Long-lived particles and other unusual signatures

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Terascale school @ DESY
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Before we start…

- **This talk is**
  - **Not exhaustive**
  - **Not about theory motivation for LL**
  - **Biased toward what I know (CMS)**
  - **About experimental techniques used @LHC**
  - **Not exhaustive at all !**

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Why searching for LL particles ?

- Predicted by many BSM models:
  - Split SUSY, GMSB, AMSB, pMSSM, Hidden Valley, RPV SUSY, UED, …
  - Long lifetime is a consequence of :
    - a new symmetry conservation (R-Parity, KK-Parity)
    - a small decay phase space

- Constraints from prompt particles searches generally don't apply.
  - Lifetime may explain why SUSY was not yet discovered at the LHC ☺

- Who knows what BSM looks like
  - Search in every single corner
  - Model independent searches when possible
  - Agnostic searches when possible

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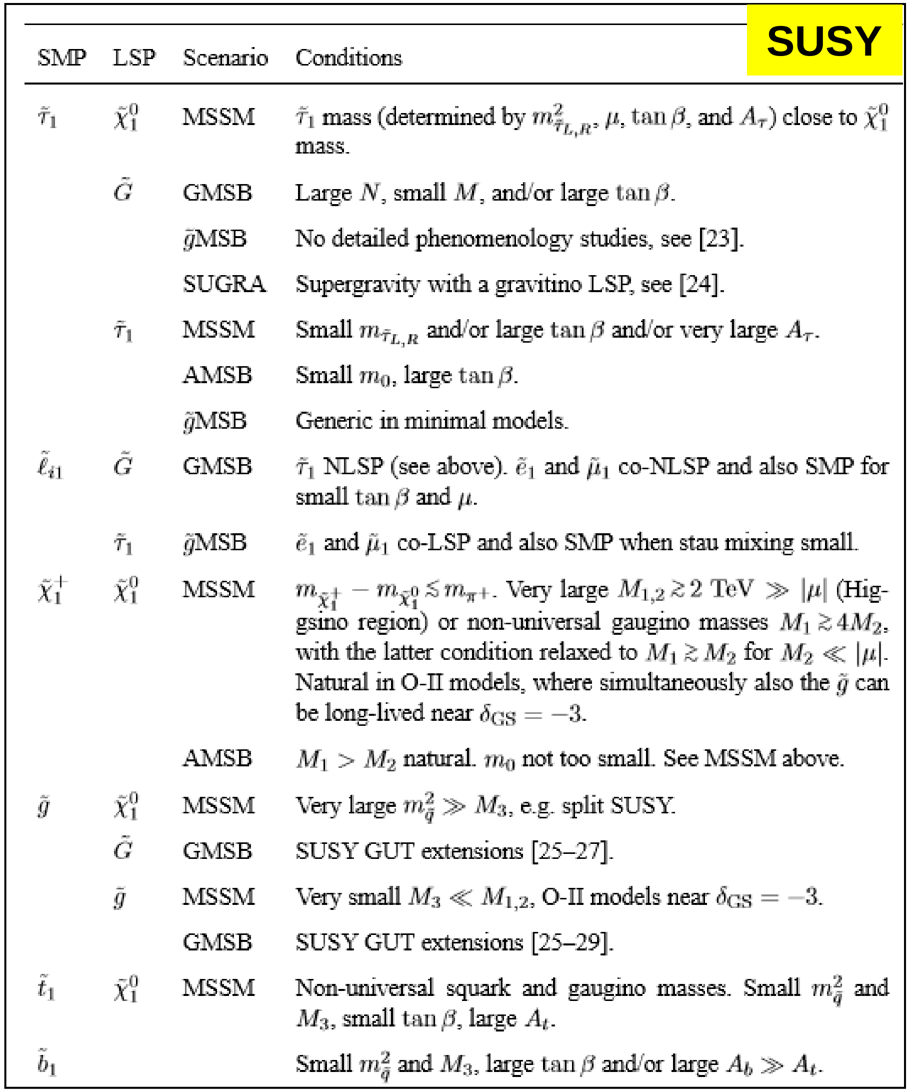
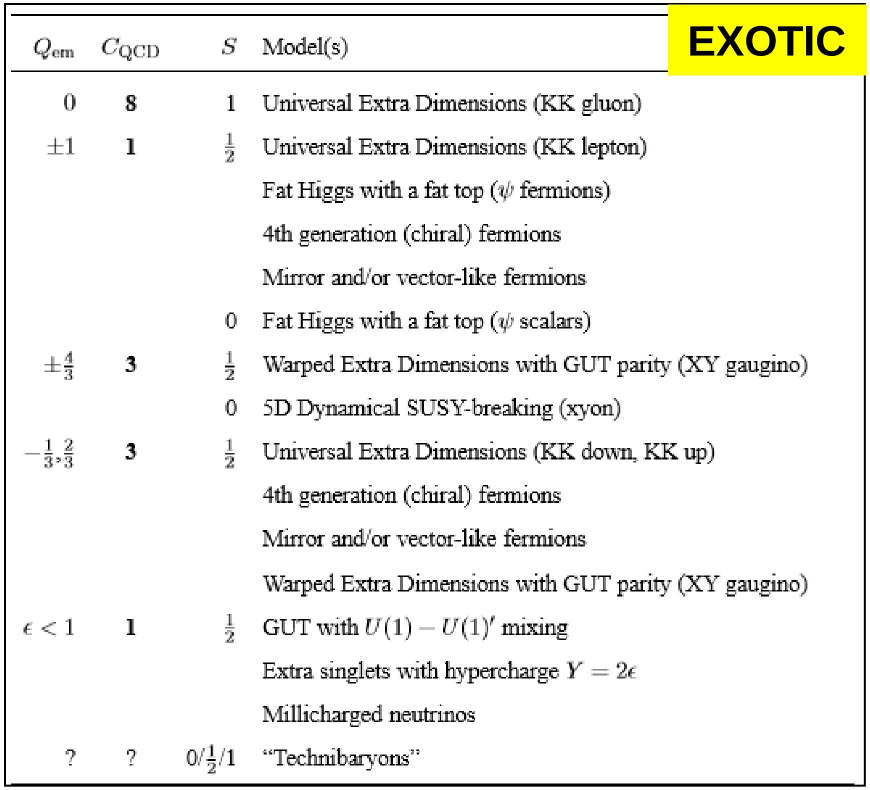
A few models

Non-exhaustive list of models predicting LL charged particles



SUSY

SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{\mathrm{GS}} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{\mathrm{GS}} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.



EXOTIC

Q_{em}	C_{QCD}	S	Model(s)
0	**8**	1	Universal Extra Dimensions (KK gluon)
±1	**1**	$\frac{1}{2}$	Universal Extra Dimensions (KK lepton)
			Fat Higgs with a fat top (ψ fermions)
			4th generation (chiral) fermions
			Mirror and/or vector-like fermions
		0	Fat Higgs with a fat top (ψ scalars)
$\pm\frac{4}{3}$	**3**	$\frac{1}{2}$	Warped Extra Dimensions with GUT parity (XY gaugino)
		0	5D Dynamical SUSY-breaking (xyon)
$-\frac{1}{3},\frac{2}{3}$	**3**	$\frac{1}{2}$	Universal Extra Dimensions (KK down, KK up)
			4th generation (chiral) fermions
			Mirror and/or vector-like fermions
			Warped Extra Dimensions with GUT parity (XY gaugino)
$\epsilon < 1$	**1**	$\frac{1}{2}$	GUT with $U(1) - U(1)'$ mixing
			Extra singlets with hypercharge $Y = 2\epsilon$
			Millicharged neutrinos
?	?	$0/\frac{1}{2}/1$	"Technibaryons"

+++ many models predicting neutral LL
+++ other more exotic models/particles (monopoles, quirks, dyons, etc.)

arXiv:hep-ph/0611040 **Fairbairn et al.**

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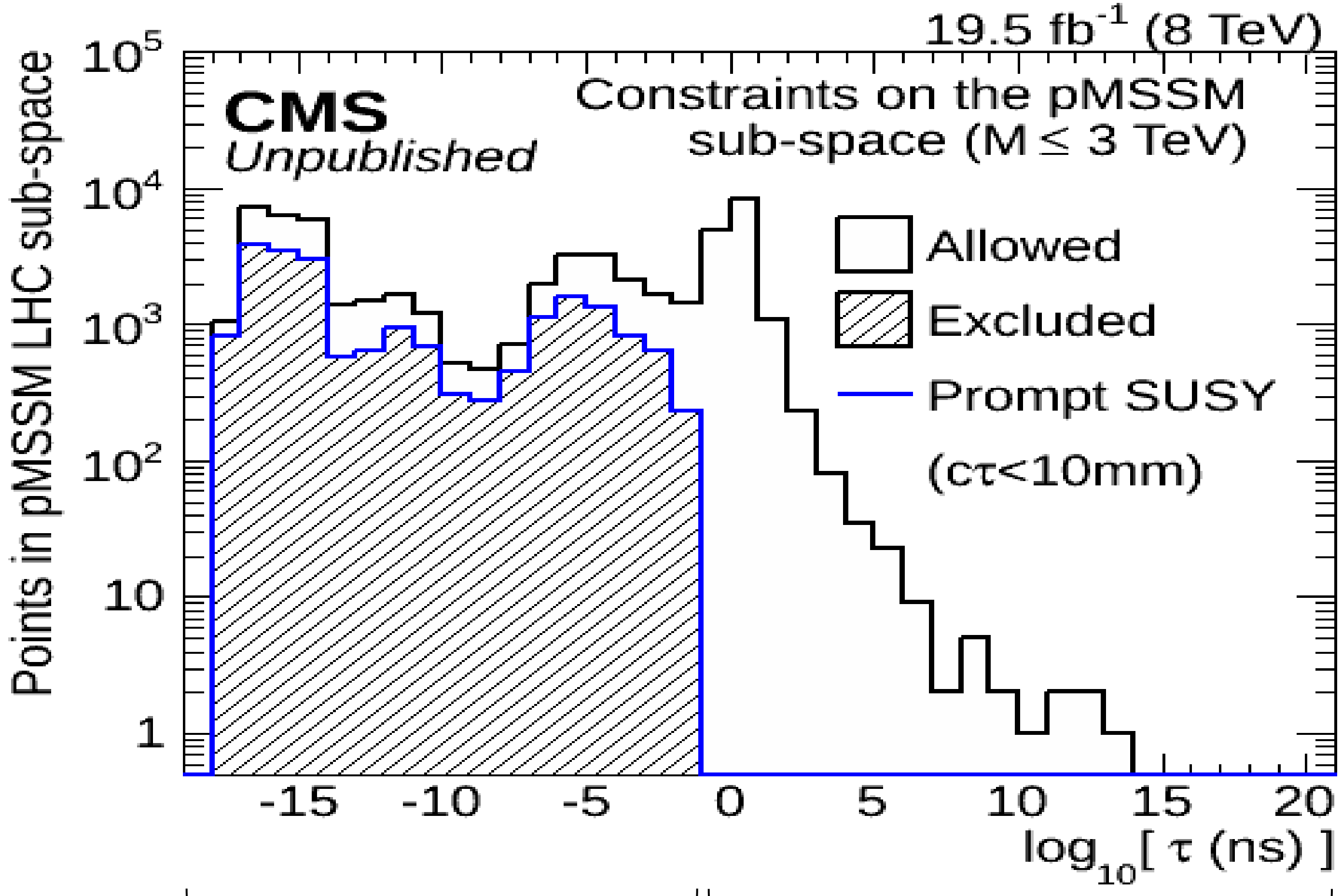
Why searching for LL particles ?

Example with the pMSSM model (generic R-parity conserving SUSY)



Each entry correspond to a point in the 19D pMSSM parameter space

→ each point is a different SUSY model

NLSP (chargino) lifetime

Promptly decaying

cτ>1cm → Long-lived
27% of the models

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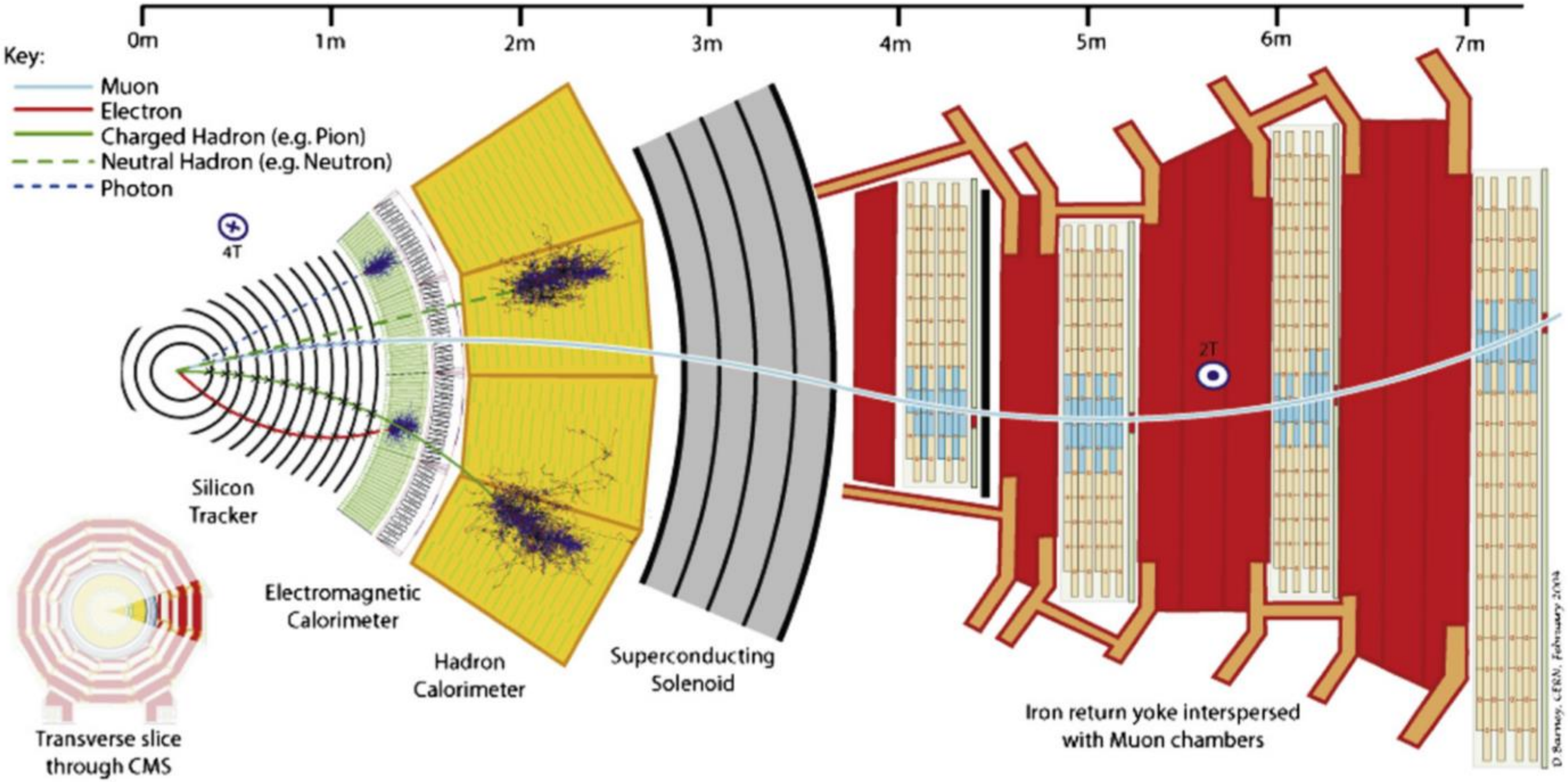
How to detect LL particles ?

- **Modern detectors are**
  - Made of layers optimized to reconstruct and identify SM particles
    - Photons, Electrons, Hadrons, Muons, Neutrino (through MET)



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How to detect LL particles ?

- **Modern detectors are**
  - Made of layers optimized to reconstruct and identify SM particles
    - Photons, Electrons, Hadrons, Muons, Neutrino (through MET)

  - Very efficient for SM physics measurements
  - Very efficient to search for BSM particles
    - Promptly decaying to SM particles (leptons or jets)
    - Being invisible (but detectable via MET like SM neutrinos)

  - **Searching for Long-Lived BSM particles is more chalenging…**
    - **Strategy depends on the particle type and lifetime**

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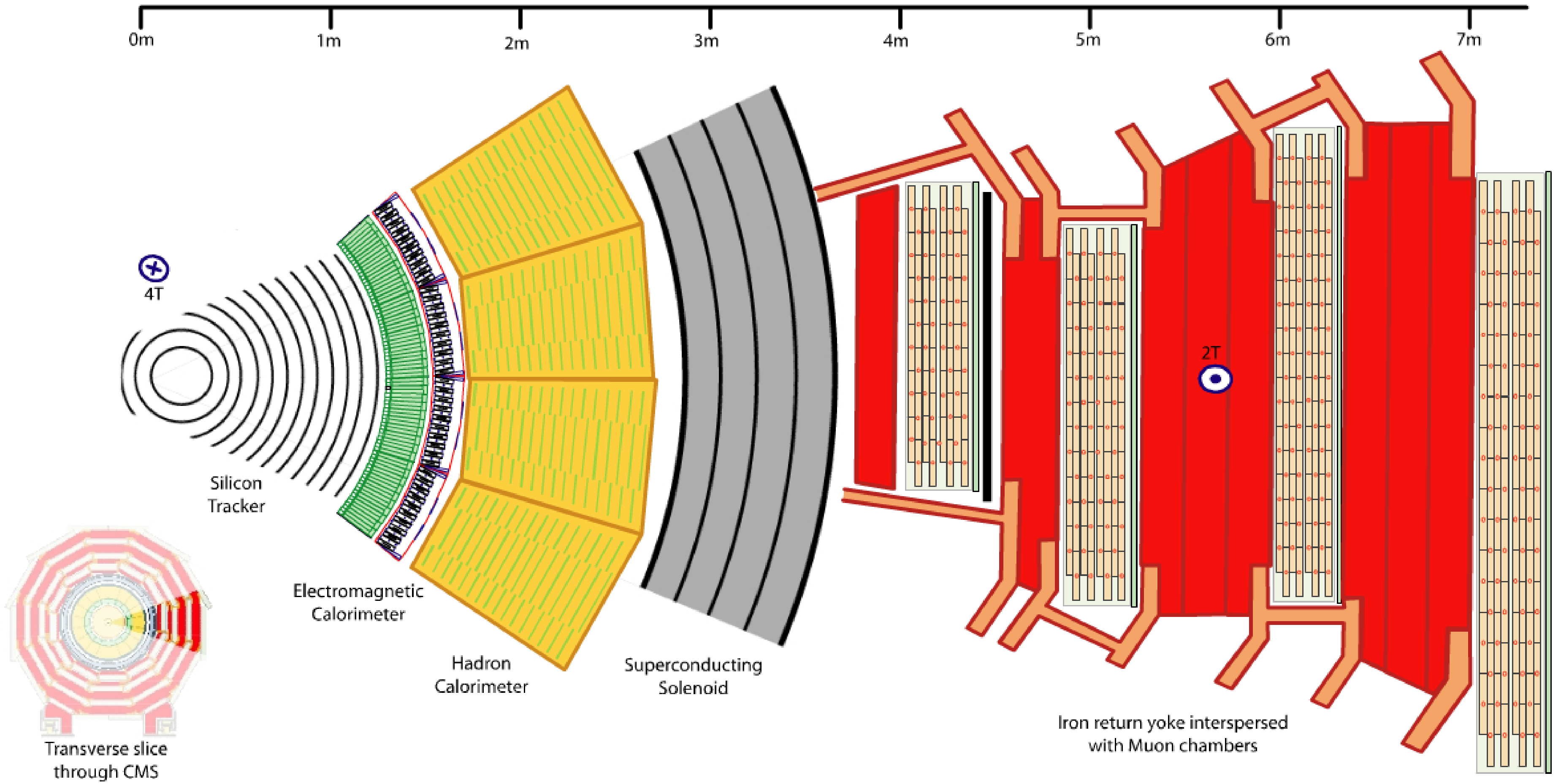
How to detect LL particles ?



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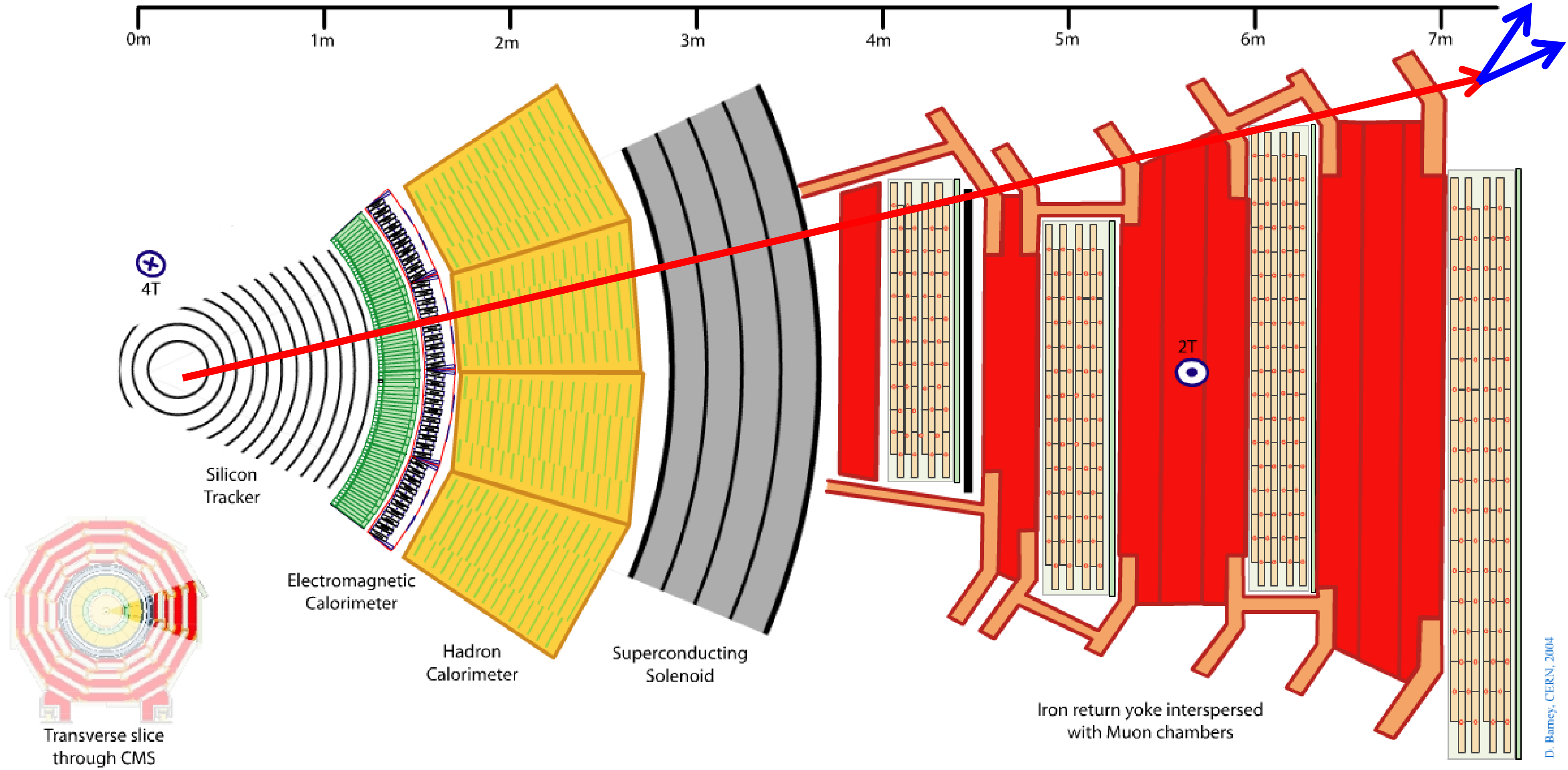
How to detect LL particles ?

Cτ ≥ O(m)

Quasi-stable

Searches based on ionization/velocity/calo



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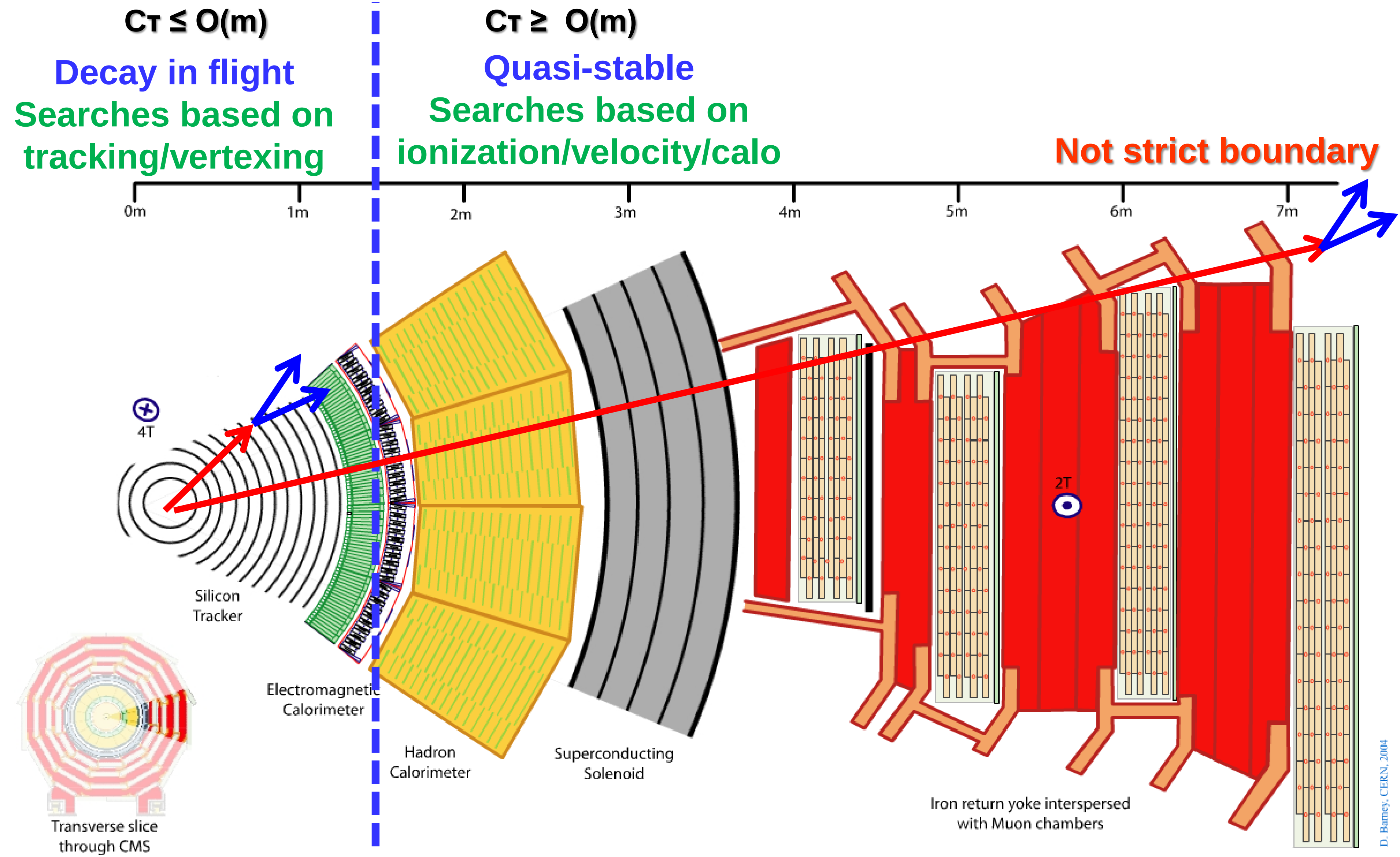

Cτ ≤ O(m)

Decay in flight

Searches based on tracking/vertexing

Cτ ≥ O(m)

Quasi-stable

Searches based on ionization/velocity/calo

Not strict boundary

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How to detect LL particles ?

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super EXOTIC

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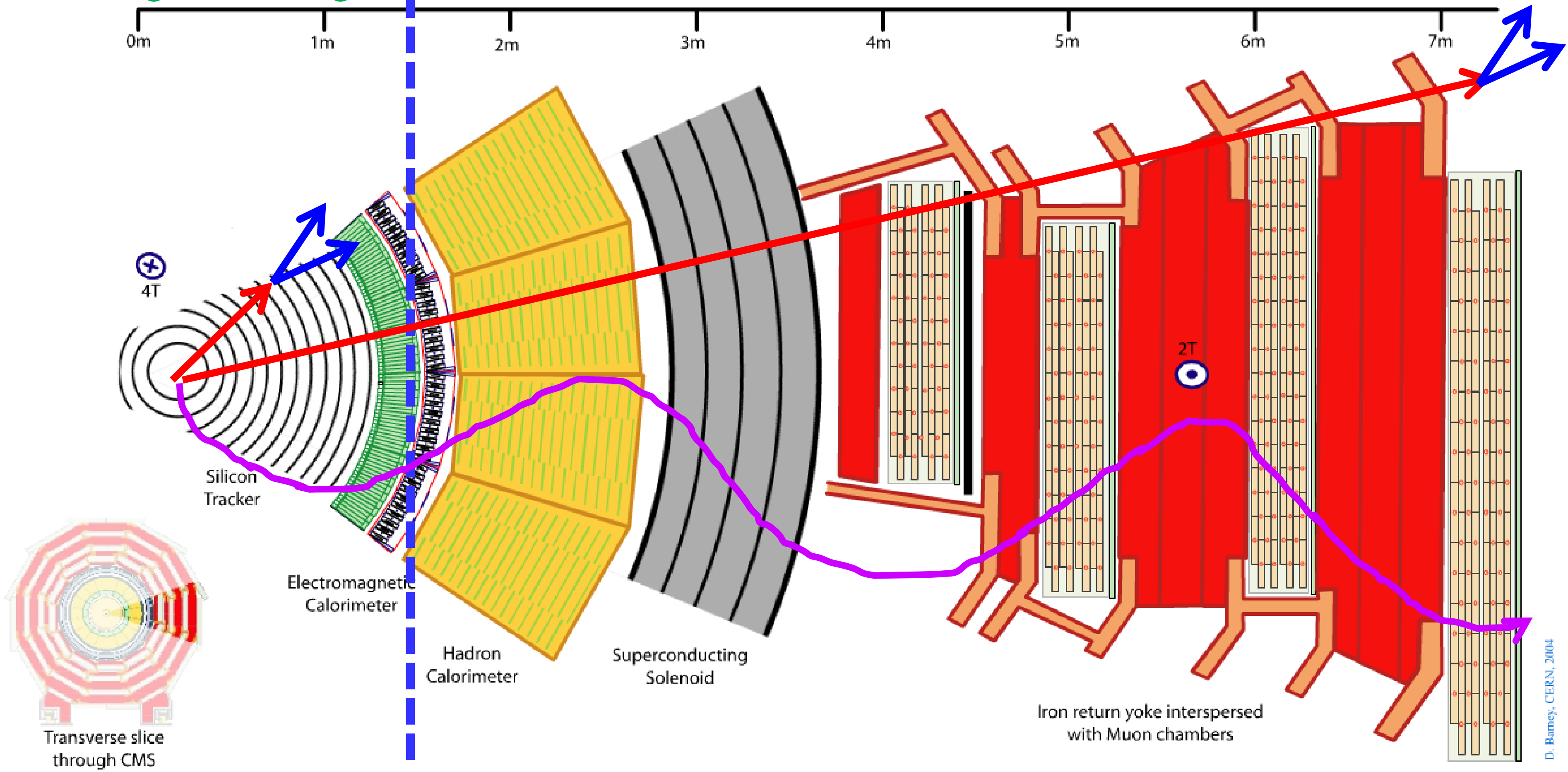

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Outline

- **Introduction to LL physics (Why ? How ?)** ✓

- **Searches for LL particles decaying OUTSIDE the detector**
  - **Neutral**
  - **Charged**

- **Searches for LL particles decaying INSIDE the detector**
  - **Charged**
  - **Neutral**

- **Super exotic particles**

- **Summary**

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- **Summary**

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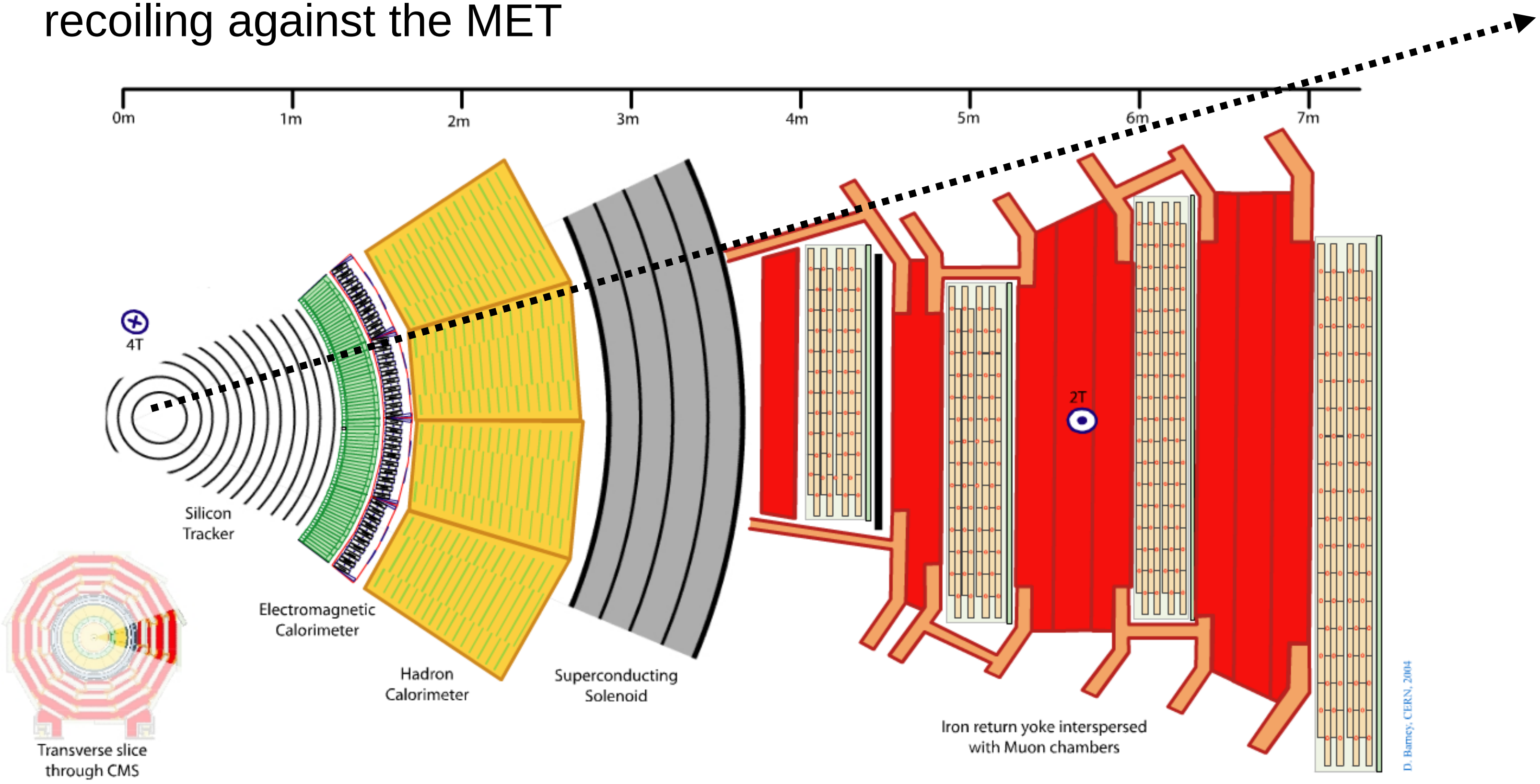
Neutral long-lived particles

- Direct detection is not possible
    - Similar to SM neutrino

- Indirect observation via MET
    - Covered by many SUSY/DM searches looking for mono-X objects recoiling against the MET



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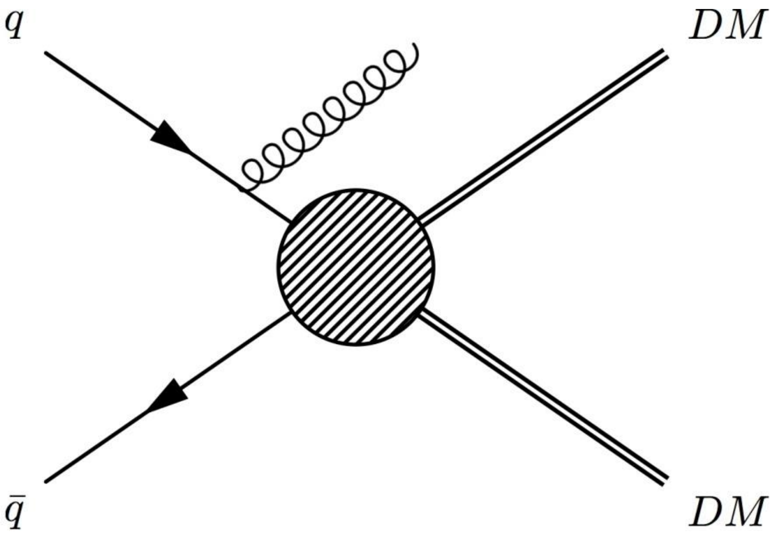
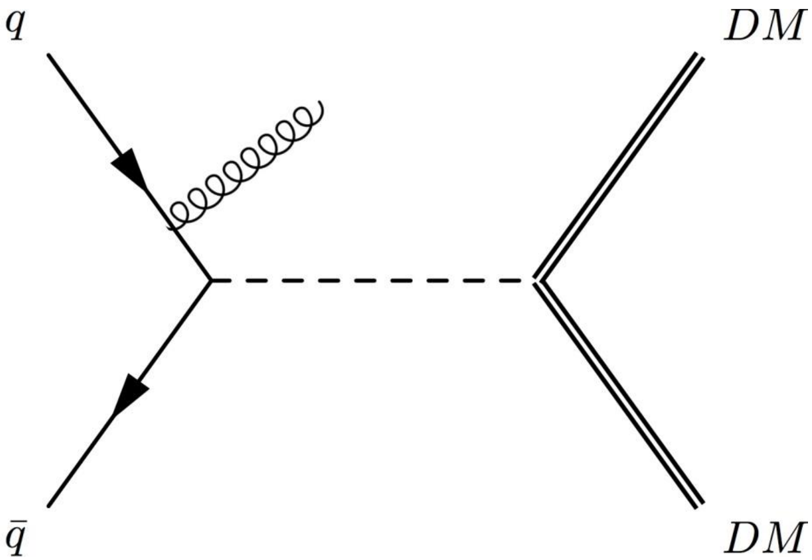
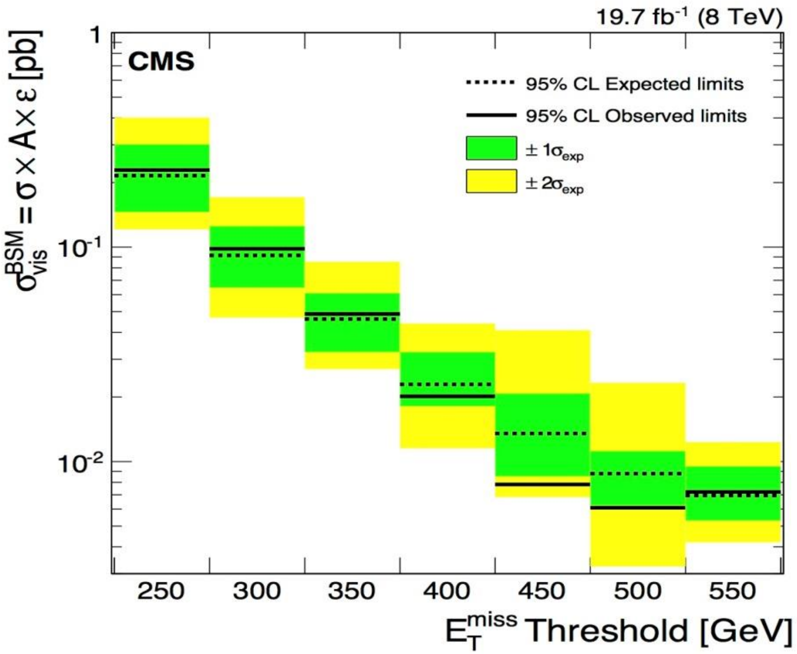
Mono Jet search





- The CMS monojet search (arXiv:1408.3583) explicitly limits pair production of dark matter particles accompanied by ISR jet.
- The same limits apply to neutral LL particles that decay outside CMS ($R \gtrsim 10$ m).



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What are we talking about ?

A rich phenomenology, dictating the experimental signature

- **Heavy**
- **Stable**
- **Charged**

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  Slow particle → $\beta<1$

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- **Heavy**
  Slow particle → $\beta<1$

- **Stable → Long-lived**
  1) Escape the tracker → $c\tau > O(1)$m
  2) Escape the detector → $c\tau > O(10)$m
  3) Stop in → Asynchronous decay → $c\tau > O(100)$m

- **Charged**

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- **Charged**
  Electric → lepton-like
  |Q|<<e, |Q|<e, |Q|=e, |Q|>e, |Q|>>e
  Color → hadron-like → R-hadron properties ?!
  (gluinoball, charge flip, interaction w/ matter, etc.)

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  IONIZATION
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Terminology : HSCP=SMP=ChaMP=CmLLP=…

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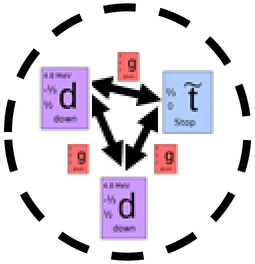
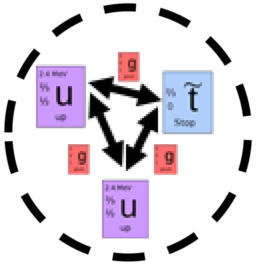
Rhadron Charge fliping



Stop R-Hadron

Q= 2/3+2/3-1/3=**+1**



Stop R-Hadron

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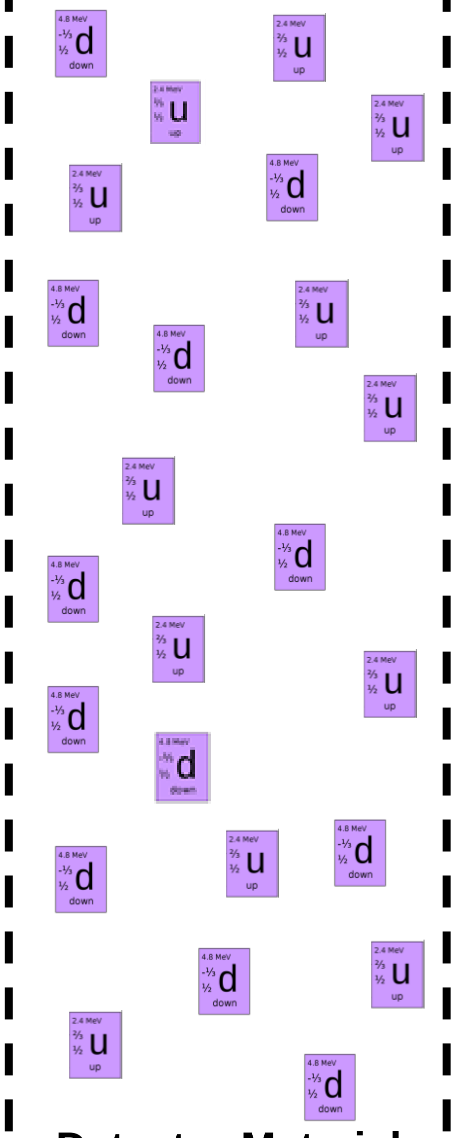
Detector Material



Detector Material

Stop R-Hadron

Q= 2/3-1/3-1/3=**0**

Stop R-Hadron

Q= 2/3+2/3+2/3=**+2**

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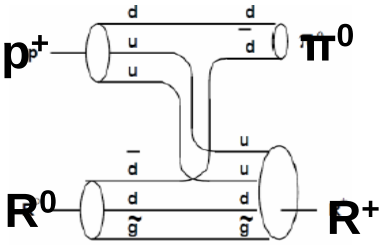
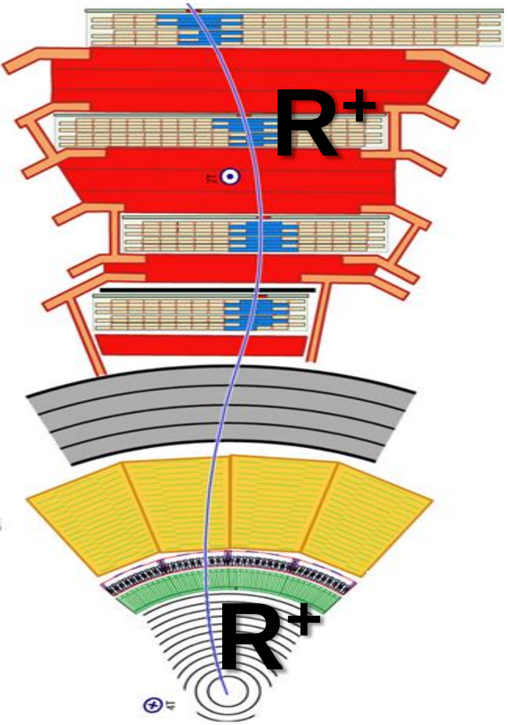
ATLAS/CMS Detectors for HSCP

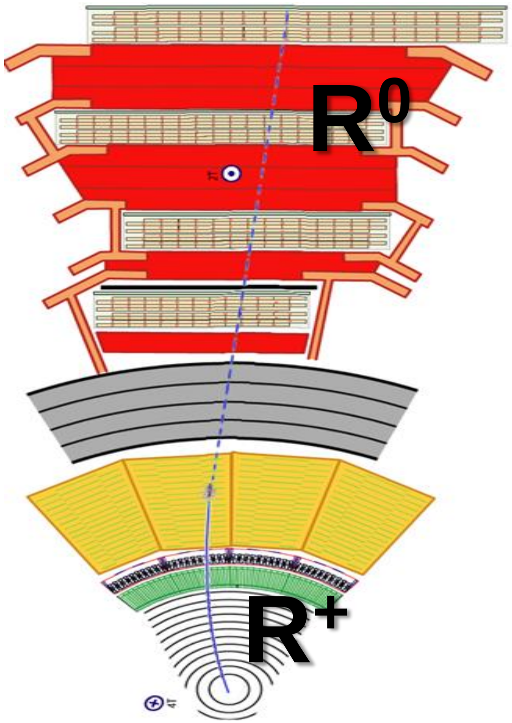
- R-Hadron charge can flip due to nuclear interaction
- Many possible R-Hadron interaction models
  → some predicts that flipping to neutral is more likely
- Gluino ball fraction (f) is also unknown (even if 10% in pythia)



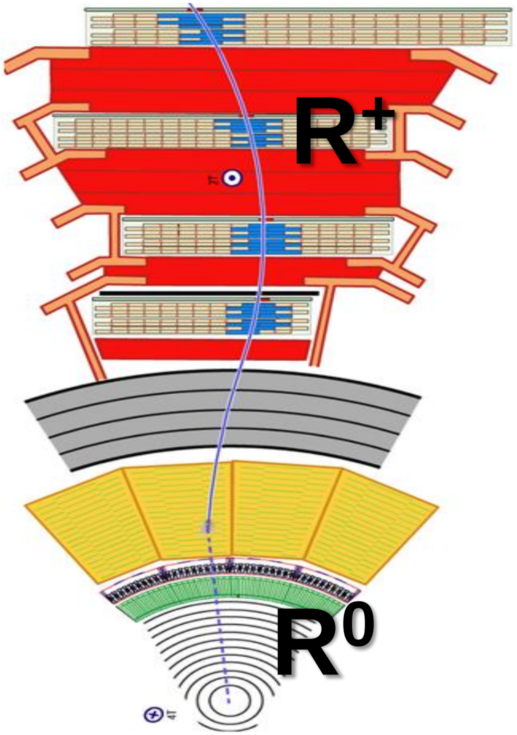
Stay charge all along



Charged in tracker only



Charged in muon syst. only



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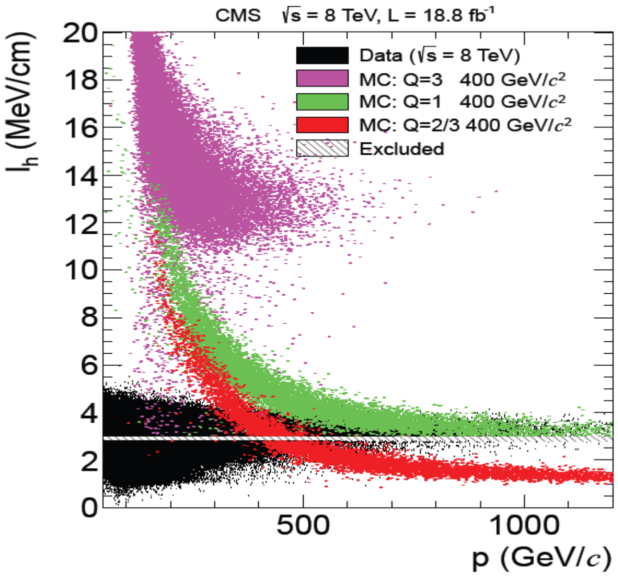
Experimental Signature

IONIZING

dE/dx

$$\frac{dE}{dx} \approx Q^2\left(\frac{A}{\beta^2} + B\right) \text{ for } \beta<<1$$

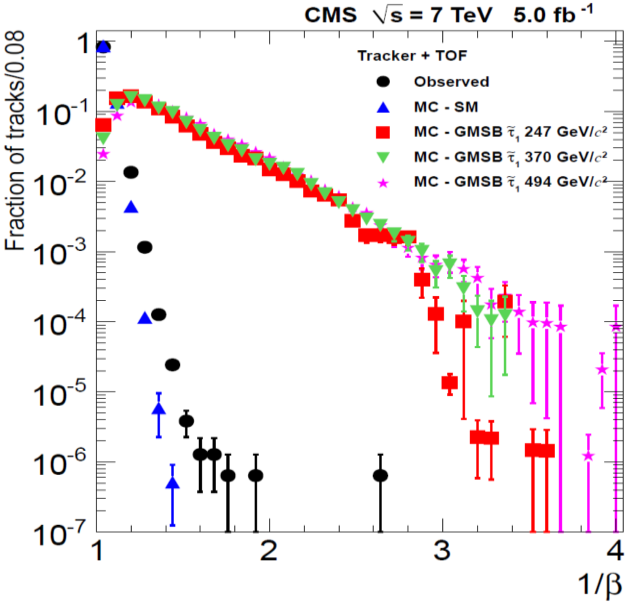


dE/dx resolution improves
with #layers, sensor thickness
and readout electronics

SLOW

Time Of Flight

$$1/\beta = 1 + \frac{c\delta_t}{L}$$ with δ_t = delay



β resolution improves
with time resolution (δt)
and with lever arm (L)

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Experimental Signature

IONIZING

⇩

dE/dx

$$\frac{dE}{dx} \approx Q^2\left(\frac{A}{\beta^2} + B\right) \text{ for } \beta<<1$$

STOPPED

⇩

Decay asynchronously w.r.t LHC bunch

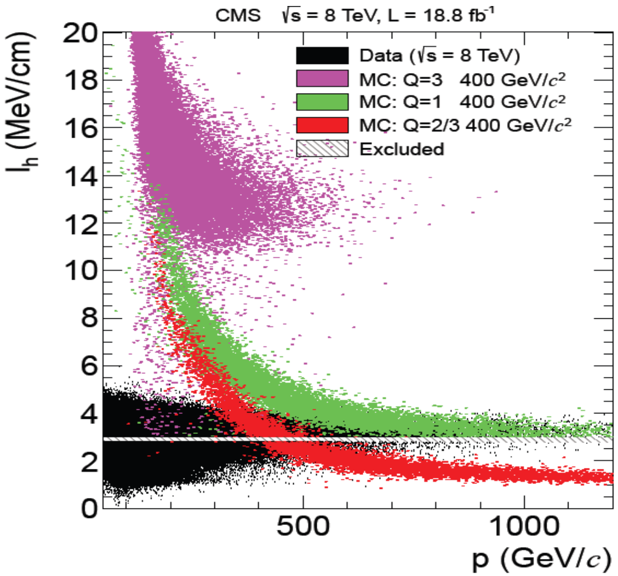
⇩

SLOW

⇩

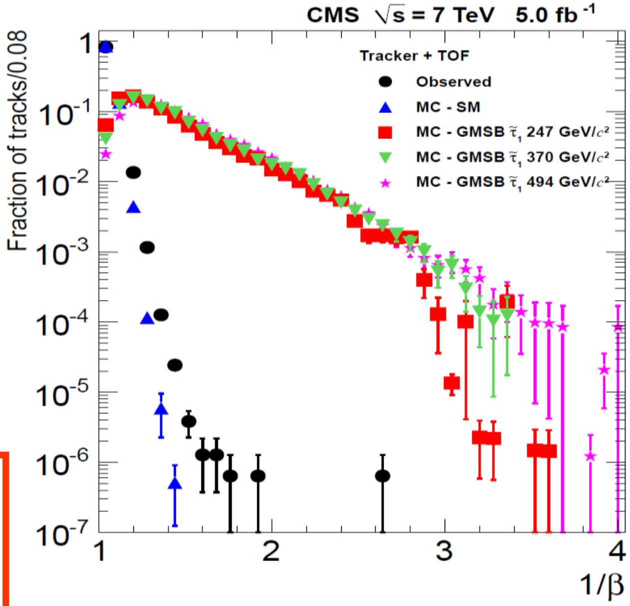
Time Of Flight

$$1/\beta = 1 + \frac{c\delta_t}{L} \quad \text{with } \delta_t = \text{delay}$$



dE/dx resolution improves with #layers, sensor thickness and readout electronics

If dE/dx is (high) comparable to the kinetic energy
The particle may stop in the detector and decay later



β resolution improves with time resolution (δt) and with lever arm (L)

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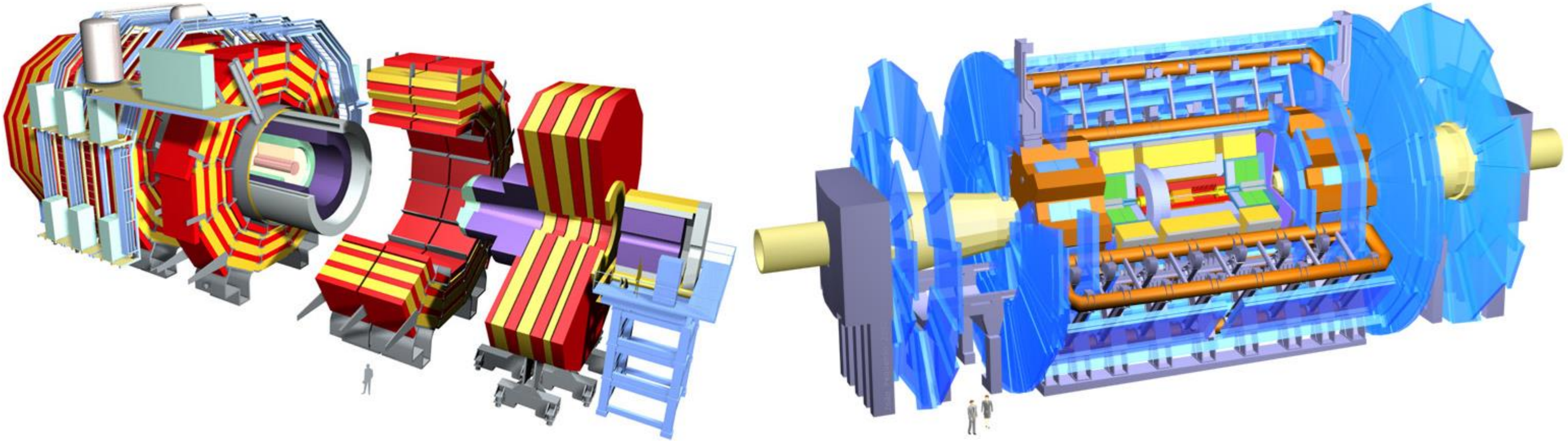
ATLAS/CMS Detectors for HSCP



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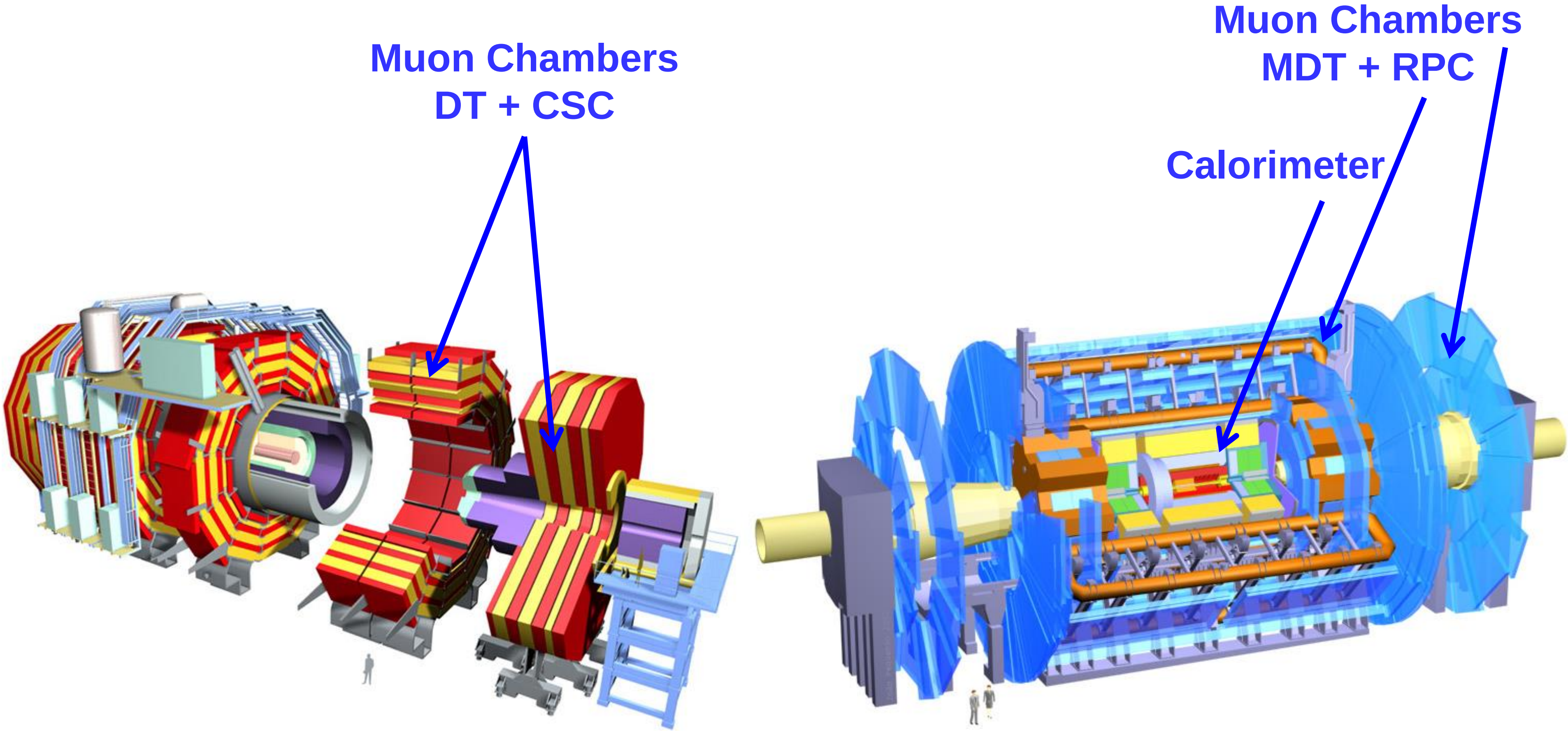
ATLAS/CMS Detectors for HSCP

Time of Flight



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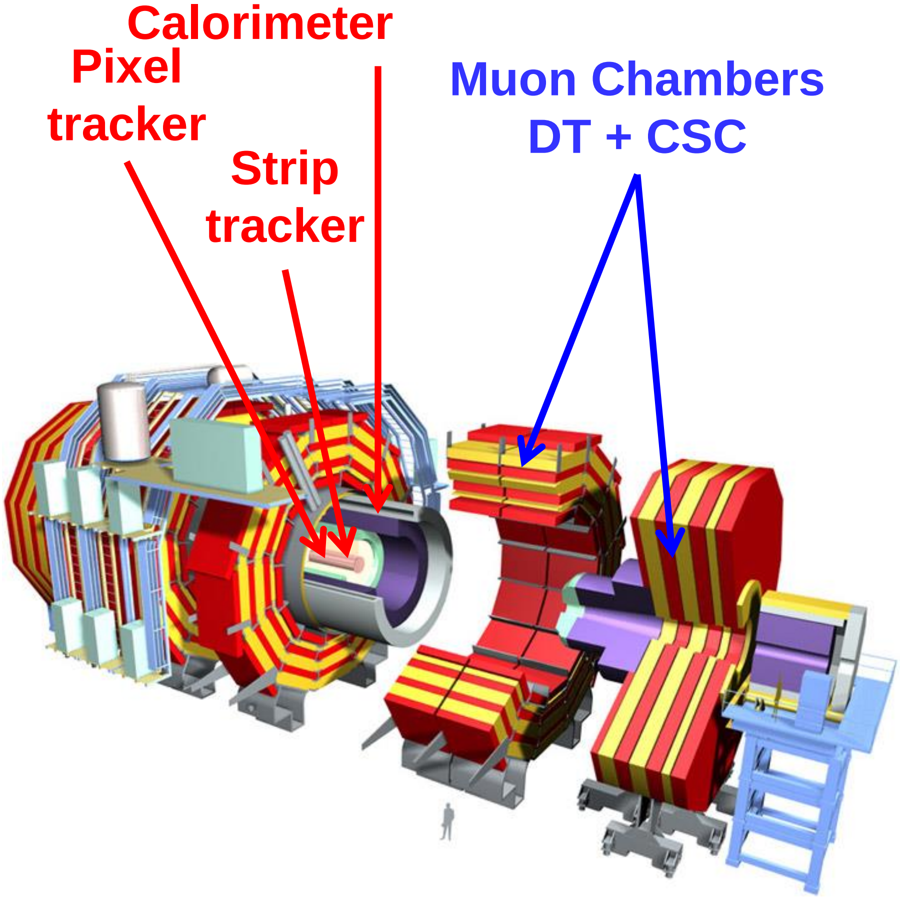
ATLAS/CMS Detectors for HSCP

dE/dx



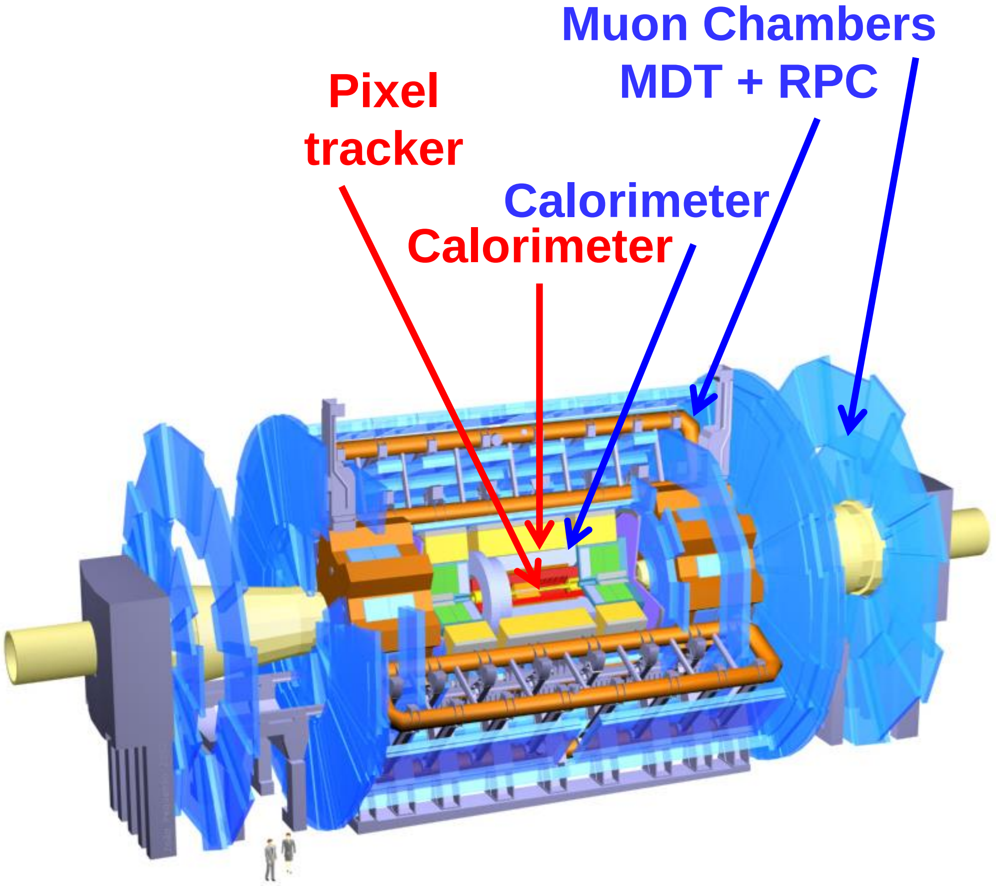
Calorimeter

Pixel tracker

Strip tracker

Muon Chambers DT + CSC

Time of Flight



Muon Chambers MDT + RPC

Pixel tracker

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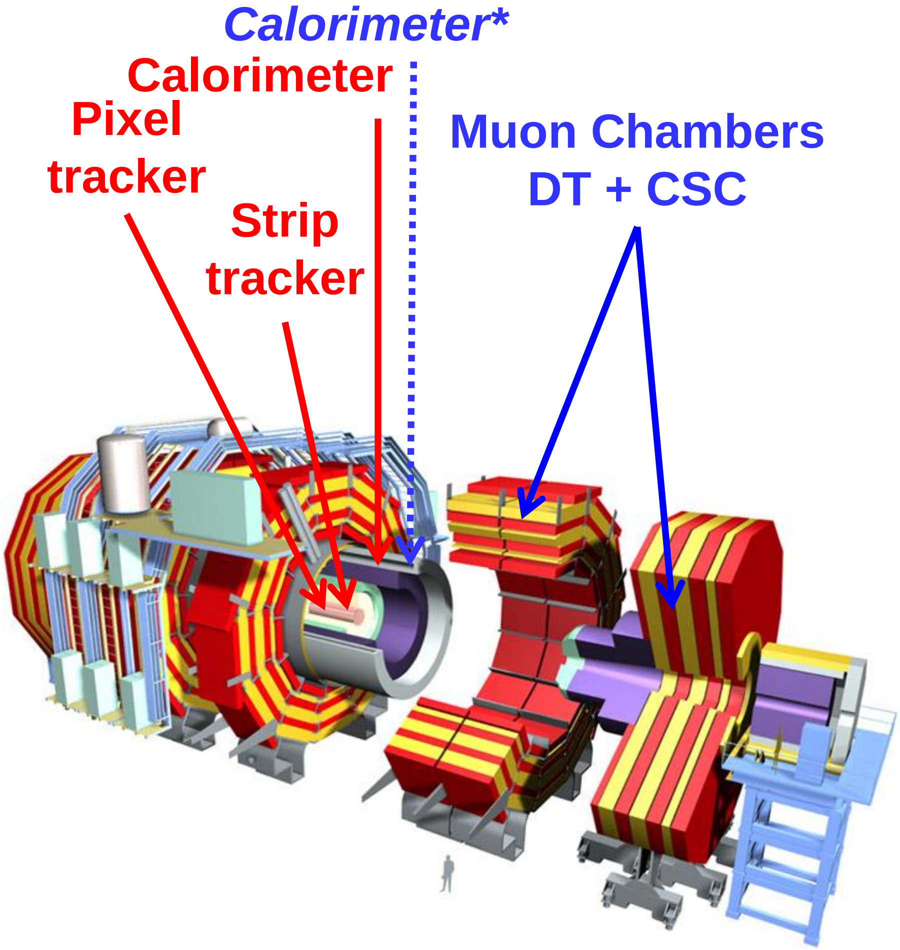
ATLAS/CMS Detectors for HSCP

dE/dx



*Calorimeter**

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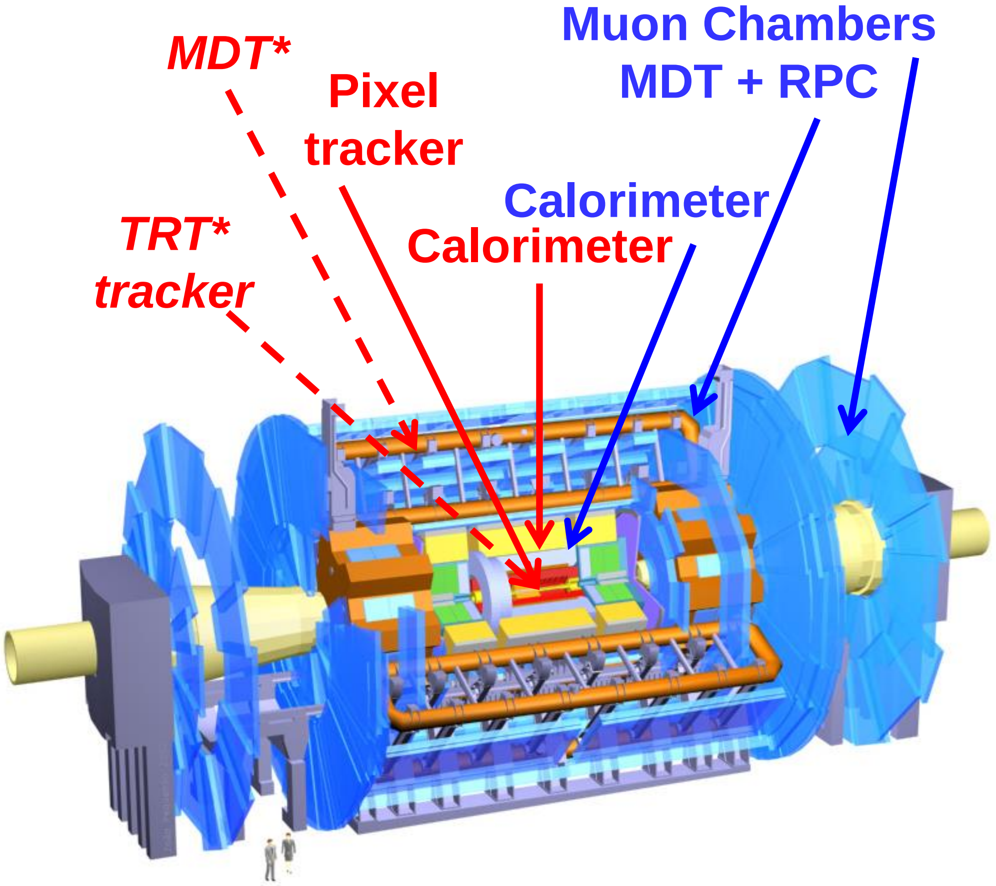

*MDT**

Muon Chambers MDT + RPC

Pixel tracker

Calorimeter

Calorimeter

TRT tracker*

*** = only if dEdx>> O(1) GeV**

*** = only in special stream**

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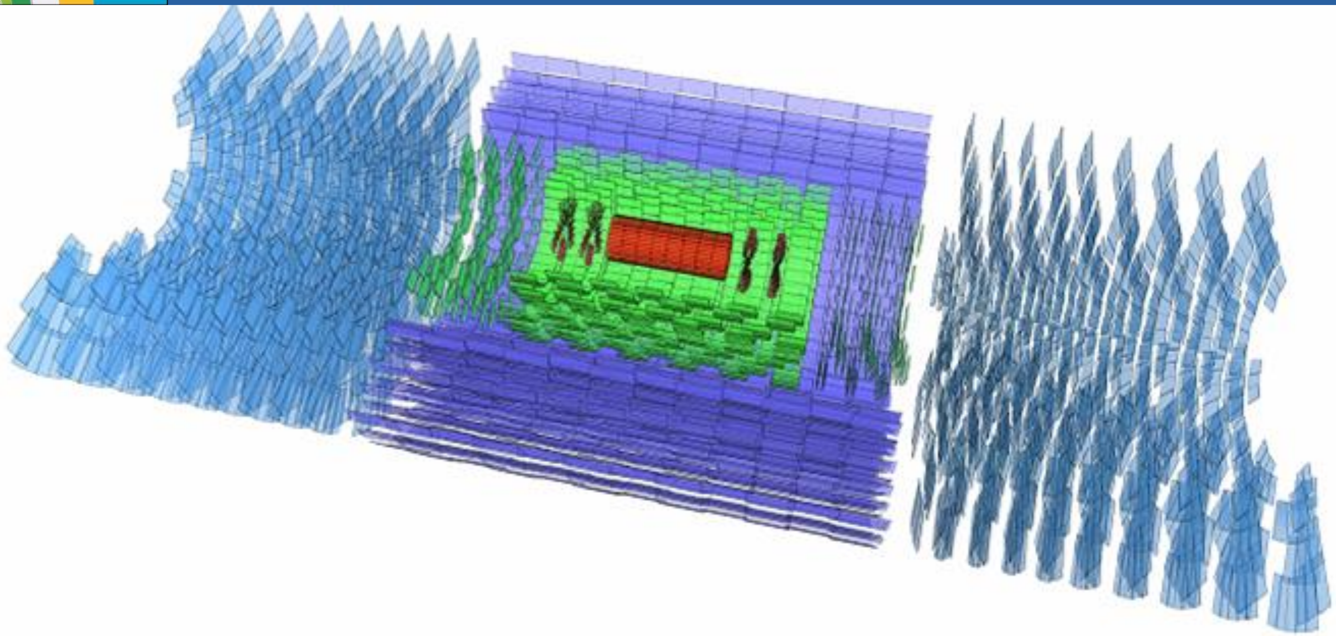
The CMS strip tracker

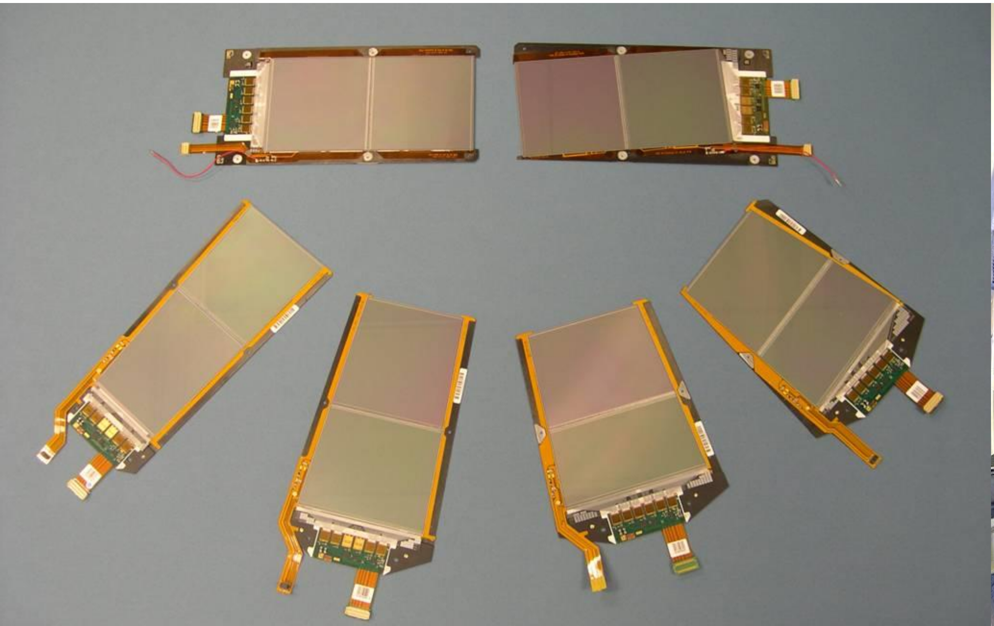


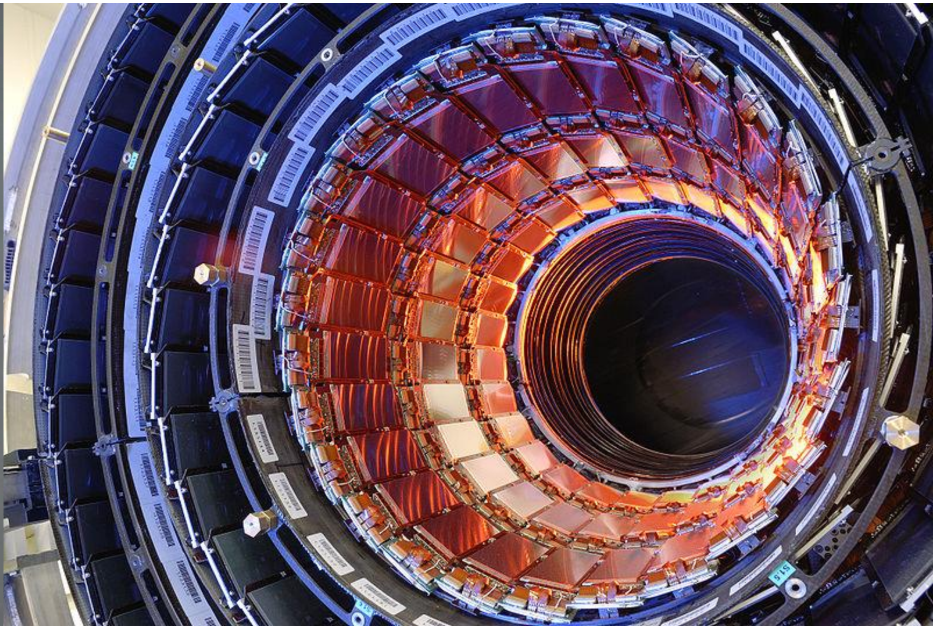
Strip Tracker

15148 Modules

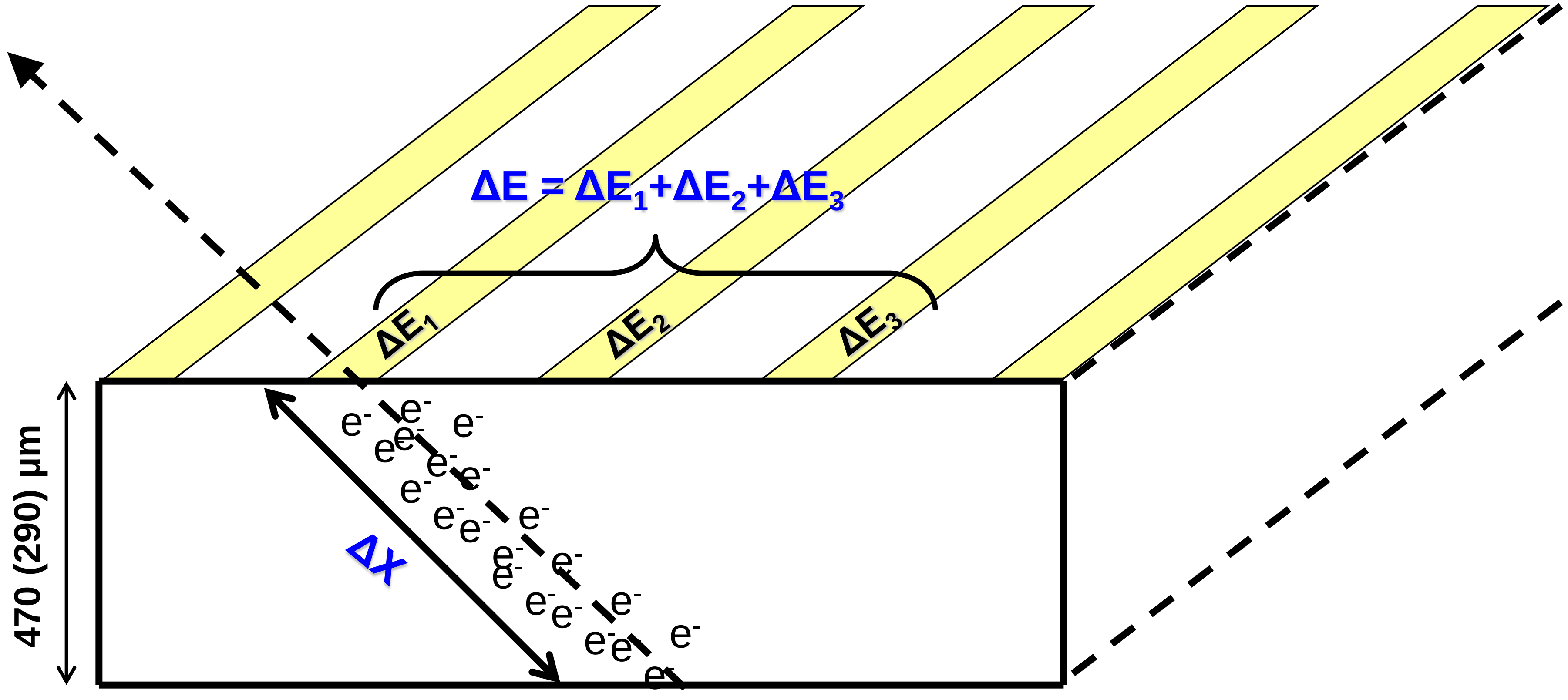
9.7M Channels

A particle go trough ~15 modules





Ionization energy loss (dE/dx)



$$\frac{\Delta E}{\Delta x} \cong K \frac{m^2}{p^2} + C$$

Slow particles lose more energy

dE/dx variables

- **dEdx discriminator - Asymmetric Smirnov (I_{as}) :**
  - Main variables to **discriminate signal from backgrounds**
  - Probability that a track as a higher energy loss than a MIP
  - P_i are hit-level probability extracted from templates of dEdx vs dx for MIPs in minimum bias samples.

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

N in [10, 30]
<N> = ~17

- **dEdx estimator - Harmonic-2 :**
  - **only used to reconstruct mass** of HSCP candidates and separate S from Bkg.

$$I_h = \left(\frac{1}{N} \sum_i^N c_i^{-2} \right)^{-1/2} = K \frac{m^2}{p^2} + C$$

mass
momentum

K,C= constants

- hamonic-2 is very **robust** against **upward fluctuation** of C_i (i.e. Landau tail)
- hamonic-2 is very much **affected** by **downward fluctuation** (i.e. noise)

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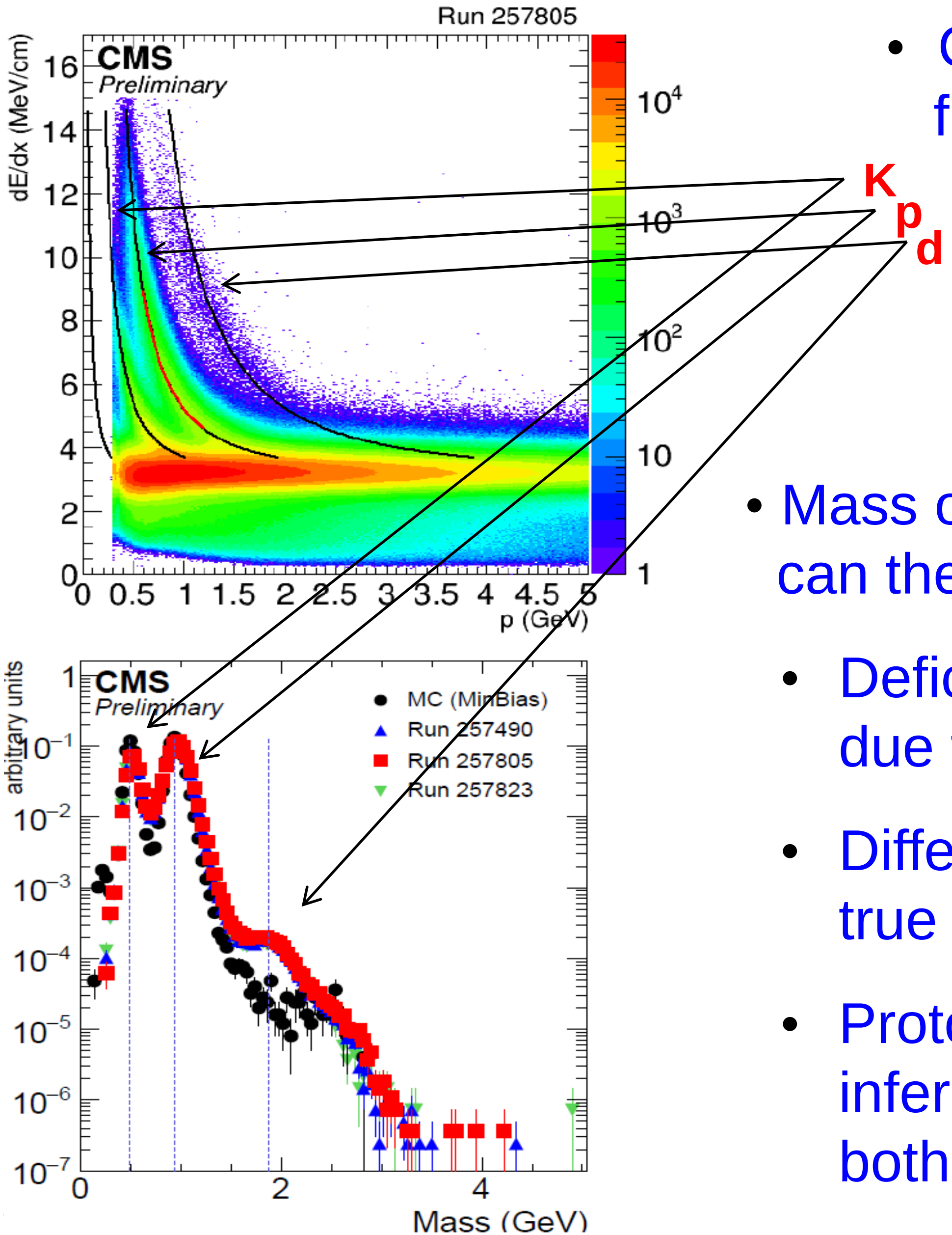
dE/dx variables



- Constant K & C are extracted from a fit to low momenta protons
  - K = 2.535 MeV/cm
  - C = 3.339 MeV/cm

- Mass of kaons, protons and deuterons can then be reconstructed in data.
  - Deficit of deuterons in the simulation is due to pythia not producing them.
  - Difference between reconstructed and true mass due to electronic saturation
  - Protons are also used as a candle to infer systematic uncertainty due to both Ias and Ih data/MC difference.

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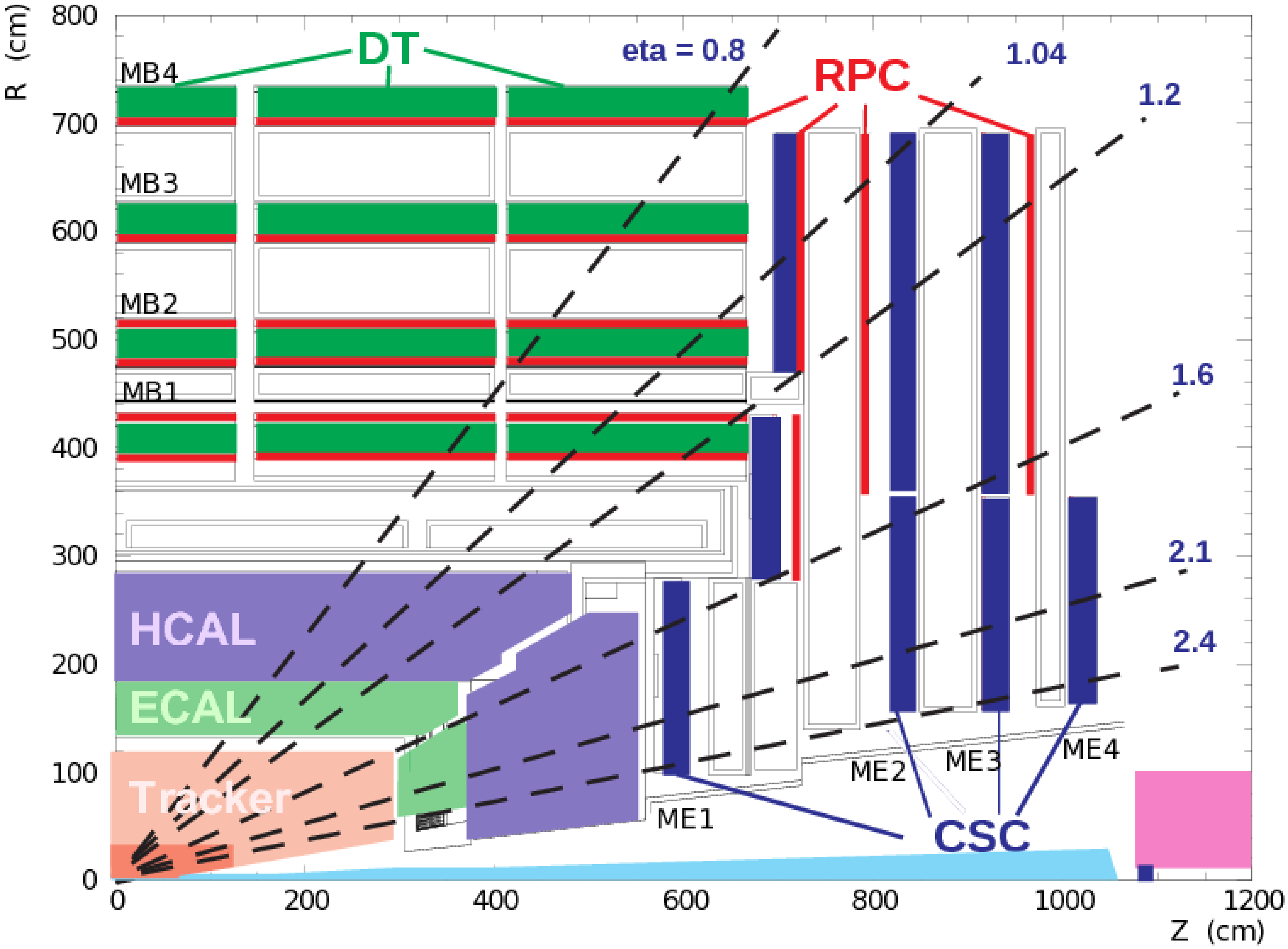
CMS Muon Detector → TOF



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Time of Flight

- **Time of flight → β^{-1}:**

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

  - **β^{-1}** measurements computed from:
    - flight distance L between IP and the muon chamber
    - δt delay with respect to a muon traveling at the speed-of-light.

  - Combine **β^{-1} is computed as the average of individual TOF m**easurement weighted by their individual resolution.

DT: $$w_i = \frac{(n-2)}{n}\frac{L_i^2}{\sigma_{DT}^2}$$

CSC: $$w_i = \frac{L_i^2}{\sigma_i^2}$$

With σ = 3ns for DT, 7ns for CSC cathode and 8.6ns for CSC anode.

$$\sigma_{1/\beta} = \sqrt{\sum_{i=1}^{N} \frac{(1/\beta_i - \overline{1/\beta})^2 \times w_i}{N-1}}$$

= ~0.065 on average for muons

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ATLAS/CMS Searches

R-Hadron ?

no

yes

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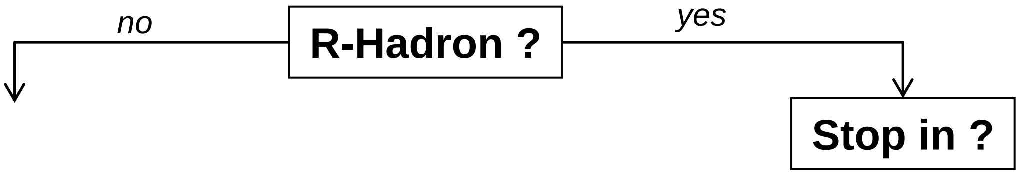
ATLAS/CMS Searches



R-Hadron ?

Stop in ?

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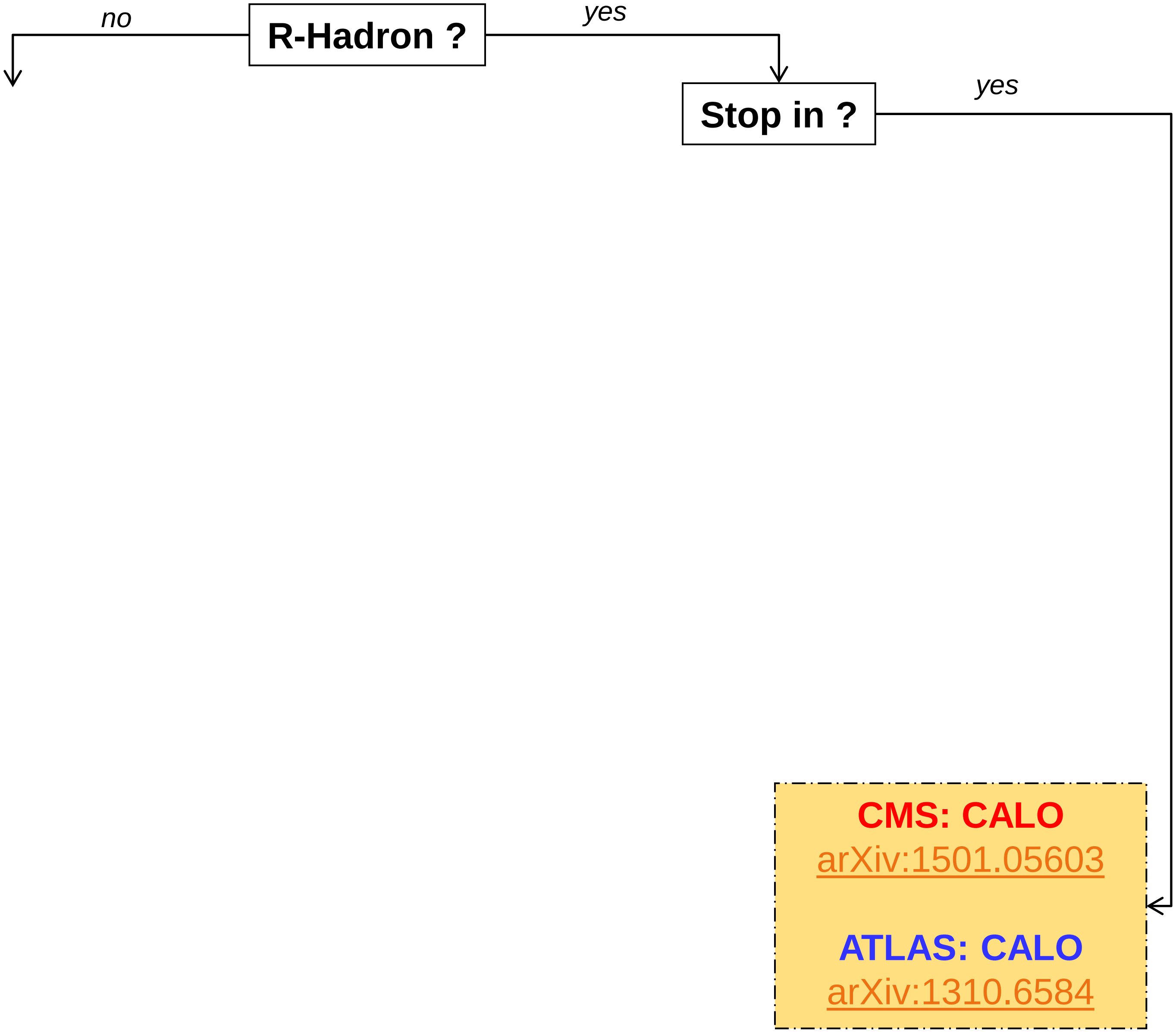
ATLAS/CMS Searches



R-Hadron ?

no

yes

Stop in ?

yes

CMS: CALO
arXiv:1501.05603

ATLAS: CALO
arXiv:1310.6584

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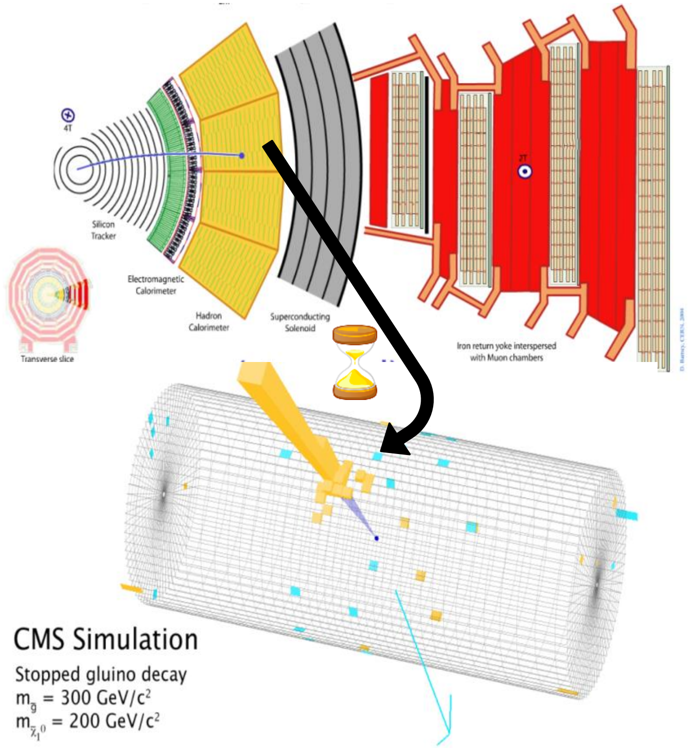
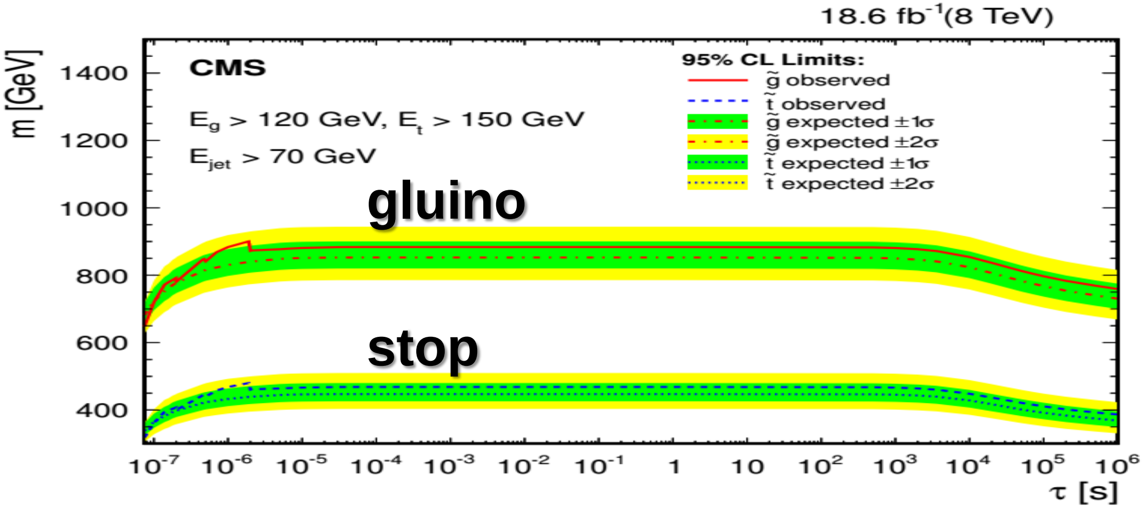
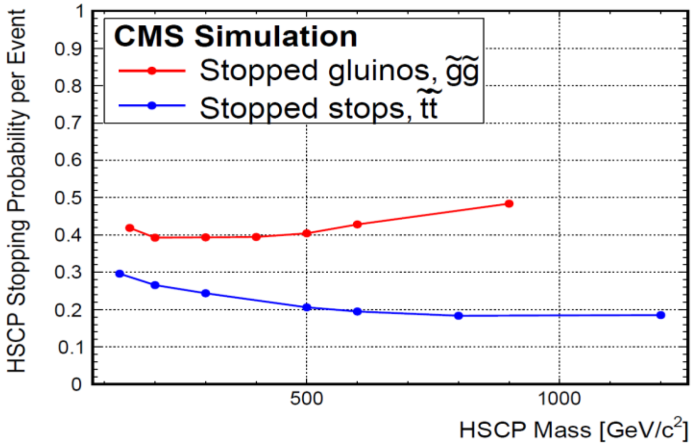
Selected Results on: **Stopped HSCP**

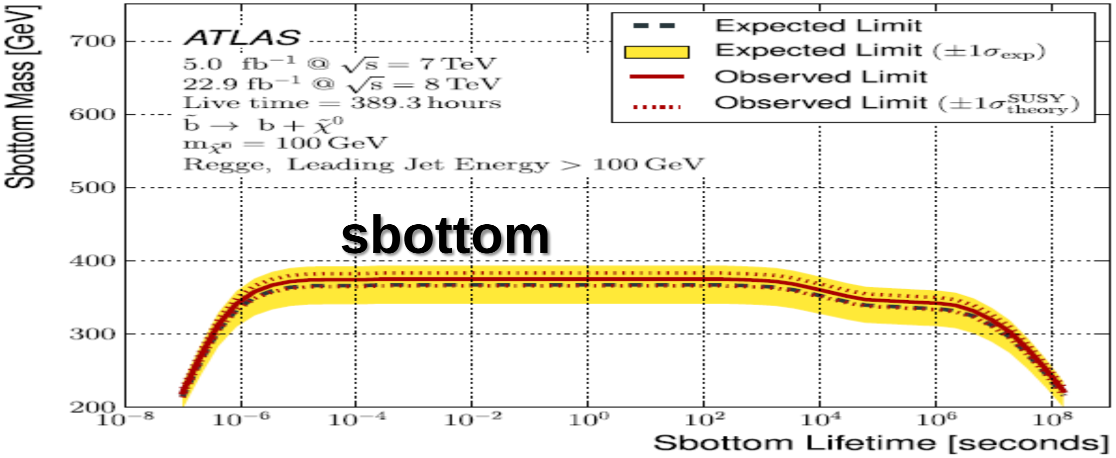


The search in a nutshell

- Signature: Energetic jet w/o pp collisions
- Backgrounds: cosmics, beam halo, det. noise







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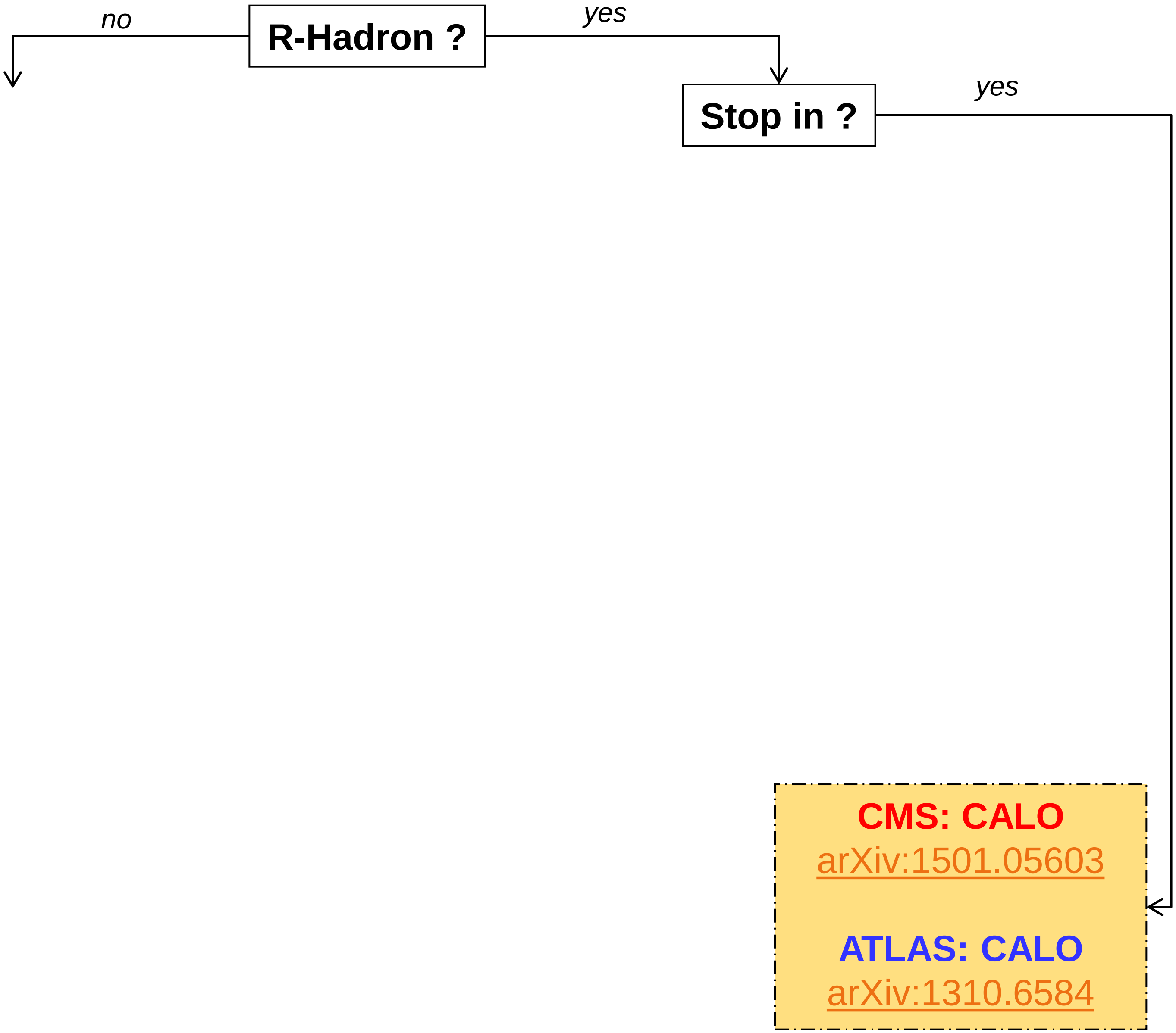
ATLAS/CMS Searches



R-Hadron ?

no

yes

Stop in ?

yes

CMS: CALO
arXiv:1501.05603

ATLAS: CALO
arXiv:1310.6584

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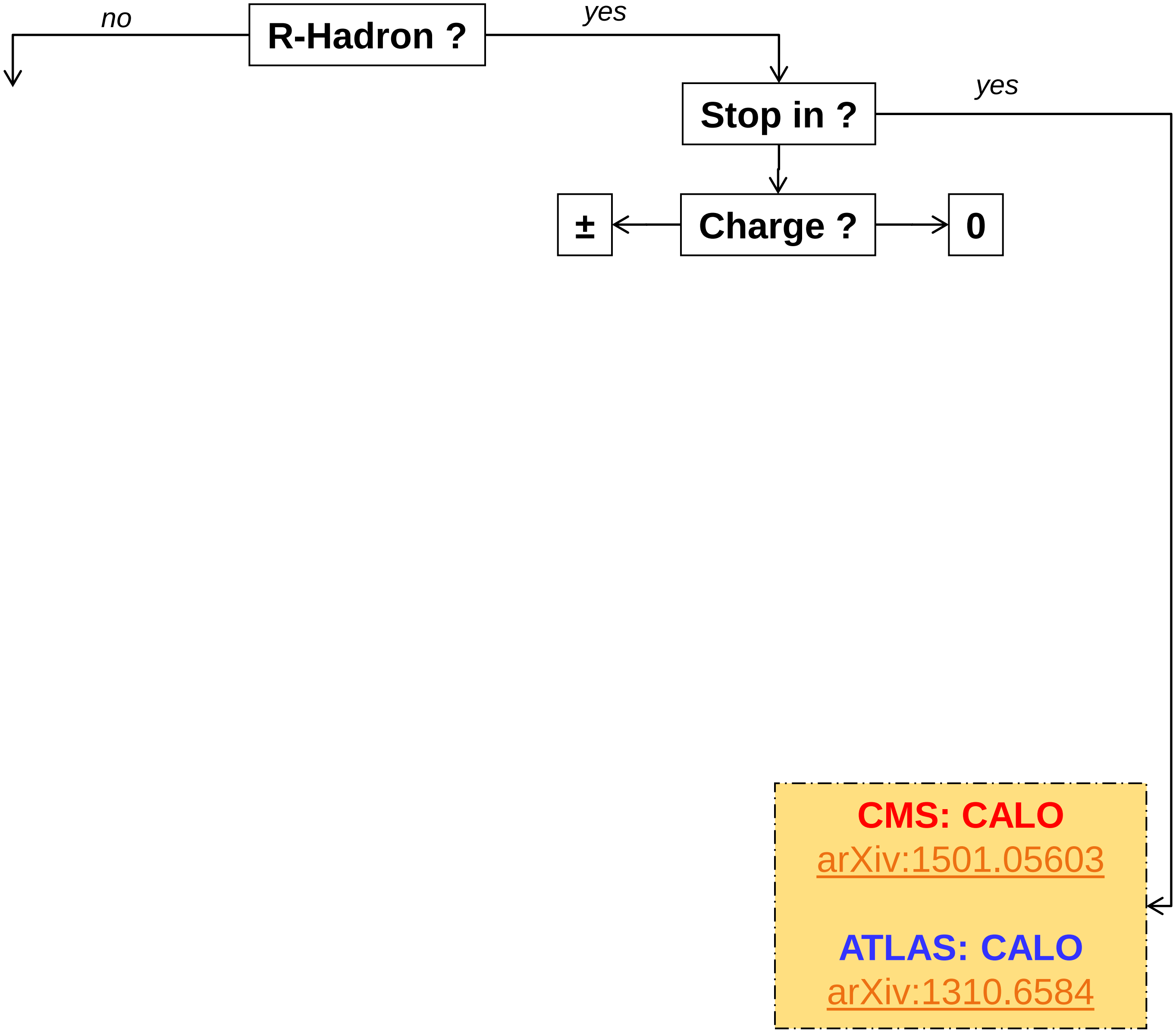
ATLAS/CMS Searches



no

R-Hadron ?

yes

Stop in ?

yes

±

Charge ?

0

CMS: CALO
arXiv:1501.05603

ATLAS: CALO
arXiv:1310.6584

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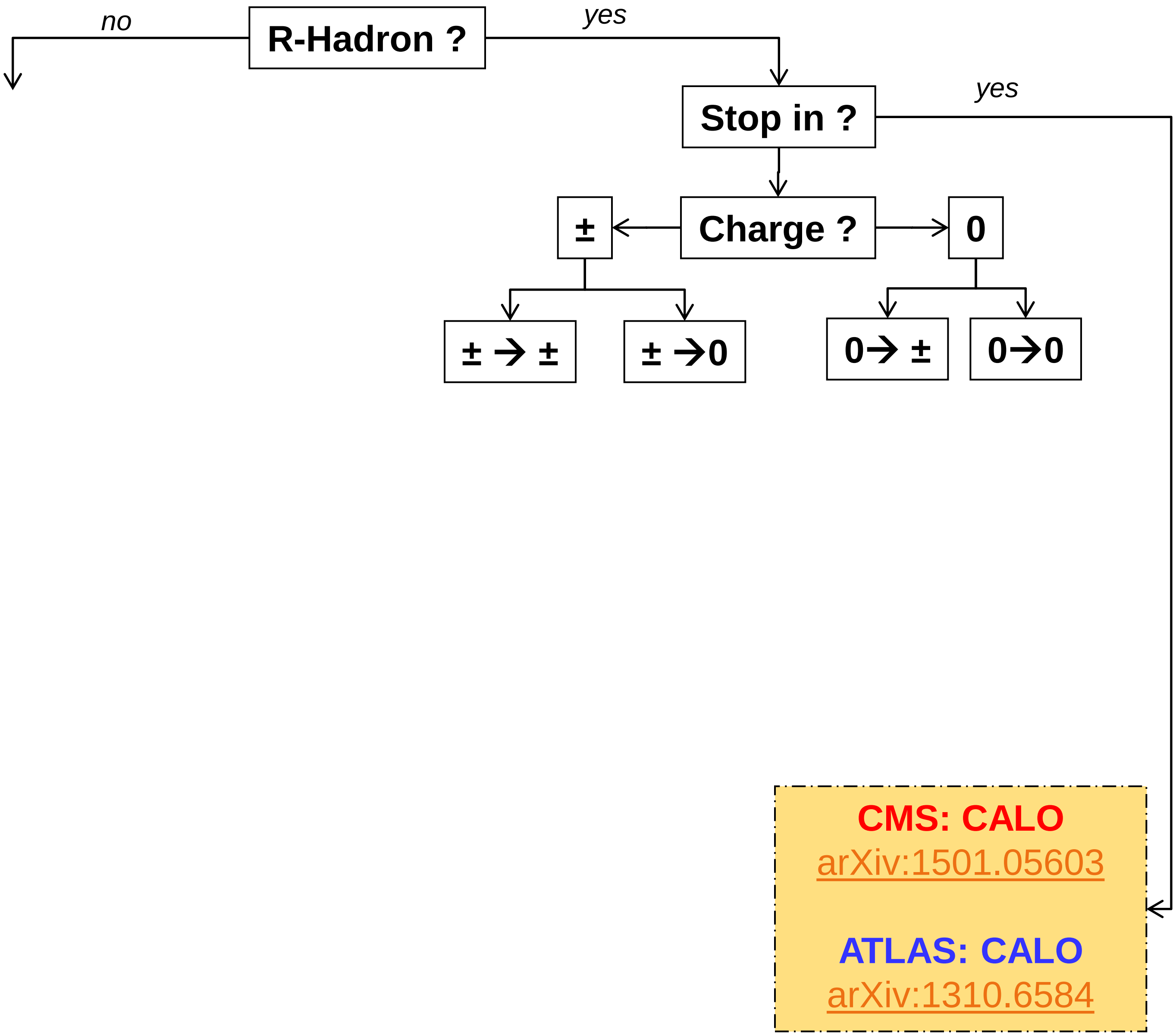
ATLAS/CMS Searches



no

R-Hadron ?

yes

Stop in ?

yes

Charge ?

±

0

± → ±

± →0

0→ ±

0→0

CMS: CALO

arXiv:1501.05603

ATLAS: CALO

arXiv:1310.6584

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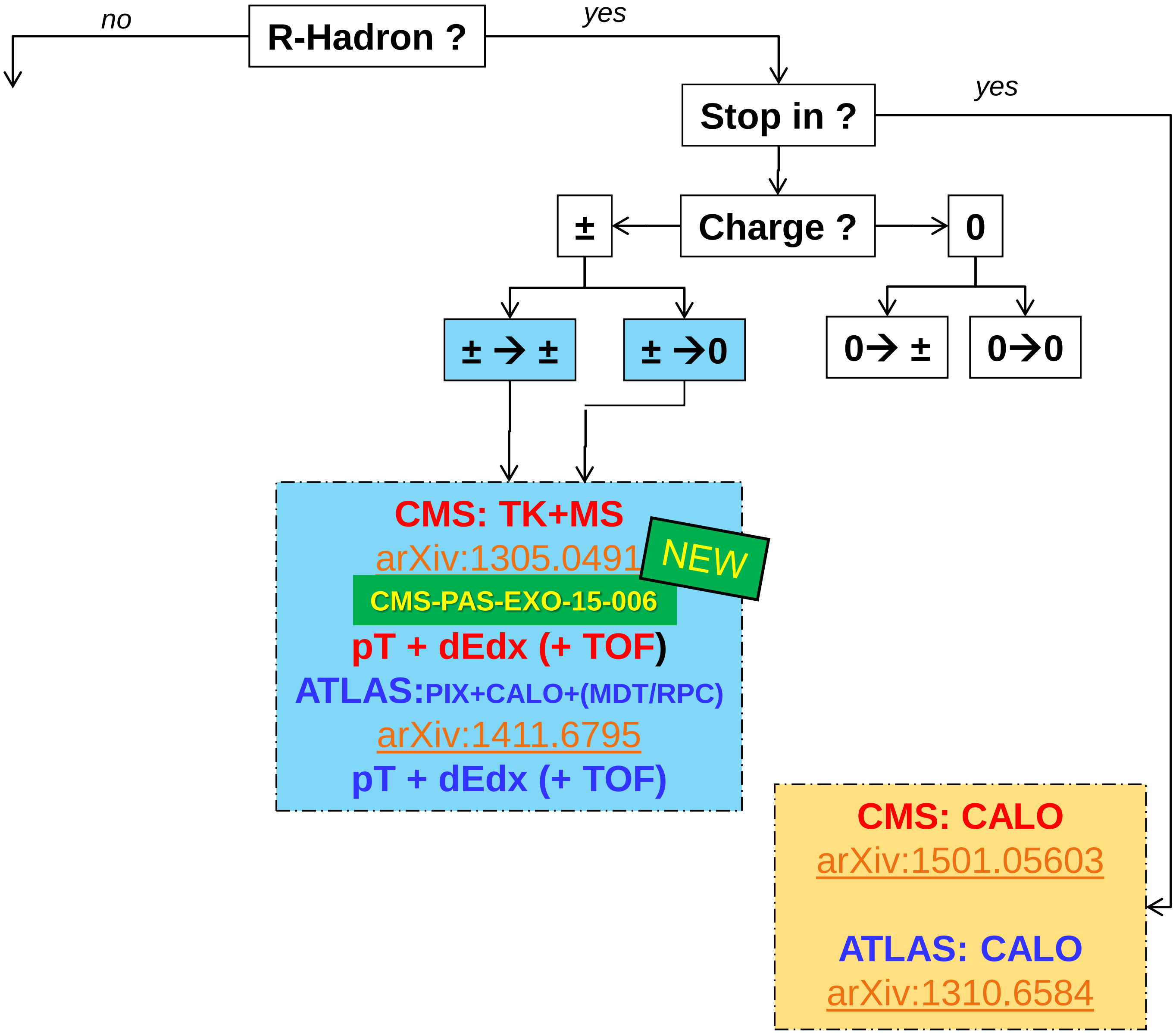
ATLAS/CMS Searches



CMS: TK+MS
arXiv:1305.0491
CMS-PAS-EXO-15-006
pT + dEdx (+ TOF)
ATLAS:PIX+CALO+(MDT/RPC)
arXiv:1411.6795
pT + dEdx (+ TOF)

CMS: CALO
arXiv:1501.05603

ATLAS: CALO
arXiv:1310.6584

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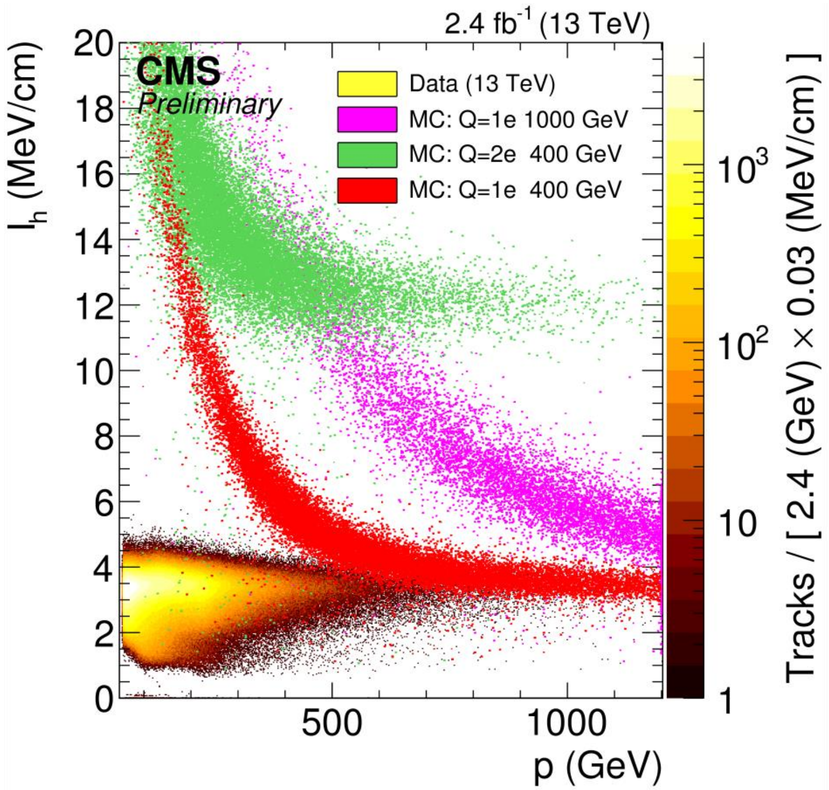
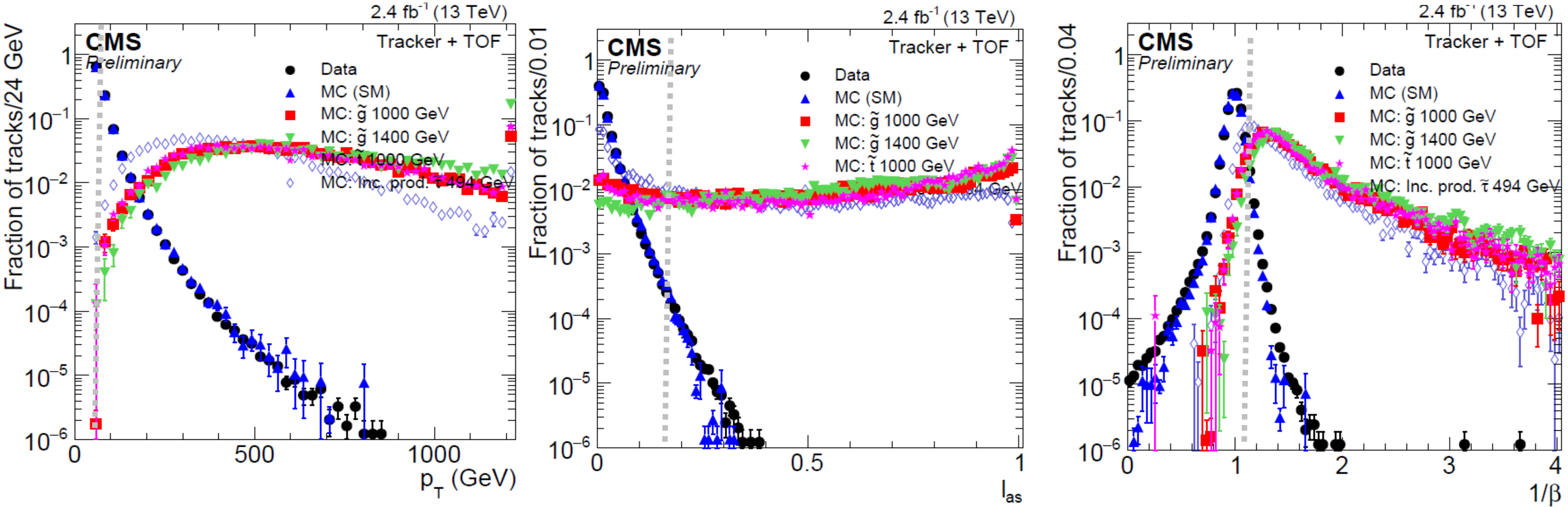
Selected Results: **Regular (±→±) HSCP**

- Very similar approaches used by ATLAS and CMS
- Trigger : Muon OR MET
- Variables: pT (tracker), dE/dx (inner detector) and TOF (Muon System)
- Background prediction based on ABCD and predicted mass sprectrum from pdf
- Main difference: ATLAS has a 2 HSCP/event category not considered by CMS

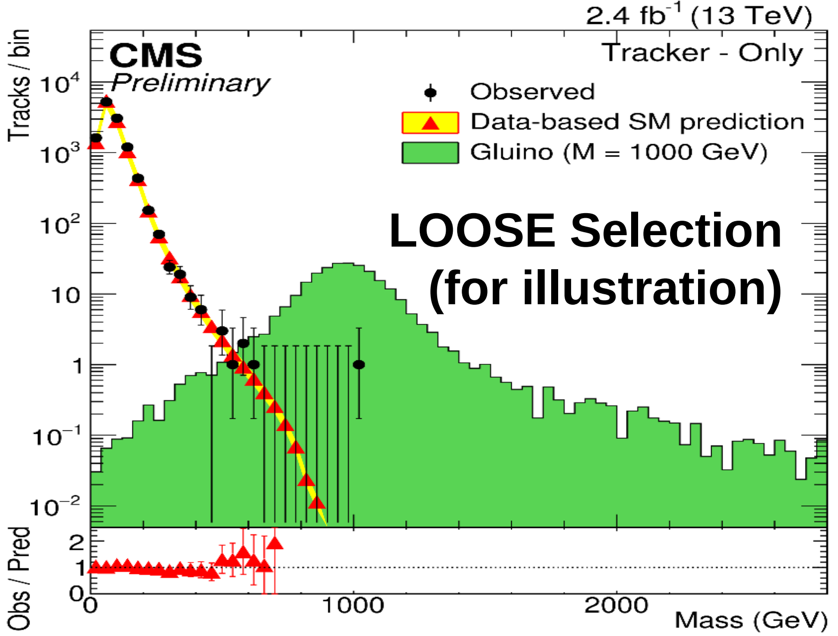


	Trk-only	Trk+TOF
Track Type	Inner Track	Global Muon
$\|\eta\|$	< 2.1	
p_T (GeV)	> 55	
d_z and d_{xy} (cm)	< 0.5	
σ_{p_T}/p_T	< 0.25	
Track χ^2/dof	< 5	
# Pixel Hits	> 1	
# Tracker Hits	> 7	
Frac. Valid Hits	> 0.8	
# dE/dx Measurements	> 5	
dE/dx Strip Shape Test	yes	
$\Sigma p_T^{trk}(\Delta R < 0.3)$ (GeV)	< 50	
$E_{cal}(\Delta R < 0.3)/p$	< 0.3	
# TOF Measurements	/	> 7
$\sigma_{1/\beta}$	/	< 0.15
$1/\beta$	/	> 1

Selection variables and background

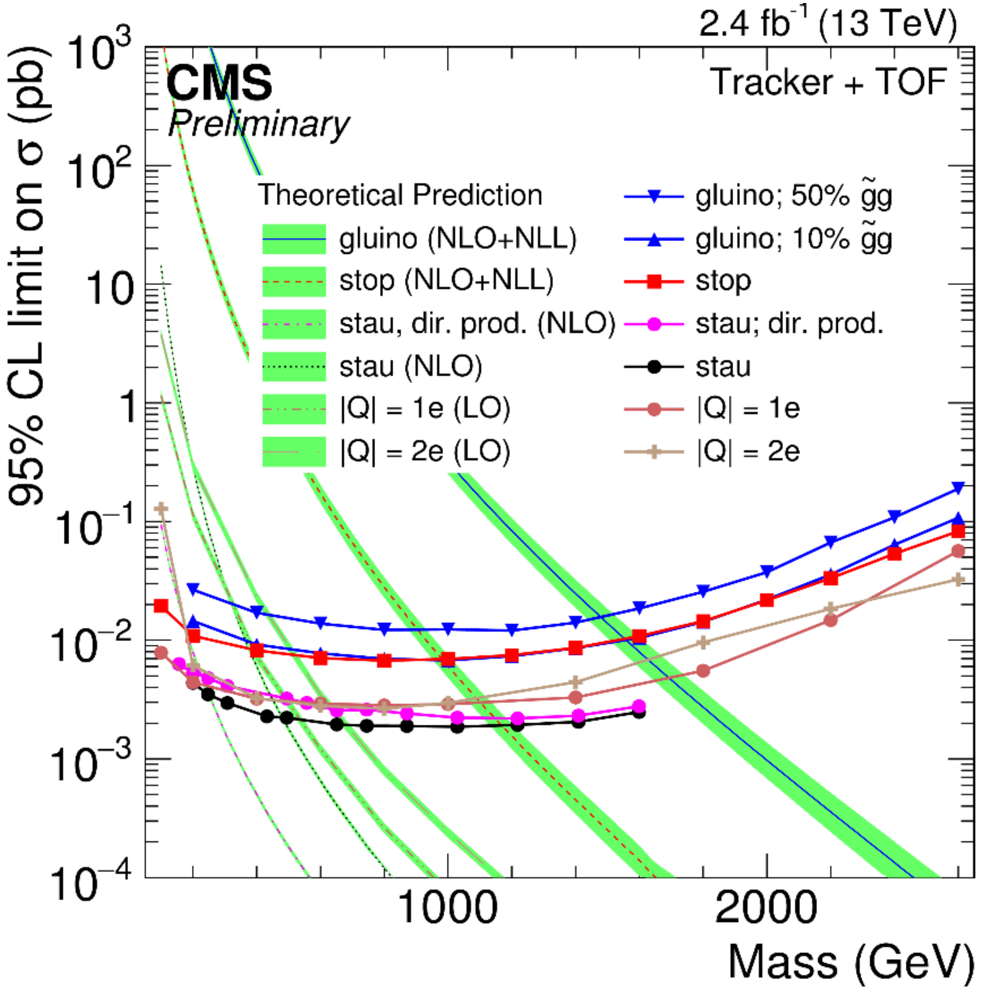


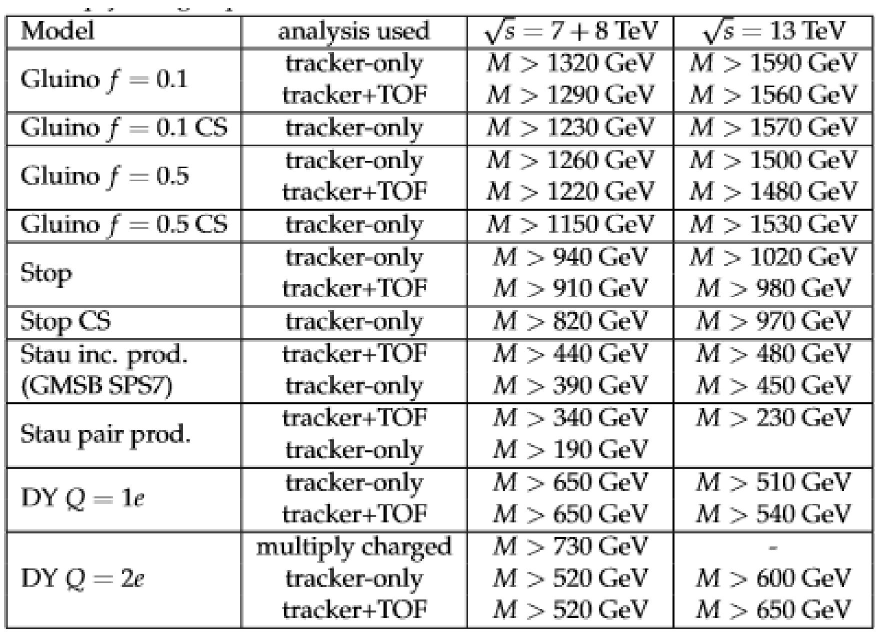
- The 3 variables are uncorrelated !
- The background rate is estimated from data using a 2D or 3D ABCD method.
- The background mass distribution is obtained from momentum and dEdx pdf in control regions.



LOOSE Selection (for illustration)

First HSCP Limits at 13TeV





Model	analysis used	$\sqrt{s} = 7 + 8$ TeV	$\sqrt{s} = 13$ TeV
Gluino $f = 0.1$	tracker-only tracker+TOF	$M > 1320$ GeV $M > 1290$ GeV	$M > 1590$ GeV $M > 1560$ GeV
Gluino $f = 0.1$ CS	tracker-only	$M > 1230$ GeV	$M > 1570$ GeV
Gluino $f = 0.5$	tracker-only tracker+TOF	$M > 1260$ GeV $M > 1220$ GeV	$M > 1500$ GeV $M > 1480$ GeV
Gluino $f = 0.5$ CS	tracker-only	$M > 1150$ GeV	$M > 1530$ GeV
Stop	tracker-only tracker+TOF	$M > 940$ GeV $M > 910$ GeV	$M > 1020$ GeV $M > 980$ GeV
Stop CS	tracker-only	$M > 820$ GeV	$M > 970$ GeV
Stau inc. prod. (GMSB SPS7)	tracker+TOF tracker-only	$M > 440$ GeV $M > 390$ GeV	$M > 480$ GeV $M > 450$ GeV
Stau pair prod.	tracker+TOF tracker-only	$M > 340$ GeV $M > 190$ GeV	$M > 230$ GeV
DY $Q = 1e$	tracker-only tracker+TOF	$M > 650$ GeV $M > 650$ GeV	$M > 510$ GeV $M > 540$ GeV
DY $Q = 2e$	multiply charged tracker-only tracker+TOF	$M > 730$ GeV $M > 520$ GeV $M > 520$ GeV	- $M > 600$ GeV $M > 650$ GeV

Gluino mass limits are at 1.6TeV with just 2.4fb

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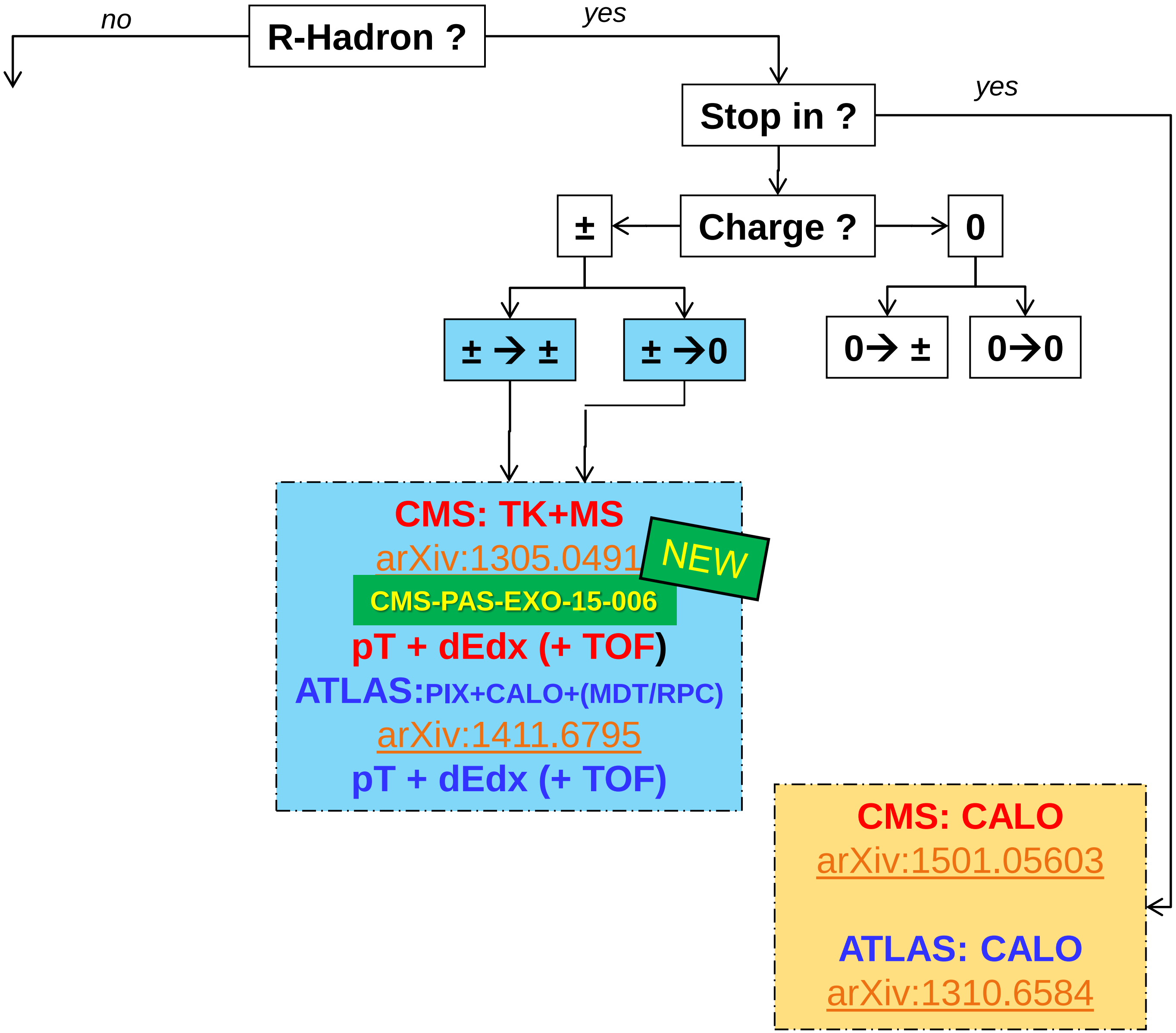
ATLAS/CMS Searches



no

R-Hadron ?

yes

Stop in ?

yes

Charge ?

±

0

± → ±

± →0

0→ ±

0→0

CMS: TK+MS

arXiv:1305.0491

NEW

CMS-PAS-EXO-15-006

pT + dEdx (+ TOF)

ATLAS:PIX+CALO+(MDT/RPC)

arXiv:1411.6795

pT + dEdx (+ TOF)

CMS: CALO

arXiv:1501.05603

ATLAS: CALO

arXiv:1310.6584

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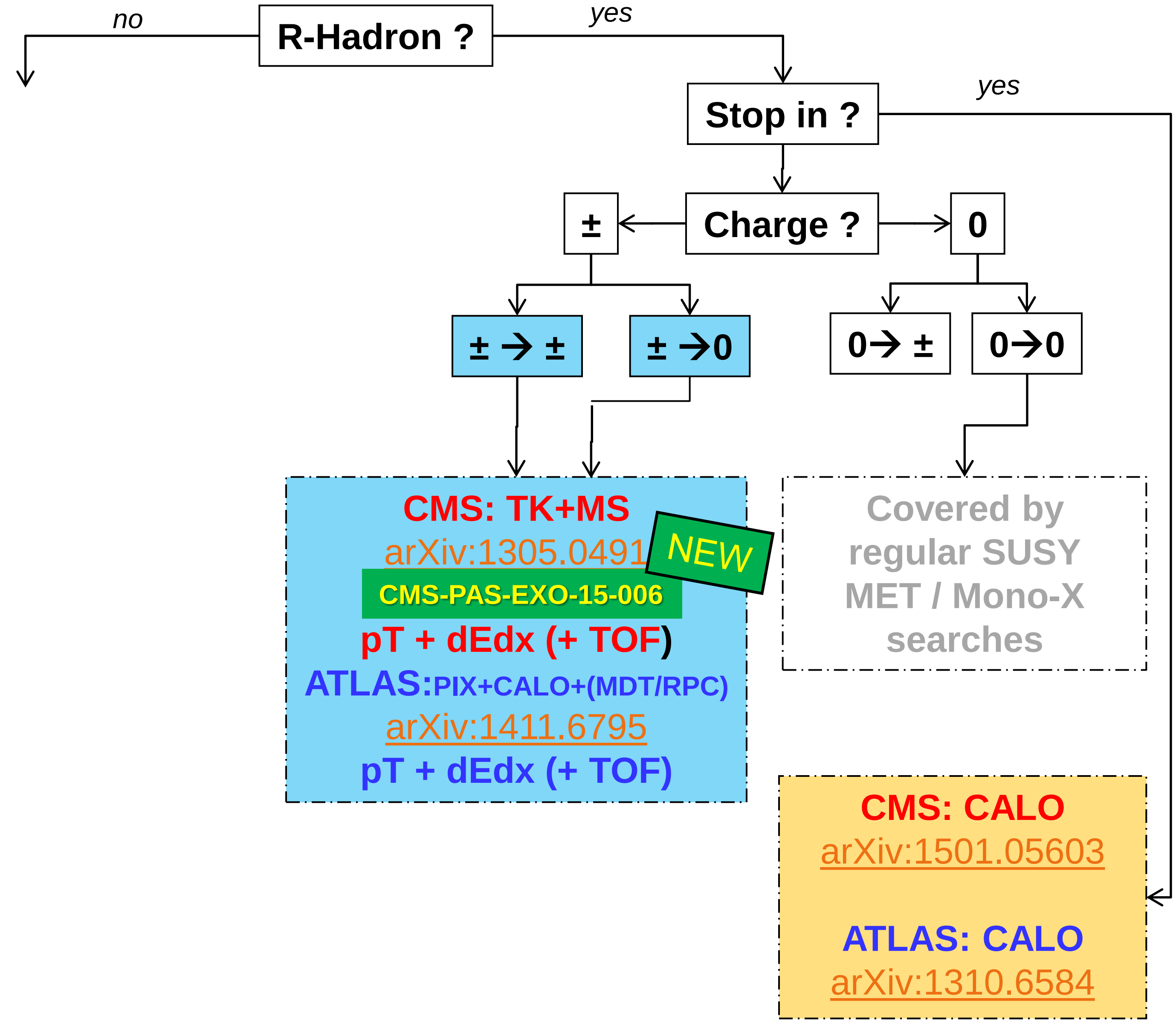
ATLAS/CMS Searches



R-Hadron ?

no

yes

Stop in ?

yes

Charge ?

±

0

± → ±

± → 0

0 → ±

0 → 0

CMS: TK+MS

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NEW

pT + dEdx (+ TOF)

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pT + dEdx (+ TOF)

Covered by regular SUSY MET / Mono-X searches

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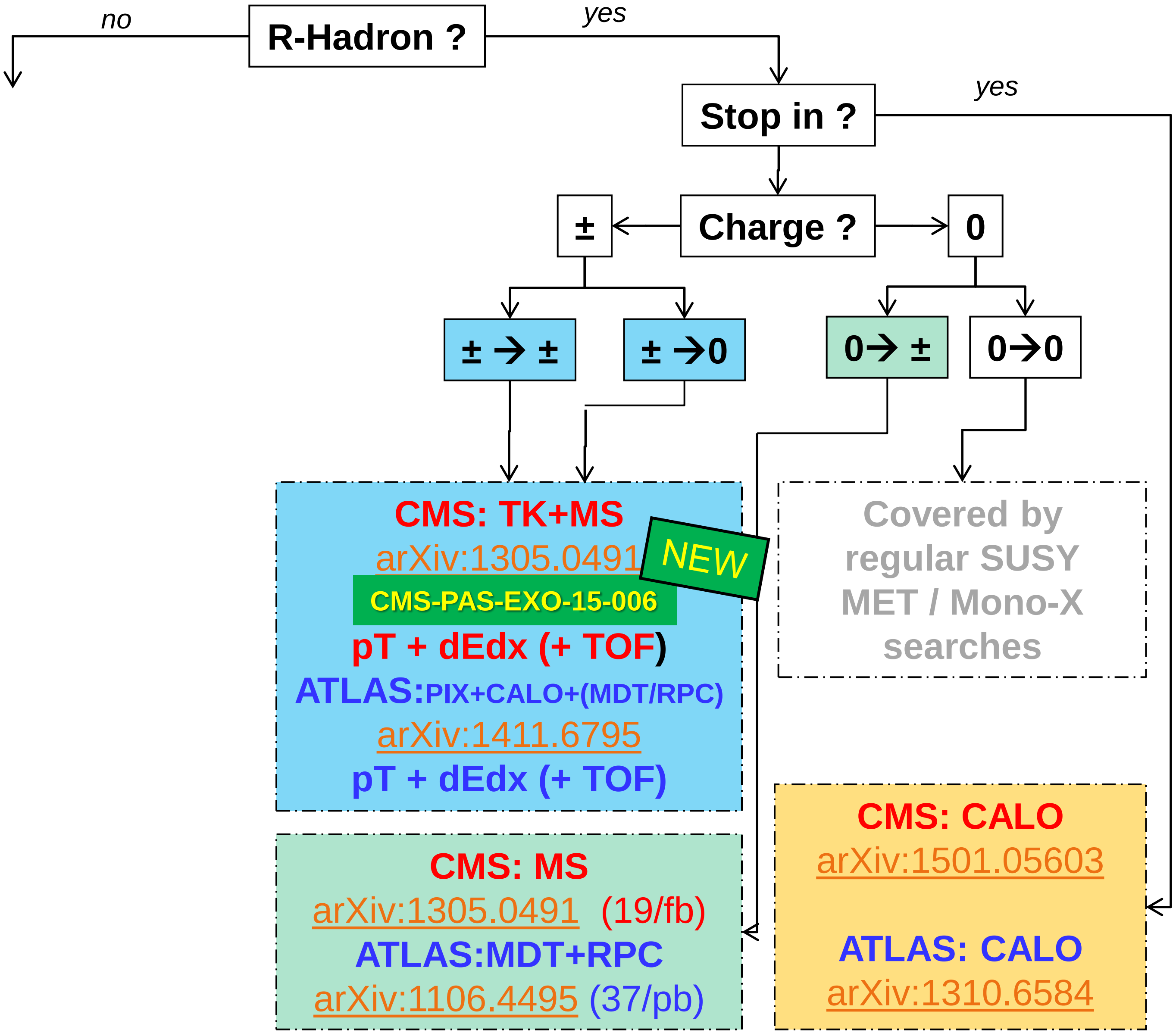
ATLAS/CMS Searches



no

R-Hadron ?

yes

Stop in ?

yes

±

Charge ?

0

± → ±

± →0

0→ ±

0→0

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CMS-PAS-EXO-15-006

pT + dEdx (+ TOF)

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arXiv:1411.6795

pT + dEdx (+ TOF)

Covered by regular SUSY MET / Mono-X searches

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arXiv:1305.0491 (19/fb)

ATLAS:MDT+RPC

arXiv:1106.4495 (37/pb)

CMS: CALO

arXiv:1501.05603

ATLAS: CALO

arXiv:1310.6584

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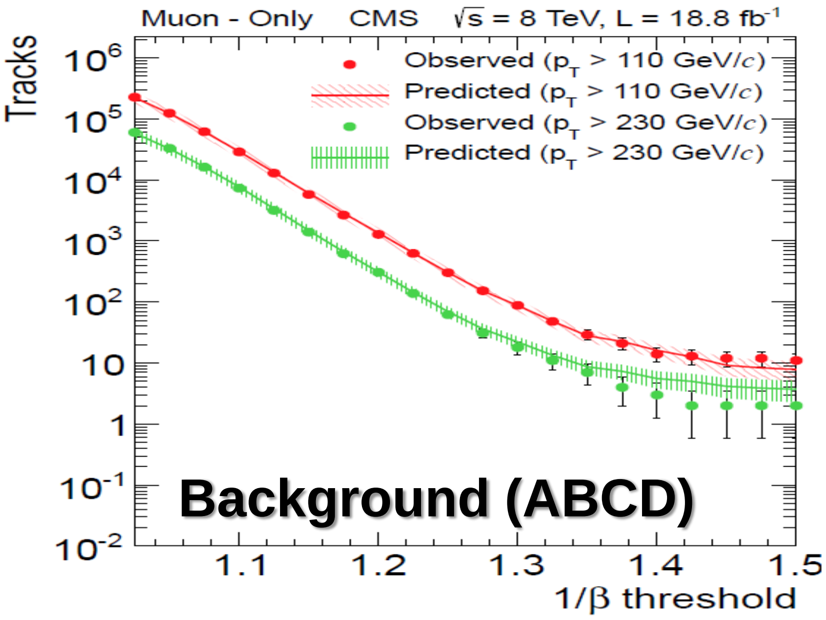
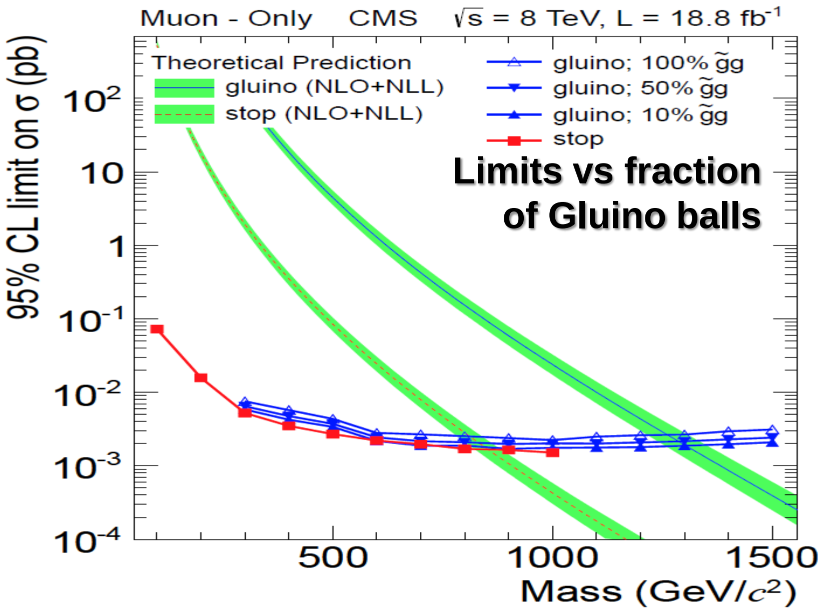
Selected Results: **R-Hadrons (0→±)**

- Challenges:
  - Invisible in the tracker
  - Worse pT resolution (due to coarser hit position in the MS)
  - High cosmic backgrounds (also out-of-time)
- Solutions:
  - Dedicated trigger (stand alone muons without inner track matching)
  - Tight Cosmic Veto
  - Muon TOF must be compatible with IP collisions

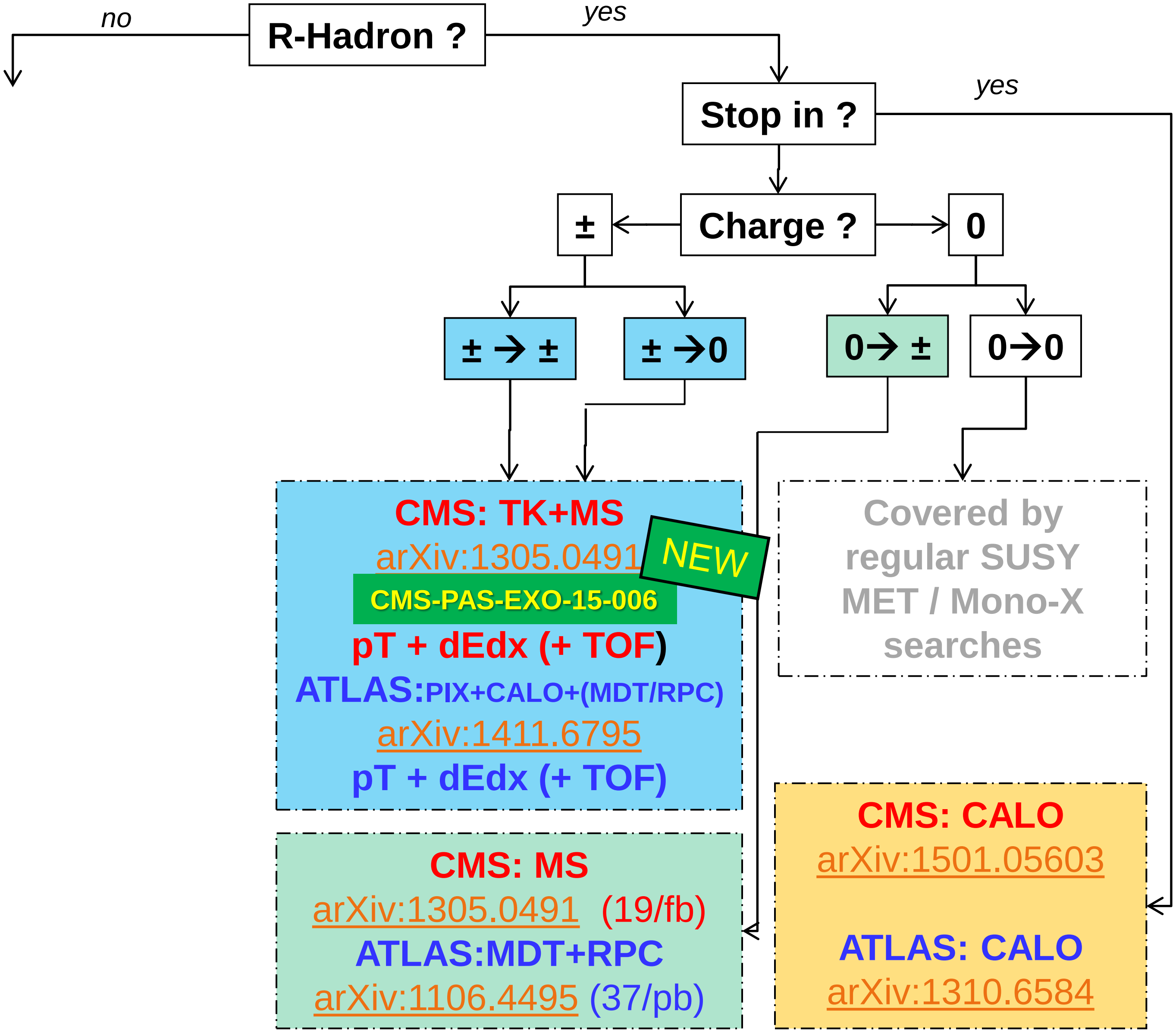


Background (ABCD)



Limits vs fraction of Gluino balls

ATLAS/CMS Searches



R-Hadron ?

no

yes

Stop in ?

yes

Charge ?

±

0

± → ±

± →0

0→ ±

0→0

CMS: TK+MS

arXiv:1305.0491

NEW

CMS-PAS-EXO-15-006

pT + dEdx (+ TOF)

ATLAS:PIX+CALO+(MDT/RPC)

arXiv:1411.6795

pT + dEdx (+ TOF)

Covered by regular SUSY MET / Mono-X searches

CMS: MS

arXiv:1305.0491 (19/fb)

ATLAS:MDT+RPC

arXiv:1106.4495 (37/pb)

CMS: CALO

arXiv:1501.05603

ATLAS: CALO

arXiv:1310.6584

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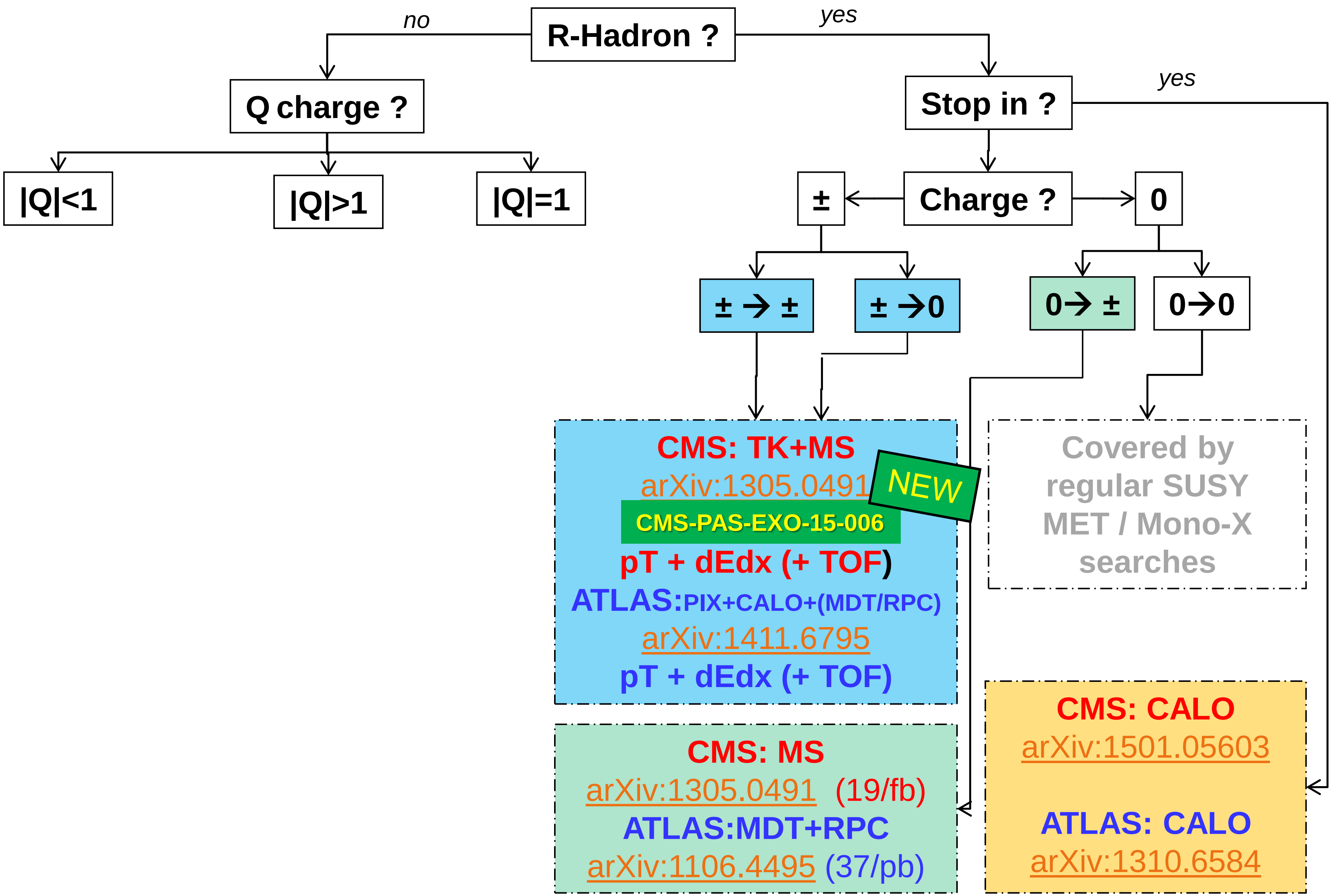
ATLAS/CMS Searches



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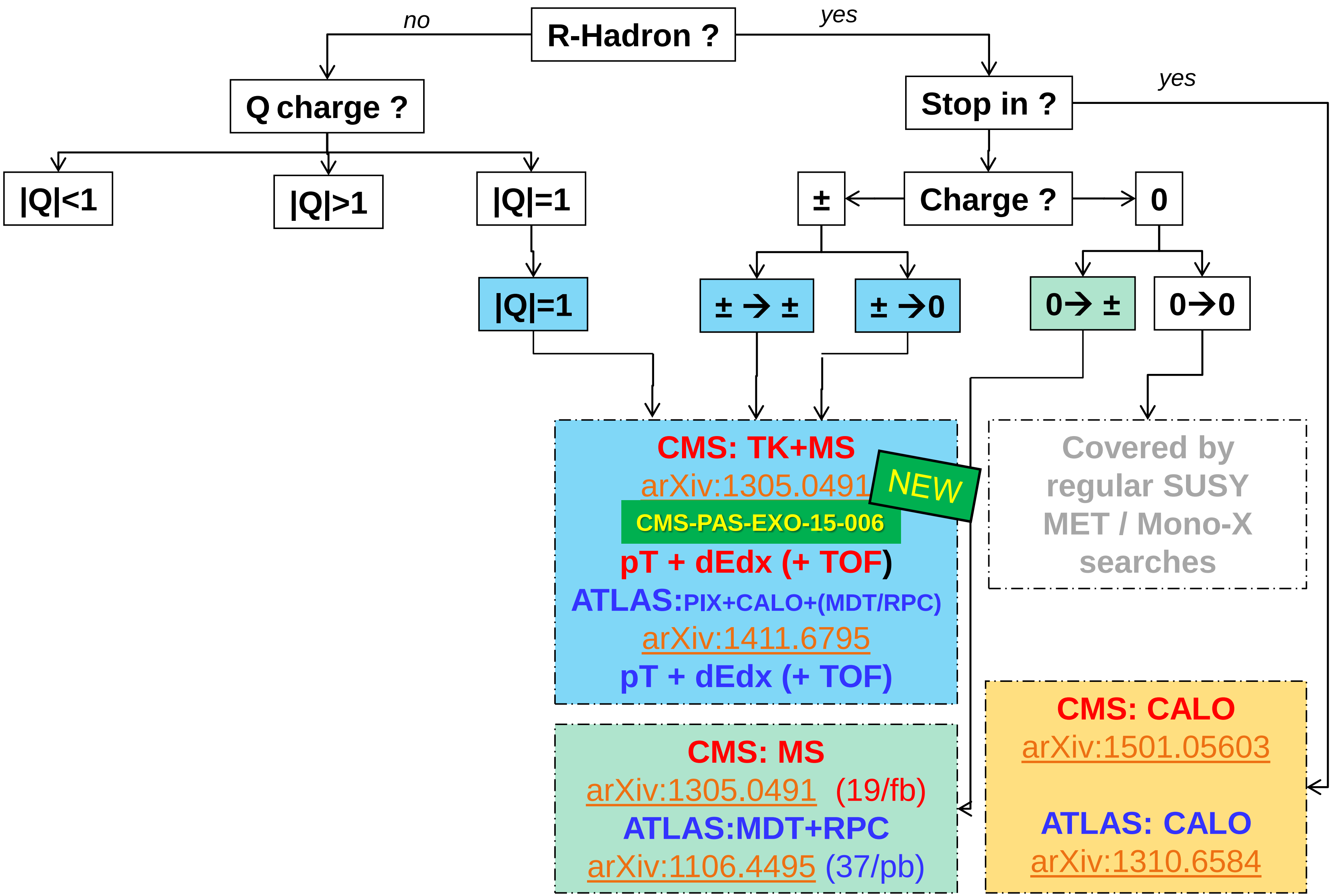
ATLAS/CMS Searches



R-Hadron ?

no

Q charge ?

|Q|<1

|Q|>1

|Q|=1

|Q|=1

yes

Stop in ?

yes

Charge ?

±

0

± → ±

± →0

0→ ±

0→0

CMS: TK+MS
arXiv:1305.0491
CMS-PAS-EXO-15-006
NEW
pT + dEdx (+ TOF)
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arXiv:1106.4495 (37/pb)

CMS: CALO
arXiv:1501.05603

ATLAS: CALO
arXiv:1310.6584

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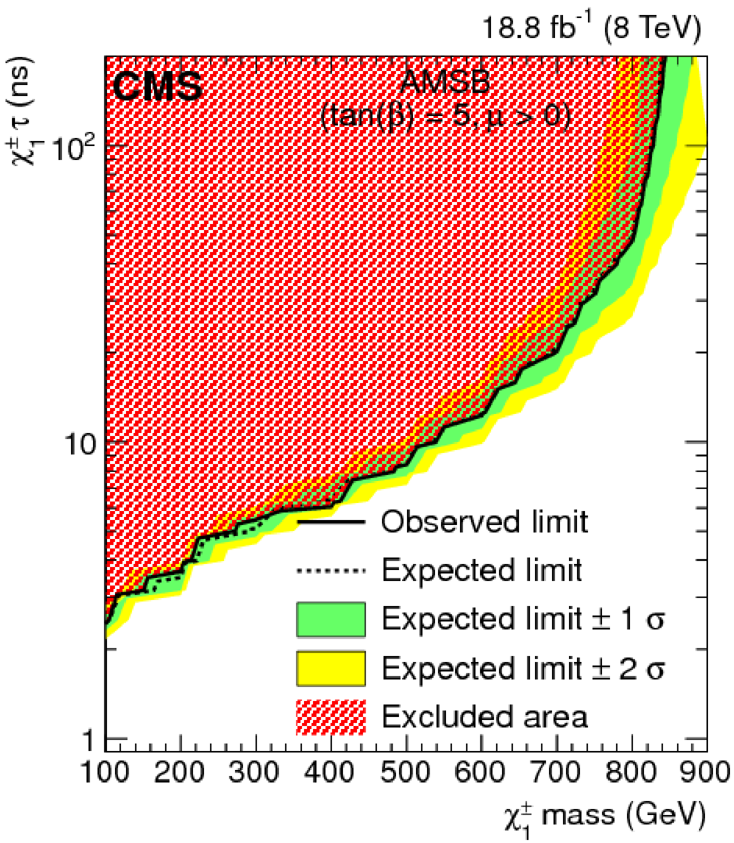
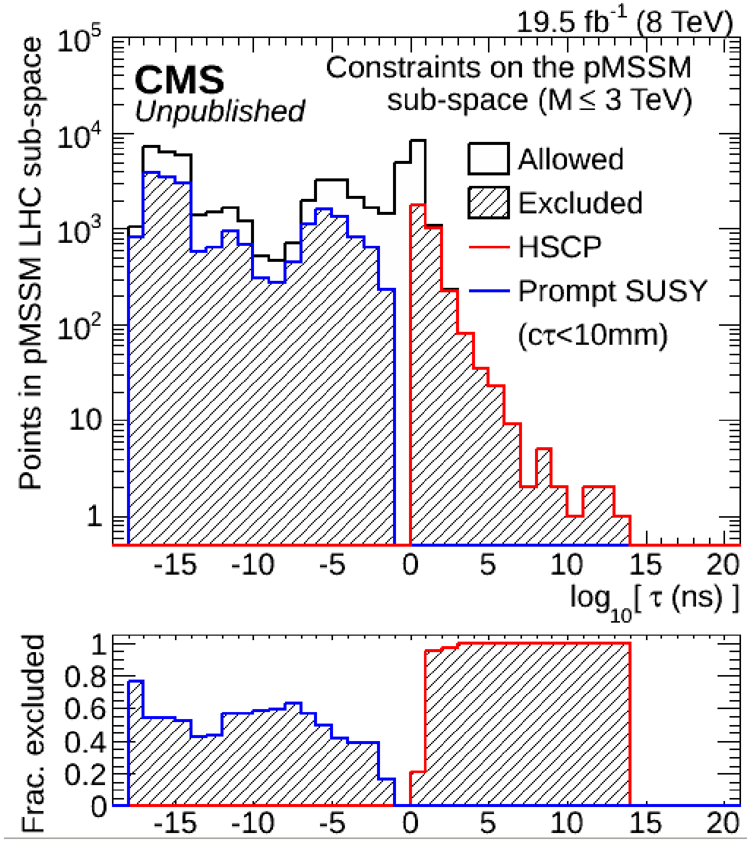
Selected Results: |Q|=1

- Identical to the case regular (± → ±) R-Hadron search
- But constrains many additional models predicting « lepton-like » HSCP
    - GMSB (staus)
    - AMSB (charginos)
    - pMSSM (charginos)





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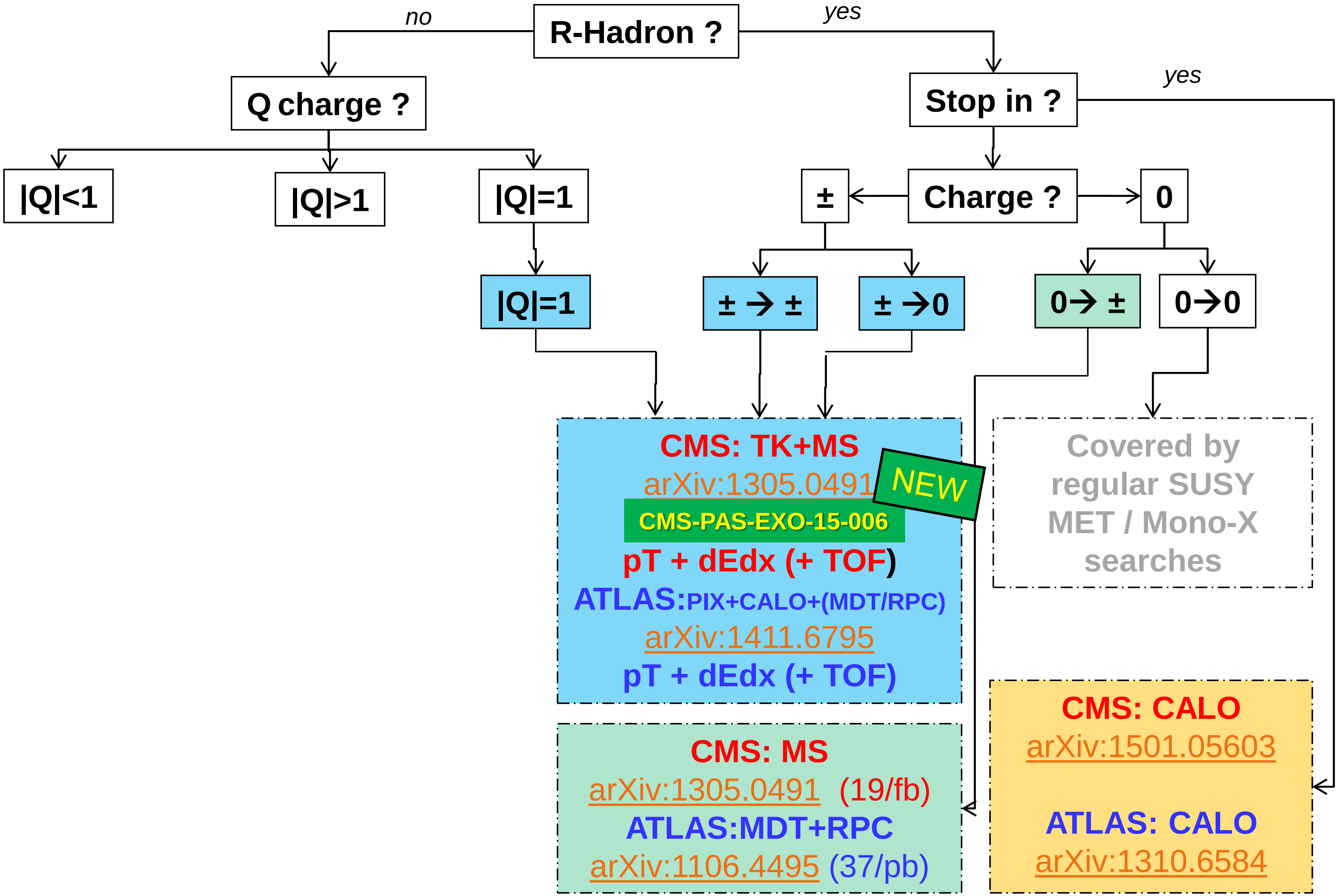
ATLAS/CMS Searches



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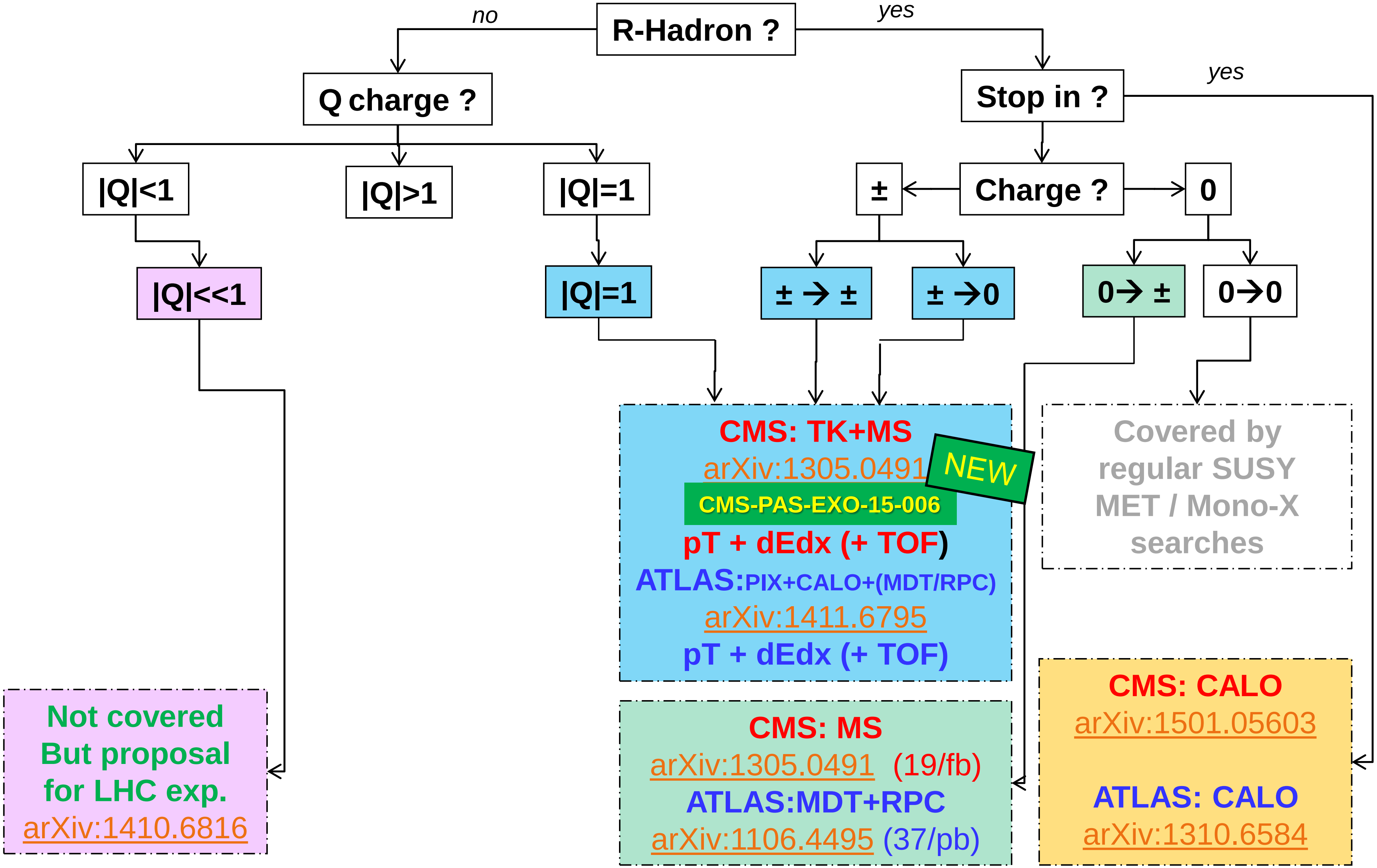
ATLAS/CMS Searches



R-Hadron ?

no

Q charge ?

|Q|<1

|Q|>1

|Q|=1

|Q|<<1

|Q|=1

yes

Stop in ?

yes

Charge ?

±

0

± → ±

± →0

0→ ±

0→0

CMS: TK+MS

arXiv:1305.0491

NEW

CMS-PAS-EXO-15-006

pT + dEdx (+ TOF)

ATLAS:PIX+CALO+(MDT/RPC)

arXiv:1411.6795

pT + dEdx (+ TOF)

Covered by regular SUSY MET / Mono-X searches

Not covered But proposal for LHC exp.

arXiv:1410.6816

CMS: MS

arXiv:1305.0491 (19/fb)

ATLAS:MDT+RPC

arXiv:1106.4495 (37/pb)

CMS: CALO

arXiv:1501.05603

ATLAS: CALO

arXiv:1310.6584

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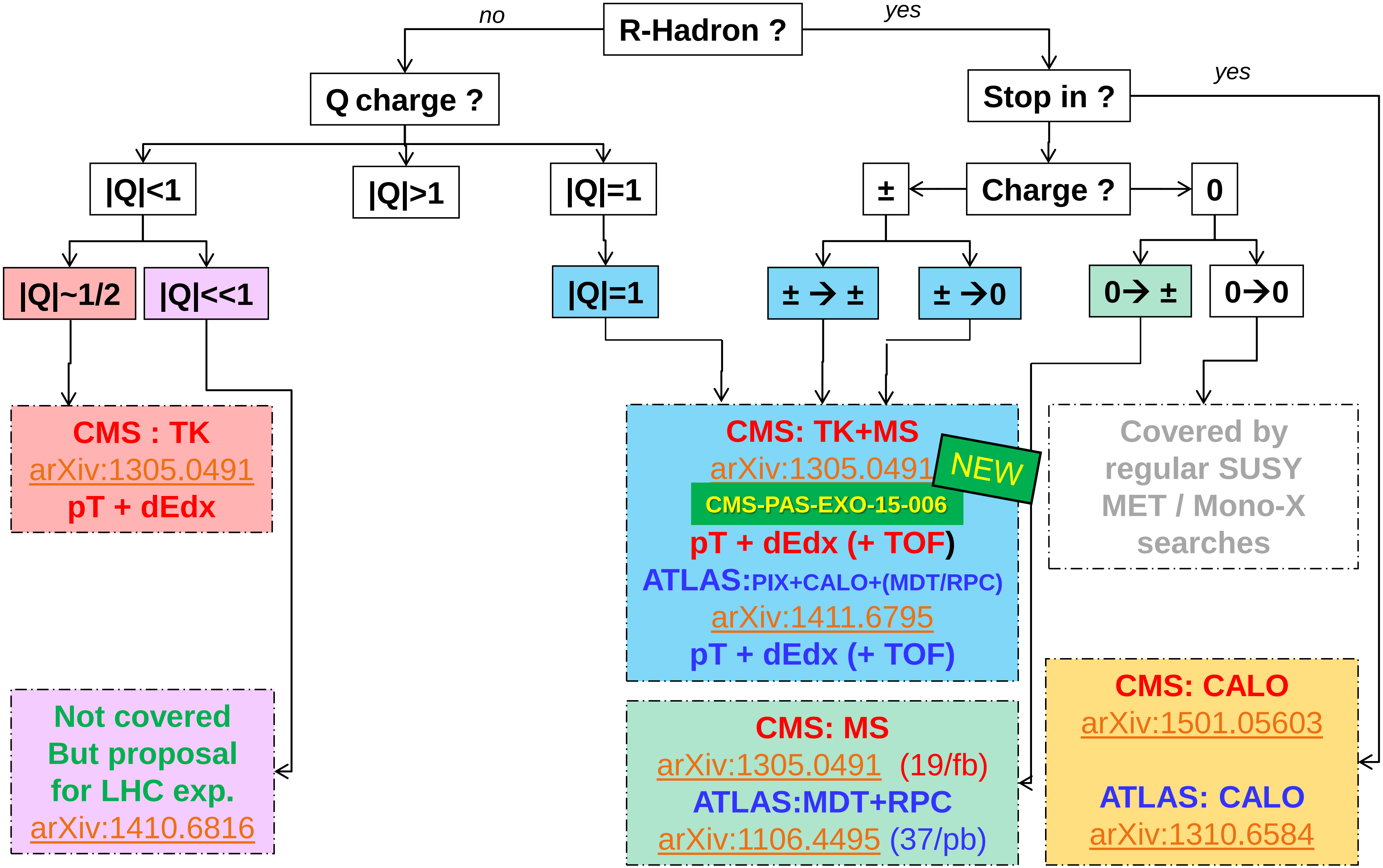
ATLAS/CMS Searches



no

R-Hadron ?

yes

Q charge ?

Stop in ?

yes

|Q|<1

|Q|>1

|Q|=1

±

Charge ?

0

|Q|~1/2

|Q|<<1

|Q|=1

± → ±

± →0

0→ ±

0→0

CMS : TK
arXiv:1305.0491
pT + dEdx

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CMS: CALO
arXiv:1501.05603

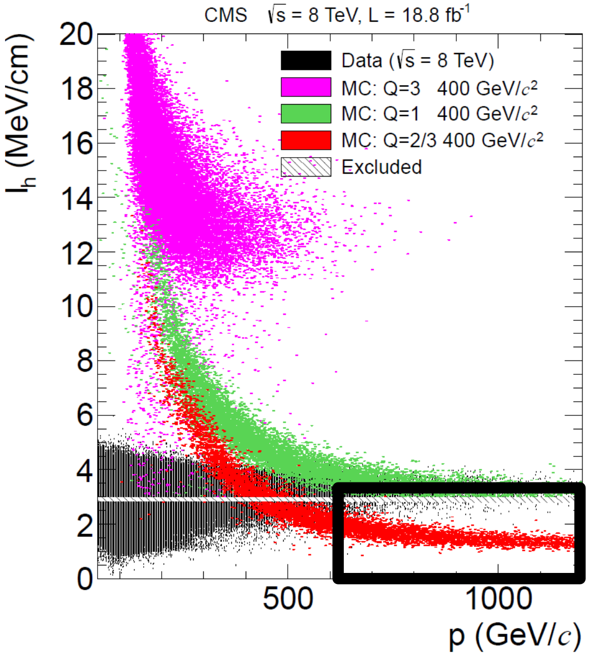
ATLAS: CALO
arXiv:1310.6584

Selected Results on: Q<1

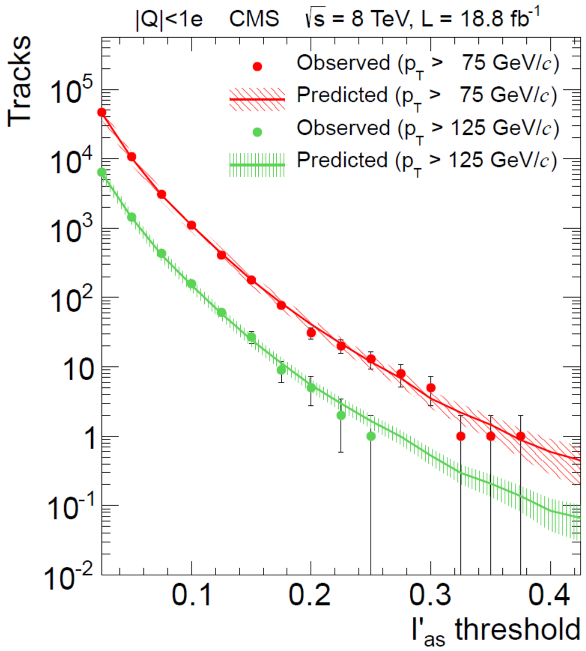
The search in a nutshell

- Challenges:
    - Small energy loss → LHC detectors and DAQ designed for Q=1
    - Out-of-time particles (cosmics/ghost) also lead to low dE/dx
- Advantage:
    - Tracking: high reco pT (=pT_{True} / Q)

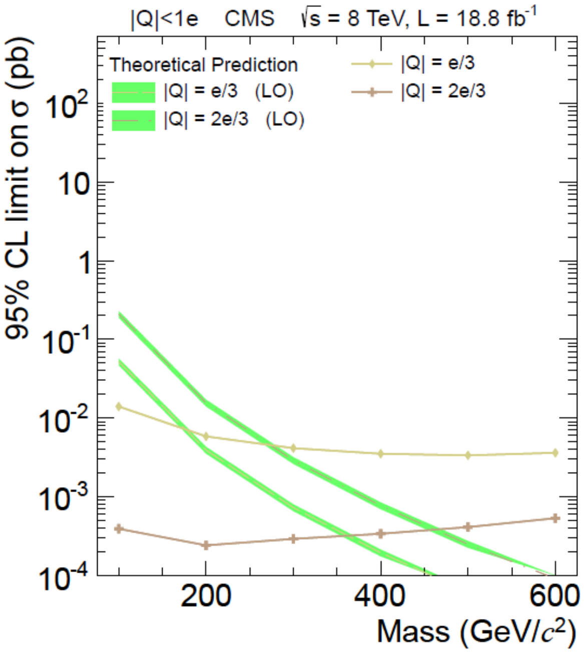
signature



Background (ABCD)



Limits



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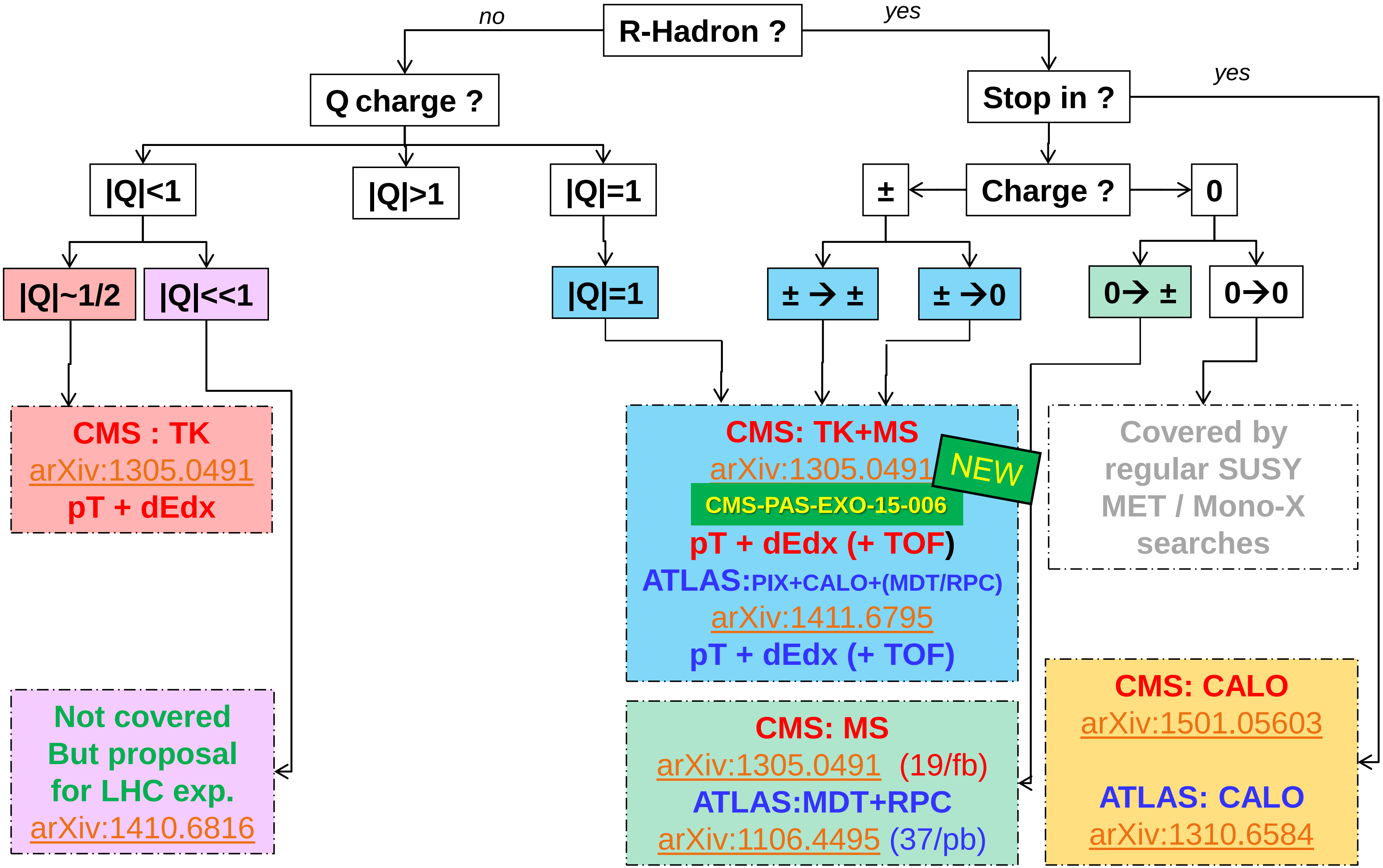
ATLAS/CMS Searches



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Stop in ?

yes

Charge ?

±

± → ±

± →0

0

0→ ±

0→0

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arXiv:1305.0491
pT + dEdx

Not covered
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NEW
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pT + dEdx (+ TOF)
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Covered by
regular SUSY
MET / Mono-X
searches

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ATLAS: CALO
arXiv:1310.6584

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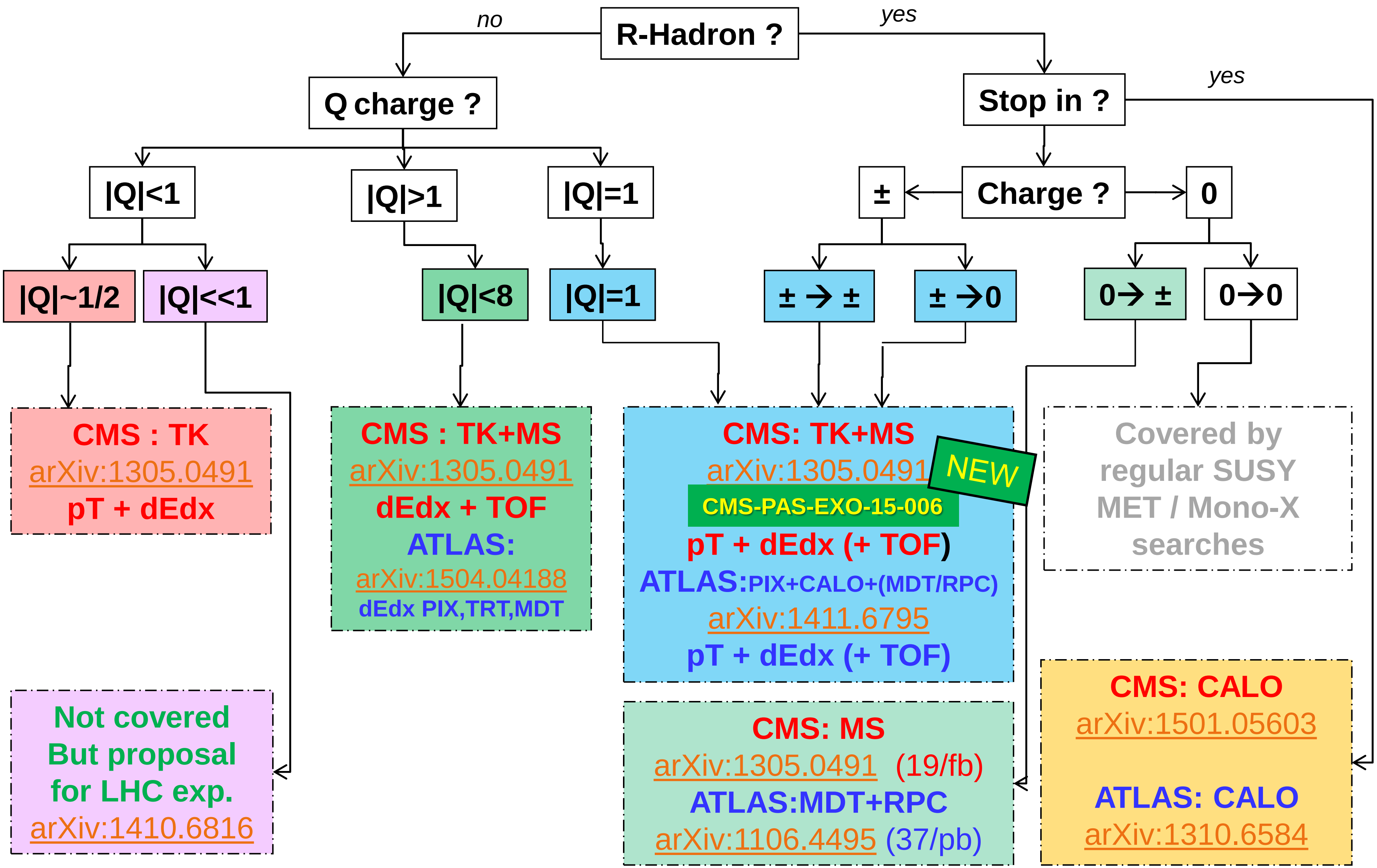
ATLAS/CMS Searches



R-Hadron ?

no

Q charge ?

|Q|<1

|Q|~1/2

|Q|<<1

|Q|>1

|Q|<8

|Q|=1

|Q|=1

yes

Stop in ?

yes

Charge ?

±

± → ±

± →0

0

0→ ±

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CMS : TK
arXiv:1305.0491
pT + dEdx

CMS : TK+MS
arXiv:1305.0491
dEdx + TOF
ATLAS:
arXiv:1504.04188
dEdx PIX,TRT,MDT

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NEW
CMS-PAS-EXO-15-006
pT + dEdx (+ TOF)
ATLAS:PIX+CALO+(MDT/RPC)
arXiv:1411.6795
pT + dEdx (+ TOF)

Covered by regular SUSY MET / Mono-X searches

Not covered
But proposal
for LHC exp.
arXiv:1410.6816

CMS: MS
arXiv:1305.0491 (19/fb)
ATLAS:MDT+RPC
arXiv:1106.4495 (37/pb)

CMS: CALO
arXiv:1501.05603

ATLAS: CALO
arXiv:1310.6584

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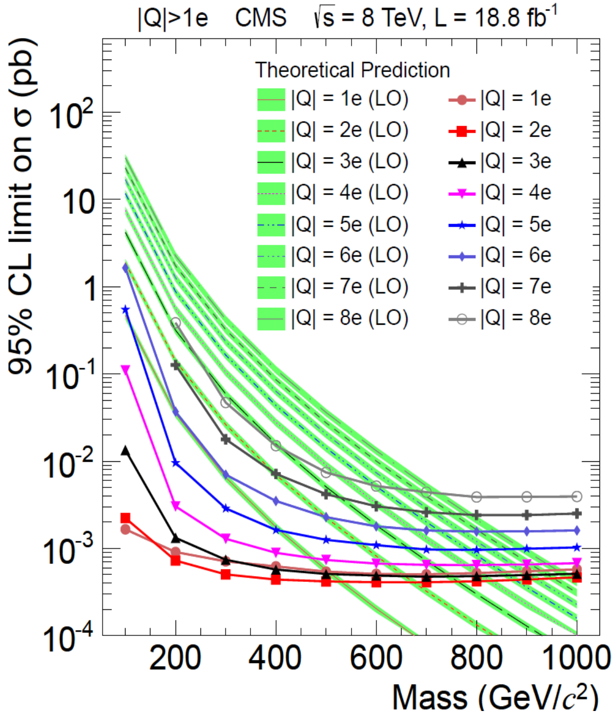
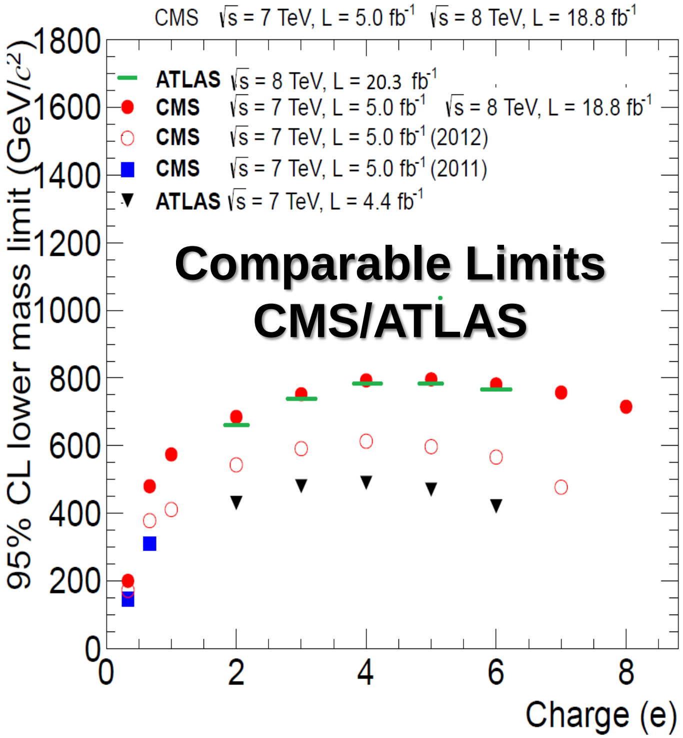
Selected Results on: 1<Q<10

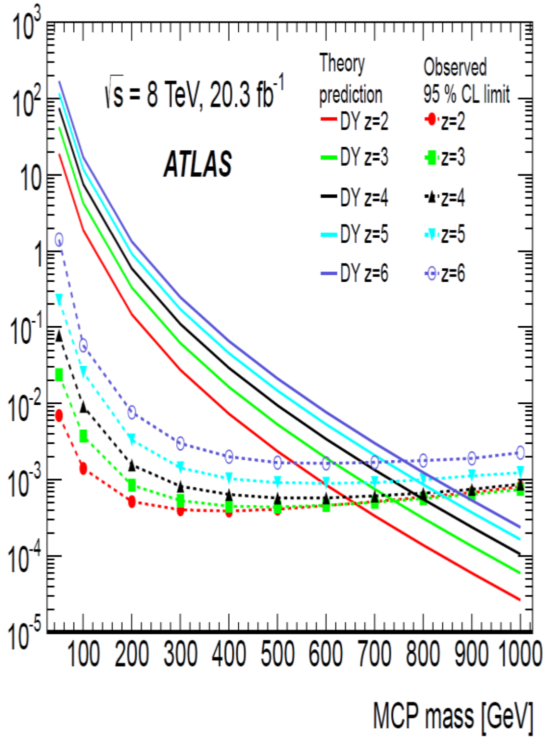
The search in a nutshell

- Challenges:
    - Tracking: smaller reco pT (=pT_{True} / Q)→ trigger & background rate
- Solutions:
    - Requires it to reach MS (many redundant measurements dE/dx or TOF)
    - Keep track pT threshold as low as possible (40GeV)





Comparable Limits CMS/ATLAS



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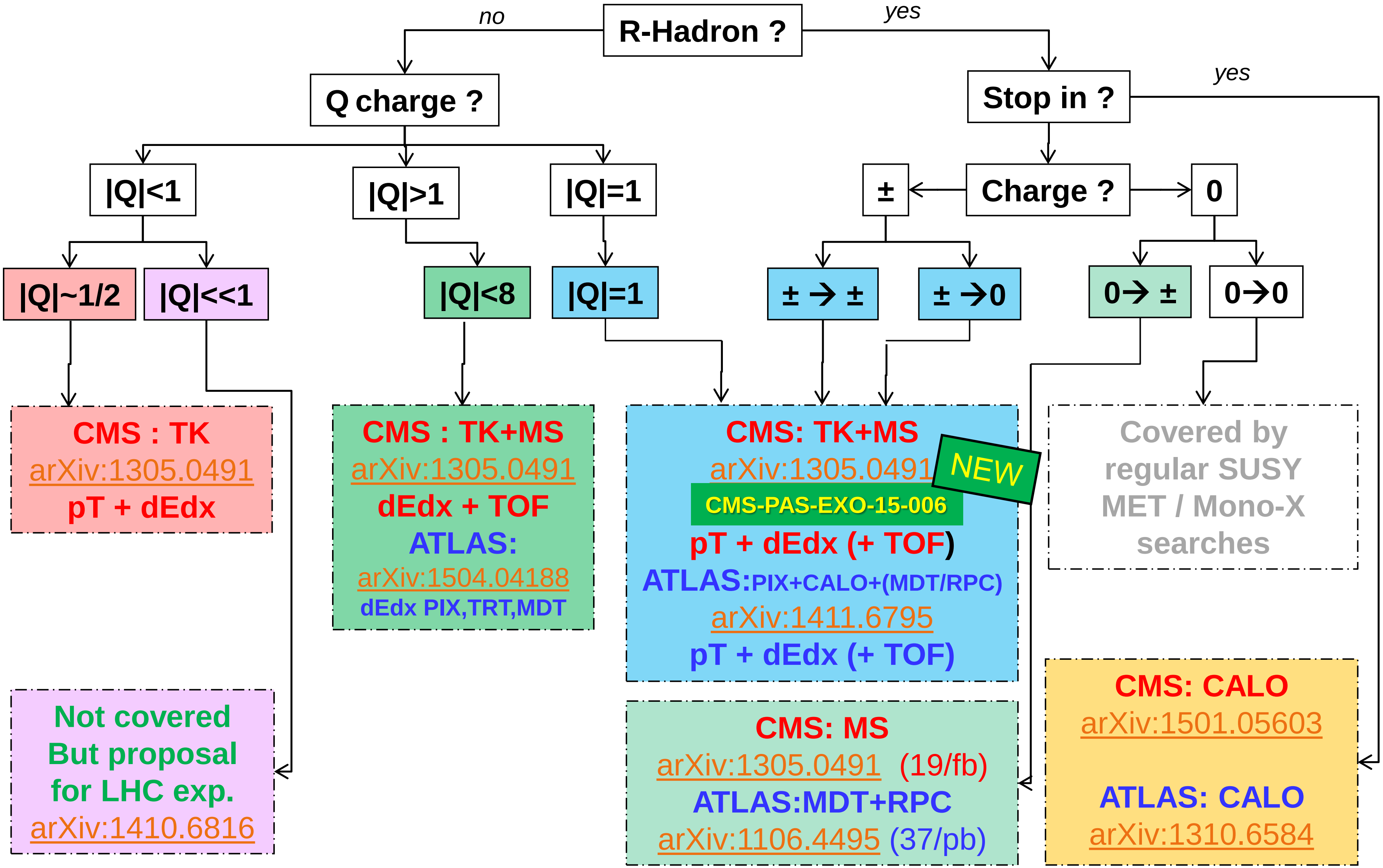

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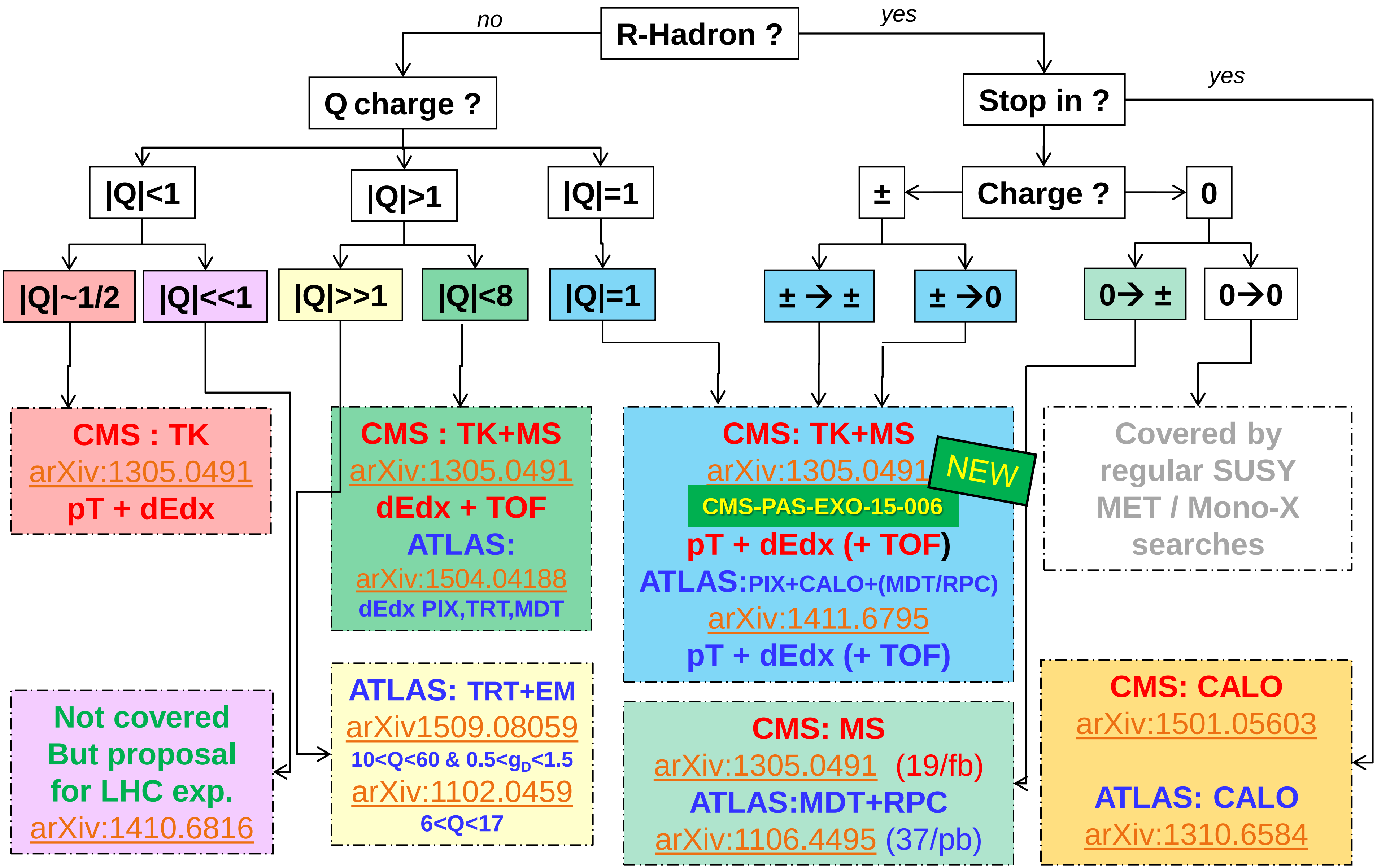

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ATLAS: TRT+EM
arXiv1509.08059
$10<Q<60$ & $0.5<g_D<1.5$
arXiv:1102.0459
$6<Q<17$

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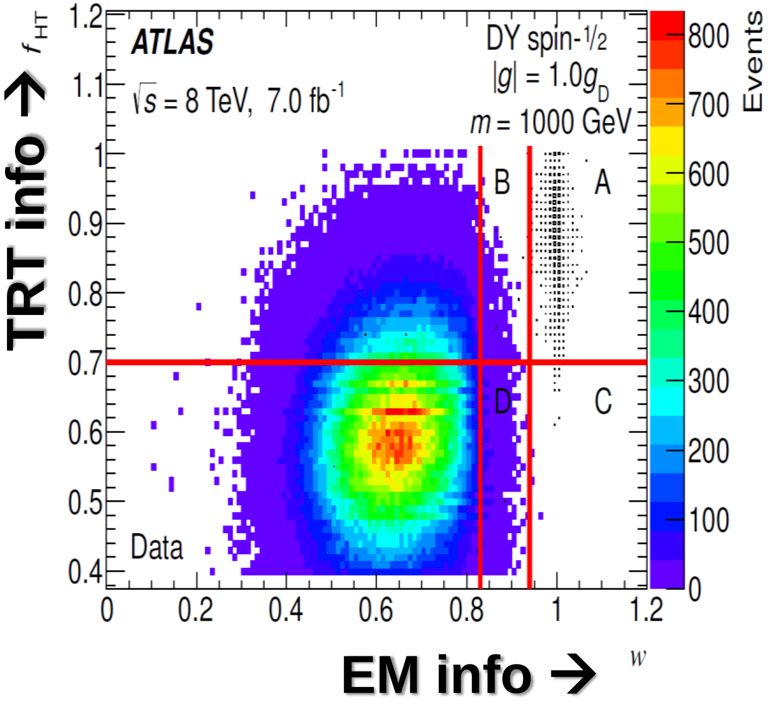
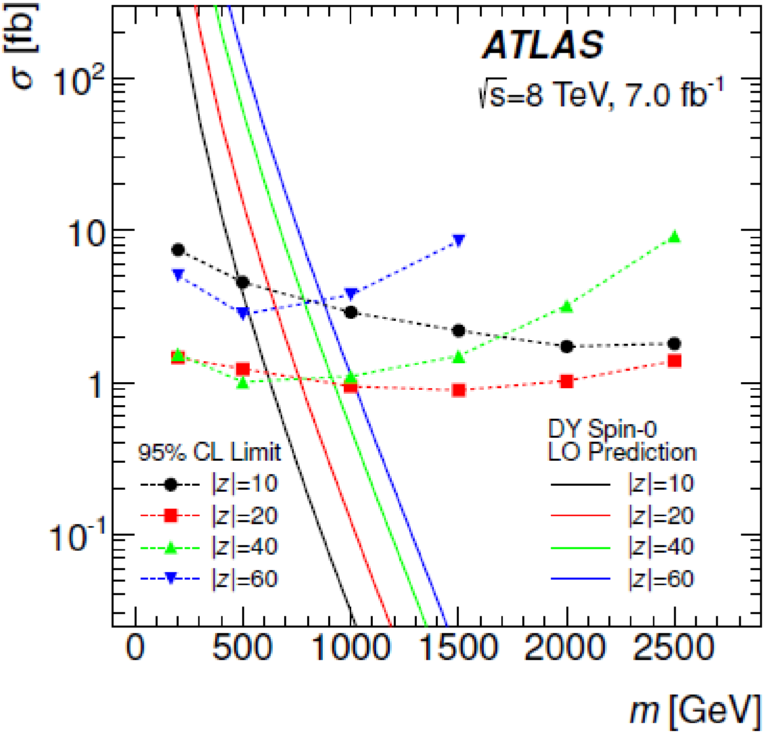
Selected Results on: Q>>1

The search in a nutshell

- Challenges:
  - Tracking: small reco pT (=pT_{True} / Q)
  - Huge energy loss: not reach outer detector (+ possible DAQ issues)
- Solutions: Dedicated trigger + no tracking + only inner detectors (TRT and EM)





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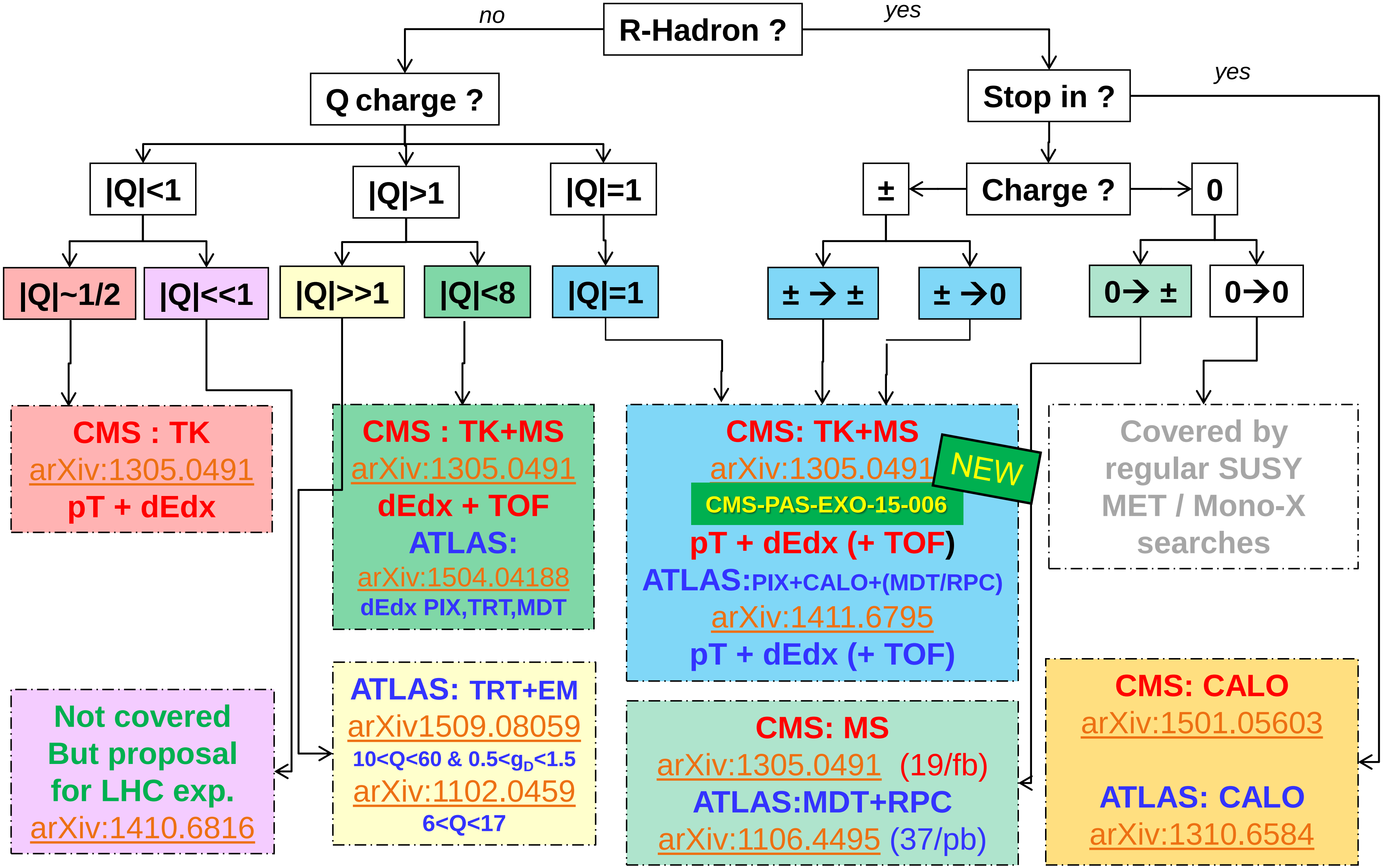

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yes

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Outline

- **Introduction to LL physics (Why ? How ?)** ✓
- **Searches for LL particles decaying OUTSIDE the detector**
  - **Neutral** ✓
  - **Charged** ✓
- **Searches for LL particles decaying INSIDE the detector**
  - **Charged** ⇐
  - **Neutral**
- **Super exotic particles**
- **Summary**

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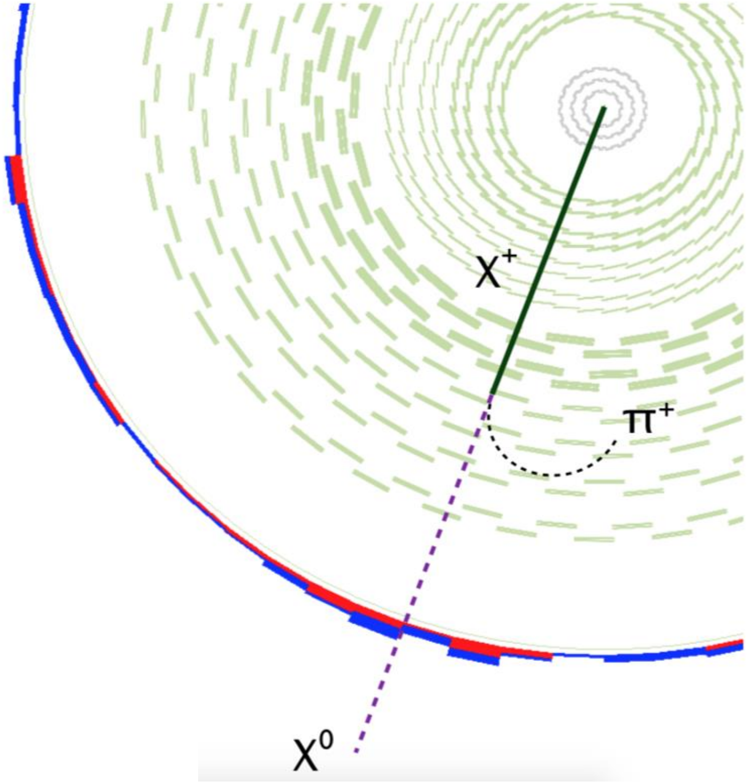
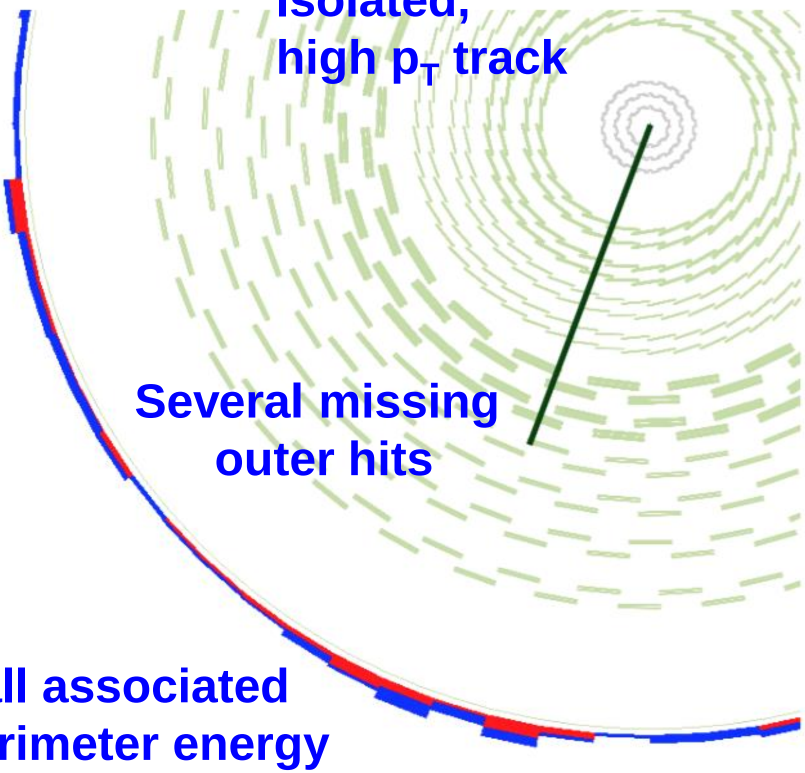
Search for disappearing tracks

AMSB SUSY predicts nearly degenerate neutralino and chargino: ΔM ≈100-200 MeV
→ Chargino is long-lived and decays to neutralino and a very soft pion

Disappearing High pT Track

- **Signature : tracker track with high pT and missing outer hits and small E_{calo}**
- **Backgrounds : fake tracks, kinked tracks (bremsstrahlung and nucl. int)**





Isolated, high p_T track

Several missing outer hits

Small associated calorimeter energy

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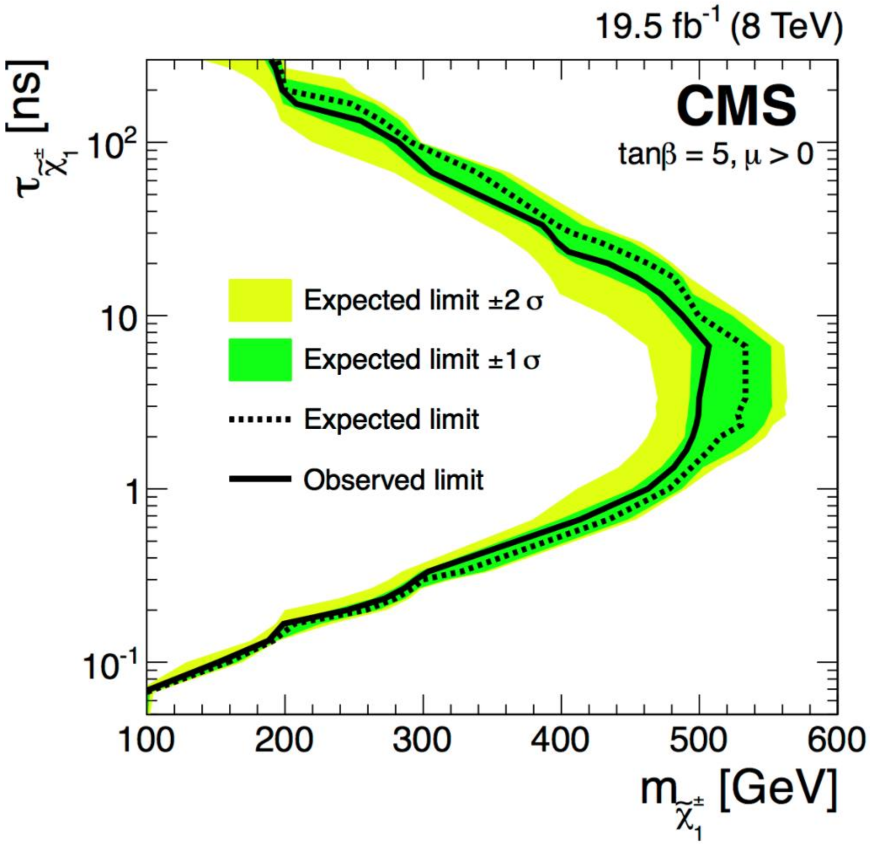
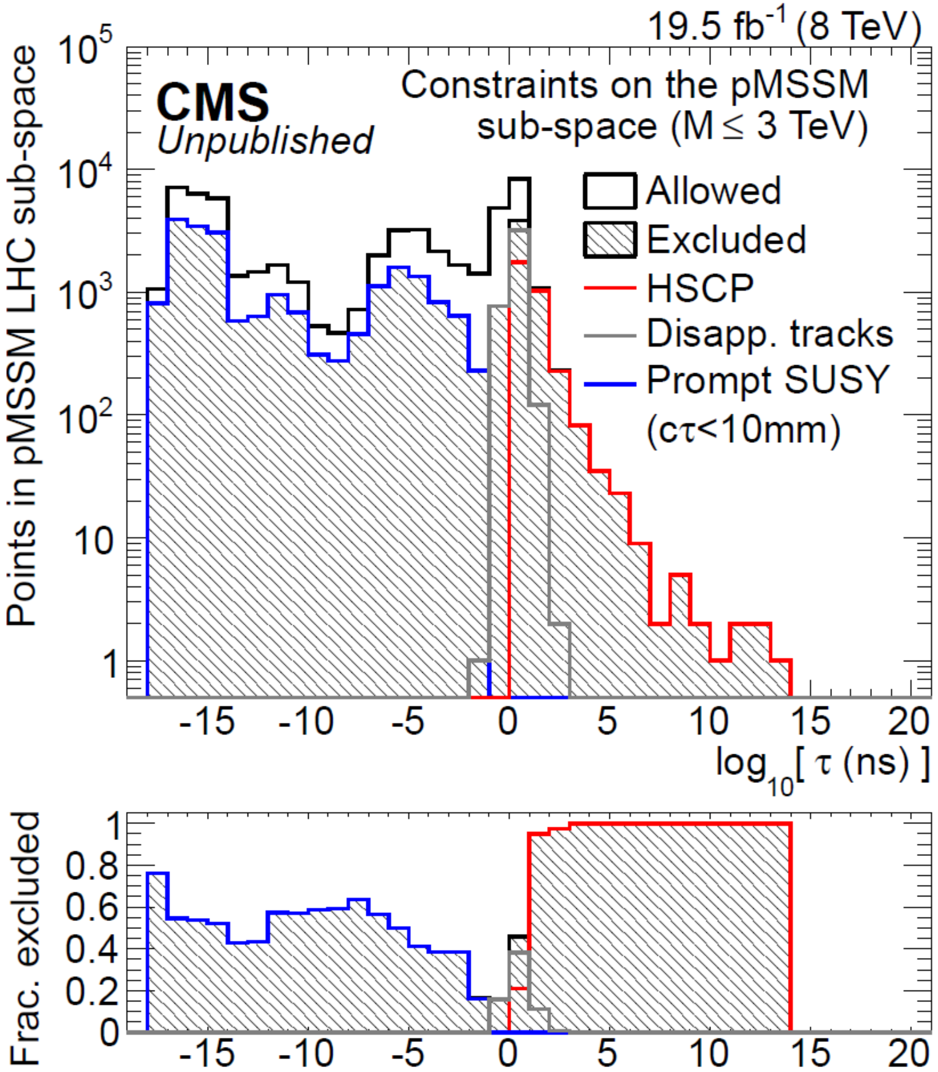
Results

AMSB models with a chargino mass less than 260 GeV, corresponding to a mean proper lifetime of 0.2 ns are excluded

Start filling the gap in pMSSM too





Still a gap to fill for intermediates lifetimes

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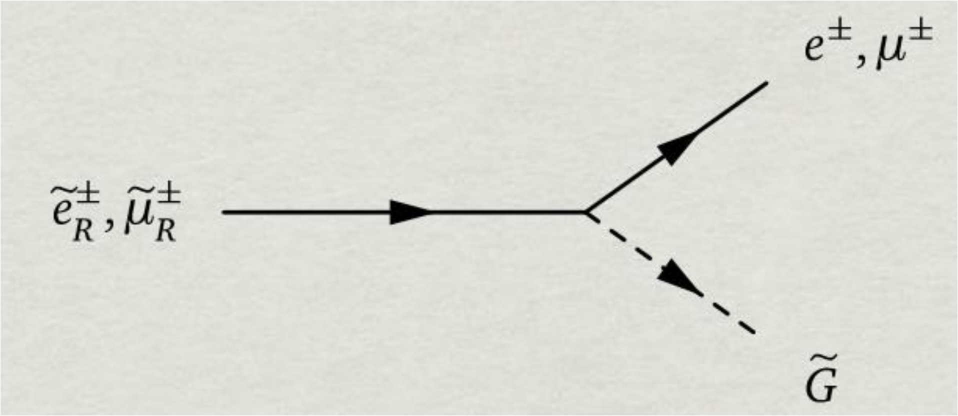
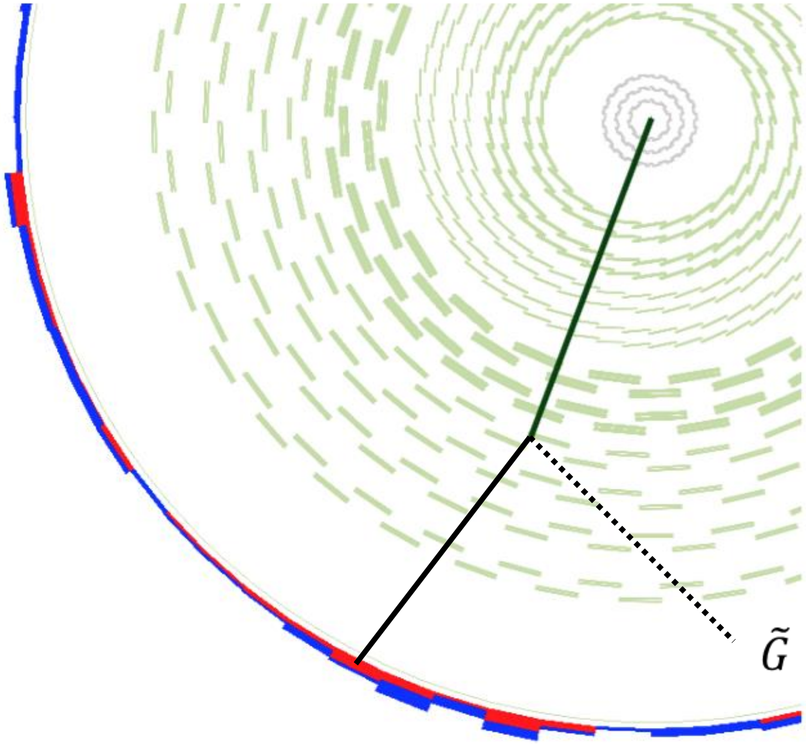
Search for kinked tracks

Similar to the disapearing track search, except that the decay product has a high pT charged candidate

High pT Kinked Track

- **Signature : tracker track with high pT and a kink somewhere**
- **Backgrounds : fake tracks, bremsstrahlung and nucl. int**





No public results on this specific search are currently public at the LHC.

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Outline

- **Introduction to LL physics (Why ? How ?)** ✓

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  - **Neutral** ✓
  - **Charged** ✓

- **Searches for LL particles decaying INSIDE the detector**
  - **Charged** ✓
  - **Neutral** ⇦

- **Super exotic particles**

- **Summary**

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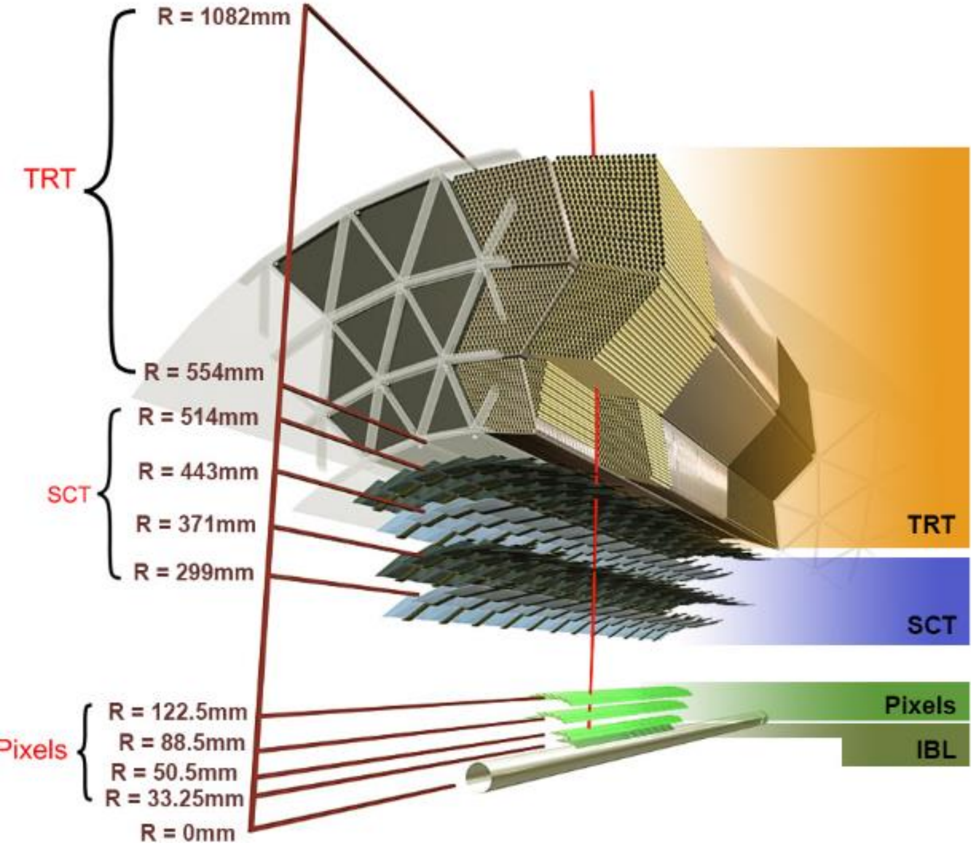
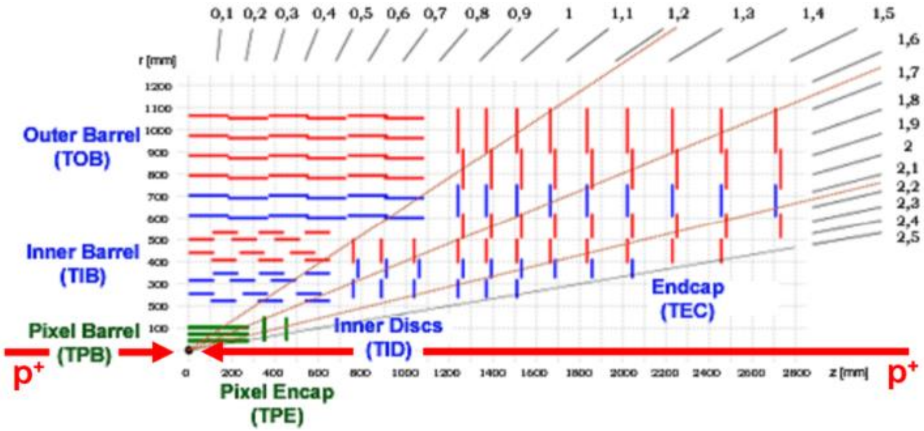
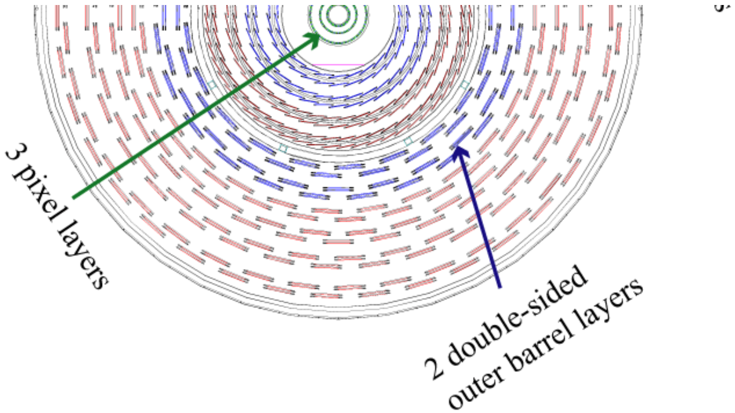
ATLAS/CMS Tracker overview







ATLAS tracker
- Inside a 2T solenoid
- Coverage up to |η|≤2.5
- R≥50mm (run1), 33mm (run2)

CMS tracker
- Inside a 4T solenoid
- Coverage up to |η|≤2.5
- R≥44mm

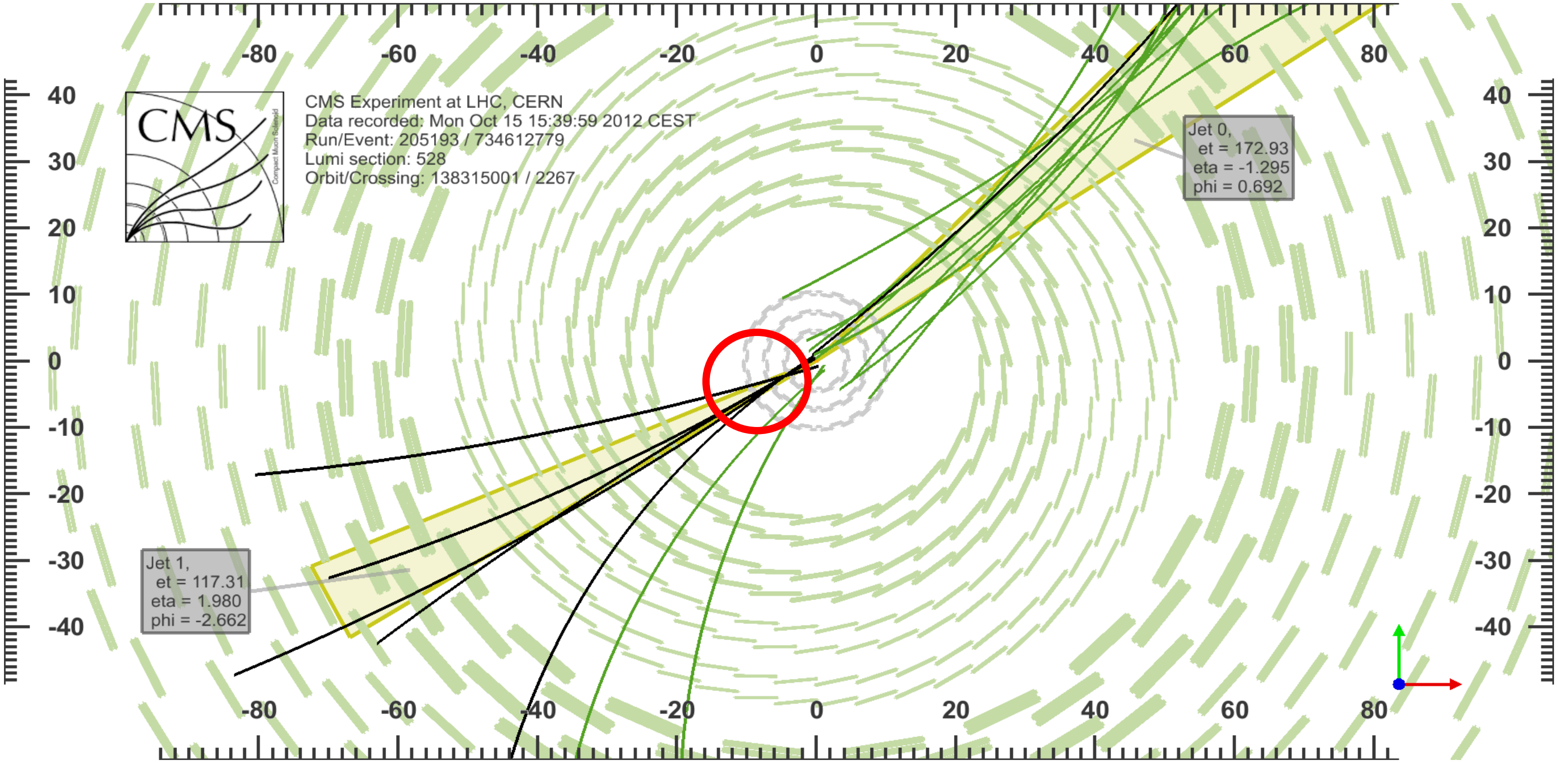
Vertexing

- Vertexing is based on (high quality) track clustering
    - Clustering in CMS is done with Deterministic Annealing
        - Minimizes a free-energy-like function to determine the best number of vertices and their locations

$$F = -T \sum_{i}^{\#\,\text{tracks}} p_i \log \sum_{k}^{\#\,\text{vertices}} \rho_k \exp\left[-\frac{1}{T}\frac{(z_i^T - z_k^V)^2}{\sigma_i^{z\,2}}\right]$$

→ Track origin

→ Vertex position



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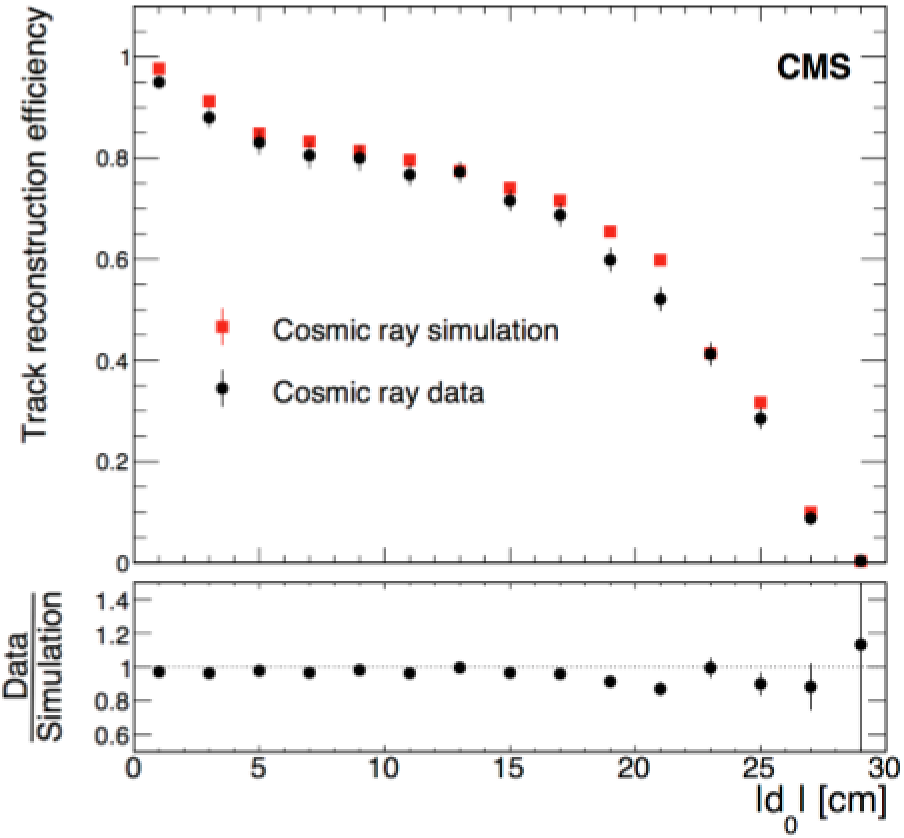
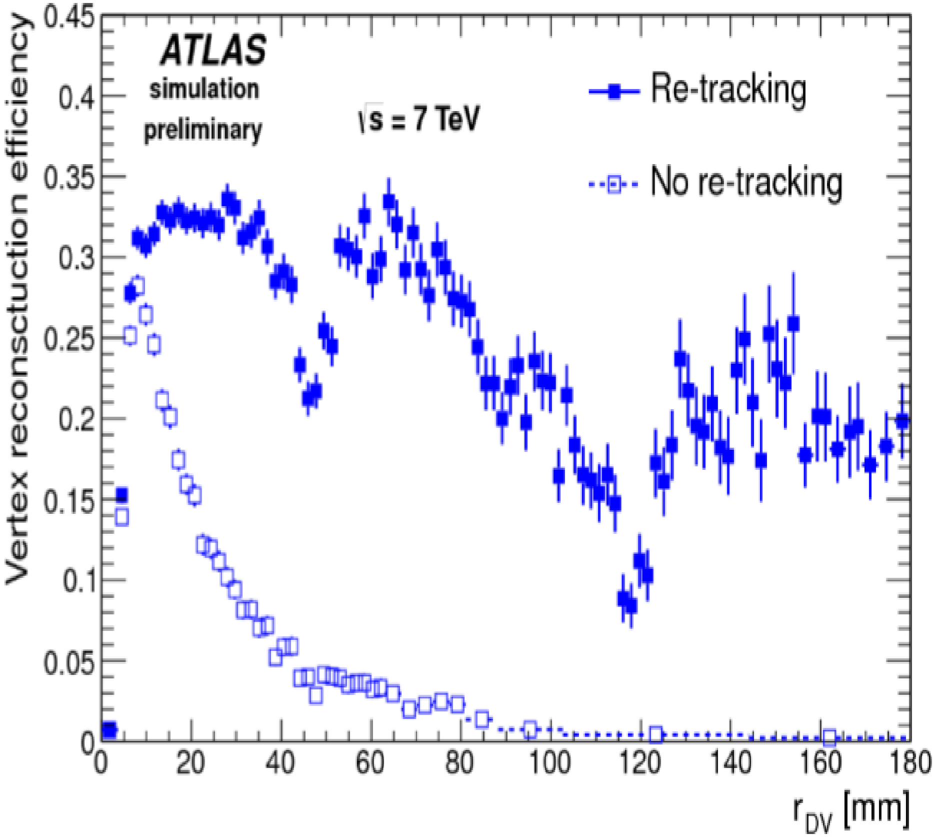
Displaced lepton pair





- **For large displacement (longer life-time), we have Less tracking layers to reconstruct the tracks**
  - **Tracking efficiency drops for large displacement**
  - **Vertex efficiency also drops (consequently)**

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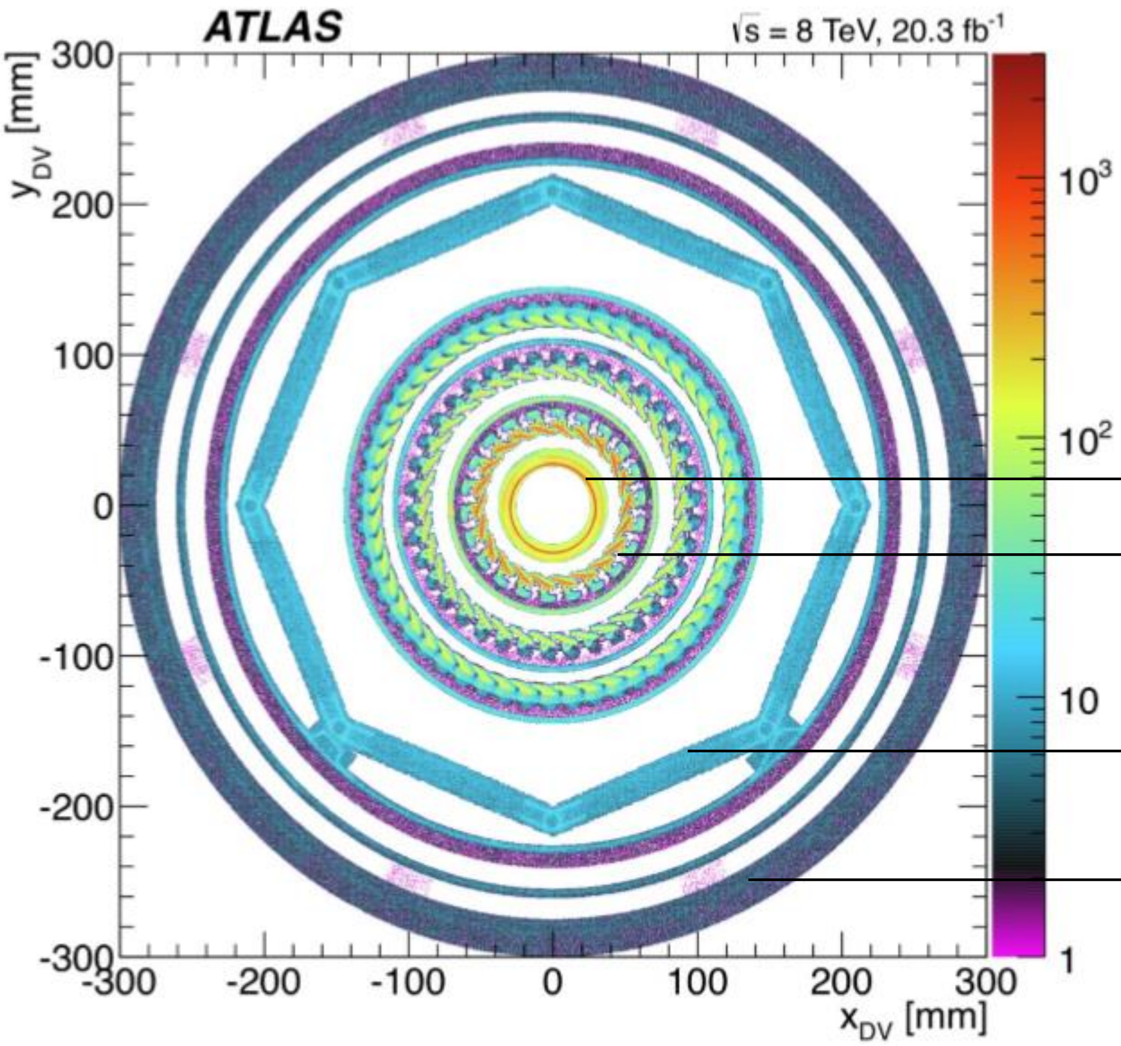
Vertexing to material budget



- **Distribution of the position of reconstructed secondary vertex with ≥5 Traks in ATLAS**

- **Mechanical structures clearly appears**

Beam pipe

Pixel layers (x3)

Mechanical structures separating pixels and SCT

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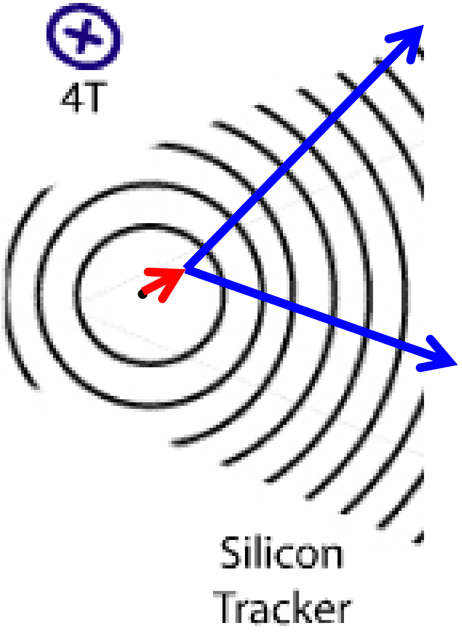
Almost prompt leptons searches

- **Challenges**

  - **Many sources of backgrounds**
    - **Pileup**
    - **Tau leptons → cτ = ~0.1mm**
    - **B hadrons → cτ = ~0.5mm**

  - **Need good vertexing algorithms**
    - **Tracker (pixel) resolution is crucial**



- **Advantages**

  - **Decay product are almost prompt**
    - **Standard object reconstruction**
    - **Analysis similar to prompt search at the exception of the vertex requirement**

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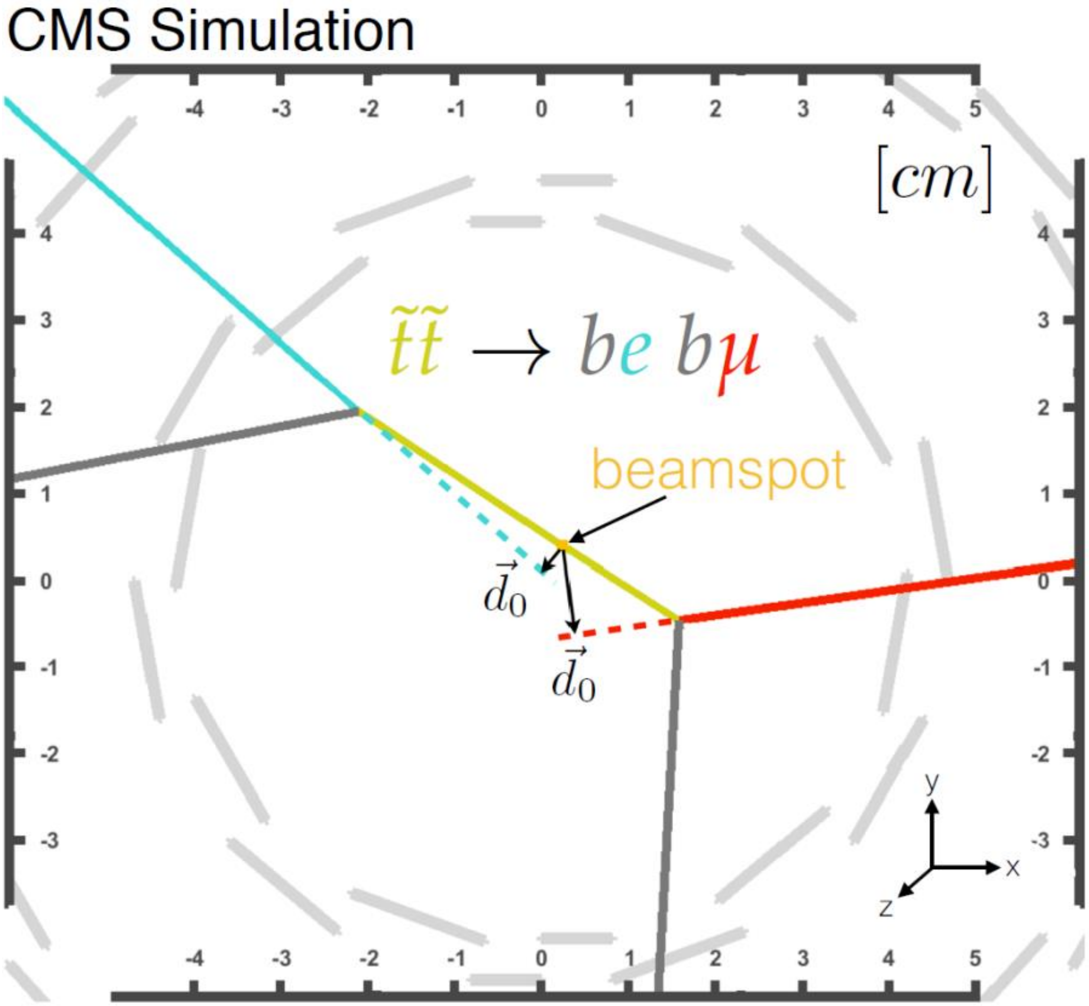
Analysis example

- **Search for Displaced SUSY in Dilepton Final States (arXiv:1409.4789)**

  - Signal model: $\tilde{t}\tilde{t}$→(be)(bμ)
  - Require
    - a displaced e
    - a displaced μ
    - (no vtx requirement)
  - D_0 is the distance of closest approach in the transverse plane between lepton and the LHC beam axis



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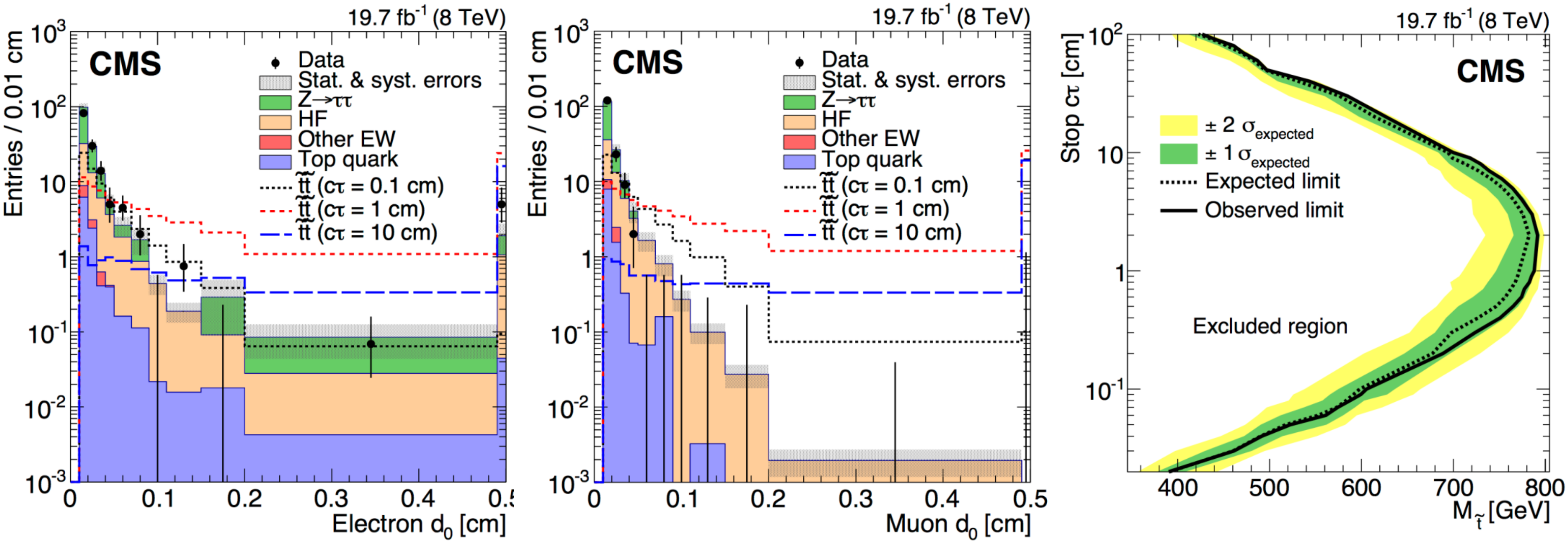
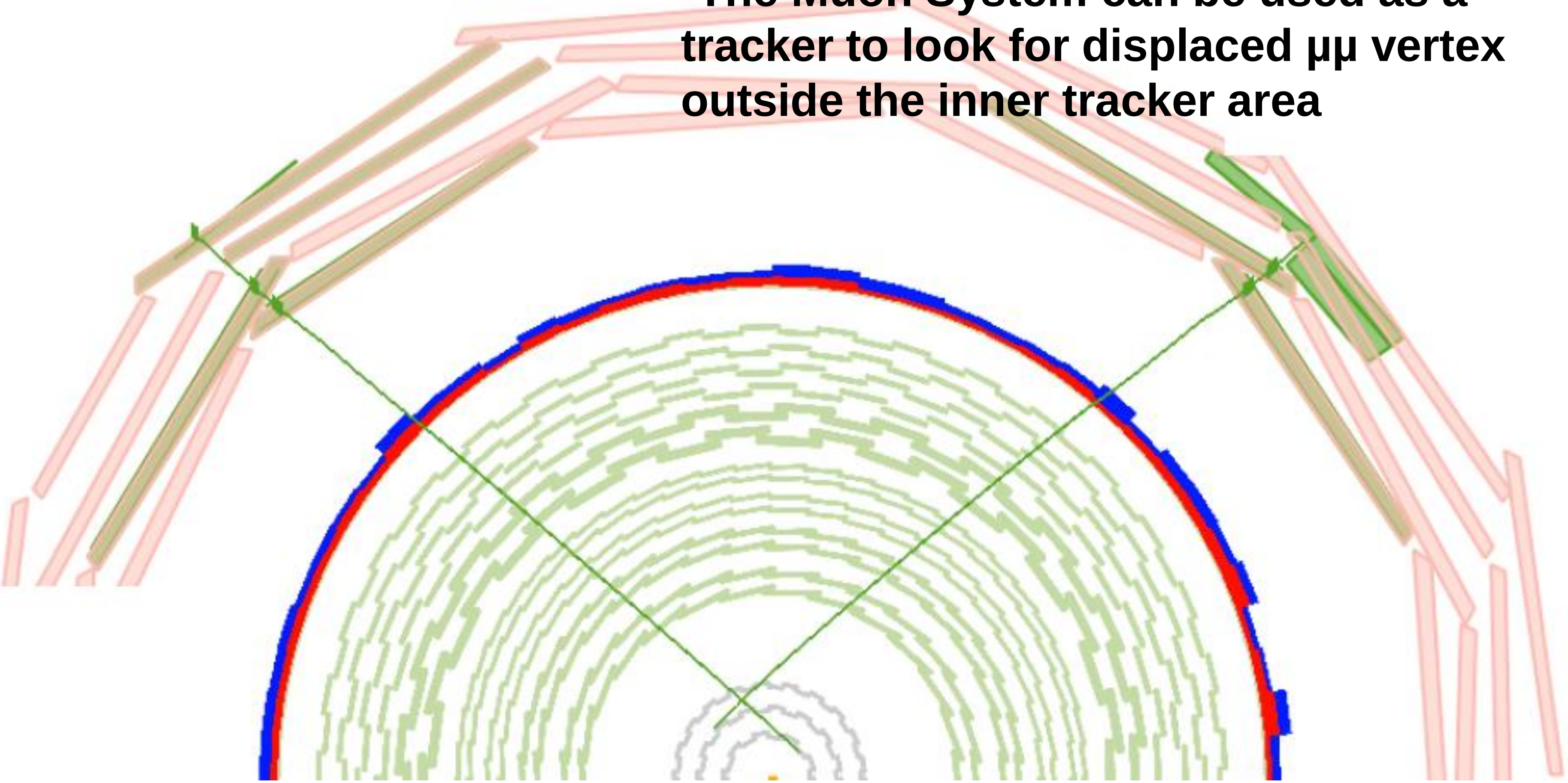


Displaced lepton pair

- **Challenges**
  - Lepton trigger and reco efficiency is lower for large displacement.

- **Advantages**
  - Pratically no backgrounds at the exception of fake / misreco tracks

  - The Muon System can be used as a tracker to look for displaced μμ vertex outside the inner tracker area



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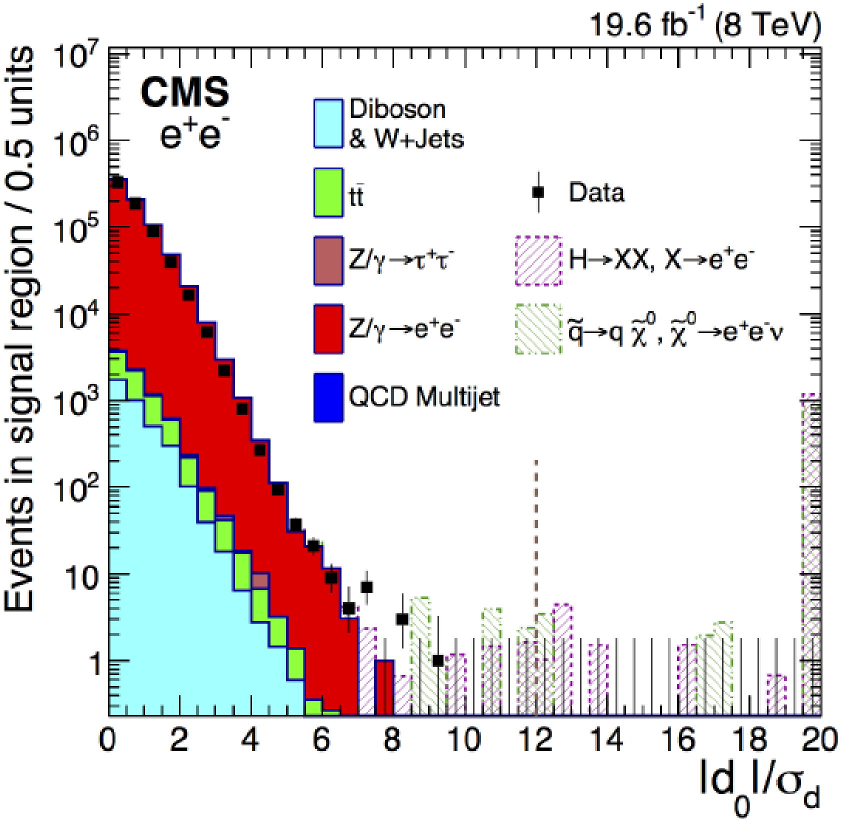
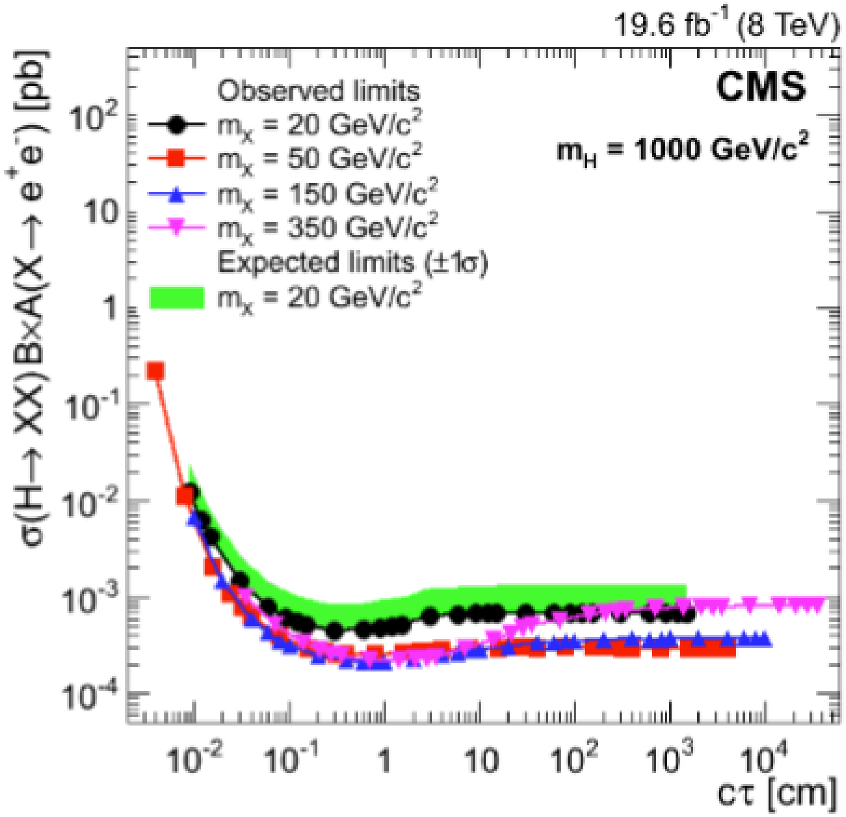
Displaced lepton pair in CMS

- **Search for Displaced Leptons (arXiv:1411.6977 + EXO-14-12)**
  - Signal model:
    - H→(X→ll)(X→ll) with X a long-lived neutral particle
    - RPV SUSY $\tilde{q} \rightarrow (q)\tilde{\chi}^0 \rightarrow \ell\ell\nu$
  - Require the track pair to be incompatible with the primary vertex





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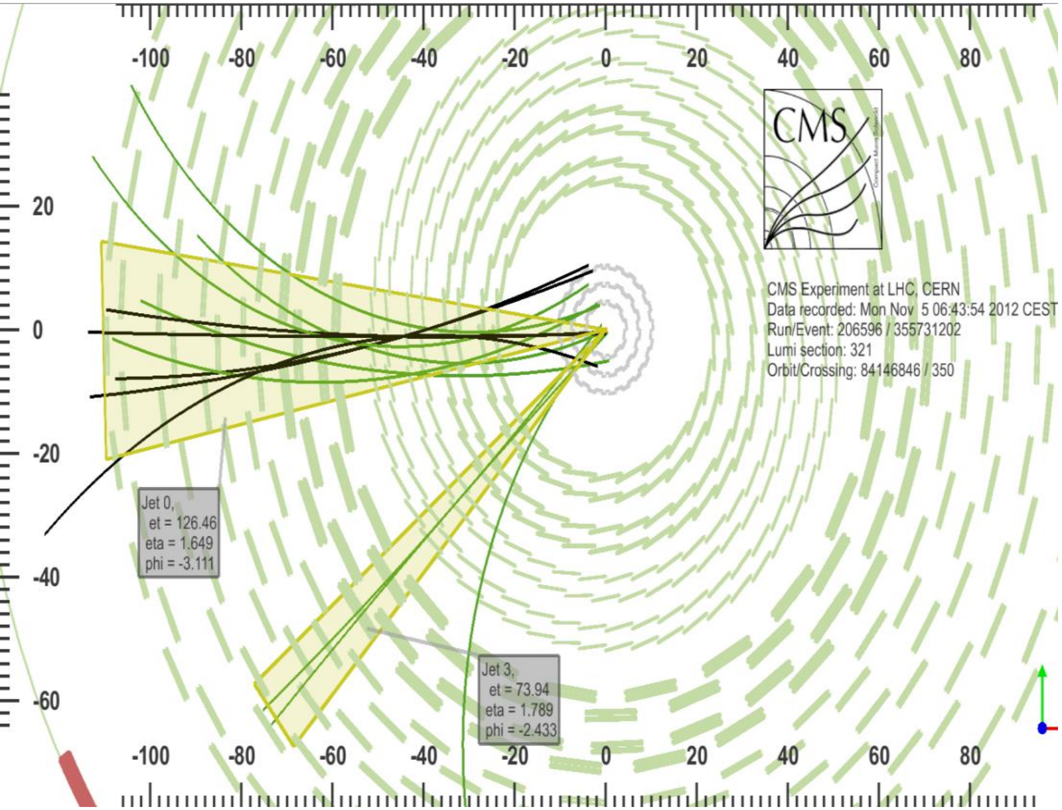
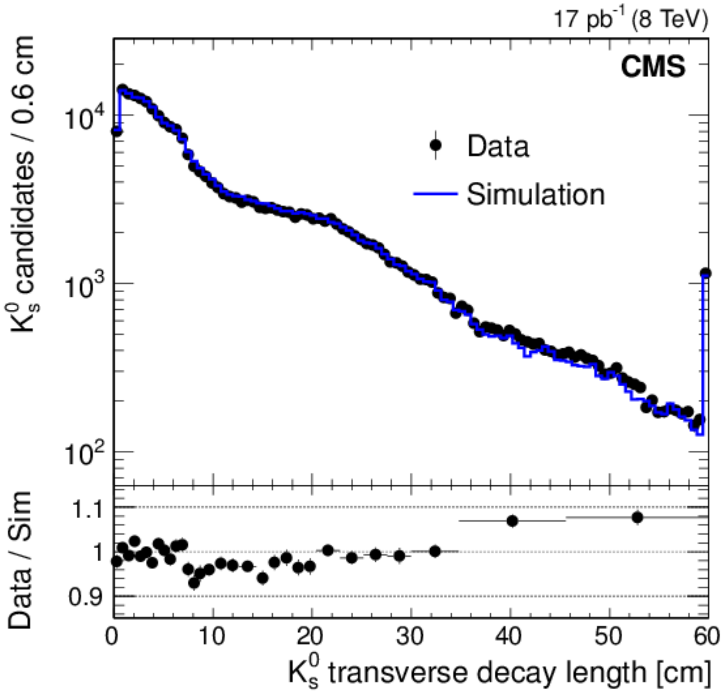
Displaced Jets

- **Challenges**
  - Triggering on such events
    - CPU time issues
    - High jet pT thresholds
    - High HT thresholds

- **Advantages**
  - Generally easier to reconstruct a displaced vertex with more tracks. Hadronization help here
  - Kaons can be used to verify data/MC for displaced vertex reconstruction





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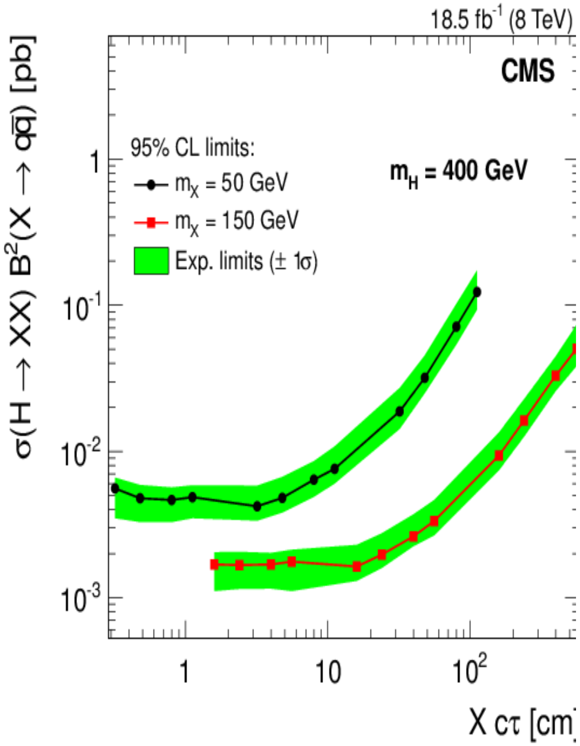
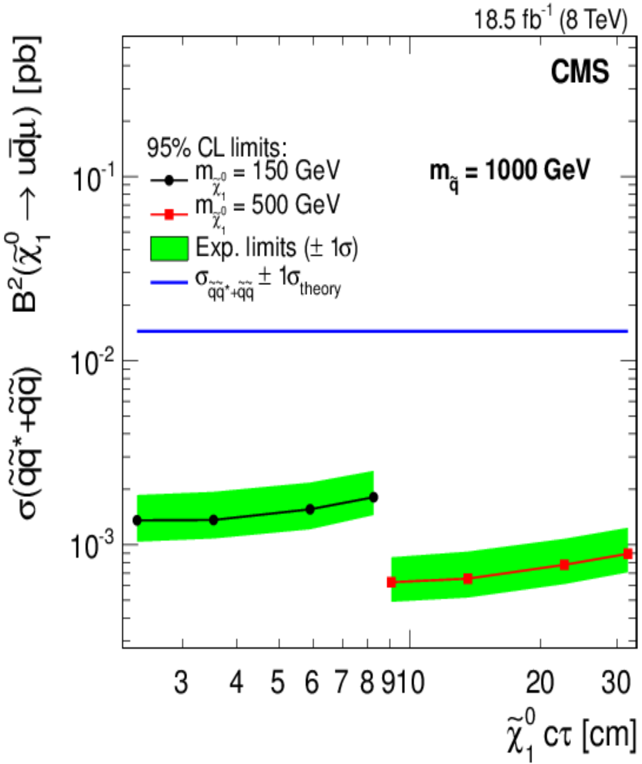
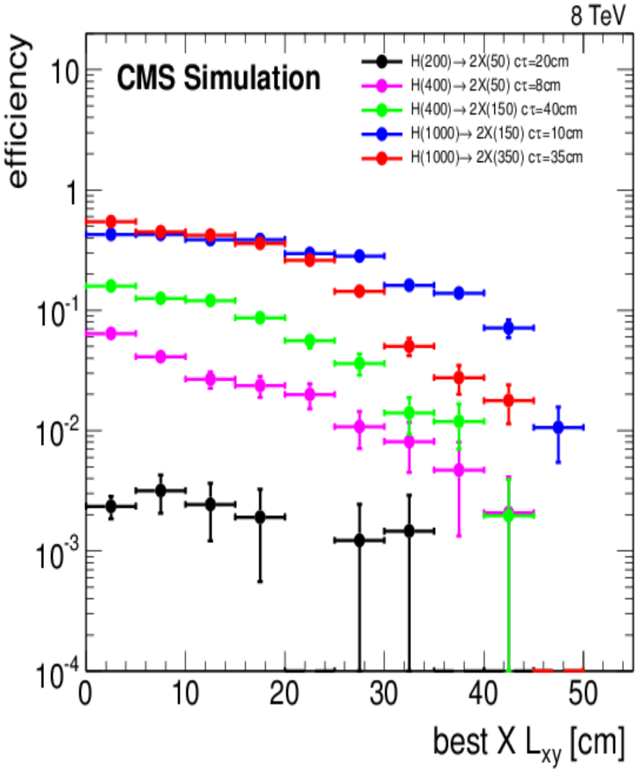
CMS Displaced Jets in the tracker

- **Search for Displaced Jets (arXiv1504.05162)**
  - Signal model:
    - H→(X→qq)(X→qq) with X a long-lived neutral particle
    - RPV SUSY $\tilde{q} \to q\tilde{\chi}_1^0 \to qq'\bar{q}''\mu$
  - Require the track pair to be incompatible with the primary vertex







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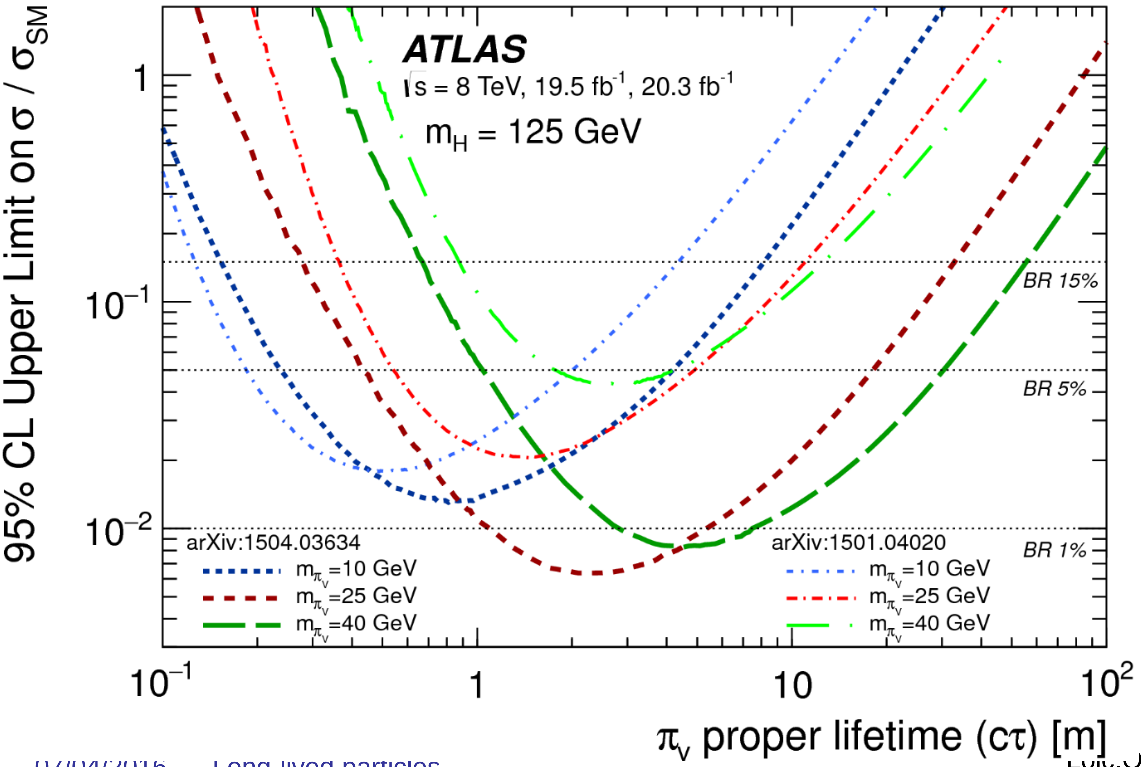
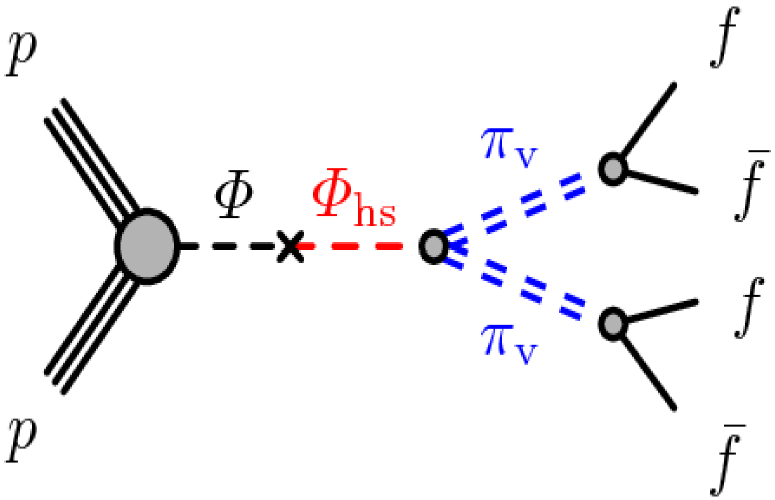
ATLAS Displaced Jets in HCAL/MS

- **Search for Displaced Jets (arXiv1504.03634 & 1501.04020)**
- ***Sensitive to large displacement***
  - ***Outer layers***
  - ***ATLAS dimensions (larger lever arm)***
- ***Calorimeter segmentation & MS is used for vertexing***
- **Consider similar types of models**





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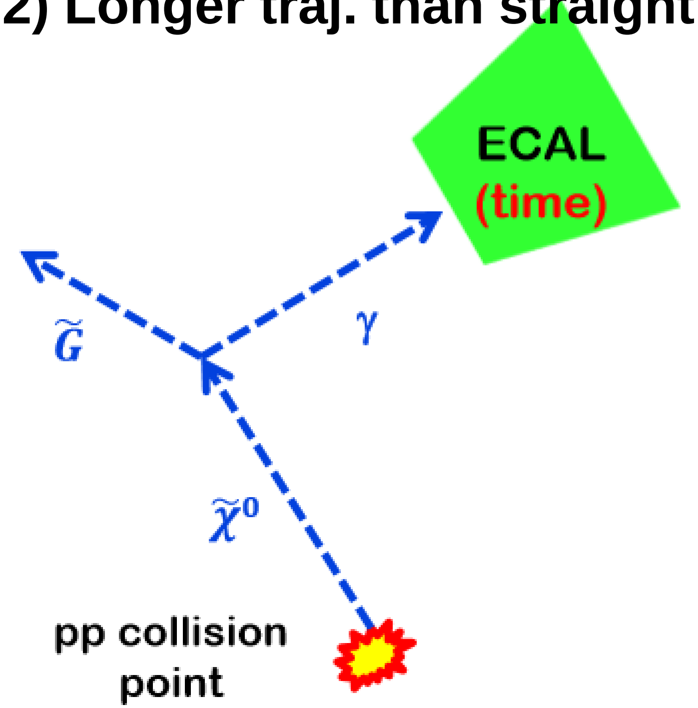
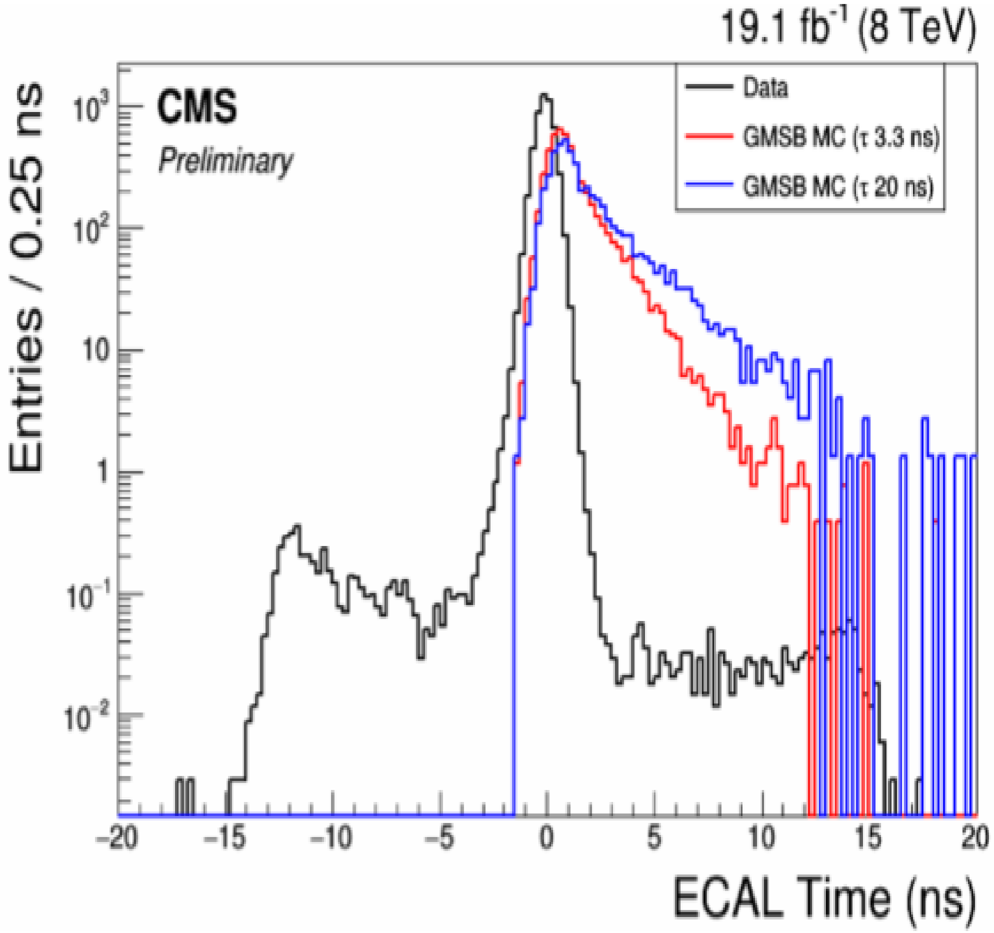
Searches for displaced photons

Technique based on timing

Uses ECAL time (σ=0.37ns) to discriminate signal and bckg.

Delay is expected because of
1) Neutralino travelling at v<<c
2) Longer traj. than straight line





Non-gaussian tails in data due to bremsstrahlung photons from LHC beam-halo or cosmic muons + ECAL detector effects

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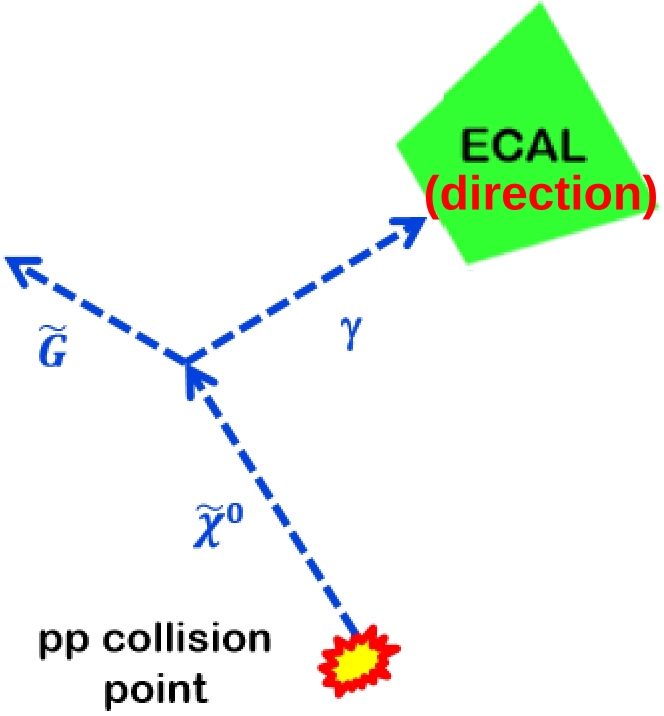
Searches for displaced photons

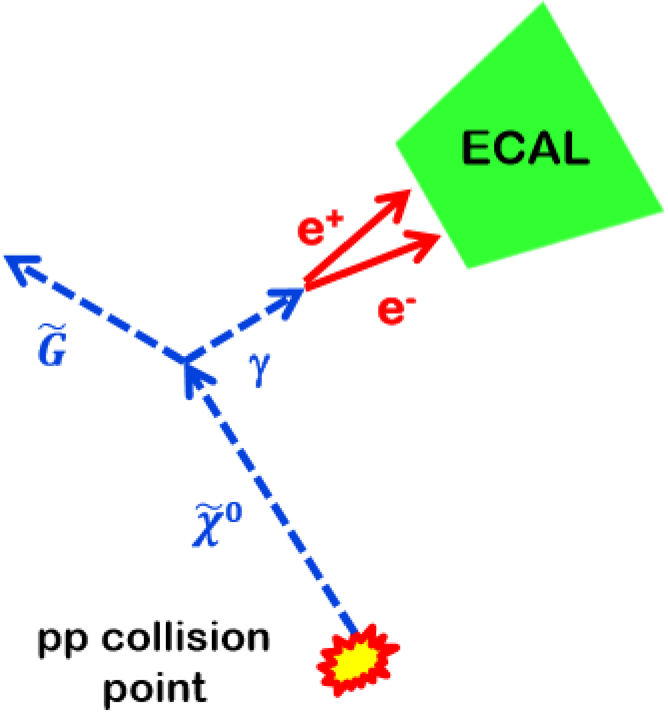
Technique based on shower profile

Take advantage of the longitudinal segmentation of the ATLAS calorimeter to verify if the shower is compatible from a photon originating from the IP.



Technique based on vertexing

Take advantage of the large amount of material in the tracker converting photons. Electron direction is used to show that photons are not originating from the IP.



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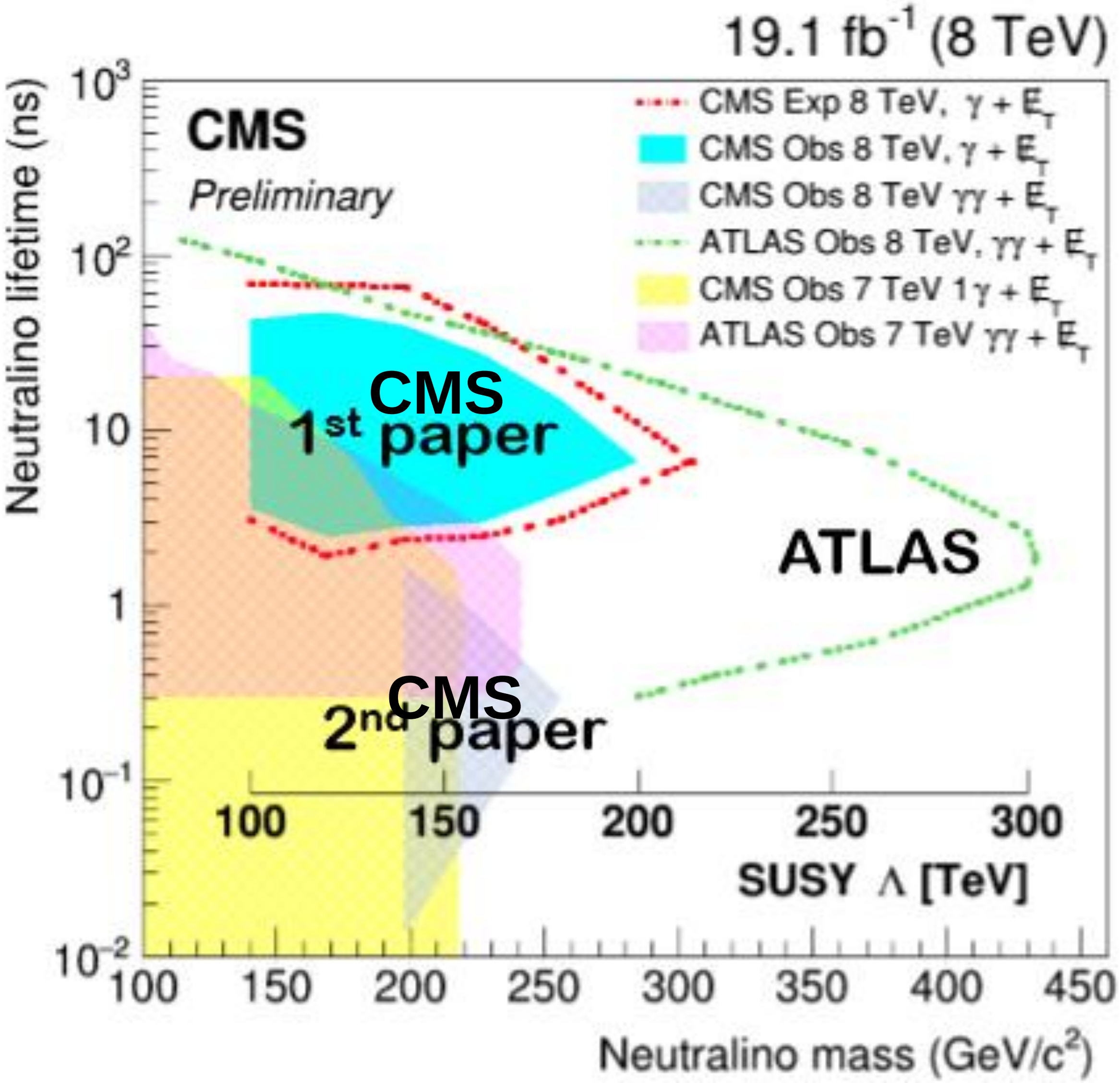
Searches for displaced photons



- **CMS 1st paper**
  CMS-PAS-EXO-12-035
  purely based on timing
- **CMS 2nd paper**
  CMS-PAS-EXO-14-017
  purely based on conversion
- **ATLAS paper**
  arXiv:1409.5542
  based on timing and direction

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Outline

- **Introduction to LL physics (Why ? How ?)** ✓

- **Searches for LL particles decaying OUTSIDE the detector**
  - **Neutral** ✓
  - **Charged** ✓

- **Searches for LL particles decaying INSIDE the detector**
  - **Charged** ✓
  - **Neutral** ✓

- **Super exotic particles** ⇐

- **Summary**

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Searches for magnetic monopoles

- **Magnetic monopoles (from Dirac and others)**
  - Theoretically interesting → quantization of the electric charge:

  - **Ionization energy loss:**

For electric charge: $$\left\langle -\frac{dE}{dx} \right\rangle = \boxed{K z^2 \frac{Z}{A} \frac{1}{\beta^2}} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

For magnetic charge: $$\left\langle -\frac{dE}{dx} \right\rangle = \boxed{(ng/e)^2 \frac{KZ}{A}} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

  - We replace ze with $ng\beta$: , dE/dx of a n_D=1 monopole is equivalent to a particle with charge Q=68.5e
    - → dE/dx 4500 higher than a proton

  - **Dions** are particles which carry BOTH an electric and a magnetic charge (their dE/dx is therefore even larger)

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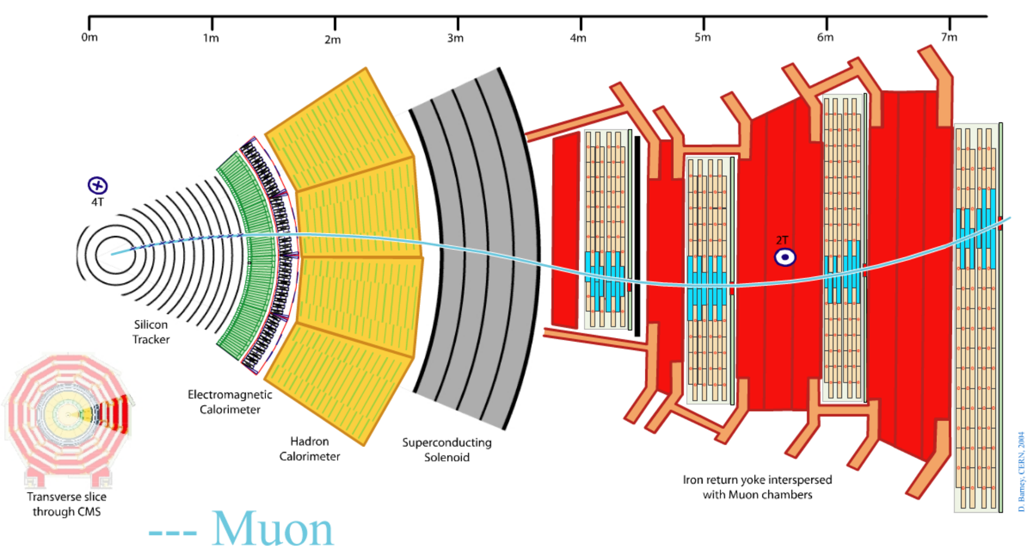
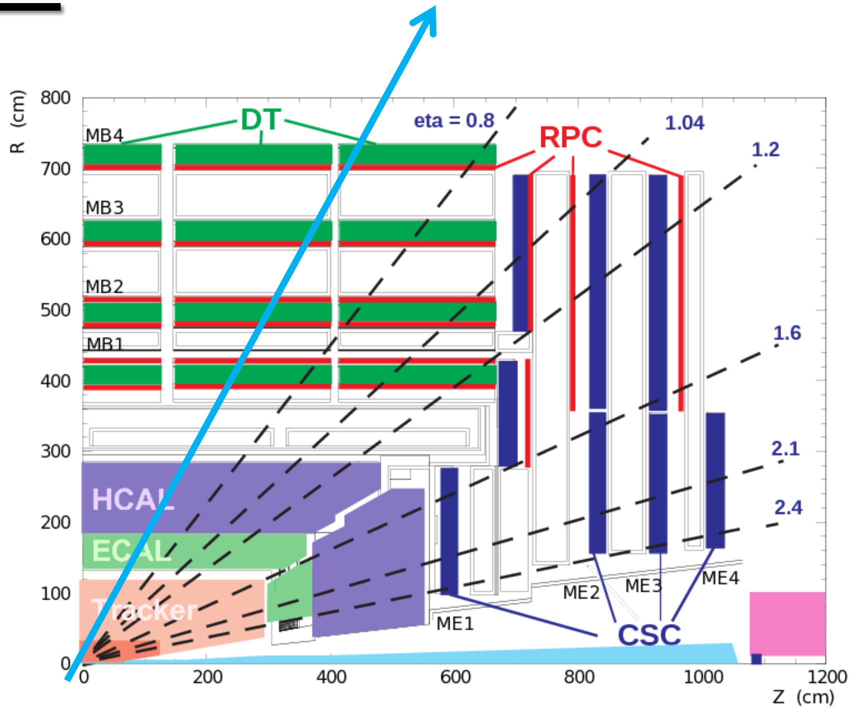
Searches for magnetic monopoles

- **Trajectory:**
  - Due to the Lorentz force:
    - Electric particles → bending → perpendicular to B
    - Magnetic particles → bending → parallel to B
  - Specific tracking might therefore be needed (depending on particle pT)

MUON





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Searches for magnetic monopoles

- **Trajectory:**
  - Due to the Lorentz force:
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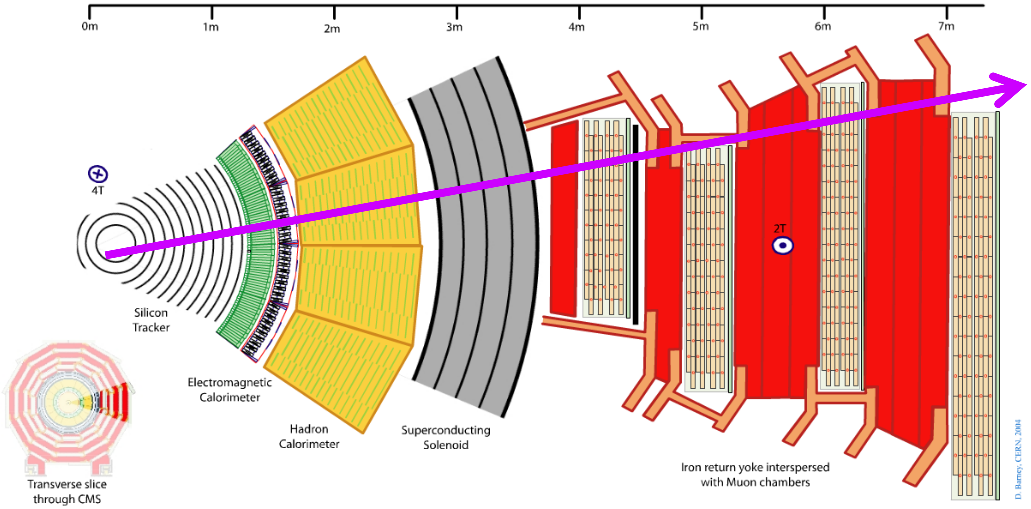
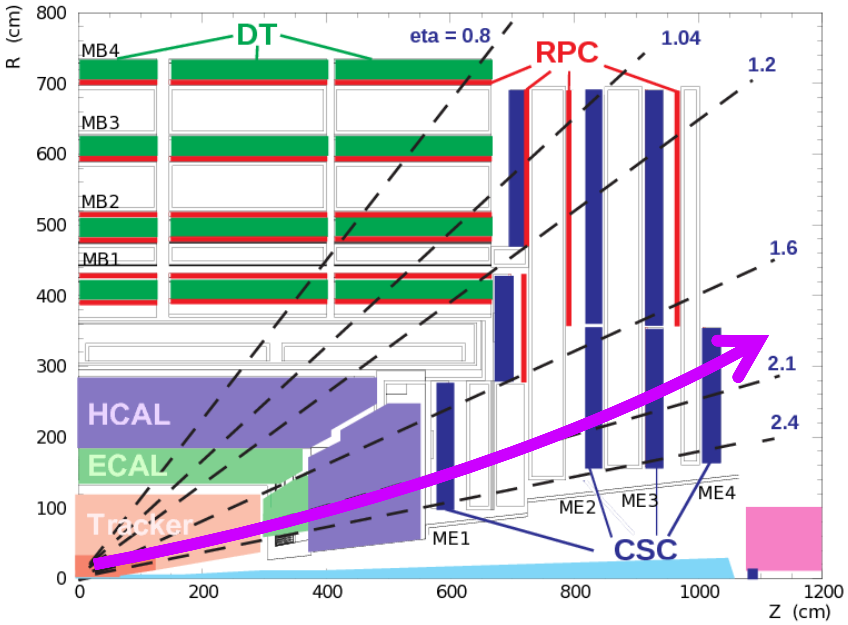
  - Specific tracking might therefore be needed (depending on particle pT)

Magnetic MONOPOLE





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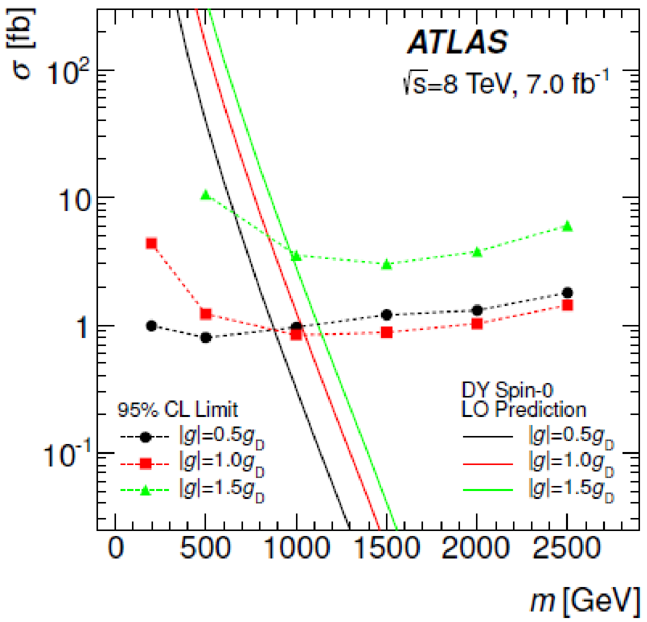
Searches at the LHC

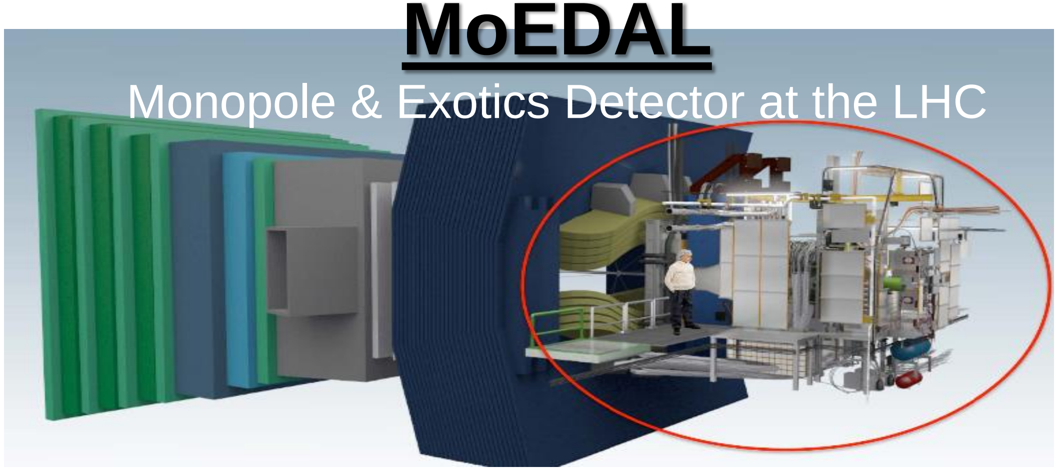
ATLAS

Search similar to
HSCP with Q>>1
Trigger on ECAL energy

	$\lvert g \rvert = 0.5 g_D$	$\lvert g \rvert = 1.0 g_D$	$\lvert g \rvert = 1.5 g_D$
spin-1/2	1180	1340	1210
spin-0	890	1050	970

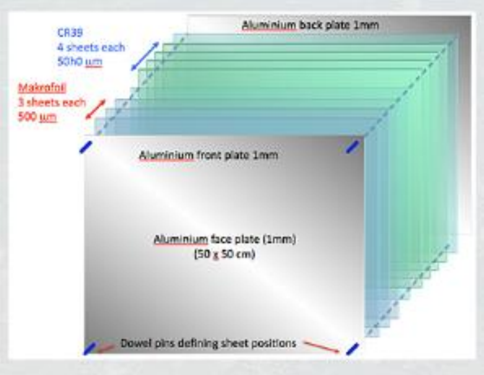


MoEDAL

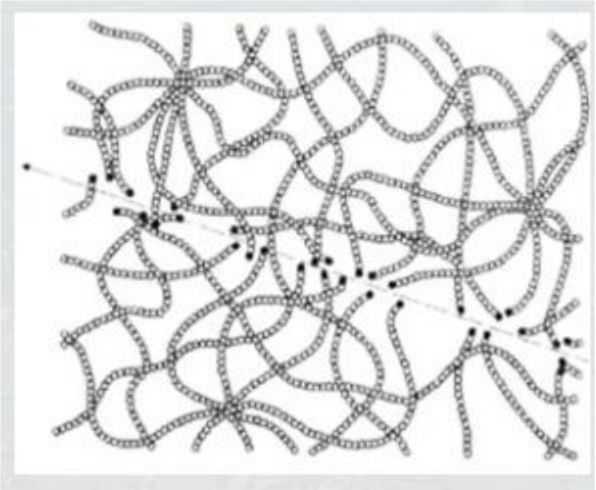


Monopole & Exotics Detector at the LHC

Search based on plastic
nuclear track detector



The basic MoEDAL stack housing 10 plastic layers (24 cm x 24cm), including 4 CR39 layers 3 MAKROFOL layers



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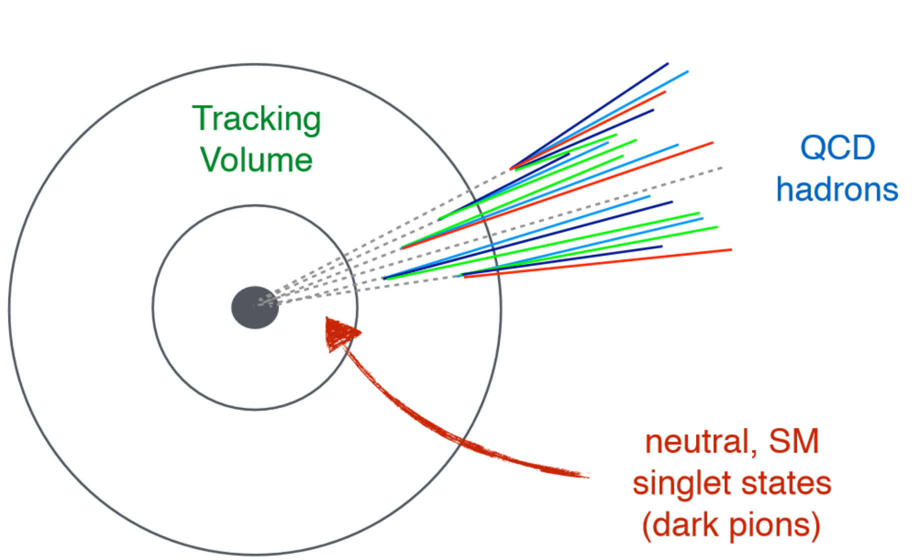
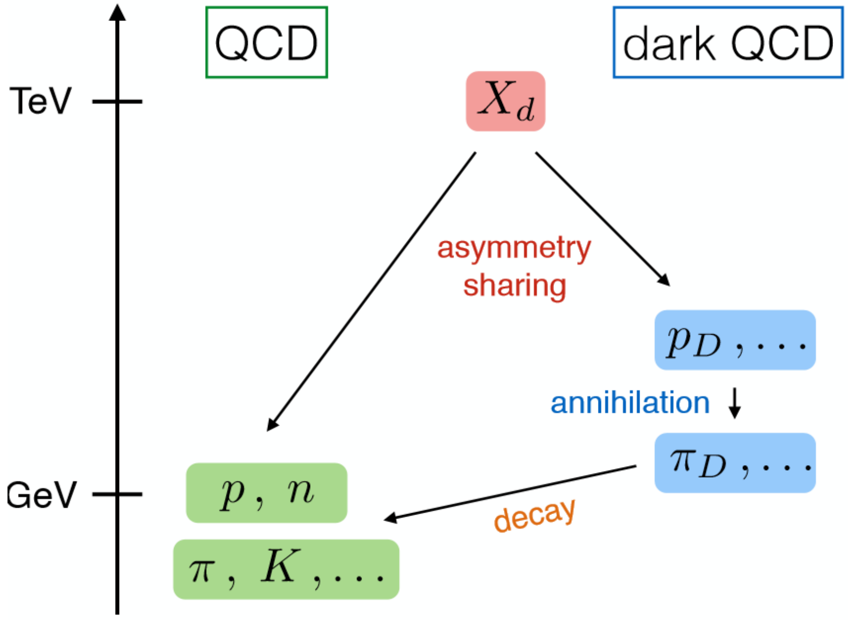
Emerging jets

Possible origin for emerging Jets:
Dark QCD: hidden sector confinement (SU(N))





No specific search for emerging jets at the LHC, yet.

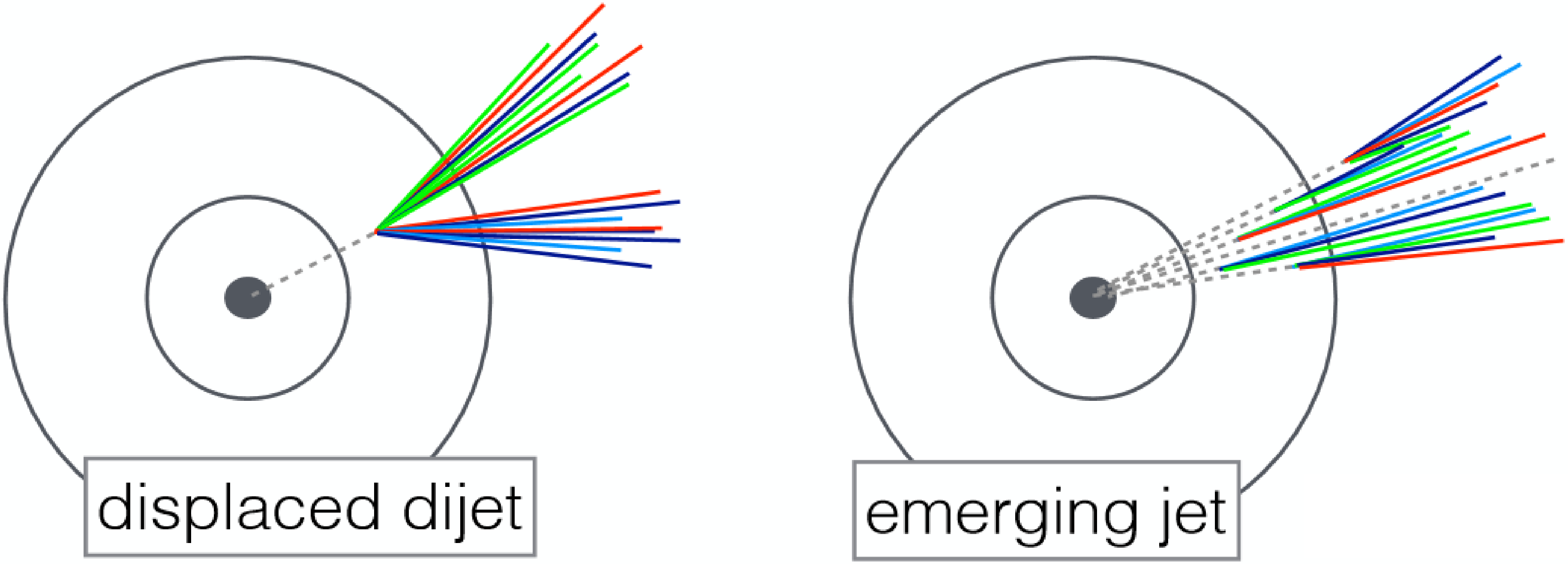
- SU(N) dark sector with neutral "dark quarks"
- Confinement scale

$\Lambda_{\mathrm{darkQCD}}$

- DM is composite "dark proton"
- "Dark pions" unstable, long lived

Slide inspired by Pedro Schwaller talk 11/13/15

Emerging jets



Displaced jet search have however some similarities and results recasting is possible in some cases

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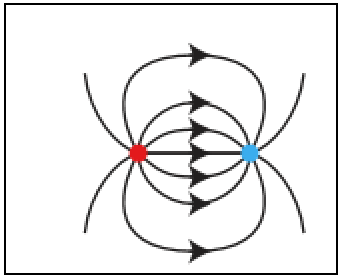
Macroscopic strings and quirks

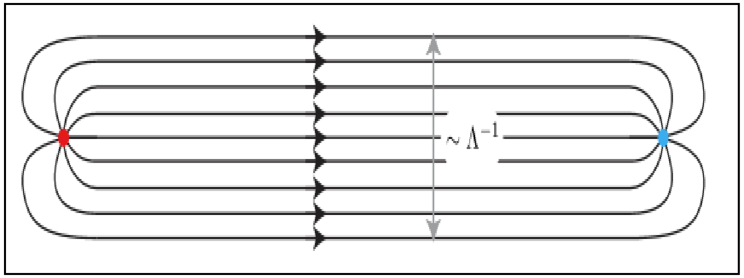
New gauge interaction (similar to QCD) with *infracolor* charge and a confinement scale that might be macroscopic.

Particle **phenomenology depends on string length** (confinement scale)…



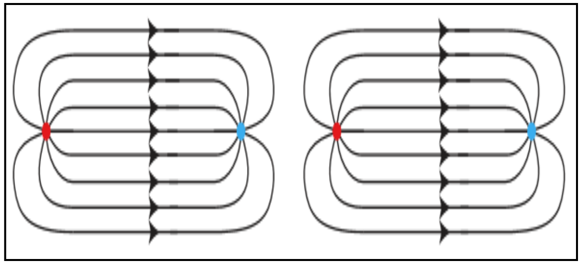
$r \ll \Lambda^{-1}$

Visible as
a single particle
with large dEdx



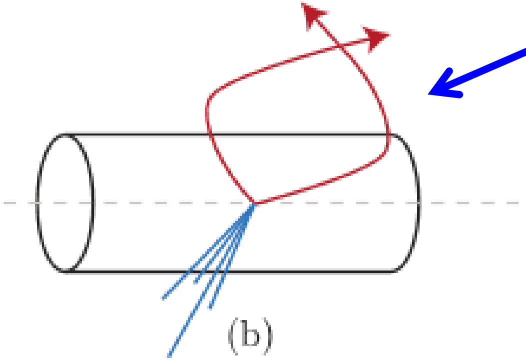
$r \gg \Lambda^{-1}$

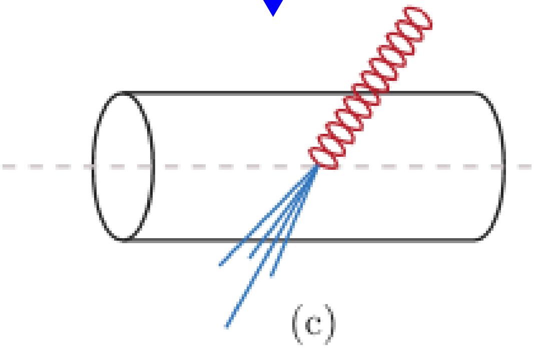
Visible as two connected particles

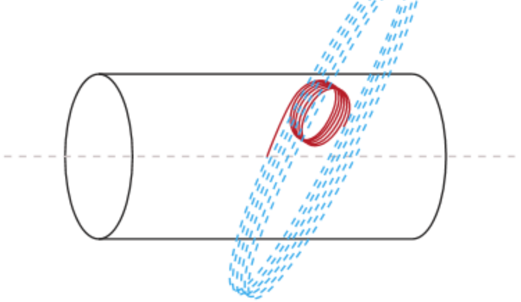


String breaking $2m_Q \gg \Lambda.$

Visible as
two particles







No specific search for quirks at the LHC, yet.

Based on arXiv:0805.4642v3

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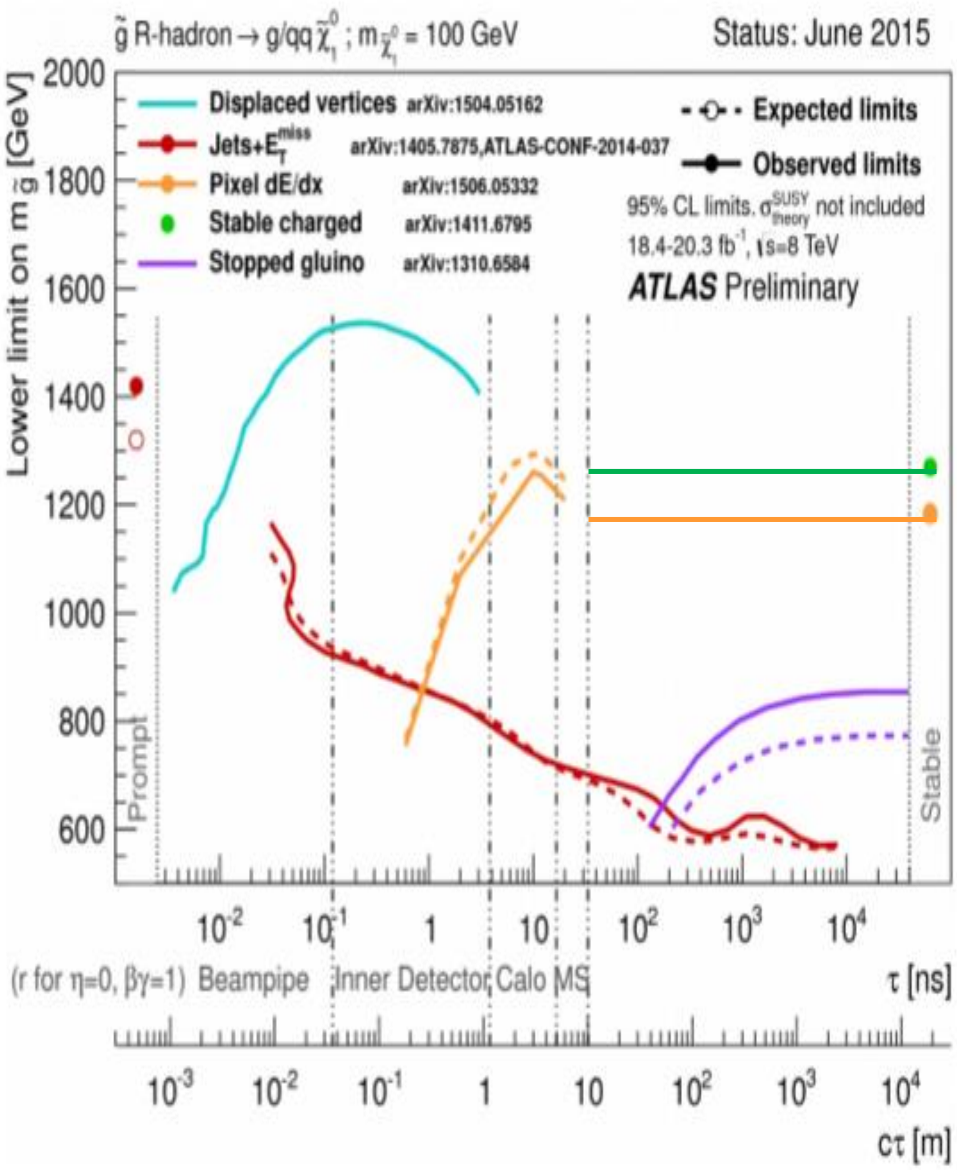
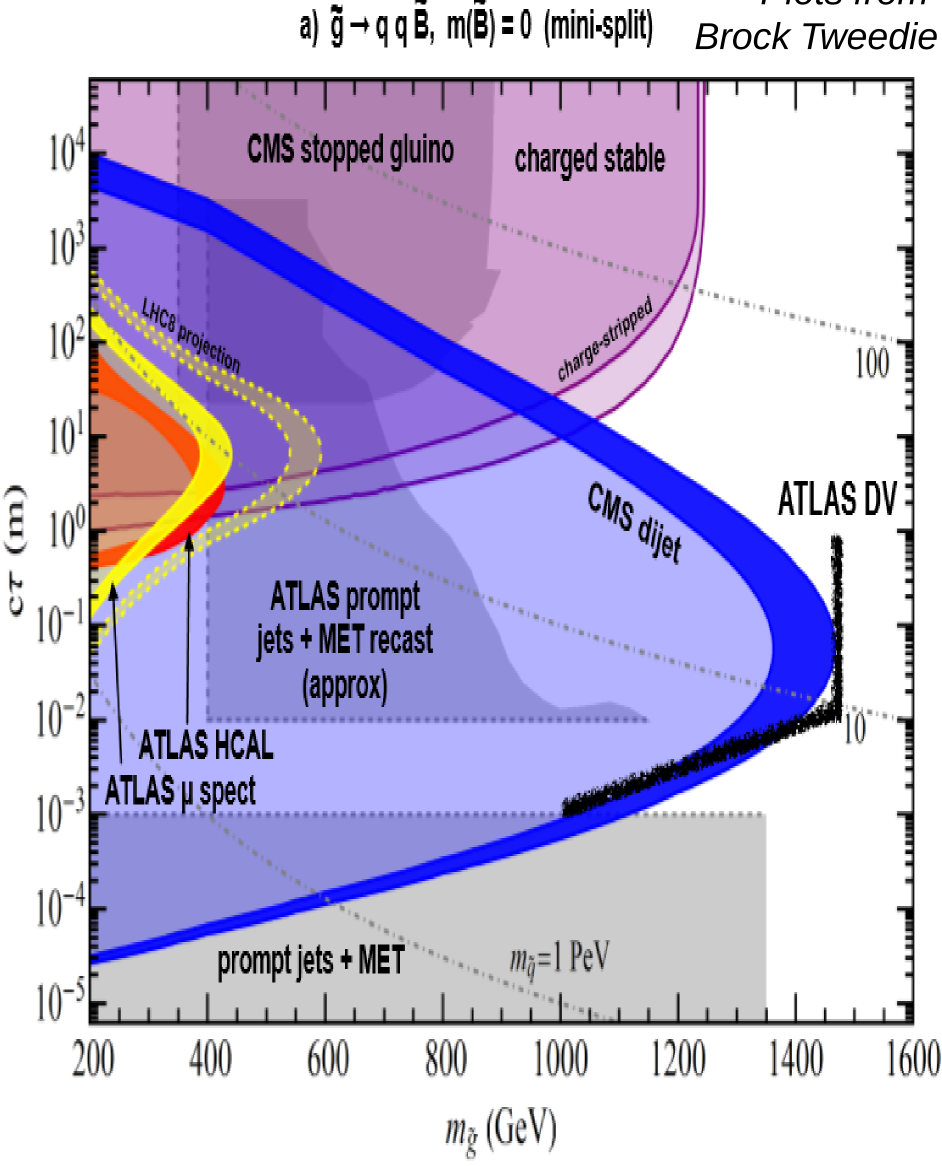
Summary
(overview of LL SUSY constraints)

Constraints on (LL) SUSY

Plots from Brock Tweedie





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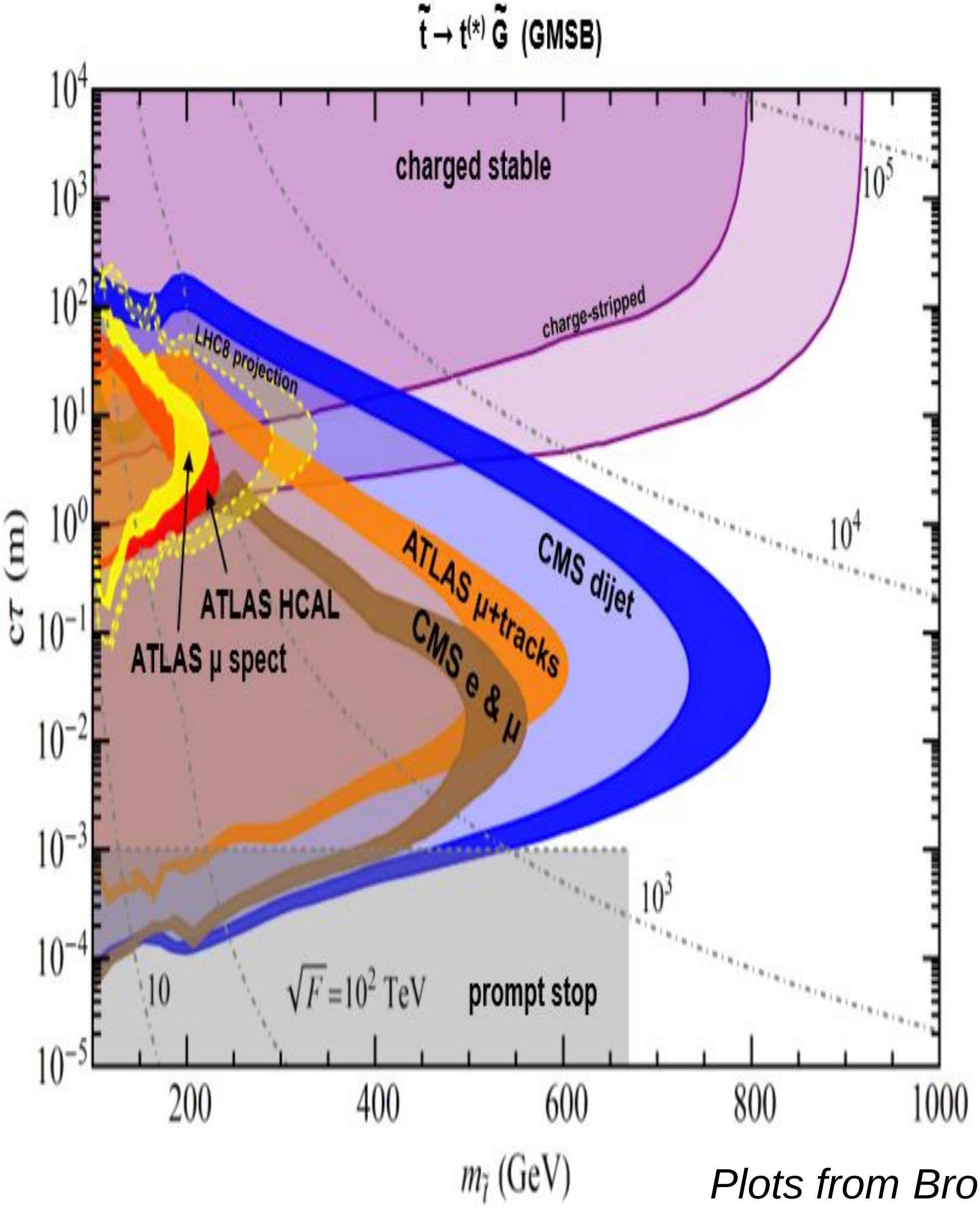
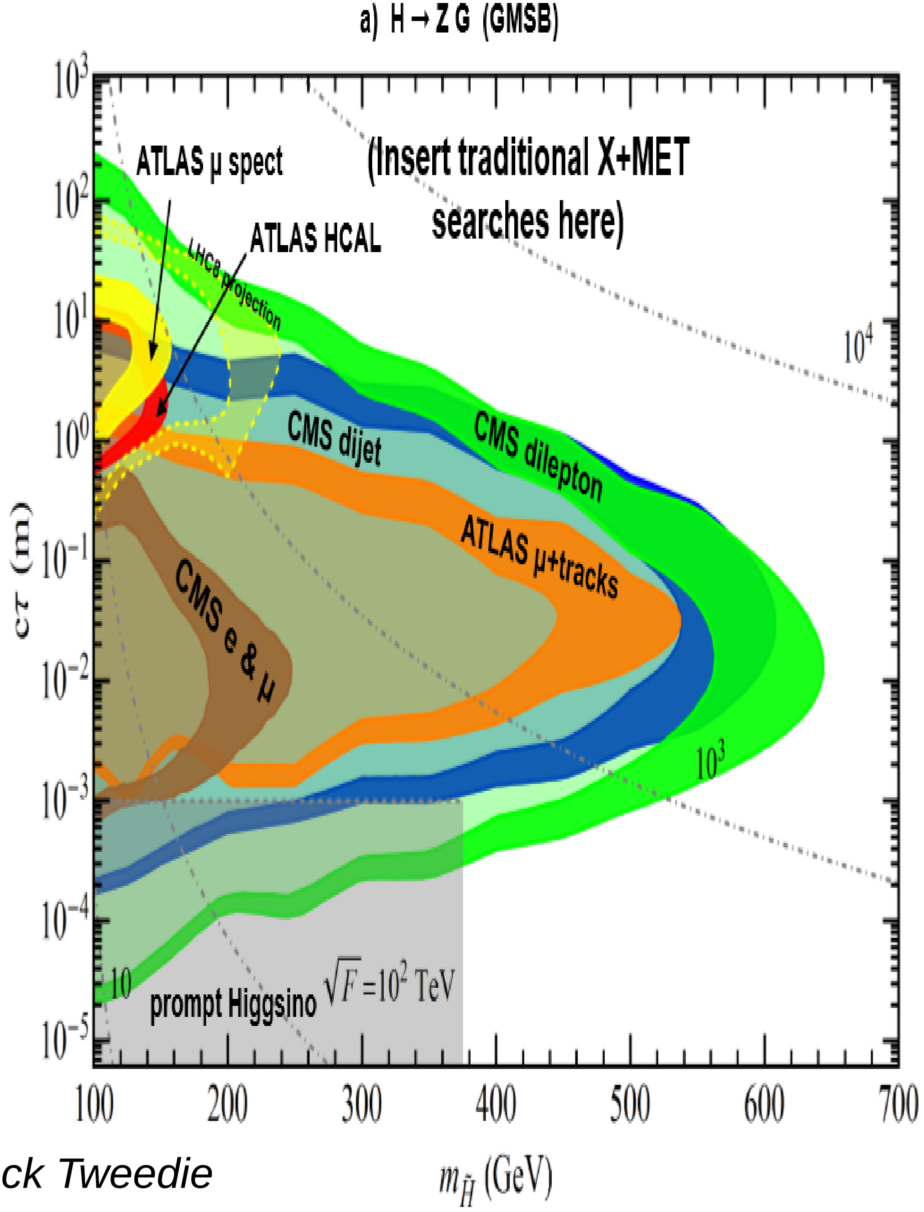
Constraints on (LL) SUSY





Plots from Brock Tweedie

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Summary

- Searches for LL particles are usually based on simple signatures that are sensitive to a wide range of models.
  - Massive, stable charged particles.
  - Displaced leptons, jets or photons.
  - Disappearing / Kinked tracks
  - Asynchrnonous (stopped) particle decay

- Searches / results are generally model independent as they are many models predicting LL particles and only a few people looking for them.

- Searches are generally quite chalenging because of our detector/software being optimized for « prompt » decay.
  - Still, we set strong limit on (LL) SUSY and other BSM models…

- A diphoton excess at 750GeV is not incompatible with long-lived particles
  - → π^0 and π^+/π^- analogy

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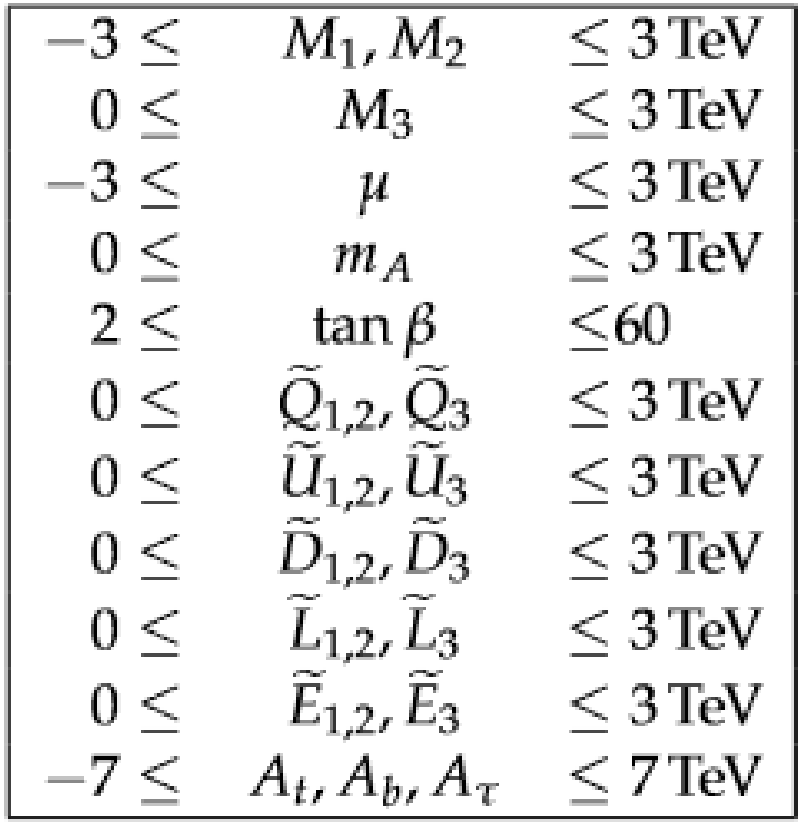
Backups

pMSSM parameter scan



$-3 \leq$	M_1, M_2	$\leq 3\,\mathrm{TeV}$
$0 \leq$	M_3	$\leq 3\,\mathrm{TeV}$
$-3 \leq$	μ	$\leq 3\,\mathrm{TeV}$
$0 \leq$	m_A	$\leq 3\,\mathrm{TeV}$
$2 \leq$	$\tan\beta$	≤ 60
$0 \leq$	$\widetilde{Q}_{1,2}, \widetilde{Q}_3$	$\leq 3\,\mathrm{TeV}$
$0 \leq$	$\widetilde{U}_{1,2}, \widetilde{U}_3$	$\leq 3\,\mathrm{TeV}$
$0 \leq$	$\widetilde{D}_{1,2}, \widetilde{D}_3$	$\leq 3\,\mathrm{TeV}$
$0 \leq$	$\widetilde{L}_{1,2}, \widetilde{L}_3$	$\leq 3\,\mathrm{TeV}$
$0 \leq$	$\widetilde{E}_{1,2}, \widetilde{E}_3$	$\leq 3\,\mathrm{TeV}$
$-7 \leq$	A_t, A_b, A_τ	$\leq 7\,\mathrm{TeV}$

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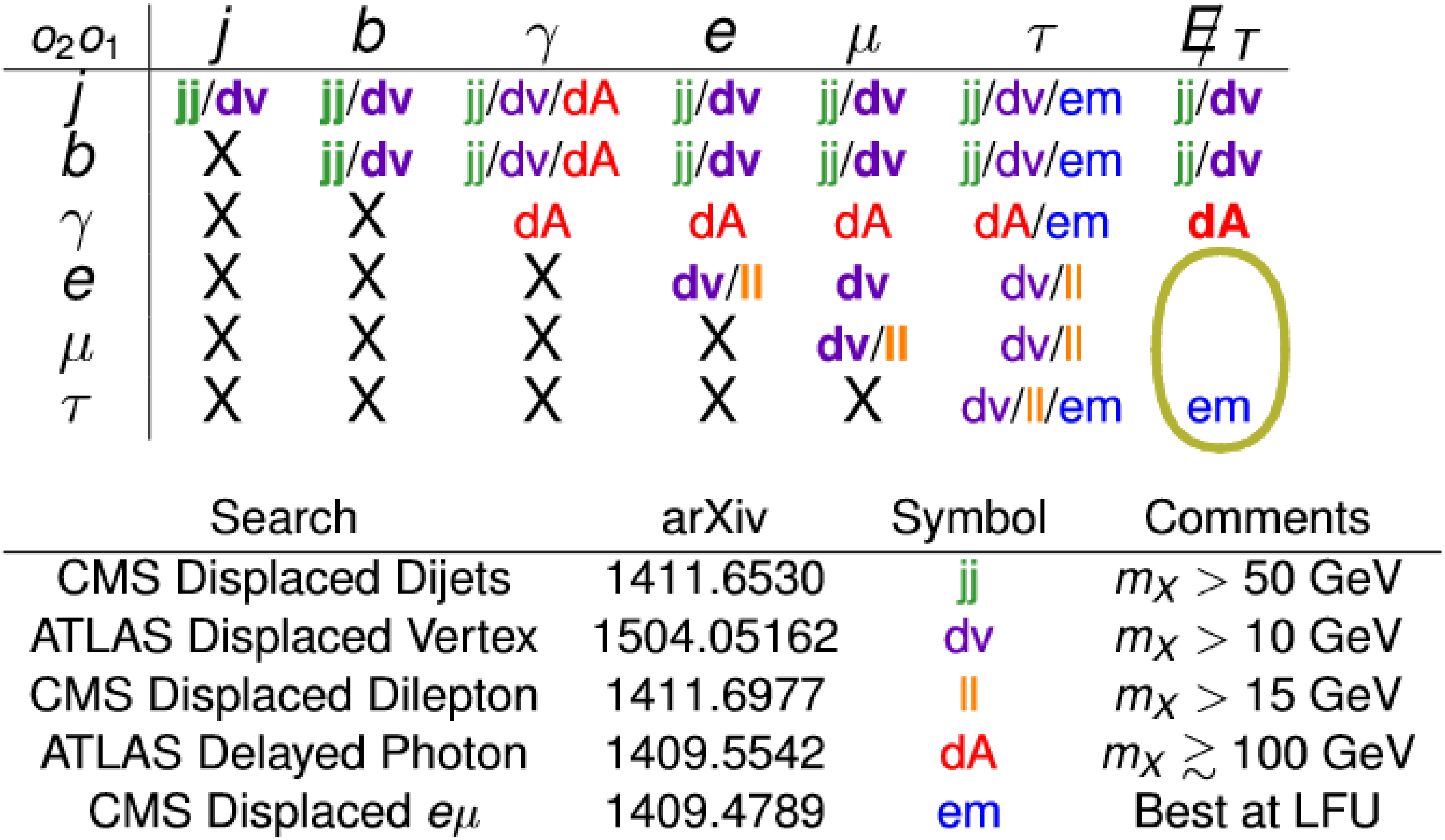
Coverage on Hidden-valey type

Exotic Objects (pp →XX, X →o1o2 or X →o1o2o3)



$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	jj/dv	jj/dv	jj/dv/dA	jj/dv	jj/dv	jj/dv/em	jj/dv
b	X	jj/dv	jj/dv/dA	jj/dv	jj/dv	jj/dv/em	jj/dv
γ	X	X	dA	dA	dA	dA/em	dA
e	X	X	X	dv/ll	dv	dv/ll	
μ	X	X	X	X	dv/ll	dv/ll	
τ	X	X	X	X	X	dv/ll/em	em

Search	arXiv	Symbol	Comments
CMS Displaced Dijets	1411.6530	jj	$m_X > 50$ GeV
ATLAS Displaced Vertex	1504.05162	dv	$m_X > 10$ GeV
CMS Displaced Dilepton	1411.6977	ll	$m_X > 15$ GeV
ATLAS Delayed Photon	1409.5542	dA	$m_X \gtrsim 100$ GeV
CMS Displaced $e\mu$	1409.4789	em	Best at LFU

Slide from Jared Evans

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