CMS Forward Physics Detectors: Plans for HL-LHC

HL-LHC Collaboration Meeting
16 October 2018

Mario Deile (CERN)
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

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

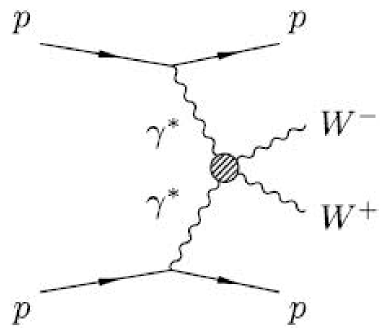
Physics motivations: central exclusive production

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

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

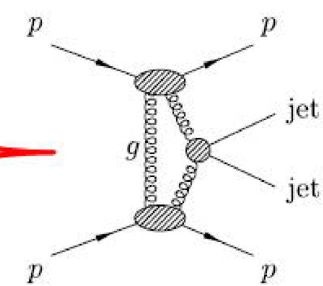
QCD

- 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^{++}



NB mass of centrally produced system measured from scattered protons momenta

CMS PPS at HL-LHC ?

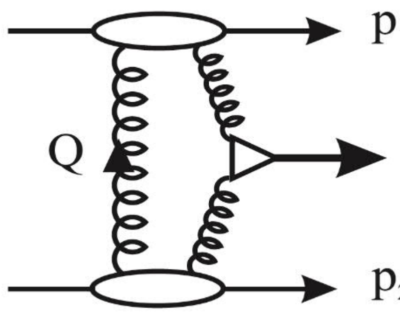
- **Flagship channels, i.e. central exclusive production of WW, dileptons and dijets are statistics limited: factor 10 more luminosity welcome.**
  Suppression of pileup (200) requires timing in the few ps range: not impossible given the current technology

- **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

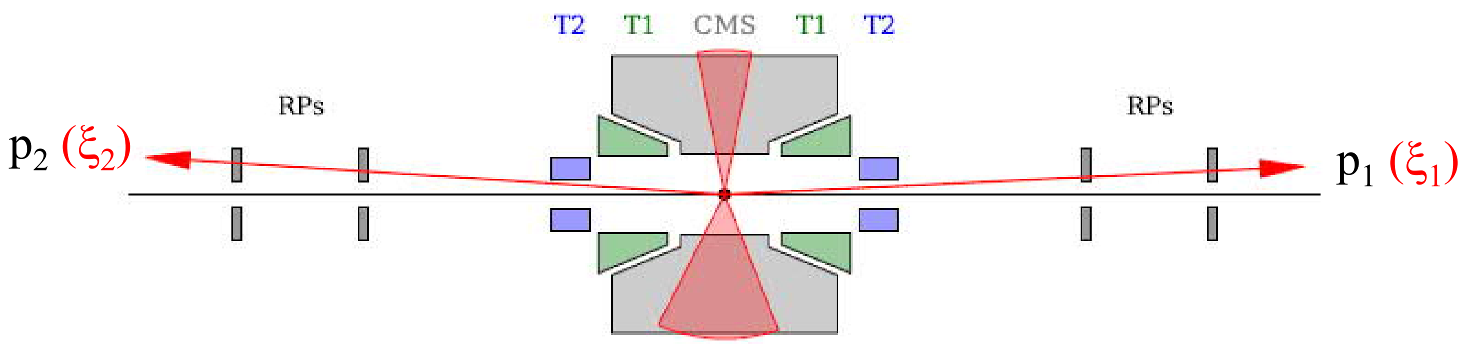
Central Diffractive Production: Kinematics



diffractive system X
with mass M_X at rapidity y_X

$\boxed{M_X^2 = \xi_1 \, \xi_2 \, s}$

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



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

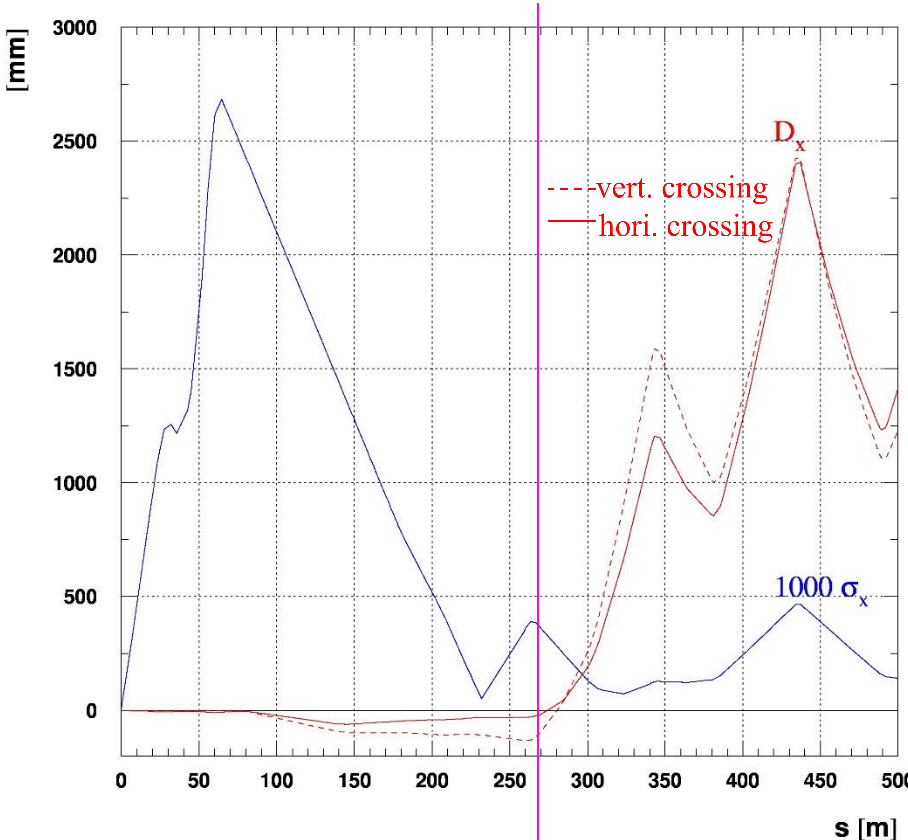
- for crossing angle ($\alpha/2$, β^*) = (250 μrad, 15 cm)
- XRPs @ (12.9 + 3) σ + 0.3 mm

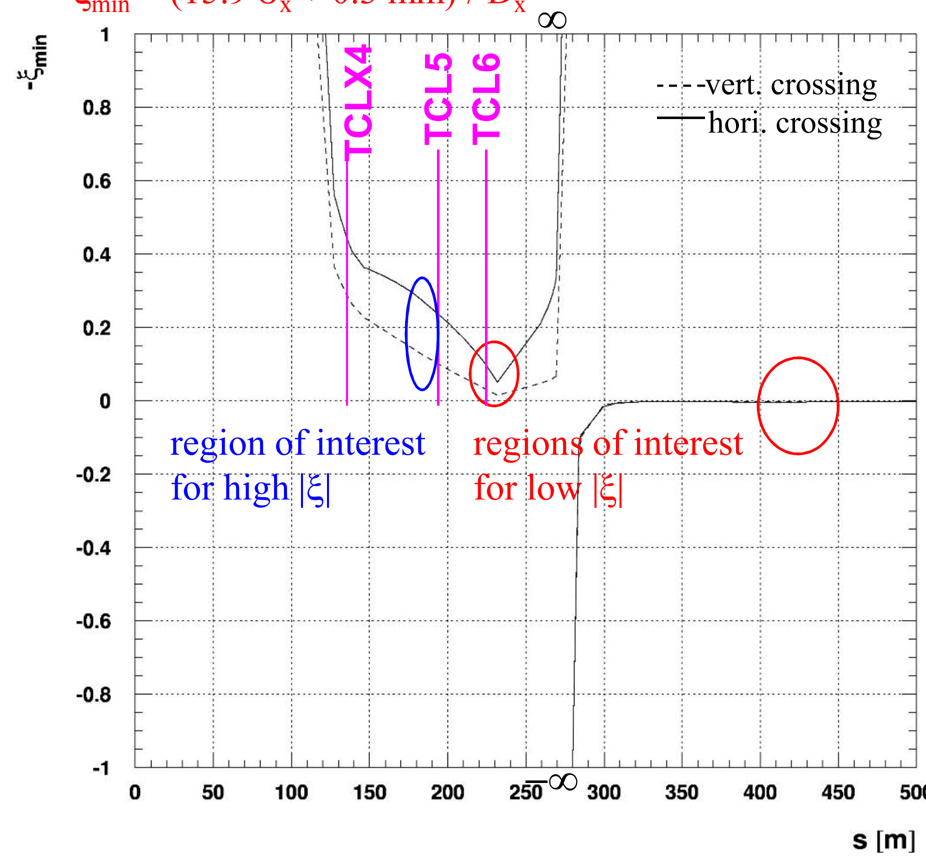
HL-LHC:
new standard emittance ε_n = 2.5 μm rad (instead of 3.5)

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

horizontal dispersion

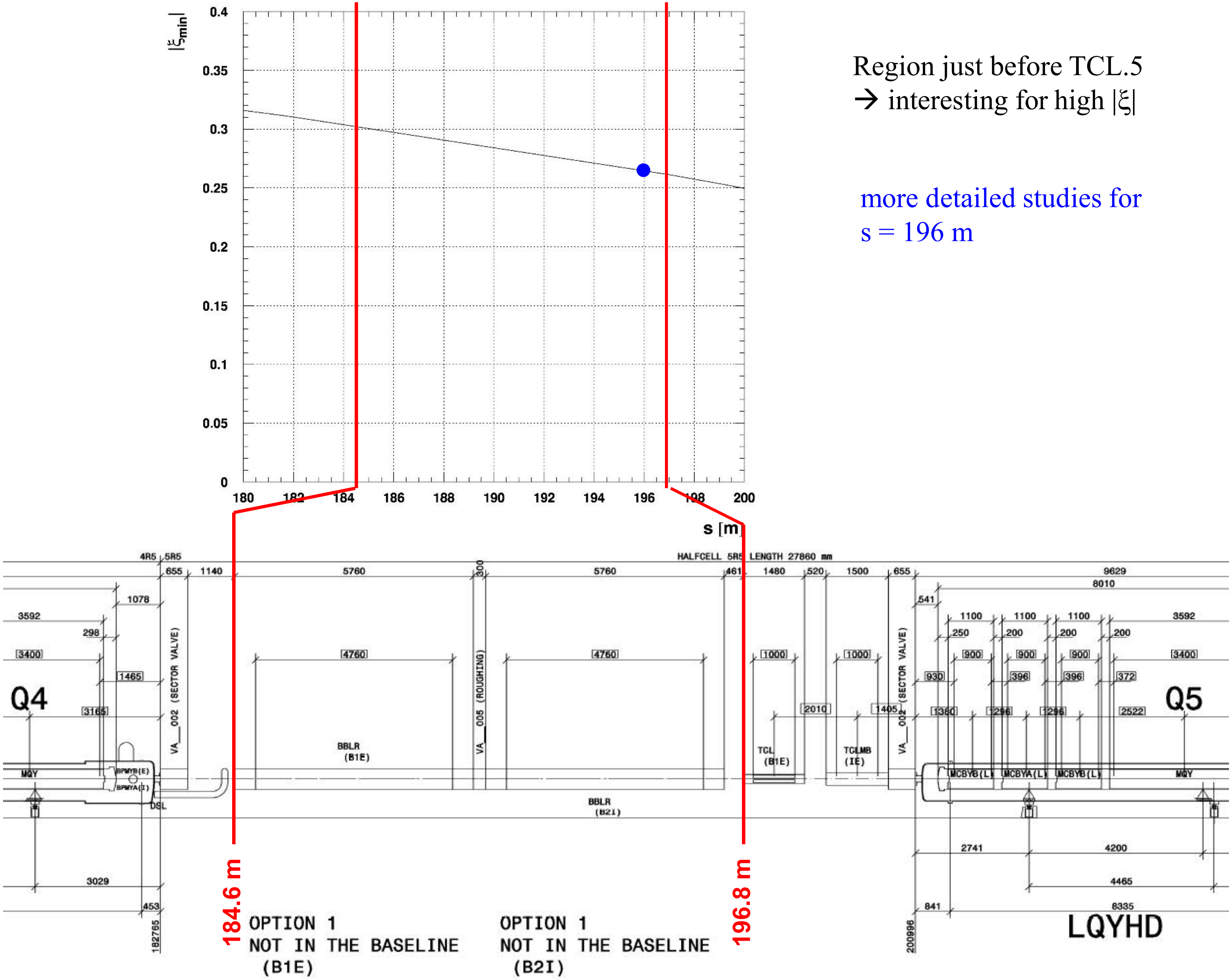
ξ_{min} = (15.9 σ_x + 0.3 mm) / D_x





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.

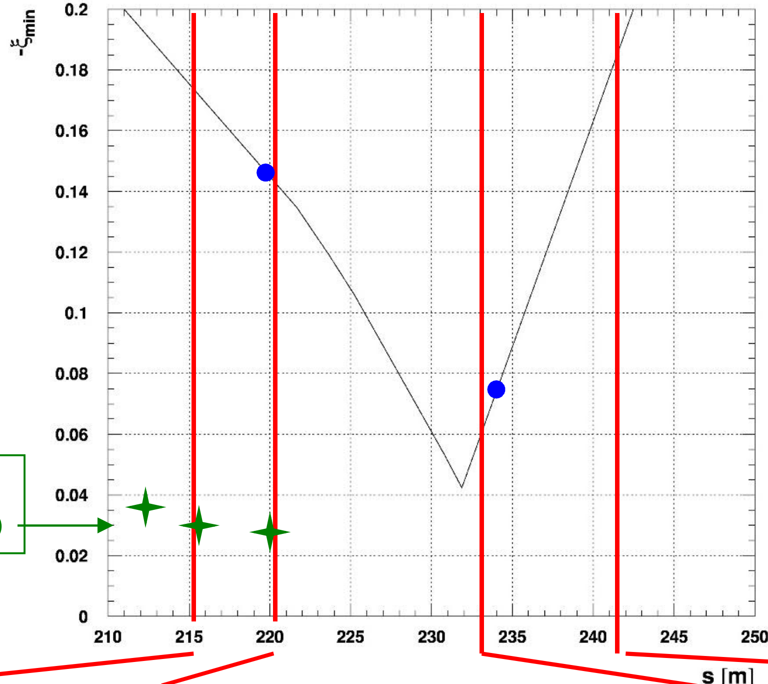
Region of Interest: 180 – 200 m
(for Classic Roman Pot Technology)



Region just before TCL.5
→ interesting for high $|\xi|$

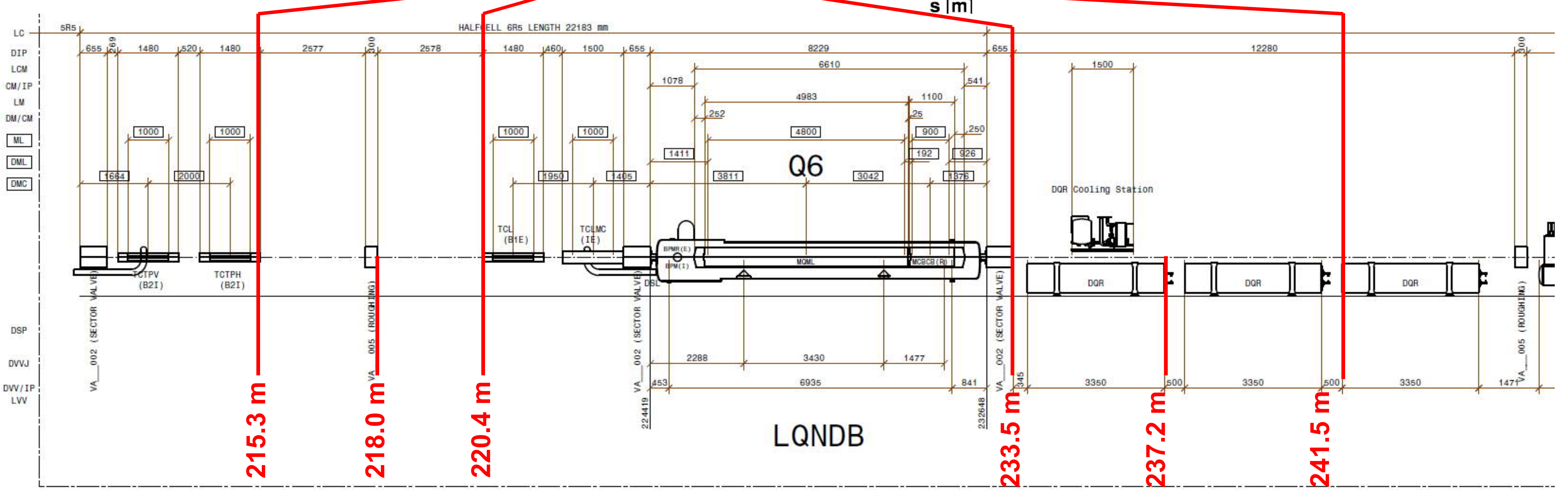
more detailed studies for
s = 196 m

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

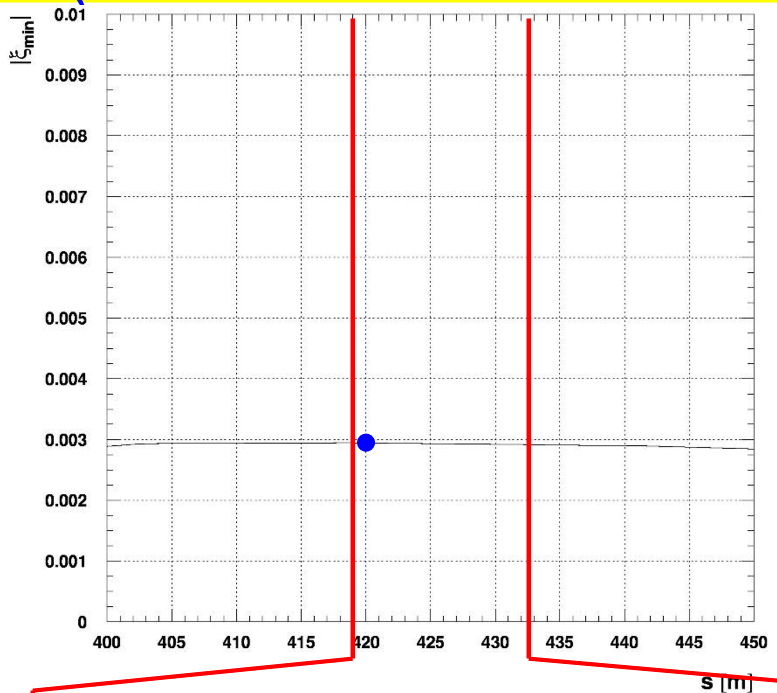


Comparison 2018
(α/2, β*) = (130 μrad, 30 cm)

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



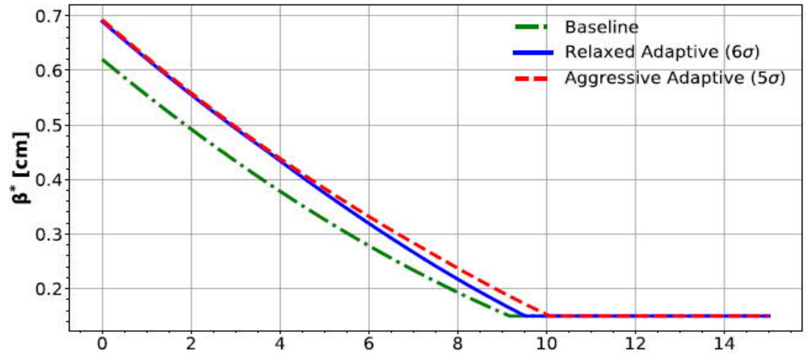
Region of Interest: 400 – 450 m
(for Future "Roman Pot" Technology)



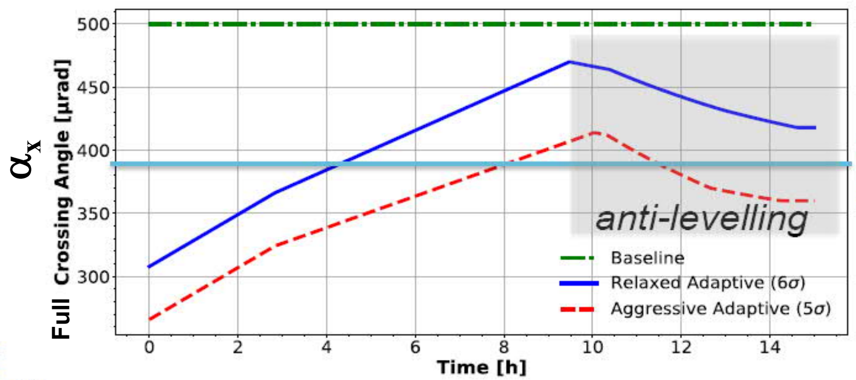
more detailed studies for
s = 420 m

Evolution of Parameters

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

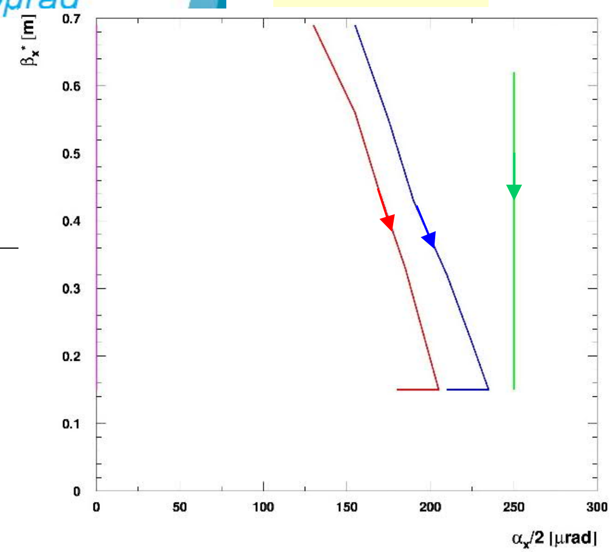


Slightly delay the end of levelling



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 $(\alpha/2, \beta^*)$ plane
(for symmetric optics in Beam 1 / Beam 2 with $\xi_{1\,\min/\max} = \xi_{2\,\min/\max}$)

Cannot simulate every $(\alpha/2, \beta^*)$ 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_{XRP}: hori. dispersion @ detector location,
parametrisation in $(\alpha/2, \xi)$ 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

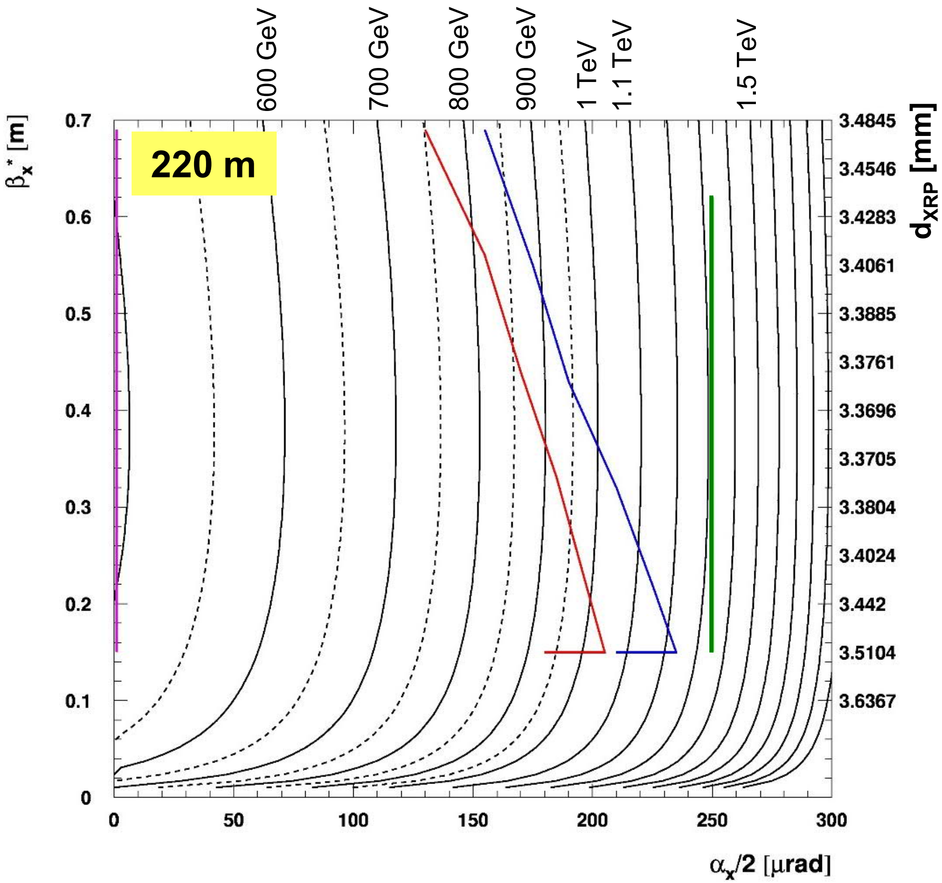
d_A: aperture limitation (hori. or vert.) upstream,
in most cases: TCLs

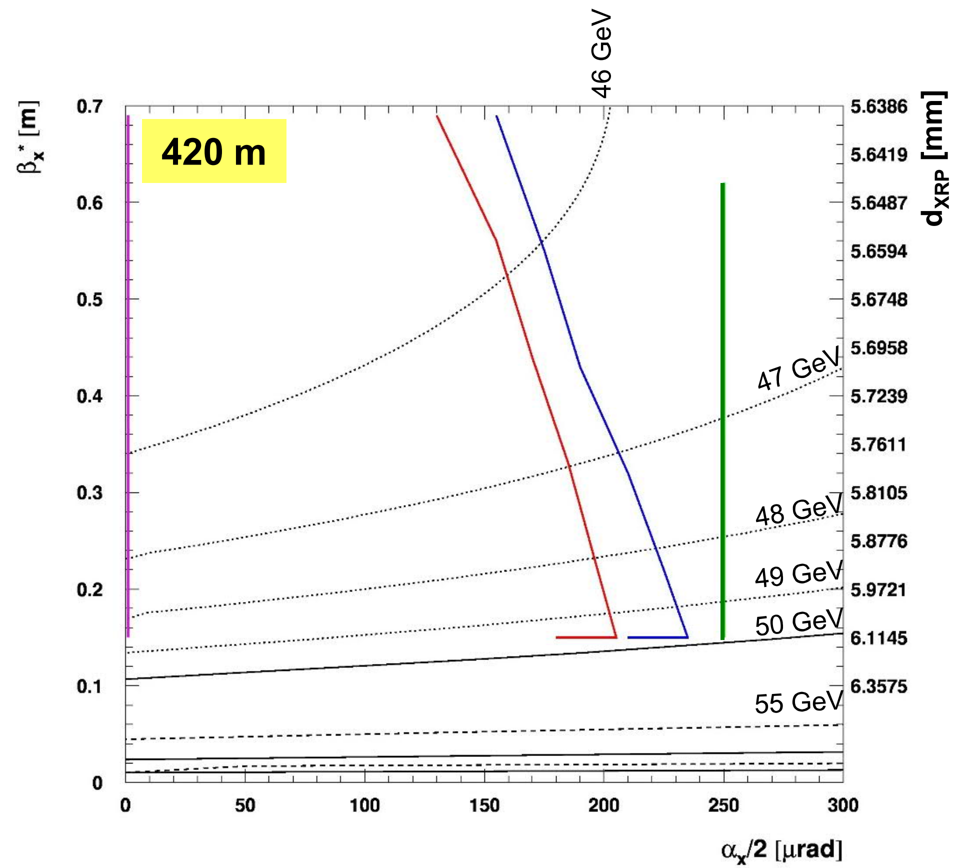
D_A: dispersion (hori. or vert.) @ aperture limit.,
parametrisation in $(\alpha/2, \xi)$ from MAD-X

Examples: Minimum "Mass" @ 220m and 420m

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

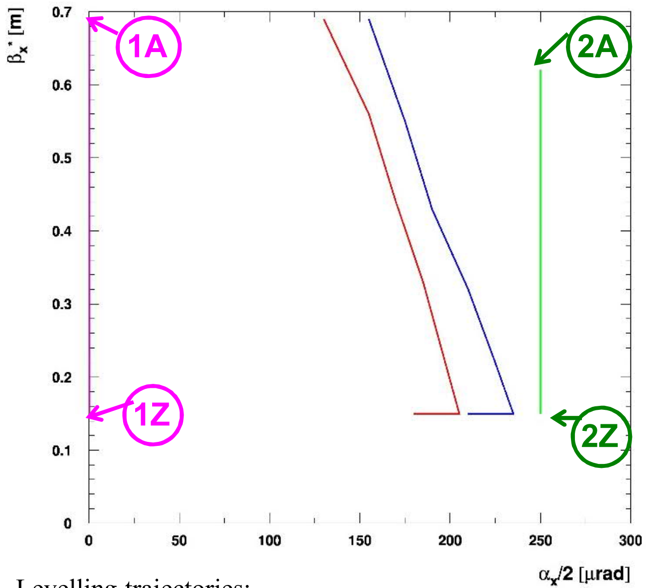
TCT settings: d_{TCT} = const. (12.9 σ @ β* = 15 cm)





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

Acceptance in the Mass – Rapidity Plane



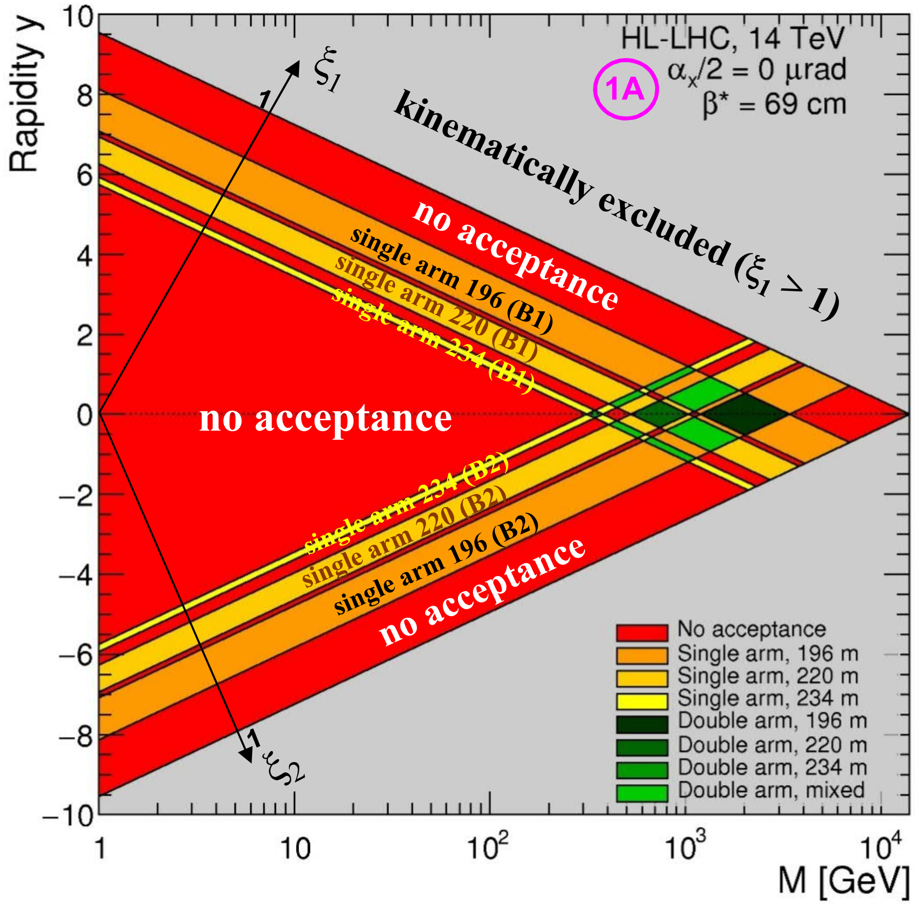
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

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):

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

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

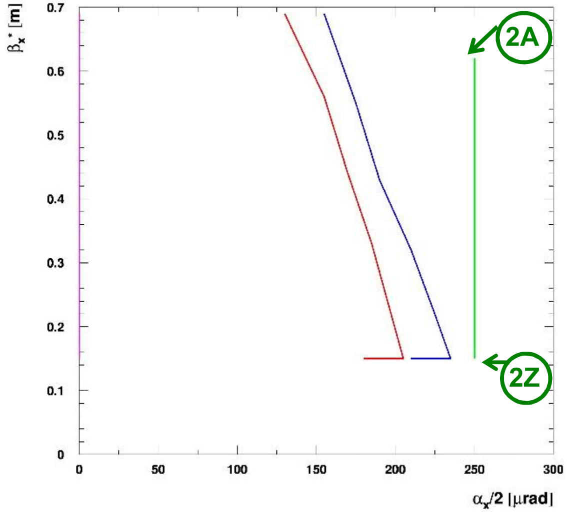


Note on t or p_T:

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

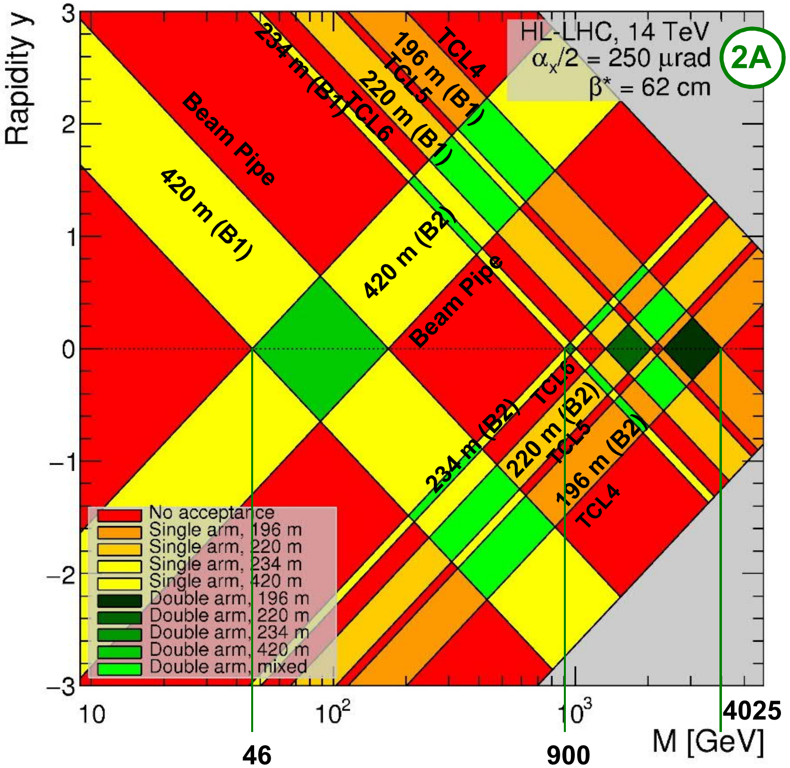
- Fixed non-zero $t_{1/2}$ would shift the contours:
  $\Delta\xi_{min} = -\frac{L_x \theta_x^*}{D_x}$ (dominated by angular vertex spread)
- Integration over process-dependent t-distribution would smear M_{min} by 2 – 3 GeV

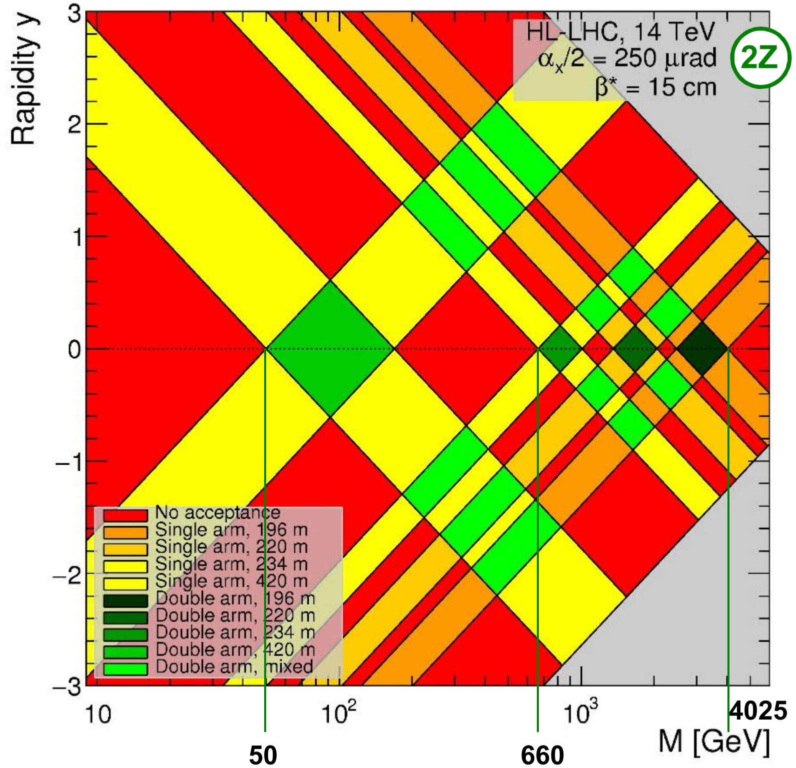
Acceptance in the Mass – Rapidity Plane: Horizontal Crossing, Baseline Trajectory



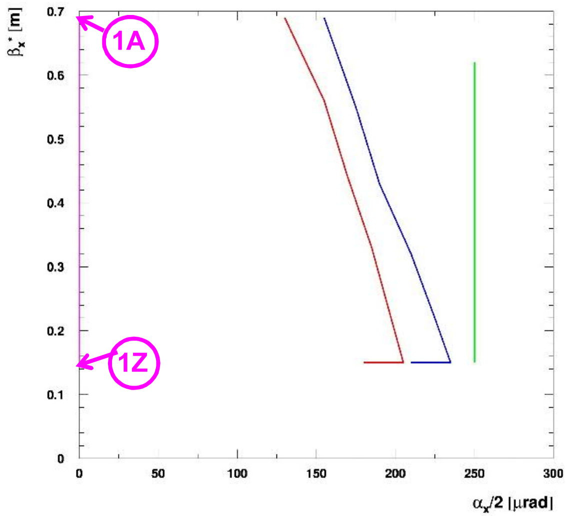
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

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





Acceptance in the Mass – Rapidity Plane: Vertical Crossing



Levelling trajectories:
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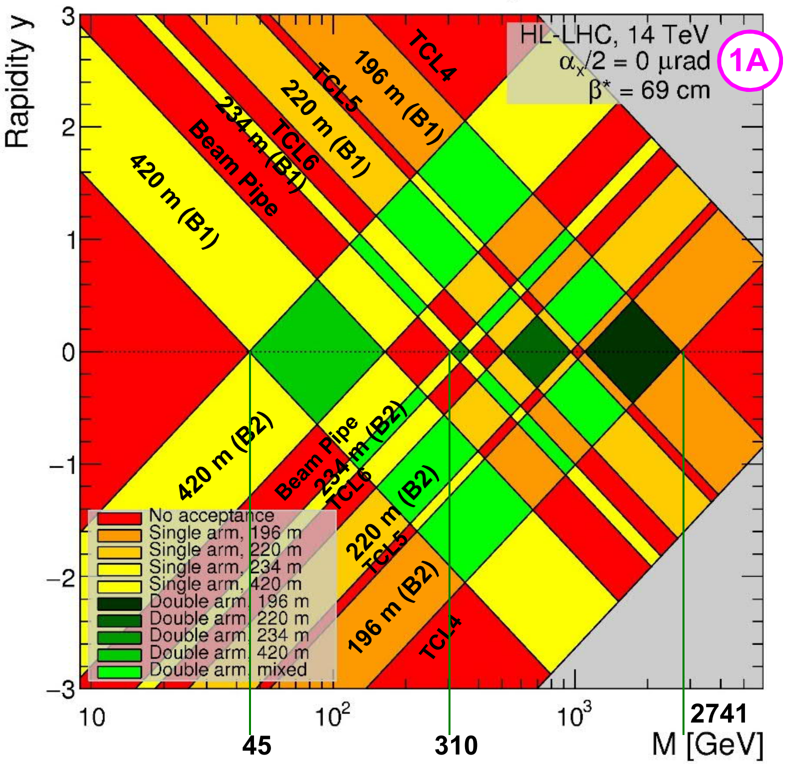
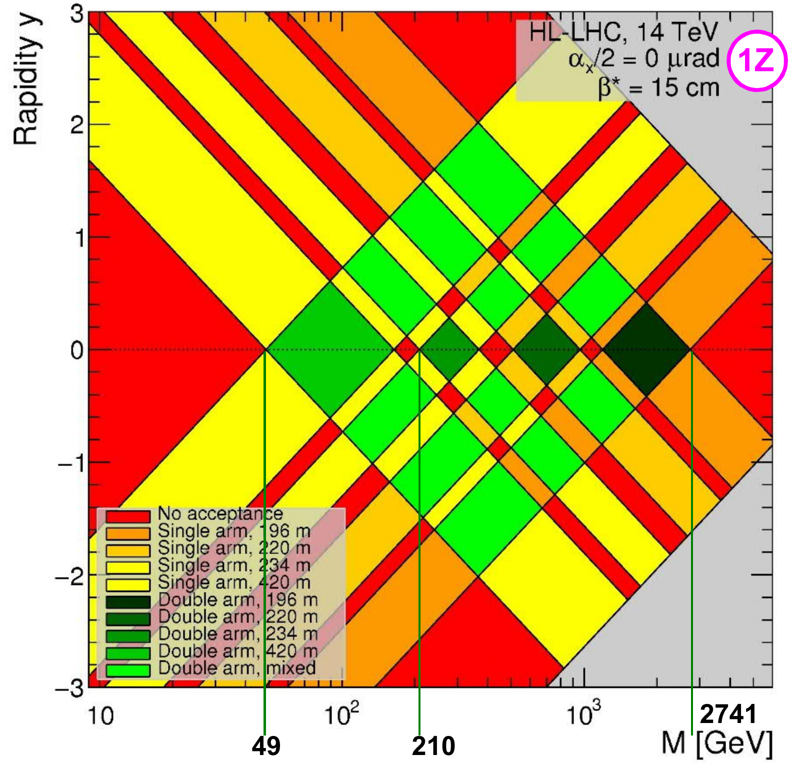
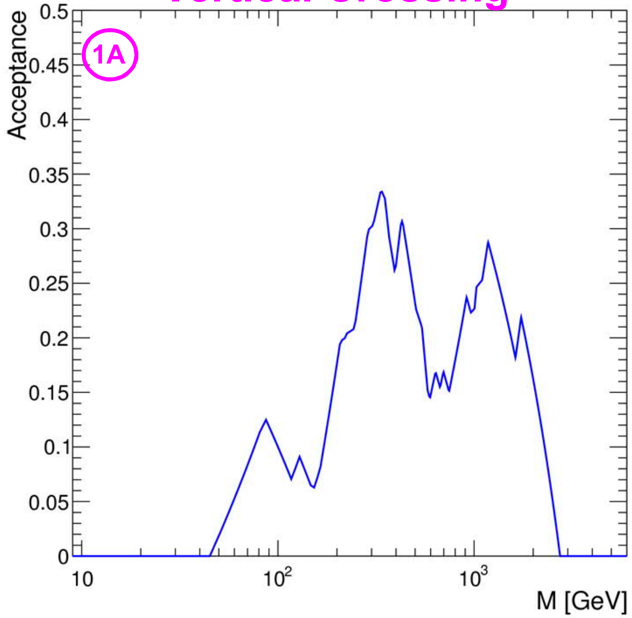
XRPs @ 196 m, 220 m, 234 m, 420 m

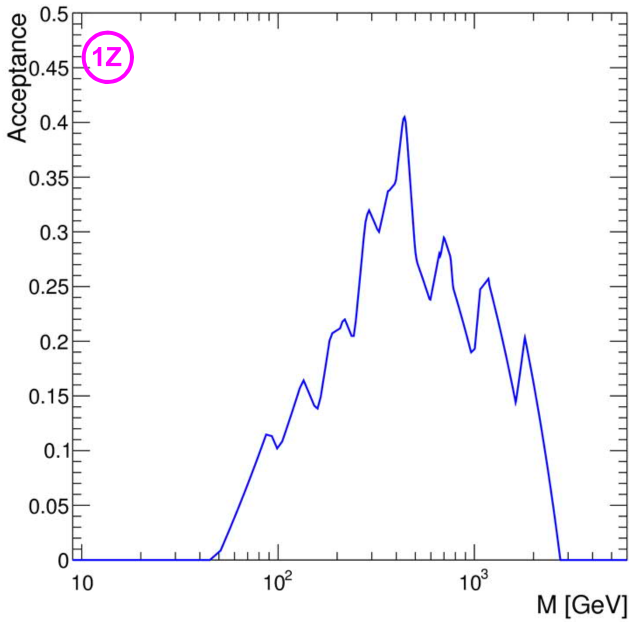




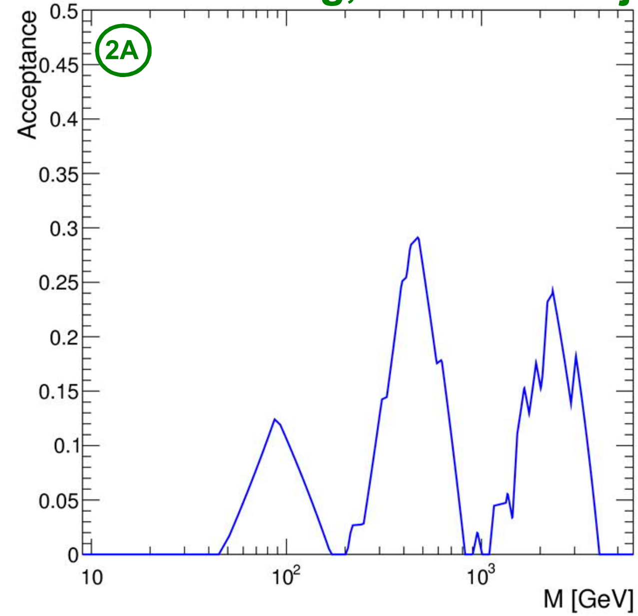
Mass Acceptance Integrated over y

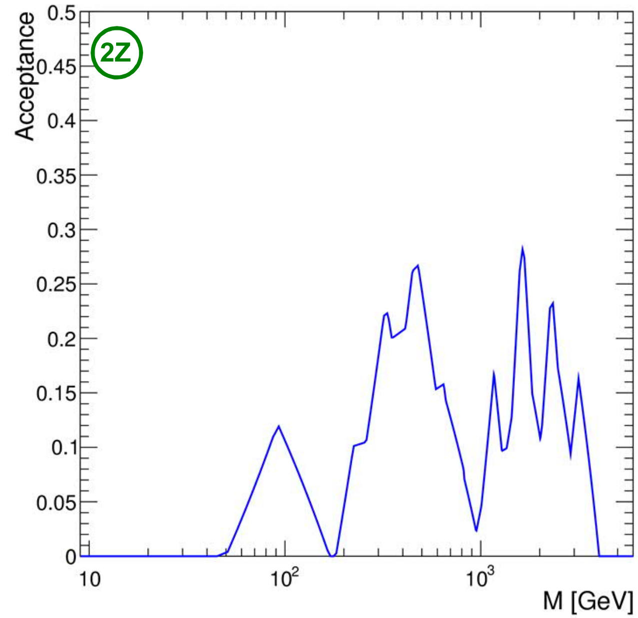
Vertical Crossing





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)

  → 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 $14.2\ \sigma_{15cm}$

- Many technical issues to be addressed !

The End.

Appendix

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

XRP Insertion Distance vs. β*

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

Collimation scheme presently foreseen:

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

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

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

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

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

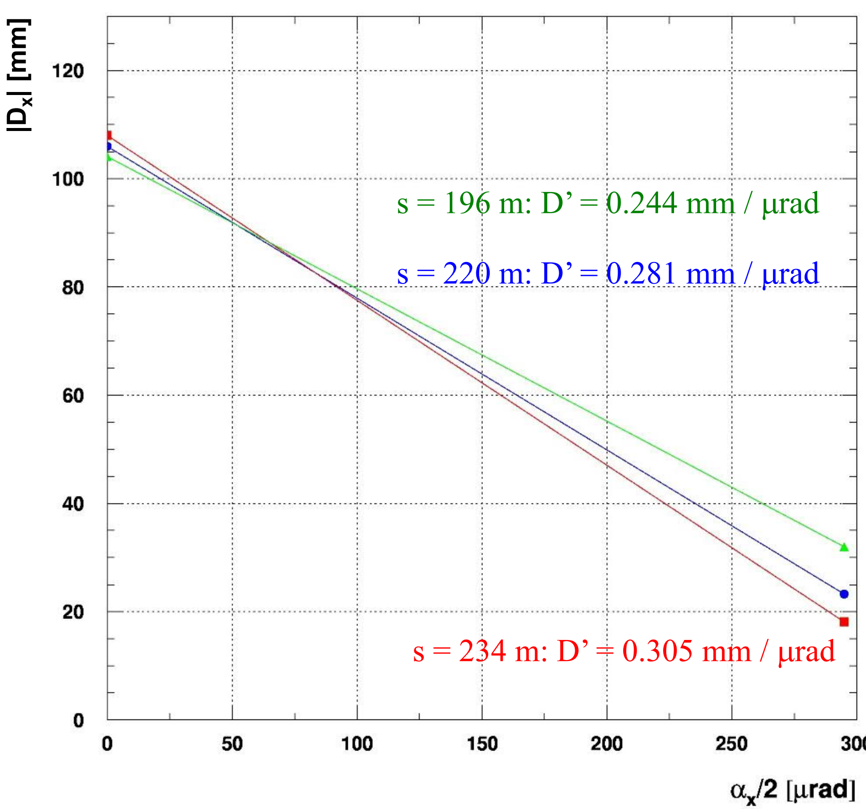
$$\sigma_{\mathrm{XRP}} = \sqrt{\frac{\varepsilon_n}{\gamma}\left(v^2_{\mathrm{XRP}}\beta^* + \frac{L^2_{\mathrm{XRP}}}{\beta^*}\right)}$$

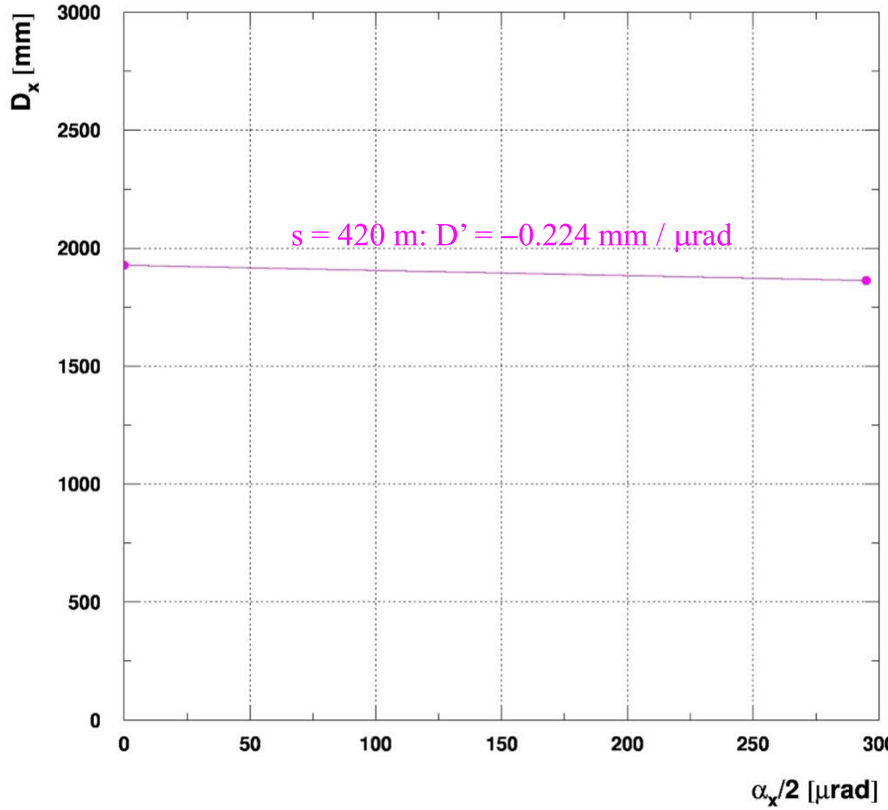
$$\boxed{d_{\mathrm{XRP}} = \left(n_{\mathrm{TCT}}(\beta^*_0)\sqrt{\frac{\beta^*}{\beta^*_0}} + 3\right)\sqrt{\frac{\varepsilon_n}{\gamma}\left(v^2_{\mathrm{XRP}}\beta^* + \frac{L^2_{\mathrm{XRP}}}{\beta^*}\right)} + 0.3\ \mathrm{mm}}$$

Dispersion vs. Crossing-Angle

MAD-X simulations:

- ($\alpha_x/2$, $\alpha_y/2$, β_x^*, β_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
- ($\alpha_x/2$, $\alpha_y/2$, β_x^*, β_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: $\boxed{D\left(\frac{\alpha}{2}\right) = D(0) + D'\frac{\alpha}{2}}$ (confirmed by 2017 data).

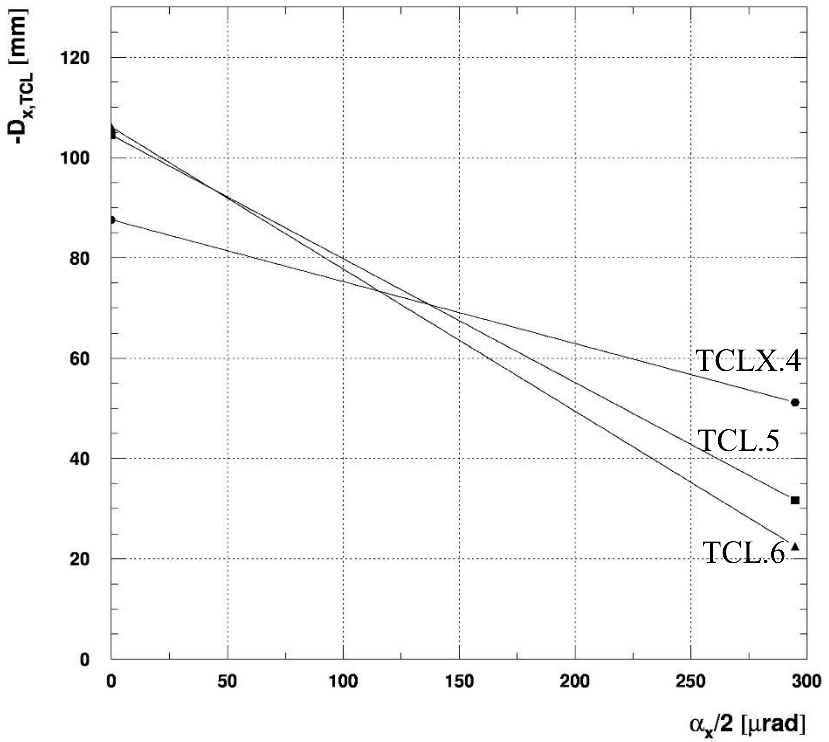
Maximum Mass: General Principle

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



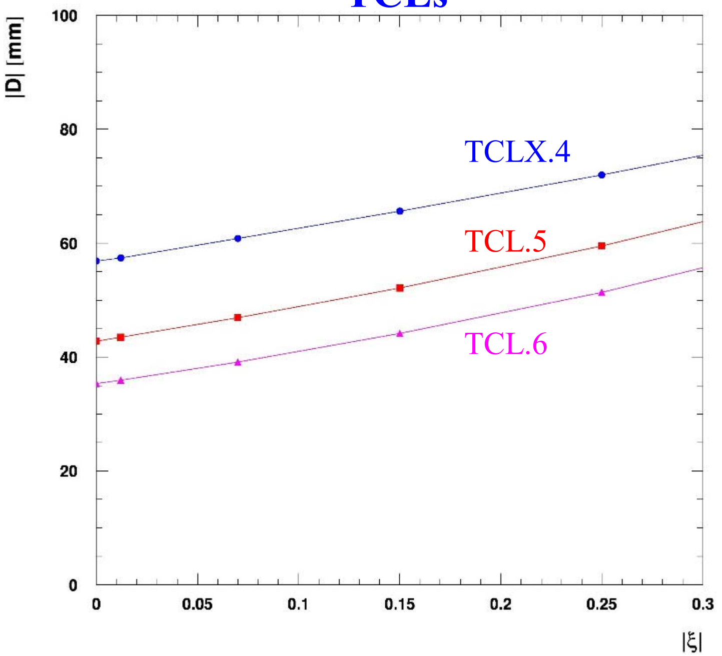
Collimation strategy for TCLs presently foreseen:

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

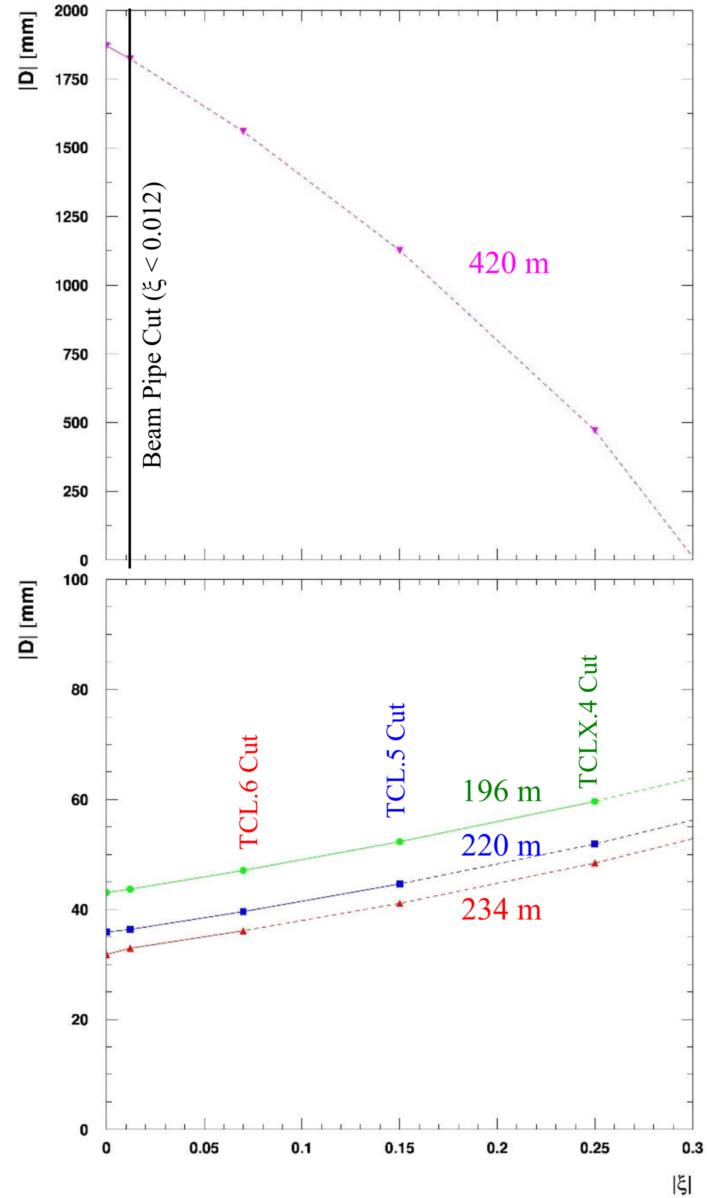
ξ-Dependence of the Dispersion: Horizontal Crossing

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

TCLs



XRPs



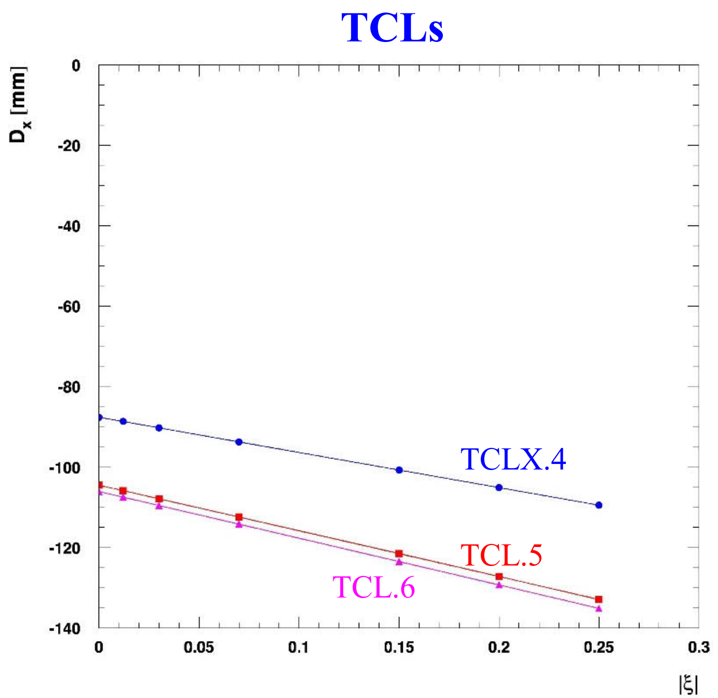
D @ TCLs increases with ξ
→ max. mass cut tighter than anticipated using D(ξ=0)

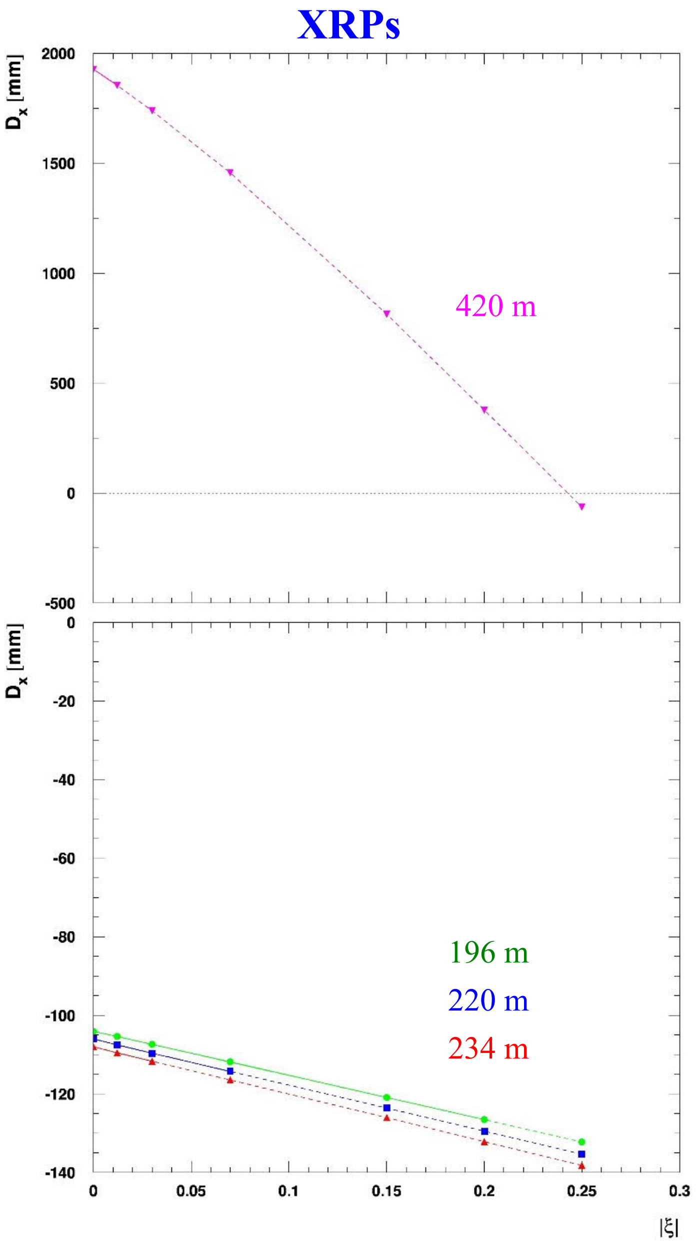
For small ξ (within acceptance): approximately linear
→ extended dispersion model:

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

ξ-Dependence of the Dispersion: Vertical Crossing

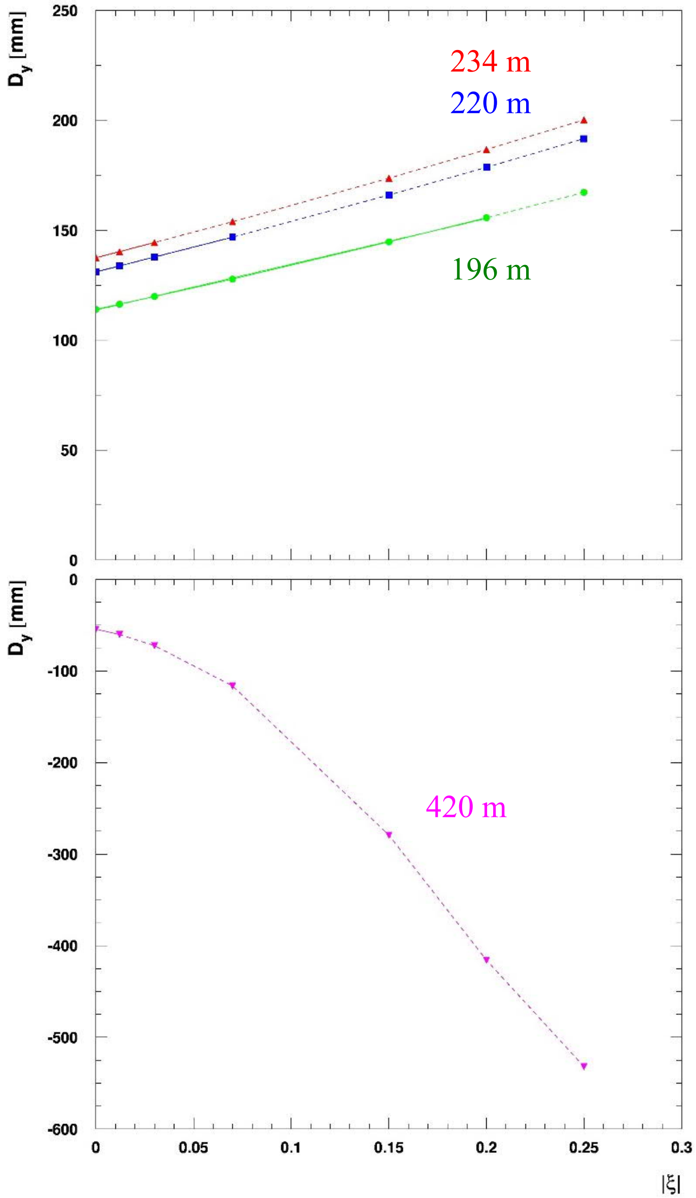
Baseline Trajectory ($\alpha_y/2 = 250\ \mu$rad) **Horizontal Dispersion**





ξ-Dependence of the Dispersion: Vertical Crossing

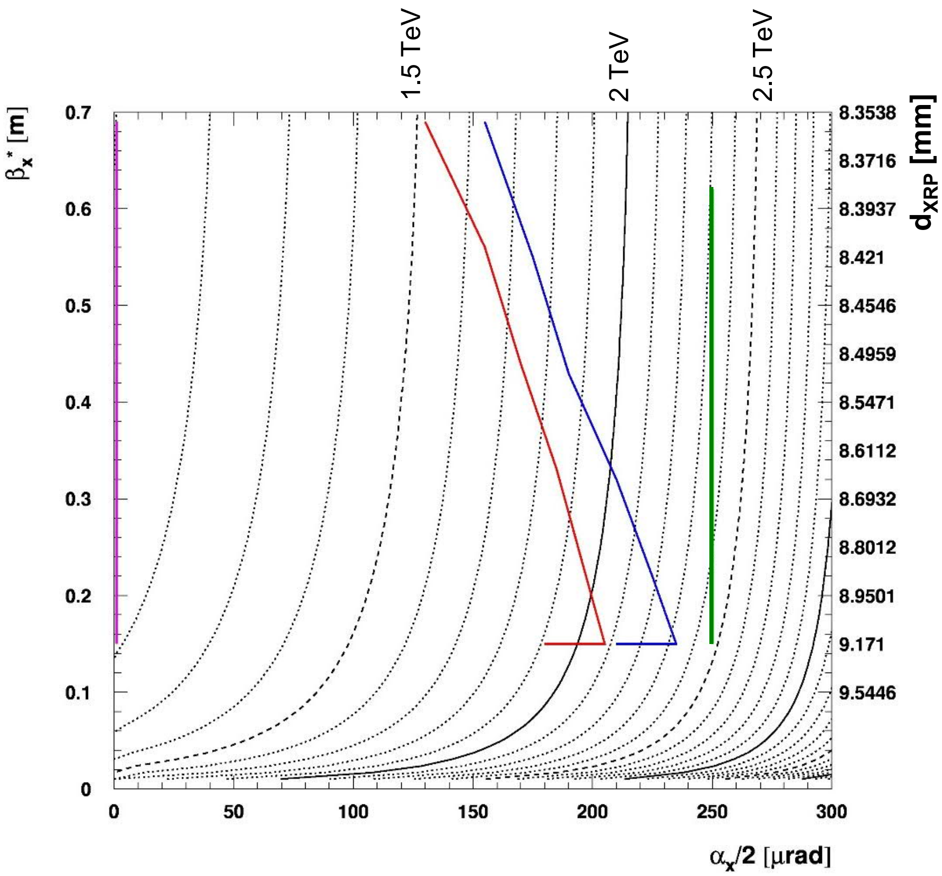
Baseline Trajectory ($\alpha_y/2 = 250\ \mu rad$) **Vertical Dispersion XRPs**



Minimum "Mass" @ 196 m with ξ-Dependent D

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

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



Insertion distances very moderate !

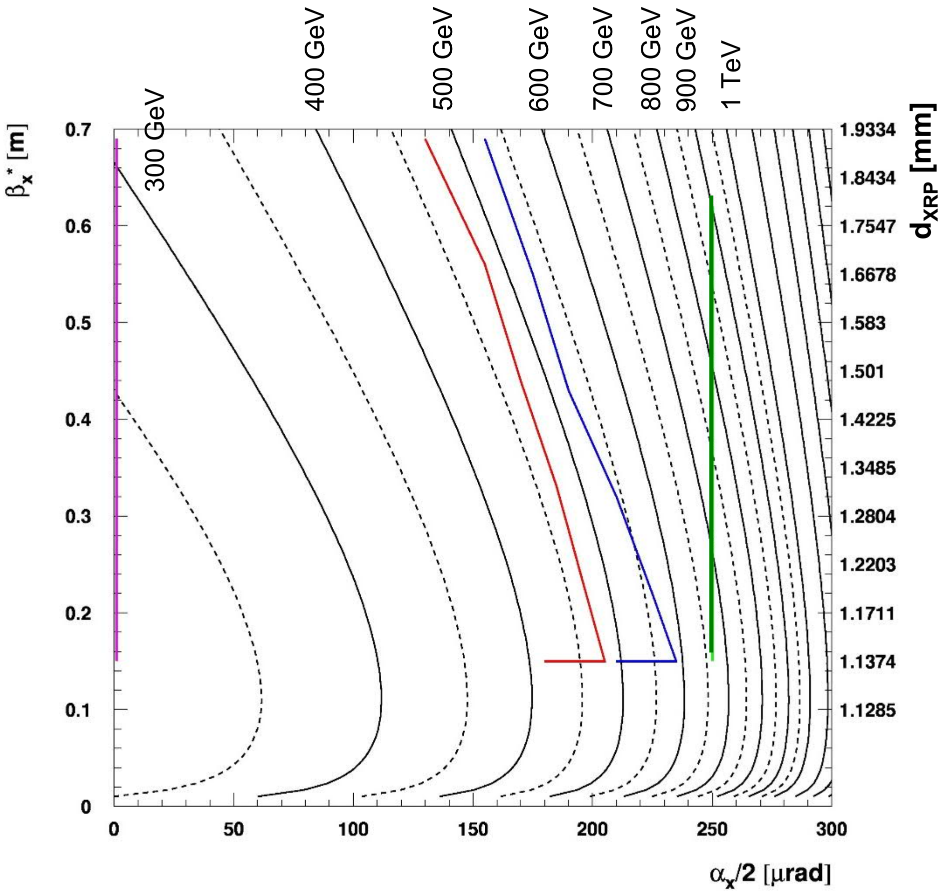
Levelling trajectories:
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

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 $\tilde{M}_{\min} = \xi_{\min}\sqrt{s}$ with $\xi_{\min} = \dfrac{d_{XRP}(\beta^*)+\delta}{D_x(\frac{\alpha}{2},\xi_{\min})}$ 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:

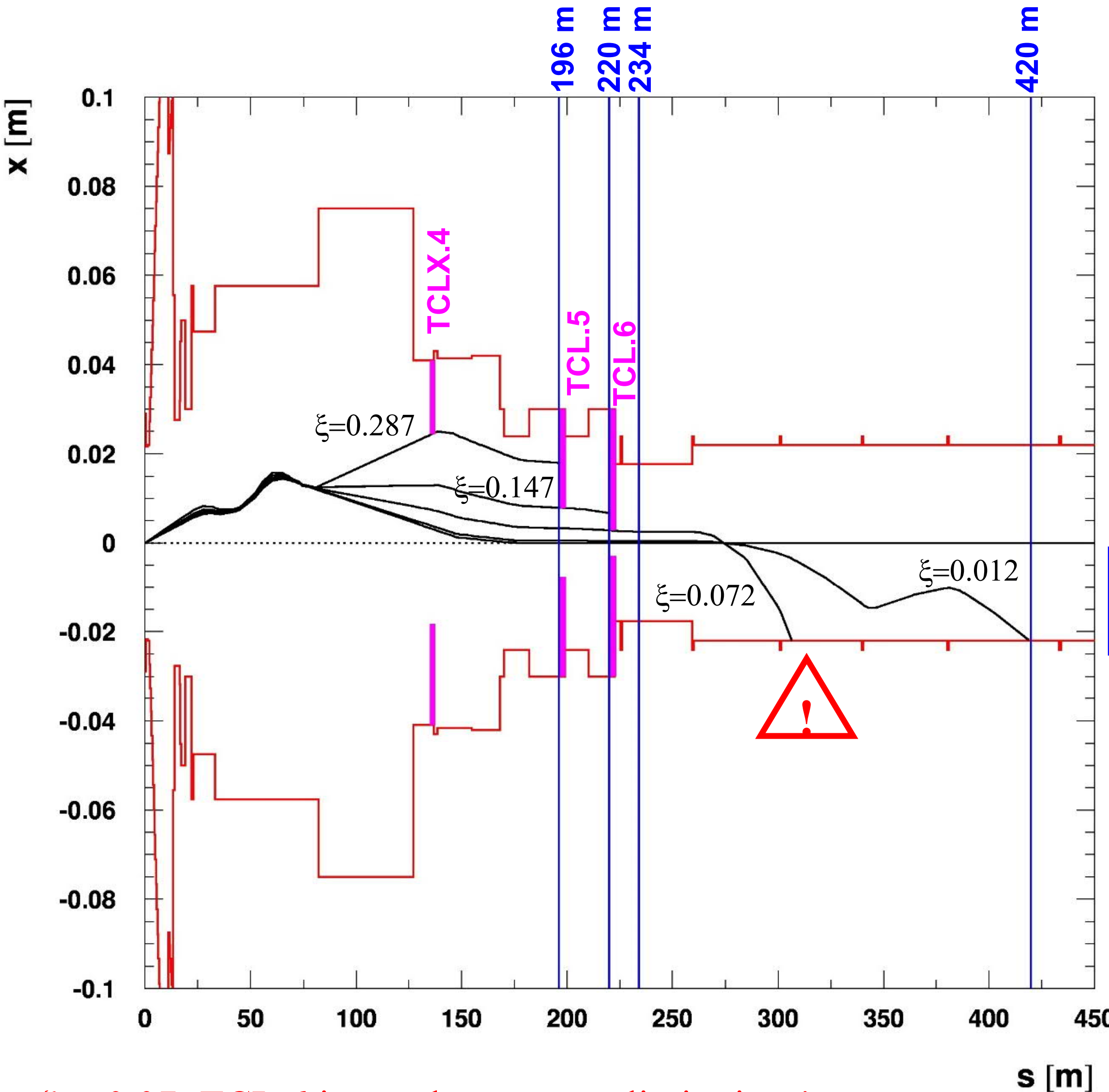
- Baseline
- Relaxed adaptive
- Aggressive adaptive
- Vertical crossing (any trajectory)

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

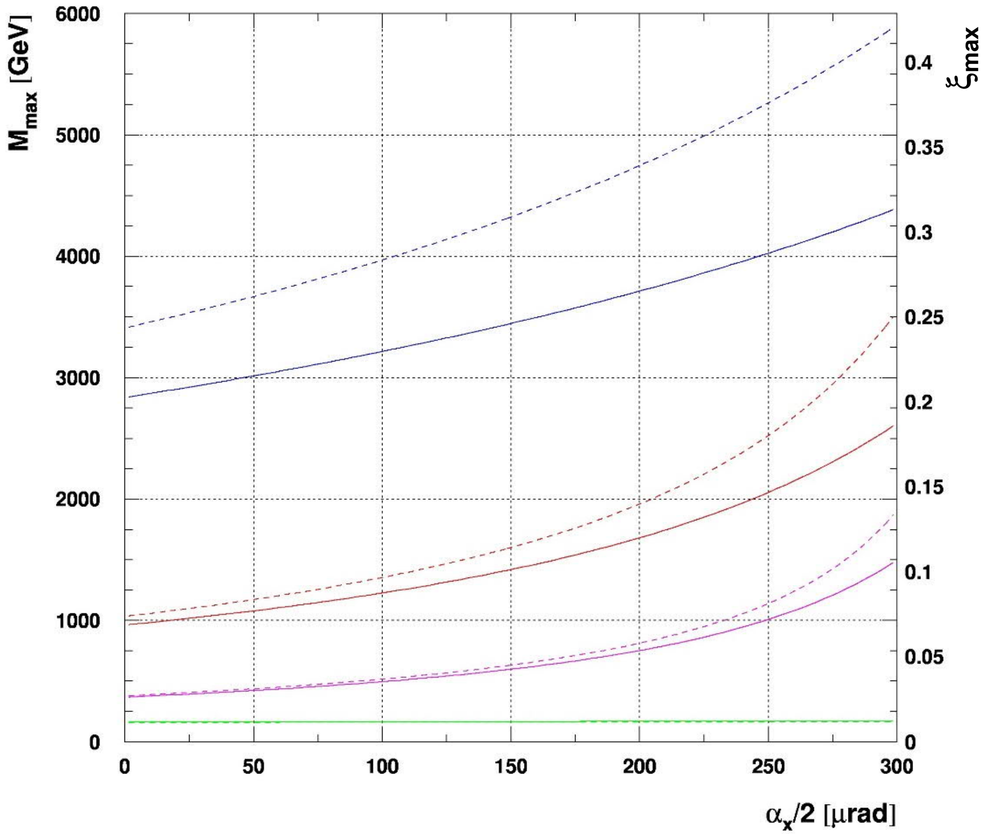
For s > 306 m or ξ < 0.07: TCL.6 is not the aperture limitation !
Protons run into the beampipe.

Maximum Mass: Horizontal Crossing

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

→ quadratic equation for ξ_{max}

dashed: naive calculation with ξ-independent D



TCLX.4 determines M_{max} at 196 m

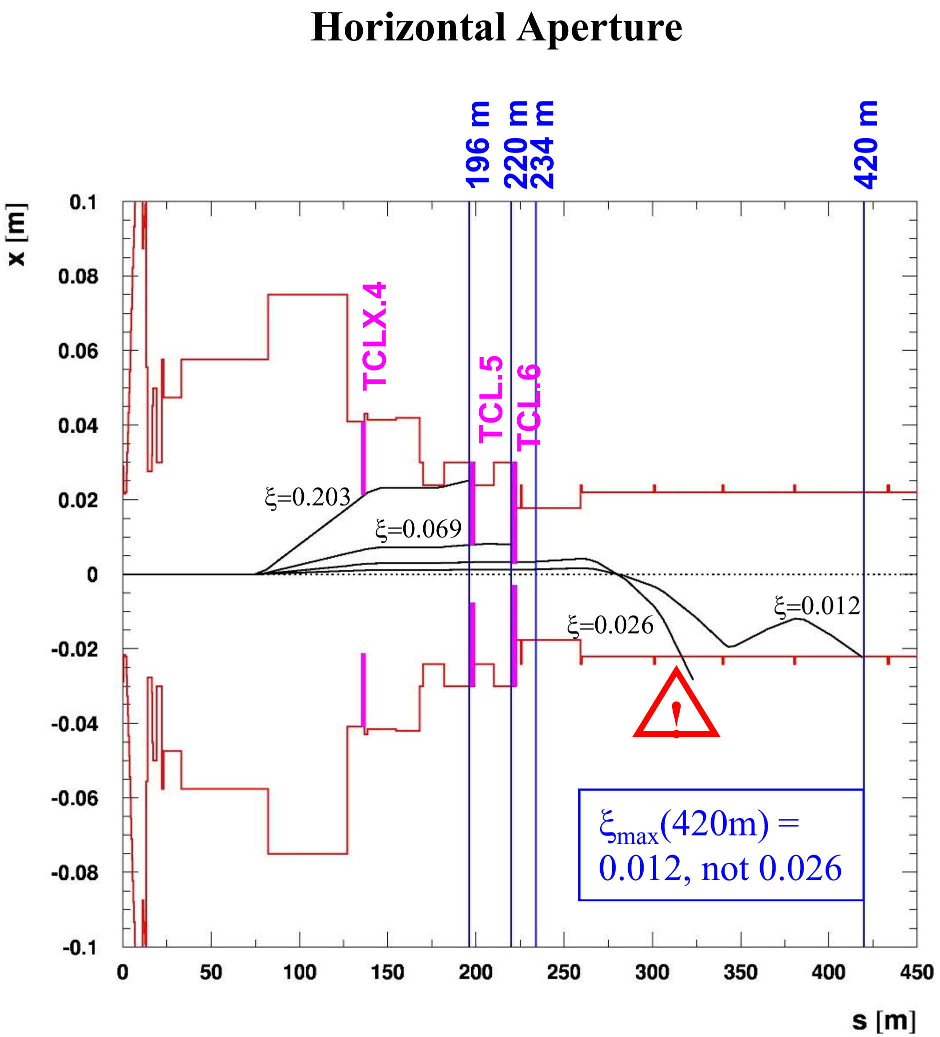
TCL.5 determines M_{max} at 220 m

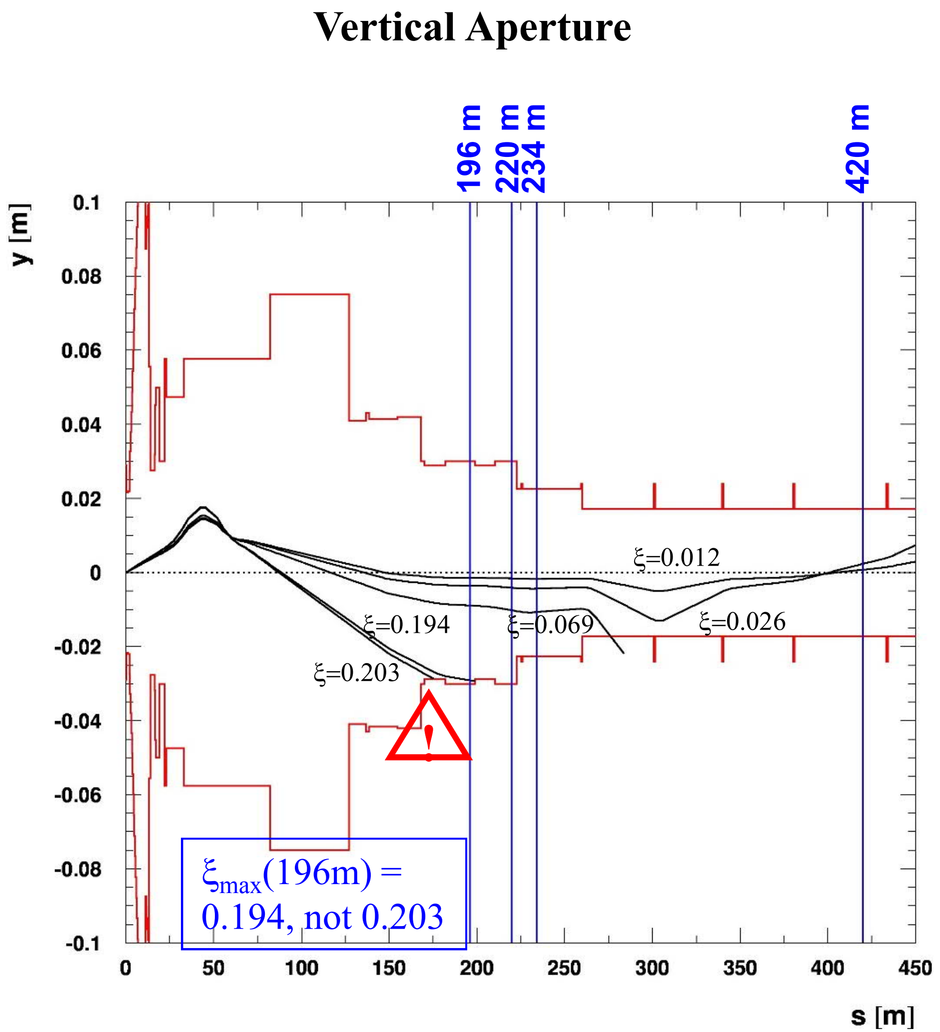
TCL.6 determines M_{max} at 234 m

Beam pipe aperture determines M_{max} at 420 m

Aperture Study: Vertical Crossing

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

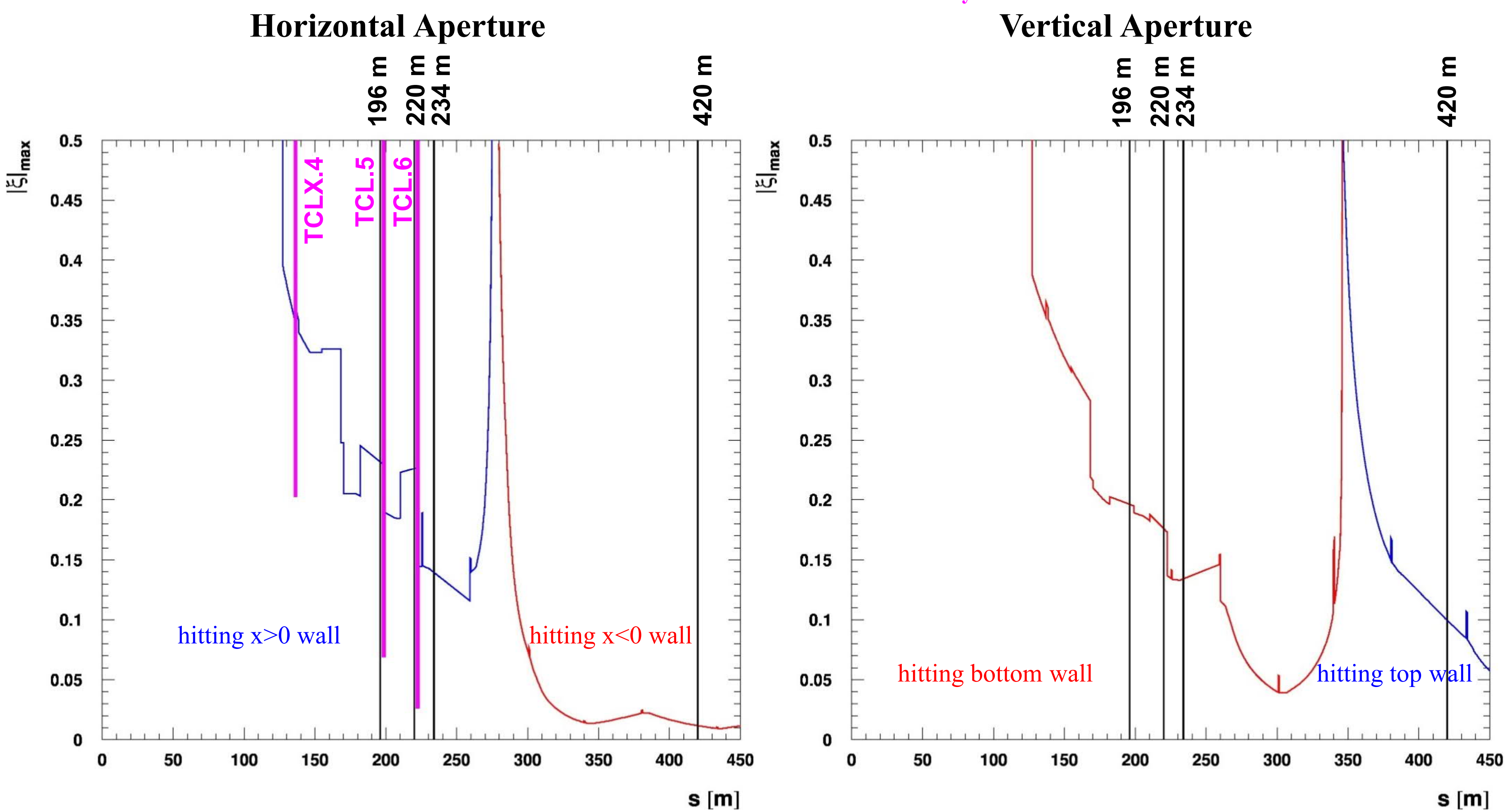




For s > 315 m or ξ < 0.026: TCL.6 is not the aperture limitation !
Protons run into the beampipe.

Maximum ξ from Aperture: Vertical Crossing

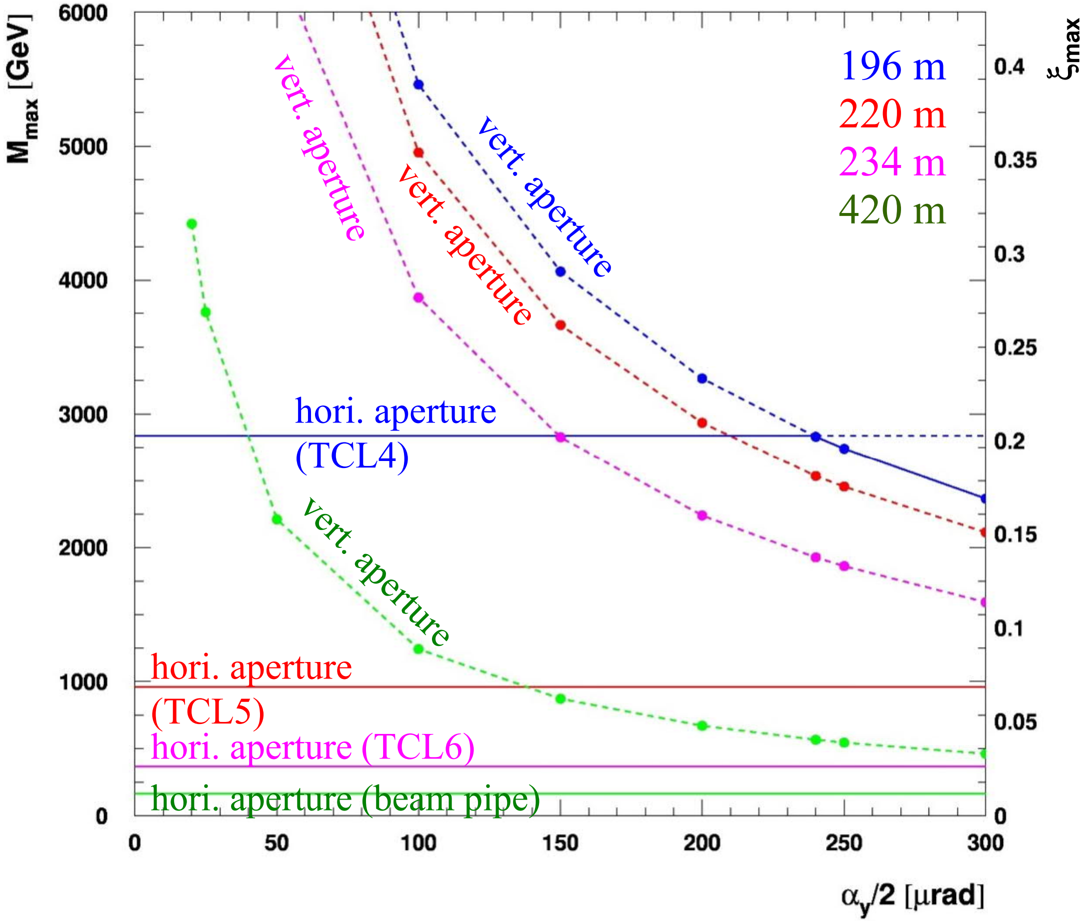
Baseline Levelling Trajectory ($\alpha_y/2 = 250\ \mu$rad)



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

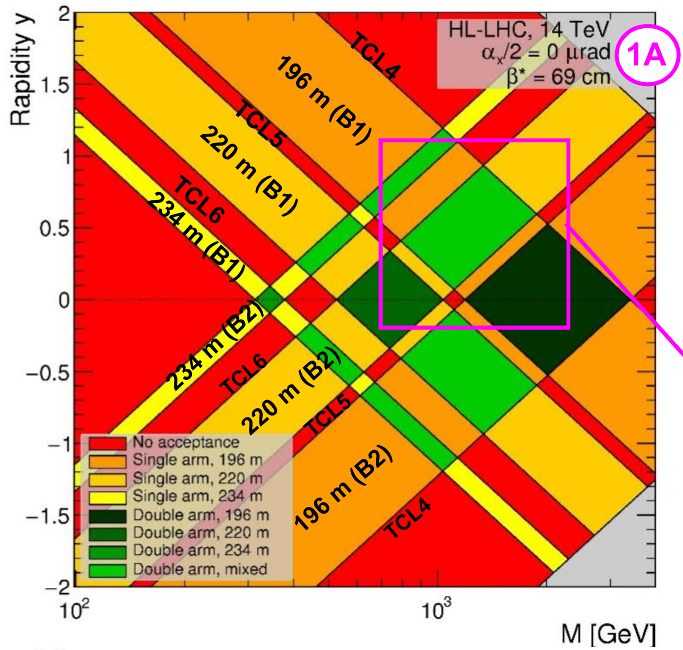
horizontal aperture determines M_{max} at 220 m

horizontal aperture determines M_{max} at 234 m

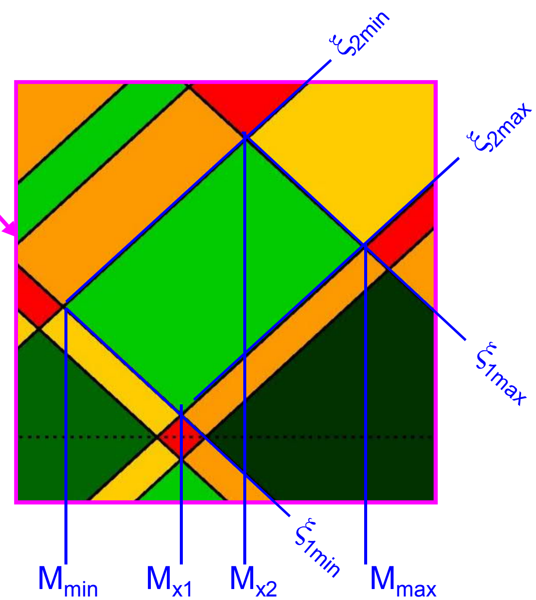
horizontal aperture determines M_{max} at 420 m

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

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**:



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

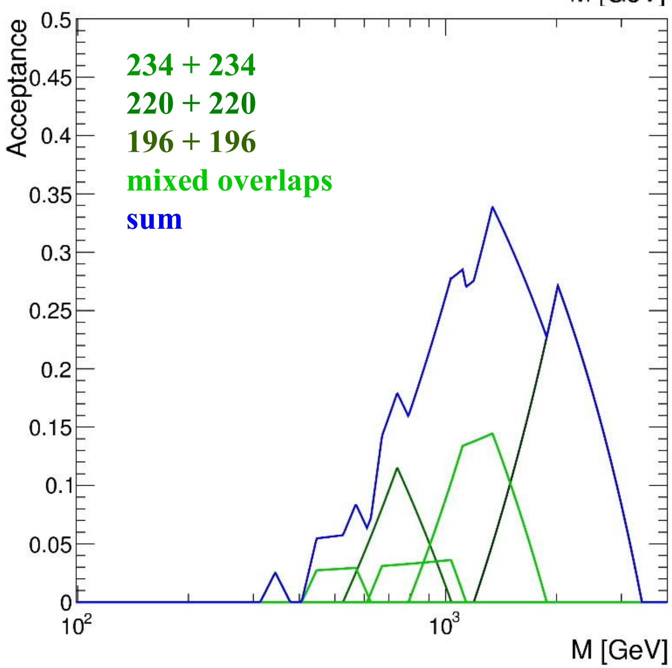
where

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

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

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

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



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