Search for long-lived particles in the CMS experiment

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on behalf of the CMS Collaboration

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OUTLINE

- Displaced lepton pairs
- Displaced photons
- Stopped HSCPs
- Flying through HSCPs
  - standard charge
  - fractional charge
  - multi charge

2012 LHC Days in Split, 4/10/2012

Motivation: long-lived particles could be very interesting

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Motivation

- various SUSY scenarios:

GMSB
RPV
SUSY
[. . .]

- ”hiden valey”
- [. . .]

BSM with
new symmetry,
weak coupling,
kinematic constraint,
potential barrier

Displaced lepton pairs

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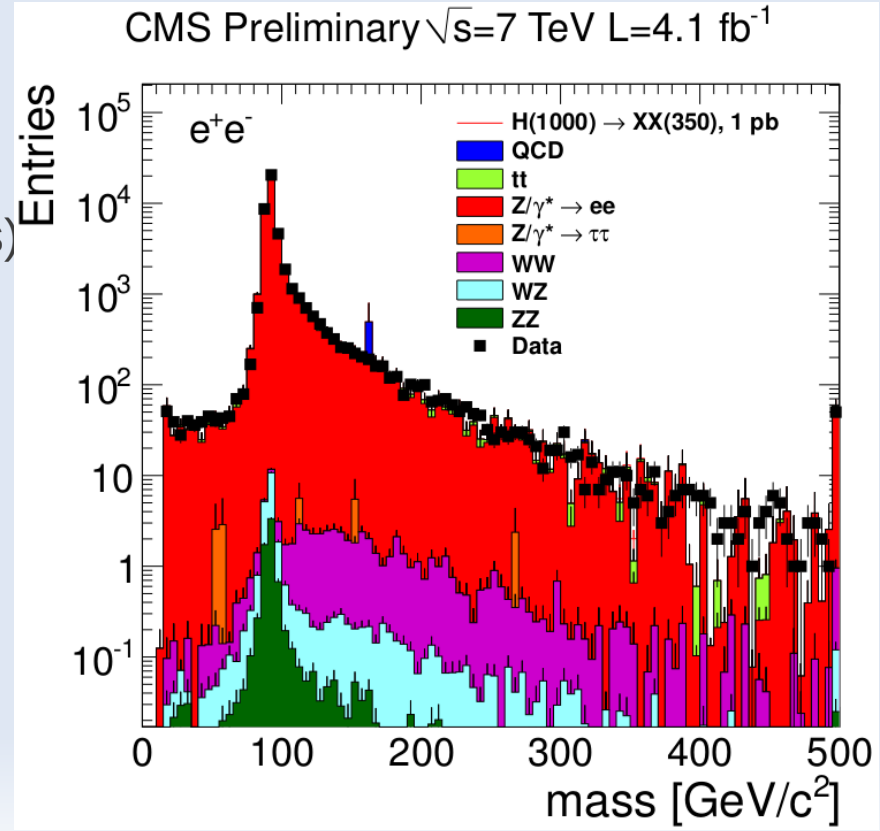
A search is performed for a heavy resonance decaying to two long-lived massive neutral particles that each decay to dileptons.
The process is detected experimentally via a distinct topological signature consisting of **a pair of leptons originating at a vertex far displaced from the LHC beam spot**.

The topological search analysis presented here is sensitive to a wide class of models ('hidden valley', 'split SUSY' etc). However, for the purpose of estimating signal selection efficiencies, a specific model $H^0 \rightarrow XX,\ X \rightarrow \ell\ell$ is used.

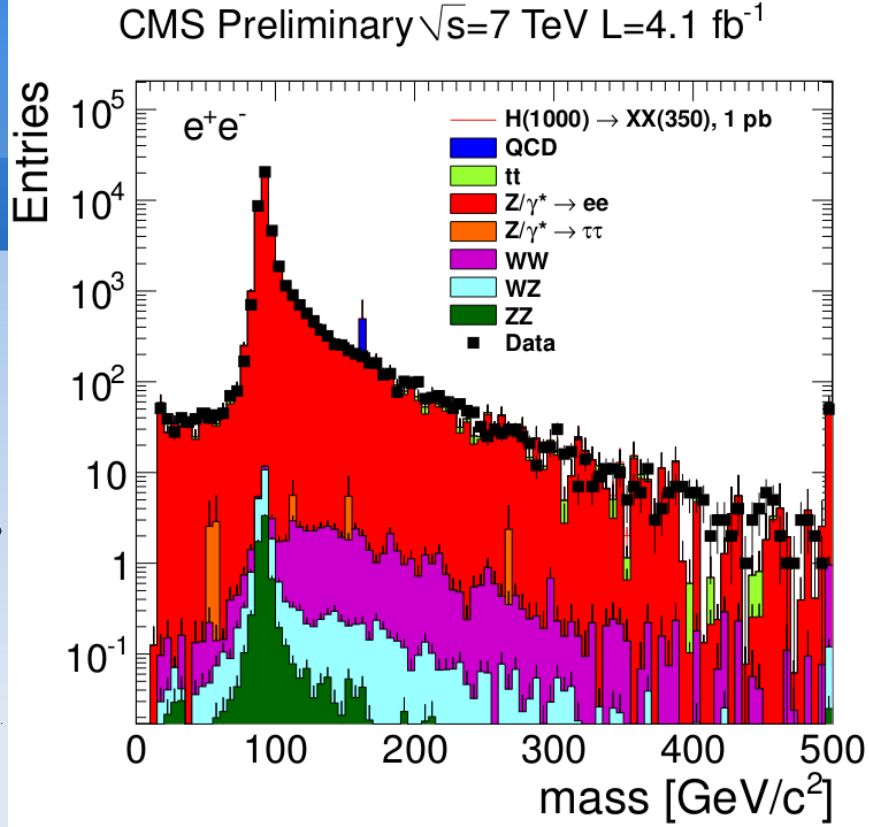
Trigger: electron channel: two ECAL deposits E_T>38GeV
muon channel: two track segments p_T>30GeV/c

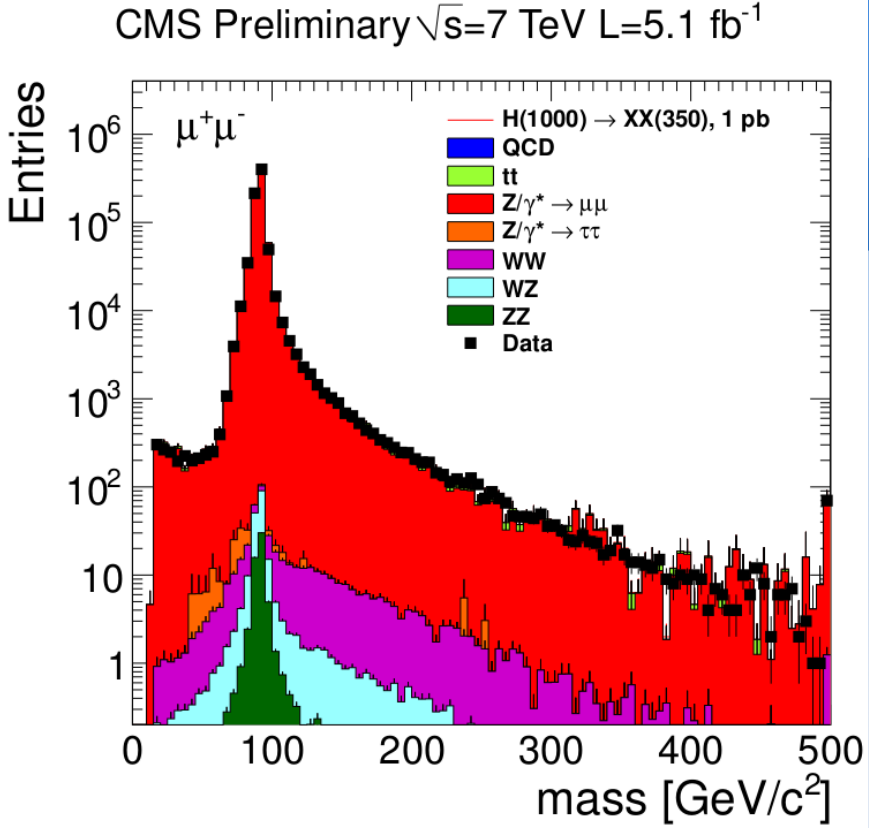
Selection: high purity tracks p_T>41GeV/c (33GeV/c muons)
$|\eta|$<2, impact par. significance >3 (2 for muons)
X bosons: pair of OSSF displaced leptons
if the vertex is good and
its distance significance >8 (5 for muons)

Background dominated **X → ee** plot → → → → → →
after all selection cuts apart form impact par. significance and with inverted vertex distance significance cut

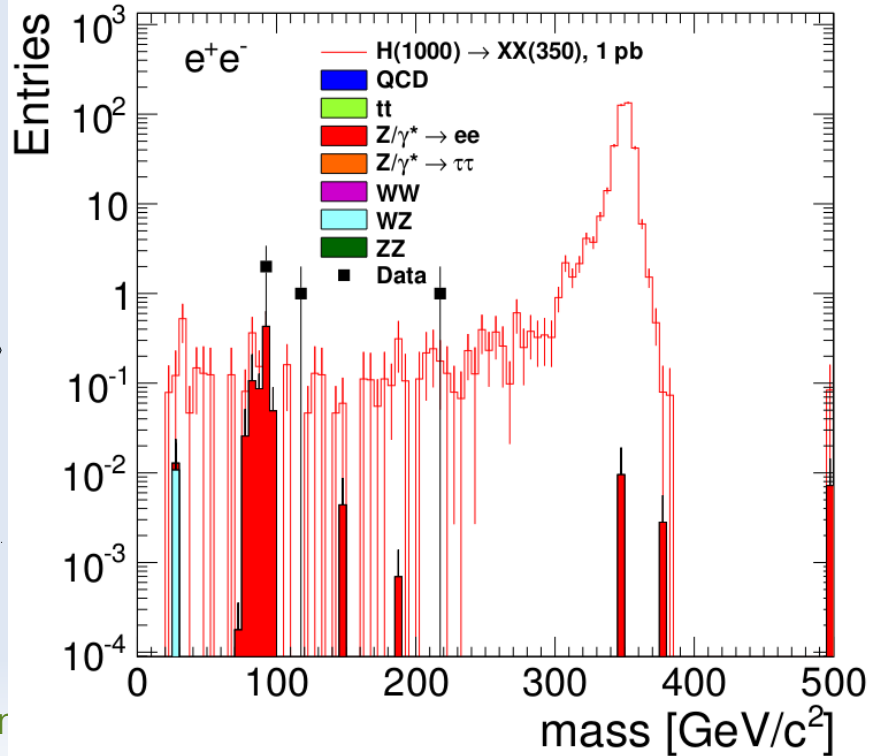


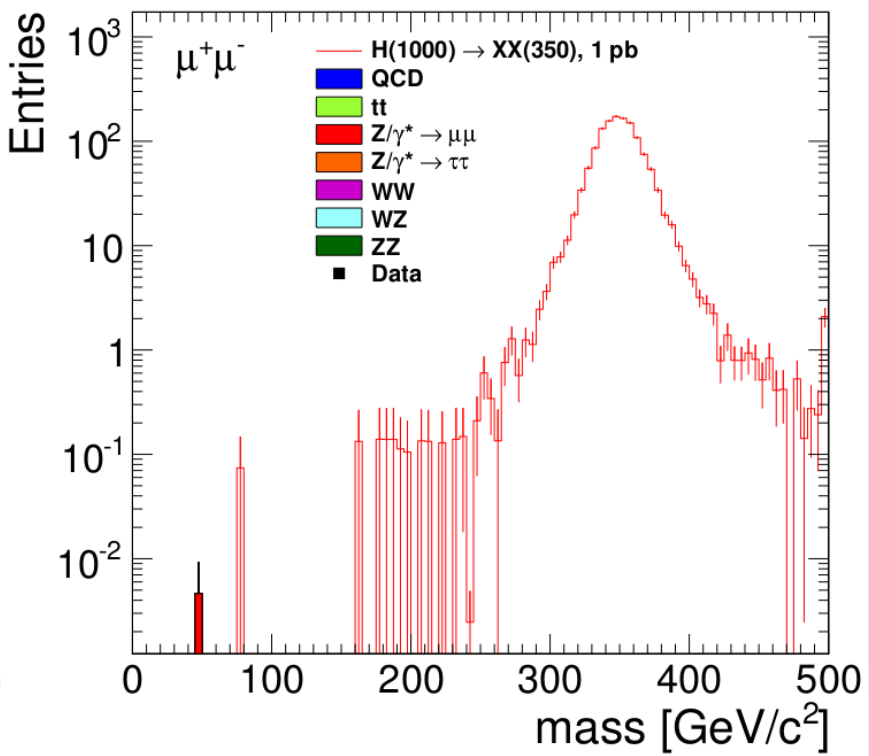
background dominated

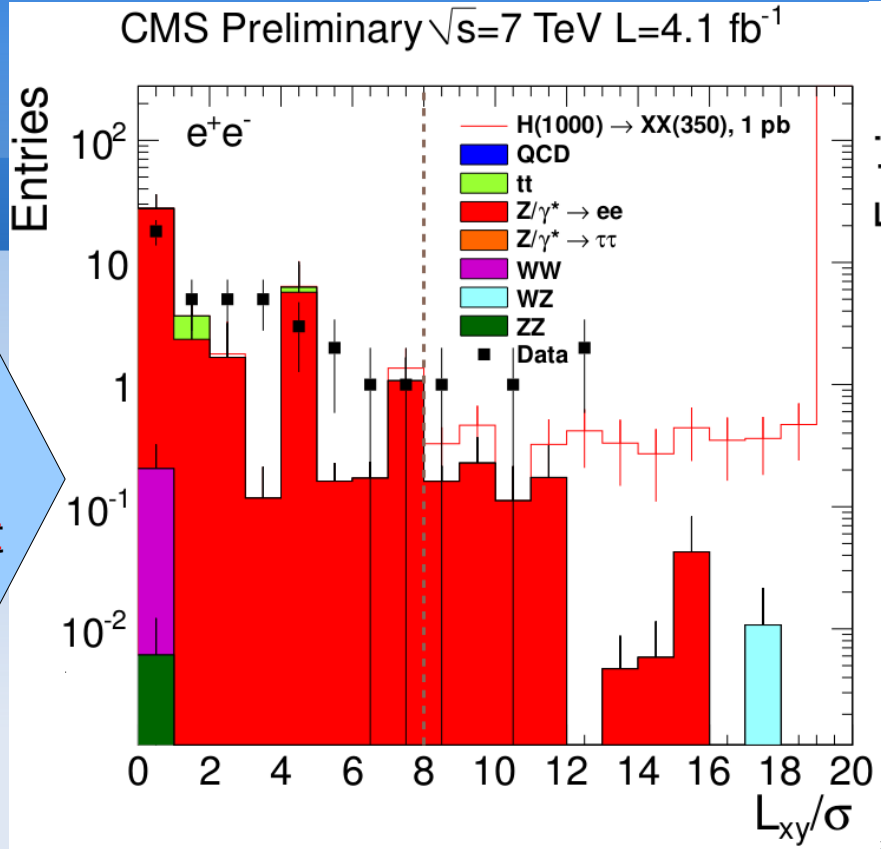


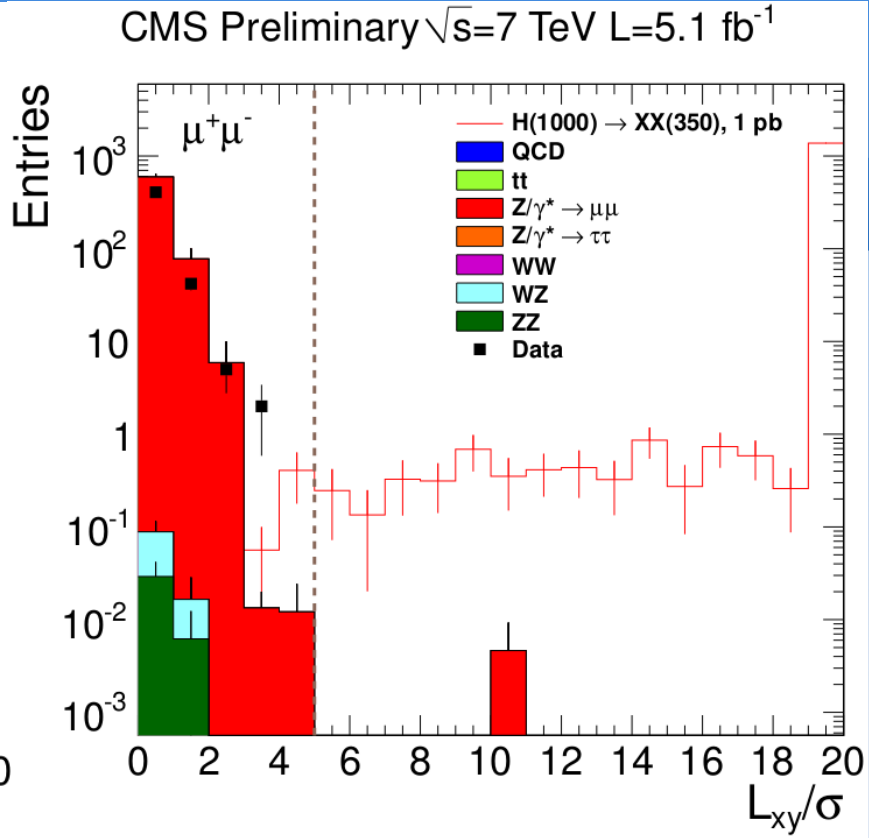


after all cuts





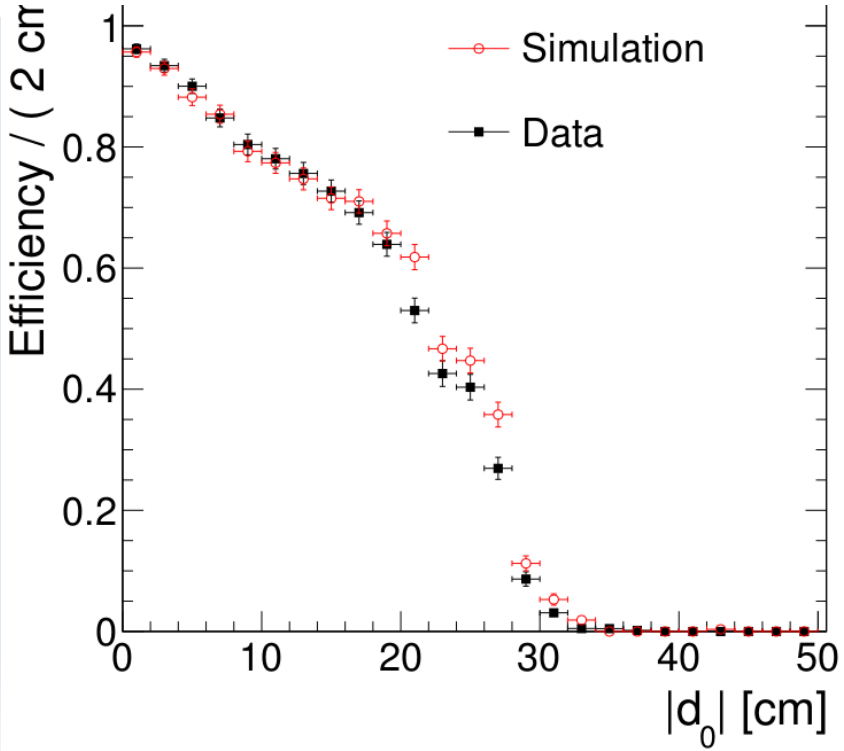




after all, but distance significance cut

Standard criteria to reject cosmics applied, but cosmics are used to evaluate displaced tracks reconstruction efficiency

Source of systematic bias	Uncertainty
Luminosity	2.2%
Systematic uncertainties in the signal efficiency	
Pileup modelling	2%
Parton distribution functions	$< 1\%$
Renormalisation and factorisation scales	$< 0.5\%$
Tracking efficiency	20%
Trigger efficiency	2.6% (e), 11% (μ)
Mass resolution	10% (e), 50% (μ)



Displaced lepton pairs

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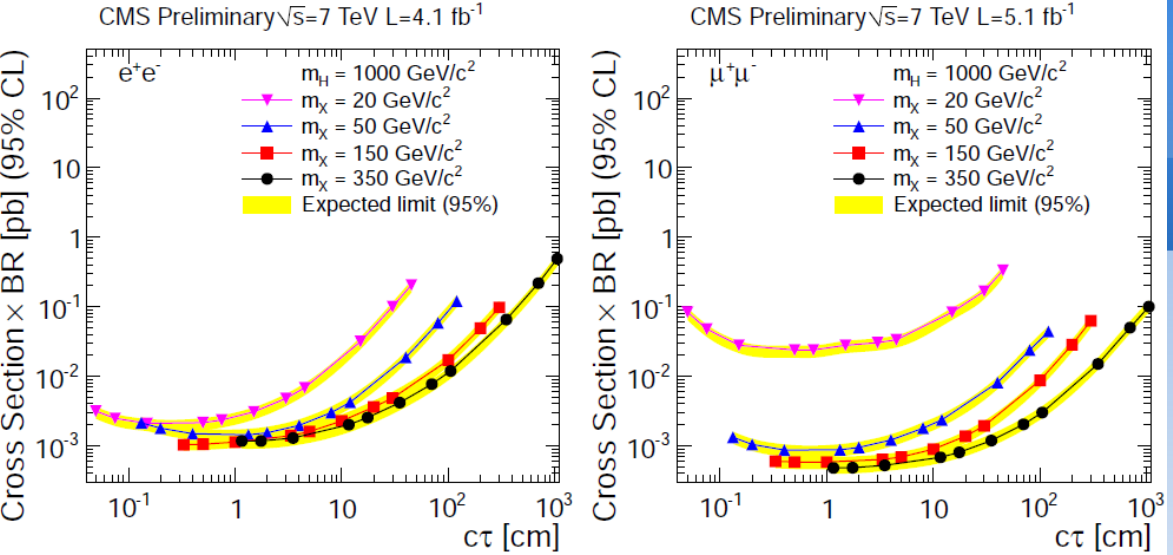
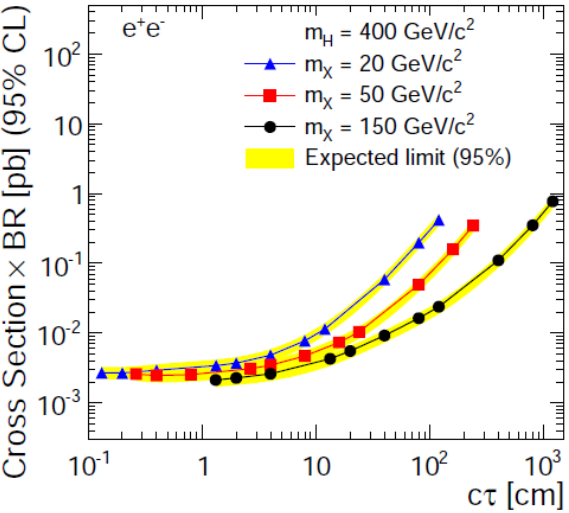
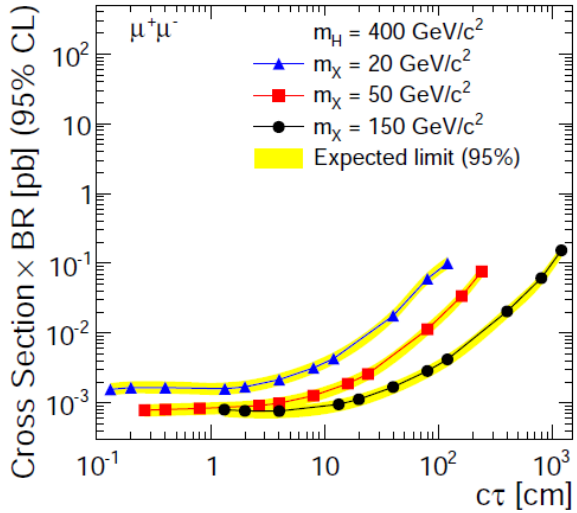
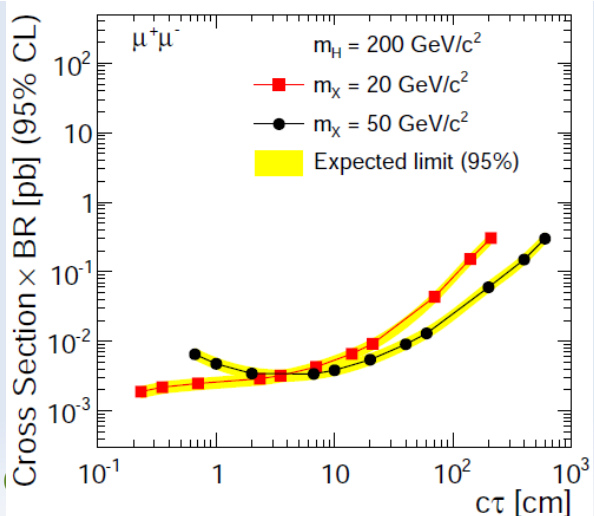
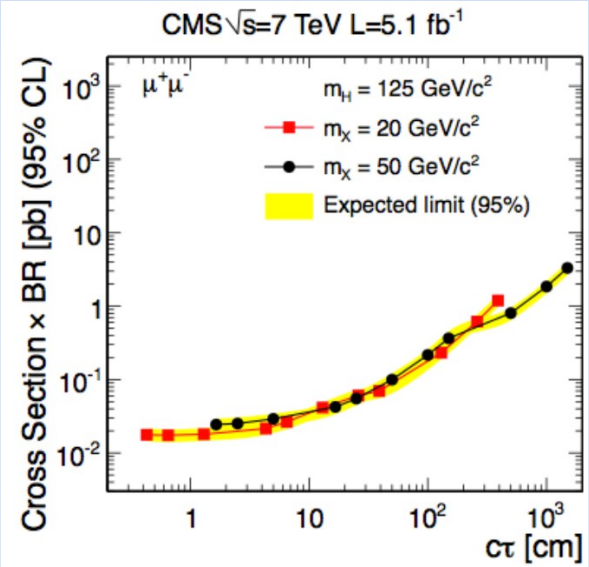








Preliminary results
PAS EXO-11-101



upgrade - **preliminary result approved last week**

Displaced photons

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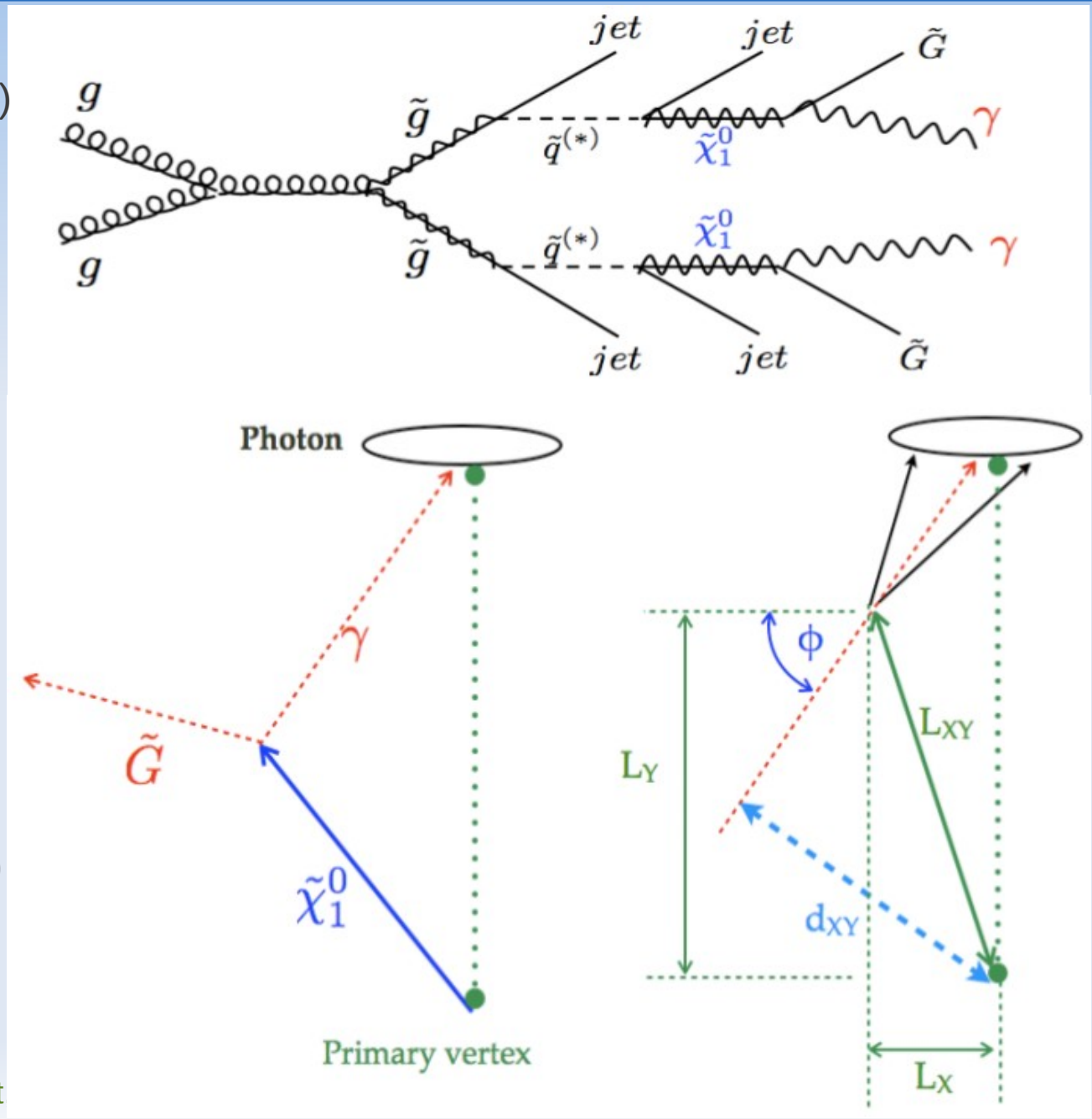
Two methods to search for decay of neutralino to gravitino+photon (GMSB)

The first uses converted photons and missing energy signature.

It Is sensitive to small neutralino lifetimes. Models with decay lenghts $c\tau$ between 2cm and 25 cm are considered.

$$d_{XY} = -L_X \cdot \sin\phi + L_Y \cdot \cos\phi$$
$$d_Z = L_Z - \frac{L_X \cdot p_X + L_Y \cdot p_Y}{p_T} \cdot \frac{p_Z}{p_T}$$

diphoton trigger is used:
ECAL energy above
32 GeV (22 GeV) to 40 GeV (28 GeV)
for leading (subleading) photon



Displaced converted photons

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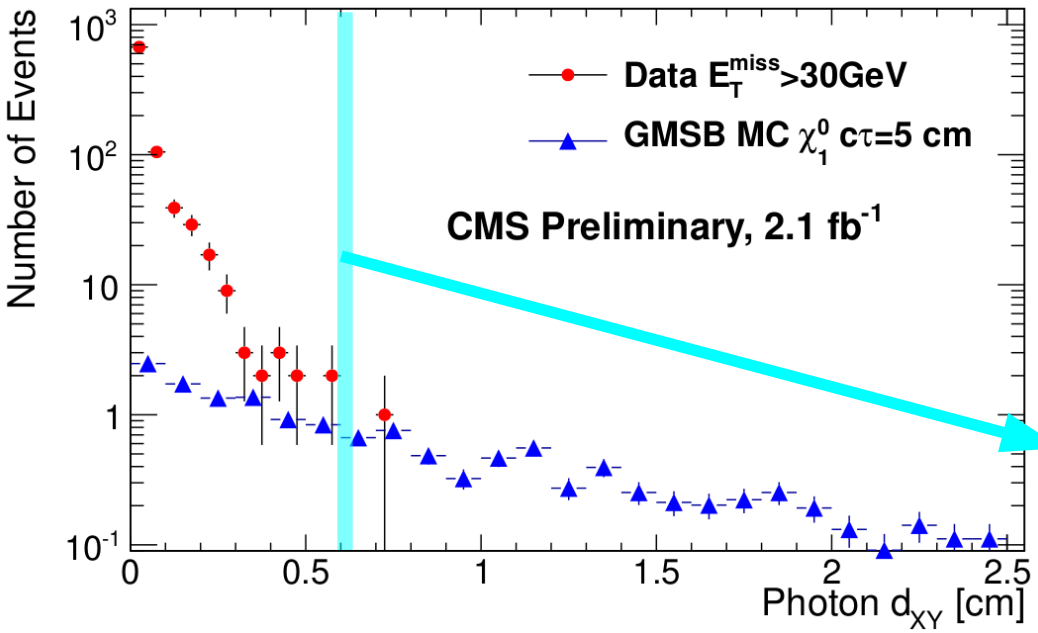

Table 1: Signal selection flow for $c\tau = 5$ cm.

Selection	Events in Monte Carlo
Total	45057
DiPhoton trigger	39988
Photon $E_T > 45$ GeV and $E_T > 30$ GeV	37398
Any ECAL barrel photon $E_T > 45$ GeV and Photon identification	27766
Jets $p_T > 80$ GeV and $p_T > 50$ GeV	26229
Conversion selection	1602
$E_T^{miss} > 30$ GeV	1542
$d_{XY} > 0.6$ cm	711

Systematics	Uncertainty (%)
Integrated luminosity	4.5
Jet p_T/E_T^{miss} energy scale	< 0.5
Pile-up	2.5
Photon identification Data/MC scale	2.6
Photon-electron difference	0.5
Conversion reconstruction efficiency	20.6
Photon d_{XY} resolution	< 0.5
Total	25

Table 3: Summary of systematic uncertainties.

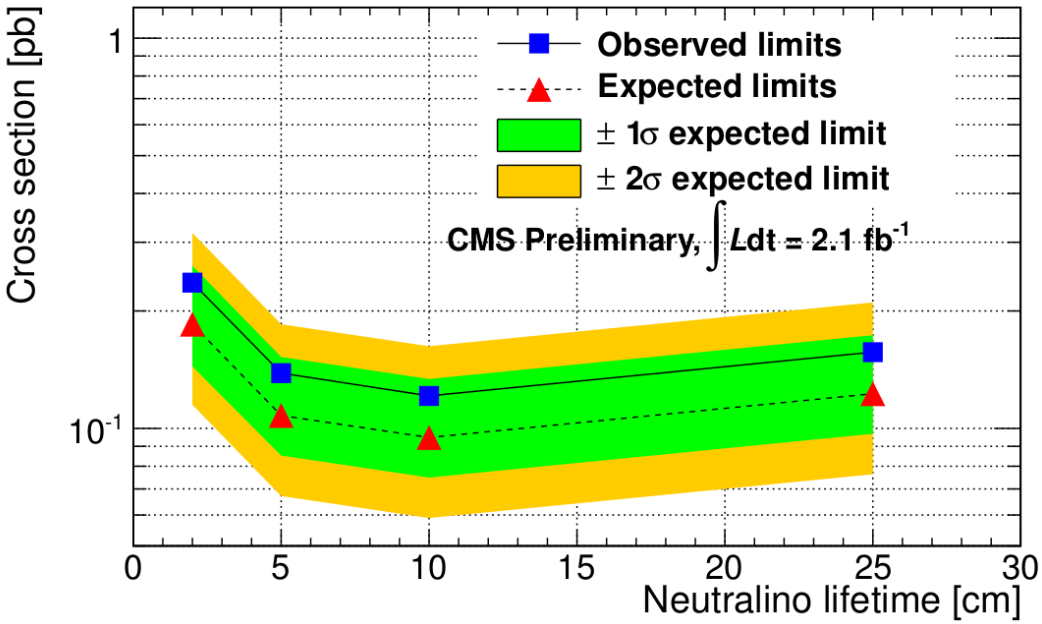

Table 2: Event selection efficiency vs $\tilde{\chi}_1^0$ lifetime.

$c\tau$ [cm]	2	5	10	25
Efficiency	0.921%	1.578%	1.797%	1.388%
Statistical errors	0.046%	0.059%	0.064%	0.055%

Displaced photons
missing E_T and ECAL time

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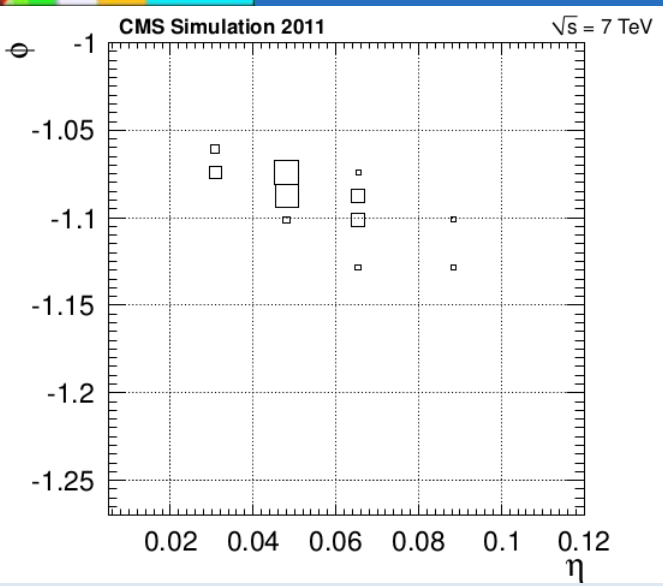
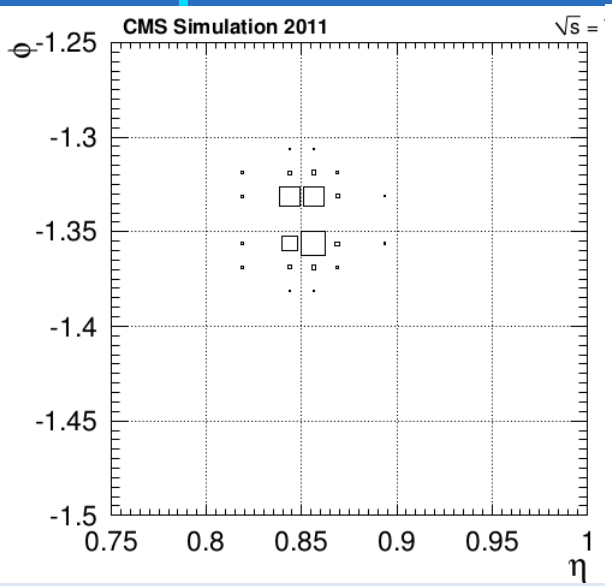
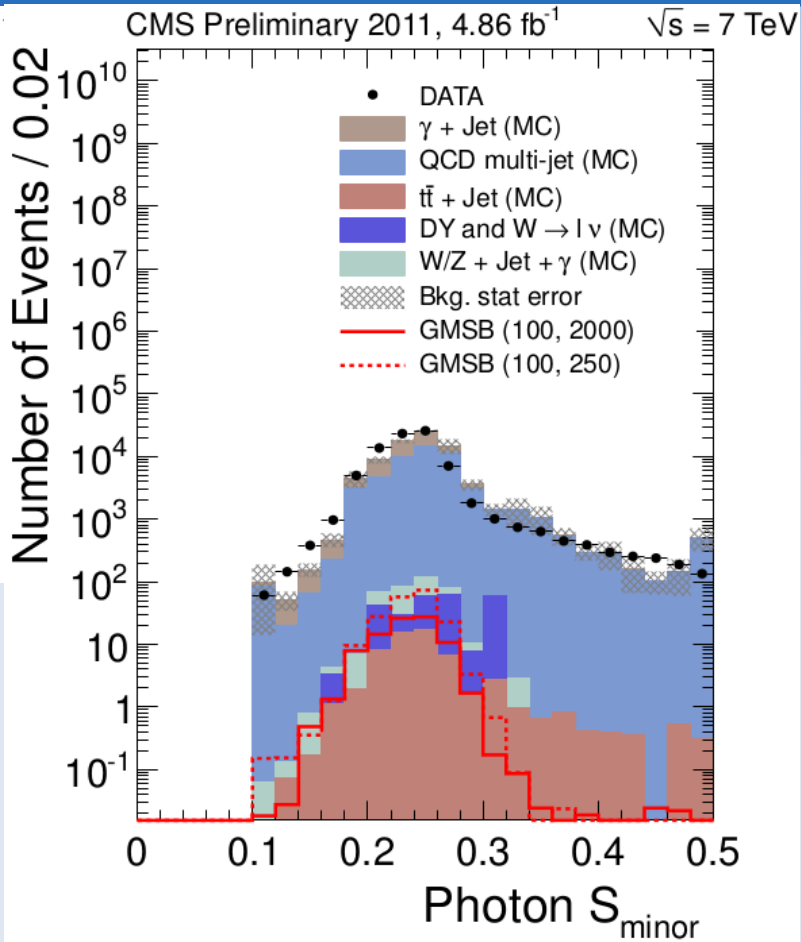




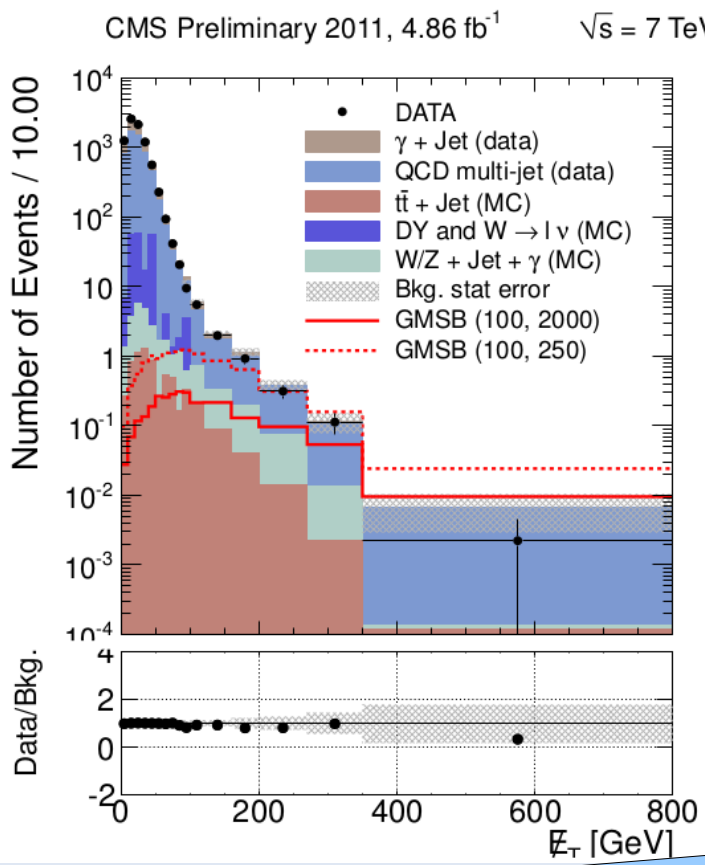


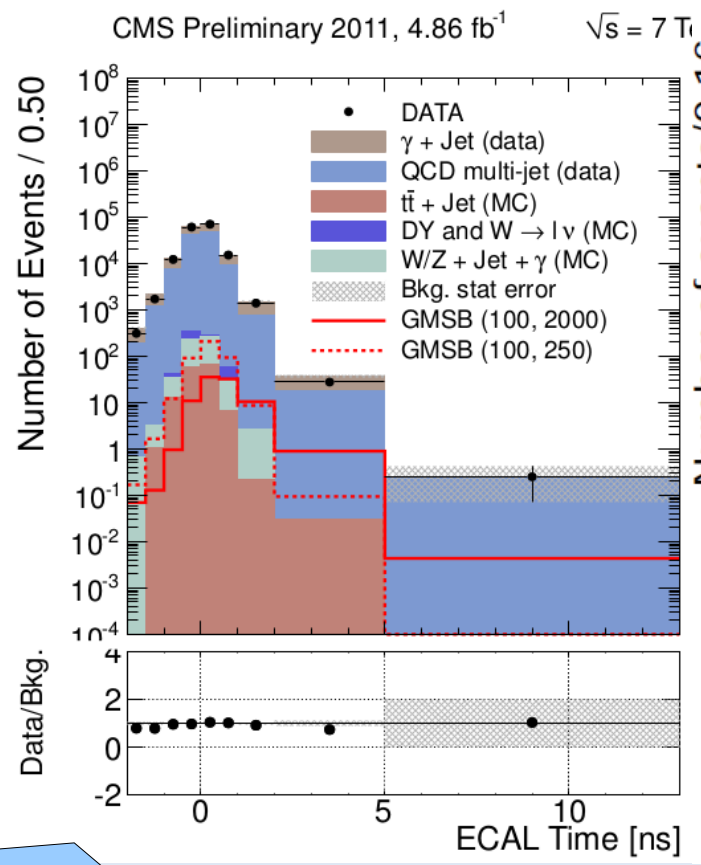
$$S_{Minor} = \frac{S_{\phi\phi} + S_{\eta\eta} - \sqrt{(S_{\phi\phi} - S_{\eta\eta})^2 + 4S_{\phi\eta}^2}}{2}$$

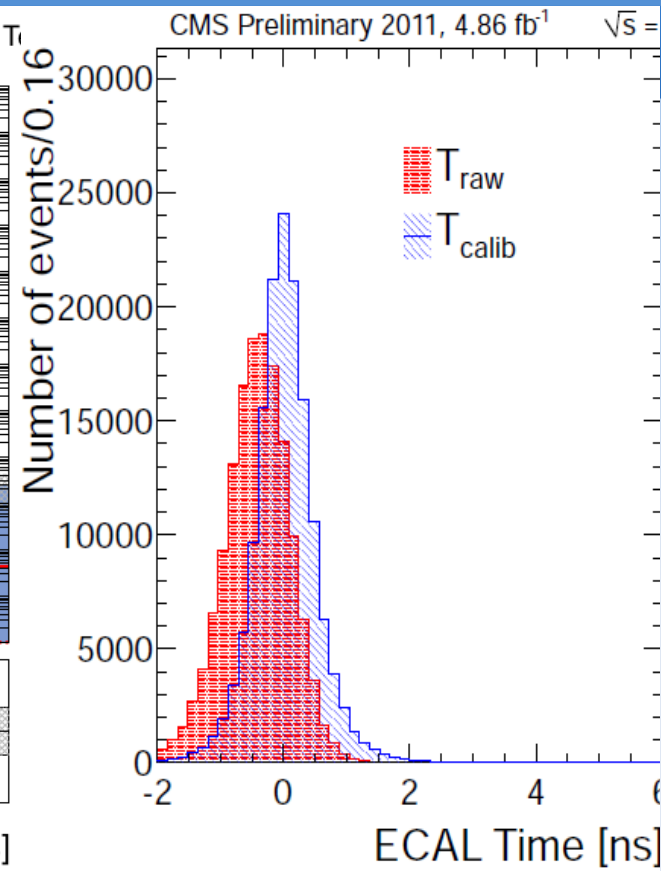
Trigger evolution: photon p_T> 75GeV → 90GeV
→ (90GeV & at least 3jets > 25GeV)

Selection: isolated photon with p_T> 100GeV, |η|<1.4 and 0.15< S_{Minor}<0.30

Displaced photons







In order to estimate the number of background and signal events in data, a maximum likelihood **fit of signal + background is performed using the E_T^{miss} and ECAL time distributions.**

signal efficiences

Λ (TeV)	$M_{\tilde{\chi}_1^0}$ (GeV/c^2)	$c\tau = 1$ mm	$c\tau = 250$ mm	$c\tau = 2000$ mm	$c\tau = 6000$ mm
100	140	18.7 ± 0.3	18.4 ± 0.2	8.4 ± 0.2	3.3 ± 0.1
120	169	24.9 ± 0.4	24.6 ± 0.3	15.1 ± 0.4	6.6 ± 0.1
140	198	30.4 ± 0.3	31.3 ± 0.3	22.2 ± 0.4	11.4 ± 0.3
160	227	35.5 ± 0.3	36.1 ± 0.6	29.4 ± 0.4	17.0 ± 0.4
180	256	40.1 ± 0.7	38.0 ± 0.5	36.0 ± 0.5	22.2 ± 0.4

Table 1: The selection efficiencies in percent for MC signal.

Displaced photons

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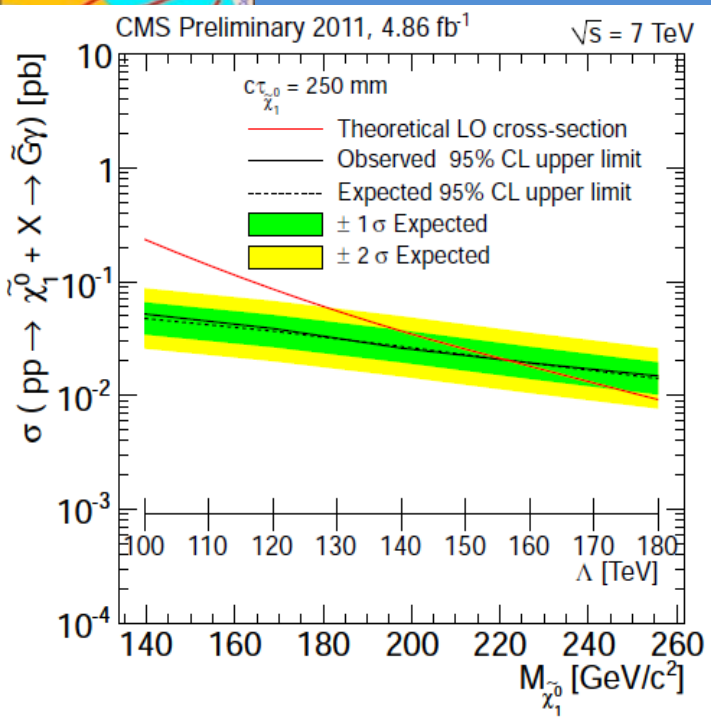
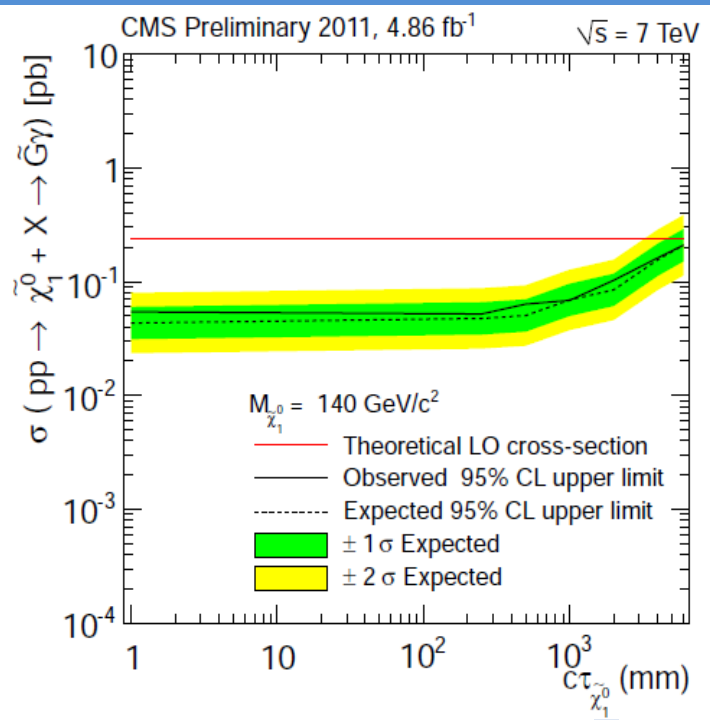
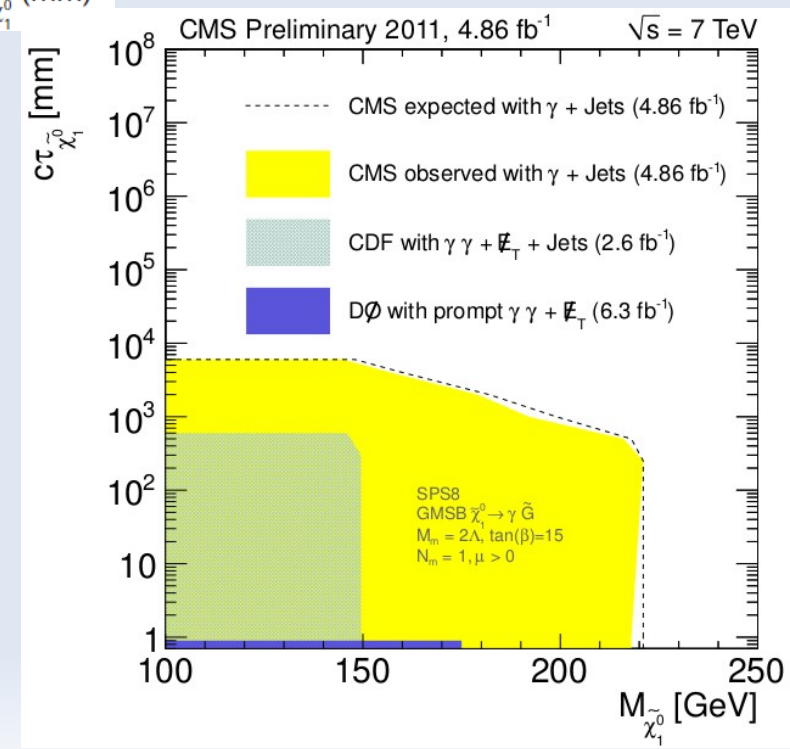




preliminary results

The final number of events estimated for each component after all selection cuts and the **fit to data**.

	No. Events
GMSB (100, 250)	6 ± 8
GMSB (100, 2000)	4 ± 4
multi-jet and γ+jet	80916 ± 290
$t\bar{t}$ + jet (fixed)	73
$W \to e\nu$ + jet (fixed)	116
Drell–Yan + jet (fixed)	67
W/Z + jet + γ (fixed)	215
Total background	81387
Data	81382



Heavy quasi-Stable Charged Particles

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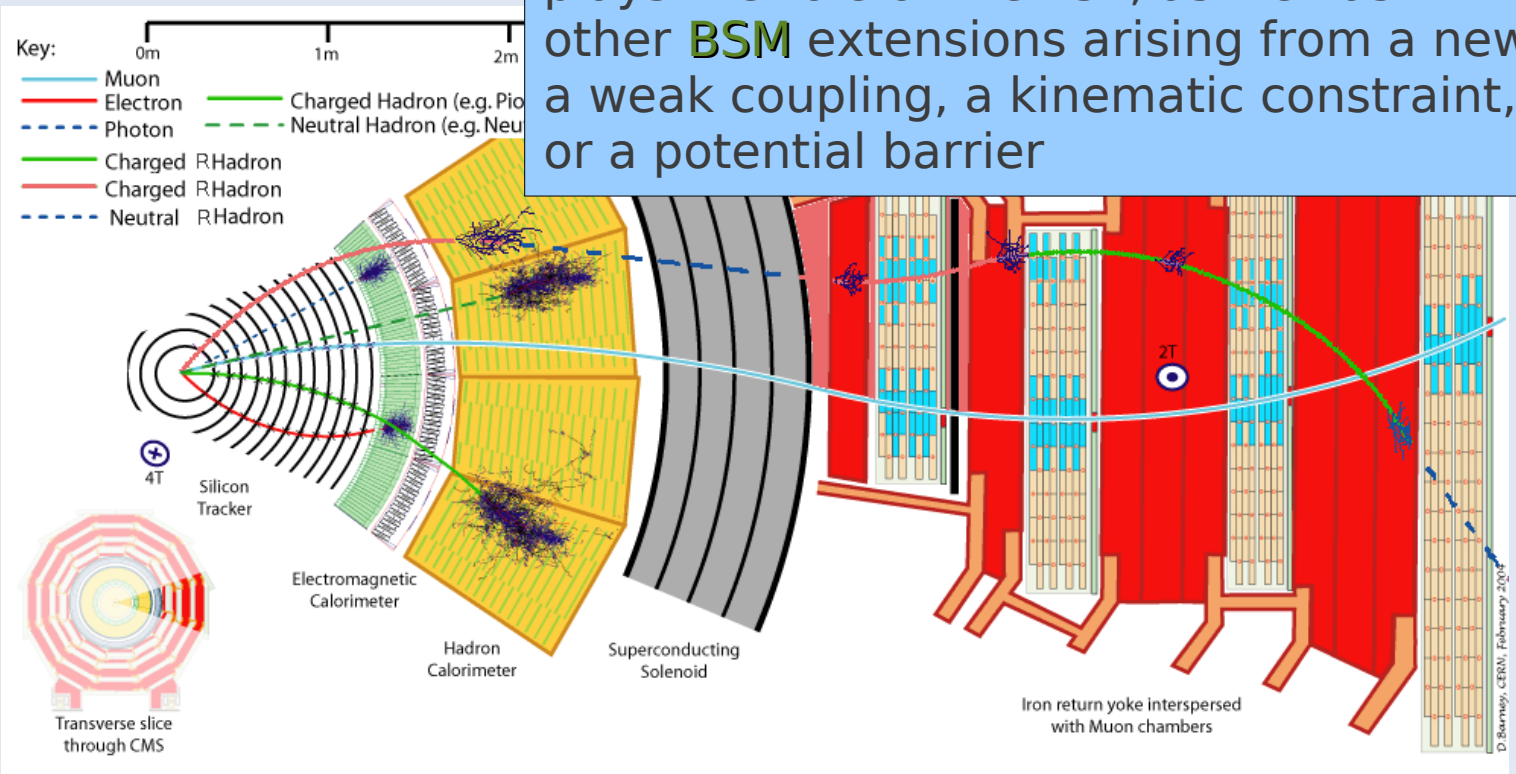
Flying through
- lepton like (stau)
- R-hadrons
- fractional charge
- mulitple charge

Stopped in the detector
R-hadrons

HSCPs - heavy quasi-stable charged particles
(or CHAMPs – charged massive particles)
are hipotetical objects that appear in various extensions of the standard model (SM) in which gravitino or axino plays the role of the LSP, as well as in other **BSM** extensions arising from a new symmetry, a weak coupling, a kinematic constraint, or a potential barrier



muon, **stau**

R-hadron

Stopped HSCP

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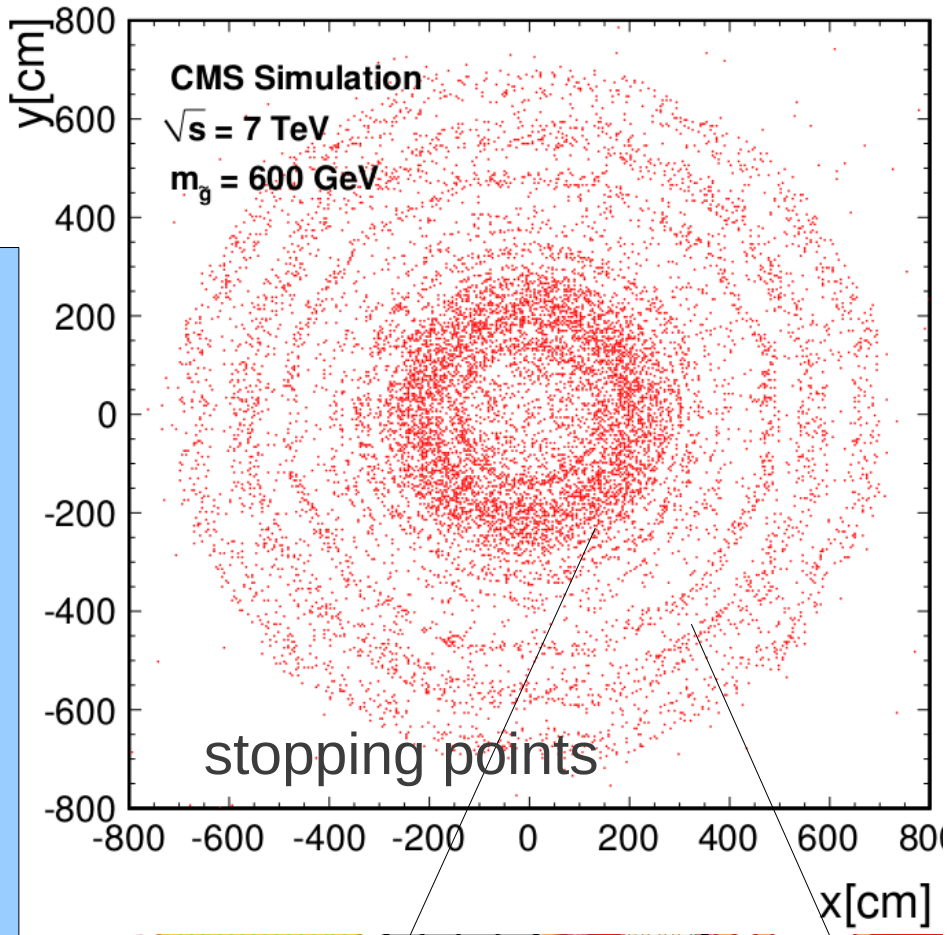
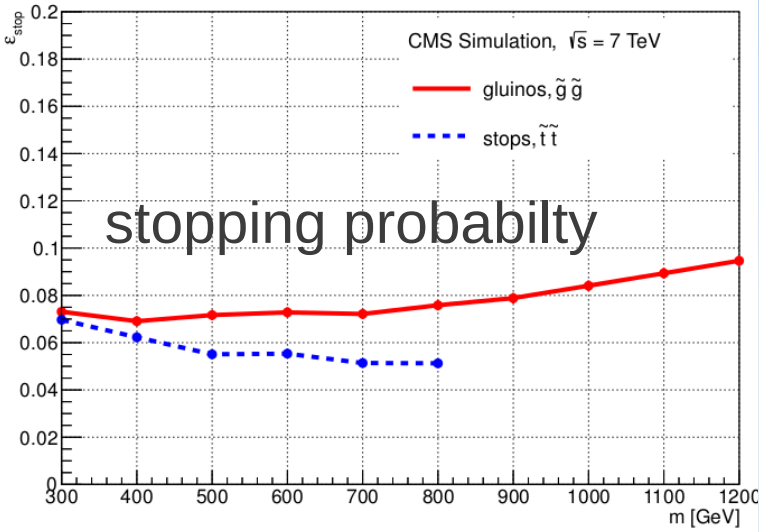
R-hadrons are hadronized semi-stable gluinos or squarks (stops, sbottoms) predicted by split-SUSY (among others).

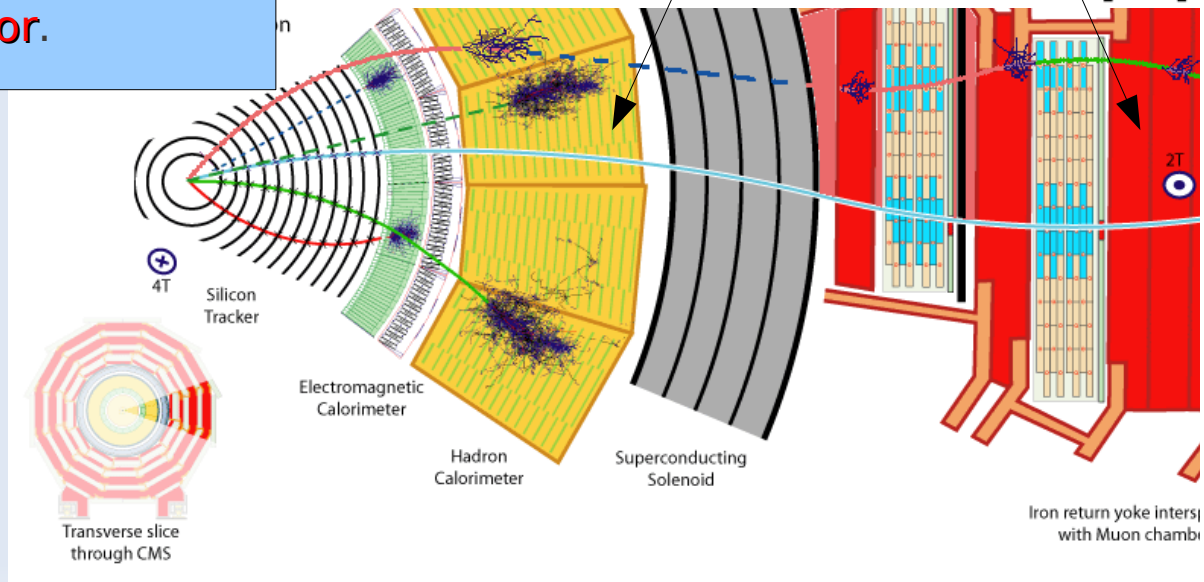
These particles have relitivelly large probability to stop in the detector.



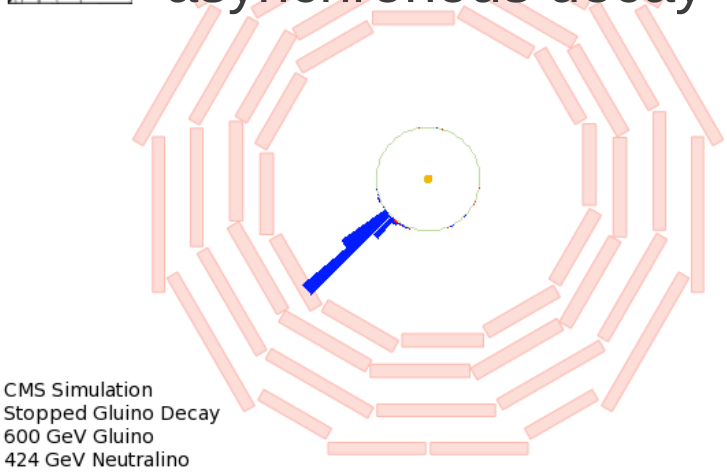
Stopped in the detector

R-hadrons





stopped gluino asynchronous decay

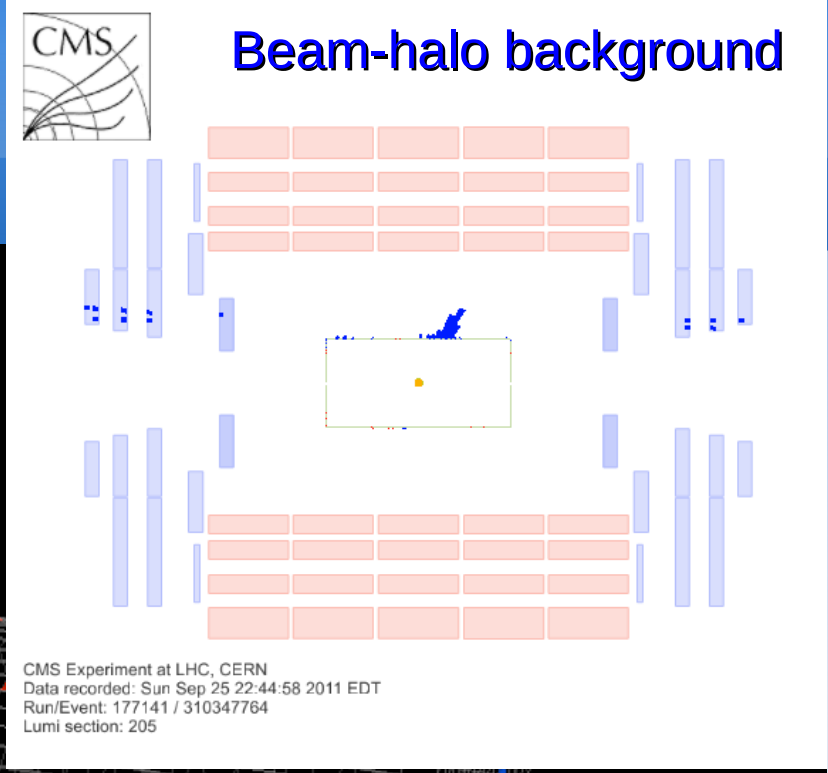


Trigger + offline veto & cleaning

Jet trigger in coincidence with "no beam" condition:
- 32 GeV E_T threshold at L1 and 50 GeV at HLT
- veto both BPTX (beam position and timing) +-1 BX
- $|\eta| < 3$
- veto L1 endcap beam halo trigger (+-1 BX)

Offline veto:
- veto +-2 BX any beam activity (at BPTX)
- veto any reconstructed beam halo event (any muon like signal in the forward muon syst. CSC)
- veto any event with primary vertex
- veto any event with at least 1 muon (or at lest 2 signals in the barrel muon syst. DT or RPC)

Cleaning and noise rejection:
- standard cleaning and noise rejection
- $|\eta| < 1$
- reconstructed jet energy > 70 GeV
- spacial distribution of the deposits requirements
- pulse time shape requirements



Cosmic rays	Beam-halo	Noise	Total
5.71 ± 0.62	1.50 ± 0.70	1.4 ± 2.2	8.6 ± 2.4

Background estimate
- cosmic rays background by MC (validated by real data)
- beam-halo by tag & probe (two endcaps)
- noise using 2010 control sample

Stopped HSCP

95 % CL X-sec limits (top) & mass limits (bottom) as a function of lifetimes

The structure visible for small lifetimes is due to time window 1.3*τ used for lifetimes shorter than LHC orbit (89μs).

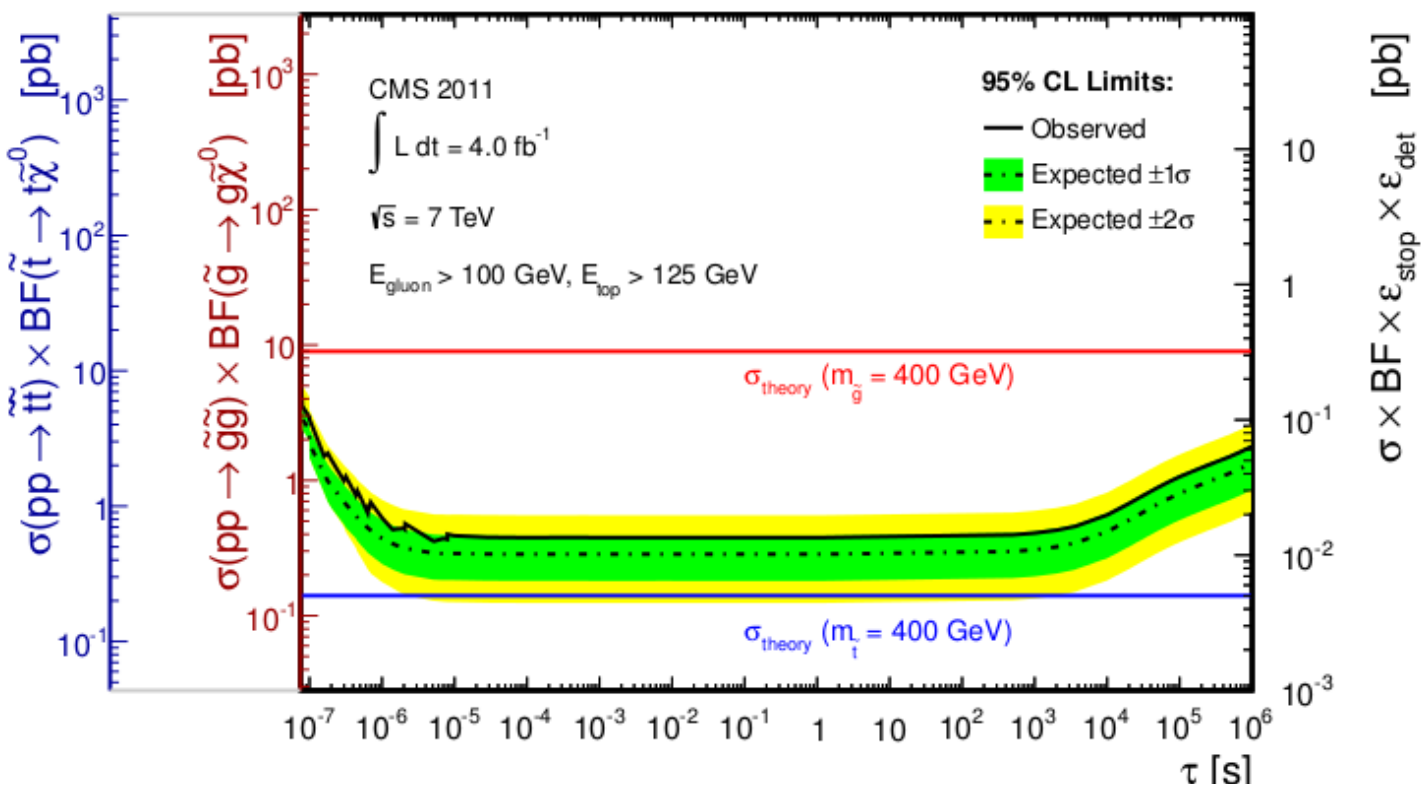
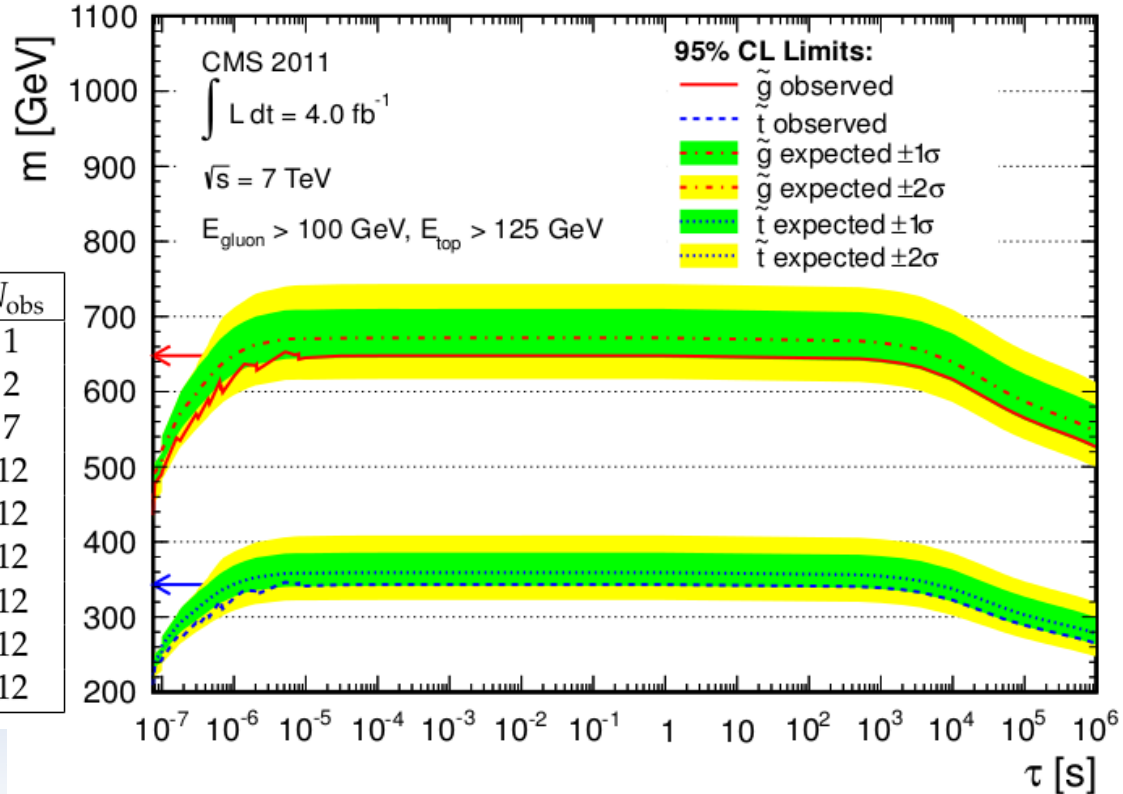


Table:
Results of countig experiments
(*Nexp* → background events)

τ	L_{eff} (pb^{-1})	Live time (s)	N_{exp}	N_{obs}
75 ns	19.6	2.06×10^4	0.200 ± 0.056	1
100 ns	57.8	6.17×10^4	0.60 ± 0.17	2
1 μs	508	4.41×10^5	4.3 ± 1.2	7
10 μs	913	8.67×10^5	8.5 ± 2.4	12
100 μs	935	8.86×10^5	8.6 ± 2.4	12
10^3 s	866	8.86×10^5	8.6 ± 2.4	12
10^4 s	636	8.86×10^5	8.6 ± 2.4	12
10^5 s	332	8.86×10^5	8.6 ± 2.4	12
10^6 s	198	8.86×10^5	8.6 ± 2.4	12



complementarity

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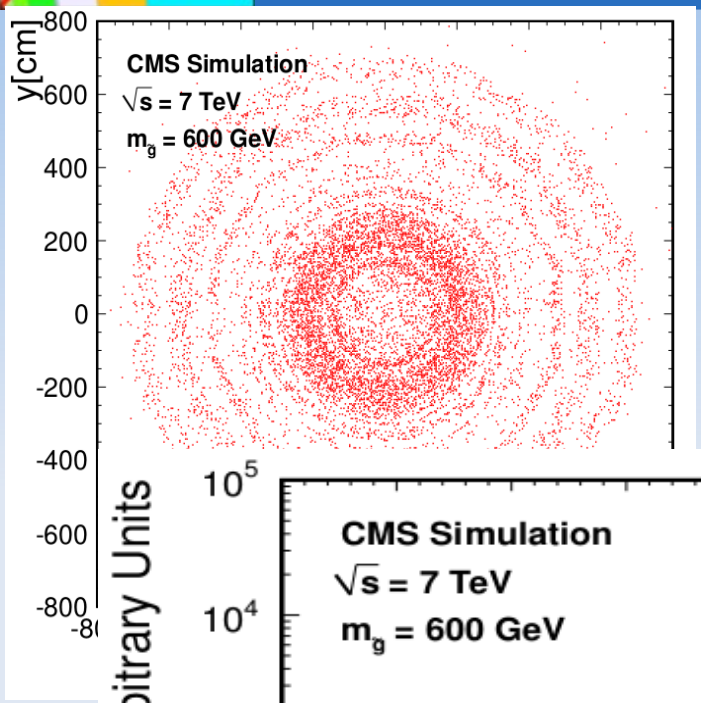
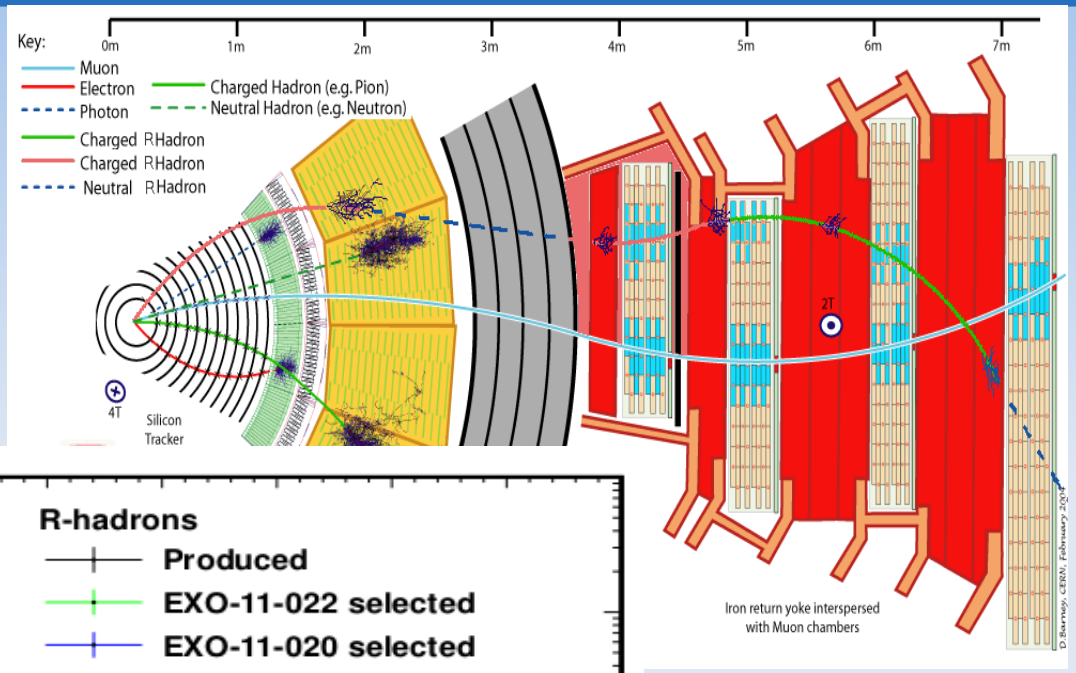
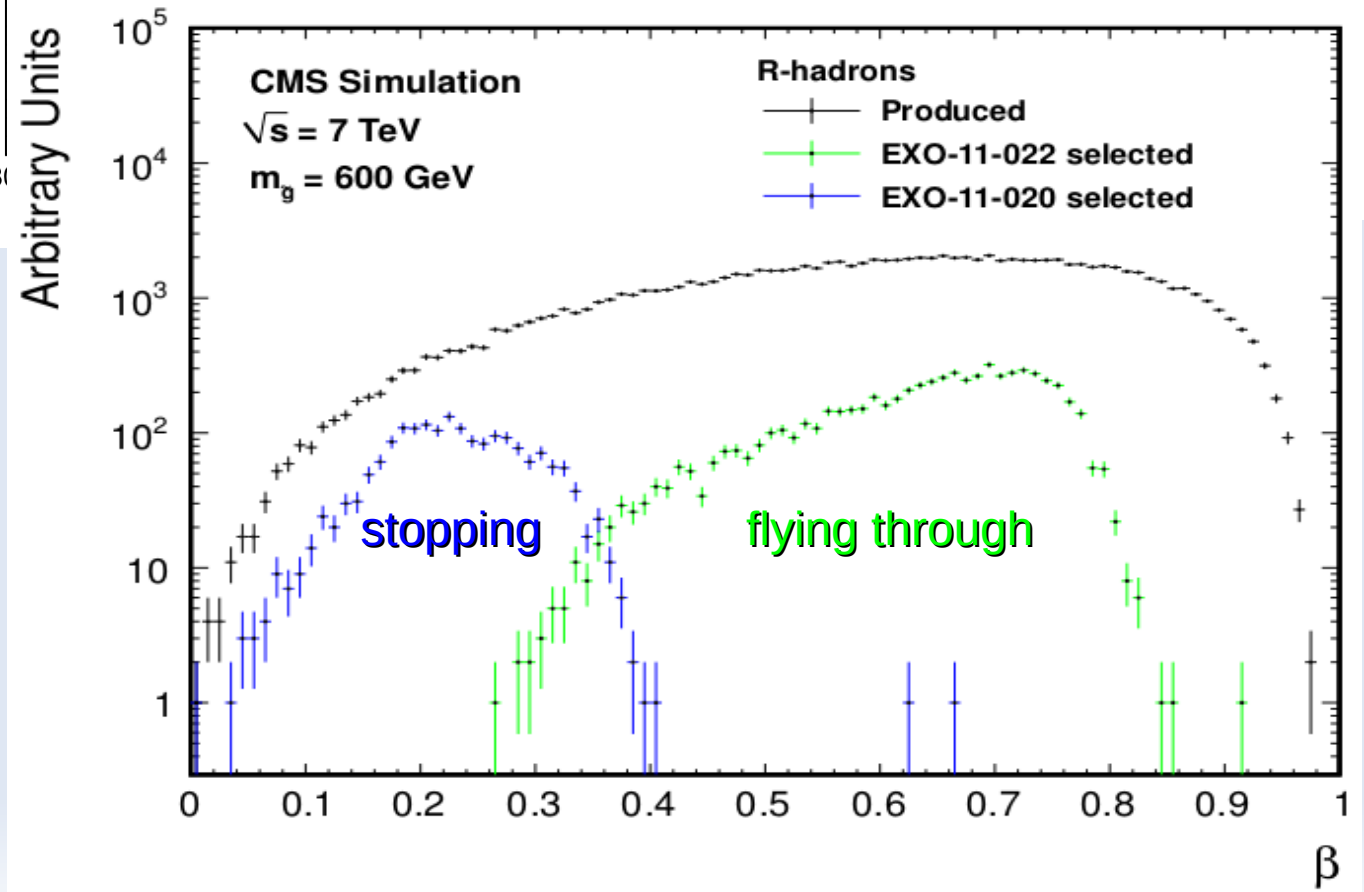




R-hadron



If the lifetime of HSCP is longer than a few nanoseconds, the particle will flight through detector.

It clould be regarded as stable from the detection point of view

Flying through HSCP
The idea & trigger

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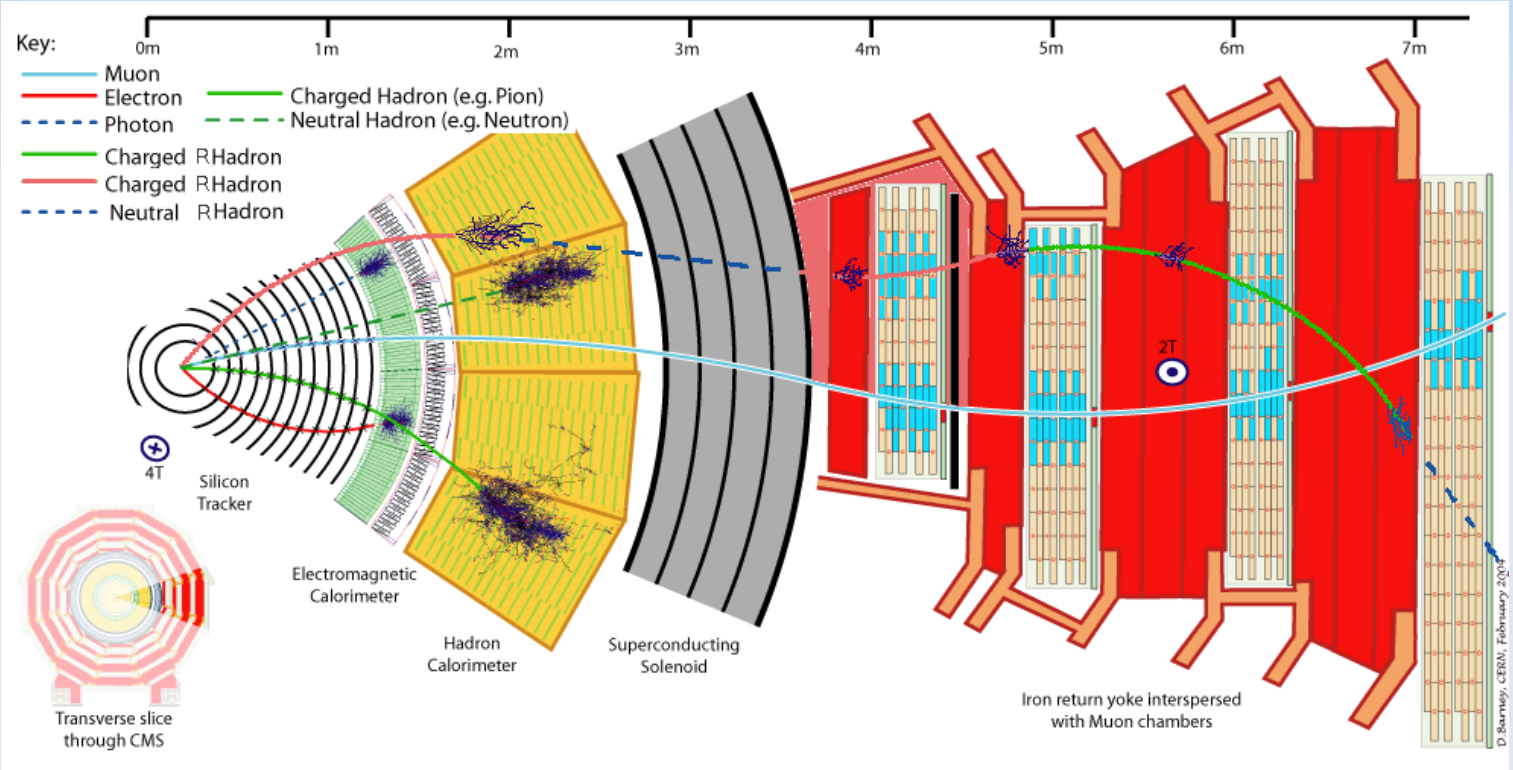
HSCP could be slow enough to
- be late with respect to relativistic muons;
- give higher d*E*/d*x* than MIPs.

Two strategies for flying through HSCPs:
- tracker only (d*E*/d*x* only) analysis;
- tracker + TOF in the muon system analysis.



muon, stau

R-hadron

Triggers:
- MET (online particle flow) > 150 GeV
- single muon p_T > 40 GeV/c
  → special BX0+BX1 muon trigger (RPC)

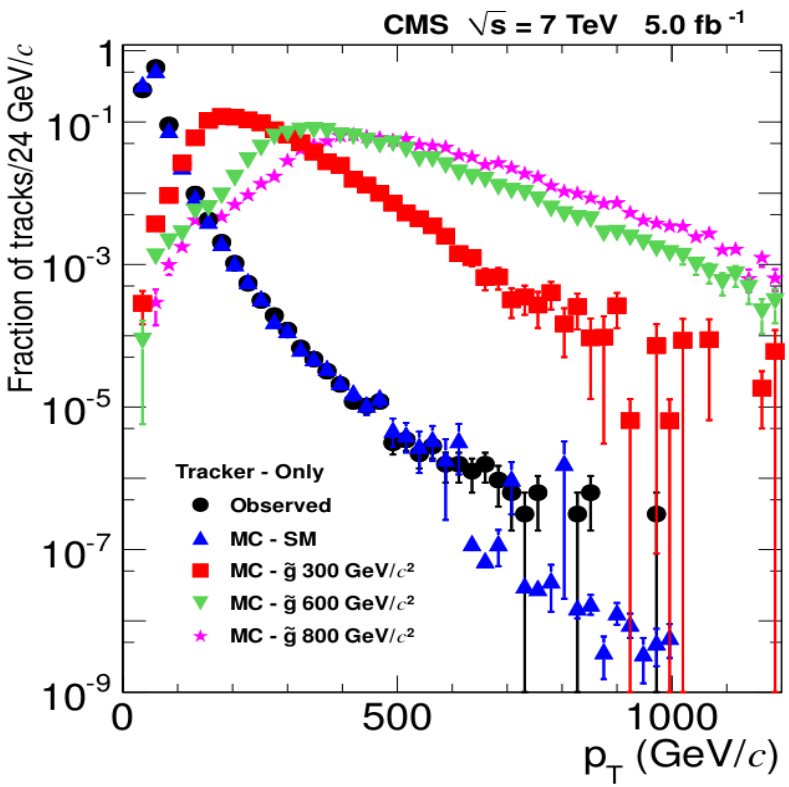
Selection

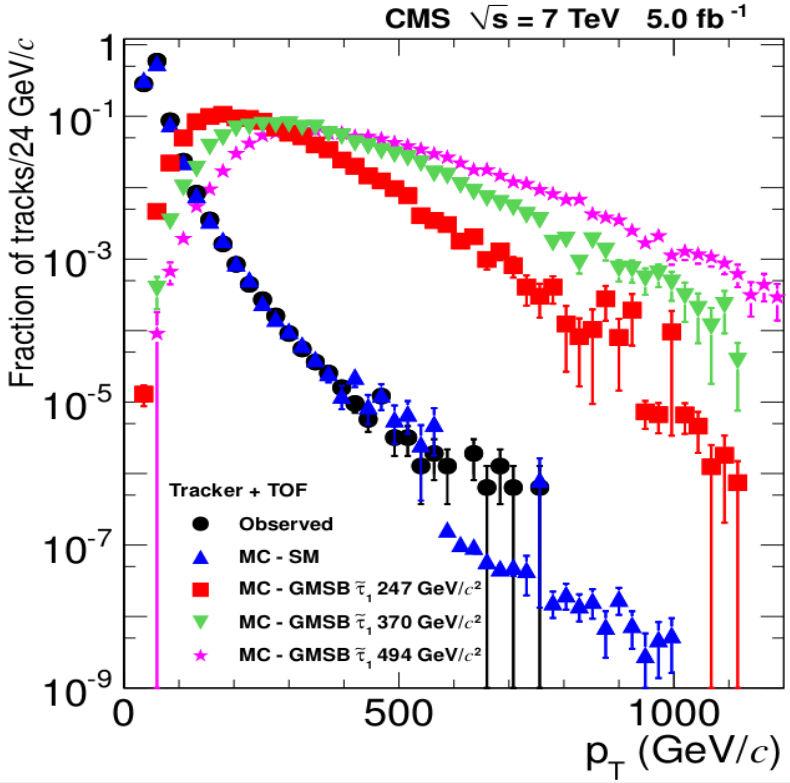
- p_T > 45 GeV/c ----------->
- track χ^2/NDOF < 5;
- $|\eta|$ < 1.5;
- 3d impact parameter < 0.5 cm;
- at least 2 hits in the pixel detector
- at least 11 hits in the inner tracker;
- less than 20% hits missing (in tracker);
- at least 6 tracker hits after cleaning;

- I_h > 3 MeV/cm (d*E*/d*x* above MIP; see next slide)

- loose isolation: in the cone ΔR < 0.3
  - less than 50 (100 Tk+TOF) GeV/c (tracks);
  - sumECAL/sumHCAL < 0.3 (0.6 Tk+TOF)

- *Tracker+TOF additional selection:*
  - $1/\beta > 1$;
  - error($1/\beta$) < 0.07;
  - NDOF($1/\beta$) > 7





dE/dx in tracker

An estimator:

$$I_h = \left(\frac{1}{N}\sum_i c_i^k\right)^{1/k} \text{ with } k = -2$$

via relation:

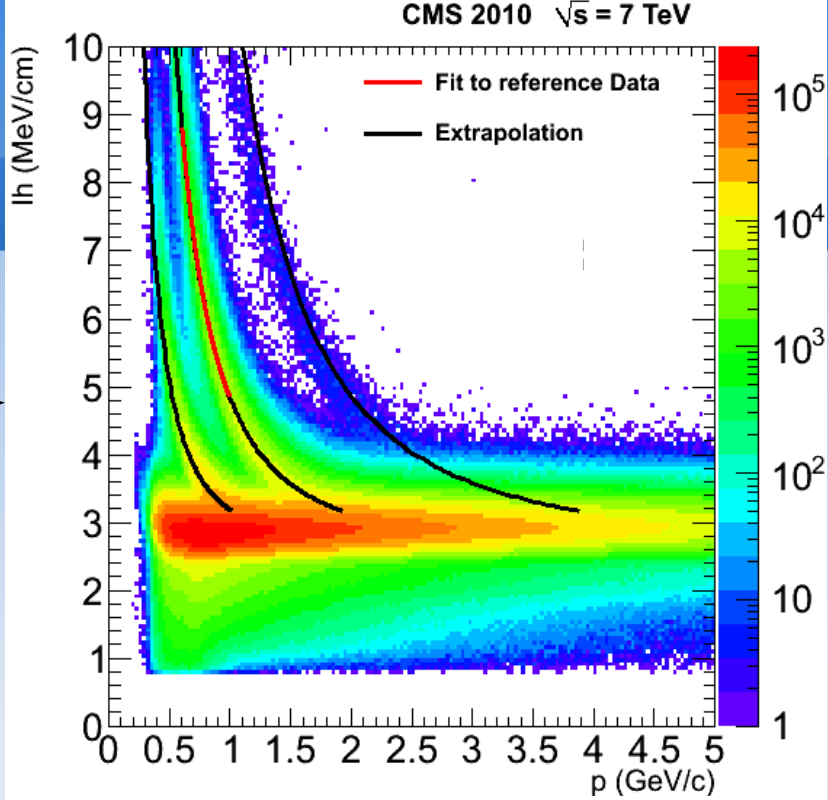
$$I_h = K\frac{m^2}{p^2} + C$$

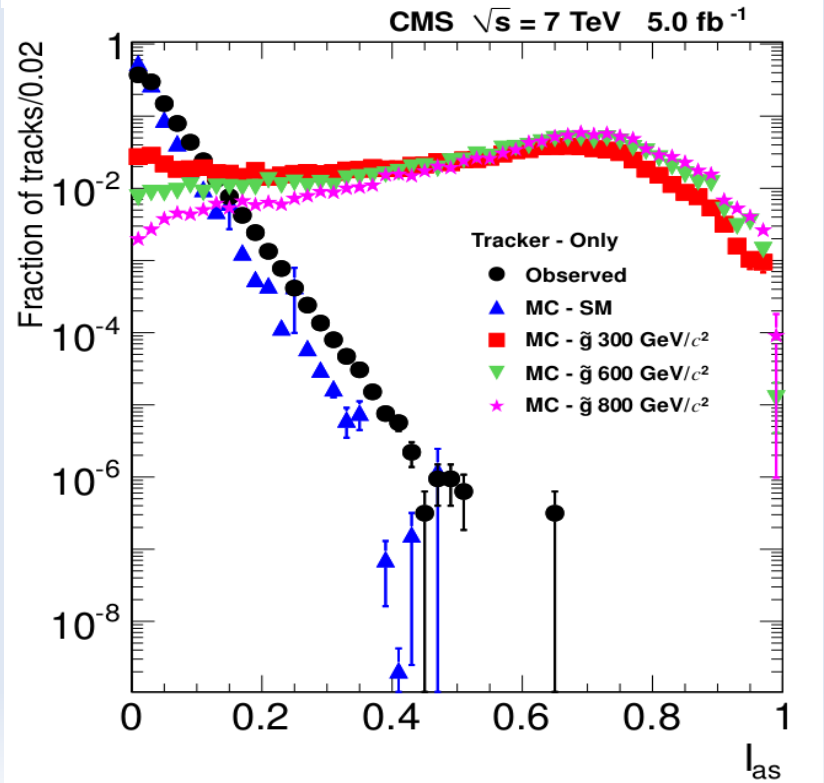
K = 2.559 MeV cm^{-1} c^{-2}
C = 2.772 MeV cm^{-1}

is used to estimate the mass of the HSCP canadidate, whereas value of a discriminator:

$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N}\left[P_i \times \left(P_i - \frac{2i-1}{2N}\right)\right]^2\right)$$

is used to obtain signal and control regions.
P_i is the probability that MIP will give signal smaller than recorded for a given hit i.





Tracker only results

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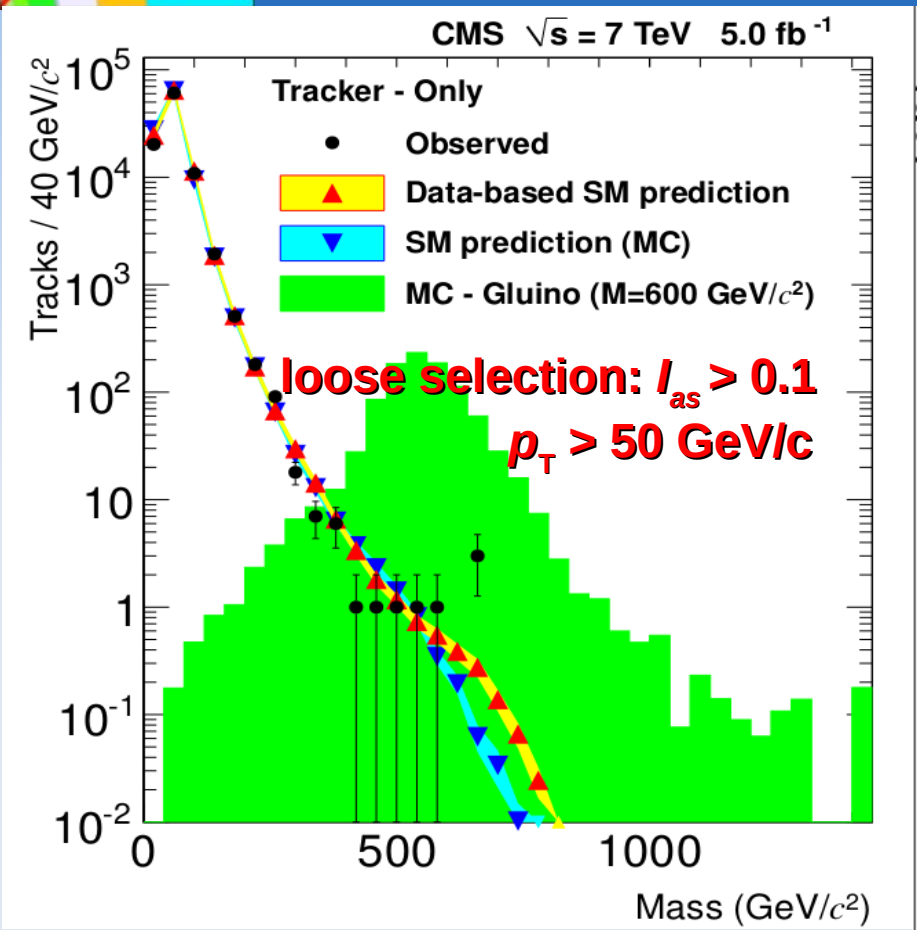

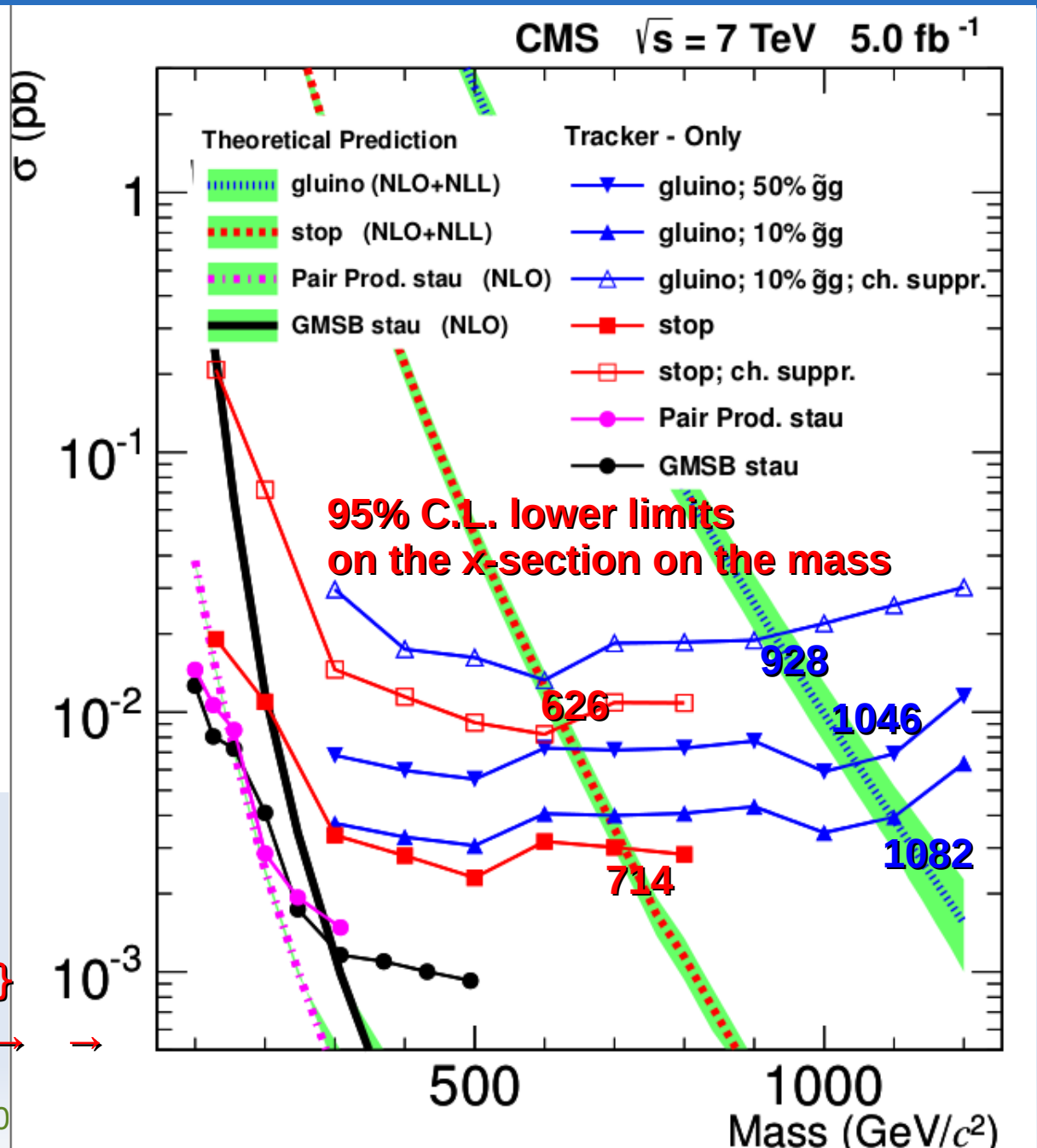

Background estimate via ABCD method because p_T and I_{as} are independent.

Counting experiment $\{p_T, I_{as}, \text{mass}(I_h)\}$

selection optimized for each point → → →

TOF by the muon system

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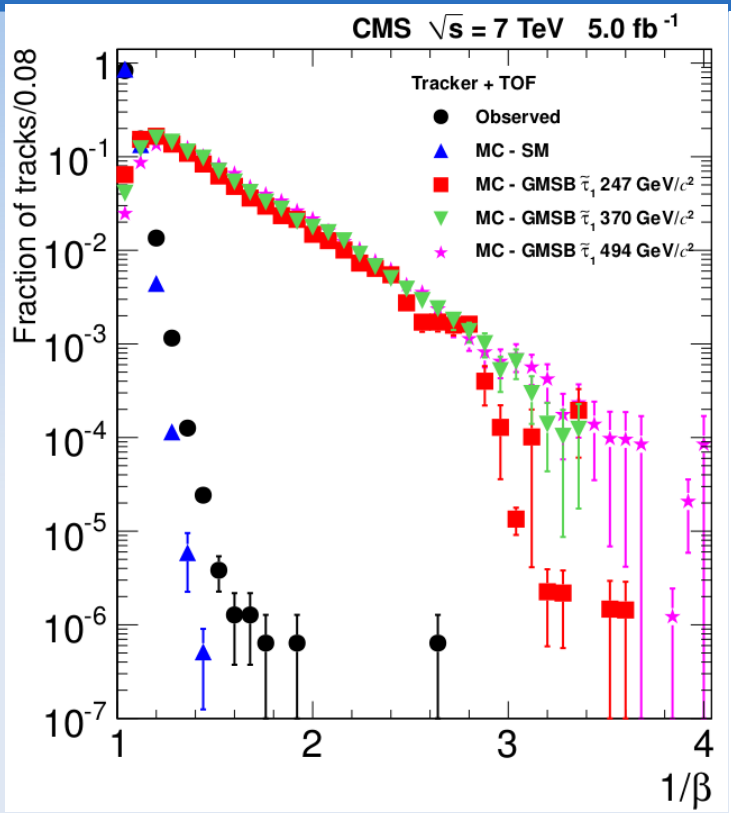

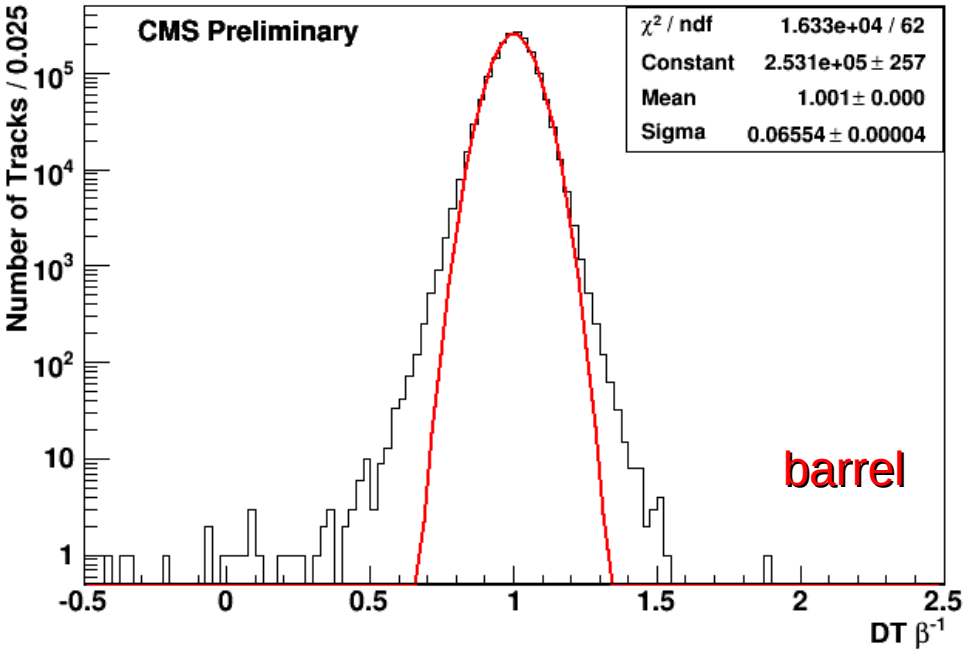

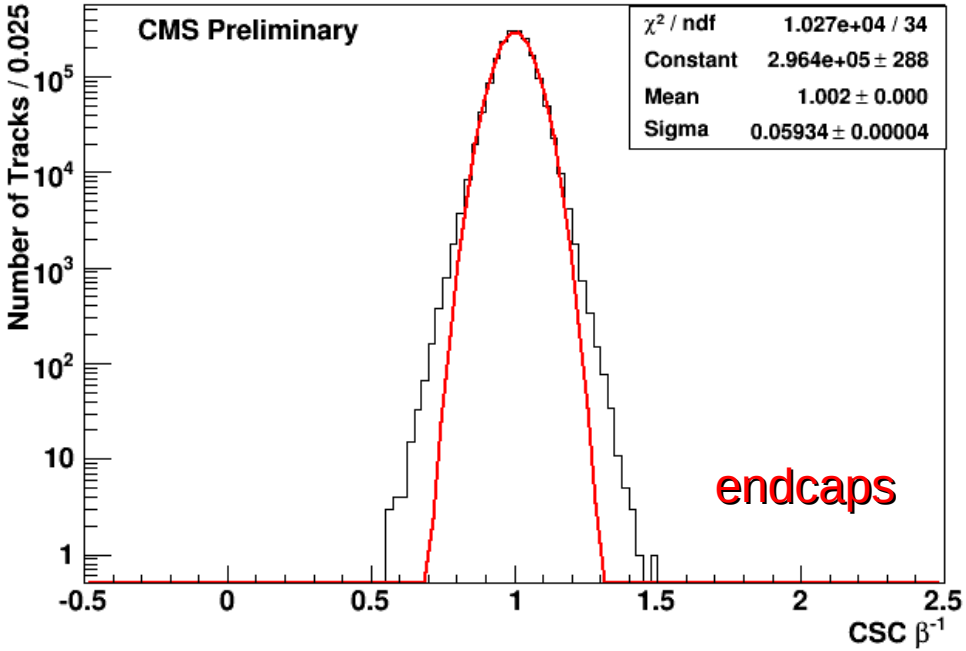

$$\frac{1}{\beta} = 1 + \frac{c\delta_t}{L}$$

Relation between candidate velocity β and the time delay δ_t at the distance L.

The third idependent measurement (if aplicable).

Tracker + TOF results

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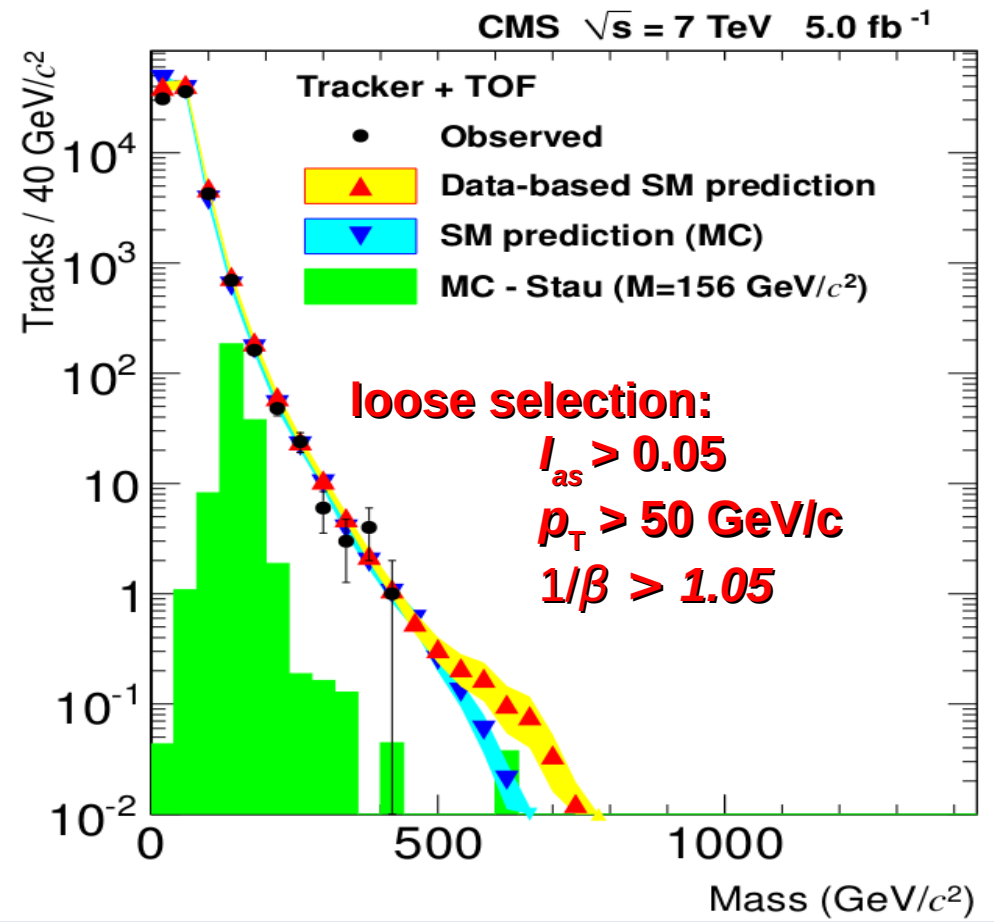
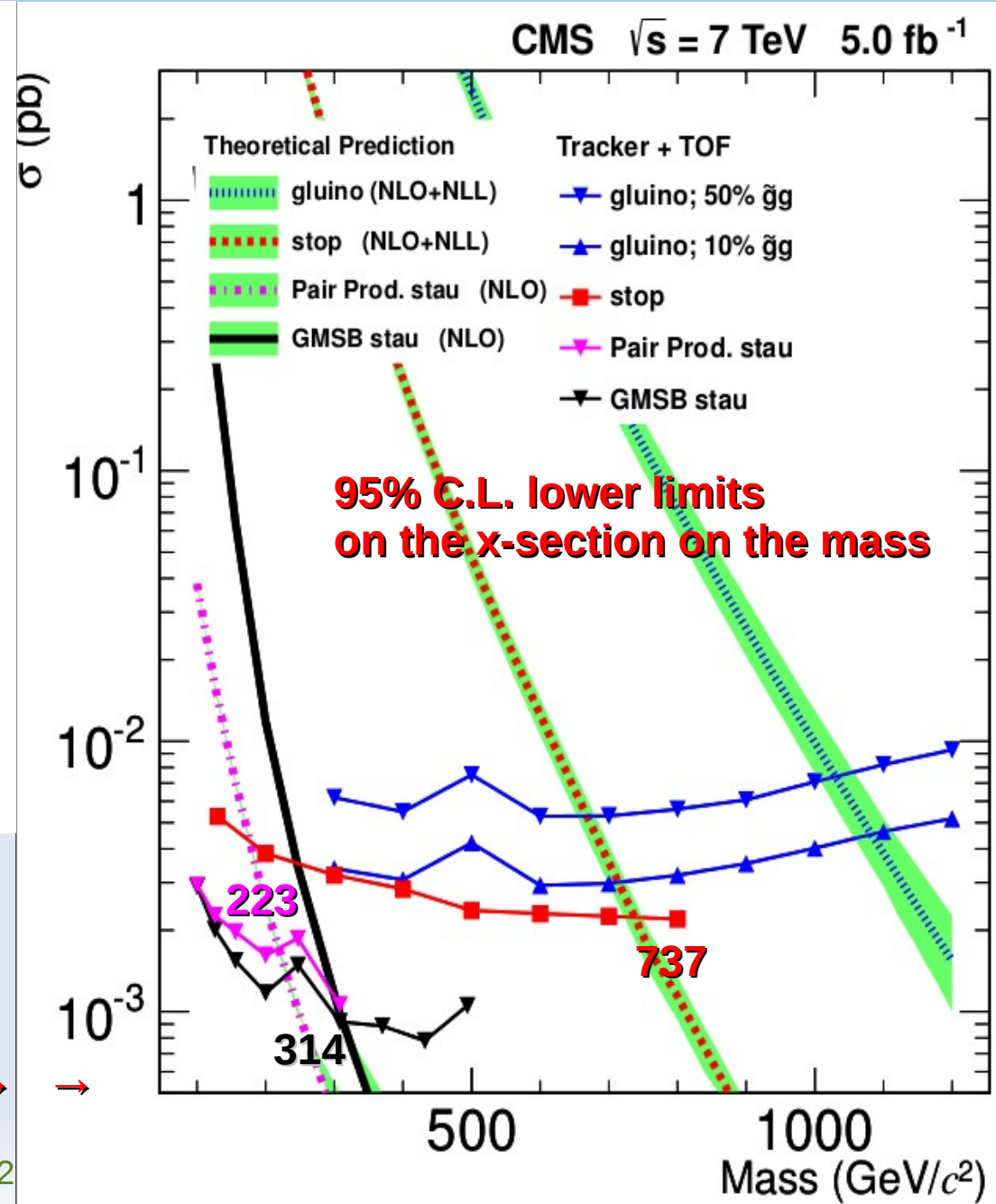


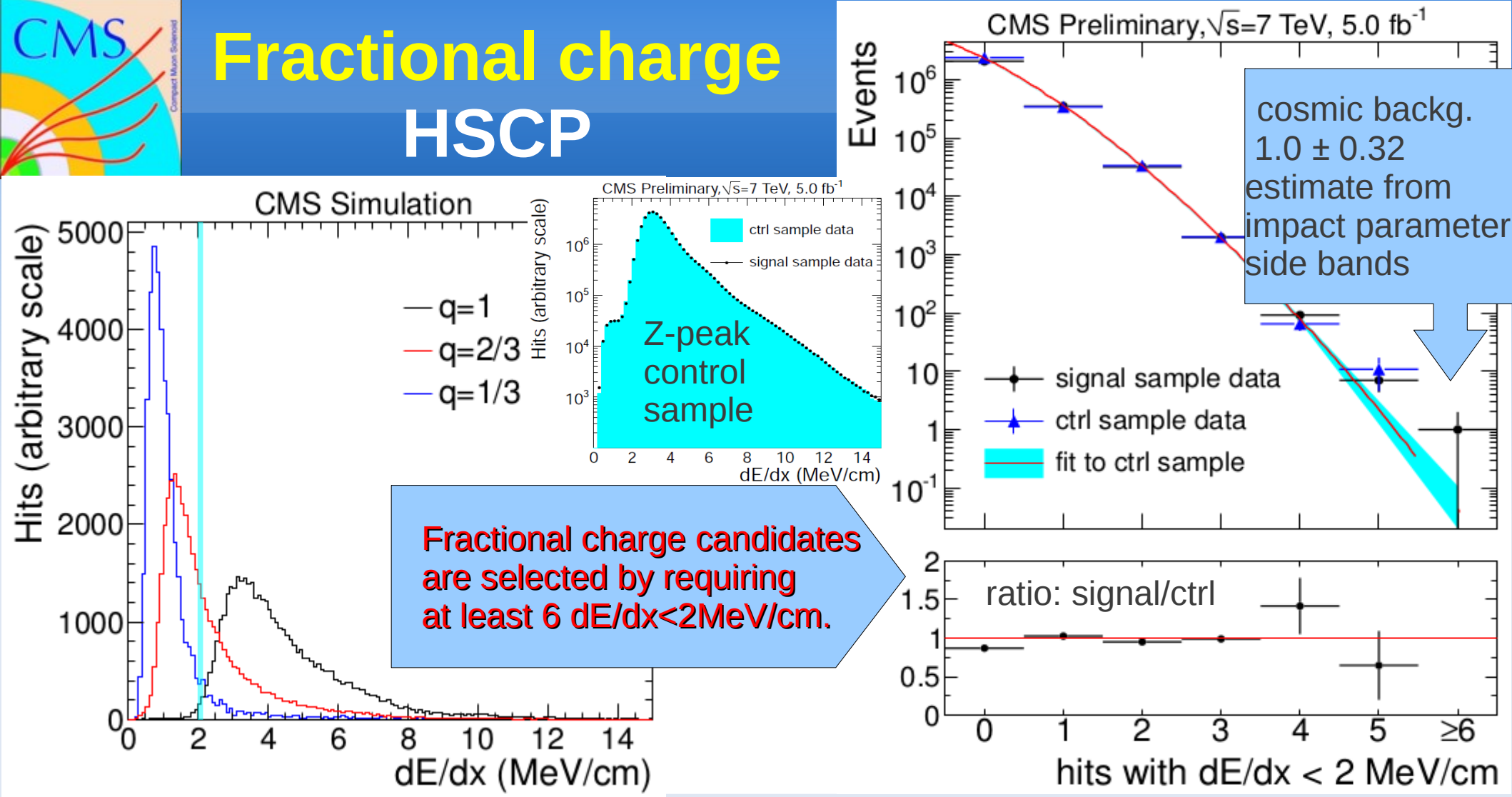
Background: extended ABCD method because p_T, I_{as} and $1/\beta$ are independent

Counting experiment $\{p_T, I_{as}, 1/\beta, \text{mass}(I_h)\}$

selection optimized for each point → → →



Fractional charge HSCP



Fractional charge candidates are selected by requiring at least 6 dE/dx<2MeV/cm.

Trigger requires p_T>40 GeV muon (the radius of curvature is invers proportional to the charge).

Pre-selection to obtain well-reconstructed tracks and to exclude cosmic ray muons.

We set limits on the cross section for Drell-Yan production of long-lived lepton-like fractional charge particles, and exclude with 95% C.L. masses below 330 GeV for q = 2/3 and below 210 GeV for q = 1/3. These are the most stringent collider limits on the production of fractional charge particles and the first collider limit on a particle of charge q = 1/3.

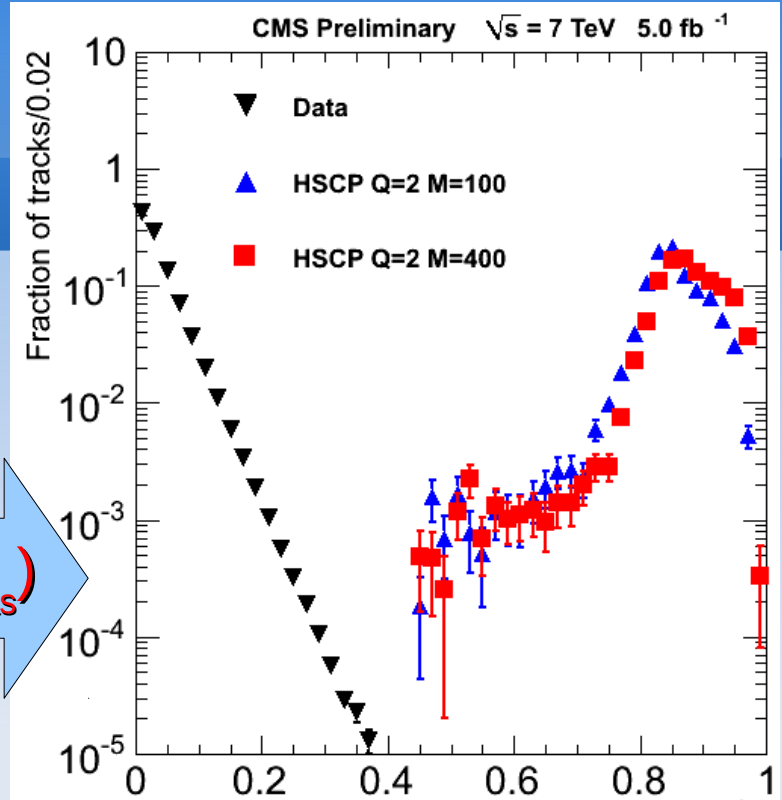
Multi charge HSCP

Trigger: muon with p_T>40 GeV

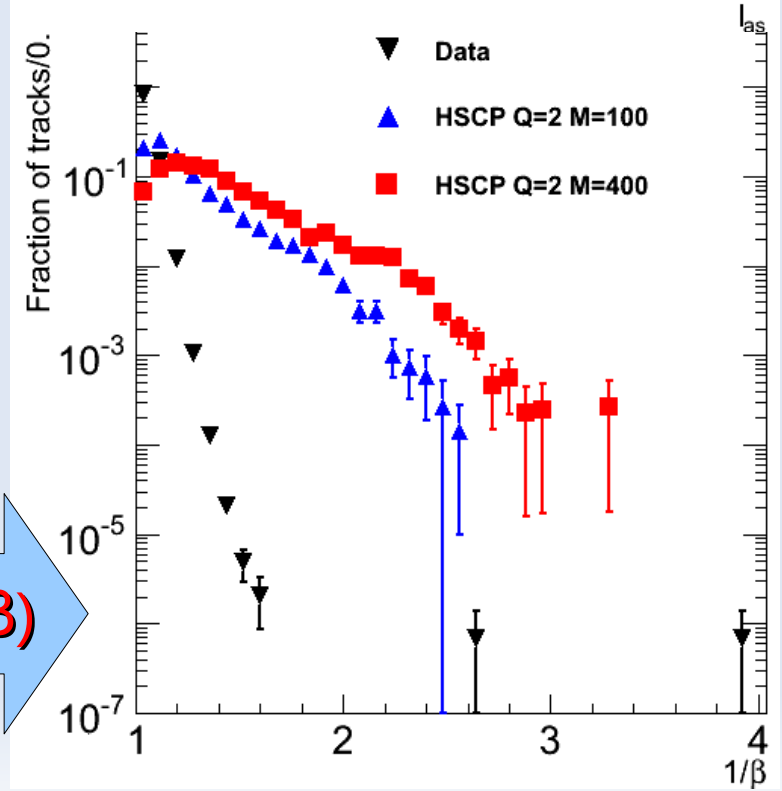
Offline: p_T>45 GeV, but the higher the particle charge the smaller the reconstructed p_T

Selection smillar to 'tracker + TOF HSCP'

Transverse momentum is not used as the discriminating variable.

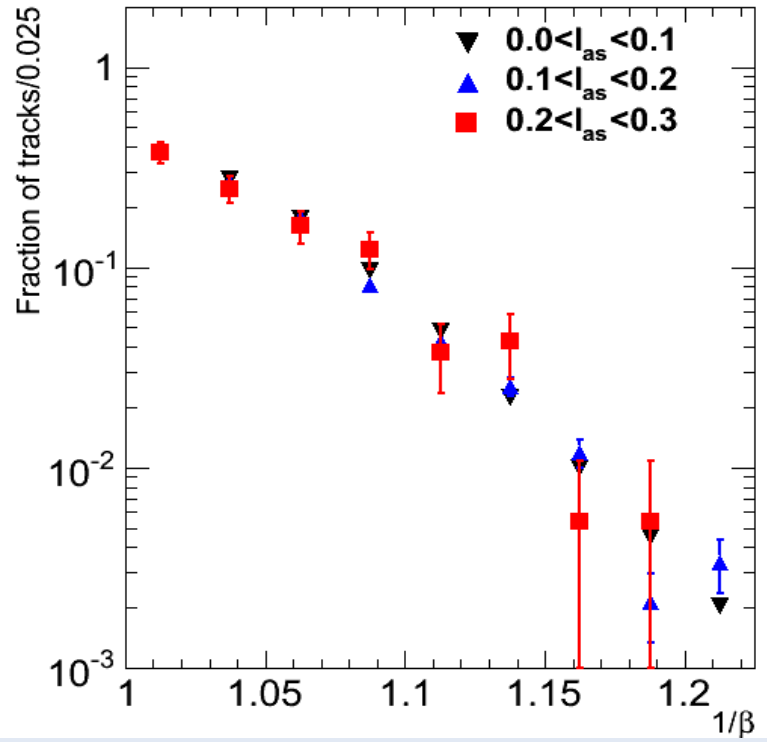


dE/dx (I_{as})



TOF (1/β)

1/β & I_{as} are independent



Multi charge HSCP results

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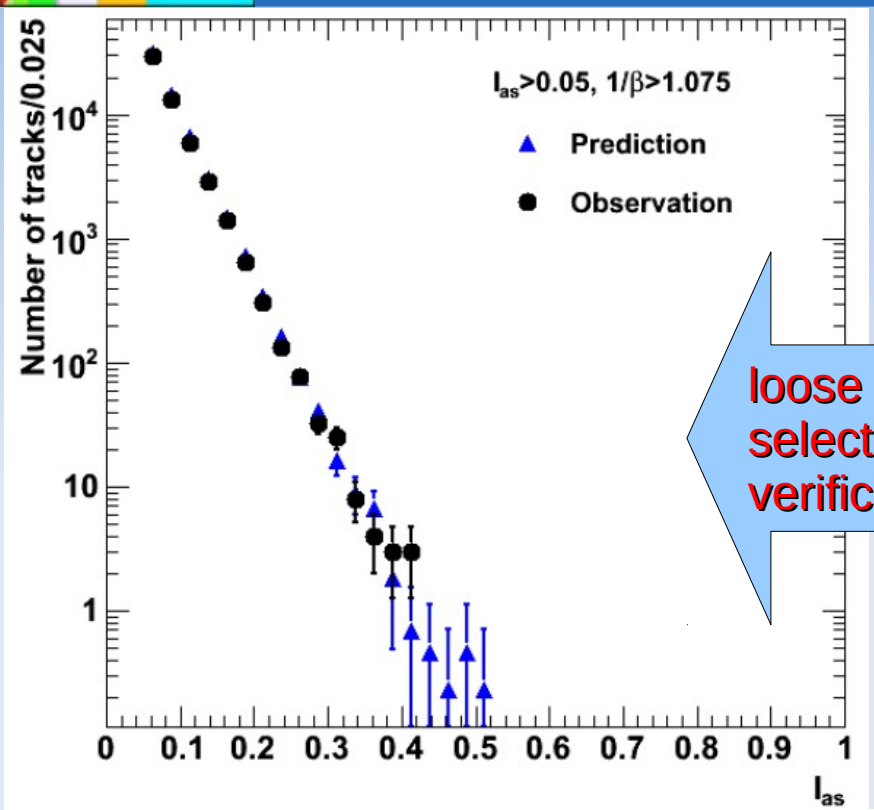
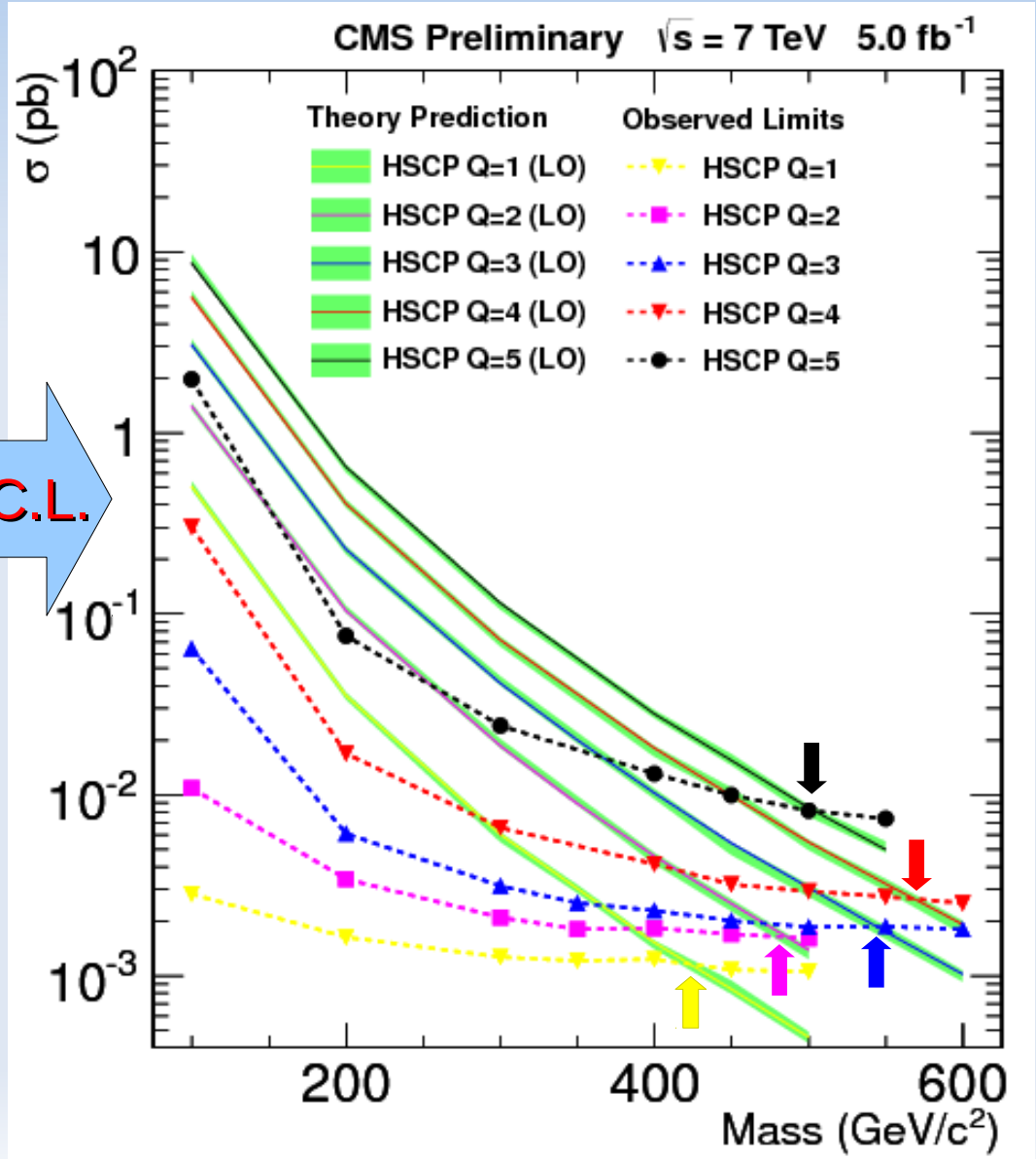


Background estimate via ABCD method because 1/β and I_{as} (dE/dx discr.) are independent.

loose selection verification

95% C.L.



Source of systematic uncertainty	Relative Uncertainty (%)
Signal efficiency	
Ionization energy loss scale	[0–1]
$1/\beta$ scale	[0–18]
Pile-up reweighting	[0–1]
Trigger efficiency	23
Track reconstruction efficiency	2
Muon reconstruction efficiency	2
Track momentum scale	1.5
Statistical uncertainty in the final selection	[1–11]
Total uncertainty on signal acceptance	[23–31]
Background prediction	20
Integrated luminosity	2.2

Summary & references

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We (CMS) have searched for various type of long-lived particles. We have not (yet) found any excess above background.
We have set stringent limits at 95% C.L. level.

[1] *Search in the displaced lepton channel for heavy resonances decaying to long-lived neutral particles;* CMS PAS EXO-11-101
[2] *Search for new physics with long-lived particles decaying to photons and missing energy;* CMS PAS EXO-11-067, arXiv:1207.0627
[3] *Search for Long-Lived Particles using Displaced Photons in pp Collisions at sqrt(s) = 7 TeV;* CMS PAS EXO-11-035
[4] *Search for stopped long-lived particles produced in pp collisions at sqrt(s) = 7 TeV*; arXiv:1207.0106, 10.1007/JHEP08(2012)026
[5] *Search for heavy long-lived charged particles in pp collisions at sqrt(s) = 7 TeV*; arXiv:1205.0272, 10.1016/Phys.Let.B.2012.06.023
[6] *Search for fractionally charged particles in pp collisions using 2011 CMS data;* CMS PAS EXO-11-074
[7] *Search for multi-charged Heavy Stable Charged Particles at sqrt(s) = 7 TeV;* CMS PAS EXO-11-090

`https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults`

Dark matter particles are also long-lived

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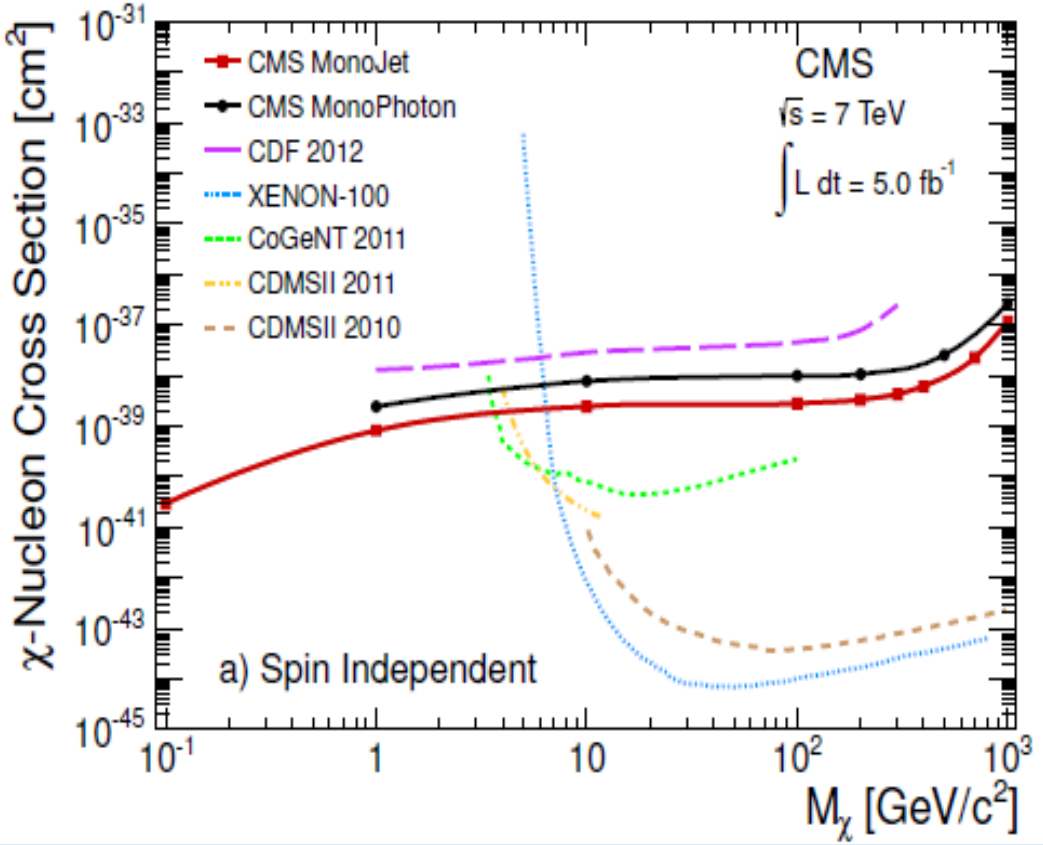

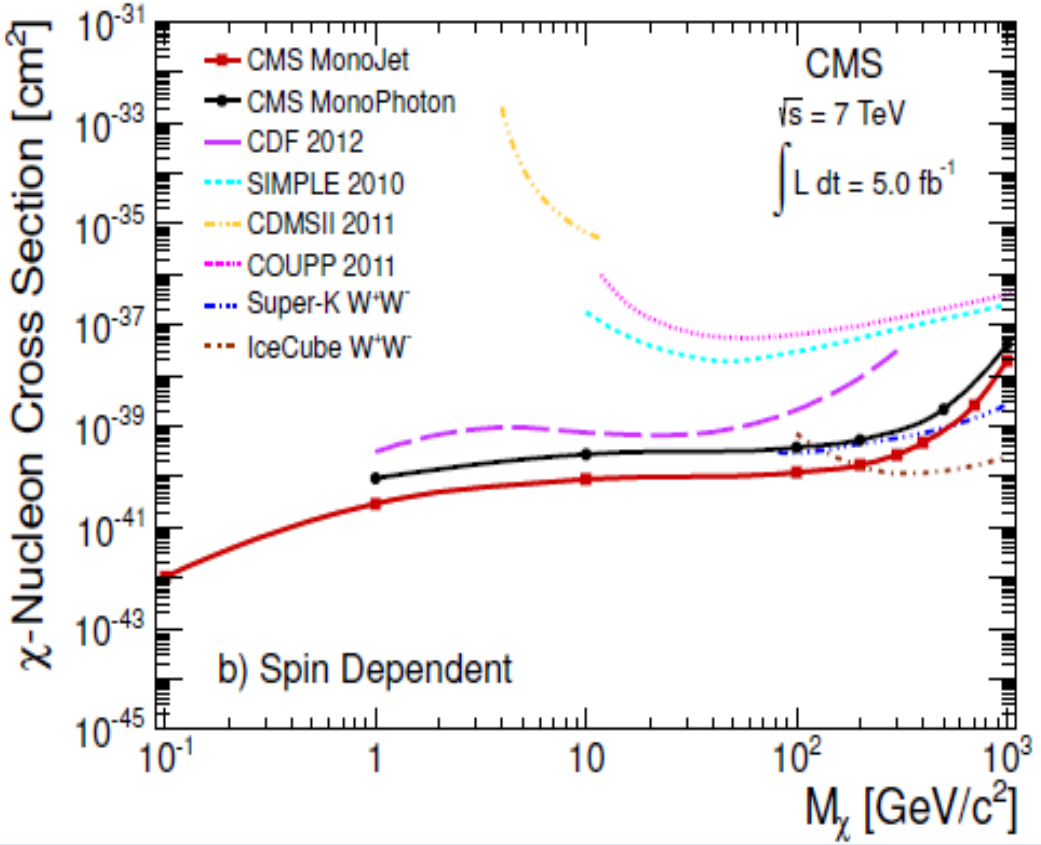

[8] *Search for Dark Matter and Large Extra Dimensions in pp Collisions Yielding a Photon and Missing Transverse Energy;* arXiv:1204.0821, Phys. Rev. Lett. 108 (2012) 261803
[9] *Search for dark matter and large extra dimensions in monojet events in pp collisions at sqrt(s) = 7 TeV;* arXiv:1206.5663