Search of exotic charged particles with the CMS Silicon Strip Tracker

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- Heavy (quasi-)stable charged particles safari
- The hunter's guide to exotic charged particles
- dE/dx in CMS
  - How-to
  - Reality check: the CMS cosmic data
  - How to calibrate dE/dx

LLN, 19 mar. 2007

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)

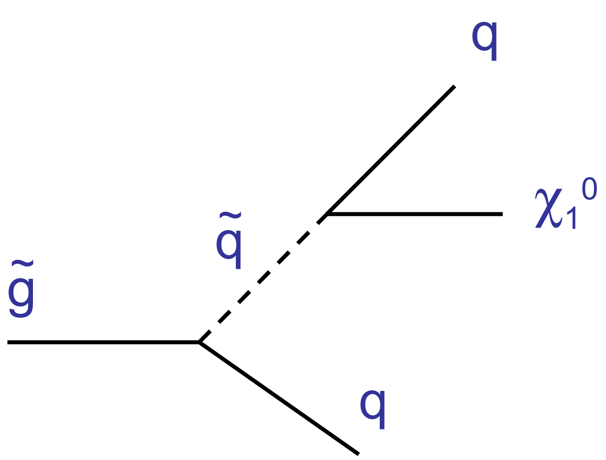
The next slide will explain the Split-SUSY case

- considered very promising by many theorists
- 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:

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

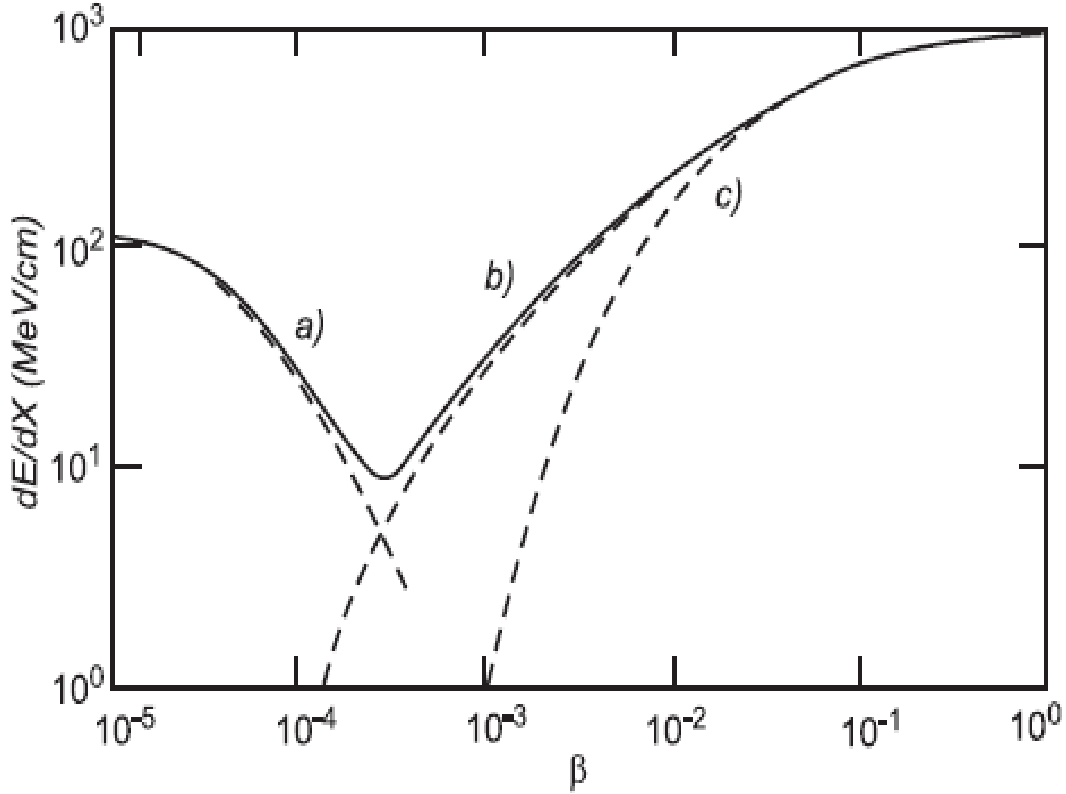


- Long lifetime: from O(ps) to O(age of the Universe)
- Slow: Time-of-Flight technique (in CMS: use Muon Chambers)
- Colored: it hadronizes ($\tilde{g}g$, $\tilde{g}q\bar{q}$), and its "hadrons" have nuclear interactions! By exchanging quarks, they can give $R^{+/-} \rightarrow R^0 \rightarrow R^{+/-}$

Magnetic monopoles

- First proposed by Dirac (1931): $q_e \leftrightarrow q_m$ dualism would explain electric charge quantization ($q_e q_m$ has to be integer, in proper units)
- Most GUTs predict the existence of massive m.m.
- Limits on m.m. are among the most stringent constraints on GUTs
- In fact, GUTs tend to predict too many "primordial" m.m.'s: since they are stable, they should still be around in the wild, easy to catch!
  - A typical superconducting loop detector should see a m.m./year
  - Instead, so far only one serious candidate event has been seen in the world (February 14, 1982)
  - Very tight limits from cosmology and astrophysics
- The m.m. hunt was popular in '70s and '80s. Not anymore, after the failure of all the searches of cosmic m.m. (e.g., MACRO exp.)
- Anyway, their search is for free with heavy charged particle searches

Magnetic monopoles: dE/dx

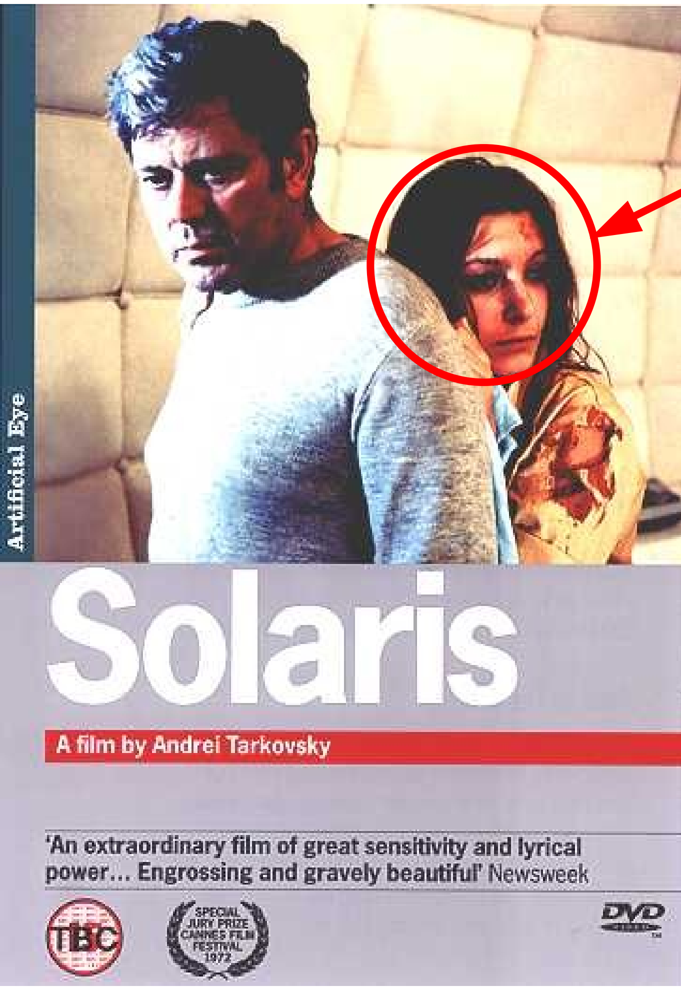


A magnetic charge q_m with velocity βc behaves like an electric charge $q_e=q_m\beta$: $\alpha=e^2/4\pi=1/137$, $\alpha_m=g^2/4\pi=34$, so this number is very high, and dE/dx is huge.

Rule of thumb: dE/dx(m.m.)~$(137/2)^2$dE/dx(MIP)

Maybe all this sounds to you like science-fiction...

...well, I like science-fiction



- In this story, Solaris is an intelligent planet
- It creates “visitors” that interact with the scientists in an orbiting station around it
- The scientists find out that these “visitors” are not made of ordinary matter
- What are they made of?
  - Andrei Tarkovsky (movie, 1971) wisely ignores the problem
  - Stanislav Lem (novel, 1961) proposes neutrinos, bound together by magnetic forces... but this is badly wrong!!!
  - Steven Soderbergh (movie remake, 2002) proposes charged Higgses... NO! they would decay too quickly!
  - I suggest R-hadrons (electric and strong charge: they can form R-nuclei and R-atoms)

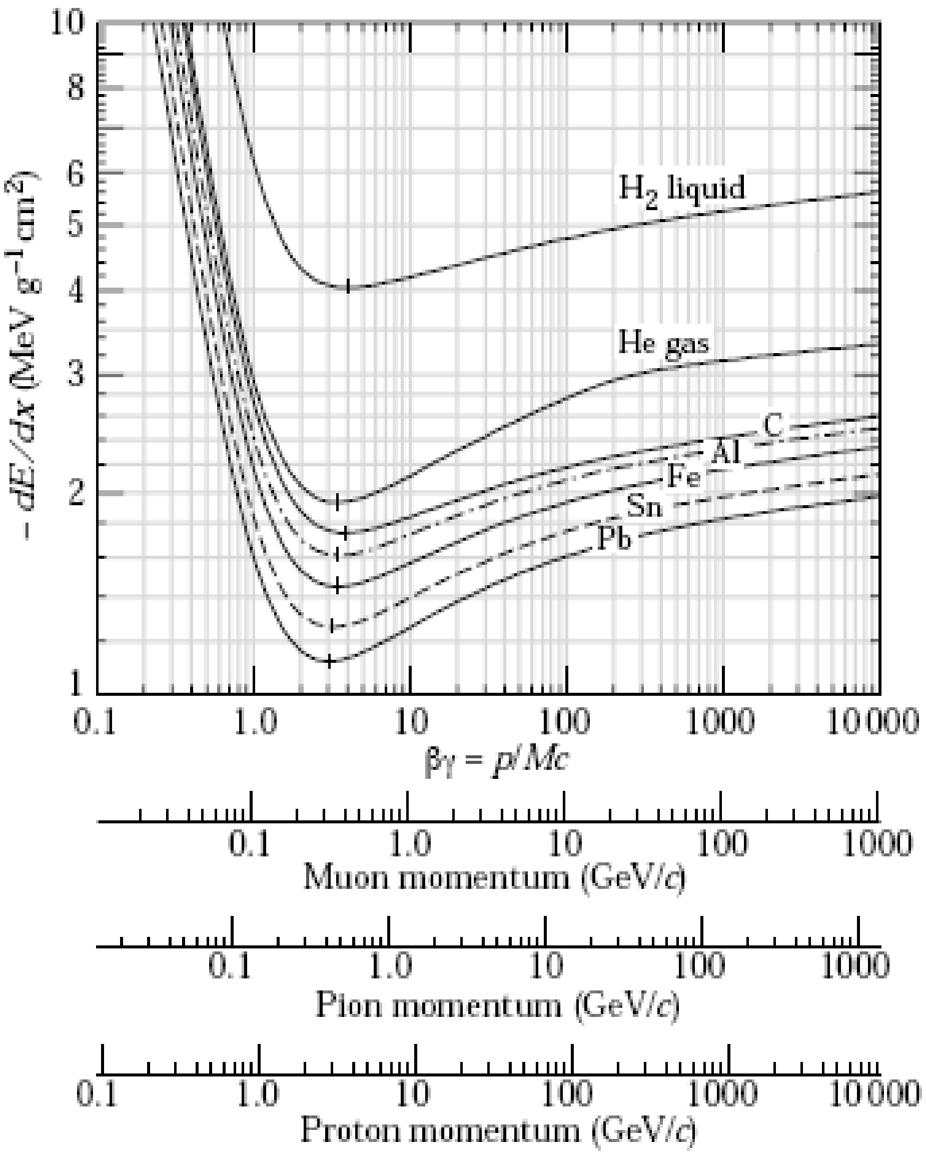
The hunter's guide

- Model-independent signatures:
  - Time-of-flight (ATLAS > CMS: larger radius)
  - dE/dx by ionization (CMS > ATLAS: more silicon)
- 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 exotic colored constituent doesn't loose a significant fraction of its energy
  - Monopoles: in the CMS solenoid the track is a parabola, not a helix ($E \leftrightarrow B$)

dE/dx

- In the next slides, I will show how the dE/dx measurement is performed and optimized
- Proton identification is used as a benchmark
  - By the way, it is important on its own:
    - It is expected to improve the Particle Flow algorithm
    - The fraction of protons in minimum bias products and inside jets depends critically on the fragmentation (non-perturbative) models, and it is a way to constrain them
- If time remains:
  - check on real data (cosmics)
  - calibration
  - systematics

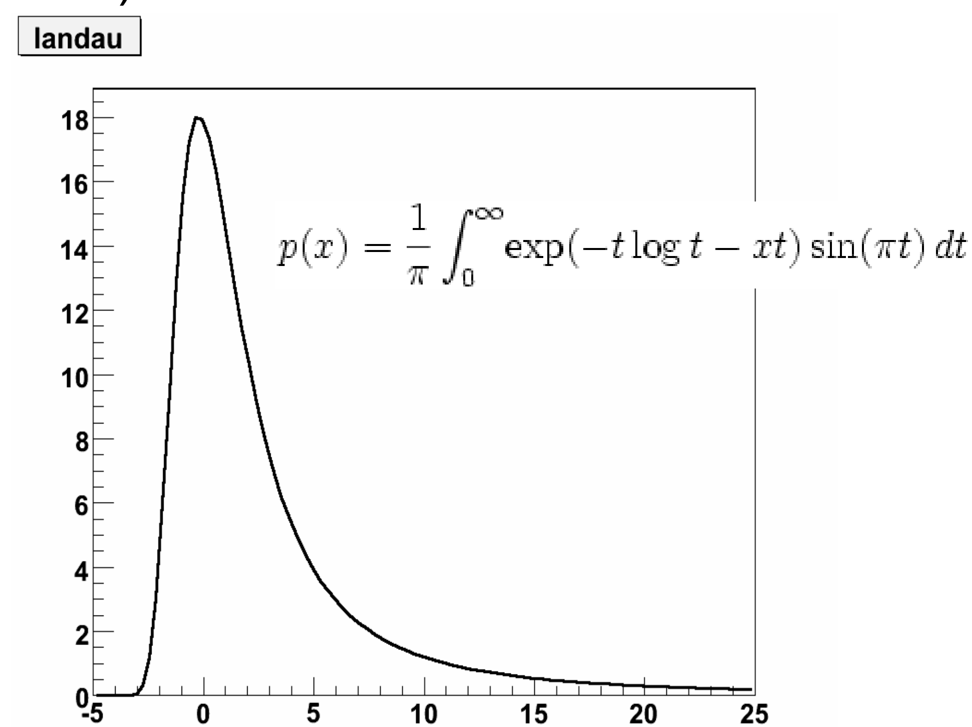
dE/dx basics



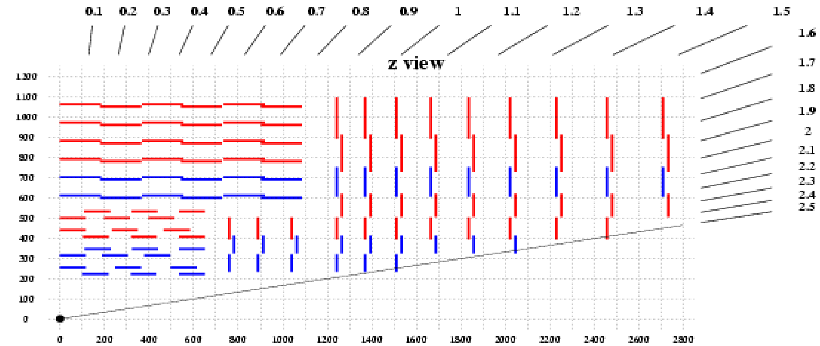
Bethe-Bloch formula:

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

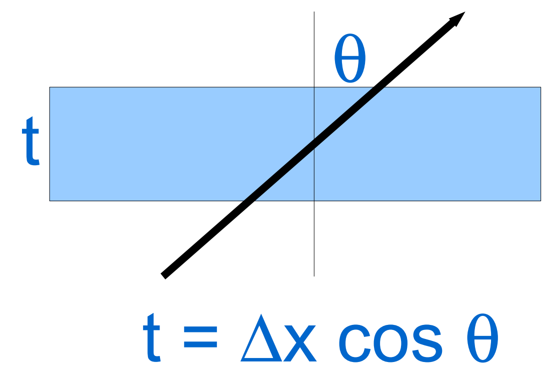
Energy deposition in a thin layer (but not too thin) follows a Landau distribution:



dE/dx in CMS

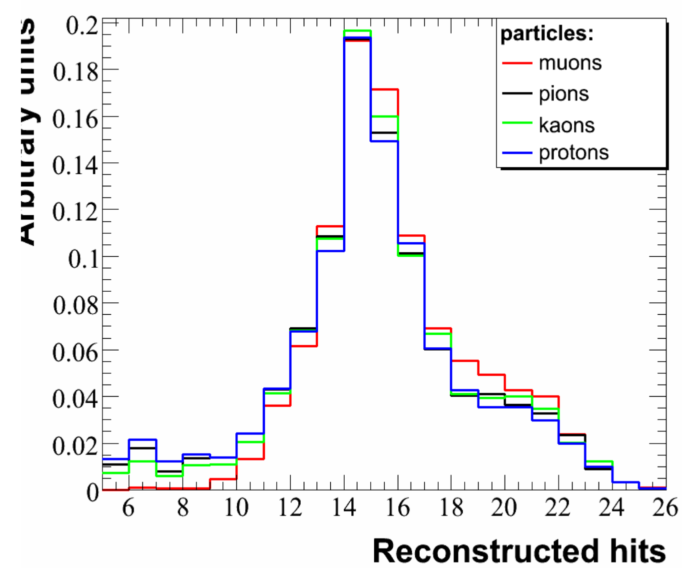


- Each crossing of a track with a silicon module gives a dE/dx measurement
  - Extra hits from double-sided modules and overlaps are taken into account



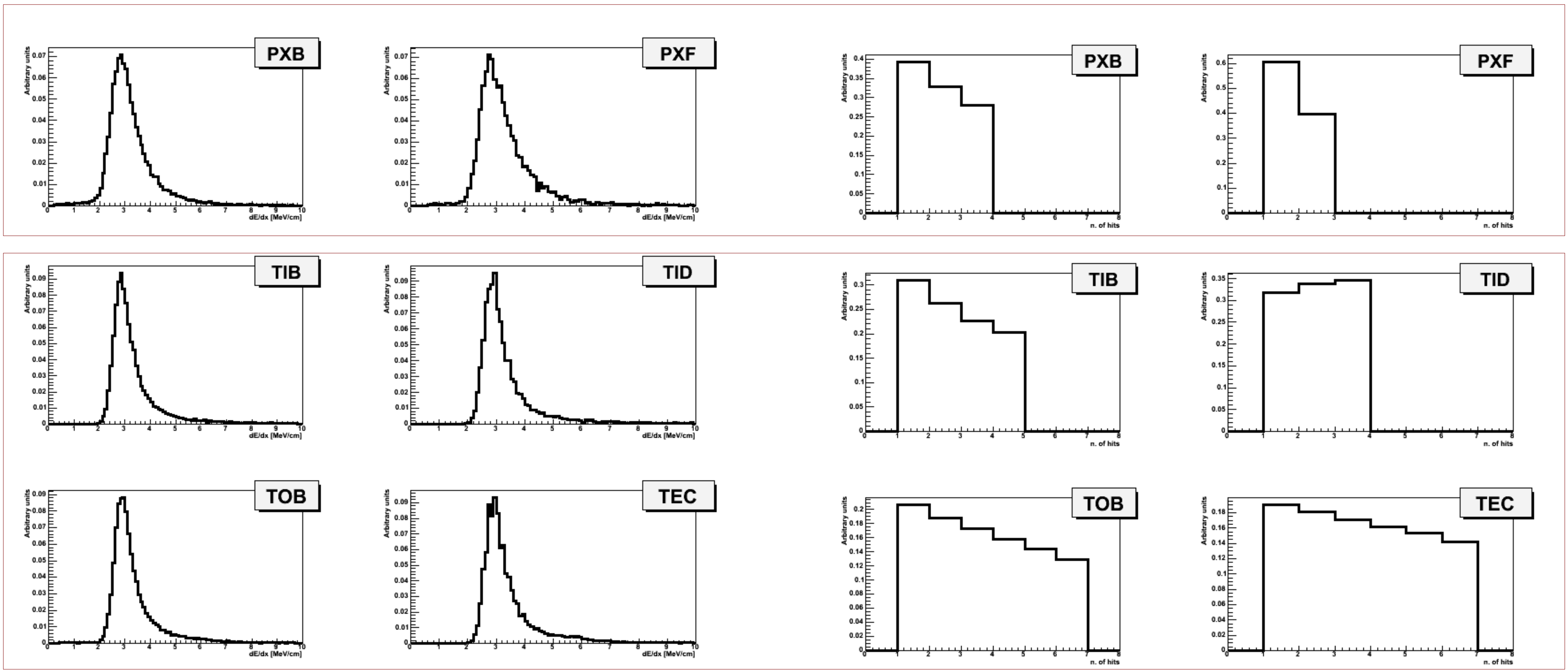
- For each measurement, dE/dx=(Q/t)cos θ
  - Q: energy deposit, t: module thickness, θ: angle between track and the normal to the module

n. of hits:



- The most probable dE/dx of the track is estimated
  - Challenge: have a sensible estimator with so few measurements per track
  - In this talk some simple estimators are compared

Single hit measurements
(muons, $3<p_T<5$ GeV)



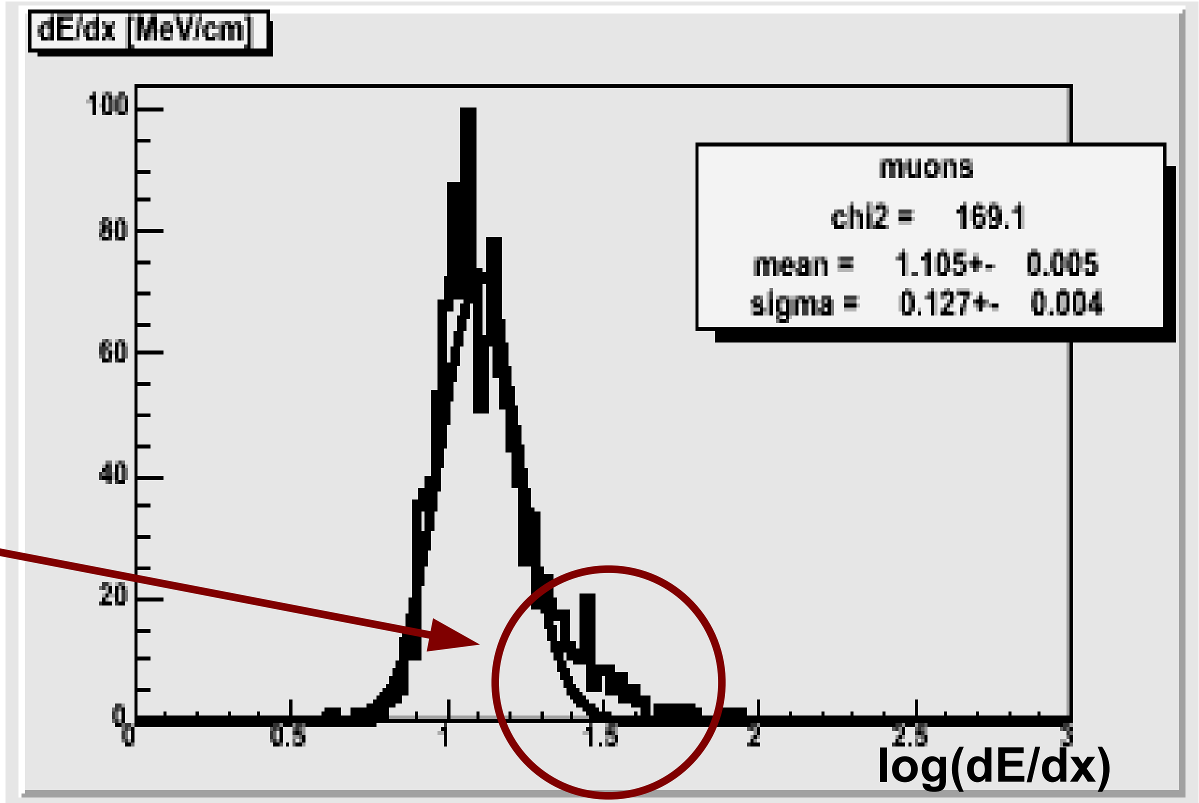
In this study the hits from pixels are only used for track reconstruction and momentum measurement, but not for dE/dx.
Reason: pixel experts are skeptical that linearity and saturation issues with the pixels can be easily corrected away. And pixels are only 3 points out of ~17: probably more trouble than help! (But they would help to go to p_T<900 MeV...)

dE/dx: estimators of the Most Probable Value for a track

- Median: usually a fair estimator of the peak position for asymmetric distributions
  - But with small samples, it's very sensitive to the tail (and to saturation effects)
- Truncated mean, i.e. the highest *xx*% of the measurements are ignored
  - The truncation fraction is arbitrary (the “Particle Detector Briefbook” suggests 20%) and heavily biases the result
    - ... but do we care for biases? Not in particle-id!
  - Still quite sensitive to the tail (unless you truncate a lot, in which case you waste a lot of precious statistics)
- H1 method: square of the harmonic mean of square roots, i.e. $E = 1/(\langle 1/(dE/dx)^{1/2} \rangle)^2$
  - But why square roots? (Let's check also other powers...)

Quality criteria

- Gaussian fit to the **log** of the estimator for 900 < P < 1100 MeV, for different particle types
- *Gauss(log(x))* is a fair approximation of *Landau(x)* in the peak region (but awful in the tail)
- Look at χ^2 and σ for μ, and at K/π and p/π separations
- Here is a plot of the truncated mean for muons (just for the sake of providing an example)



Track dE/dx: and the winner is...

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

Estimator	muon $\chi^2/d.o.f.$	muon σ (%)	K/π separation	p/π separation
Median	13.1	14.1	0.65	2.5
Truncated mean (20 %)	10.2	10.4	0.7	3.1
Truncated mean (40 %)	11.3	10.5	0.7	3.0
Harmonic mean	3.9	7.4	1.1	4.2
Generalized harmonic mean ($k = 1/2$)	3.5	8.2	1.0	3.9
Generalized harmonic mean ($k = 1/3$)	4.4	8.2	0.9	3.9
Generalized harmonic mean ($k = 2$)	3.8	6.7	1.3	4.9

“generalized mean of grade k”:

$$M_k = 1/(\langle 1/(dE/dx)^k \rangle)^{1/k}$$

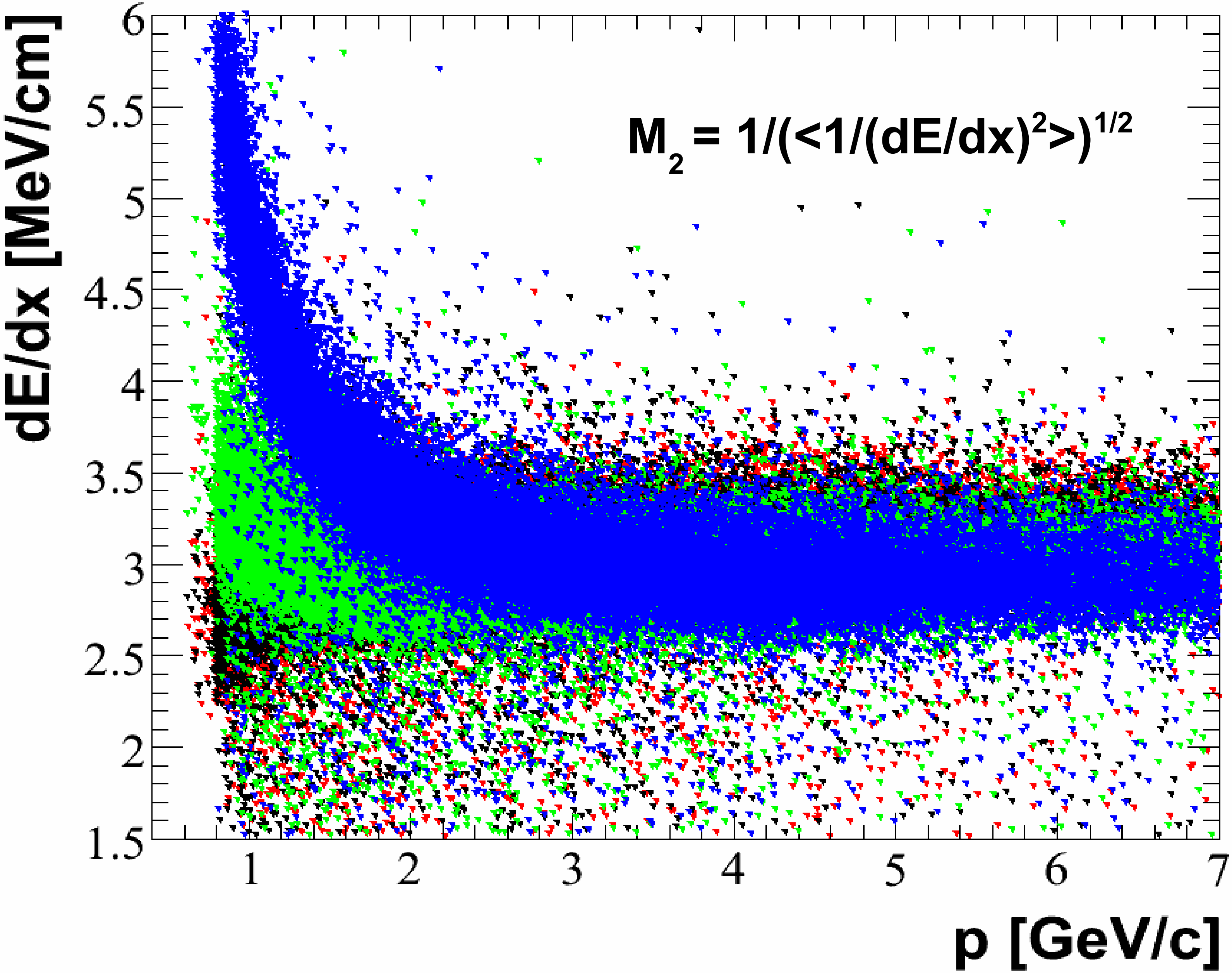
(to be exact, this is a generalized / power / Hölder mean of grade -k.)

Harmonic mean: k=1

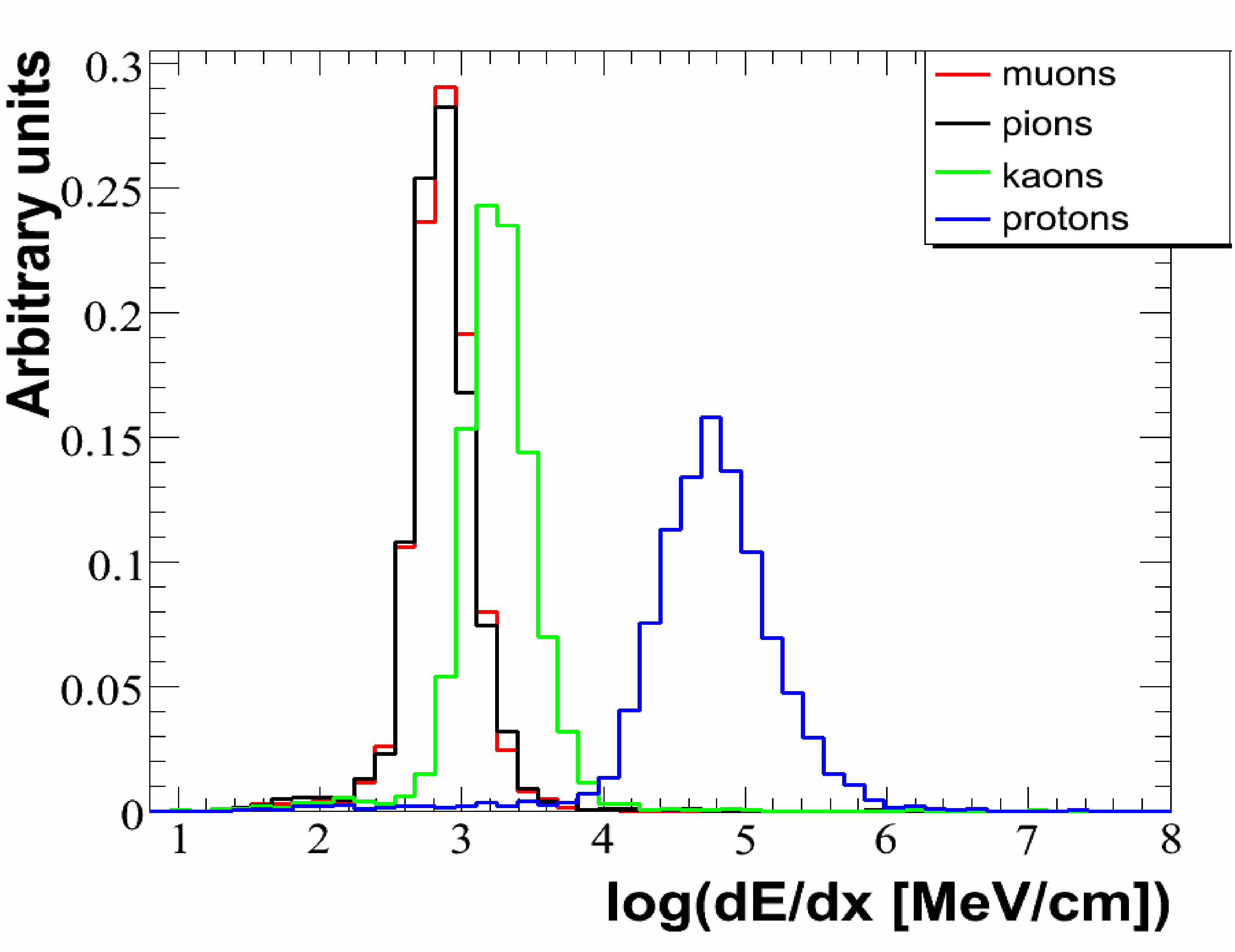
H1 method: k=1/2

My method: from now on, k=2

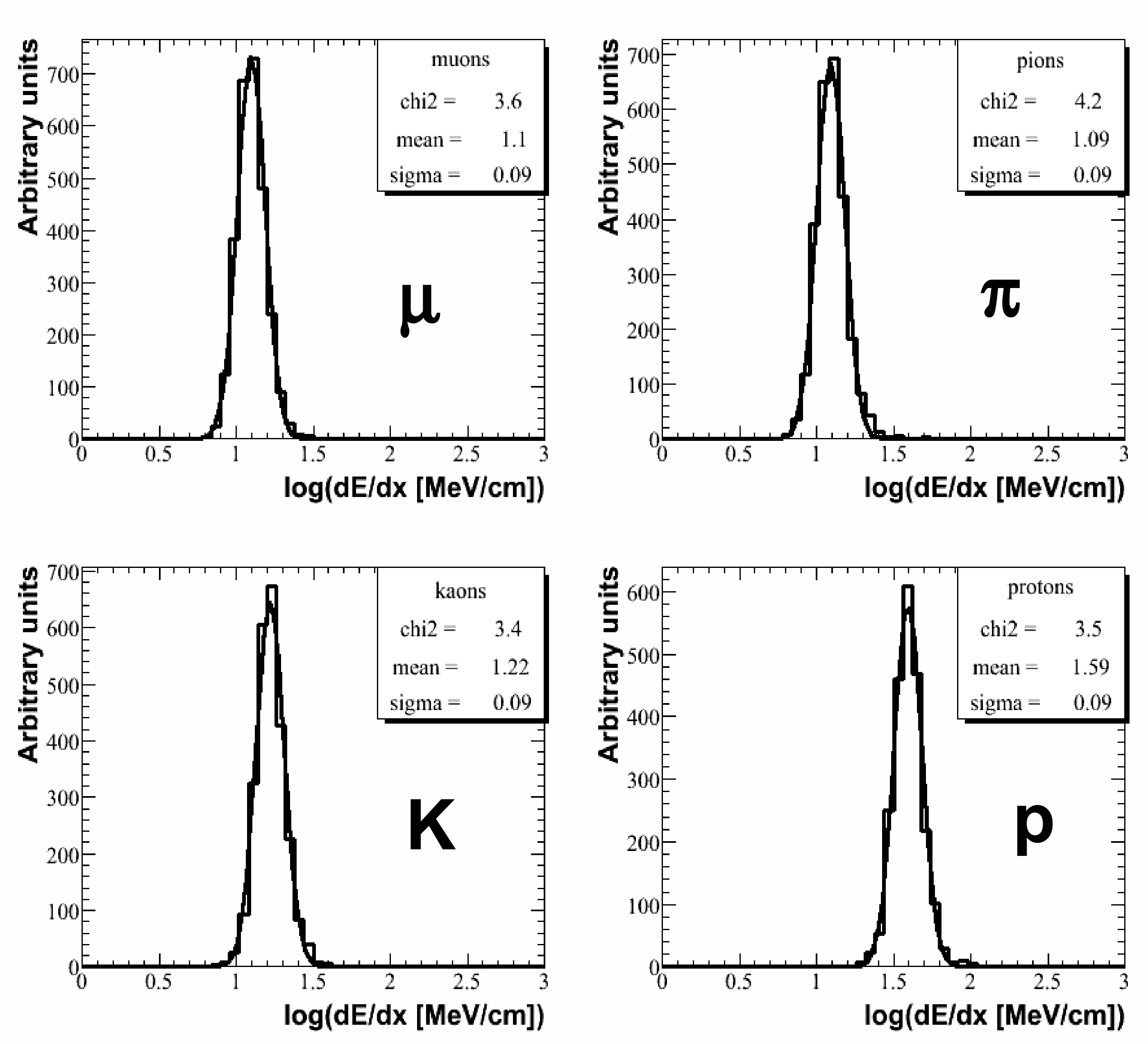
Tracks generated with “particle guns” of:
pions, muons, kaons, protons



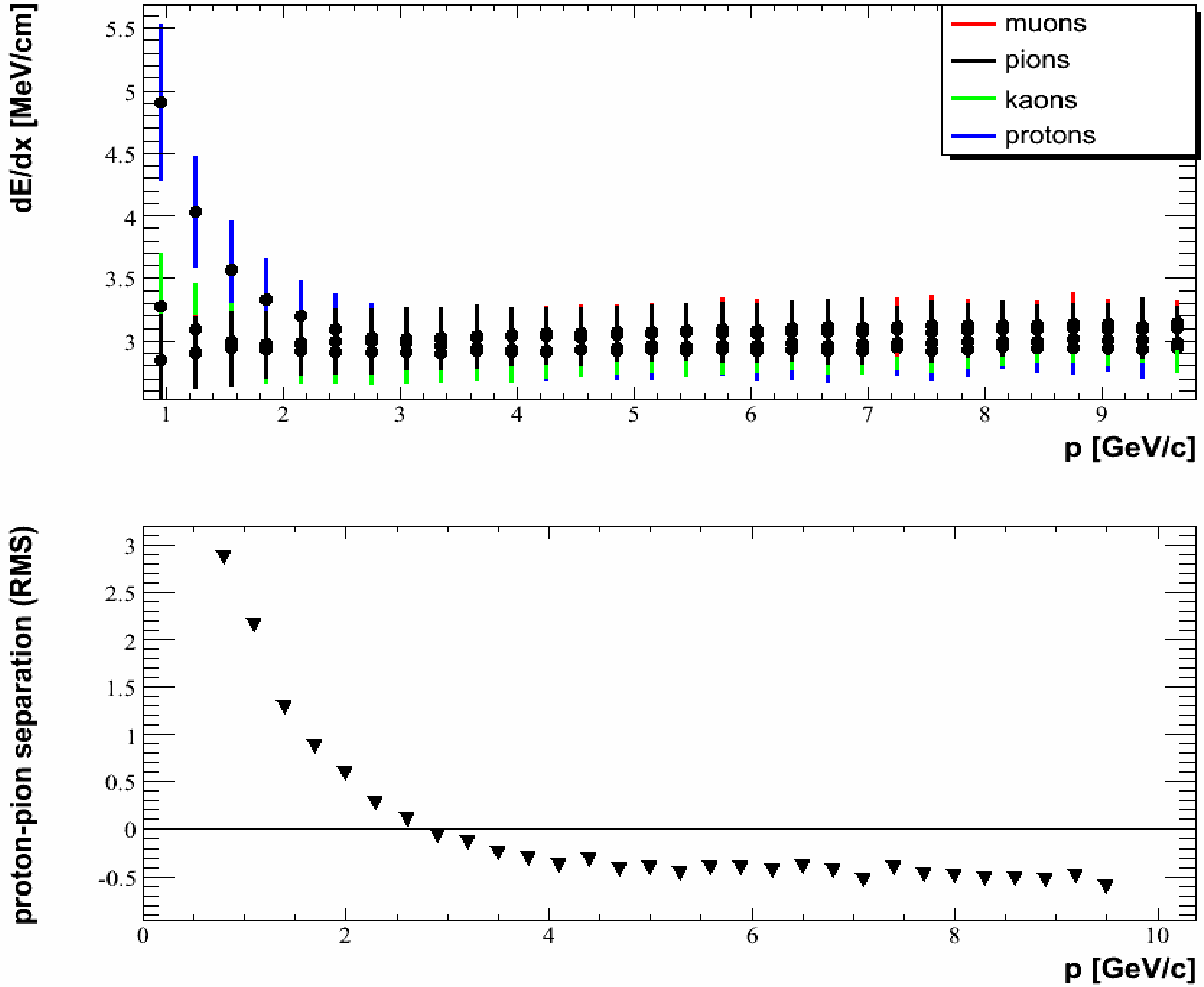
dE/dx for 900 < P < 1100 MeV



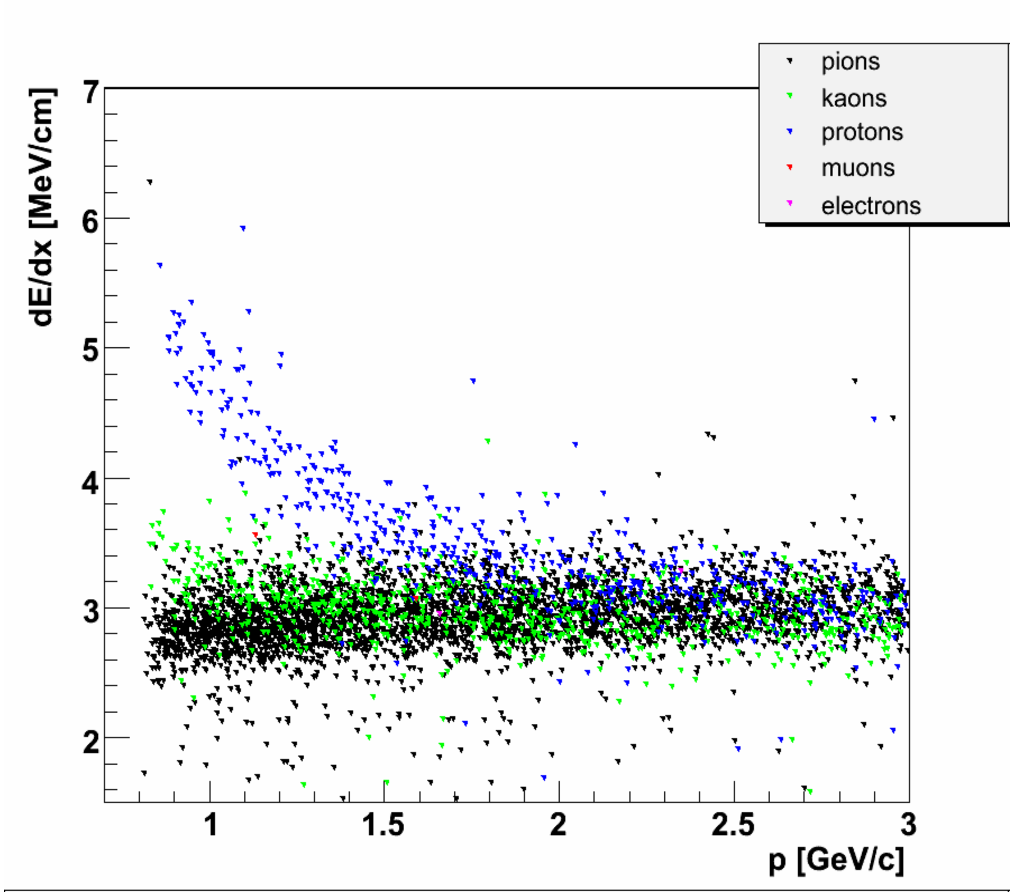
log(dE/dx) for 900 < P < 1100 MeV

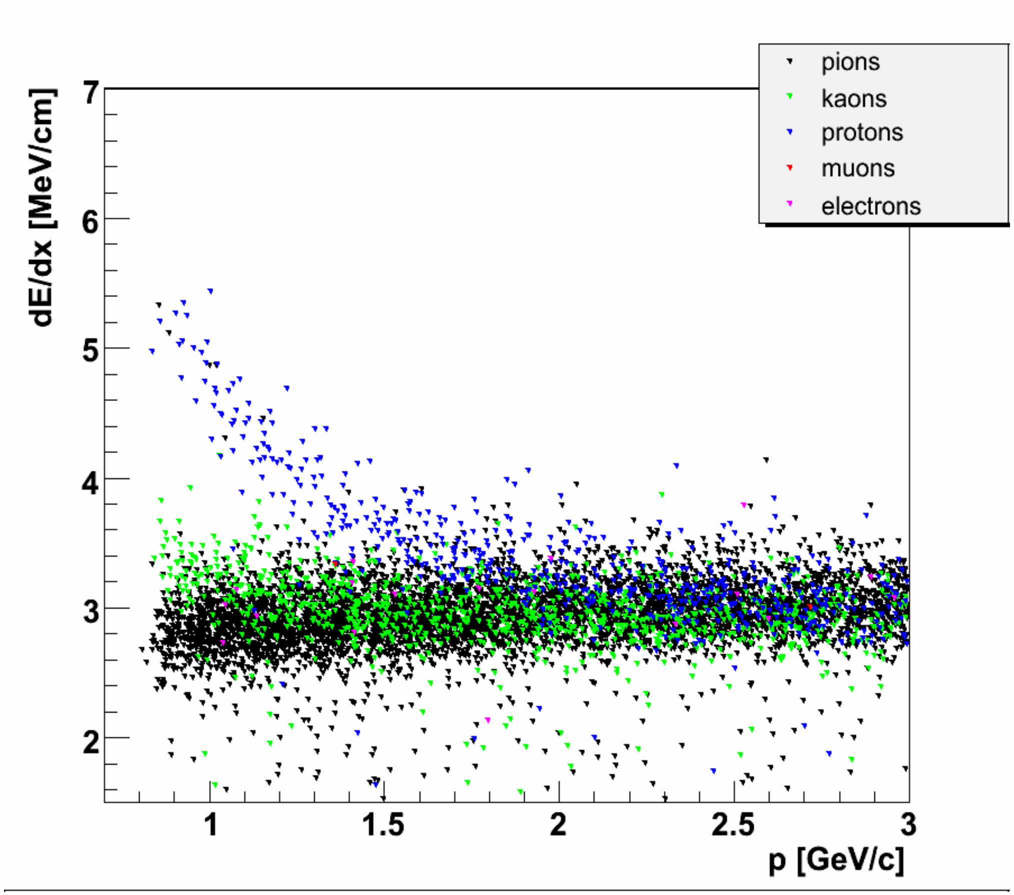


Identification power vs P



What we expect to see at LHC

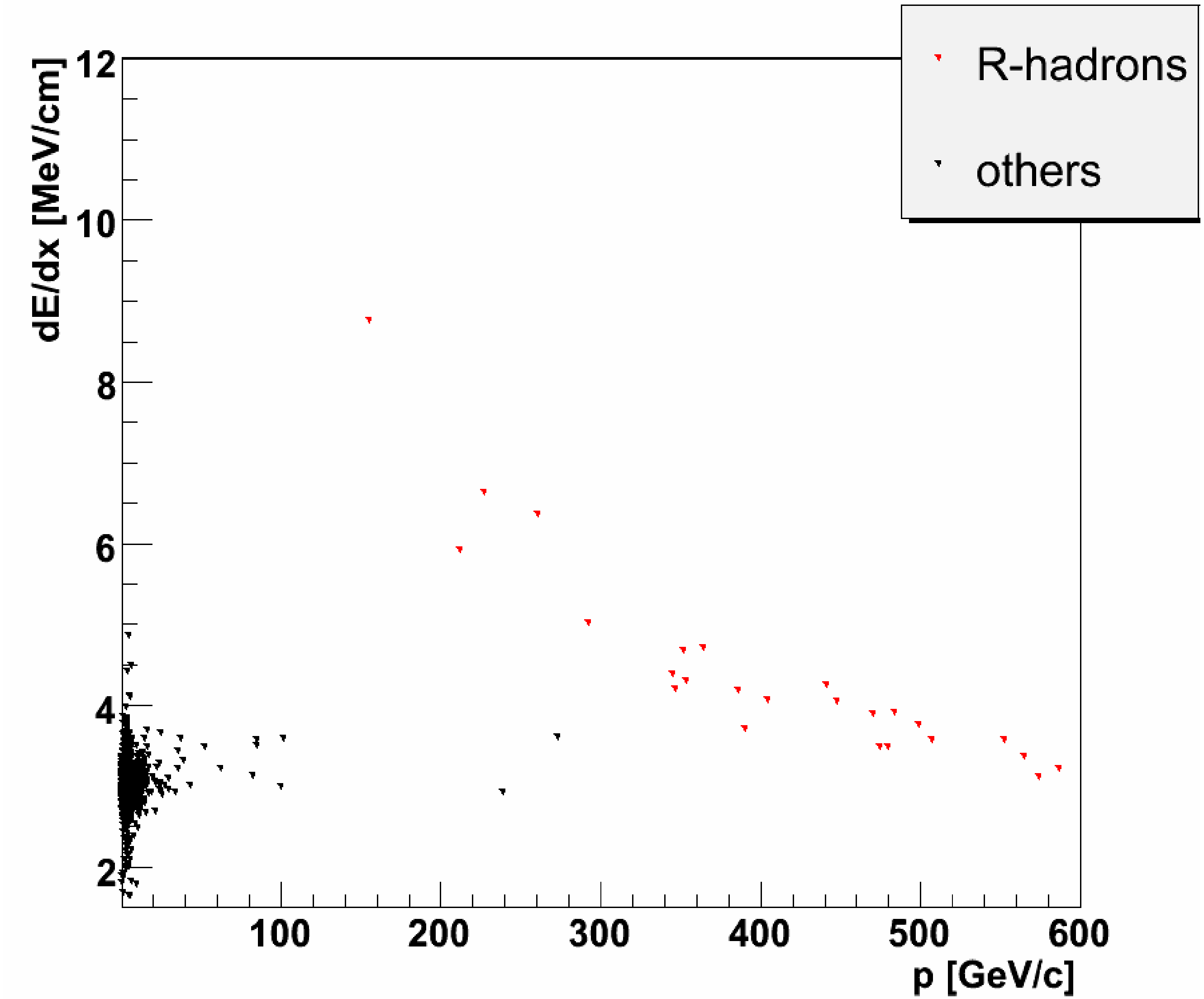




Minimum bias, 3000 events
(σ~80 mb: 80 MHz at L=$10^{33}cm^{-2}s^{-1}$)

QCD, 500 events, 80<$\hat{p}_T$<120 GeV
(σ~3 μb: 3 kHz at L=$10^{33}cm^{-2}s^{-1}$)

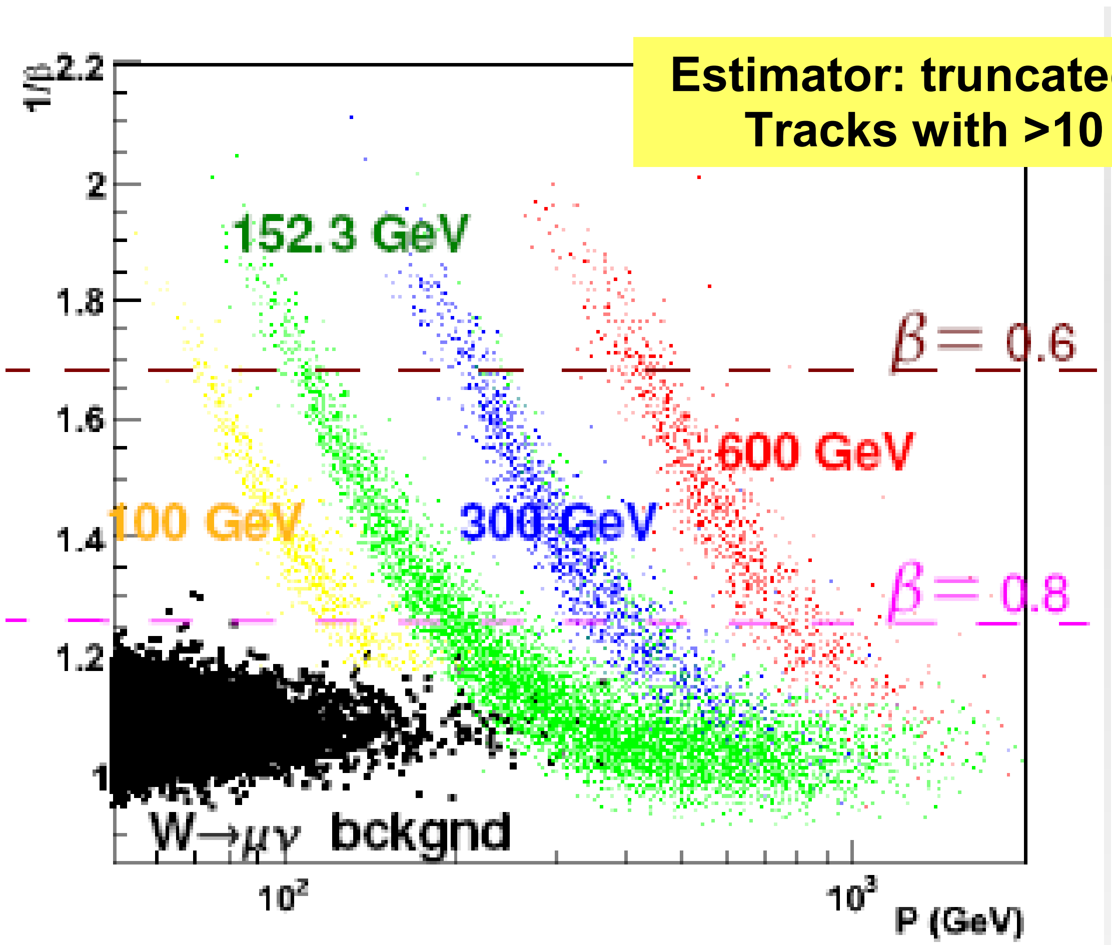
R-hadron events, M=600 GeV



To be used in combination with the Time-of-flight from the Muon Chambers

R-hadron mass from dE/dx in CMS (analysis in ORCA by A.Rizzi)

Estimator: truncated mean
Tracks with >10 hits

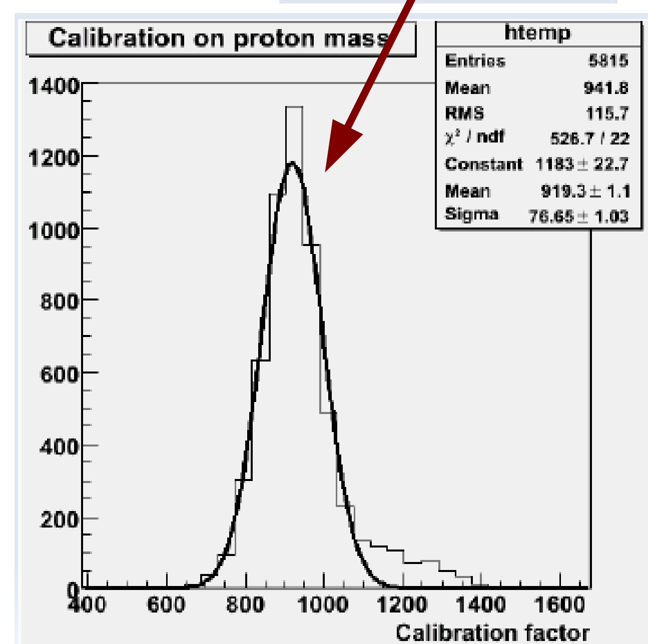


$$m = \frac{p}{\beta\gamma}$$

$$\frac{dE}{dX} = \frac{1}{k\beta^2}$$

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

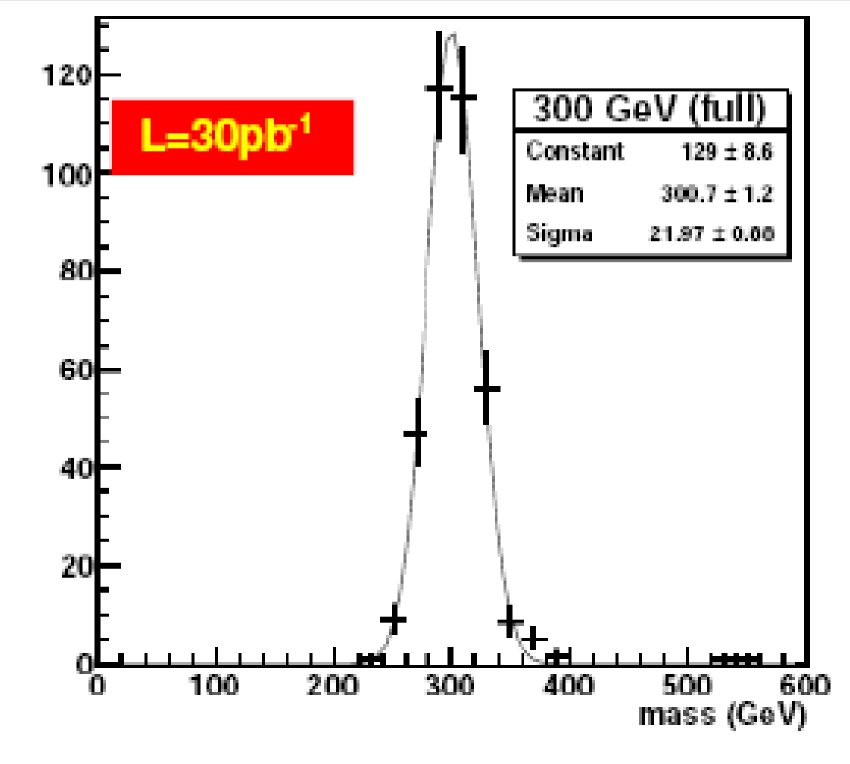
$$m = p\sqrt{k\frac{dE}{dX} - 1}$$

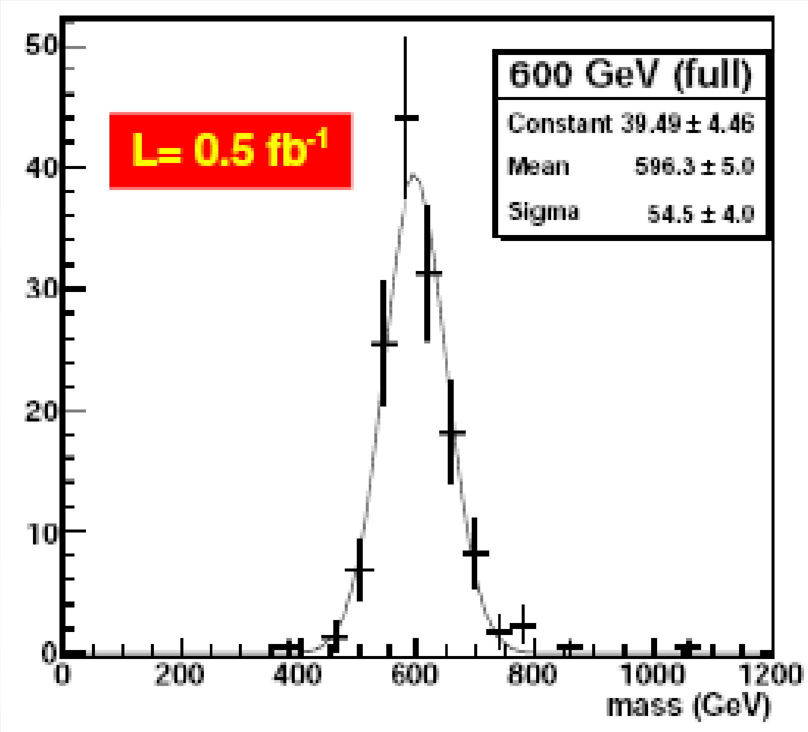


ΔM/M ~ 10%
(with Time-of-flight: ~30%)

R-hadron search (A.Rizzi)

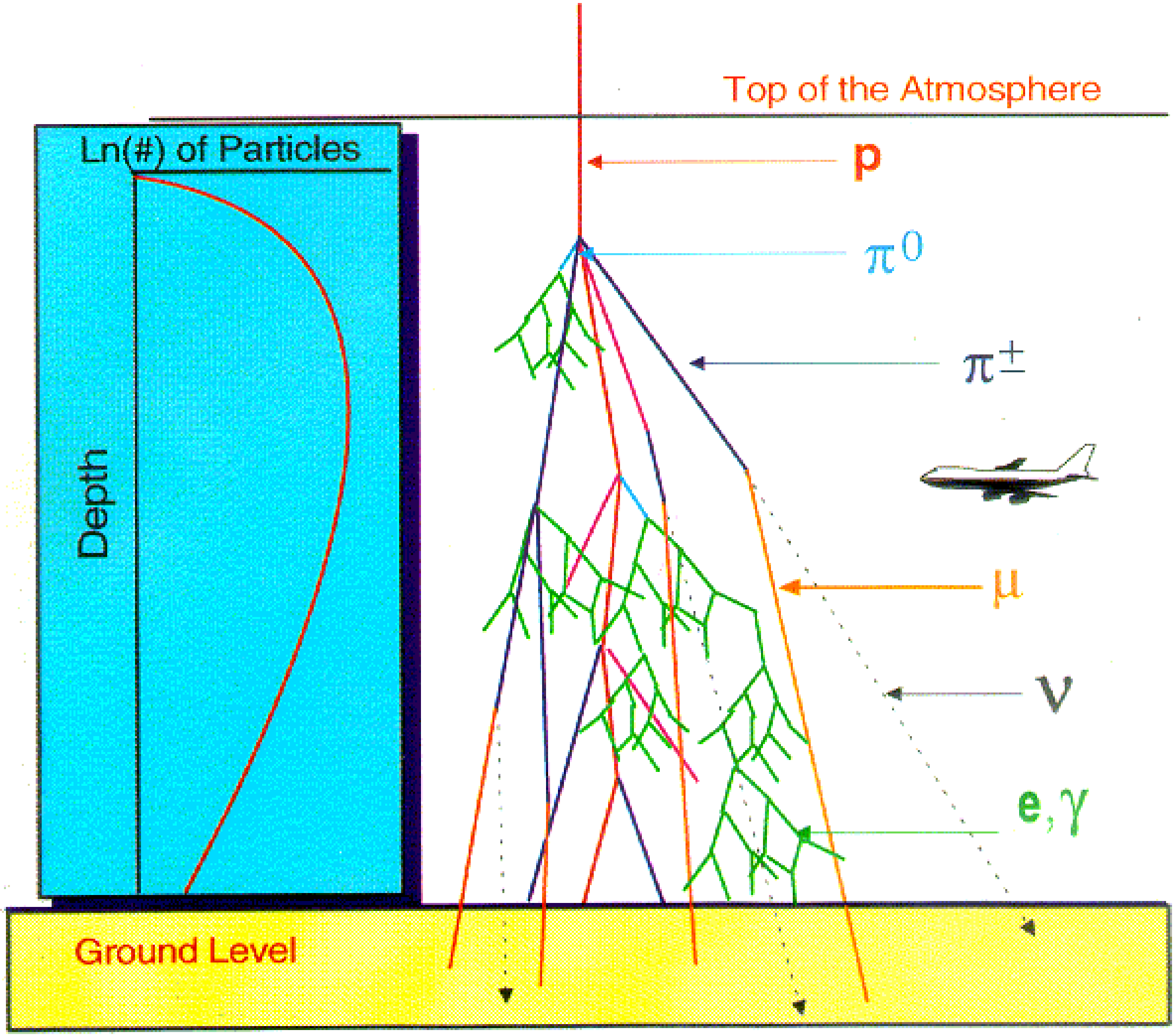
- ~10% mass resolution in the golden region
- ~100 events to have a < 1% stat. error on the mass
- 0.5 fb^{-1} are enough for 600 GeV stable gluino discovery





Reality check: cosmic data

Parker's Piece, Cambridge, England

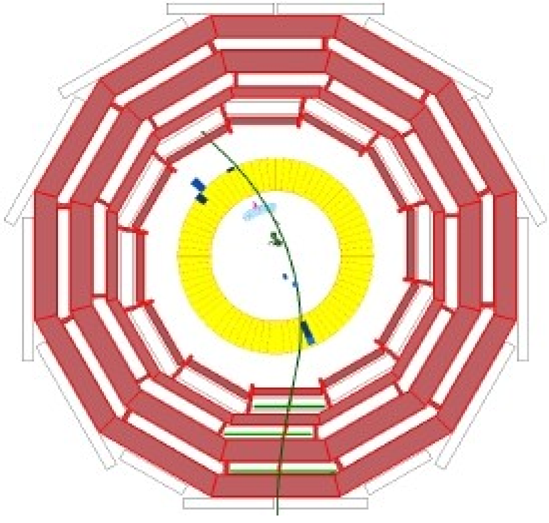


The cheapest particle factory available

MTCC
(Magnet Test / Cosmic Challenge)

- A test of the CMS solenoid, in order to check its performance, map the field in the whole detector, check the control systems, etc.
- While the Magnet people were playing with their toy, we (subdetector/software/analysis people) did some practice with the integration of a sub-set of the final system
- Cosmic rays → tracks in Muon Chambers and Tracker

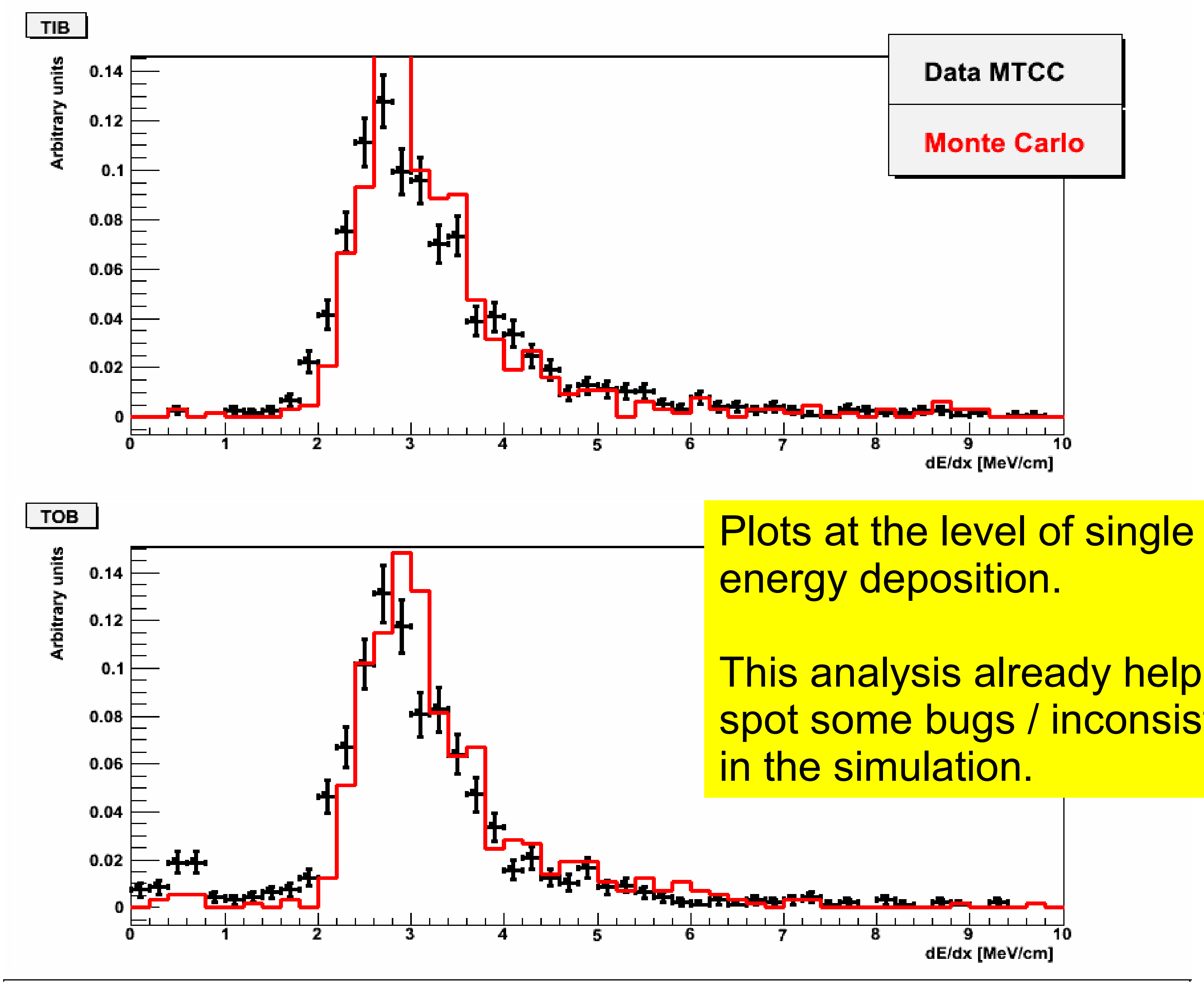
Only very few Tracker units (1%) were instrumented.



The data of our interest were taken in July/August 2006

In the next slide: validation of the dE/dx simulation with MTCC data at B=3.8 T

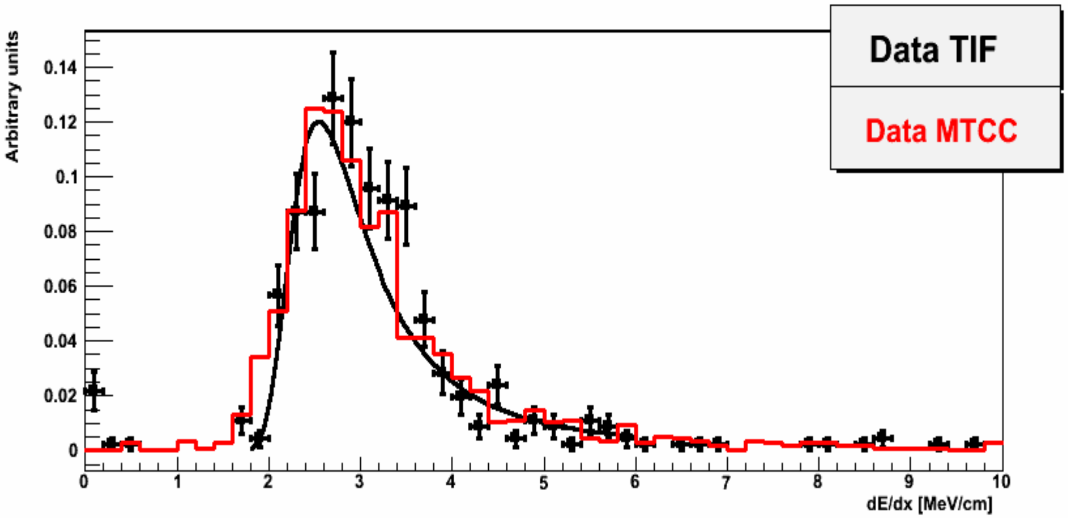
Data/MC comparison

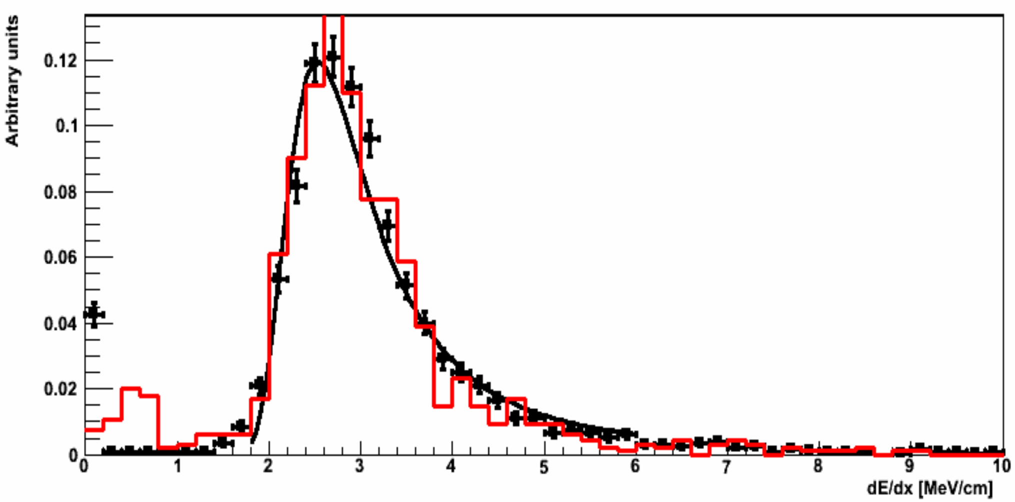


Plots at the level of single hits energy deposition.

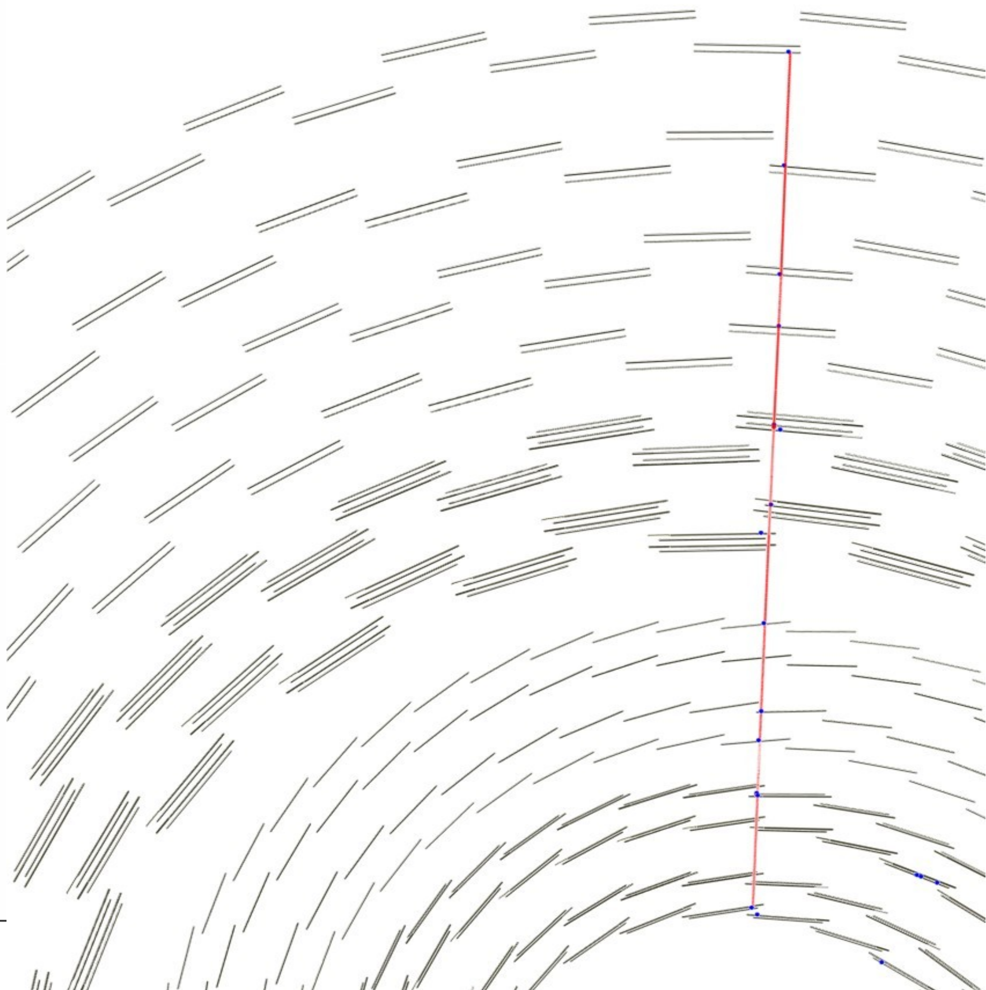
This analysis already helped to spot some bugs / inconsistencies in the simulation.

Other real data: TIF (Tracker Integration Facility)





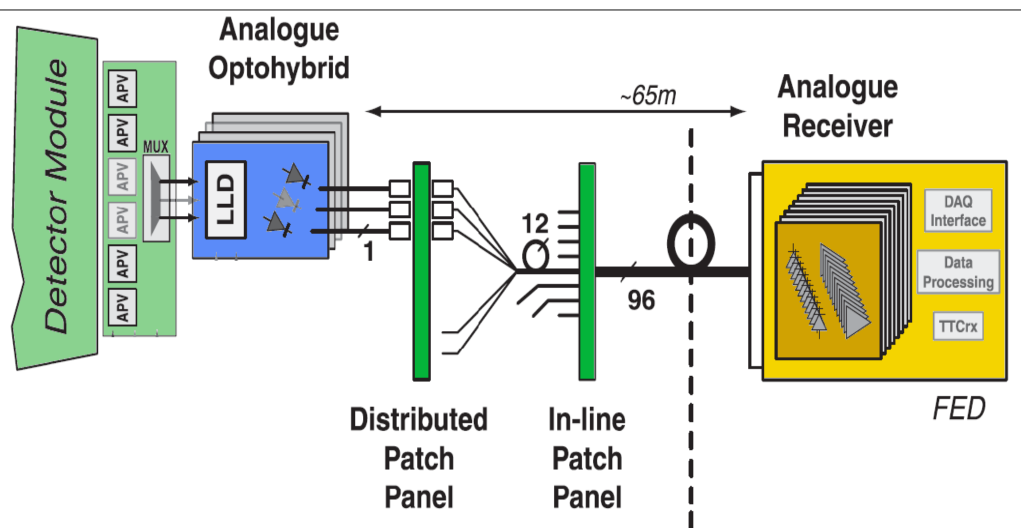
Data taking is ongoing right now

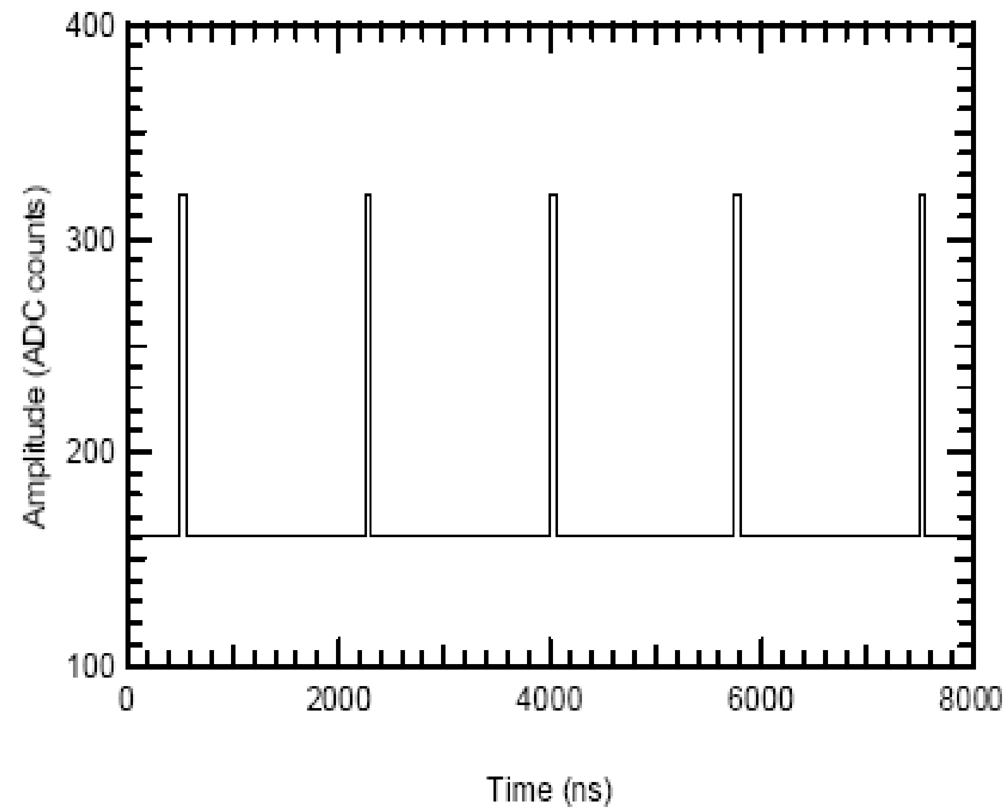


Calibration strategies

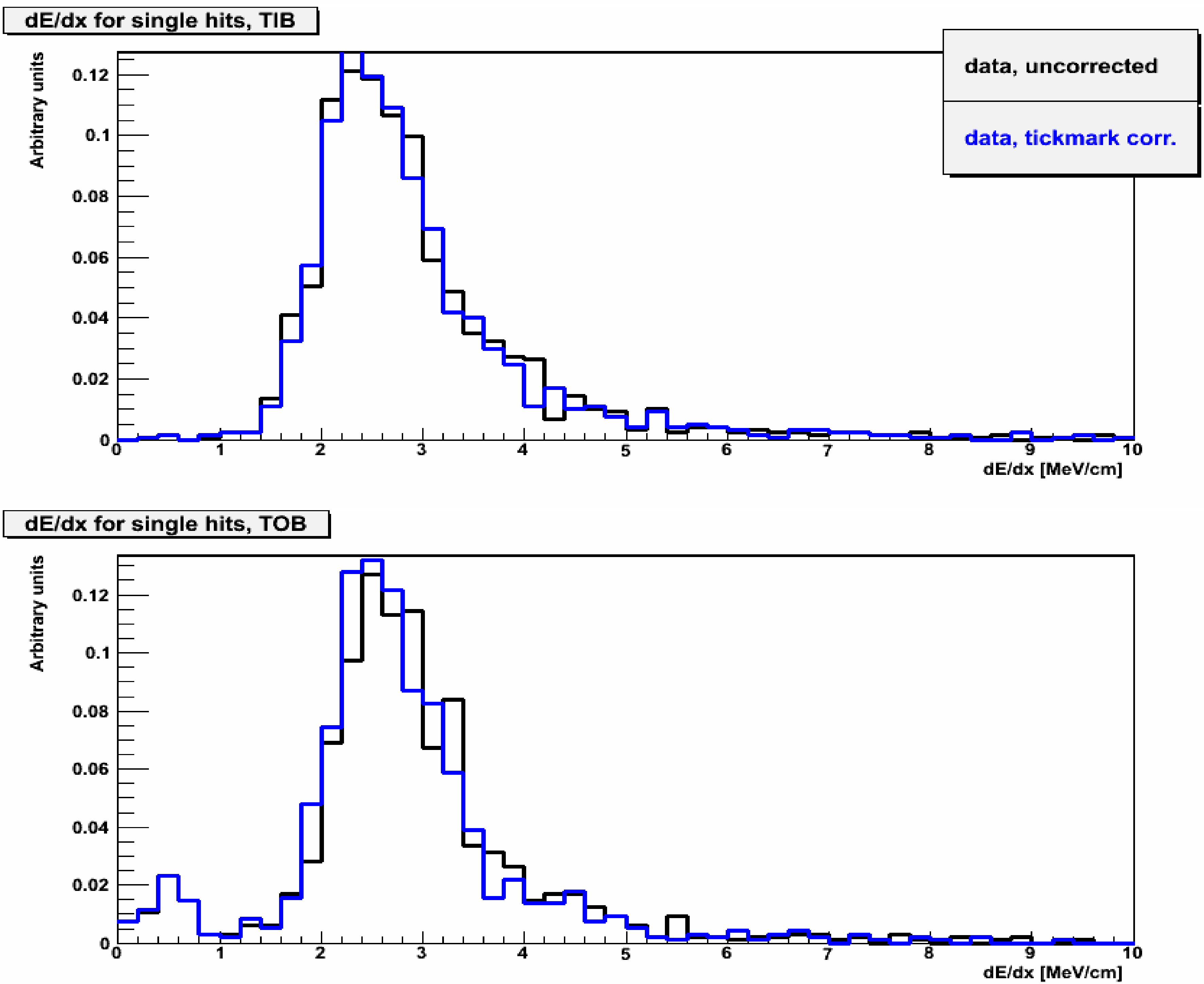
- Detector inter-calibration: spreads in the gains degrade the dE/dx resolution
- Absolute calibration: in principle not important for particle-id (where only differences matter), it's nevertheless needed from time to time if the gains are not stable
  - Which is what is expected due to irradiation...
  - Opto-link gains depend on temperature. (But this shouldn't be an issue: operation of the Tracker is at fixed temperature)

Tickmarks

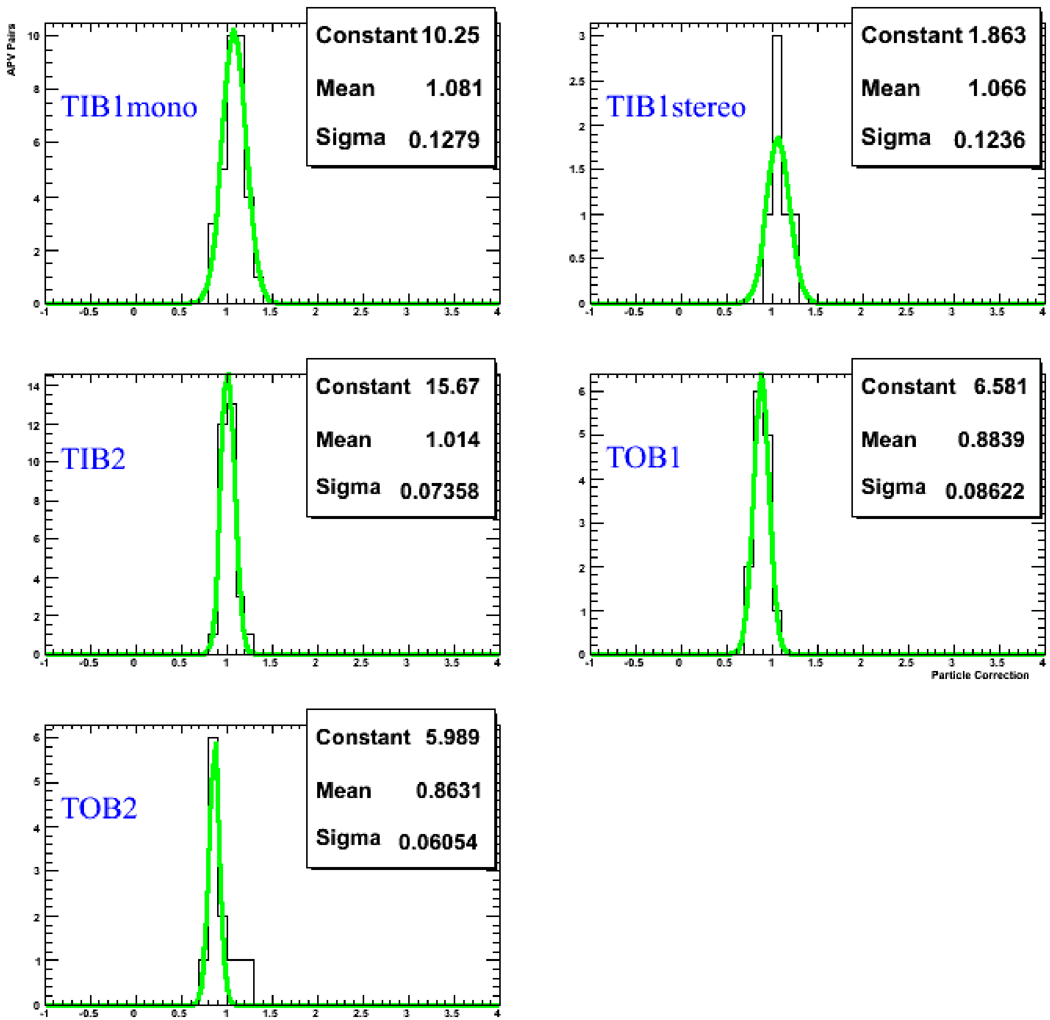




In absence of trigger, each APV sends these signals every 1.75 μs.
Essential for the synchronization of the detector components.
Their nominal height is known, and permits to intercalibrate the gains of the opto-links. ("Gain scan": specific run done from time to time)


dE/dx for single hits, TIB
Arbitrary units
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
7
8
9
10
dE/dx [MeV/cm]
data, uncorrected
data, tickmark corr.
dE/dx for single hits, TOB
Arbitrary units
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
7
8
9
10
dE/dx [MeV/cm]

Cosmics (Giacomo, Dorian, Pierre)



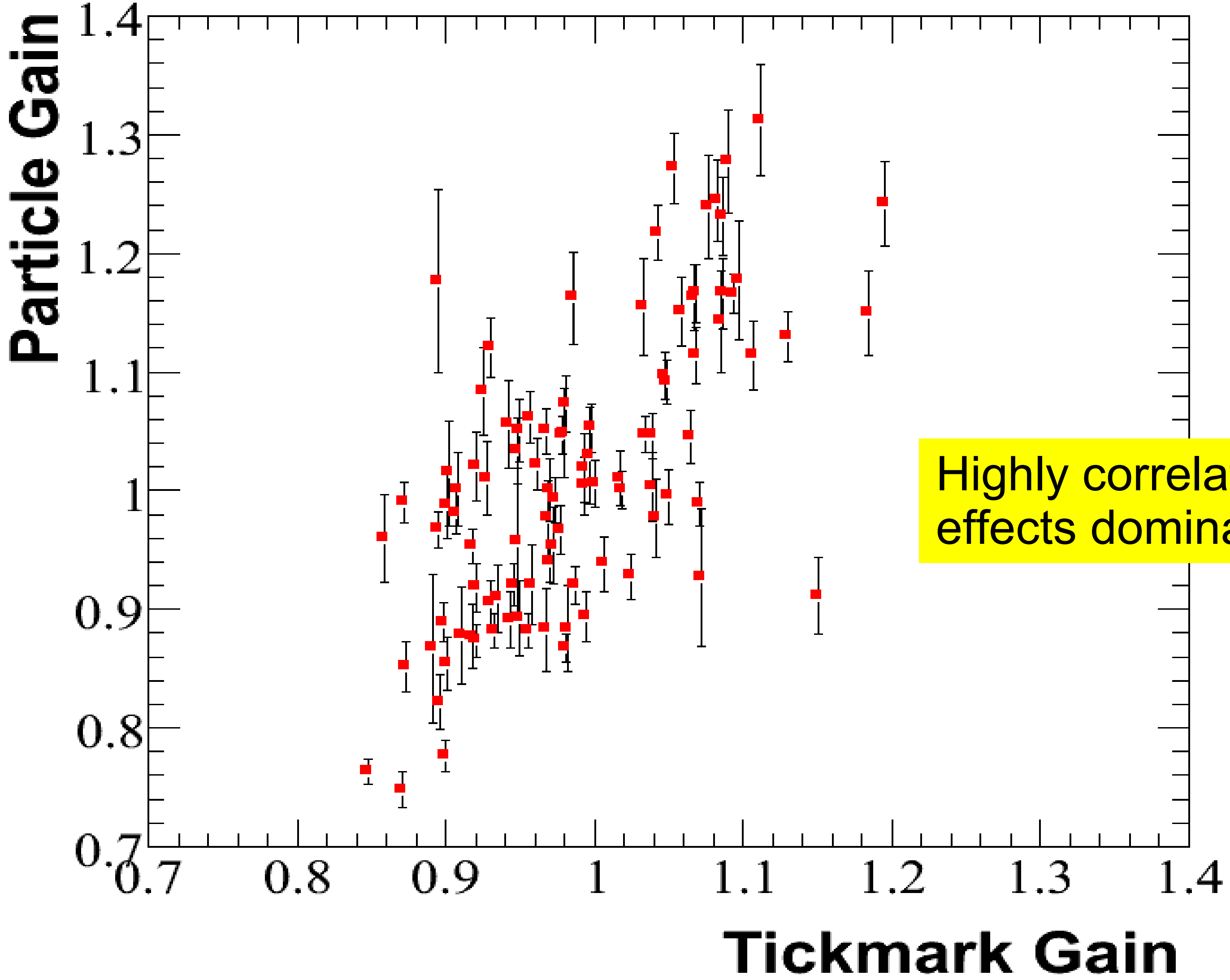
The opto-link gain is not the only source of miscalibration.

E.g., V_{bias}/V_{depl} has an effect on the electron-hole pairs creation.

It is always better to intercalibrate the detector units with known particles: this simultaneously takes into account both front-end and sensor effects.

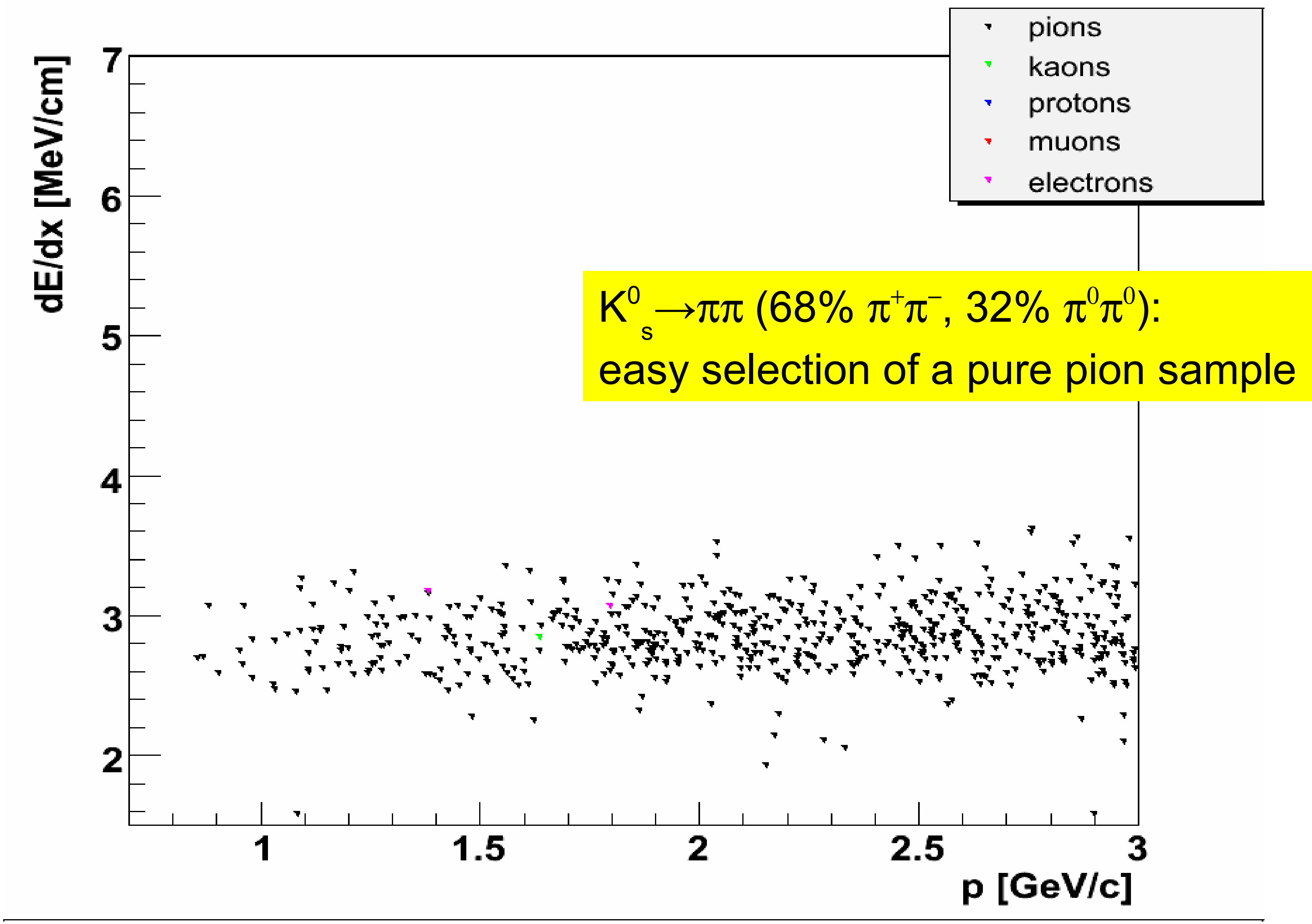
The method has been demonstrated with cosmics at MTCC; spreads are large, but the modules were “grade B” (V_{depl} out of specification, or too many faulty strips, or scratches).

Cosmic vs Tickmark calibrations (Giacomo, Dorian, Pierre)



Highly correlated: front-end effects dominate.

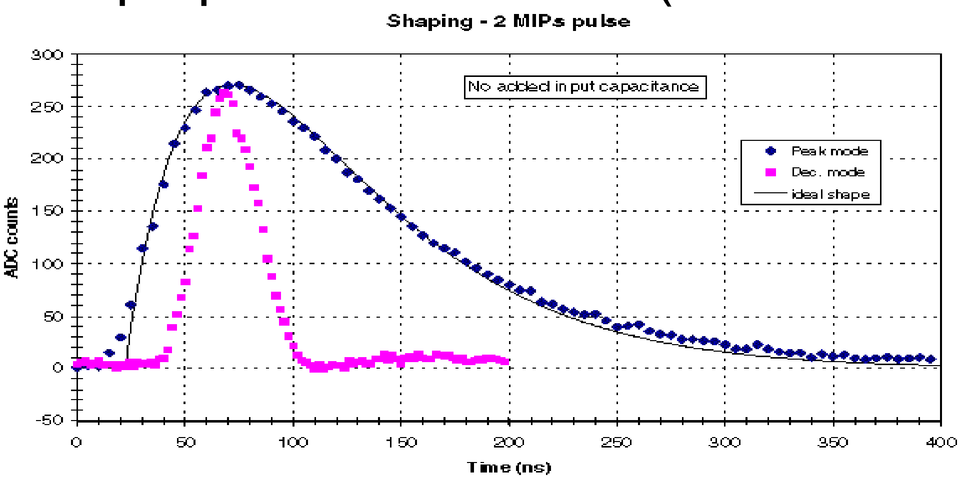
Calibration with K^0

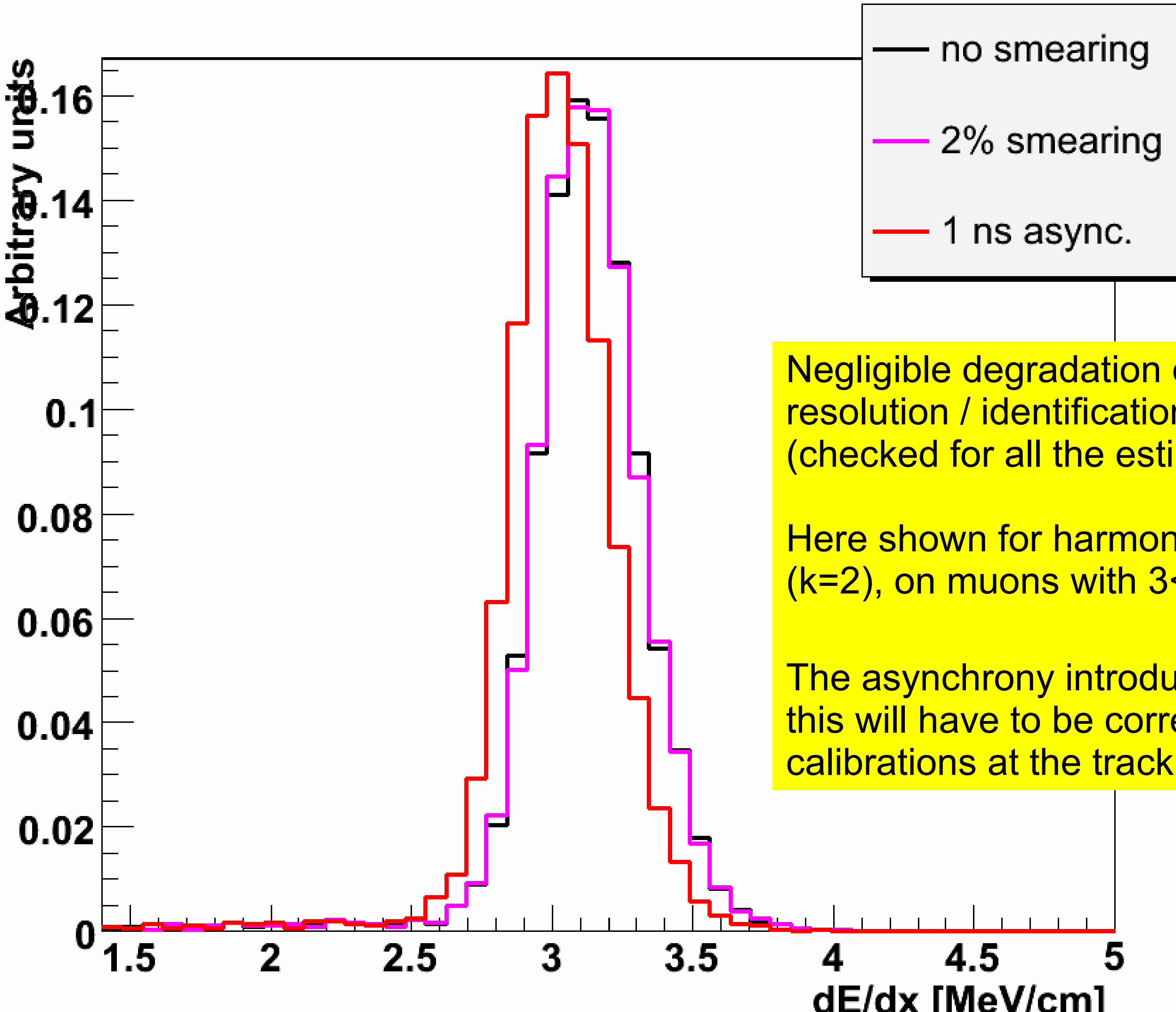


(Sample provided by Massimiliano Chiorboli)

Systematics

- Two systematics were considered so far:
  - Temperature
    - +1 C in temperature → -0.64% variation in gain
    - ±3 C → ±2% uncertainty on dE/dx for each hit (independently)
    - Modeled by a gaussian smearing with σ=2% (hit by hit)
  - Synchronization
    - The detector units are synchronized to better than 1 ns
    - 1 ns after or before the pulse-shape peak means -4% (in "deconvolution mode")
    - Modeled by -|*Gauss(σ=4%)*|





Negligible degradation of the resolution / identification power (checked for all the estimators).

Here shown for harmonic mean (k=2), on muons with $3<p_T<5$ GeV

The asynchrony introduces a bias: this will have to be corrected with calibrations at the track level.

Conclusions

The crew of the scientific lab orbiting around Solaris would probably perform a dE/dx measurement of the “visitor” in order to understand what she is made of.

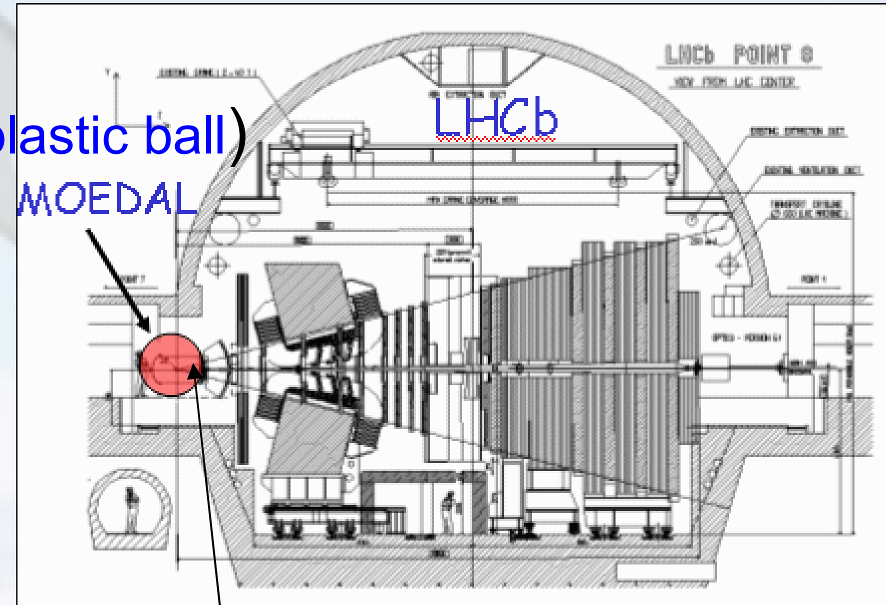
dE/dx in CMS: references

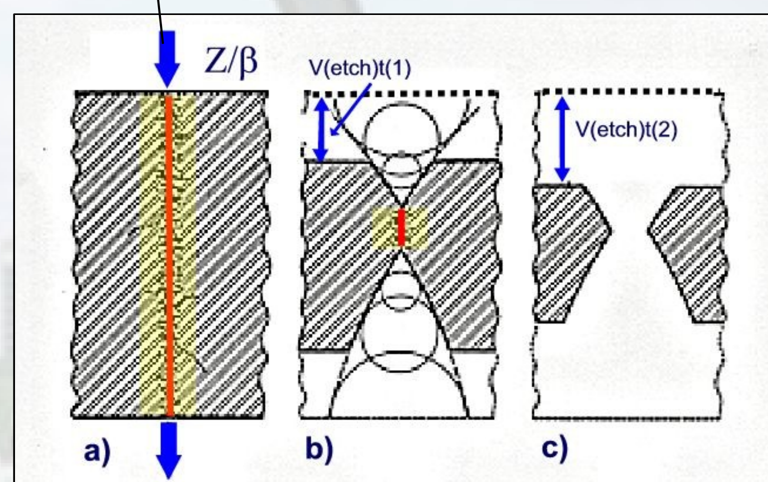
- On the search of Heavy Stable Charged Particles:
  - Wiki page of the “SUSY working group C”: https://twiki.cern.ch/twiki/bin/view/CMS/SusyBsmHscp
- On the technicalities of dE/dx extraction and calibration:
  - http://cern.ch/andrea.giammanco/dedx/
  - CMS note in preparation; you can peek the draft (in progress) here: http://cern.ch/andrea.giammanco/dedx/an/dedx.pdf

Extra slides

LHC- Direct Search for Monopoles

- An LOI for the MoEDAL experiment to search for monopoles, dyons & other highly ionizing objects has been accepted by the LHCC.
- The MoEDAL detector is essentially a “partial” plastic ball deployed around the LHCb vertex chamber region.
- Highly ionizing objects are detected by etching the plastic’s “ionization damage” zones
- Threshold Z/b > ~10. (Z/b for a highly relativistic monopole ~1500)
- Advantages:
  - **Minimizes assumptions about the nature of the monopole or dyon**
  - **Essentially no SM background. In principle 1 event should be enough for a discovery**
  - **Very Very cost effective**

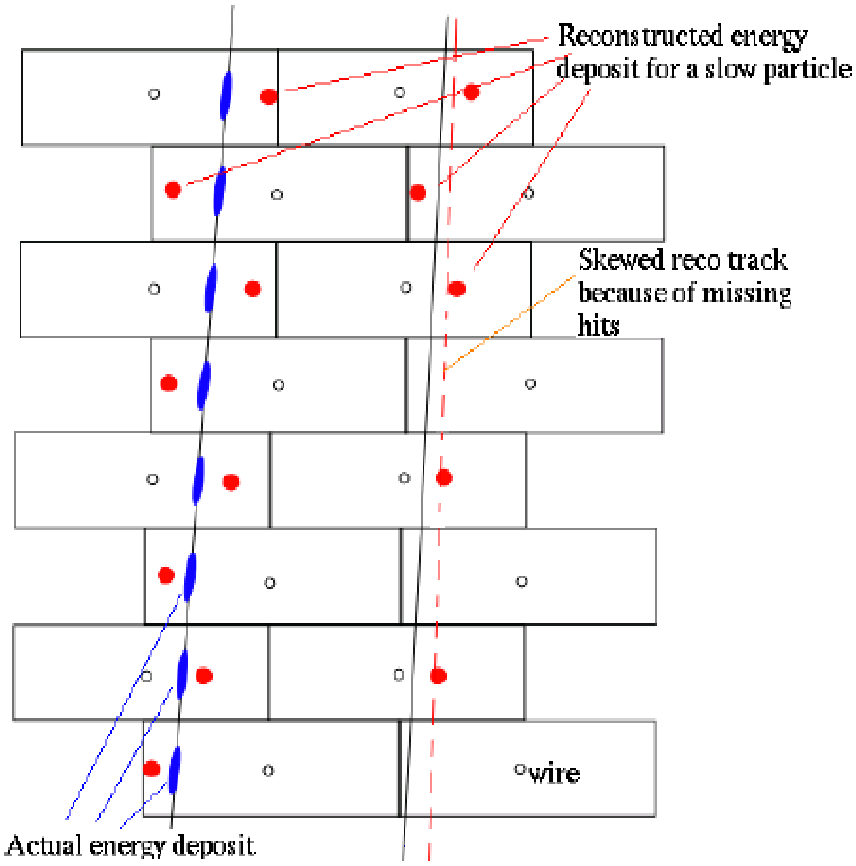




Detection medium, plastic track-etch detectors (CR39)

(from a talk by J.Pinfold, 2005)

Time-of-flight with Drift Tubes (A.Rizzi)



$\Delta x = v_{drift} \Delta t$

The fit for muon tracks assumes $\beta=1$.

For slow particles, an alternate displacement wrt a straight line is clearly visible.

A specific fit can extract β.

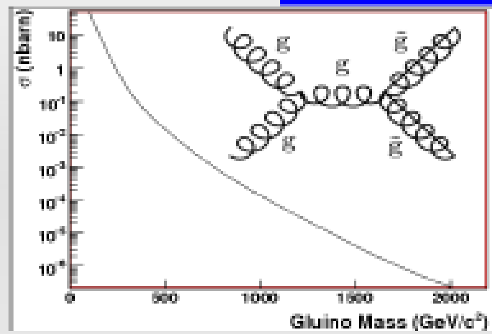
Major source of systematic: drift velocity uncertainty (~2% at the time of the paper; this will be improved with real data).

LHC R-hadron production

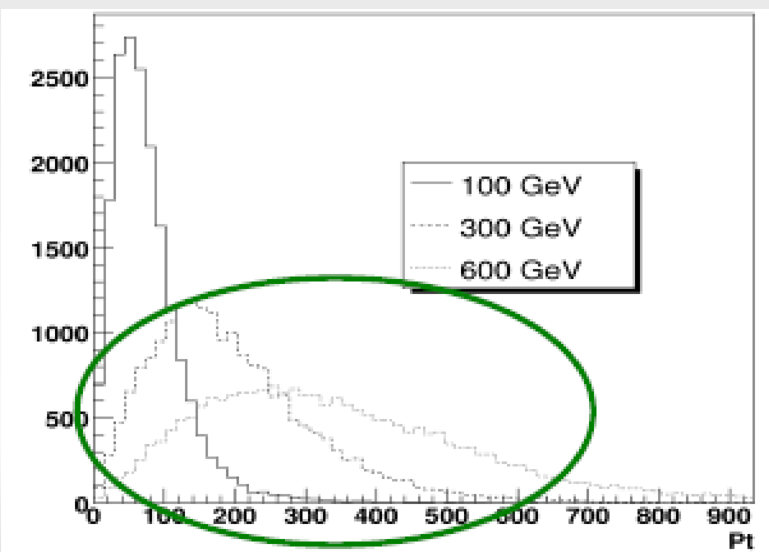
- In proton-proton interaction the predicted HSCP can be produced
- Gluino pairs can be produced and should show up as charged or neutral hadrons
- The main process for gluino production at LHC gg->~g~g

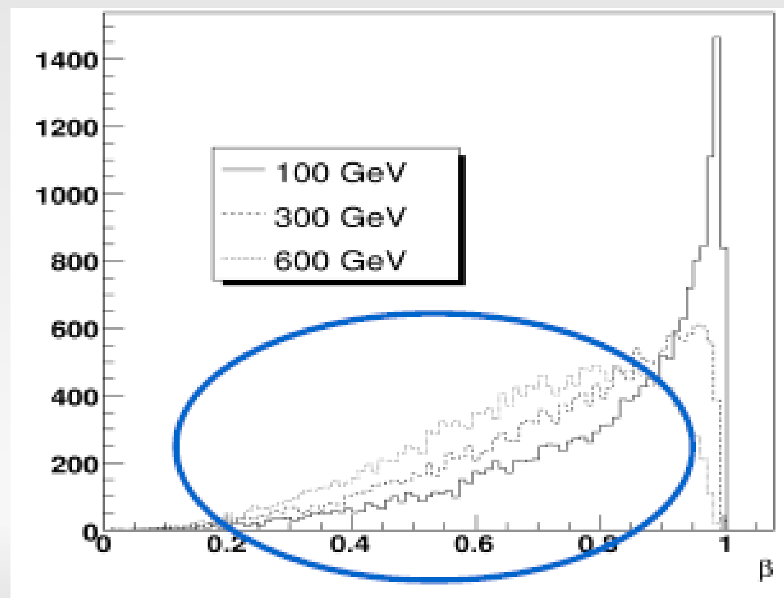
→ High Momentum and low velocity

Cross sections @LHC:



~g Mass	Xsec
100 GeV	50nb
300 GeV	0,3nb
600 GeV	5pb
1 TeV	0,1pb





(A.Rizzi)

Trigger efficiencies (A.Rizzi)

Sample	L1 s.m.	L1 d.m	L1 tot	HLT 30	HLT 50	Ev 1 fb^{-1}
gluino 100	1562 (18%)	1595 (18%)	2311 (26%)	394 (4.5%)	384 (4.4%)	2.4M
gluino 300	2870 (30%)	3530 (38%)	4323 (46%)	882 (9.4%)	873 (9.3%)	26K
gluino 600	3527 (35%)	4075 (41%)	5058 (51%)	1301 (13%)	1292 (12.9%)	650
stau	8892 (94%)	8033 (85%)	8975 (94.5%)	8476 (89%)	8253 (87%)	1025

Muon streams w/o isolation. (Isolation kills the R-hadron efficiency.) Particles assigned to the wrong bunch crossing are considered as non-triggered.

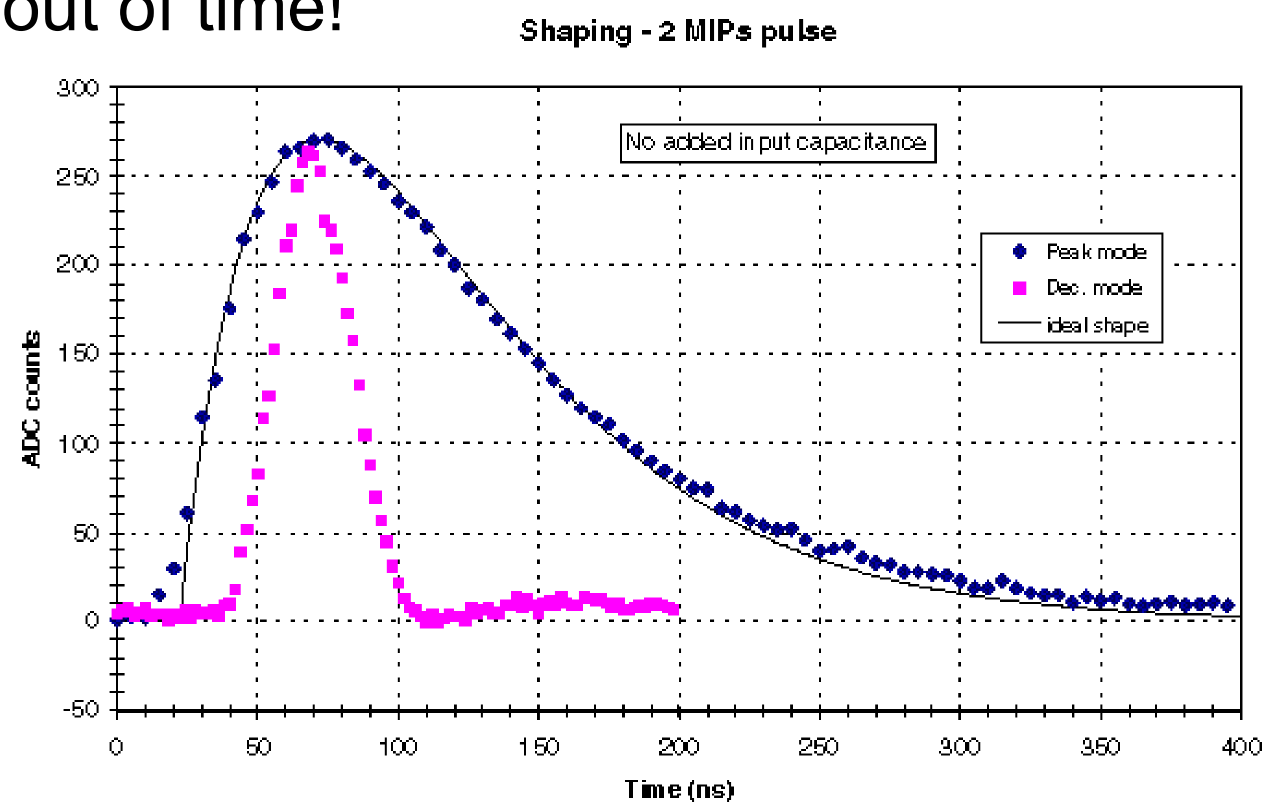
For R-hadrons, the problem are nuclear interactions.

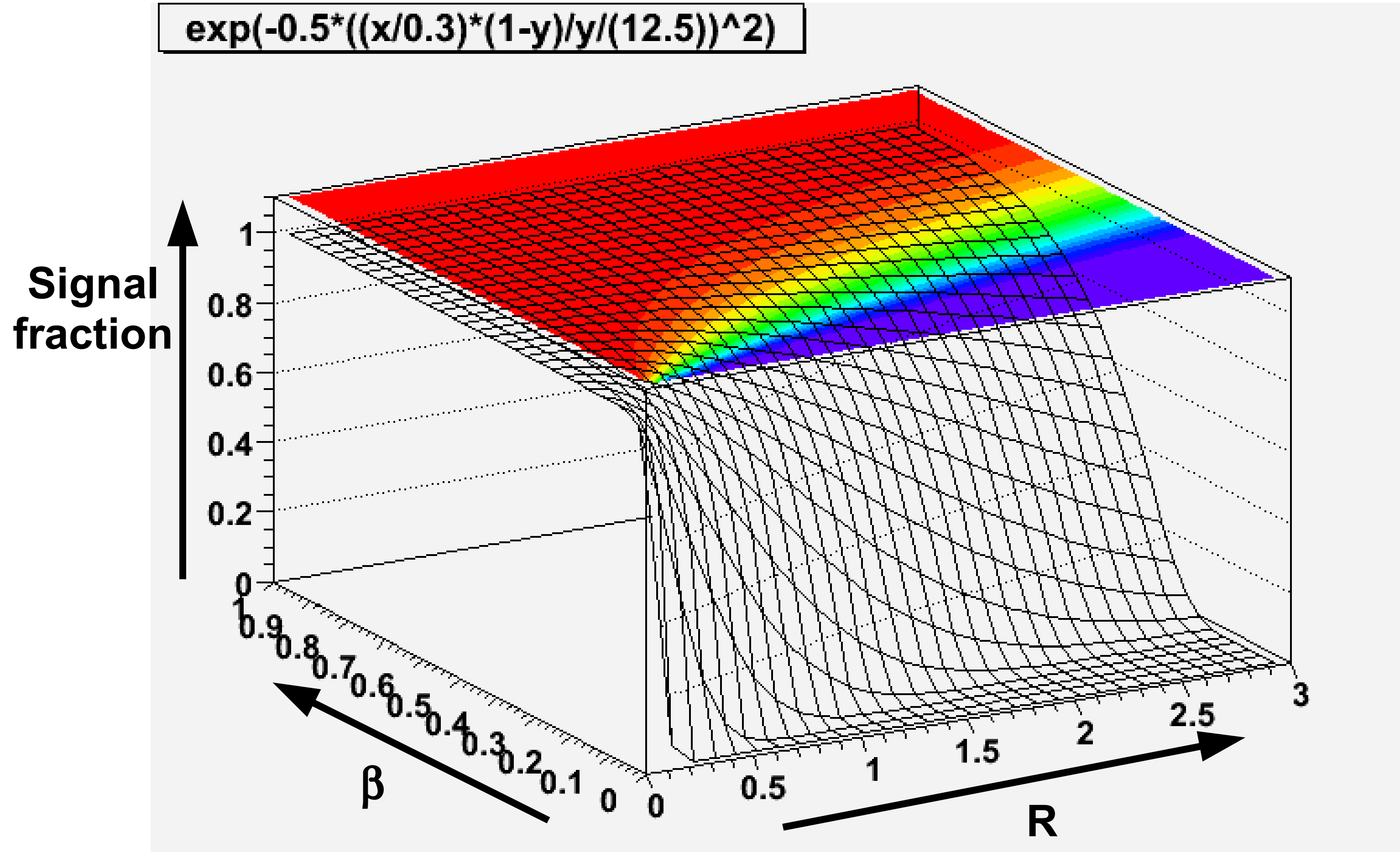
A new trigger path with dE/dx information has been proposed.

When the gluino is the last step of a cascade, you usually trigger on high-pt jets from the cascade; but we want to be as model-independent as possible!

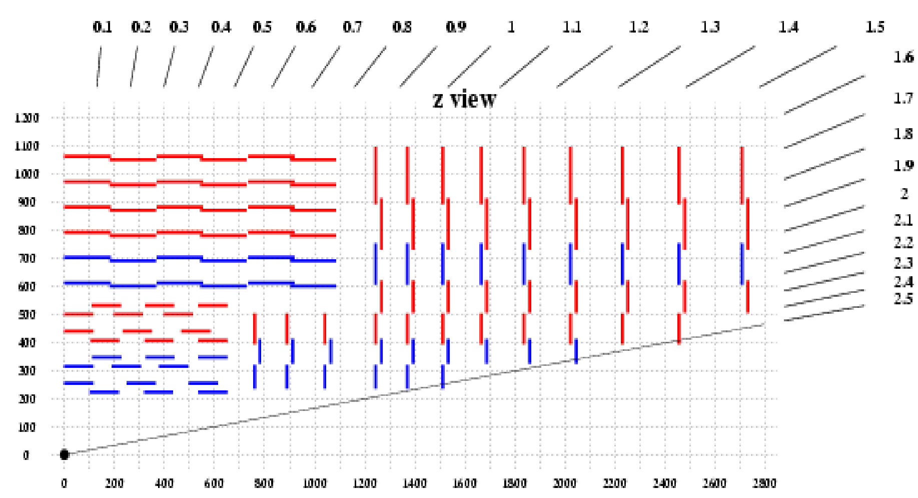
Specific problems of slow particles

- All the Tracker modules are synchronized to each other, to better than 1 ns, taking into account the time needed for a relativistic particle (β~1) to reach them
- A very low-momentum proton, or a very heavy R-hadron, may be out of time!





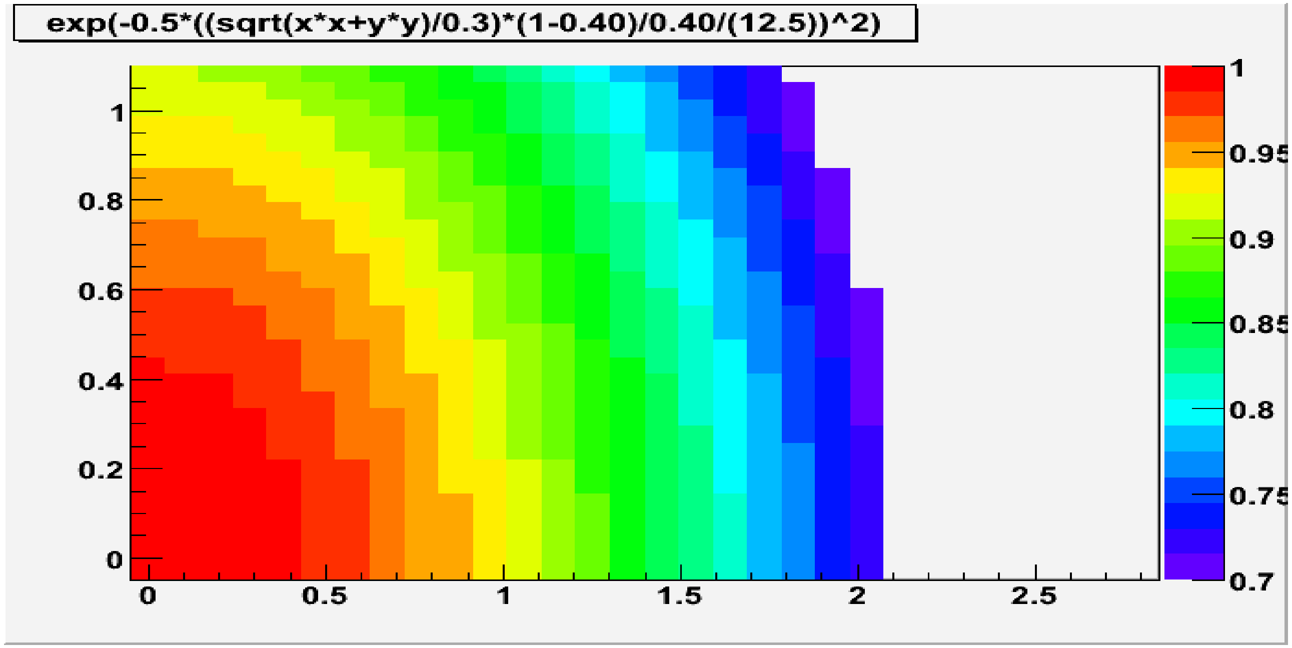
Silicon Strip Tracker layout:

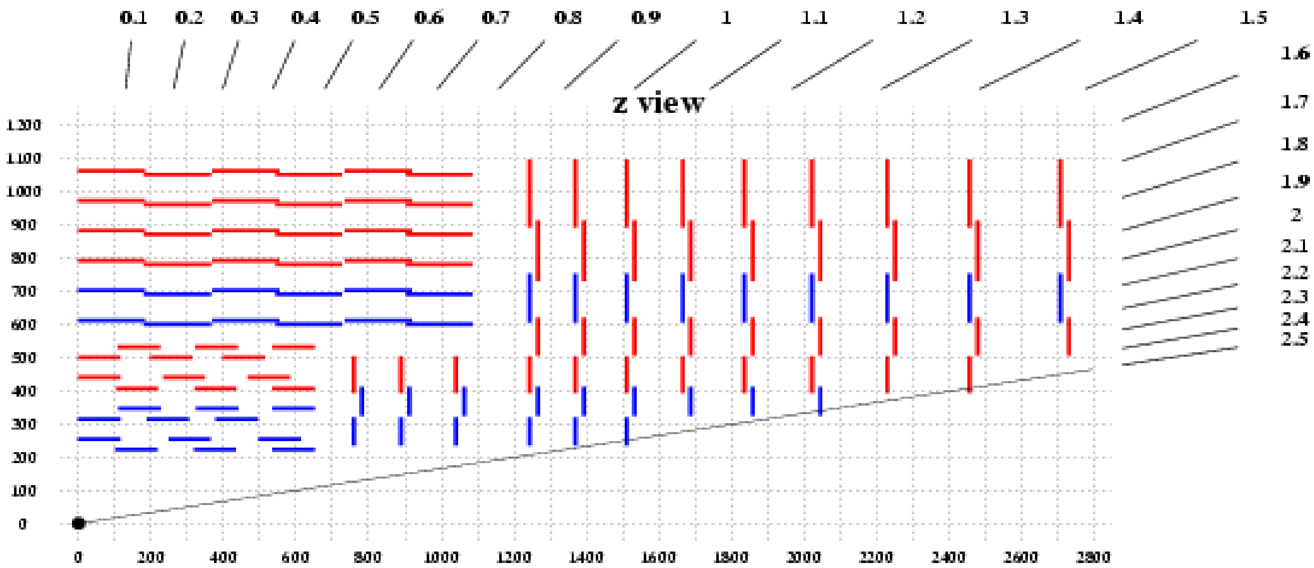


Signal attenuation in (x,y)

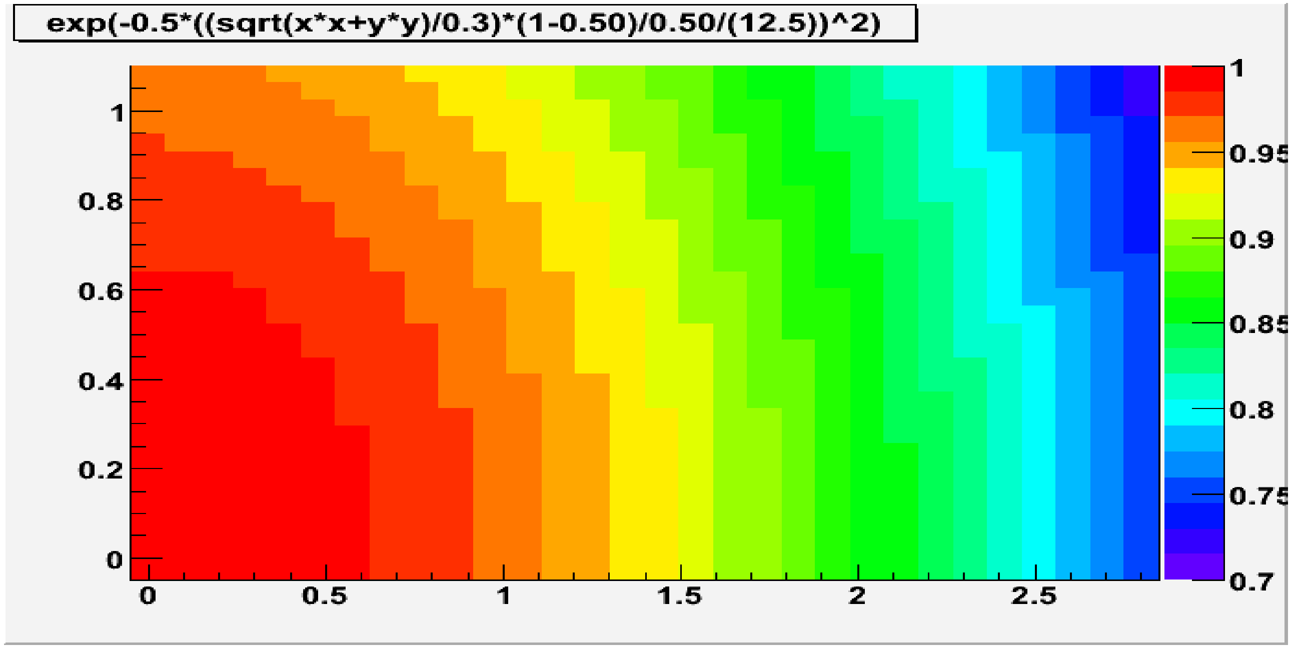
β=0.4:

P=0.4 GeV for protons
P=43 GeV for M=100 GeV



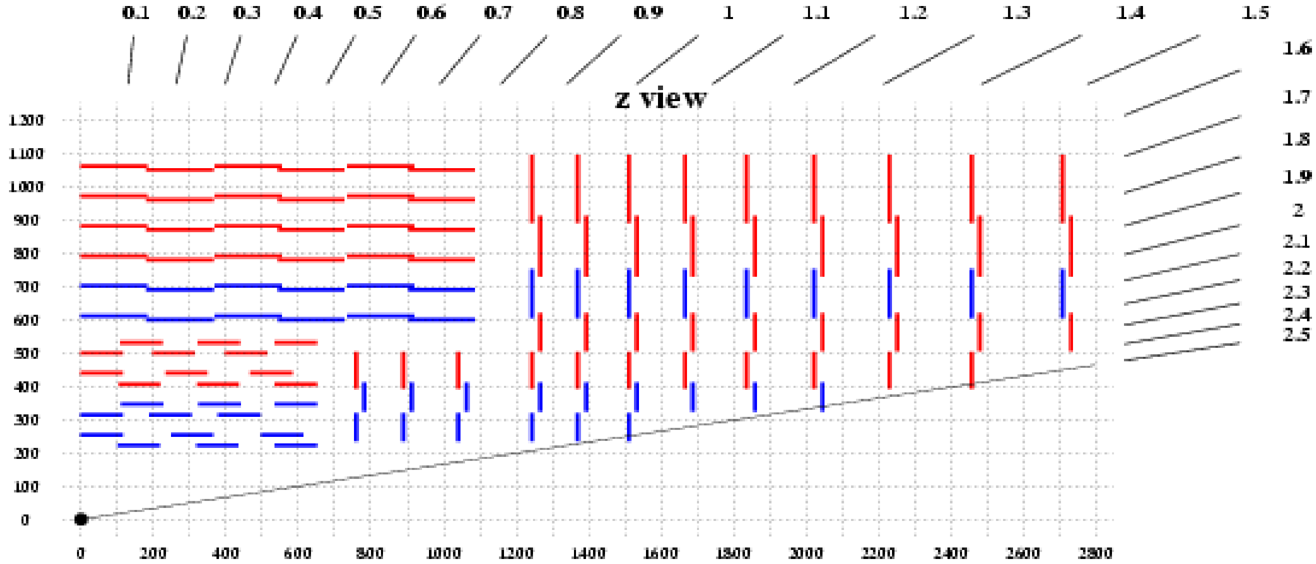


Signal attenuation in (x,y)

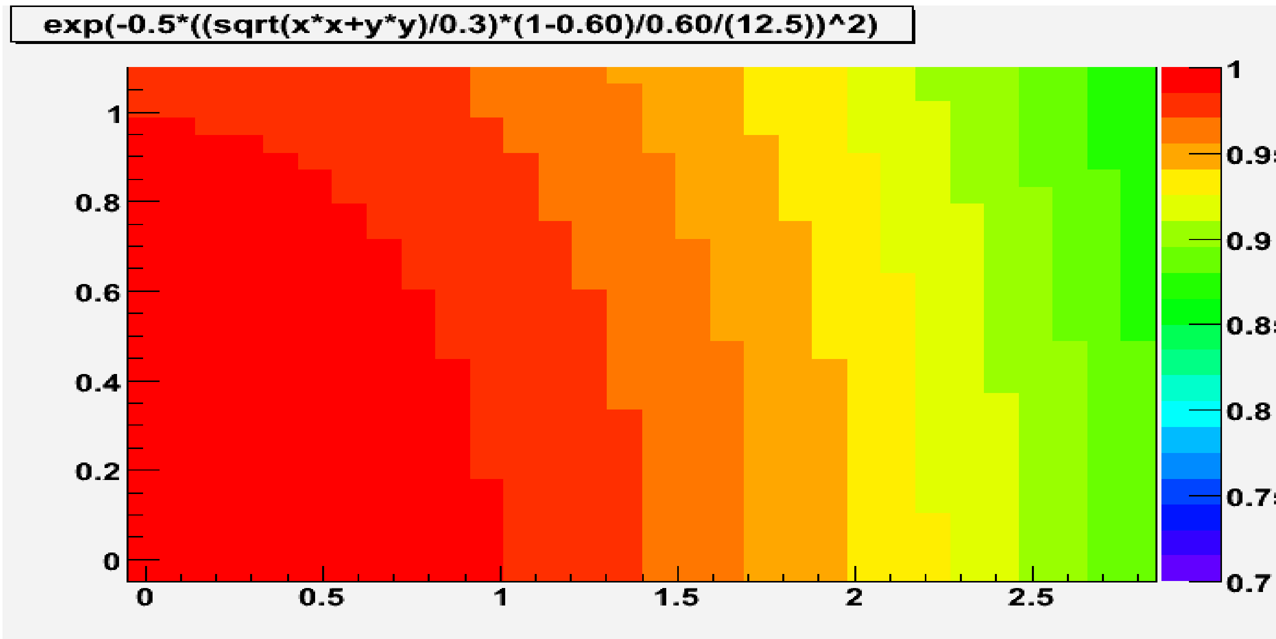


β=0.5:

P=0.55 GeV for protons
P=58 GeV for M=100 GeV

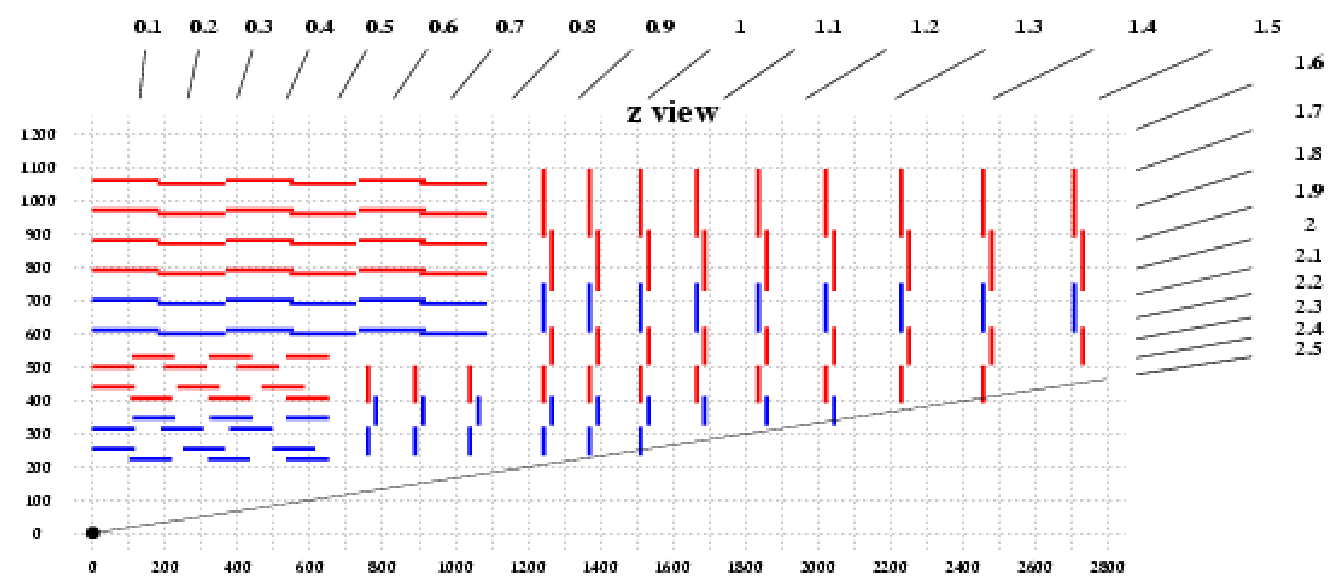


Signal attenuation in (x,y)



β=0.6:

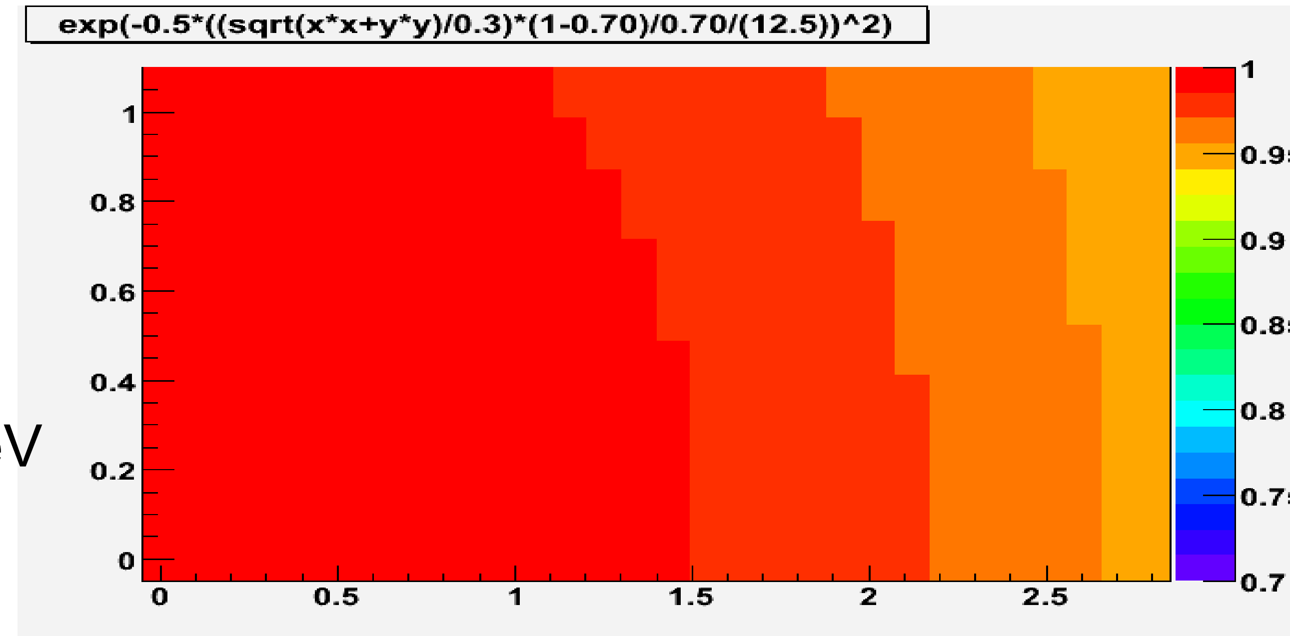
P=0.75 GeV for protons
P=75 GeV for M=100 GeV

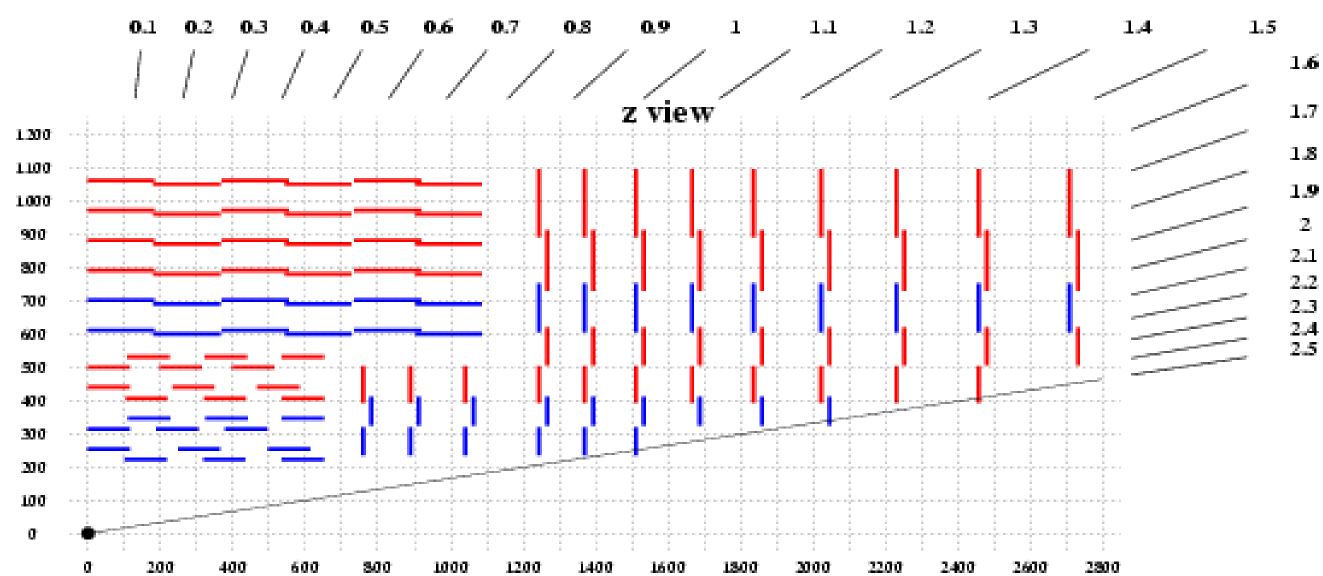


Signal attenuation in (x,y)

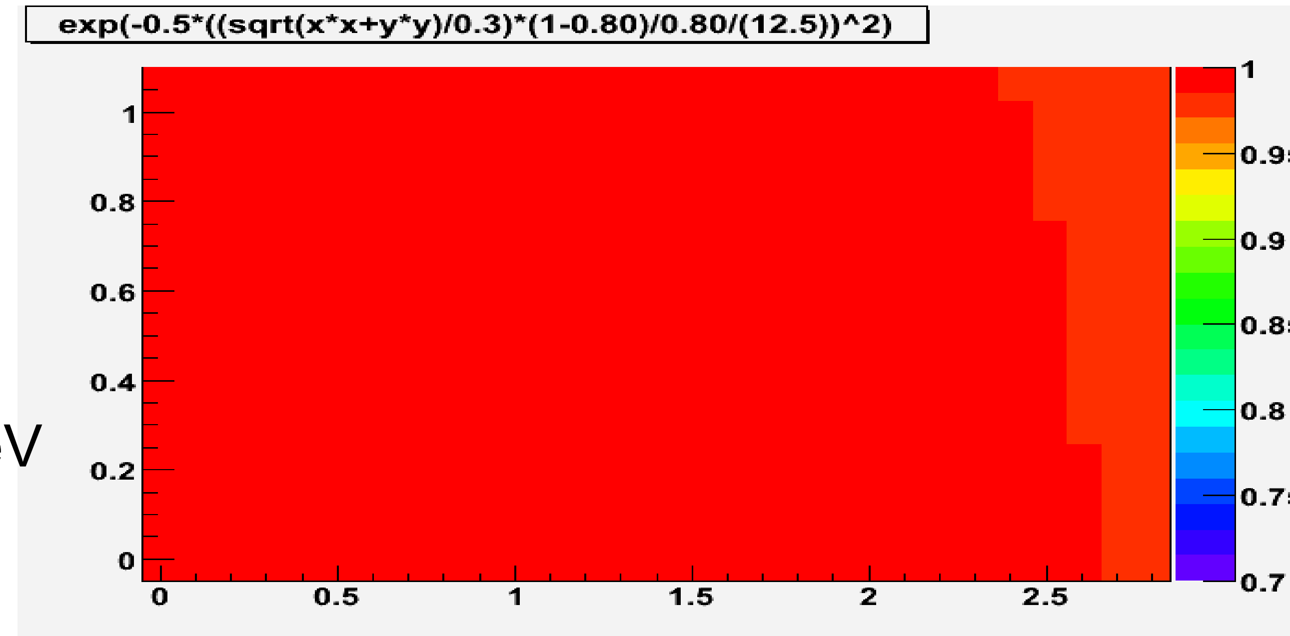
β=0.7:

P=1 GeV for protons
P=100 GeV for M=100 GeV





Signal attenuation in (x,y)



β=0.8:

P=1.3 GeV for protons
P=130 GeV for M=100 GeV