Exclusive production at LHC: Resolution and Trigger

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Work done within the Helsinki Forward Project

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Overview

- Physics motivation
- LHC machine layout and optics
  - → Only for nominal (high luminosity) optics
- Leading proton / central mass resolution
  - → Momentum reconstruction procedure
  - → Smearing and systematic effects
  - → Resolution results
- Triggering issues
  - → ATLAS/CMS trigger and DAQ constraints
  - → Leading proton trigger for LVL1
  - → Other possibilities for LVL1 selections
- Outlook

(Forward) physics motivation

- total cross-section
- elastic scattering
  - → $d\sigma/d|t|$, $\sigma_{el}/\sigma_{total}$, ρ parameter
- diffractive scattering
  - → Soft processes: (differential) cross-sections, contribution to σ_{total}
  - → Hard processes: partonic structure (high p_T probes: jets, W/Z, γ, ...)
- exclusive production ($pp \rightarrow p + X + p$) via central diffraction
  - → Higgs bosons, SUSY particles, $t\bar{t}$ pairs, ...
  - → di-jets as gluon factory
- leading particle production (p-p and p-A)
  - → understand better cosmic ray induced air-showers
- photon-nucleus interactions
  - → ultra-peripheral collisions, two photon exclusive production

mostly leading particle measure-ments

- minimum bias event structure
- properties of rapidity gaps
  - → survival probability, multi-gap events, ...
  - → rapidity gaps as tools for new physics
- low-x physics (in p-p, p-A and A-A collisions)
  - → parton distributions, QCD dynamics (BFKL, CCFM, ...)
  - → shadowing, multi-parton scattering

extended coverage inside exp. cavern (?)

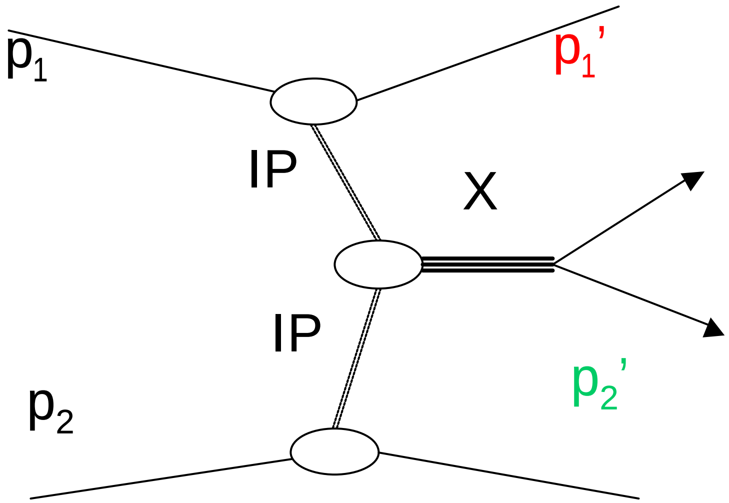
Physics motivation (cont'd)

- exclusive production:

  $p\,p \rightarrow p + X + p$

  → Observe and measure leading (diffractive) protons
    - determine momentum loss ξ

  → Reconstruct mass M_X of the central system X
    - $M_X^2 = x_1\ x_2\ s$
      - → e.g. M_X = 140 GeV $\rightarrow \sqrt{\xi_1 \xi_2} = 10^{-2}$

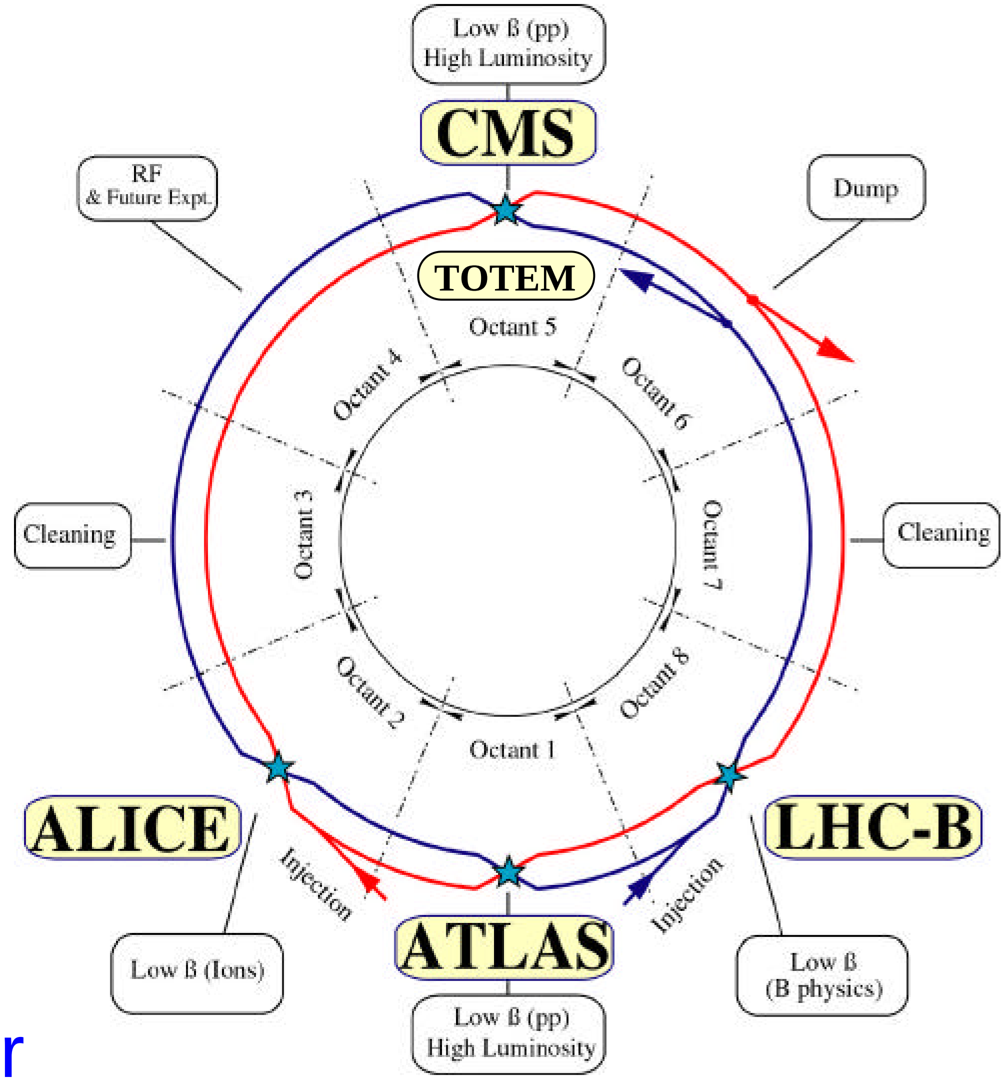


- Mass measurement precision from the leading p's?

  → Concentrate on M_X determination
    - Whether object of interest (e.g. H) is or is not accompanied by remnant system ($M_X > M_H$ or $M_X = M_H$)

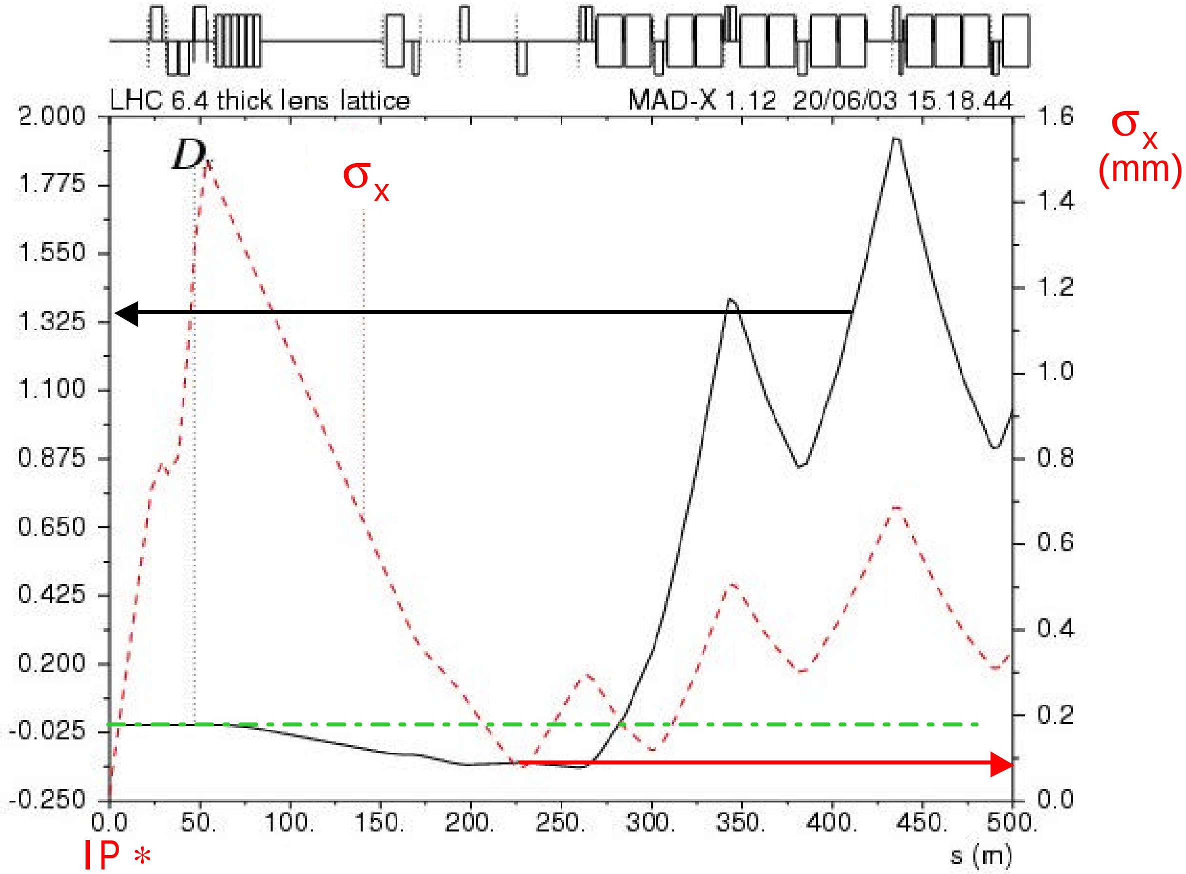
LHC machine overview

- p-p @ $\sqrt{s}$ = 14 TeV
  - → >1000 dipoles B = 8.3 T
    - NbTi @ 1.9 K
  - → Strong focussing
    - β^* = 0.5 m
  - → 2835 bunches
    - 10^{11} p / bunch
  - → 25 ns bunch spacing
- L_{design} = 10^{34} cm^{-2} s^{-1}
  - → 100 fb^{-1} per year
    - ~ 20 inelastic events per bunch crossing
- Outgoing p beams for ATLAS/CMS on outside of ring!



Leading proton measurements

- Diffractive Scattering
  - → Proton(s) on one or both sides
  - → Determine $-t$ and $\xi = \Delta p/p$
- Example nominal optics (low β^*)



  - → Small beam size (σ_x) at 200 - 250 m from IP
  - → Large dispersion (D_x) at more than 300 m from IP
    - $\Delta x = \xi D_x$ (deviation from nominal beam position)

Accelerator optics

- Dispersion: $D(s)$
- Emittance: ε
- β-function (at IP): $\beta_{x,y}(s)$ (β^*)
- Phase advance: $\mu(s)$
- Beam size at IP: $\sigma^*_{x,y} = \sqrt{\frac{\epsilon}{\gamma}\beta^*}$
- Beam divergence: $\sigma^*_{\theta_{x,y}} = \sqrt{\frac{\epsilon}{\gamma\beta^*}}$

- Effective length:

$$L^{eff}_{x,y}(s) = \sqrt{\beta_{x,y}(s)\beta^*}\sin\Delta\mu(s)$$

- Magnification:

$$v_{x,y}(s) = \sqrt{\frac{\beta_{x,y}(s)}{\beta^*}}\cos\Delta\mu(s)$$

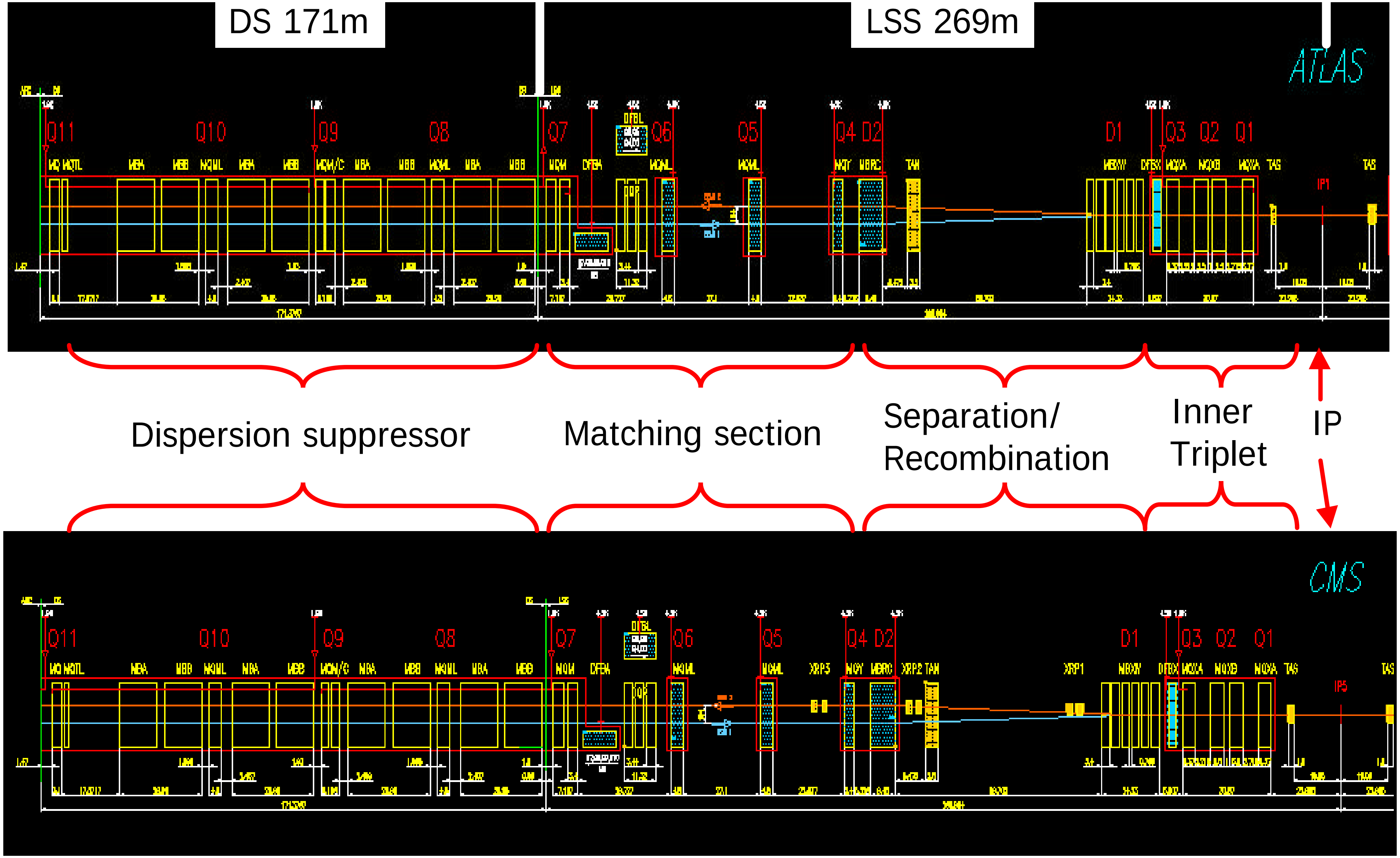
- Position/angle at IP: x^*, y^*, θ_x^*, θ_y^*

$$y(s) = v_y(s)\cdot y^* + L^{eff}_y(s)\cdot\theta^*_y$$

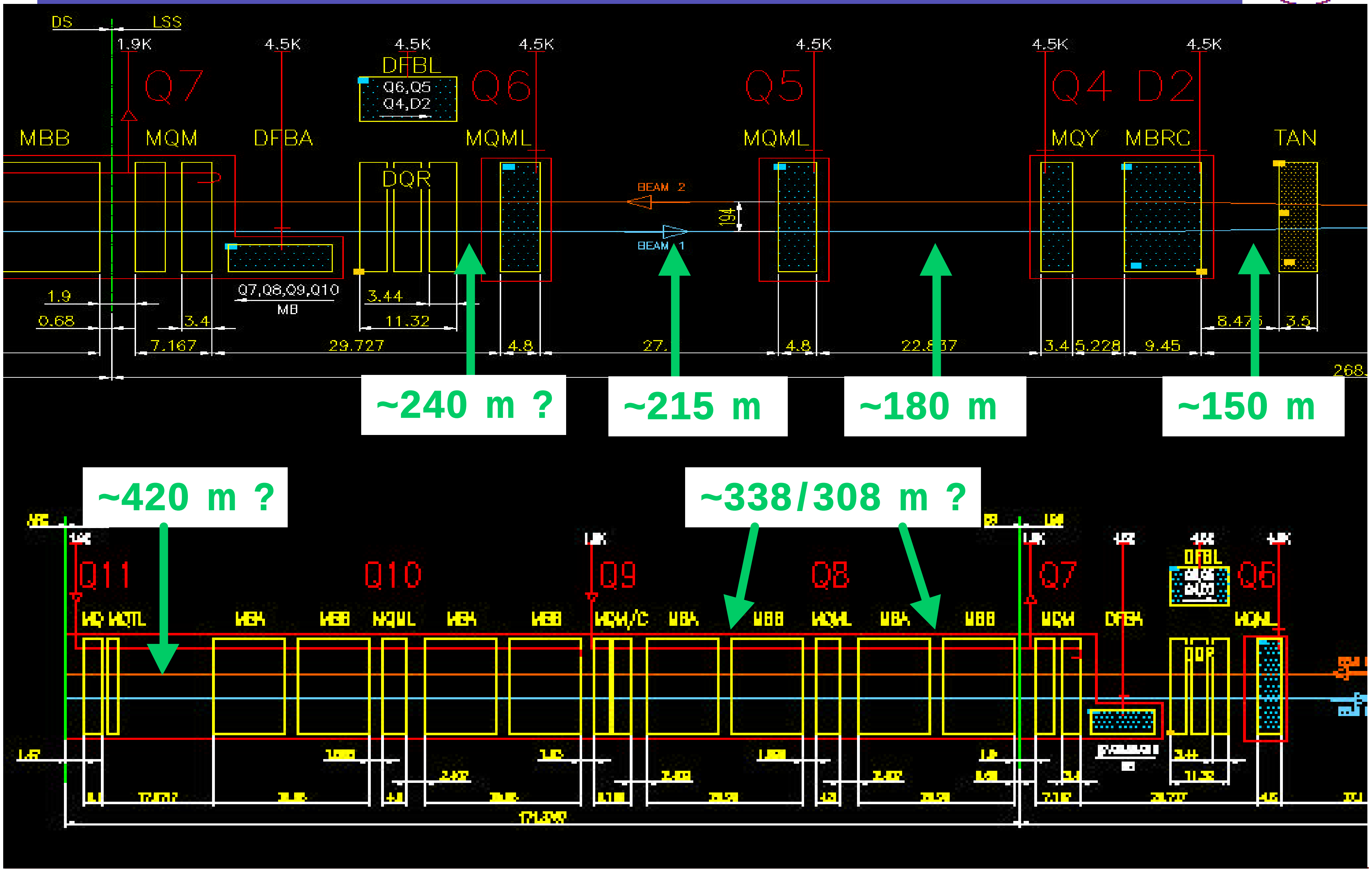
$$\boxed{x(s) = v_x(s)\cdot x^* + L^{eff}_x(s)\cdot\theta^*_x + \xi\cdot D(s)}$$

- Similar for the angles $\theta_{x,y}(s)$ at the detector location s

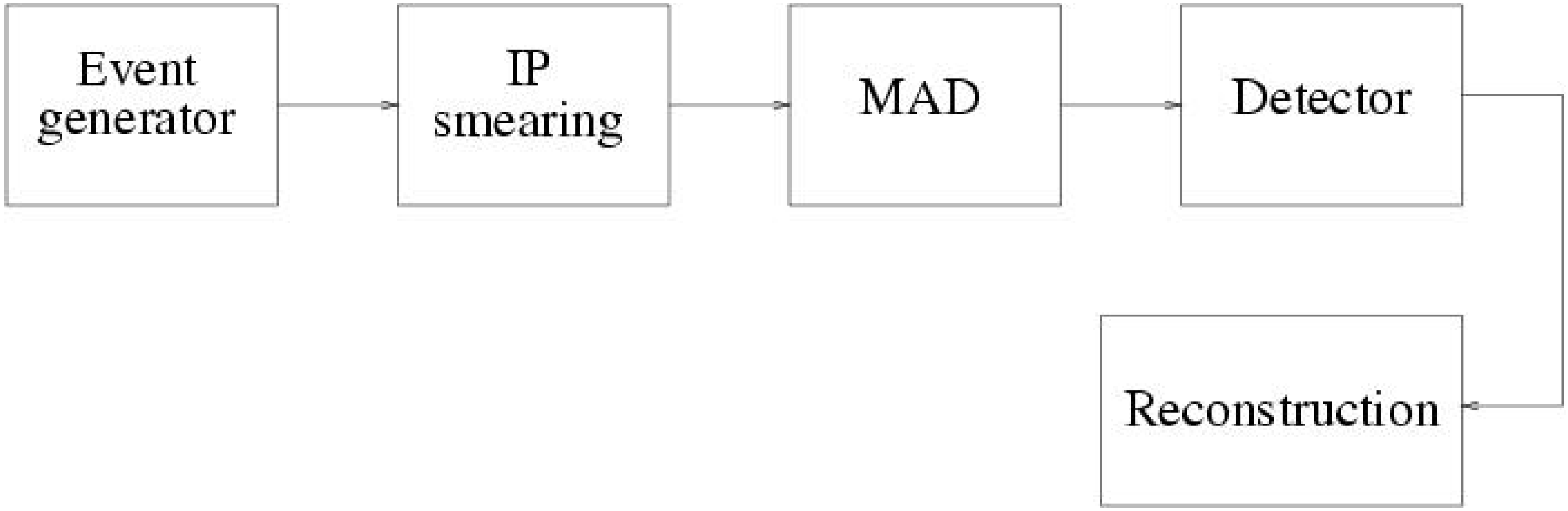
Layout of IP1 and IP5



Possible locations

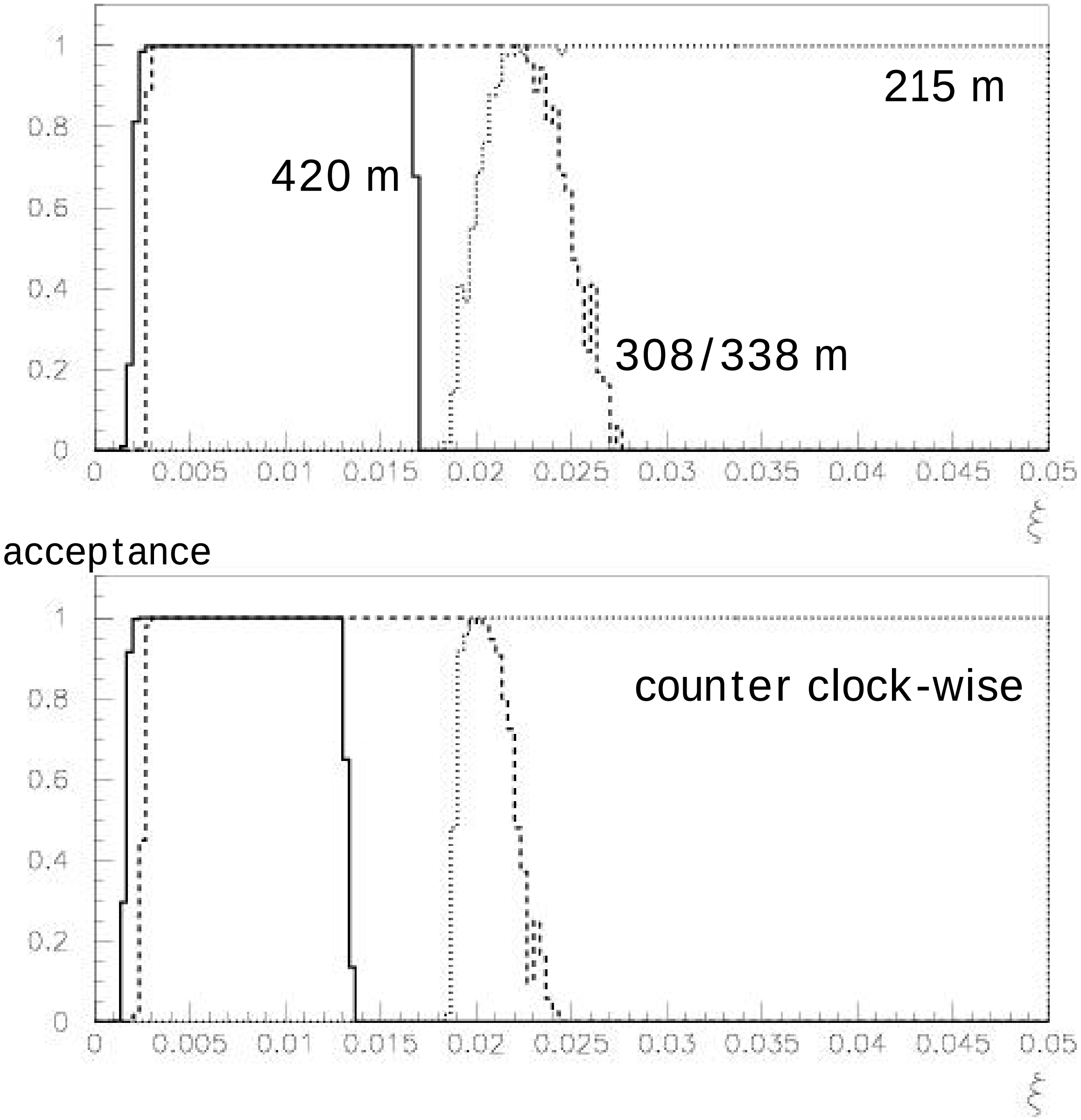


Simulation chain



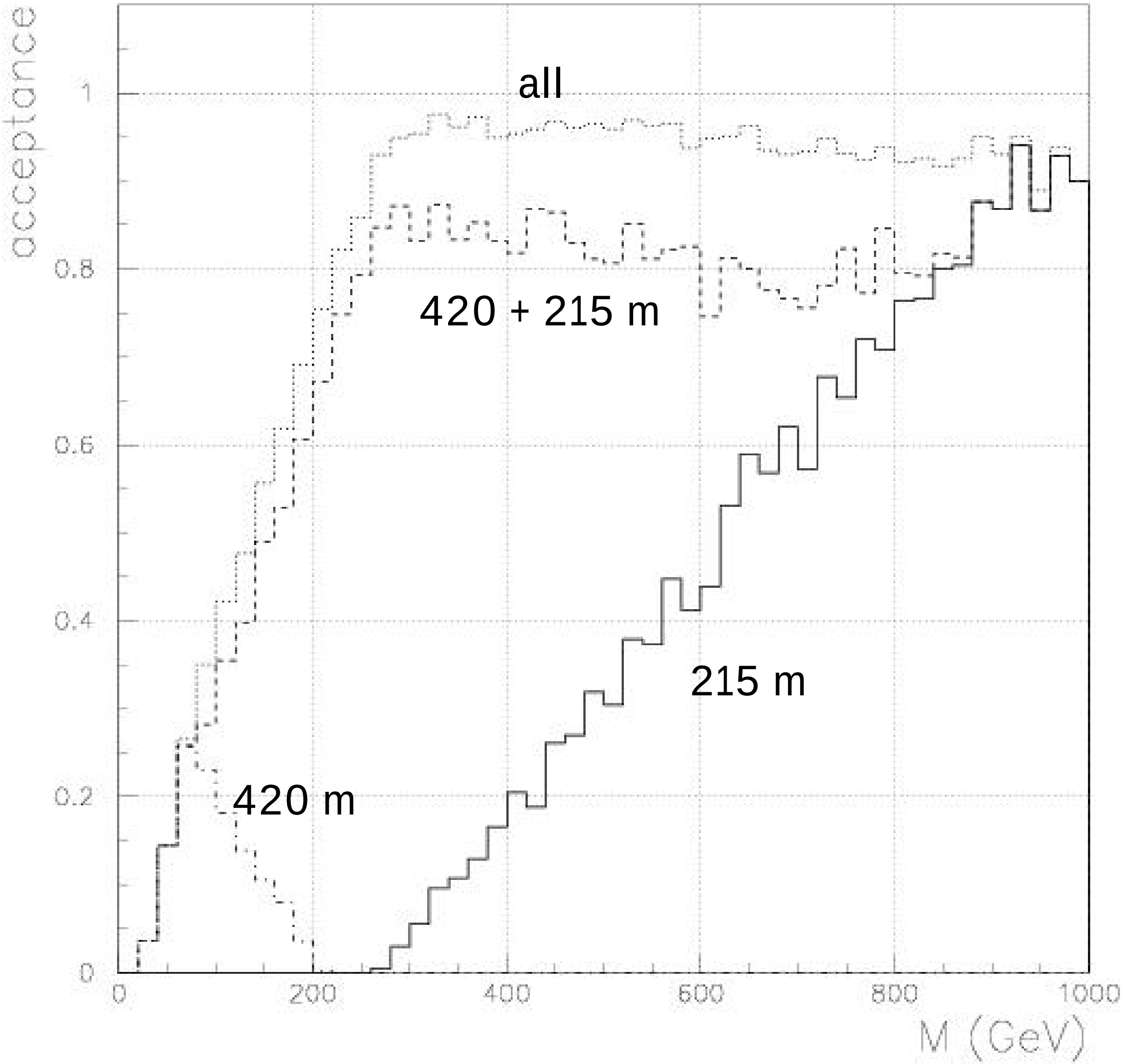
- Generator: PHOJET + PYTHIA for pp → p+H(bb)+p
  - → Kinematic event properties (not cross-sections !)
- Initial conditions (IP smearing)
  - → Vertex spreads, beam energy spread, beam divergence
- Proton tracking along beam line (MAD)
  - → Version 6.2 of LHC optics, simplified beam pipe aperture, clock- and anticlockwise
- Detector simulation
  - → Position resolution, beam position resolution, mis-alignment, absolute beam position
- Momentum reconstruction
  - → Unfold from two 'independent' measurements the initial variables (ξ, θ^*_x)

Leading proton acceptance



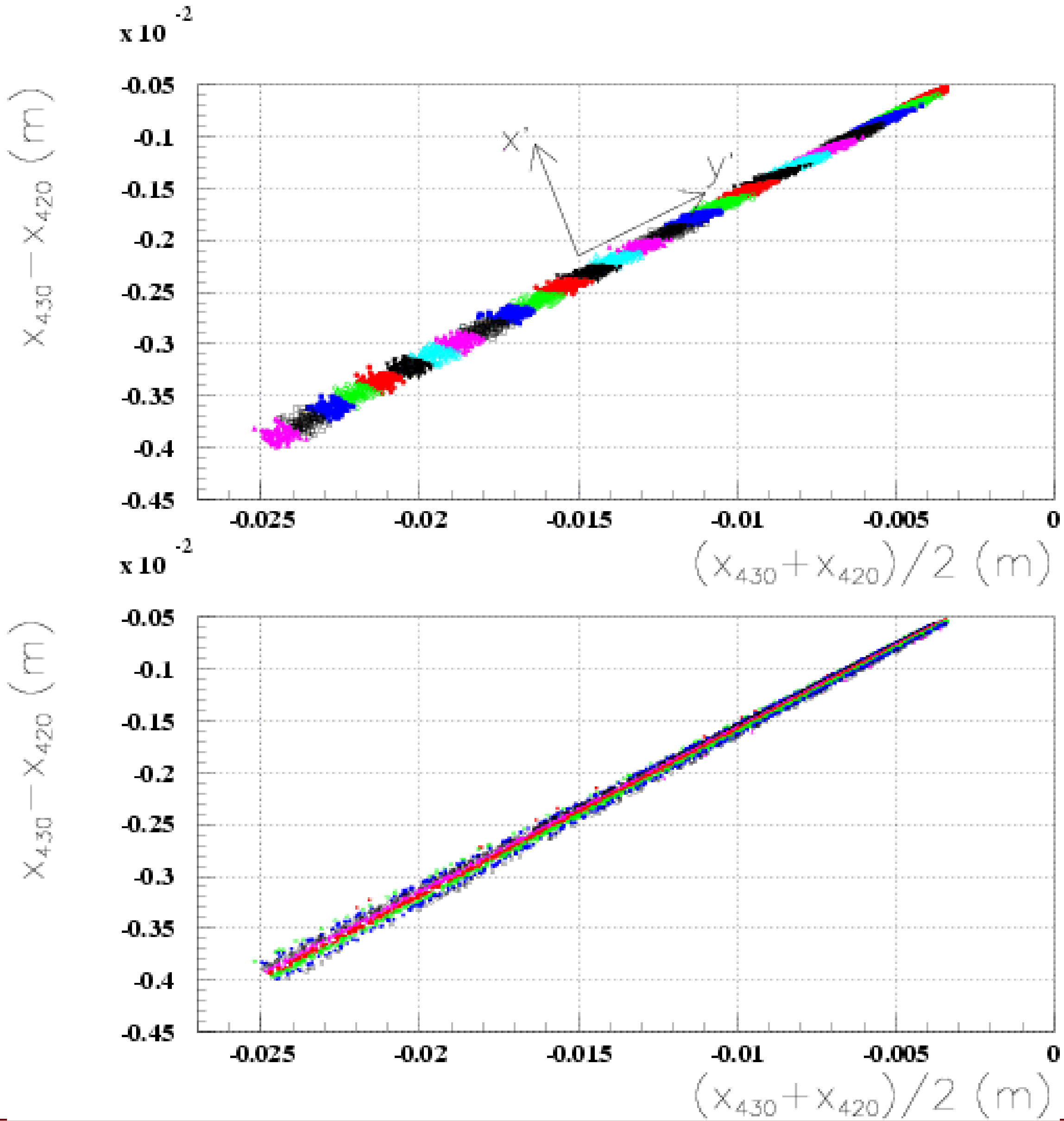
- Detector locations at
  - → 215 m (+10 m)
    - Dotted line
  - → 308 m / 338 m
    - Dashed line
  - → 420 m (+10 m)
    - Solid line
- Optimistic assumption on approach
  - → 10 σ_x(beam size)
  - → 0.1 mm dead space only

Acceptance for central production



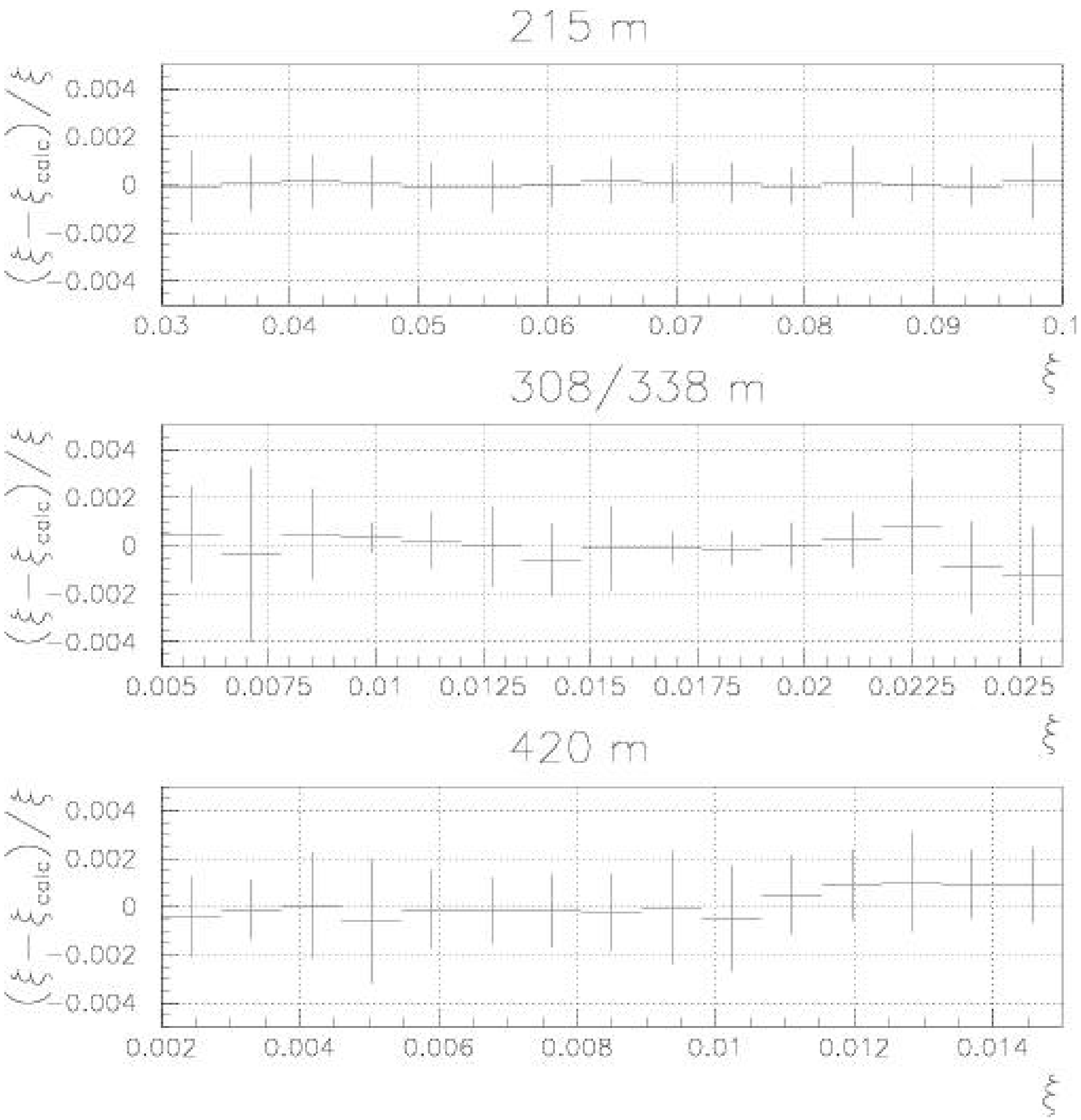
- Combined acceptance of
  - → All detectors
    - Dotted line
  - → 420 m + 215 m
    - Dashed line
  - → 215 m alone
    - Solid line
  - → 420 m alone
    - Dash-dotted line
- without 308 / 338 m location
  - → 10-15 % loss in acceptance

Observables at 420 m



- Two sensor planes 10 m apart
  - → Measure twice the horizontal coordinate x
    - Angle θ_x
  - → Bin size in
    - ξ: $5*10^{-4}$
    - θ_x*: 28 μrad
  - → Transform coordinates to ease unfolding method
    - (x', y')

Accuracy of method (clock-wise)



- Relative deviation of reconstructed ξ_{calc} wrt true ξ value using
  - → Functional parametrisation for
    - 420 m
    - 308/338 m
  - → Linear interpolation for
    - 215 m
- Accuracy of method: better than 0.2%
  - → Sufficient !

Simulation parameters

- Initial conditions
  - → Transverse beam size ($\sigma_{x,y}$ = 16 μm)
  - → Longitudinal vertex position (not used)
  - → Beam energy spread ($\sigma_E = 10^{-4}$)
  - → Beam divergence (σ_θ = 30 μrad)
- Detector simulation
  - → Position resolution ($\sigma_{x,y}$ = 10 μm)
  - → Beam position resolution ($\sigma_{x,y}$ = 5 μm)

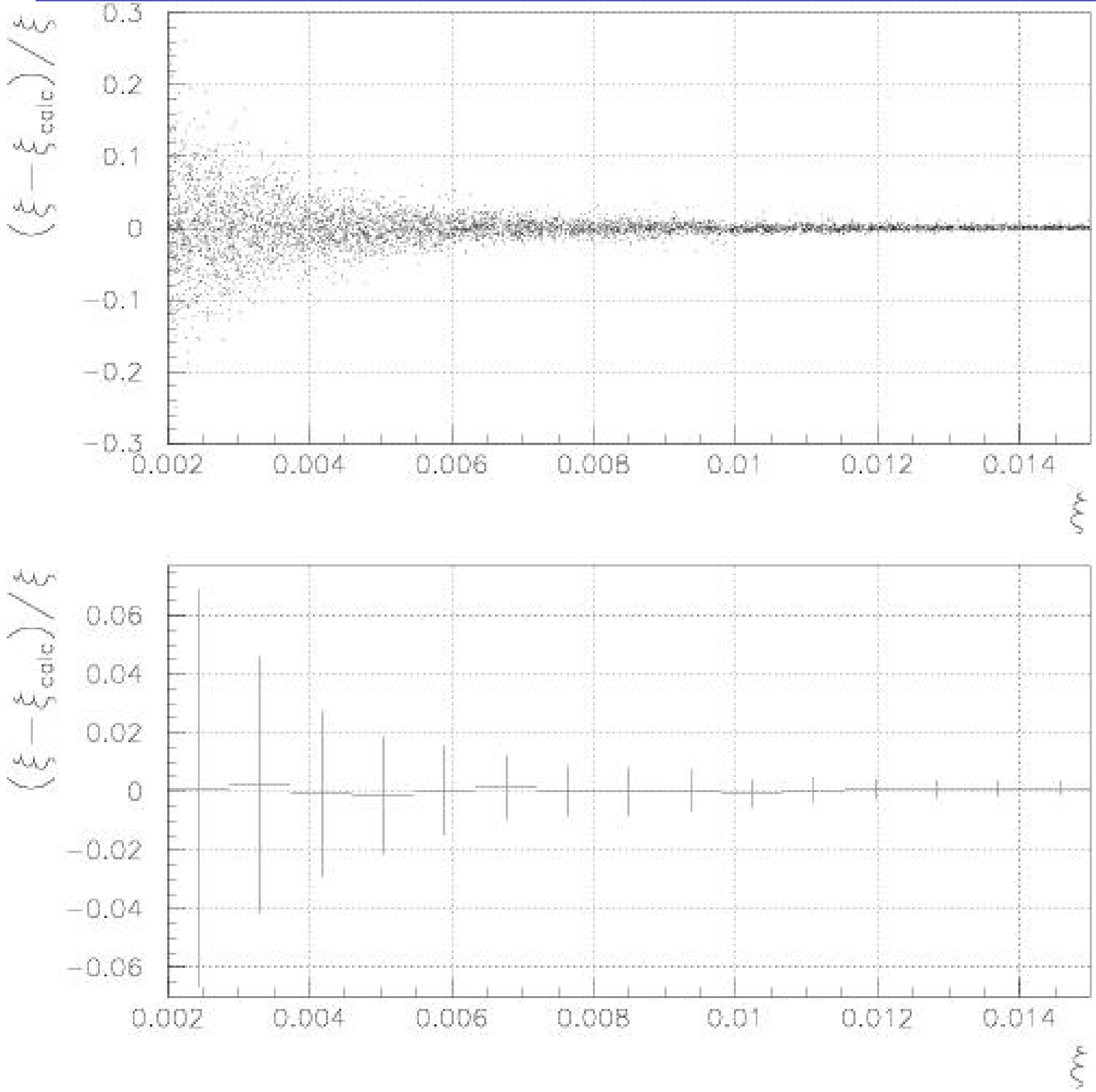
smearing

  - → Detector mis-alignment ($\Delta_{x,y}$ = 10 μm)
  - → Absolute beam position ($\Delta_{x,y}$ = 10 μm)

offset

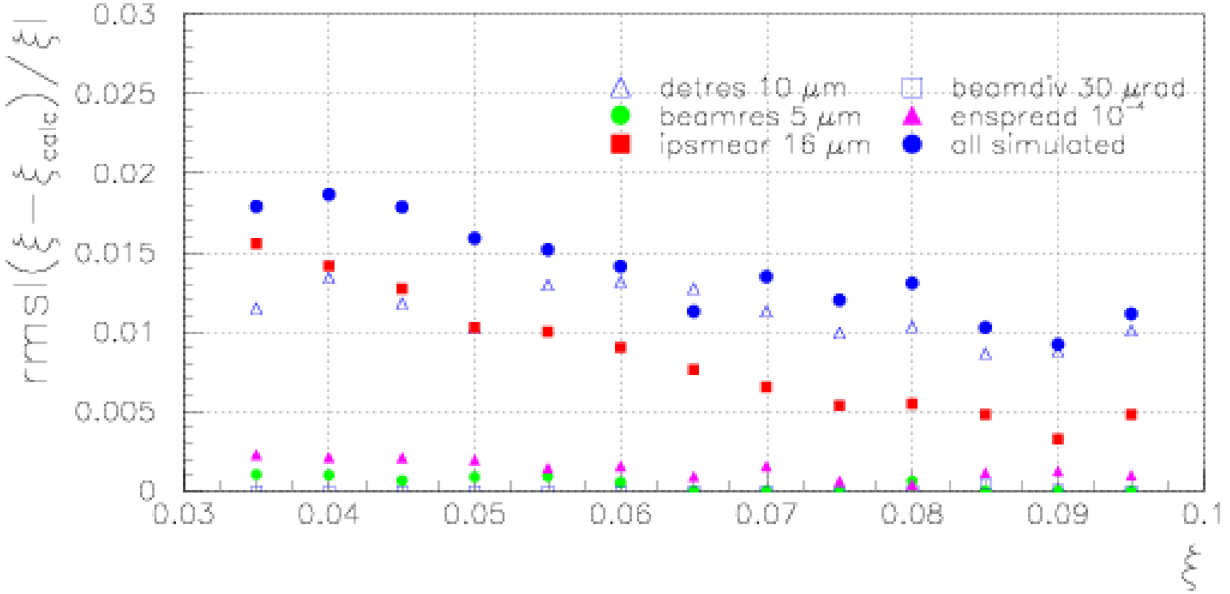
- Not studied yet
  - → Alignment of magnetic elements
  - → Field strength of magnetic elements
  - → Long term stability, reproducibility

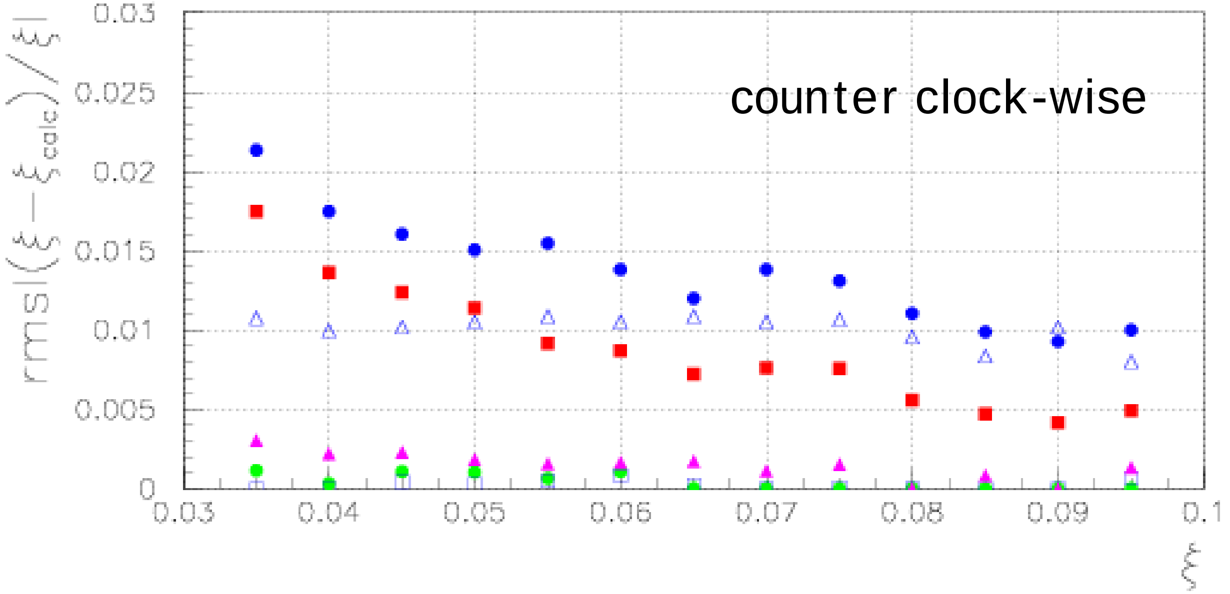
Example of detector simulation



- For 420/430 m location
  - → Smear measurement in both sensor planes with a Gaussian distrib. (width: 10 μm)
  - → Larger effect for smaller ξ values
    - Smaller deviation from nominal beam position

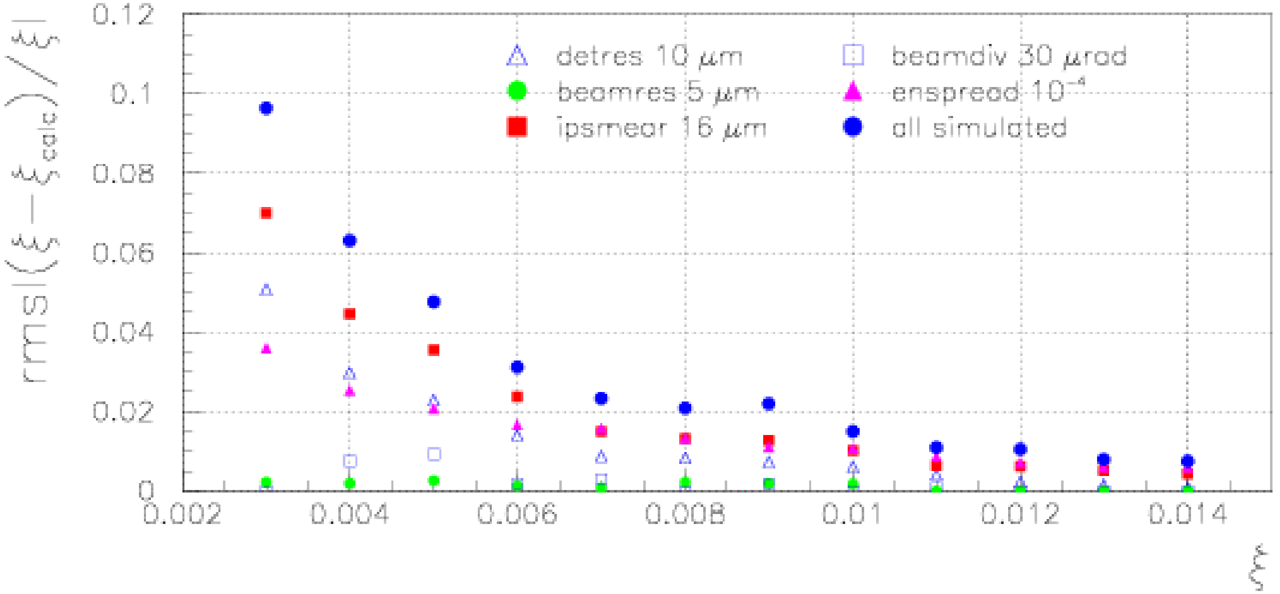
Resolution in x for 215 m

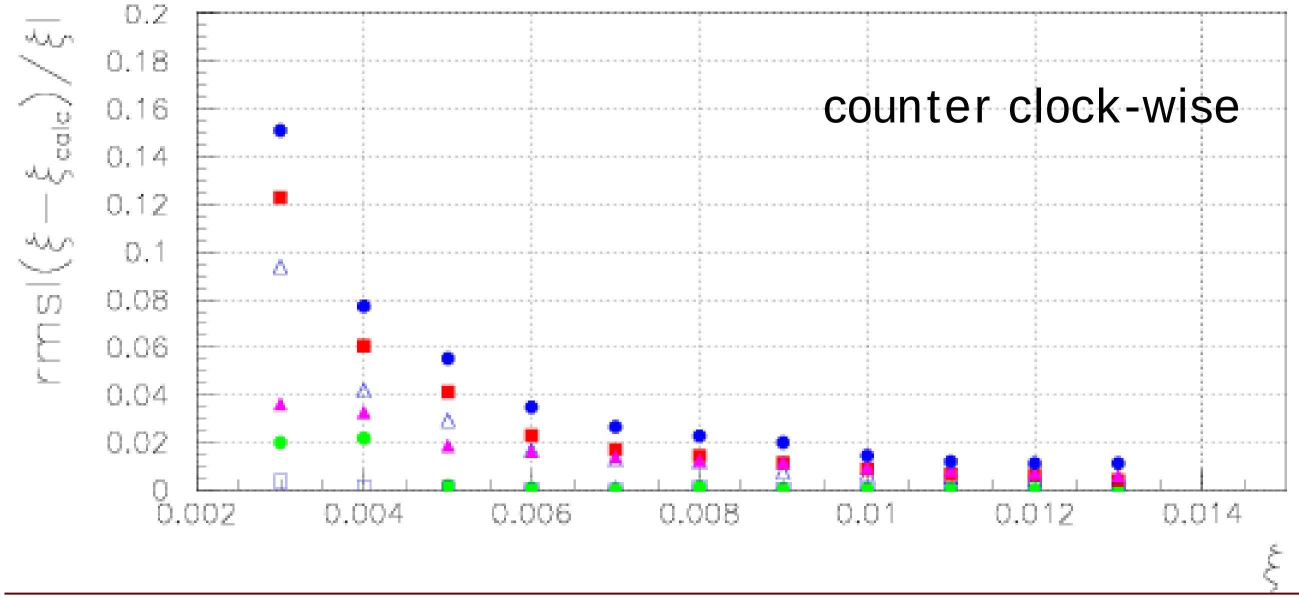




- All five effects on resolution
  - → Sum of all: between 2% and 1%
  - → Dominating source
    - Small ξ: transverse vertex position
    - Large ξ: detector resolution

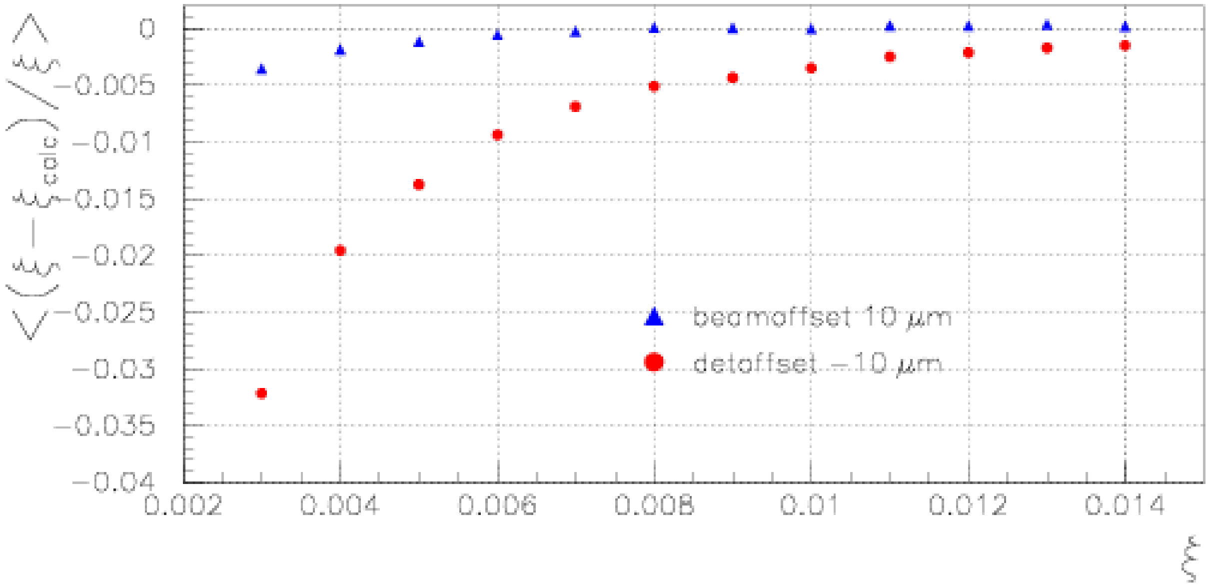
Resolution in x for 420 m

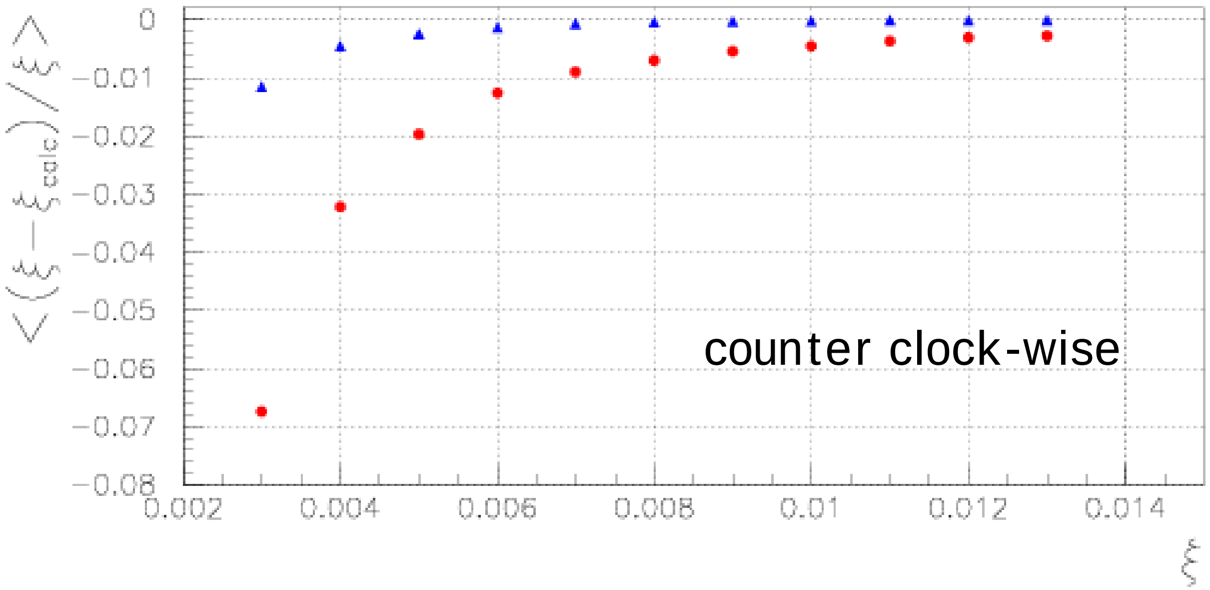




- All five effects on resolution
  - → Sum of all: between 10-15% and 1%
  - → Dominating source
    - Small ξ: transverse vertex position
    - Large ξ: beam energy spread

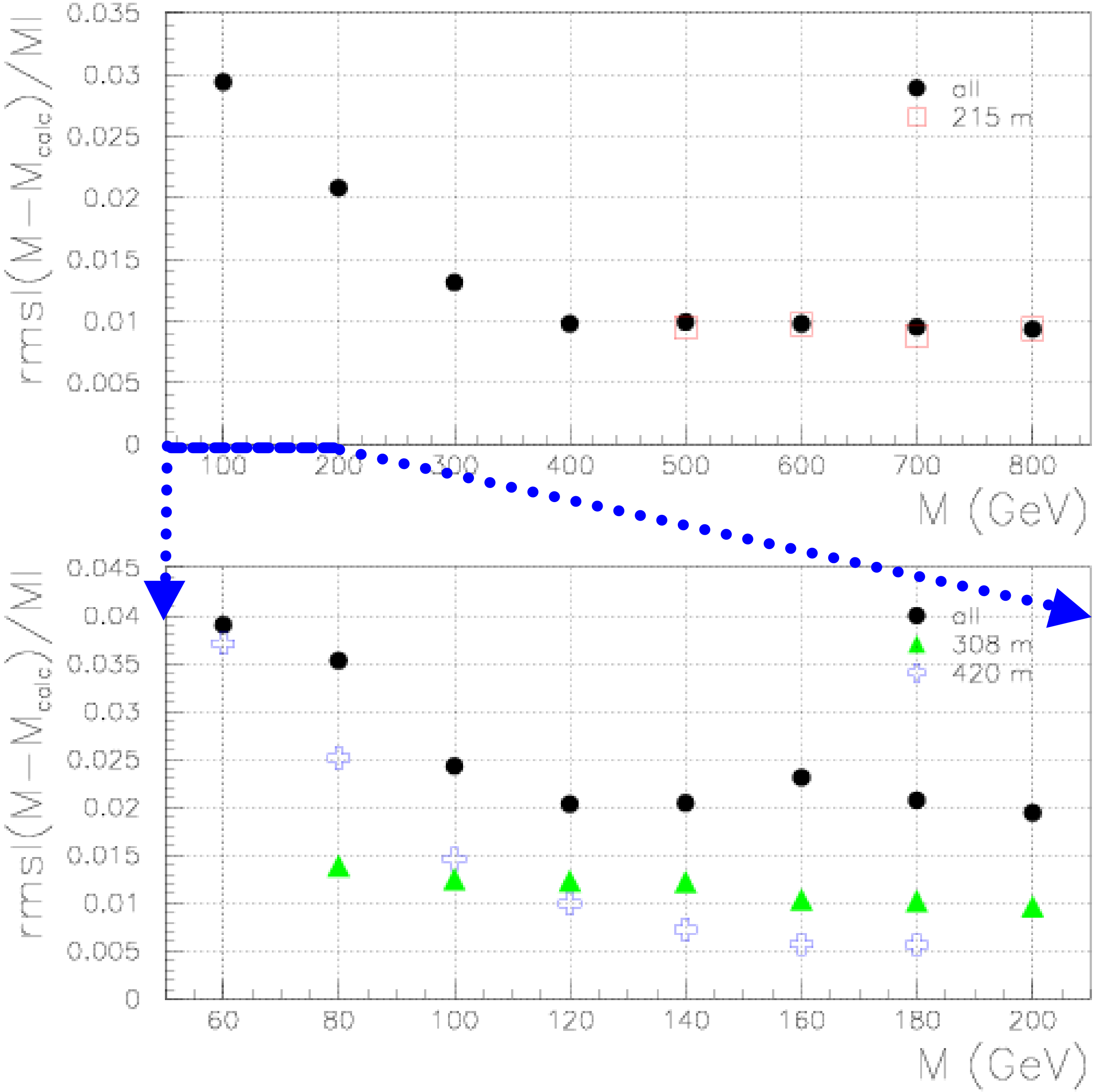
Offsets in x for 420 m





- For the values chosen
  - → Detector mis-alignment dominates
  - → Sizeable effects between 3 and 7 % for the small ξ region

Resolution on central mass



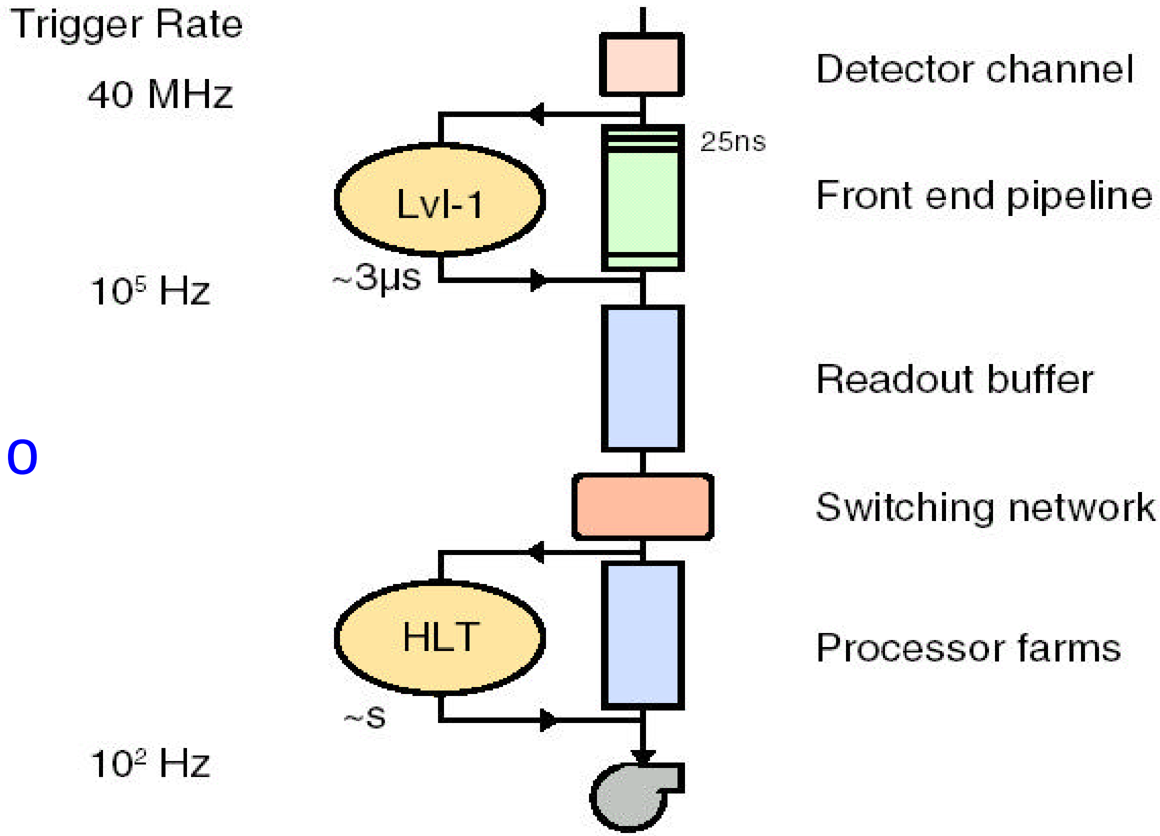
- Resolution obtained
  - → From simple method
    - Use estimate from most distant station first
      - 420 m
      - 308 m
      - 215 m
  - → Between 4% at small ξ and 1% for large ξ

Challenge: trigger

- Boundary conditions
  - → LHC: 40 MHz bunch crossing frequency
    - At 10^{34} cm^{-2}s^{-1} → ~ 1 GHz interaction rate
  - → Detectors with ~ 10^8 electronic channels (1MB/event)
  - → Need to reduce to rate to ~ 100 Hz to mass storage
- Processes with small cross-sections
    - E.g. for exclusive Higgs production
  - → Need to have very efficient and unbiased trigger
    - Must be affordable at the same time!
      - → Not to saturate available trigger bandwidth, ...
- Exclusive production pp → p + X + p
  - → Available signatures (for analysis and, earlier, trigger)
    - Leading protons
    - Rapidity gaps ('+' between protons and system X)
    - Final state of system X (e.g. Higgs decay objects)

ATLAS/CMS Trigger/DAQ system

- Trigger issues (latency constraints)
  - → Example for CMS trigger and DAQ system
- Ideally: leading p signatures @ LVL1
  - → Readout of central detector possible
- Thus: trigger signal to reach electronics cavern < 2 μs after collisions occurred
  - → Time-of-flight from IP → detector
  - → Signal formation / simple decision
  - → Signal transport to electronics cavern (distance > direct line!)
- Upper limit of ~ 215 m for detectors (less for ATLAS!)



Example: ATLAS LVL1 trigger menu

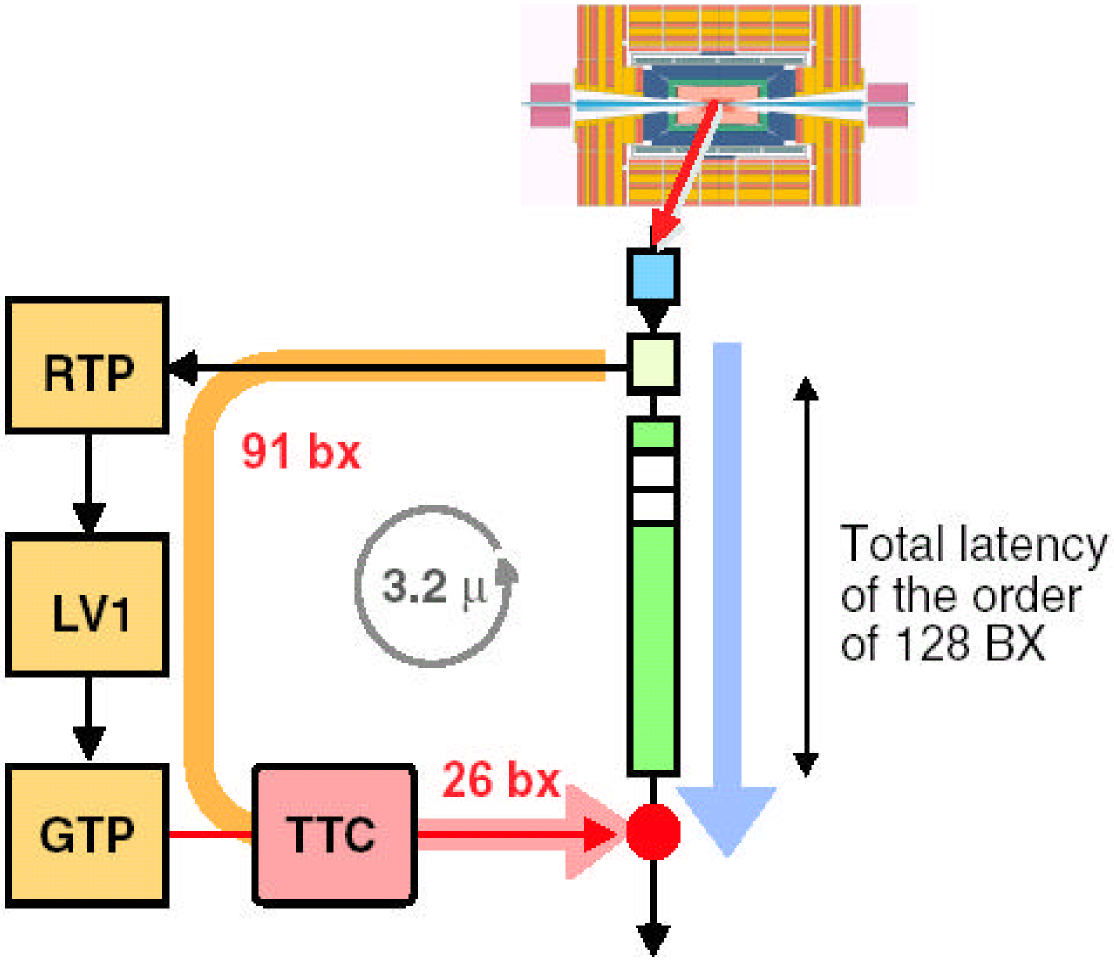
Selection for L = $2*10^{33}$ $cm^{-2}s^{-1}$	Rate [kHz]
MU20	0.8
2MU6	0.2
EM25I	12.0
2EM15I	4.0
J200	0.2
3J90	0.2
4J65	0.2
J60 + xE60	0.4
TAU25 + xE30	2.0
MU10 + EM15I	0.1
Others (pre-scales, calibration, …)	5.0
Total	~ 25

Jet triggers

LVL1 latency constraints: CMS

Timing (TTC):
- All frontend electronics is synchronized with the machine 40 MHz clock
- All data and control signals are synchronized with bunch crossing (timing calibration procedures, programmable delays etc.)

Trigger latency&pipeline
- All detector frontend electronics must be able to save the event data occurring during the level-1 trigger decision time (of the order of 3.2μs)

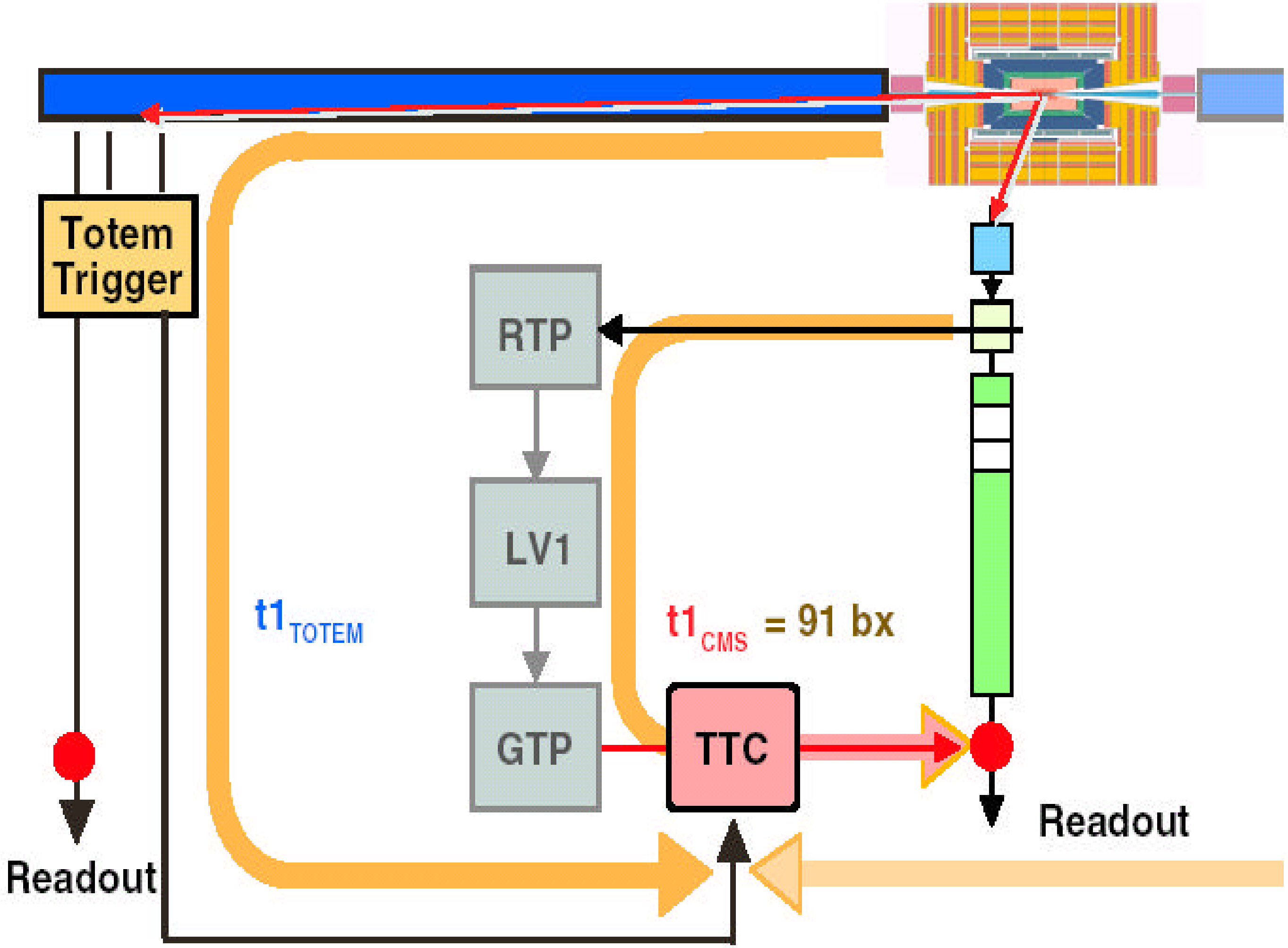


TPG Trigger Primitive Generator
RTP Regional Trigger Processor
LV1 Calo & μ Trigger Processors
GTP Global Trigger Processor
TTC Timing, Trigger & Control

(S. Erham)

LVL1 latency constraints: CMS

CMS detector data can be readout at the occurrence of a Totem trigger under the condition that Totem trigger signal (time of flight, Totem Trigger, propagation of decision to the CMS control room TTC system) be less than the corresponding CMS time (equal to about 91bx).
Totem detector data can then be readout as a CMS FrontEnd System



$$t1_{TOTEM} \leq t1_{CMS} = 91 \text{ bx}$$

(S. Erham)

Trigger latency determination

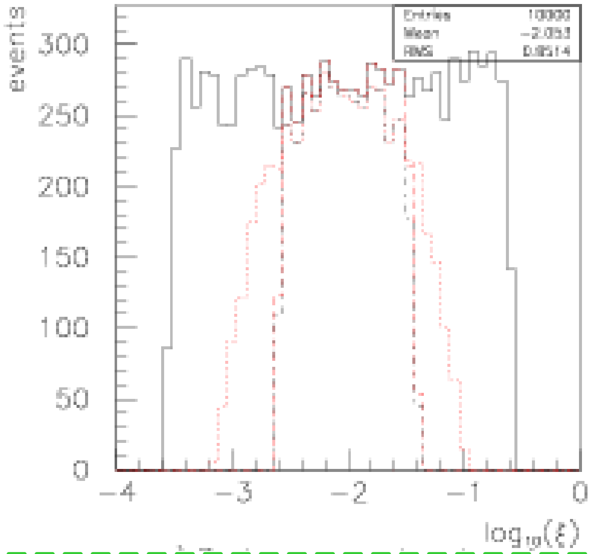
- Example TOTEM/CMS (calculation by M. Oriunno)
    - Even 'worse' for ATLAS (maximum latency 2.5 μs instead of 3.2 μs)
  - → Distance from detector location, e.g. 150 m, to the trigger electronics rack is 150 m + 23 m
- Breakdown
  - → Time-of-flight IP → 150 m: 20 bx
  - → Signal and trigger primitive: 6 bx
  - → signal to electronics rack (5ns/m): 35 bx
  - → CMS global trigger + TTC: 15 bx
  - → Signal to proton detector (5ns/m): 35 bx

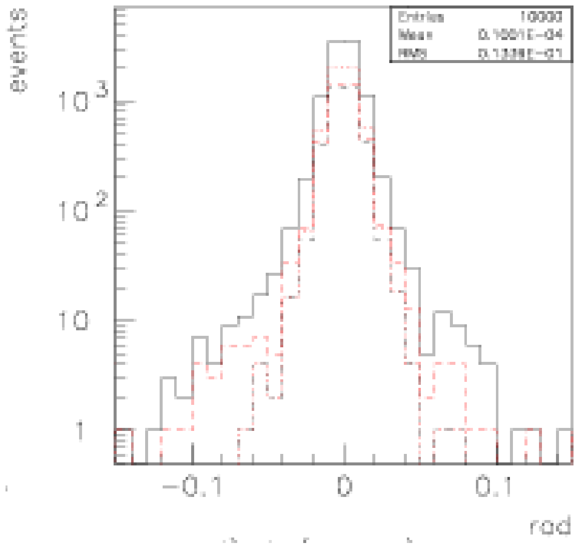
  76 bx

  111 bx
- Compare to maximum time of 91 bx up to TTC
  - → Gives maximum distance of ~ 195 m (no safety margin)
    - Improve slightly by using air-core cables / optical transmission ?
- Additional issue: buffering of data during LVL1 latency
  - → if proton detector electronics are identical to central detector
    - Maximum distance of ~ 240 m (pipeline depth of 128 bx)
      - ➔ use faster transmission if necessary (trigger time will be limiting)

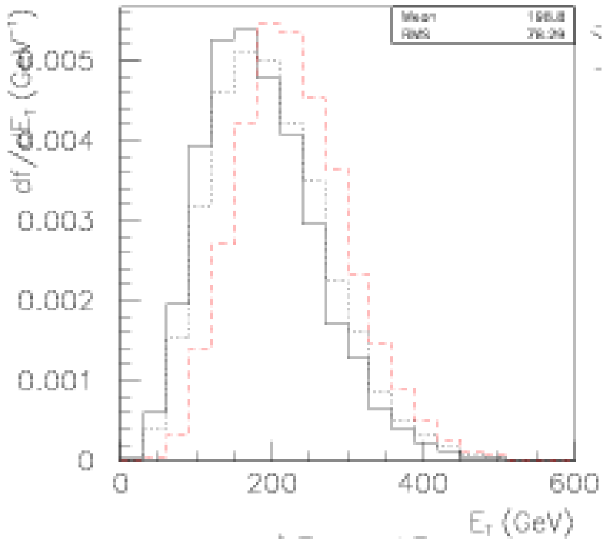
Example: pp → p+H(bb)+p

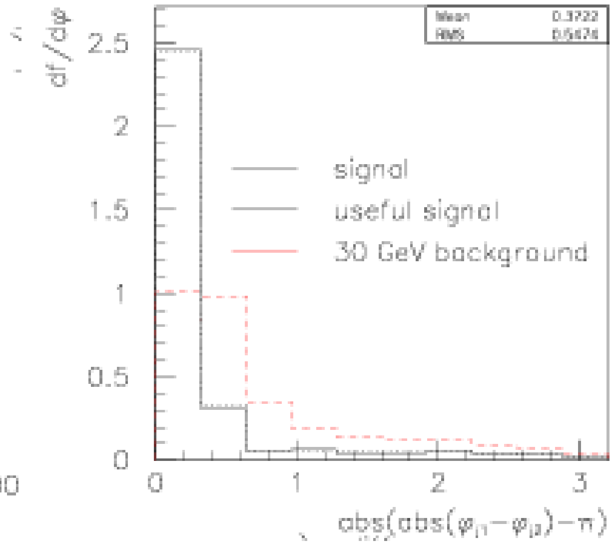
- Results from on-going master thesis by V. Bergholm
  - → VERY PRELIMINARY
- Kinematics of signal
  - → Protons seen: $\xi > 0.002$
  - → b-quarks seen: $|\eta| < 2.5$





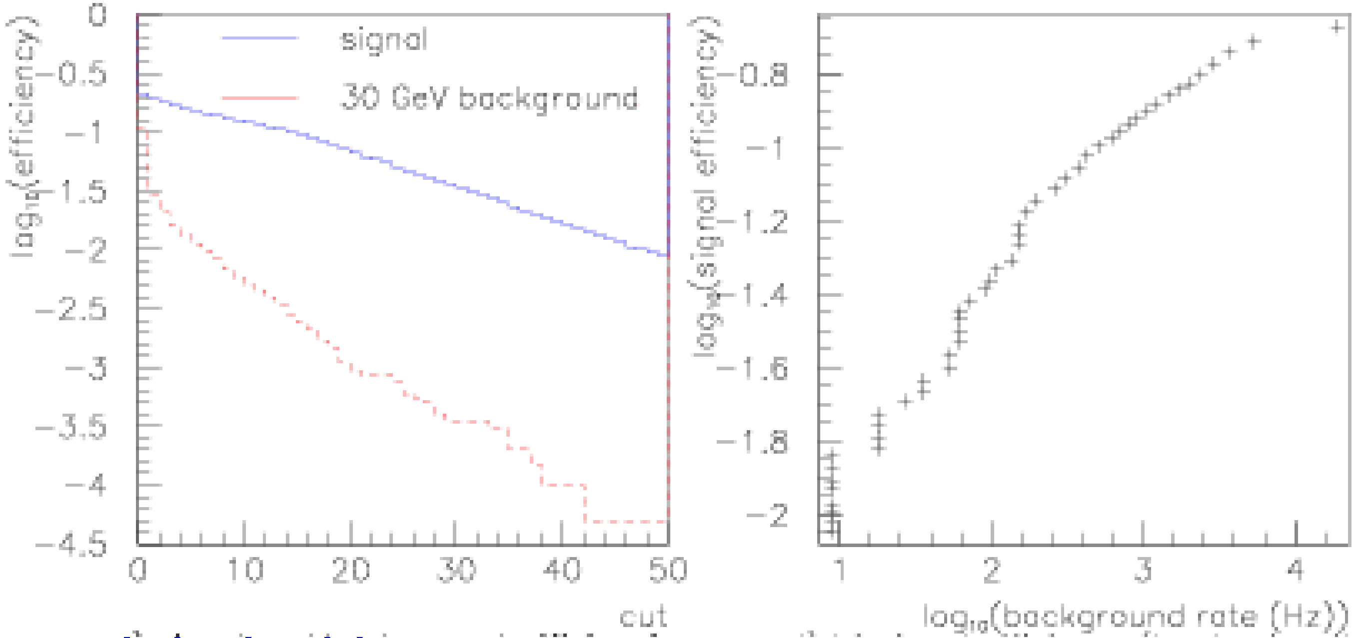
- Comparison signal - background shapes
  - → Useful signal
    - ○ $\xi > 0.002$
    - ○ $|\eta| < 2.5$





Example: pp → p+H(bb)+p (cont'd)

- VERY PRE-PRELIMINARY
  - → Luminosity $10^{33}\ cm^{-2}s^{-1}$
  - → on-going master thesis by V. Bergholm



- Ingredients for global efficiency
  - ❍ Relative to production cross-section pp → p H p
  - → Fiducial cuts ($|\eta|<2.5$, $\xi>0.002$): 37 %
  - → BR(H → bb): 68 %
  - → b-tagging efficiency: 60 % (= $(0.77)^2$)
  - → combined 15 %
  - → Trigger efficiency: X %

Trigger possibilities

- Direct trigger on leading protons with momentum losses $\xi < 2\%$ is excluded
  - → For an unbiased sample use random trigger at LVL1
    - ➔ Only small accept rate possible: O(Hz)
  - → And require leading proton conditions at HLT
- Alternatives
  - → Rapidity gaps (FCAL/HF, LUCID/T2+CASTOR, ... ?)
    - ❍ How to implement in LVL1 hardware?
  - → Central high p_T objects (need one per decay mode!)
    - ❍ With topological criteria to allow lower thresholds than for inclusive selection
- Design luminosity even more challenging
  - → 20-25 inelastic ('pile-up') events / bunch crossing
  - → Rapidity gap signatures is 'destroyed', fake signatures

Outlook

- Resolution for leading protons and central mass in exclusive production at LHC ($\beta^* = 0.5$ m)
  - → Promising results on central mass accuracy
    - σ(M): 4% (60 GeV), 2% (120 GeV) and 1% (> 400 GeV)
    - Some improvement still possible
  - → For masses M < 400 GeV → need to go beyond 215 m
- Trigger issues for leading protons at LVL1
  - → Challenge: efficient, unbiased and affordable trigger
  - → No possibility to have leading p signal at LVL1 (>250 m)
  - → Use other final state criteria?
    - Rapidity gaps, high p_T central objects with topological criteria, ...
- Not discussed here: implementation challenges
  - → Cold region, radiation hardness, vacuum and impedance compatibility, background contributions, ...