - With **minimum** of assumptions and free parameters.
  - Describes all interactions from **small to cosmological** scales.

- The Standard Model (SM) is our *best* attempt
  - Successful theory of interactions of elementary particles and fields
  - Describes *essentially* all lab data so far
    - but $(g\text{-}2)_\mu$…



The new particle



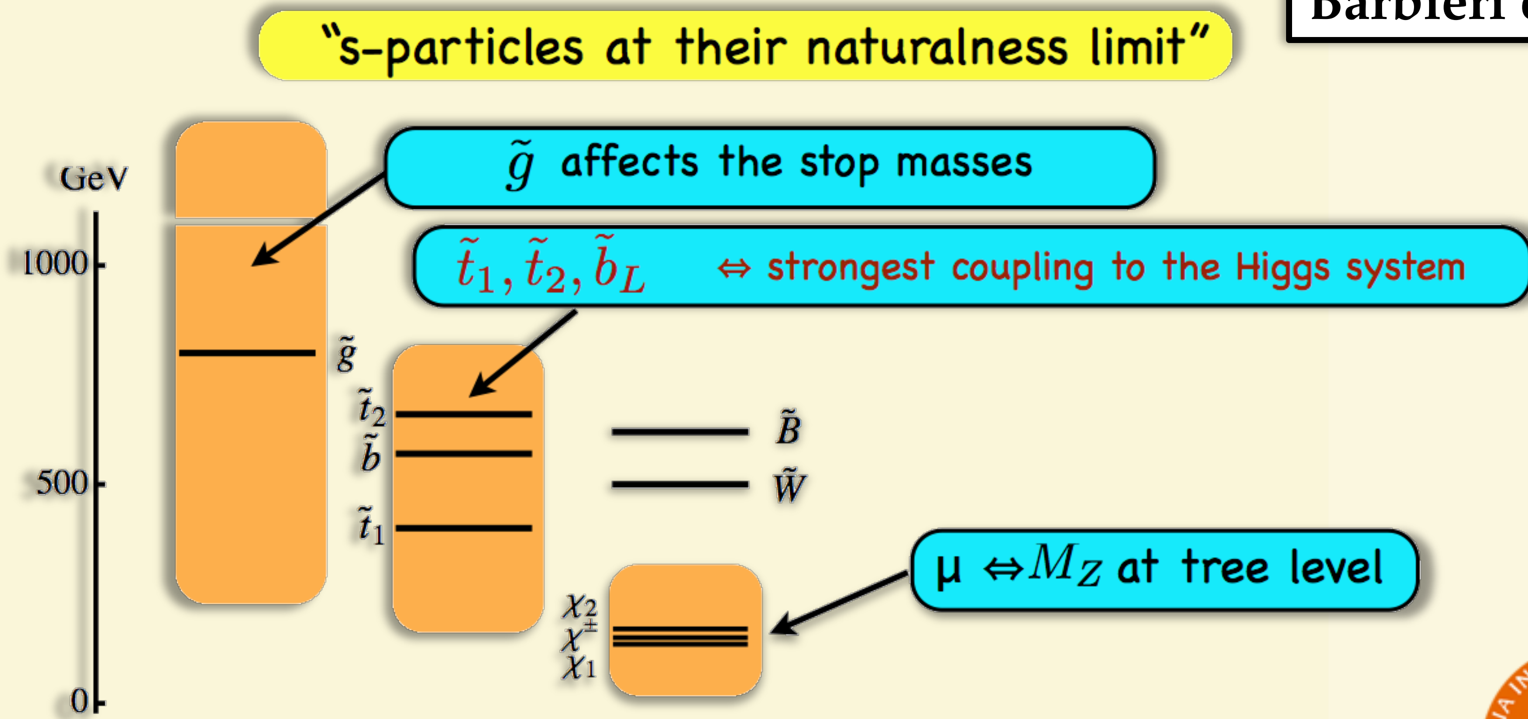


- Not too heavy (as SUSY would have liked), but not too light either…
  - Are we in metastable vacuum? Is the quartic coupling→0 at Plank scale?
- New physics needed to stabilize its mass *(is Nature fine-tuned?)*
- SUSY theories can provide an appealing solution
  - Large radiative corrections to Higgs mass are cancelled mostly by the stop and sbottom.

“Natural” SUSY spectrum

- *“Natural”* SUSY spectrum:
  - two higgsinos: one chargino and two neutralinos below 200 – 350 GeV.
  - two stops and one (left-handed) sbottom: both below 500 – 700 GeV.
  - a *not too heavy* gluino, below 900 GeV – 1.5 TeV.

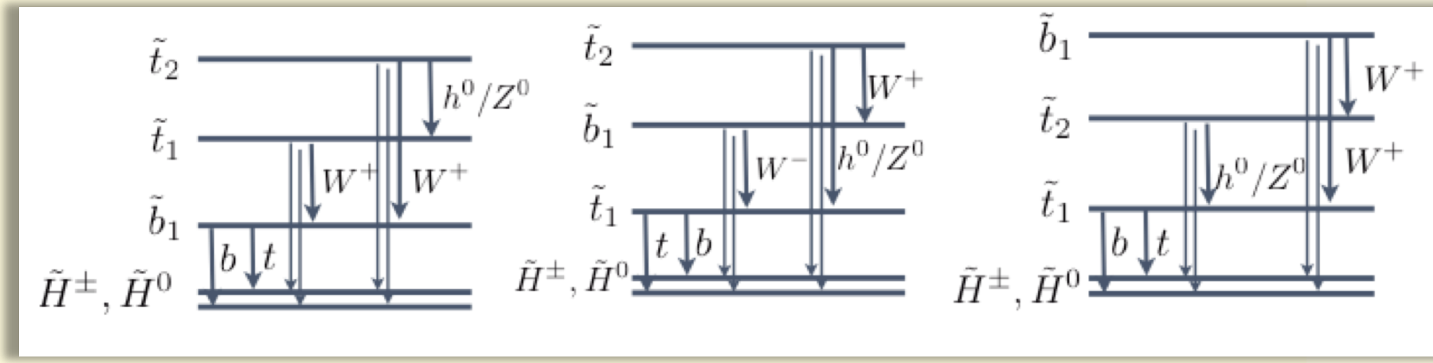
Barbieri et al



$\tilde{q}_1, \tilde{q}_2, \tilde{b}_R$ are much heavier: may be inaccessible at LHC

Searching for Natural SUSY

- Different possibilities exist, depending on model



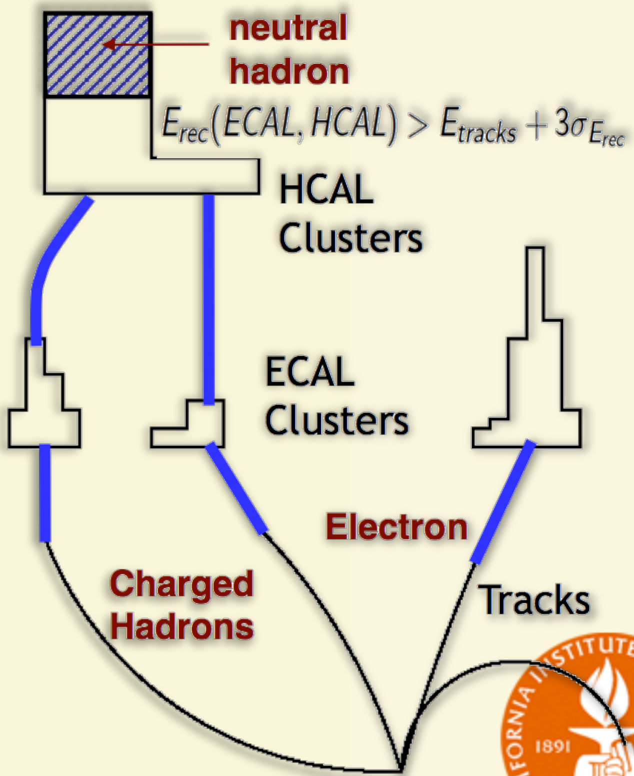
- But common approaches can be used to target different decays
  - e.g. T_b, $T_{b'}$, $T_{t'}$ are all with all $bbW^+W^-\chi^0\chi^0$ (but on-shell $t \rightarrow Wb$ in T_t)

Abbreviation	Decay mode	Conditions
T_t	$\tilde{t} \rightarrow t\chi^0$	$m_{\tilde{t}} > m_t + m_{\chi^0}$
T_b	$\tilde{t} \rightarrow b\chi^+ \rightarrow bW^+\chi^0$	$m_{\tilde{t}} > m_b + m_{\chi^+}, \quad m_{\chi^+} > m_{\chi^0} + m_W$
$T_{b'}$	$\tilde{t} \rightarrow b\chi^+ \rightarrow bW^{+*}\chi^0$	$m_{\tilde{t}} > m_b + m_{\chi^+}, \quad m_{\chi^+} < m_{\chi^0} + m_W$
$T_{t'}$	$\tilde{t} \rightarrow t^*\chi^0 \rightarrow bW^+\chi^0$	$m_{\tilde{t}} < m_t + m_{\chi^0}, \quad m_{\tilde{t}} < m_{\chi^+} + m_b$
T_c	$\tilde{t} \rightarrow c\chi^0$	$m_{\tilde{t}} < m_t + m_{\chi^0}, \quad m_{\tilde{t}} < m_{\chi^+} + m_b$
B_b	$\tilde{b} \rightarrow b\chi^0$	
B_t	$\tilde{b} \rightarrow t\chi^- \rightarrow tW^-\chi^0$	$m_{\tilde{b}} > m_t + m_{\chi^-}, \quad m_{\chi^-} > m_{\chi^0} + m_W$
$B_{t'}$	$\tilde{b} \rightarrow t\chi^- \rightarrow tW^{-*}\chi^0$	$m_{\tilde{b}} > m_t + m_{\chi^-}, \quad m_{\chi^-} < m_{\chi^0} + m_W$

The third generation: how?

- Excellent performance of reconstruction is needed for high sensitivity
  - Complex final states with multiples objects
  - *b*-tagging to identify jets originating from *b*-hadrons
  - *jets and escaping particles* most of the time: good understanding of jets, MET

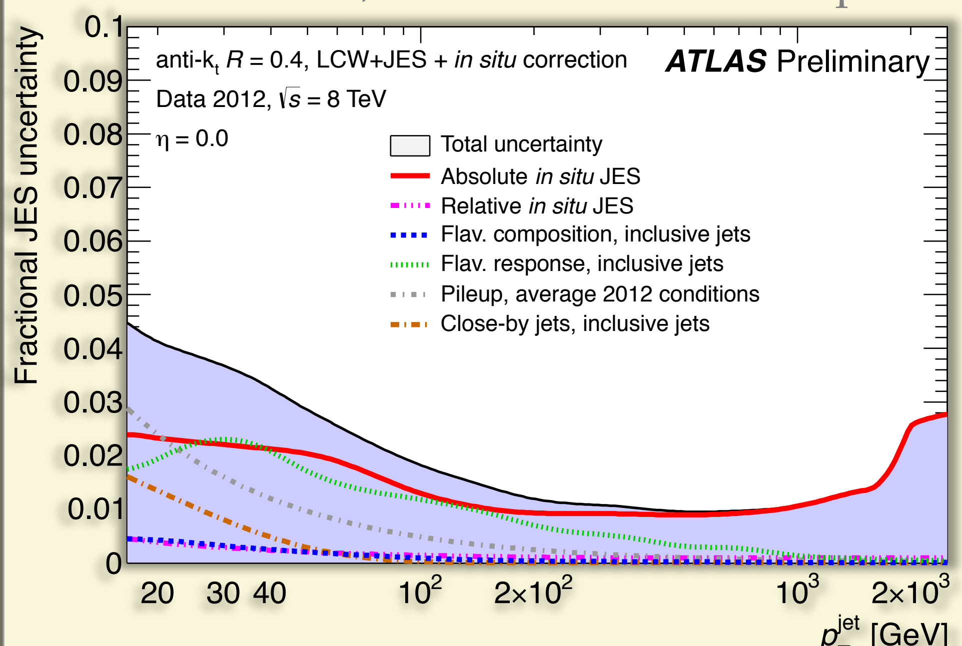
- CMS uses **particle flow (PF)** technique for global event reconstruction
  - Use a combination of all CMS sub-detectors to get the best estimates of energy, direction, particle ID
  - Improve HCAL resolution with tracker

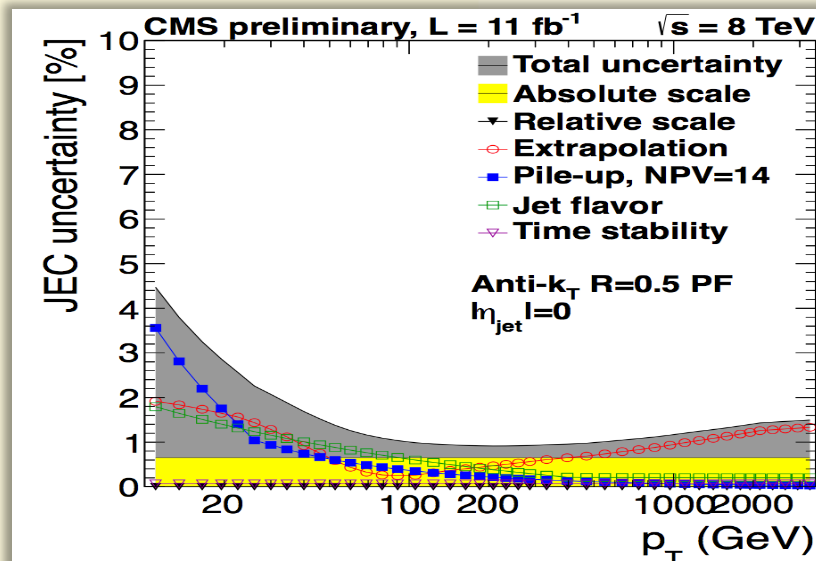


- ATLAS uses detector based event reconstruction for jets, MET,…
  - Combine into more sophisticated tools, e.g. for b-tagging

Event reconstruction: jets

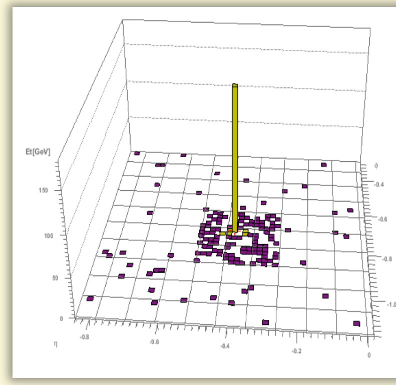
- Factorized approach to set the jet energy scale
  - PU offset corrections: derived from from zero-bias data and MC simulations
  - Absolute: obtained from MC; residual differences corrected from Z and γ+jet
- JEC uncertainties dominated by :
  - PU at low p_T, jet flavor, extrapolation to high p_T
  - CMS time stability (forward region) is a temporary artifact of using prompt reco data, will be fixed in the reprocessed data

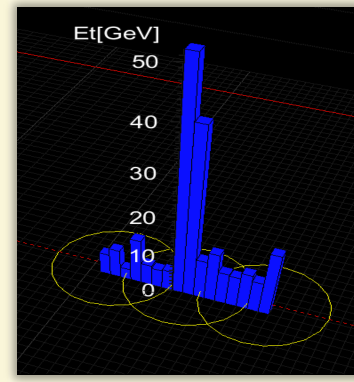




Event reconstruction: missing energy (MET)

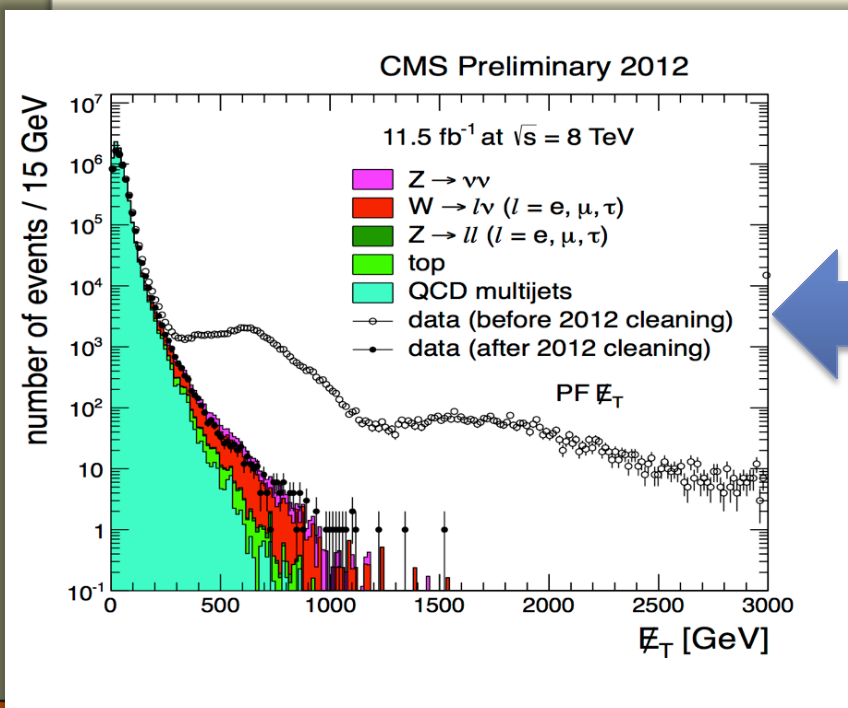
- MET is one of the crucial variables in
  - Susceptible to imperfections:
  - Hot calorimeter cells, detector noise, beam-halo particles
- Good control over the instrumental noise: data agrees with simulation

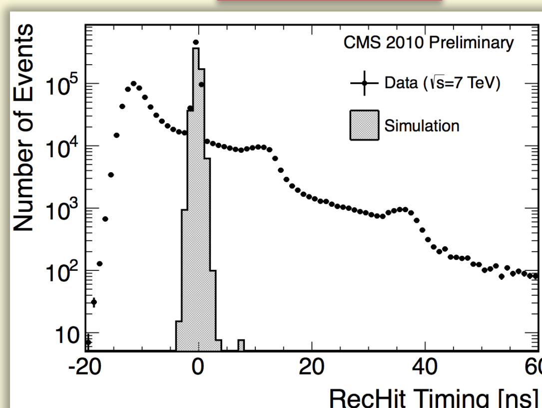


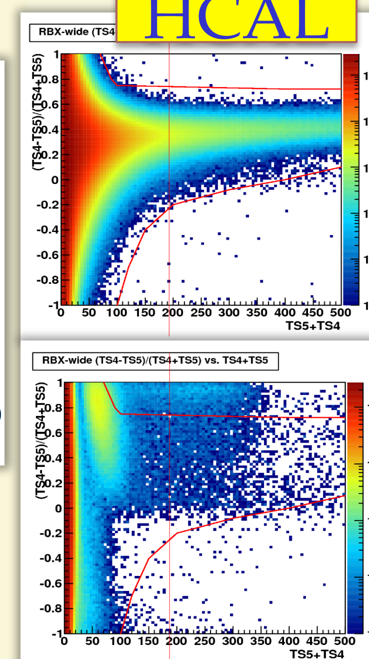


ECAL

HCAL

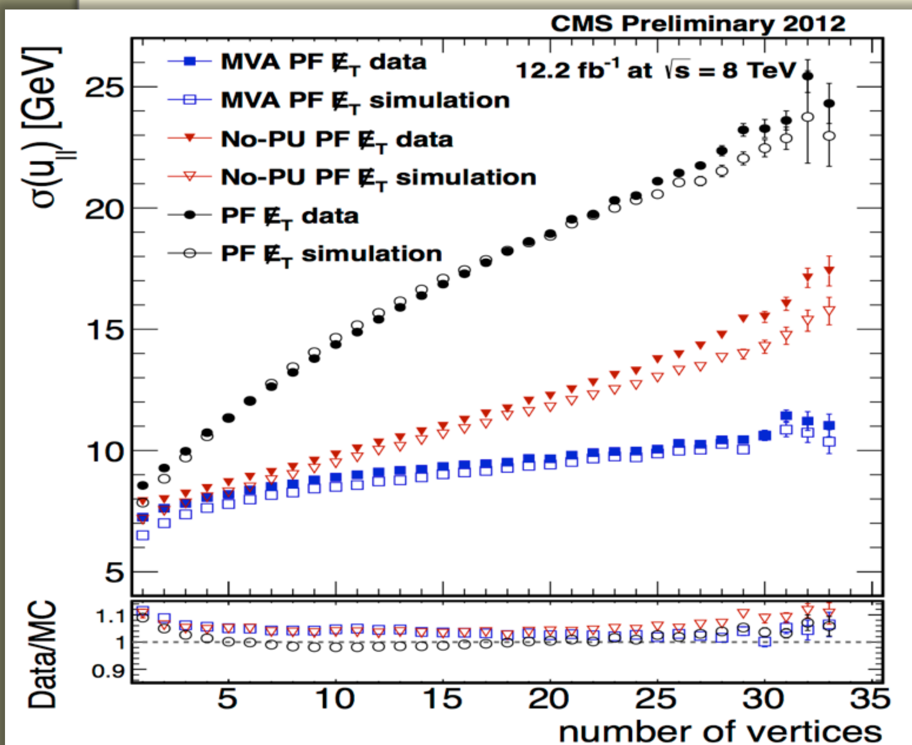


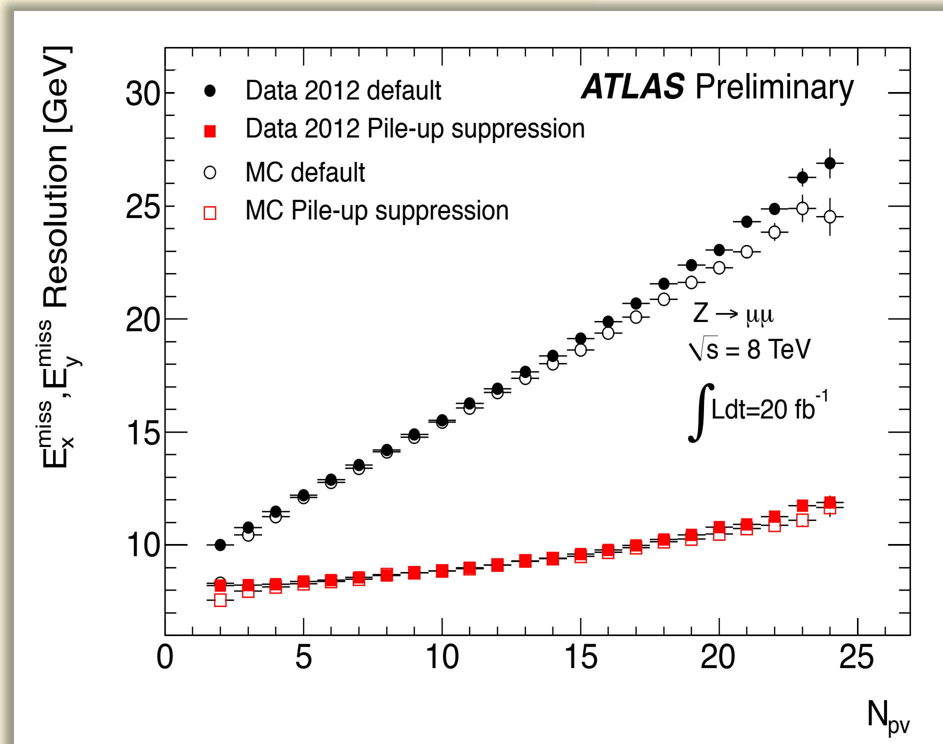




Event reconstruction: missing energy (MET)

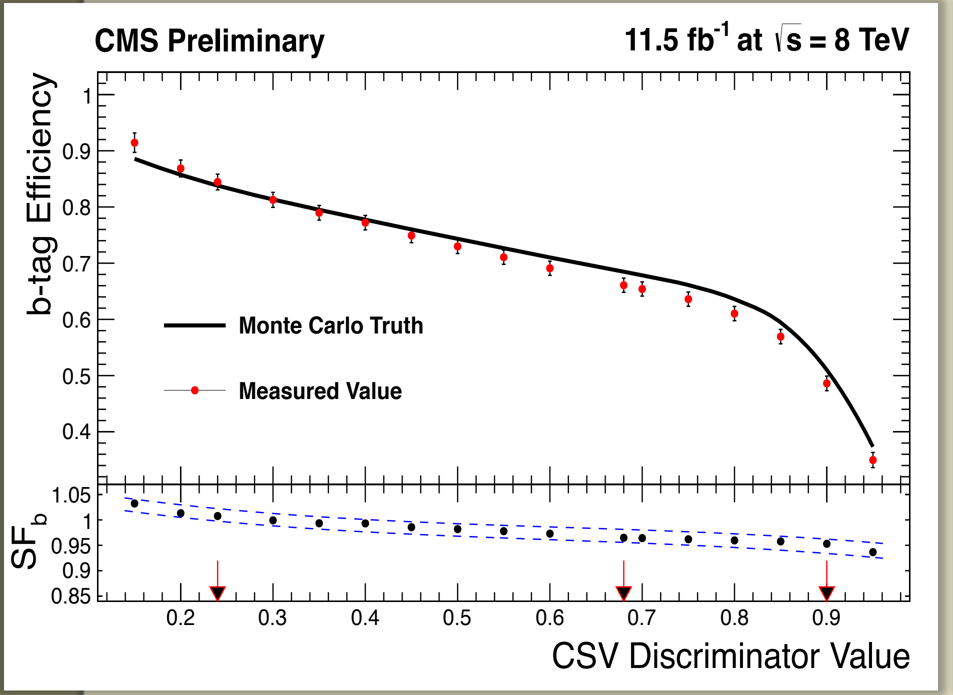
- PU worsens the MET resolution by ~3.5 GeV per additional vertex (in quadrature)
  - Both experiments have developed sophisticated algorithms to improve MET resolution degradation from PU

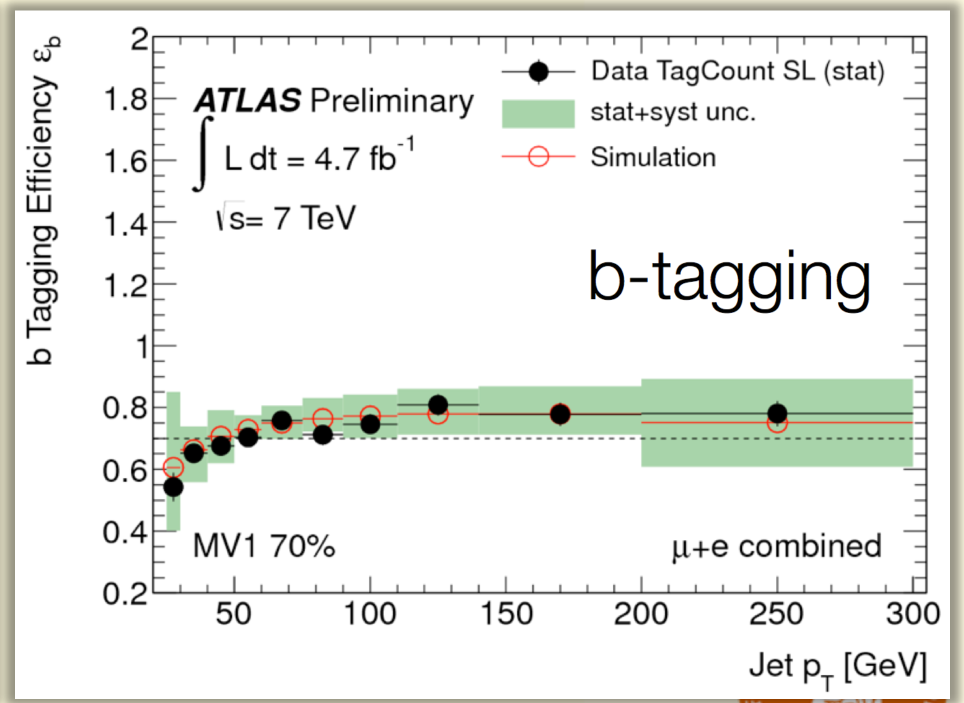




Event reconstruction: *b*-tagging

- Several algorithms based on variables such as
  - the impact parameters of charged-particle tracks
  - properties of reconstructed decay vertices, the presence/absence of a lepton
  - neural network using the output weights of the IP3D, JetFitter+IP3D, and SV1 algorithms (ATLAS)





Background estimation

- A crucial element is to have a good control of the backgrounds
  - Both shapes and normalizations need to be very well understood

Standard Model
QCD, EWK, ttbar, dibosons, …

fake MET, fake leptons
can't rely on simulation: fully data-driven methods

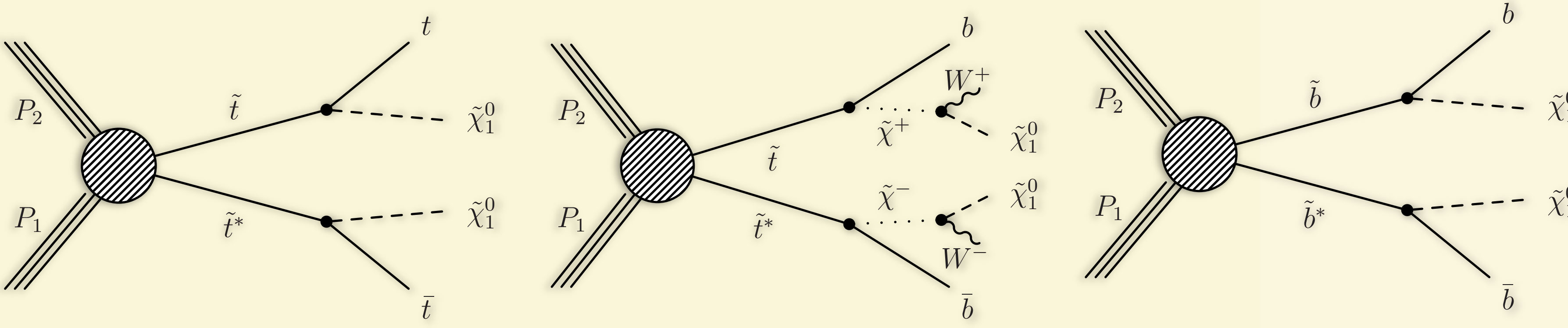
Irreducible backgrounds
ttbar, EWK: derive normalizations from CR, transfer functions from MC

control regions

Systematic uncertainties

- Background (and uncertainty) determination verified and constrained in control regions
  - Small systematic uncertainty on the background is essential, especially in small Δm regions
- Experimental uncertainties
  - Jet energy scale and resolution, MET resolution
  - Lepton energy scale and efficiency
  - b-tagging and mis-tagging efficiency
  - Trigger efficiency, luminosity, pileup modeling
- Theoretical uncertainties
  - Generator modelling (μ_F,μ_R, ME/PS matching, α_s scale choice when possible)
  - PS uncertainties (typically compare Pythia and Herwig)
  - PDF choice
  - Understanding ISR modeling in MC

Direct stop/sbottom searches



- Searches are challenged by
  - Small signal Xsections (*t- and u-channels suppressed*)
  - Often similar in kinematics to large backgrounds

- Targeted efforts, specific channels (*0, 1, 2* leptons)
  - MET and *b*-tagging requirements reduce backgrounds
  - All hadronic modes: larger branching ratio, lots of backgrounds
  - Leptonic searches are *"cleaner"* at the expense of statistics

0-lepton final state: CMS

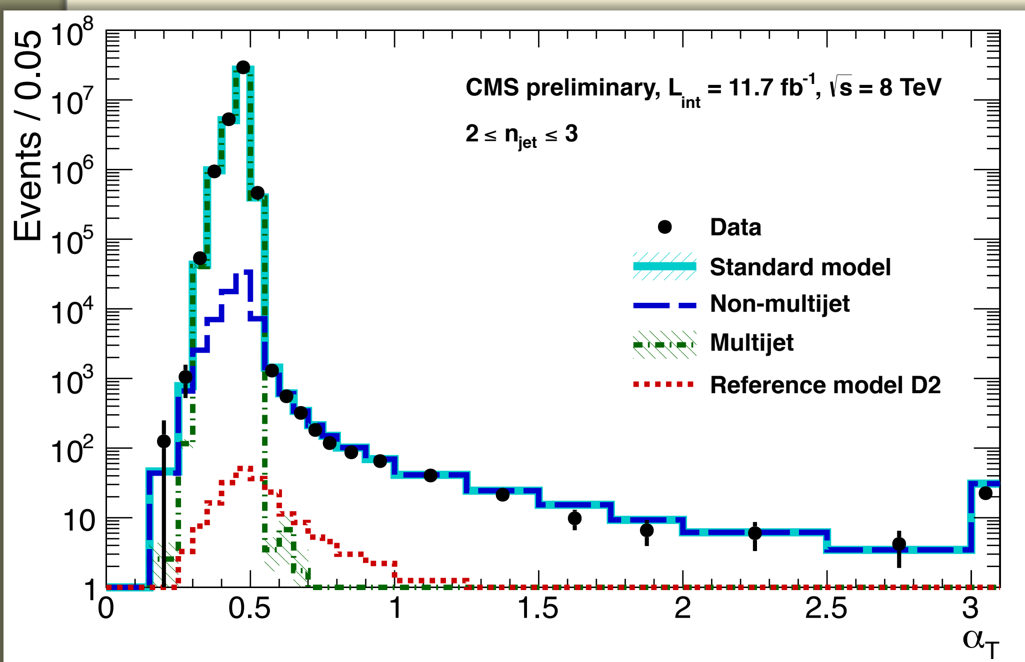
- Suppress large QCD backgrounds with α_T> 0.55 cut

$$\alpha_T = \frac{E_T^{j_2}}{M_T} \quad , \quad M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2} .$$

>2 jets

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - (MH_T)^2}}$$

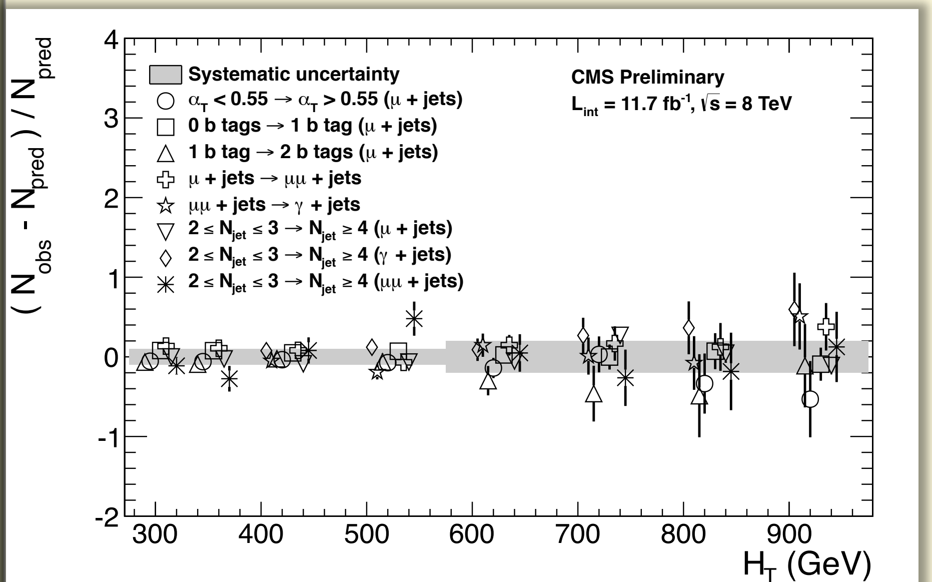
- Remaining backgrounds with real MET
  - W/Z+jets, ttbar+jets: estimate from data

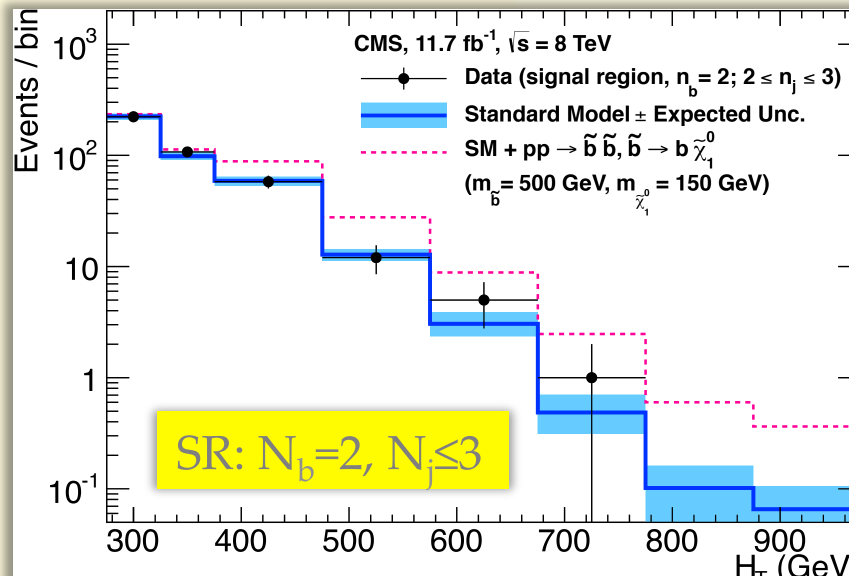


- Signal regions are defined as:
  - 8 bins in H_T (275 to ≥875 GeV),
  - 2 bins N_{jet} (2-3, ≥4),
  - 5 bins in N_{bjet} (0,1,2,3, ≥4)

0-lepton final state: CMS

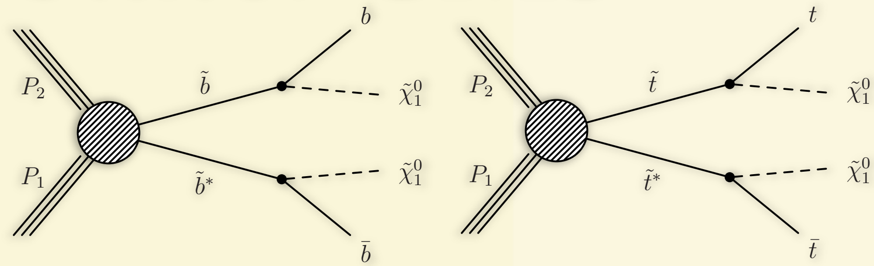
- Different backgrounds in N_{bjet} bins:
  - 0 bjets: W+jets with lepton not identified, or $W \rightarrow \tau\nu$, $Z \rightarrow \nu\nu$+jets
  - 1 bjet: W/Z+jets and ttbar are comparable in contributions
  - ≥2 bjets: ttbar is the dominant background
- Build models of backgrounds from data control regions:
  - W+jets and ttbar estimated from μ+jets; $Z \rightarrow \nu\nu$ from $Z \rightarrow \mu\mu$ and γ+jets
  - QCD estimated from the sideband in $0.52<\alpha_T<0.55$

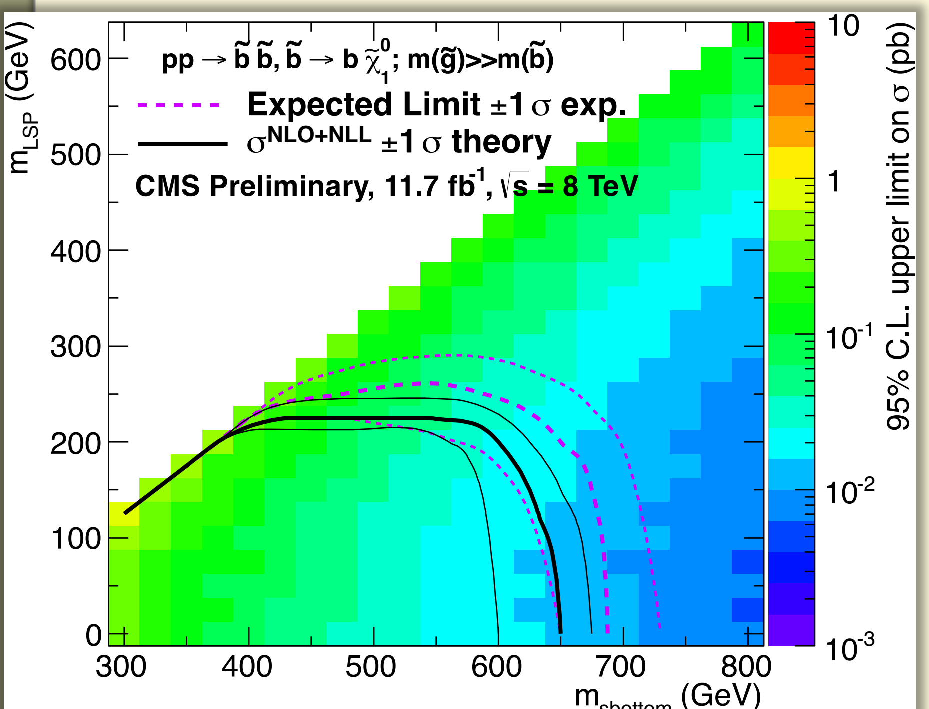


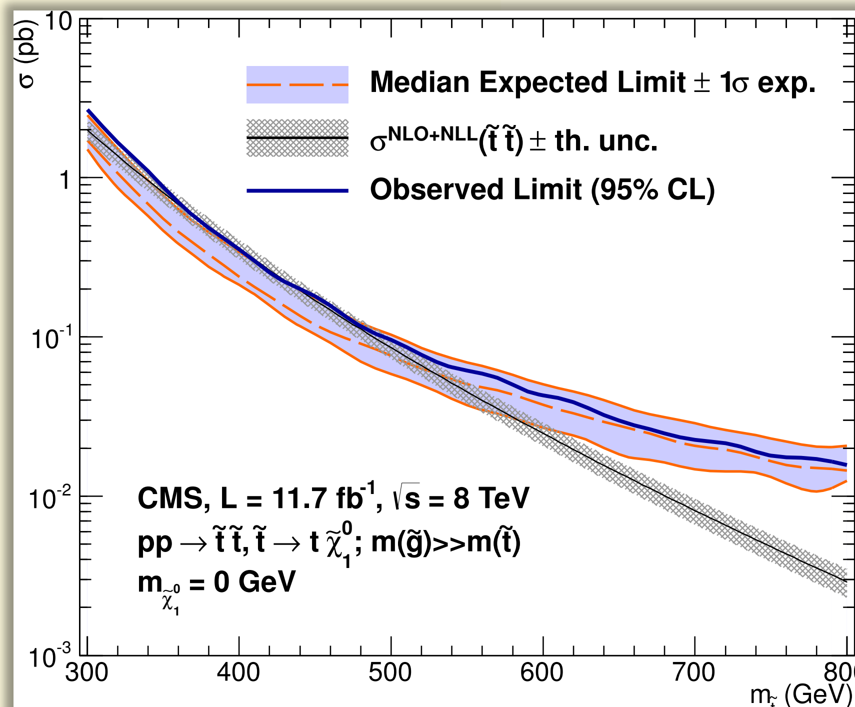


0-lepton final state: CMS

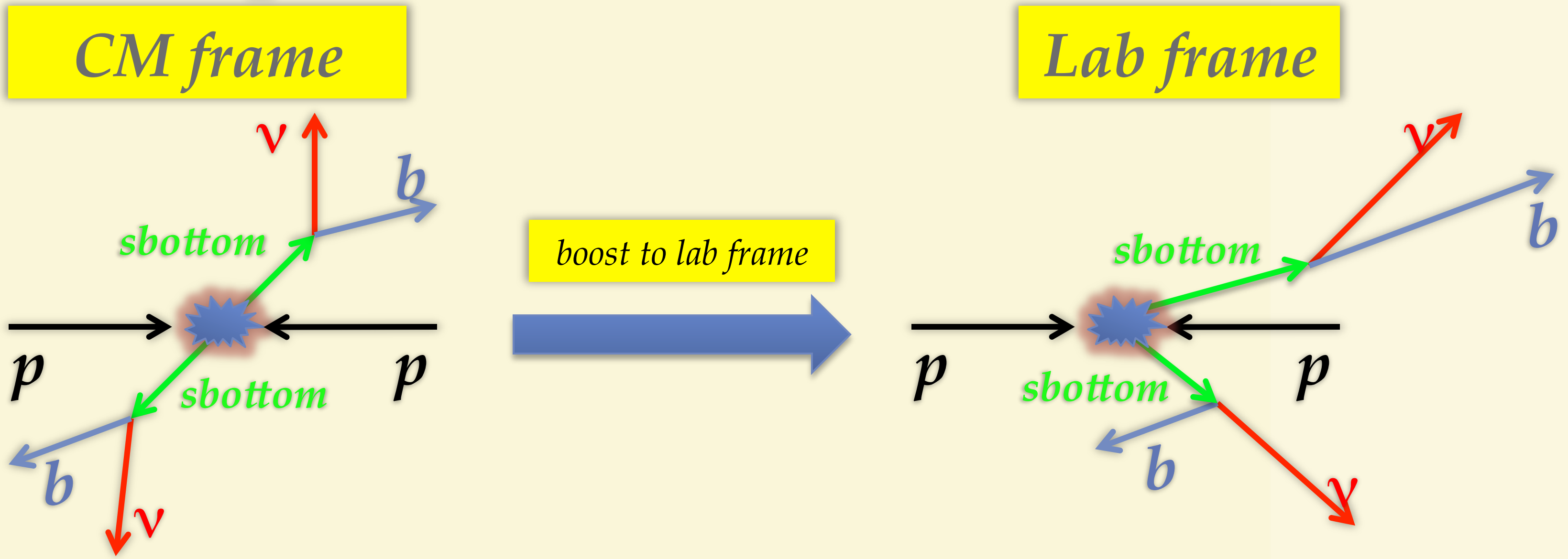
- No significant excess above the SM
  - Set limits on SMS models
  - Consider T2bb and T2tt
- Exclude sbottom quarks up to **$m_{sbottom} \approx 600$ GeV**
  - For T2tt use only $N_{jet} \geq 4$ and $N_{bjet} = 1$ or $N_{bjet} = 2$ events







0-lepton final state: CMS



- Devise variables to increase the sensitivity
  - Razor variables to recast tail search into a bump-hunt
- Stops/Sbottoms are heavy→produced at threshold
  - Longitudinal boost to the frame where jets momenta are equal (*R*-frame)
- $M_R \rightarrow 2|p|$ in the *R*-frame (*a la* invariant mass), and M_T^R is transverse
  - Define $R = M_T^R / M_R$ → characterizes the angle between jets

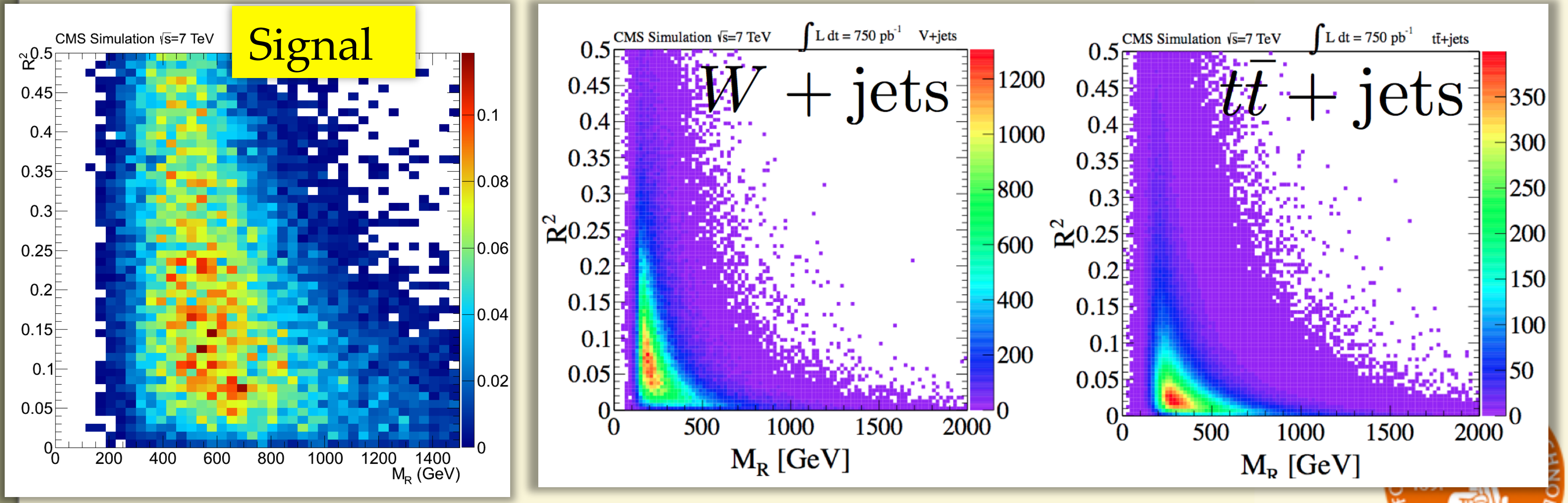
$$M_R \sim \frac{M^2_{squark} - M^2_{\chi}}{M_{squark}}$$

0-lepton final state: CMS

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

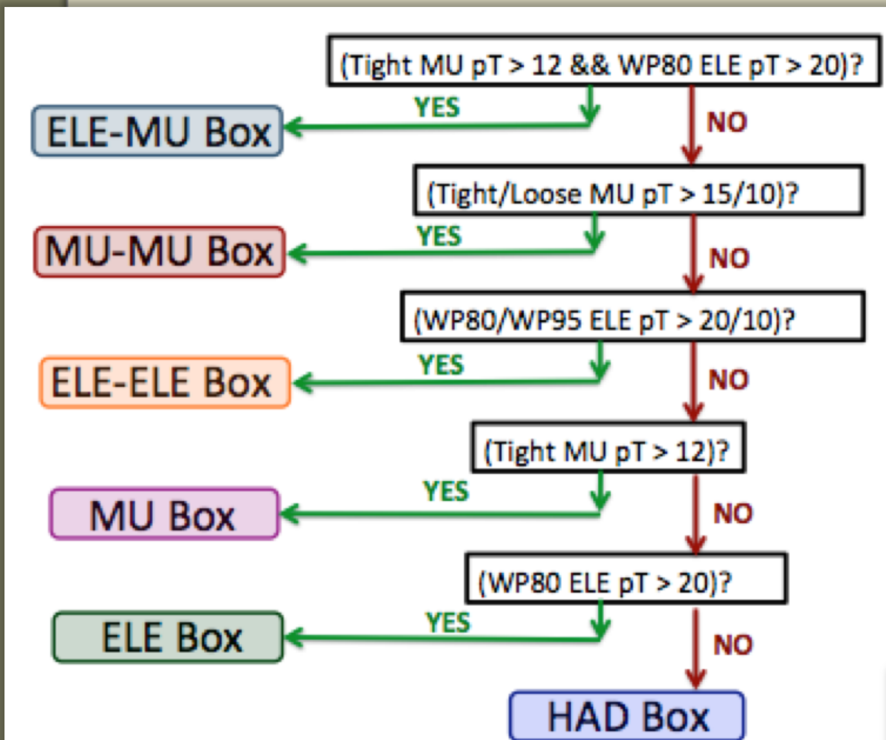
$$M_T^R \equiv \sqrt{\frac{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

$$R \equiv \frac{M_T^R}{M_R}$$



0-lepton final state: CMS

- Apply the razor analysis technique in a multi-box approach

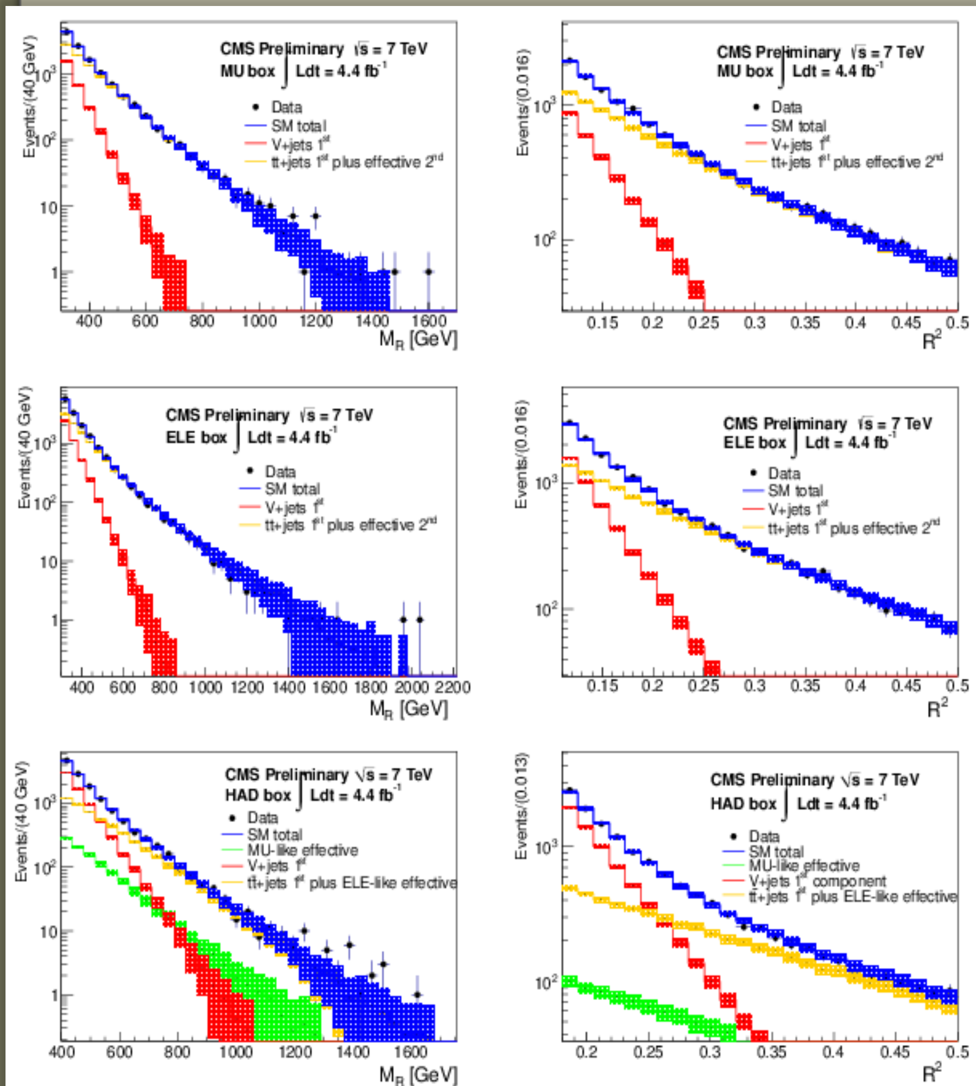


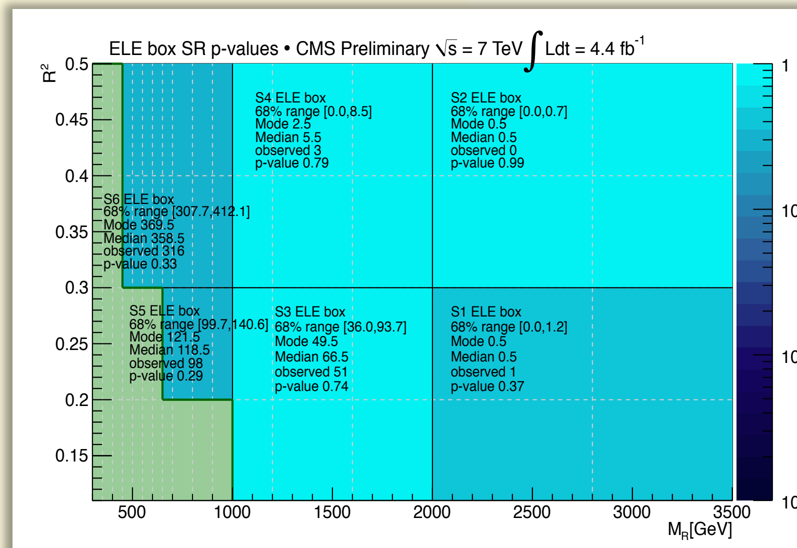
Classify various boxes based on lepton multiplicities

$$\mathcal{L}_b = \frac{e^{-(\sum_{j\in SM} N_j)}}{N!}\prod_{i=1}^{N}\Big(\sum_{j\in SM} N_j P_j(M_{R,i}, R_i^2)\Big)$$

- Extended and unbinned maximum likelihood fit performed in 2D R^2-M_R plane independently in each BOX
- Extrapolate background shape into the signal region

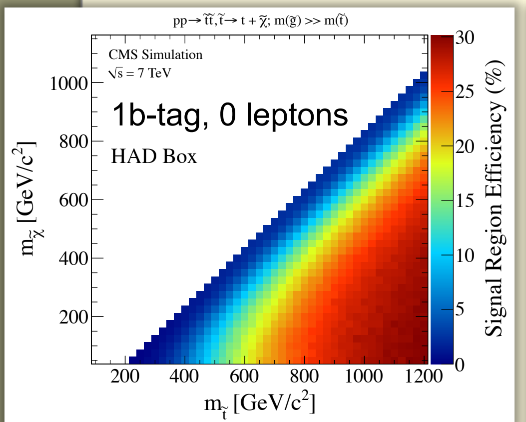
0-lepton final state: CMS

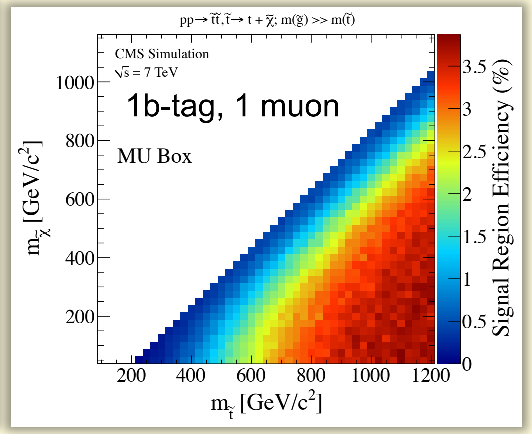


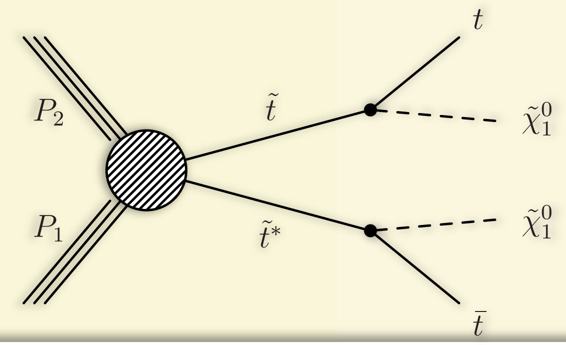


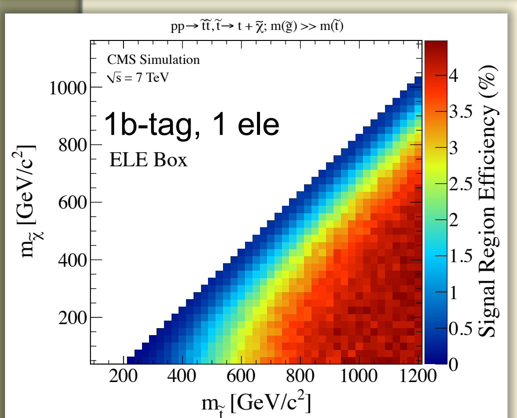
Model independent results showing data/prediction compatibility

0-lepton final state: CMS

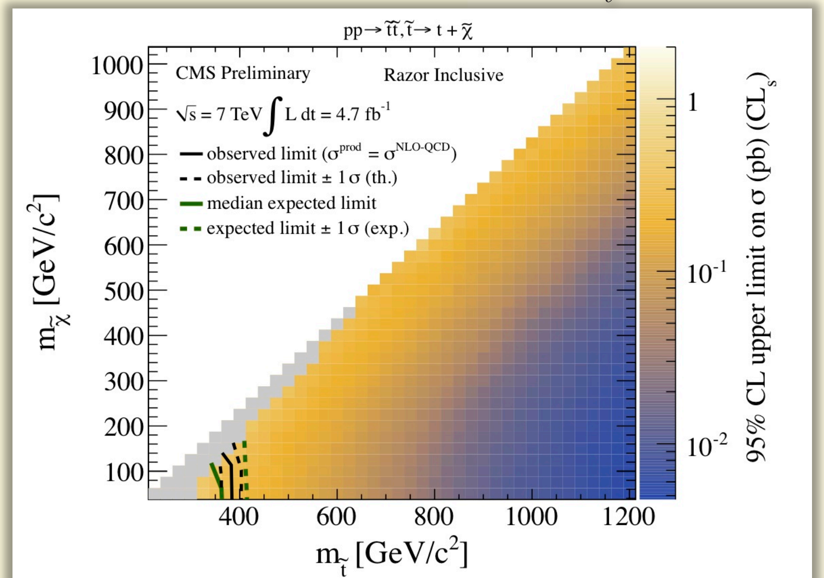








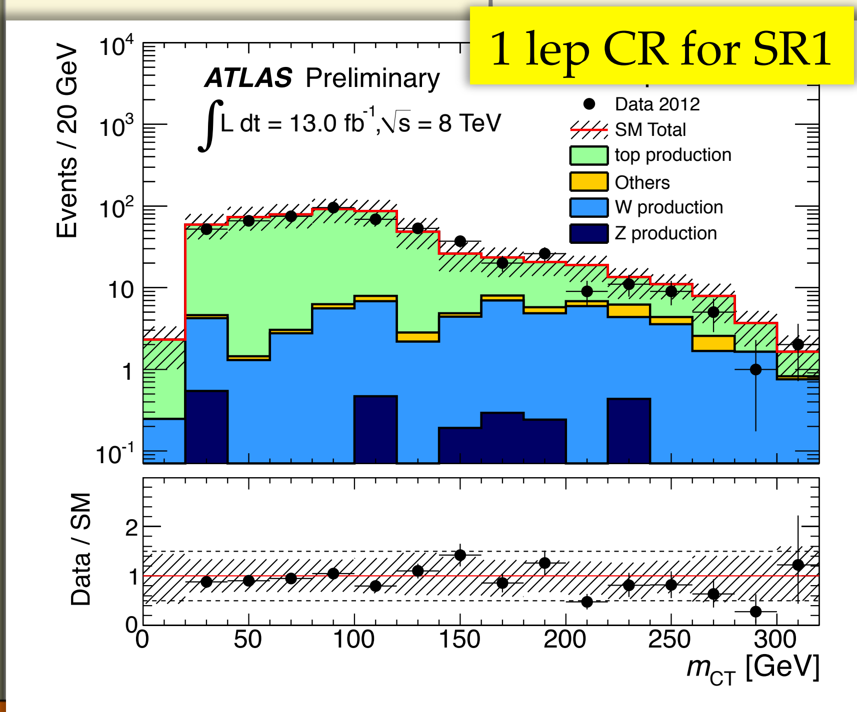
+ other boxes →

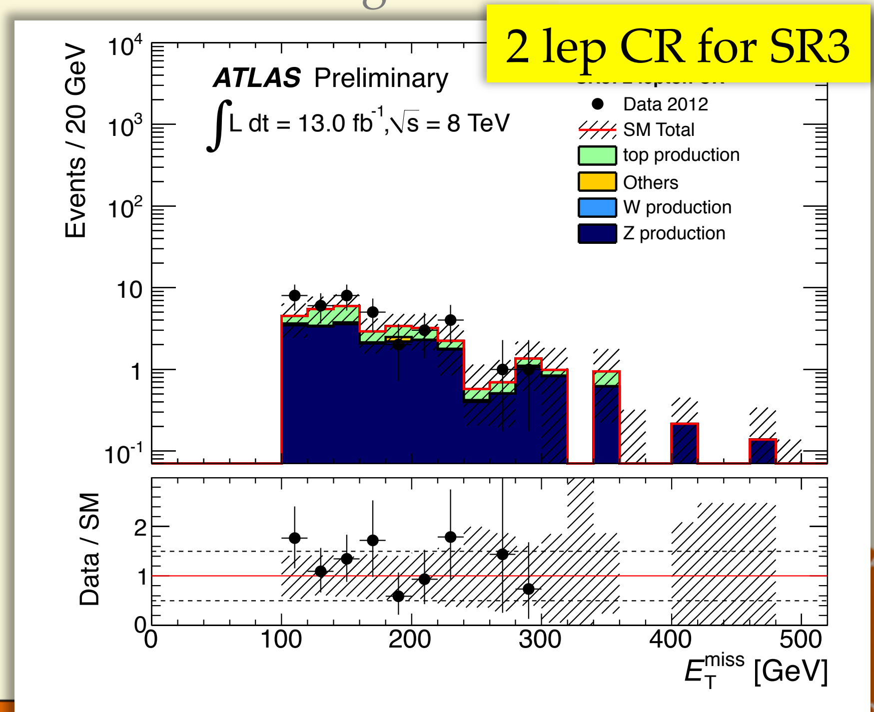


Exclude stop masses up to **~420 GeV** for neutrualino masses of ~50 GeV

0-lepton final state: ATLAS

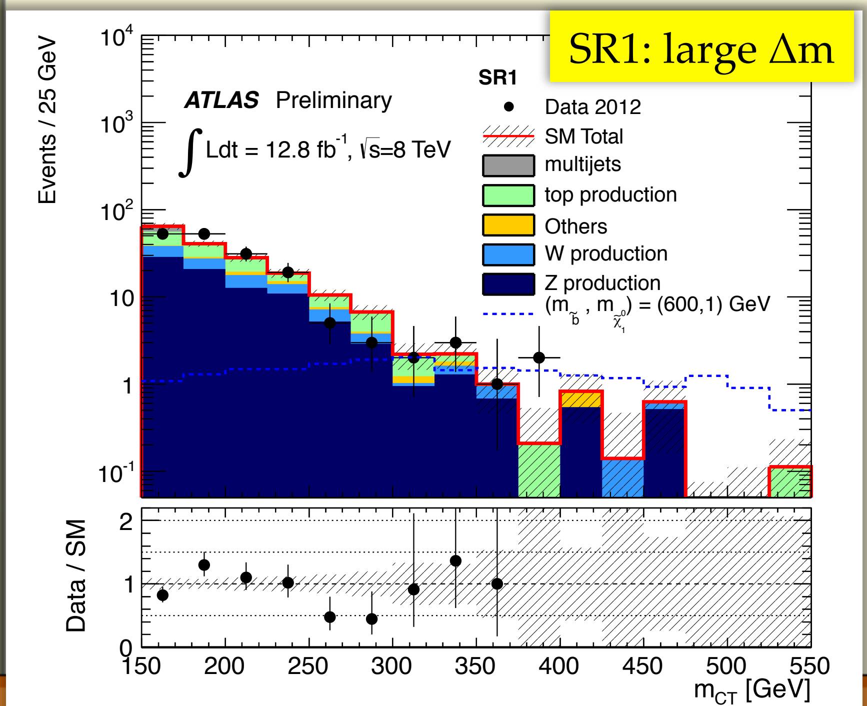
- Variables used to define signal regions: MET, $\Delta\phi_{min}$, m_{eff}, $H_{T,x}$, m_{CT}
- Multijet background estimated using jet response smearing technique
  - Gaussian core of the jet response function from di-jet events
  - non-Gaussian tails from three-jet events: MET is from mis-measurements
- top (pair and single), W/Z+bjets from control regions with 1 or 2 leptons
  - Simultaneous profile likelihood fit in the control regions

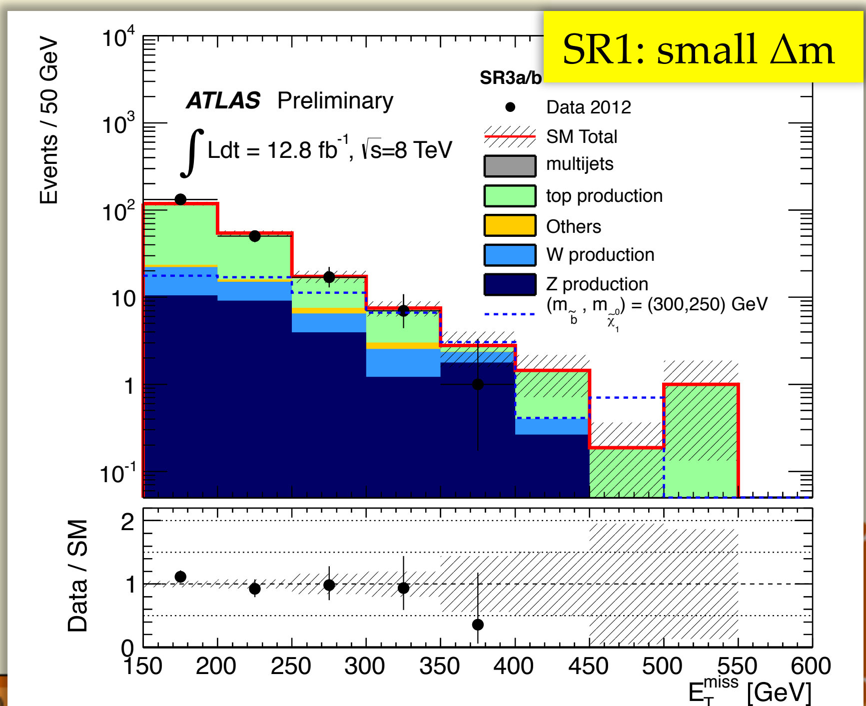




0-lepton final state: ATLAS

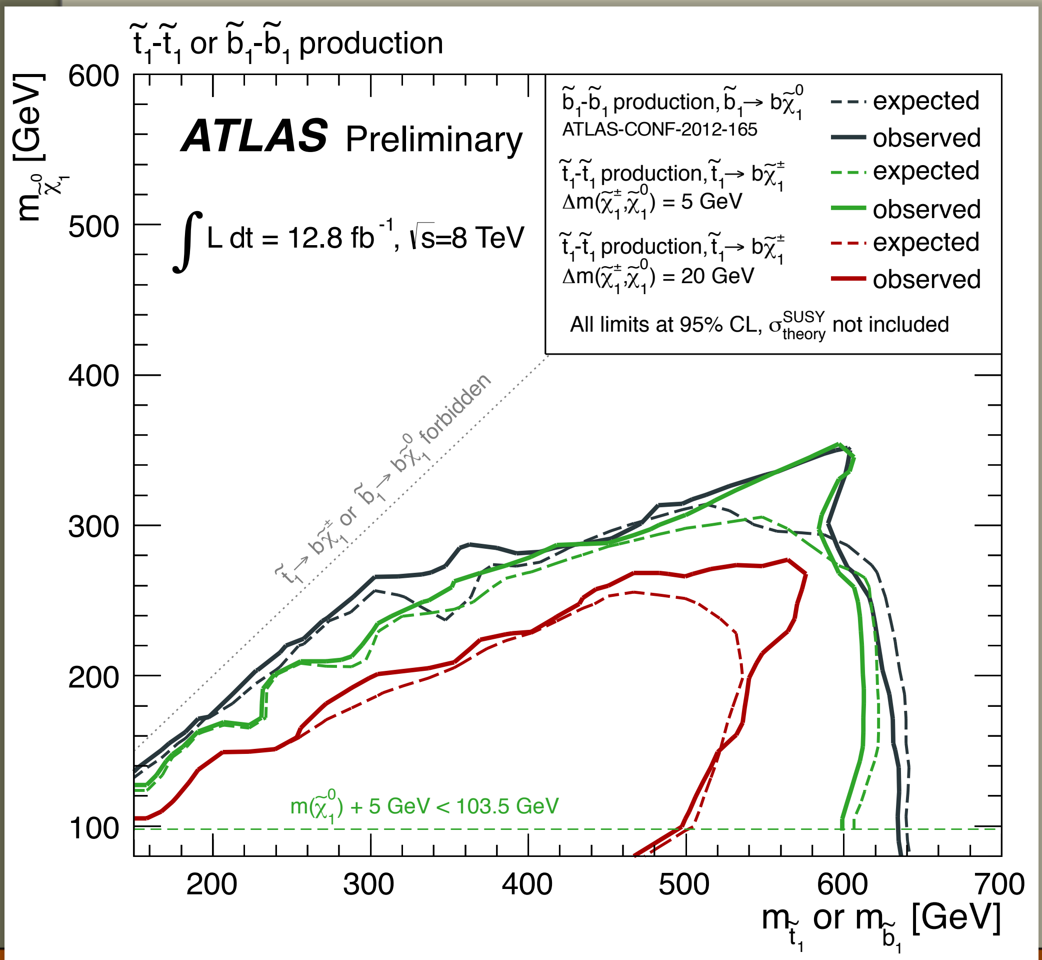
- Optimized signal region definitions for various mass-splittings (Δm)
- Three sets of signal regions defined:
  - SR1 for **large Δm**: 2 b-jets (veto on third jet), large MET
    - Cut on m_{CT} to suppress backgrounds. Edge at $(\mathbf{m^2_{sbottom}-m^2_{\chi 10}})/\mathbf{m_{sbottom}}$
  - SR2 for **medium Δm**: looser than SR1 cuts, due to softer kinematics
  - SR3 for **small Δm**: select events with high p_T *non*-b-jet (ISR), two softer b-jets



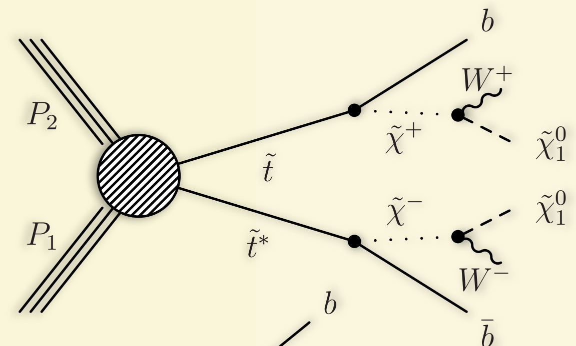


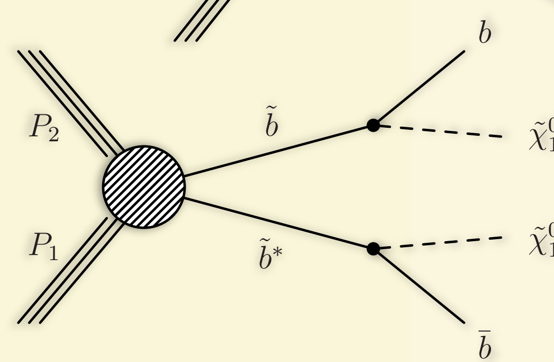
0-lepton final state: ATLAS

- Sensitive to sbottom and stop production (stop→$b\chi^{\pm}_1$)
  - for small $\Delta m(\chi_1^+, \chi_1^0)$ fermions are soft and are reconstructed



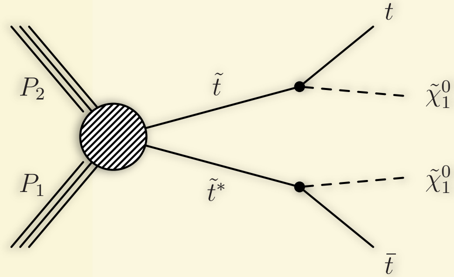
- Exclude a range of masses:
  - $m_{sbottom}$≈**620 GeV,**
  - m_{stop}≈**580GeV** (Δm=5GeV)
  - m_{stop}≈**480 GeV** (Δm=20GeV)





0-lepton final state: ATLAS

- Target the all-hadronic decays of the stop (stop→tχ_1^0)
- Large MET from LSP, use as discriminant
  - o 3 SR targeting different ranges of the stop mass



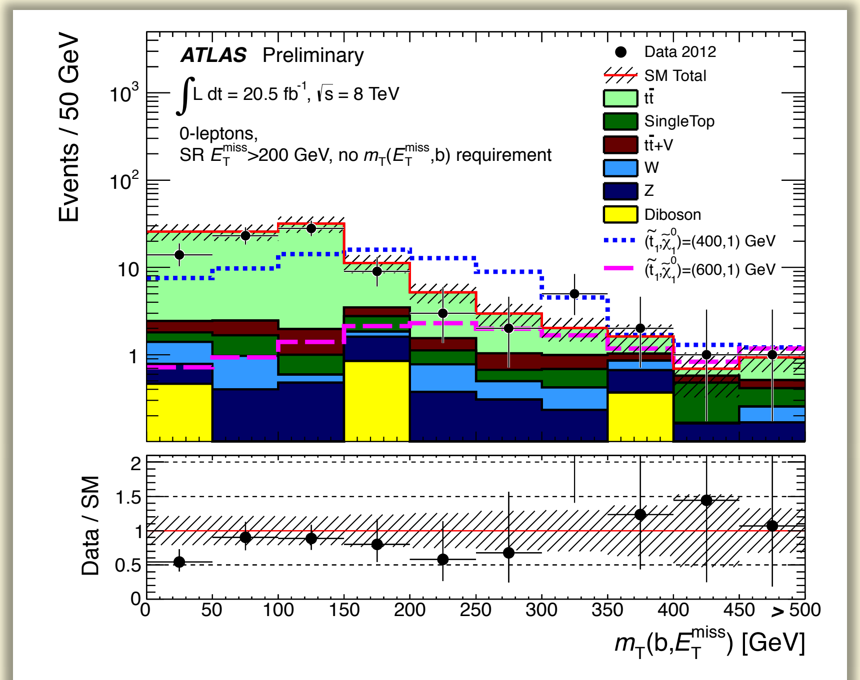
lepton veto / signal selection / QCD veto / top veto

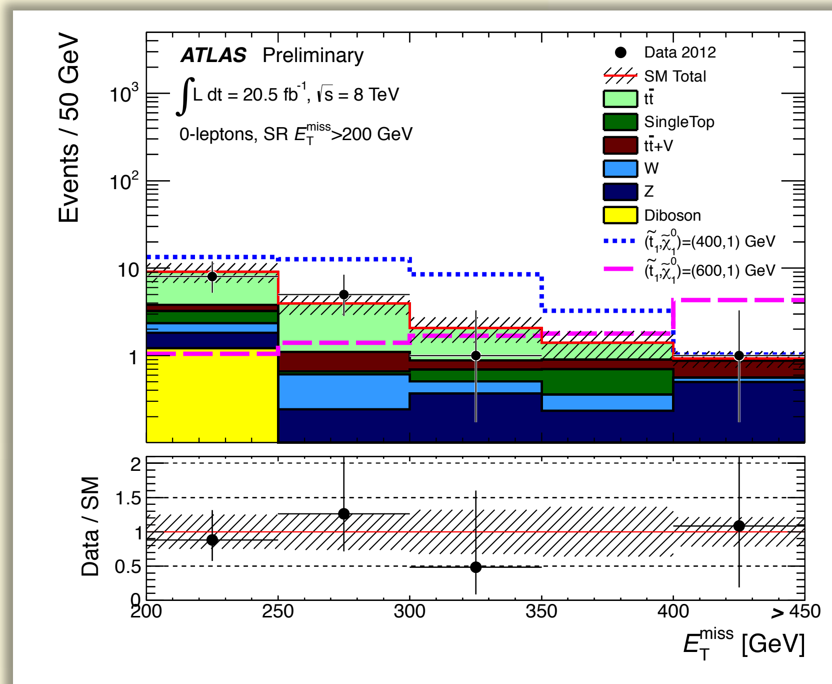
	Signal	$t\bar{t}$ CR	Z+jets CR	Multijet CR
Trigger	E_T^{miss}	single electron (muon)	two electron (muon)	E_T^{miss}
N_{lep}	0	1	2	0
p_T^{ℓ}	< 10 (10)	> 35 (35)	> 20 (20)	< 10 (10)
$p_T^{\ell_2}$	—	< 10 (10)	> 20 (10)	—
$m_{\ell\ell}$	—	—	81 to 101	—
N_{jet}	≥ 6	≥ 6	≥ 6	≥ 6
p_T^{jet}	$> 80,80,35,...35$	$> 80,80,35,...35$	$> 80,80,35,...35$	$> 80,80,35,...35$
$N_{b\text{-jet}}$	≥ 2	≥ 2	≥ 2	≥ 2
m_{jjj}	80 to 270	0 to 600	80 to 270	—
E_T^{miss}	$> 200, 300, 350$	$> 200, 300, 350$	> 70	> 160
$E_T^{miss,track}$	> 30	> 30	> 30	> 30
$\Delta\phi(E_T^{miss}, E_T^{miss,track})$	$< \pi/3$	$< \pi/3$	$< \pi/3$	$> \pi/3$
$m_T(\ell, E_T^{miss})$	—	40 to 120	—	—
$\Delta\phi(\text{jet}, E_T^{miss})$	$> \pi/5$	$> \pi/10$	$> \pi/5$	$< \pi/5$
$m_T(b\text{-jet}, E_T^{miss})$	> 175	—	> 175	> 175
Tau veto	yes	no	yes	no

ATLAS-CONF-2013-024

0-lepton final state: ATLAS

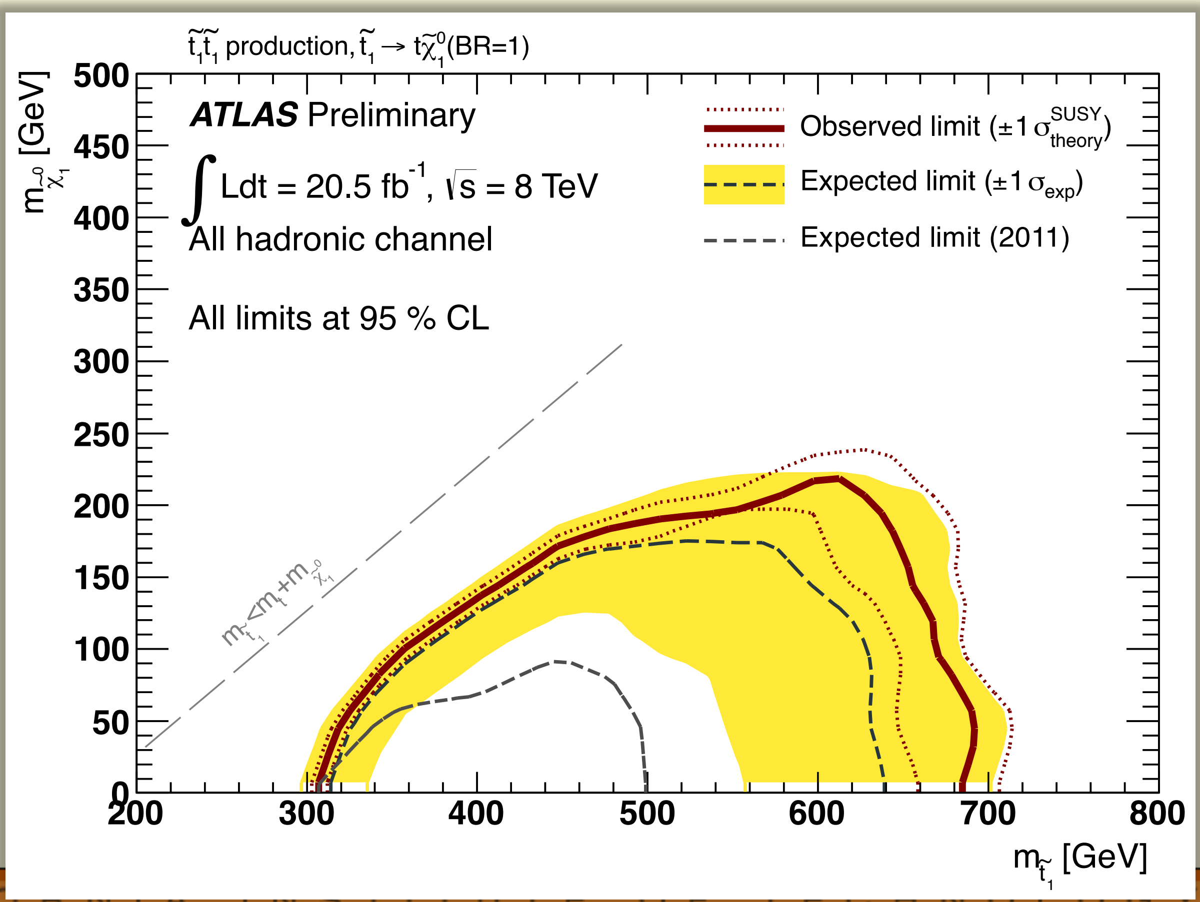
- At high MET the dominant background is semileptonic ttbar ($W\to\tau\nu$)
  - Derive from a sample with one charged lepton; remove top veto
  - Treat the lepton as a *non*-b-jet
- Z+jets derived from $Z\to ll$ sample: remove leptons from the event
- Multijet derived from a dijet sample with JER smearing technique





0-lepton final state: ATLAS

- No excess in any of the signal regions considered
  - stop pair production: t_1 mostly t_R (95%), BR($t_1 \rightarrow t\chi_1^0$) = 100%
  - exclude stop quarks **320<m_{stop}<660 GeV**



CMS-PAS-12-023

1-lepton final state: CMS

- Target the cleaner final state with one leptons from:
  - $pp \to \tilde{t}\tilde{t}^* \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
  - $pp \to \tilde{t}\tilde{t}^* \to b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \to b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
  - Signal looks like ttbar+MET
- Largest backgrounds: semi-leptonic ttbar and W+jets
  - Have an edge at $M_T<M_W$ ➔ search in the region above M_W
  - Suppress ttbar background: veto events with addl. isolated tracks
  - Require at least one b-jet

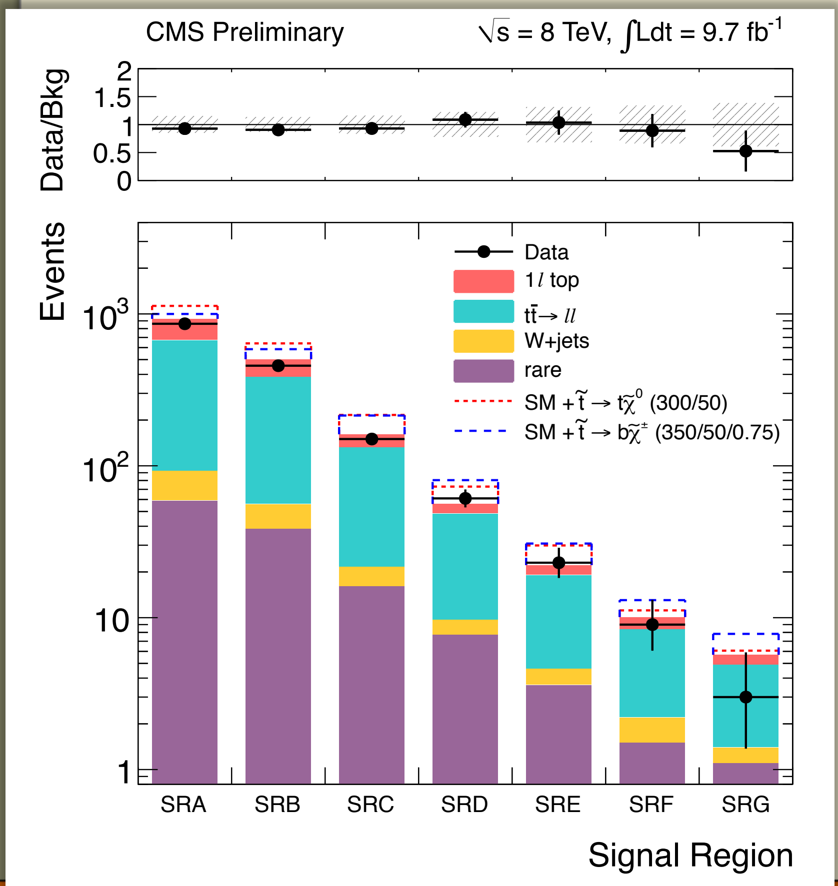
Signal Region	Minimum M_T [GeV]	Minimum E_T^{miss} [GeV]
SRA	150	100
SRB	120	150
SRC	120	200
SRD	120	250
SRE	120	300
SRF	120	350
SRG	120	400

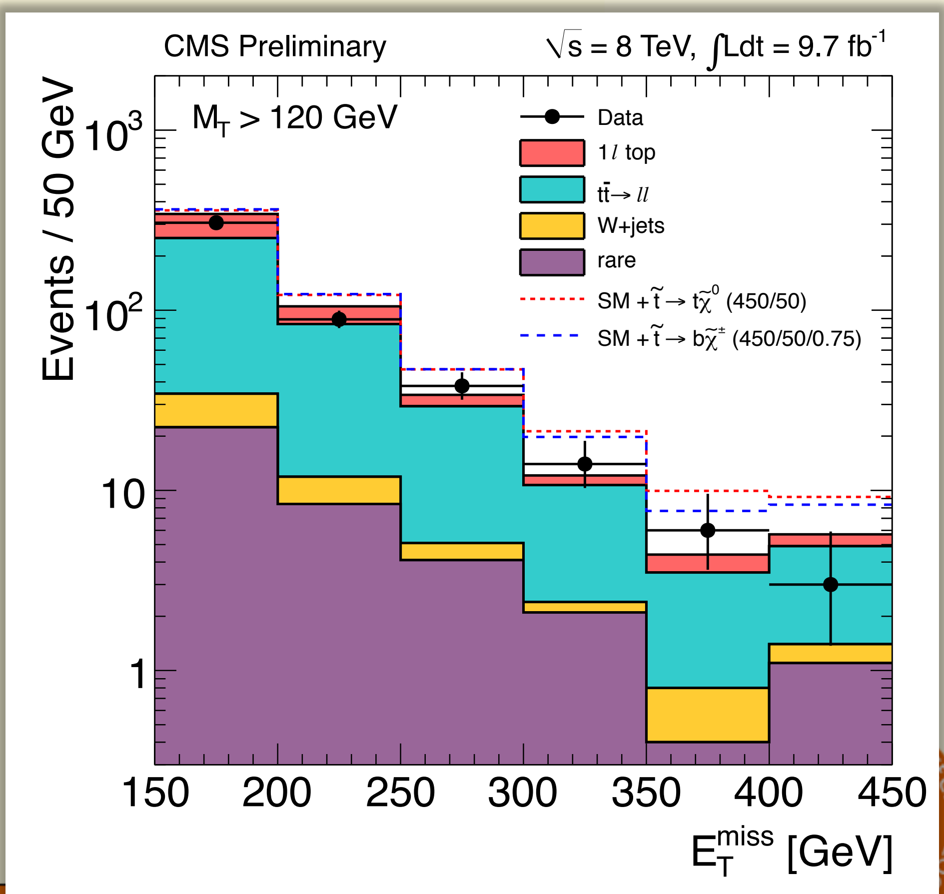
Loose: sensitive to small Δm (SRA–SRC)

Tight: sensitive to larger Δm (SRD–SRG)

1-lepton final state: CMS

- Backgrounds estimated using MC simulation
  - Validated in control regions: derive the MC scale factors
  - Normalize in 50<M_T<80 GeV peak region: reduce the uncertainty

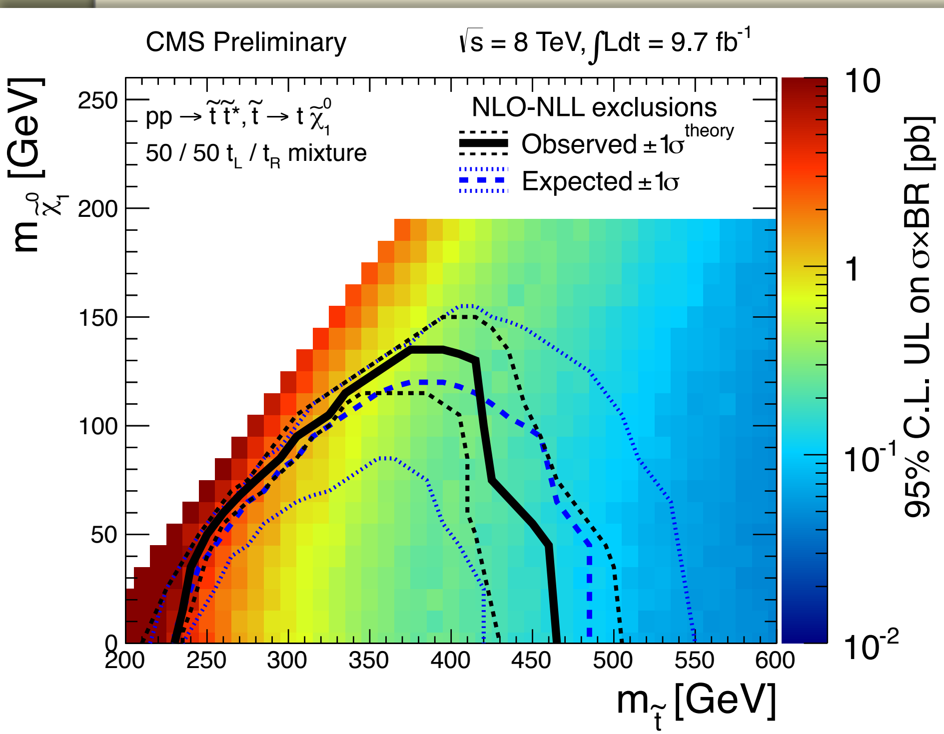




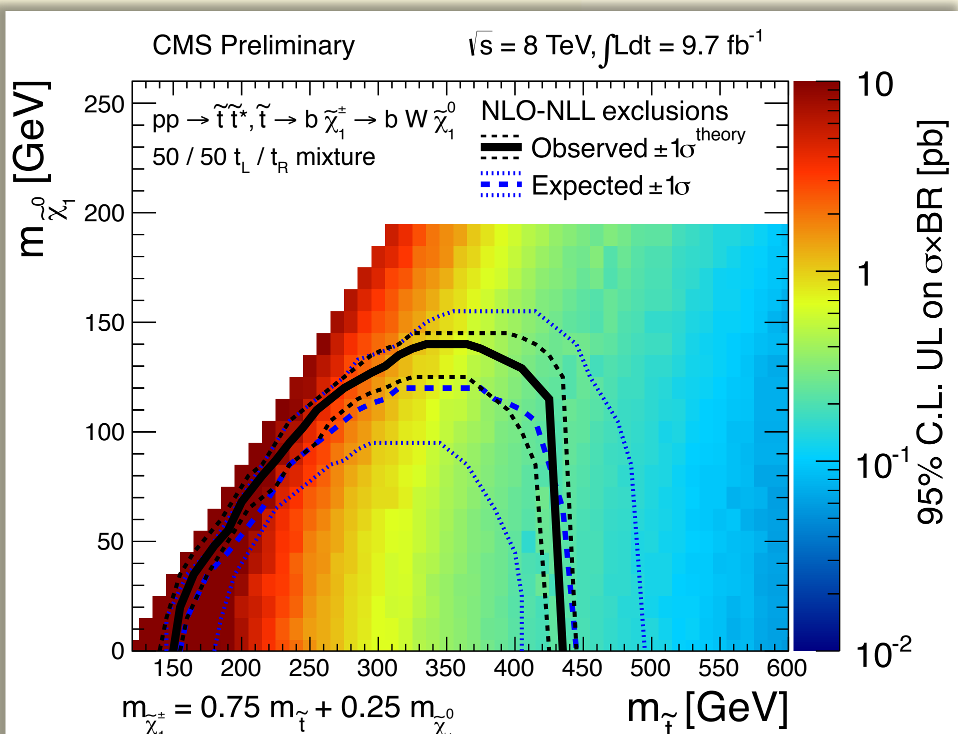
CMS-PAS-12-023

1-lepton final state: CMS

- Interpret results in several models
  - stops are generated as a 50/50 mixture of t_R and t_L
  - exclude stop quarks **160<m_{stop}<430 GeV**



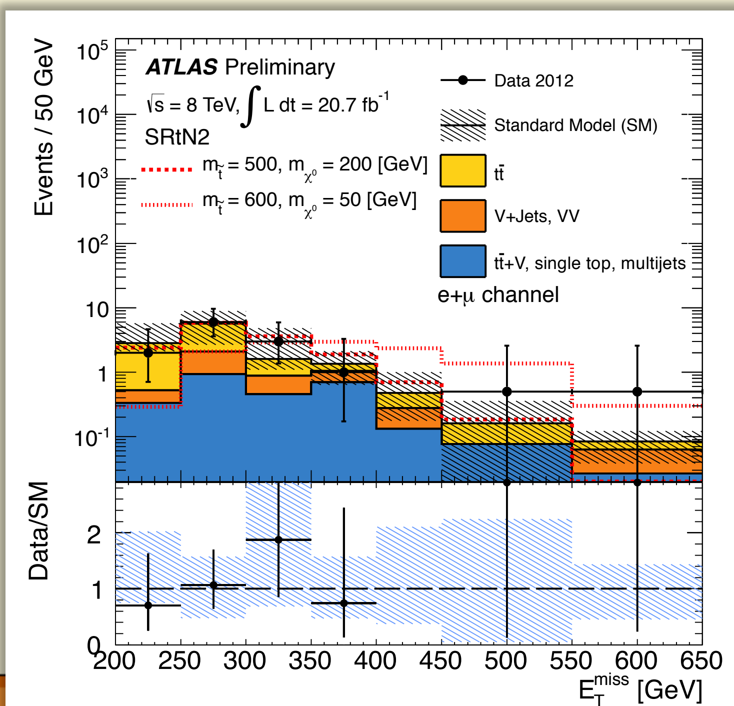
$\tilde{t} \to t\tilde{\chi}^0_1$ 50/50 t_L t_R mixing

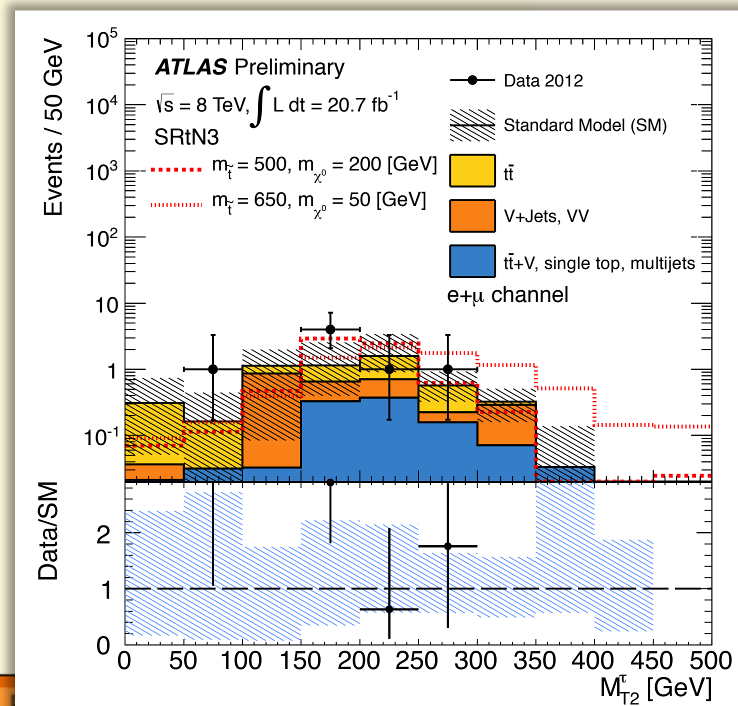


$\tilde{t} \to b\tilde{\chi}^{\pm}_1 \to bW\tilde{\chi}^0_1$ 50/50 t_L t_R mixing, chargino mass close to neutralino

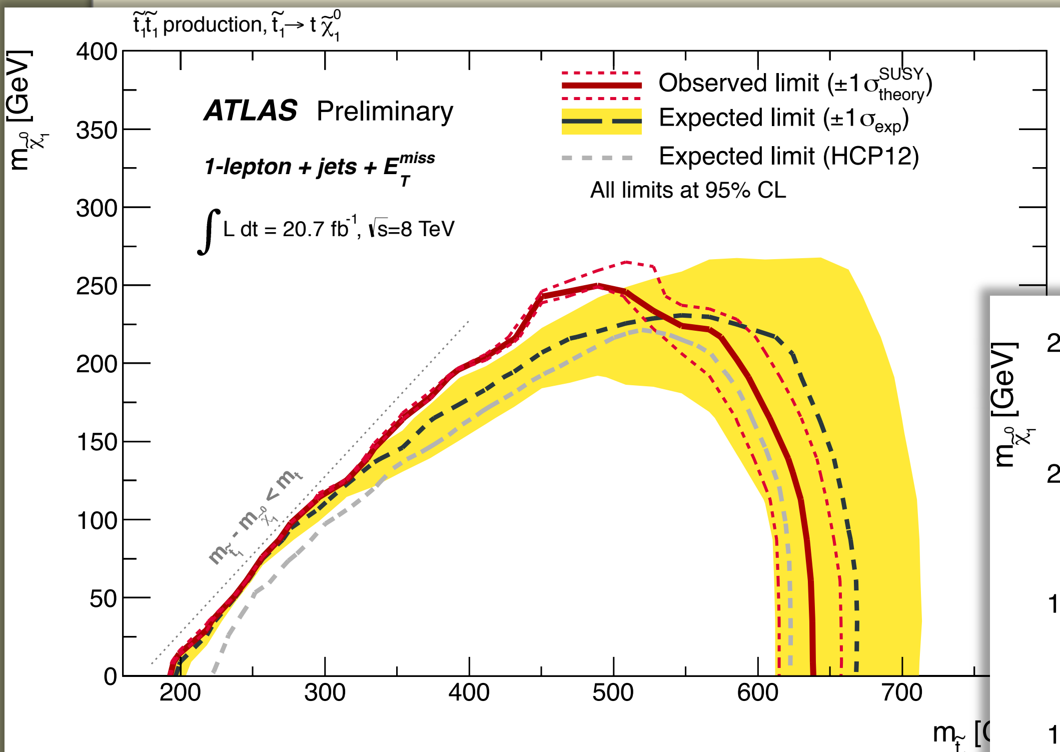
1-lepton final state: ATLAS

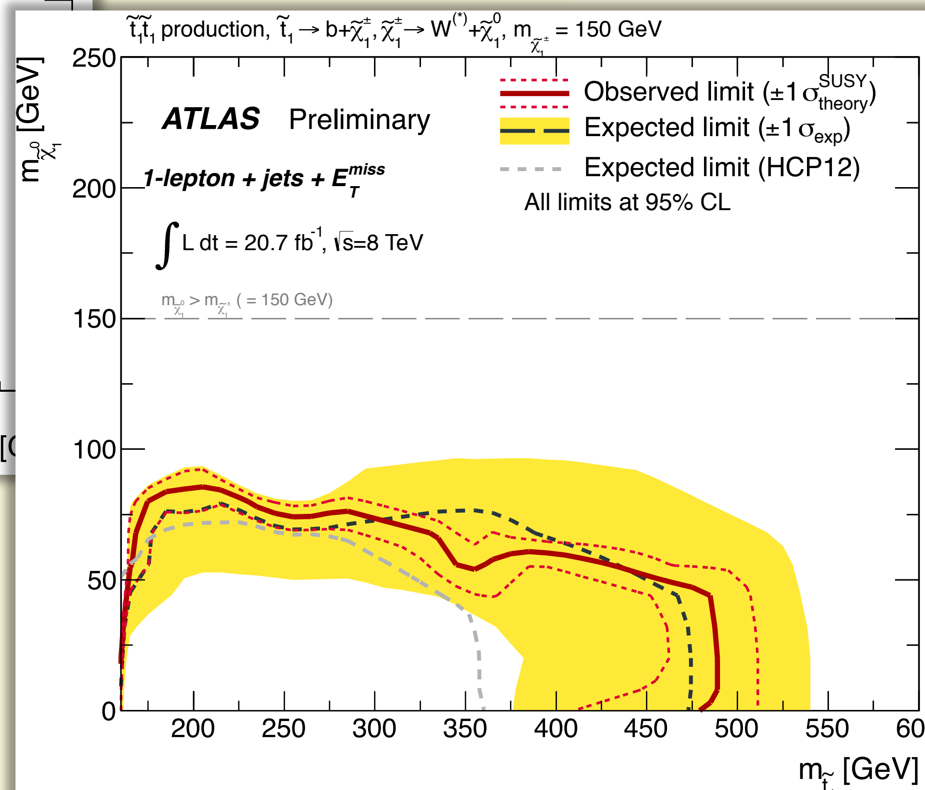
- Same final states targeted as in CMS search, similar event selection
  - Dedicated signal regions for various Δm hypotheses
  - Loosest selection for small Δm:
    - use a 2D shape fit in MET-M_T plane to increase sensitivity
  - tag one b-jet, identify one all-hadronic top candidate
- Backgrounds estimated from control regions in data





1-lepton final state: ATLAS





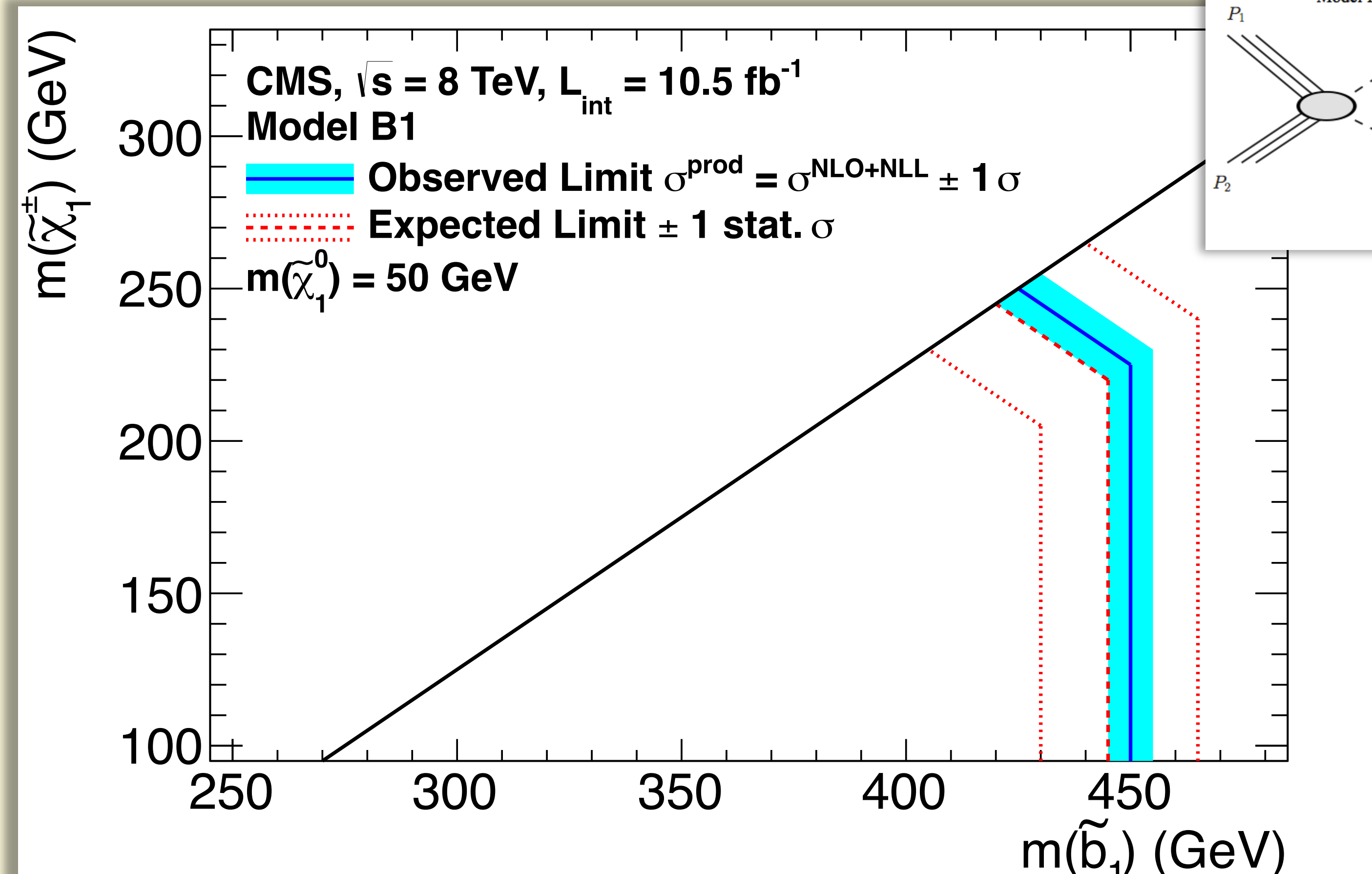
- exclude **$200 < m_{stop} < 610$ GeV ($m\chi^0_1 = 0$)**
- exclude **$m_{stop} < 410$ GeV ($m\chi^{\pm}_1 = 150$)**

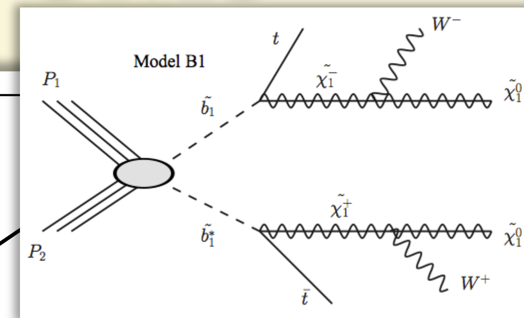
2-lepton final state: CMS

- Select same-sign (SS) di-leptons + b-jets:
  - very rare in SM, sensitive to $\tilde{b}_1 \to t\tilde{\chi}_1^-$ and $\tilde{\chi}_1^- \to W^-\tilde{\chi}_1^0$
- Select events with 2 SS, high p_T isolated e/μ leptons and ≥2 jet
  - Require 2 b-jets to suppress dominant background (ttbar)
- Misidentified leptons are main background
  - HF decay, misidentified hadrons, muons from meson DIF, electrons from conversions, or charge "flips": extrapolation method in lepton ID/iso

No. of jets	≥ 2	≥ 2	≥ 2	≥ 4	≥ 4	≥ 4	≥ 4	≥ 3	≥ 4
No. of btags	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
Lepton charges	$++/--$	$++/--$	$++$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$
E_T^{miss}	> 0 GeV	> 30 GeV	> 30 GeV	> 120 GeV	> 50 GeV	> 50 GeV	> 120 GeV	> 50 GeV	> 0 GeV
H_T	> 80 GeV	> 80 GeV	> 80 GeV	> 200 GeV	> 200 GeV	> 320 GeV	> 320 GeV	> 200 GeV	> 320 GeV
Charge-flip BG	3.35 ± 0.67	2.70 ± 0.54	1.35 ± 0.27	0.04 ± 0.01	0.21 ± 0.05	0.14 ± 0.03	0.04 ± 0.01	0.03 ± 0.01	0.21 ± 0.05
Fake BG	24.77 ± 12.62	19.18 ± 9.83	9.59 ± 5.02	0.99 ± 0.69	4.51 ± 2.85	2.88 ± 1.69	0.67 ± 0.48	0.71 ± 0.47	4.39 ± 2.64
Rare SM BG	11.75 ± 5.89	10.46 ± 5.25	6.73 ± 3.39	1.18 ± 0.67	3.35 ± 1.84	2.66 ± 1.47	1.02 ± 0.60	0.44 ± 0.39	3.50 ± 1.92
Total BG	39.87 ± 13.94	32.34 ± 11.16	17.67 ± 6.06	2.22 ± 0.96	8.07 ± 3.39	5.67 ± 2.24	1.73 ± 0.77	1.18 ± 0.61	8.11 ± 3.26
Event yield	43	38	14	1	10	7	1	1	9
N_{UL} (13% unc.)	27.2	26.0	9.9	3.6	10.8	8.6	3.6	3.7	9.6
N_{UL} (20% unc.)	28.2	27.2	10.2	3.6	11.2	8.9	3.7	3.8	9.9
N_{UL} (30% unc.)	30.4	29.6	10.7	3.8	12.0	9.6	3.9	4.0	10.5

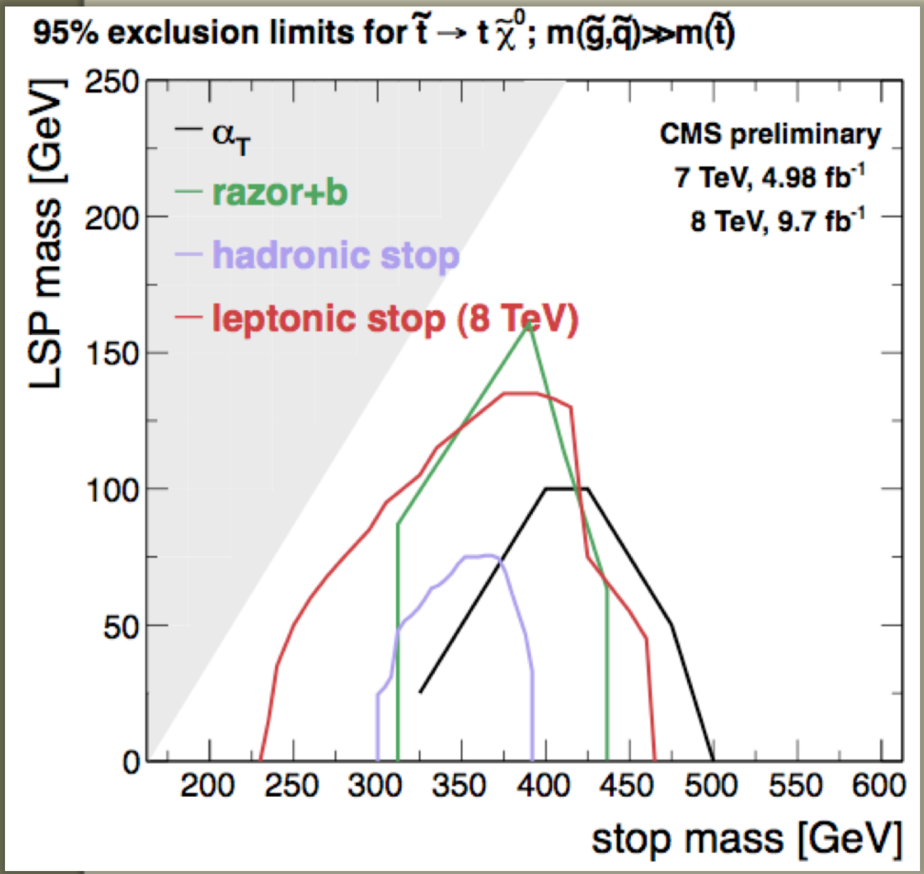
2-lepton final state: CMS

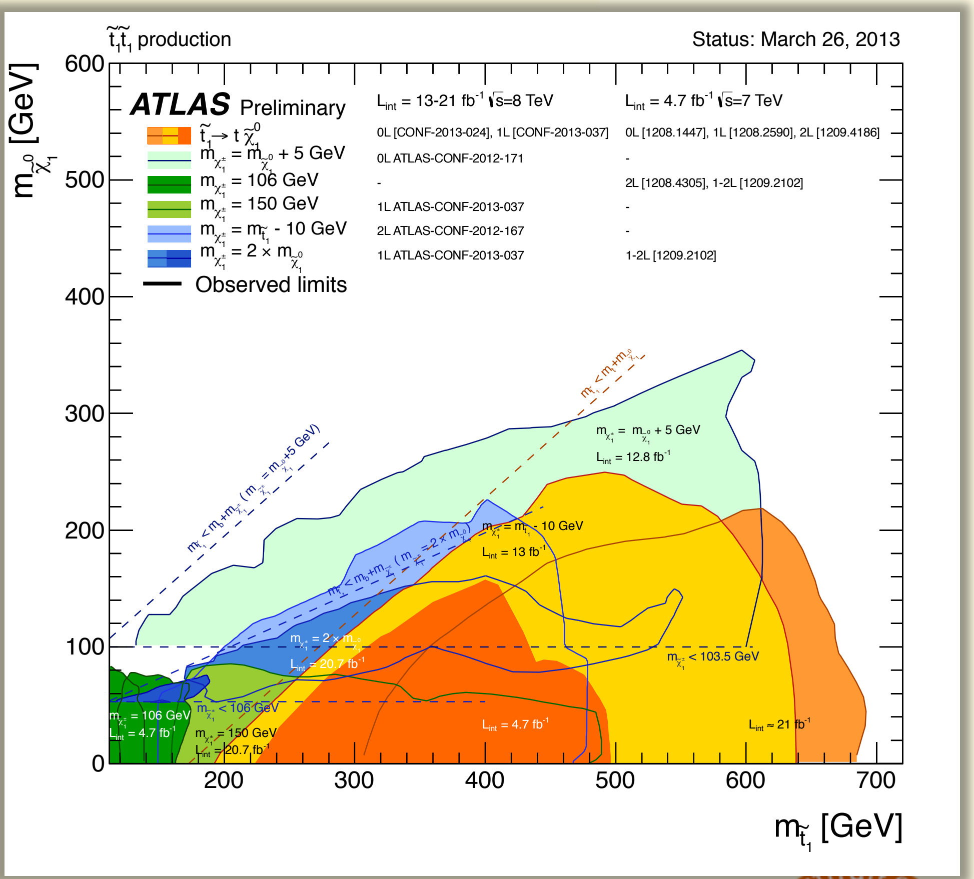




- Exclude sbottom quarks decaying up to **$m_{sbottom}$~450** GeV
- Similar limits from the ATLAS search

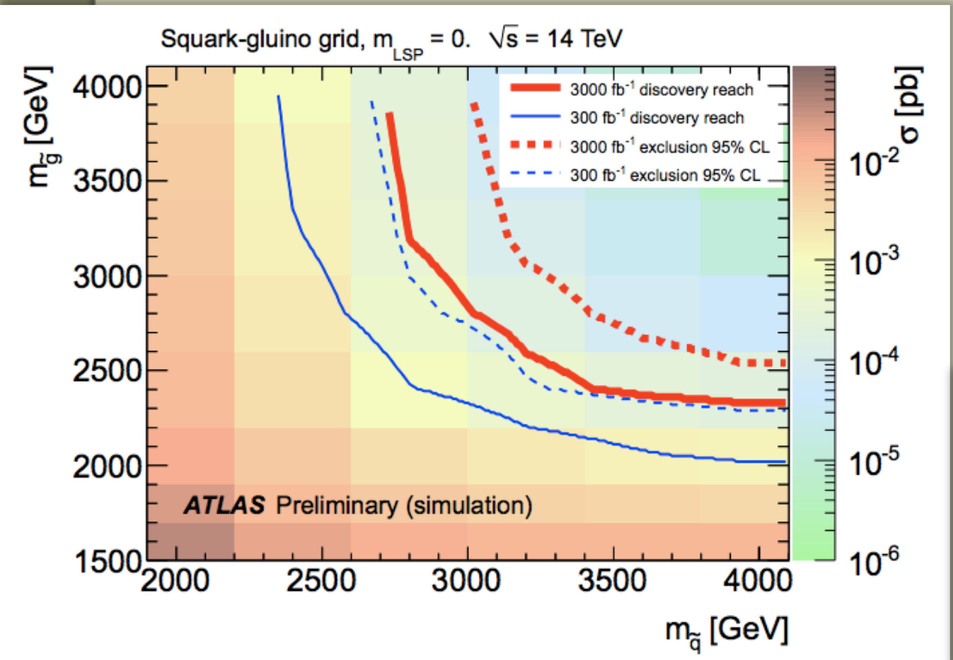
3^{rd} generations searches summary

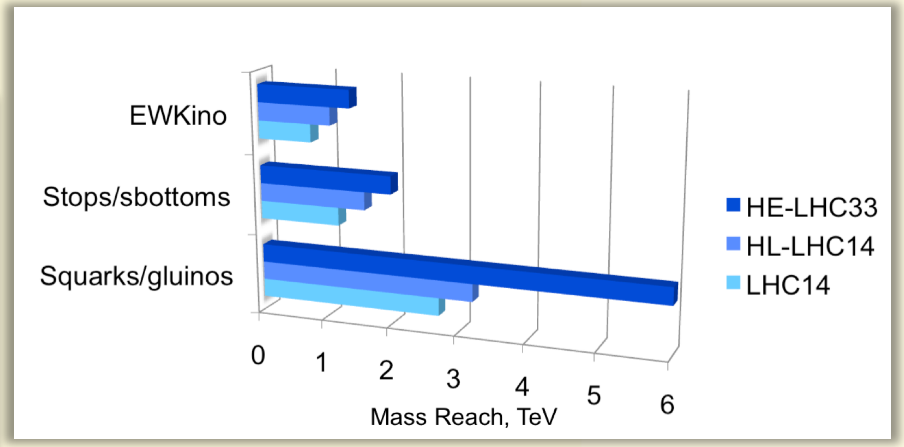


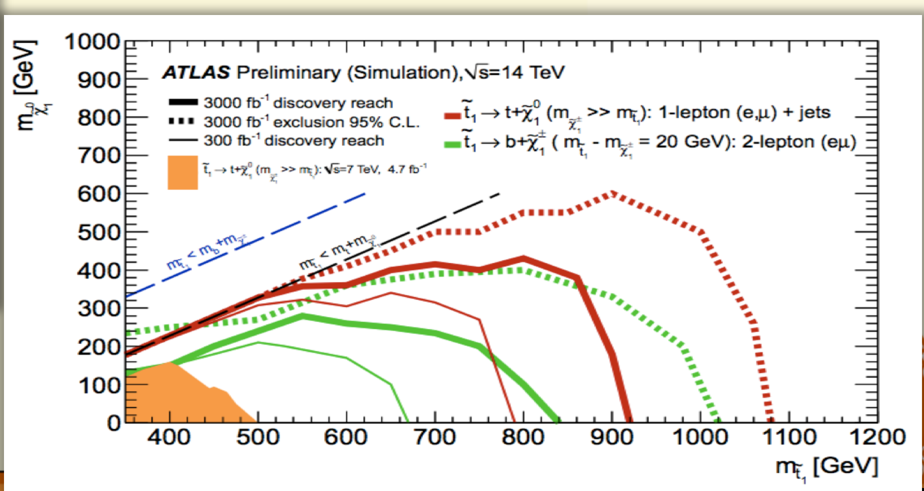


Prospects with HL-LHC

- Projection for HL-LHC sensitivity assuming realistic running conditions and no improvement on the analyses







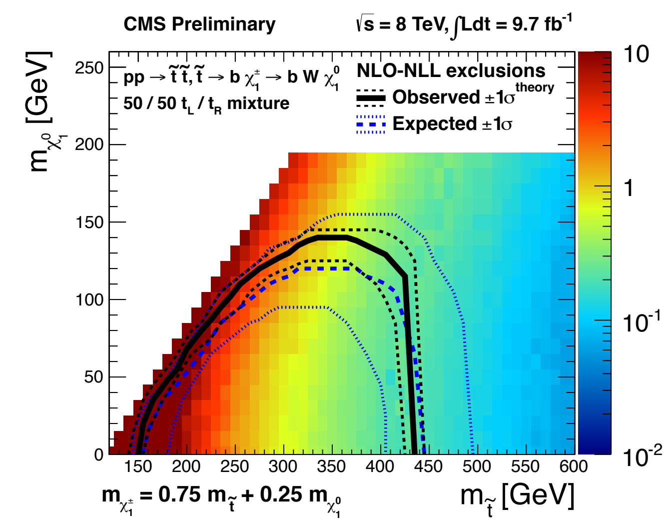
Conclusion

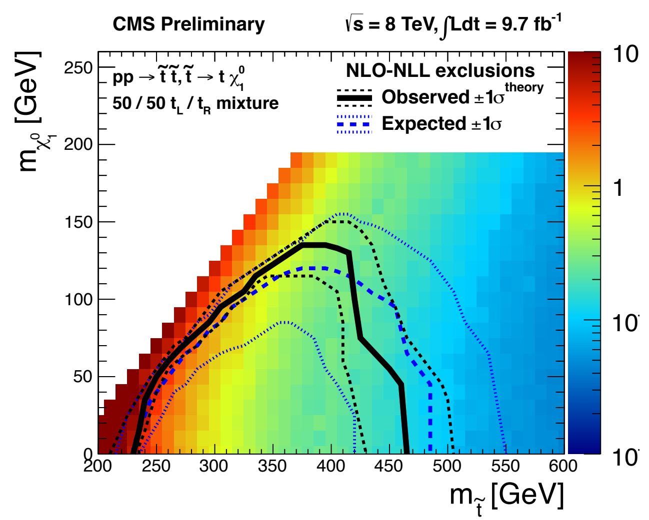
- A broad search program for 3rd generation direct production
  - Many novel approaches, new variables, search regions, final states
  - No excesses observed so far
  - Probe stop/sbottom masses up to ~500-600 GeV
- Several scenarios where stop/sbottom may have eluded detection in existing searches
  - Stops with mass near top quarks, or mass > 500 GeV
  - Compressed spectra, e.g. stop→top+χ, with small $\Delta m = m_{stop} - m_{\chi}$
  - Consider other decays: stop→cχ, higgs, taus
  - Boosted stops reconstruction, to reach higher masses
- Many new analysis in the pipeline, stay tuned

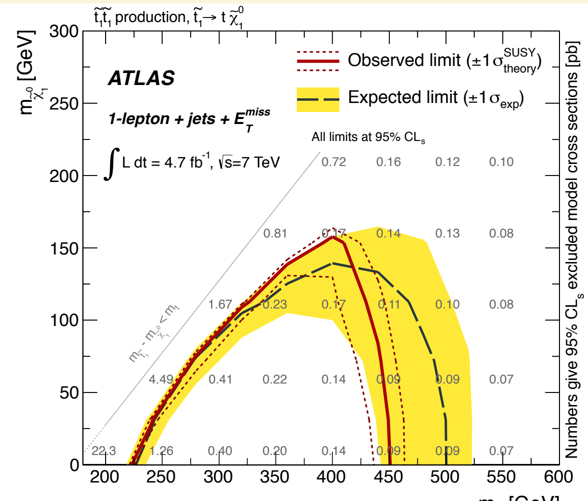
Backup

CMS vs. ATLAS comparison

$\tilde{t} \rightarrow b\chi^{\pm}$ x = 0.75 $\tilde{t} \rightarrow t\chi^{0}$ $\tilde{t} \rightarrow t\chi^{0}$



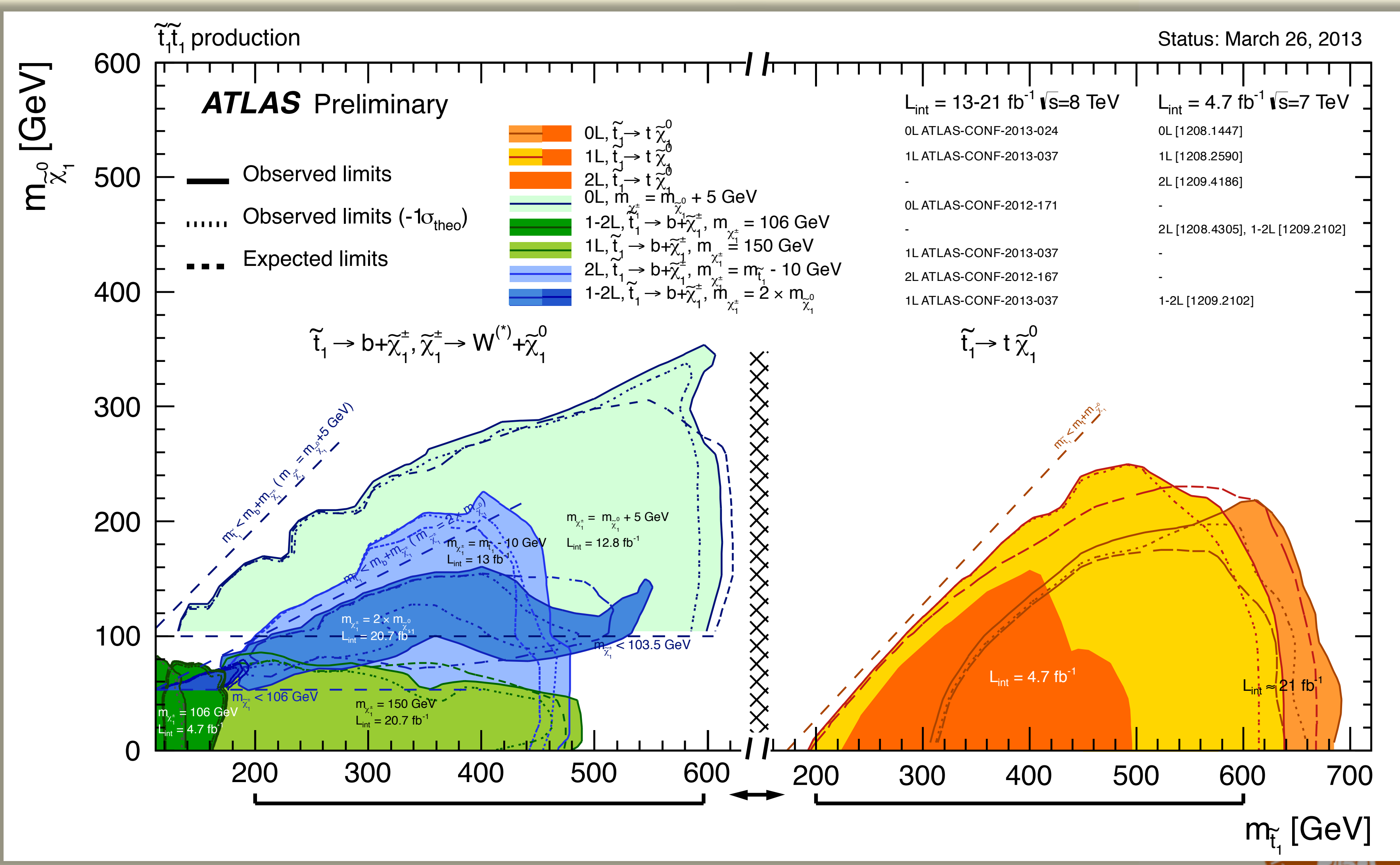




arXiv:1208.2590 [hep-ex]

- When correcting for luminosity and √s, the ATLAS limit covers more of the t → t χ^0 space for 2 reasons:
  - 1) Different signal model: CMS signal model has **unpolarized tops** from t→t χ^0. ATLAS signal model has **top quarks which are mostly right-handed**. This choice increases the large lepton p_T and M_T(ℓ,MET) acceptance because it causes the lepton to be emitted preferentially parallel to the top boost. **We estimate the size of this effect to be ~25%**.
  - 2) Tuned kinematical requirements: The most important one appears to be the **hadronic top reconstruction**. This is not currently implemented in the CMS analysis in order to **maintain sensitivity to both the t → t χ^0 and t → b $\chi^{\pm}$ decay modes**

ATLAS stop combination



Jets

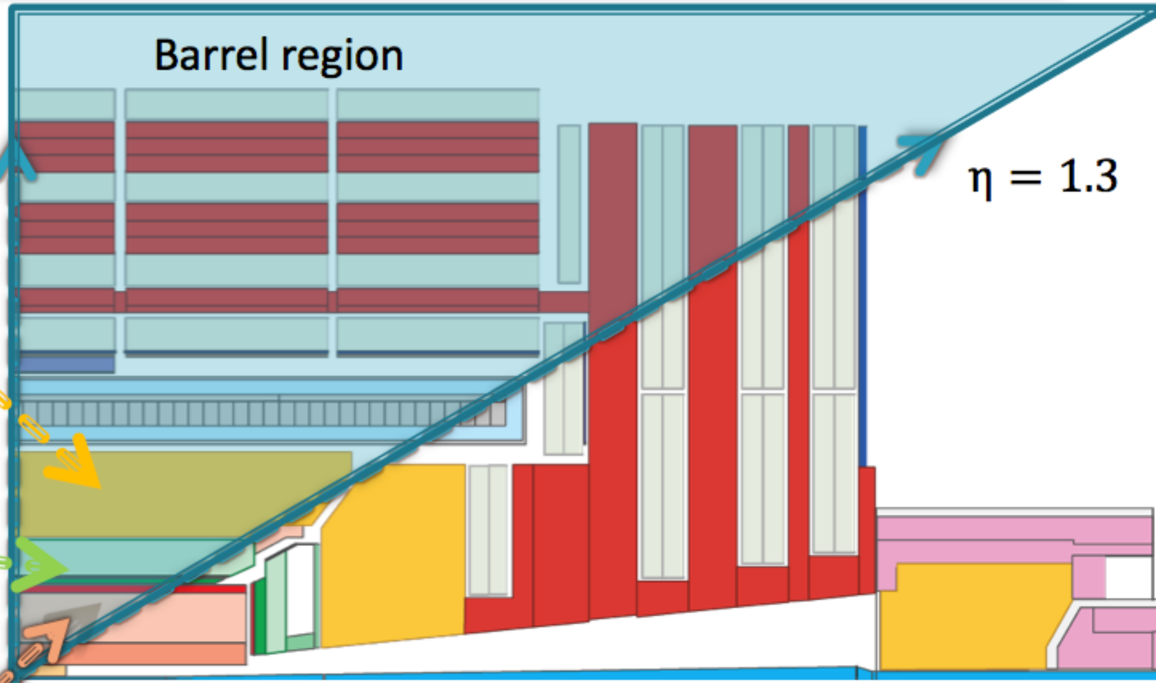
η = 0.0

HCAL: Brass/scintillator(|η| < 3)

- $\frac{\sigma_{HCAL}(E)}{E} \sim \frac{120\%}{\sqrt{E}}$

ECAL: $PbWO_4$ Crystal calorimeter

- $\frac{\sigma_{ECAL}(E)}{E} \sim \frac{3\%}{\sqrt{E}}$



Tracker: Silicon Pixel and Strip detector

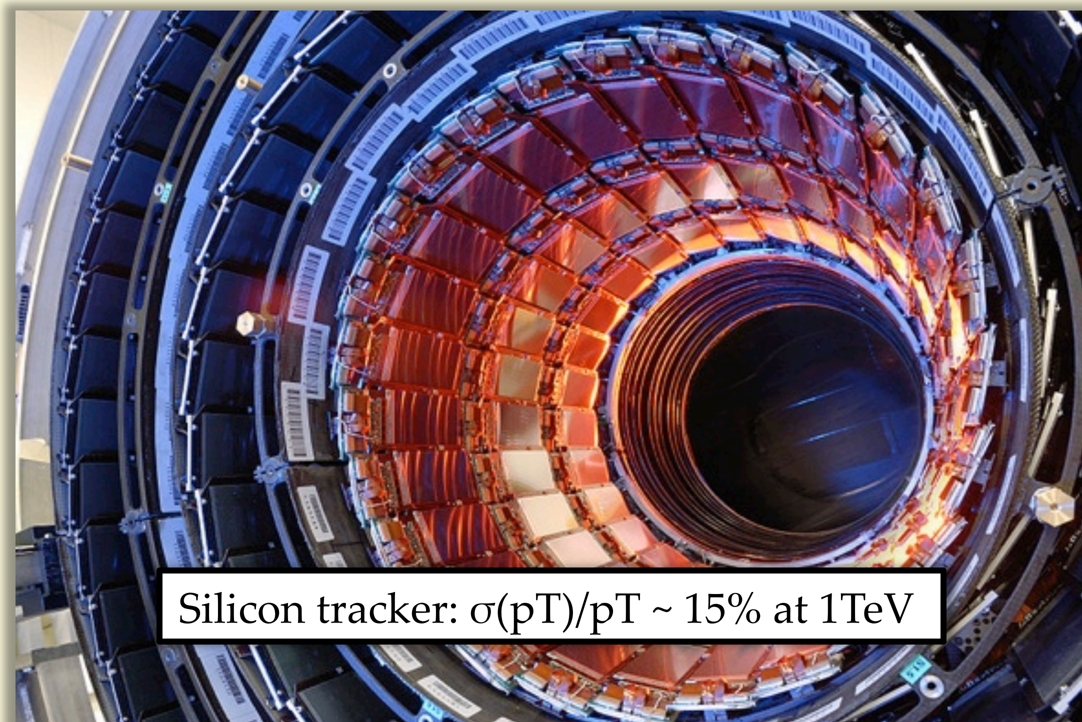
- $\frac{\sigma_{tracker}(p_T)}{p_T} \sim 1\%$

CMS specifics

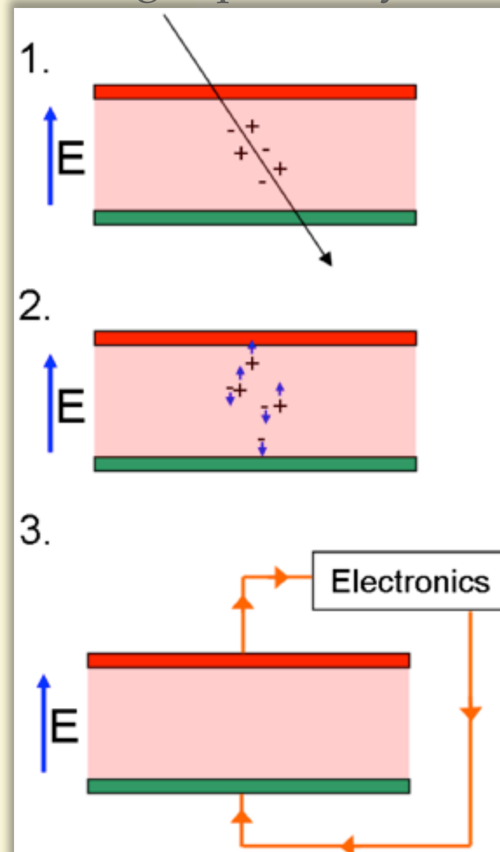
- Very precise tracker
- Highly granular ECAL
- Strong magnetic field (3.8 T)
- Tracking and calorimeters contained within superconducting magnet

Measuring the products of collisions

- Where did the particle originate from?→ **tracking detectors**
    - Long-lived particles travel substantial distance before decaying
    - For precise reconstruction of objects' P_T need to know origin precisely

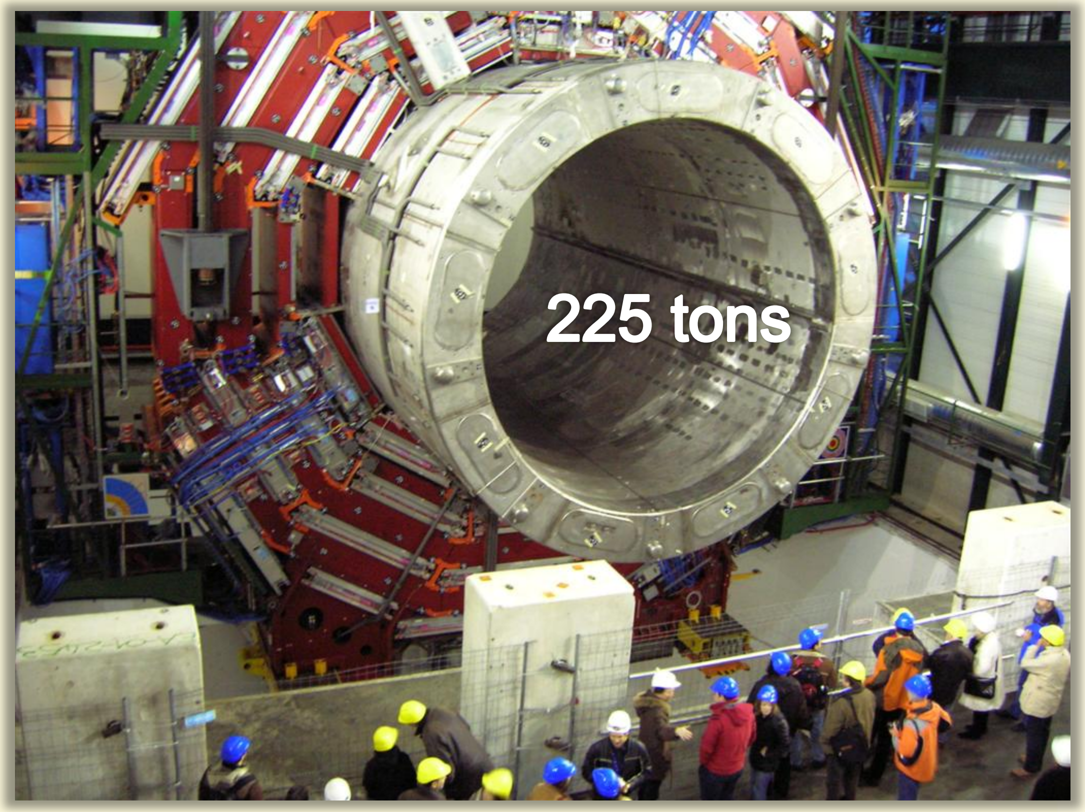


CMS all silicon tracker



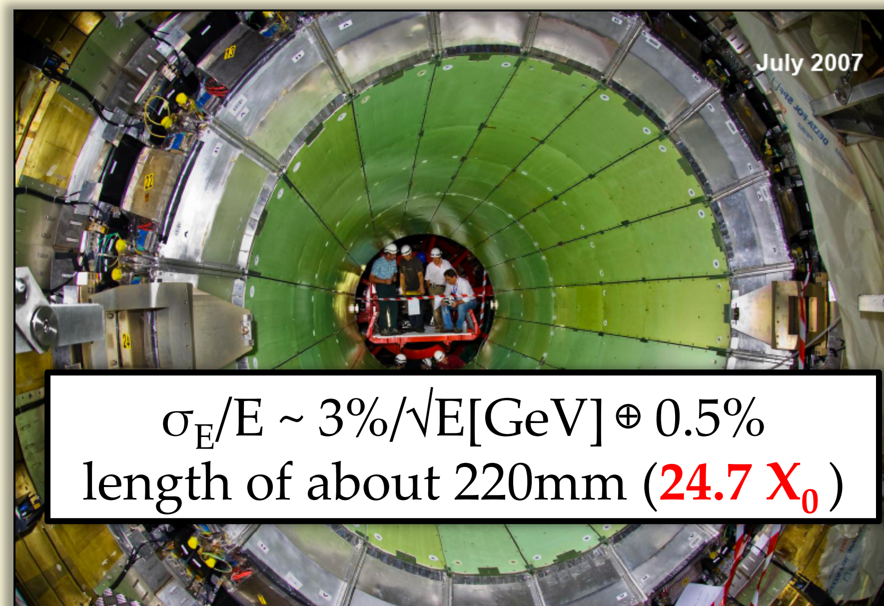
Measuring the products of collisions

- Momenta of the particles→ **tracking detectors and magnet**
  - The higher the magnetic field, the better we can measure: $R = p/(qB)$
  - CMS magnetic field: **3.8 Tesla**



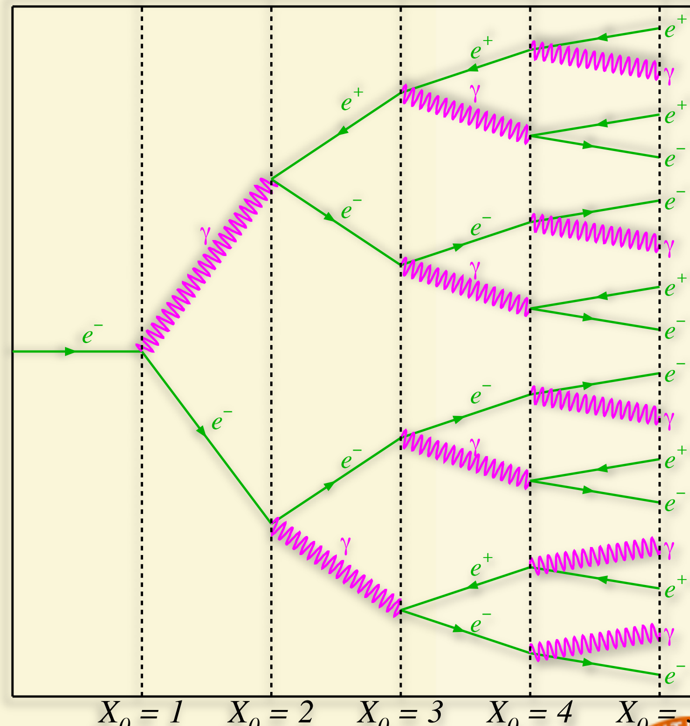
Measuring the products of collisions

- Energy of all particles produced in the collision
  - Photons and pions measured in **electromagnetic calorimeters**
  - homogeneous Lead-Tungstate crystal



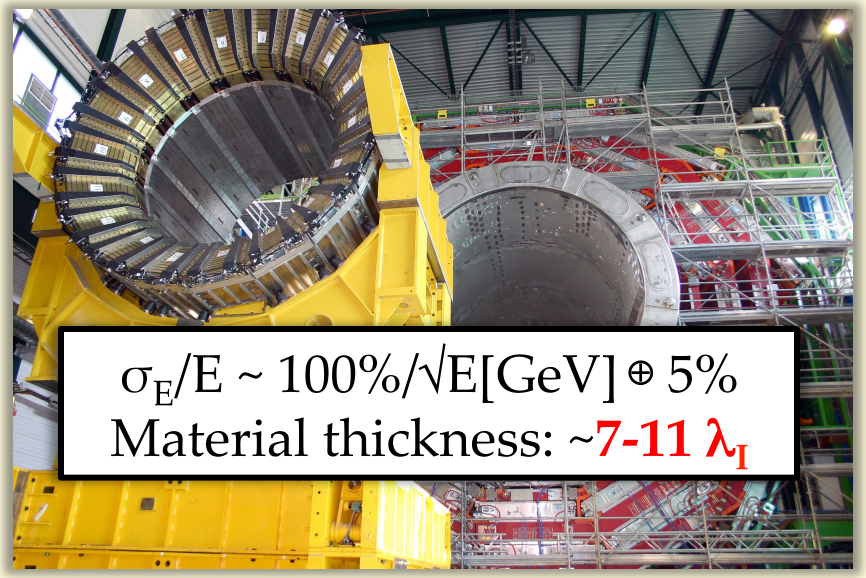
$\sigma_E/E \sim 3\%/\sqrt{E[\mathrm{GeV}]} \oplus 0.5\%$
length of about 220mm (**$24.7\ X_0$**)

CME Electromagnetic calorimeter

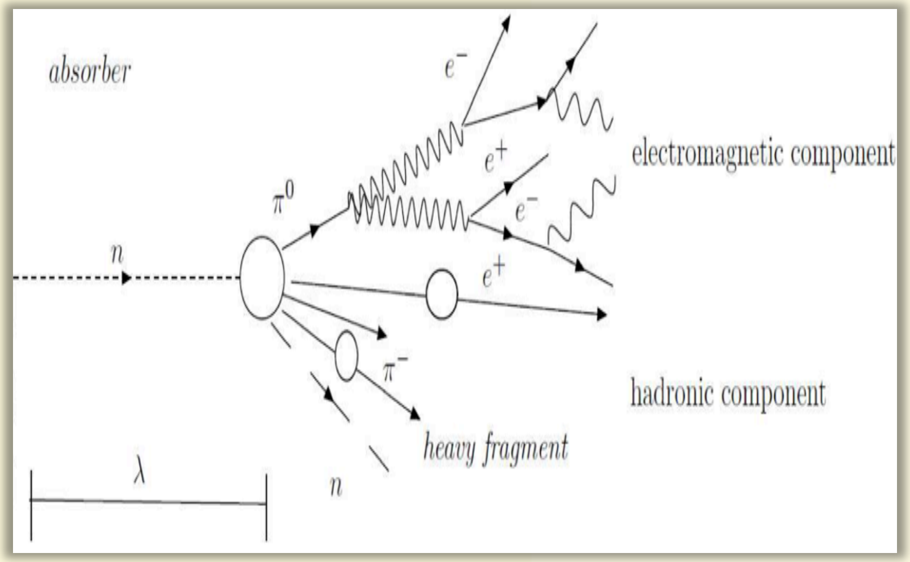


Measuring the products of collisions

- Energy of all particles produced in the collision
  - Strongly interacting hadrons measured in **hadronic calorimeter**

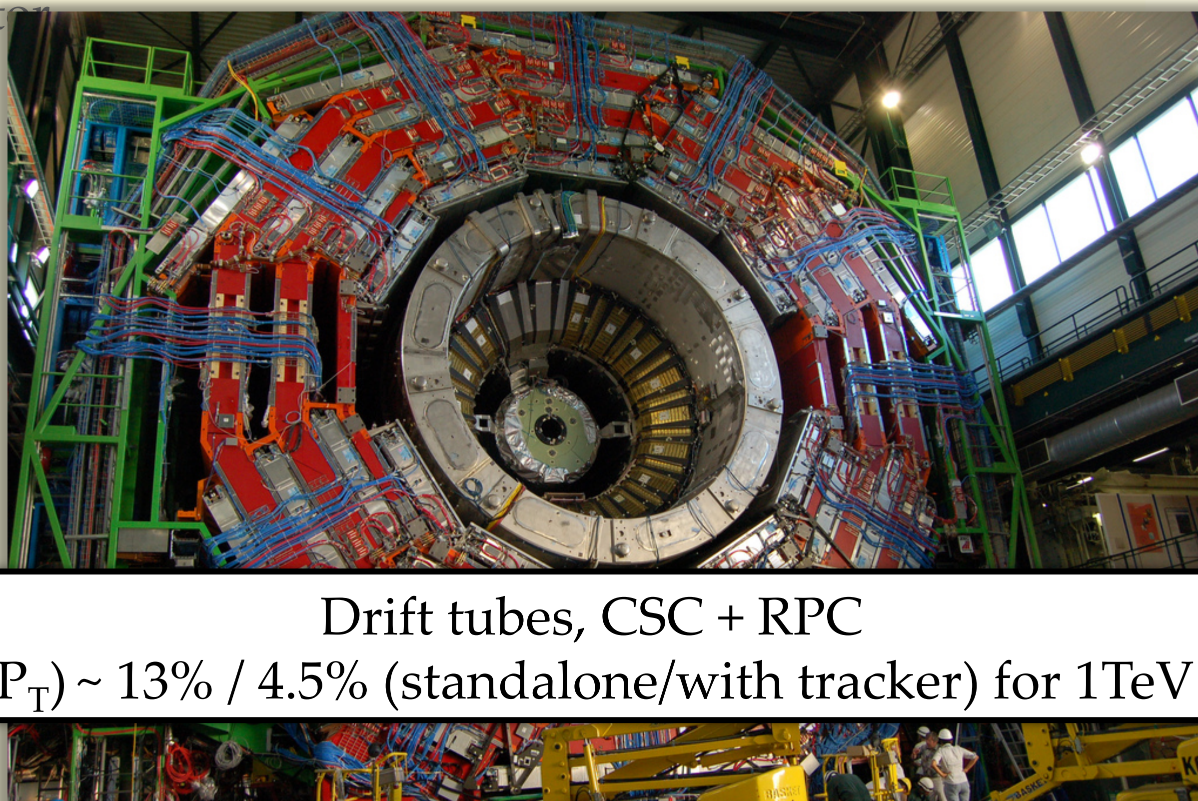


CMS Hadronic calorimeter



Measuring the products of collisions

- **Muon detectors** at the outermost edges of the detector
  - Negligible energy loss in the calorimeters: minimum ionizing particles
  - Combine measurements in the inner tracker with hits in the outermost detector

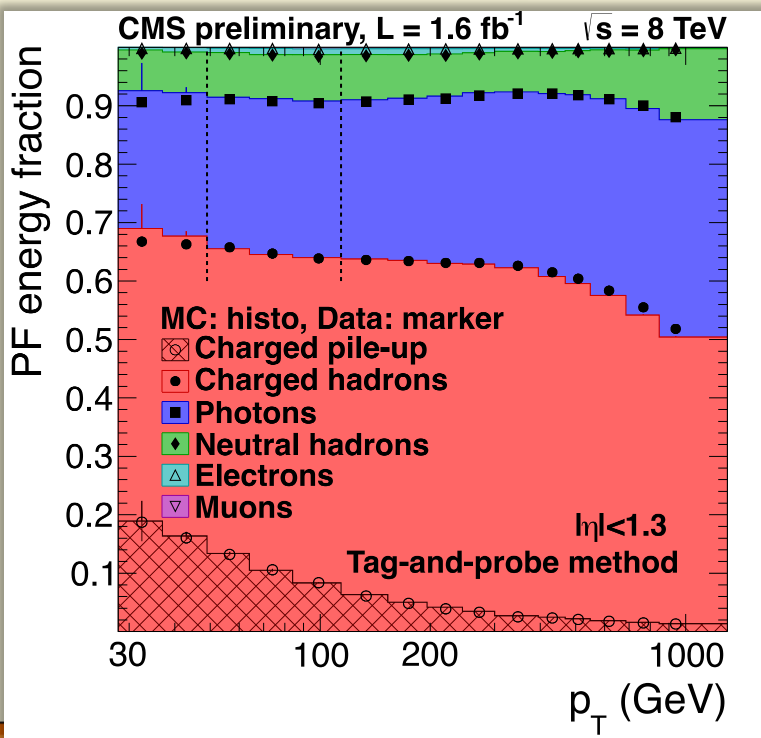


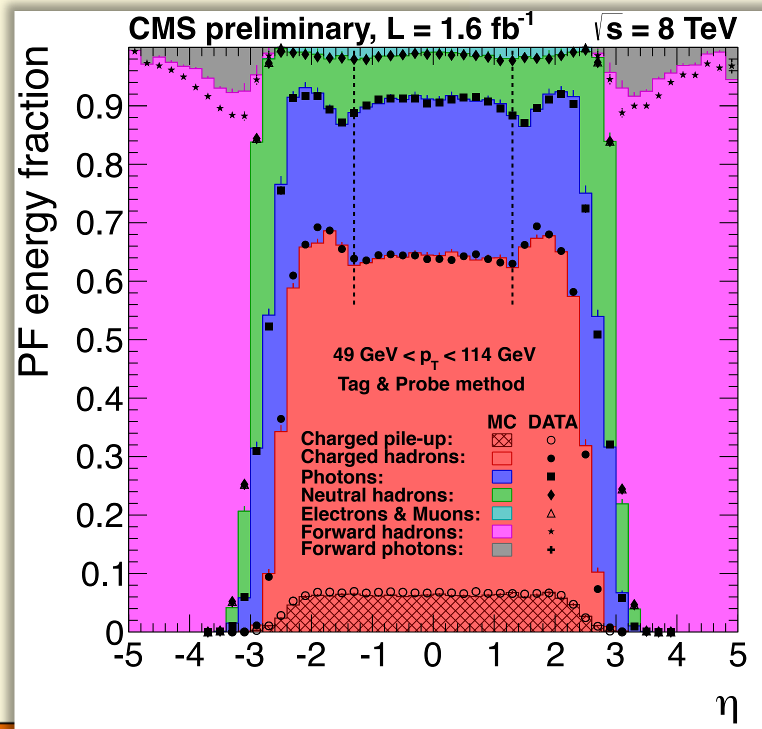
Drift tubes, CSC + RPC

$\sigma(P_T)$ ~ 13% / 4.5% (standalone/with tracker) for 1TeV μ

The third generation: how?

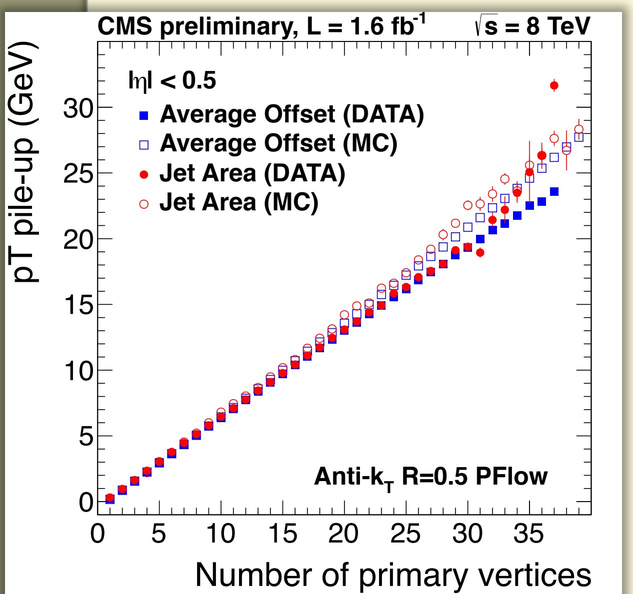
- **Particle Flow (PF)** technique for global event reconstruction
  - Charged particles : ~60% (**Tracker**)→Charged π, Ks and γs, some electrons and μs
  - Photons : ~25% (**ECAL**) → Mostly from π^0
  - Long-lived neutral hadrons : ~10% (**HCAL**) → K^0_L, neutrons
  - Short-lived neutral hadrons : ~5% (**Tracker**) → $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow \pi^- p$, γ conversions, nuclear interactions in the detector material.

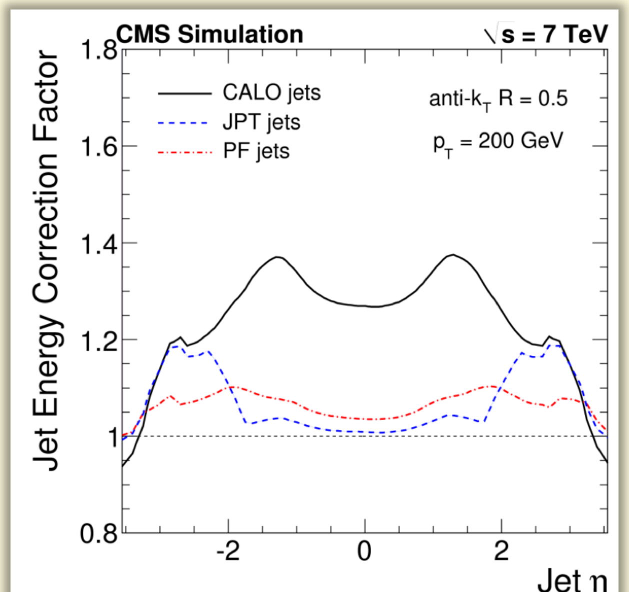


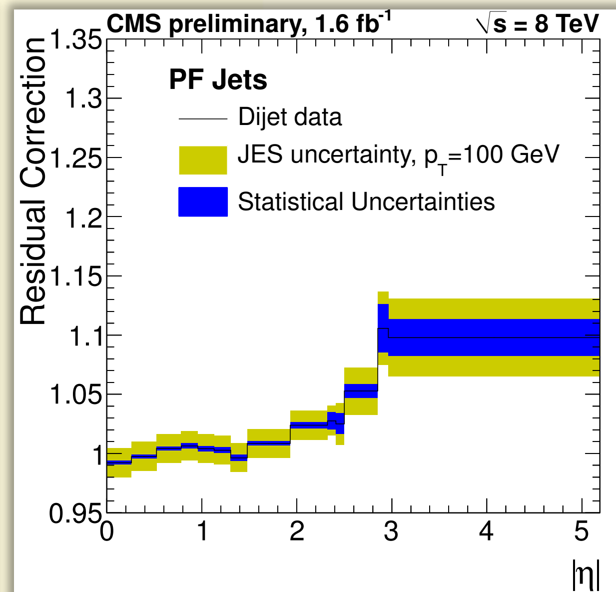


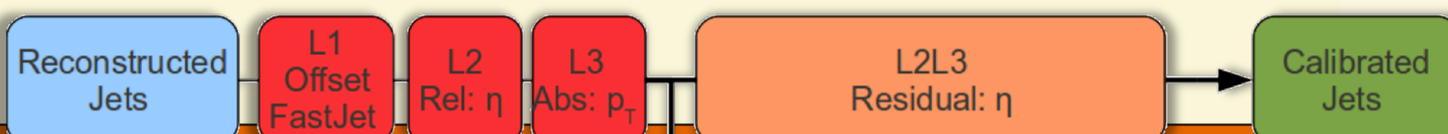
Event reconstruction: jets

- Factorized approach to set the jet energy scale
- L1: derived from from zero-bias data and MC simulations
- L2L3: obtained from MC; residual differences corrected from Z and γ+jet
  - The response of different flavors is within the 2-3% of QCD flavor mixture.



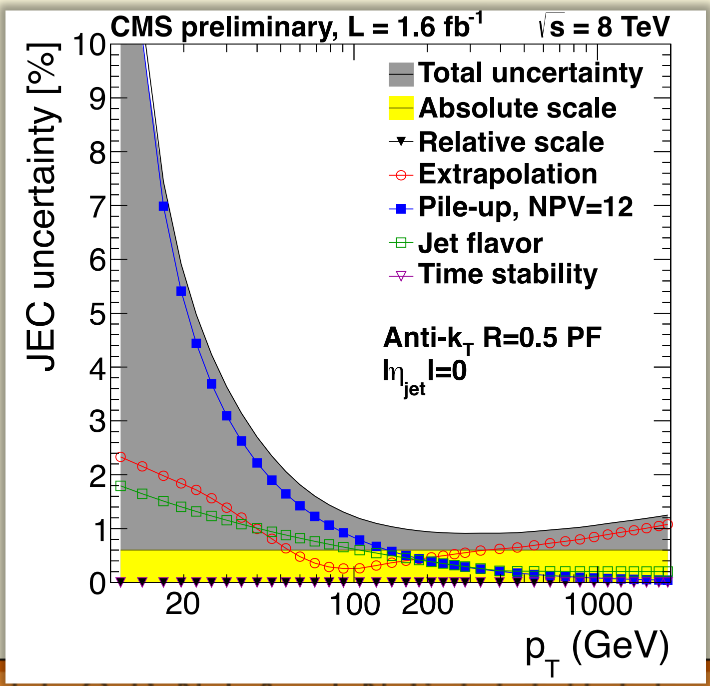


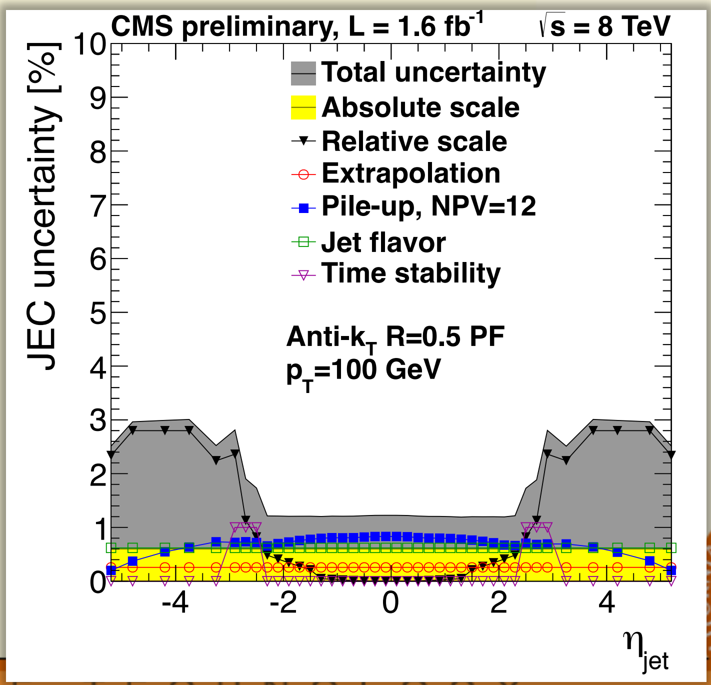




Event reconstruction: jets

- Uncertainties in the jet energy corrections come from different sources
  - Physics modeling in MC (showering, underlying event, etc.)
  - MC modeling of detector response and properties (noise, etc.)
- 16 sources of sub-uncertainties
  - Main uncertainty sources in $|\eta|<1.3$: pile up, jet flavor, and extrapolation.
  - In $2.5 < |\eta| < 3$: time dependence and out-of-time pile up.

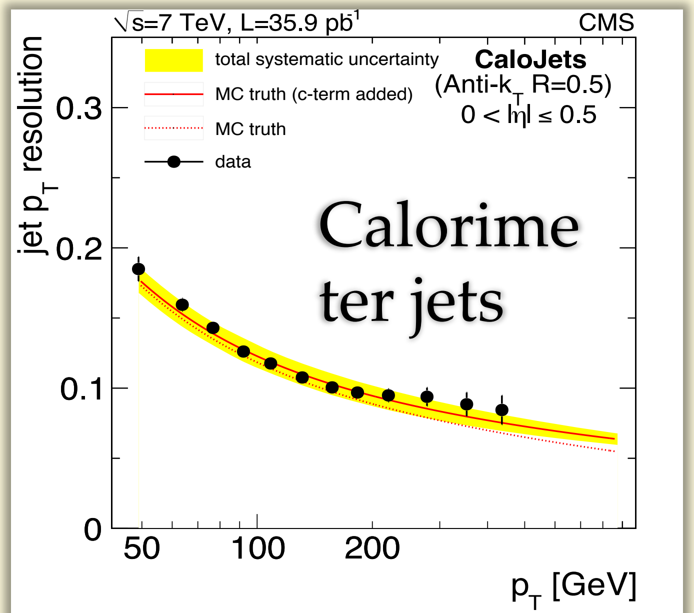


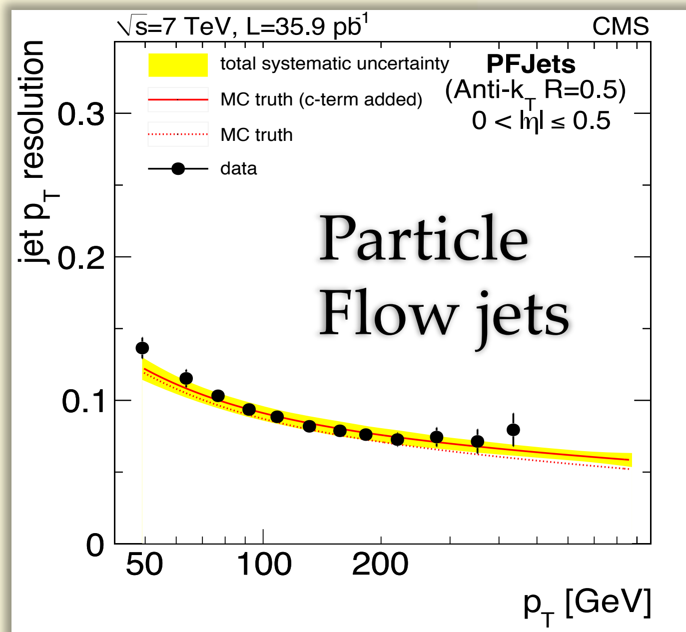


Event reconstruction: jets

- Jet resolution: important to achieve good data/MC agreement
  - Affects not only jets, but also any analysis with MET: need to smear MC jets
- Measure from data using dijet and γ+jet events

$$A = \frac{(p_T^{Jet1} - p_T^{Jet2})}{(p_T^{Jet1} + p_T^{Jet2})} \rightarrow \left(\frac{\sigma(p_T)}{p_T}\right) = \sqrt{2}\sigma_A$$





Event reconstruction: *b*-tagging

- Exploit specific characteristics of b-hadrons
  - Lifetime ~1.5 ps ($c\tau$ = 450 μm); p~20 GeV/c → decay length ~1.8 mm.
  - The high mass of ~5.2 GeV and a decay multiplicity of ~5 charged tracks.
  - High p_T of decay products, relative to the flight direction of b-hadrons.
  - The semi-leptonic decays, branching fraction of ~11 %

- Variety of algorithms based on variables such as
  - the impact parameters of charged-particle tracks
  - properties of reconstructed decay vertices, the presence/absence of a lepton
  - neural network using the output weights of the IP3D, JetFitter+IP3D, and SV1 algorithms (ATLAS)