SUSY searches at CMS

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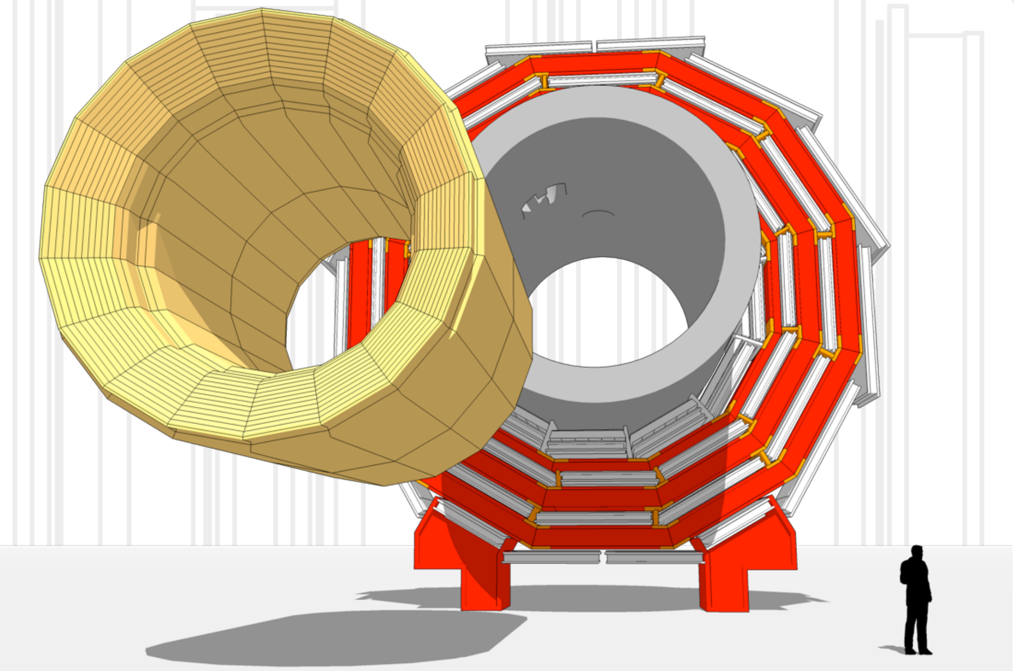
29 April 2016

at IIHE

http://indico.iihe.ac.be/indico/conferenceDisplay.py?confId=1000



University of BRISTOL

Supersymmetry (SUSY)

- a hypothetical extension of space-time symmetry
  - relates fermions and bosons
  - combines internal and space-time symmetries
  - predicts every particle has a partner (*superpartner*) whose spin is differ by 1/2
    - fermisons - *sfermions*
    - gauge bosons - *gauginos*
    - no known particle is a superpartner
    - at least double the number of particles

$$\delta\phi = -i\varepsilon^T\sigma^2\chi$$

$$\delta\chi = \varepsilon F + \sigma\cdot\partial\phi\sigma^2\varepsilon^*$$

$$\delta F = -i\varepsilon^\dagger\bar{\sigma}\cdot\partial\chi$$

A broken symmetry

- SUSY is a broken symmetry

The exact symmetry contradicts the real world. In the exact SUSY, a particle and its superpartner would have the same mass. e.g., as bosons with the electron mass, all *selections* in an atom would occupy the ground state

- SUSY is not *spontaneously broken* in the visible sector of SUSY models,

A spontaneous SUSY breaking often contradicts experimental observations. e.g., it predicts a massless or light fermion that would have been observed

- *"soft" SUSY breaking*

In SUSY models, the SUSY is broken by hand, but "softly" so that it still solves the hierarchy problem. SUSY breaking occurs in the hidden section and is transmitted to the visible section by "messengers"

Fermilab today

Minimal supersymmetric standard model (MSSM)

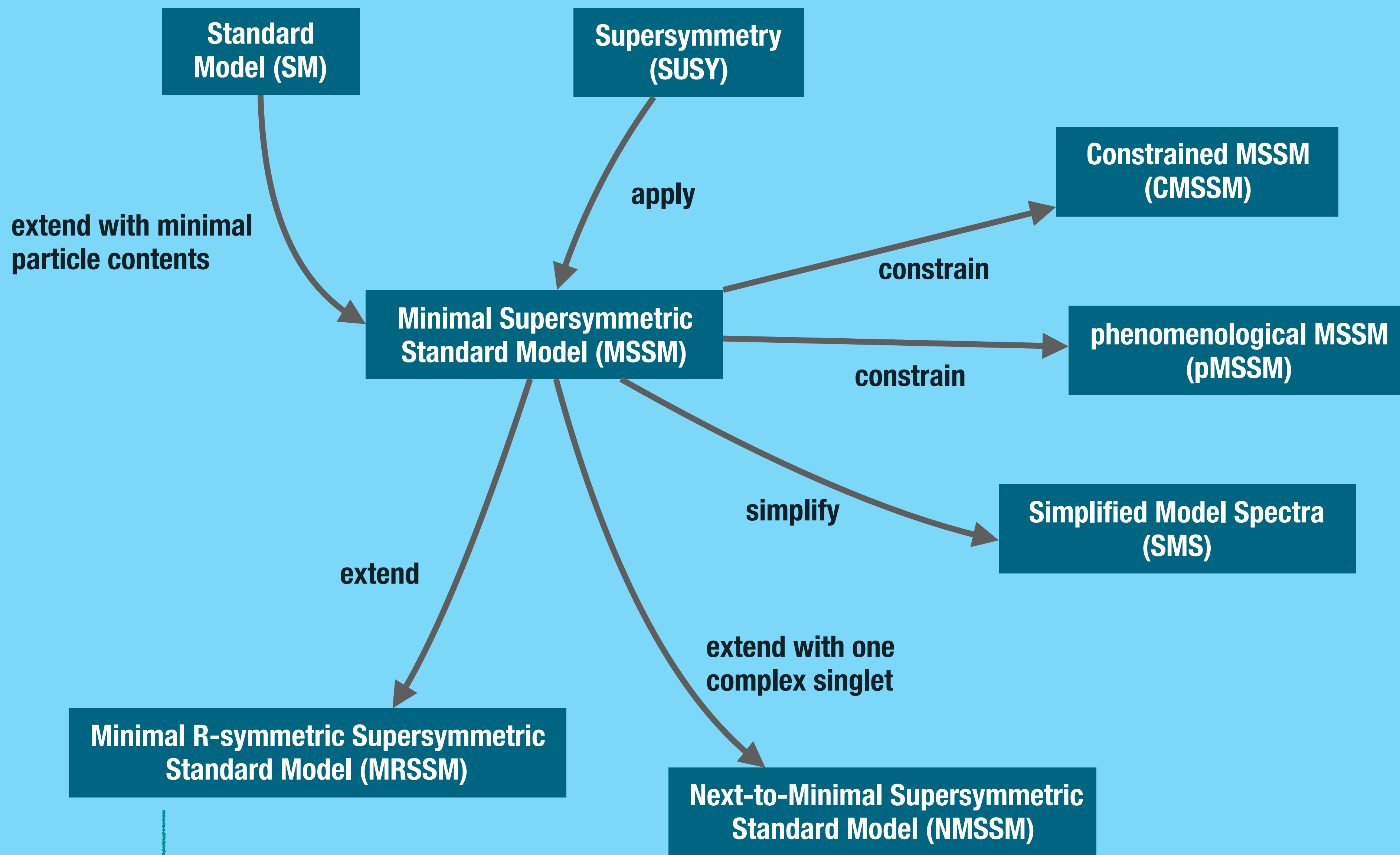
- a supersymmetric extension of the standard model with minimal particle contents
- adds another Higgs double to the standard model

  ➡ two Higgs doubles, 5 Higgs bosons
- adds a boson to each fermion, a fermion to each boson
- softly breaks SUSY
  - the breaking is parameterized
- has many parameters, more than 120
  - most of them are for the breaking

The number of the parameters is so large that it is impractical to constrain with experimental data. Theoretical constraints among parameters or simplifications of the model can reduce the number of parameters, which can be explored at LHC.

MSSM particle contents

	R = +1	R = -1	
	leptons	sleptons	
e	e_L ν_e e_R	$\tilde{e}_L$ $\tilde{\nu}_e$ $\tilde{e}_R$	
μ	μ_L ν_μ μ_R	$\tilde{\mu}_L$ $\tilde{\nu}_\mu$ $\tilde{\mu}_R$	
τ	τ_L ν_τ τ_R	$\tilde{\tau}_L$ $\tilde{\nu}_\tau$ $\tilde{\tau}_R$	$\tilde{\tau}_1$ $\tilde{\tau}_2$
	quarks	squarks	
u d	u_L d_L u_R d_R	$\tilde{u}_L$ $\tilde{d}_L$ $\tilde{u}_R$ $\tilde{d}_R$	
c s	c_L s_L c_R s_R	$\tilde{c}_L$ $\tilde{s}_L$ $\tilde{c}_R$ $\tilde{s}_R$	$\tilde{b}_1$ $\tilde{b}_2$
t b	t_L b_L t_R b_R	$\tilde{t}_L$ $\tilde{b}_L$ $\tilde{t}_R$ $\tilde{b}_R$	$\tilde{t}_1$ $\tilde{t}_2$
	gluon g	$\tilde{g}$ gluino	
	gauge bosons	gauginos	charginos
γ Z	$W^\pm$ W^0 B	$\tilde{W}^\pm$ $\tilde{W}^0$ $\tilde{B}$	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_2^\pm$
	Higgs bosons	Higgsinos	neutralinos
h H A^0 $H^\pm$	H_u^+ H_u^0 H_d^0 H_d^-	$\tilde{H}_u^+$ $\tilde{H}_u^0$ $\tilde{H}_d^0$ $\tilde{H}_d^-$	$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$
mass eigenstates (if different)	gauge eigenstates		mass eigenstates (if different)



Gluinos are Dirac ferminos. (they are Majorana fermions in MSSM) (Dirac fermions have twice as many degrees of freedom as Majorana fermions.)

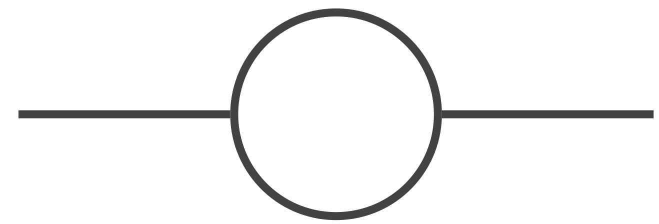
Gluons are partners of only half the degrees of freedom of Dirac gluinos.

Sgluons are the partners of the other half

Natural solution to hierarchy problem

- Higher order correction to Higgs boson mass
  - In SM, one-loop fermion correction quadratically depends on the cutoff scale

$$\Delta m_H^2 \propto -\Lambda_{\mathrm{UV}}^2$$



The ***fine-tuning problem***: e.g., suppose $\Lambda_{UV} \simeq M_{PL} \simeq 10^{19}$ GeV. In order for $m_H \simeq 10^2$ GeV, the first ~16 digits of the bare Higgs boson mass and Λ_{UV} need to be the same

The problem is specific to a scalar particle, e.g., a correction to a fermion mass is proportional to the mass and logarithmically depends on the cutoff scale

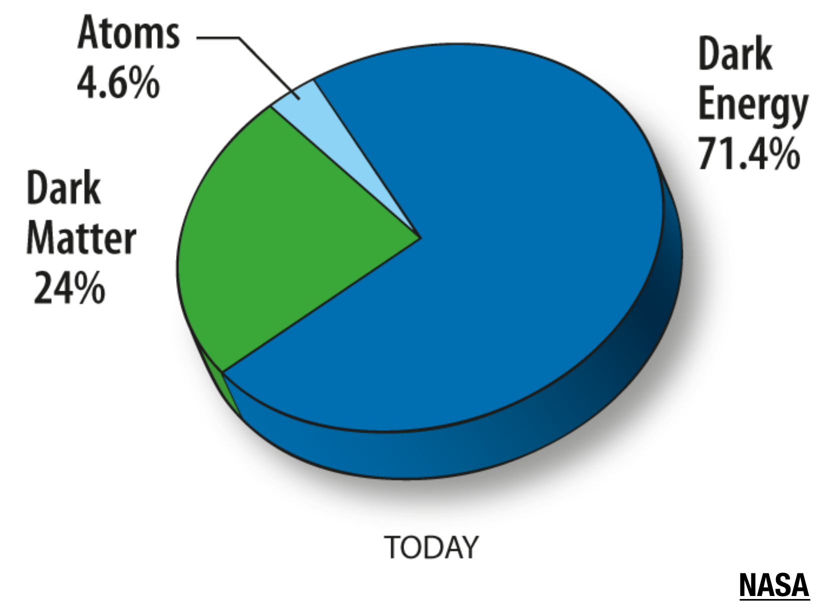
  - In SUSY models, sfermion significantly moderates the correction:

$$\Delta m_H^2 \propto (m_{\tilde{f}}^2 - m_f^2) \ln \frac{\Lambda_{\mathrm{UV}}^2}{m_f^2}$$

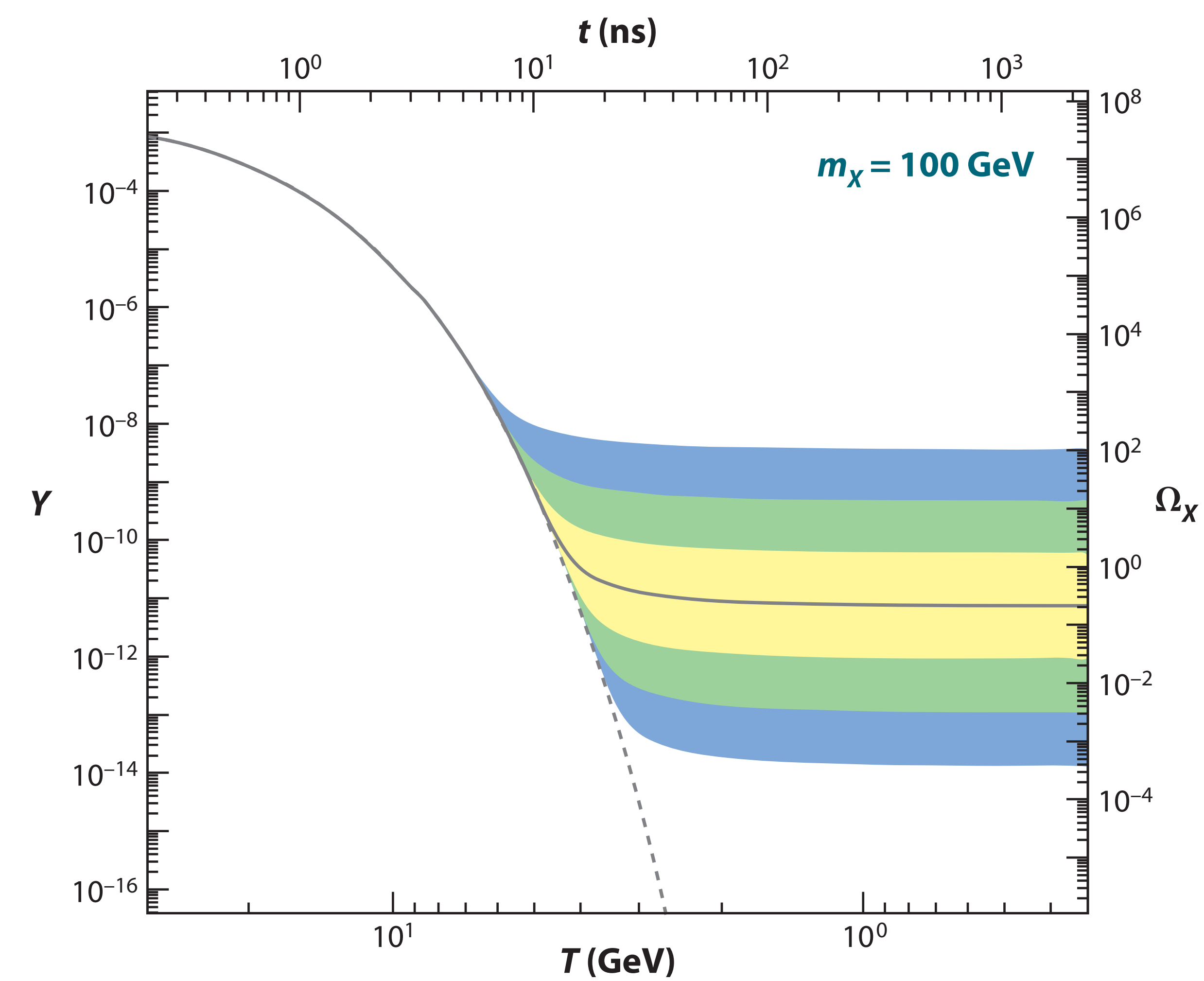
    - logarithmic dependence on the cutoff
    - proportional to the mass square difference - cancel at the exact SUSY

Natural SUSY models - the level of the tuning is small enough to believe that it happened by chance, e.g., 1 in 100 or 1000 rather than 10^{16}

Identity of dark matter



- Dark matter (DM)
  - unknown substance that comprises 24% of the universe
  - its existence is inferred from gravitational effects
  - does not consist of particles in the SM



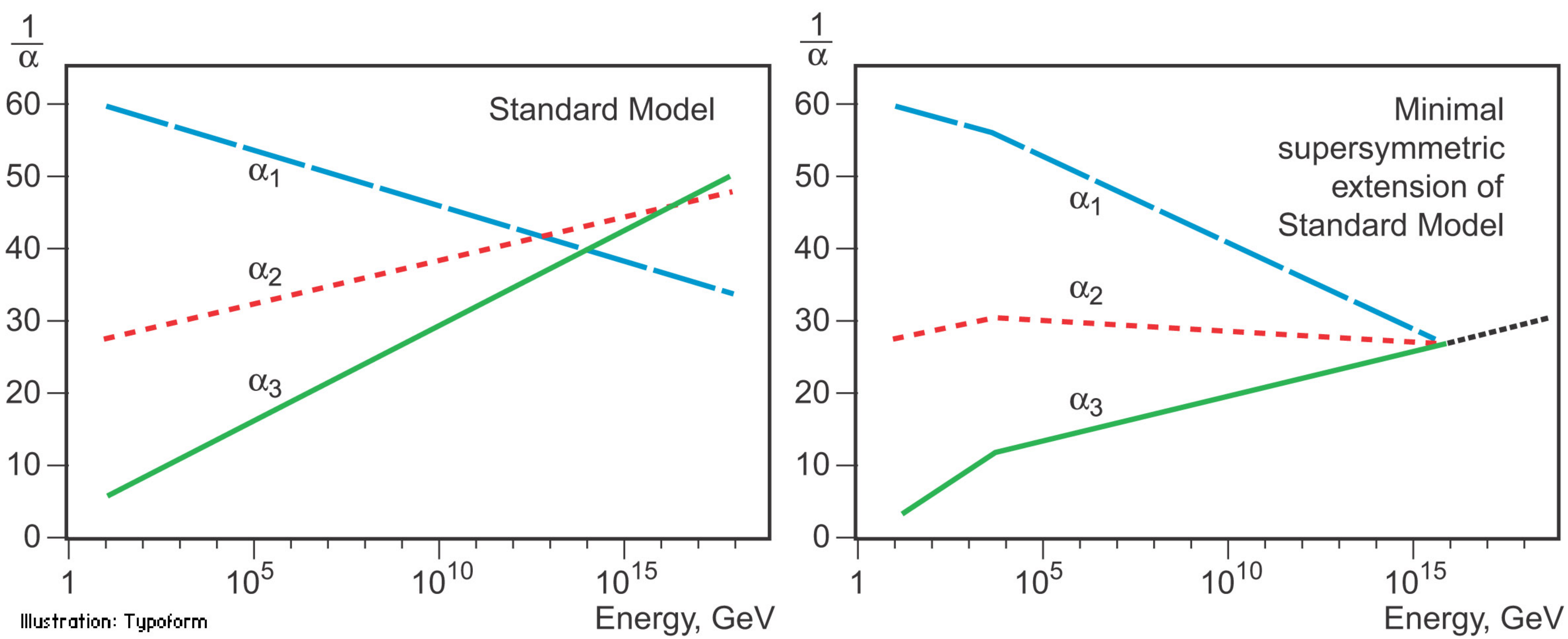
- ***WIMP***
  - weakly interacting massive particle
  - among the hypothetical DM candidates which are being extensively searched for by direct detection, indirect detection, and collider experiments

- SUSY
  - ***R-parity***: +1 for SM particles, -1 for superpartners
  - If R-parity is conserved, the lightest supersymmetric particle (***LSP***) is stable and often WIMP candidate
    - e.g., *neutralinos*, *gravitinos*, *sneutrinos*

http://www.ps.uci.edu/~jlf/research/presentations/presentations.html

Unification of gauge couplings

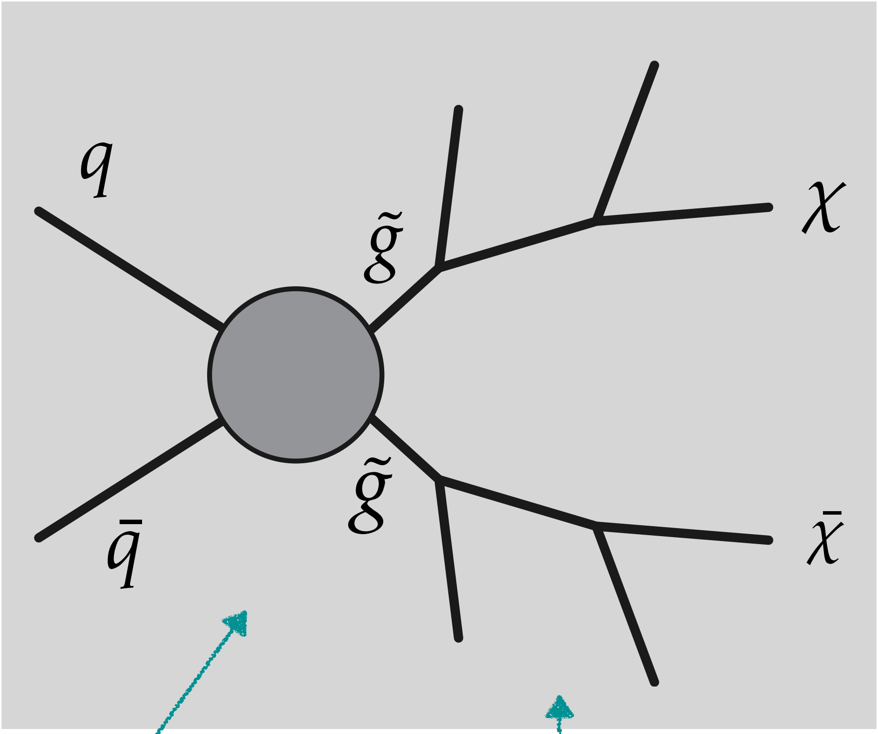
- Running coupling constants
  - The couplings of the three gauge interactions, i.e, weak, electromagnetic, strong, depend on the energy scale
  - In the SM, the three couplings do not meet at a single point
  - In SUSY, they meet at around 10^{16} GeV



nobelprize.org

SUSY production at LHC

A typical SUSY production at LHC predicted by SUSY models with conserved R-parity



Each cascade decay chain ends with the LSP, invisible and causes missing transverse momentum (MET)

SUSY particles will be pair-produced

Each SUSY particle successively decays to another SUSY particle and SM particle (the cascade decay)

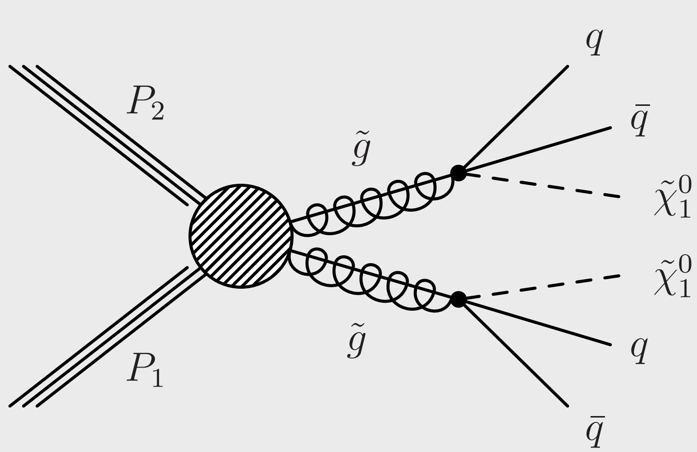
The final states will contain large MET, jets, and possibly leptons or photons

Simplified Model Spectra (SMS)

- A **simplified model** is defined by a few new particles and their production and decay
  - New particles have the same names as the SUSY particles
    - e.g., *gluinos*, *squarks*, *stops*, *neutralinos*, *charginos*, *LSP* (neutral)
  - New particles are produced in pairs. Each decay chain ends with LSP
  - Relevant for "natural" SUSY models
- SUSY analysis results are used to set upper limits on the production cross section as a function of new particle masses
- SMS can allows us to explore different kinematic phase space of final states from particular models predict
- The upper limits can be compared with predictions of particular SUSY (or non-SUSY) models
  - This comparison can be used to set limits on new particle masses

http://dx.doi.org/10.1103/PhysRevD.88.052017

Example simplified models



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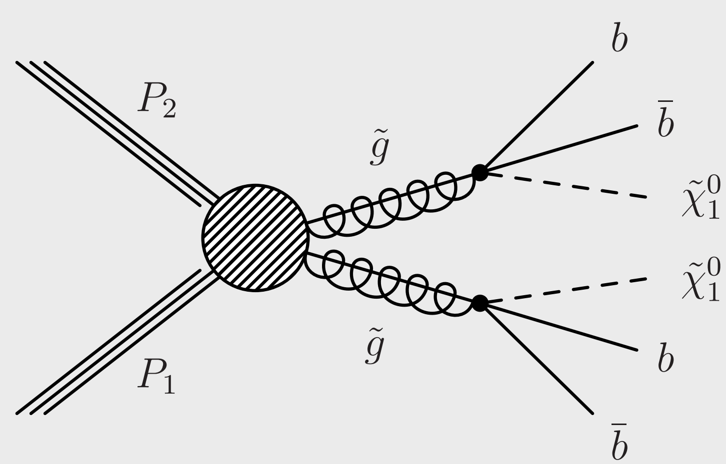

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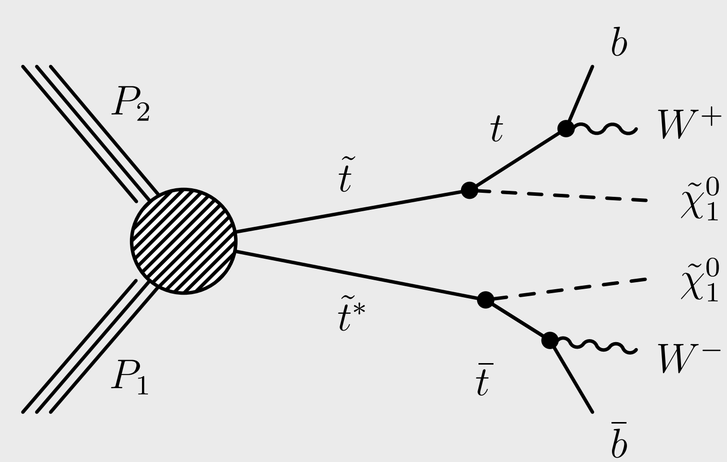


T2tt

Large Hadron Collider (LHC)

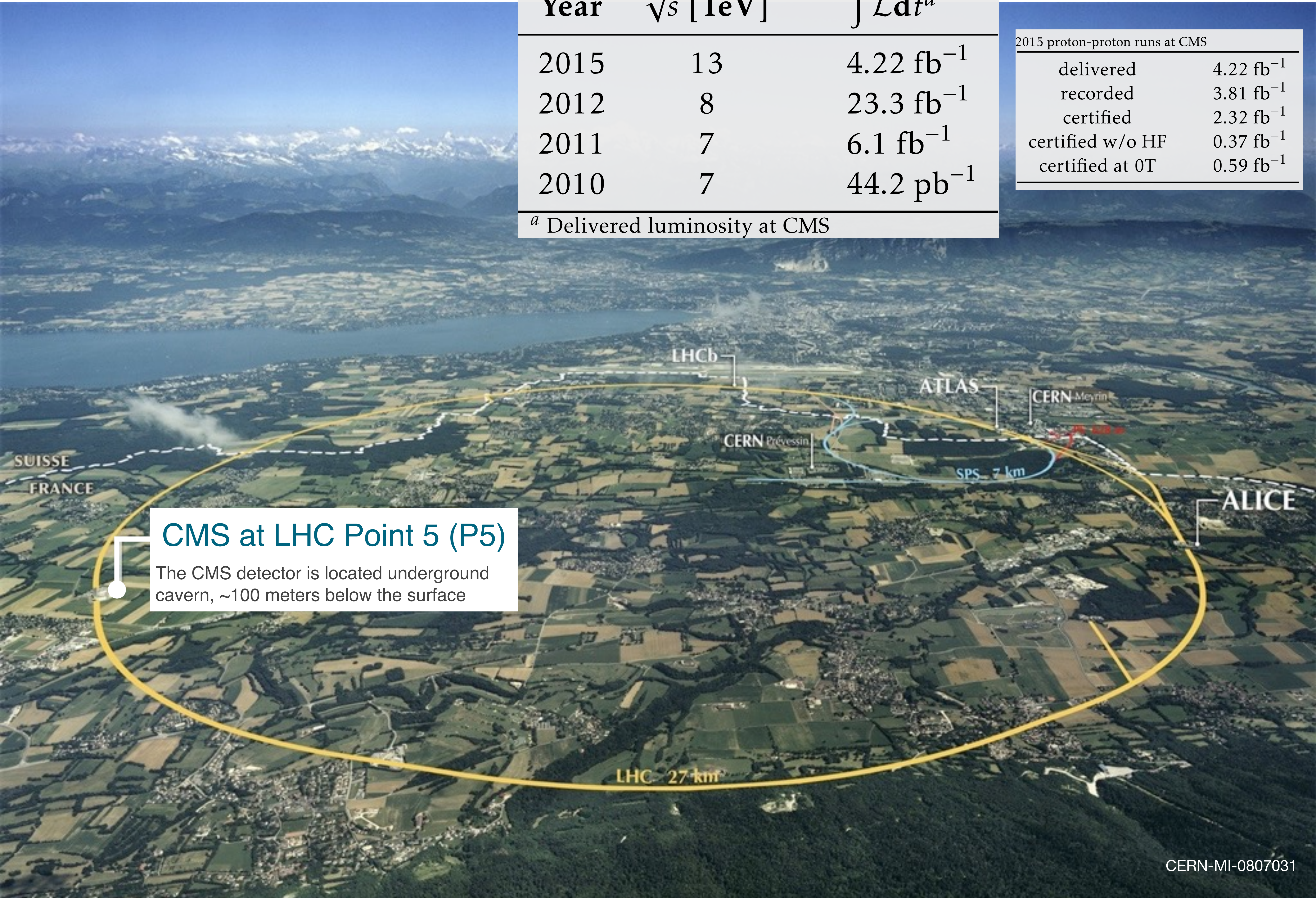
Proton-proton runs

Year	$\sqrt{s}$ [TeV]	$\int \mathcal{L} dt^{a}$
2015	13	4.22 fb^{-1}
2012	8	23.3 fb^{-1}
2011	7	6.1 fb^{-1}
2010	7	44.2 pb^{-1}

[a] Delivered luminosity at CMS

2015 proton-proton runs at CMS

delivered	4.22 fb^{-1}
recorded	3.81 fb^{-1}
certified	2.32 fb^{-1}
certified w/o HF	0.37 fb^{-1}
certified at 0T	0.59 fb^{-1}



CMS at LHC Point 5 (P5)

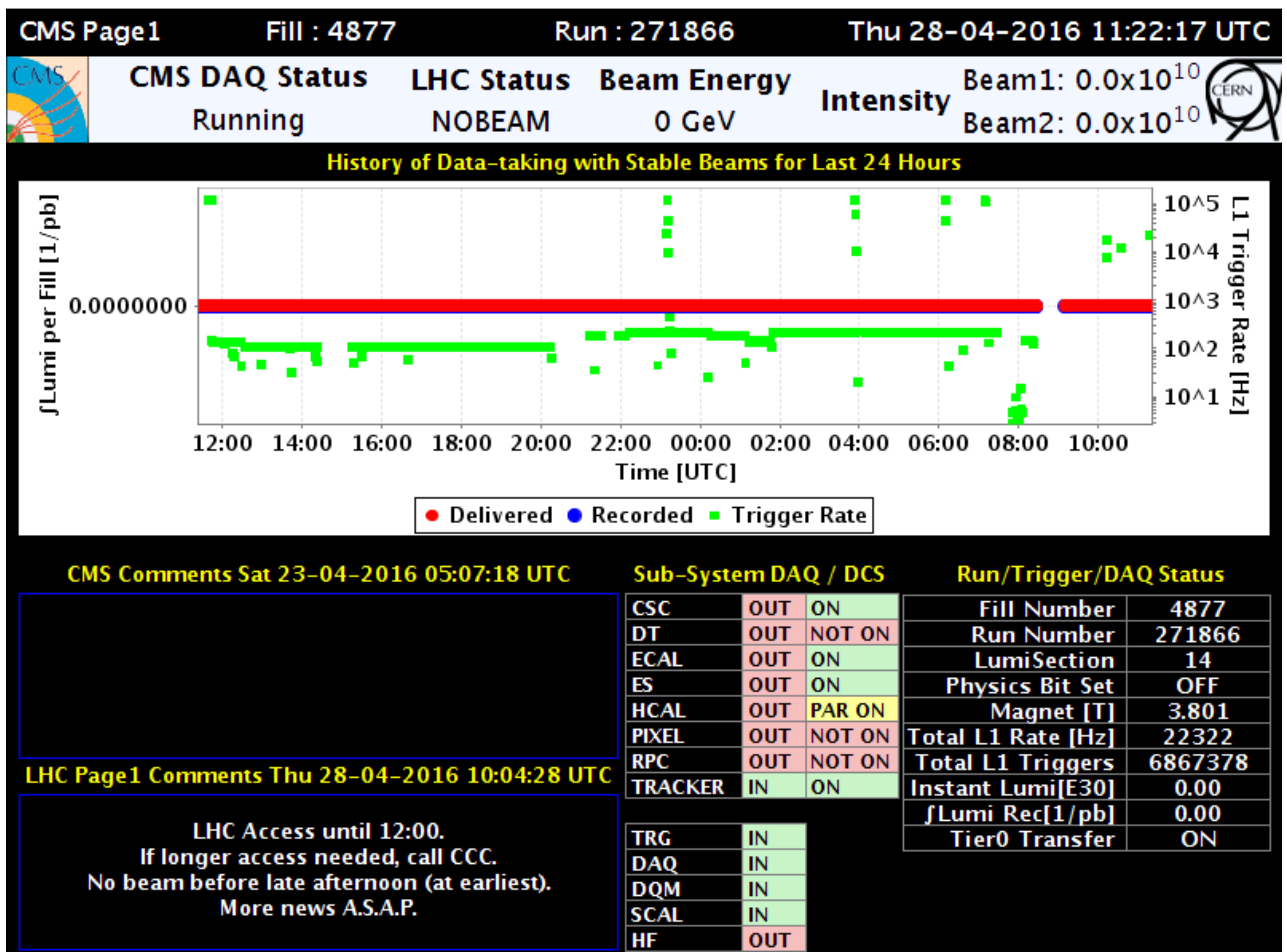
The CMS detector is located underground cavern, ~100 meters below the surface

CERN-MI-0807031

CMS Magnet

- The status of the magnet (from CERN Courier http://cerncourier.com/cws/article/cern/64664)
    - "The cryogenic plant delivering the necessary liquid helium to operate the superconducting solenoid was disrupted during 2015 by the presence of contaminants. The filters inside of the cryogenic plant had to be regenerated several times, in conjunction with the magnet being ramped down. Before continuing the story of the 0 T data set, we want to reassure the reader that the system underwent an extensive programme of cleaning and maintenance during the end-of-year technical stop, and it is now on track for reliable operation in 2016."

- CMS Page 1- http://cmspage1.web.cern.ch/cmspage1/



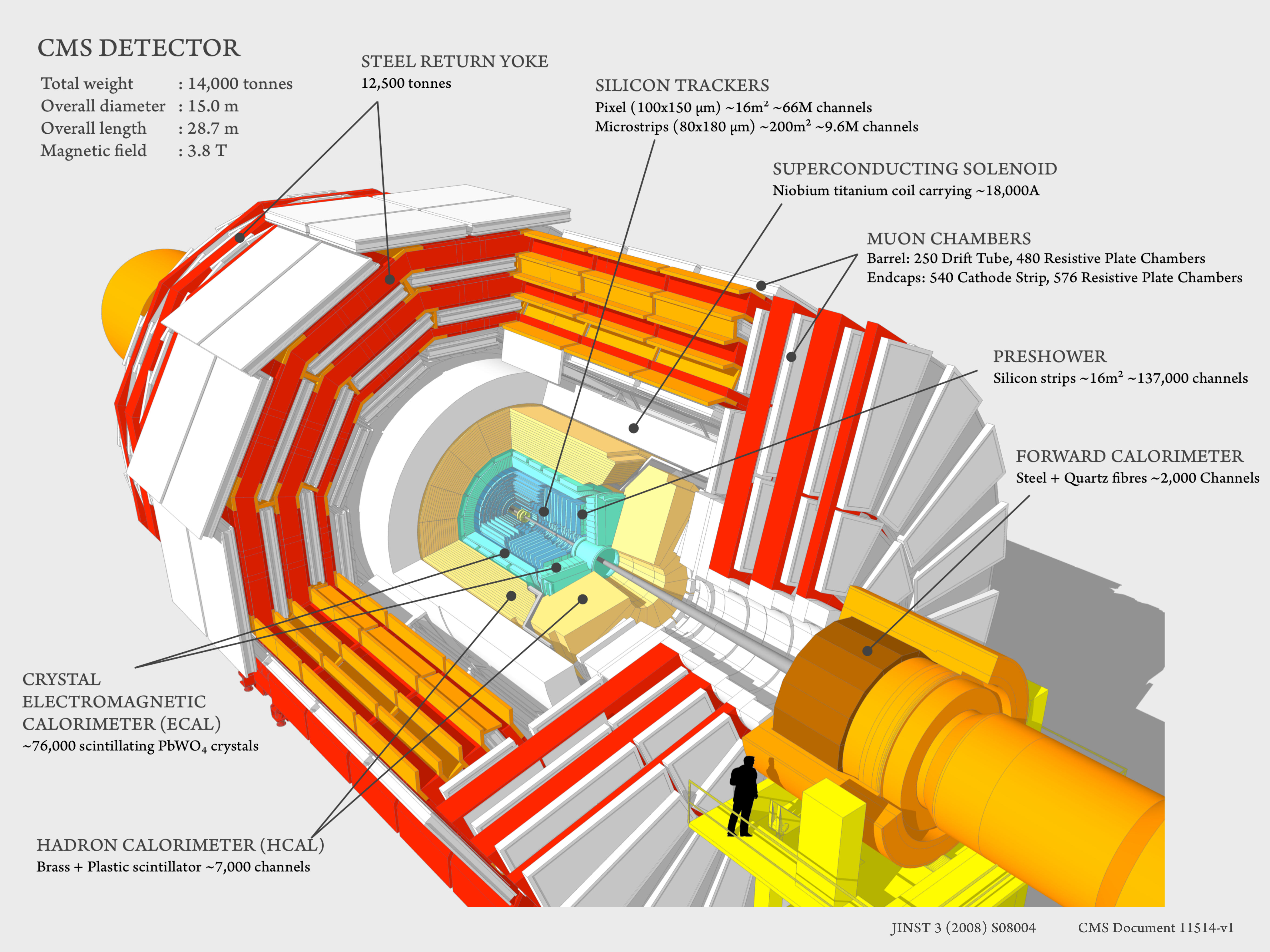
CMS Collaboration

summer 2012, in a surface building at P5
(CMS-PHO-COLLAB-2012-004)

- 2680 physicists
- 859 engineers
- 281 technicians
- 182 institutes
- 42 countries

http://cms.web.cern.ch/content/people-statistics

http://cms.web.cern.ch/content/cms-collaboration


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
JINST 3 (2008) S08004
CMS Document 11514-v1

Online event selection (triggers) at CMS

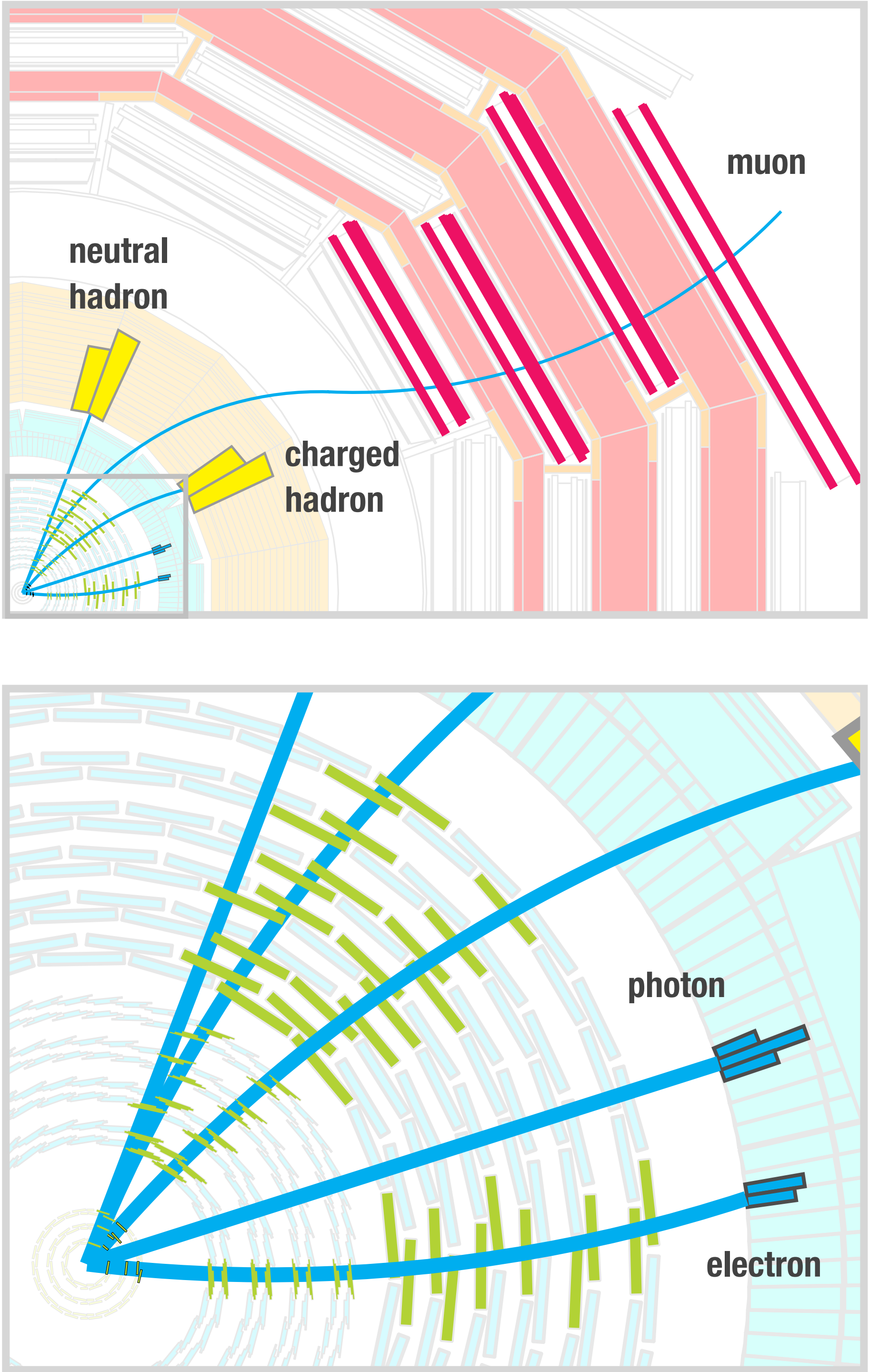
- LHC makes bunches of protons (10^{11} protons in each bunch) cross each other at CMS at 20~40 MHz
- **L1 Trigger (custom hardware processors, underground P5)**
  - selects interesting events based on signals from muon systems and calorimeters, reducing the event rate to 100 kHZ
- **HLT, High-Level Trigger (computing farm, surface building at P5)**
  - reconstructs full events and selects interesting events, reducing the event rate further down to 300~500 Hz, the recording rate of the storage system

Event reconstruction at CMS

Particle flow (PF) algorithm

CMS-PAS-PFT-09-001

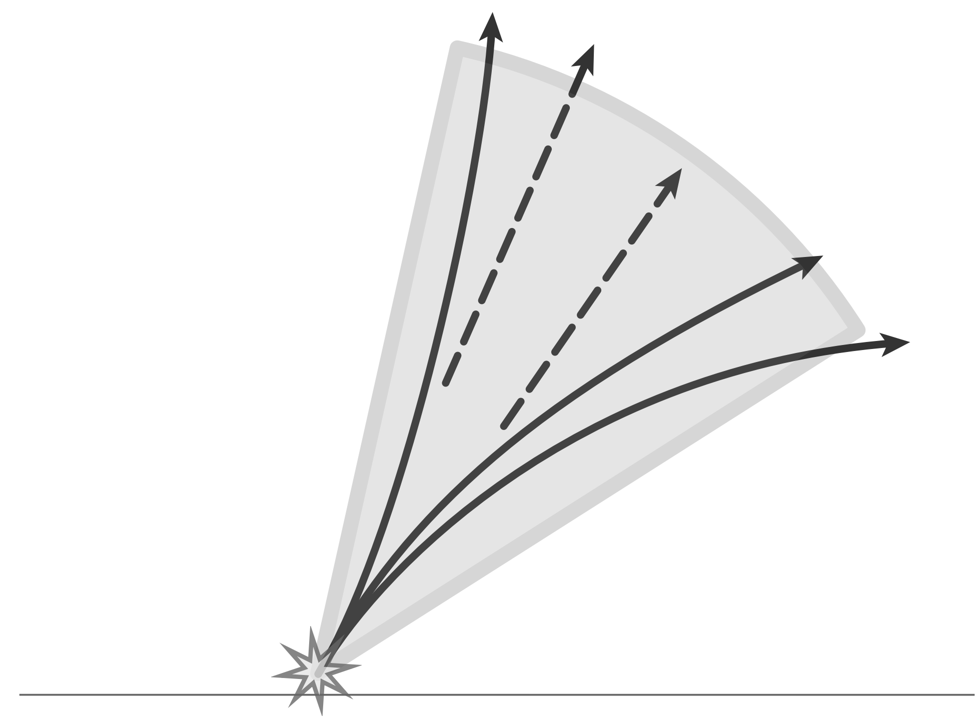
- the primary particle reconstruction algorithm in CMS
- uses all CMS detector subsystems
- reconstructs four momenta of all visible stable particles (***particle flow candidates*** or ***PF candidates***)
- identifies each particle as muon, electron, charged hadron, photon, or neutral hadron



particle flow candidates $\mu^{\pm}, e^{\pm}, h^{\pm}, \gamma, h^{0}$

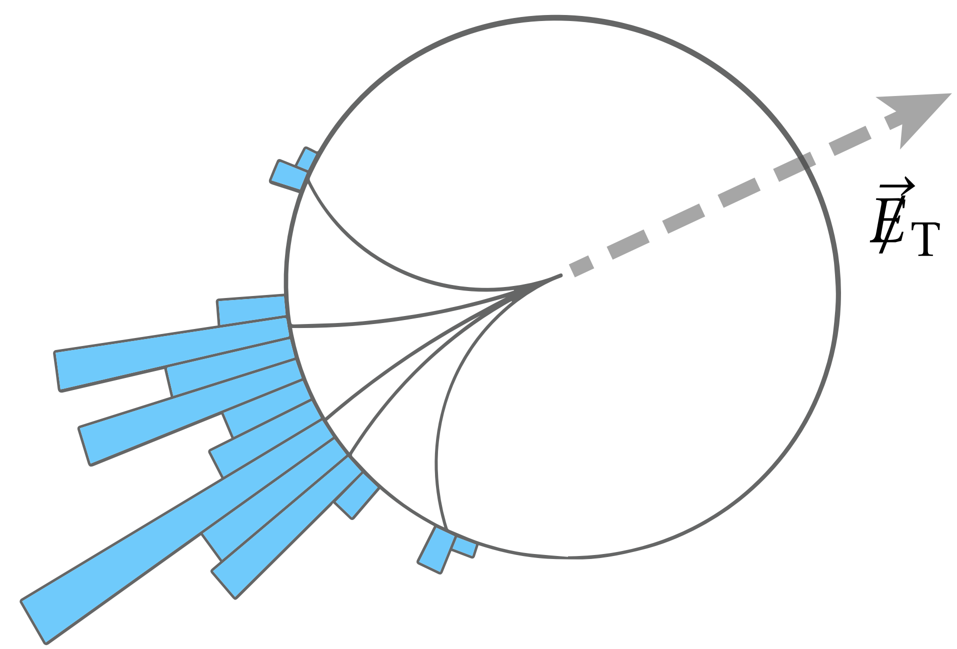
Jets and missing energy

- **Jets:**
  - defined as sets of PF candidates clustered by the anti-kT jet-clustering algorithms with the distance parameter 0.4
  - corrected for detector effects (jet energy corrections, JEC)
  - can be tagged to indicate possible origins, e.g., b-quarks, tau leptons, boosted-W bosons, boosted-top quarks.



CMS DocDB 12503

- **MET (missing transverse momentum):**
  - sensitive to the presence of *invisible particles* and their total pT
  - reconstructed from all jets to which JEC is applied and all remaining visible unclustered particles reconstructed by the PF algorithm
  - cleaned for detector noise, cosmic rays, beam halos and corrected for pileup events, detector mis-alignment



CMS DocDB 12312

Major event variables used in CMS SUSY searches

HT - a measure of how energetic the event was

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

MET - sensitive to the presence of invisible particles and their total pT

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

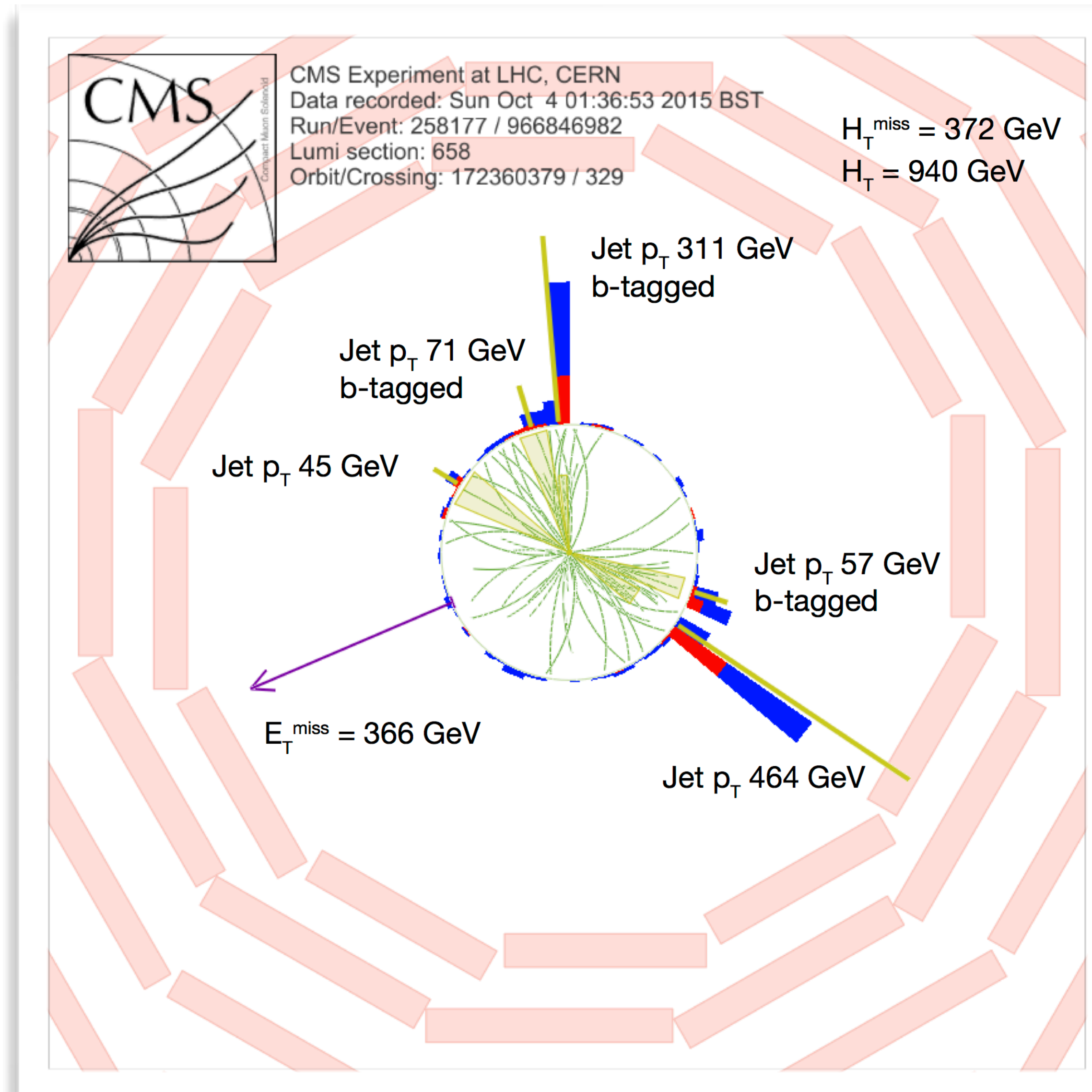
MHT - alternative to MET, defined only by jet pT

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

$$H_\mathrm{T}^\mathrm{miss} = \not{H}_\mathrm{T} = \left| \vec{H}_\mathrm{T}^\mathrm{miss} \right| = \left| \vec{\not{H}}_\mathrm{T} \right|$$

Jet multiplicity n_jet

b-jet multiplicity n_b



an event with large MET and multiple hight-pT jets

Examples of special event variables used in CMS SUSY searches

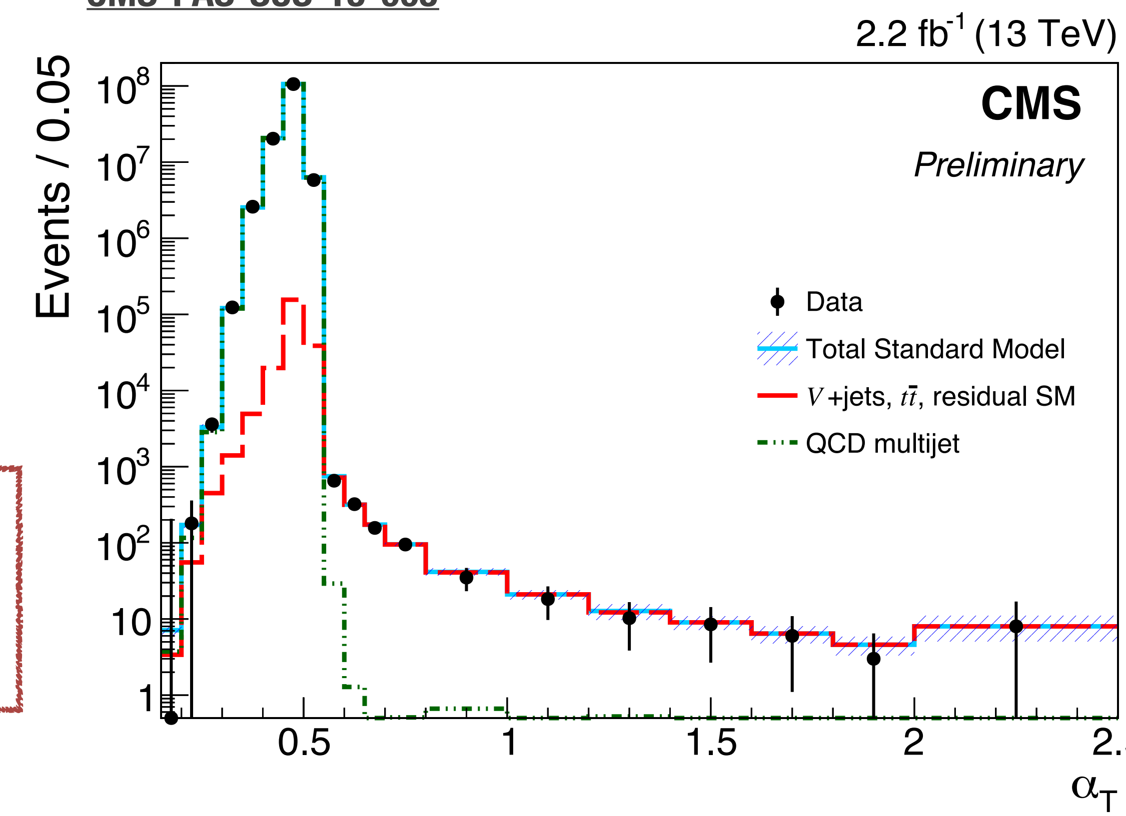
alphaT

$$\alpha_T = \frac{\sum_i E_T^{j_i} - \Delta E_T}{2\sqrt{\left(\sum_i E_T^{j_i}\right)^2 - H_T^{\text{miss}\,2}}}$$

ΔE_T: the jets in the event are combined into two ***pseudo-jets*** such that ΔE_T, the difference in E_T of two pseudo-jets, is minimized

$\alpha_T \lesssim 0.5$ for QCD events, α_T can be greater than 0.5 for events with invisible particles

CMS-PAS-SUS-15-005



MT2 - *stransverse* mass

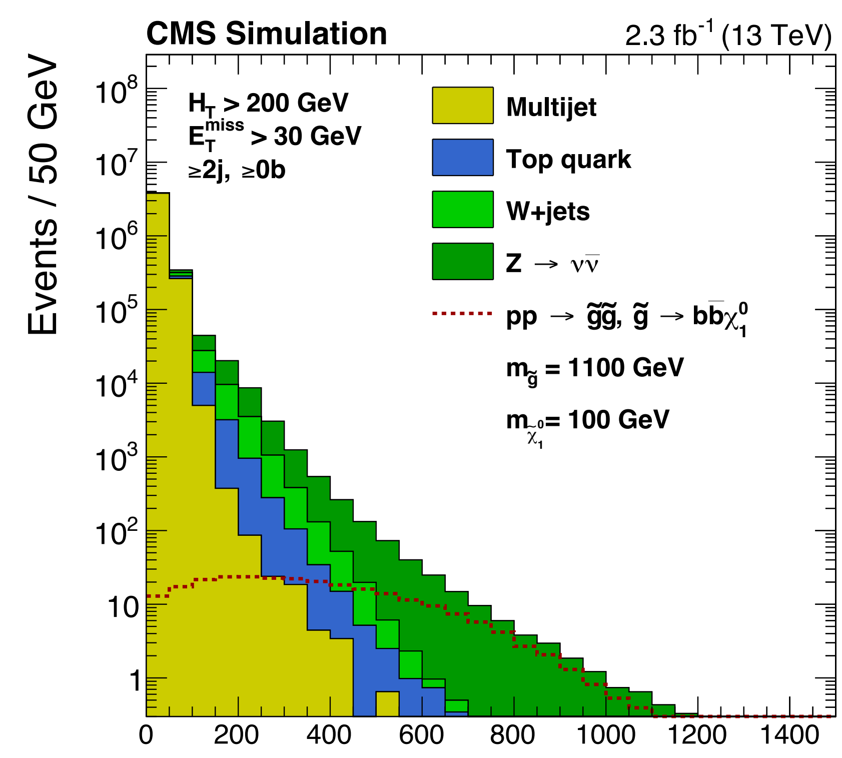
$$M_{T2} = \min_{\vec{q}_T + \vec{r}_T = \vec{E}_T^{\text{miss}}} \left[\max\left(M_T(\vec{p}_T^{\,j_1}, \vec{q}_T), M_T(\vec{p}_T^{\,j_2}, \vec{r}_T)\right)\right]$$

transverse mass

$$M_T(\vec{p}_T, \vec{q}_T) = \sqrt{2\left(|\vec{p}_T||\vec{q}_T| - \vec{p}_T \cdot \vec{q}_T\right)}$$

p_T^{j1}, p_T^{j2}: p_T of each of two pseudo-jets which are formed to maximize their invariant mass

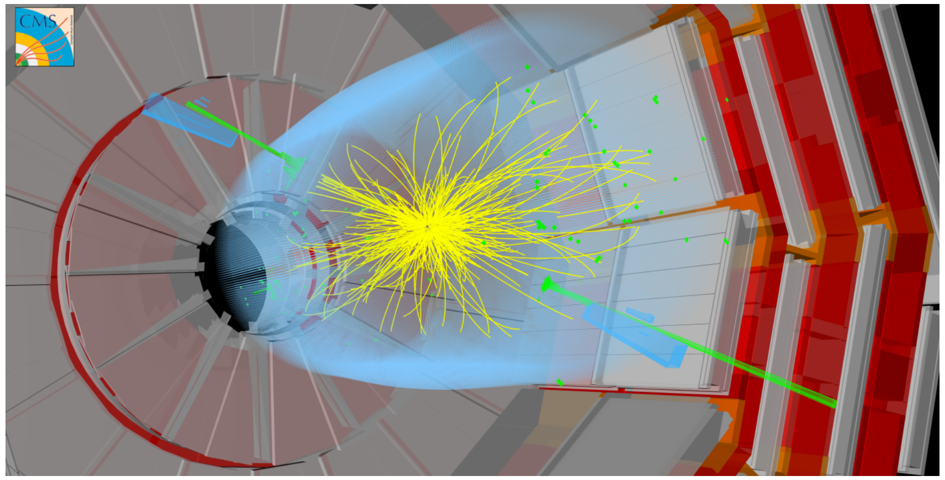
While MT2 is small for QCD events, it can be large for signal events



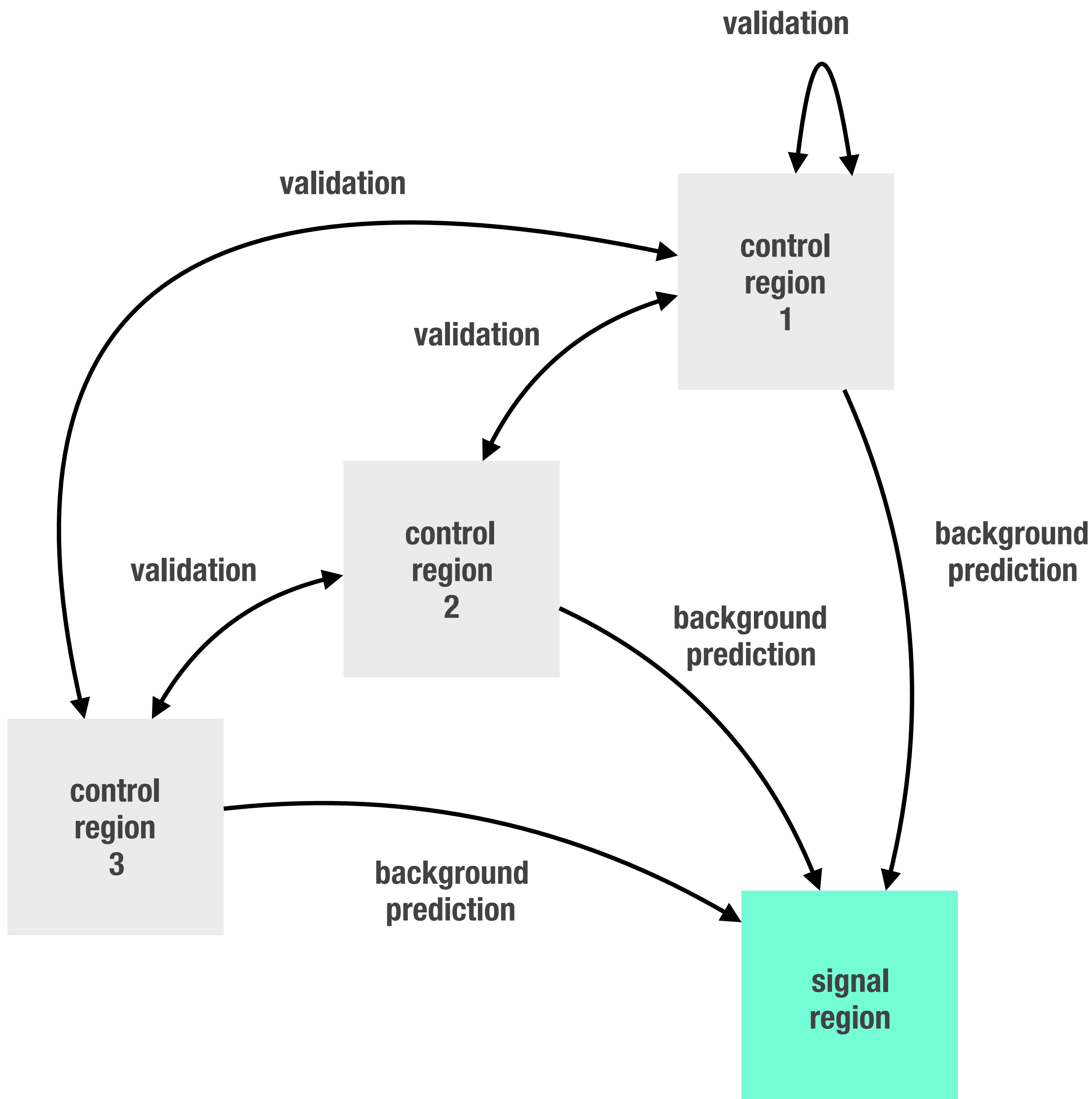
arXiv:1603.04053

An example of overall procedure of CMS SUSY searches

- Define signal and control regions
  - ***signal region***: high signal-to-background ratio
  - ***control regions***: used to predict background in the signal region. ideally, no signal, dominated by the same SM processes as in background in signal region
- Analyze data in control regions
  - ***blind analysis***: do not analyze data in signal region until later
- Compare data and MC in the control regions
  - Investigate any significant discrepancy
- Validate data and method of prediction
  - more in the next slide
- Predict background in the signal region
- Analyze data in the signal region (***unblind***)
- Compare the data in the signal region with the prediction
  - if a significant excess is observed, follow special procedures for discovery
  - otherwise, interpret results in SUSY models and place exclusion limits



Validation, background prediction, transfer factors



prediction

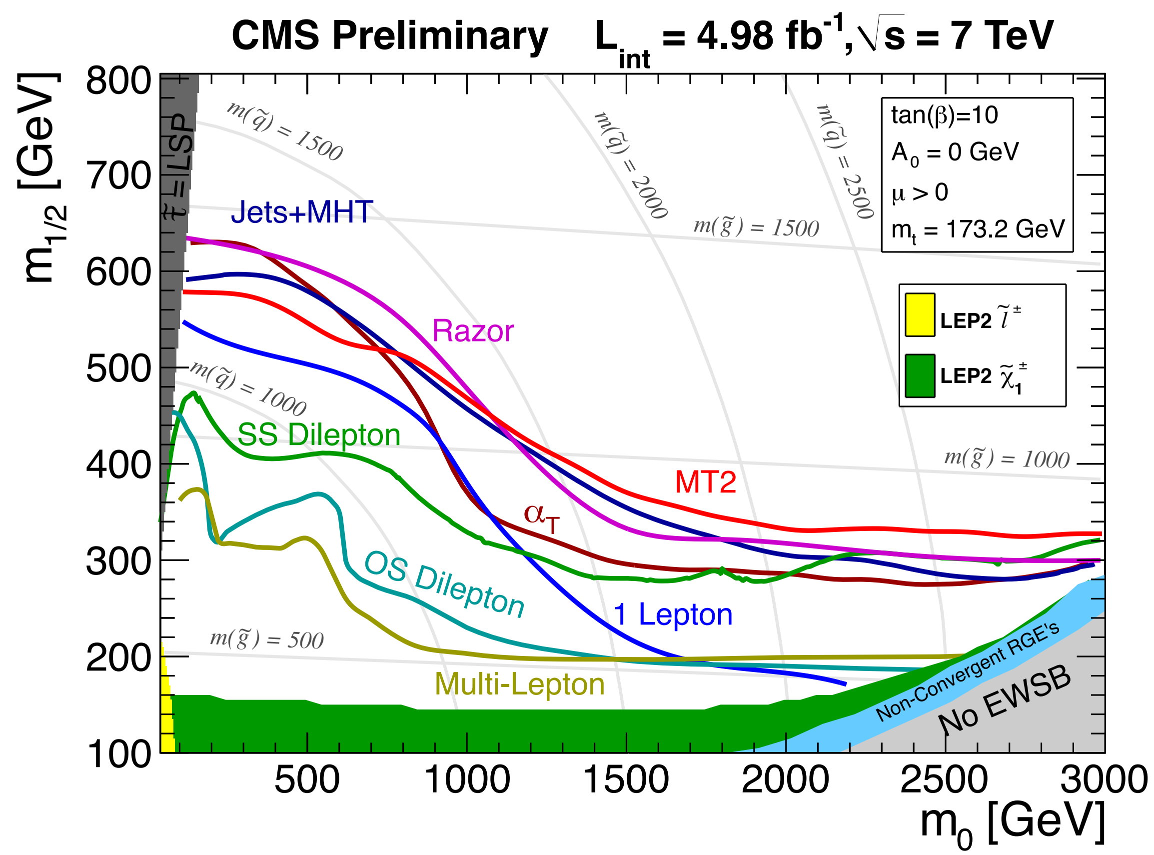
$$N^{\mathrm{A}}_{\mathrm{pred.}} = \frac{N^{\mathrm{A}}_{\mathrm{MC}}}{N^{\mathrm{B}}_{\mathrm{MC}}} \cdot N^{\mathrm{B}}_{\mathrm{data}}$$

transfer factor

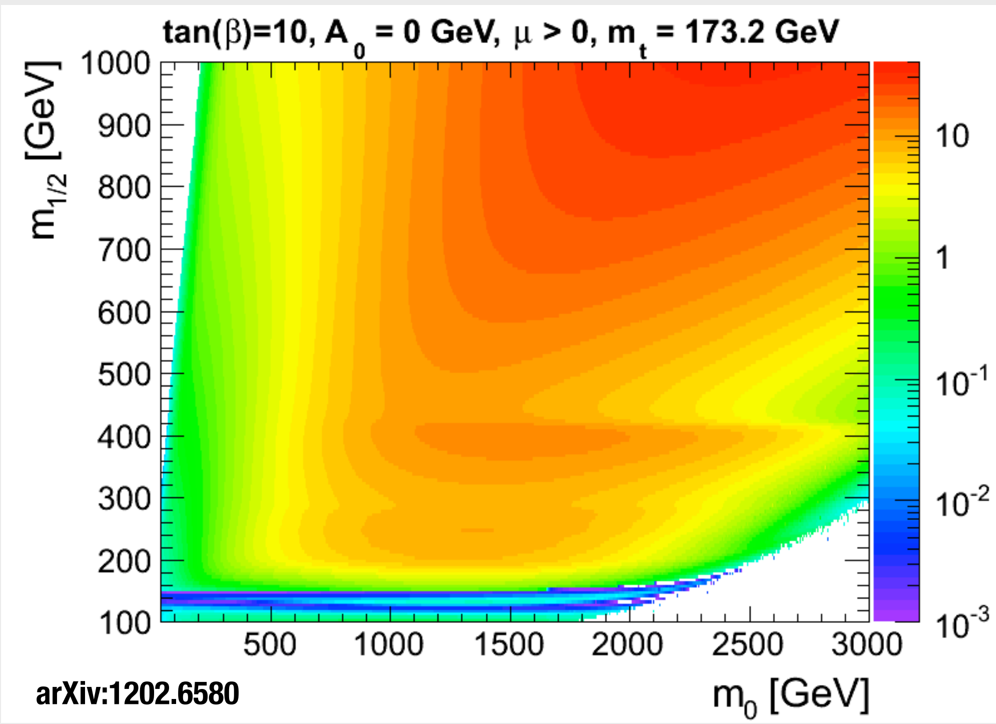
$$\mathrm{TF}_{\mathrm{B}\rightarrow\mathrm{A}} = \frac{N^{\mathrm{A}}_{\mathrm{MC}}}{N^{\mathrm{B}}_{\mathrm{MC}}}$$

A summary of Run 1 results - limits in CMSSM

- CMSSM was one of the popular SUSY models in interpreting the results of CMS SUSY analyses in 7 TeV data
- CMSSM adds five new parameters to SM
  - m_0, $m_{1/2}$, tanβ, A_0, sign(μ)
- In most of the its parameter spaces, LSP is a neutralino, a dark matter candidate
- The right figure summaries the exclusion limits of several CMS SUSY analyses on the m_0 - $m_{1/2}$ plane for tanβ=10, A_0=10GeV, and positive μ



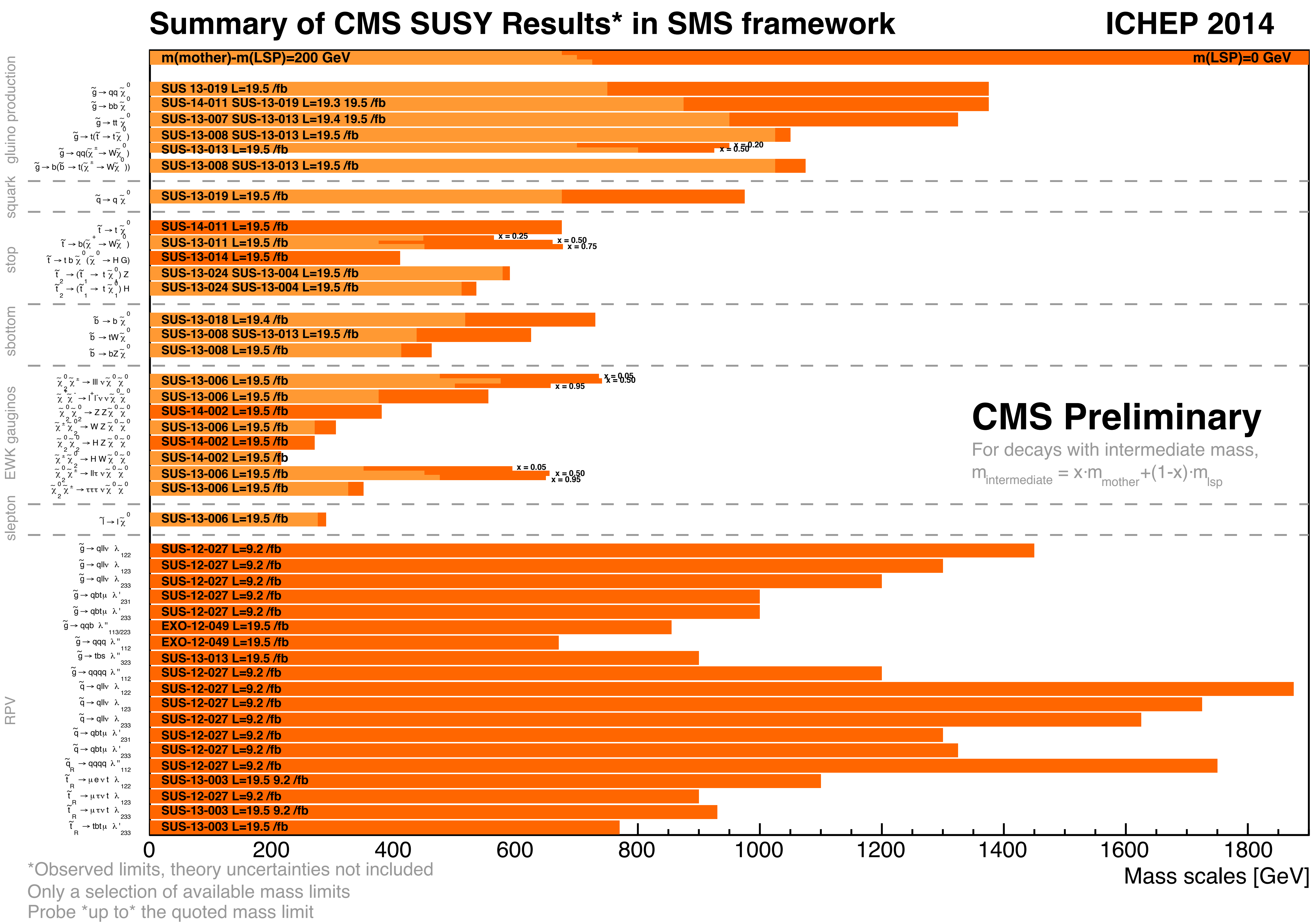
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSYSMSSummaryPlots7TeV



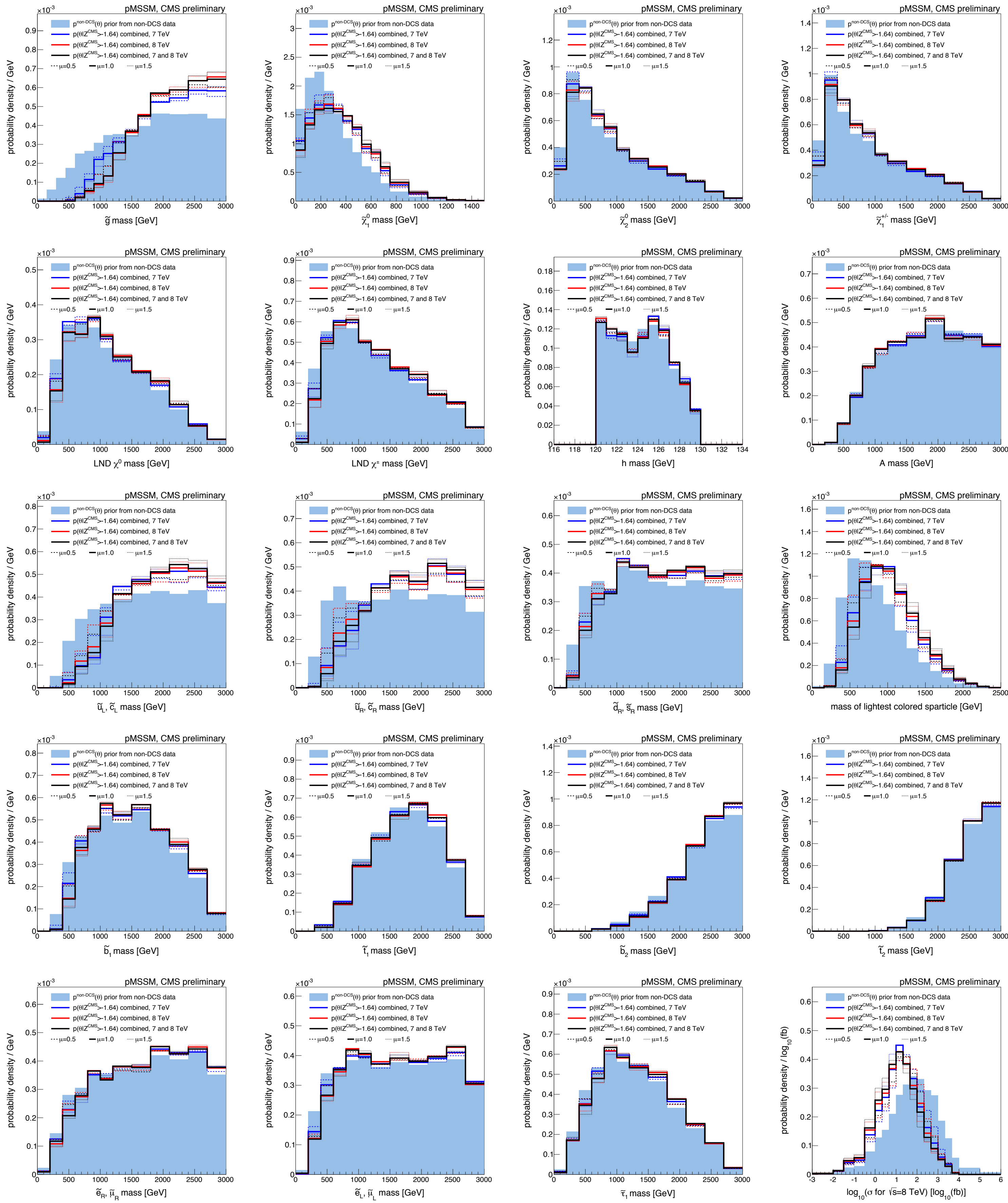
Dark matter relic density

- the corresponding neutralino relic density $\Omega_\chi h^2$ on the m_0 - $m_{1/2}$ plane can be calculated under certain assumptions (arxiv:1202.6580)
- which can be compared with the cold dark matter relic density derived from cosmological observations
  - $\Omega_{dm}h^2 = 0.1196 \pm 0.0031$ [planck 2013 arXiv:1303.5076]

A summary of Run 1 results - limits in SMS



Run 1 results - interpretation in pMSSM



- **pMSSM (phenomenological MSSM)**
  - 19 parameters at the electroweak scale
  - the number parameters is reduced from 120 of MSSM by assuming the flavor and CP structures without by imposing a SUSY breaking mechanism
  - allows us to explore regions of the MSSM phase space where SMS don't

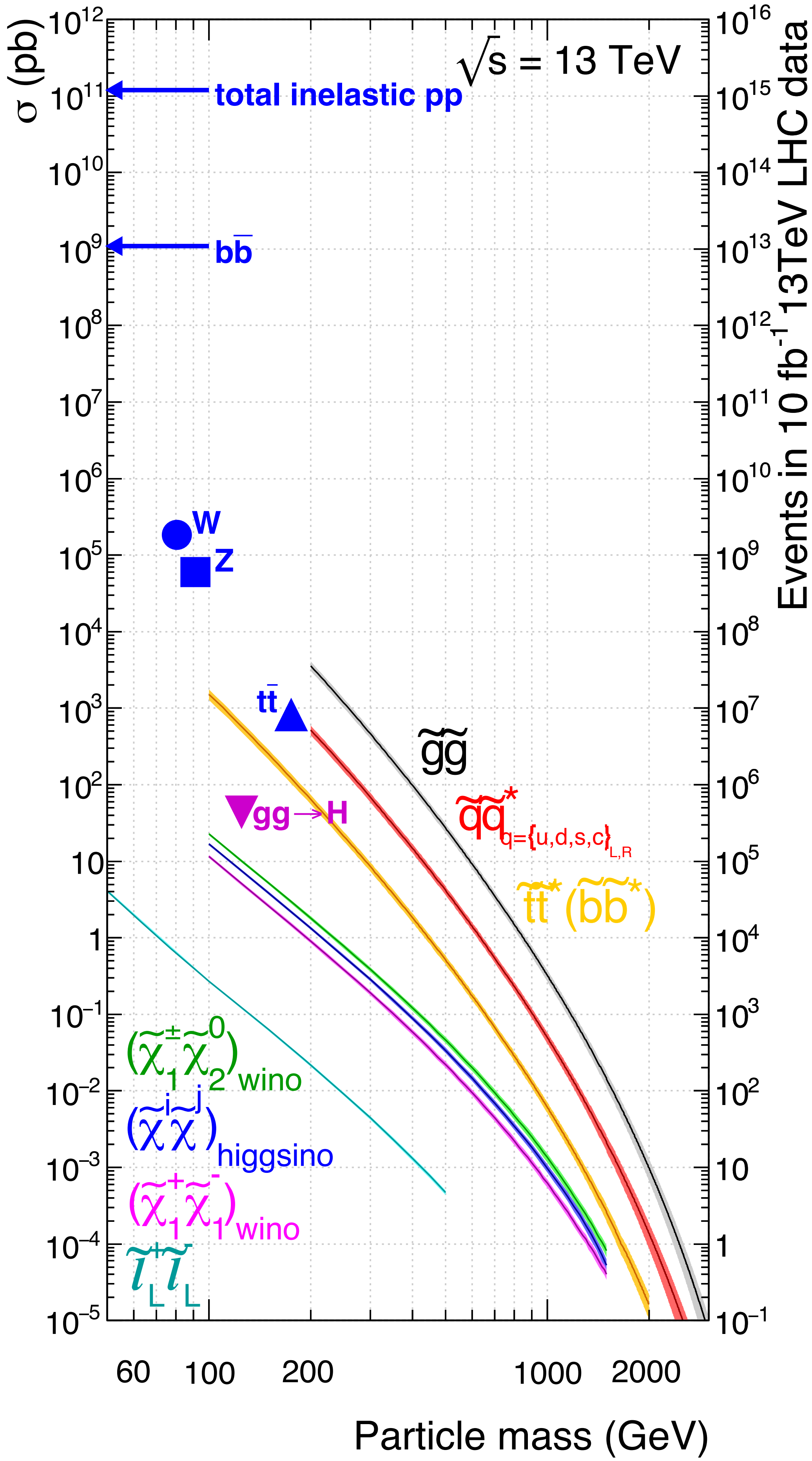
SUS-15-010: a global Bayesian analysis of CMS Run 1 SUSY search results — prior distributions are constructed from results other than CMS SUSY searches such as $b \to s\gamma$, $b_s \to \mu\mu$, g-2, etc.

Marginal distributions of prior and posterior distributions of sparticle masses and cross sections

SUS-15-010

SUSY cross sections at 13 TeV

The SUSY searches stats from the processes with the larger cross sections and extends to the smaller cross sections.



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSYSMSSummaryPlots13TeV

Public CMS SUSY search results with 2015 data

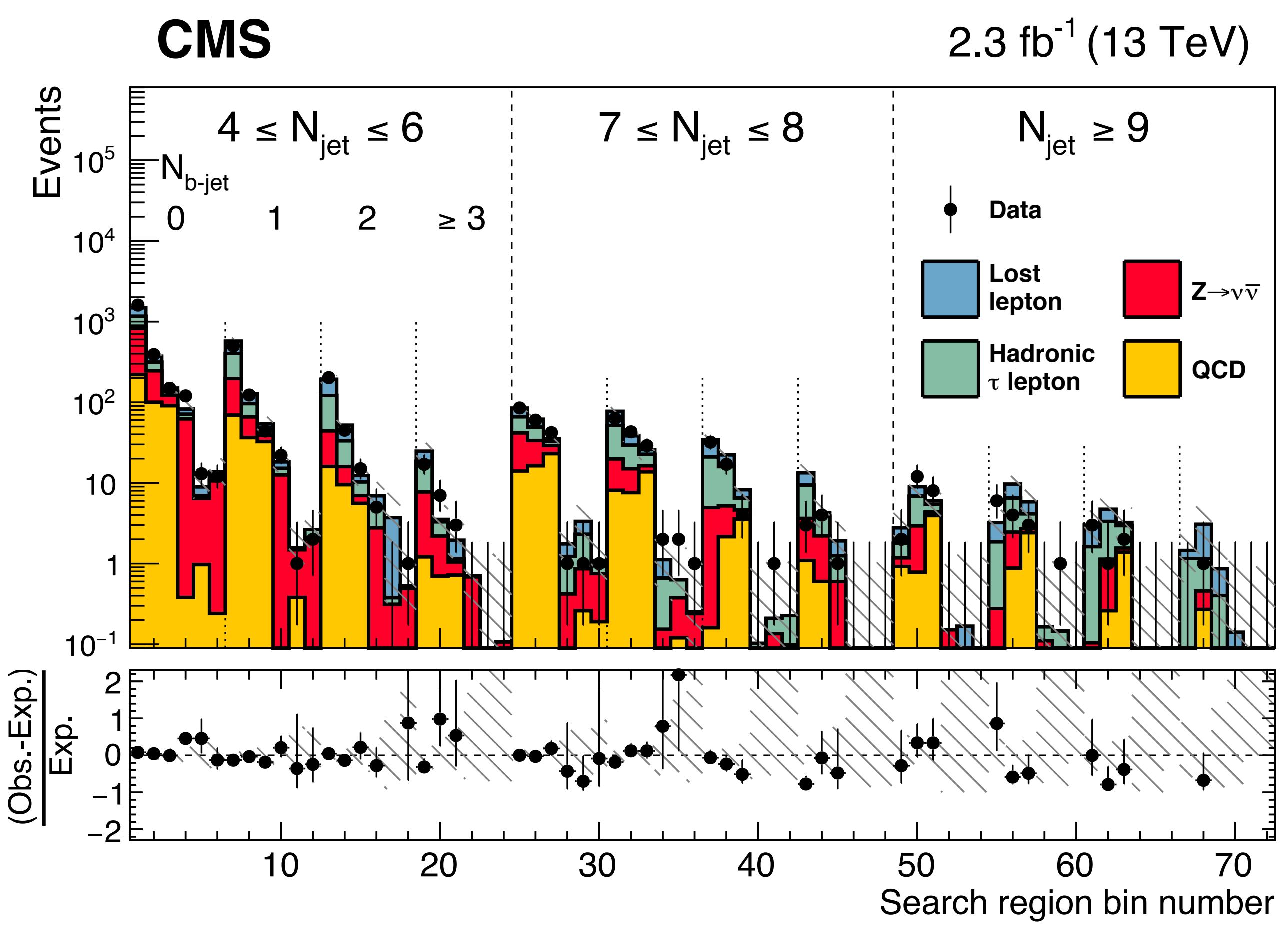
SUS-15-002	Dec 2015	jets + MHT	arXiv:1602.06581
SUS-15-003	Dec 2015	jets + MT2	arXiv:1603.04053
SUS-15-004	Dec 2015	0/1 lepton + jets + razor	
SUS-15-005	Dec 2015	jets + α_T	
SUS-15-007	Dec 2015	1 lepton + jets + M_J	
SUS-15-008	Dec 2015	2 leptons (same-sign) + jets	
SUS-15-011	Dec 2015	2 leptons (opposite-sign) + jets	
SUS-16-004	Mar 2016	further SMS interpretaions	
SUS-15-006	Mar 2016	1 lepton + jets + $\Delta\phi$	
SUS-16-001	Mar 2016	sbottom, stop search	
SUS-16-002	Mar 2016	1 lepton, stop search	
SUS-16-003	Mar 2016	3 or more leptons + jets	
SUS-16-007	Mar 2016	jets + t-tagging	
SUS-15-012	Apr 2016	2 photons + jets	

http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html

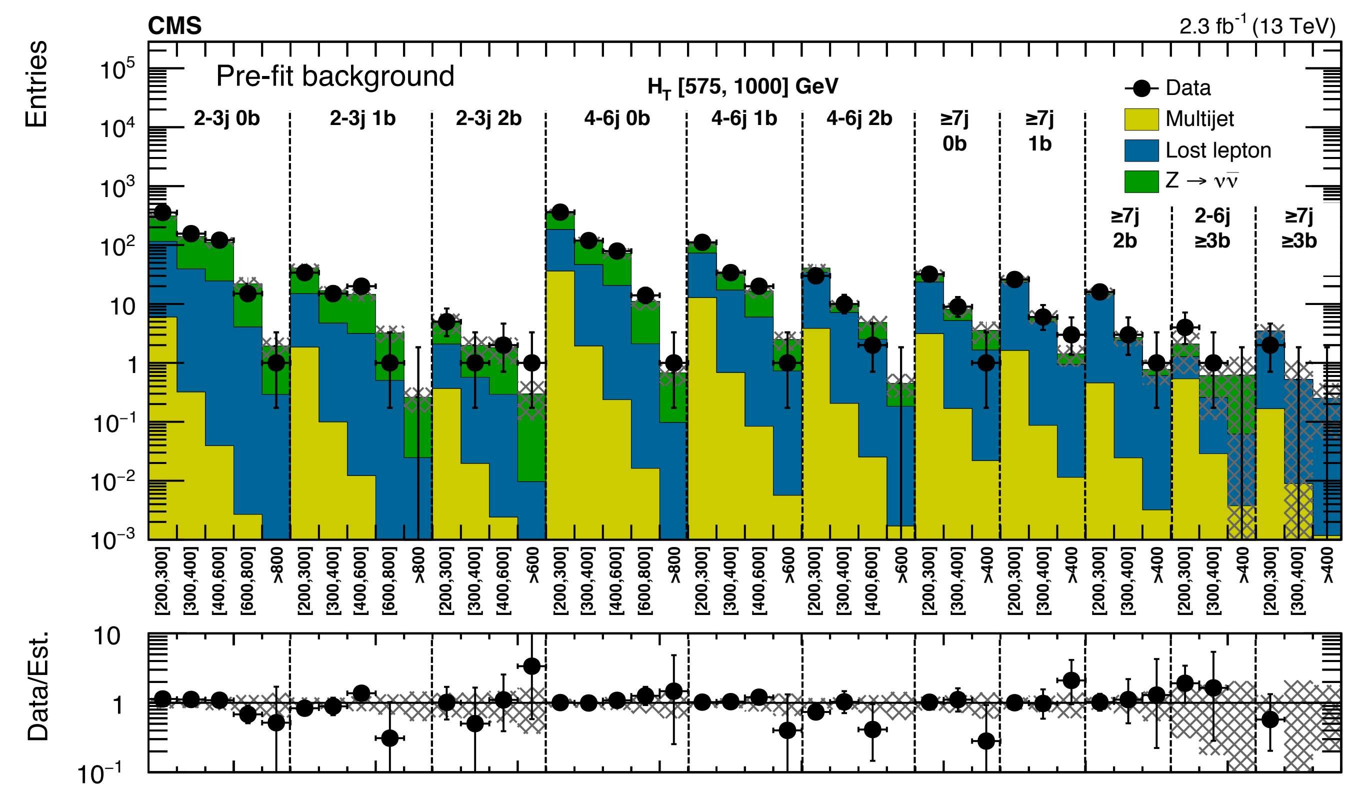
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html

Data and background predictions in signal regions

SUS-15-002



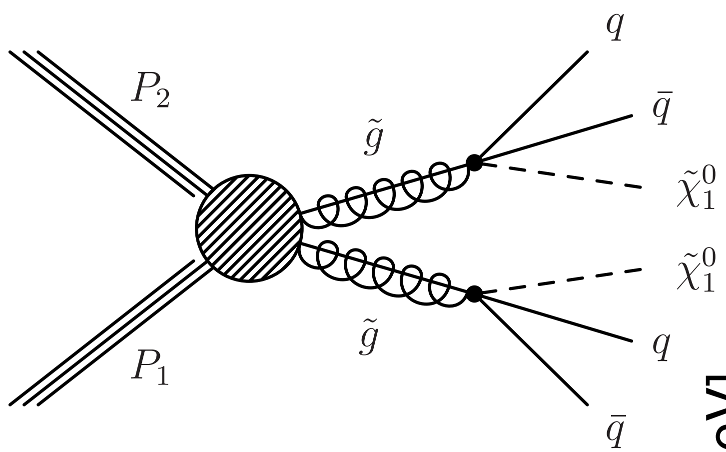
SUS-15-003



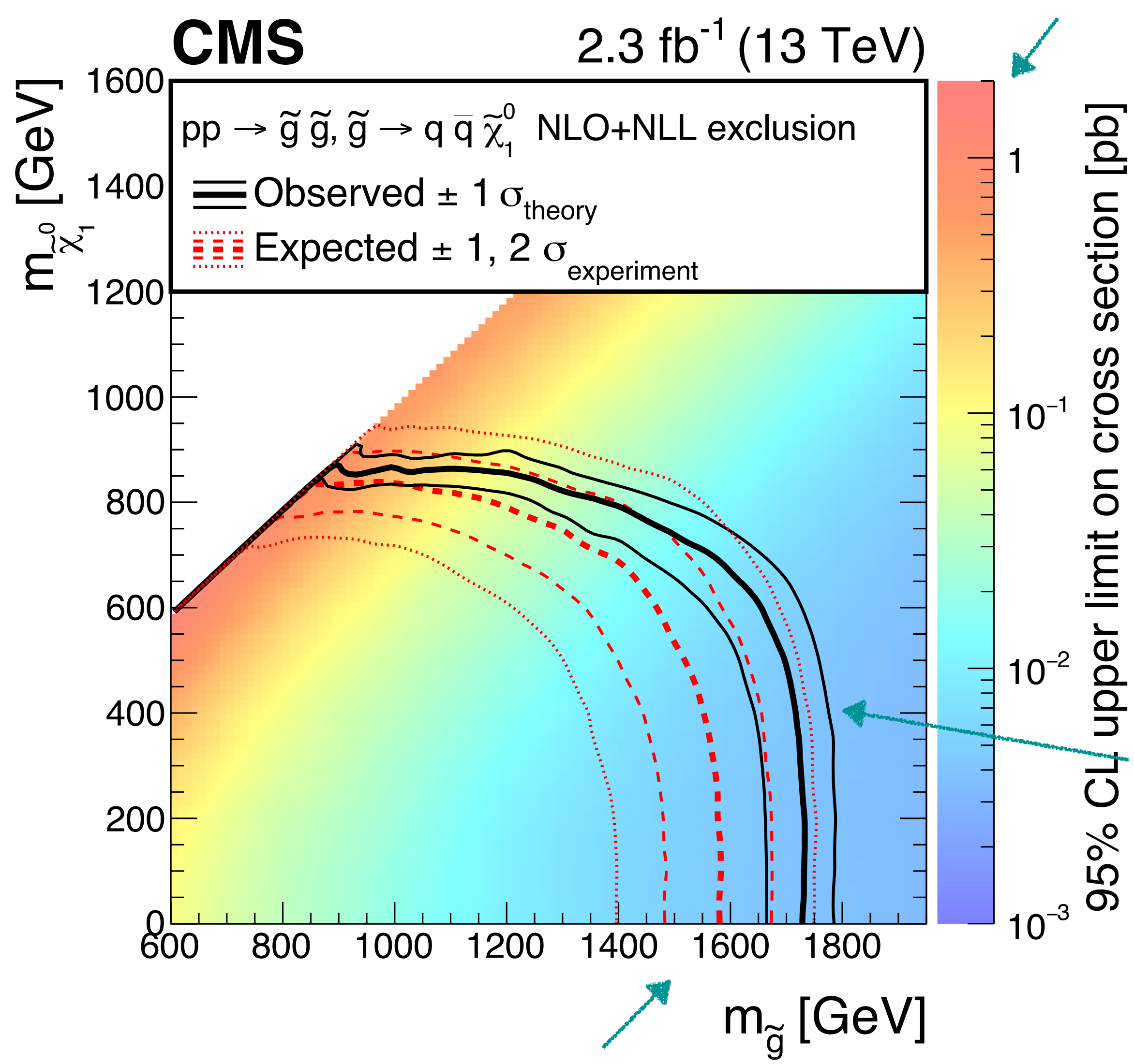
Events in signal (search) regions are divided into categories (bins) according to their values of event variables, e.g., HT, njet, nb. The number of the background events is predicted for each category (x-axis). The data agree well with the predictions.

Search for gluinos

T1qqqq



SUS-15-003



***The color scale** - the upper limit on the cross section derived from the acceptance, the observed and predicted number of events in the signal region and their uncertainties.*

The signal acceptance is evaluated with signal MC samples generated at each point in the grid of the mass plane

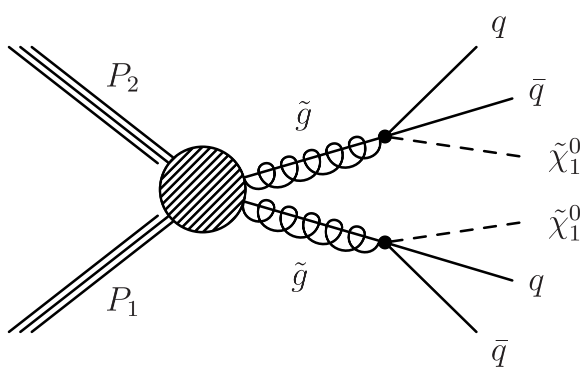
***The thick black line** - the observed lower mass limit, the contour at which the theoretical cross sections calculated in SUSY NLO+NLL intersect with the upper cross section limit.*

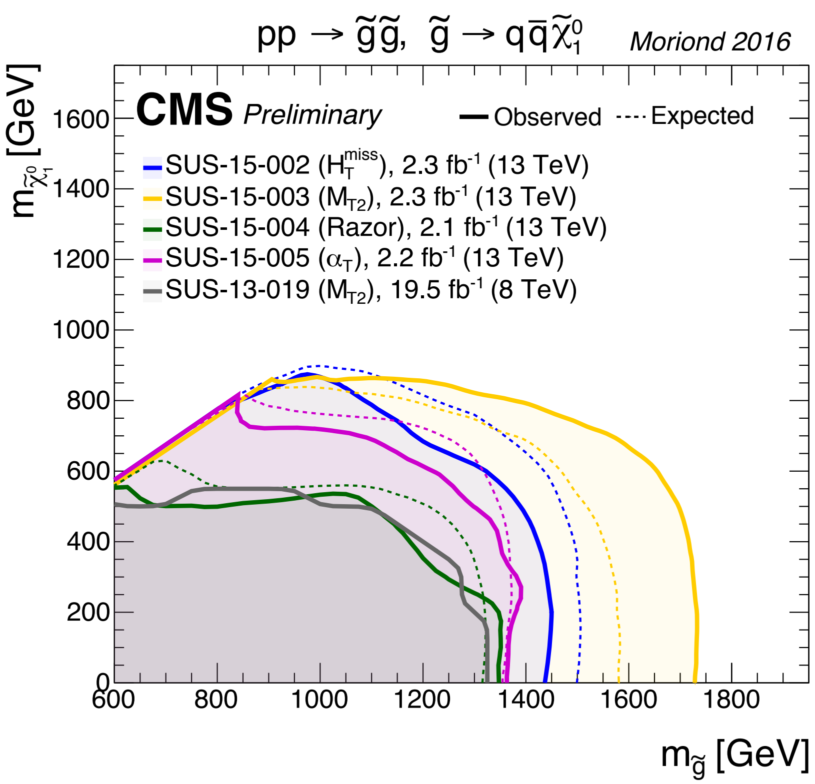
***The thick red dotted line** - the expected lower mass limit, the contour at which the theoretical cross sections intersect with the expected upper cross section limit, the limit that would be obtained if the predicted number of the events is actually observed*

***The thin black lines** - the contours at which 1 sigma variations of the theoretical cross sections intersect with the upper cross section limit.*

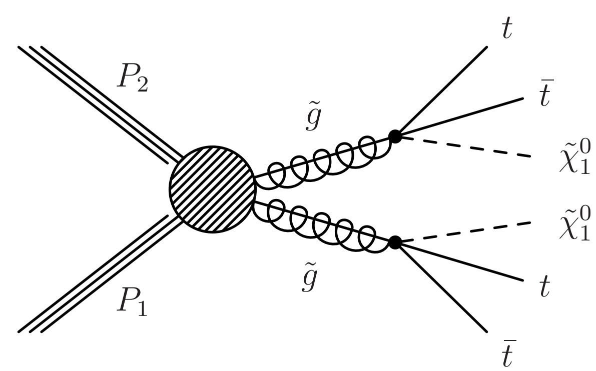
Search for gluinos

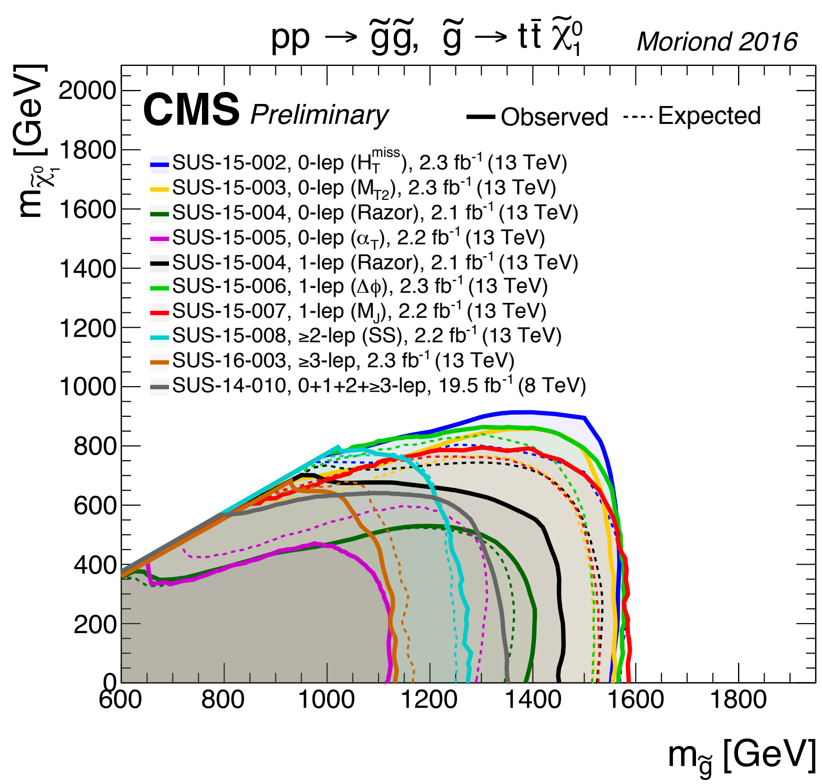
T1qqqq



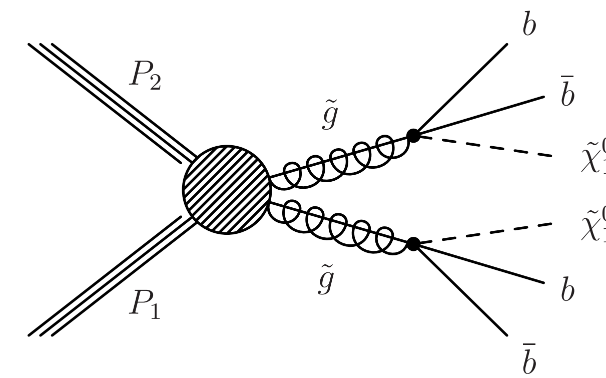


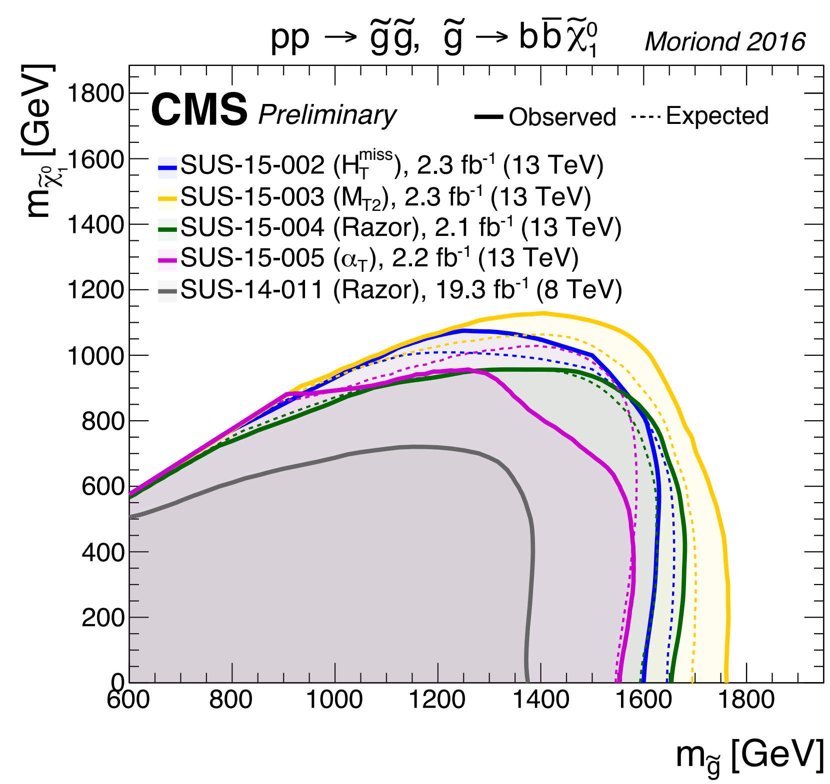
T1tttt





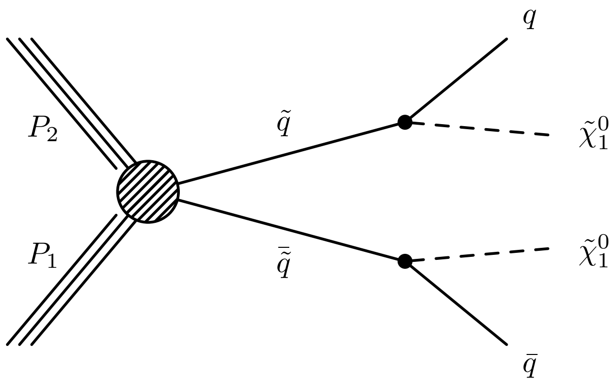
T1bbbb



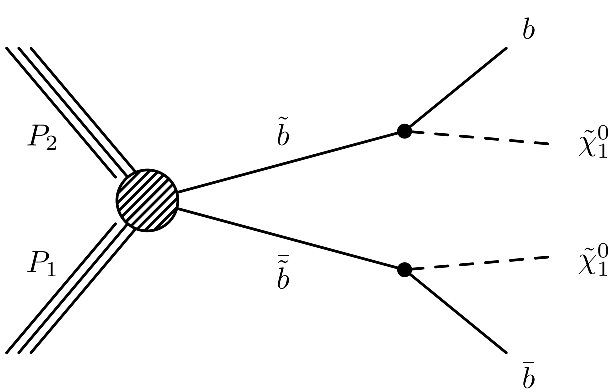


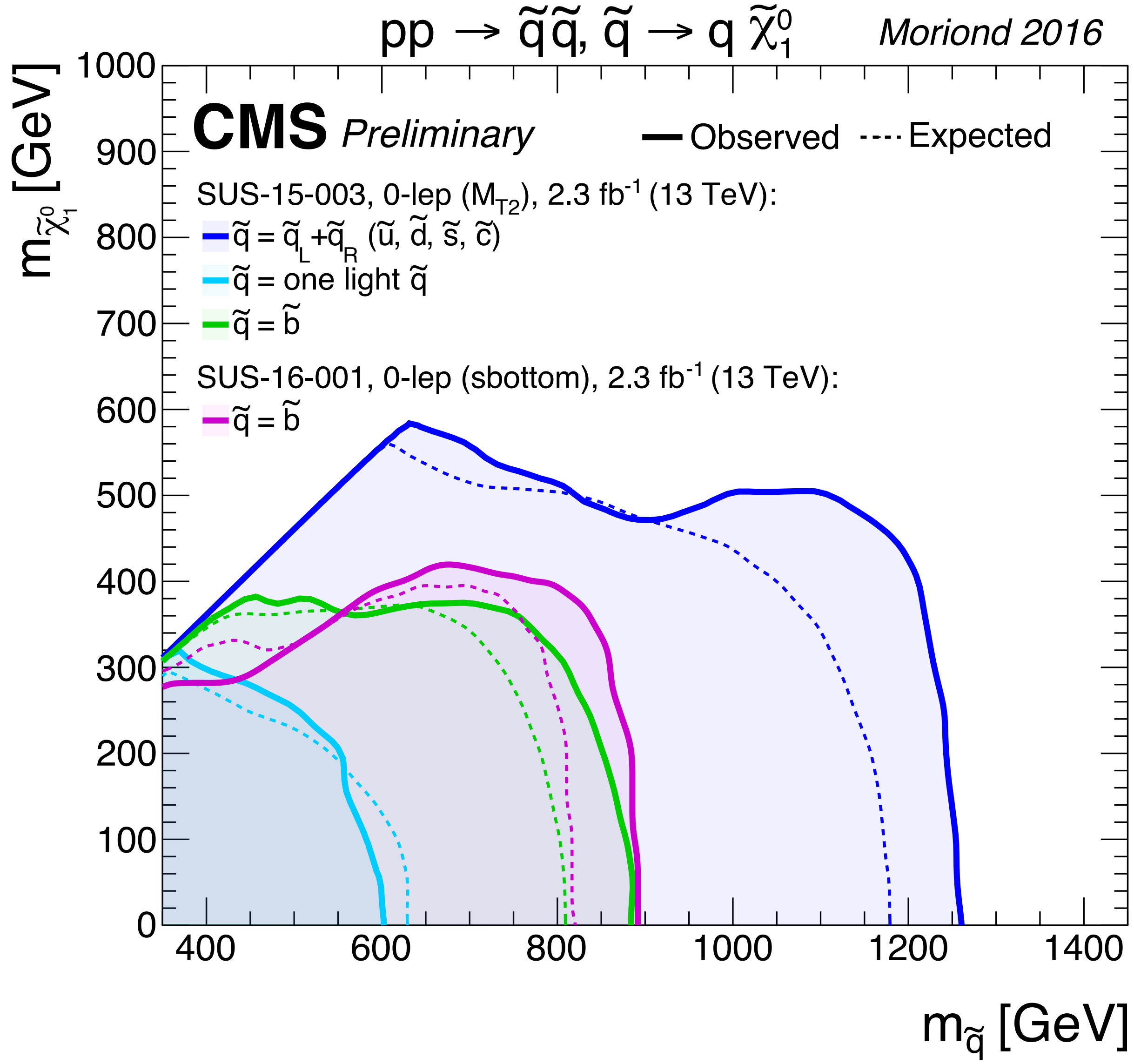
Searches for squarks

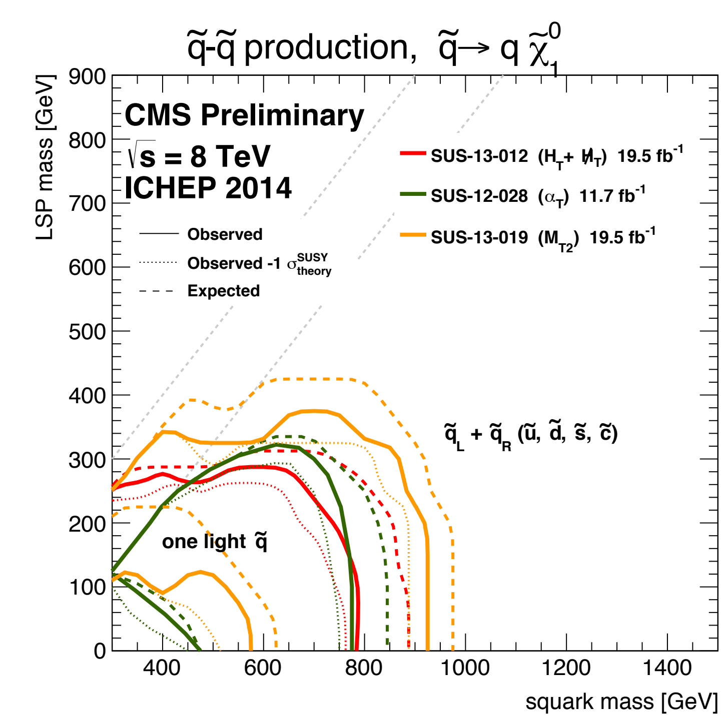
T2qq



T2bb



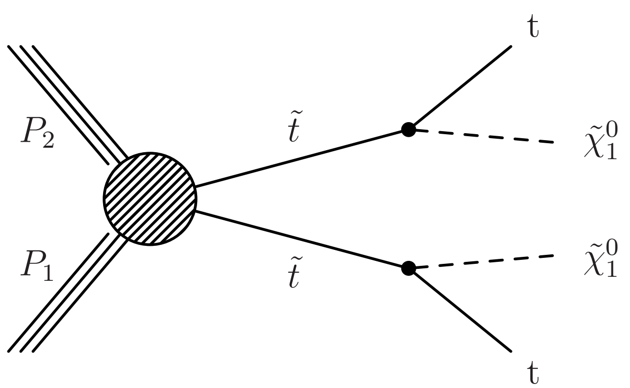


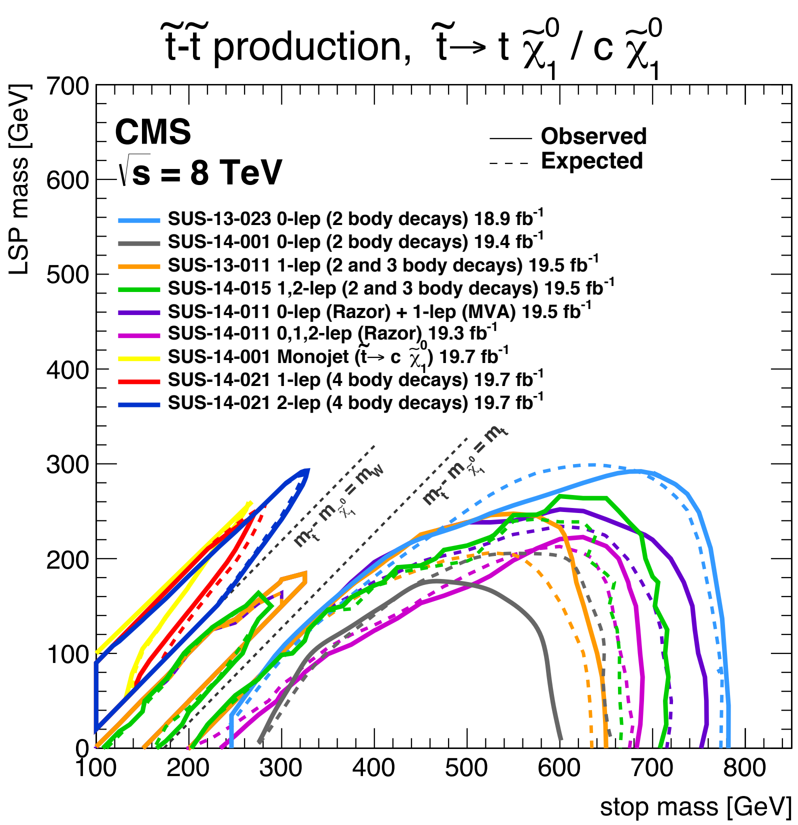


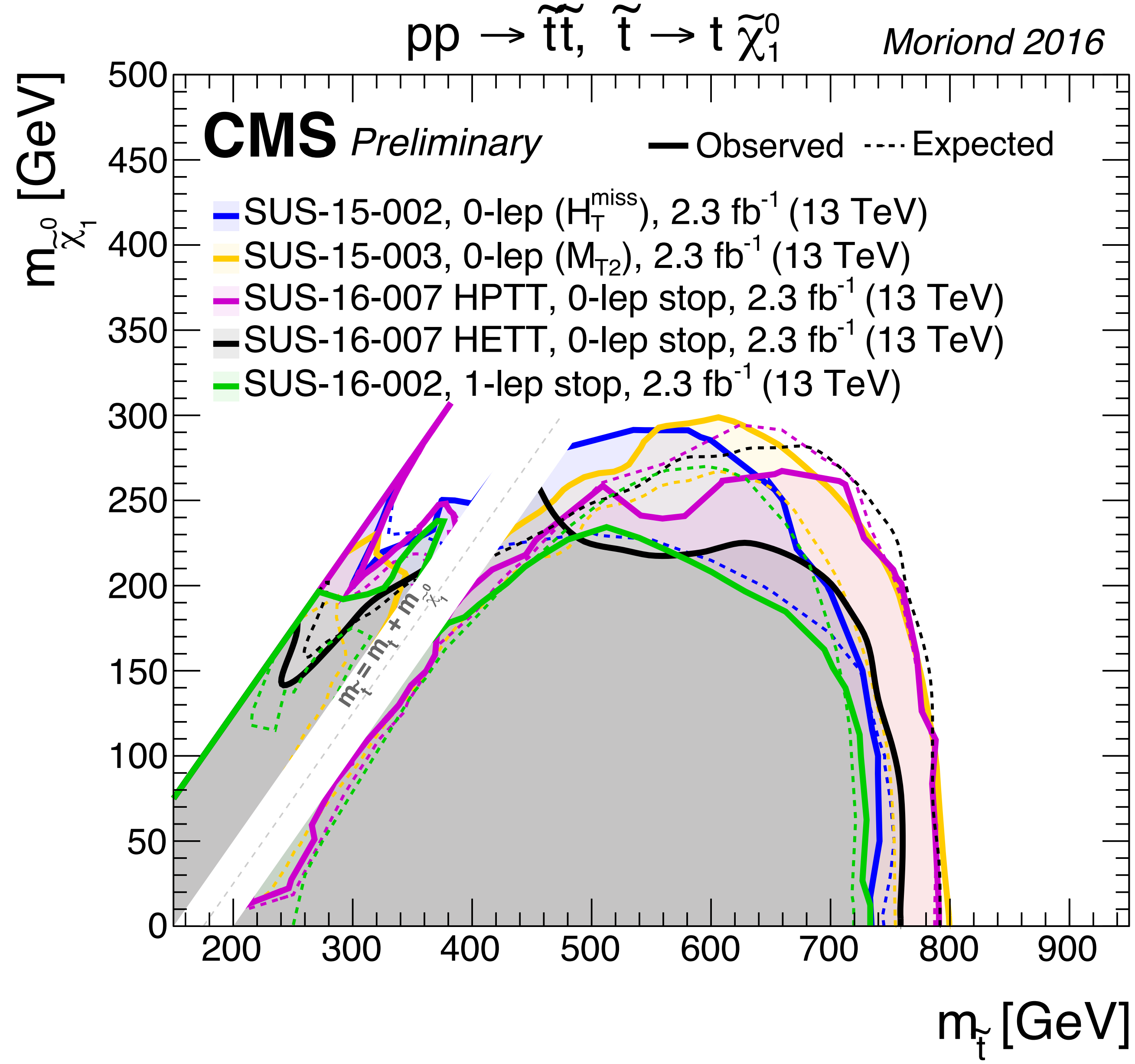
SUS-15-003 — *inclusive SUSY searches*
SUS-16-001 — *dedicated sbottom, stop searches*

Searches for stop

T2tt







A "natural" SUSY model

***SUS-15-002, SUS-15-003 —** inclusive SUSY searches*
***SUS-16-007 —** dedicated stop searches with top-tagging*
***SUS-16-002 —** dedicated stop searches in multiple decay modes (T2tt, T2tb) with 1 lepton*

Summary

- Supersymmetric (SUSY) extensions of the standard model can have attractive features. They have unified gauge coupling and dark matter candidates. They do not have the quadratic divergency in the Higgs boson mass calculation.
- SUSY models predict production of new particles, superpartners, at LHC Run 2, which started in 2015
- CMS searched for strongly produced superpartners in 2015 data and extended their mass limits
- The 2016 run is about to start. CMS continues to search for superpartners and extends the searches to processes with lower cross sections and challenging region of the phase space

End