Dark Matter Searches at CMS

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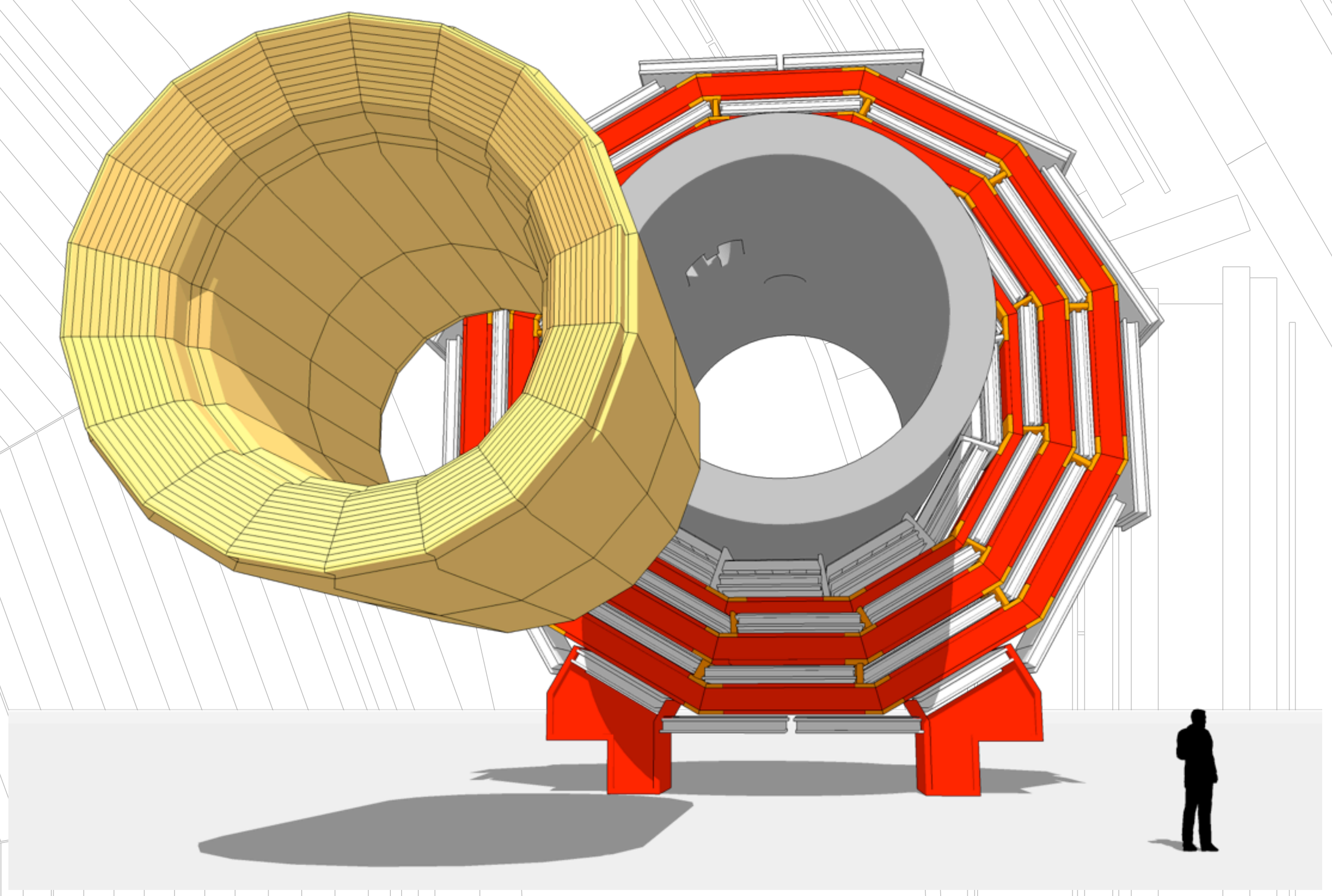
for the CMS collaboration



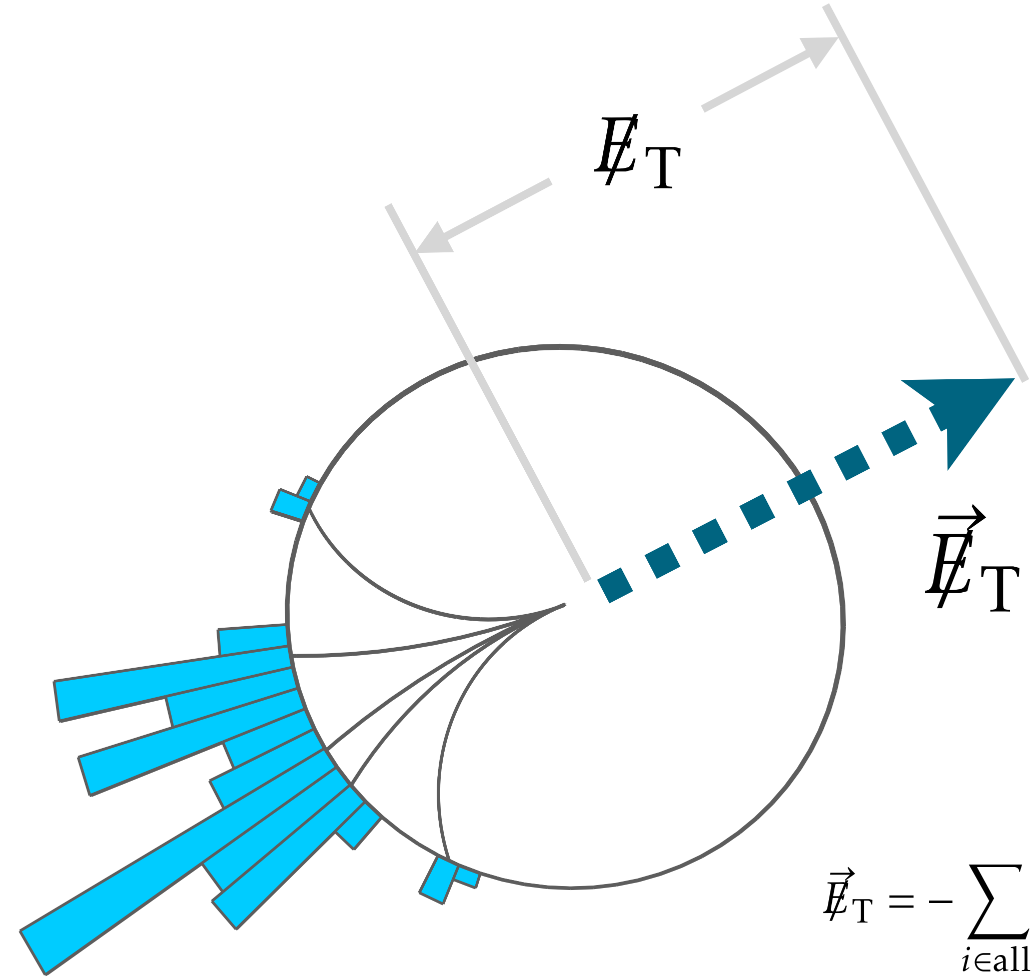
3 February 2013

Aspen 2013 Closing in on Dark Matter

https://indico.cern.ch/contributionDisplay.py?contribId=65&confId=197862

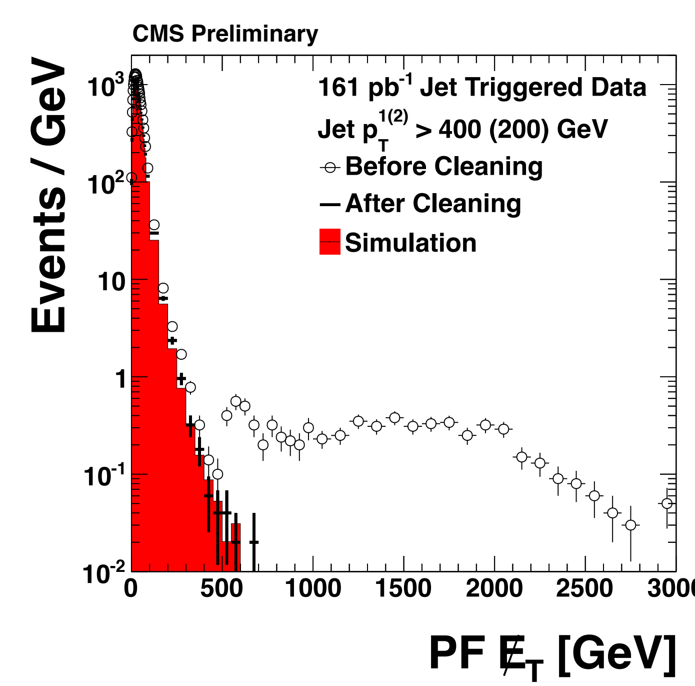
Missing Transverse Momentum (MET) and Dark Matter Particles

- **MET**
  - the form in which the dark matter particles would appear in CMS
  - the imbalance in the transverse momentum of all visible particles
    - ➡ the transverse momentum that must have been carried by invisible particles



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

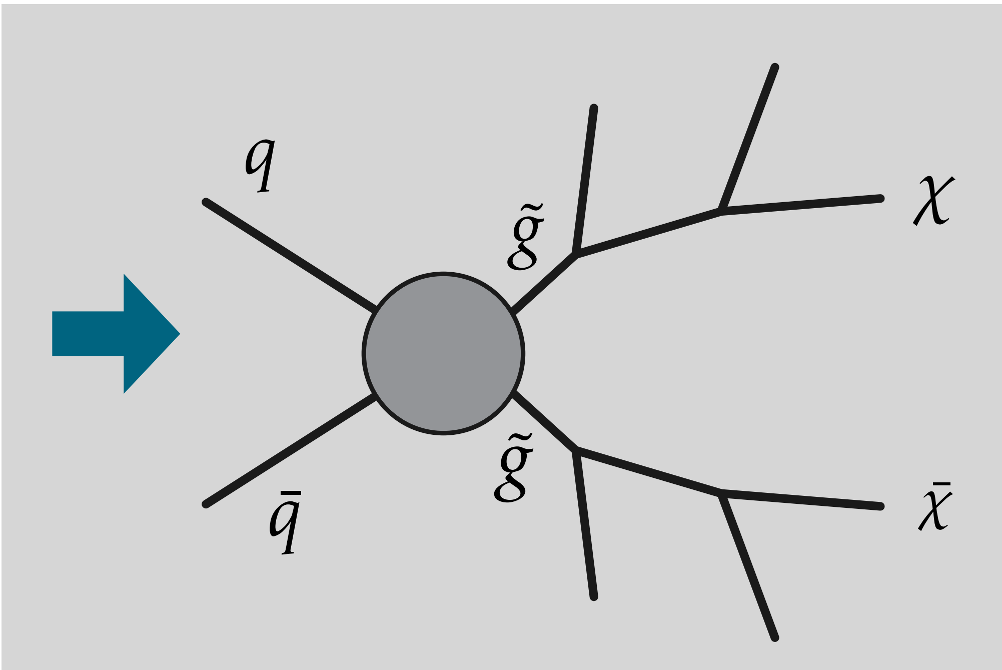
- **MET reconstruction**
  - ➡ requires hermetic detector
  - ➡ entails reconstruction of all particles with electromagnetic and strong interactions with precision
  - ➡ susceptible to many types of imperfections, e.g., hot calorimeter cells, detector noise, beam-halo particles



CMS-DP-2011-010

JINST 6 P09001 (2011)

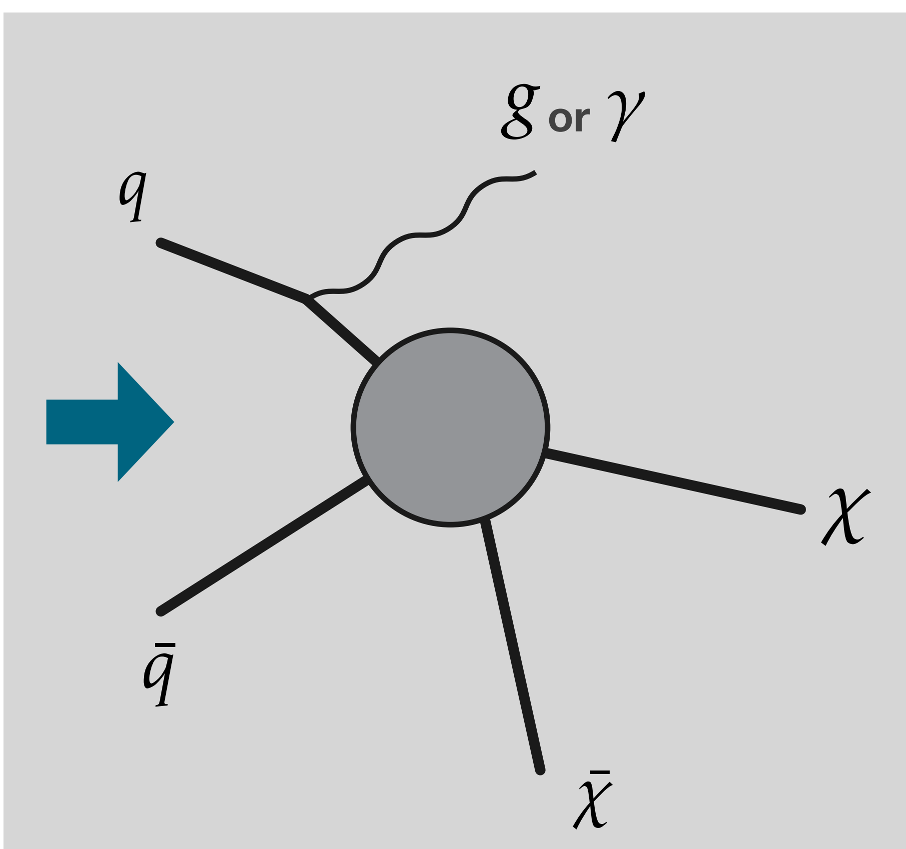
Possible dark matter particle pair-production and its signature at LHC



Heavier unstable new particles are produced
Their decay chains end with dark matter particles

e.g. SUSY models

Signature: large MET + jets (+ leptons) (+ photons)



Dark Matter particles are directly produced in pairs
after initial-state radiation (ISR)

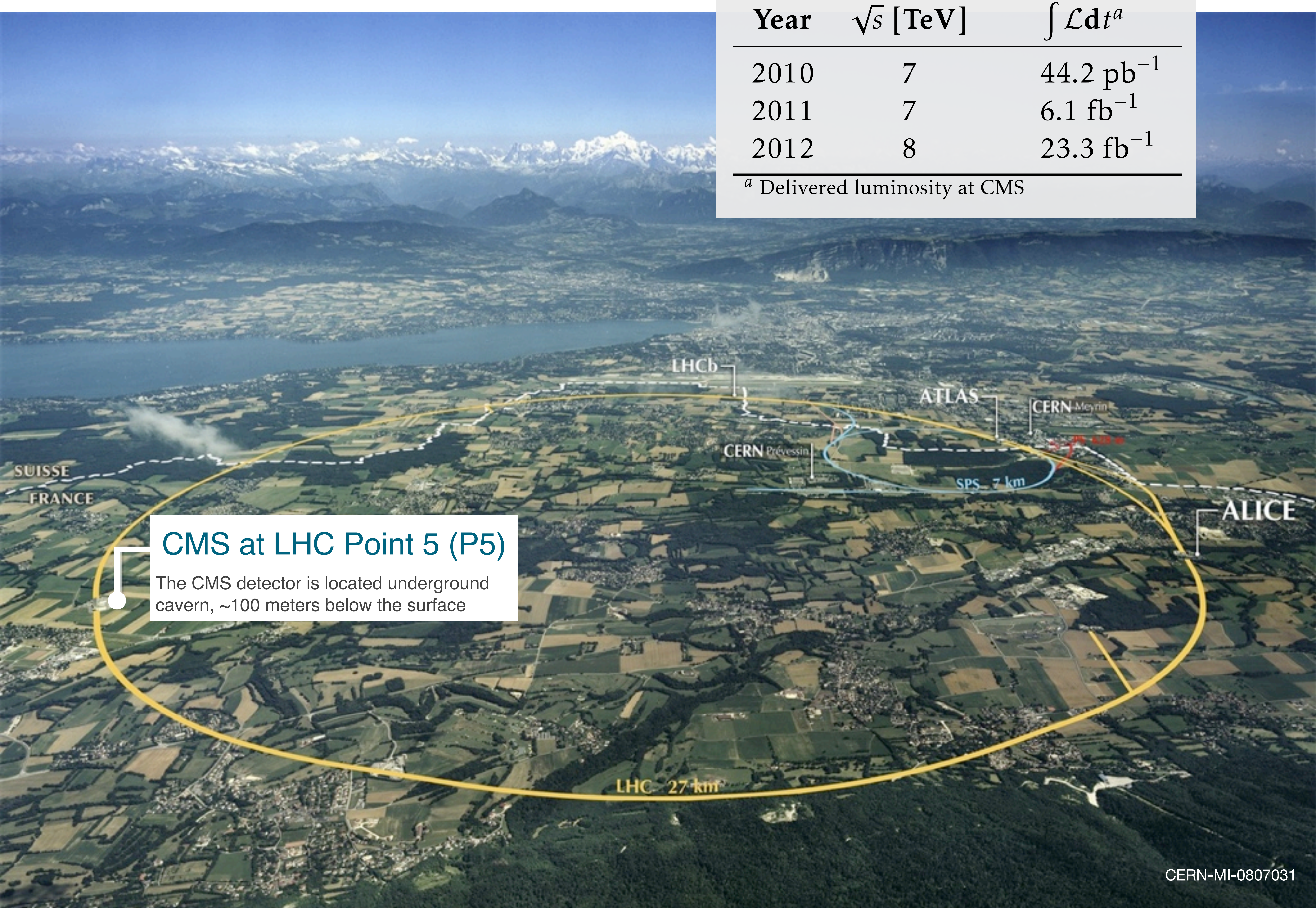
Signature: large MET + mono-jet (or mono-photon)

Large Hadron Collider (LHC)

Proton-proton runs in the last 3 years

Year	$\sqrt{s}$ [TeV]	$\int \mathcal{L}\mathrm{d}t$ [a]
2010	7	44.2 pb^{-1}
2011	7	6.1 fb^{-1}
2012	8	23.3 fb^{-1}

[a] Delivered luminosity at CMS

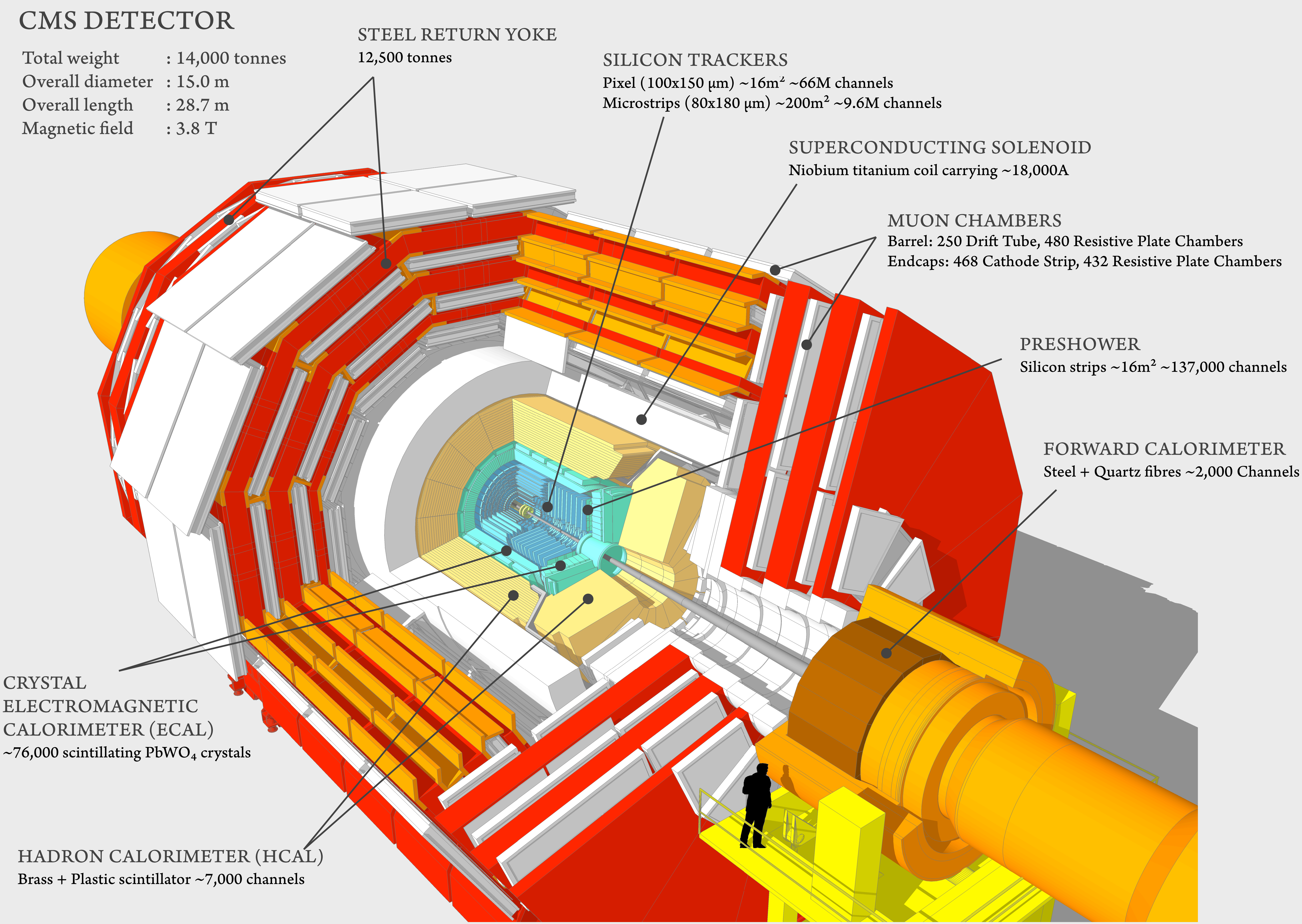


CMS Collaboration

- 3275 physicists
- 790 engineers and technicians
- 179 institutes
- 41 countries

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

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

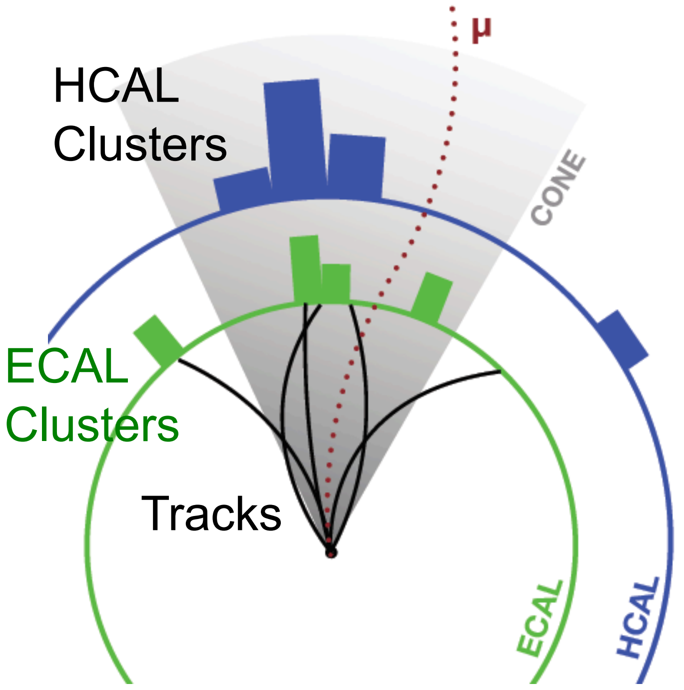


JINST 3 (2008) S08004 CMS Document 11514-v1

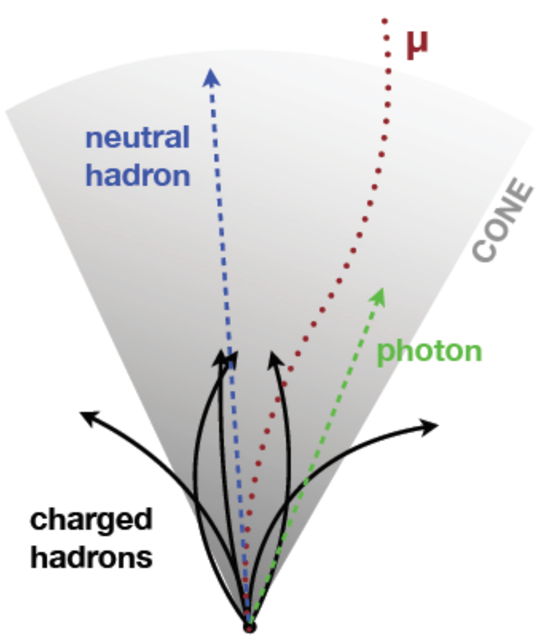
Online Event Selection and Offline Event Reconstruction at CMS

Online Event Selection

- 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

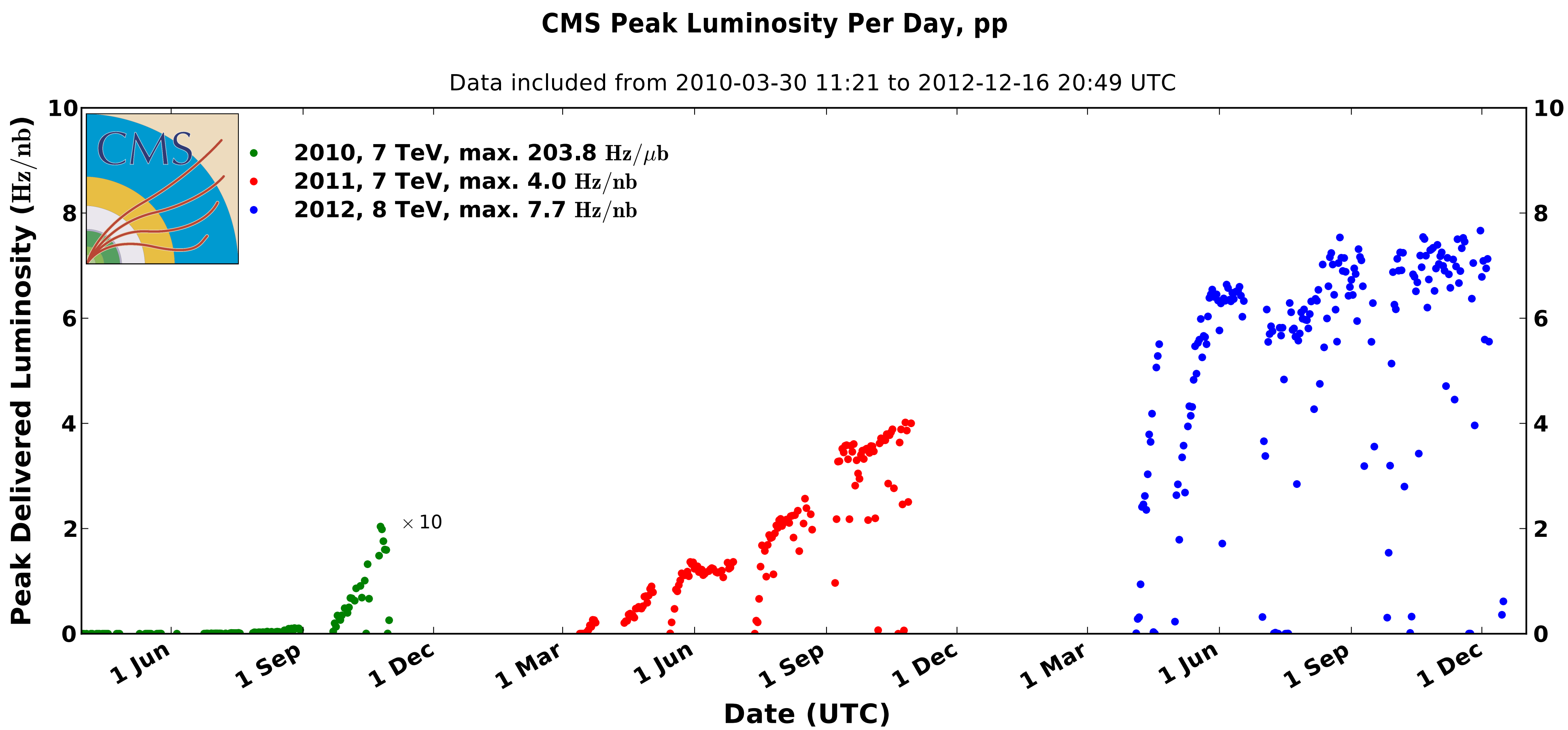


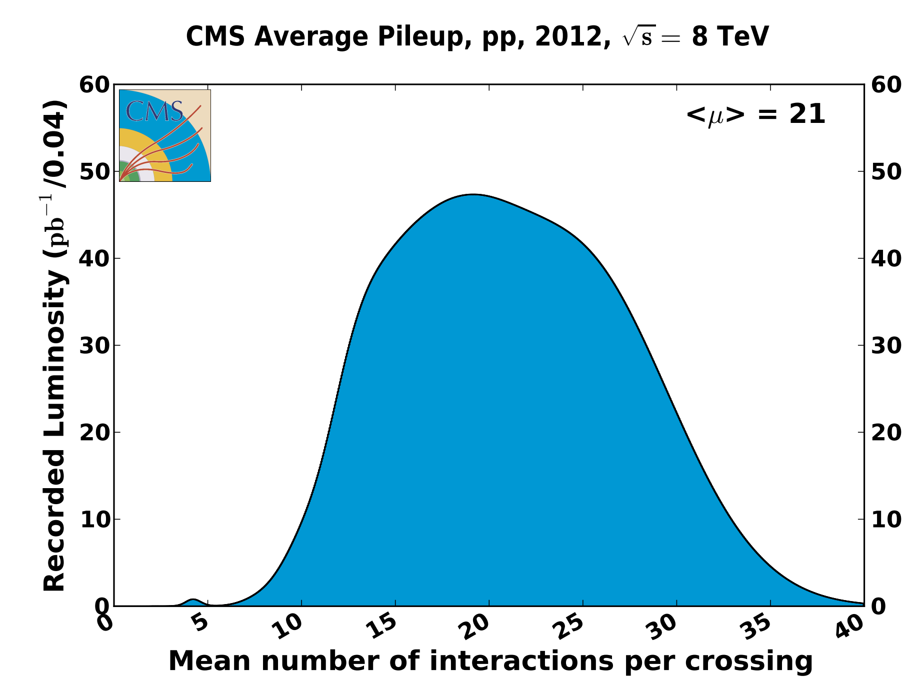
Particle-flow algorithm



- Offline Event Reconstruction (**on grid, ~60 computing sites worldwide**)
  - **Global Event Description, GED**
  - Visible particles (muons, electrons, charged hadrons, photons, neutral hadrons)
    - reconstructed and identified by **particle-flow (PF) algorithm**, which uses all CMS detector subsystems, i.e., trackers, calorimeters, muon systems
  - Jets
    - defined as sets of particles clustered by jet-clustering algorithms, e.g., anti-k_T
    - 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.
  - MET (missing transverse momentum)
    - 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 pile-up events, detector mis-alignment

High luminosity, high pile-up events



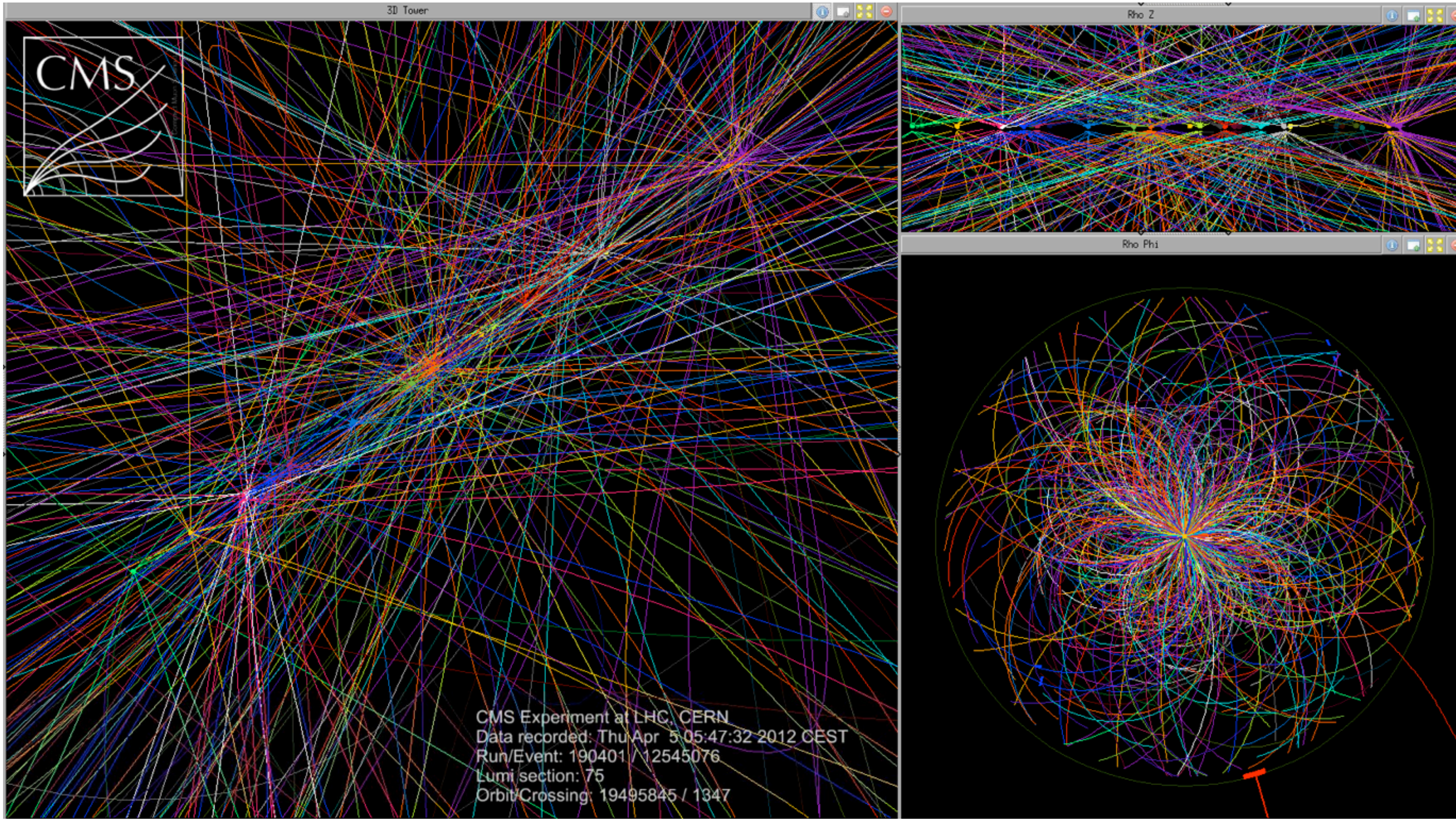


Inelastic proton-proton cross section at 8 TeV: ~70 mb
for example, if the luminosity is 7nb^{-1}/s,
490M(= 7nb^{-1} x 70 mb) interactions per second
20M times proton bunches cross each other per second (when bunch spacing is 50ns)
The average numbers of interaction per crossing (pile-up events) would be 24.5(=490/20)

note: nb^{-1}/s = 10^{33}cm^{-2}/s

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

Vertex reconstruction in high pile-up events



http://cms.web.cern.ch/news/new-world-record-first-pp-collisions-8-tev

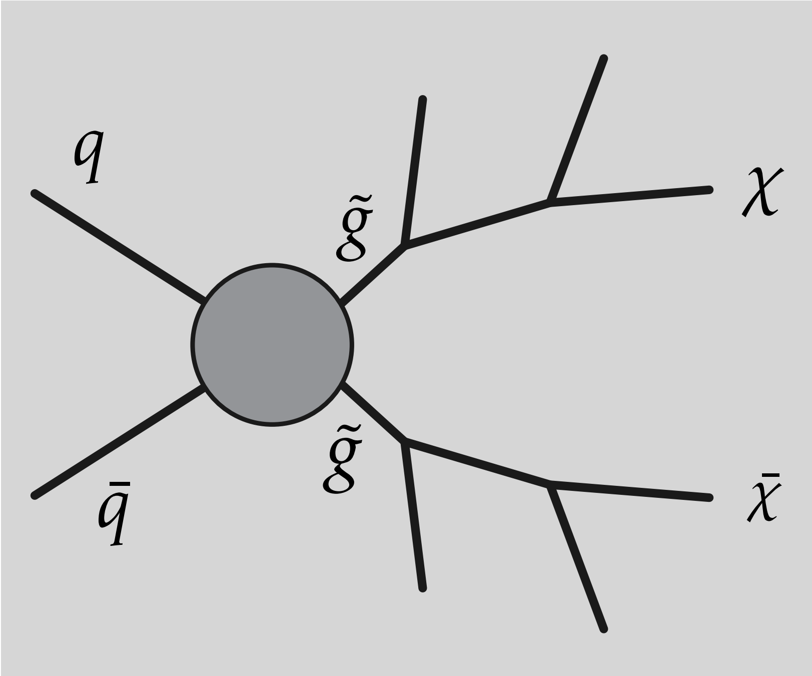
The image above is the CMS event display showing 29 vertices reconstructed, which correspond to 29 distinct proton-proton collisions in the same bunch crossing.

Charged particles produced in the interesting collision are easy to identify from the vertices

CMS develops various techniques to mitigate the effect of neutral particles produced in the pile-up events

Supersymmetry (SUSY) searches at CMS

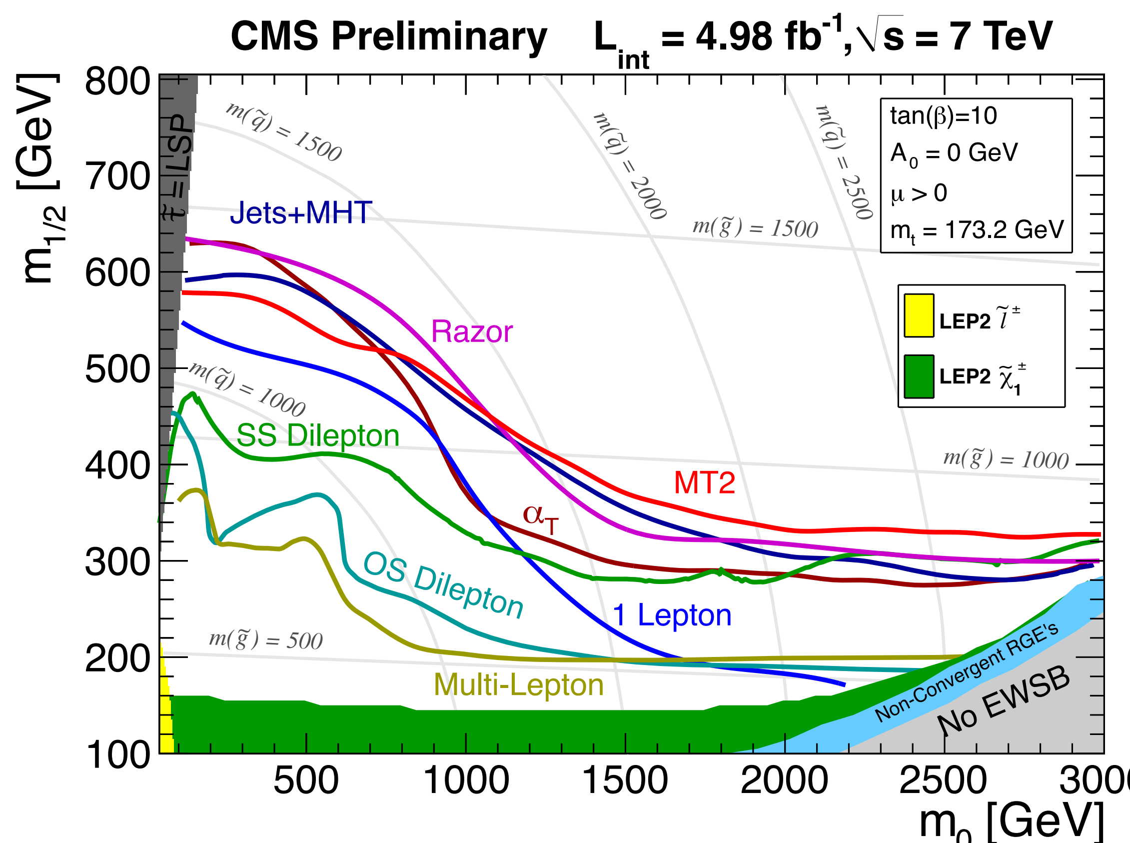
- SUSY
  - a hypothetical extension of space-time symmetry
  - solves several outstanding problems in particle physics
    - ➡ stabilizes radiative corrections to Higgs boson mass
    - ➡ unifies the three gauge couplings
    - ➡ provides a dark matter candidate
  - a broken symmetry as the exact symmetry contradicts the real world
  - has many parameters (>100), most of which are for its breaking mechanism
    - impractical to constrain by experimental data
  - further hypotheses can reduce the number of parameters, which could be explored at LHC
    - e.g., m_0 - $m_{1/2}$ plane in CMSSM



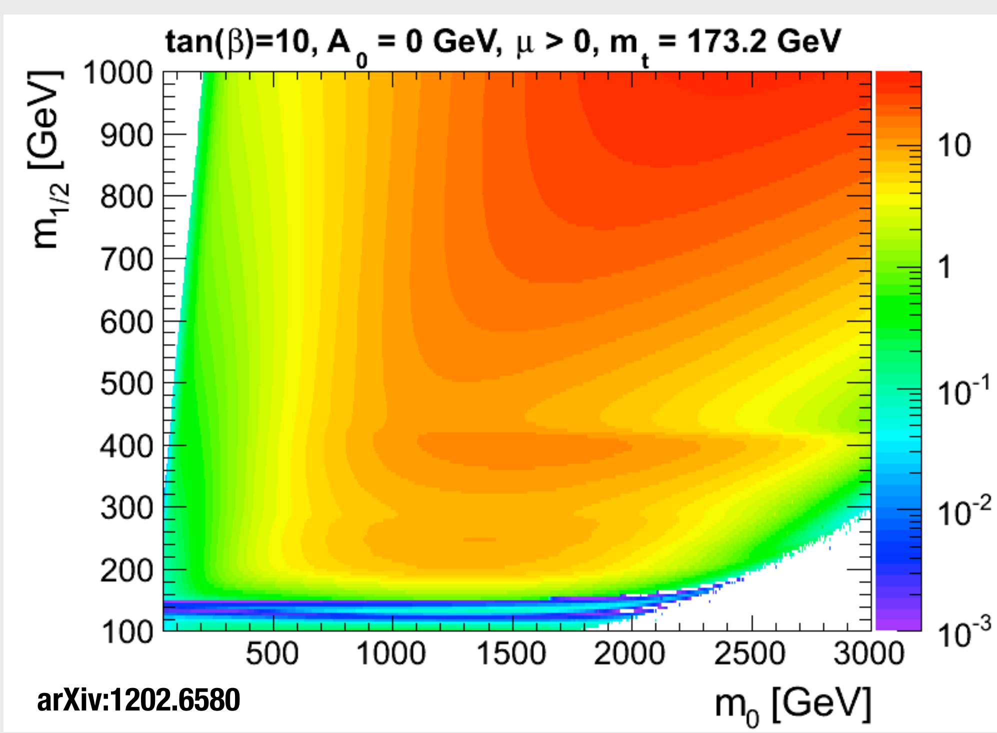
- SUSY searches at CMS
  - SUSY models predict that SUSY particles will be pair-produced at LHC and each of their decay chains will end with a LSP
    - the final states will contain large MET, jets, and possibly leptons and photons
  - CMS selects events with such final states. Some analyses use discriminating variables such as α_T, M_{T2}, *razor* variables
  - CMS evaluates if the rate of such events exceed the SM predictions
    - the SM predictions are estimated by data-driven methods, MC simulation
  - No such excess has been observed by now
  - The results have been interpreted in terms of CMSSM, other SUSY models, and Simplified Models (SMS)
    - exclusion limits have been placed on parameters of the models

CMS limits in CMSSM (Constrained MSSM)

- CMSSM is one of the popular SUSY models in interpreting the results of CMS SUSY analyses
- 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/PhysicsResultsSUS



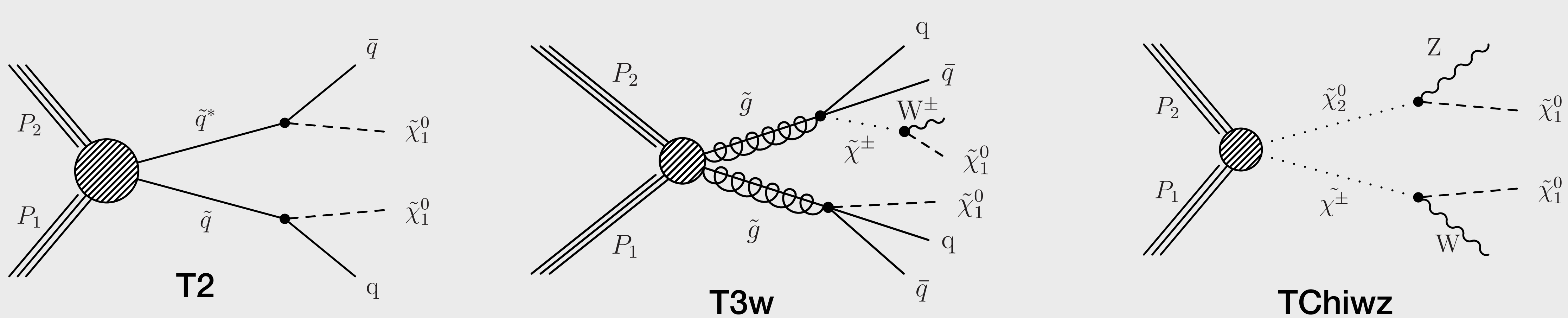
Dark matter relic density

- 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
  - $\Omega_{cdm}h^2 = 0.112 \pm 0.006$ [Phys. Rev. Derived**86**, 010001 (2012)]

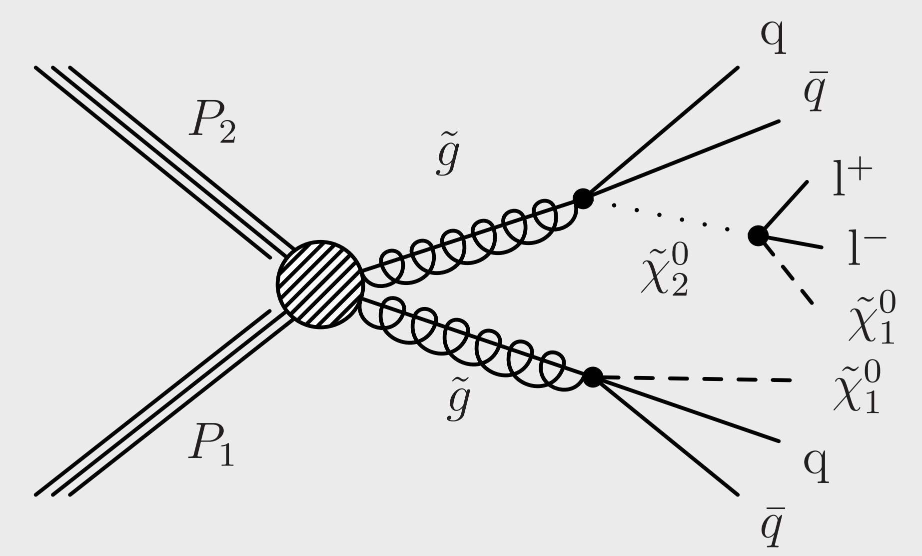
Interpretation of SUSY results in Simplified Model Spectra (SMS)

- 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*, *neutralinos*, *charginos*, *LSP* (neutral)
  - New particles are produced in pairs. Each decay chain ends with LSP
- SUSY analysis results are used to set upper limits on the product of the production cross section and branching fraction (σxBR) as a function of new particle masses
- SMS allows us to explore wider kinematic phase space of final states than 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

Example simplified models

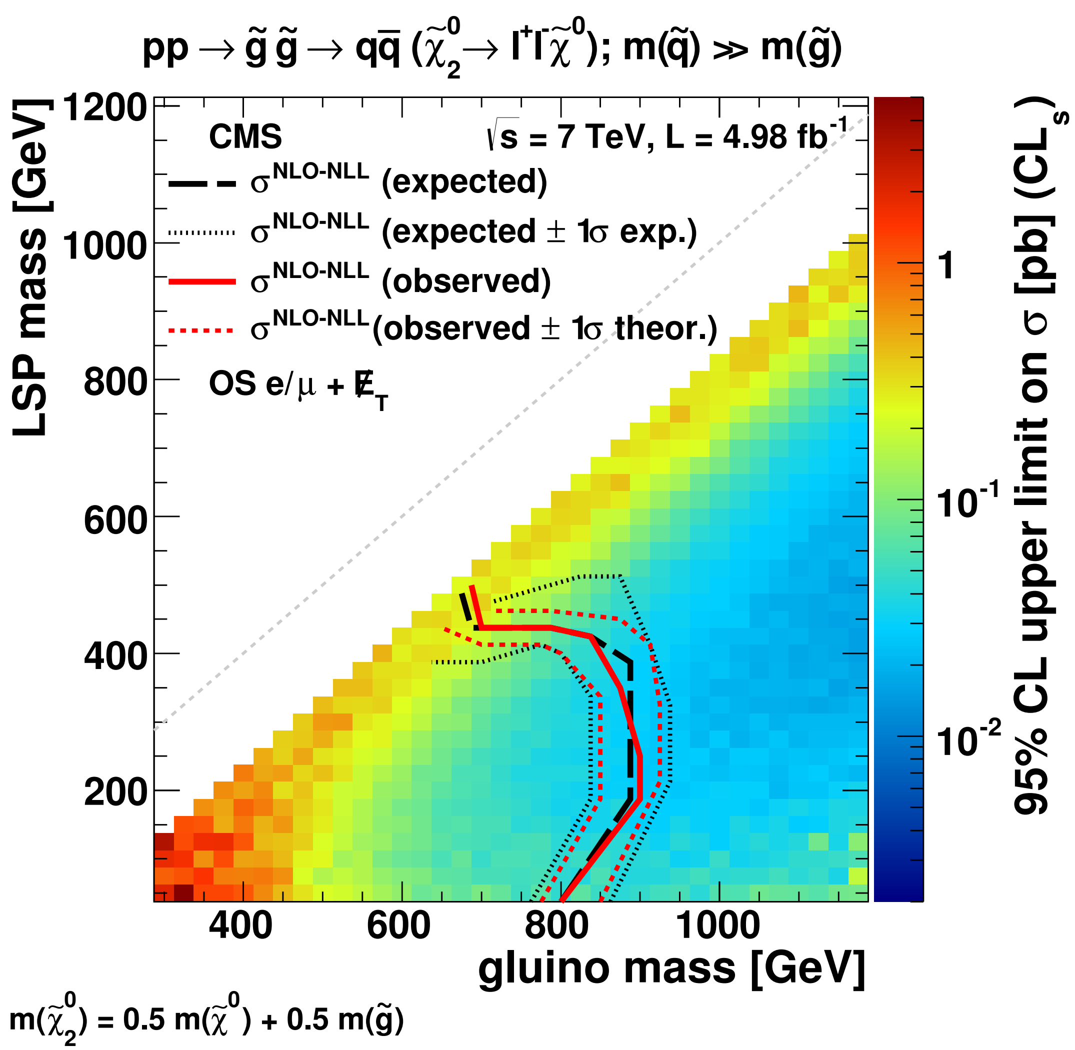


Interpretation of SUSY results in Simplified Model Spectra (SMS)



T3lh gluino pair-production with the final states containing large MET, jets and opposite-sign dileptons

- An interpretation of a CMS SUSY result [*Phys.Lett*. **B718** (2013) 815] in the SMS T3lh



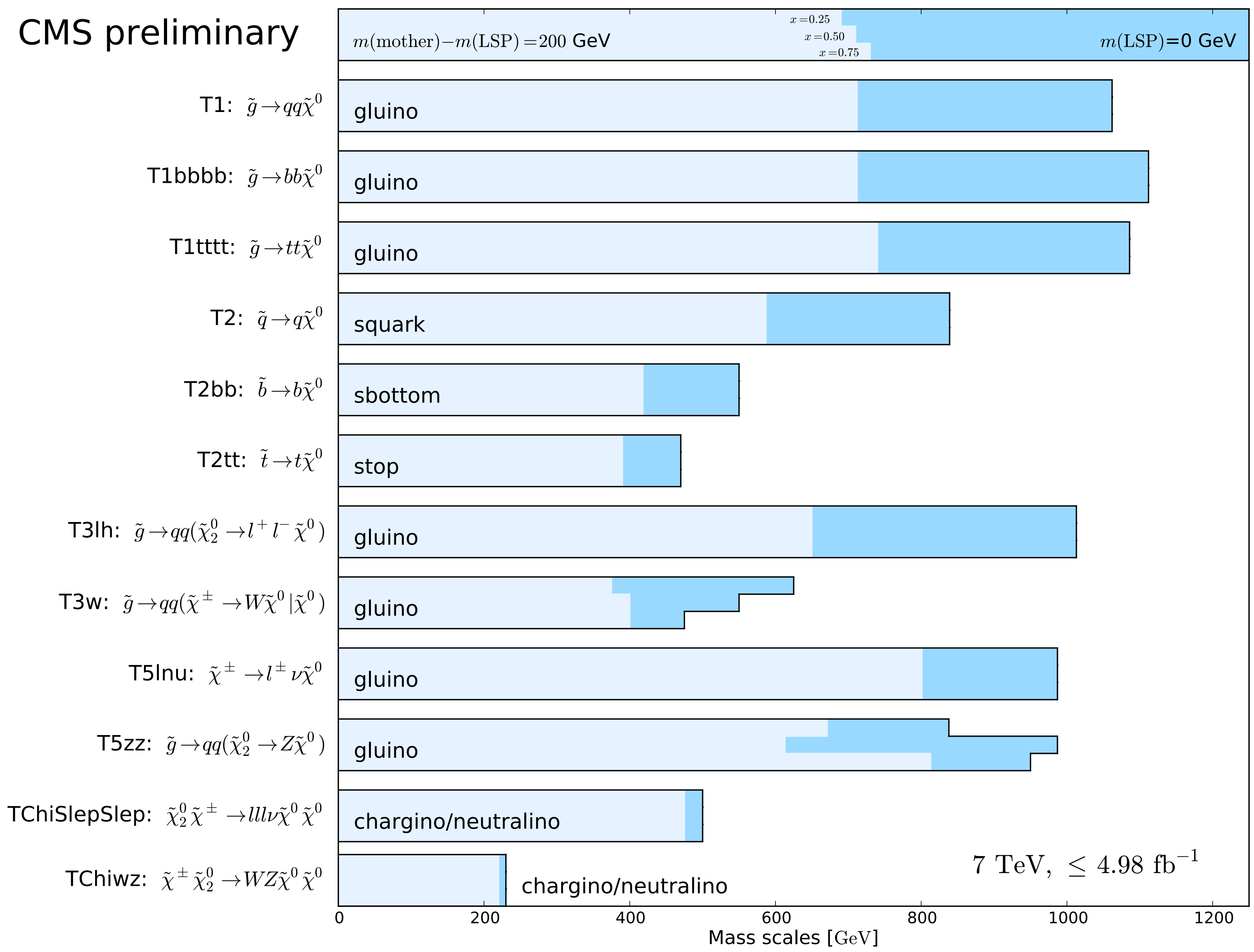
The color scale shows the upper limit on σ x BR (the product of the cross section and the branching fraction)

The lines show the contour at which the reference cross sections calculated in SUSY NLO+NLL intersect with the upper limit, indicating the lower mass limits in the reference theory

arXiv:1301.2175

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS11016

Interpretation of SUSY results in Simplified Model Spectra (SMS)

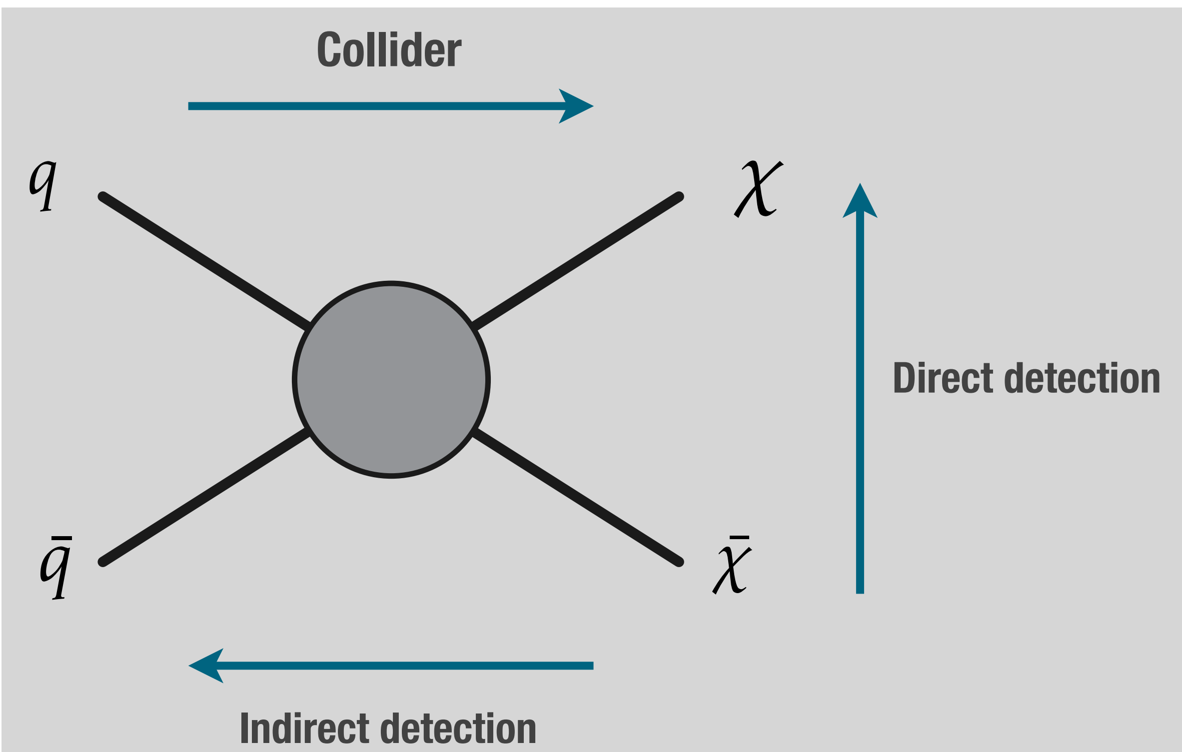


This bar chart summarizes exclusion limits of masses of the produced new particle in each SMS with the reference theory in the cases in which LSP is massless and in which LSP is 200 GeV lighter than the produced particle. For the SMSs with intermediate new particles, limits with up to three different assumptions of the intermediate particles are shown

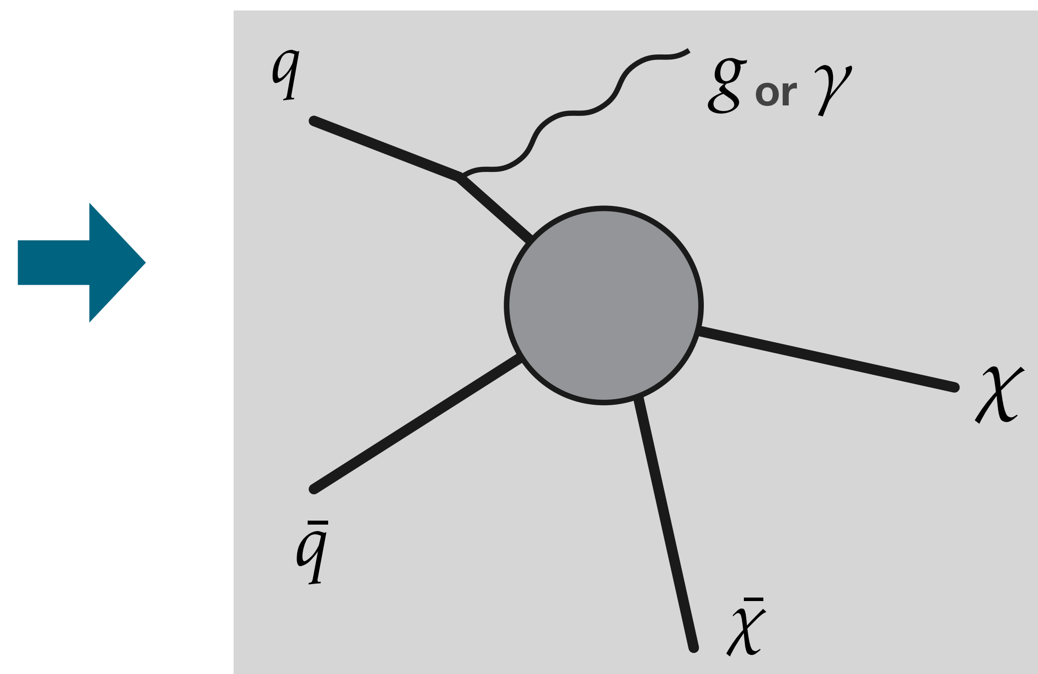
[**https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS11016**](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS11016)

Direct dark matter production and its signature at collider

Instead of being at the end of decay chains, dark matter particles could be directly produced in pairs



The DM pair-production event can be tagged if it occurs after ISR (initial-state radiation)



It will appear as monojet or mono-photon event

As the coupling between SM and DM can be evaluated, results can be compared with direct detection results

Dark matter searches in monojet and mono-photon events in CMS

- The event rates did not exceed the standard model and background expectation in the analysis of 5.0 fb^{-1} of data at $\sqrt{s}$=7 TeV

- **The dark matter-nucleon cross section limit:**
  - The following assumptions were made in the limit setting:
    - The mediator is heavy (an effective contact operator)
    - The dark matter particles are Dirac fermions
    - The interaction is vector or axial-vector interaction
  - The lower limits were set on the cutoff Λ
  - The upper limits were set on the dark matter-nucleon cross section
    - The vector interactions correspond the spin-independent interactions
    - The axial-vector interactions correspond the spin-dependent interactions
  - The limits were compared with the limits from the direct detection results

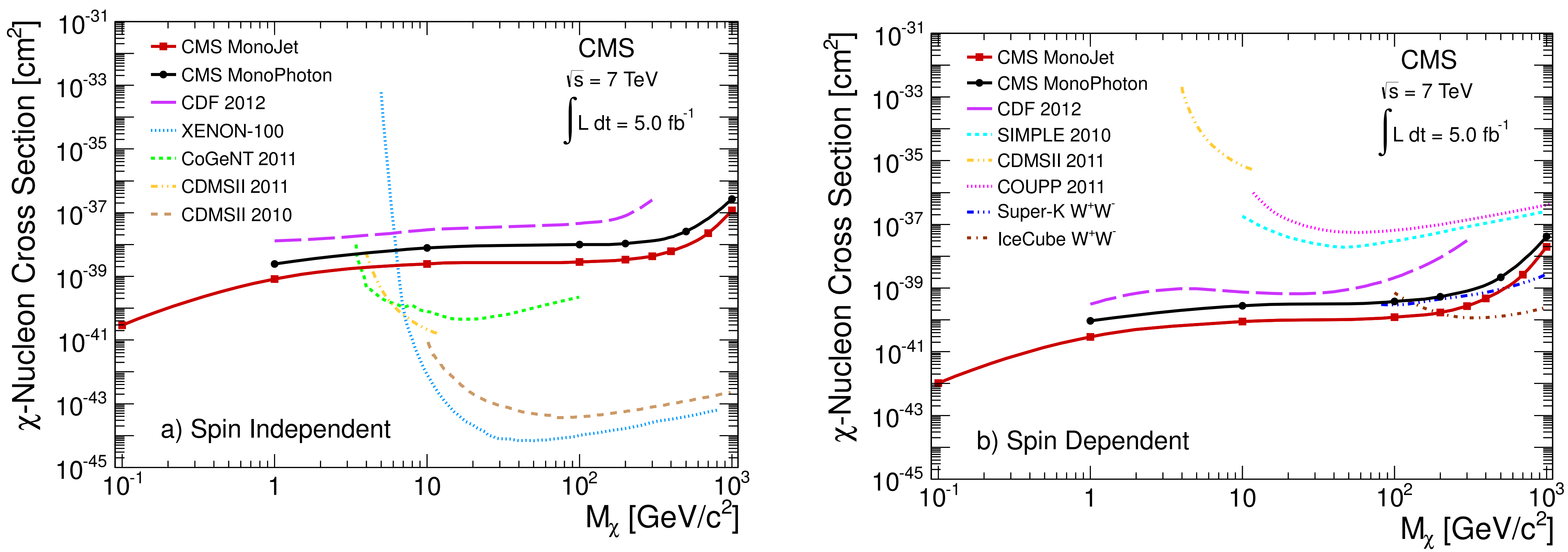
vector interaction

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

axial-vector interaction

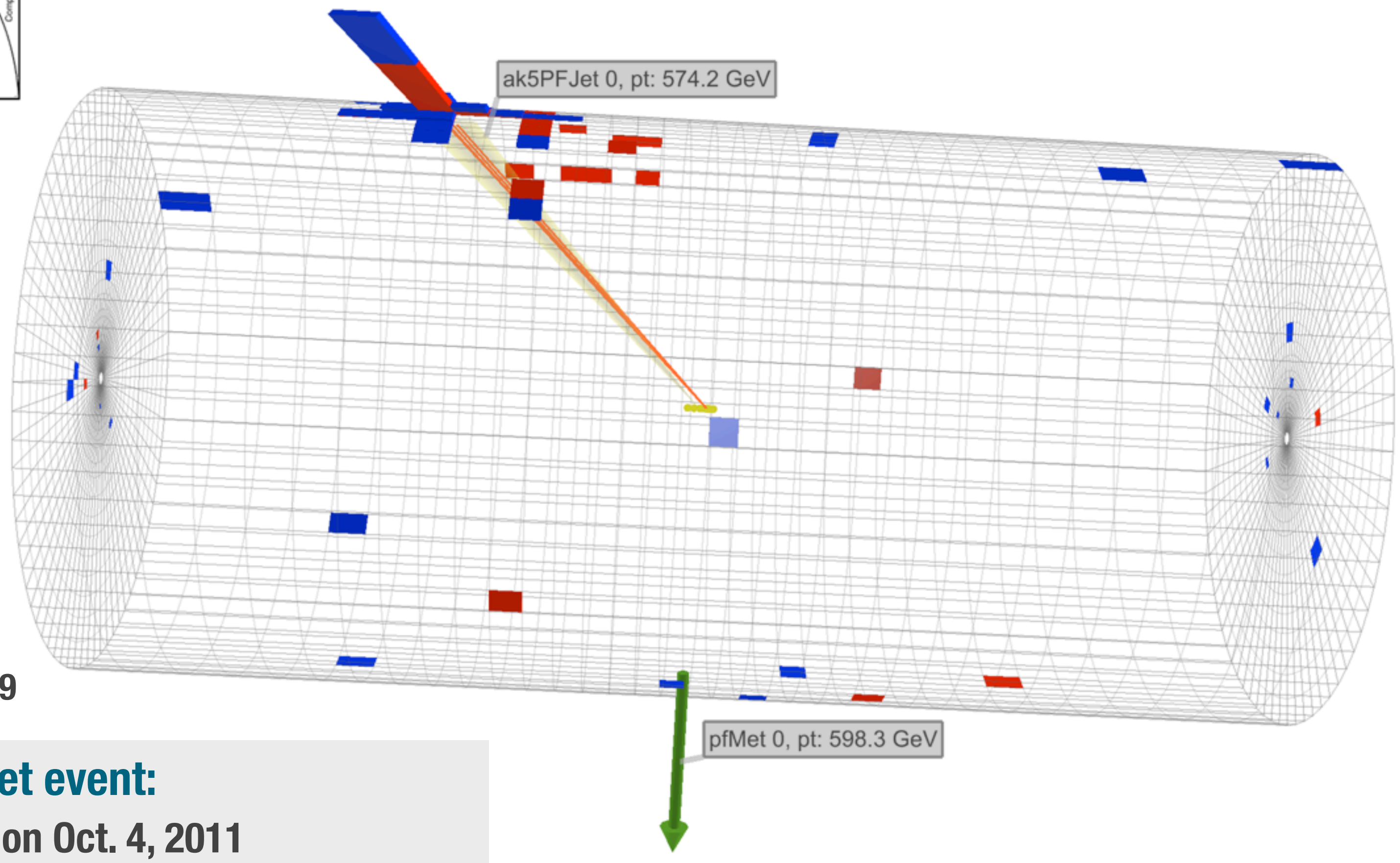
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

cutoff $\Lambda \equiv M/\sqrt{g_\chi g_q}$



EXO-11-059: monojet analysis

EXO-11-096: mono-photon analysis

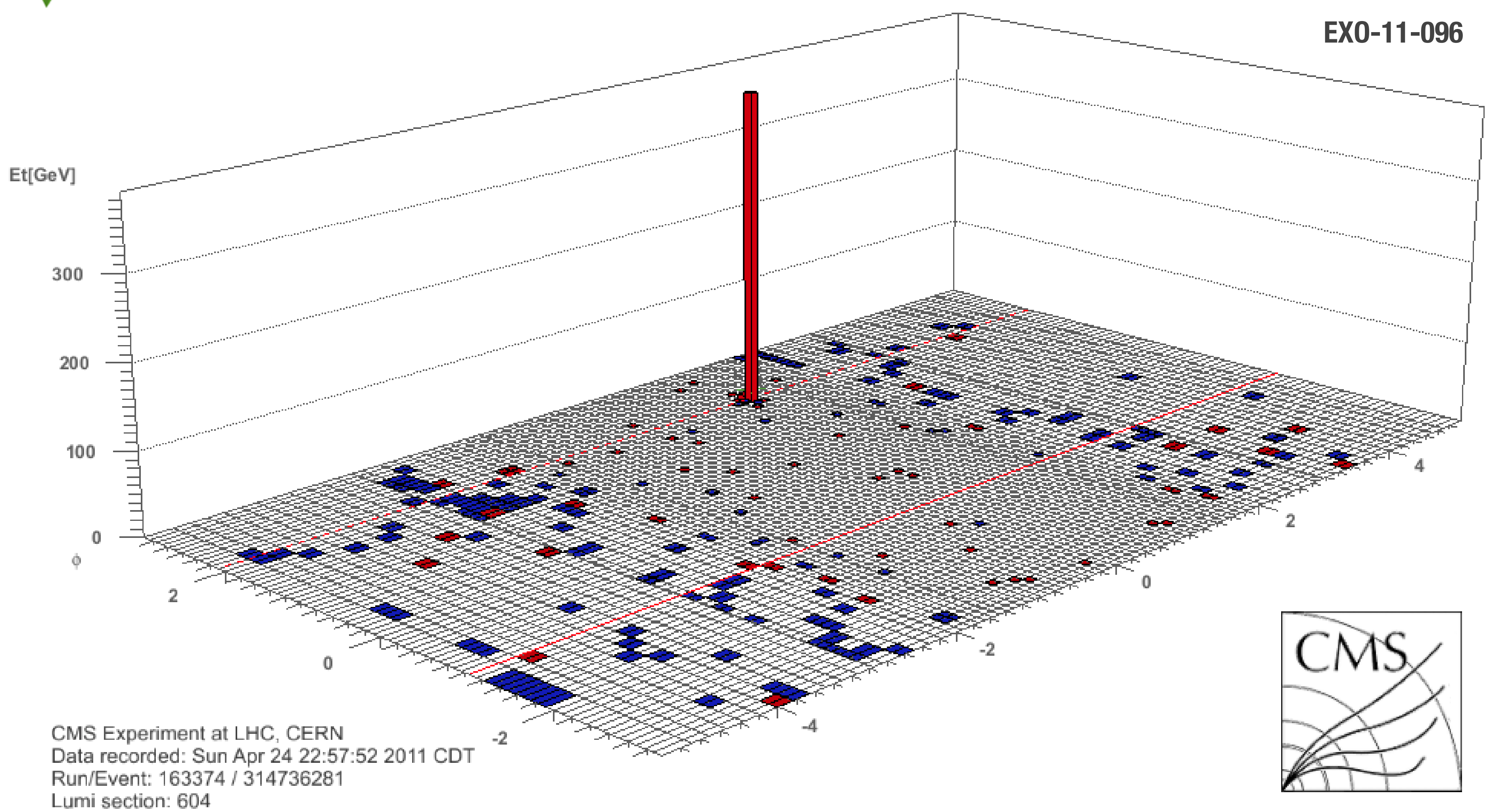


EXO-11-059

A monojet event:
recorded on Oct. 4, 2011
p_T(jet)=574.2 GeV, MET = 598.3 GeV

A mono-photon event:
recorded on Apr. 24, 2011
p_T(photon)=384 GeV, MET = 407 GeV

EXO-11-096



Summary

- This presentation showed the results of dark matter searches in up to $5 fb^{-1}$ of proton-proton collision data at $\sqrt{s}=7$ TeV collected with the CMS detector at LHC in 2011
- If dark matter particles are produced in the collision, they will be invisible to the CMS detector; their existence can be inferred by large MET
- The results of CMS SUSY searches were summarized as exclusion limits on a m_0-$m_{1/2}$ plane in CMSSM. The limits can be compared with calculated corresponding neutralino relic density on the plane and the cold dark matter density derived from cosmological observations
- CMS SUSY search results were interpreted in Simplified Models (SMSes), in which LSPs are dark matter candidates. In each SMS, upper limits were placed on the product of the production cross section and branching fraction. With the benchmark theory, lower limits were set on the mass of the produced new particles in the SMS.
- Direct productions of the pairs of dark matter particles can be tagged by the initial-state radiation (ISR). CMS monojet and mono-photon analyses searched for events with only the final state of ISR and large MET and placed upper limits on the dark matter-nucleon cross sections, which can be compared with direct detection results.
- We are currently analyzing $20 fb^{-1}$ of proton-proton collision data at $\sqrt{s}=8$TeV collected in 2012 and continuing the search

End