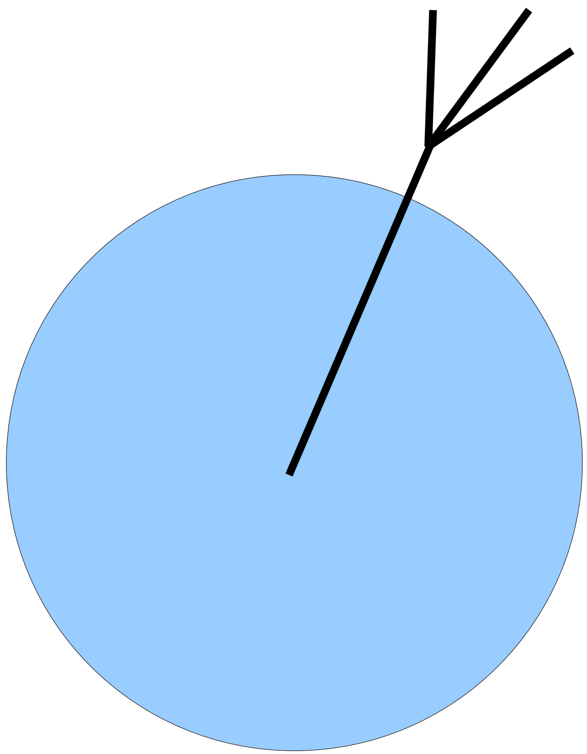
Challenges in the search for long-lived massive particles at LHC

Andrea Giammanco (Louvain)

on behalf of CMS and ATLAS

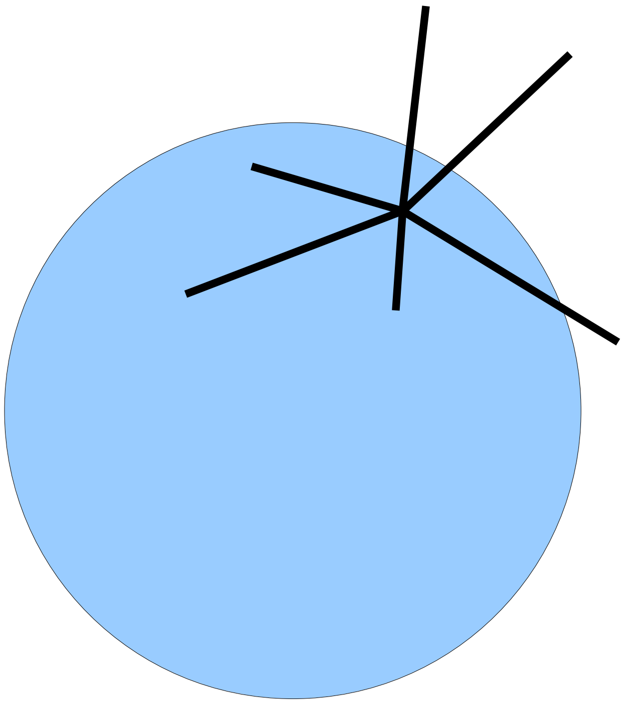
What I will talk about

(note: this is a signature-oriented talk)



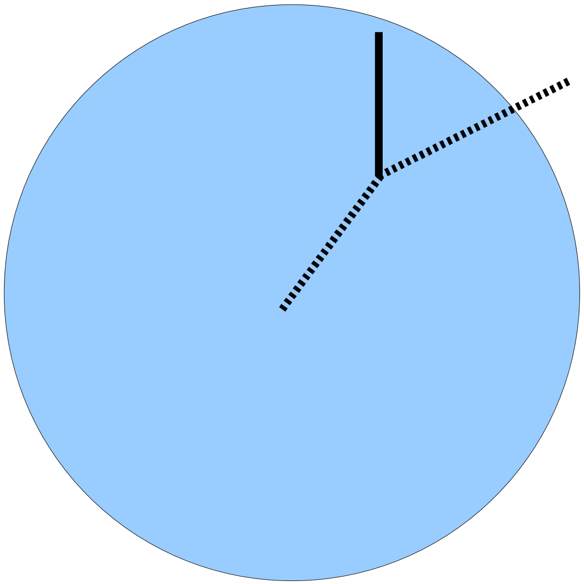
Charged exotic **traversing** the detector before decaying

CMS: PAS-EXO-08-003
ATLAS: CERN-OPEN-2008-020



Exotic **stopped** in the detector, then decaying at a later time

CMS: PAS-EXO-09-001

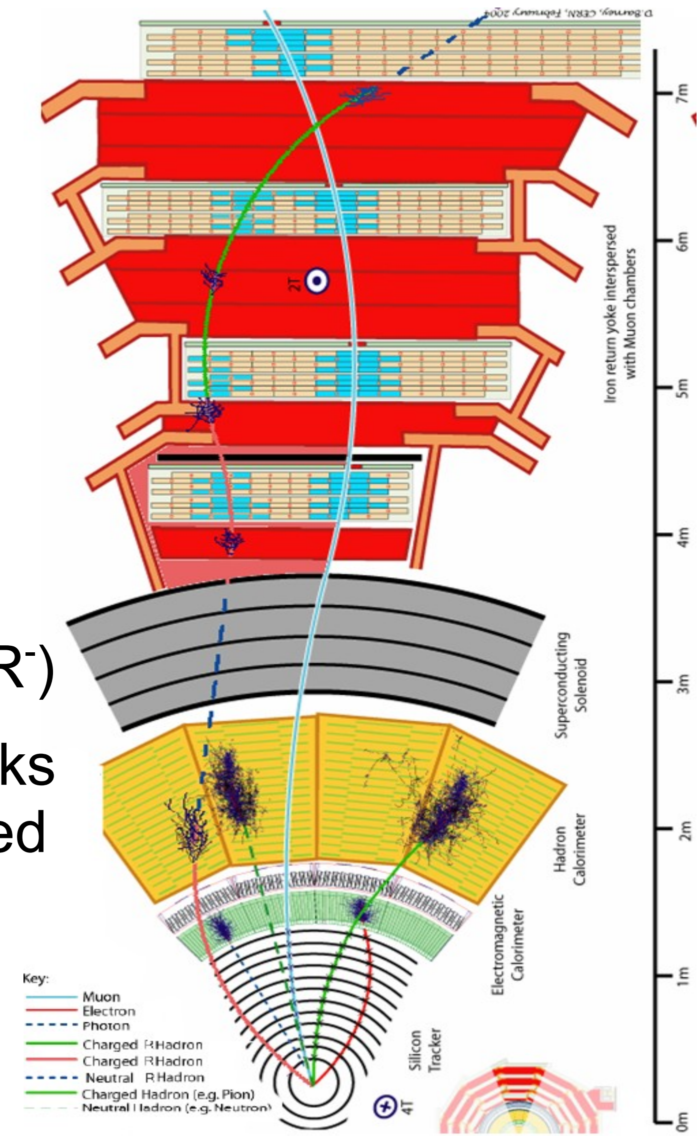


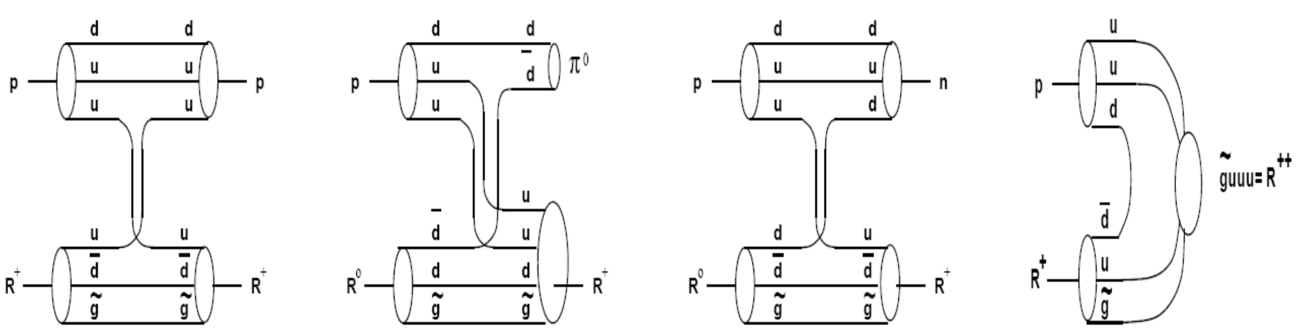
Neutral exotic decaying in the detector into a **non-pointing γ**

CMS: AN-2006/095
ATLAS: ibid.

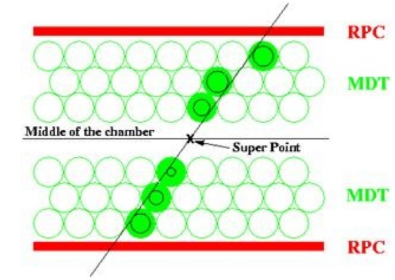
Charged exotics traversing the detector

- R-hadrons: bound states of $\tilde{g}$ or $\tilde{q}$ + light quarks
- Sleptons and charginos behave as “heavy muons”
- Model-independent signatures:
  - dE/dx by ionization (trickiest bkg: nuclear int.)
  - Time-of-flight (trickiest bkg: cosmic muons)
- Model-dependent signatures for R-hadrons:
  - charge flipping ($\tilde{q}$: $R^+ \leftrightarrow R^0$, $R^0 \leftrightarrow R^-$; $\tilde{g}$: also $R^+ \leftrightarrow R^-$)
  - “long” energy deposition in the calo's: light quarks are exchanged, but the $\tilde{g}/\tilde{q}$ is almost unperturbed

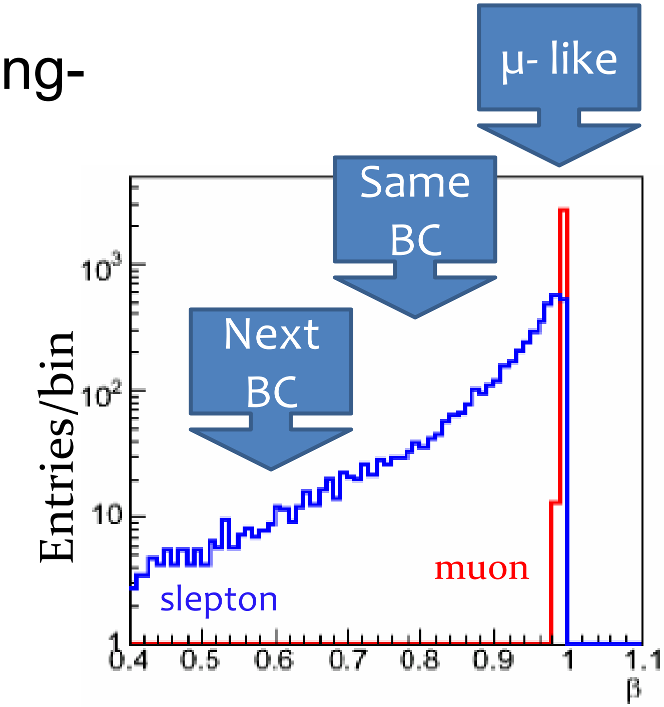


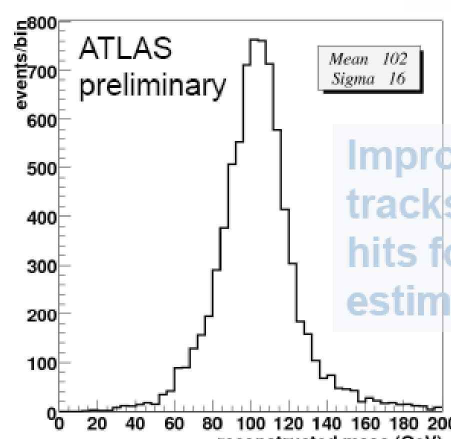


TOF in the ATLAS muon system

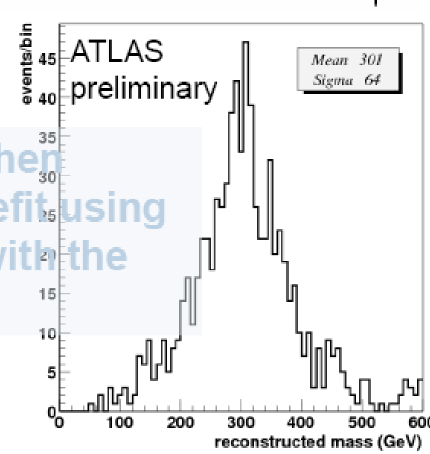


- Special trigger path based on TOF, designed for long-lived massive charged particles
- L1: standard muon candidate from RPC's; a slow particle may be associated to the wrong BX
- L2:
  - Re-examines the L1 candidates
  - Allows hits from different BX's
  - TOF from RPC's in barrel
- Event Filter:
  - Re-measure TOF with RPC+MDT
    - MDT: minimize χ^2 wrt β
  - Allow charge-flipping R-hadrons





Improves when tracks are refit using hits found with the estimated β

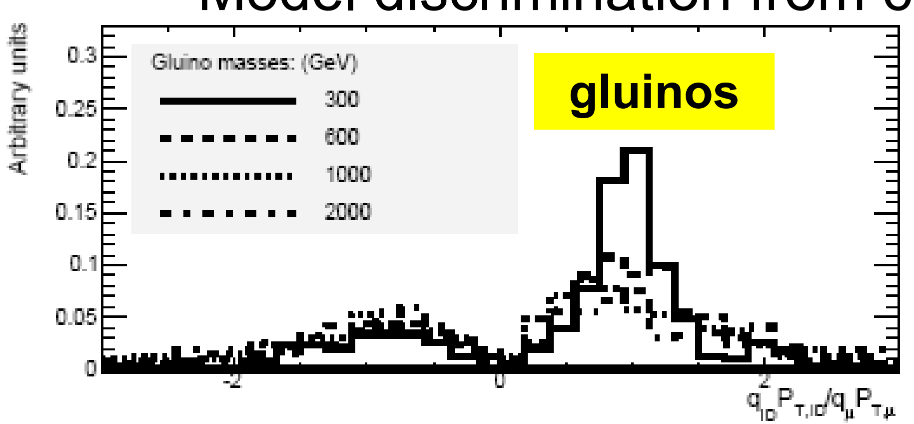


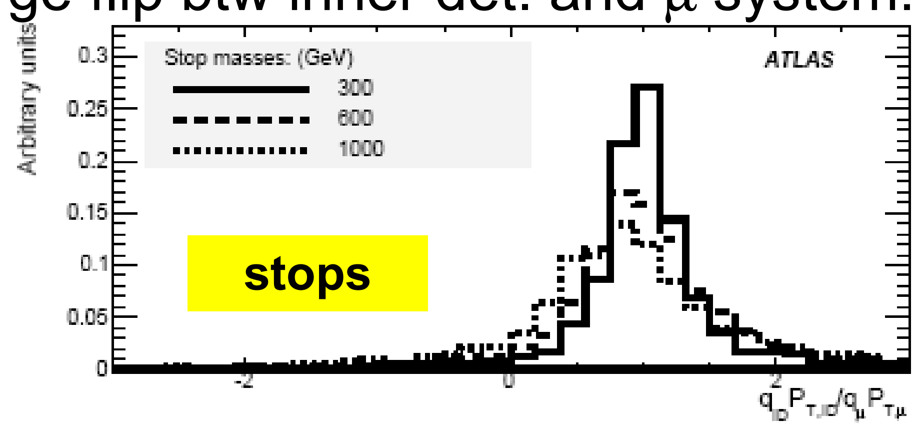
Sleptons generated with m=100 GeV

R-Hadrons generated with m=300 GeV

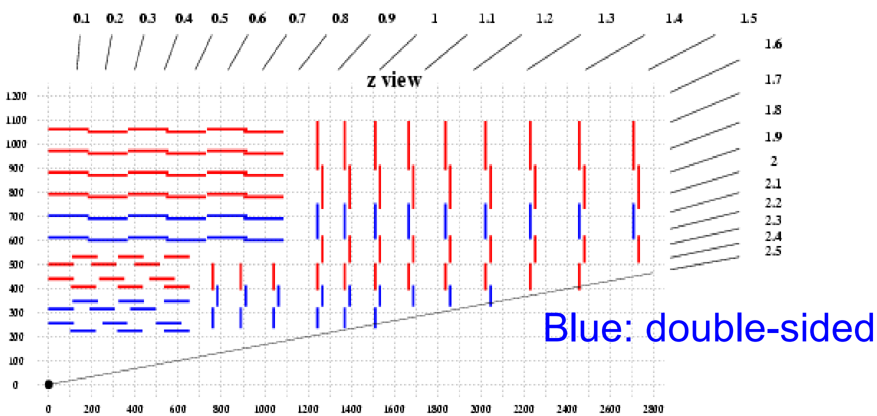
Topological selection of R-hadrons in ATLAS

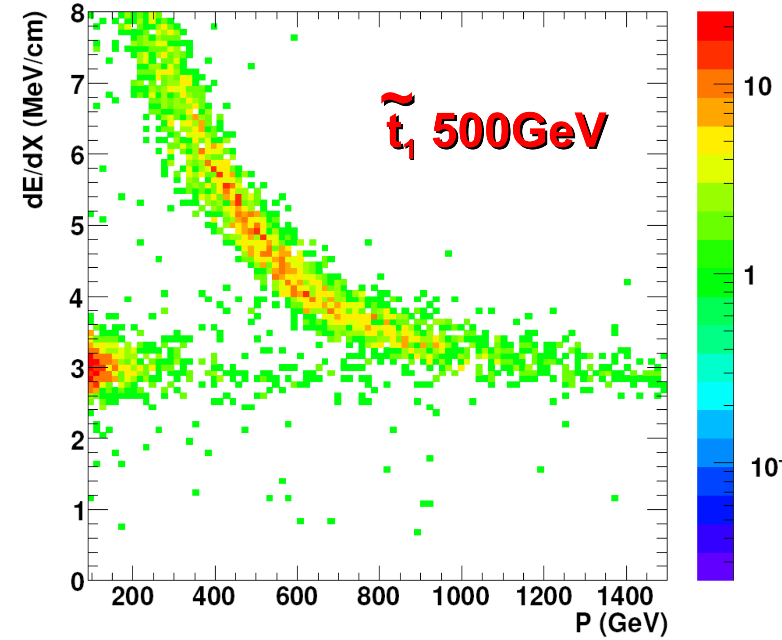
- Start from muon-like tracks; further selection by:
  - Transverse momentum
  - Ratio of the number of hits in TRT passing the low (>200 eV) and the high (>6.5 keV) thresholds
  - cos $\theta_{\mu\mu}$ (R-hadron pairs tend to be back-to-back)
  - The R-hadron tends to be isolated: low number of tracks and no hard jet (>100 GeV) around it (energy loss in calo is some GeV: very high for a track, not so high for a jet)
  - Model discrimination from charge flip btw inner det. and μ system:



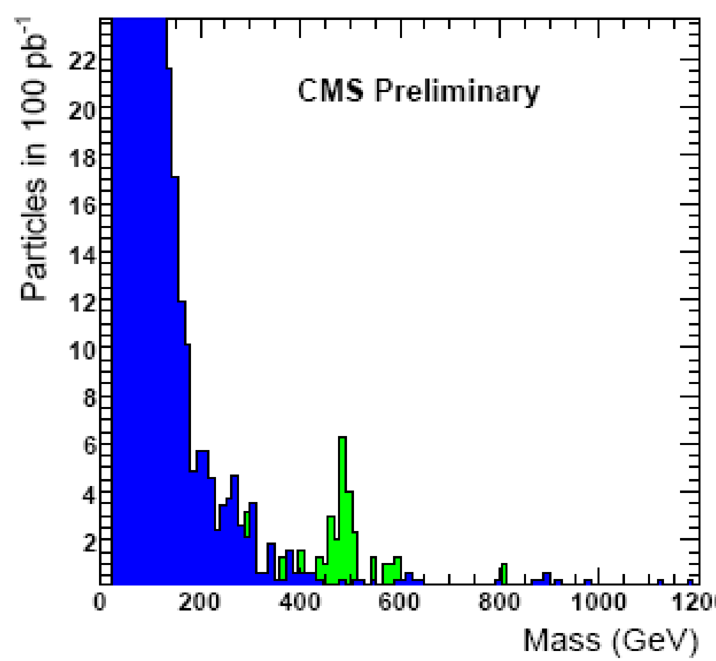


dE/dx in the CMS silicon tracker

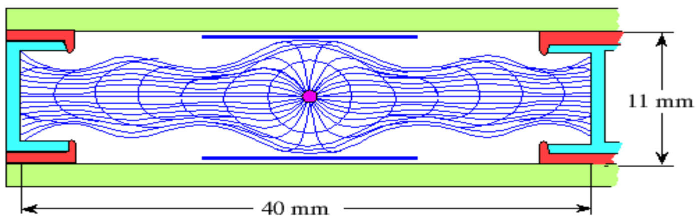


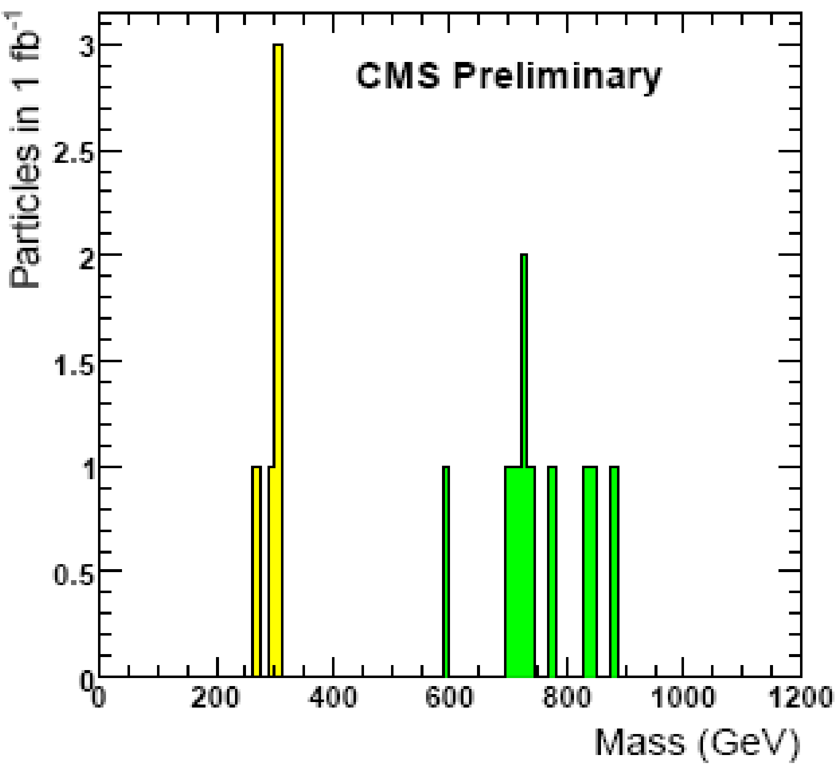


- Each silicon sensor traversed gives a dE/dx measurement
  - 10-20 measurements per track
  - Best estimator of the “real” dE/dx: sqrt of the harmonic mean of $(dE_i/dx_i)^2$
- Experimental issues:
  - Calibration with MIPs
  - Saturation at high ΔE values
  - Pixels not considered so far



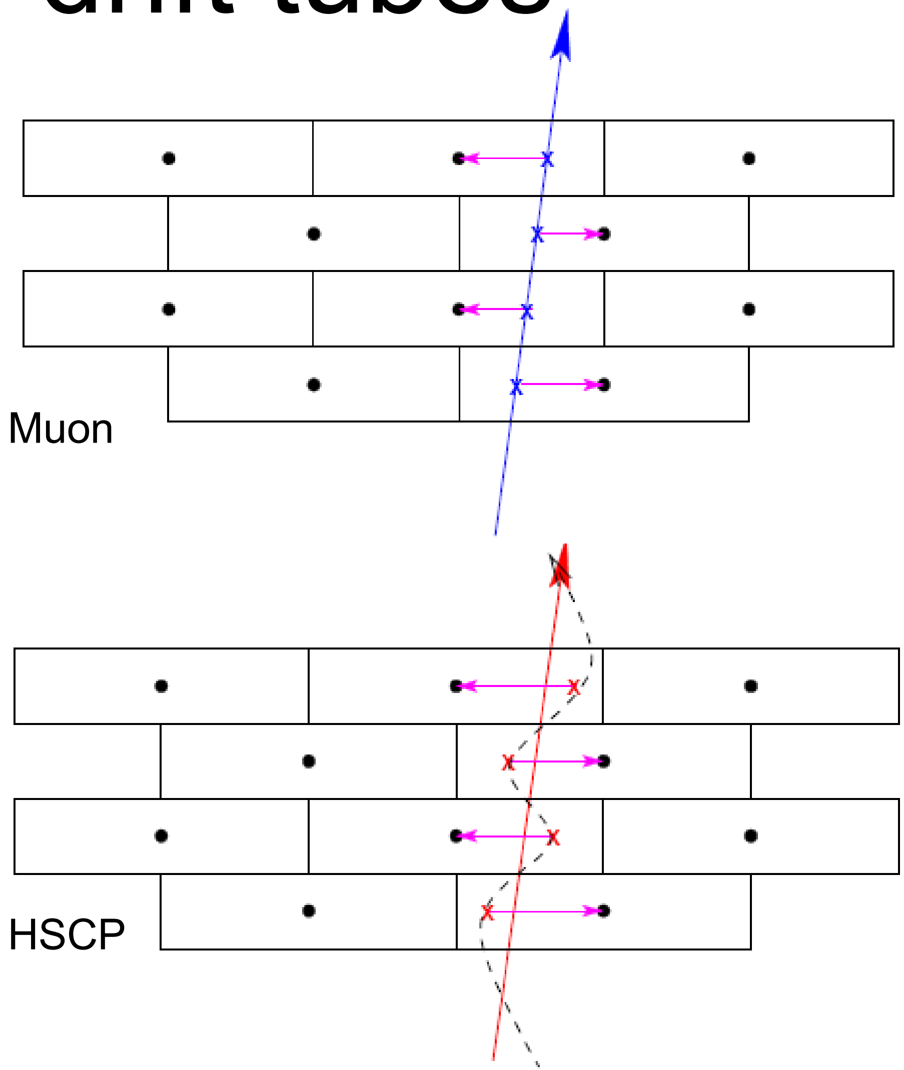
TOF in the CMS drift tubes





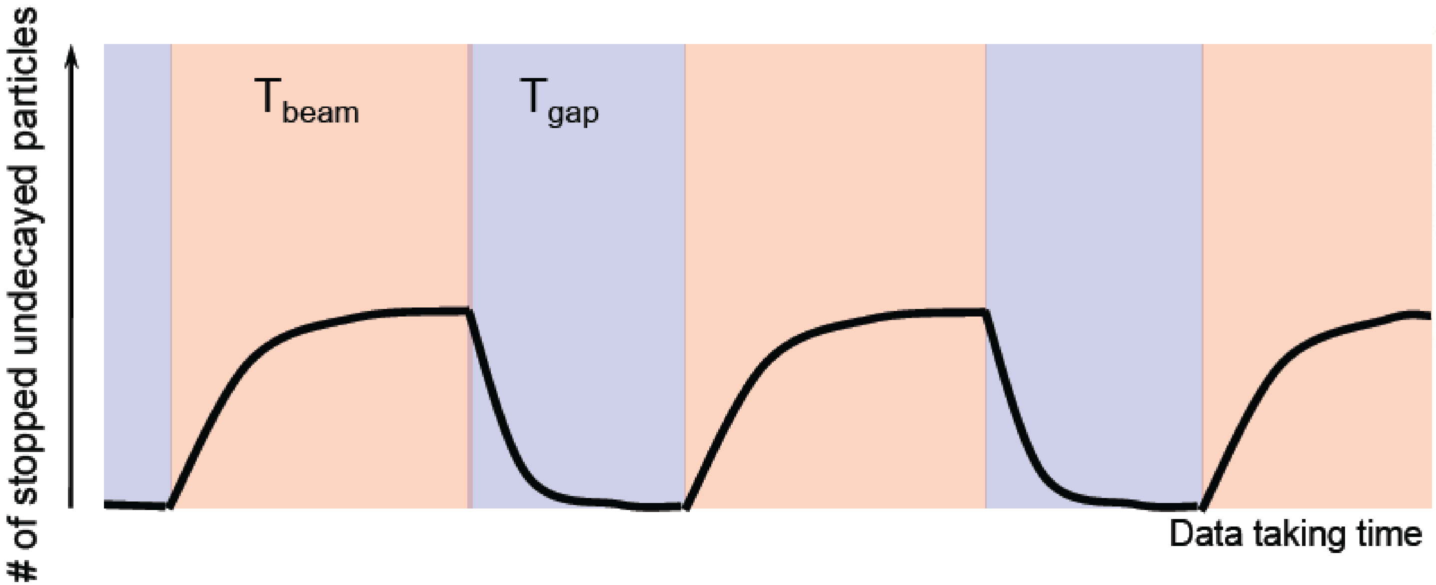
300 GeV KK tau

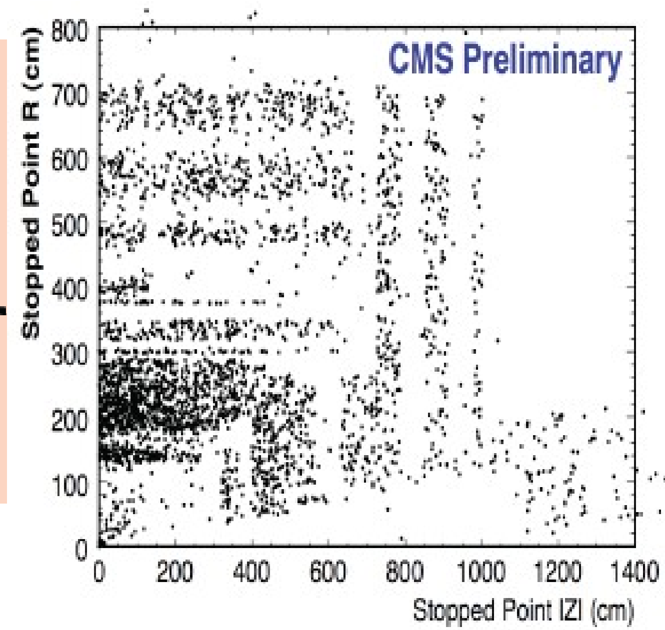
800 GeV stop



Normally the fit assumes β=1; here δt is left as a free parameter in the fit
=> TOF measurement

Stopped R-hadrons in CMS

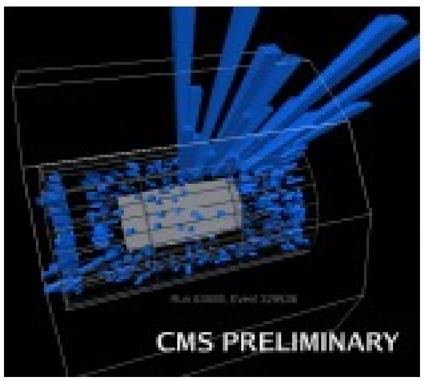




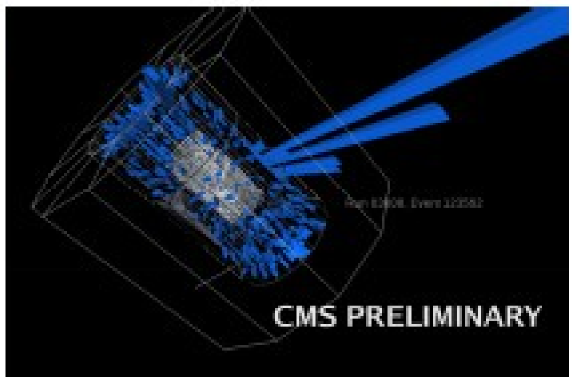
- R-hadrons can loose enough energy in the detector to stop somewhere inside (usually in the calorimeters)
- Sooner or later they must decay
- Trigger: (jet) && !(beam)
- Only backgrounds: cosmics and noise
- Offline selection based on topology and pulse shape

From the CMS cosmic runs in 2008

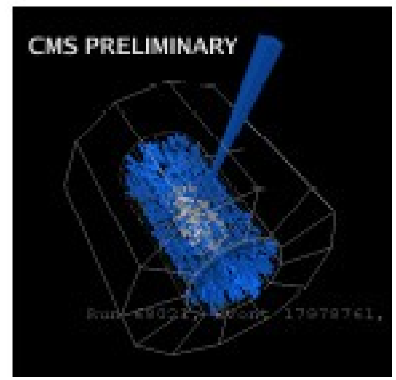
Examples of triggered noise events removed by topological cuts (cosmic run data, Fall 2008):



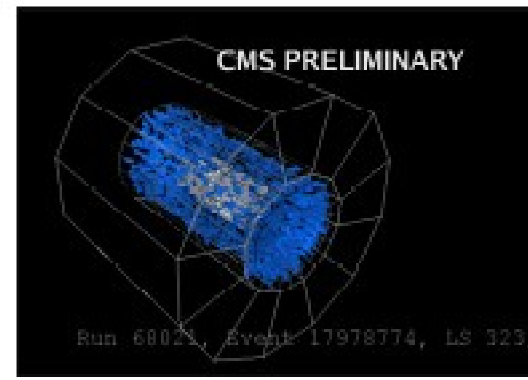
“Readout Box” fault



Photodiode discharge

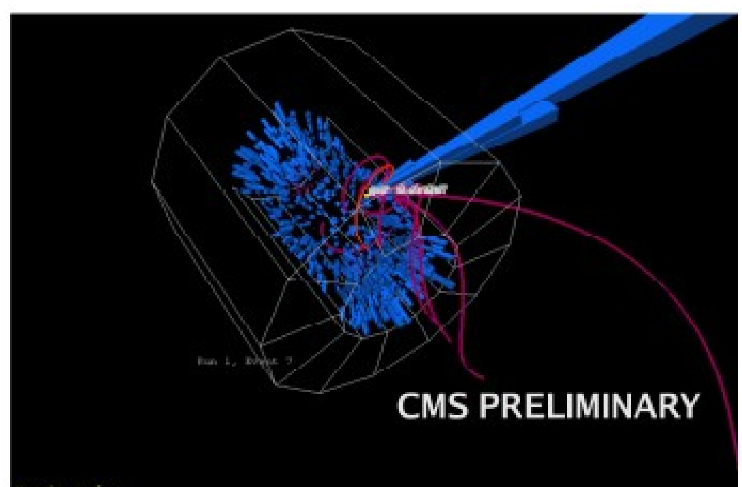


Noisy tower (or cosmic?)



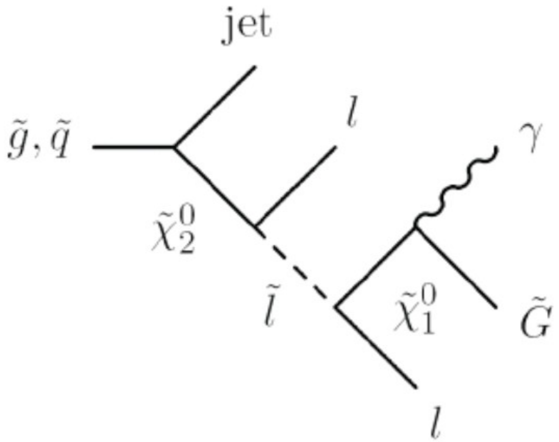
Fluctuation over jet threshold

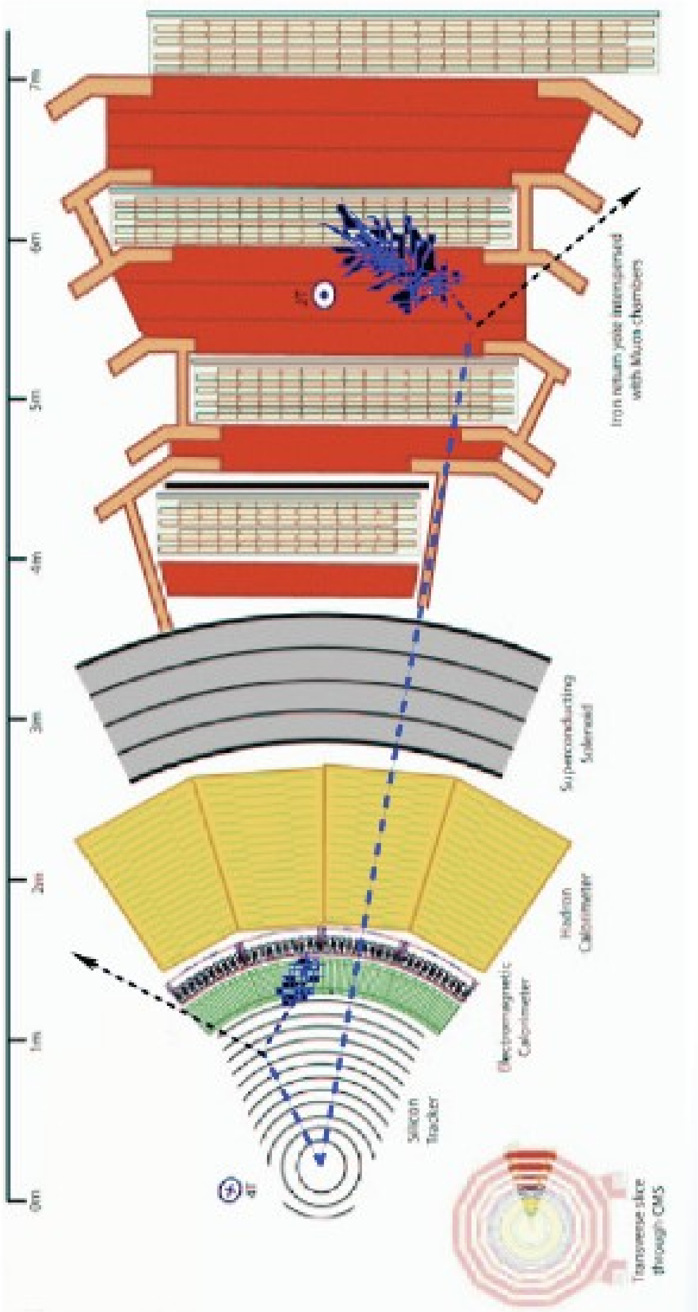
Compare w/ stopped-gluino signal (MC):



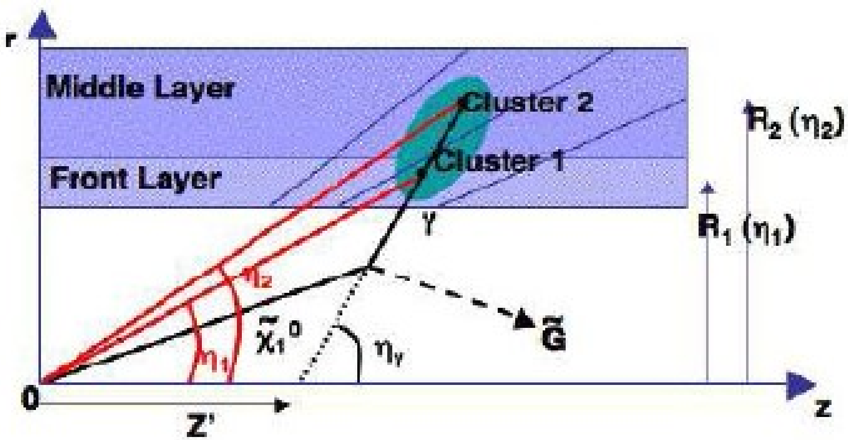
Non-pointing photons

- Possible signature of GMSB
  - LSP is the gravitino
  - Neutralino (or stau) can be the NLSP
    - The decay time can be long
    - If stau, go back to the “charged exotic” case...
  - Neutralino can decay to $\tilde{G}\gamma$
    - Final state: leptons, jets, MET (from gravitino), photons (pointing or not)





Non-pointing photons in ATLAS



Longitudinal segmentation (2 layers) in ATLAS LAr calorimeter

Table 9: Trigger efficiencies and statistical errors for the GMSB3 event sample for ($\mathscr{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$).

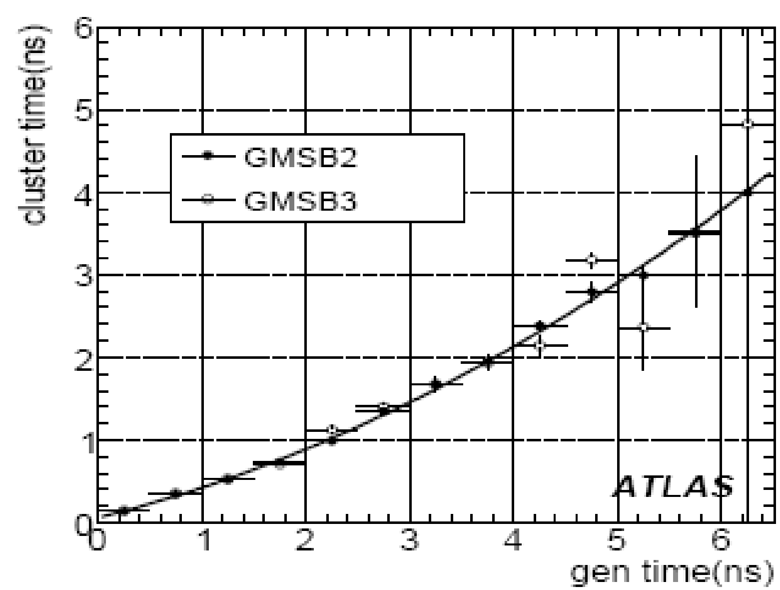
Trigger item	L1	L1+L2	L1+L2+EF
g55	90.19 ± 1.08	46.04 ± 1.81	36.88 ± 1.75
2g17i	34.13 ± 1.72	17.77 ± 1.39	12.87 ± 1.22
j65+xE70	80.38 ± 0.56	80.24 ± 0.56	71.18 ± 0.64
3j65	79.80 ± 0.57	79.66 ± 0.57	79.62 ± 0.57

Table 10: Number of selected signal (GMSB3) and background events for $1\,\mathrm{fb}^{-1}$ for different cuts on the number of photons and opposite sign same flavour (OSSF) lepton pairs.

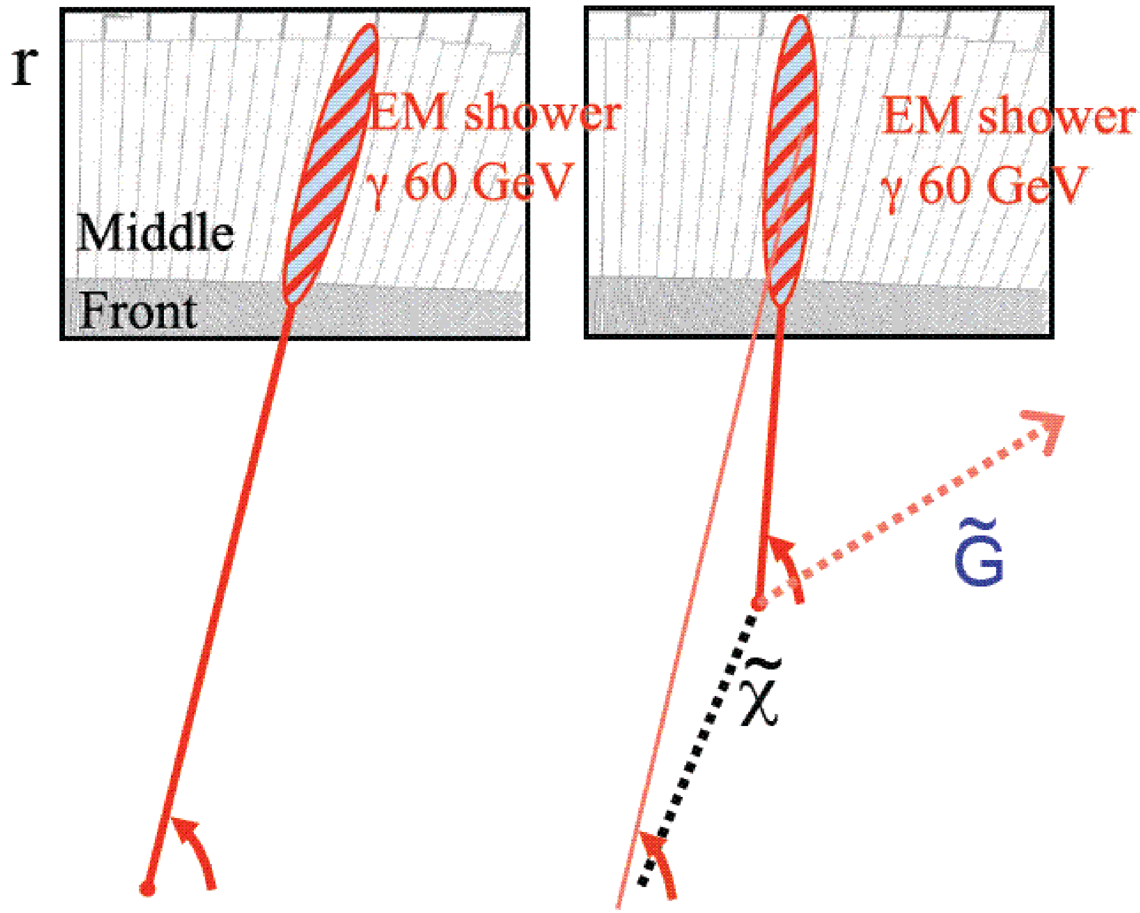
N_γ	N_{OSSF}	Signal	$\sum$ Background	Sig	N_W	N_Z	$N_{t\bar{t}}$
0	0	825.2	929.6	27.1	274.4	21.0	632.8
0	1	265.2	73.0	33.2	8.7	1.4	63.0
1	0	255.8	51.7	35.7	19.5	2.0	30.1
1	1	68.6	1.4	58.6	0.2	0.0	1.2
2	0	12.5	0.1	12.5	0.0	0.0	0.1
2	1	4.7	0.0	4.7	0.0	0.0	0.0

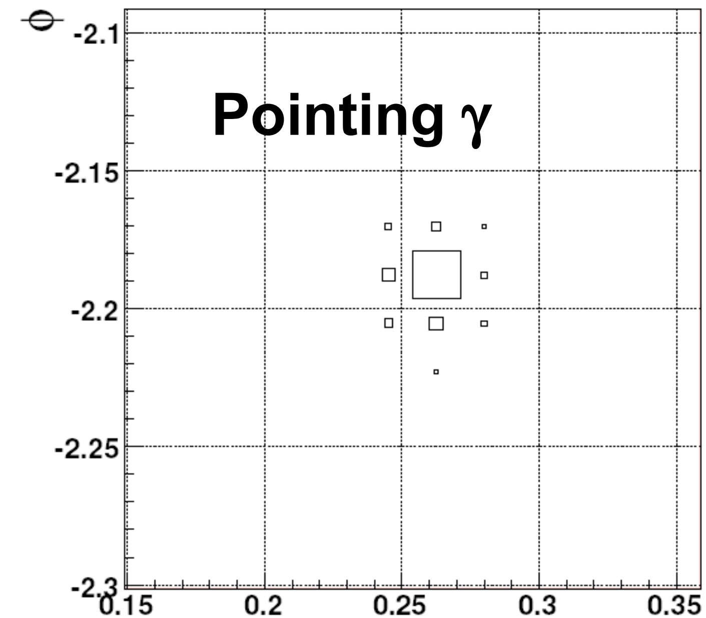
GMSB search based on number of photons and of opposite-sign same-flavor (OSSF) lepton pairs, see talk by M.-H. Genest

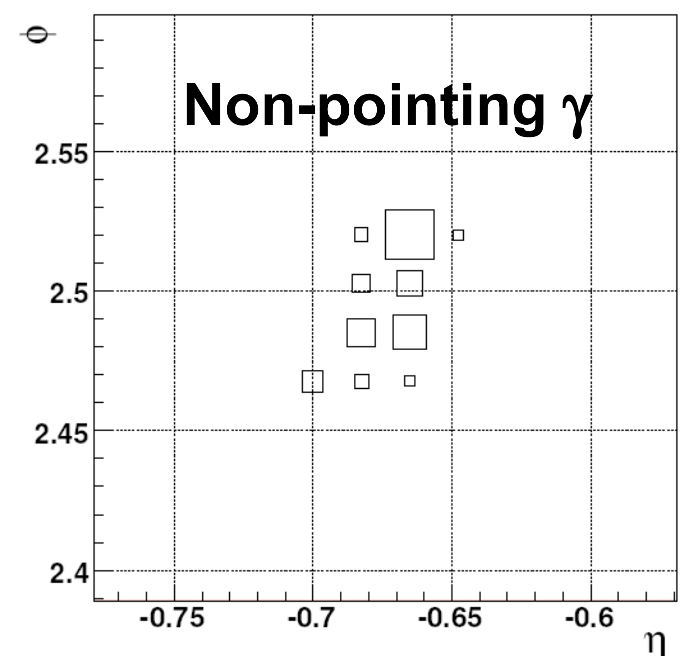
In case of evidence for signal, the neutralino lifetime can be inferred by the photon shape (cluster1 vs cluster2 position) and timing in ECAL



Non-pointing photons in CMS







CMS ECAL: no longitudinal segmentation; this analysis is based on the elongation (major / minor axes asymmetry) and the inclination of the ellipse in η/ϕ

Expectations for LHC data

- **Charged exotics:**
  - Very early (<~100/pb) exclusion/discovery for sub-TeV masses, if the exotic can be produced by strong interaction
- **Stopped gluinos:**
  - with $L=10^{32}$ $cm^{-2}s^{-1}$, sensitive to lifetimes from μs to weeks within a few days of operation
  - Note: background doesn't scale with L!
- **GMSB:**
  - Non-pointing γ's complement the standard counting exp by giving sensitivity to parameter-space regions where the neutralino is long-lived
  - Few fb^{-1} needed over a large range of lifetimes

Summary

- Long-lived exotica have non-standard signatures which open parameter space regions inaccessible to standard searches
- They often require a use of the detector information that was not foreseen when designing the hardware
- CMS and ATLAS mostly complementary, thanks to different choices in detector design
- Physics bkg's negligible => focus on detector behavior
  - Cosmics are precious data (and in some cases will be the main background, so better know your enemy soon)
  - Close link between analysis and commissioning
  - In some sense, *the analyses have already started*!

Extra slides

- Theoretical motivations
- Expectations for LHC data, more infos
- Technical details

Many thanks to the following people for their feedback:
Giacomo Polesello, David Milstead, Greg Landsberg, Shlomit Tarem

SUSY models with heavy quasi-stable charged particles

- AMSB: chargino (muon-like)
  - (mass difference with LSP may be <150 MeV)
- GMSB: stop (R-hadrons), stau (muon-like)
- SUSY-5D: stop (R-hadrons)
- Split SUSY: gluino (R-hadrons)

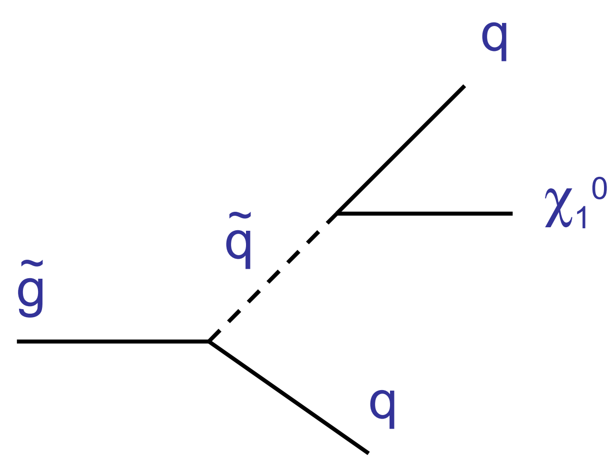
Also non-SUSY examples exist (e.g., KK taus)

The next slide will explain the Split-SUSY case
• it tries to solve the “big” hierarchical problem (i.e. the fine tuning of the cosmological constant), by allowing a %-level fine tuning of the Higgs mass
• (analogy: there is no deep reason behind the surprising %-level fine tuning of Moon/Sun relative sizes and distances that results in total eclipses)

Split SUSY

- Gauginos at TeV scale, sfermions higher (e.g., at GUT scale)
- The gluino is colored, so it has to decay to colored particles
- (If R-parity holds) it has to couple to a super-particle and a particle
- The only other colored super-particles are the squarks, but they are much heavier!
- So, it decays through a virtual squark:

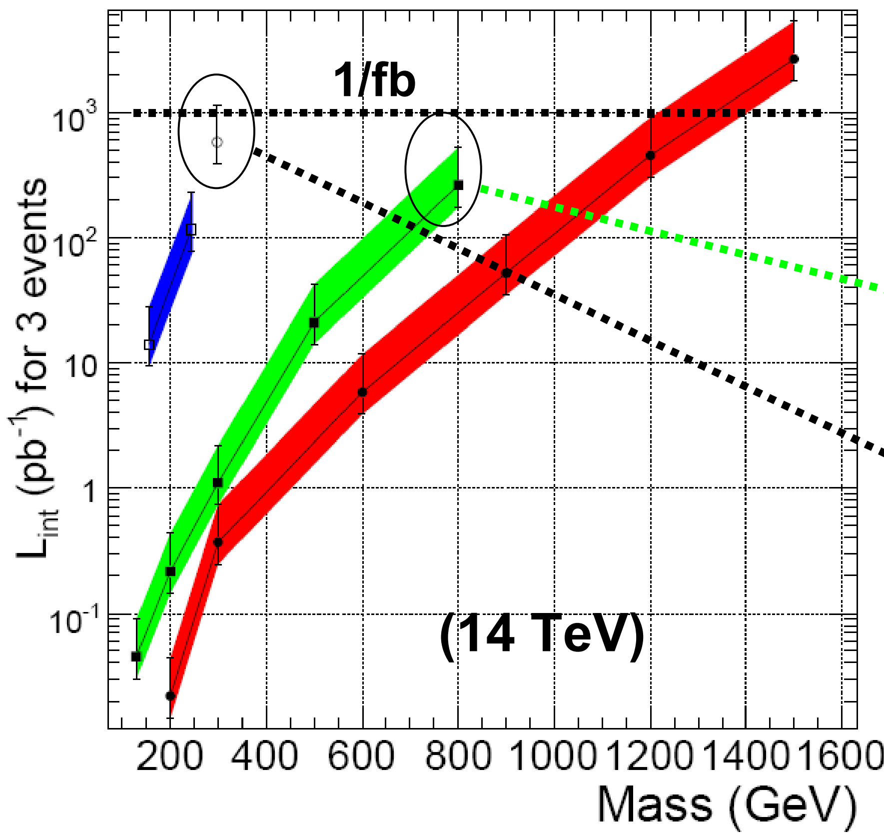
$$\tau \simeq 8 \left(\frac{m_S}{10^9 \text{ GeV}} \right)^4 \left(\frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^5 \text{s}$$

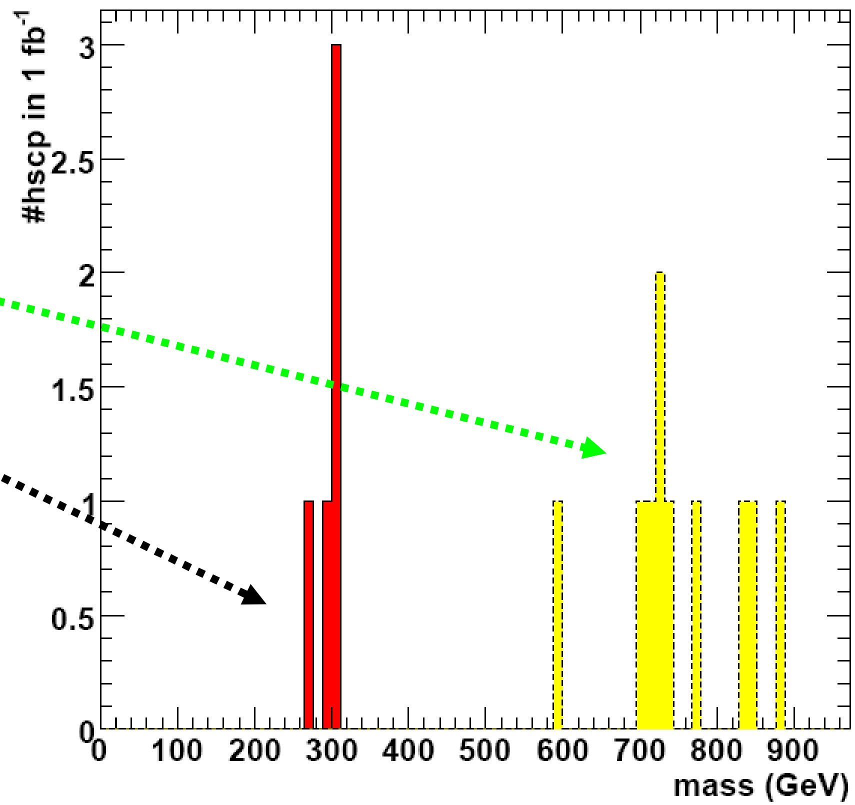


- Long lifetime: from O(ps) to O(age of the Universe)
- Slow: Time-of-Flight technique (in CMS: use Muon Chambers)
- Colored: it hadronizes ($\tilde{g}g$, $\tilde{g}q\bar{q}$), and its "hadrons" have nuclear interactions! By exchanging quarks, they can give $R^{+/-} \to R^0 \to R^{+/-}$

Expectations for LHC data

Expectations for charged exotics

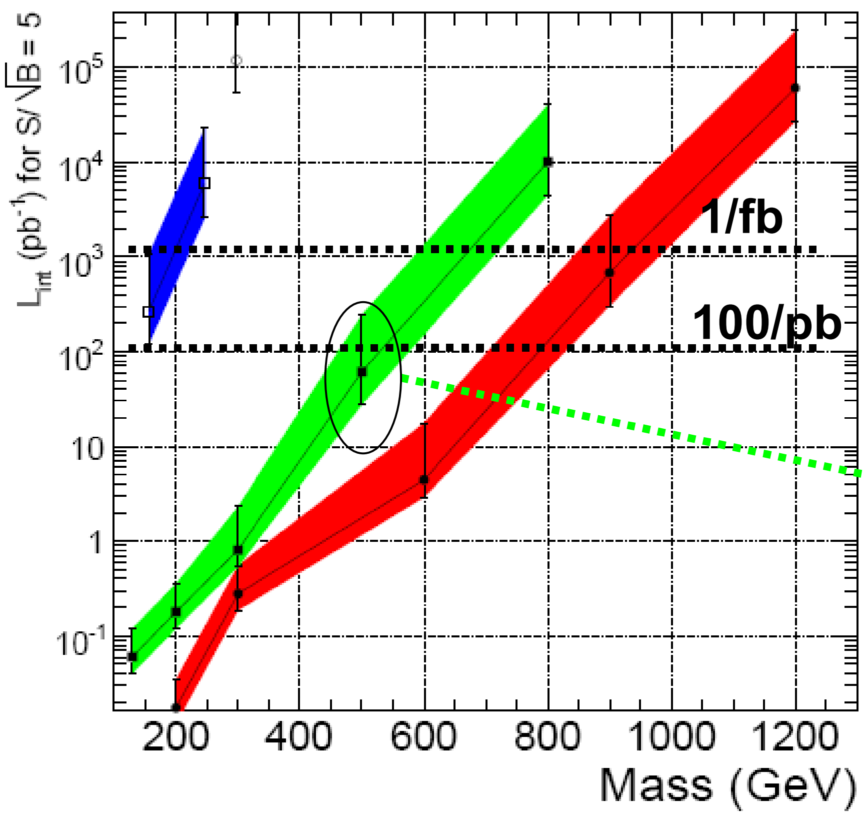




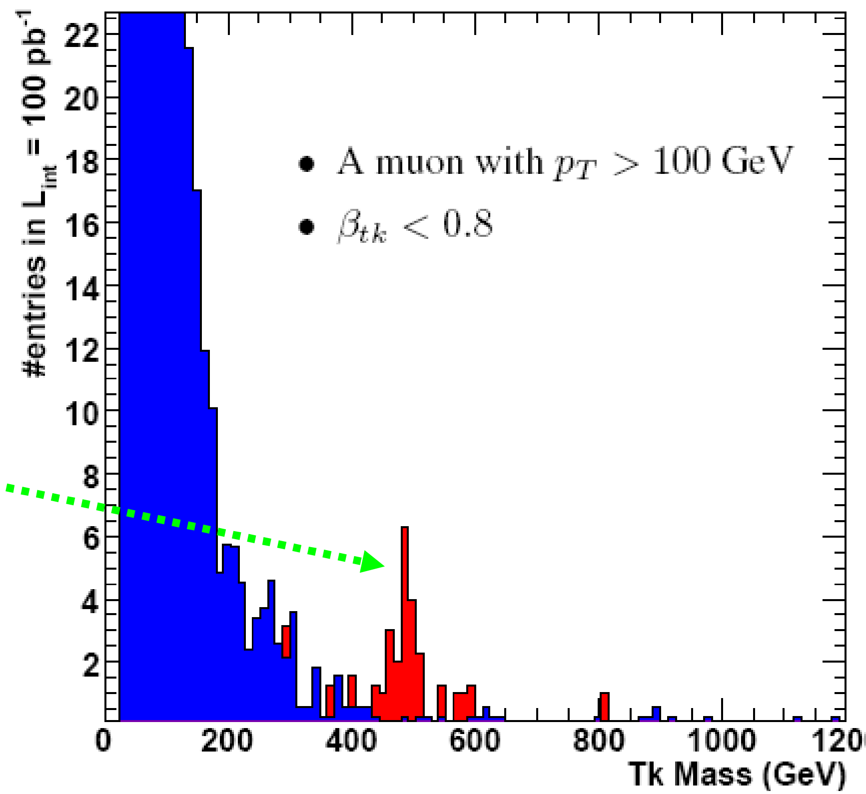
Integrated luminosity needed for more than 3 events for four signal models
gluino full circles, **stop full squares**,
KK tau empty circle, **stau empty squares**

Mass distribution with 1/fb for two of the lowest cross section models
300 GeV KK tau **800 GeV stop**

Expectations for Tracker-only analysis

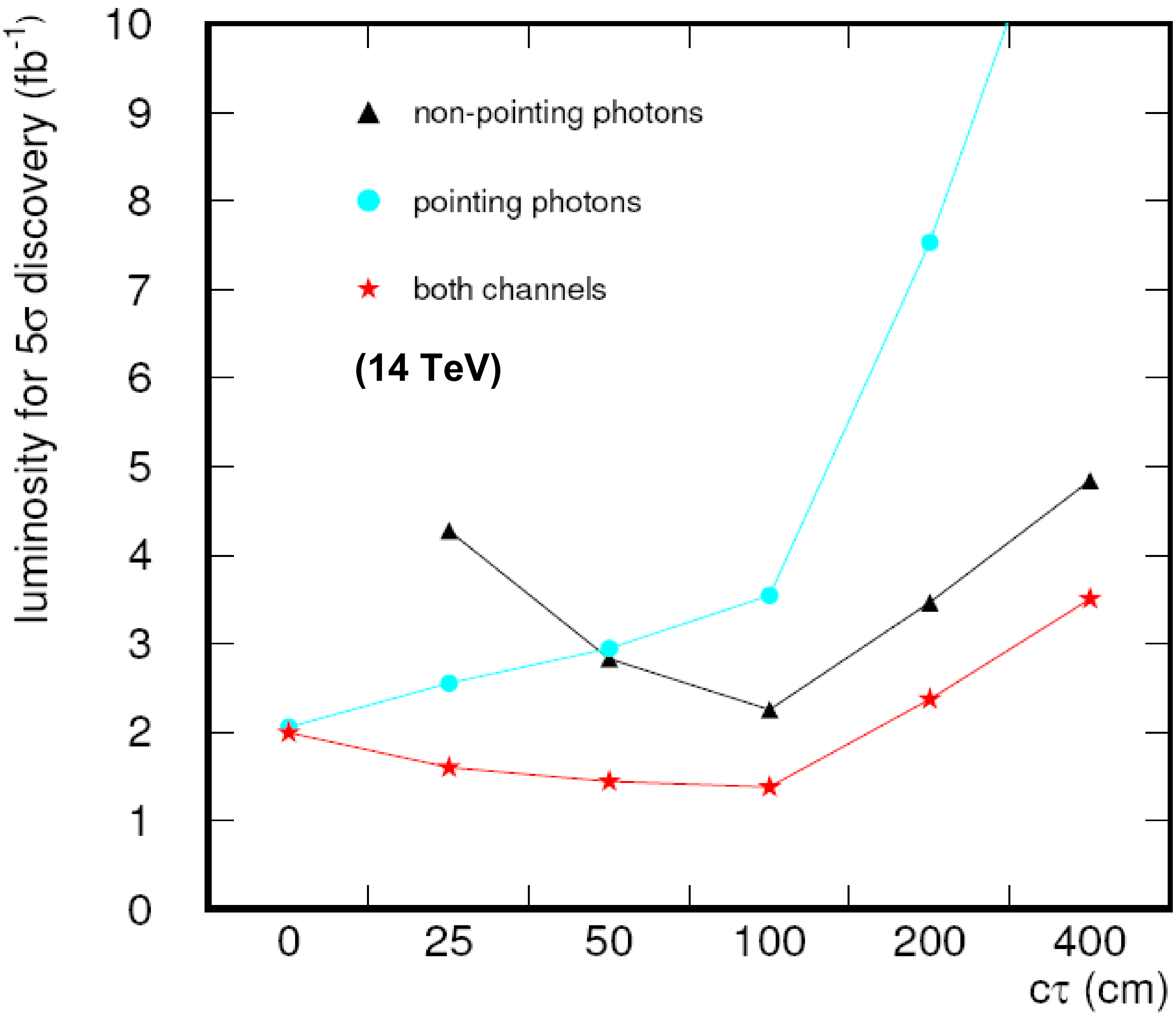


Integrated luminosity needed for 5σ discovery, for four signal models:
gluino full circles, **stop full squares**,
KK tau empty circle, **stau empty squares**

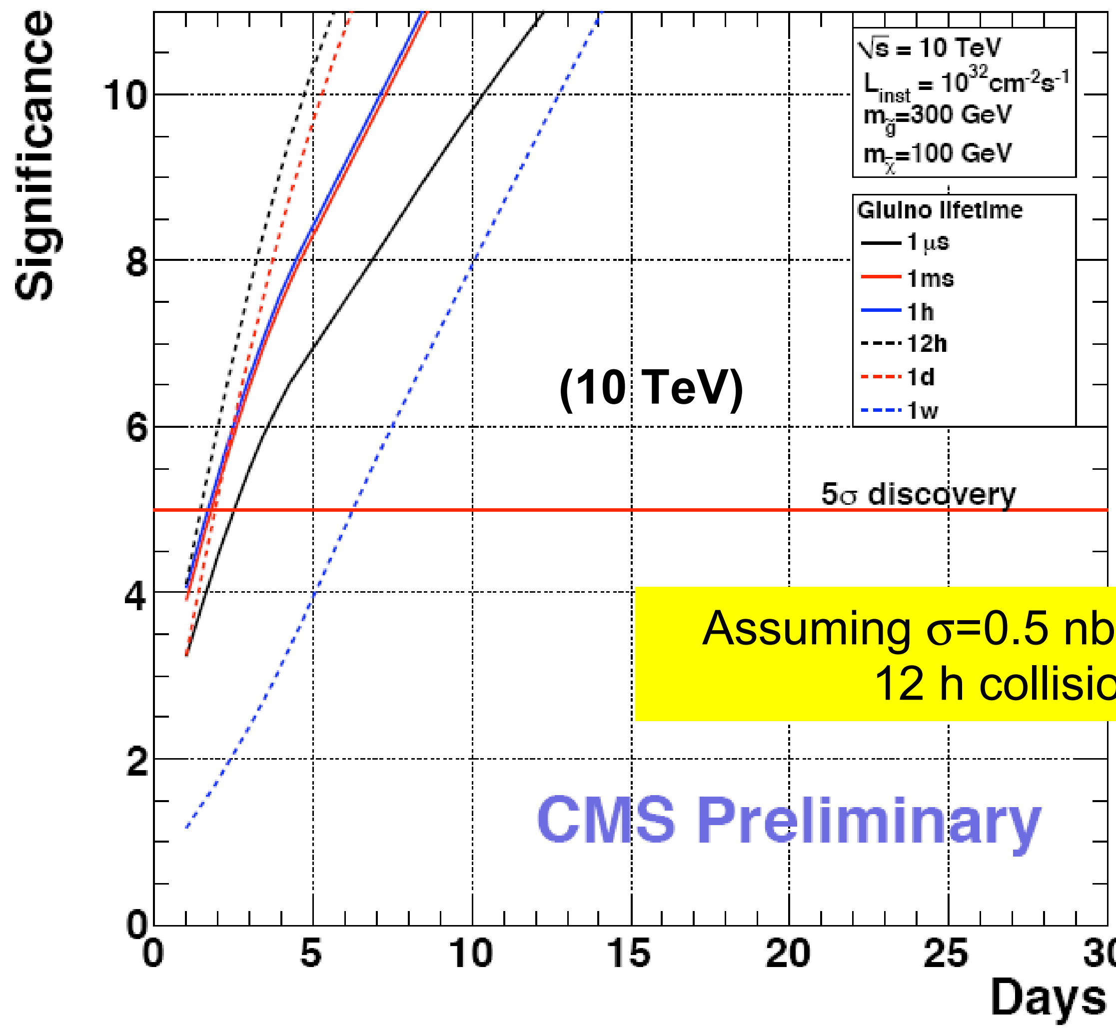


Mass distribution with 100/pb for
500 GeV stop

Expectations for GMSB



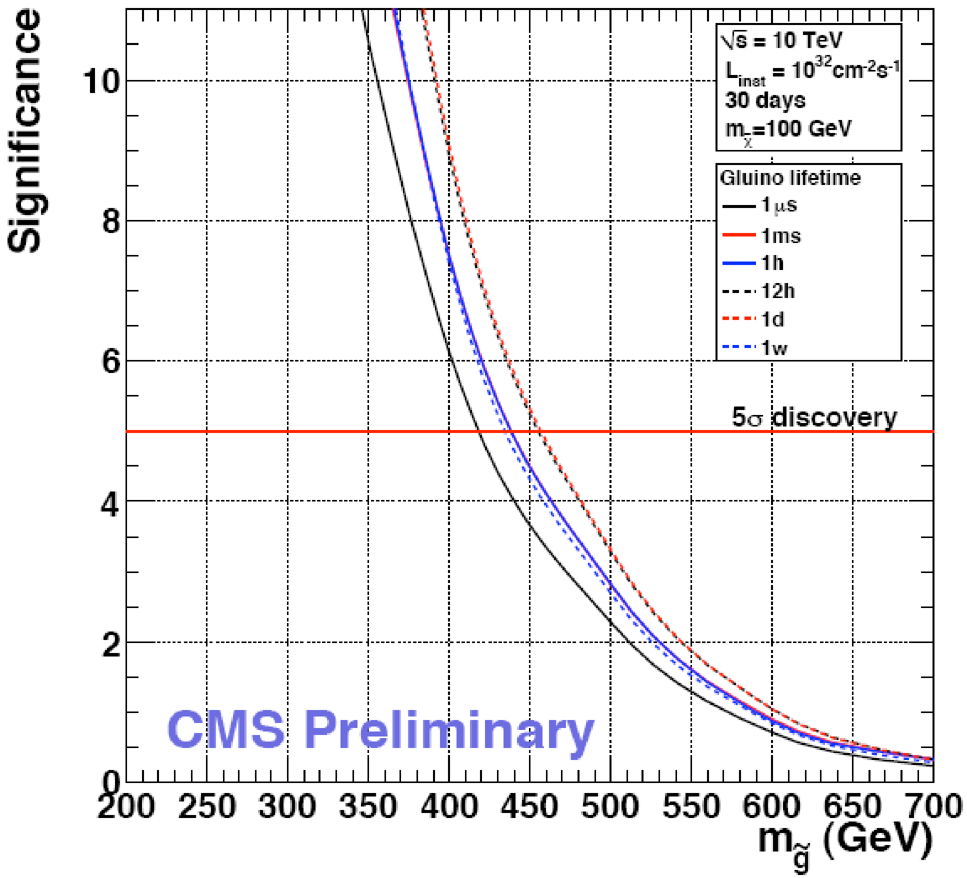
Expectations for stopped gluinos

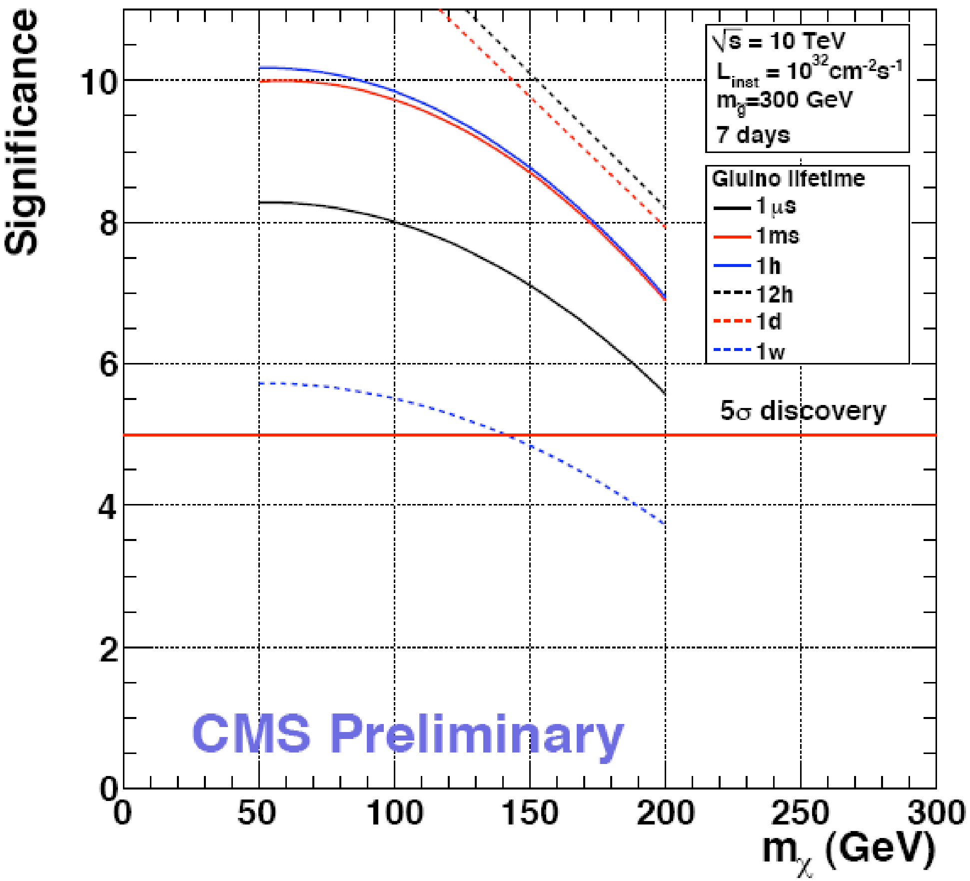


Assuming σ=0.5 nb, L=10^{32} cm^{-2}s^{-1}
12 h collisions/day

At L=10^{32} cm^{-2}s^{-1}, sensitive to **lifetimes from μs to weeks** within a **few days of operation**. Note: background doesn't scale with luminosity...

Stopped gluinos





Stopped gluinos, systematics

Source of Systematic Error	Estimated Fractional Uncertainty
PDF uncertainty on $\sigma(pp \to \tilde{g}\tilde{g})$ at NLO	$\pm 13\%$
Scale uncertainty on $\sigma(pp \to \tilde{g}\tilde{g})$ at NLO	$\pm 5 - 10\%$
Theoretical Uncertainty on Stopping Efficiency (Cloud Model)	-60%
Uncertainty on Background Rate	$< 1\%$
Uncertainty on Duration of Interfill Period	*
Uncertainty on Trigger live-time during Interfill Period	*
Uncertainty on Instantaneous Luminosity	$\pm 20\%$

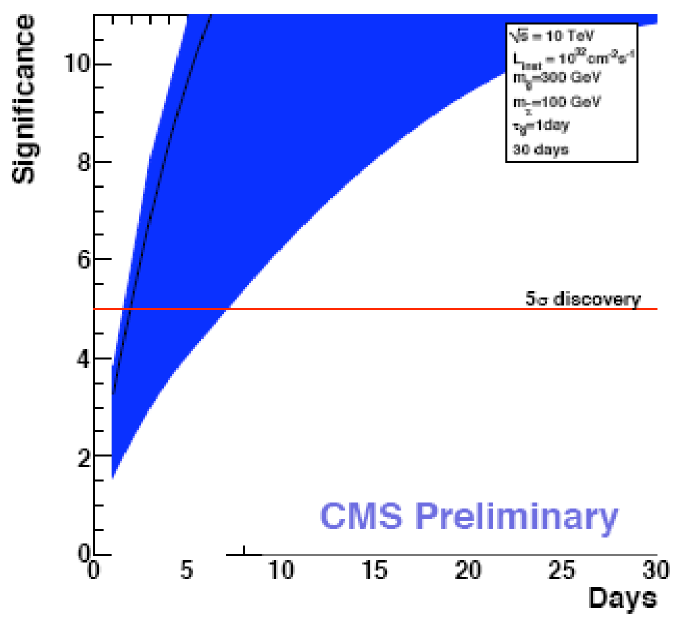
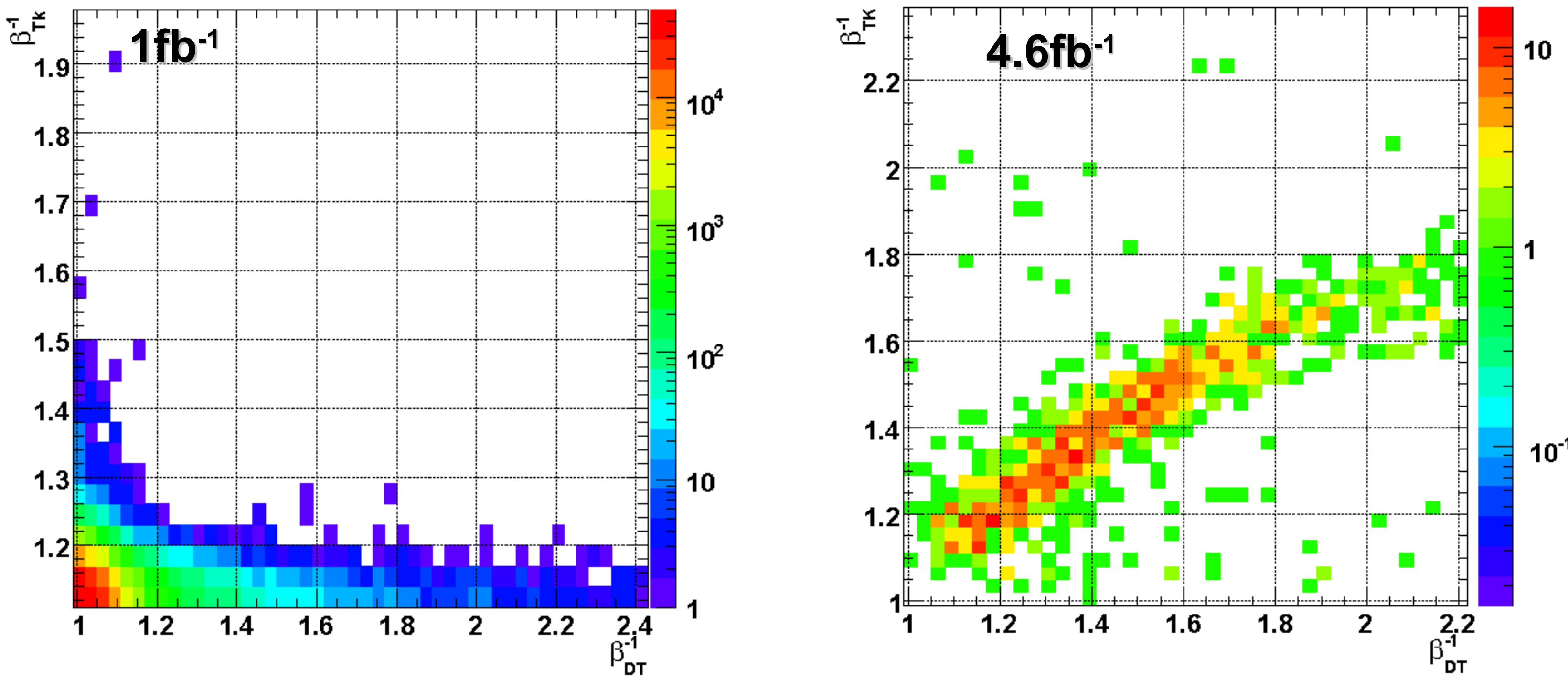


Figure 11: Discoverability of a 300 GeV gluino, with a lifetime of 1 day, from a counting experiment using both beamgap and interfill periods. Assumes instantaneous luminosity of 10^{32} cm^{-2}. Systematic uncertainty in the discoverability is indicated by the blue band.

Technical details

dE/dx+TOF in CMS

β_{DT}^{-1} vs. β_{Tk}^{-1}



SM Muons

$\tilde{t}_1$ 500GeV

Notice the effect of saturation in β from dE/dx

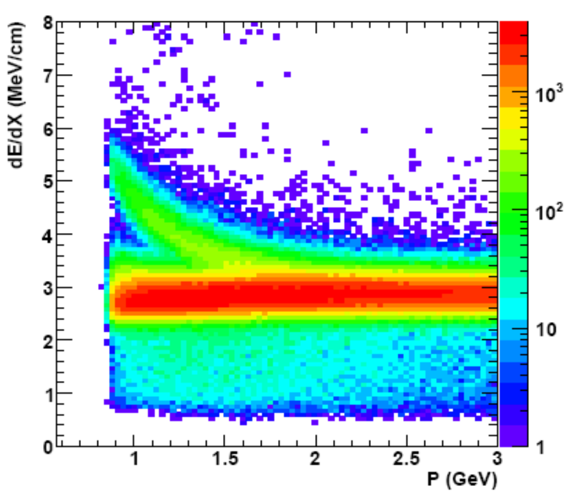
dE/dx calibration

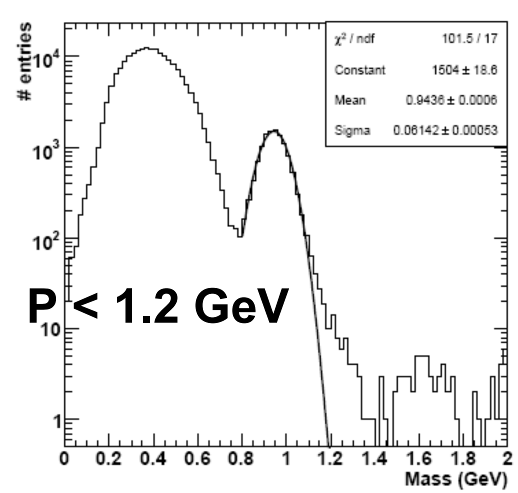
- Intercalibration and absolute calibration from:
  - "Gain scan" (calibration of the opto-electronic chain)
  - Cosmic muons
  - high-P tracks
- Linearity check through a high-purity proton sample
  - Minimum bias, P < 1.2 GeV
  - $\Lambda^0 \rightarrow p\pi$

$$m = \frac{p}{\beta\gamma} \qquad \frac{1}{\beta\gamma} = \sqrt{\frac{1}{\beta^2} - 1}$$

$$\frac{dE}{dX} = \frac{1}{k\beta^2} \qquad m = p\sqrt{k\frac{dE}{dX} - 1}$$

Extract k from a proton sample





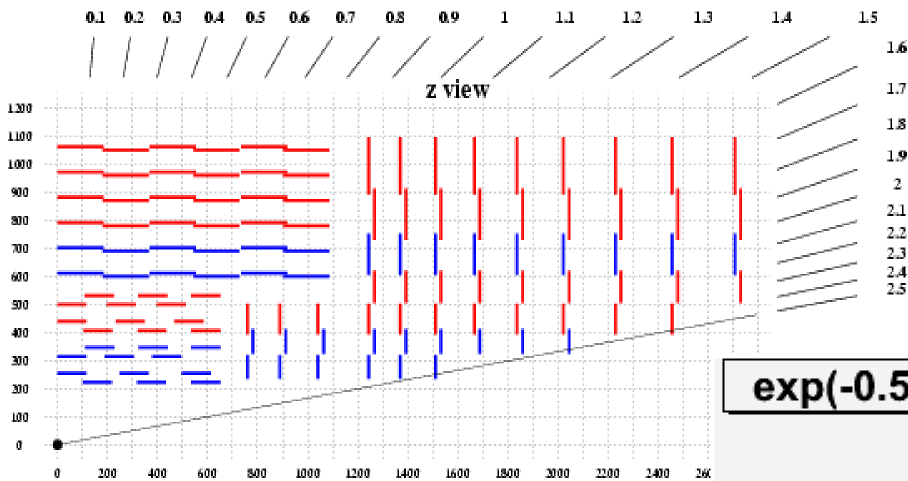
dE/dx: estimator comparison
(CMS NOTE 2008/005)

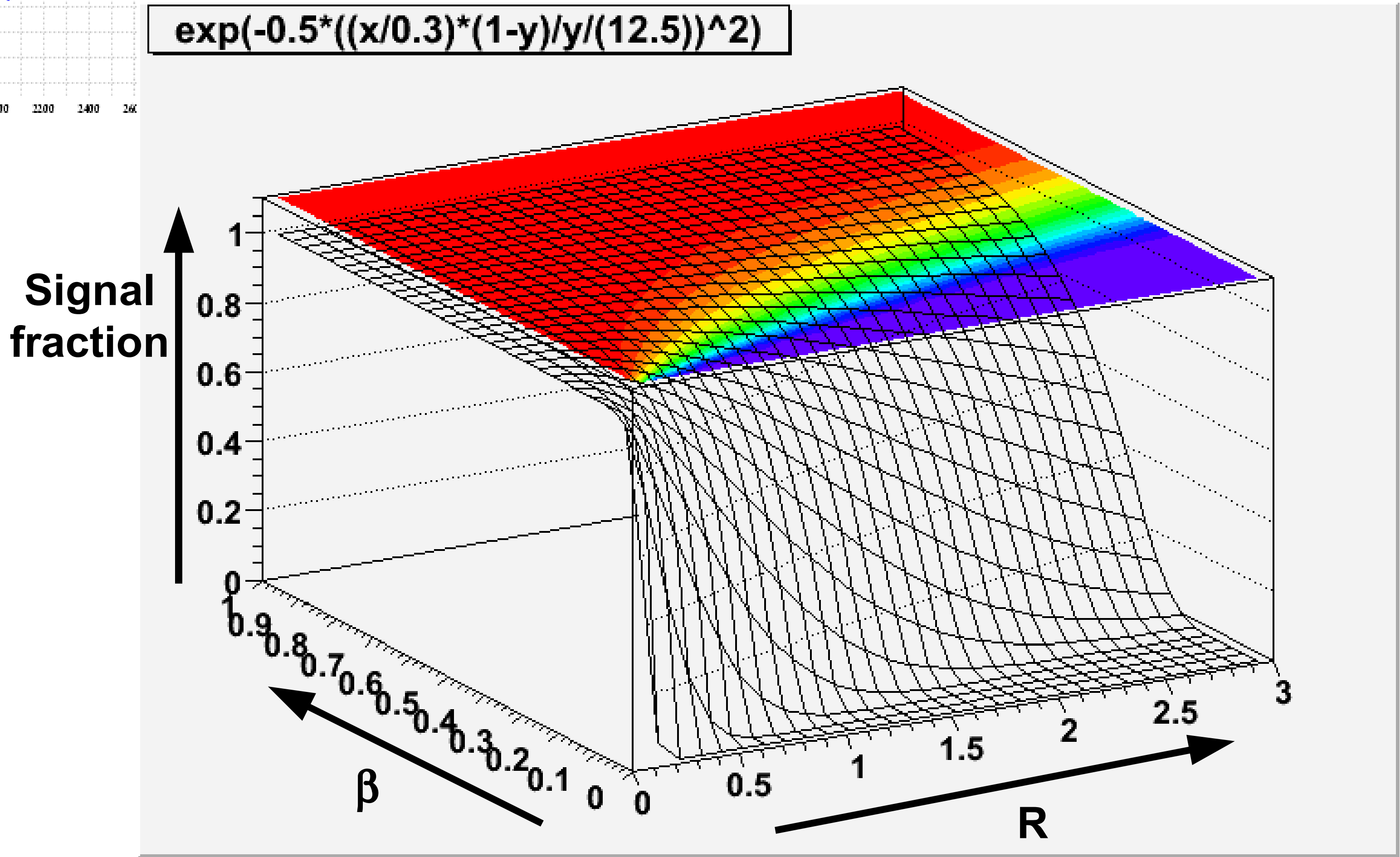
Table 1: Performances of some dE/dx estimators for particles of momentum between 900 and 1100 MeV$/c$.

Estimator	muon σ (%)	K/π separation	p/π separation
Median	14.5	0.61	2.45
Truncated mean (20 %)	6.82	1.28	4.76
Truncated mean (40 %)	6.27	1.50	5.29
Harmonic mean	7.45	1.11	4.26
Generalized mean ($k = 1/2$)	7.97	1.03	3.97
Generalized mean ($k = 1/3$)	8.12	0.98	3.97
Generalized mean ($k = 2$)	6.58	1.29	4.76
Generalized mean ($k = 4$)	6.03	1.50	5.38
Generalized mean ($k = 6$)	5.98	1.58	5.58
Landau fit	6.30	1.57	5.44

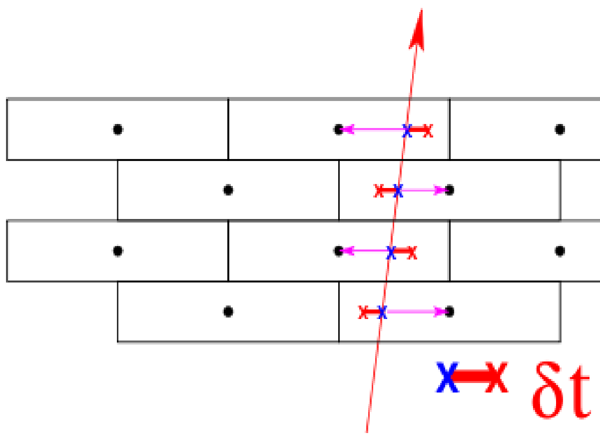
The Landau unbinned fit (performed with MINUIT in ROOT) is not strikingly better (and it is actually worse than some), and it is much slower.

Attenuation for slow particles





TOF from Drift Tubes



$$\frac{\delta_x}{v_{\mathrm{drift}}} = \delta_t = t_{\beta<1} - t_c = \frac{L}{c}\left(\frac{1}{\beta} - 1\right)$$

and hence

$$\frac{1}{\beta} = 1 + \frac{\delta_x}{L}\frac{c}{v_{\mathrm{drift}}}$$

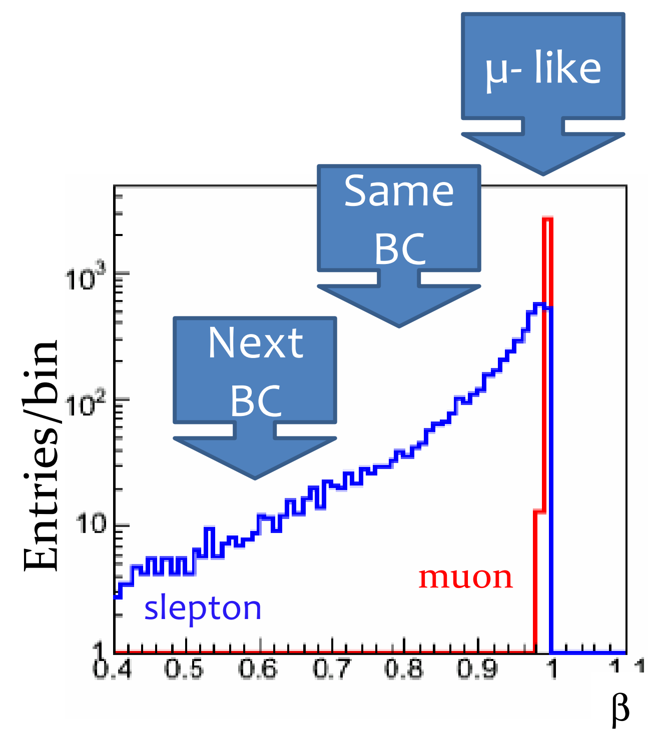
and finally

$$\frac{1}{\beta} = 1 + \frac{c}{v_{\mathrm{drift}}}\frac{1}{N}\sum_{i=1}^{N}\frac{\delta_x^i}{L_i}$$

where L is the flight distance, v_{drift} is the drift velocity and $\delta_x^i = |x_i^{\mathrm{hit}} - x_i^{\mathrm{wire}}| - |x_i^{\mathrm{reco}} - x_i^{\mathrm{wire}}|$

Charged exotics: triggering issues

- Timing issue:
  - Trigger systems were designed for β~1
  - Slow particles can fail reco or be attributed to wrong BX
  - Constraint: Δt<12.5 ns => β>~0.6
- Muon triggers:
  - Useful for most models
    - But if R-hadron interacts (nucl.), it is lost
  - Efficiency is β-dependent
- Jets/MET triggers:
  - More model-dependent
    - Higher efficiency for cascades (MET), R-hadrons (more radiation)
  - Not sensitive to timing/β issues



Charged exotics: triggering in CMS

CMS Trigger Efficiency with full simulation

HLT Trigger Path	1MuonNonIso		1MET		1SumET		1Jet		Global
Efficiency (%)	Abs	Inc	Abs	Inc	Abs	Inc	Abs	Inc	Abs
$\tilde{\tau}_1$ 156 (GeV)	96.8	**96.8**	84.1	**1.9**	91.3	**0.5**	74.9	**0.0**	**99.2**
$\tilde{\tau}_1$ 247 (GeV)	96.8	**96.8**	81.5	**2.1**	87.4	**0.6**	63.5	**0.0**	**99.5**
tau 300 (GeV)	75.2	**75.2**	7.8	**2.2**	7.9	**1.2**	2.1	**0.0**	**78.6**
$\tilde{t}_1$ 130 (GeV)	21.9	**21.9**	18.1	**12.5**	17.3	**3.2**	3.9	**0.0**	**37.6**
$\tilde{t}_1$ 200 (GeV)	23.7	**23.7**	26.0	**18.1**	25.1	**4.1**	7.0	**0.0**	**45.9**
$\tilde{t}_1$ 300 (GeV)	23.5	**23.5**	33.4	**24.4**	35.7	**5.8**	10.8	**0.0**	**53.7**
$\tilde{t}_1$ 500 (GeV)	23.4	**23.4**	39.3	**29.6**	48.3	**8.4**	17.3	**0.0**	**61.4**
$\tilde{t}_1$ 800 (GeV)	22.0	**22.0**	44.8	**34.5**	62.9	**14.0**	21.7	**0.0**	**70.5**
$\tilde{g}$ 200 (GeV)	22.4	**22.4**	28.5	**21.3**	44.6	**13.6**	9.8	**0.0**	**57.3**
$\tilde{g}$ 300 (GeV)	22.6	**22.6**	35.3	**26.7**	58.0	**17.8**	14.0	**0.0**	**67.0**
$\tilde{g}$ 600 (GeV)	21.3	**21.3**	47.1	**36.1**	83.2	**27.9**	23.1	**0.0**	**85.4**
$\tilde{g}$ 900 (GeV)	16.6	**16.6**	49.5	**40.0**	92.4	**36.3**	29.2	**0.0**	**92.9**
$\tilde{g}$ 1200 (GeV)	11.7	**11.7**	55.6	**47.6**	95.0	**36.0**	34.0	**0.0**	**95.3**
$\tilde{g}$ 1500 (GeV)	11.3	**11.3**	56.2	**49.1**	96.0	**35.7**	45.2	**0.0**	**96.1**

mGMSB $\tilde{\tau}_1$~ 99%

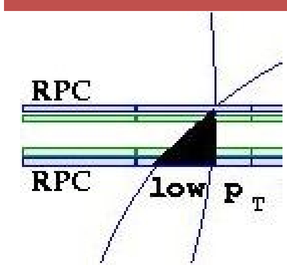
UED KK $\tilde{\tau}_1$ ~ 80%

MSSM $\tilde{t}_1$~ 40% to 70%

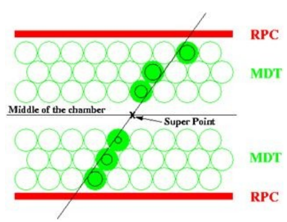
Split SUSY $\tilde{g}$ ~ 60% to 95%

Charged exotics: triggering in ATLAS

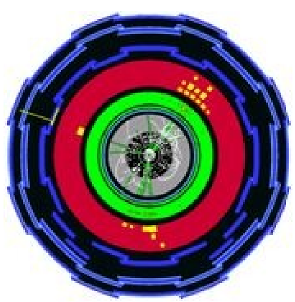
ATLAS trigger



Level 1:
- 40MHz to < 75KHz
- Defines region & BC
- Custom HW



Level 2:
- 75KHz to ~1KHz
- Process region of L1 trigger
- Quick SW



Event filter:
- 1KHz to ~100Hz
- Full event data
- Offline code

Slow particle

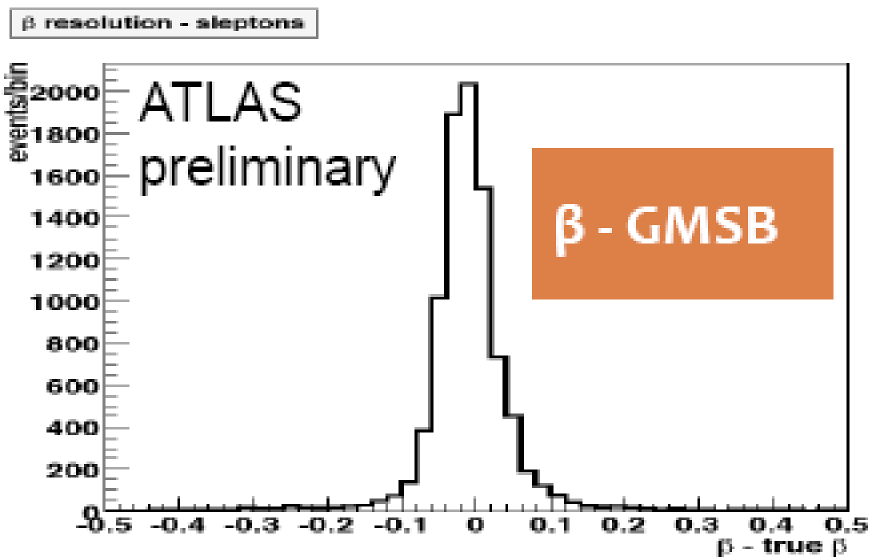
- Particles trigger as muon
- Hits may be with next BC
- Particle may trigger late

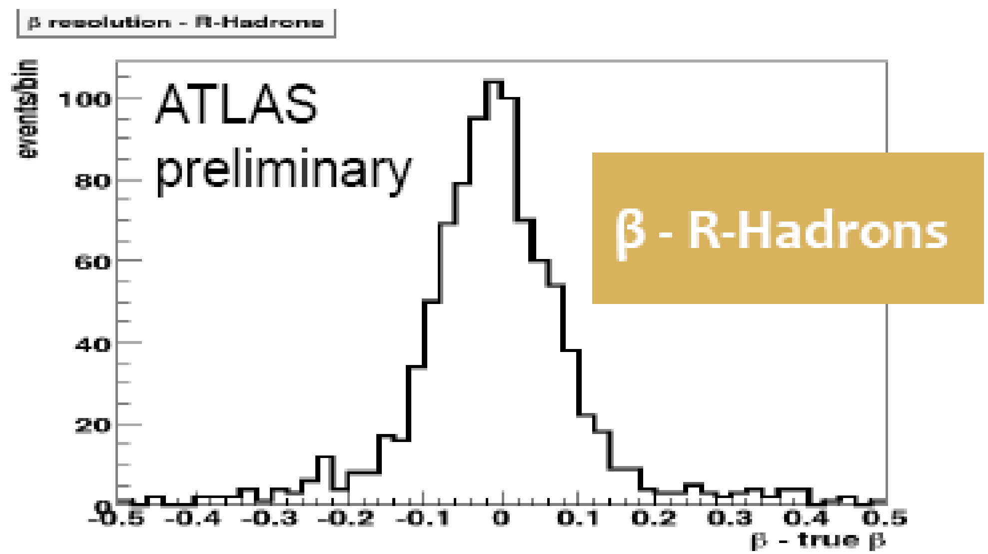
- Dedicated trigger for slow particles with TOF measurement in RPC

- Measure β with MDT and RPC
- Reconstruct charge-flipped R-Hadrons

Slide taken from S.Tarem, more info in SN-ATLAS-2008-071

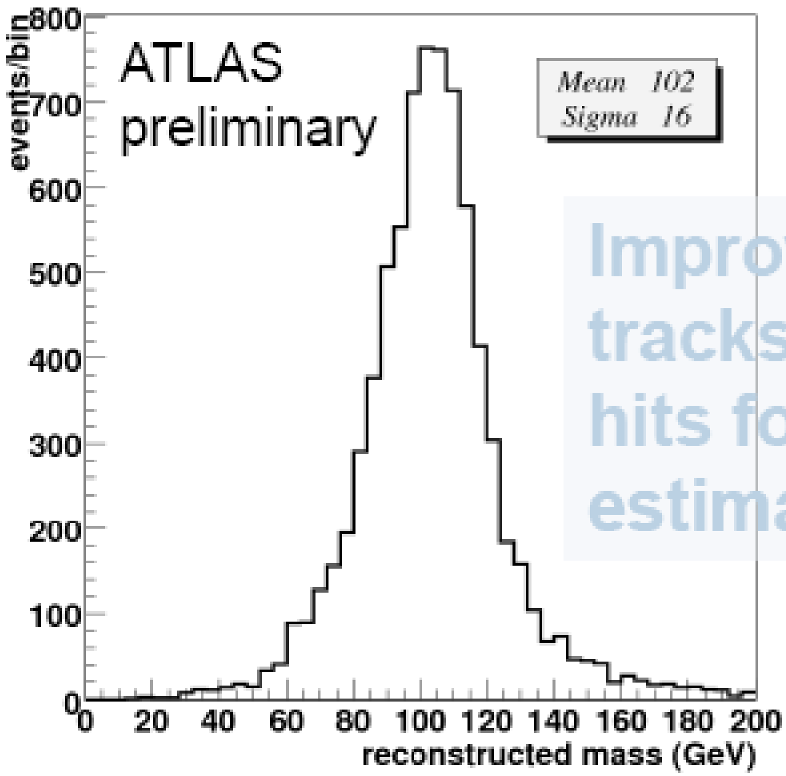
Charged exotics:
β resolution in ATLAS



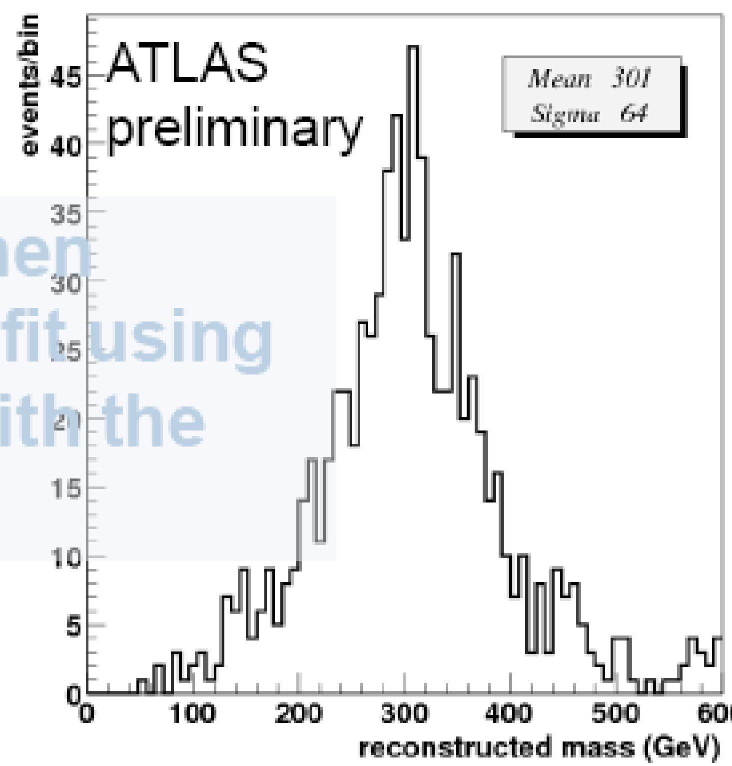


Slide taken from S.Vallecorsa, PANIC'08

Charged exotics: mass reconstruction in ATLAS



Improves when tracks are refit using hits found with the estimated β



Sleptons generated with m=100 GeV

R-Hadrons generated with m=300 GeV

Slide taken from S.Vallecorsa, PANIC'08

DEDICATED TRIGGER AT L2

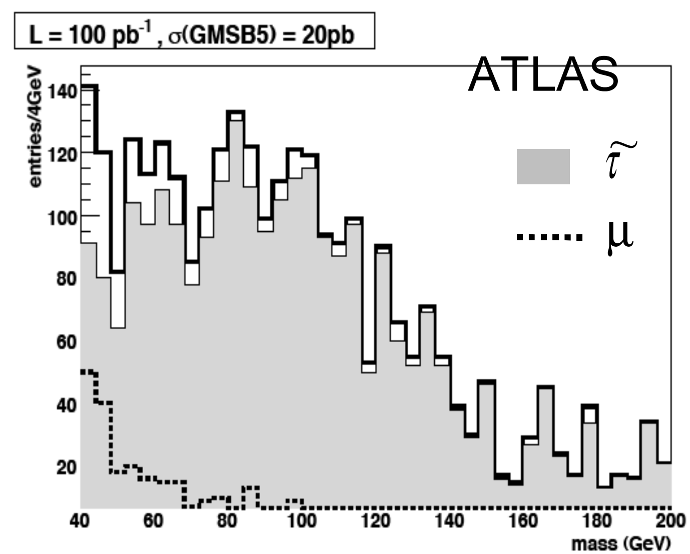
- L2 algorithm using RPC in barrel / EF MDT & RPC

Trigger type	R-hadros m=300		R-hadrons m=1000		Stau β=0.6
	Barrel	End-cap	Barrel	End-cap	Barrel
L2 MS	0.99		1.00		1.00
L2 Ms Slow	0.92	NA	0.93	NA	0.99
L2 Comb	0.49		0.50		1.00
Muon EF	0.24		0.28		0.39
Slow EF	0.85		0.85		0.79

Charge flip*

Low β reconstruction efficiency

- Background
  - L2 Barrel
    - 1 Hz @ 10^{33}

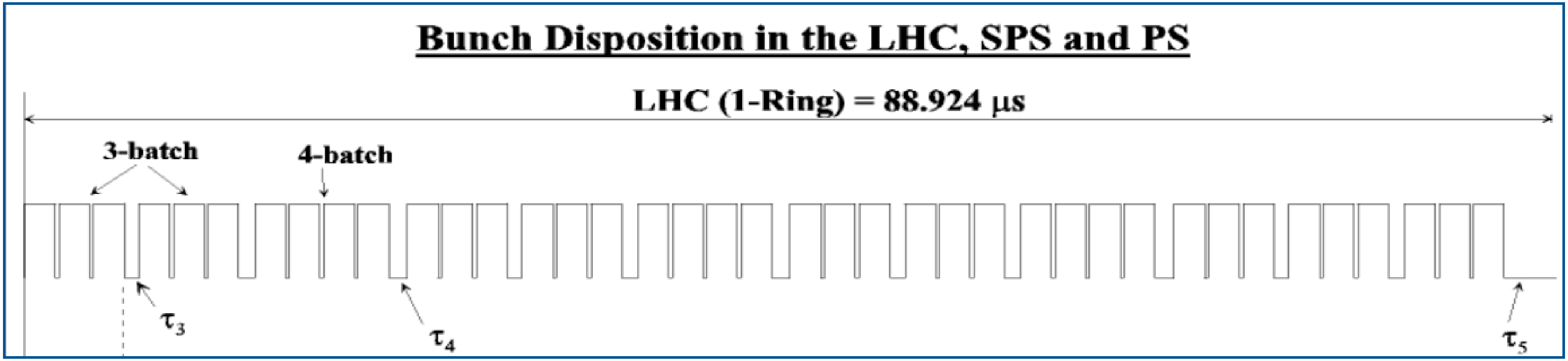


    - 0.5% $\mu(p_T>20)$
    - 5% of $\mu(p_T=100)$

Slide by Shlomit Tarem

Stopped gluinos, triggering

- Two trigger scenarios:
  - Run the (jet, E>50 GeV) && !(beam) trigger after a fill has been dumped ("interfill period")
  - Same trigger also during normal run times, in the gaps in the beam structure ("beam gap period")
- Together, these give (in principle) sensivity to lifetimes from ~100 ns to ~months (12 orders of magnitude!)



Stopped gluinos, topological selection

- E(jet) > 50 GeV
- Barrel only: $|\eta|<1.3$
- Veto events where 90% of energy is in ≤3 towers
- Leading jet must have ≥60% of energy in the leading ≤6 towers
- Veto on muons found by the Cosmic Track Finder
- These cuts are survived by 0.09% of the events passing the High Level Trigger; $\varepsilon_{signal}=61\%$

Stopped gluinos, timing selection

- The pulse shape for signal has
  - a clear maximum (at bunch crossing BX_{Peak})
  - significant energy at BX_{Peak}-1
  - an exponential decay for several BX's after
- Cross checked with events containing a cosmic muon
- Cuts:
  - $E(BX_{Peak}+1)/E(BX_{Peak})>15\%$, $10\%<E(BX_{Peak}+2)/E(BX_{Peak}+1)<50\%$
  - 40-70% of total energy has to be in BX_{Peak}
  - <10% of total energy outside of range $[BX_{Peak}-1, BX_{Peak}+2]$

Stopped gluinos, cut flow table

Cut	Background Rate	Signal Efficiency (% of Stopped)
L1 Rate (online)	200 ± 2.9 Hz	35.6 %
HLT Rate (online)	5.2 ± 0.25 Hz	31.8 %
$\lvert\eta_{jet}\rvert < 1.3$	1.39 Hz	26.1 %
Jet $n90 > 3$	0.218 Hz	24.8 %
Jet $n60 < 6$	0.076 Hz	21.7 %
$E_{jet} > 50$ GeV	0.024 Hz	20.3 %
Muon Veto	0.0049 Hz	19.4%
$0.15 < R_1$ and $0.10 < R_2 < 0.50$	0.00063 Hz	16.5%
$0.4 < BX_{Peak}$ / Total Energy < 0.7	0.00050 Hz	16.5%
$BX_{1+2+9+10}$ / Total Energy < 0.1	0.00039 Hz	16.4%