Proton Scattering and Losses in HL-LHC

8th HL-LHC Collaboration Meeting

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CERN

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Contents

Motivation:

▶ A need for a realistic prediction of pile-up and beam lifetime for HL-LHC (Work Package 8).

▶ Pile-up: $81 \pm 3\,\mathrm{mb}$ (inelastic).
Source: Expected Pileup Values at the HL-LHC .

▶ A need to understand where the protons scattered by elastic and single diffractive processes end up in the machine (magnets, TAN, TAS, collimators).
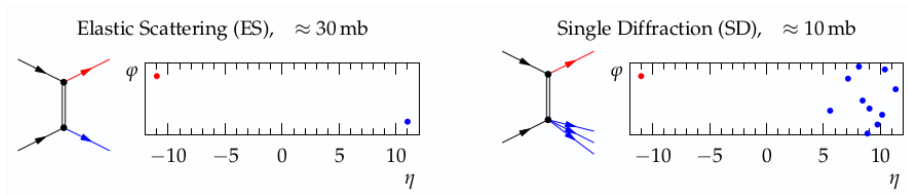

Figure: From Kaspar, Jan. 'Elastic Scattering at the LHC'. PhD Thesis, Charles University, 2012 .

Currently Being Studied in Parallel with Code Development:

- ► Losses in the LHC from protons "surviving" elastic and single diffractive scattering events at the experiments.
- ► Tracking these protons for a few turns with detailed aperture checks for the full machine.
- ► Tracking with collimation enabled and RF @ 16 MV.
- ► Special interest in the losses in Q1–6 and the arc.

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▶ Extensions to the tracking simulation code still in development.

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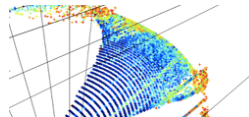- ▶ Extensions to the tracking simulation code still in development.

Planned Continuation:

- ▶ Study of momentum acceptance in apertures.
- ▶ Improvements to the aperture checking code (collimation group).
- ▶ Possibility to revisit beam–gas, but requires further code extensions.

SixTrack – 6D Tracking Code
CERN – BE/ABP Accelerator Beam Physics Group

SixTrack is a single particle 6D symplectic tracking code optimized for long term tracking in high energy rings. It is mainly used for the LHC for dynamic aperture studies, tune optimization, and collimation studies.
http://sixtrack.web.cern.ch

► Multiple modules are available to extend SixTrack for other types of studies, including failure studies, beam–gas, aperture losses, FMA, dynamic kicks, and more. It also runs on BOINC for LHC@Home.

► Supports integration with other simulation codes like Fluka and Geant4, as well as generic interfaces for passing particles to and from external tools.

► Output formats include plain text, HDF5 and ROOT.
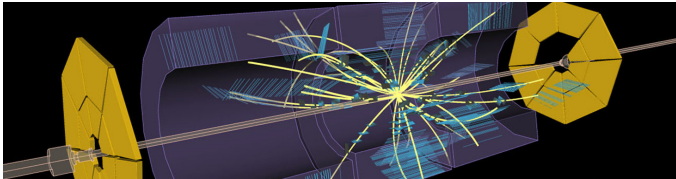
Scatter Module Extension – Proposal (2017):

► Presented by Helmut Burkhardt and Kyrre Sjobak in March/April 2017.

► Intended as a quick way of evaluating the effect of proton–proton elastic scattering at the IPs, and where they end up in the machine.
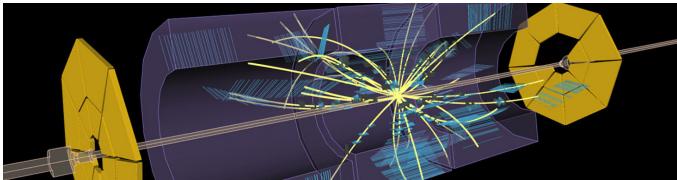
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Implemented:

► Elastic event generator written by Helmut Burkhardt based on a fit to experimental data TOTEM.

► First implementation by Kyrre Sjobak and myself in late 2017.

► Currently being extended to allow for diffractive scattering.

Currently: Extending SixTrack to allow for diffractive scattering.

Linking SixTrack and Pythia8:

- ▶ This is done via the `PYTHIA` compiler flag.
- ▶ This builds a C–Fortran interface making Pythia's event generator accessible directly in SixTrack.
- ▶ The event generator can be configured in SixTrack's standard input file.

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Pythia SoftQCD Processes Available in SixTrack:
- ▶ Elastic with or witout Coulomb
- ▶ Single Diffractive (with or without losses)
- ▶ Central Diffractive (with or without losses)
- ▶ Double Diffractive (lost particle)

Generated Internally in SixTrack

- ▶ Based on a simple parametrisation of 13 TeV TOTEM data.

- ▶ Presented by Helmut Burkhardt in 2017 in LHC Background Study Meeting #81.

- ▶ It samples the Mandelstam variable t based on a set of fit parameters a, b_1, b_2 and ϕ.

- ▶ It also takes a t_{min} cut-off to force the generation of larger angles.
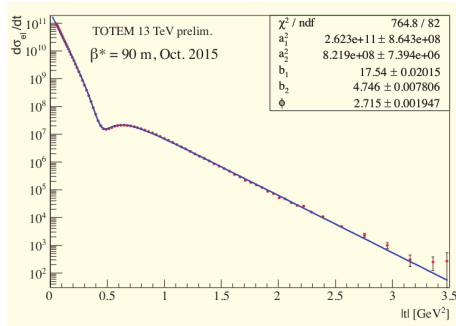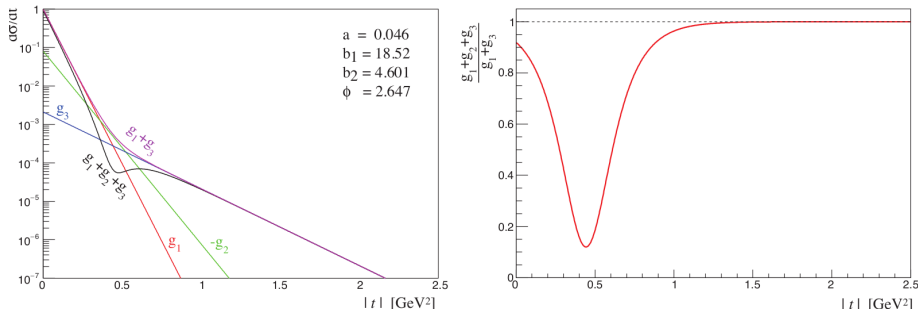
- ▶ Exponential fits to soft/hard scatter and the interference region.
- ▶ Randomly select 1st or 3rd term.
- ▶ Get exact $g(t)$ w/hit & miss on 2nd term.

$$g(t) = \frac{1}{a_1^2}\frac{\mathrm{d}\sigma}{\mathrm{d}t} = e^{-b_1 t} + 2ae^{(b_1+b_2)t/2}\cos\phi + a^2 e^{-b_2 t}$$

Applying Pythia Single Diffractive Events to SixTrack Particles

▶ Single Diffractive events are generated as needed by Pythia.

▶ We use back–to–back 7 TeV events generated 1000 at a time.

▶ Momentum loss is extracted from the i–th event:

$$\frac{\Delta \mathbf{p}_i}{\mathbf{p}_i} = \frac{\mathbf{p}_{i,3} - \mathbf{p}_{i,1}}{\mathbf{p}_{i,1}}, \qquad t_i = (p_{i,1} - p_{i,3})^2,$$

where p_1 is the incoming particle and p_3 is the outgoing particle.

▶ The relative momentum loss is then projected onto an actual SixTrack beam particle j, and the scattering angle calculated:

$$\mathbf{p}_j = (1 + \Delta \mathbf{p}_i / \mathbf{p}_i) \mathbf{p}_{j_0}, \qquad E_j = \sqrt{\mathbf{p}_j^2 + m_j^2},$$

$$\theta_j = \cos^{-1} \left(1 - \frac{t_i}{2\mathbf{p}_j^2 (1 + \Delta \mathbf{p}_i / \mathbf{p}_i)} \right),$$

where $\mathbf{p}_{j_0}$ is the particle momentum before scattering, and $\mathbf{p}_j$ after.

Test Case Setup

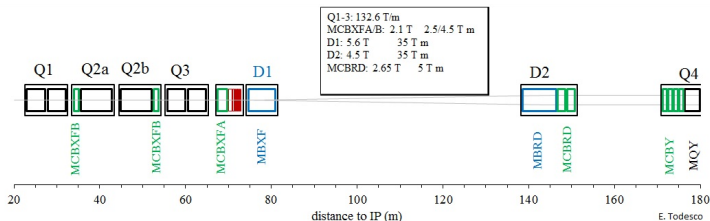- ► Single diffractive scattering in IP5 for one turn only (turn 3).
- ► Scaled up scattering probability to 90% (realistic is $\approx 6\,\mathrm{mb}$).
- ► A single bunch of 500 000 protons, 2.5 $\mu\mathrm{m}$ emittance and the HL-LHC lattice @ 30m VDM.
- ► Tracking with RF at 16 MV for 20 turns.

Simulation Test Case
Single Diffractive in IP5

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Aperture Limits

- ▶ Aperture checks every $10\,\mathrm{cm}$.
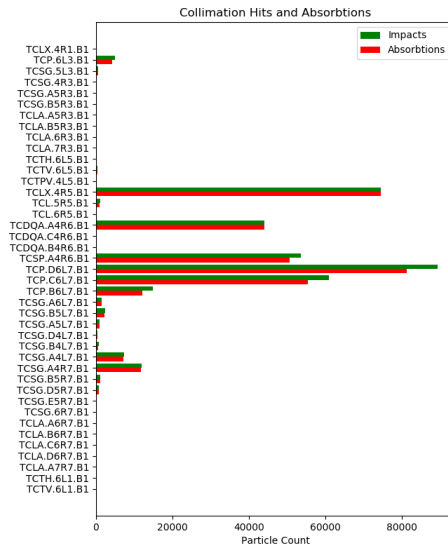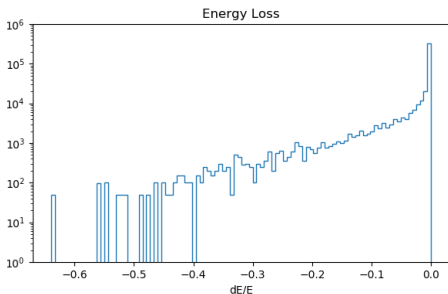- ▶ Underestimates losses in D1/TAN as offest is not currently considered.
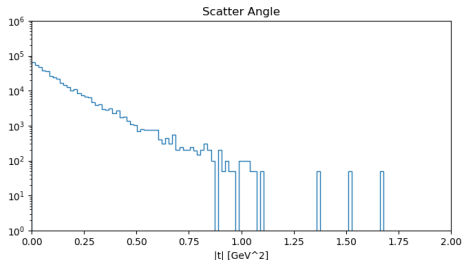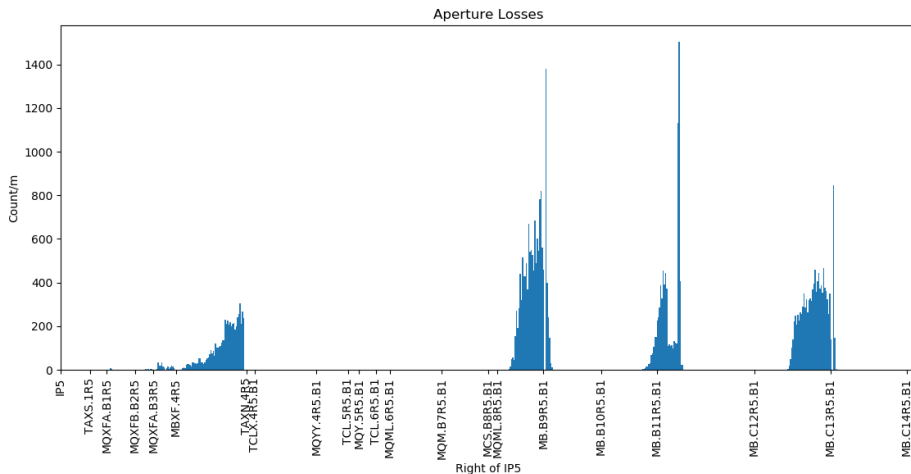
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Spectrum of energy loss, scattering "angle" |t| & Collimators.

Aperture Loss Counts in the First 600 m after IP5

Ratios: Q2: 0.003%, Q3: 0.002%, D1: 0.047%, TAN: 1.25%, MB9: 2.55%, MB10: 0.59%, MB11: 0.15%, MB12: 1.58%, MB13: 2.26%, MB14: 0.24%.

Collimation:

- ▶ A large fraction of the scattered particles, 78.1%, are absorbed by the collimators.
- ▶ Some further particles, 4.6%, hit collimators, but are not absorbed.
- ▶ The bulk is absorbed in IP7, 33.1% by the primary, and 6.0% by the secondary collimators.
- ▶ Note especially that 16.6% are absorbed in the TCL4 before Q4.
- ▶ A few protons are also absorbed in TCL5 and TCL6.

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Aperture Losses:

▶ In this test case, 8.7% of the protons are lost in apertures in the first 600 m after IP5.

▶ The bulk of these are lost in the arc.

▶ Some are lost in the D1/TAN area, but those numbers are likely Underestimated due to current limitations of the conversion between Mad-X and SixTrack (code updates in progress).

Scattering Processes:

► Elastic scattering generator based on TOTEM data successfully implemented and produces reasonable results (not shown).

► Single diffractive generator (plus potentially other diffractive processes) added through Pythia8 looks promising, but requires further development and testing.

Summary and Conclusion

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► Losses in the machine over multiple turns is being studied.

► The aperture model and the backtracking of losses in SixTrack is still being improved in collaboration with the collimation group.

► Continuing acceptance scans of off-momentum protons, also looking at survival over multiple turns.

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Continuation:

- ▶ A number of further developments in the pipeline, including a better integration with Pythia event generator.
- ▶ Possibility to revisit beam–gas using the new Scatter module.

Thanks!