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Status of Merlin simulations: 4 TeV cases and new scattering

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HiLumi 2014 KEK

The Cockcroft Institute of Accelerator Science and Technology

High Luminosity LHC

LARP

Science & Technology Facilities Council

Merlin

- Accelerator simulation library
  - Initially developed for the ILC by N. Walker et al at DESY, Storage ring functionality added by A. Wolski
  - Object oriented, modular, C++
  - 29,000 Lines of code (+4000 of examples)
  - Extensible, can add additional physics processes
  - Multi-threaded, MPI
  - CMake for building
  - Git for revision control
  - User writes a simulation program using library (Similar to GEANT4)

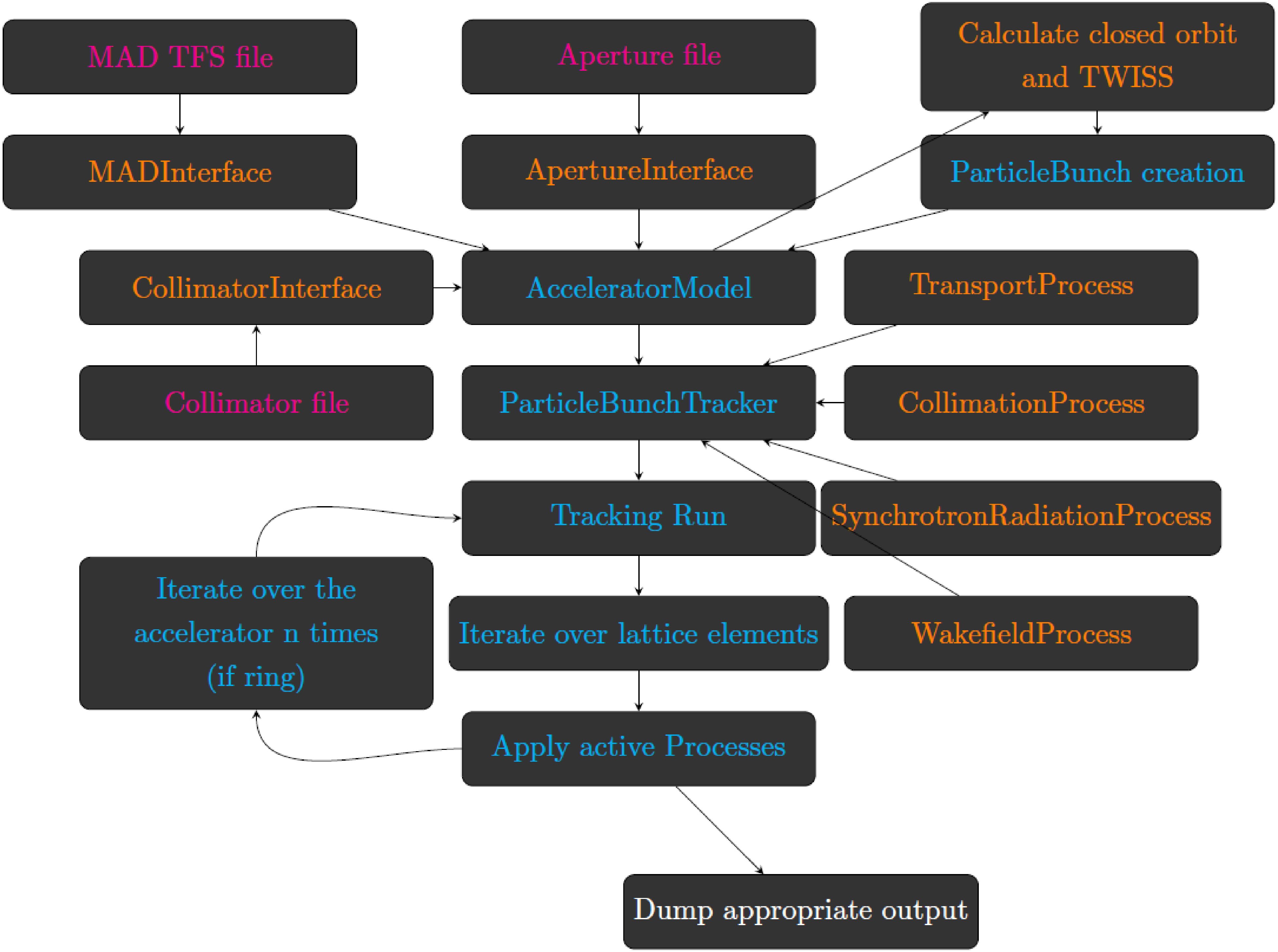
Merlin Implementation

Main sections of Merlin

- AcceleratorModel
  - The description of the lattice, made of AcceleratorComponents e.g. Quadrupole
  - Fields, geometry, apertures
  - Also frames for girder misalignment
- Beam transport
  - The trackers and integrators for particles and macroparticles
- Physics processes
  - E.g. collimation (scattering), wakefields, synchrotron radiation
    - MPI allows multithreading even for bunch effects
  - Can be enabled as required

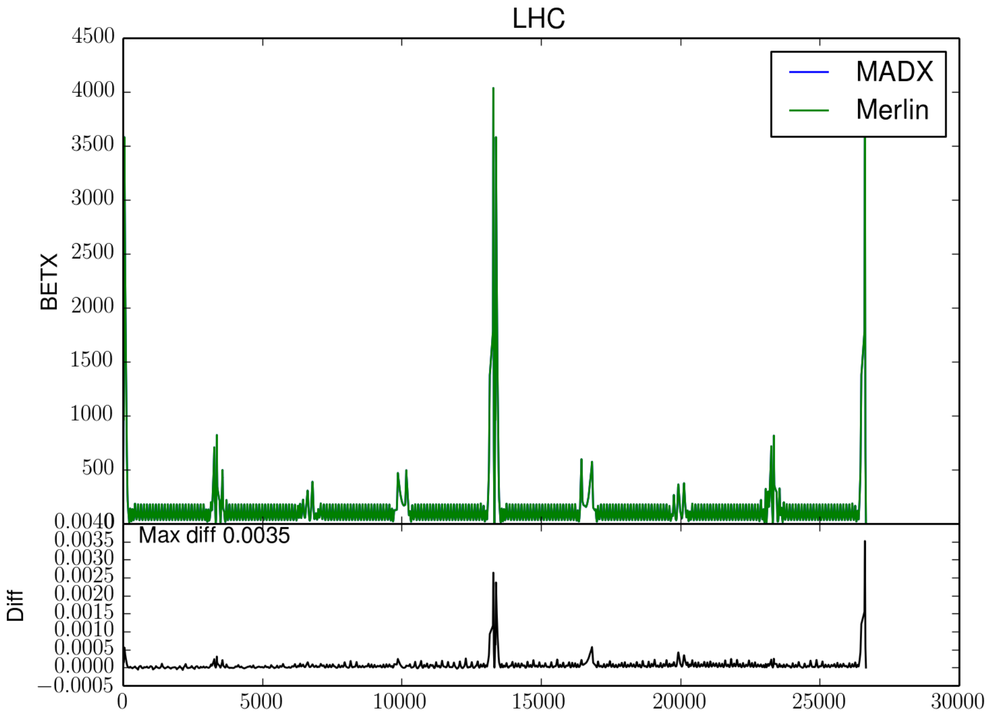
MADInterface

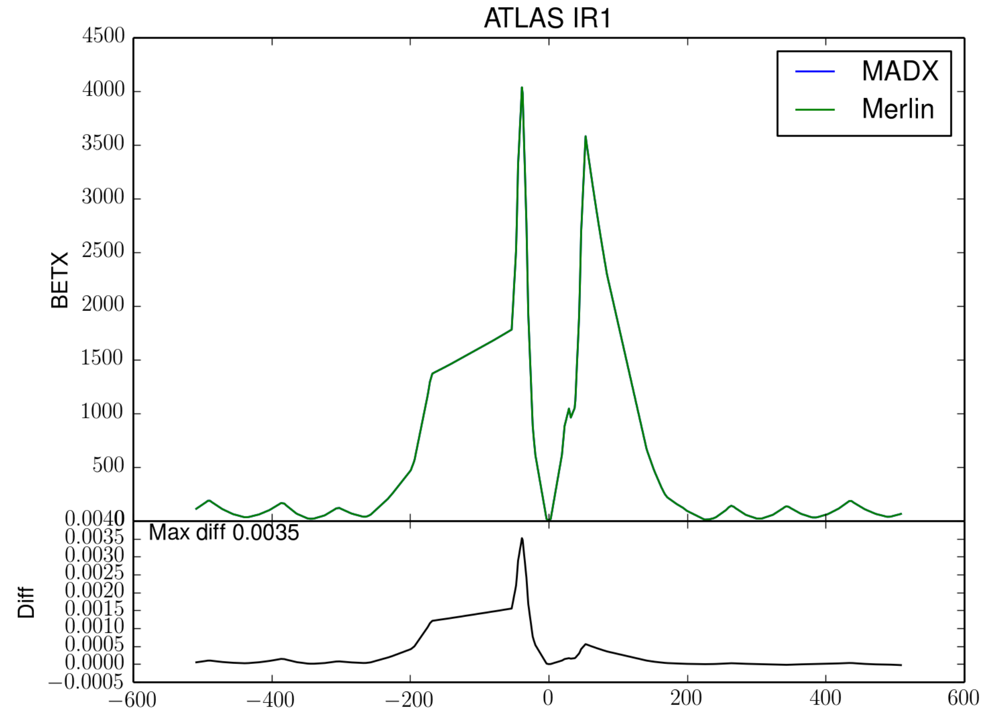
- If you have an existing lattice in MAD-X you can generate a TFS file with TWISS command and import it into merlin with MADInterface
- Can use MADX to design, optimise and match optics, then Merlin for collimation studies
- Can also supply a collimator and aperture file with dimensions and materials


MAD TFS file
Aperture file
Calculate closed orbit and TWISS
MADInterface
ApertureInterface
ParticleBunch creation
CollimatorInterface
AcceleratorModel
TransportProcess
Collimator file
ParticleBunchTracker
CollimationProcess
Tracking Run
SynchrotronRadiationProcess
Iterate over the accelerator n times (if ring)
Iterate over lattice elements
WakefieldProcess
Apply active Processes
Dump appropriate output

Compare optics with MADX

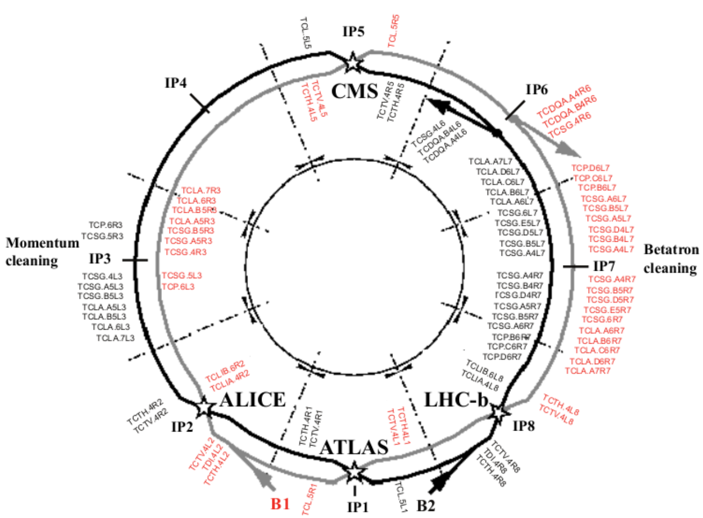
- Import LHC into merlin.
- Calculate optics functions by tracking
- Good agreement, max difference in beta is 3mm

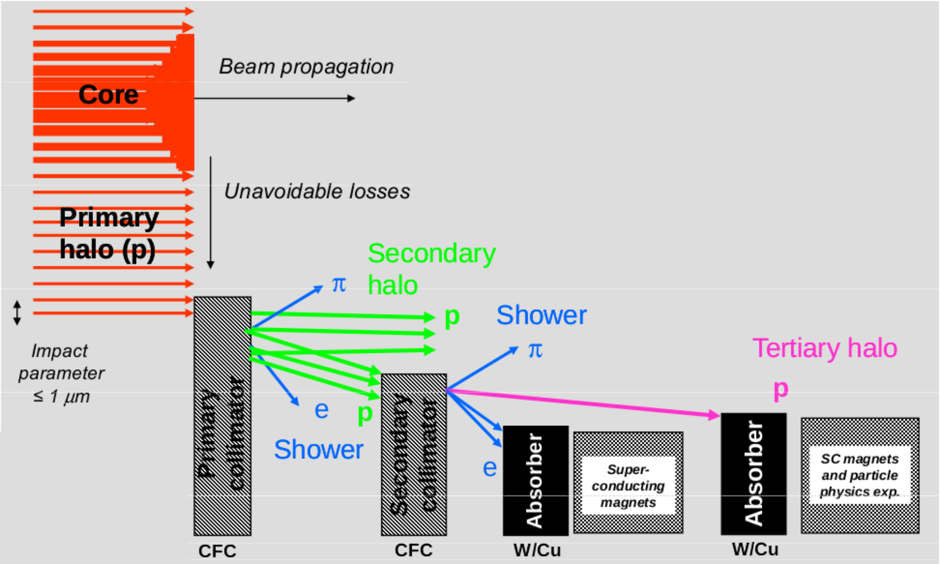




LHC Collimation System

- LHC uses multi-stage collimation system, as high energy protons can pass through large amounts of material
- Primary collimator 'TCP' sit close to the beam to intersect the halo
- Secondary collimators 'TCSG' and absorbers 'TCLA' to absorb secondary halo
- Tertiary collimators 'TCT' protect magnets in the interaction regions
- Protons that have only suffered a small energy loss can be transported long distances around the LHC

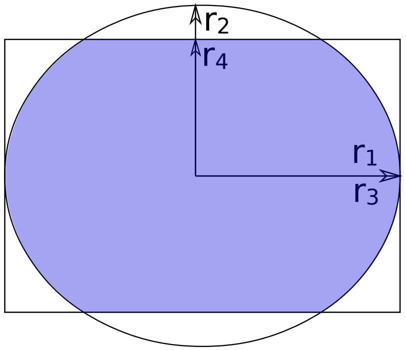


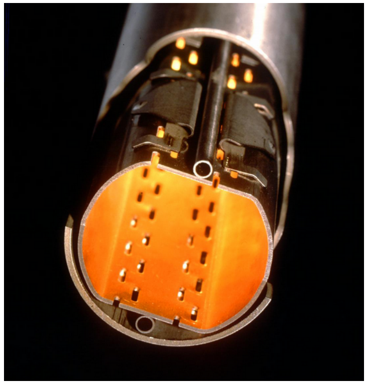


S. Redaelli

Collimation in Merlin

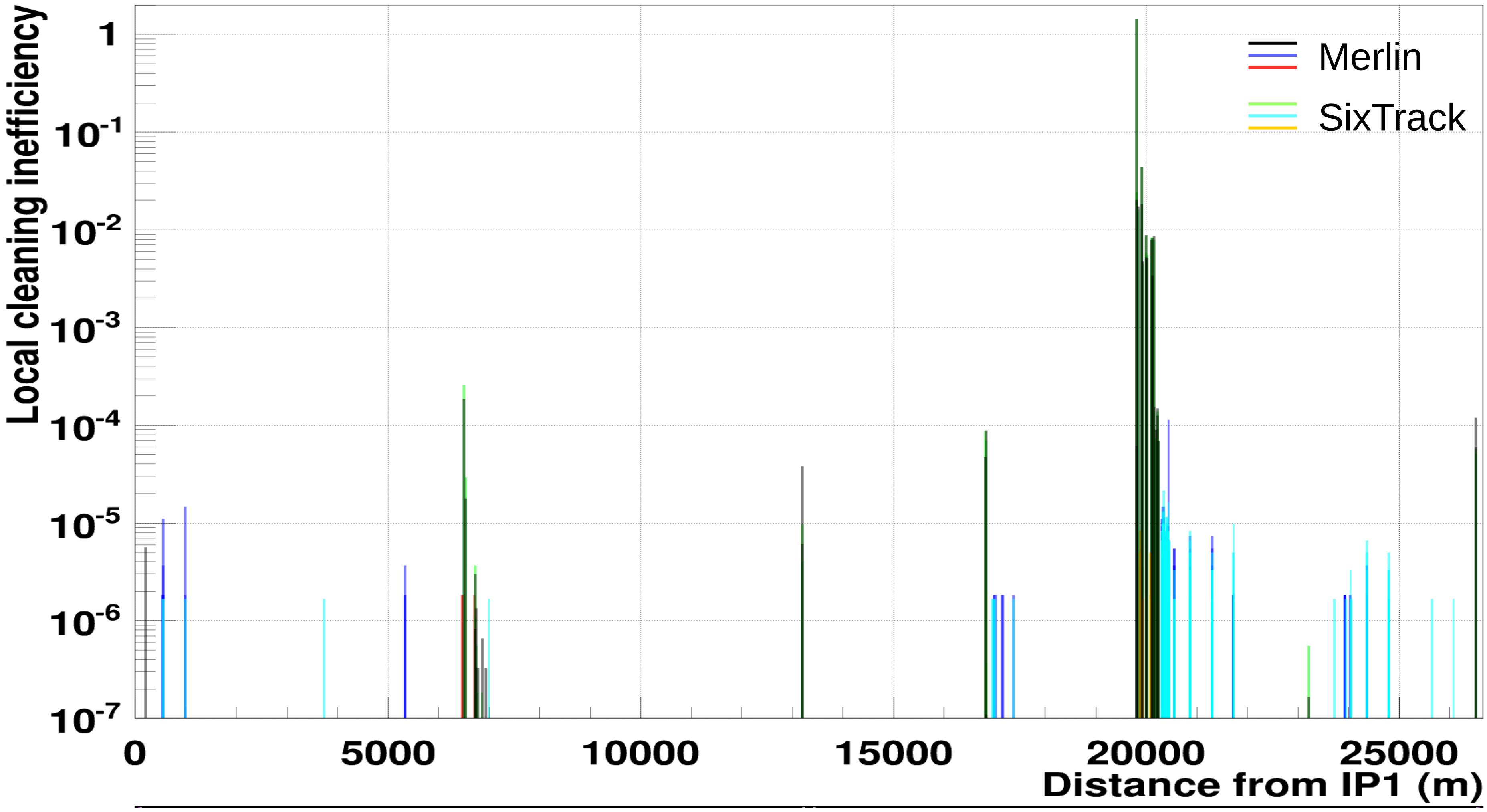
- Each element in the lattice has an aperture attached to it
  - Circular, rectangular, rect-ellipse
- If a proton is outside the aperture and the element is a collimator then the passage of the proton through the material is modelled.
- If the proton returns to inside the aperture and is not below an energy cut it is returned to beam and tracking continues, otherwise the loss is recorded
- If the proton is outside the aperture in any other element the loss is recorded



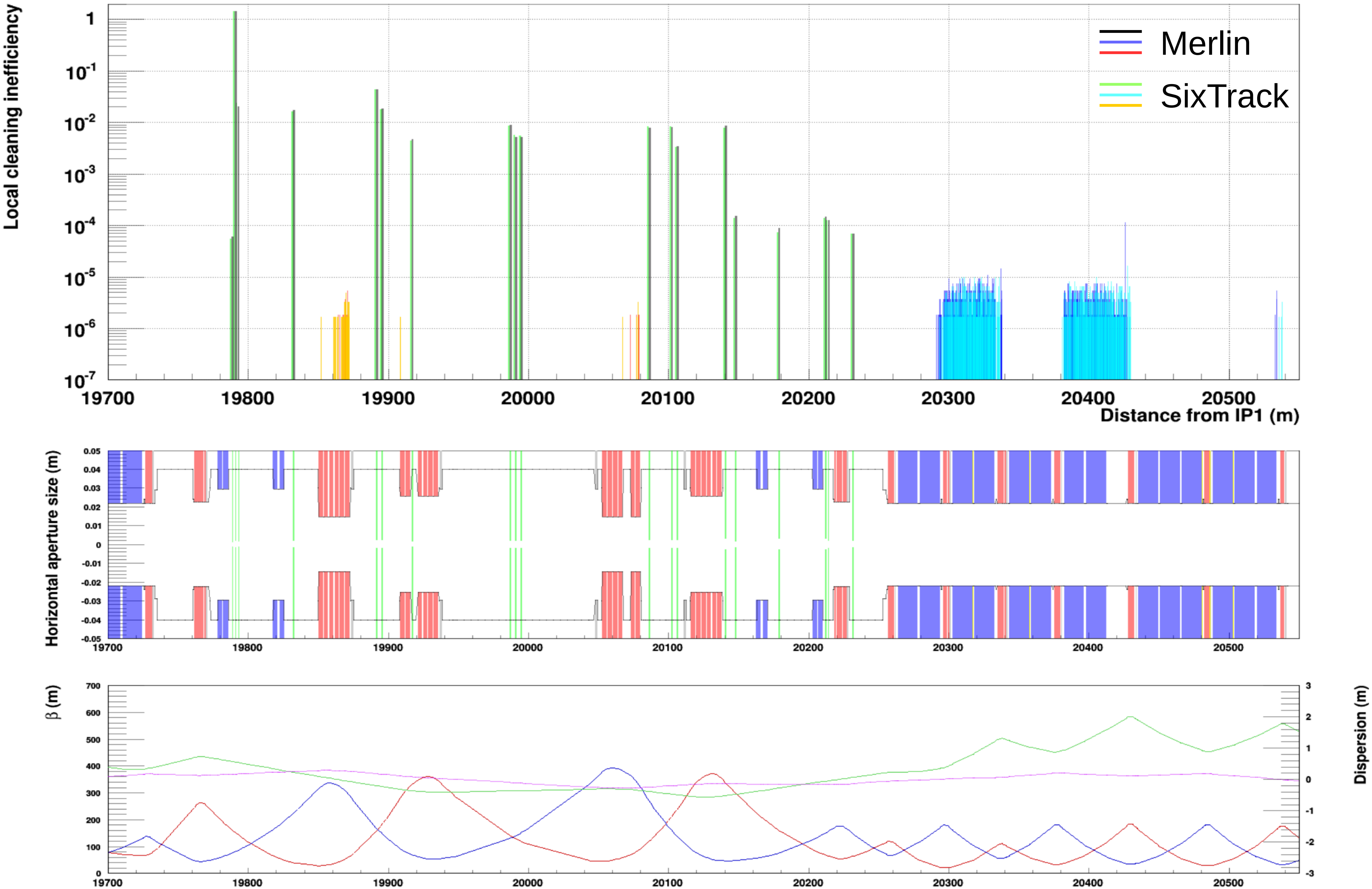


Merlin and Sixtrack

- Merlin with SixTrack physics implemented
- 7 TeV. ß*=55cm



At IR7



Local cleaning inefficiency
Merlin
SixTrack
Distance from IP1 (m)
Horizontal aperture size (m)
β (m)
Dispersion (m)

Scattering physics

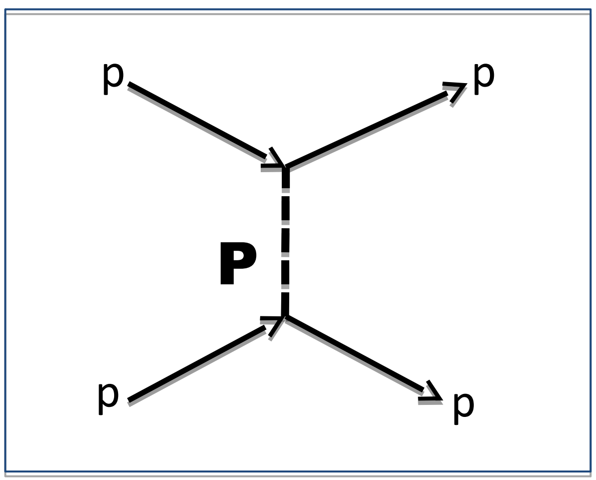
- The scattering physics has been upgraded by Merlin team
- Models processes:
  - **New Elastic scattering**
  - **New Single Diffraction dissociation**
  - Multiple Coulomb scattering
  - Updated Ionization based on Landau theory
  - Rutherford scattering
- For performance only follows leading proton, not full shower
- Small angle scatters are very important especially for IR7 dispersion suppressor region

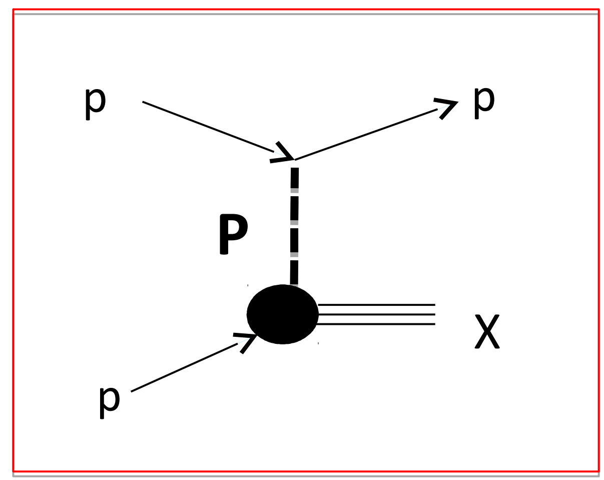
Improved scattering physics for high energy collimation studies

Main processes :
- Multiple Coulomb scattering
- New Ionization based on Landau theory
- Rutherford scattering
- New Elastic scattering
- New Single Diffraction dissociation

} Point-like interaction on fixed target

The main idea is to model the single diffraction and elastic scattering with the Regge theory and get the parameters of the model from a fit from all the existing data for p-p and p-pbar scattering.(Donnachie & Landshoff model)

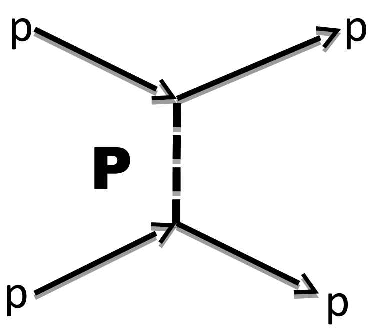




The Regge theory of soft interaction at high energy is based on exchange of Pomerons and Reggeons (colorless exchange).

“The Practical Pomeron for High Energy Proton Collimation Studies” to be submitted to PR-STAB

(D-L) Elastic model



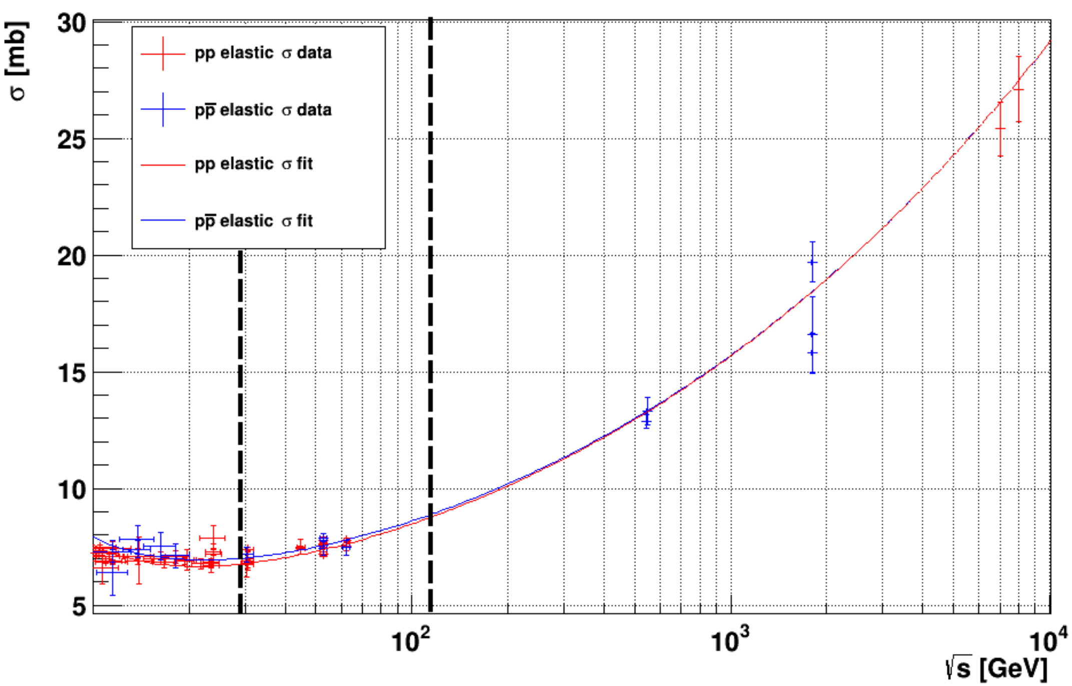
$$\frac{d\sigma}{dt} = \pi \left| f_c + f_n \right|^2$$

Coulomb term at low |t|

Nuclear term at higher |t|: Multiple pomeron and reggeon exchange and triple gluon and hard pomeron exchange

$$\sqrt{s} = \sqrt{2M_P^2 + 2M_P E}$$

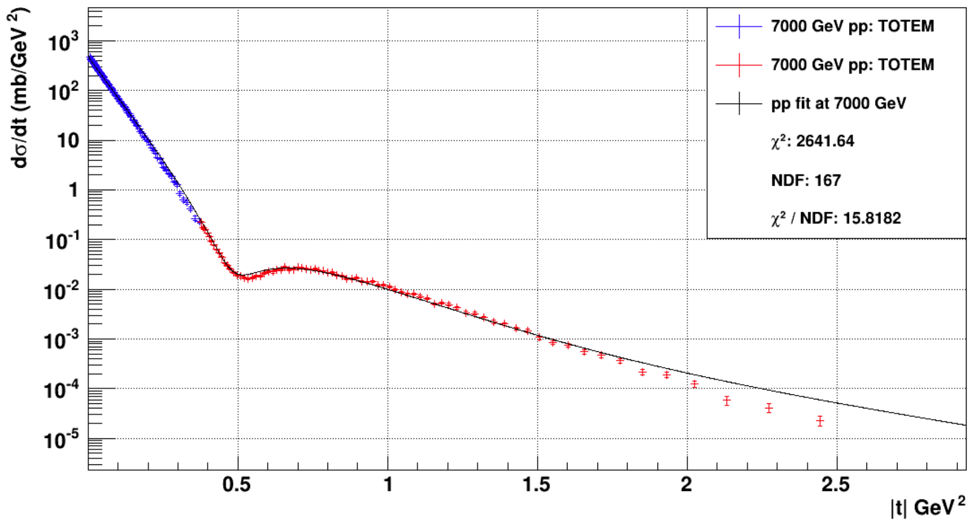
Total elastic cross section



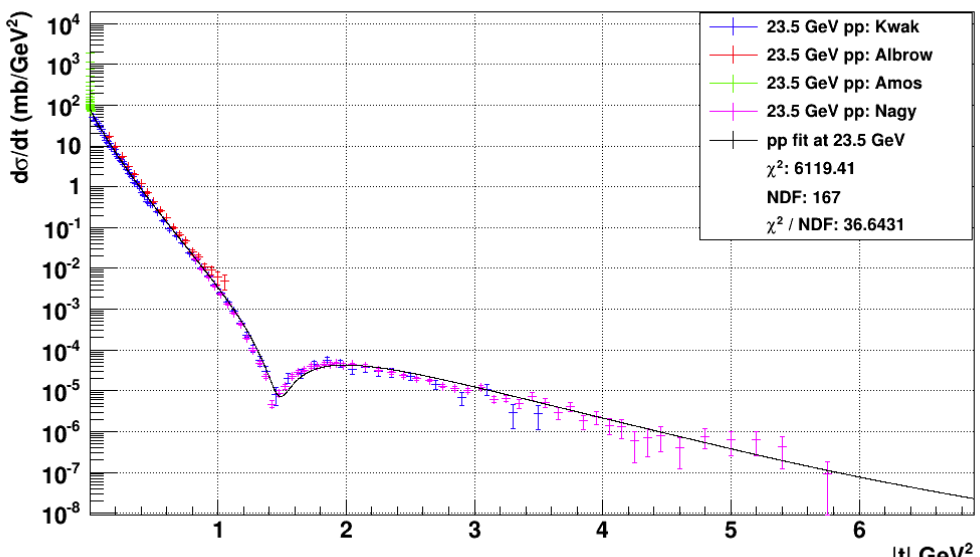
Energy [GeV]	$\sqrt{s}$ [GeV]	σ_{el} [mb]
450	29.0	6.781
3500	81.0	8.114
4000	83.9	8.242
7000	114.6	8.824

(D-L) Elastic model fit and data sources

Accelerator (Experiments)	Collision particles	$\sqrt{s}$ (GeV)
Fermilab (E177A)	pp	19.464
ISR (CHLM)	pp	23.46
ISR (CHLM)	pp	26.926
Fermilab (E177A)	pp	27.426
ISR (CHLM)	pp	30.54
ISR (CHLM)	pp	32.357
ISR (CHLM)	pp	35.199
ISR (CHLM)	pp	38.262
ISR	pp	44.64
ISR (R211,SFM?)	pp	52.81
ISR	pp	62.5
RHIC (pp2pp)	pp	200
LHC (TOTEM)	pp	7000
ISR	$p\bar{p}$	30.4
ISR	$p\bar{p}$	52.6
ISR	$p\bar{p}$	62.3
$\text{SP}\bar{\text{P}}\text{S}$ (UA4/2)	$p\bar{p}$	541
$\text{SP}\bar{\text{P}}\text{S}$ (UA4),Tevatron (CDF)	$p\bar{p}$	546
$\text{SP}\bar{\text{P}}\text{S}$ (UA4)	$p\bar{p}$	630
Tevatron (CDF,E710)	$p\bar{p}$	1800
Tevatron (D0)	$p\bar{p}$	1980



S = √7000 GeV

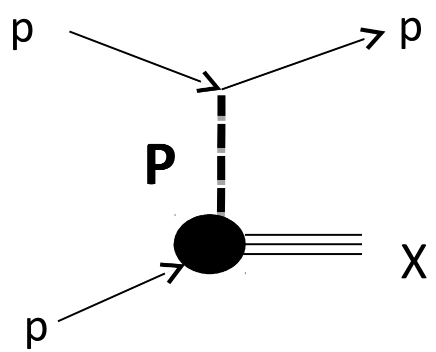


S = √23.5 GeV

(D-L) Single Diffraction (SD) scattering physics

$$\frac{d^2\sigma}{dM_X^2\,dt}$$

Kinematical variables
- momentum transfer t
- centre-of-mass energy s
- missing mass M_X of the system X or $\xi = \frac{M_X^2}{s}$



$$\sqrt{s} = \sqrt{2M_P^2 + 2M_P E}$$

E (GeV)	sqrt(s)
3500	81 GeV
7000	115 GeV

Model divided into High mass $M_X > M_C$ and Low mass $M_X < M_C$

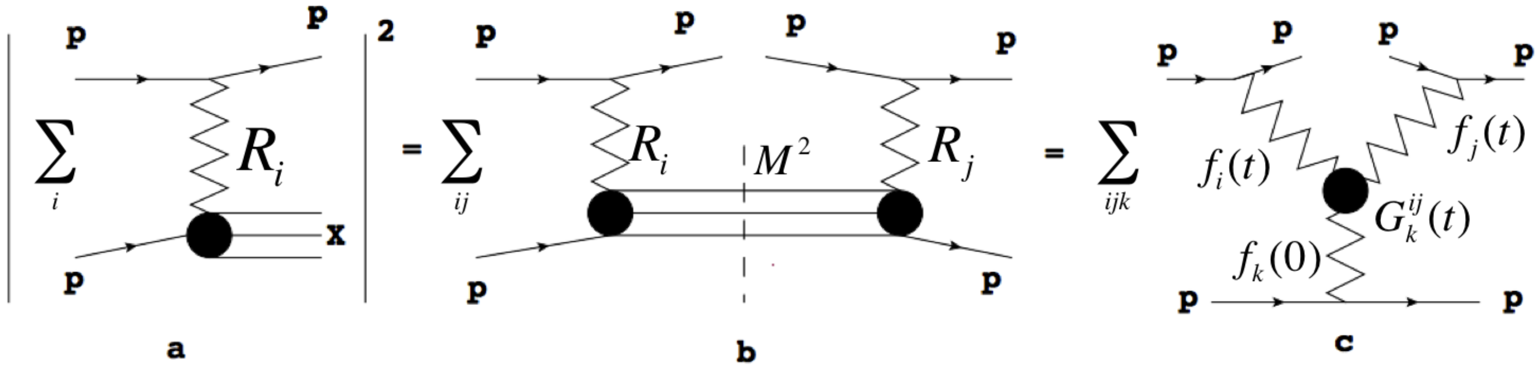
Mass Cut: $M_C = 3 + a \ln(s/s_o)$, with a = 0.6 and s_o= 4000 GeV

High Mass :
Model with triple Regge formalism

Low Mass:
Model with background and resonances

(D-L) Single Diffraction (SD): High Mass

High Mass :
Model with triple Regge formalism



$$\frac{\partial^2\sigma}{\partial t\partial\xi} = g_{\mathbb{PPP}}(t)s^{\alpha_{\mathbb{P}}(0)-1}\xi^{\alpha_{\mathbb{P}}(0)-2\alpha_{\mathbb{P}}(t)} + g_{\mathbb{PPR}}(t)s^{\alpha_{\mathbb{R}}(0)-1}\xi^{\alpha_{\mathbb{R}}(0)-2\alpha_{\mathbb{P}}(t)} + g_{\mathbb{RRP}}(t)s^{\alpha_{\mathbb{P}}(0)-1}\xi^{\alpha_{\mathbb{P}}(0)-2\alpha_{\mathbb{R}}(t)} + g_{\mathbb{RRR}}(t)s^{\alpha_{\mathbb{R}}(0)-1}\xi^{\alpha_{\mathbb{R}}(0)-2\alpha_{\mathbb{R}}(t)}$$

a pion-exchange term, important at low t, is also added

Four triple-regge exchanges

$\mathbb{PP}$	$\mathbb{PP}$	$\mathbb{RR}$	$\mathbb{RR}$
$\mathbb{P}$	$\mathbb{R}$	$\mathbb{P}$	$\mathbb{R}$

Pomeron and reggeon trajectories

$$\alpha_{\mathbb{P}}(t) = 1.08 + 0.25t$$
$$\alpha_{\mathbb{R}}(t) = 0.55 + 0.93t$$

Fit parameterization:

$g_{ijk} = A_i\, e^{B_j t} + C_k$

A. Donnachie and P.V. Landshoff. Elastic scattering and diffraction dissociation. Nuclear Physics B, 244(2):322 – 336, 1984

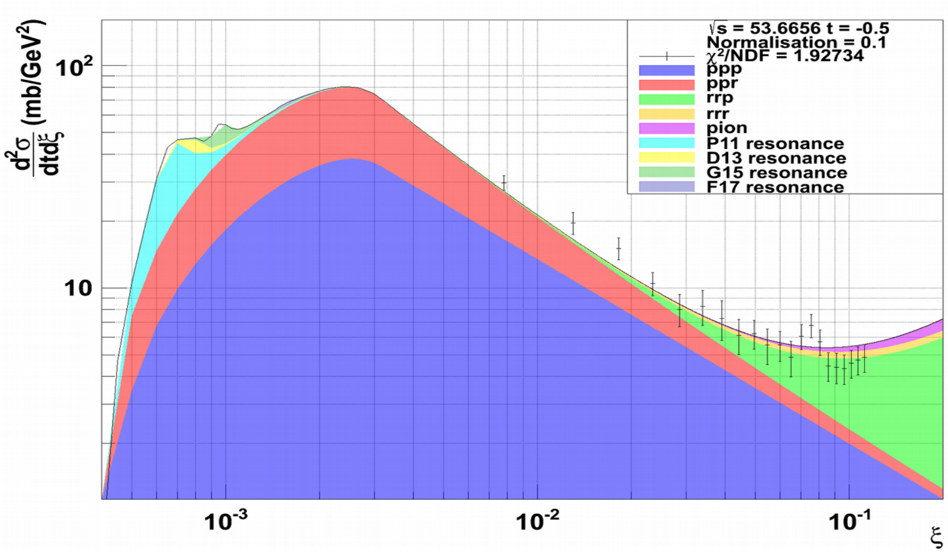
(D-L) Single Diffraction (SD): High Mass

Accelerator (Experiments)	Collision particles	s (GeV^2)
FERMI ITA (E211)	pp	16.19
FERMI ITA	pp	17.58
FERMI ITA	pp	19.13
ISR	pp	23.46
FERMI ITA	pp	23.77
ISR	pp	26.93
FERMI ITA	pp	27.22
ISR	pp	23.46
ISR	pp	30.54
ISR	pp	44.64
ISR (R211,SFM)	pp	52.81
ISR	pp	62.5
SP$\bar{\text{P}}$S (UA4)	$p\bar{p}$	546

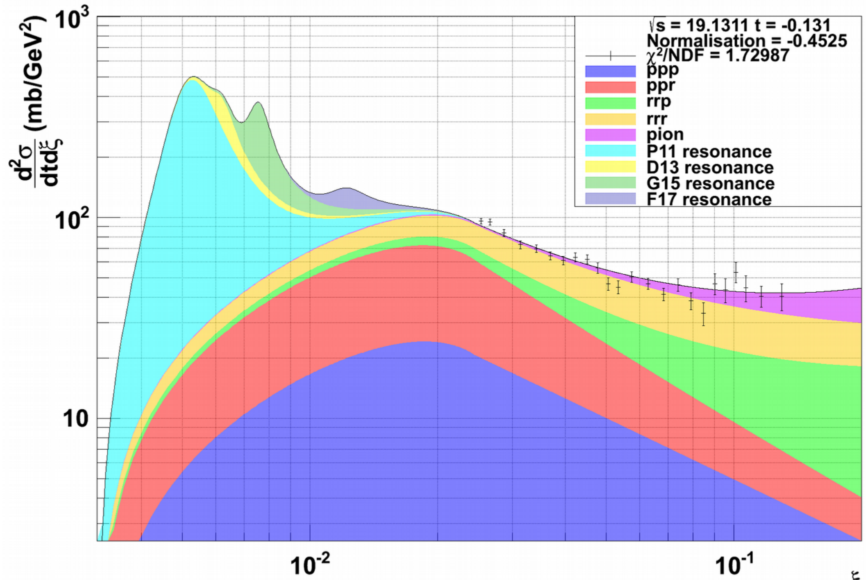
$$g_{ijk} = A_i\, e^{B_j t} + C_k$$

Term	A_i	B_j	C_k
ppp	0.624529	2.5835	0
ppr	3.09088	4.51487	0.186211
rrp	4.0	3.03392	10.0
rrr	177.217	5.86474	21.0029

Examples of fit result (~ 300 plots)



S = √53.66 GeV and t = - 0.5 GeV 2



S = √19.13 GeV and t = - 0.131 GeV^2

(D-L) Single Diffraction (SD): Low Mass

Background: simple parabolic curve

$$B(\xi,t,s) = a(\xi,t)\cdot(\xi-\xi_c)^2 + b(\xi,t)\cdot(\xi-\xi_c)$$

a and b functions are calculated from boundary conditions:
same value and slope of high mass and low mass at M_X = 3 GeV

Resonances:

$$\frac{d\sigma_{Res}}{dM_X^2} = \sum_{l=1}^{4}\left[\frac{c_l}{M_X^2}\frac{m_l\Gamma_l}{(M_X^2-m_l^2)^2+(m_l\Gamma_l)^2}\right]$$

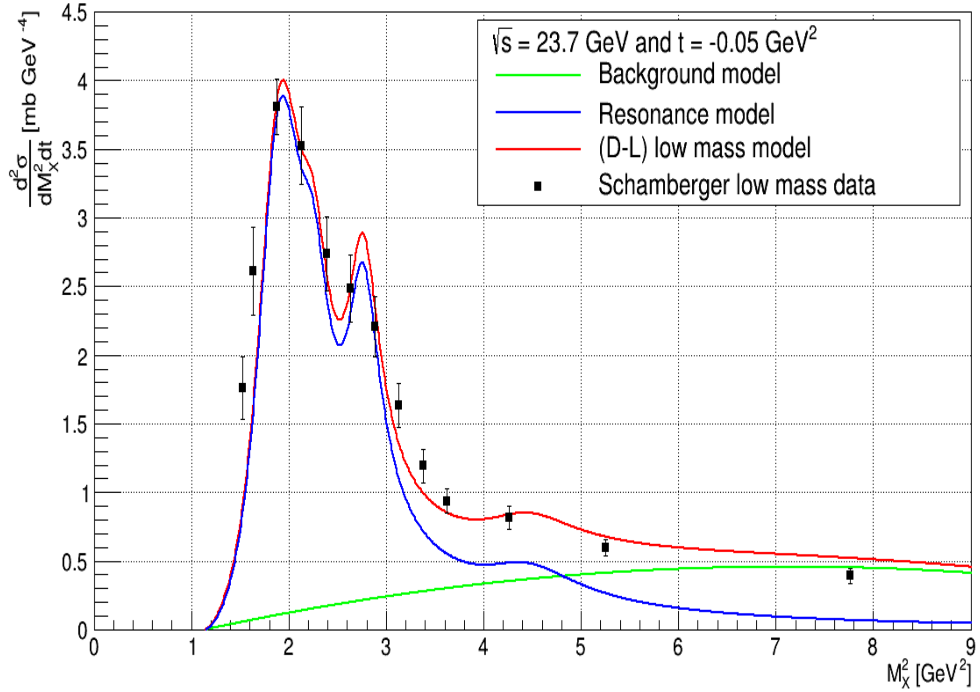
$$\Gamma_l = \gamma_l\left(\frac{q}{q_l}\right)^{2l+1}\cdot\left(\frac{1+5q_l}{1+5q}\right)^l$$

$$q(M_X^2) = \sqrt{\frac{(M_X^2-(M_p+M_\pi)^2)\cdot(M_X^2-(M_p-M_\pi)^2)}{4M_X^2}}$$

$$q_l = \sqrt{\frac{(m_l^2-(M_p+M_\pi)^2)\cdot(m_l^2-(M_p-M_\pi)^2)}{4m_l^2}}$$

Resonance	l	m_l [GeV]	γ_l	c_l
P_{11}	1	1.44	0.325	3.07
D_{13}	2	1.52	0.13	0.4149
F_{15}	3	1.68	0.14	1.108
G_{17}	4	2.19	0.45	0.9515

Resonances mass and width from PDG

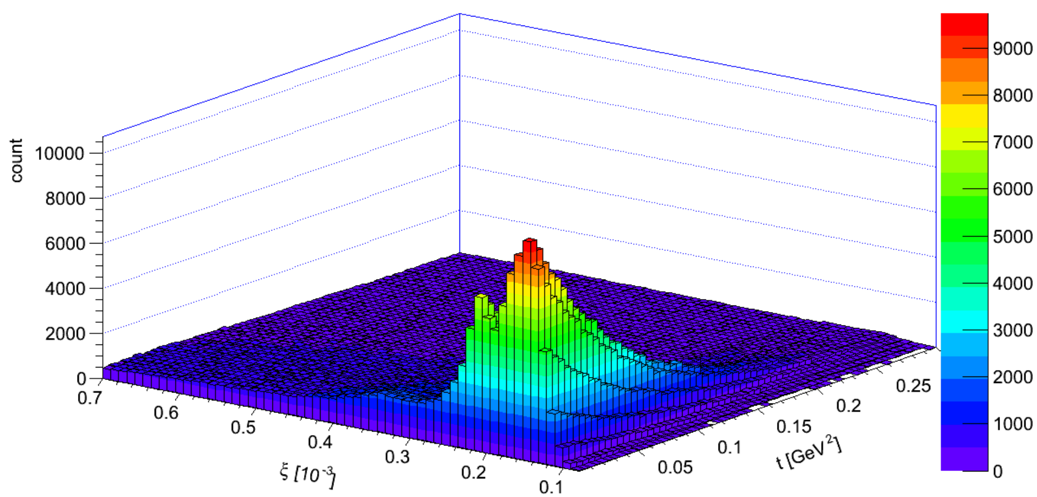


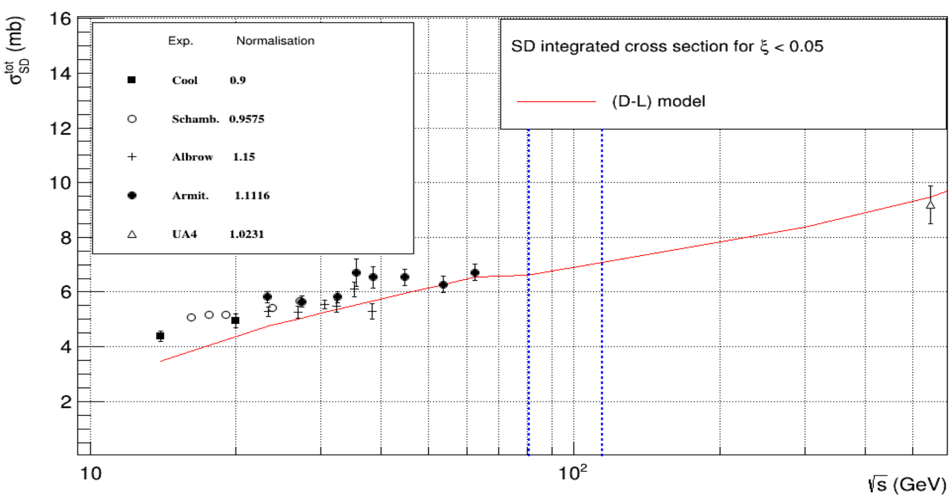
S = √23.7 GeV and t = - 0.05 GeV 2

- Background + resonances
- Data(blue points) from Schamberger at s = 565 GeV^2

Single Diffraction total and differential cross section

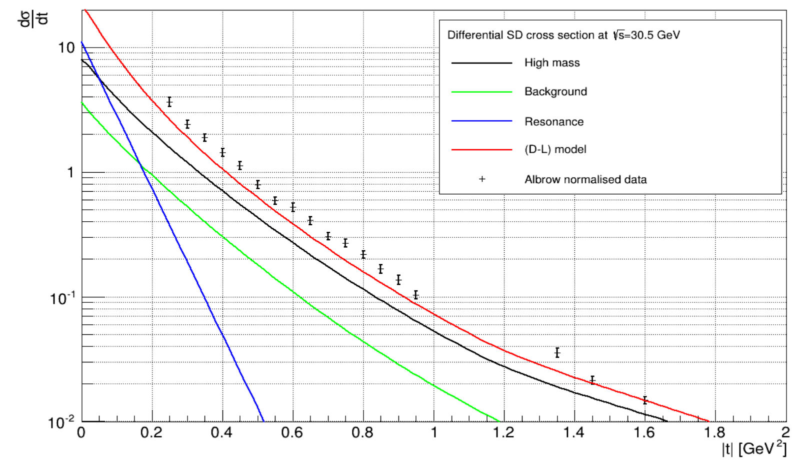
Histogram of the double differential cross section generated by the (D-L) model



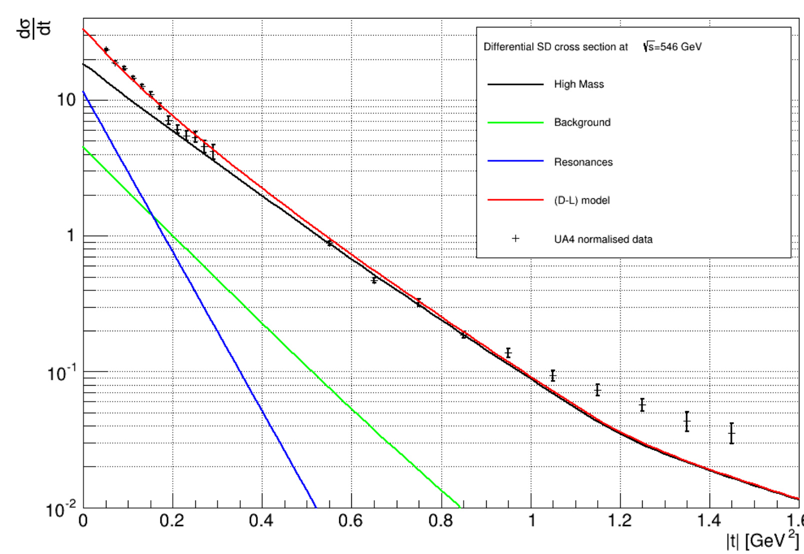


E[GeV]	$\sqrt{s}$[GeV]	$\sigma_{SD}(\xi < 0.05)$	$2\sigma_{SD}(\xi < 0.05)$	$\sigma_{SD}(\xi < 0.12)$
3500	81.05	3.385	6.77	4.33
7000	114.62	3.548	7.09	4.49

d.c.s at low centre of mass energy



d.c.s at high centre of mass energy



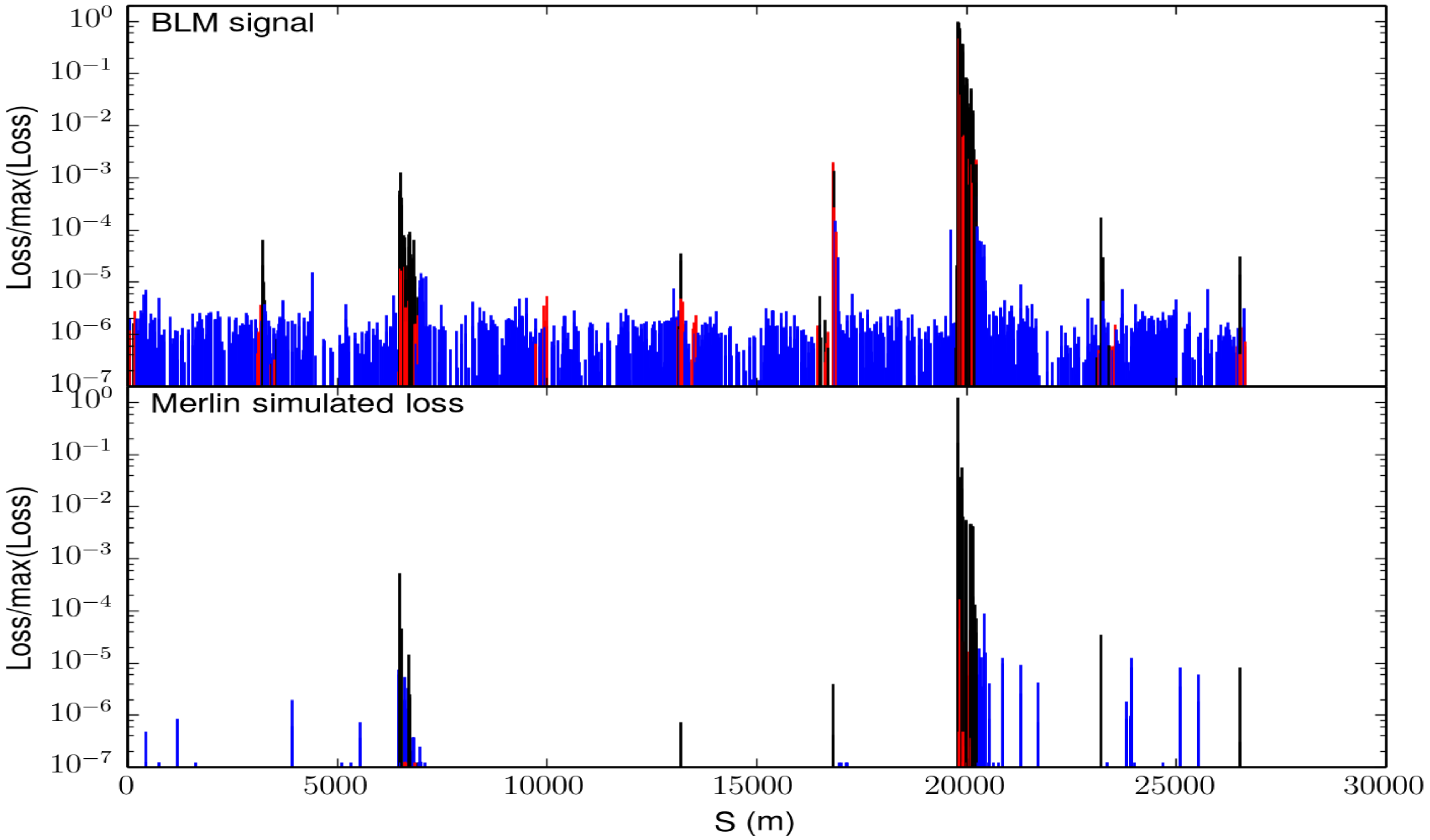
Loss maps

- Several comparisons between Merlin and Sixtrack have been made in the past, good agreement
- Lots of new loss simulations are needed for HiLumi LHC
- New optics, ATS
- Novel collimation schemes
- Loss map data taken during runs can be used to validate simulations
- Not a staight forward comparison
  - Merlin/Sixtrack give proton loss locations
  - Beam Loss Monitors (BLM) measure the shower outside the elements

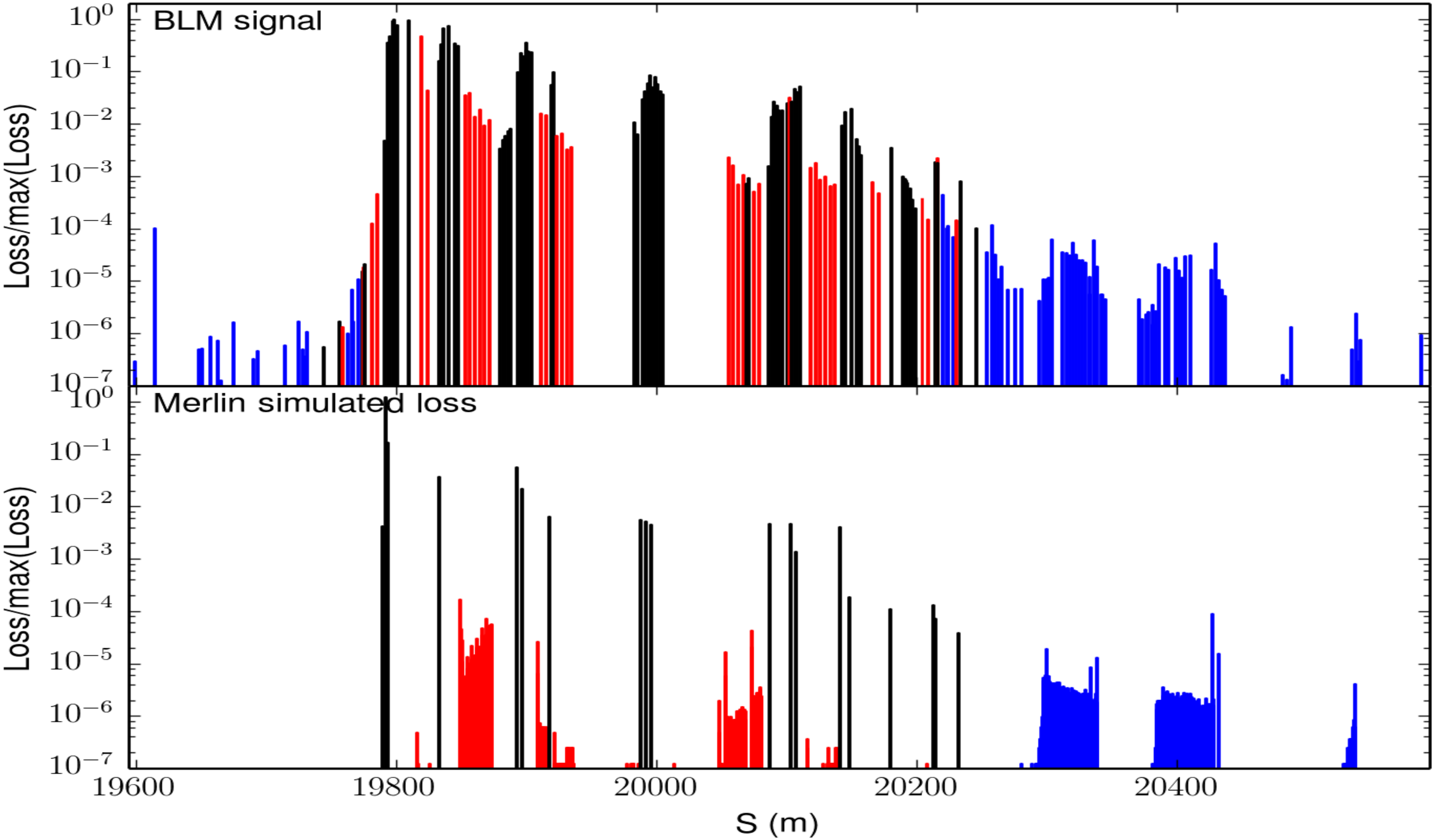
Loss maps

- 4 TeV, 60cm squeeze
- 100 million particles, 200 turns
- 1600 cpu hours (a few hours/over night on Manchester condor cluster)
- BLM data from April 2012
- First look at results and early analysis

4TeV, 60cm Squeeze



4TeV, 60cm Squeeze IR7



Future work

- Merge development branches
- Release version containing new scattering physics
- Complete validation against BLM data
- Use Merlin to generate loss maps for HiLumi configurations
  - ATS
  - Novel materials and schemes
- Scattering physics paper pending submission

Conclusion

- Merlin is a modern general simulation code capable of simulating LHC including collimation system
- New physics models for elastic and single diffraction, important for small angle scatters
- Code is modular and extensible, users can easily add new physics and new elements for specific studies
  - Useful out side of collimation studies
- Now that scattering physics are complete we are nearing release