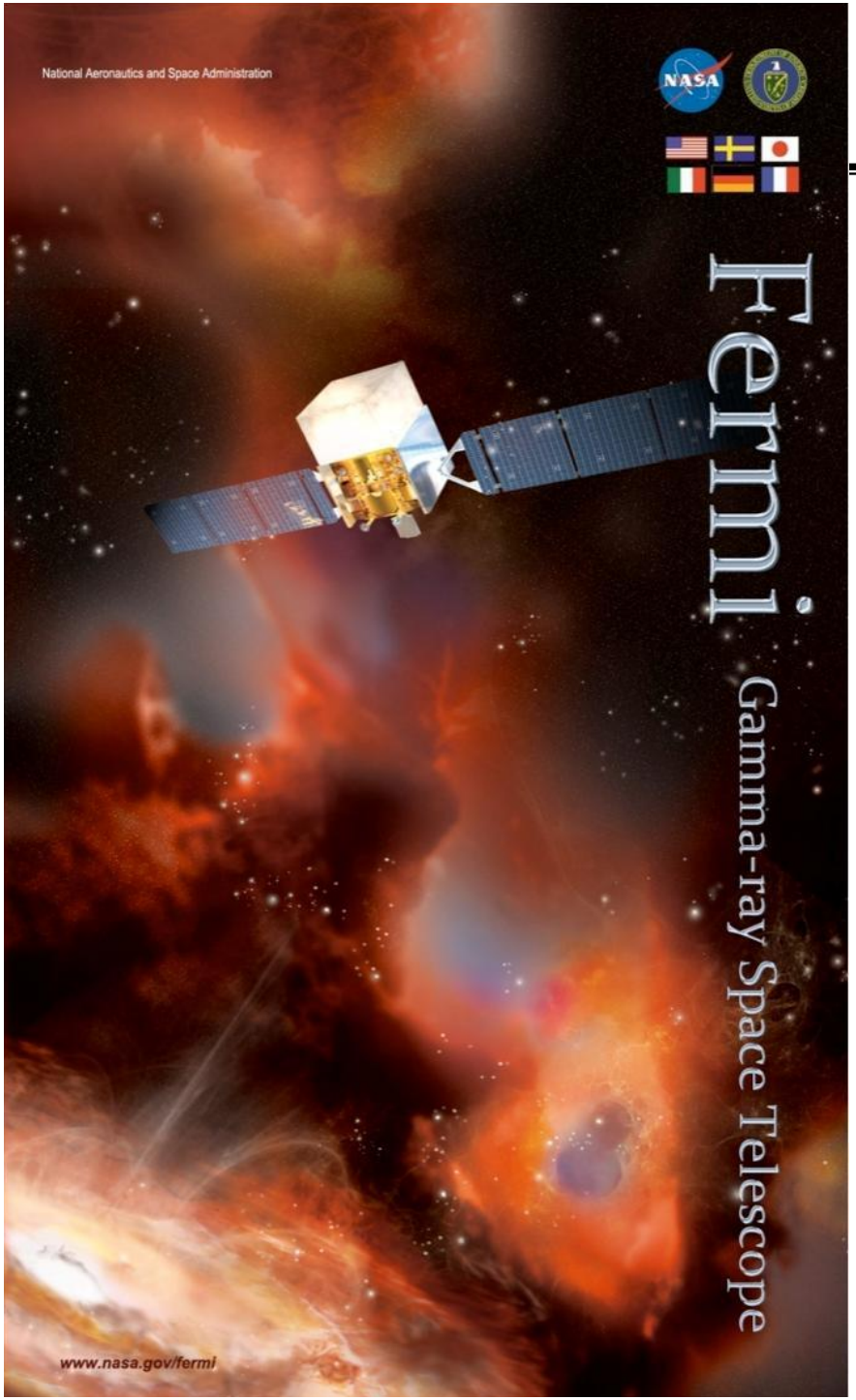

Fermi-LAT likelihood analysis (2)

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on behalf of the *Fermi*-LAT collaboration

Credits for the likelihood talks:
J. Chiang, S. Digel, F. Longo

Note on optimizers

From the “fhelp” tool on gtlike:

“Generally speaking, the fastest way to find the parameters estimation in the likelihood FERMI Science tool is to use DRMNGB (or DRMNFB) approach to find initial values and then use MINUIT (or NEWMINUIT) to find more accurate results.”

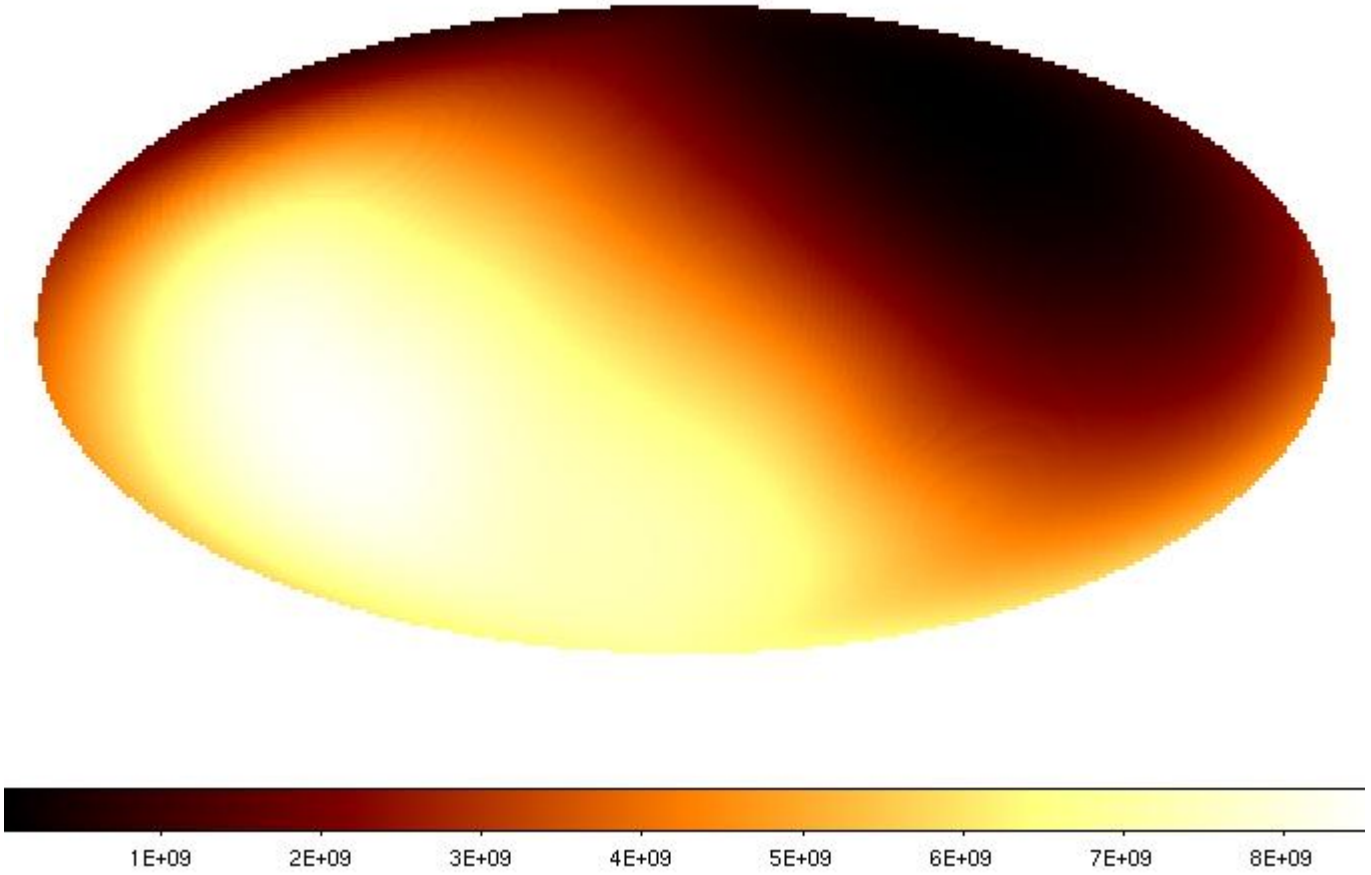
To do so, use the xml file output in the DRMNGB pass as an input for the MINUIT pass.

gtexpcube

Generates an exposure map, or a set of exposure maps for different energies. Units are $cm^2 s^{-1}$

```
/COSPAR < 88 >gtexpcube
This is gtexpcube version N/A
Exposure cube input file name[3c454_expcube.fits]
FT1 events input file name[3c454_100_300000_evt02.fits]
Count map input file name (NONE for manual input of map geometry)[NONE]
Exposure map output file name[3c454_exposure.fits]
Response function to use. Run gtirfs for a list[P6_V3_DIFFUSE]
Size of the X axis in pixels (leave at 1 for auto full sky (1:) [1]
Size of the Y axis in pixels (leave at 1 to copy nxpix or auto full sky) (1:) [1]
Image scale (in degrees/pixel)[1]
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [GAL]
First coordinate of image center in degrees (RA or galactic l)[0]
Second coordinate of image center in degrees (DEC or galactic b)[0]
Rotation angle of image axis, in degrees[0]
Projection method (AIT|ARC|CAR|ZEA|GLS|MER|NCP|SIN|STG|TAN) [AIT]
Start value for first energy bin[100]
Stop value for last energy bin[10000]
Number of logarithmically uniform energy bins[4]
How are energy layers computed from count map ebounds? (CENTER|EDGE) [CENTER] EDGE
Creating an Exposure object from file 3c454_expcube.fits
Using Aeff(s)
Combining exposure from the response function(s), specified by "P6_V3_DIFFUSE":
      P6_V3_DIFFUSE::FRONT
      P6_V3_DIFFUSE::BACK
Cutoff used: 6.12303e-17
Creating an Image, will write to file 3c454_exposure.fits
Generating layer 0 at energy 100 MeV  Aeff(0): 534.168 cm^2
Generating layer 1 at energy 316.228 MeV  Aeff(0): 4771.66 cm^2
Generating layer 2 at energy 1000 MeV  Aeff(0): 6980.26 cm^2
……..
```

gtexpcube (2)



Exposure map for 1 GeV for the 3C454.3 ROI

gtfindsrc

Optimizes a point source location using the likelihood test-statistic

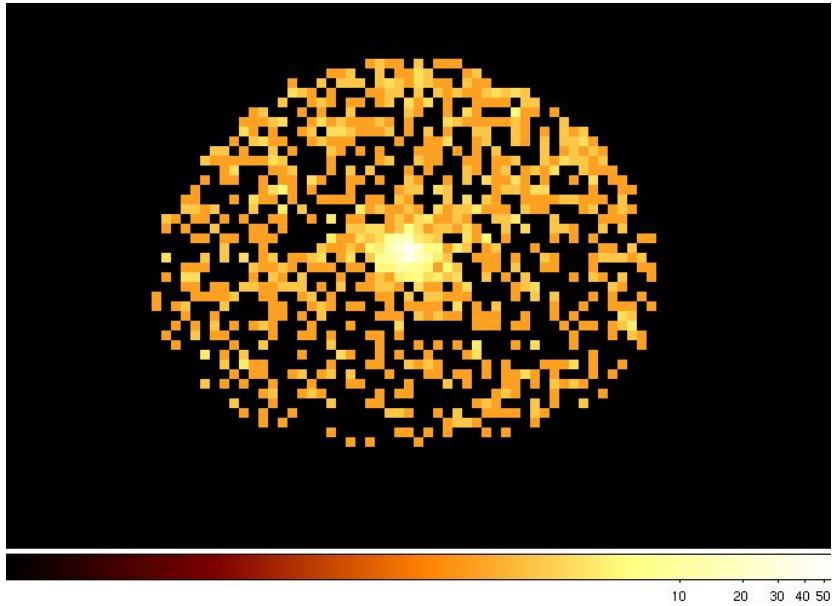
/COSPAR < 66 >**gtfindsrc**
Event file[3c454_100_300000_evt02.fits]
Spacecraft file[L090923112502E0D2F37E71_SC00.fits]
Output file for trial points[out_findsrc]
Response functions to use[P6_V3_DIFFUSE]
Livetime cube file[3c454_expcube.fits]
Unbinned exposure map[3c454_expmap.fits]
Source model file[3c454_srcmdl.xml]
Building source model from 3c454_srcmdl.xml
-log-likelihood of input source model: 326013
Target source name[3c454] _3c454
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [MINUIT]
Tolerance for -log(Likelihood) at each trial point[0.01]
Covergence tolerance for positional fit[0.01]
Best fit position: 343.517, 16.1597
Error circle radius: 0.0175704

gtobssim

Generate photon events from astrophysical sources and process those photons according to the specified instrument response functions

/obs < 161 >gtobssim

File of flux-style source definitions[obsSim_source_library.xml]
File containing list of source names[source_names.dat]
Pointing history file[../L090923112502E0D2F37E71_SC00.fits]
Prefix for output files[sim]
Simulation time (seconds)[86400]
Simulation start date[2009-07-02 00:00:00]
Apply acceptance cone?[yes]
RA of cone center (degrees) (-360:360) [343.5]
Dec of cone center (degrees) (-90:90) [16.15]
Acceptance cone radius (degrees) (0:180) [20]
Response functions[P6_V3_DIFFUSE]
Random number seed[293049]



added source "Extragalactic_diffuse"
added source "Galactic_diffuse"
added source "_3c454"
Generating events for a simulation time of 86400 seconds....
Warning: 268188711 seems to be in an invalid interval: it is 67.1292 seconds beyond the start of the current FT2 entry
----
Warning: 268188711 seems to be in an invalid interval: it is 67.36 seconds beyond the start of the current FT2 entry
Done.
132.096u 5.238s 2:29.17 92.0% 0+0k 0+0io 0pf+0w
/obs < 162 >

Photon file is sim_events_0000.fits

gtobssim (2)

/obs < 82 >more obsSim_source_library.xml

```
<!-- $Header -->
<source_library title="Source Library">
<source name="Galactic_diffuse">
      <spectrum escale="MeV">
        <SpectrumClass name="MapCube" params="25,../gll_iem_v02.fit"/>
        <use_spectrum frame="galaxy"/>
      </spectrum>
   </source>
<source name="Extragalactic_diffuse">
      <spectrum escale="MeV">
        <SpectrumClass name="Isotropic"
                  params="flux=10.7,gamma=2.1,emin=20.,emax=2e5,ra=0,dec=0,radius=180"/>
        <use_spectrum frame="galaxy"/>
      </spectrum>
    </source>
<source name="_3c454" flux="0.0980184334659">
     <spectrum escale="MeV">
       <particle name="gamma">
         <power_law emin="100.0" emax="1000000.0" gamma="2.46"/>
       </particle>
       <celestial_dir ra="343.5" dec="16.5"/>
     </spectrum>
</source>
</source_library>
```

/obs < 83 >more source_names.dat

```
Extragalactic_diffuse
Galactic_diffuse
_3c454
```

Plotting results

Assuming a power law model: $F(E) = dN/dE = F_0(E/E_0)^{-\Gamma}$

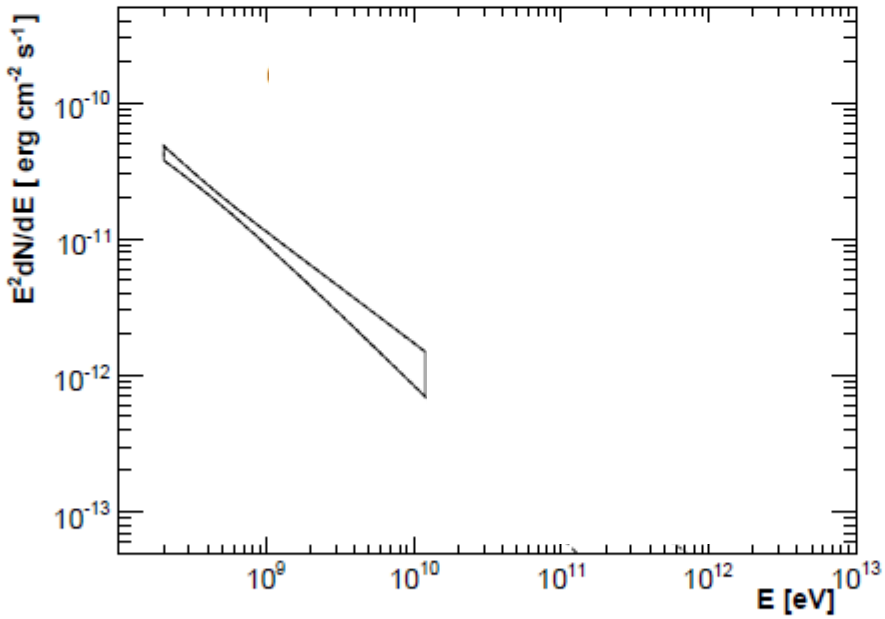
The uncertainty on F at a given energy E is:

$$\frac{\Delta F^2}{F^2} = \frac{\Delta F_0^2}{F_0^2} - \frac{2\,\mathrm{cov}(F_0,\Gamma)}{F_0}\log\left(\frac{E}{E_0}\right) + \Delta\Gamma^2\log^2\left(\frac{E}{E_0}\right)$$

which is minimum at: $E_d = E_0\exp[\mathrm{cov}(F_0,\Gamma)/F_0\,\Delta\Gamma^2]$

The cross term of the covariance matrix must be obtained using python….

Beware of the maximum energy:
the maximum energy of photons potentially coming from the source (small ROI) is an option.



covariance matrix

gtlike display output

Final values:
Normalizat = 0.615683
Integral = 1.57847
Index = 2.32047
Integral = 0.434516
Index = 2.21215
Integral = 1.57868
Index = 3.15148
Prefactor = 1.29008
Prefactor = 0.0235878
Index = 2.5075

parameters for source of interest

Minuit fit quality: 3 estimated distance: 0.0001474
Minuit parameter uncertainties:
1 0.0453642
2 0.154493
3 0.0684055
4 0.122061
5 0.151336
6 0.20743
7 0.148624
8 0.0425466
9 0.000754517
10 0.0205287

ΔF_0
$\Delta\Gamma$

EXTERNAL ERROR MATRIX. NDIM= 10 NPAR= 10 ERR DEF= .500
.206E-02 -.478E-03 -.219E-03 -.526E-03 -.586E-03 -.205E-02 -.737E-03 -.184E-02 -.444E-05 -.100E-03
-.478E-03 .239E-01 .737E-02 .253E-03 .215E-03 .988E-03 .194E-03 .140E-03 .158E-05 .172E-04
-.219E-03 .737E-02 .468E-02 .672E-04 .590E-04 .338E-03 .835E-04 .128E-03 .465E-06 .637E-05
-.526E-03 .253E-03 .672E-04 .149E-01 .151E-01 .907E-03 .224E-03 .281E-03 -.876E-05 -.150E-03
-.586E-03 .215E-03 .590E-04 .151E-01 .229E-01 .927E-03 .244E-03 .358E-03 -.948E-05 -.166E-03
-.205E-02 .988E-03 .338E-03 .907E-03 .927E-03 .430E-01 .176E-01 .152E-02 .213E-05 .346E-04
-.737E-03 .194E-03 .835E-04 .224E-03 .244E-03 .176E-01 .221E-01 .643E-03 -.239E-06 -.354E-05
-.184E-02 .140E-03 .128E-03 .281E-03 .358E-03 .152E-02 .643E-03 .181E-02 .297E-05 .797E-04
-.444E-05 .158E-05 .465E-06 -.876E-05 -.948E-05 .213E-05 -.239E-06 .297E-05 .569E-06 .129E-04
-.100E-03 .172E-04 .637E-05 -.150E-03 -.166E-03 .346E-04 -.354E-05 .797E-04 .129E-04 .421E-03

using python

```
from UnbinnedAnalysis import *
my_obs=UnbinnedObs('3c454_100_300000_evt02.fits',
                   scFile='L090923112502E0D2F37E71_SC00.fits',
                   expMap='3c454_expmap.fits',
                   expCube='3c454_expcube.fits',
                   irfs='P6_V3_DIFFUSE')
analysis= UnbinnedAnalysis (my_obs,'3c454_srcmdl.xml',optimizer='MINUIT')
print analysis
dir(analysis)
loglike=analysis.fit(covar=True)
print loglike
cov=analysis.covariance
print cov
analysis.plot()
analysis.model
print analysis['_3c454']
analysis.writeCountsSpectra("spectra.fits")
analysis.writeXml("results.xml")
analysis.sourceNames()
ts=analysis.Ts('_3c454')
npred=analysis.logLike.NpredValue('_3c454')
```

gets you the covariance matrix

/data(1)/Fermi_data/script.py

Upper limits

Some analysis results may be not statistically significant, $TS<TS_{thresh}$. Typically, $TS_{thresh}=25$ but it can be lower for some purposes.

The resulting flux should then not be considered as the real source flux.

An upper limit associated with a given confidence level (90% in the following) has then to be reported.

Ex: Catalog, light curves…

Profile Likelihood Intervals

meas n, meas. b

ML of b given s

$$\lambda(s) = \frac{\mathcal{L}(n, b_m | s, \hat{b}(s))}{\mathcal{L}(n, b_m | \hat{s}, \hat{b})}$$

$$-2\ln\mathcal{L}(n|s)$$

ML of b and s given observations

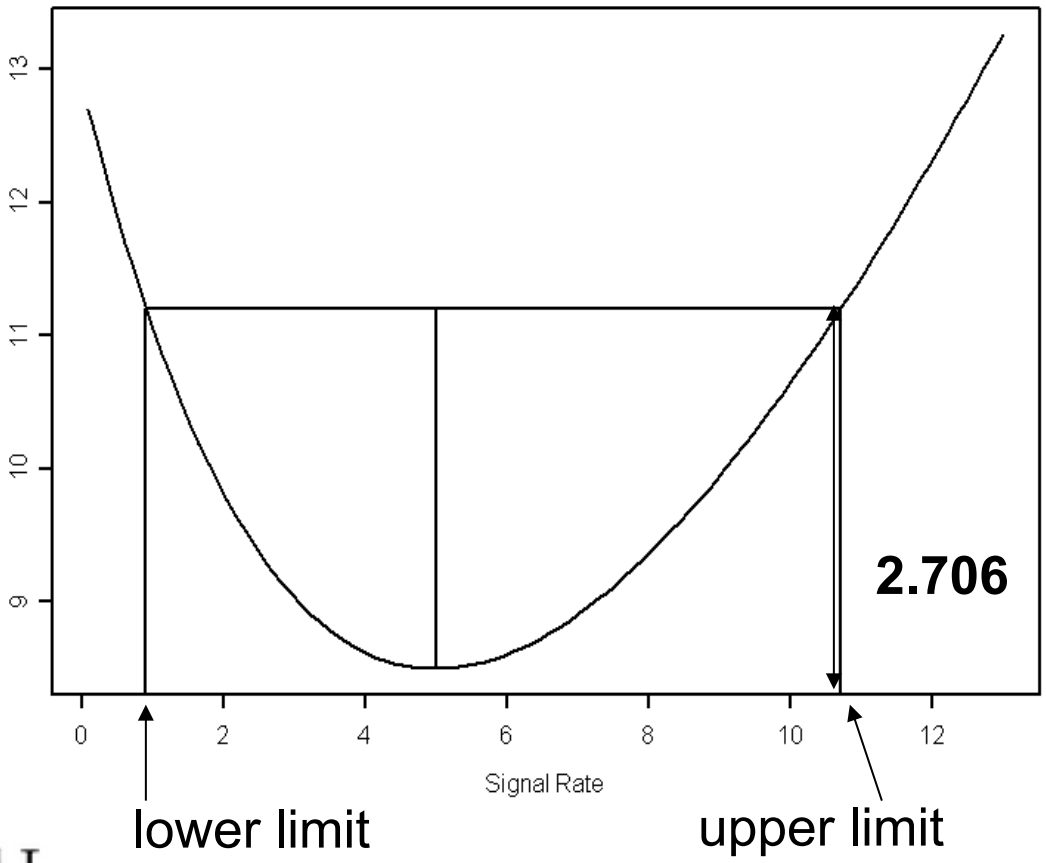
$\hat{s}, \hat{b}$ **fitted signal and background levels respectively**

To extract limits:

$$-2\ln\lambda \approx \chi^2$$

$$\chi^2 - \chi^2_{min} = 2.706 \quad \equiv 90\%\ \text{C.I.}$$

stolen from Jan Conrad



www.particle.kth.se/~conrad/NuFACT_25082006_Conrad.ppt

Computing the upper limit with python

```
from UnbinnedAnalysis import *
from UpperLimits import *
run the analysis as described earlier
Final values:
  Normalizat = 0.611601
  Integral   = 1.57993
  Index      = 2.32102
  Integral   = 0.43457
  Index      = 2.21217
  Integral   = 1.58454
  Index      = 3.15335
  Prefactor  = 1.29348
  Integral   = 15.6587
  Index      = 2.50804
ul=UpperLimits(analysis)
ul['_3c454'].compute()
>>> v1,v2=ul['_3c454'].compute()
0 15.6587330996 0.000156784255523 1.57338580306e-06
1 15.7965473761 0.0848209382384 1.58725912491e-06
2 15.9343616525 0.326505145233 1.60113212085e-06
3 16.0721759289 0.722714903357 1.61500547877e-06
4 16.2099902053 1.27068113437 1.6288792121e-06
5 16.3478044817 1.9678234919 1.64275331967e-06
>>> print v1
1.63055727541e-06
```

python scripting 101

Take a look at:

/data(1)/Fermi_data/script_loop.py