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TOTEM - answer to the questions of the referees

1 Physics

1.1 Running conditions

1.1.1 Total cross section at 14 TeV

- *Insertion optics:* high-β with $\beta^* \simeq 1100$ m.
- *Reduced number of bunches* such as for instance 36, compatible with zero crossing angle.
- *Effective luminosity:* L $\simeq 10^{28}\text{cm}^{-2}\text{s}^{-1}$, scaled down from nominal machine luminosity by reduced bunch number and high-β optics, including a safety factor of 5.
- *Effective integrated luminosity* in one day (50% running efficiency): $\simeq 5\times10^5\text{mb}^{-1}$.
- *Detectors used:* the Roman pot stations RP2 and the inelastic detectors T1 and T2. The detectors in the Roman pots will measure both the horizontal and vertical coordinates with accuracy of about 30μm.
- *Setting-up* will be done in the early weeks of operation of the machine with *any kind of optics* which might be available, running the TOTEM detectors parasitically. The Roman pot detectors of all stations RP1, RP2 and RP3 will see particles of the beam halo and very forward secondaries from beam-gas interactions.
- *Running time:* 3 or 4 short runs, distributed in the first 2 years of operation of the machine should be foreseen. Each run should have an integrated luminosity of the order of 10^5mb^{-1} in order to provide a sufficient amount of events. High statistics (a few 10^6 elastic events for each run) is very important to study the proper alignment of the Roman pot telescopes on the actual beam axis which may differ slightly but significantly from the nominal machine axis. Statistics is also needed to monitor the efficiency of the detectors close to the edge facing the beam by studying the density population of elastic events having the same polar scattering angle along the ellipse which corresponds to different azimuthal angles.
  The basic requirement for a reliable result, once good statistics is achieved for each individual run, is the control of systematic errors and reproducibility.

1.1.2 Total cross section at 2 TeV

In our Technical Proposal we mentioned (pag.21) the interest of running at the Tevatron energy ($\sqrt{s}$=2 TeV) because the optics with β^*=1100 m would make the measurement of Coulomb interference feasible at that energy.
In order to put the measurement of σ_{tot} at lower energy in the right perspective we recall here the relevant *scaling relations*

- The emittance ϵ at beam momentum p is related to the invariant emittance ϵ_n by $\epsilon = \epsilon_n/\gamma \simeq \epsilon_n/p$, with p in GeV.
- The minimum accessible scattering angle is $\vartheta_{min} \sim \sqrt{\epsilon}/\sqrt{\beta^*}$ and therefore $\text{t}_{min} \sim \epsilon p^2/\beta^* = \epsilon_n p/\beta^*$.

- The luminosity scales as L $\sim 1/\epsilon\beta^* = $ p $/\epsilon_n\beta^*$

If we demand the same value of t_{min} at different energies, we have to scale the optics with the beam momentum as $\beta^* \sim p$. This scaling implies $\beta^* \simeq 160$ m at 2 TeV. Using this scaling law, the luminosity of the high-β runs for the total cross section will remain the same at different energies for a given beam intensity.

The running scenario at 2 TeV will therefore be essentially the same as at 14 TeV.
We are now studying a suitable optics at 2 TeV with β^* in the range 150 - 250 m. There is a continuity of optical solutions from the injection optics (β^*=18 m) to the high-β optics (β^*=1100 m). We are also confident that the phase advance from the IP to the Roman pot station RP2 can be optimised to fulfill our requirements.

1.1.3 Large t at 14 TeV

In order to extend the measurement of elastic scattering above 1 GeV^2, a "medium"-β optics must be used. In our Technical Proposal we have considered the injection optics (β^*=18 m).
For this measurement the Roman pot stations RP1 will be used.

Two running conditions can be envisaged:

- *Number of bunches*: 36
  Luminosity L$\simeq 3\times 10^{30}$cm^{-2}s^{-1}
  Maximum value of t: $\simeq$5 GeV^2, (a few events per day in a t-bin equal to 0.2 GeV^2).

- *Number of bunches*: 2835 (nominal)
  Luminosity L$\simeq 3\times 10^{32}$cm^{-2}s^{-1}
  Maximum value of t: $\simeq$10 GeV^2, (a few events per day in a t-bin equal to 0.2 GeV^2).

Running scenario: We envisage 2 or 3 short runs, each of few days as soon as the intensity of the beams will be close to the nominal values.

1.1.4 Luminosity calibration at 14 TeV

The calibration of the inelastic detectors of TOTEM is obtained in the "total cross section runs" when the elastic scattering rate at low-t and the overall inelastic rate are measured simultaneously. The results of the "total cross section runs" will provide at the same time σ_{tot} and the luminosity.

In order to obtain an accurate value of σ_{tot}, observation of single diffraction dissociation events by a single arm trigger is needed, to ensure that the loss of inelastic events is at the 1% level. The subset of events obtained with single arm trigger (about 10% of N_{inel}) is of course affected by not negligible background.
On the other hand, the various combinations of Left-Right coincidences are good candidates for luminosity measurement because they will be much less affected by background. During the "total cross section runs" we will get the absolute calibration of each Left-Right trigger combination.

Simulation indicates that the coincidences $T_{1L}\times T_{1R}$, $T_{2L}\times T_{2R}$, $(T_1+T_2)_L\times$ $(T_1+T_2)_R$ cover a large fraction of N_{inel} (87%, 84% and 90% respectively).

1.2 Run at the Tevatron energy

Discussions with the Accelerator physicists designing the LHC have taken place. They did not point out any problem of principle to run the machine at 2 TeV.

1.3 Conditions for an intermediate t run

For a given machine energy the appropriate scaling relations are L$\sim 1/\beta^*$ and $t_{min} \sim 1/\beta^* \sin^2 \Delta\psi$. The condition $\sin \Delta\psi = 1$ is verified for the high-β optics at the Roman pot stations RP2 and for the injection optics at the exit of D1. i.e. approximately at the station RP1.

For the specific case of the injection optics (β^*=18 m) the geometric acceptance is shown in Fig.15 of our Technical Proposal. We take as minimum measurable t the value of 1.2 GeV^2 which is comfortably above the threshold. We quote in Table 1 the value of t_{min} for different values of β^*. The corresponding luminosity is calculated for 36 bunches. For the nominal number of bunches of 2835, the luminosity must be increased by a factor of 80.

β^*(m)	t_{min}(GeV^2)	Luminosity (cm^{-2}s^{-1})
5	4.3	1.3×10^{31}
18	1.2	3.5×10^{30}
50	0.43	1.3×10^{30}
100	0.22	6.3×10^{29}

Table 1. Values of t_{min} referring to optics with different β^* for the intermediate-t runs.

1.4 Physics in integration with CMS

The CMS/TOTEM physics programme is based on the use of the forward magnetic spectrometers and the telescopes T1/T2 of TOTEM in conjunction with the detectors of CMS which cover the central region. Specific topics are Single and Double Diffraction Dissociation and Double Pomeron exchange. However, a more general experimental programme should be envisaged to study the correlations between forward protons of high momentum with large angles secondaries, jets, rapidity gaps etc.

We are planning a "CMS/TOTEM Workshop on Diffractive Physics" at the end of 1999.
In addition to physics topics, also the technical issue of suitable triggers will be discussed.

2 Integration with the machine

2.1 Services for the Roman pots

The path of the power and signal cables for the Roman pot stations has been extensively discussed with the machine experts. At present a technical design study is underway and a complete layout is being prepared according to the prescriptions of the machine staff.

2.2 Cost of the Roman pots

The cost of a Roman pot unit (Fig.2 of the Technical Proposal) which includes the overall mechanical structure, the "pots" (Fig.1), the bellows of the pots and the bellows for connection to the main pipe of the machine is estimated to be about 40 kSF. The cost of the remote controls and services is being studied at the SL/BI Division.

2.3 RF implications of the Roman pots

The machine experts are aware of the TOTEM proposal and of the presence of the Roman pots. They will evaluate their impact on the impedance budget of the LHC. According to their results, we may need to adapt the design of the Roman pots or install a beam screen when running with high beam current. These issues are currently discussed in the LHC Impedance Working Group where we are represented.

3 Integration with CMS

3.1 Telescope T1

It is mandatory to build T1 in such a way that it is compatible with the standard CMS runs. This requirement is a part of the integration.

The option of moving T1 closer to the IP has been discussed in detail in the working group on "CMS/TOTEM integration". It was concluded that the position shown in our Technical Proposal is, but for small adjustements, the only one which is realistic.

Moving T1 closer to the IP would interfere with the supports of the CMS vacuum chamber. In any case if by rediscussing the matter it will come out that the installation of T1 closer to the IP is acceptable to CMS, we are very much willing to design a more compact T1.

3.2 Switching from TOTEM to CMS

It was estimated in the working group on "CMS/TOTEM integration".
After the TOTEM run in order to reestablish the CMS conditions it is required to close HF around the beam pipe and then close the rotating shielding around T2. The total time needed is less than half a day. We assume that T1 and T2 will remain in place.

3.3 Radiation damage

The detectors of T1 and T2 will be built using the same technology and materials as the ones foreseen for CMS in the angular range for η below 2.7.
In the range of T1 and T2, the radiation dose integrated over 10 years is evaluated by CMS to be 10 to 100 times larger. However, in the first low luminosity phase of the LHC (assuming 3 years at average luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) our detectors will receive only a few percent of the nominal 10 years integrated dose.

Therefore we feel that T1 and T2 can survive at least the first 3 years of LHC operation. In the region of T2 there is more uncertainty on the expected dose. If it will turn out to be larger than expected, the front-end electronics of T2 will be removed after each TOTEM run.

3.4 Preliminary cost estimate

As discussed in our Technical Proposal we assume that each telescope is made of 5 detector planes, each plane being subdivided into 6 sectors, shaped as 60^0 wedges. The electronics is evaluated for the Cathode Strip Chambers which operate with non flammable gas and therefore no special safety system is foreseen.

The breakdown of our present estimate is:

- Chambers (honeycomb, printed boards) : 250 kSF
- Electronics (15.000 channels) and trigger : 900 kSF
- Gas system, supports, cables etc. : 250 kSF

The total cost of T1 and T2 is estimated to be about 1.5 MSF.

3.5 Trigger in CMS latency

A first round of discussions has shown that the TOTEM first level trigger could be provided within the CMS requirement.

4 Extrapolation to the optical point - alignment

A sample of 10^6 elastic events were generated with distribution $dN/dt \sim \exp(-B \mid t \mid)$ and B=20 GeV^{-2}. After acceptance correction the events were fitted in the t interval from t_{min}=0.02 GeV^2 to the maximum of 0.1 GeV^2. The statistical error on the extrapolation to the optical point is about 0.5% and the error on the slope parameter B is $\Delta B = \pm 0.08$ GeV^{-2}.

4.1 Alignment of the elastic scattering set-up

The first step in the alignment procedure is the relative alignment of the two detectors of the same telescope. Next step is the relative alignment of the opposite telescopes of the same coincidence arm.
This is easily done using the straight tracks from elastic events, identified from the collinearity requirement.

Afterwards, in order to evaluate the scattering angle correctly, alignment with respect to the actual beam axis is performed. This is needed because the beam axis deviates from the nominal machine axis which is the reference frame for the survey of the Roman pots. The deviation may also be different for different machine runs. The alignment of each Roman pot unit (set of Up and Down detectors) is done using the collected sample of elastic events and taking advantage from the fact that the angular distribution is very steep. The two dN/dt distributions for the two arm combinations (Left-up$\times$Right-down) and (Left-down$\times$Right-up) are fitted with an exponential in t. In general, because of the misalignment, the two distribution will not be equal. A correction parameter is introduced which is geometrically equivalent to *displace rigidly* up and down the two Roman pots of the same unit *without changing their relative distance.* Varying this correction parameter has opposite effects on the shape of the two dN/dt distributions. Alignment is achieved when the two distributions are the same i.e. when the two fits give the same value of the slope parameter B. For a sample of 10^6 events the uncertainty on the correction parameter is at the level of $\pm$ 30 μm which then reflects in an error on the optical point extrapolation less than 0.3%.

Our experience indicates that with a reasonably high statistics (a few 10^6 events for each run), the experimental set-up can be *self-aligned* with the required accuracy.

4.2 Alignment of the Roman pot spectrometer

The alignment is done using elastic scattering events as reference. The trigger will be the standard Left-right Roman pot trigger which will be used together with a diffractive trigger. The sample of elastic events provides the reference trajectories for x=1.

The internal geometry of the detectors (in case of Si detectors, the distance between the vertical strips which can be very accurately known) together with the known value of the bending angle of D2 will give the value of x for protons with momentum below the beam momentum.

In the spectrometer the measurement of t comes mainly from the vertical coordinate while the measurement of the Feynman x comes entirely from the horizontal displacement.