Special signatures in CMS

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on behalf of the CMS Exotica group

Outline

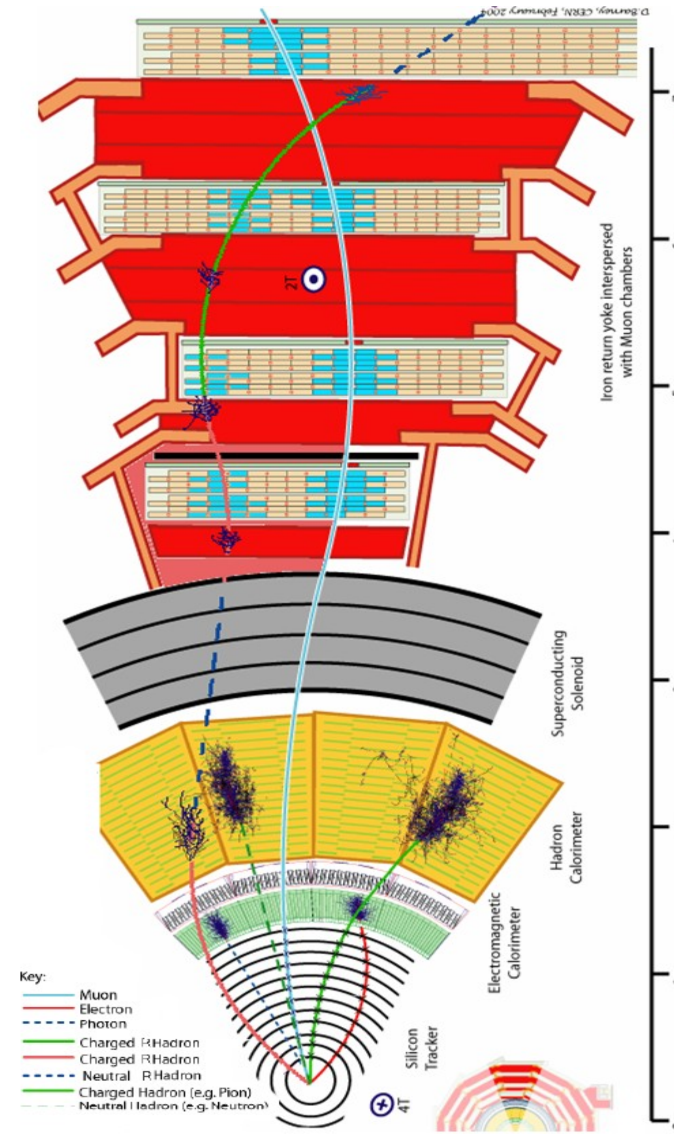
- Heavy Stable Charged Particles (HSCP)
  - Latest reference: CMS PAS EXO-08-003
  - This topic will be over-represented in this talk, because of my own bias :)
- Stopped gluinos (actually, stopped HSCPs)
  - Nothing published yet, I will discuss the strategy and the ongoing work
- Non-pointing photons
  - Reference: CMS AN-2006/095

This talk will be signature-oriented

More meat in Extra Slides, feel free to ask

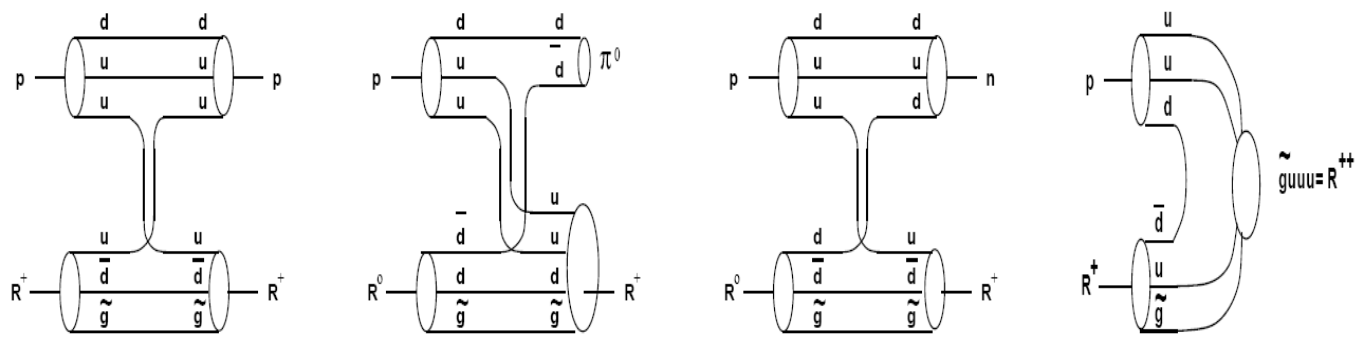
HSCP

- Signatures
- dE/dx in Silicon Strip Tracker
- Time Of Flight in Drift Tubes
- Expectations for standalone and combined dE/dx+TOF analyses
- Work in progress and preparation to first collisions



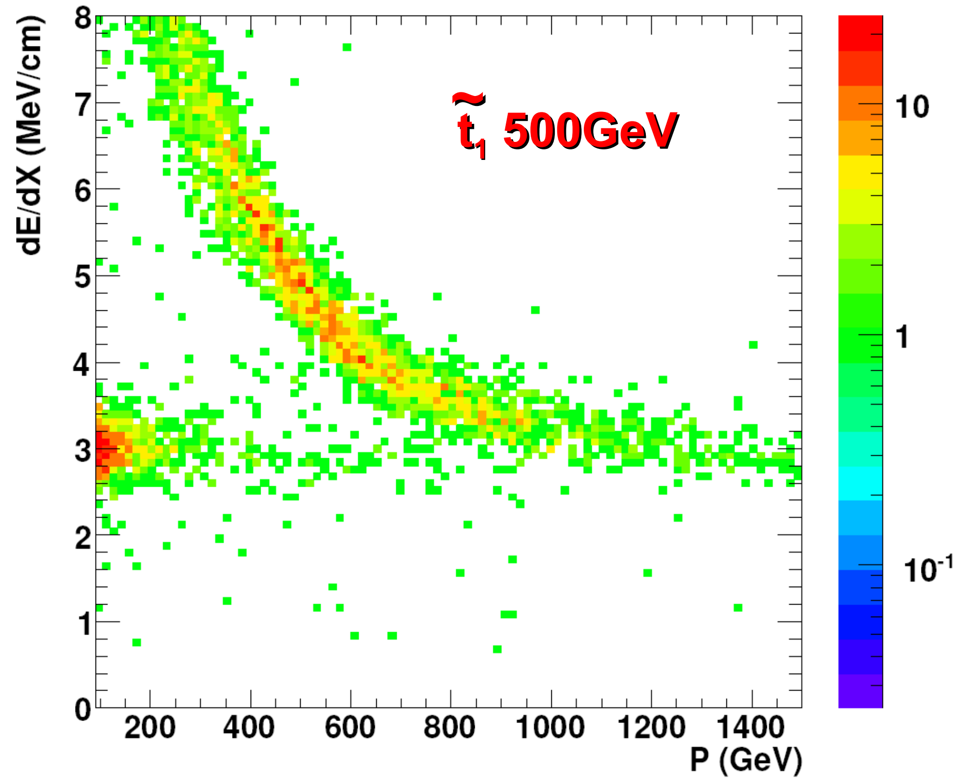
The HSCP hunter's guide

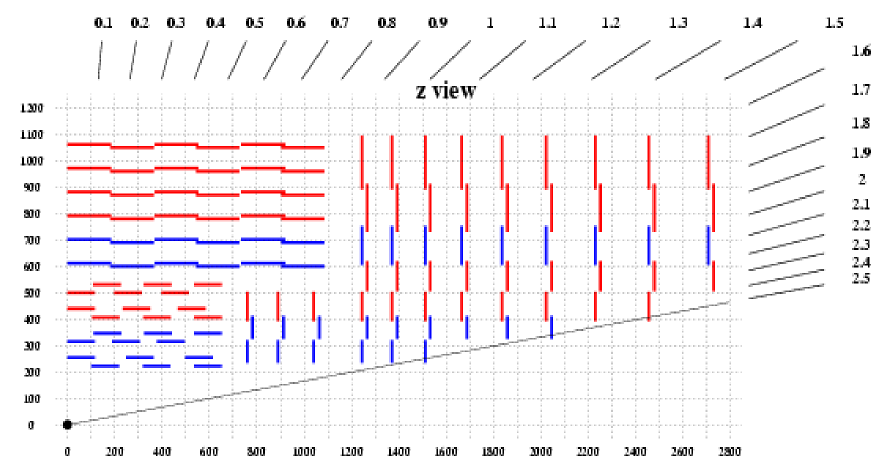
- Model-independent signatures:
  - dE/dx by ionization
  - Time-of-flight
- Model-dependent signatures:
  - R-hadrons: charge may change in Muon Chambers
    - stop: $R^+ \leftrightarrow R^0$, $R^0 \leftrightarrow R^-$; gluino: also $R^+ \leftrightarrow R^-$
  - R-hadrons: large (and “long”) energy deposition in the calorimeters: the light quarks are stripped away, but the gluino/stop doesn't loose a significant fraction of its energy



dE/dx in the Silicon Strip Tracker

- Each silicon sensor traversed gives a dE/dx measurement
  - Overlaps and double-sided modules give 2 measurements
  - 10-20 measurements per track
  - Best estimator of the “real” dE/dx: sqrt of harmonic mean of $(dE_i/dx_i)^2$
- Pixels not considered (non-linear response, calibration is tricky – quite a lot of work to add only 3 points...)
  - But soft-QCD analyses want to use this information for hadron-ID





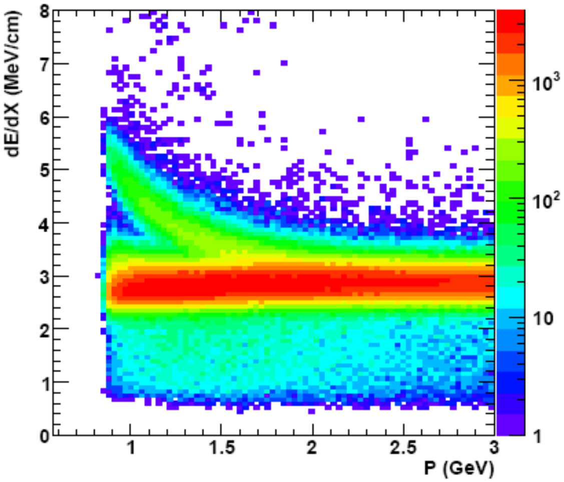
dE/dx calibration

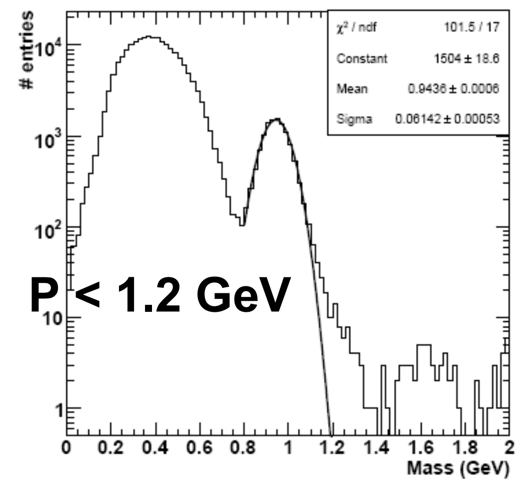
- Intercalibration and absolute calibration from:
  - "Gain scan" (calibration of the opto-electronic chain)
  - Cosmic muons
  - high-P tracks
- Linearity check through a high-purity proton sample
  - Minimum bias, P < 1.2 GeV
  - $\Lambda^0 \rightarrow p\pi$

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

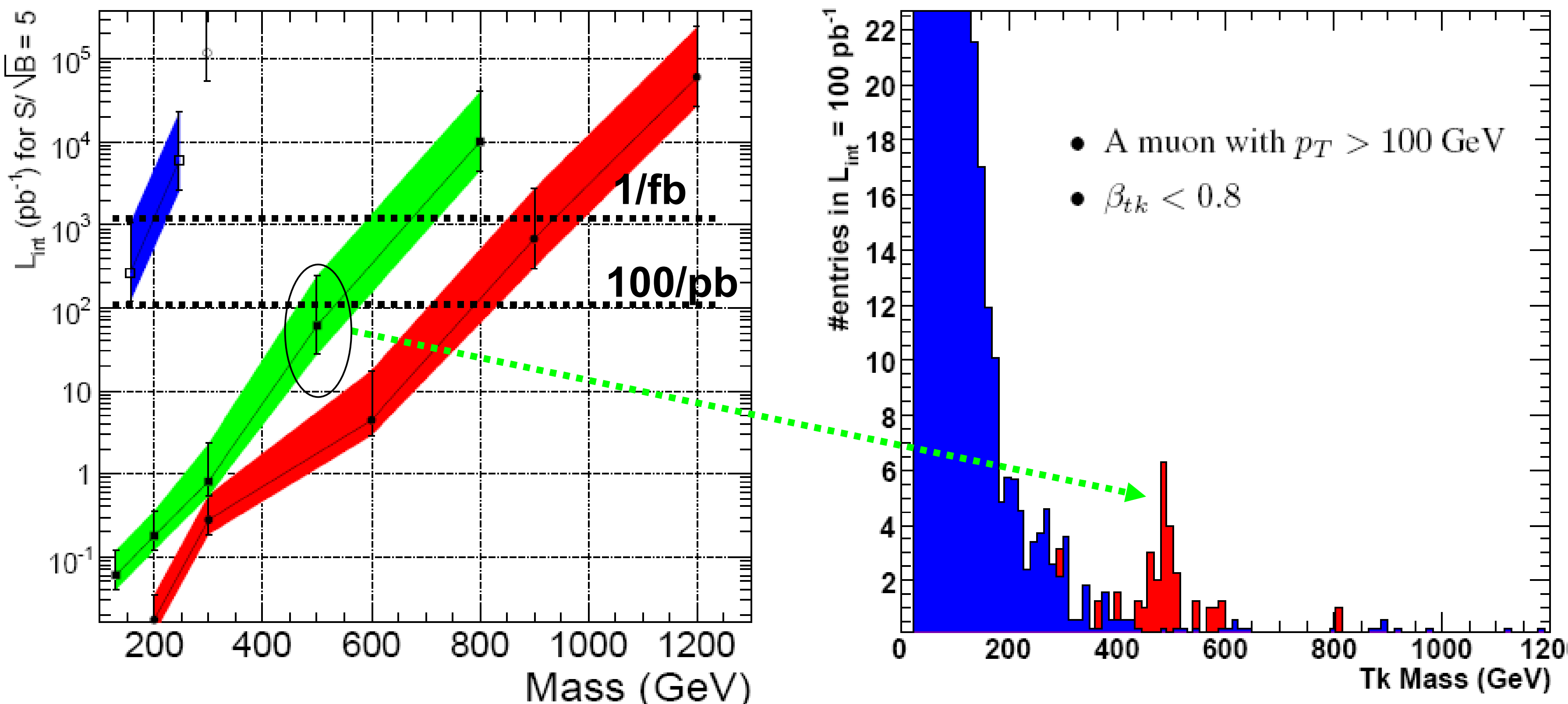
$$\frac{dE}{dX} = \frac{1}{k\beta^2} \qquad m = p\sqrt{k\frac{dE}{dX} - 1}$$

Extract k from a proton sample





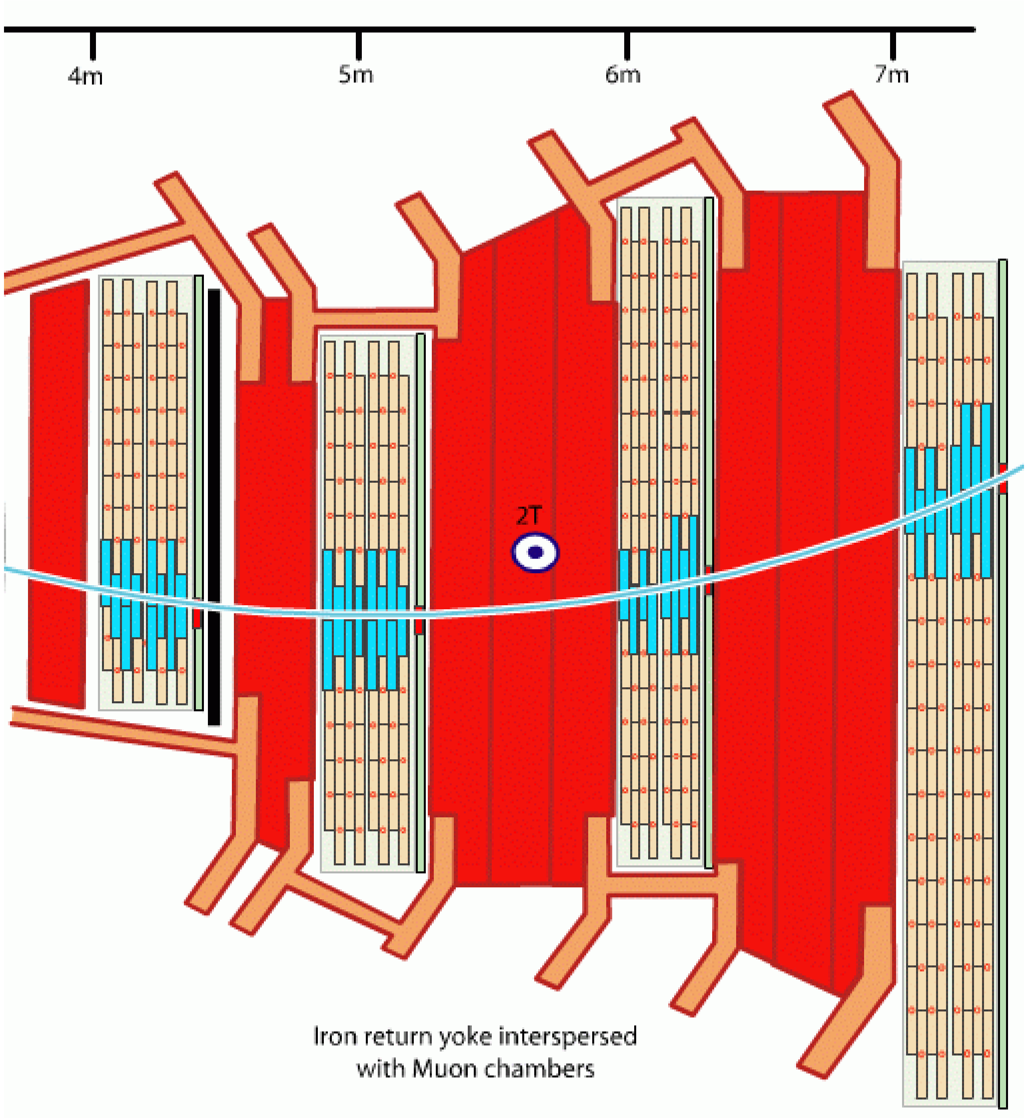
dE/dx expectations

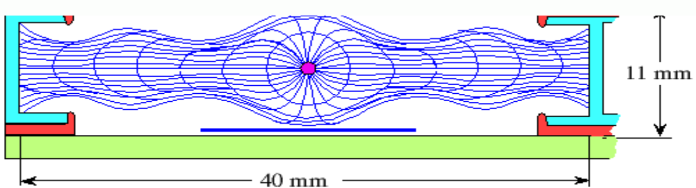


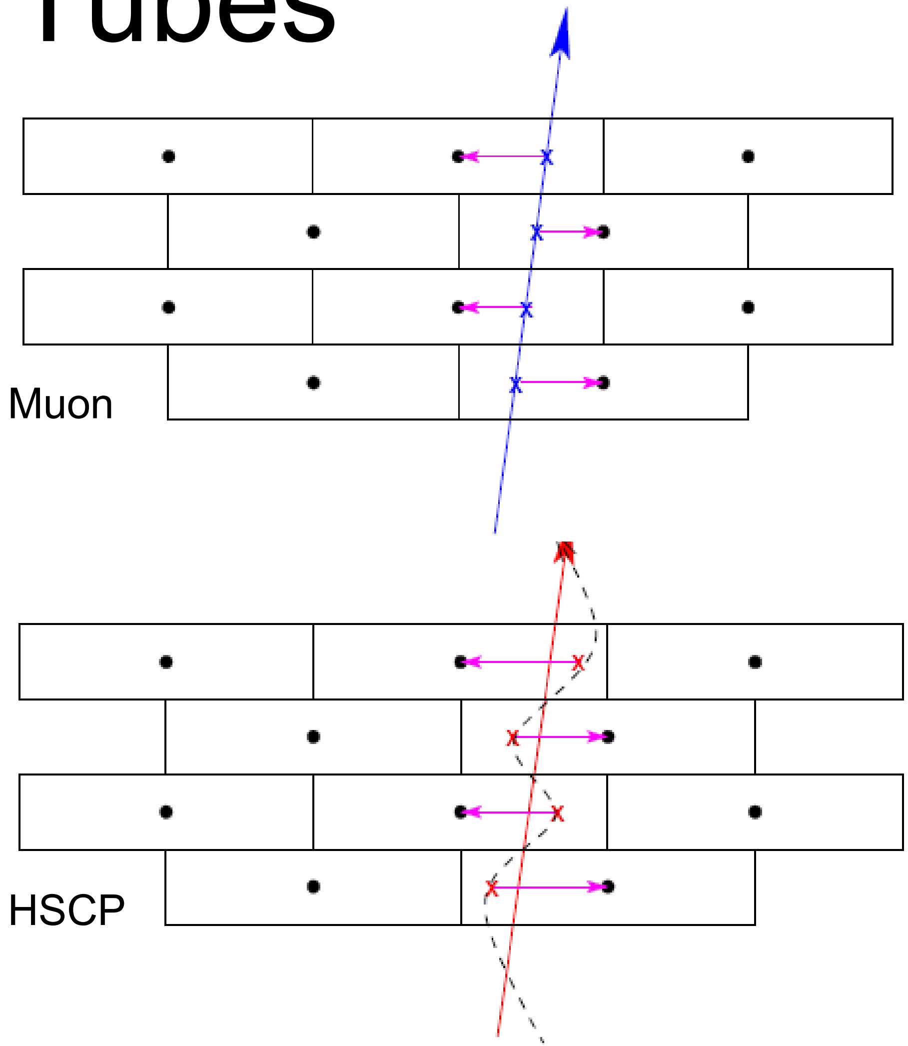
Integrated luminosity needed for 5σ discovery, for four signal models:
gluino full circles, **stop full squares**,
KK tau empty circle, **stau empty squares**

Mass distribution with 100/pb for
500 GeV stop

TOF in Drift Tubes

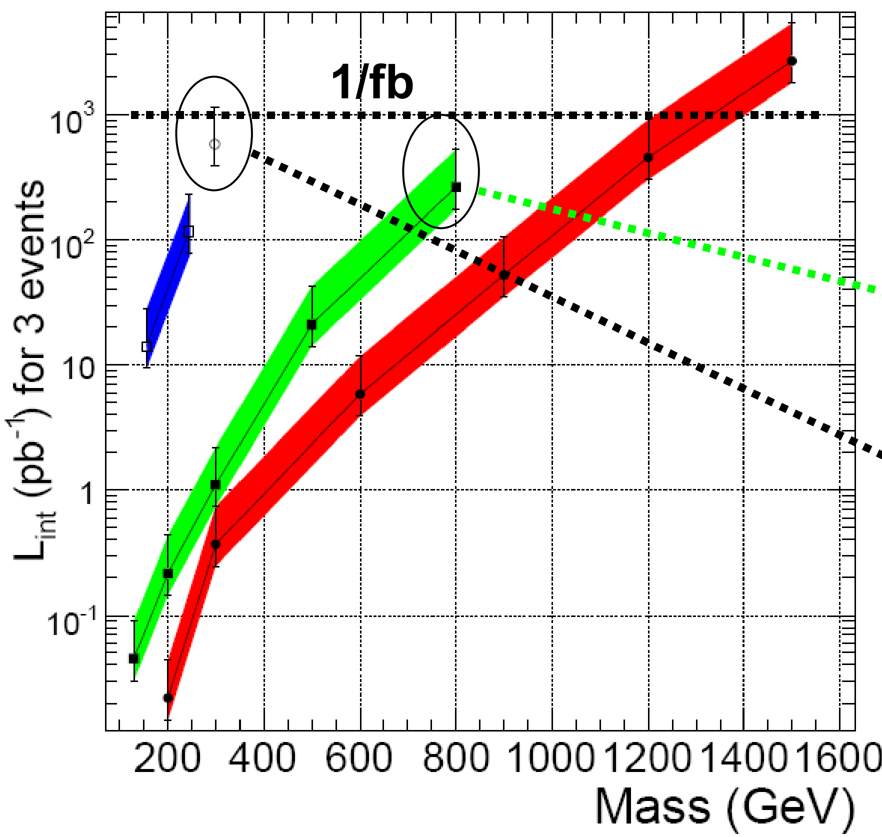




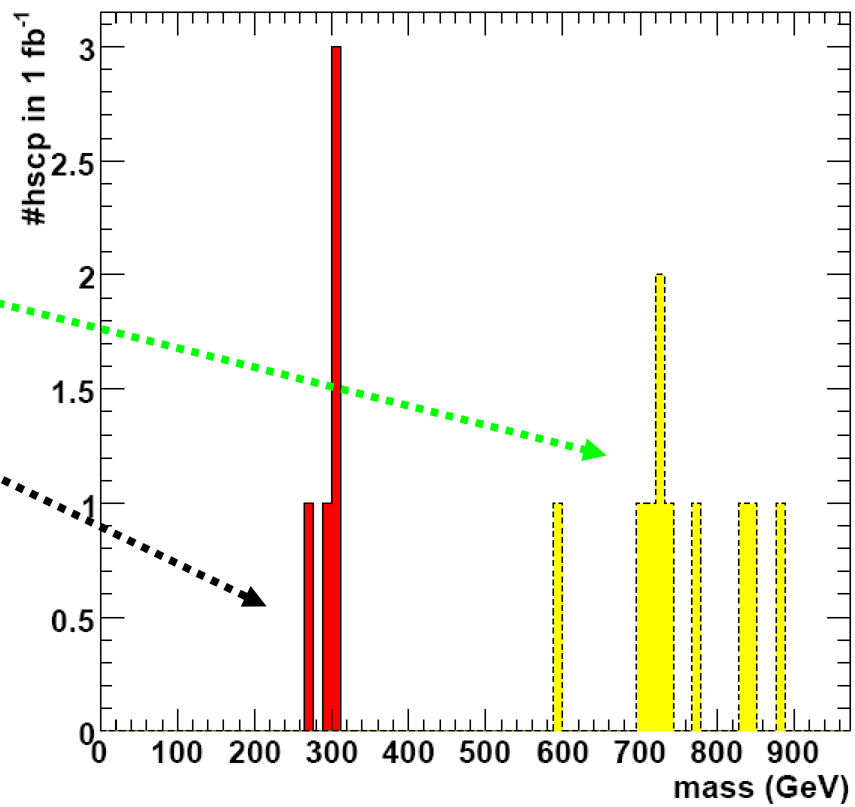


Normally the fit assumes $\beta=1$; here δt is left as a free parameter in the fit
=> TOF measurement
(see extra slides)

TOF expectations



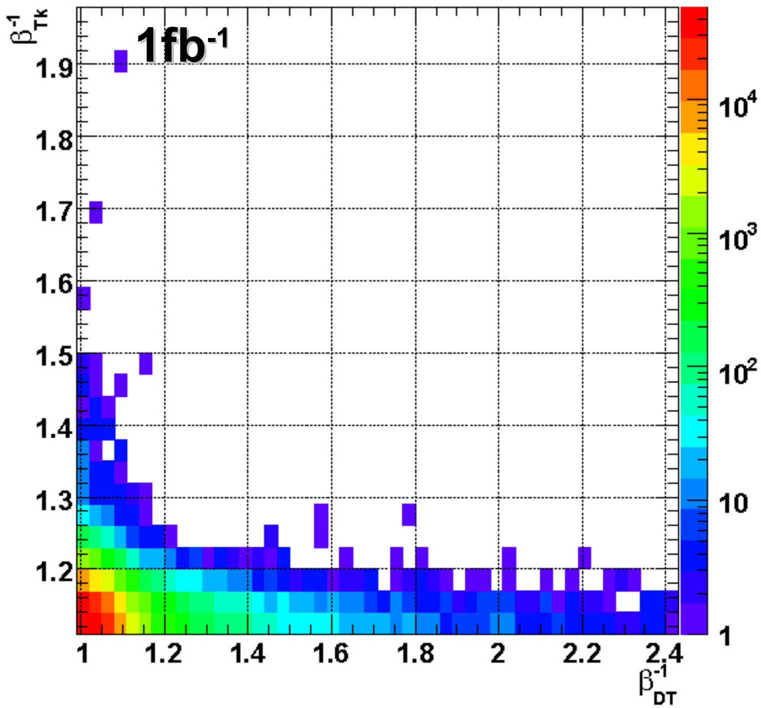
Integrated luminosity needed for more than 3 events for four signal models
gluino full circles, **stop full squares**,
KK tau empty circle, **stau empty squares**



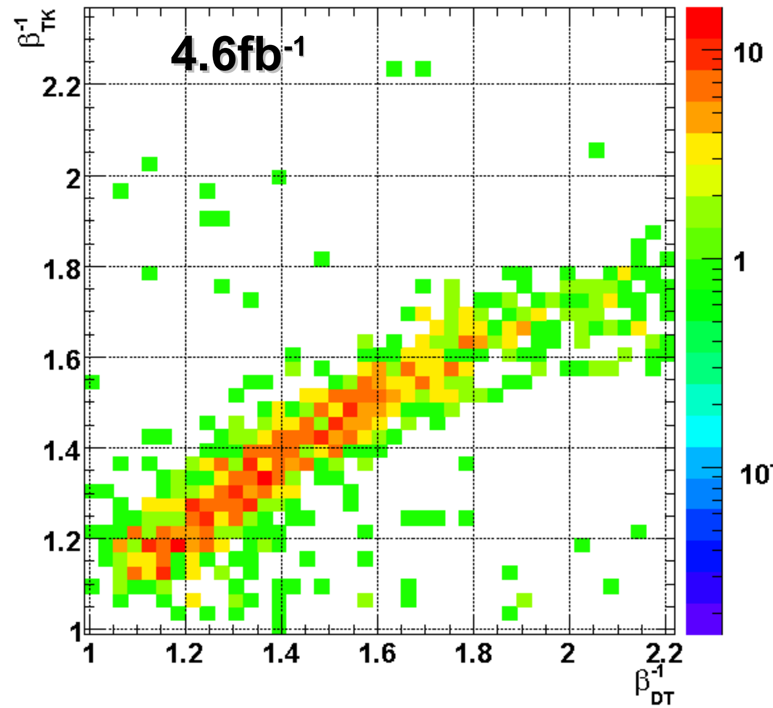
Mass distribution with 1/fb for two of the lowest cross section models
300 GeV KK tau **800 GeV stop**

dE/dx+TOF expectations

β_{DT}^{-1} vs. β_{Tk}^{-1}



SM Muons

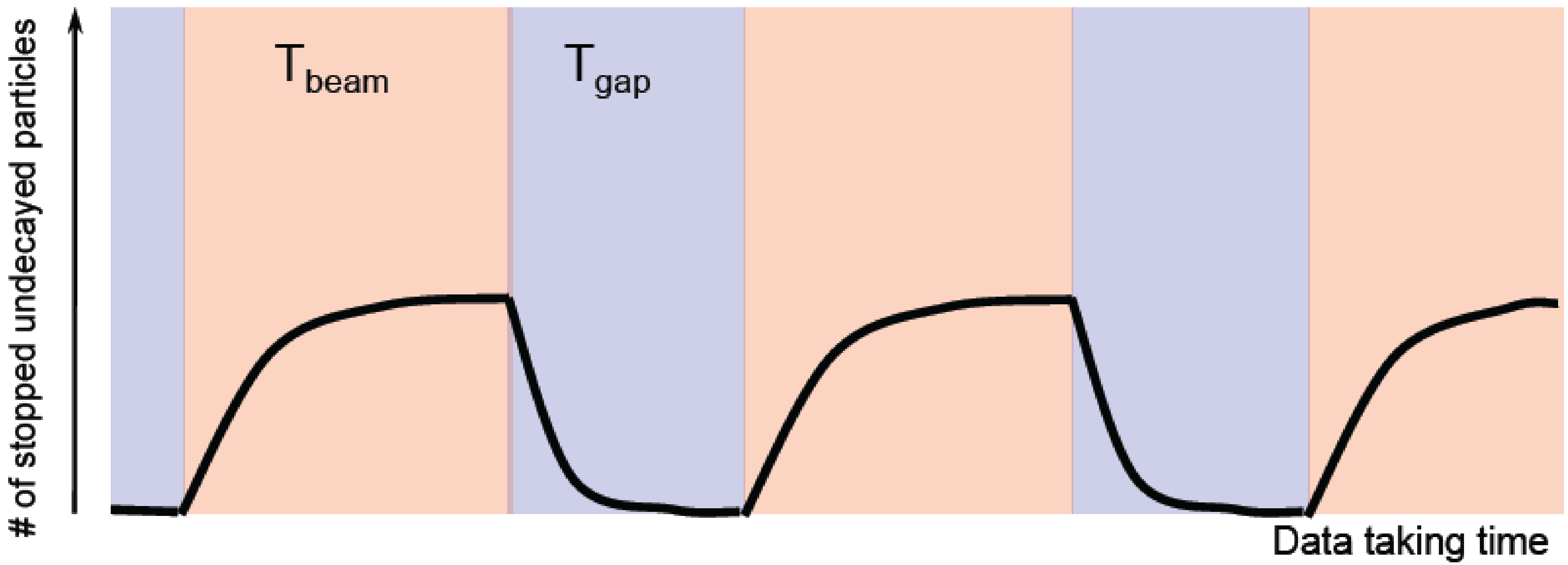


$\tilde{t}_1$ 500GeV

HSCP: work in progress

- Other detectors:
  - dE/dx from ECAL: HSCP(β~0.8)/MIP sep. >4σ
  - TOF from ECAL: resolution ~1 ns
  - TOF from CSC (muon endcaps): resolution ~3 ns
- Analysis:
  - Data-driven estimation of tails from CRAFT cosmics
  - Check of uncorrelation (P vs dE/dx vs TOF) for MIPs with MC and CRAFT cosmics
  - dE/dx: combined discriminators for particle-ID (to be exercised with proton- and kaon-ID with the first collisions, exploiting the new low-p_T tracking)

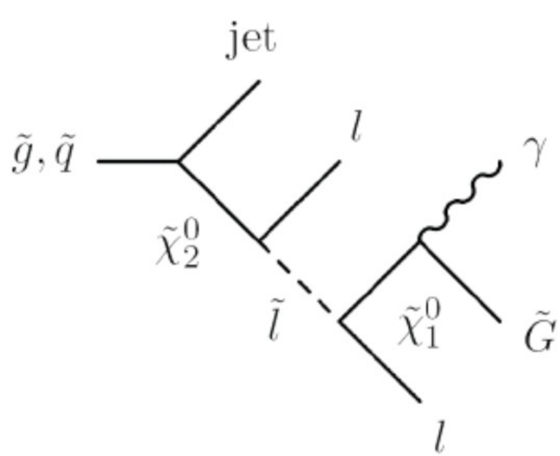
Stopped gluinos

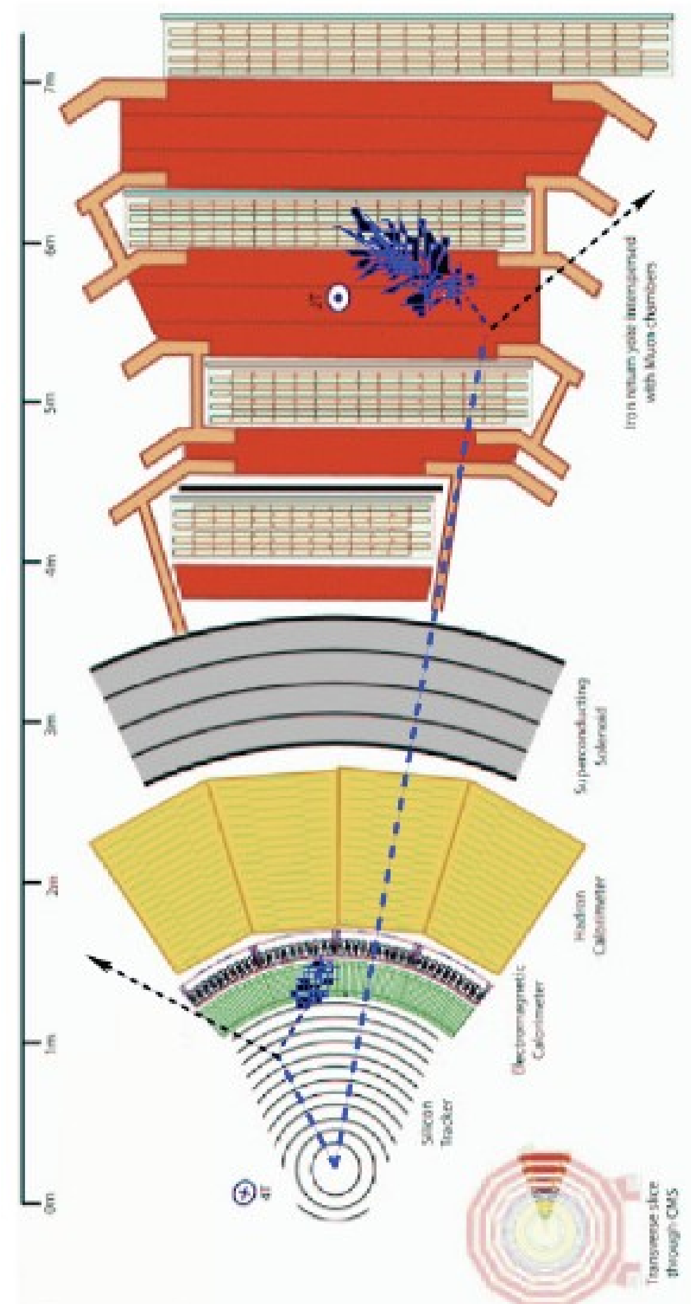


- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise
  - Being already studied with CRAFT data

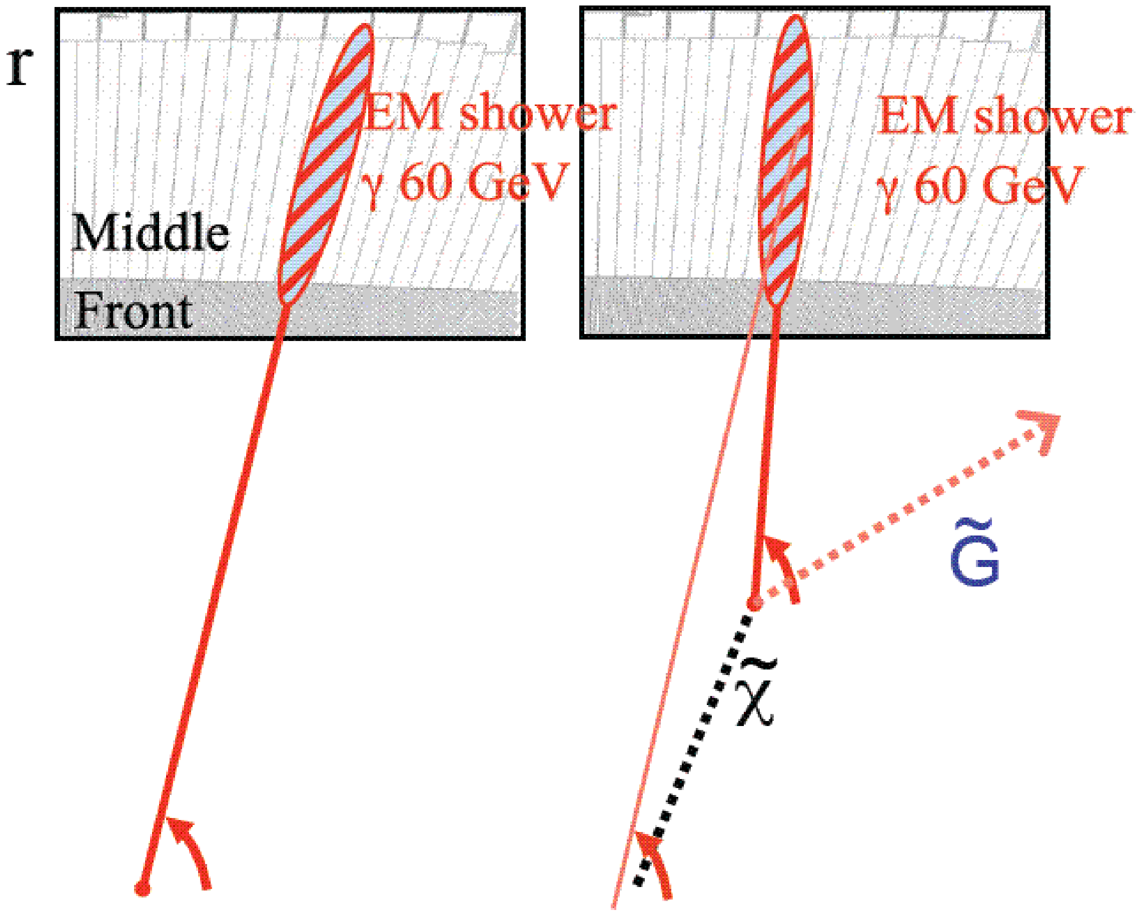
Non-pointing photons

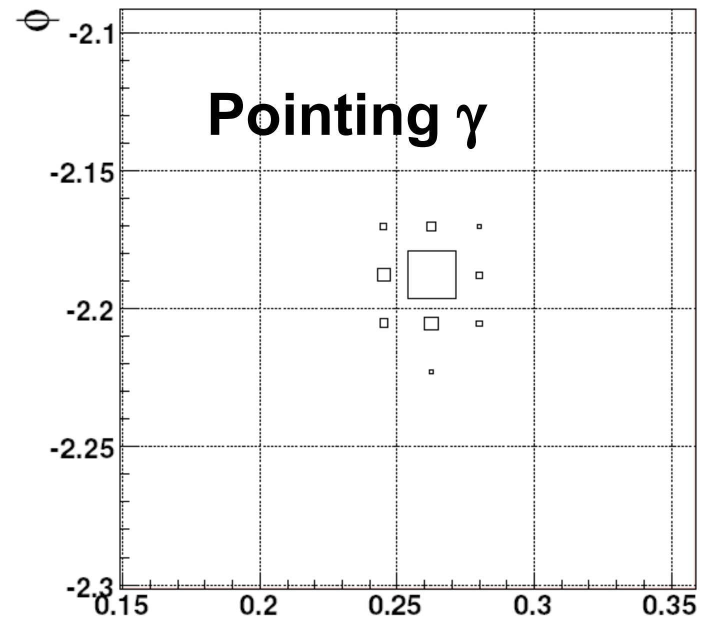
- Possible signature of GMSB
  - LSP is the gravitino
  - Neutralino (or stau) can be the NLSP
    - The decay time can be long
  - Neutralino can decay to Gγ
    - Final state: leptons, jets, MET (from gravitino), hard photons (p. or non-p.)

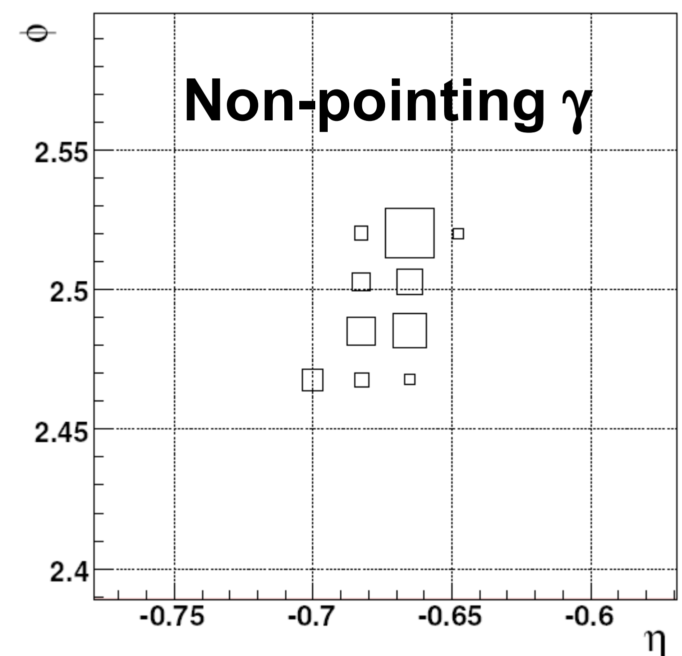




Non-pointing photons: signature

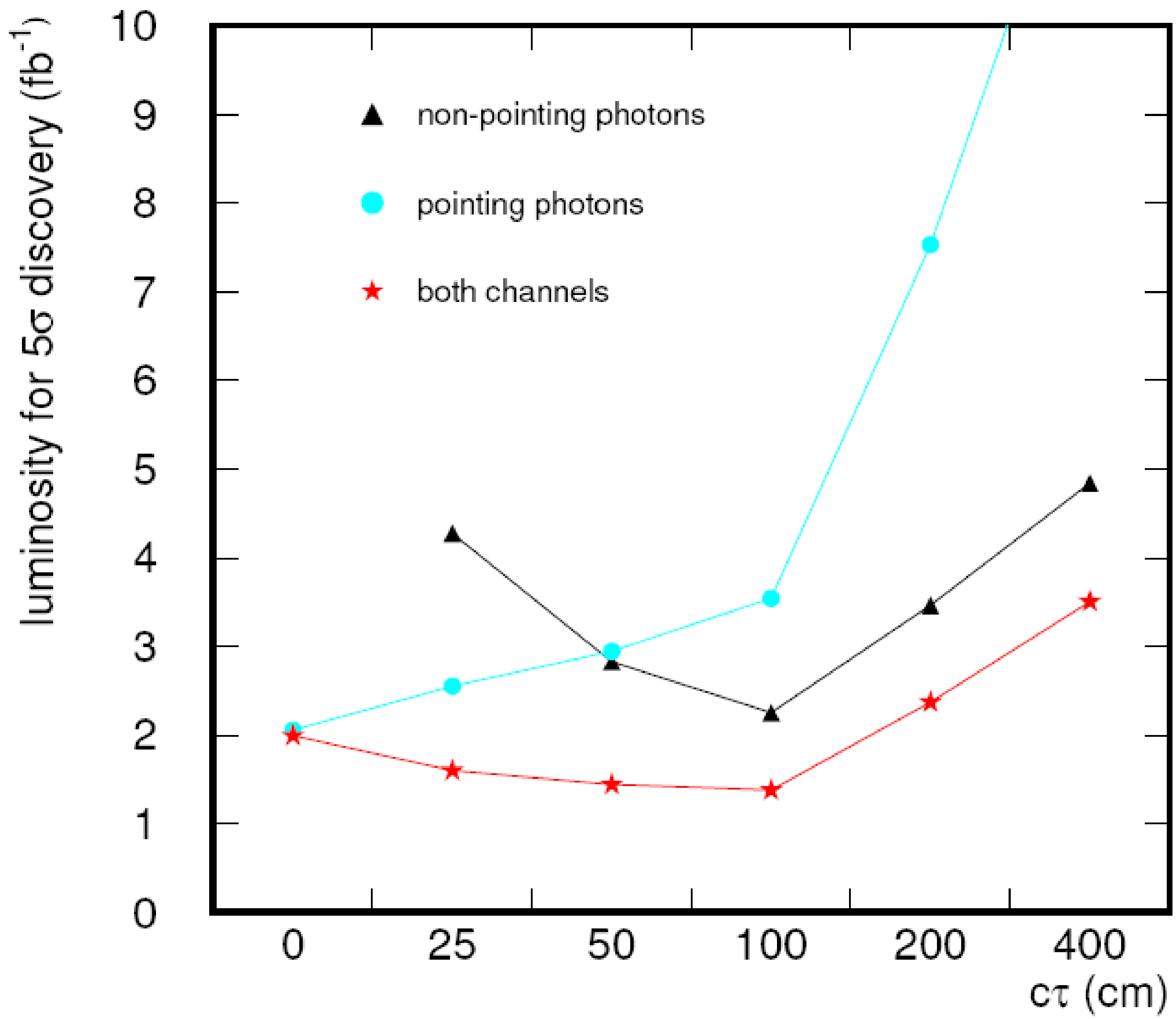






CMS ECAL: no longitudinal segmentation; this analysis is based on the elongation (major / minor axes asymmetry) and the inclination of the ellipse in η/ϕ

GMSB expectations with photons



Non-pointing photons complement the standard search in the parameter space regions where the neutralino is long-lived

Summary

- Non-standard signatures open parameter space regions often inaccessible to standard techniques
- They can require a use of the detector information that was not foreseen when designing the hardware
- Physics backgrounds can be negligible; in this case the analysis is mostly based on controlling the behaviour of the detector
  - In some sense, *the analysis has already started*!
  - The already available cosmics are precious data (and often are the main background, so better know your enemy soon)
  - Often one single sub-detector is sufficient for a standalone analysis => close link between analysis and commissioning

Extra slides

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)

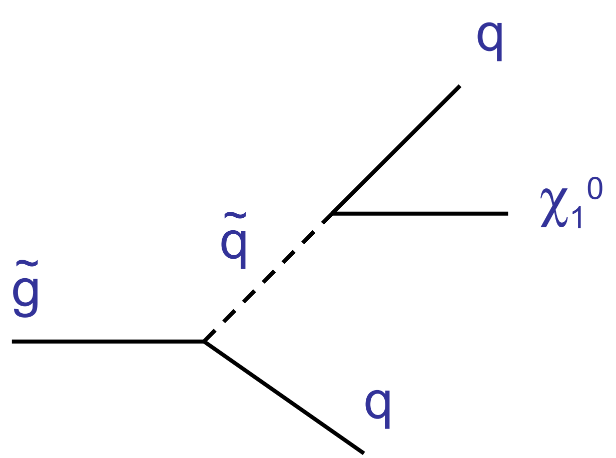
The next slide will explain the Split-SUSY case

- 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

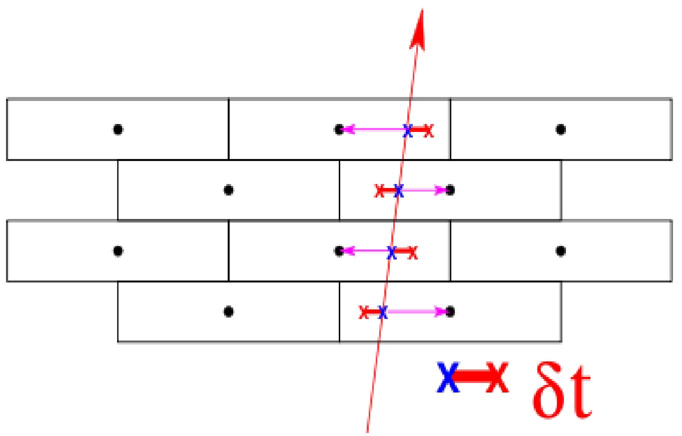
- Gauginos at TeV scale, sfermions higher (e.g., at GUT scale)
- The gluino is colored, so it has to decay to colored particles
- (If R-parity holds) it has to couple to a super-particle and a particle
- The only other colored super-particles are the squarks, but they are much heavier!
- So, it decays 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 $R^{+/-} \rightarrow R^0 \rightarrow R^{+/-}$

HSCP: TOF from Drift Tubes



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

and hence

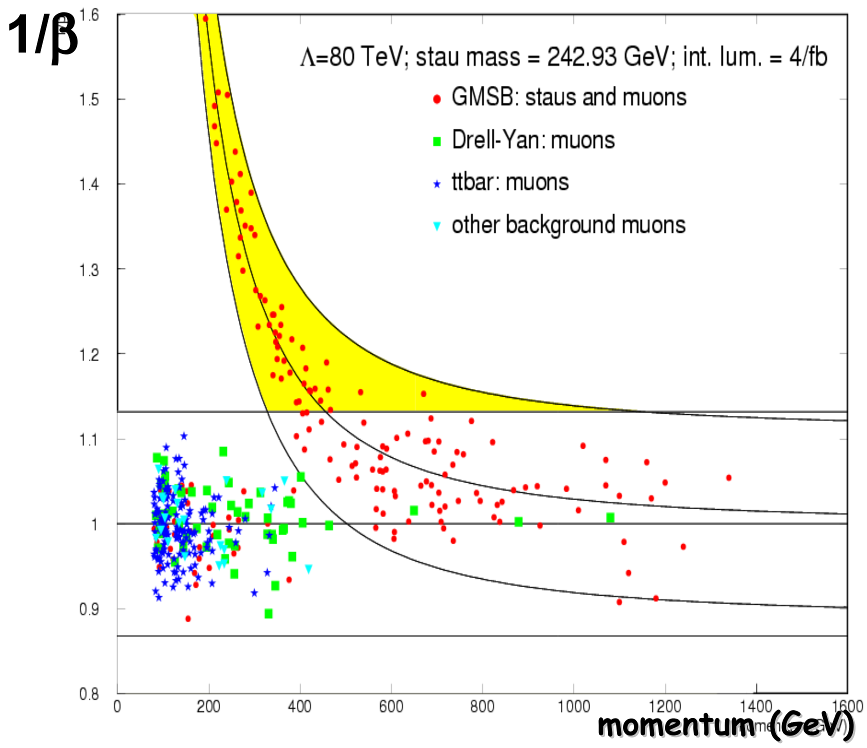
$$\frac{1}{\beta} = 1 + \frac{\delta_x}{L}\frac{c}{v_{\text{drift}}}$$

and finally

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

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

TOF, physics backgrounds



- SM background negligible
- Cosmics are the main potential issue
- Partial compensation for the long delay: data-driven determinations have already started!

HSCP: triggering (1)

- Timing issue:
  - L1/HLT 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 when R-hadron interacts nuclearly, it is usually 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

HSCP: triggering (2)

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%

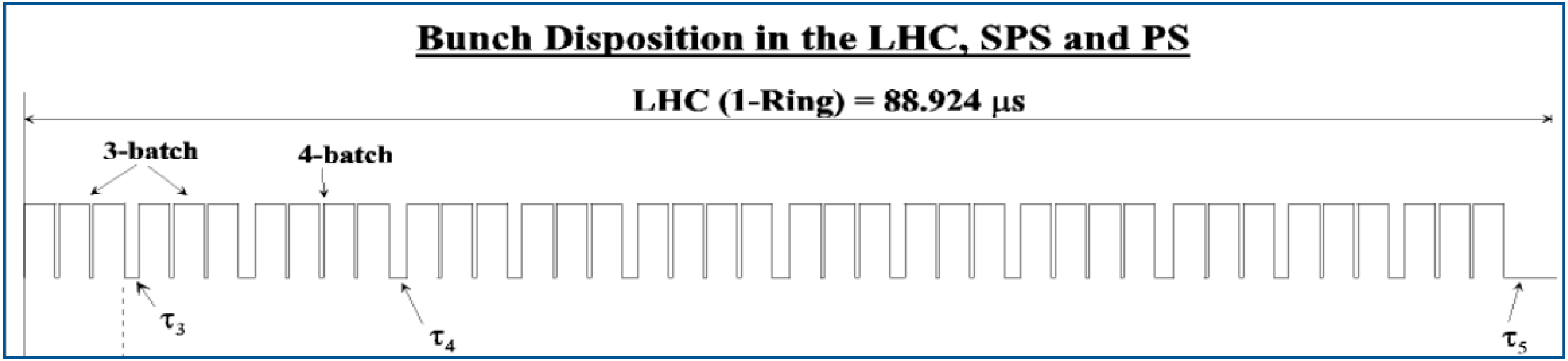
UED KK $\tilde{\tau}_1$ ~ 80%

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

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

Stopped gluinos, triggering

- Two trigger scenarios:
  - Run the (jet) && !(beam) trigger after a fill has been dumped ("interfill period")
  - Also trigger 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!)



dE/dx: different estimators checked
(CMS NOTE 2008/005)

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

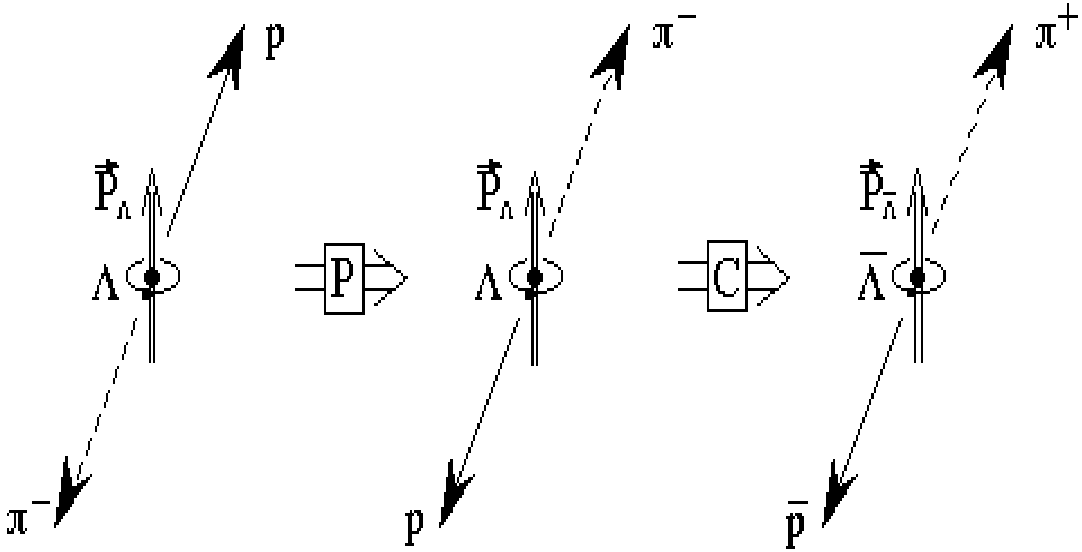
Estimator	muon σ (%)	K/π separation	p/π separation
Median	14.5	0.61	2.45
Truncated mean (20 %)	6.82	1.28	4.76
Truncated mean (40 %)	6.27	1.50	5.29
Harmonic mean	7.45	1.11	4.26
Generalized mean ($k = 1/2$)	7.97	1.03	3.97
Generalized mean ($k = 1/3$)	8.12	0.98	3.97
Generalized mean ($k = 2$)	6.58	1.29	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

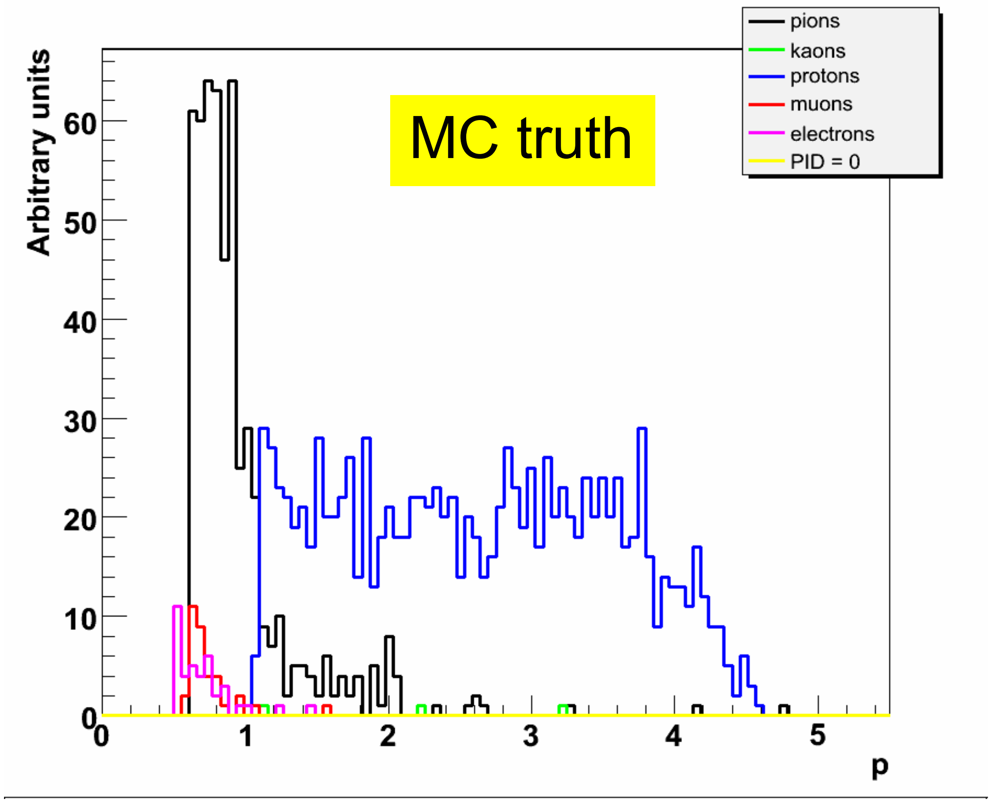
The Landau unbinned fit (performed with MINUIT in ROOT) is not strikingly better (and it is actually worse than some), and it is much slower.

dE/dx calibration with V^0s

- Goal: reproducing the Bethe-Bloch curve (in the dE/dx vs P plane) for known particles
- K_s^0 decays: very pure π sample
  - 68% into $\pi^+\pi^-$, the rest mostly into $\pi^0\pi^0$
- Λ decays: pure proton sample
  - 64% into $p\pi$, the rest mostly into $n\pi^0$
  - The highest-momentum particle in the pair is always the proton (textbook example of V-A interaction...)

Lambda decays





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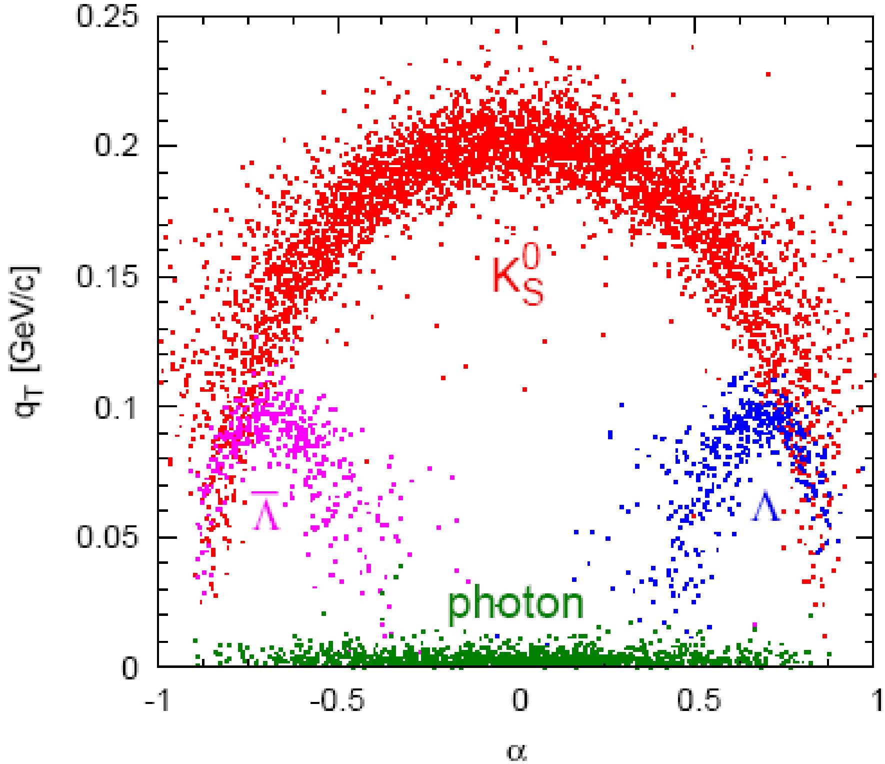
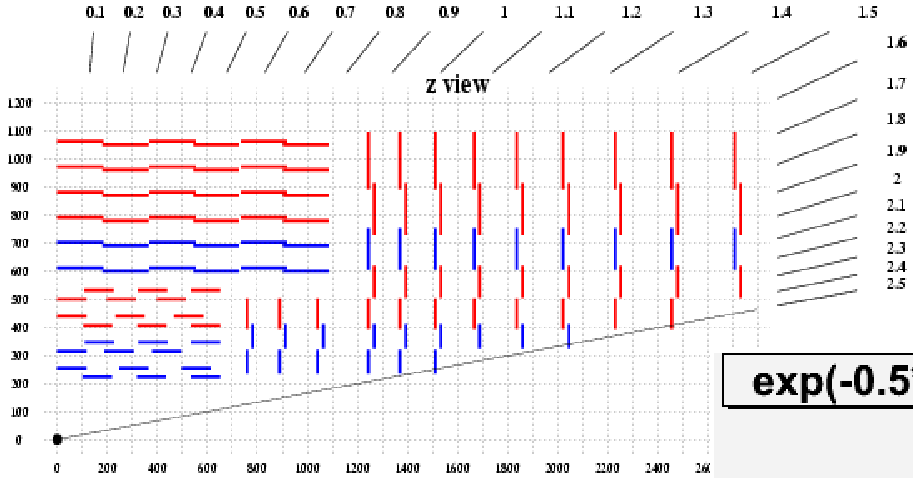
Armenteros variables

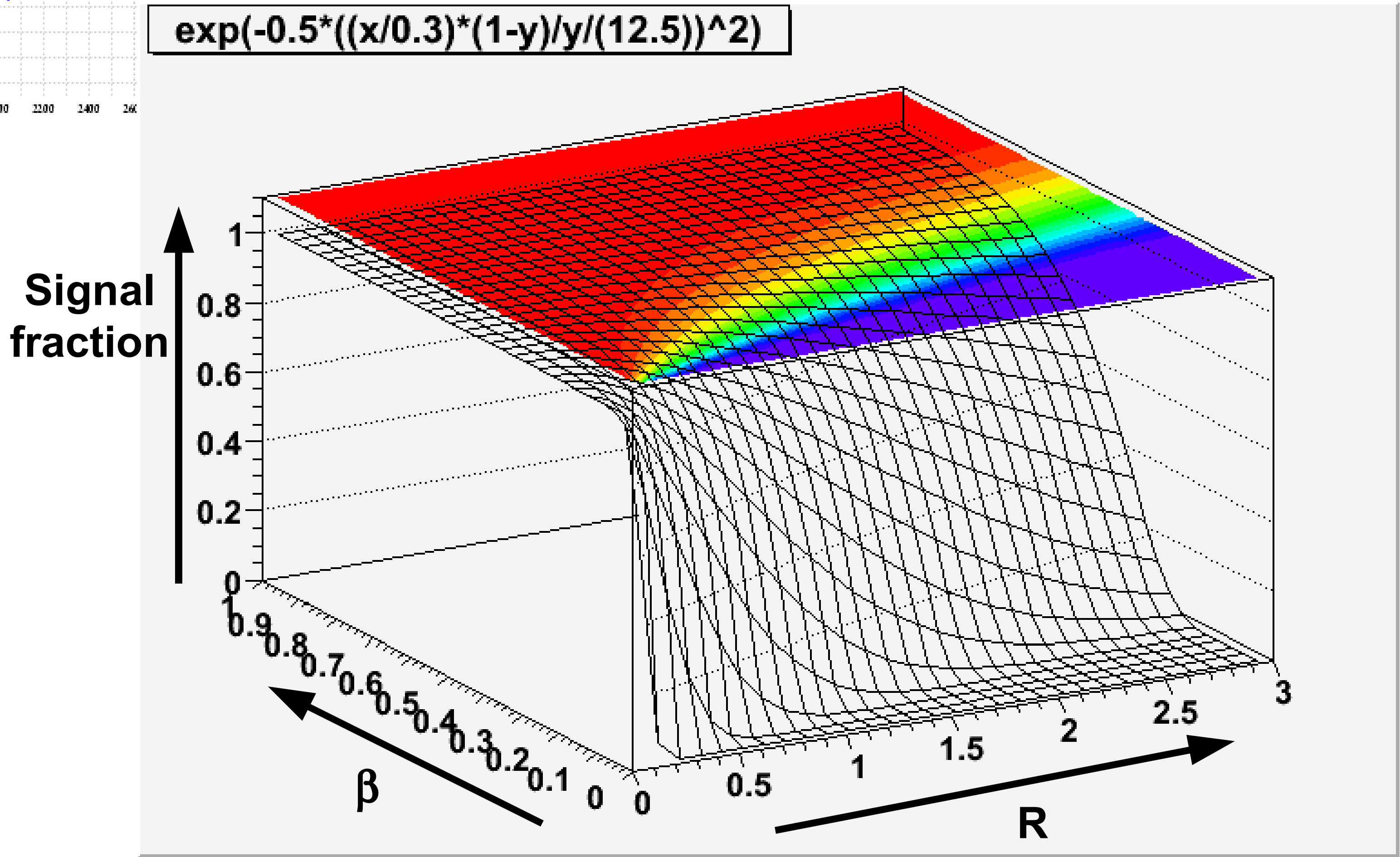


Plot at simulation level taken from CMS AN-2006/101 (pixels only)

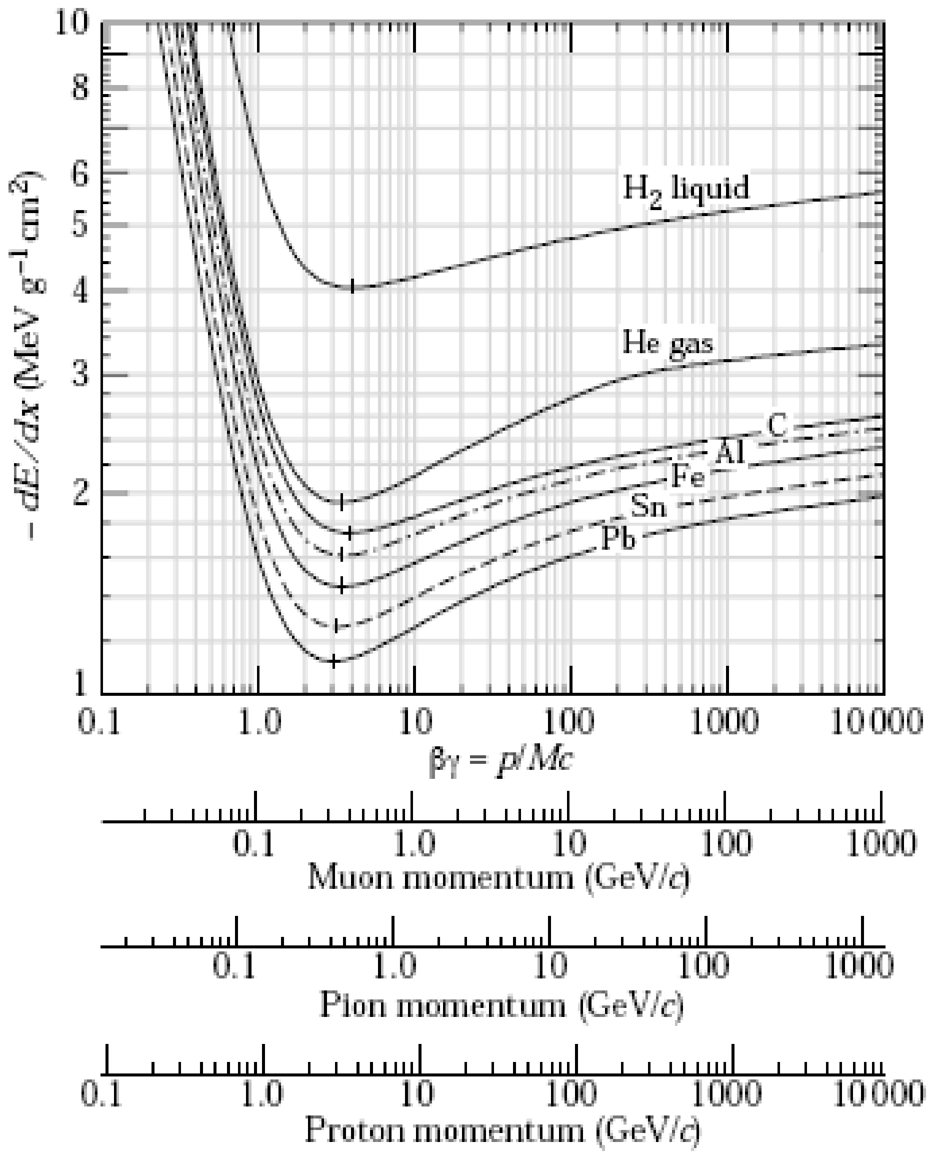
$q_T = p_1 p_2 \sin\theta / p$, $\alpha = (p_1^{\ 2} - p_2^{\ 2}) / p^2$
$p_{1,2}$: daughters, p: mother

Attenuation for slow particles





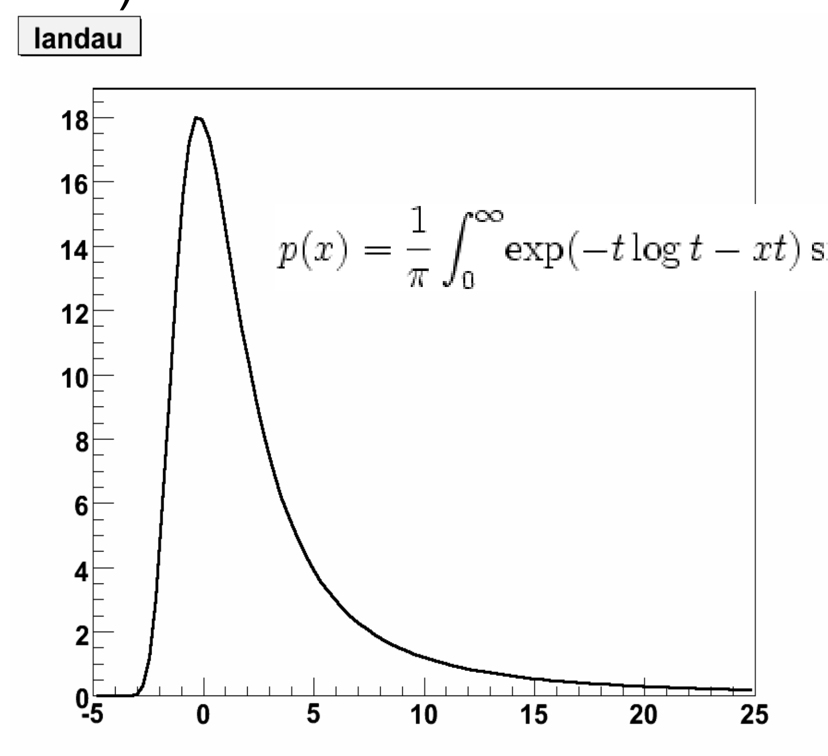
dE/dx basics



Bethe-Bloch formula:

$$\frac{dE_q}{dX} = 4\pi NZ \frac{z^2 e^4}{mv^2}\left[\ln\left(\frac{2\gamma^2 mv^2}{\hbar\omega}\right) - \frac{v^2}{c^2}\right].$$

Energy deposition in a thin layer (but not too thin) follows a Landau distribution:



$$p(x) = \frac{1}{\pi}\int_0^\infty \exp(-t\log t - xt)\sin(\pi t)\,dt.$$