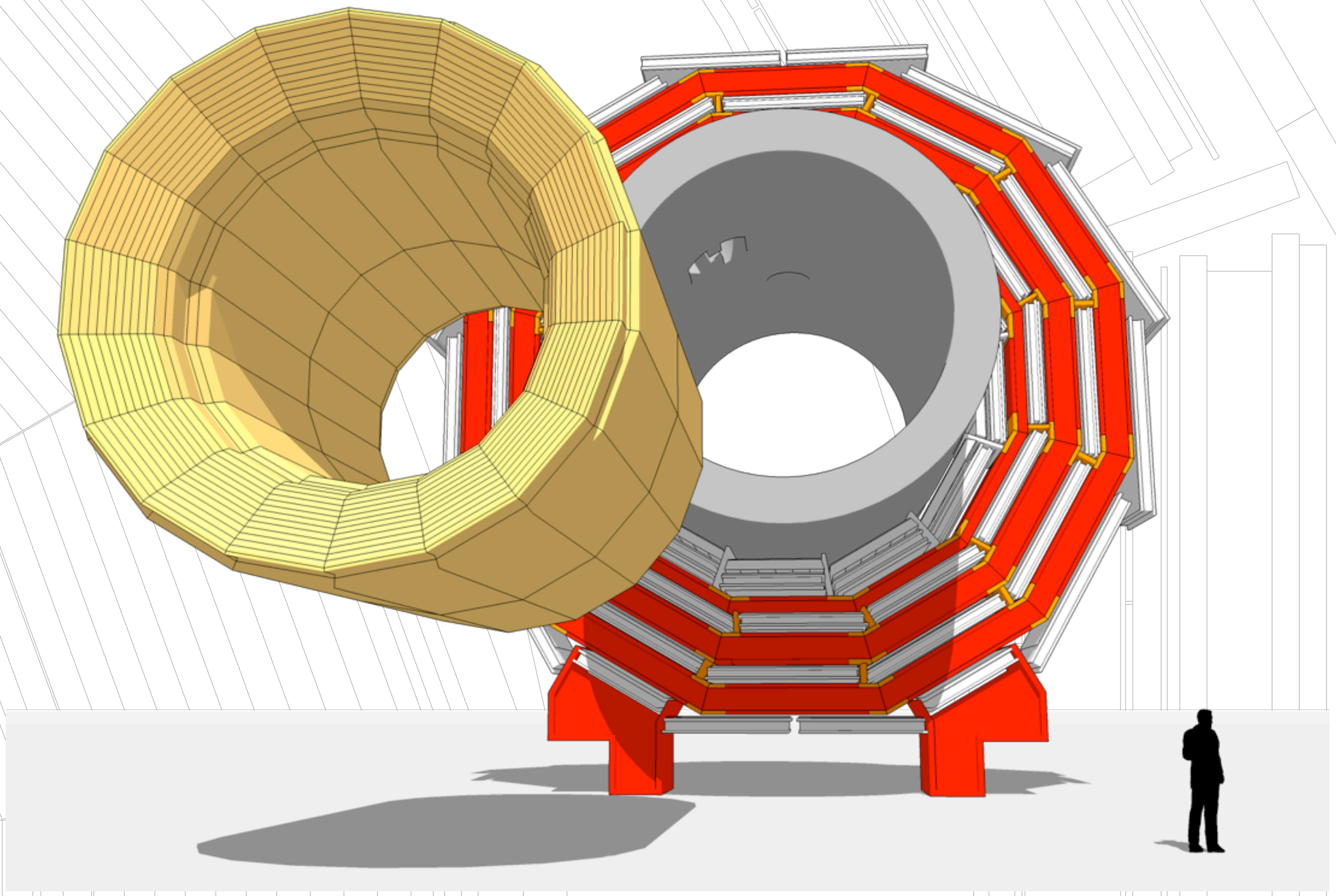
Dark Matter Searches in Monojet Events at CMS



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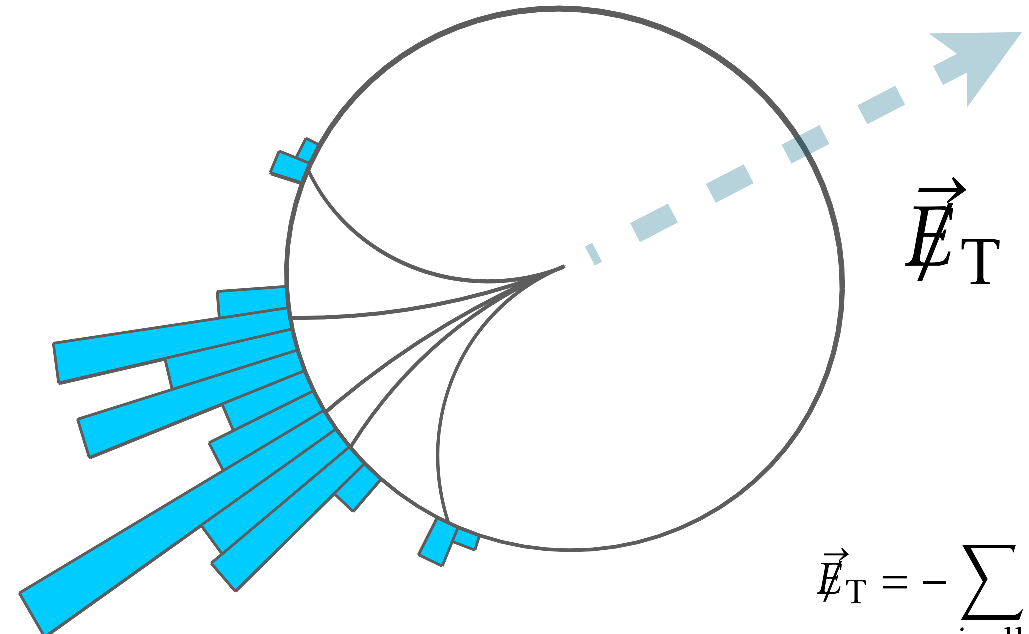
for the CMS collaboration

27 August 2013, SUSY 2013

http://susy2013.ictp.it

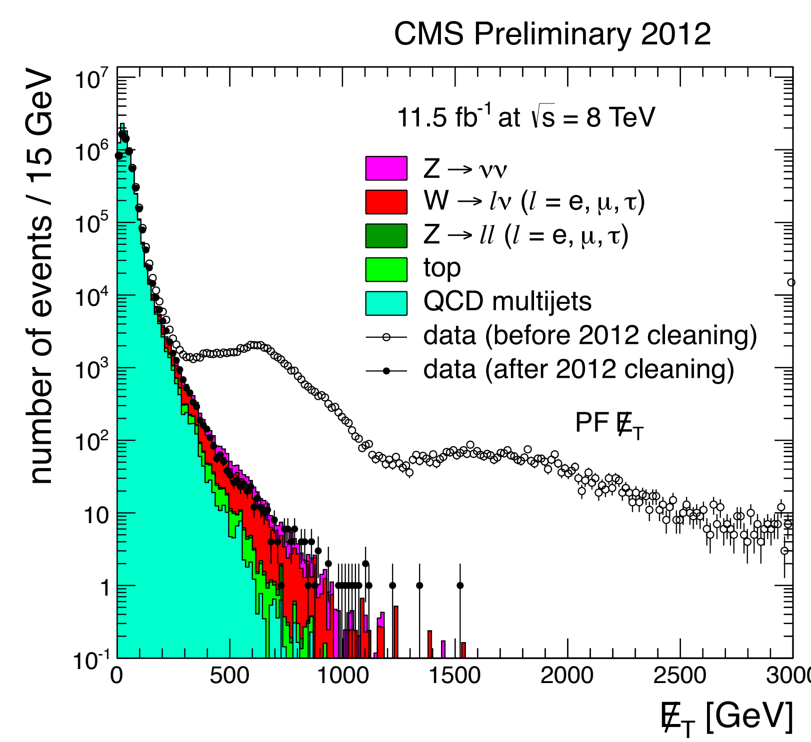
Dark Matter Particles and Missing Transverse Momentum (MET)

- **Dark Matter Particles**
  - can potentially be produced in high-energy proton-proton collisions at LHC
  - would not interact with an LHC detector material; invisible to the CMS detector
  - would leave ***missing transverse momentum (MET)***, the imbalance in the transverse momentum of all visible particles



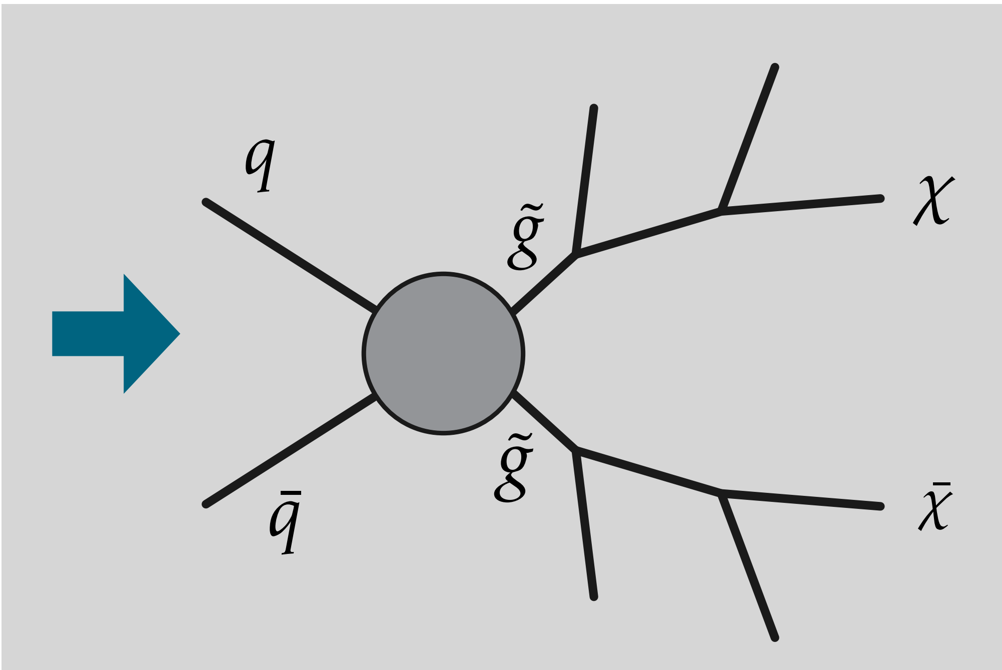
$$\vec{\not{E}}_{\mathrm{T}} = -\sum_{i \in \mathrm{all}} \vec{p}_{\mathrm{T}i}$$

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



CMS-PAS-JME-12-002

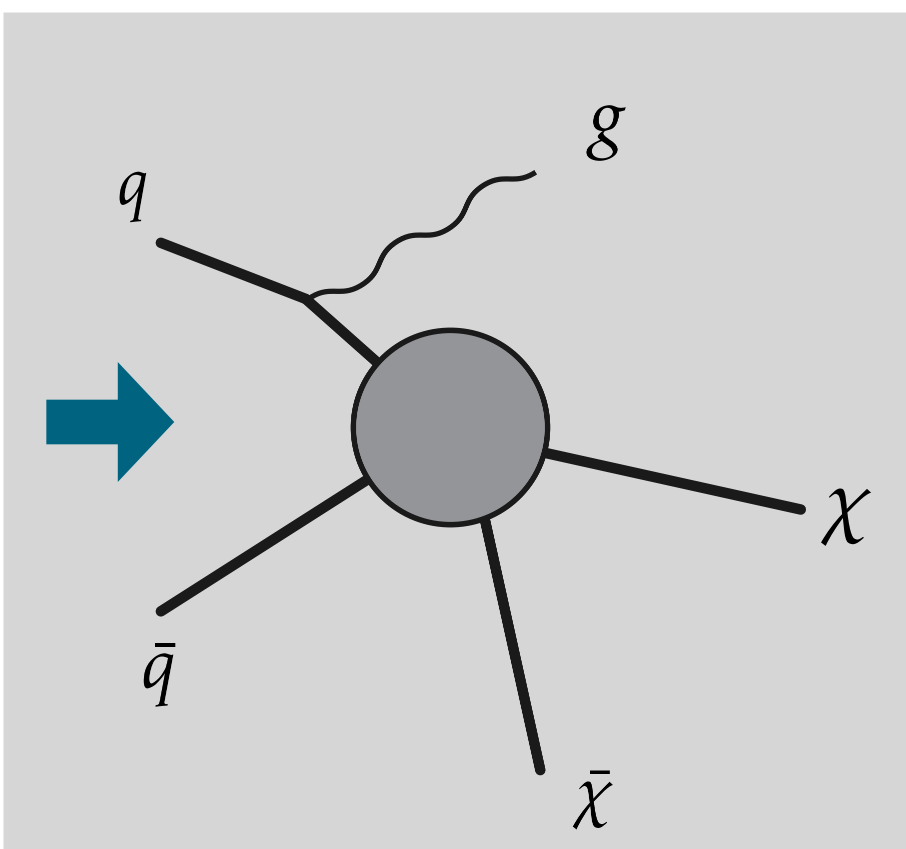
Possible dark matter particle pair-production and its signature at LHC



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)

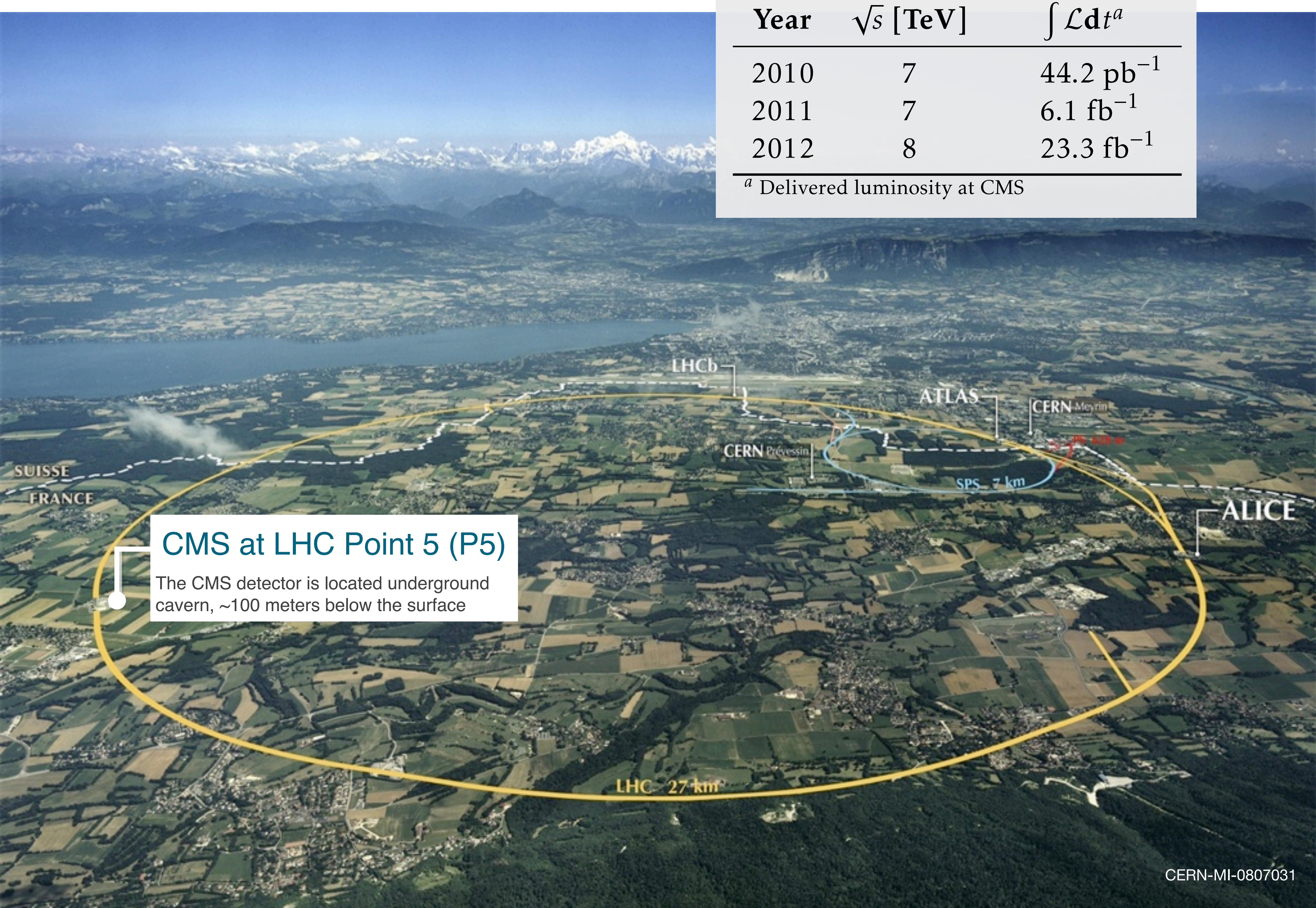
Signature: large MET + mono-jet

Large Hadron Collider (LHC)

Proton-proton runs in the last 3 years

Year	$\sqrt{s}$ [TeV]	$\int \mathcal{L} dt$[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 at LHC Point 5 (P5)

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

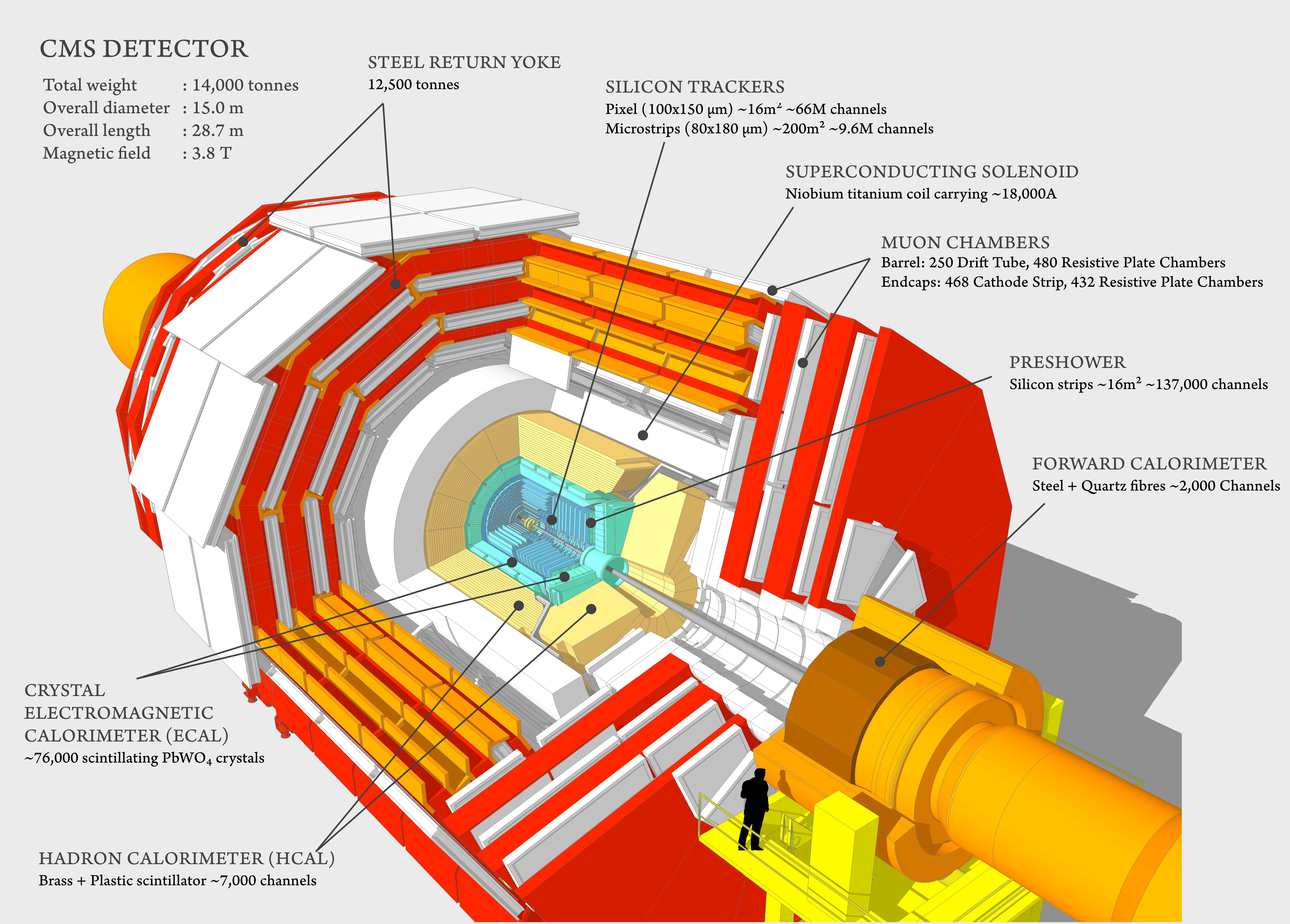
CMS Collaboration

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

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

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

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

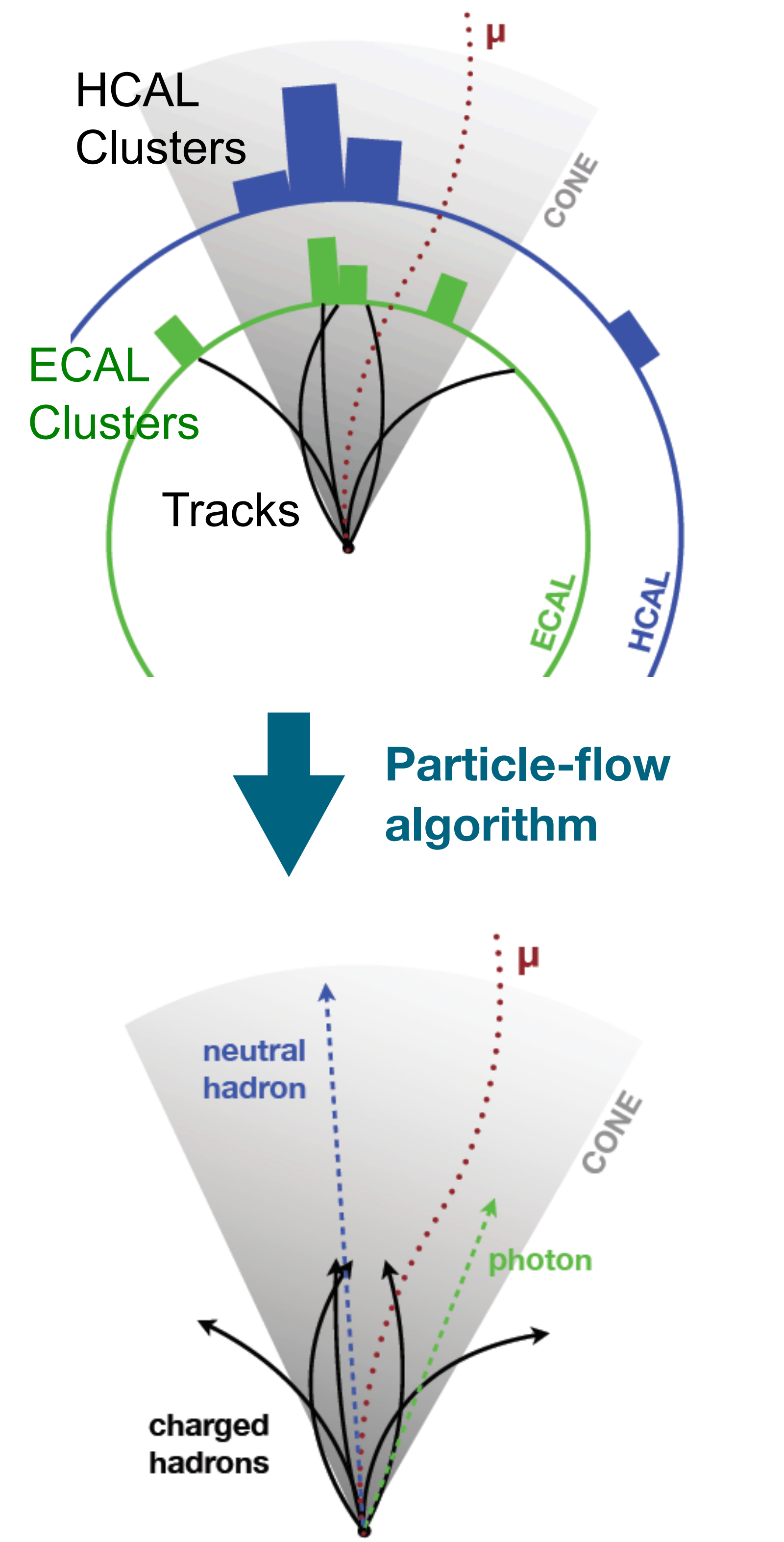


JINST 3 (2008) S08004 CMS Document 11514-v1

Online Event Selection and Offline Event Reconstruction at CMS

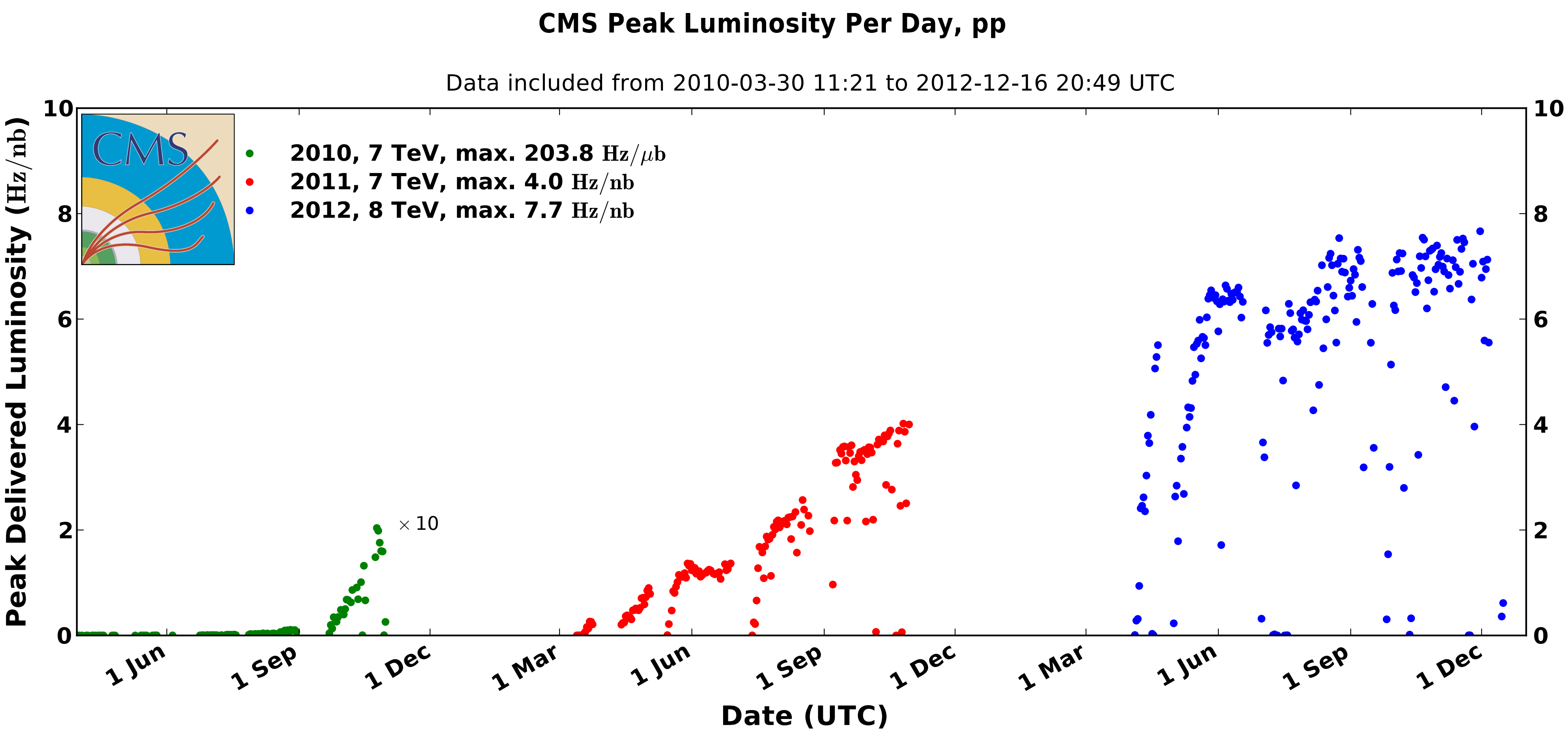
Online Event Selection

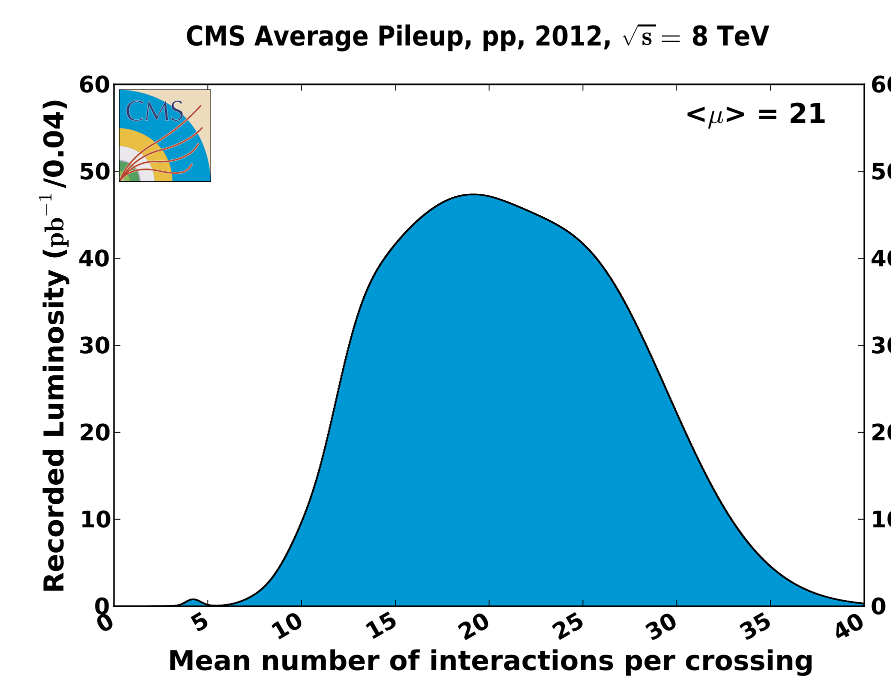
- LHC makes bunches of protons (10^{11} protons in each bunch) cross each other at CMS at 20~40 MHz
- L1 Trigger (**custom hardware processors, underground P5**)
  - selects interesting events based on signals from muon systems and calorimeters, reducing the event rate to 100 kHZ
- HLT, High-Level Trigger (**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



- 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



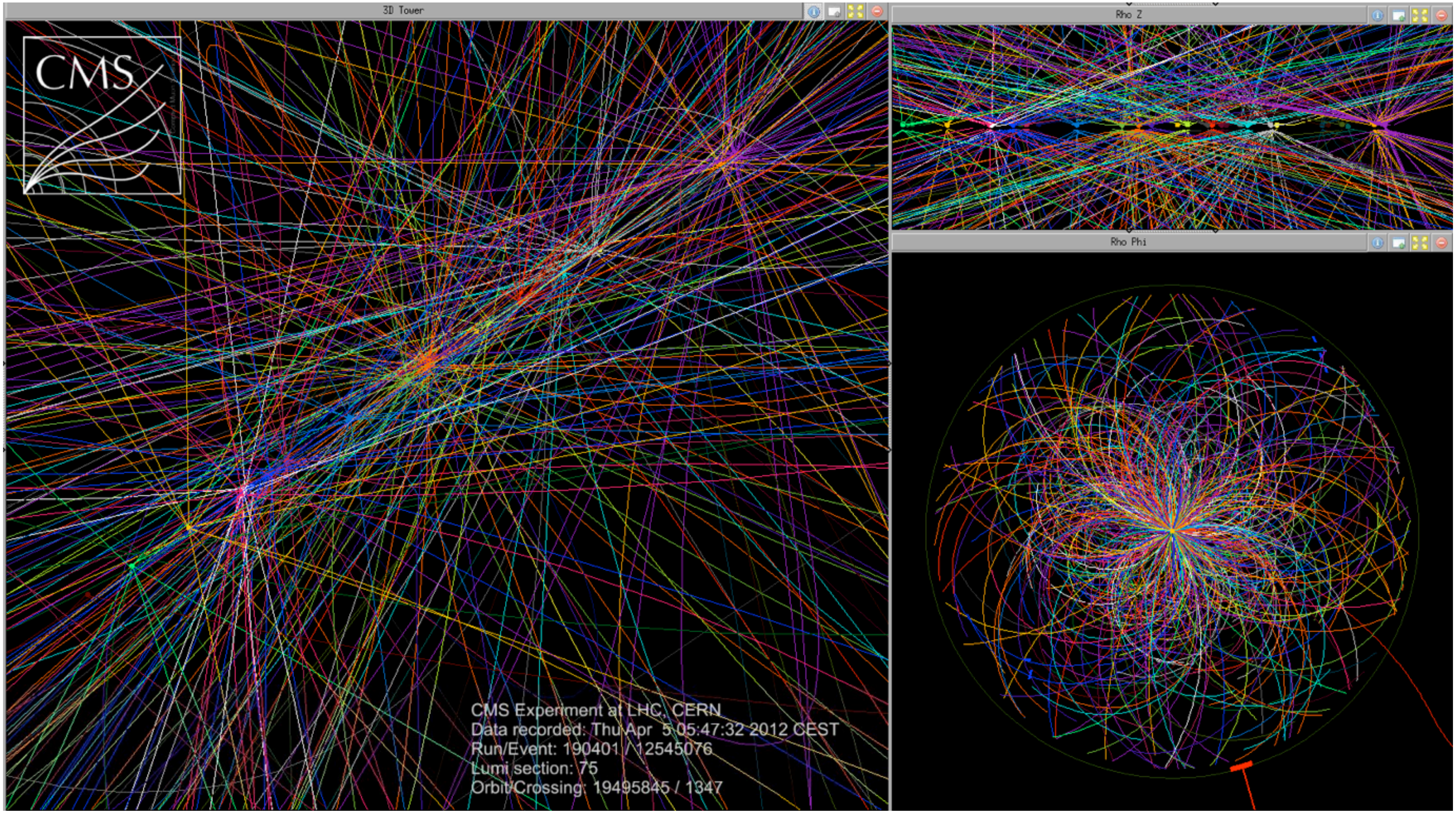


Inelastic proton-proton cross section at 8 TeV: ~70 mb
for example, if the luminosity is 7nb^{-1}/s,
490M(= 7nb^{-1} x 70 mb) interactions per second
20M times proton bunches cross each other per second (when bunch spacing is 50ns)
The average numbers of interaction per crossing (pile-up events) would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



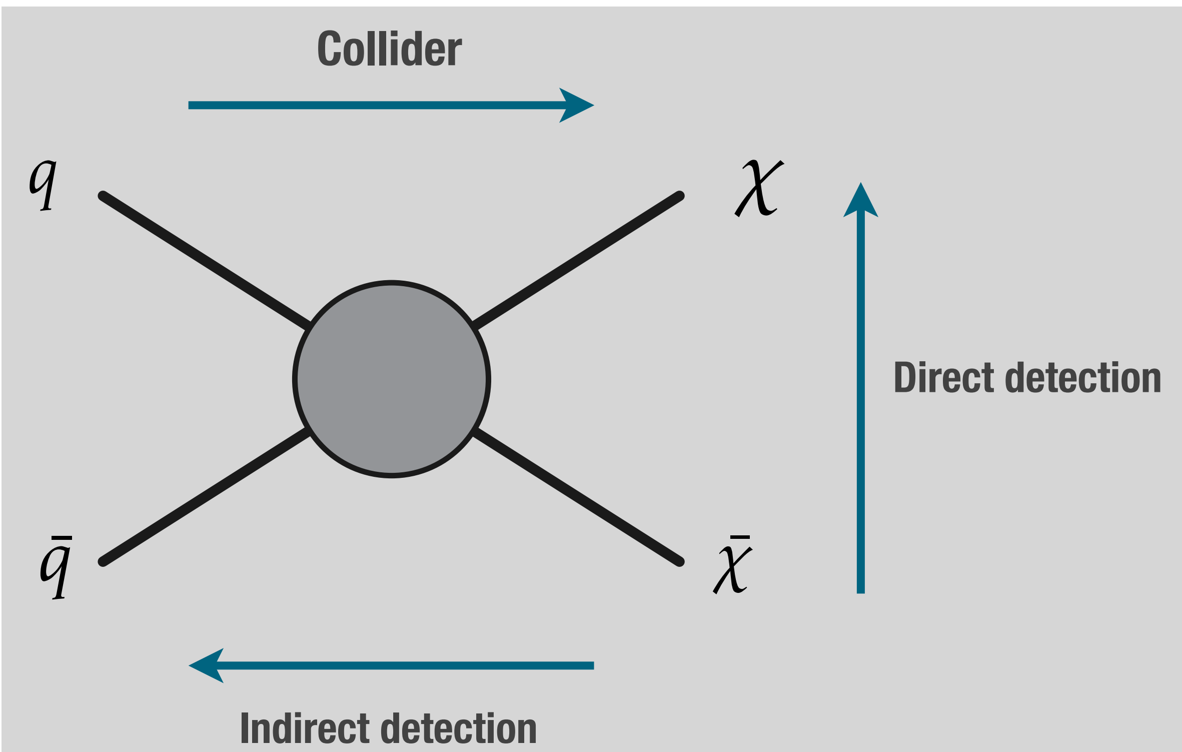
http://cms.web.cern.ch/news/new-world-record-first-pp-collisions-8-tev

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.

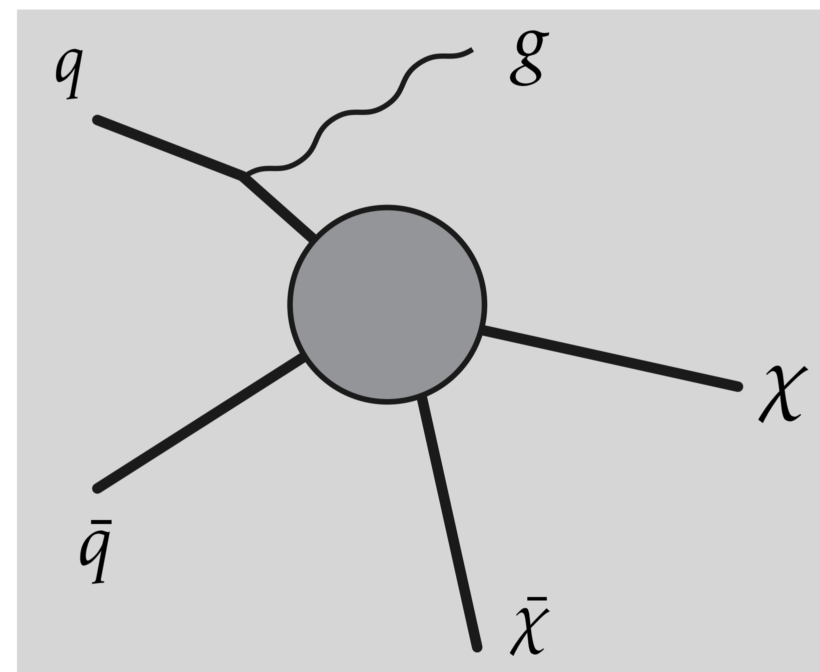
Charged particles produced in the interesting collision are easy to identify from the vertices

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

Direct dark matter production and its signature at collider



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



It will appear as monojet event

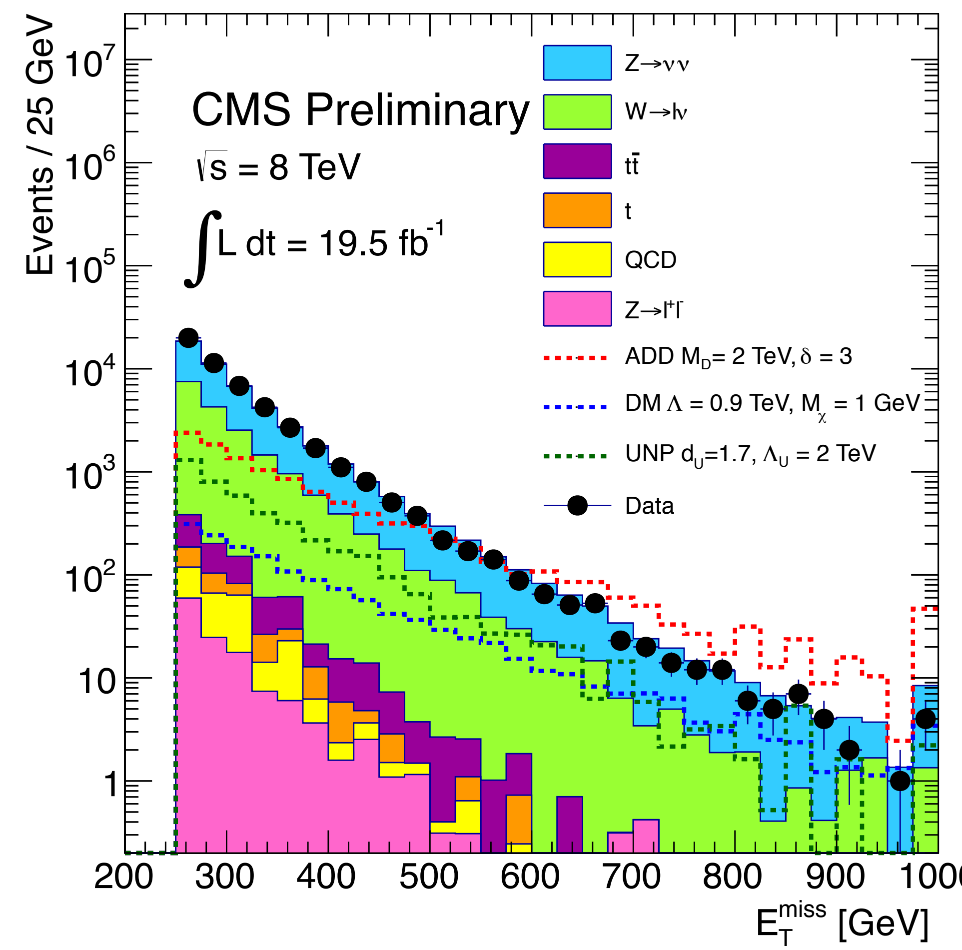
As the coupling between SM and DM can be evaluated, results can be compared with direct detection results

CMS Monojet analysis digest

- **Dataset:** 19.5 fb^{-1} of pp collisions at $\sqrt{s}$=8 TeV collected in 2012
- **Event selection**
  - **Online:** unprescaled jet + MET trigger, fully efficient for p_T(jet) > 110 GeV, MET > 200 GeV
  - **Offline**
    - at least one jet with p_T > 110 GeV in $|\eta|$ < 2.4
    - no more than two jets with pT > 30 GeV in $|\eta|$ < 4.5 (two jets are allowed provided they are not back-to-back, $\Delta\phi$(jet1, jet2) < 2.5)
    - no isolated charged lepton with p_T > 10 ~ 20 GeV
    - MET > 250, 300, 350, 400, 450, 500, 550 GeV
- **Estimates of Standard Model contributions**
  - Z(νν) + jets: the largest contributions. the Z boson and jets events where Z decays to neutrinos. estimated from the rate of Z(μμ) + jets
  - second largest contribution from W + jets. small contributions from top pair, Z(ll) + jets, single top, QCD
- **Upper limit on new physics contributions**
  - σ^{CLs}: upper limit on production cross sections of new physics by CLs. generic limit and limit on models of dark matter, extra dimensions, unparticles

CMS-PAS-EXO-12-048

CMSPublic.PhysicsResultsEXO12048



MET distribution of the selected events

MET (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Z(νν) + jets	30,600 ± 1,493	12,119 ± 640	5,286 ± 323	2,569 ± 188	1,394 ± 127	671 ± 81	370 ± 58
W + jets	17,625 ± 681	6,042 ± 236	2,457 ± 102	1,044 ± 51	516 ± 31	269 ± 20	128 ± 13
⋮							
Total SM	49,154 ± 1,663	18,506 ± 690	7,875 ± 341	3,663 ± 196	1,931 ± 131	949 ± 83	501 ± 59
Data	50,419	19,108	8,056	3,677	1,772	894	508

of the selected events and the estimates of the SM contributions for 7 different lower MET cuts

Collider dark matter searches to direct detection searches

conversion of the dark matter production cross section in pp collision to the dark matter-nucleon cross section

This slide considers the case where DM is a Dirac fermion and the interaction to quarks is mediated by a very heavy boson. So DM-quark interaction here is a four-fermion contact interaction, similar to the one in Fermi's weak interaction.

$$\boxed{\sigma_{\chi\chi}^{\mathrm{CLs}}}$$

1. We set the upper limit on $\sigma_{\chi\chi}$, the DM production cross section in proton-proton collisions

2. We convert it to the lower limit on Λ

$$\boxed{\Lambda_{\mathrm{CLs}}^4 = M^4 \frac{\sigma_{\chi\chi}^{\mathrm{MG}}}{\sigma_{\chi\chi}^{\mathrm{CLs}}}}$$

σ^{MG} is the cross section in MadGraph

$g_\chi g_q = 1$ in MadGraph

Λ is a cutoff appeared in the vector interaction

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

χ: the DM spinor field
q: the quark spinor field

Λ can be written as

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

M: the mediator mass (very large)
g_χ, g_q: the couplings

Λ is related to DM production cross section as

$$\sigma_{\chi\chi} \sim \frac{1}{\Lambda^4}$$

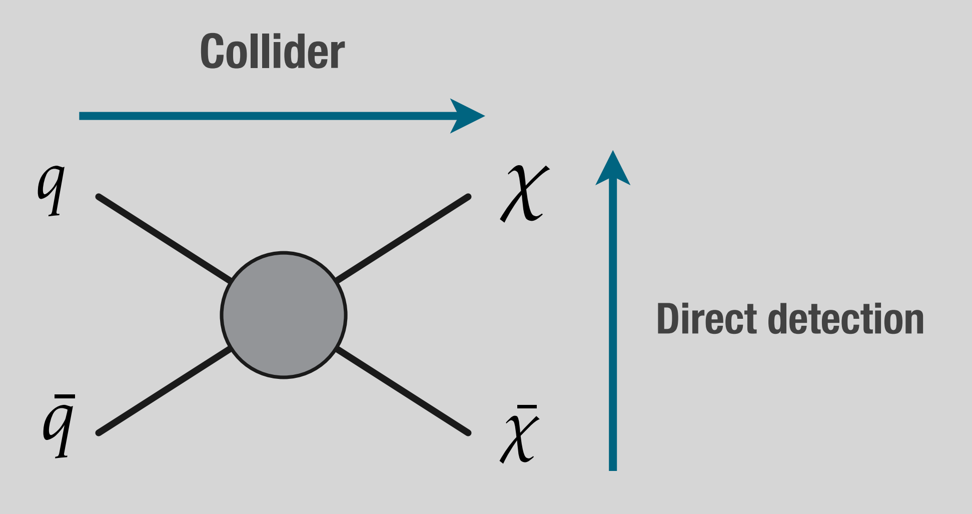
3. Then the upper limit on the spin independent DM-nucleon cross section is

$$\boxed{\sigma_{SI}^{\mathrm{CLs}} = 9\frac{\mu^2}{\pi\Lambda_{\mathrm{CLs}}^4}}$$

μ is a reduced mass

$$\mu = \frac{m_\chi m_\mathrm{p}}{m_\chi + m_\mathrm{p}}$$

ref: JHEP12(2010)048



Dark matter searches in monojet events in CMS

- **The dark matter-nucleon cross section limit:**
  - The following assumptions are 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 limits are compared with the limits from the direct detection results

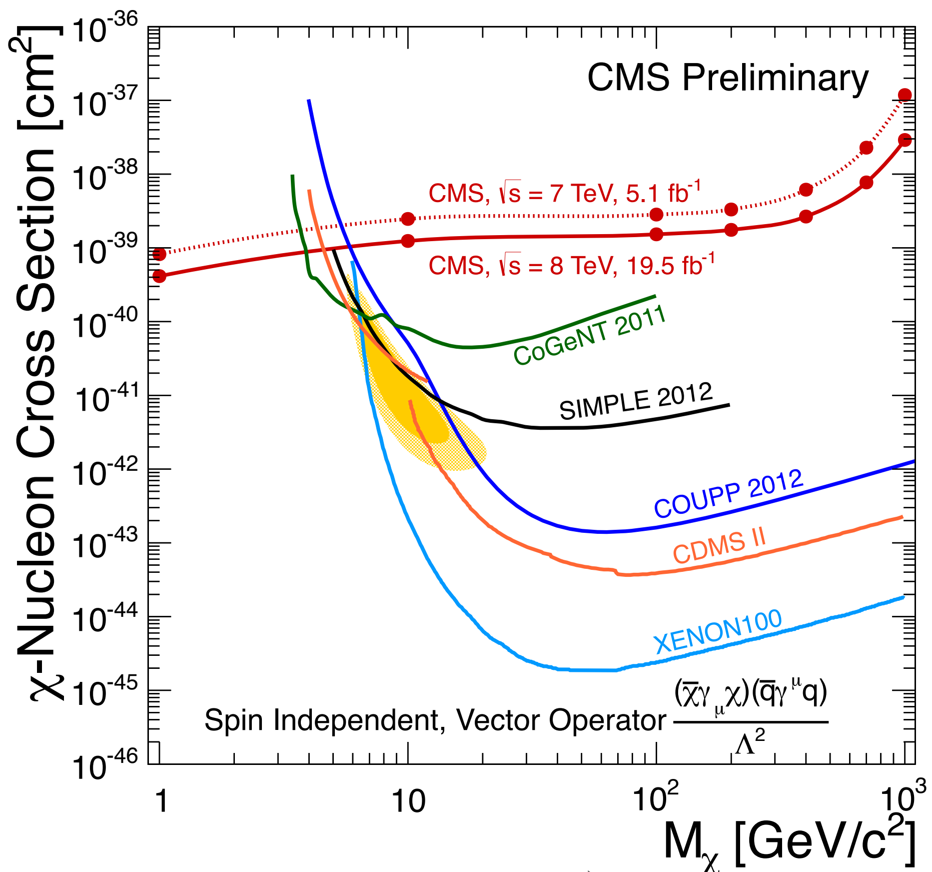
vector interaction

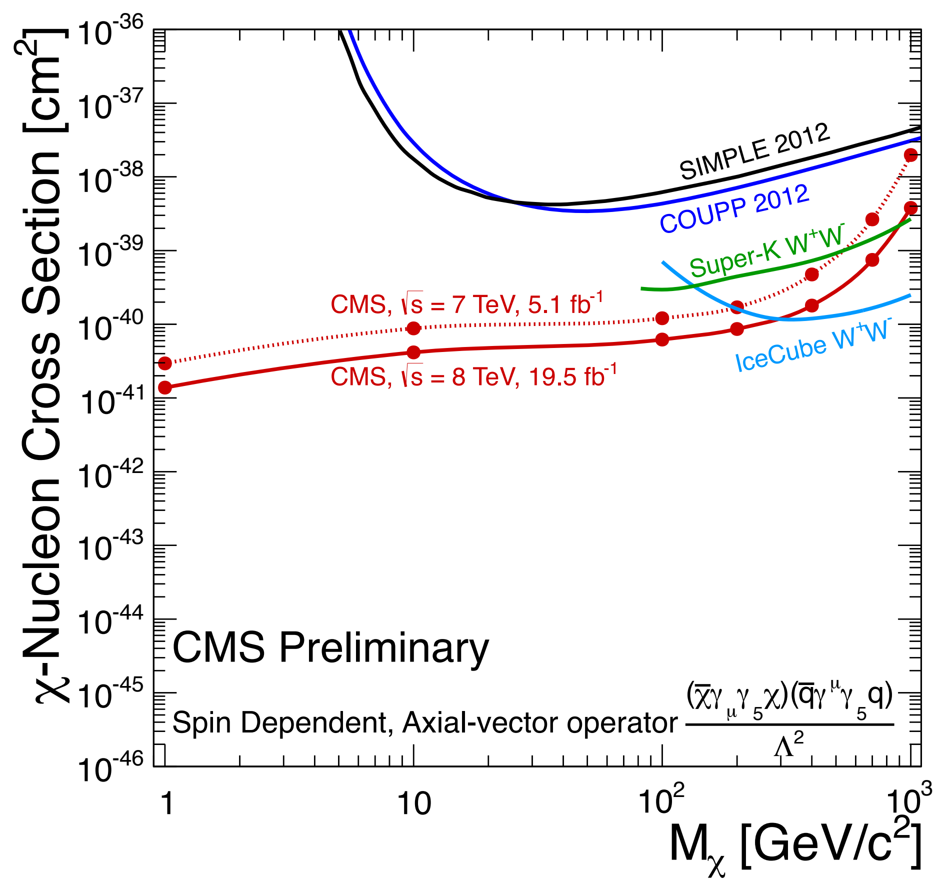
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

axial-vector interaction

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

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





The yellow region shows 60% and 90% C.L. contours for a possible signal from CDMS II (arXiv:1304.4279)

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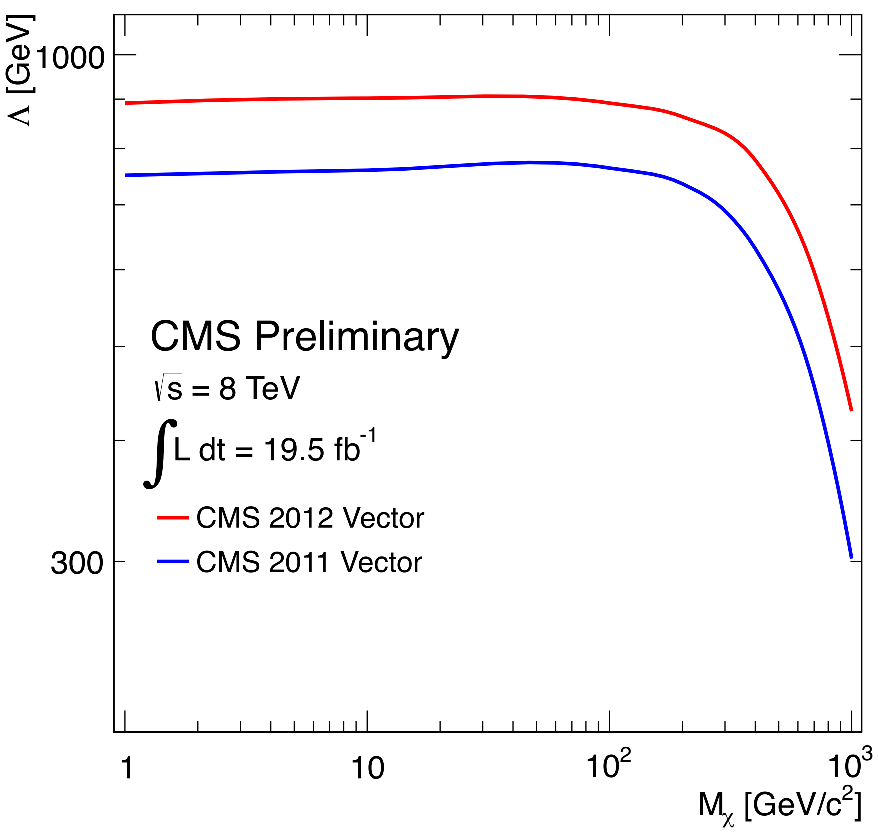
CMSPublic.PhysicsResultsEXO12048

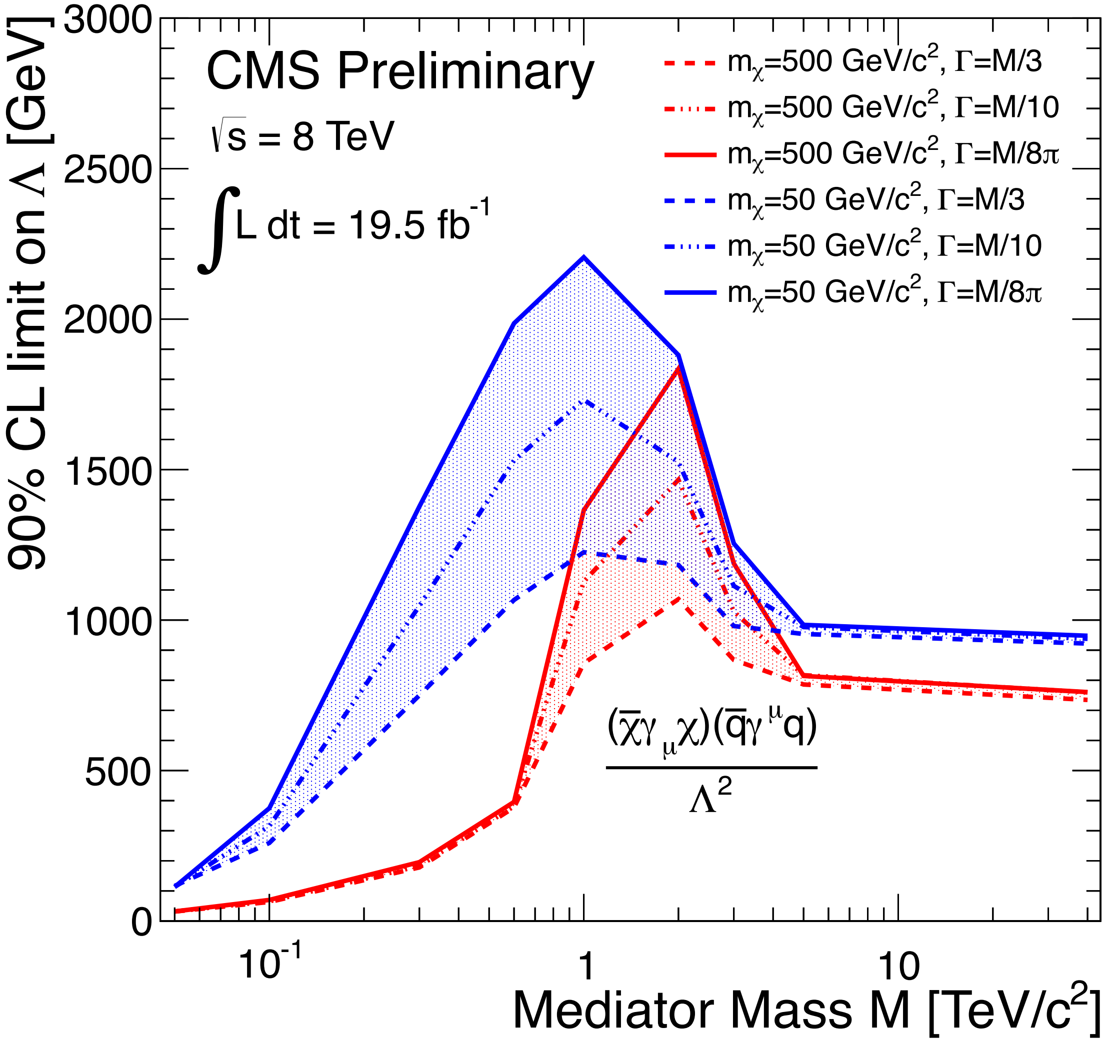
Dark matter searches in monojet events in CMS

Limits on Λ

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



Limits on Λ as functions of dark matter particle mass when the mediator is heavy



Limits on Λ as functions of the mediator mass when the mediator is light for two different dark mater particle masses each for three different mediator widths

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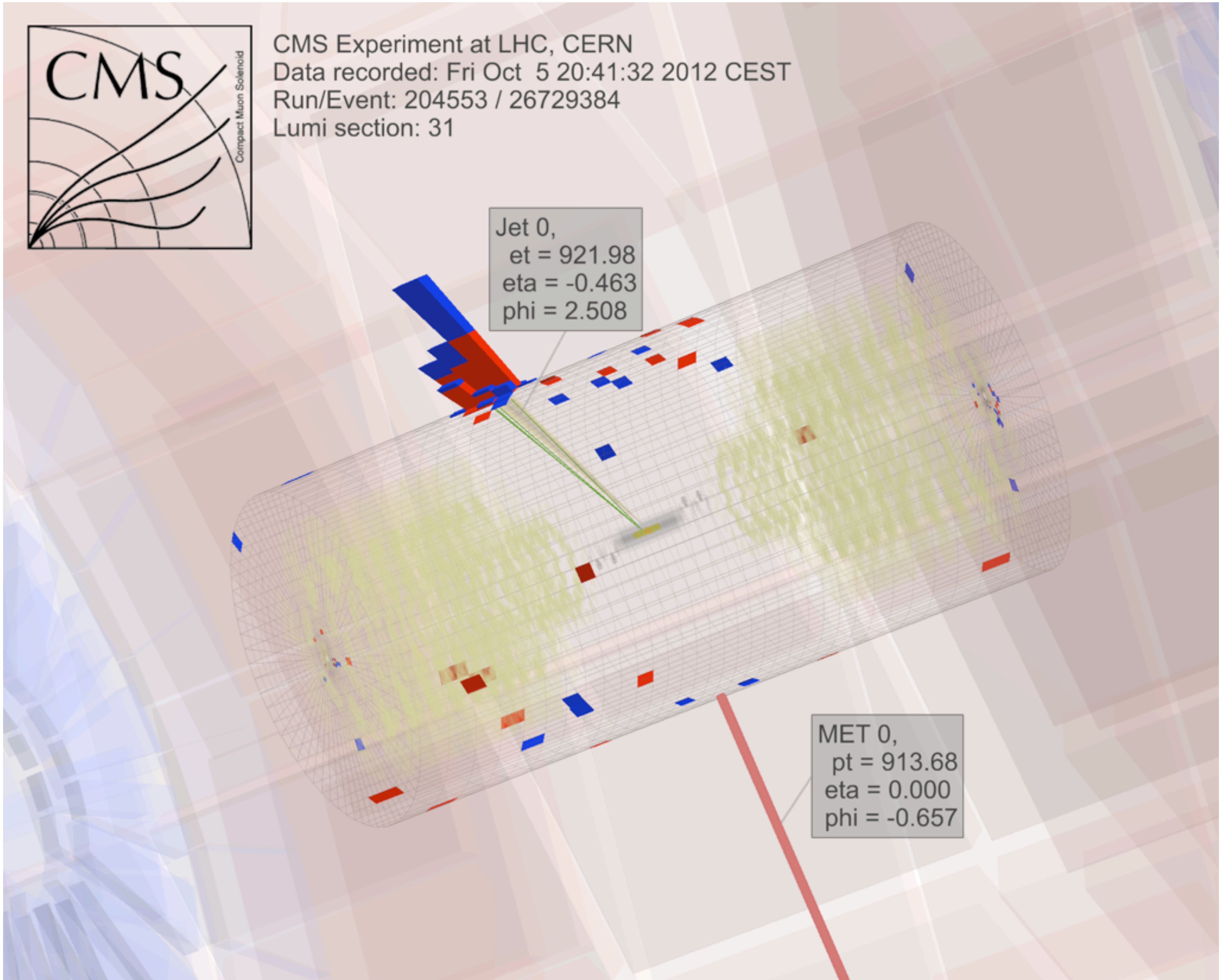

A monojet event

EXO-12-048

Summary

- Dark matter was searched for in proton-proton collision data at $\sqrt{s}$=7, 8 TeV collected with the CMS detector at LHC before the Long Shutdown 1
- If produced at LHC, dark matter will be invisible to the CMS detector; their existence can be inferred by large missing transverse momentum (MET)
- Direct productions of the pairs of dark matter particles can be tagged by the initial-state radiation (ISR). The CMS monojet analysis placed upper limits on the dark matter-nucleon interaction cross sections, which can be compared with direct detection results.
- Analyses of $\sqrt{s}$=8 TeV data collected in 2012 are still ongoing. Further, after the Long Shutdown 1, the CMS will collect proton-proton collision data at higher energy and at higher rate. The dark matter searches in CMS will continue.

End