PPS Acceptance Studies for Tagging Protons at HL-LHC

LHC Working Group on Forward Physics and Diffraction
19 December 2018

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on behalf of
The CMS Collaboration

Many thanks for valuable discussions and material to
Riccardo De Maria, Stéphane Fartoukh, Paolo Fessia, Daniele Mirarchi,
many PPS colleagues

CMS PPS at HL-LHC ?

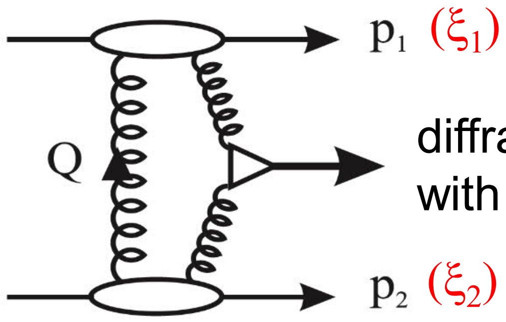
- **Flagship channels, i.e. central exclusive production of WW, dileptons and dijets are statistics limited: factor 10 more luminosity welcome.**
  Suppression of pileup (200) requires timing in the few ps range: not impossible extrapolating the current technology

- **Only interested in standard high-lumi running (no special runs)**

- **Would need access to central diffractive masses**
  – **from O(100 GeV)**: Standard Model processes for alignment/calibration
  – **to a few TeV**: new physics.

- **Focus of this presentation:**
  Calculation of mass reach at 4 promising forward detector locations using:
  - preview optics as presently available
    (simulations with MAD-X)
  - luminosity levelling trajectories (crossing-angle, β^*) as presently foreseen
    for horizontal and vertical crossing at IP5
  - collimation scheme as presently foreseen
  - rules for near-beam detector insertions as presently foreseen

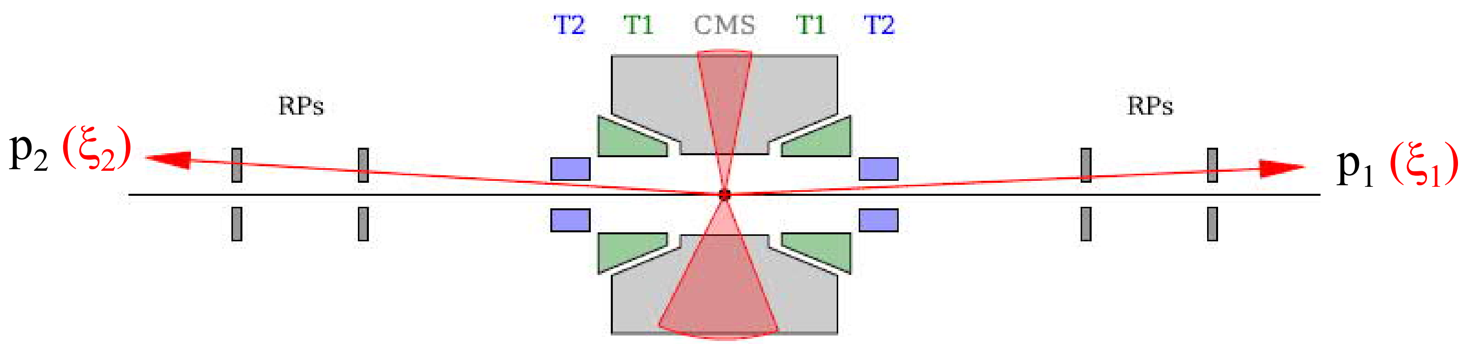
Central Diffractive Production: Kinematics



diffractive system X
with mass M_X at rapidity y_X

$$M_X^2 = \xi_1 \xi_2 s$$

$$y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$$



X = all products except the 2 leading protons

$$\xi_{1/2} = \frac{\Delta p_{1/2}}{p} = \text{fractional momentum loss of surviving proton } 1/2$$

The acceptance for diffractive mass M is determined by acceptance for ξ_1 and ξ_2 in the 2 spectrometer arms.

$M_{min}^2 = \xi_{1,min}\, \xi_{2,min}\, s$

The rapidity y quantifies how central (y = 0) or forward (large |y|) the centre-of-mass of X is:

Under certain conditions: y ≈ pseudo-rapidity $\eta = -\ln \tan(\theta/2)$

HL-LHC Optics 1.3 up to 500 m

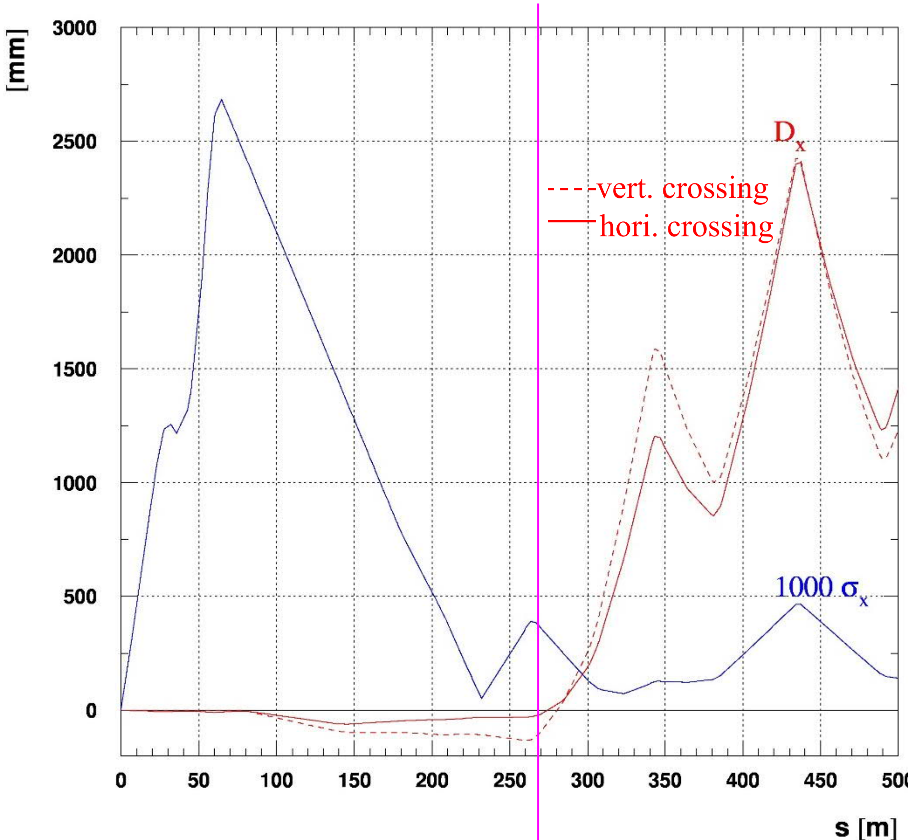
- for crossing angle $(\alpha/2, \beta^*) = (250\ \mu\text{rad}, 15\ \text{cm})$
- XRPs @ $(12.9 + 3)\ \sigma + 0.3$ mm

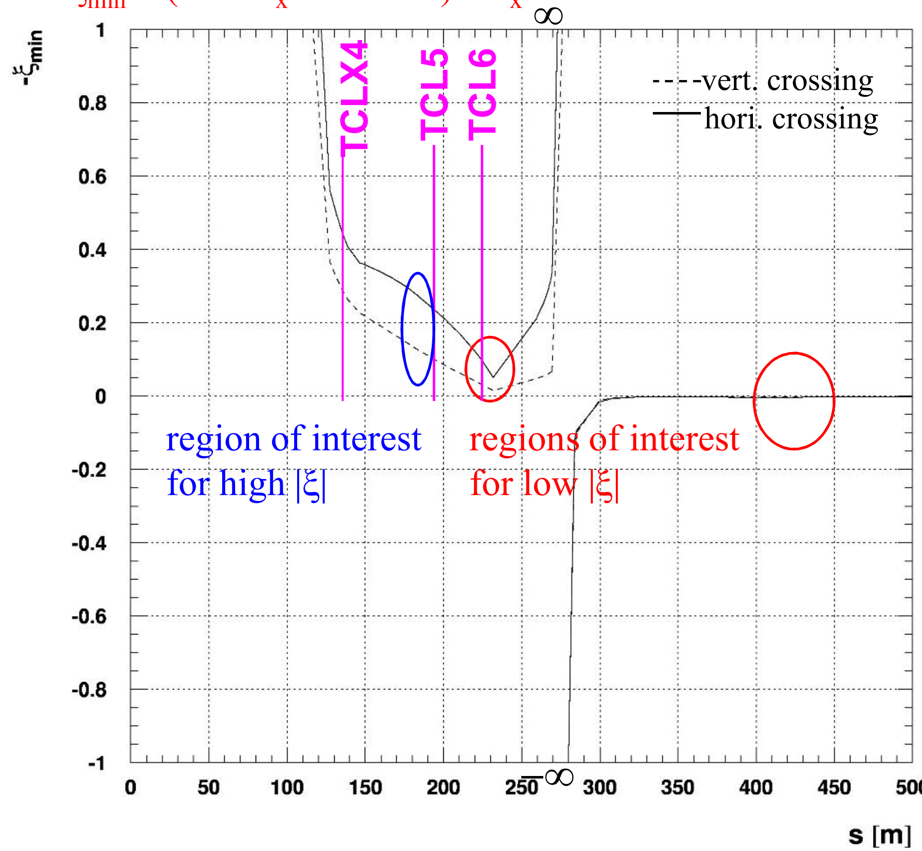
HL-LHC:
new standard emittance $\varepsilon_n = 2.5\ \mu$m rad (instead of 3.5)

$$\xi \equiv \frac{\Delta p_{\text{proton}}}{p_{\text{proton}}} = \frac{x_{\text{track}}}{D_x}$$

← horizontal dispersion

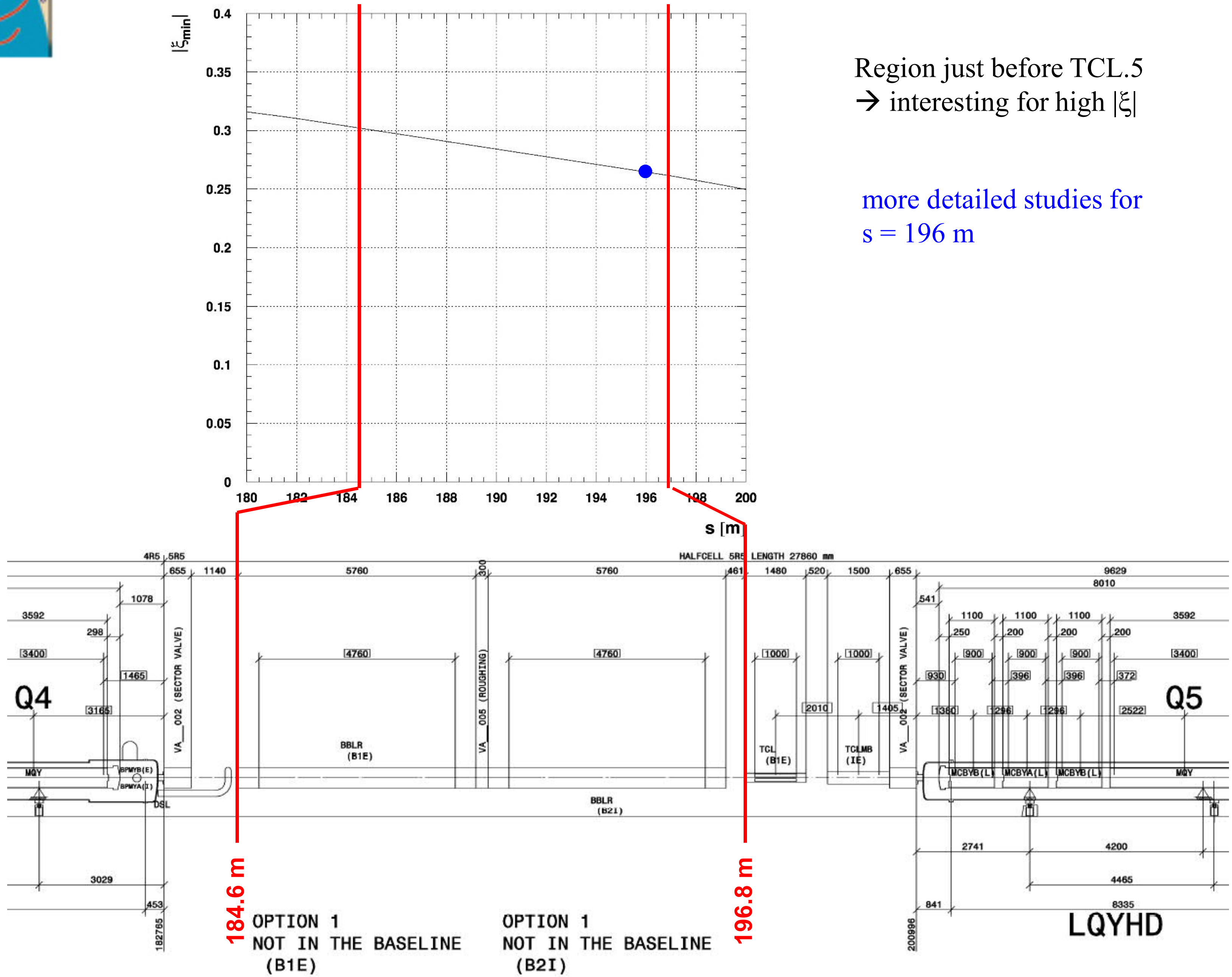
$\xi_{min} = (15.9\ \sigma_x + 0.3\ \text{mm}) / D_x$





for s > ~270 m : $D_x > 0$
→ diffractive protons between the beam pipes
→ no standard Roman Pot possible → needs new technology
Free only around 420 m.

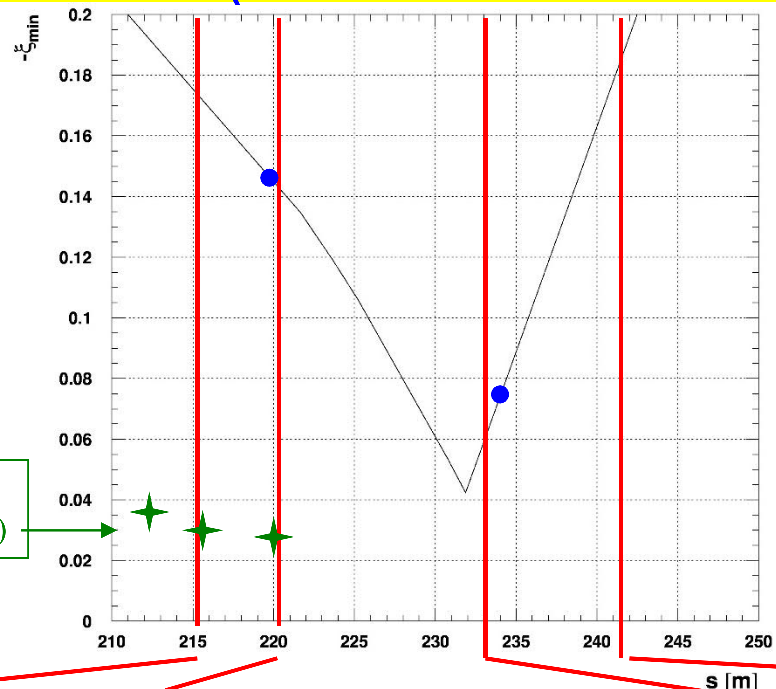
Region of Interest: 180 – 200 m
(for Classic Roman Pot Technology)



Region just before TCL.5
→ interesting for high |ξ|

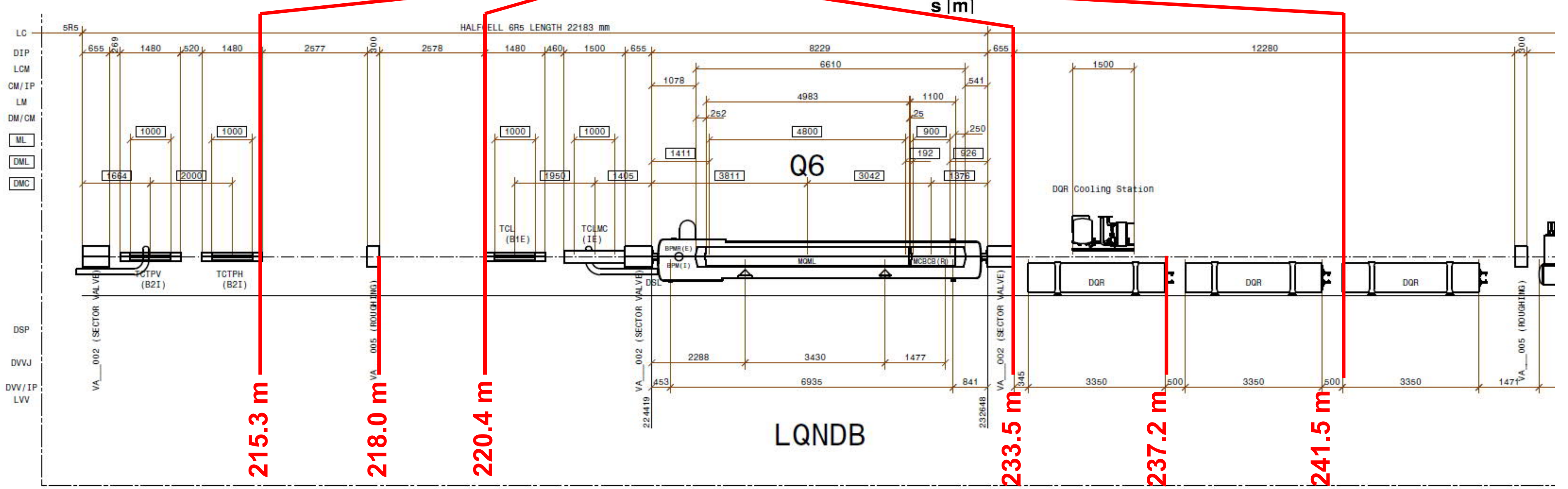
more detailed studies for
s = 196 m

Region of Interest: 210 – 250 m
(for Classic Roman Pot Technology)

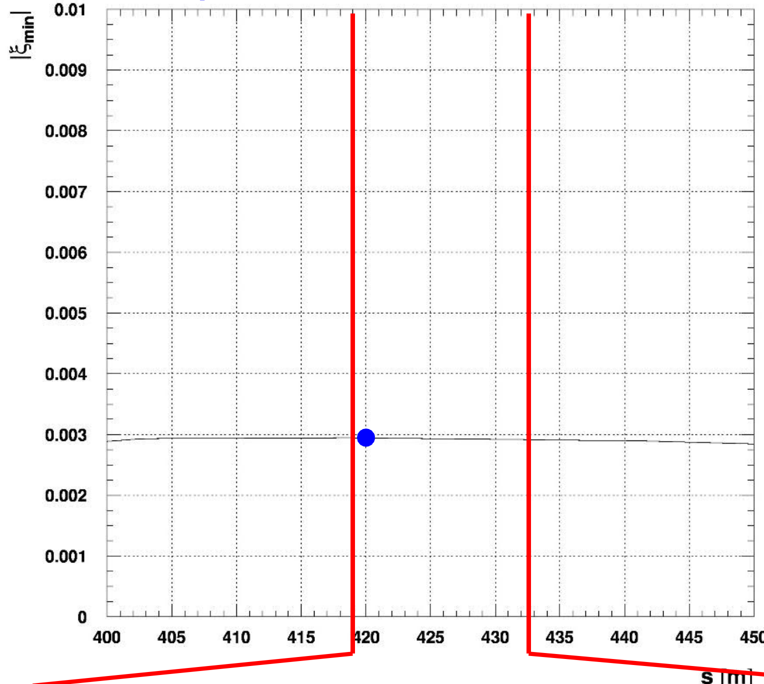


more detailed studies for
- s = 220 m
- s = 234 m

Comparison 2018
(α/2, β*) = (130 μrad, 30 cm)



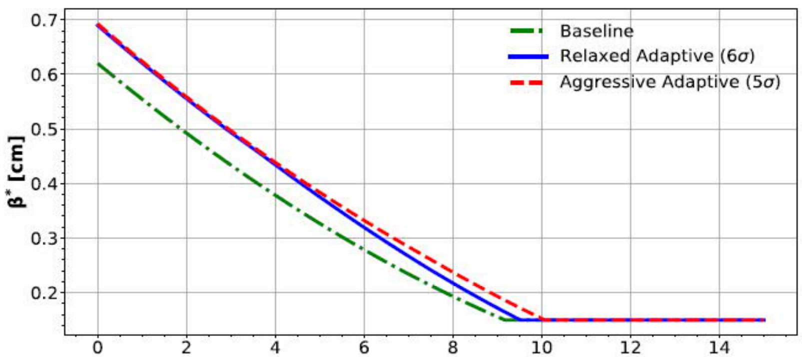
Region of Interest: 400 – 450 m
(for Future "Roman Pot" Technology)



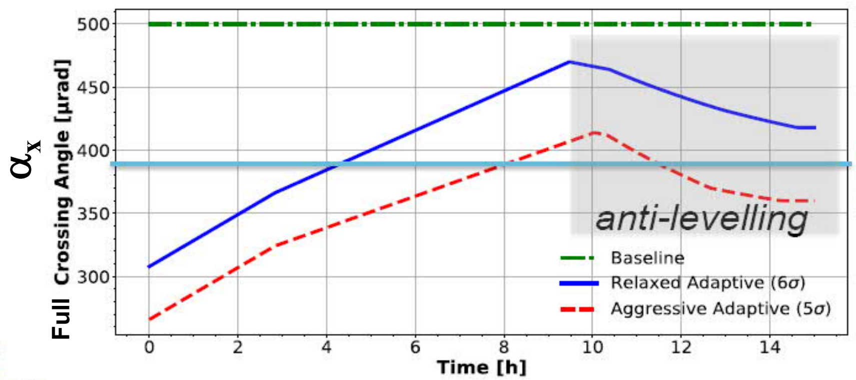
more detailed studies for
s = 420 m

Evolution of Parameters

- For the adaptive scenarios, include **crossing angle "anti-levelling"** *à la* LHC after the end of levelling

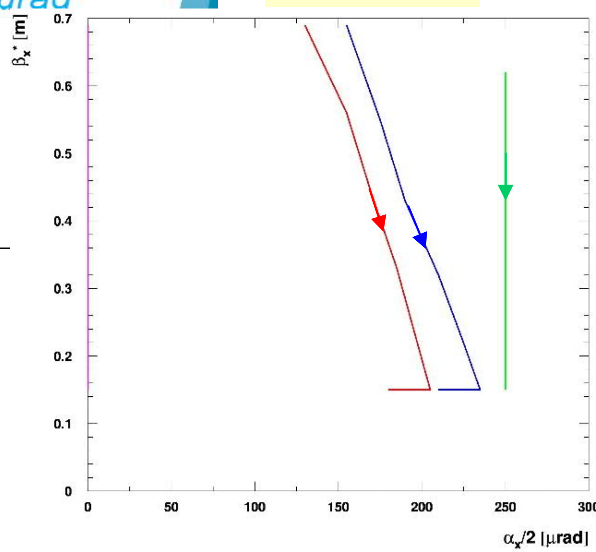


Slightly delay the end of levelling



max crabbing angle: 380μrad

as 2-D plot:



N. Karastathis, D. Pellegrini et al., HL-LHC collaboration meeting 2017

Mass Acceptance Calculation

Calculate mass limits: $M_{\min/\max} = \xi_{\min/\max}\sqrt{s}$ in ($\alpha/2$, β^*) plane
(for symmetric optics in Beam 1 / Beam 2 with $\xi_{1\ \min/\max} = \xi_{2\ \min/\max}$)

Crossing-angle can be horizontal or vertical → distinguish $\alpha_x/2$, $\alpha_y/2$

Cannot simulate every ($\alpha/2$, β^*) point → analytical approach:

gap + insensitive XRP detector margin

$$M_{\min} = \xi_{\min}\sqrt{s} \quad \text{with} \quad \xi_{\min} = \frac{d_{\mathrm{XRP}}(\beta^*) + \delta}{D_{x,\mathrm{XRP}}(\frac{\alpha_x}{2}, \xi_{\min})} \quad \text{resolved for } \xi_{\min}$$

d_{XRP}: detector distance from beam centre:
analytical expression depending on
TCT collimator settings
and optics properties

$D_{x,\ XRP}$: horizontal dispersion @ detector location,
parametrisation in ($\alpha/2$, ξ) from MAD-X

$$M_{\max} = \xi_{\max}\sqrt{s} = \frac{d_{\mathrm{A}}}{D_{\mathrm{A}}(\frac{\alpha}{2}, \xi_{\max})}\sqrt{s}$$

Based on full aperture study

d_A: aperture limitation (hori. or vert.) upstream,
in most cases: TCLs

D_A: dispersion (hori. or vert.) @ aperture limit.,
parametrisation in ($\alpha/2$, ξ) from MAD-X

XRP Insertion Distance vs. β*

Assume insertion rule: $d_{\mathrm{XRP}} = (n_{\mathrm{TCT}} + 3)\sigma_{\mathrm{XRP}} + 0.3$ mm

Collimation scheme presently foreseen:

$\mathrm{d_{TCT}} = \mathrm{const.}$ → $n_{\mathrm{TCT}}(\beta^*) = n_{\mathrm{TCT}}(\beta^*_0)\sqrt{\frac{\beta^*}{\beta^*_0}}$

$\sigma_{\mathrm{XRP}} = \sqrt{\frac{\varepsilon_n \beta_{\mathrm{XRP}}}{\gamma}}$ We need $\beta_{\mathrm{XRP}}(\beta^*)$!

ATS invariance of optical functions: $v_{\mathrm{XRP}} = \sqrt{\frac{\beta_{\mathrm{XRP}}(\beta^*)}{\beta^*}} \cos\mu_{\mathrm{XRP}}(\beta^*)$: magnification independent of β^*

$L_{\mathrm{XRP}} = \sqrt{\beta_{\mathrm{XRP}}(\beta^*)\beta^*} \sin\mu_{\mathrm{XRP}}(\beta^*)$: eff. length independent of β^*

$$\Rightarrow \left\{ \begin{array}{c} \tan\mu_{\mathrm{XRP}}(\beta^*) = \frac{L_{\mathrm{XRP}}}{v_{\mathrm{XRP}}}\frac{1}{\beta^*} \\ \beta_{\mathrm{XRP}}(\beta^*) = \frac{L_{\mathrm{XRP}} v_{\mathrm{XRP}}}{\sin\mu_{\mathrm{XRP}}(\beta^*)\cos\mu_{\mathrm{XRP}}(\beta^*)} \end{array} \right\} \Rightarrow \beta_{\mathrm{XRP}}(\beta^*) = v^2_{\mathrm{XRP}}\beta^* + \frac{L^2_{\mathrm{XRP}}}{\beta^*}$$

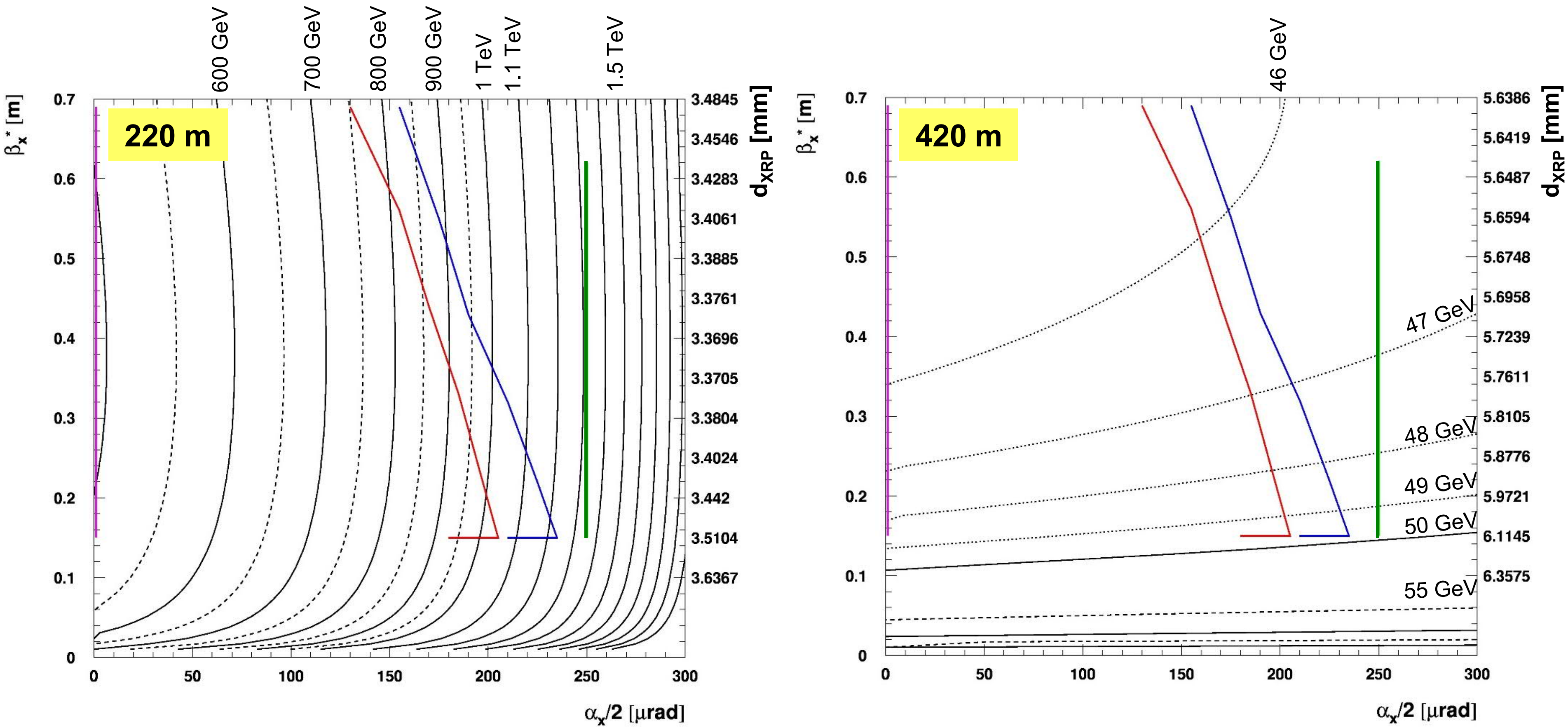
$$\sigma_{\mathrm{XRP}} = \sqrt{\frac{\varepsilon_n}{\gamma}\left(v^2_{\mathrm{XRP}}\beta^* + \frac{L^2_{\mathrm{XRP}}}{\beta^*}\right)}$$

$$d_{\mathrm{XRP}} = \left(n_{\mathrm{TCT}}(\beta^*_0)\sqrt{\frac{\beta^*}{\beta^*_0}} + 3\right)\sqrt{\frac{\varepsilon_n}{\gamma}\left(v^2_{\mathrm{XRP}}\beta^* + \frac{L^2_{\mathrm{XRP}}}{\beta^*}\right)} + 0.3\ \mathrm{mm}$$

Examples: Minimum Mass @ 220m and 420m

Contour lines for $M_{\min} = \xi_{\min} \sqrt{s}$

TCT settings: d_{TCT} = const. (12.9 σ @ β* = 15 cm)



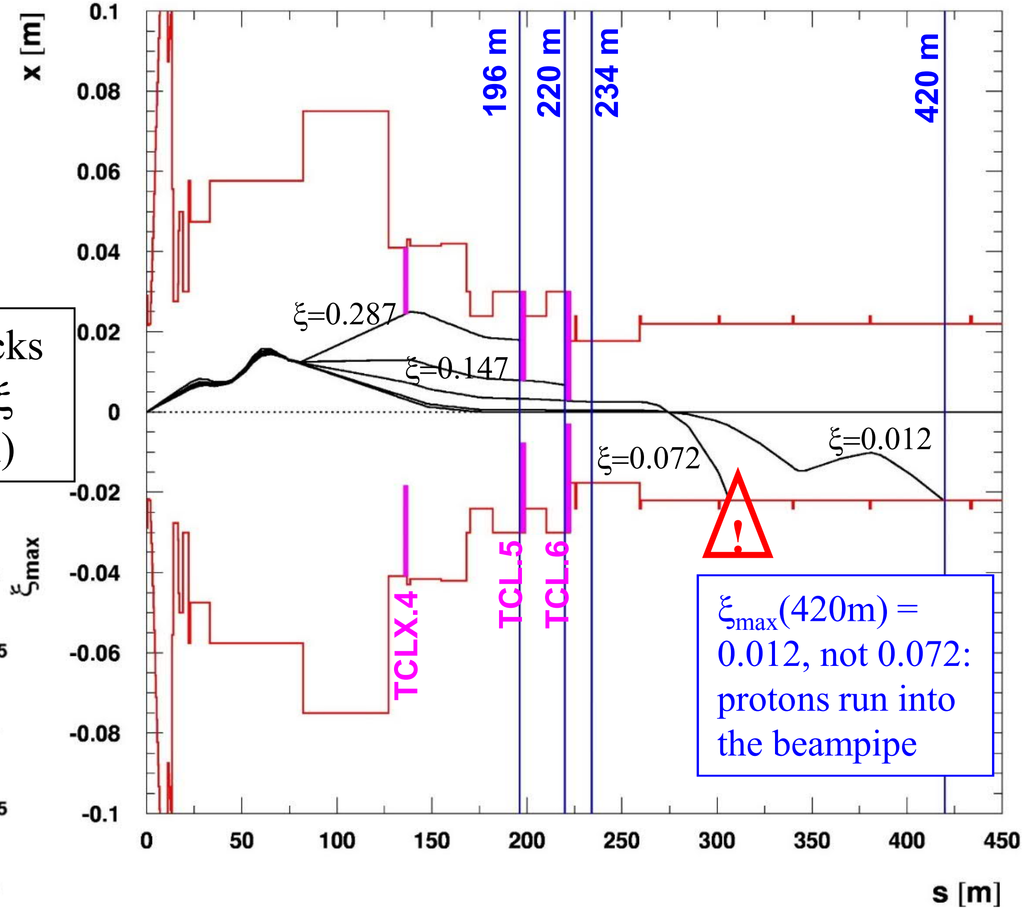
Levelling trajectories:

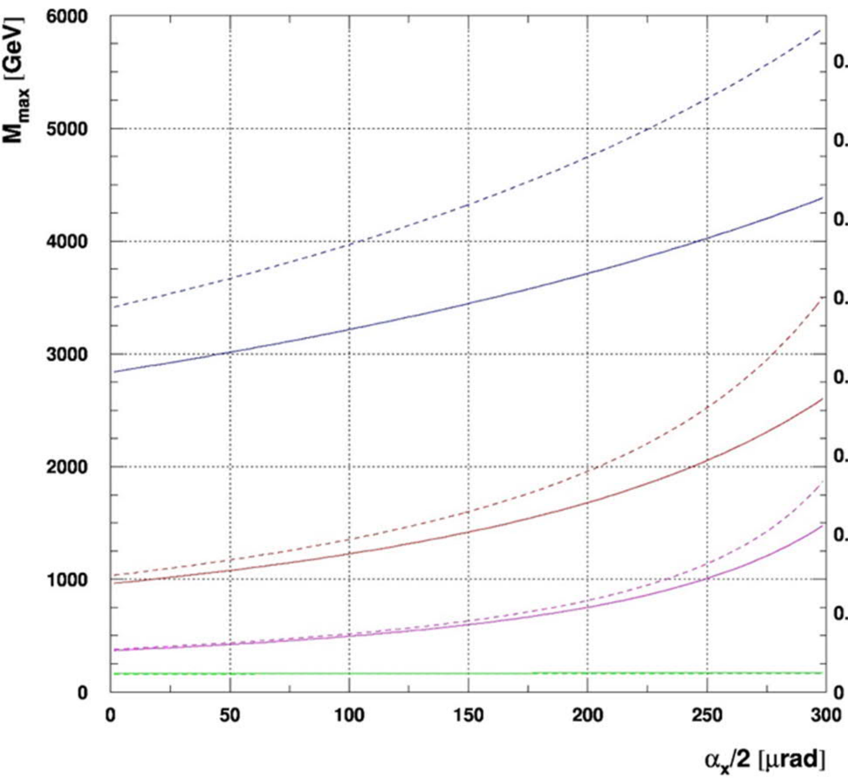
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

Aperture Study: Maximum Mass for Horizontal Crossing

Baseline Levelling Trajectory ($\alpha/2 = 250\ \mu$rad)

Horizontal tracks with different ξ (from MAD-X)





TCLX.4 determines M_{max} at 196 m

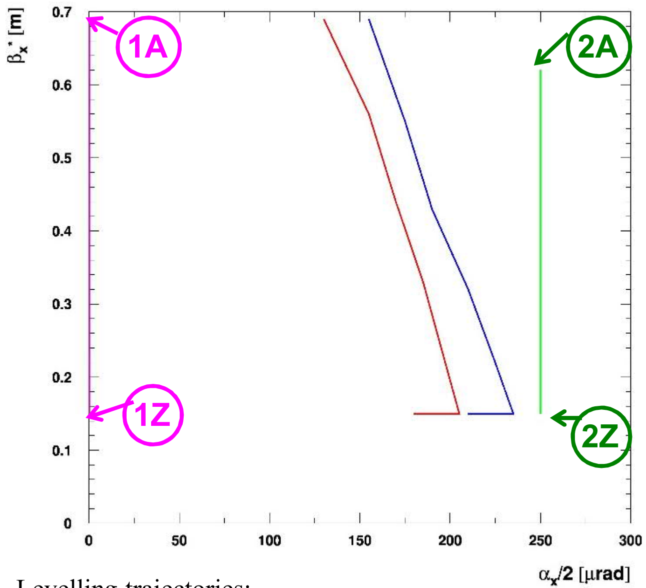
TCL.5 determines M_{max} at 220 m

TCL.6 determines M_{max} at 234 m

Beam pipe aperture determines M_{max} at 420 m

(dashed: naive calculation with ξ-independent D)

Acceptance in the Mass – Rapidity Plane



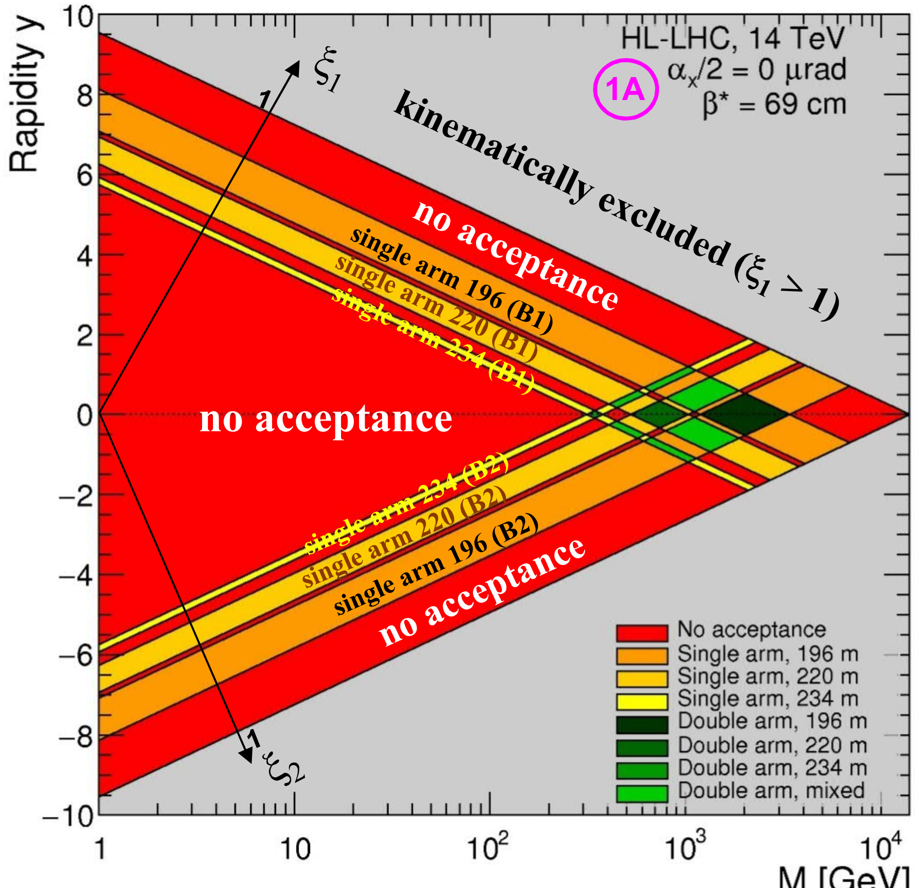
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

For each point ($\alpha/2$, β_x^*):

Acceptance for central diffractive events is defined in 2-dim space (ξ_1, ξ_2) or equivalently – after basis rotation – in (M, y):

$$M^2 = \xi_1 \xi_2 s \qquad y = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}$$

$$\ln\frac{M}{\sqrt{s}} = \tfrac{1}{2}(\ln\xi_1 + \ln\xi_2) \qquad y = \tfrac{1}{2}(\ln\xi_1 - \ln\xi_2)$$

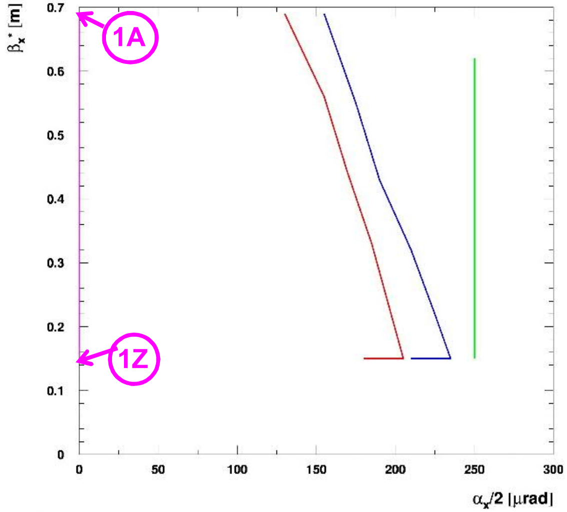


Note on t or p_T:

The M-y plot is for $t_1 = t_2 = 0$

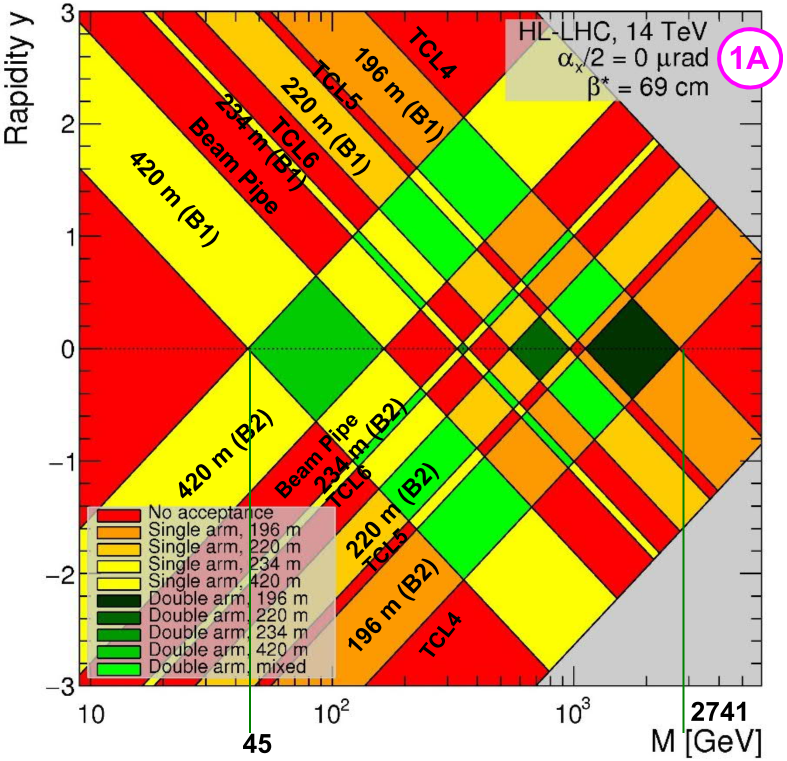
- Fixed non-zero $t_{1/2}$ would shift the contours:
  $$\Delta\xi_{min} = -\frac{L_x \theta_x^*}{D_x}$$ (dominated by angular vertex spread)
- Integration over process-dependent t-distribution would smear M_{min} by 2 – 3 GeV

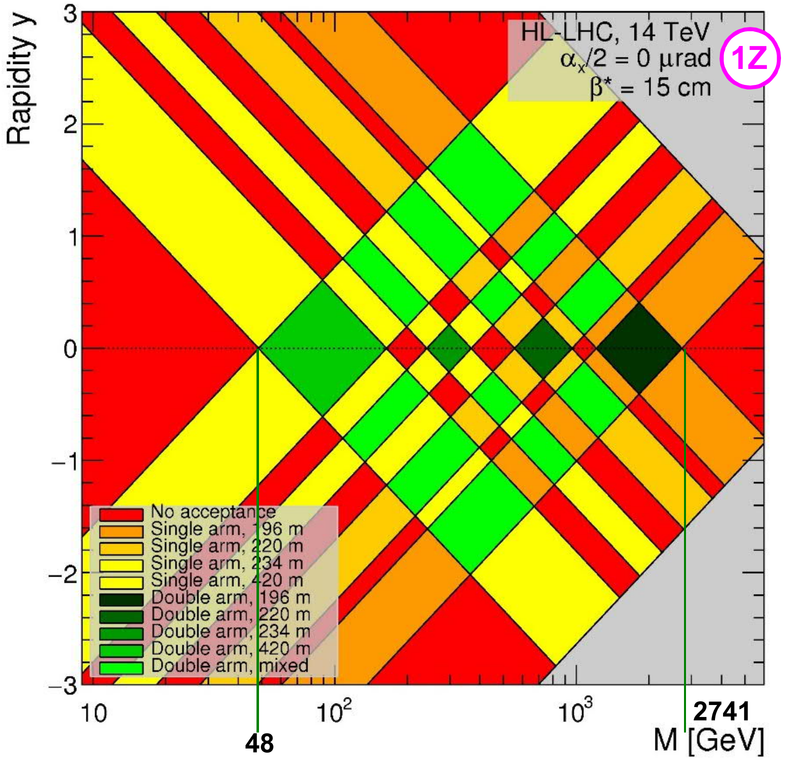
Acceptance in the Mass – Rapidity Plane: Vertical Crossing



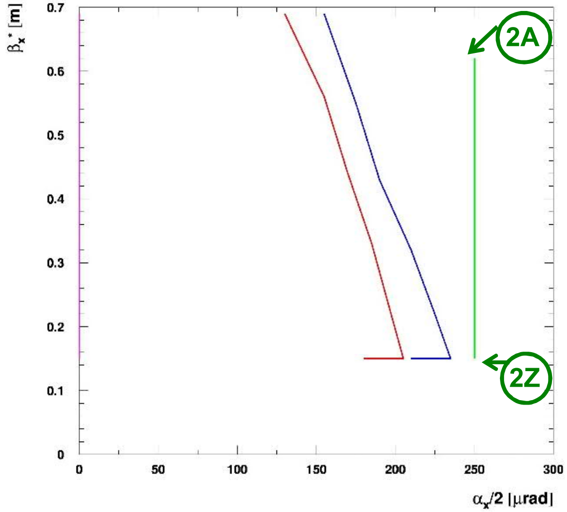
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

XRPs @ 196 m, 220 m, 234 m, 420 m



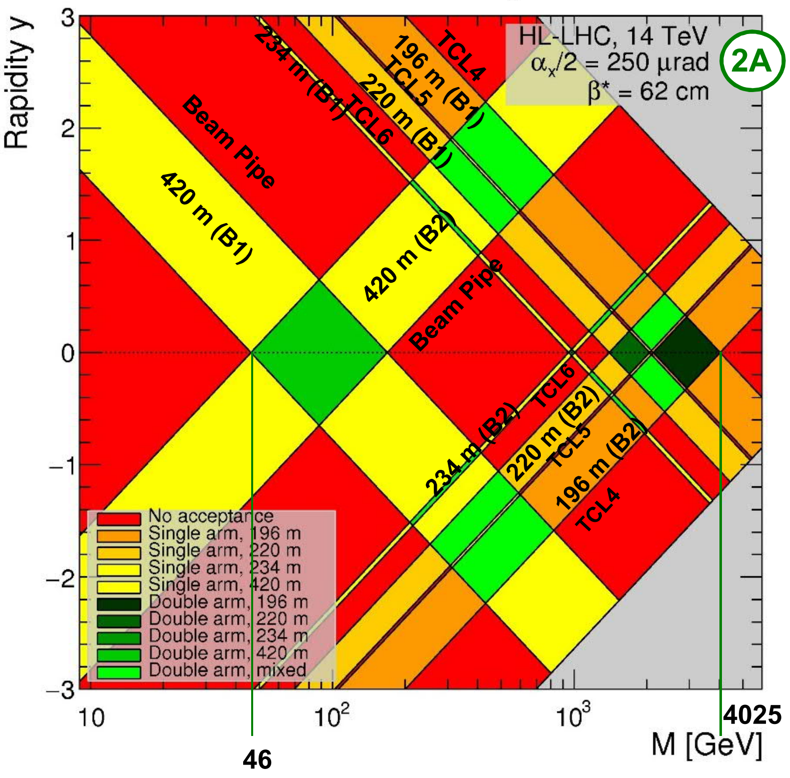


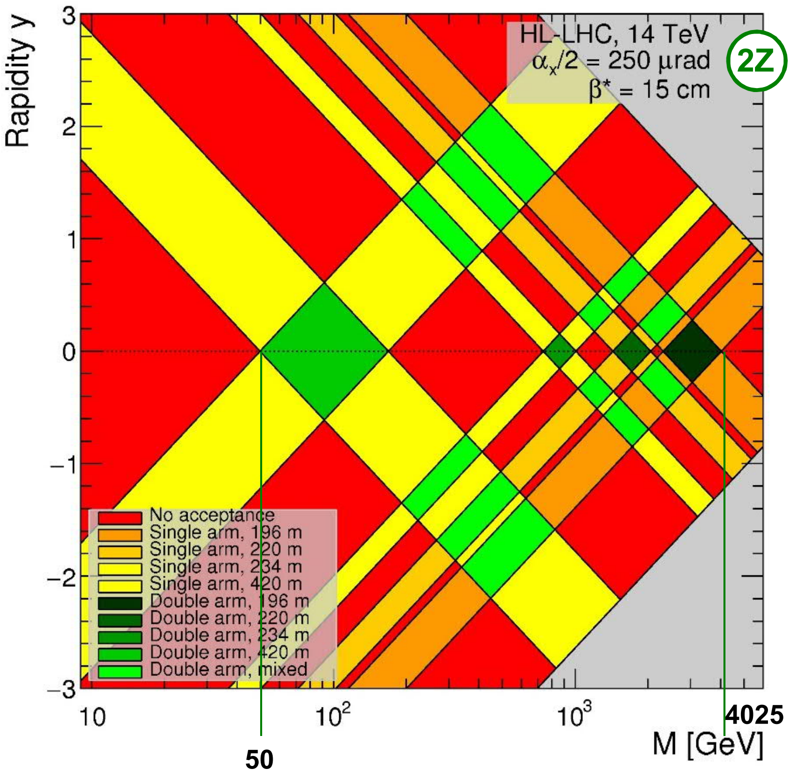
Acceptance in the Mass – Rapidity Plane: Horizontal Crossing, Baseline Trajectory



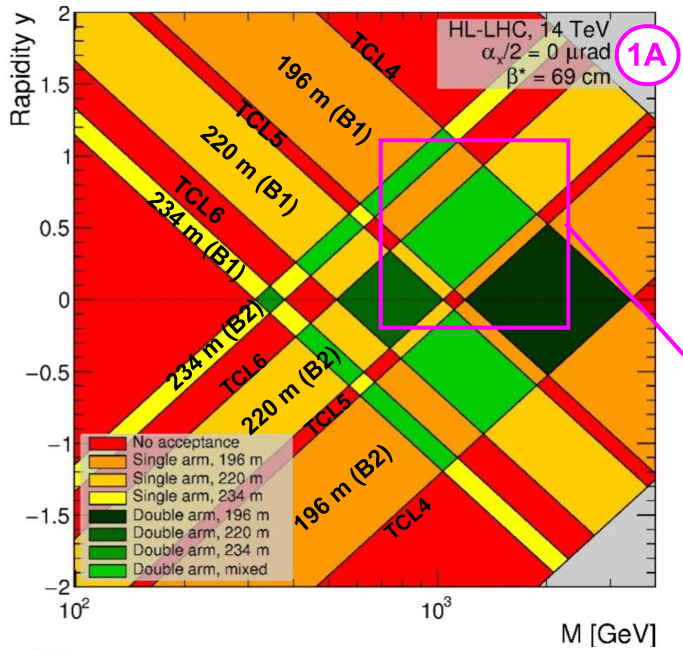
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

XRPs @ 196 m, 220 m, 234 m, 420 m

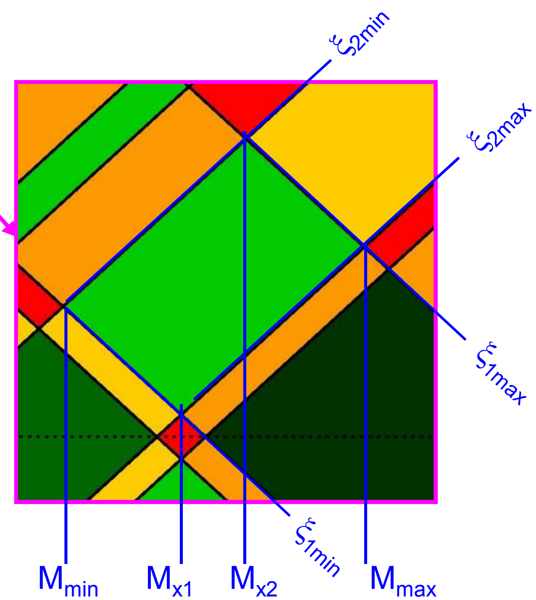




Mass Acceptance Integrated over y: Principle



M-acceptance of an overlap area relative to the total kinematically allowed y-interval, **assuming a flat rapidity distribution**:



$$A(M) = \begin{cases} \dfrac{\ln \dfrac{M}{M_{\min}}}{\ln \dfrac{\sqrt{s}}{M}} & \text{for } M < M_{x1} \\[2ex] \dfrac{\ln \dfrac{M_{x1}}{M_{\min}}}{\ln \dfrac{\sqrt{s}}{M}} & \text{for } M_{x1} < M < M_{x2} \\[2ex] \dfrac{\ln \dfrac{M_{\max}}{M}}{\ln \dfrac{\sqrt{s}}{M}} & \text{for } M > M_{x2} \end{cases}$$

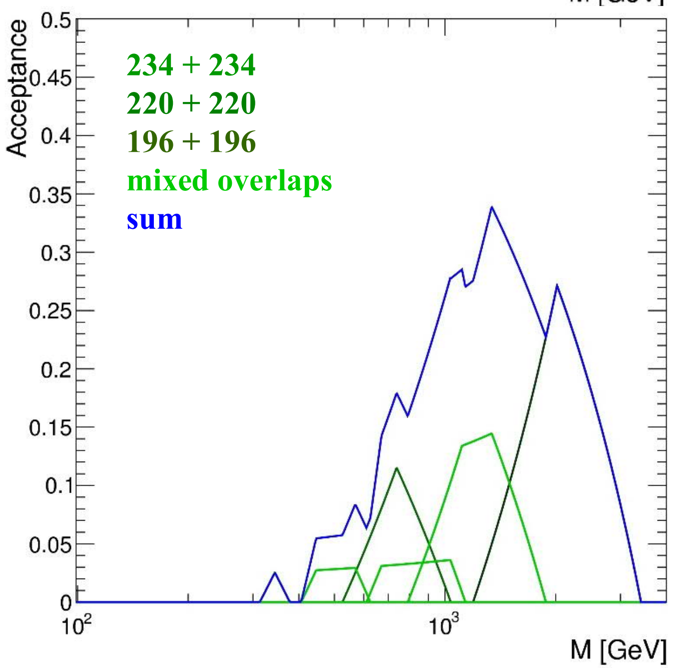
where

$$M_{\min} = \sqrt{\xi_{1\min}\xi_{2\min} s}$$

$$M_{\max} = \sqrt{\xi_{1\max}\xi_{2\max} s}$$

$$M_{x1} = \min(\sqrt{\xi_{1\min}\xi_{2\max} s}, \quad \sqrt{\xi_{2\min}\xi_{1\max} s})$$

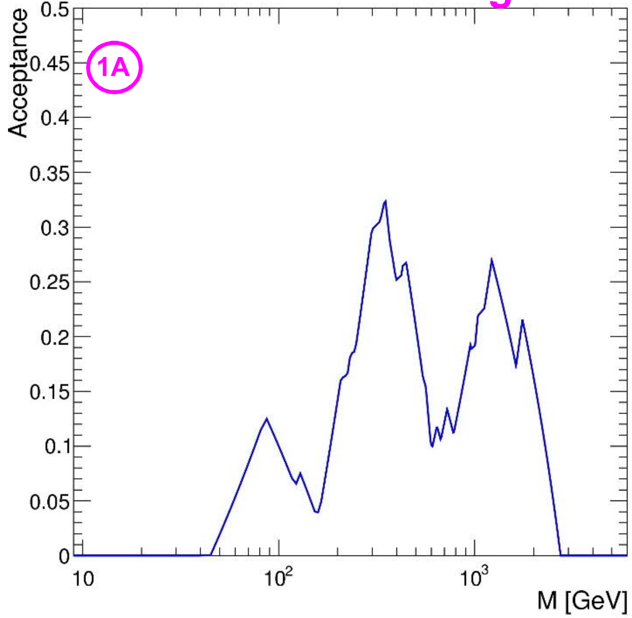
$$M_{x2} = \max(\sqrt{\xi_{1\min}\xi_{2\max} s}, \quad \sqrt{\xi_{2\min}\xi_{1\max} s})$$

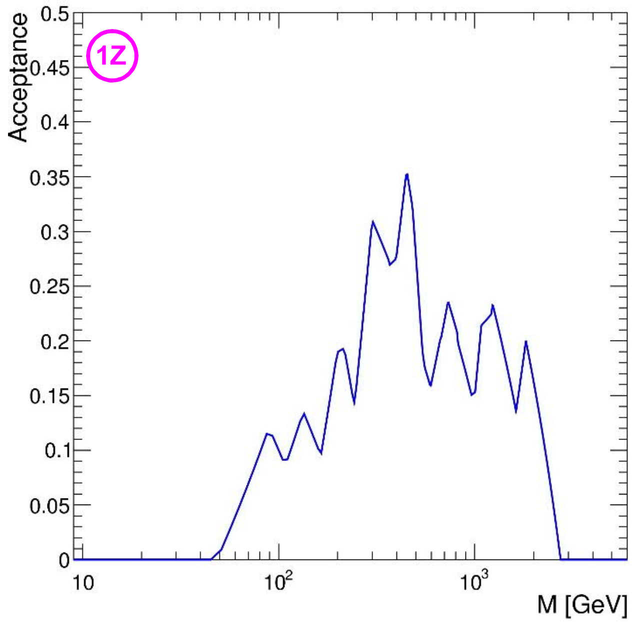


Reminder: this is for $t_1 = t_2 = 0$!
Including t would introduce process-dependent smearing.

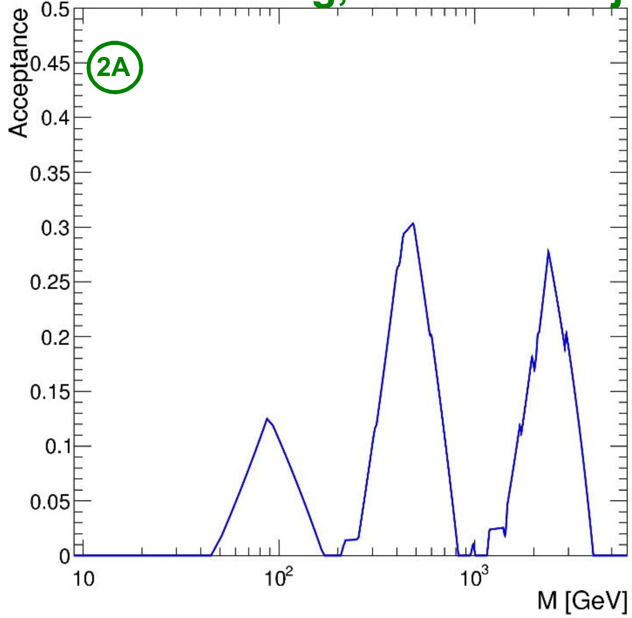
Mass Acceptance Integrated over y

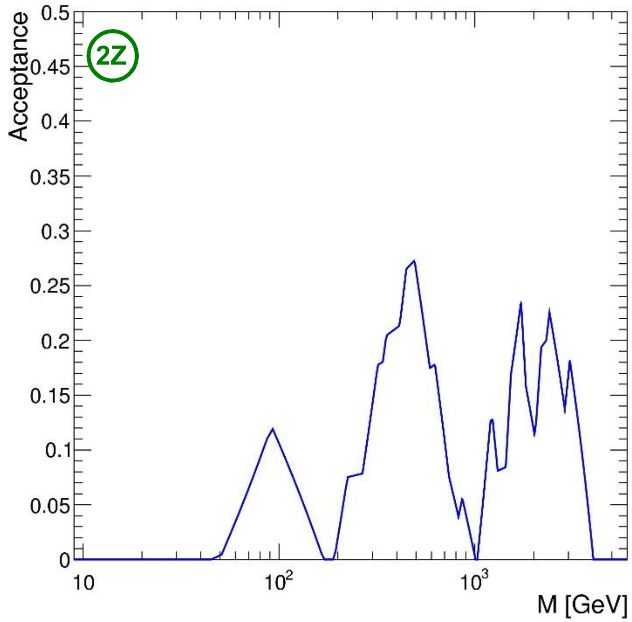
Vertical Crossing





Horizontal Crossing, Baseline Trajectory





Conclusions

- 4 relevant locations:
  - just before TCL5 (~ 196 m) (high masses)
  - just before TCL6 (~ 220 m) (intermediate masses)
  - just after Q6 (~ 234 m) (lower masses)
  - 420 m: $D_x > 0$ → diffractive p between beam pipes → needs new technology (lowest masses)

- Main driving factor for acceptance: dispersion !

- Advantages of vertical and horizontal crossing:

  Vertical:
  - if 420 m unit is **not** present: better low-mass limit (210 GeV instead of 660 GeV)
    if 420 m unit is present: same low-mass limit (50 GeV)
  - smaller acceptance gaps in the 100 – 200 GeV region

  Horizontal:
  - access to higher masses (4 TeV instead of 2.7 TeV)

  → strong preference for vertical crossing

- Mass acceptance gaps in ~1 TeV region could be closed if TCLs were slightly more open:
  $d_{TCL5} = 18\ \sigma_{15cm}$ instead of $14.2\ \sigma_{15cm}$
  $d_{TCL6} = 20\ \sigma_{15cm}$ instead of $14.2\ \sigma_{15cm}$

- All technical issues still to be addressed !

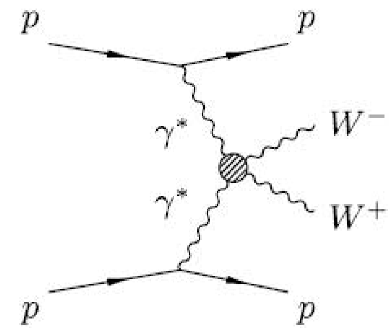
The End.

Appendix

From M. Arneodo, HL-LHC Coordination Meeting, 10 October 2017:

Physics motivations: central exclusive production

1) LHC as tagged photon-photon collider



EWK

- Measure $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for AQGC with high sensitivity
- Search for SM forbidden $ZZ\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings

2) LHC as tagged gluon-gluon collider

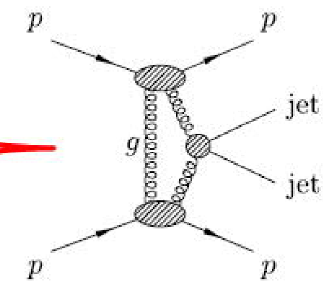
QCD

- Exclusive two and three jet events, M up to ~ 700-800 GeV.
- Test of pQCD mechanisms of exclusive production.
- Gluon jet samples with small quark jet component
- Proton structure (GPDs)

BSM

Search for new resonances in CEP

- Clean events (no underlying pp event)
- Independent mass measurement from pp system
- J^{PC} quantum numbers 0^{++}, 2^{++}



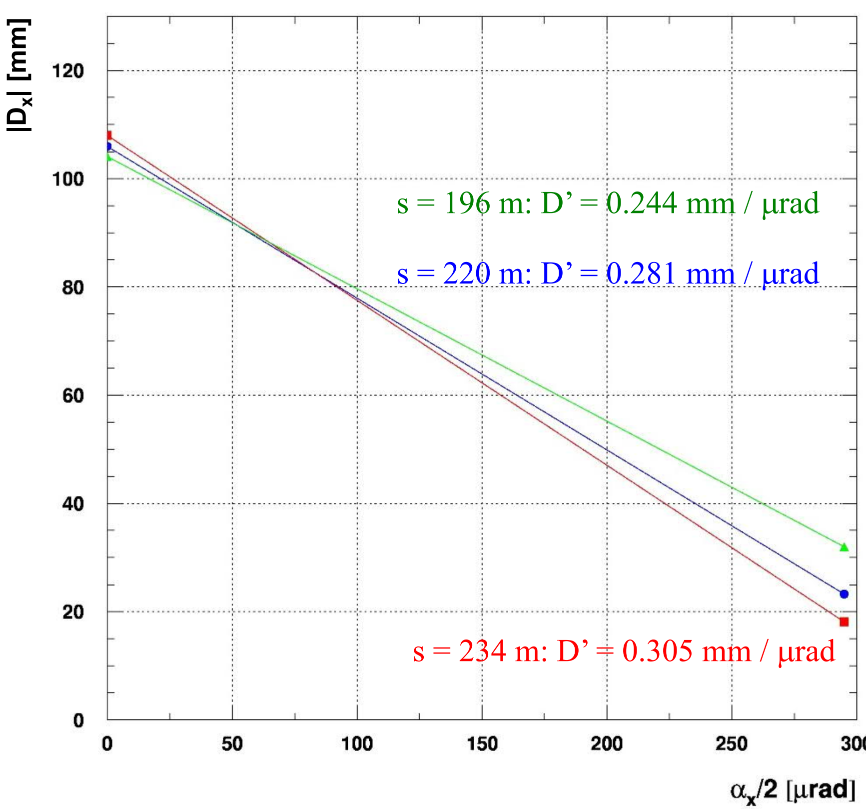
From CT-PPS TDR: CERN-LHCC-2014-021

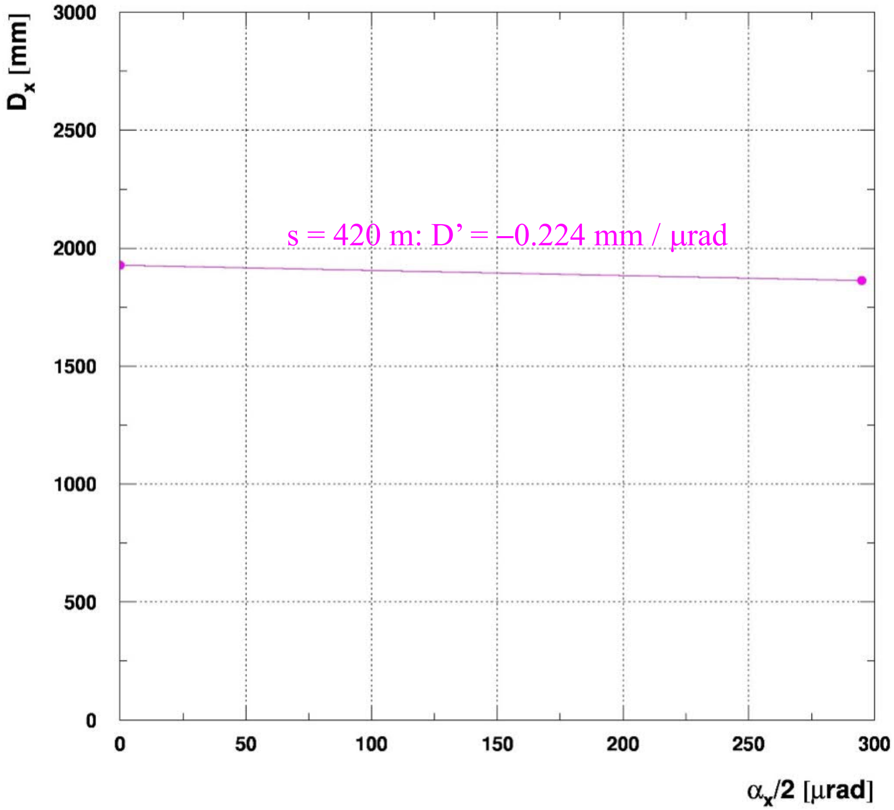
NB mass of centrally produced system measured from scattered protons momenta

Dispersion vs. Crossing-Angle

MAD-X simulations:

- $(\alpha_x/2, \alpha_y/2, \beta_x^*, \beta_y^*)$ = (295 μrad, 0, 15 cm, 15 cm):
  D_x(196m) = –32.0 mm, D_x(220m) = –23.3 mm, D_x(234m) = –18.1 mm, D_x(420m) = +1862 mm
- $(\alpha_x/2, \alpha_y/2, \beta_x^*, \beta_y^*)$ = (0, 295 μrad, 15 cm, 15 cm):
  D_x(196m) = –104 mm, D_x(220m) = –106 mm, D_x(234m) = –108 mm, D_x(420m) = +1928 mm





Assume linearity: $$D\left(\frac{\alpha}{2}\right) = D(0) + D'\frac{\alpha}{2}$$ (confirmed by 2017 data).

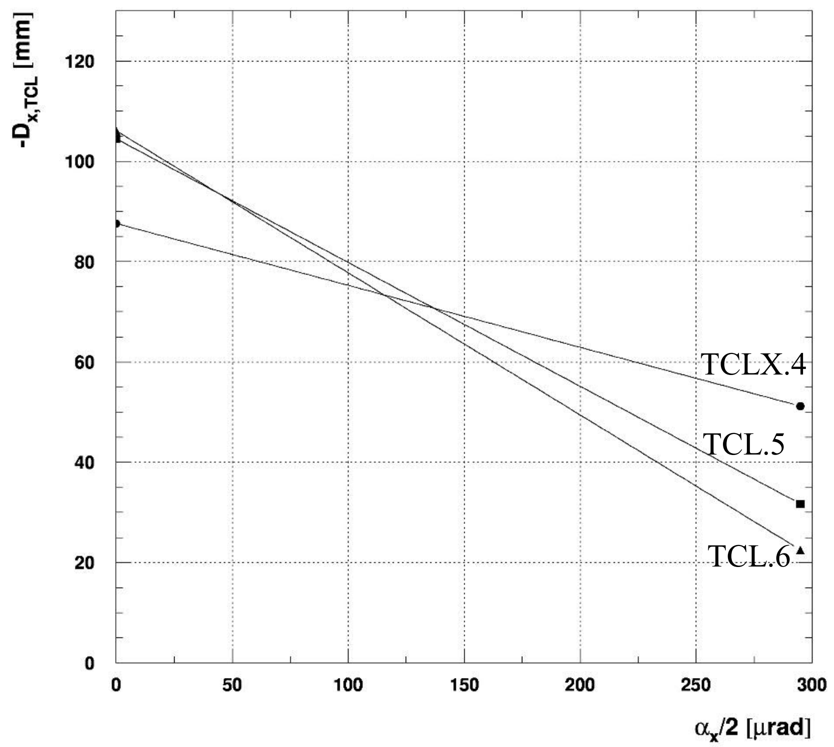
Maximum Mass: General Principle

M_{max} is given by the tightest aperture cut of all TCL collimators upstream of the detector.

$$\tilde{M}_{max} = \frac{d_{TCL}}{D_{TCL}(\frac{\alpha_x}{2})}\sqrt{s}$$

M_{max} depends only on $\alpha/2$, not on β^* !

Dispersion at TCLX.4, TCL.5, TCL.6 vs. crossing-angle



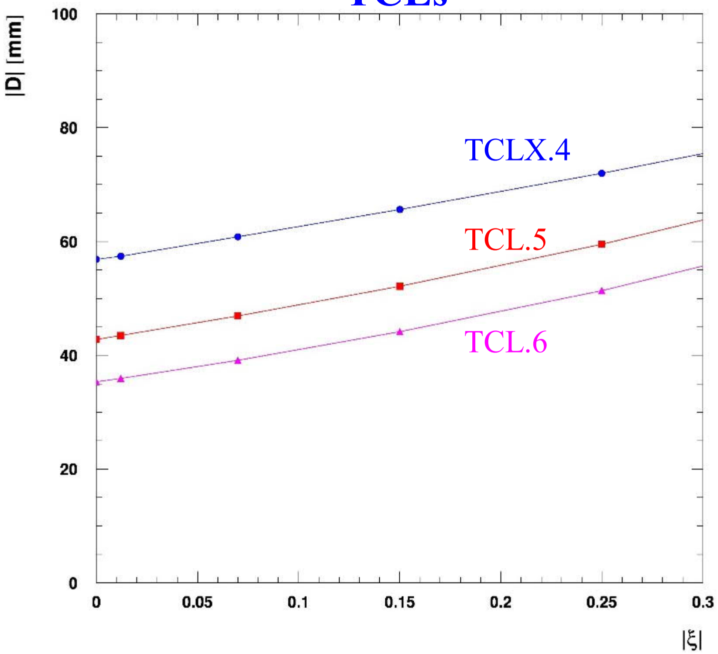
Collimation strategy for TCLs presently foreseen:

d_{TCL} = 14.2 $\sigma(\beta^*$=15cm) constant in absolute distance

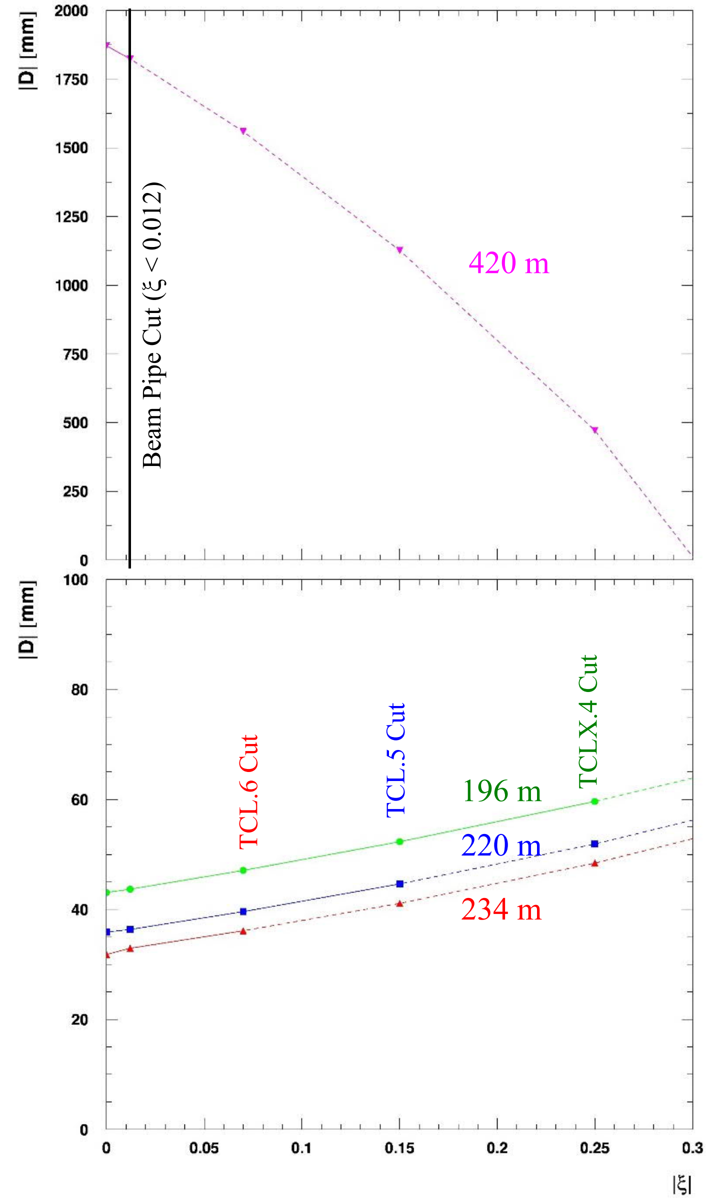
ξ-Dependence of the Dispersion: Horizontal Crossing

Baseline Trajectory ($\alpha_x/2 = 250\ \mu rad$)

TCLs



XRPs



D @ TCLs increases with ξ
→ max. mass cut tighter than anticipated using D(ξ=0)

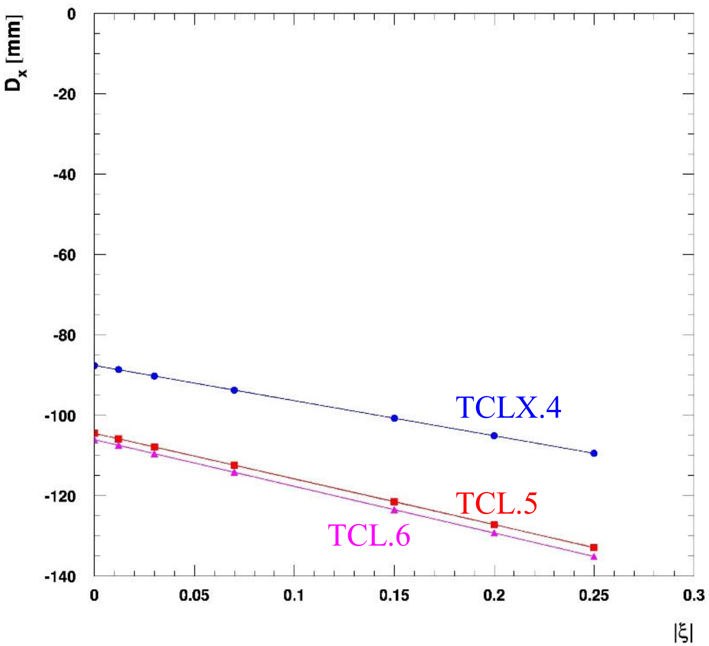
For small ξ (within acceptance): approximately linear
→ extended dispersion model:

$$D\left(\frac{\alpha}{2},\xi\right) = D_0 + d_\alpha \frac{\alpha}{2} + d_\xi\, \xi + d_{\alpha\xi} \frac{\alpha}{2} \xi$$

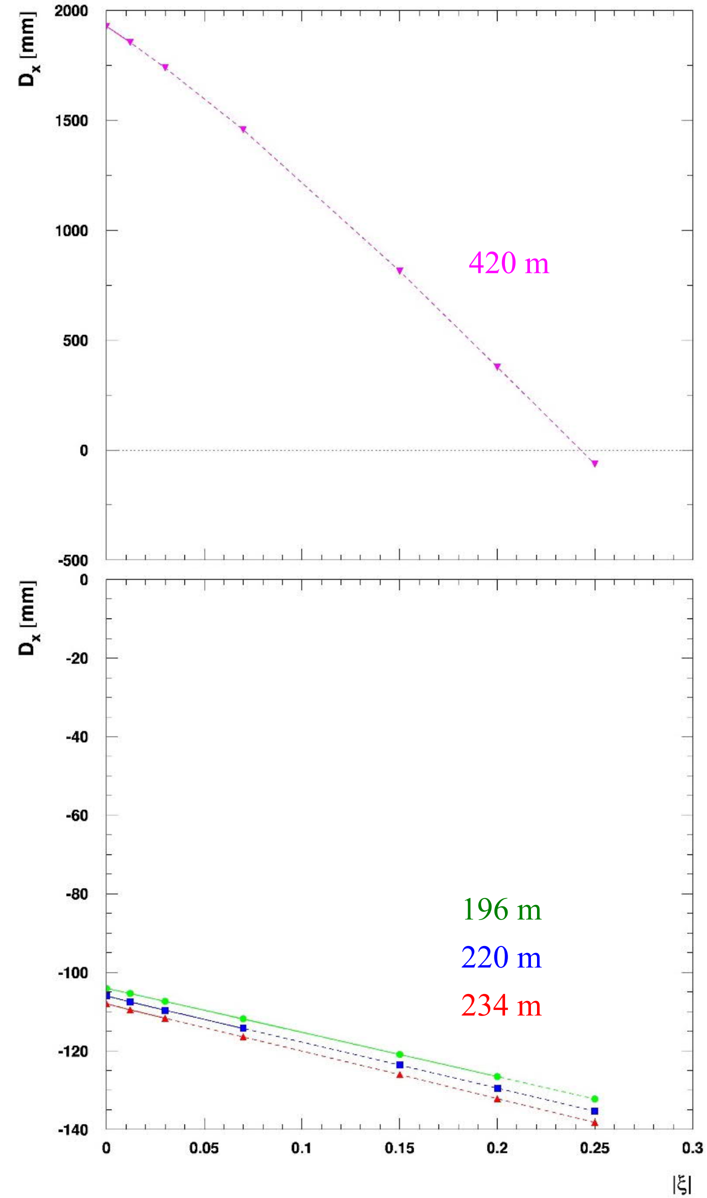
ξ-Dependence of the Dispersion: Vertical Crossing

Baseline Trajectory ($\alpha_y/2 = 250\ \mu\text{rad}$) **Horizontal Dispersion**

TCLs

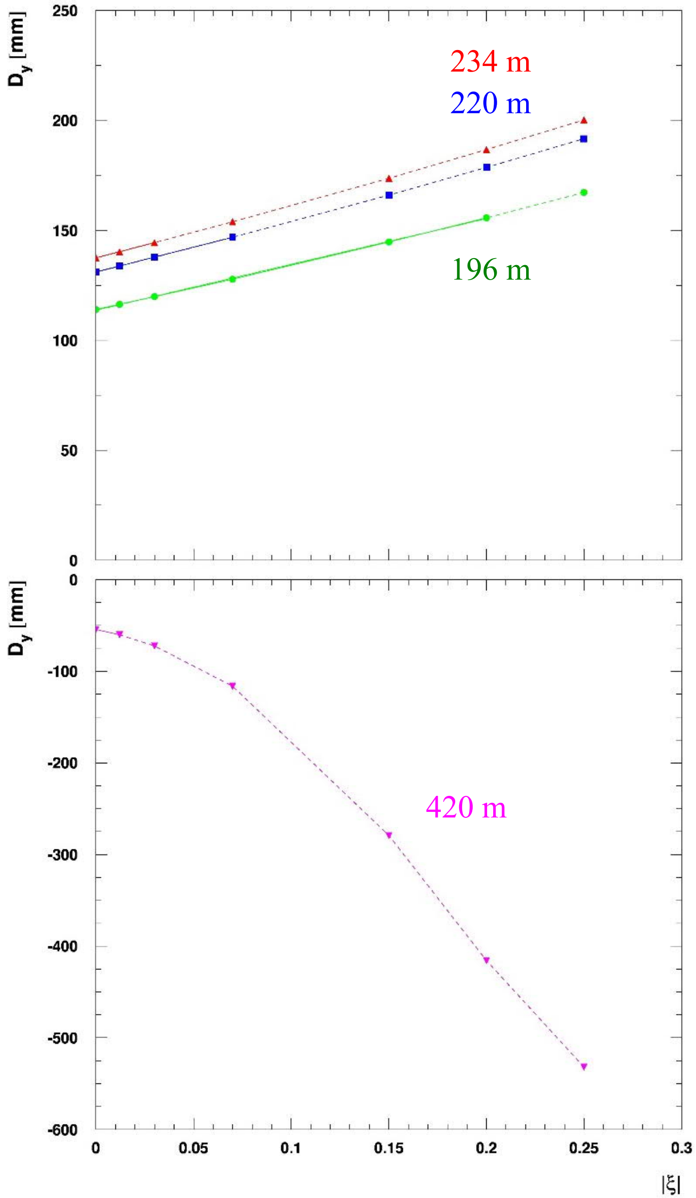


XRPs



ξ-Dependence of the Dispersion: Vertical Crossing

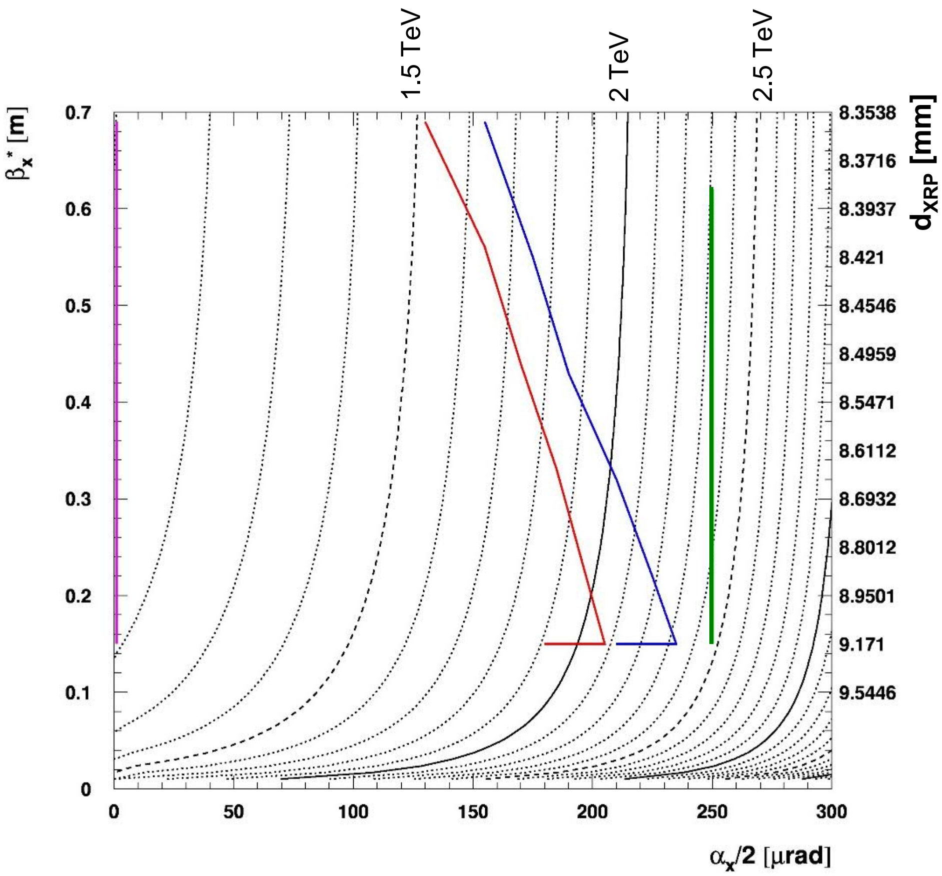
Baseline Trajectory ($\alpha_y/2 = 250\ \mu rad$) **Vertical Dispersion XRPs**



Minimum Mass @ 196 m with ξ-Dependent D

Contour lines for $M_{min} = \xi_{min} \sqrt{s}$ with $\xi_{min} = \dfrac{d_{XRP}(\beta^*) + \delta}{D_x(\frac{\alpha}{2}, \xi_{min})}$ resolved for ξ_{min}

TCT settings: d_{TCT} = const. (12.9 σ @ β* = 15 cm)



Insertion distances very moderate !

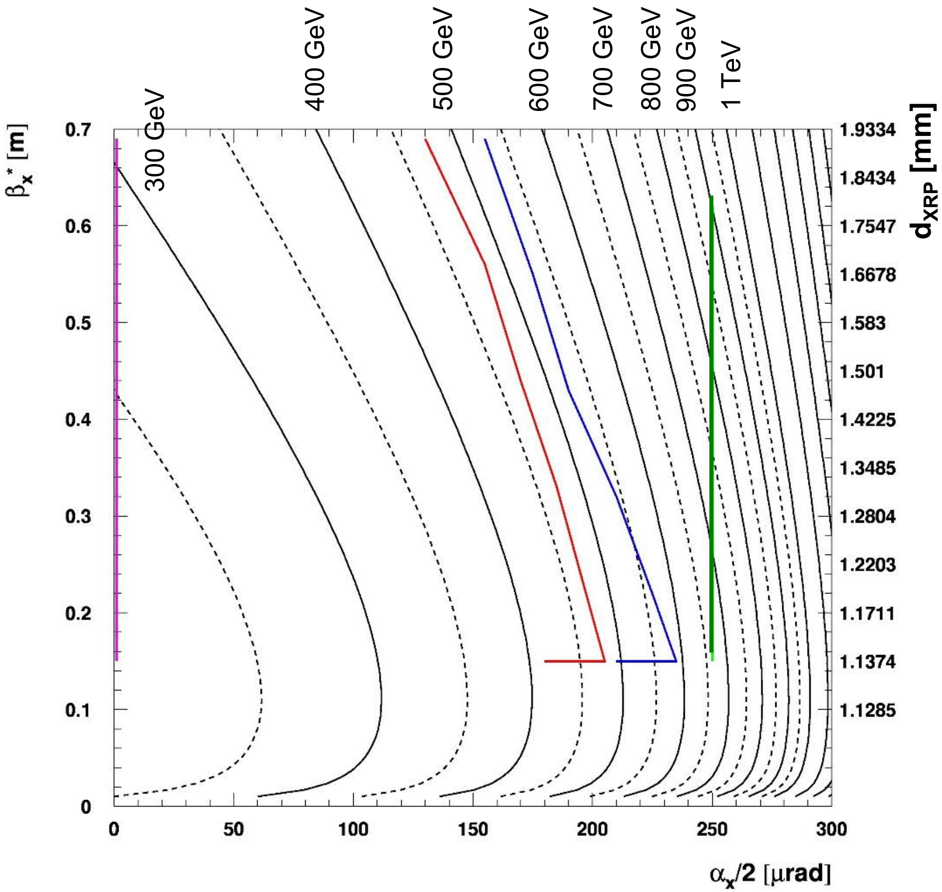
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

Inclusion of ξ-dependence improved M_{min} by:
Horiz., baseline: ~580 GeV (20%)
Vert.: ~100 GeV (10%)

Minimum Mass @ 234 with ξ-Dependent D

Contour lines for $M_{\min} = \xi_{\min}\sqrt{s}$ with $\xi_{\min} = \frac{d_{XRP}(\beta^*) + \delta}{D_x(\frac{\alpha}{2}, \xi_{\min})}$ resolved for $\xi_{\min}$

TCT settings: d_{TCT} = const. (12.9 σ @ β* = 15 cm)



← assuming that the pots move during the fill to adapt to β* !

Insertion distances more aggressive (< 1.5 mm)

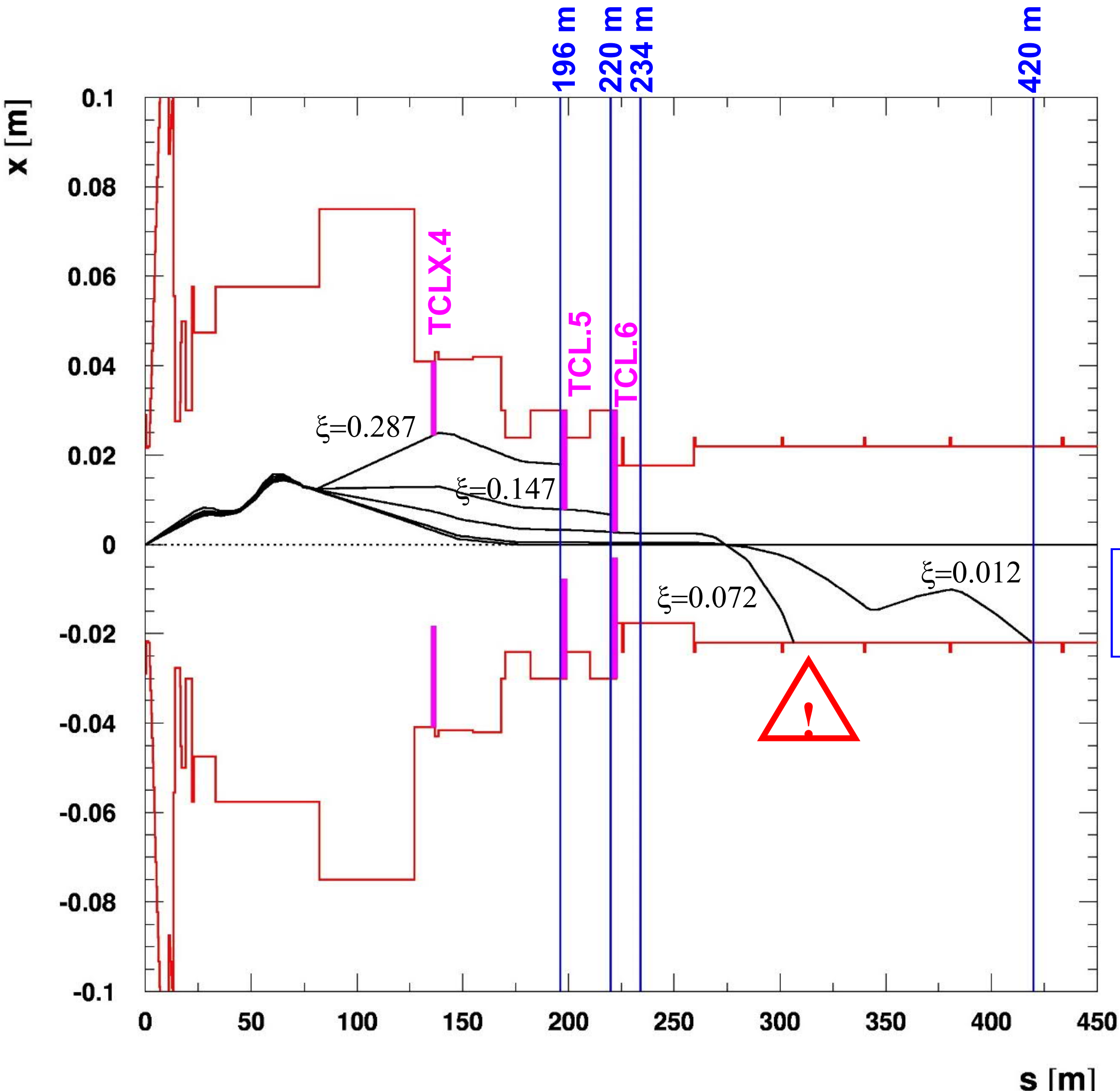
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

Inclusion of ξ-dependence improved $M_{\min}$ by:
Horiz., baseline: ~100 GeV (10%)
Vert.: ~ 5 GeV (2%)

Aperture Study: Horizontal Crossing

Baseline Levelling Trajectory ($\alpha/2 = 250\ \mu$rad)

Horizontal tracks with different ξ (from MAD-X)



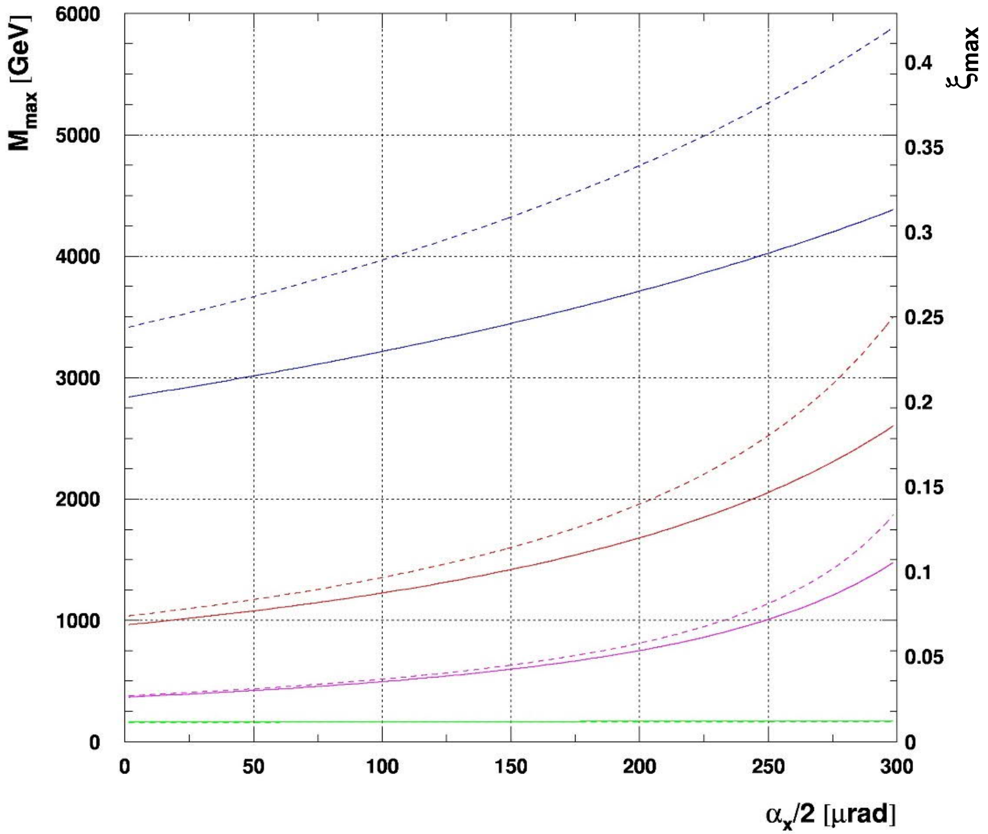
ξ_{max}(420m) = 0.012, not 0.072

For s > 306 m or ξ < 0.07: TCL.6 is not the aperture limitation !
Protons run into the beampipe.

Maximum Mass: Horizontal Crossing

$$\widetilde{M}_{\max} = \xi_{\max}\sqrt{s} = \frac{d_{\mathrm{TCL}}}{D_{\mathrm{TCL}}(\frac{\alpha_x}{2}, \xi_{\max})}\sqrt{s}$$

→ quadratic equation for ξ_{max}



dashed: naive calculation with ξ-independent D

TCLX.4 determines M_{max} at 196 m

TCL.5 determines M_{max} at 220 m

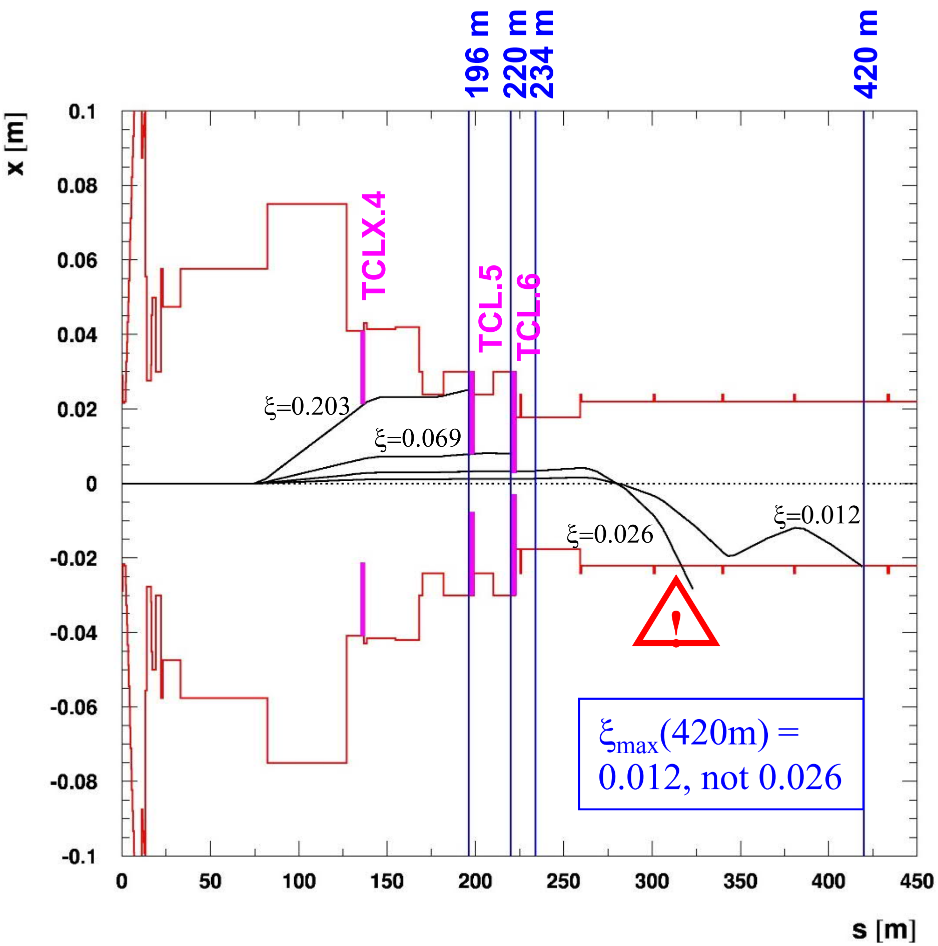
TCL.6 determines M_{max} at 234 m

Beam pipe aperture determines M_{max} at 420 m

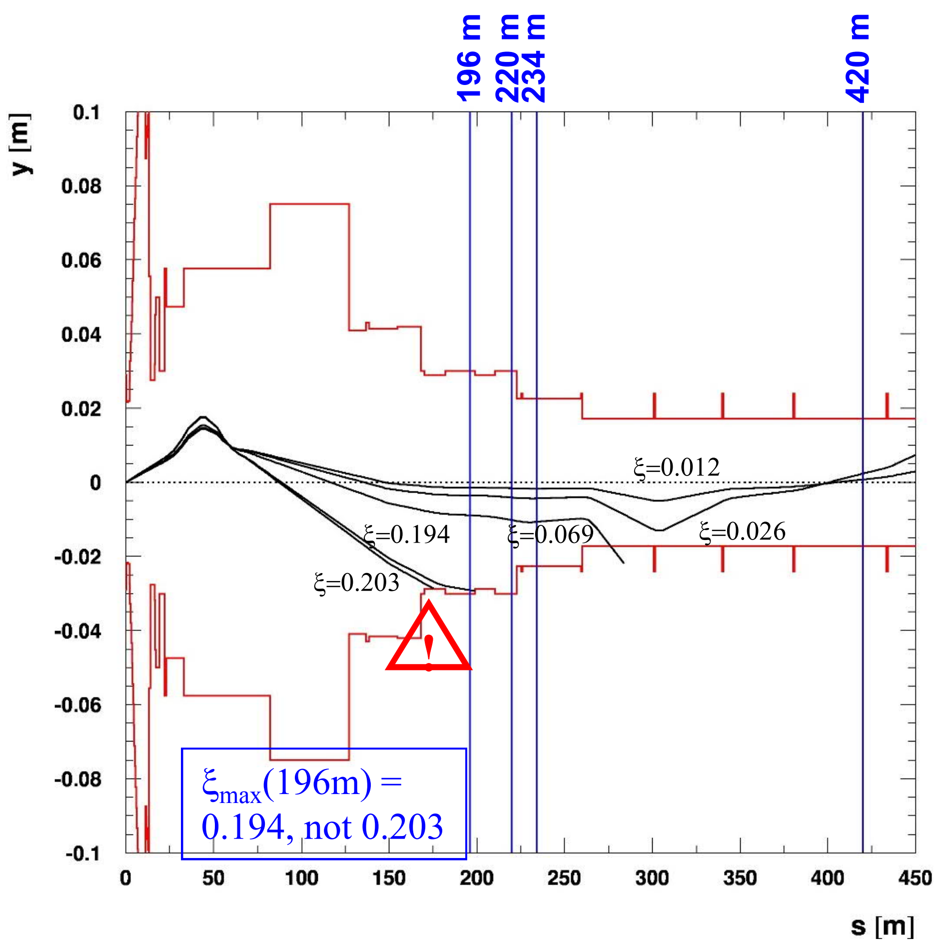
Aperture Study: Vertical Crossing

Baseline Levelling Trajectory ($\alpha_y/2 = 250\ \mu rad$)

Horizontal Aperture



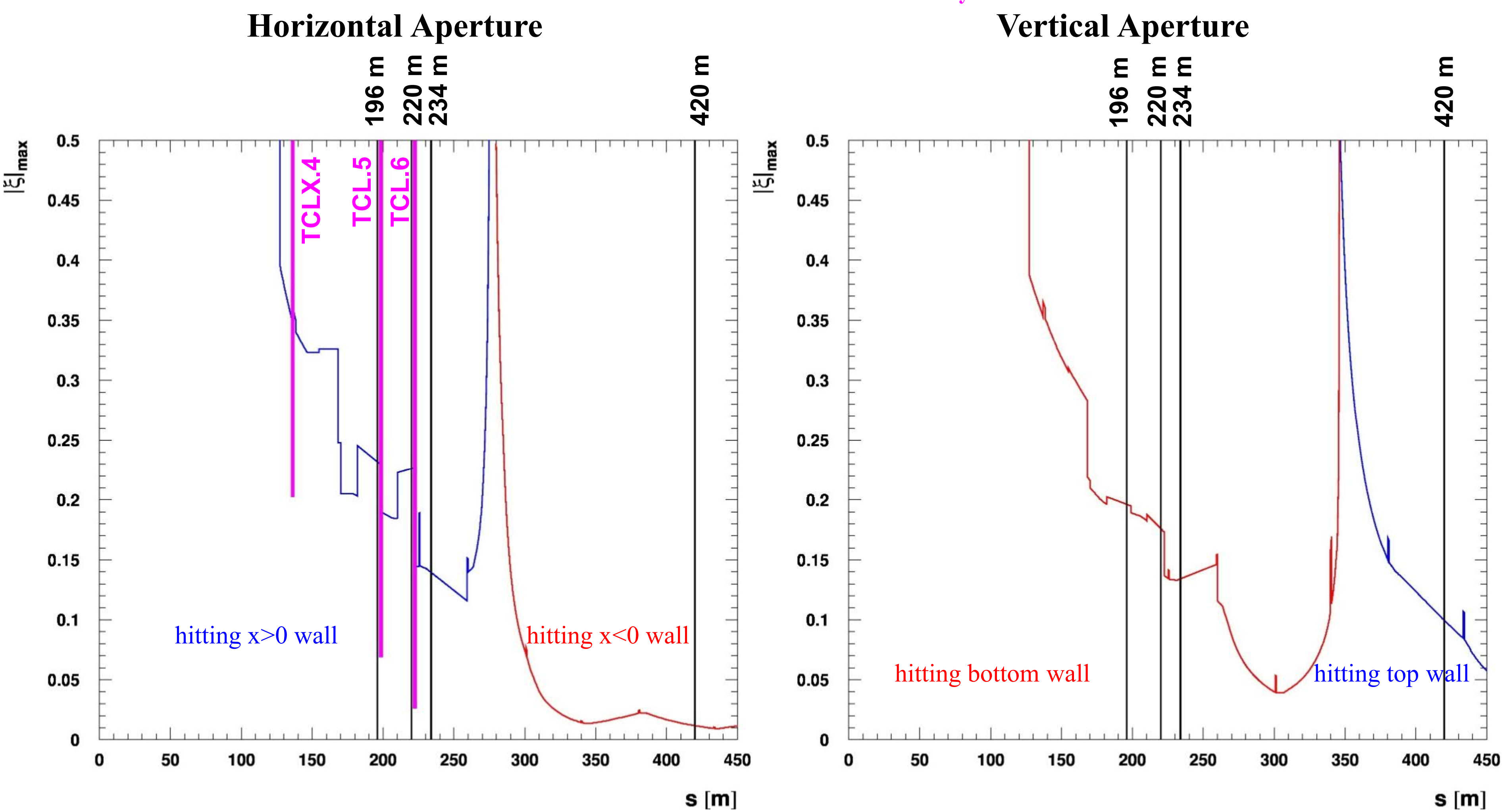
Vertical Aperture



For s > 315 m or ξ < 0.026: TCL.6 is not the aperture limitation !
Protons run into the beampipe.

Maximum ξ from Aperture: Vertical Crossing

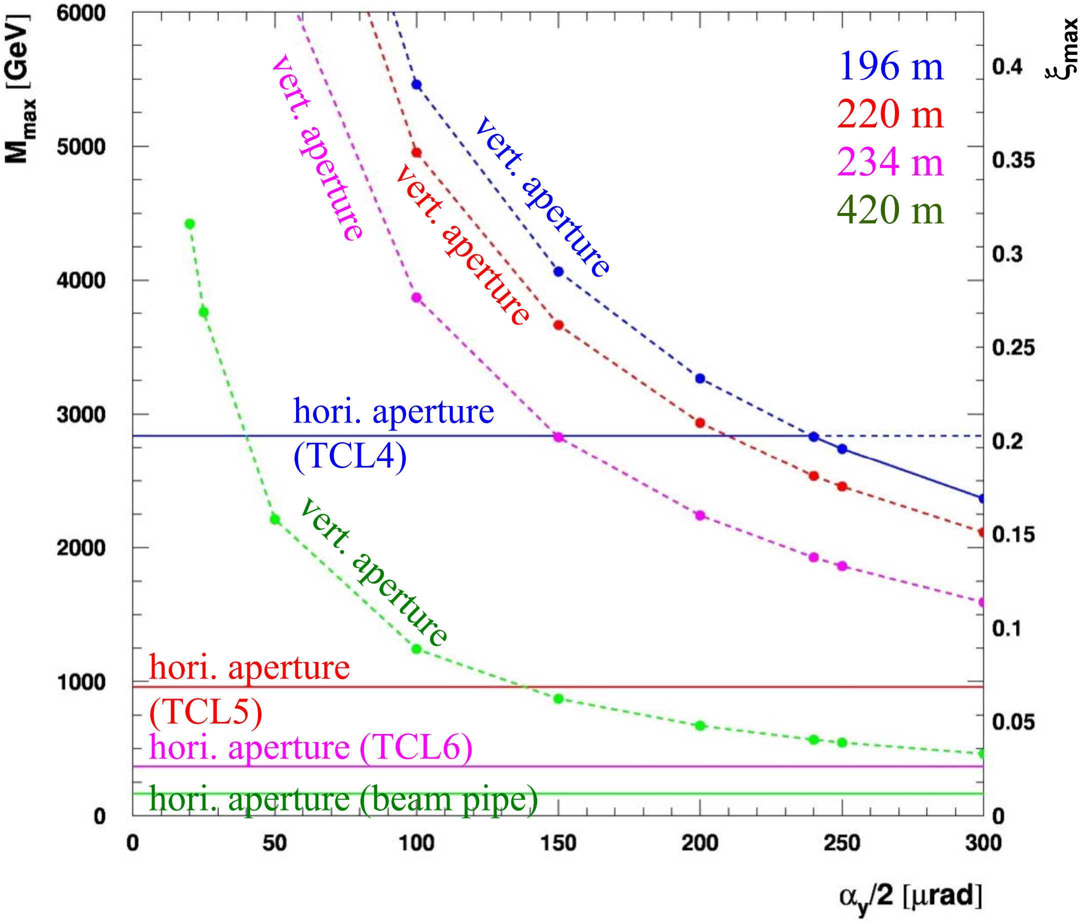
Baseline Levelling Trajectory ($\alpha_y/2 = 250\ \mu rad$)



Repeat this as a function of $\alpha_y/2$,
at each $\alpha_y/2$ look for the horizontal and vertical bottleneck upstream of each detector location.
→ $|\xi|_{max}(\alpha_y/2)$ for each detector location

Maximum Mass from Aperture: Vertical Crossing

Take minimum of horizontal and vertical aperture limitations.



horizontal and vertical aperture determine M_{max} at 196 m

horizontal aperture determines M_{max} at 220 m

horizontal aperture determines M_{max} at 234 m

horizontal aperture determines M_{max} at 420 m

For vertical crossing the maximum mass is independent of the crossing-angle (except at 196 m location for $\alpha/2 > 240$ μrad).

Outlook: Other Issues to be Studied

- Debris showers → BLM rates:

  max. lumi 2018: 2×10^{34} cm^{-2} s^{-1}
  max. lumi HL-LHC: 20×10^{34} cm^{-2} s^{-1}
  → factor 10

  At 2×10^{34} cm^{-2} s^{-1} : BLM of cylindrical pot is below threshold by factor 15 → should be ok
  But all designs will change → to be watched

- Impedance:

  - max protons / beam 2018: 3.2×10^{14}
    HL-LHC: 6×10^{14}
    → factor 2 in current → factor 4 in heating
  - bunch length ? → impact on power spectrum
  - RP distance: already studied down to 1 mm
  - impedance budget of the machine might become tighter

- Influence from crab cavities on scattered p trajectories should be negligible (H. Burkhardt)

- For detector instrumentation: the pileup:

  $\mu \leq 200$ (w/o levelling, w/o crab cav.)
  $\mu \leq 140$ (w/ levelling, w/ crab cav.)

- Radiation issues