ATLAS-ALFA measurements on the total cross section and diffraction

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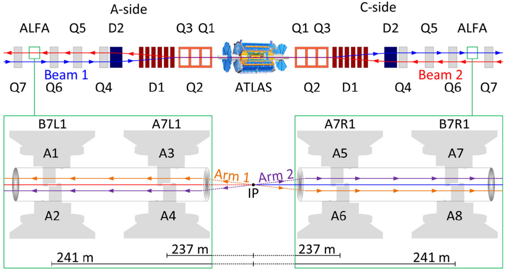
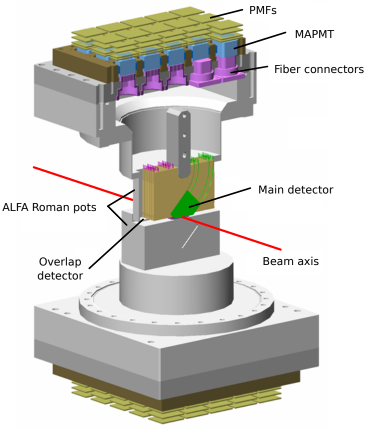
Outline:

- The ALFA detector
- Elastic scattering and total cross section measurement at $\sqrt{s} = 7$ TeV (main part)
- Diffractive prospects with ALFA
- Conclusion

The ALFA detector

- Build to measure elastically scattered protons at μrad angles.
- Located 240 m from the ATLAS interaction point (IP) inside Roman Pots.
- Approaches outgoing beams in vertical direction.
- The main detector (MD) is build of 10 $\times$ 2 orthogonal layers of scintillating fibers.
  - The fiber width of 500 μm and layer staggering gives $\approx$ 30 μm tracking resolution.
- The overlap detectors (OD) also use scintillating fibers and are used for detector alignment.
- Trigger tiles of scintillating plastic cover MDs and ODs.





[ATL-LUM-2010-001]

Elastic scattering and total cross section measurement at $\sqrt{s} = 7$ TeV

Total cross section - introduction

- The total cross section in pp collisions can't be calculated.
- From the optical theorem we get:

$$\sigma^2_{\text{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \frac{d\sigma_{\text{el}}}{dt}\Big|_{t=0}$$

- ρ is the ratio of the real and the imaginary elastic scattering amplitude at $t = 0$.
- The Mandelstam t-variable is given by $t \simeq -(p\theta^*)^2$.
- The scattering angle is calculated from ALFA tracks:

$$\begin{pmatrix} u \\ \theta_u \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} u^* \\ \theta^*_u \end{pmatrix} , \quad u = (x, y) \, .$$

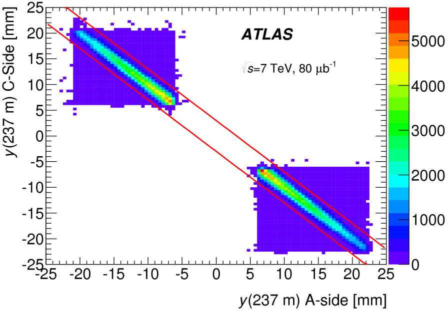
- Data are taken in runs with special beam optics where
  - $\beta^* = 90$ m in order to access small t-values since $-t_{\text{min}} \propto \frac{p^2}{\beta^*}$.
  - we have vertical parallel-to-point focusing: $\theta^*_y = \frac{y}{M_{12}}$
- The subtraction method is the nominal for the t-reconstruction:

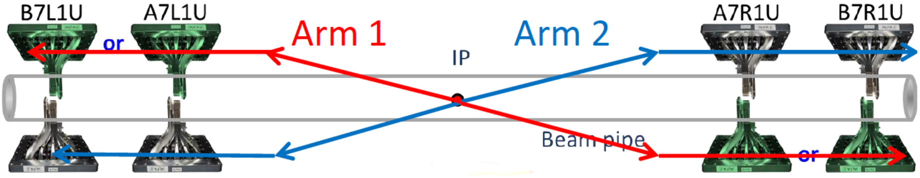
$$\theta^*_u = \frac{u_A - u_C}{M_{12,A} + M_{12,C}} \, .$$

- Different methods to reconstruct t is available using other matrix element combinations.

Elastic event selection

- Elastic events are selected with tracks in all four stations in an arm.
- The tracks are also required to fulfill certain correlations between inner-outer stations and between A-side and C-side.

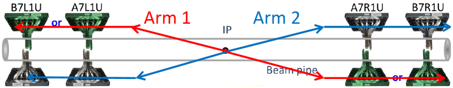




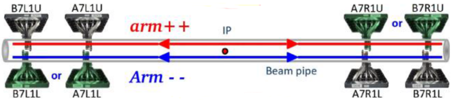
Background

- Sources of irreducible background is:
  1) two incident halo particle,
  2) a single diffractive proton and a halo particle,
  3) double pomeron exchange with two protons in ALFA.
- A t-spectrum for background is determined from anti-golden events by flipping the coordinates of one of the tracks.
- Background fraction is $\sim 0.5\%$ and halo+halo is the dominant source.

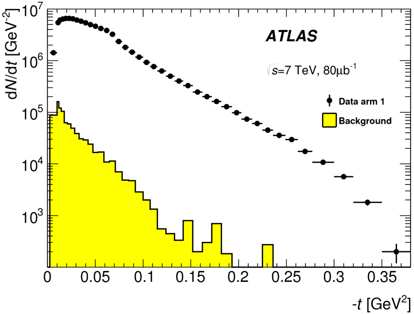
Golden elastic topology



Anti-golden topology

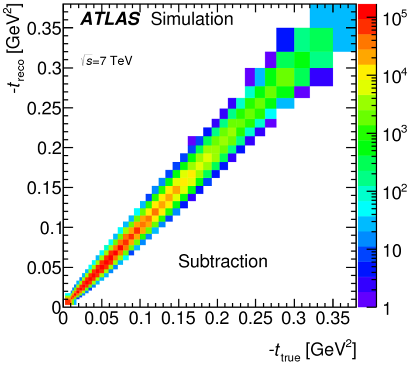


Reconstructed t-spectrum

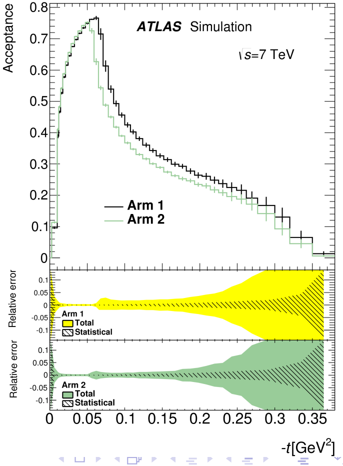


- The measured t-spectrum is affected by detector resolution and acceptance and must be corrected for these effects.
- PYTHIA8 used as elastic scattering generator.
- Beam transport from IP to ALFA done using MadX.
- Simulated tracks are used to find a reconstructed t.
- Transition matrix used to unfold the raw t-spectrum.

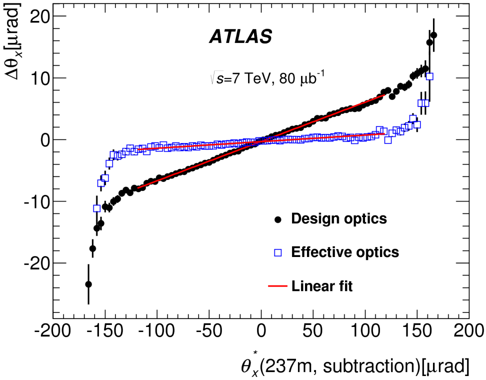
Transition matrix



Acceptance



- The beam optics has direct influence on the *t*-reconstruction through the transport matrix.
- The different *t*-reconstruction methods should give same answer but they don't with initial **design** optics.
- Elastic data are used to constrain an optics fit whereby an **effective** optics in obtained.



Theoretical prediction

- The differential elastic cross section is a superposition of the strong interacting amplitude f_N and the Coulomb amplitude f_C added in quadrature

$$\frac{d\sigma_{el}}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2 .$$

- This gives the following fit function to the elastic data:

$$\frac{d\sigma_{el}}{dt} \propto \frac{G^4(t)}{|t|^2} - \frac{\boldsymbol{\sigma}_{\mathbf{tot}} G^2(t)}{|t|}\left[\sin(\phi(t)) + \rho\cos(\phi(t))\right]\cdot\exp\left(\frac{-\mathbf{B}|t|}{2}\right) + \boldsymbol{\sigma}_{\mathbf{tot}}^2(1+\rho^2)\cdot\exp(-\mathbf{B}|t|)$$

$$G(t) = \left(\frac{\Lambda}{\Lambda + |t|}\right)^2$$ Proton dipole form factor

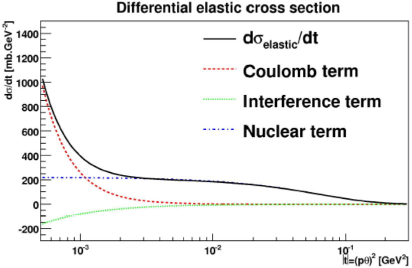
$$\phi(t) = -\ln\left(\frac{B|t|}{2}\right) - \phi_C$$ Coulomb phase

$$\rho = 0.14$$

$$\Lambda = 0.71\ \text{GeV}^2$$

$$\phi_C = 0.577$$

Simulation



$\sigma_{tot} = 100$ mb , $B = 18$ GeV^{-2} , $\rho = 0.13$

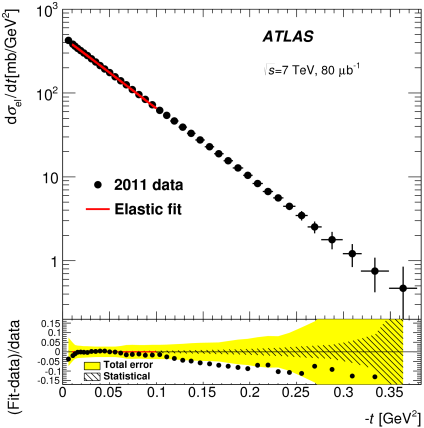
Differential elastic cross section

- The t-spectra in the two arms are corrected for different effects and added together.

$$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{t_i} \cdot \frac{M^{-1}[N_i - B_i]}{A_i \cdot \varepsilon^{\text{reco}} \cdot \varepsilon^{\text{trig}} \cdot \varepsilon^{\text{DAQ}} \cdot L}$$

A: Acceptance(t)
M: Unfolding procedure (symbolic)
N: Selected events
B: Estimated background
$\varepsilon^{\text{reco}}$: Track reconstruction efficiency
$\varepsilon^{\text{trig}}$: Trigger efficiency
ε^{DAQ}: Dead-time correction
L: Luminosity

- The spectrum is fitted in $0.01\ \text{GeV}^2 \leq -t \leq 0.1\ \text{GeV}^2$.



- The results including all statistical and systematical uncertainties are:

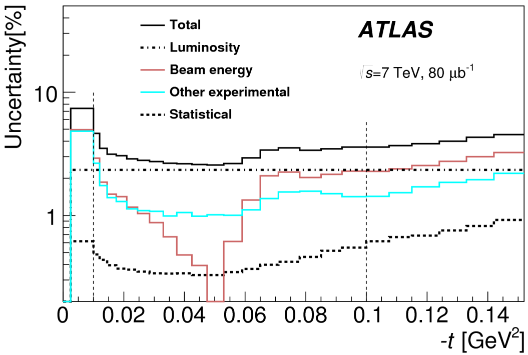
$$\sigma_{\text{tot}} = 95.4 \pm 1.4\ \text{mb}$$

$$B = 19.73 \pm 0.24\ \text{GeV}^{-2}$$

Uncertainties

- The dominant overall systematic uncertainty comes from luminosity.
- Dominant t-dependent systematic uncertainty comes from beam energy.
- The statistical uncertainty is small.
- The extrapolation error is only $\Delta\sigma_{tot} = \pm 0.4$ mb , $\Delta B = \pm 0.17$ GeV^2 and includes:
  - variation of the fit range
  - different theoretical models

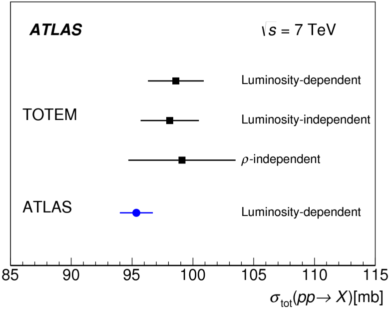
Uncertainties for $\frac{d\sigma_{el}}{dt}$



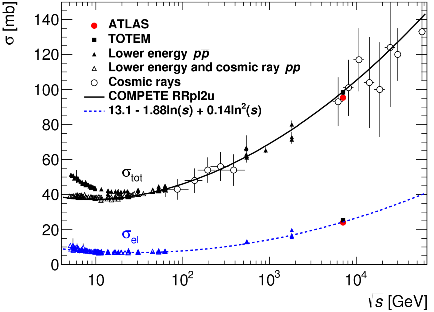
Results for the total cross section

- The ALFA measurement gives $\sigma_{tot} = 95.4 \pm 1.4$ mb
- ALFA provides the most precise measurement of the total cross section at $\sqrt{s} = 7$ TeV.
  - Compared to TOTEM, we benefit from a more precise luminosity measurement.
- The evolution of $\sigma_{tot}(s)$ is described by COMPETE RRpl2u.

Comparison with other measurements



Energy evolution of σ_{tot}



Result for elastic and in-elastic cross section

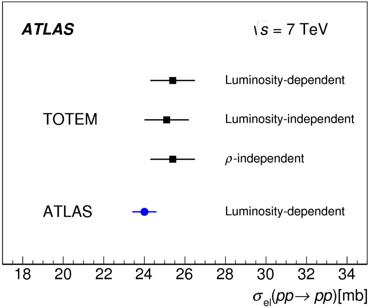
- The elastic cross section is found as the integrated nuclear differential cross section

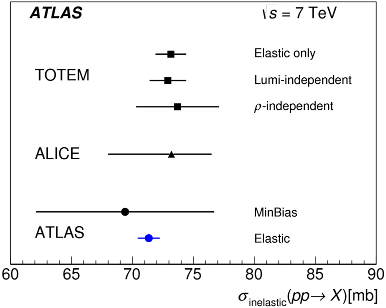
$$\sigma_{el} = \int_{t=0}^{t=\infty} \sigma_{tot}^2 \frac{1+\rho^2}{16\pi(\hbar c)^2} \cdot \exp(-B|t|)dt = 24.00 \pm 0.60 \text{ mb}$$

- The inelastic cross section is found as

$$\sigma_{inelastic} = \sigma_{tot} - \sigma_{el} = 71.34 \pm 0.90 \text{ mb}$$

- For both measurements, the uncertainties are substantially reduced, in particular wrt. the ATLAS MinBias inelastic cross section.

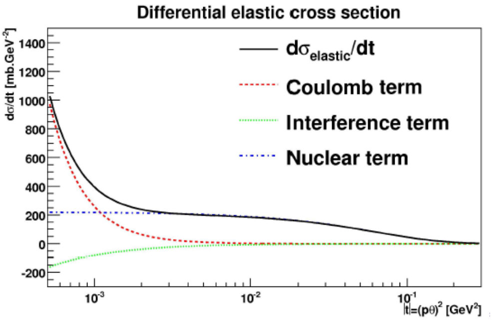




Outlook for elastic and total cross section measurements:

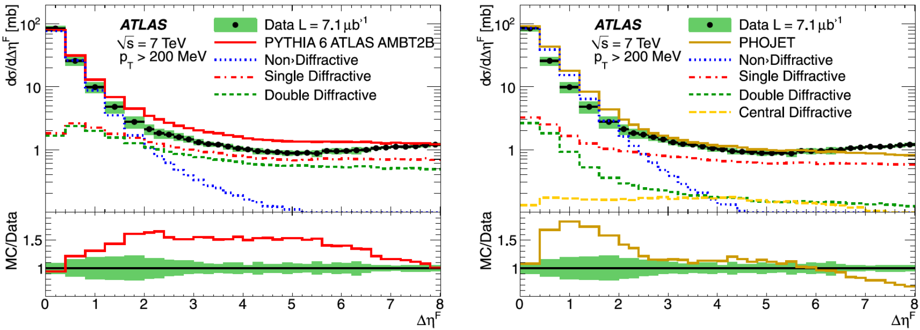
- The analysis of data from $\sqrt{s} = 8$ TeV with same optics is ongoing.
- Data will be collected at $\sqrt{s} = 13$ TeV with same optics.
- Data with a $\beta^* = 1$ km optics at $\sqrt{s} = 8$ TeV has been collected.
  - The purpose is to observe the rise of the elastic cross section at small t due to CNI.
  - A measurement of the ρ-parameter might be possible with enough CNI events.
- A run with $\beta^* \approx 2$ km optics at $\sqrt{s} = 13$ TeV is planned where a larger amount of CNI can be obtained.
  - The Coulomb term can be calculated and thus gives a further constrain to the $d\sigma/dt$ fit.
  - This will give a luminosity independent measurement of σ_{tot} and provide luminosity calibration to ATLAS.

Reminder: $-t_{min} \propto \frac{p^2}{\beta^*}$

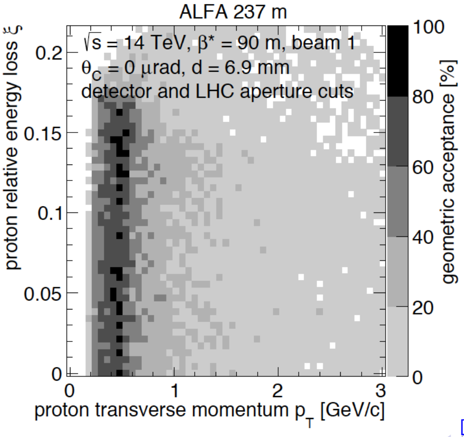


Diffractive prospects with ALFA

- Rapidity gaps are characteristic for diffractive processes.
- ATLAS has measured rapidity gaps in $-4.9 < \eta < 4.9$ using the calorimeters.
  - Deviations from both PYTHIA and PHOJET are observed.
- ALFA has an acceptance of $8.5 \lesssim |\eta| \lesssim 10.5$
- Using ALFA+ATLAS data, the true rapidity gap in diffractive events between the proton and the dissociated system can be measured.



- ALFA can also provide kinematic information about diffractively scattered protons.
- The transport matrix for diffractive events include also the energy of the proton.
- The inversion is possible with ALFA tracks and a vertex in ATLAS.
- The kinematic acceptance in ALFA depends on the optics but is rather good at $\beta^* = 90$ m.



[ATLAS-TDR-024]

Analyses with 7 and 8 TeV data are ongoing, e.g.

- Central exclusive production (CEP): $p+p \rightarrow p+X+p$
  - Protons measured by ALFA, dissociated system by ATLAS.
  - The anti-golden topology provides information about the elastic background sample.
- Single diffraction: $p+p \rightarrow p+X$.
  - Proton measured by ALFA, (part of) dissociated system by ATLAS.

Analyses with 13 TeV data:

- Similar studies will be carried out with 13 TeV, $\beta^* = 90$ m data.
- Upgrade of trigger menu gives much more statistics for CEP processes.
- Data collected with ATLAS and LHCf at $\beta^* = 19$ m allows:
  - Combined analyses with e.g. measurement of π^0 spectrum in diffractive events.
  - Measurement of $d\sigma/dt$ in single diffraction at another kinematic acceptance than with $\beta^* = 90$ m.

Conclusion

- The most precise measurement of the total cross section at $\sqrt{s} = 7$ TeV has been measured by the ALFA detector:

$$\sigma_{tot} = 95.4 \pm 1.4 \text{ mb} .$$

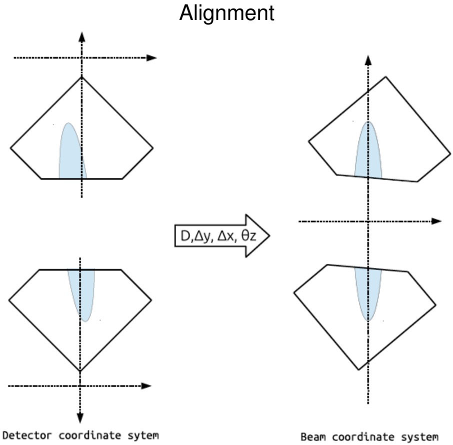
- ALFA has the possibility to perform a luminosity independent total cross section measurement using data in the CNI region.
- ALFA is able to track intact protons from diffractive collisions and thereby
  - significantly extend the η-range of ATLAS for rapidity gap measurements.
  - provide kinematic information about diffractively scattered protons.

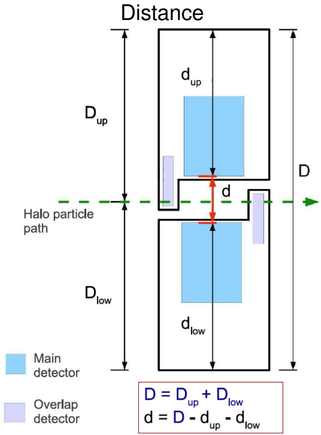
Thanks for your attention

Back Up

Back Up - Detector alignment

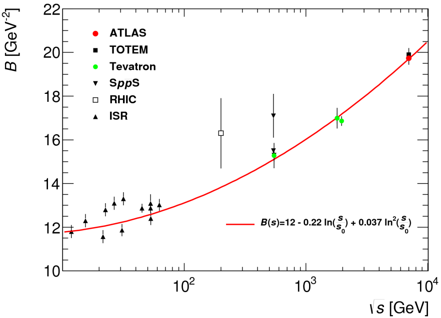
- The ALFA detectors are aligned to the coordinate system of the beam:
  - Distance between upper and lower detector is found using halo particles in ODs.
  - Horizontal alignment and rotation of detectors are found using elastic events assuming isotropic scattering in azimuth angle.





Back Up - Results for the nuclear B-slope

- ALFA measurement: $B = 19.73 \pm 0.24\ \text{GeV}^{-2}$
- Pre-LHC expectations was a linear evolution of the B-slope with $\ln(s)$
- LHC measurements of the B-slope favours a second $\ln^2(s)$ term.



Back Up - *t*-reconstruction methods

- Subtraction method:

$$\theta_u^* = \frac{u_A - u_C}{M_{12,A} + M_{12,C}} \;, \quad u = x, y$$

- Local angle method method:

$$\theta_x^* = \frac{\theta_{x,A} - \theta_{x,C}}{M_{22,A} + M_{22,C}} \;, \quad \theta_y^* \text{ as for subtraction}$$

- Local subtraction method:

$$\theta_{x,S}^* = \frac{M_{11,S}^{241} \cdot x_{237,S} - M_{11,S}^{237} \cdot x_{241,S}}{M_{11,S}^{241} \cdot M_{12,S}^{237} - M_{11,S}^{237} \cdot M_{12,S}^{241}} \;, \quad S = A, C \;, \quad \theta_y^* \text{ as for subtraction}$$

- Lattice method:

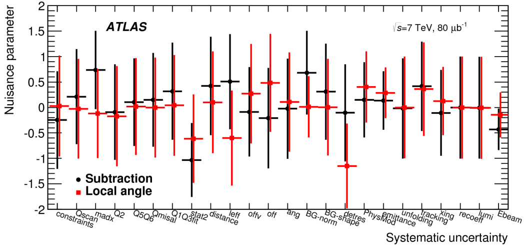
$$\theta_x^* = M_{12}^{-1} \cdot x + M_{22}^{-1} \cdot \theta_x \;, \quad \theta_y^* \text{ as for subtraction}$$

Back Up - Fitting the t-spectrum: Profile method

The statistical covariance matriz accounting for correlations between t-bins after unfolding and systematic uncertainties are included through nuisance parameters in a modified χ^2 minimization:

$$\chi^2 = \sum_{i,j} \left(ex(i) - \left(1 + \sum_l \alpha_l\right) \cdot th(i) - \sum_k \beta_k \cdot \delta^k(i) \right) \cdot cov^{-1}(i,j)$$
$$\cdot \left(ex(j) - \left(1 + \sum_l \alpha_l\right) \cdot th(j) - \sum_k \beta_k \cdot \delta^k(j) \right) + \sum_k \beta_k^2 + \sum_l \frac{\alpha_l^2}{\varepsilon^2} ,$$

$cov(i,j)$ = stat. cov matrix
$\delta_k(i)$ = nuisance parameters
α_l = parameters for normalisation errors
ε_l = normalisation errors
β_k = parameters for shape error



Back Up - Study of alternative models

- Several models for the nuclear amplitude featuring a non-exponential behavior are tested.
- All models come with more parameters and are intended to be extended to larger t.

1. Fit with Ct^2 term

$$f_N(t) = (\rho + i)\frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2 - Ct^2/2}$$

2. Fit with $\sqrt{t}$ term

$$f_N(t) = (\rho + i)\frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2 - c/2(\sqrt{4\mu^2 - t} - 2\mu)}$$

3. SVN model

$$f_N(t) = \rho\frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_R t/2} + i\frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_I t/2}$$

4. BP model

$$f_{\text{el}} = i\left(G^2(t)\sqrt{A}e^{-Bt/2} + e^{i\phi}\sqrt{C}e^{-Dt/2}\right)$$

5. BSW model

$$\Re[f_{\text{el}}(t)] = c_1(t_1 + t)e^{-b_1 t/2}$$
$$\Im[f_{\text{el}}(t)] = c_2(t_2 + t)e^{-b_1 t/2}$$