Luminosity Calibration

Outline:

- Motivation and Target Precision
- Methods
- 2010 Results
- 2011 Requests & Strategy
- High-β Experiments

S. White

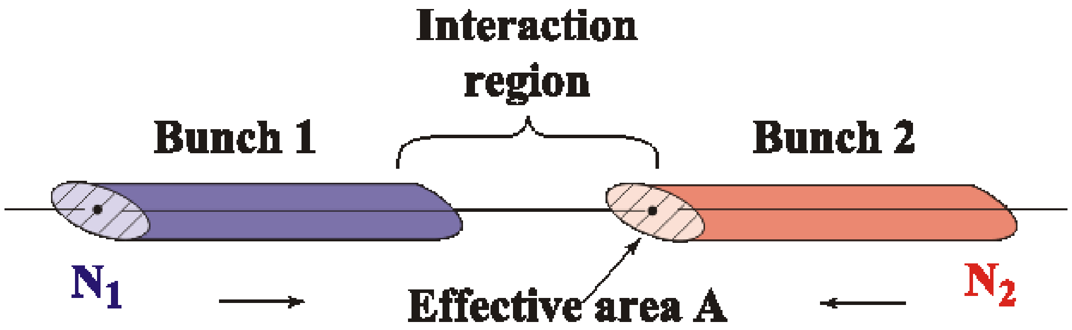
LHC Performance Workshop

Chamonix, 27 January 2011

Acknowledgments: participants of the Lumi Days workshop for the fruitful and motivating discussions
http://indico.cern.ch/conferenceDisplay.py?confId=109784

What is Luminosity?

For a given physics process, the luminosity L is the proportionality factor between the event rate N and the cross section σ



- General expression:

$$L_0 = \frac{N_1 \, N_2 \, n_b \, f}{A_{\text{eff}}} = \frac{\dot{N}}{\sigma}$$

Event rate: measured by the luminosity monitors

Effective area: determined by the overlap integral, depends on the crossing, offset, …

Visible cross section: depends on the physics process, energy, detectors efficiency and acceptance

- Gaussian bunches colliding head-on, no crossing angle:

$$A_{\text{eff}} = 2\,\pi\,\sqrt{\sigma_{x1}^2 + \sigma_{x2}^2}\,\sqrt{\sigma_{y1}^2 + \sigma_{y2}^2} = 2\,\pi\,\sigma_{x\text{eff}}\,\sigma_{y\text{eff}}$$

Motivation for an Absolute Measurement

The knowledge of the absolute luminosity is essential to normalize the experimental data:

$$L = \frac{\dot{N}}{\sigma}$$

- **Absolute luminosity measurements give a handle on:**

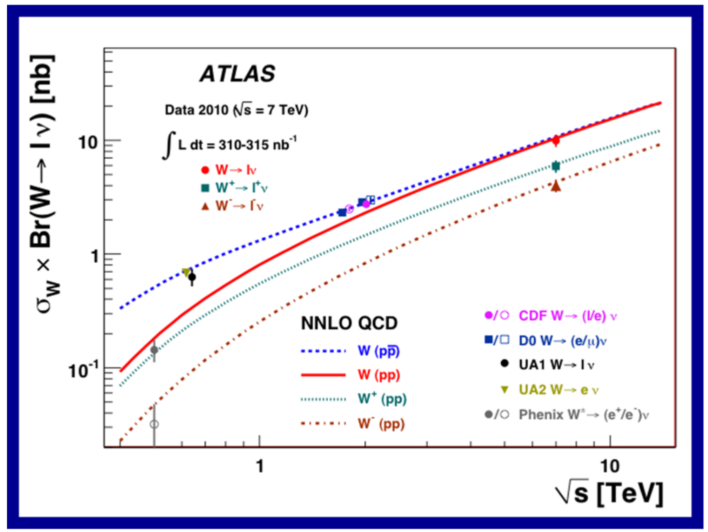
⇒ Physics absolute cross sections: test the model, theoretical calculations

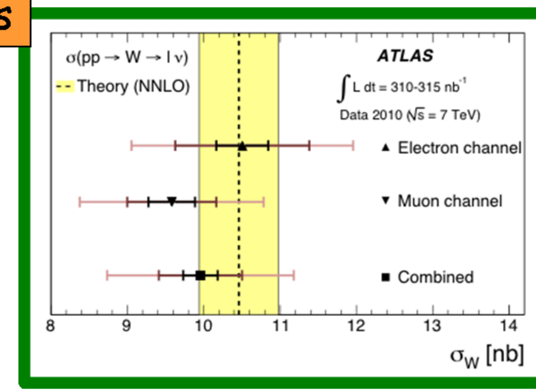
⇒ Measurement of the accelerator performance

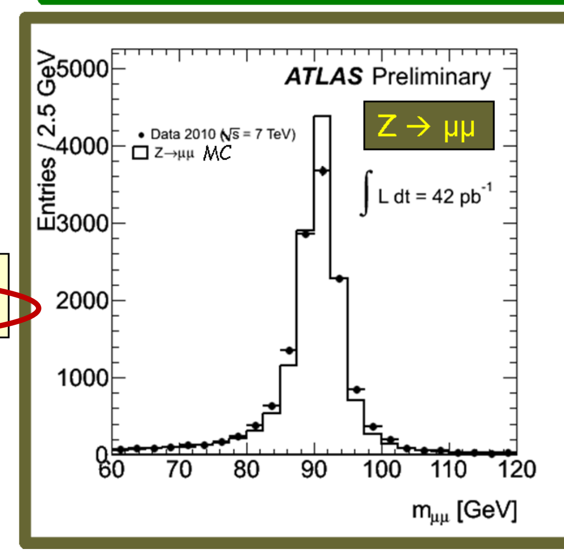
⇒ Useful both for the machine and the experiments

Already dominated by the systematic uncertainty on the luminosity

First W → lν and Z → ll measurements







- Excellent agreement with Standard Model
- Error dominated by 11% luminosity uncertainty

F. Gianotti @ Evian

Target Precision

Summary

- W and Z production cross sections are the hard process at the LHC with the best **intrinsic** precision (O(**2%**)).
- Thus **2%** sets a natural **benchmark scale for the target precision** of the luminosity measurement at the LHC
- A complete assessment of the consequences of O(2-5%) measurements of W and Z production properties is under way (*).
- It is already clear, nevertheless, that a cross section measurement to better than 5% allows an improved determination of PDFs, with an indirect benefit for the measurements of the W mass, and improved predictivity for all other hard processes.

M. Mangano @ Lumi Days:

⇒ **A measurement to better than 5% would start challenging the models**

⇒ **Ultimately aim for 2% , no clear interest to go below**

Methods for Luminosity Calibration

• Several methods exist and were used or are planned to be used at the LHC:

⇒ **Use a theoretically well known process:** in $e^+ e^-$ collider: Bhabba scattering. In hadron colliders: W and Z production

⇒ **Luminosity independent:** elastic scattering of protons (TOTEM and ATLAS).
Requires dedicated high-β optics, direct cross section measurement

⇒ **Machine parameters:** measure intensity + IP beam sizes
- Van der Meer method, scans in separation. Direct measurement of the overlap area
- beam imaging: reconstruct the individual beam profile from vertex data from p-p interaction (CMS/LHCb), or beam-gas (LHCb)

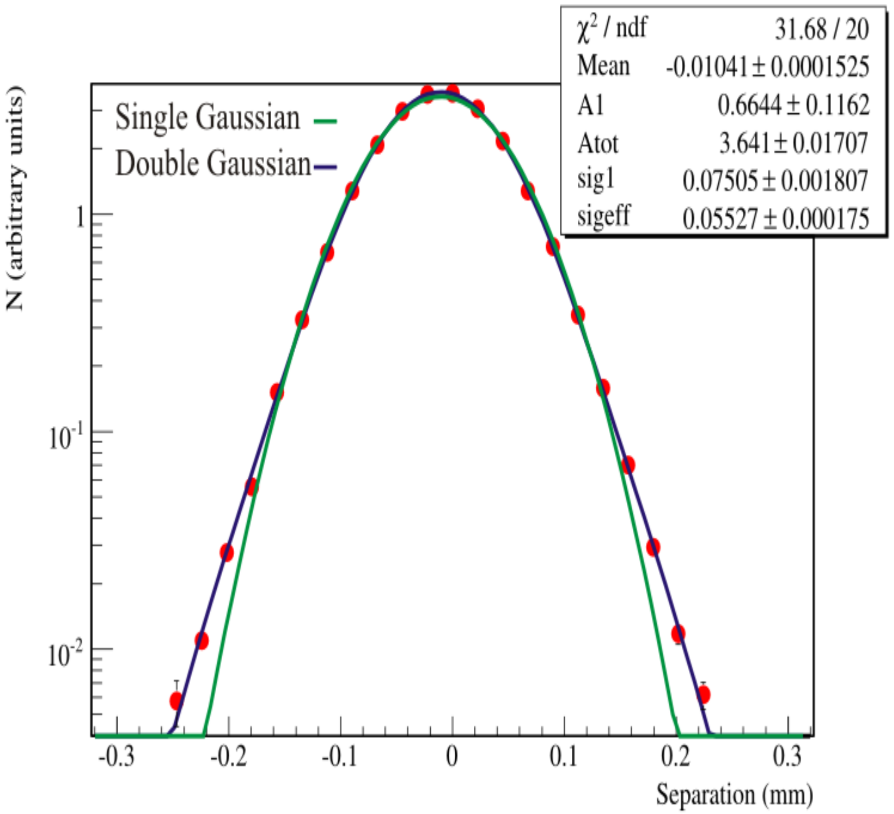
⇒ Find a clear and coherent picture comparing the results from all methods
⇒ Reach the % level with high-β experiments

Van der Meer Method

Luminosity in the presence of transverse offsets:

$$\frac{L}{L_0} = \exp\left[-\frac{\delta x^2}{2\ (\sigma_{x1}^2 + \sigma_{x2}^2)} - \frac{\delta y^2}{2\ (\sigma_{y1}^2 + \sigma_{y2}^2)} \right]$$

Revolution frequency known with good accuracy, intensity measured with BCTs. The effective overlap area can be determined by scans in separation



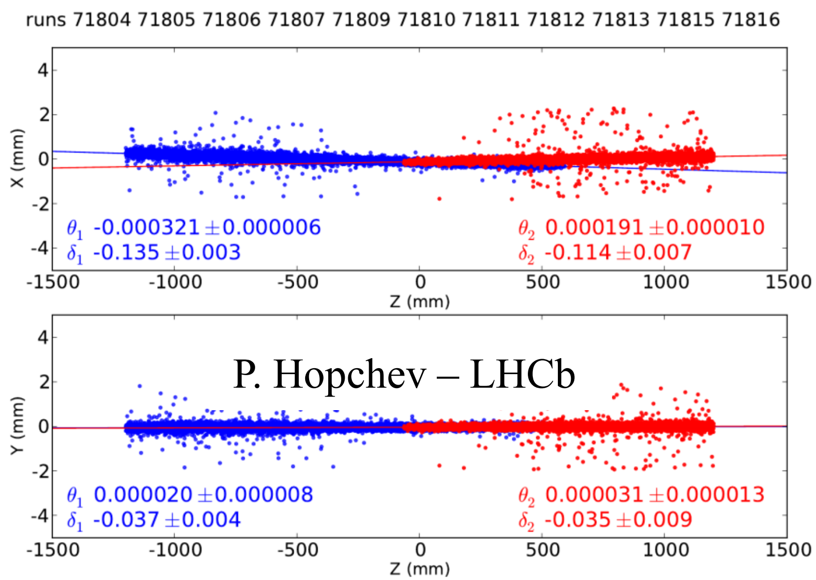
X-axis : beam displacement
Y-axis : any relative luminosity monitor

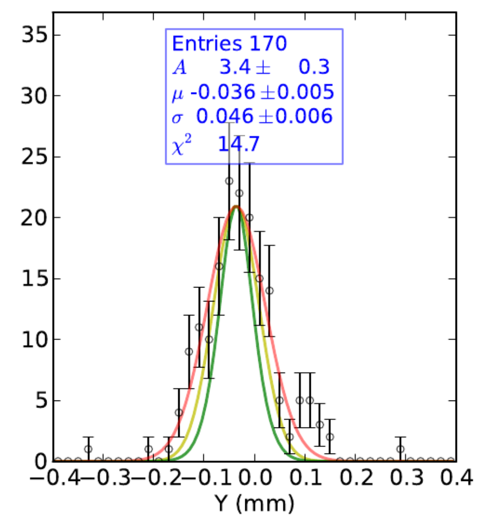
- **Potential sources of systematic uncertainty:**

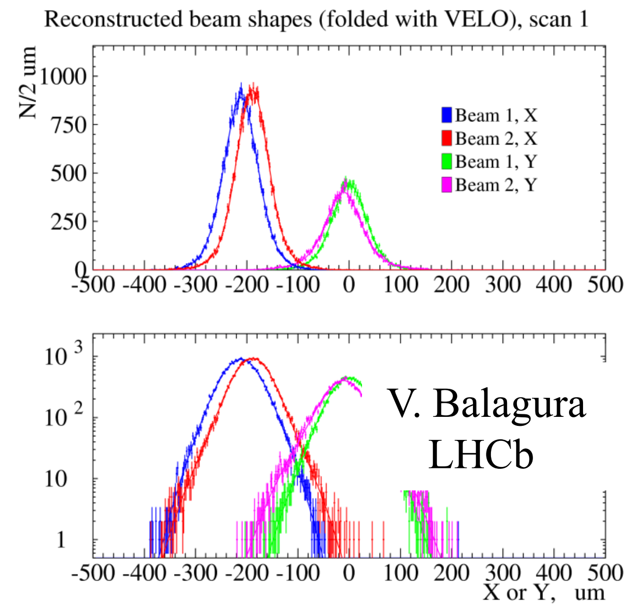
⇒ **Beam displacement scale**
⇒ **Bunch intensity measurements**
⇒ **Non stable beam conditions (emittance, orbit, …)**
⇒ **Requires excellent performance of beam diagnostics and machine stability**
⇒ **Ideally performed at low beam-beam parameter**

Beam Imaging

• First introduced by LHCb, can be done using p-p interaction profits from separation scans (LHCb/CMS), or beam-gas interaction with head-on collisions







• Potential sources of systematic uncertainty:

⇒ Bunch intensity knowledge

⇒ Vertex resolution: large beam sizes

⇒ Beam-gas: residual gas profile, beam-gas rates - integration over a long time: beam parameters stability – beams don't move can be done parasitically

⇒ p-p: complementary to VdM scans – additional information on uncertainty

⇒ Desirable to perform during VdM fills for direct cross check

⇒ Low beam-beam parameter would help (but large beam sizes + high rates?)

Scale Calibration

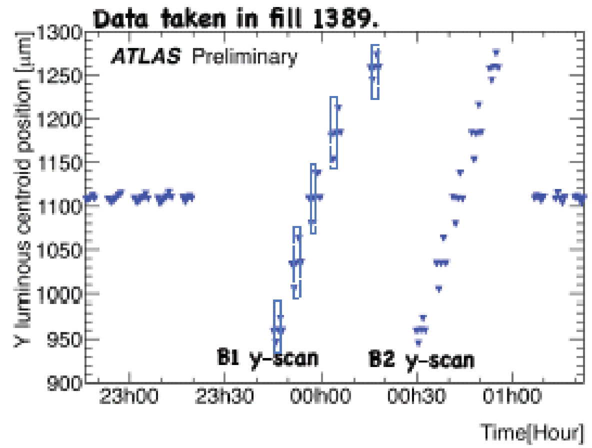
• Dedicated measurements done to calibrate the orbit bump scale. Needs to be done only once for the optics used for the scans. Two methods used in 2010.

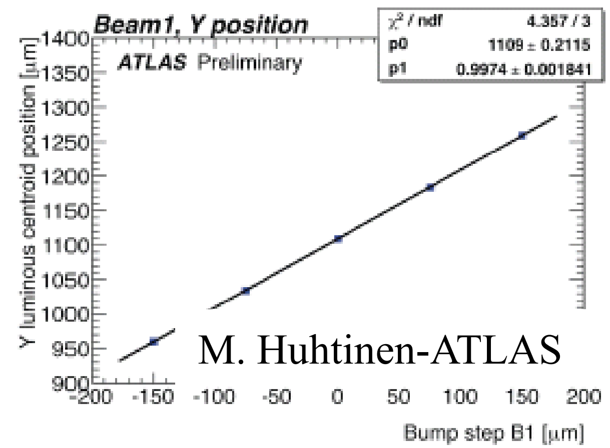
• **ATLAS:**

⇒ Shift the two beams colliding head-on transversally

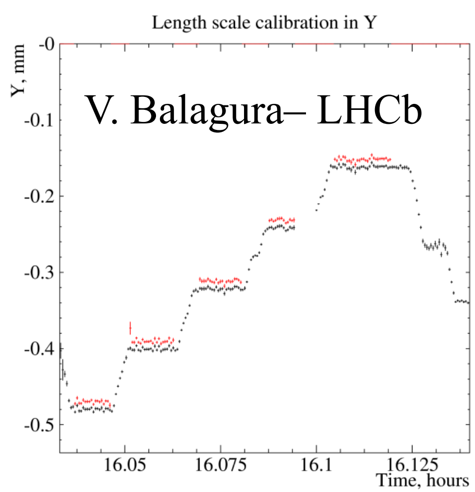
⇒ Mini-scans at each point to compute Δ

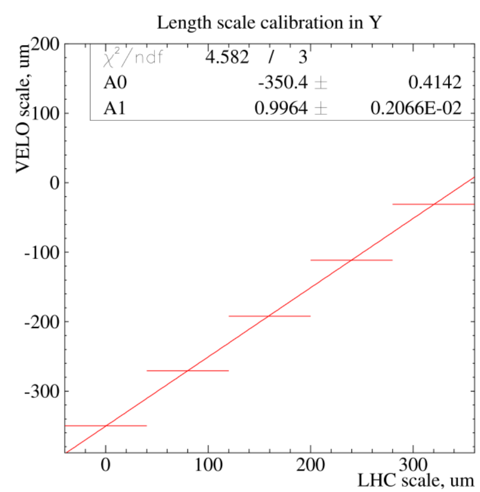
⇒ Compare with luminous region displacement





All 4 scans fit very well. Seen movement agrees with nominal displacement within <0.5%





•**ALICE/CMS/LHCb:**

⇒ Shift the two beams with constant offset (√2σ) transversally

⇒ Δ given by the slope in luminosity

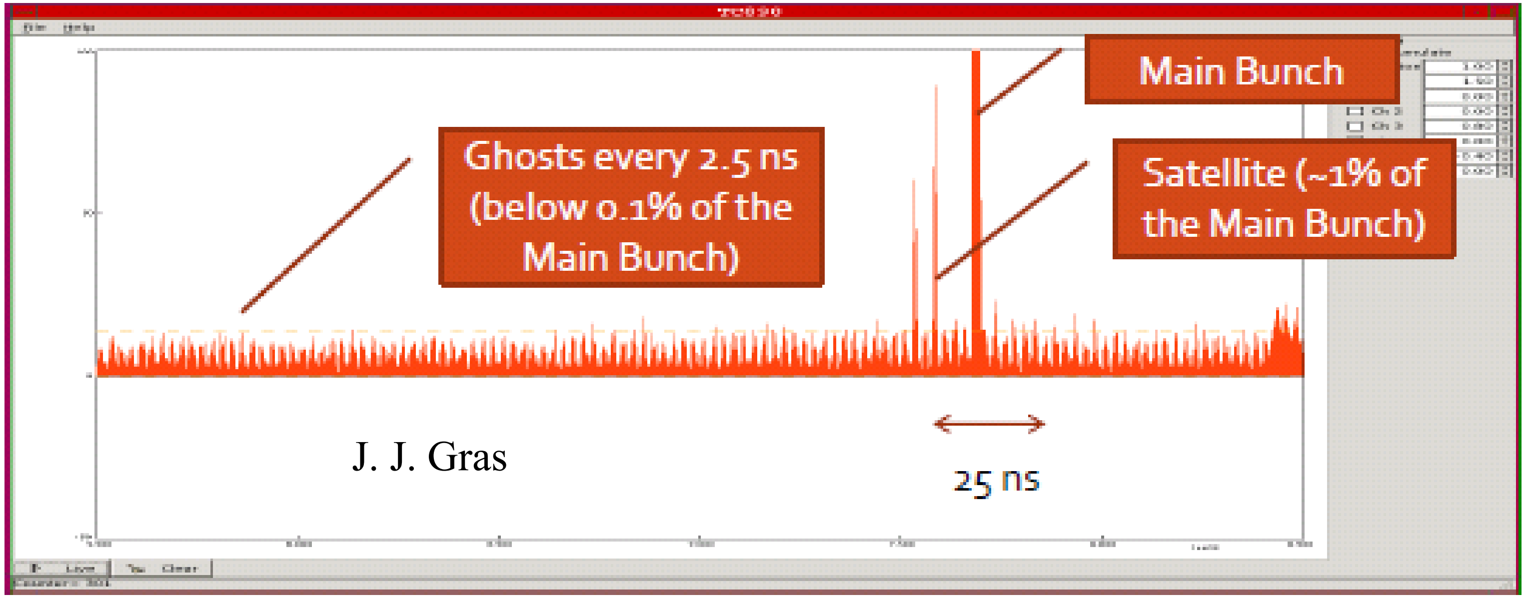
⇒ Scale given by the displacement of the luminous region

• **Both methods work equally well, agreement within 1%. ATLAS much longer.**

Beam Intensity

• Both methods rely on a precise bunch intensity measurement. Several issues were addressed and are under investigation (See J. J. Gras @ Lumi Days, BCNWG).

• **BCTDC, total beam intensity used as reference for absolute calibration:**
⇒ **2011 target: reduce the error down to below 1% for next year**
• **BCTFR, bunch by bunch intensity**
⇒ **Achieved 1% relative uncertainty between bunches in October**
⇒ **Latest results: total uncertainty on the product N_1N_2 ~3%**
⇒ **2011 challenge: properly estimate the satellite bunches and un-bunched population**



• **Longitudinal density monitor:**
⇒**Should provide the required information**
⇒ **To be commissioned as soon as possible**

2010 Results

- **Two sets of scans performed in 2010 at the four interaction points. Beam-gas imaging done for few selected fills**

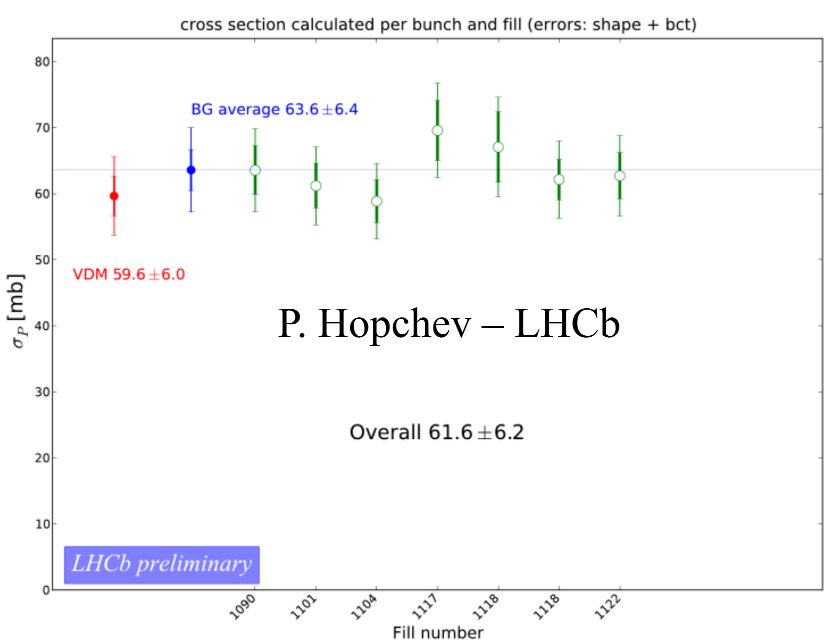
- **Excellent results for a first experience:**

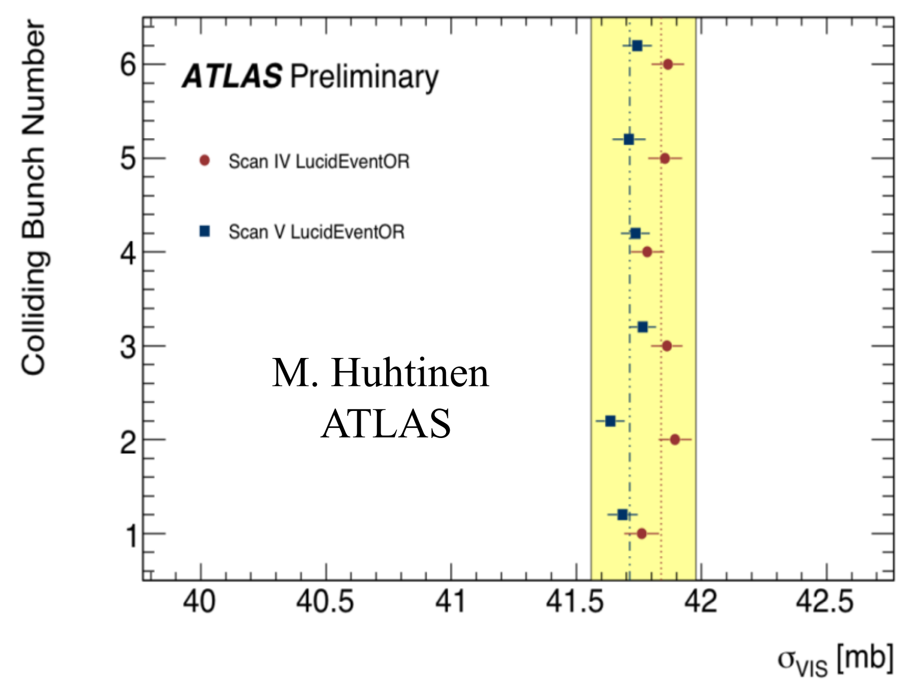
⇒ Consistency between methods, fills, bunches and detectors

⇒ April-May scans gave a first calibration to 11% dominated by intensity uncertainty

⇒ Expect to reduce the uncertainty to ~5% in view of latest measurements (improved knowledge of the beam intensity, better beam stability)

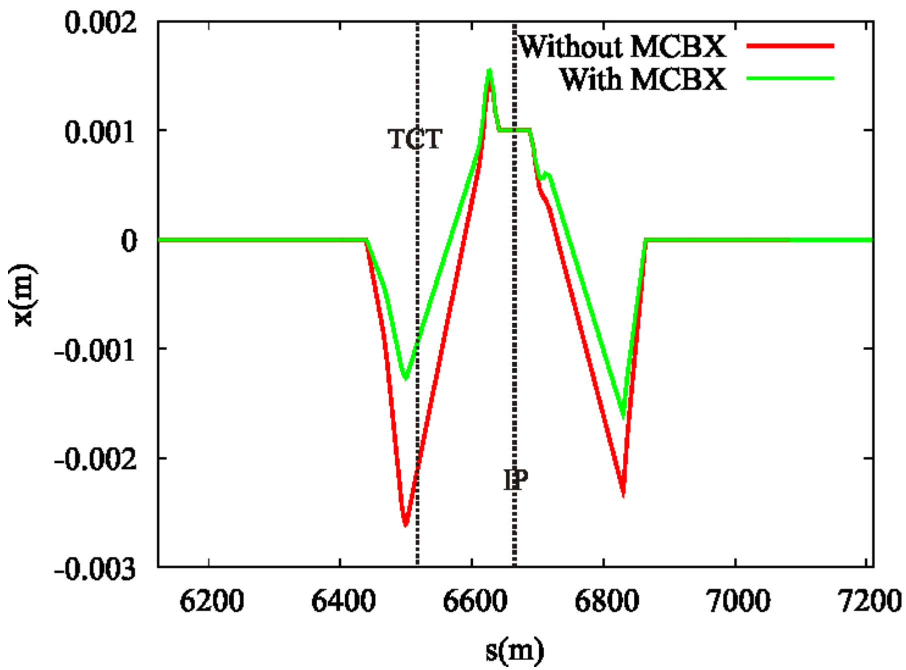
⇒ 2011: aim for below 5%





2011 - Interaction with Machine Protection

- Hierarchy between cleaning stages must be preserved to guarantee protection - limits orbit variation (R. Bruce @ Evian)



Example of an IP bump with and without MCBX:
⇒ Creates a large offset in the TCT region, cannot be avoided
⇒ MCBX magnets not used for luminosity optimization
⇒ **Last year:** split the amplitude between beams + loss maps with TCT closed by 2σ with respect to reference settings

- **Outcome of Evian, strategy for 2011:**

⇒ **MUST move the TCT with the beam:** increased margin dump protection/TCT
⇒ Implementation done, tests required
⇒ **Does not prevent from breaking the TCT/triplet margin:** requires detailed study for each scenario, assess aperture reduction in the crossing angle plane

Experiments Requests for 2011

- **General agreement:** no trains, crossing angle on, bunch by bunch analysis (rates)

- **ATLAS:** $\mu \sim 1.5 - 2$, driven by low acceptance detector
- **CMS:** $\mu \sim 1$, large beam size, use p-p beam imaging method
- **LHCb:** $\mu \sim 1$, large beam size + pressure bump, use beam-gas imaging
- **ALICE:** $\mu \sim 0.1 – 0.5$

- **Diverse (conflicting?) wishes:**
  - ⇒ How do we accommodate these requests in one fill? Knobs are ε, β, N
  - ⇒ Large beam sizes + high rates → high bunch intensity: not ideal to reach very high precision (beam-beam, non-linearity)

- **Instrumentation:** set priorities on BCTs and LDM. Emittances, BPMs also on the list

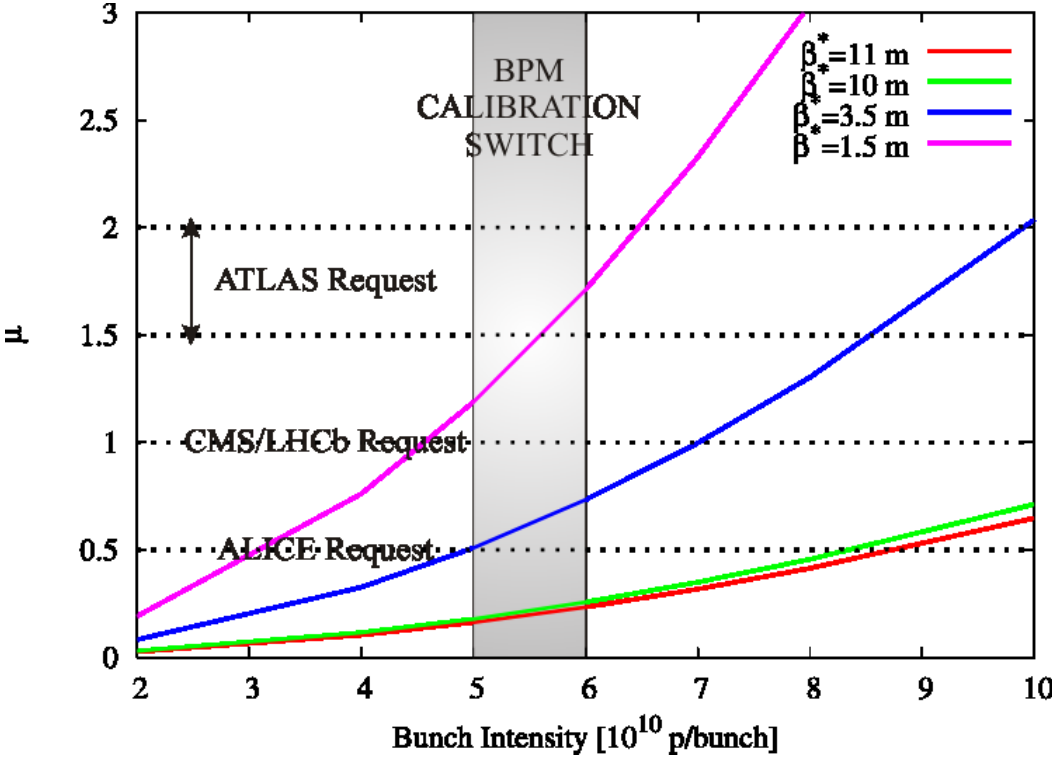
- **Other requests:** equalize emittances B1/B2 and bunch by bunch, minimize satellite bunches, more flexible software: scans driven by editable files, intermediate β^*, investigate hysteresis, coupling, parallel scans, longitudinal scans, etc…

⇒ Requires a lot of effort, developments, beam studies and time: set priorities

⇒ 2 fills requested - measurement early in the run if energy is changed

Parameter Space

- **Limitations:**
  - use standard optics, injection or physics, to reduce setup time
  - stay away from the BPM calibration switch, below or well above (no crossing during the fill)
- **Assumptions:**
  - normalized emittance ~ 3.0 μm
  - physics β^*: IP1/IP5 1.5 m, IP2 10 m, IP8 3.5 m



- **IP1:** requested μ out of range for injection optics, too close to BPM calibration switch for physics optics
- **IP5:** requested μ out of range for injection optics (large beam size)
- **IP2/IP8:** requirements could be fulfilled in the same fill

⇒ **Experiments requirements are too constraining to be accommodated within a single fill using standard optics**

⇒ **Different bunch intensities?**

⇒ **Squeeze only one IP?**

Proposed Strategy

- **Remarks:**

  -2 special fills requested for VdM: balance setup time / measurements
  -any exotic request (non standard operation) comes at a cost: avoid if possible
  -rely on beam stability and linearity of the system: low beam-beam parameter
  -reaching < 5% is (very) challenging: cannot rely on a couple of measurements, are 2 fills really sufficient if the target is below 5%? Cross checks!

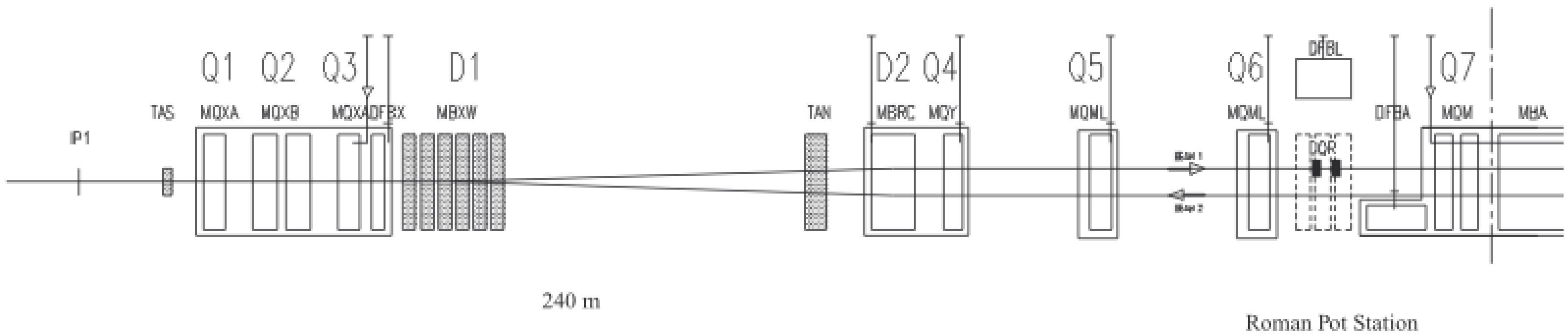
- **Proposal (assuming 2 special fills):**
  - **High precision: 1 fill for Van der Meer scans at physics optics and reduced bunch intensity < 5.0e10 p/bunch, minimal setup time**
  - **Vertex methods: 1 fill at injection optics (large beam size) with highest possible μ, assuming co-moving TCT, is full MP qualification for STABLE BEAM required? Collision tunes?**
  - **Reproducibility: few end of fill scans, provide calibration at high μ (check extrapolation), no setup time, "parasitic", define conditions**

- **Comments:**

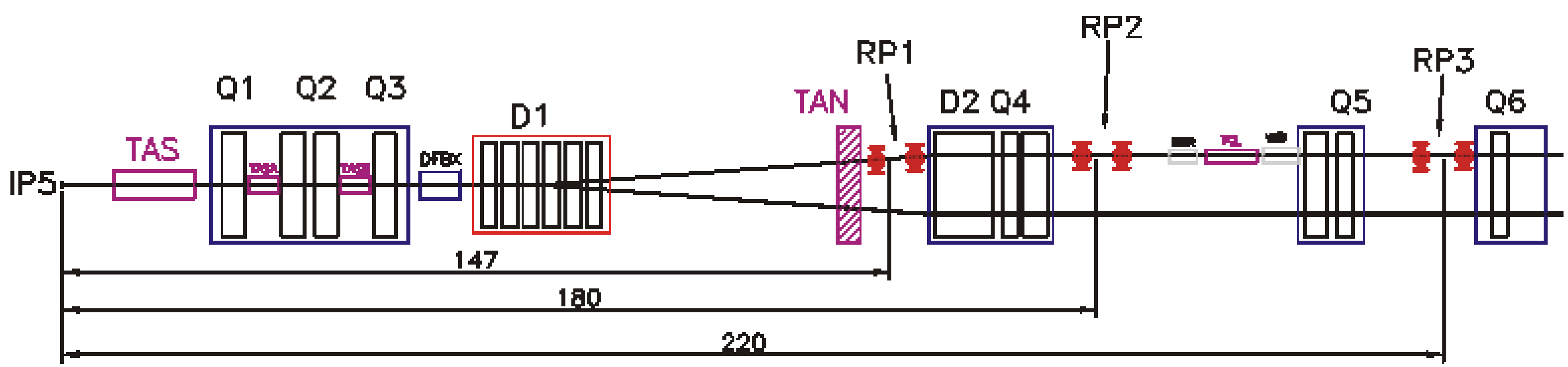
  -LHCb beam-gas method could also profit from the special high-β run
  -ATLAS low acceptance detector can be cross calibrated with other signals

High-β Experiments

• Two experiments in the LHC, ATLAS (IP1) and TOTEM (IP5): determine the total p-p cross section from the measurement of elastic scattering angles



ATLAS IR layout



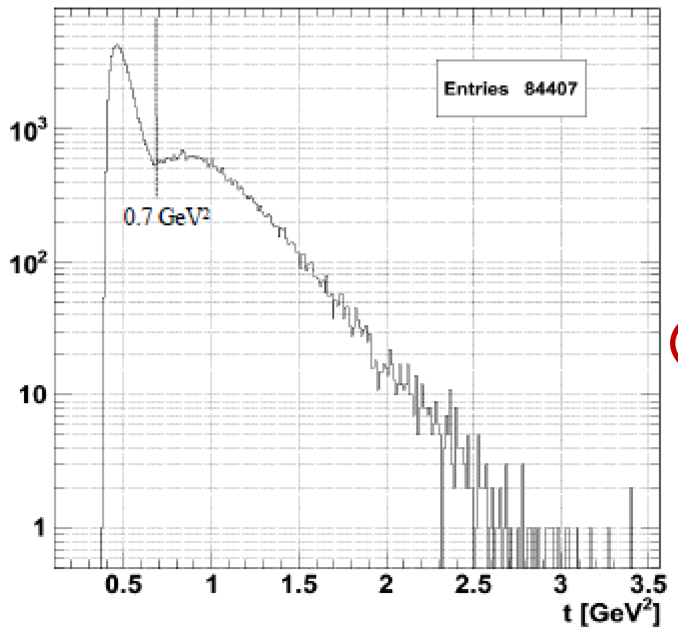
TOTEM IR layout

• Dedicated moveable detectors (Roman Pots) installed in both IRs
• "Parallel-to-point" focusing optics with (very) high β*
• Expected precision on the cross section: few percents (1% ultimate)
• Independent from other methods – different systematic uncertainties

Preliminary t-distribution

~ 84K elastic scattering candidate events TOTEM special run (~ 9 nb^{-1})

M. Deile @ Lumi Days



$\sqrt{s}$ = 7 TeV
β^* = 3.5 m
RPs @ 7 σ (V) and 16 σ (H)

Summary

TOTEM is ready for a first σ_{tot} and luminosity measurement in 2011 with β^* = 90m using the Optical Theorem.
Expected precision: ~3% in σ_{tot} , ~4% in L

Wish: start soon with the development of the β^* = 90m optics to have enough time for learning.

Desired running conditions: low beam intensity, small RP distance to the beam

Longer term:
Measurement at the 1% level with very-high-β^* optics (~1 km);
might give access to the ρ parameter if the energy is still low ($\sqrt{s}$ ~ 8 TeV);
needs optics development work.

Mario Deile – p.16

- **Independent measurement:**

⇒ Challenge the machine parameters methods

⇒ Most needed cross check to get confidence on the 5% level

ATLAS - ALFA

- **Status and roadmap:**

⇒ ALFA Roman Pots are installed and ready to start commissioning

⇒ Start commissioning in garage position

⇒ Repeat the 2010 TOTEM exercise (alignment with collimators, etc..)

⇒ Expect to finish commissioning and be ready for physics at 90 m for summer

- **Cross section measurement:** 5-7% level with 90 m optics

Main installation activities in the LHC tunnel

December 2010:

- ❑ removal of detector ALFA2 in station B7L1 (installed 2009/10)
- ❑ breaking of Roman Pot and LHC vacuum
- ❑ removal of ALFA2 Roman Pot
- ❑ installation of 2nd station A7L1 in sector 8-1
- ❑ installation of both stations in sector 1-2
- ❑ reinstallation of ALFA2 Roman Pot with new ferrites
- ❑ station alignment in LHC coordinate system
- ❑ restoring of Roman Pot and LHC vacua
- ❑ bake out of stations and close by beam pipes

All stations including Roman Pots were installed. Stations aligned to LHC system, bake out done.

January 2011:

- ❑ replacement and adjustment of new springs for auto-retraction
- ❑ insertion of the fiber detectors
- ❑ installation of the electronics and cabling
- ❑ commissioning of the station movement systems
- ❑ survey and final LVDT calibration for detector positioning
- ❑ commissioning of the data readout by LED signals

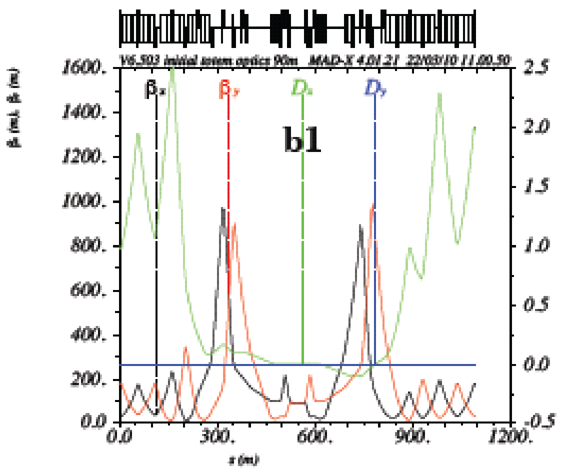
End of January all 4 stations on both sides should be ready for movement and data taking.

K.Hiller LHC Lumi Days, January, 2011 13

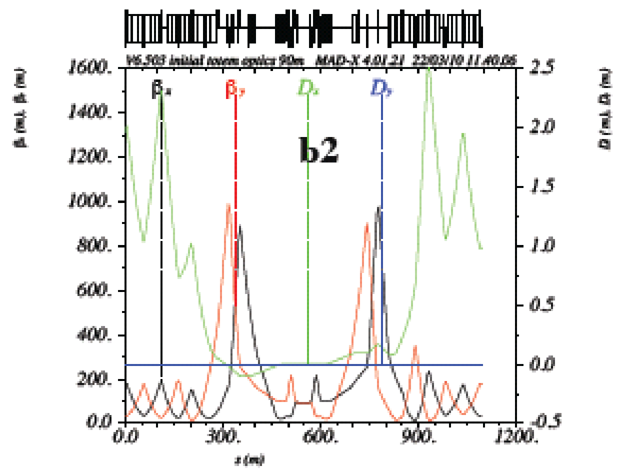
K. Hiller @ Lumi Days

High-β Optics

IP5 90 m optics – RP at 220 m from the IP



$\Delta Qx = 0.222$ $\Delta Qy = 0.055$



$\Delta Qx = 0.220$ $\Delta Qy = 0.053$

- **Status:**

⇒ **90 m meter optics + un-squeeze in IP5 ready for commissioning**

⇒ **Settings imported in LSA (S. Redaelli, G. Muller)**

⇒ **IP1: same un-squeeze + optimization of the last steps**

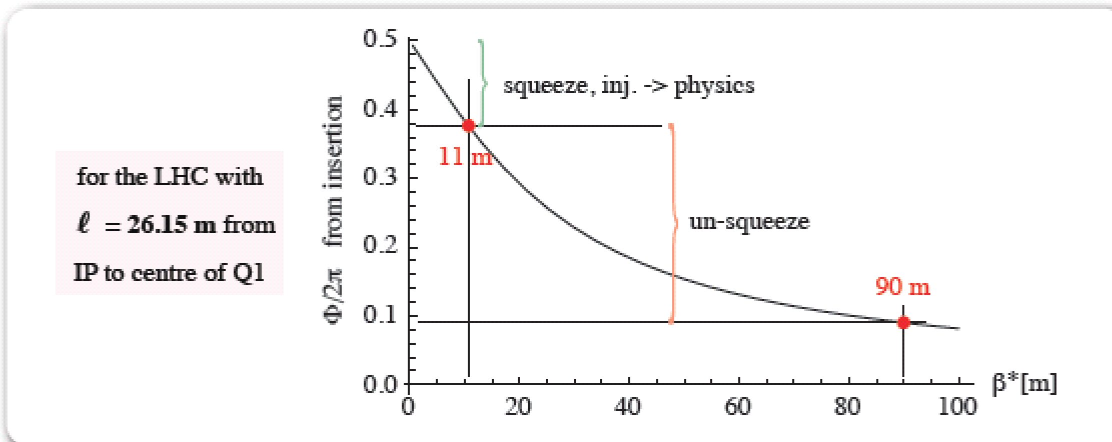
- **Constraints & requests:**

⇒ **Tune compensation**

⇒ **π/2 phase advance between IP and the detector**

⇒ **Very high precision optics measurements ($\Delta\beta/\beta \sim 1\%$)**

⇒ **Very challenging: start commissioning as early as possible**



The tune change in the un-squeeze is much bigger than in the squeeze to low β

H. Burkhardt @ Lumi Days

Physics & Commissioning Strategy

High-β in 2011 :

- 90 m optics commissioning concentrate on one goal in 2011, which is the 90 m optics ; the commissioning should start in MD a.s.a.p and will tell us a lot about the feasibility of these optics and the requirements in terms of commissioning and set up time
  if things go really well : commissioning in 5 shifts, simultaneously 2 beams and IP 1&5
  IP 2/8 left by default at 10m inj, r&s settings
- Physics operation at 90 m at the current physics energy, simultaneously in IP 1&5, in the 2nd part of the year, about a week, split in several parts

- **Commissioning:**
  ⇒ IP1 & IP5 simultaneously
  ⇒ About 5 shifts
- **Tune compensation:**
  ⇒ First try with arcs (kqf, kqd)

- **Physics at 90 m:**
  ⇒ Special runs, IP1 & IP5 simultaneously
  ⇒ 4 fills split in several parts
  ⇒ No crossing angle (BPMWF), reduced emittance and luminosity per bunch

three alternatives for the required tune adjust of $\Delta Qx = +0.222$, $\Delta Qy = +0.055$ / IP

- use another IP, for example IP4
  advantage : local to IPs , no β-beating in arcs
  disadvantage : limited to ~ 0.2, no way to compensate 90 m in several IPs
  implications for instrumentation and damper in IP4
- use the trim quadrupoles, the tune adjust (of a single IP)
  results in up to 8.5% β-beat in x and 4.5 % in y / IP
- ramp up the main quads during the un-squeeze to compensate the loss in tune
  proposed first by O. Brüning in LCCWG#4 on 19/4/2006
  results in up to 4.5% β-beat in x and 1.6 % in y / IP

Summary

- **Luminosity calibration is important and useful both for physics and the understanding of the machine performance**

- **Machine parameters methods:**
  ⇒ **Very successful first experience, results went beyond expectations**
  ⇒ **Expect to reach 5% accuracy for 2010, aim for <5% in 2011**
  ⇒ **Special fills: 2 requested, conditions to be discussed, try to reduce setup time**
  ⇒ **Developments & beam studies: a lot on the list, set priorities**
  ⇒ **Hardware: lots of efforts already done and very much appreciated. Beam intensity measurements still limits the precision: set priority on the BCTs and LDM**

- **High-β experiments:**
  ⇒ **TOTEM is commissioned and ready for physics at 90 m**
  ⇒ **ALFA will start commissioning, expects to be ready for summer**
  ⇒ **Optics are ready for commissioning, operational challenges very different from squeezed optics: start commissioning as soon as possible (~5 shifts)**
  ⇒ **Direct cross section measurement independent from machine parameters: would provide a very useful (and required) cross check of other methods**
  ⇒ **Physics: 4 fills, expect to reach 3% accuracy on the cross section (TOTEM)**