High Luminosity LHC

Update on tracking simulations for HL-LHC

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Introduction

- History of tracking activities
  - Layout: SLHCV3.1b
    - Collision
    - Injection
  - Layout: HLLHCV1.0
    - Collision
    - Injection

Time line

NB: expected FQ tables evolved with time during the studies

All FQ tables are stored under afs:

- **/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors**
- **/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors**

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Field quality specifications for IT quadrupoles at collision energy (r_0 = 50 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	0.800	0.550	0.550
a7	0	0.152	0.095		b7	0	0.095	0.095
a8	0	0.088	0.055		b8	0	0.065	0.065
a9	0	0.064	0.040		b9	0	0.035	0.035
a10	0	0.040	0.032		b10	0.075	0.100	0.100
a11	0	0.026	0.0208		b11	0	0.0208	0.0208
a12	0	0.014	0.014		b12	0	0.0144	0.0144
a13	0	0.010	0.010		b13	0	0.0072	0.0072
a14	0	0.005	0.005		b14	-0.020	0.0115	0.0115

$$B_y + iB_x = 10^{-4} B_{ref} \times \sum_{n=1}^{\infty} (b_n + ia_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

Red values represent requests from WP2

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Field quality specifications for D1 separation dipoles at collision energy (r_0 = 50 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	0	0.200	0.200
a3	0	0.282	0.282		b3	-0.900	0.727	0.727
a4	0	0.444	0.444		b4	0	0.126	0.126
a5	0	0.152	0.152		b5	0	0.365	0.365
a6	0	0.176	0.176		b6	0	0.060	0.060
a7	0	0.057	0.057		b7	0.4→0.2	0.165	0.165
a8	0	0.061	0.061		b8	0	0.027	0.027
a9	0	0.020	0.020		b9	-0.59→-0.295	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0.470	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	-0.040	0.002	0.002

Red values represent requests from WP2

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Field quality specifications for D2 separation dipoles at collision energy (r_0 = 35 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	±25→~1*	2.5→~1*	2.5→~1*
a3	0	0.282	0.282		b3	3.0→1.5	1.5	1.5
a4	0	0.444	0.444		b4	±2.0	0.2	0.2
a5	0	0.152	0.152		b5	-1.0	0.5	0.5
a6	0	0.176	0.176		b6	0	0.060	0.060
a7	0	0.057	0.057		b7	-0.200	0.165	0.165
a8	0	0.061	0.061		b8	0	0.027	0.027
a9	0	0.020	0.020		b9	0.090	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0.030	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	0	0.002	0.002

This is an initial very optimistic FQ

Red values represent requests from WP2

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Field quality specifications for Q4 matching quadrupoles at collision energy (r_0 = 30 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.682	1.227		b3	0	1.282	1.500
a4	0	0.428	0.893		b4	0	0.483	0.465
a5	0	0.177	0.406		b5	0	0.203	0.431
a6	0	0.484	0.277		b6	0	5.187	1.487
a7	0	0.094	0.189		b7	0	0.094	0.189
a8	0	0.193	0.257		b8	0	0.193	0.257
a9	0	0.088	0.088		b9	0	0.088	0.088
a10	0	0.120	0.120		b10	0	3.587	0.956
a11	0	0.326	0.489		b11	0	0.326	0.489
a12	0	0.445	0.222		b12	0	0.445	0.222
a13	0	0.606	0.303		b13	0	0.606	0.303
a14	0	0.827	0.413		b14	0	2.067	0.413
a15	0	1.127	0.564		b15	0	1.127	0.564

Red values represent requests from WP2

Field quality specifications for Q5 matching quadrupoles at collision energy (r_0 = 17 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.500	0.900		b3	0	0.940	1.100
a4	0	0.230	0.480		b4	0	0.260	0.250
a5	0	0.070	0.160		b5	0	0.080	0.170
a6	0	0.140	0.080		b6	0	1.500	0.430
a7	0	0.020	0.040		b7	0	0.020	0.040
a8	0	0.030	0.040		b8	0	0.030	0.040
a9	0	0.010	0.010		b9	0	0.010	0.010
a10	0	0.010	0.010		b10	0	0.300	0.080
a11	0	0.020	0.030		b11	0	0.020	0.030
a12	0	0.020	0.010		b12	0	0.020	0.010
a13	0	0.020	0.010		b13	0	0.020	0.010
a14	0	0.020	0.010		b14	0	0.050	0.010
a15	0	0.020	0.010		b15	0	0.020	0.010

Red values represent requests from WP2

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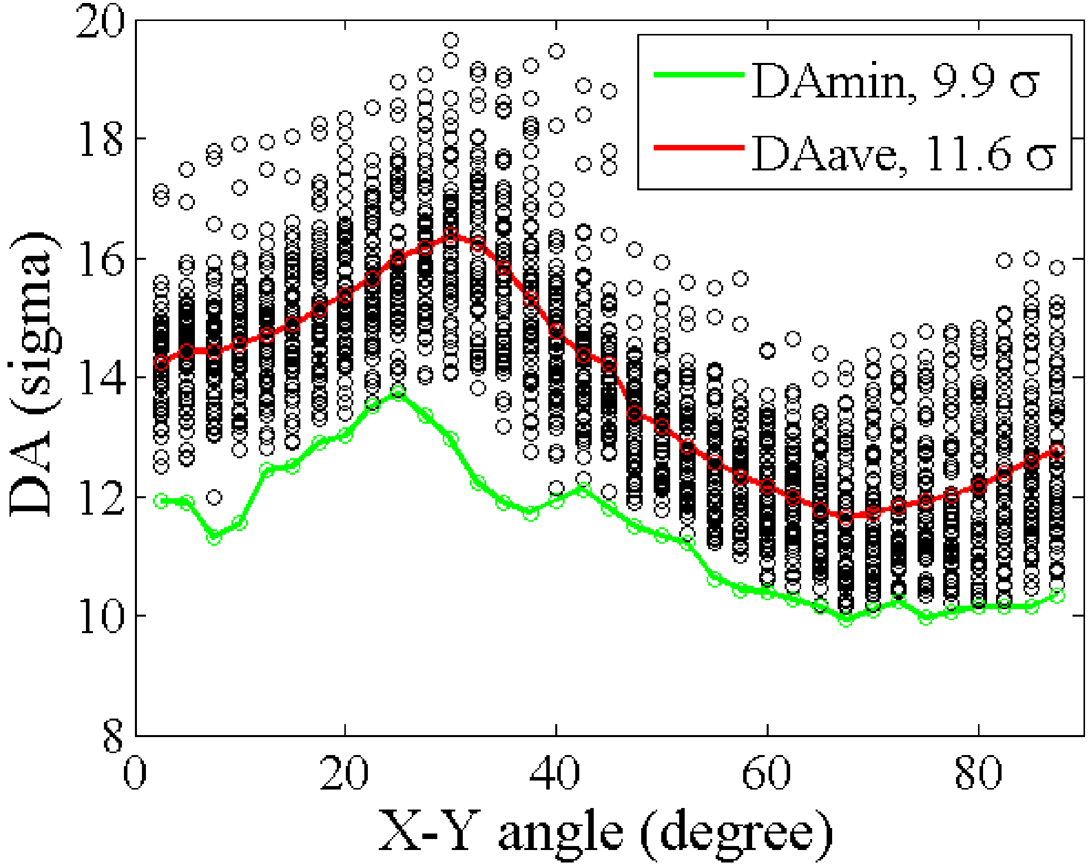
Dynamic aperture at collision energy

The simulation is performed for the SLHCV3.1b collision optics with β*=15 cm at E=7 TeV. It includes arc errors and corrections, the new specification errors for the IT, D1, D2, Q4, Q5 magnets, feed-down effect in the D1, D2 dipoles, and IT non-linear field correctors of order n = 3 to 6.

The minimum DA for 60 random seeds and 35 x-y angles is 9.9σ.



Impact of single magnet families are reported in IPAC13 paper.

Field quality specifications for IT quadrupoles at injection energy (r_0 = 50 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	-16.0	1.100	1.100
a7	0	0.190	0.190		b7	0	0.190	0.190
a8	0	0.110	0.110		b8	0	0.130	0.130
a9	0	0.080	0.080		b9	0	0.070	0.070
a10	0	0.040	0.040		b10	4.15	0.200	0.200
a11	0	0.026	0.026		b11	0	0.026	0.026
a12	0	0.014	0.014		b12	0	0.018	0.018
a13	0	0.010	0.010		b13	0	0.009	0.009
a14	0	0.005	0.005		b14	-0.040	0.023	0.023

Red values represent requests from WP2

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Field quality specifications for D1 separation dipoles at injection energy (r_0 = 50 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	0	0.200	0.200
a3	0	0.282	0.282		b3	-16.0	0.727	0.727
a4	0	0.444	0.444		b4	0	0.126	0.126
a5	0	0.152	0.152		b5	-0.500	0.365	0.365
a6	0	0.176	0.176		b6	0	0.060	0.060
a7	0	0.057	0.057		b7	0.900	0.165	0.165
a8	0	0.061	0.061		b8	0	0.027	0.027
a9	0	0.020	0.020		b9	-0.660	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0.440	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	-0.040	0.002	0.002

Red values represent requests from WP2

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Field quality specifications for D2 separation dipoles at injection energy (r_0 = 35 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	0	0.200	0.200
a3	0	0.282	0.282		b3	3.8	0.727	0.727
a4	0	0.444	0.444		b4	±8.0	0.126	0.126
a5	0	0.152	0.152		b5	3.0	0.365	0.365
a6	0	0.176	0.176		b6	0	0.060	0.060
a7	0	0.057	0.057		b7	0.100	0.165	0.165
a8	0	0.061	0.061		b8	0	0.027	0.027
a9	0	0.020	0.020		b9	0.020	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	0	0.002	0.002

Red values represent requests from WP2

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Field quality specifications for Q4 matching quadrupoles at injection energy (r_0 = 30 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.682	1.227		b3	0	1.282	1.500
a4	0	0.428	0.893		b4	0	0.483	0.465
a5	0	0.177	0.406		b5	0	0.203	0.431
a6	0	0.484	0.277		b6	-10.373	10.373	2.974
a7	0	0.094	0.189		b7	0	0.094	0.189
a8	0	0.193	0.257		b8	0	0.193	0.257
a9	0	0.088	0.088		b9	0	0.088	0.088
a10	0	0.120	0.120		b10	0	3.587	0.956
a11	0	0.326	0.489		b11	0	0.326	0.489
a12	0	0.445	0.222		b12	0	0.445	0.222
a13	0	0.606	0.303		b13	0	0.606	0.303
a14	0	0.827	0.413		b14	0	2.067	0.413
a15	0	1.127	0.564		b15	0	1.127	0.564

Red values represent requests from WP2

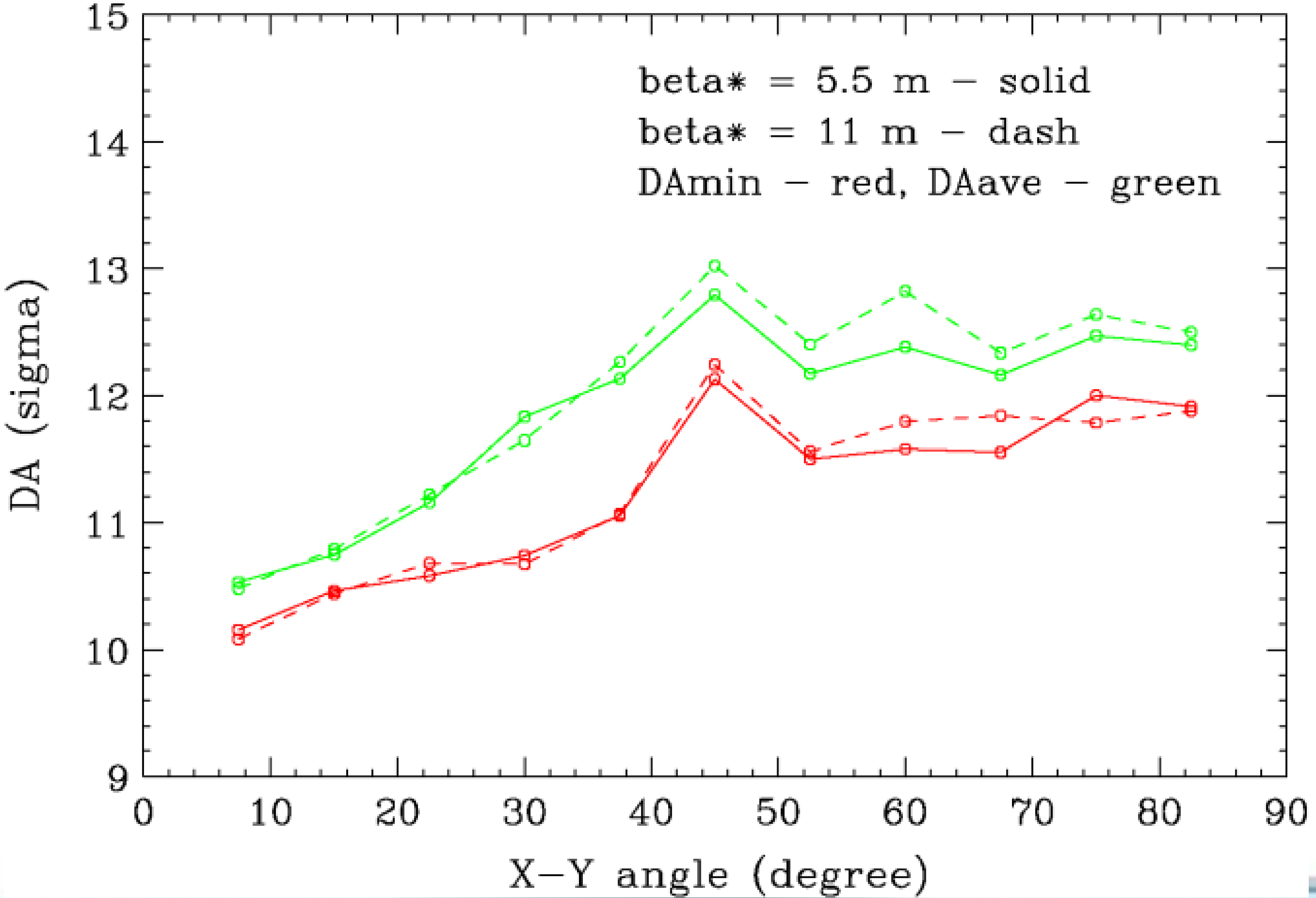
Field quality specifications for Q5 matching quadrupoles at injection energy (r_0 = 17 mm)

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.500	0.900		b3	0	0.940	1.100
a4	0	0.230	0.480		b4	0	0.260	0.250
a5	0	0.070	0.160		b5	0	0.080	0.170
a6	0	0.140	0.080		b6	-3.000	3.000	0.860
a7	0	0.020	0.040		b7	0	0.020	0.040
a8	0	0.030	0.040		b8	0	0.030	0.040
a9	0	0.010	0.010		b9	0	0.010	0.010
a10	0	0.010	0.010		b10	0	0.300	0.080
a11	0	0.020	0.030		b11	0	0.020	0.030
a12	0	0.020	0.010		b12	0	0.020	0.010
a13	0	0.020	0.010		b13	0	0.020	0.010
a14	0	0.020	0.010		b14	0	0.050	0.010
a15	0	0.020	0.010		b15	0	0.020	0.010

Red values represent requests from WP2

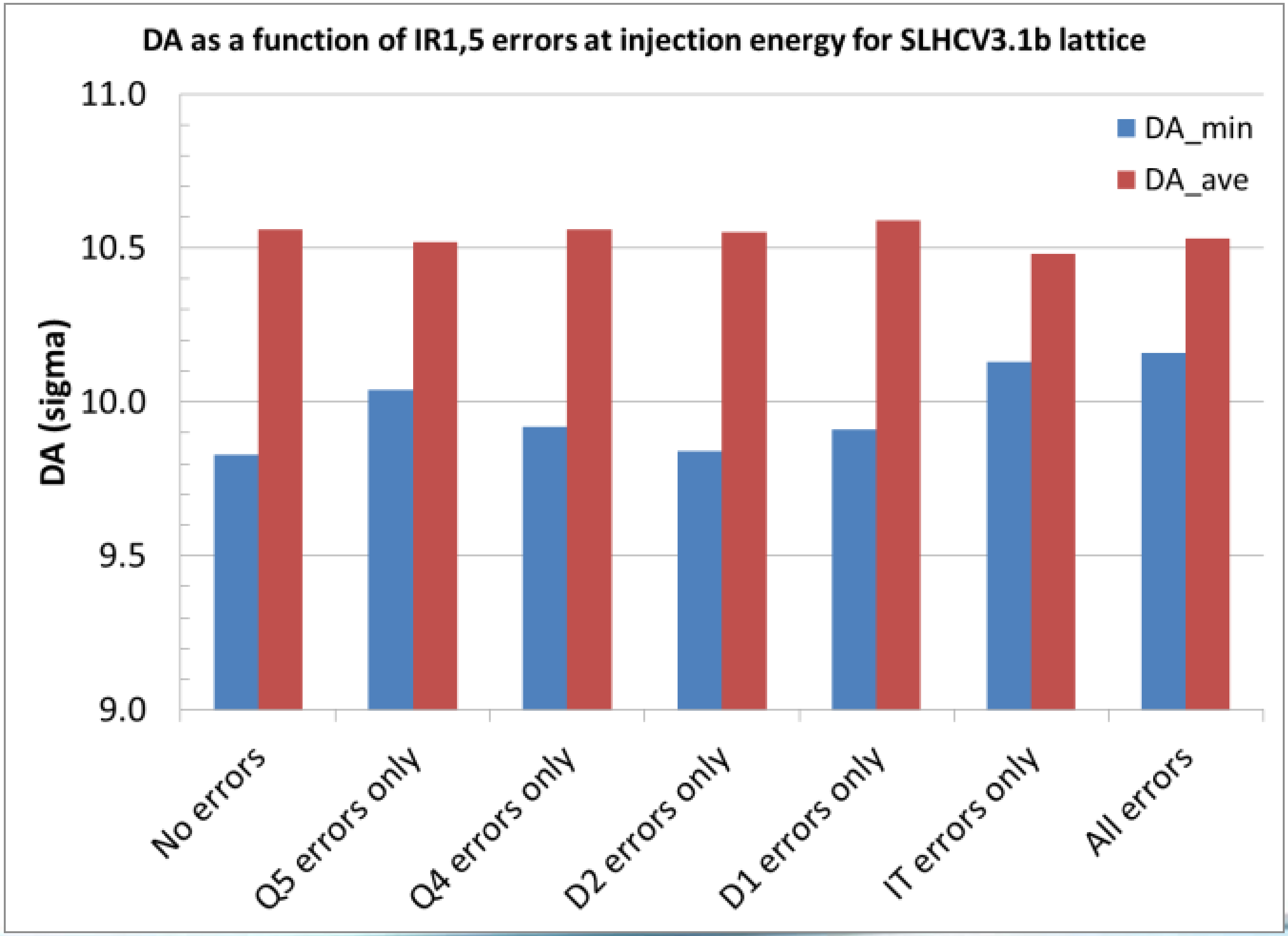
Dynamic aperture at injection energy

The simulation is performed for the SLHCV3.1b injection optics at E=450 GeV.
It includes arc errors and corrections, the specification errors for the IT, D1, D2, Q4, Q5 magnets, and feed-down effect in the D1, D2 dipoles.
The minimum DA for 60 random seeds and 11 x-y angles is 10.2σ.



DA sensitivity to IR magnet errors in SLHCV3.1b lattice at injection energy

Arc errors and standard corrections are always included. Injection lattice with β^* = 5.5 m at IP1,5.
DA is not sensitive to the IR magnet errors – the DA fluctuation is comparable to accuracy of the calculation.



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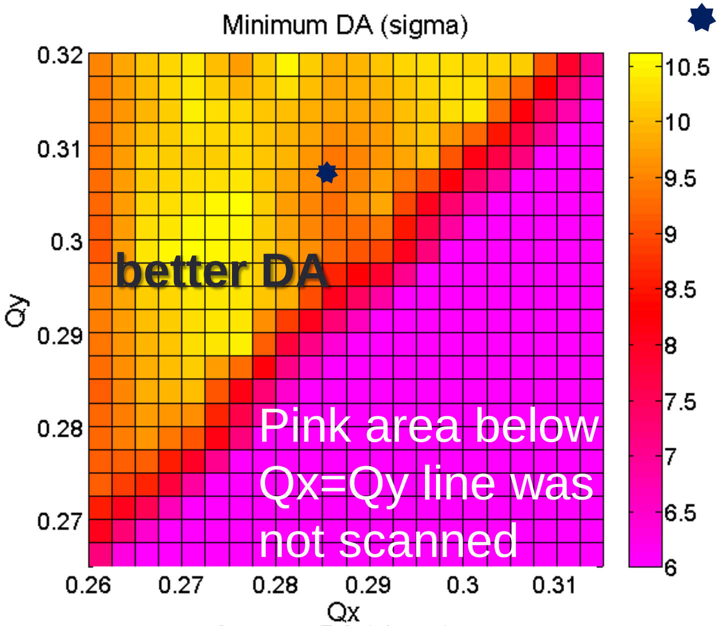
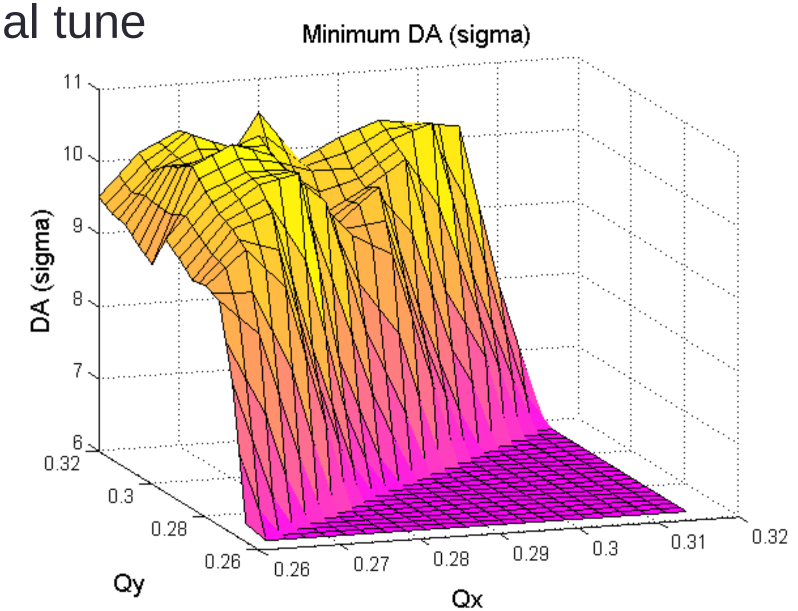
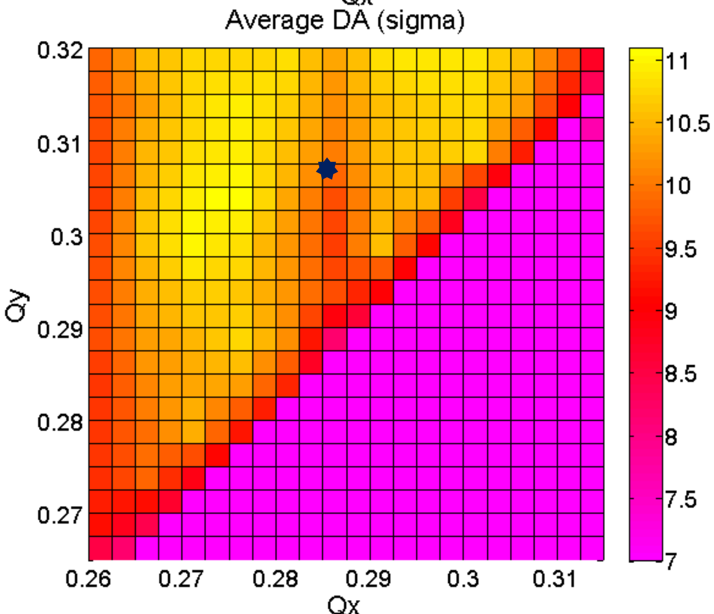
Tune scan for SLHCV3.1b lattice at injection energy

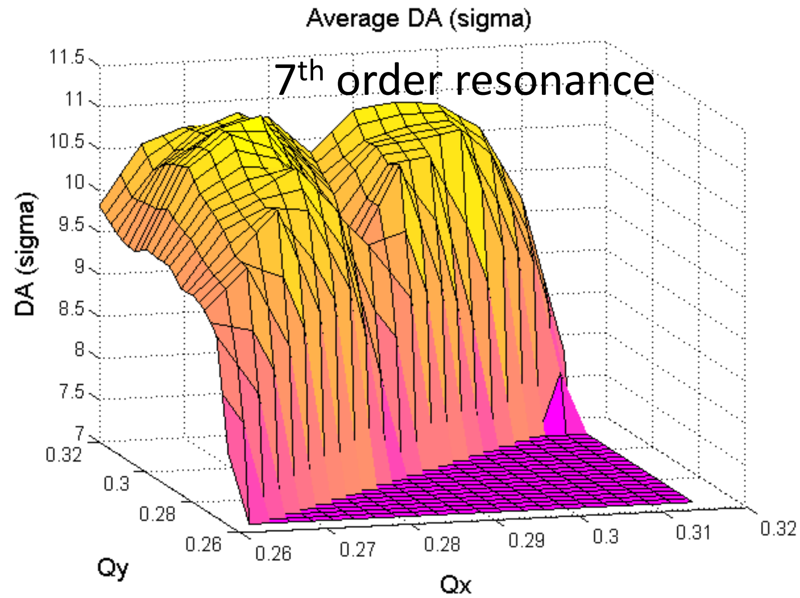
The minimum DA can be increased by ~0.5σ by reducing the x and y tune by 0.01.

★ Nominal tune







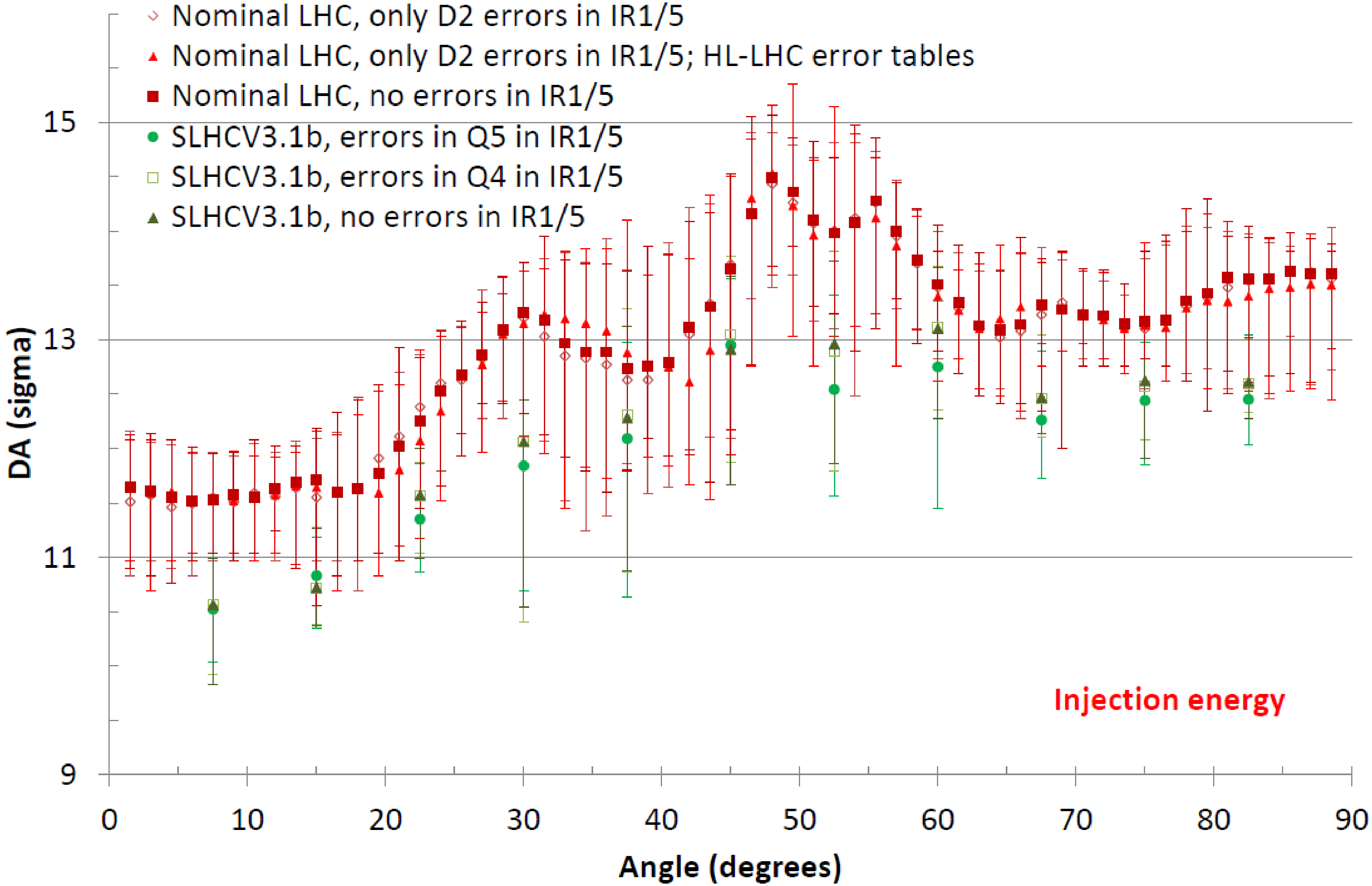


Comparison of DA at injection energy

1 σ DA loss with respect to nominal LHC.

Probably due to vanishing arc cell phase split: exactly in s12/45/56/81 and approximately in the other 4.

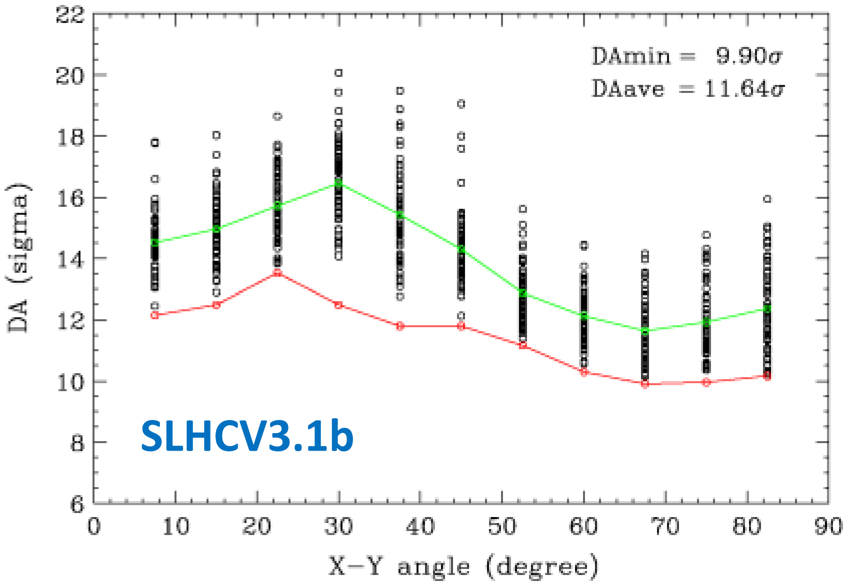
No DA-related problems observed during ATS MDs.

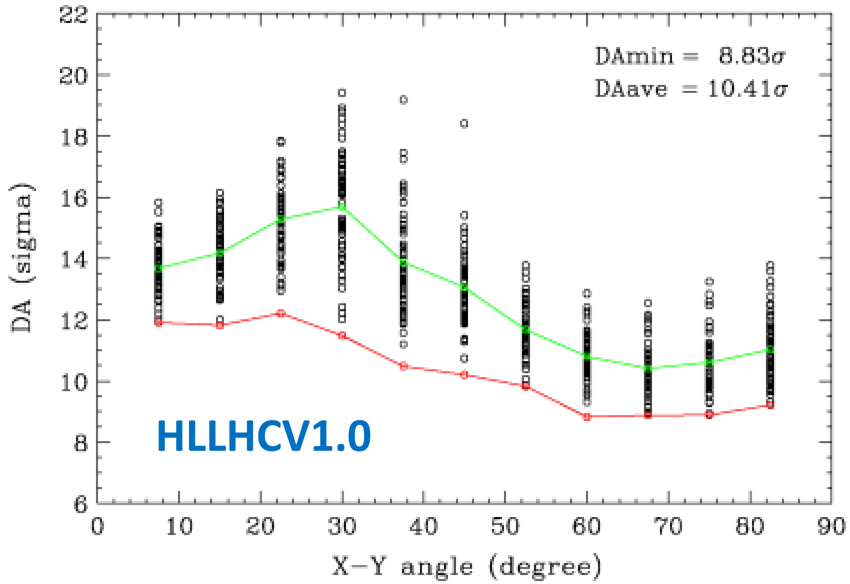


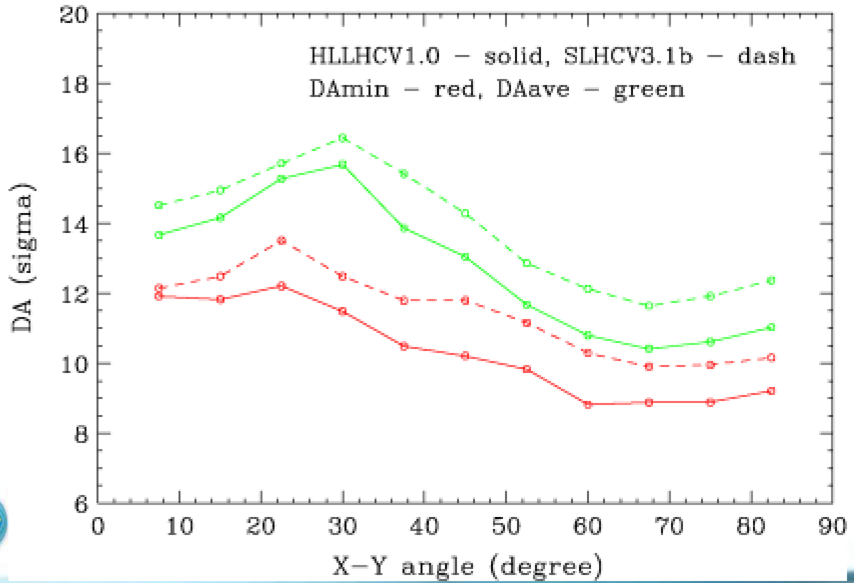
Intermediate summary

- DA situation for SLHCV3.1b
  - Collision:
    - Minimum DA (35 angles): **9.9 σ**
    - FQ: **several multipoles to be improved**
  - Injection:
    - Minimum DA (11 angles): **10.2 σ**
    - FQ: **acceptable**

SLHCV3.1b versus HLLHCV1.0: DA at collision energy



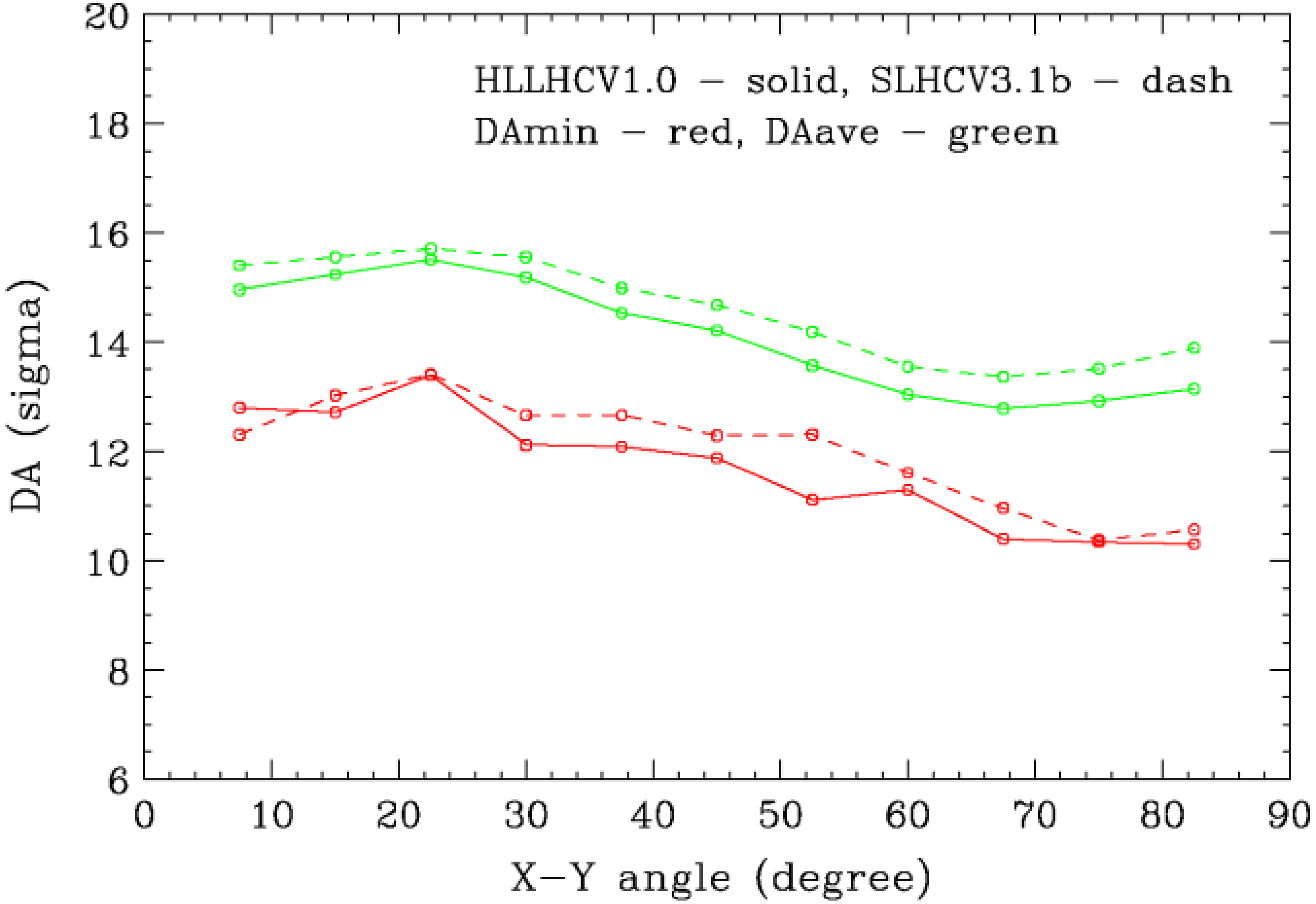




DA of HLLHCV1.0 lattice at collision energy is reduced by ~1σ relative to SLHCV3.1b lattice

SLHCV3.1b versus HLLHCV1.0: Effect of IT errors at collision energy

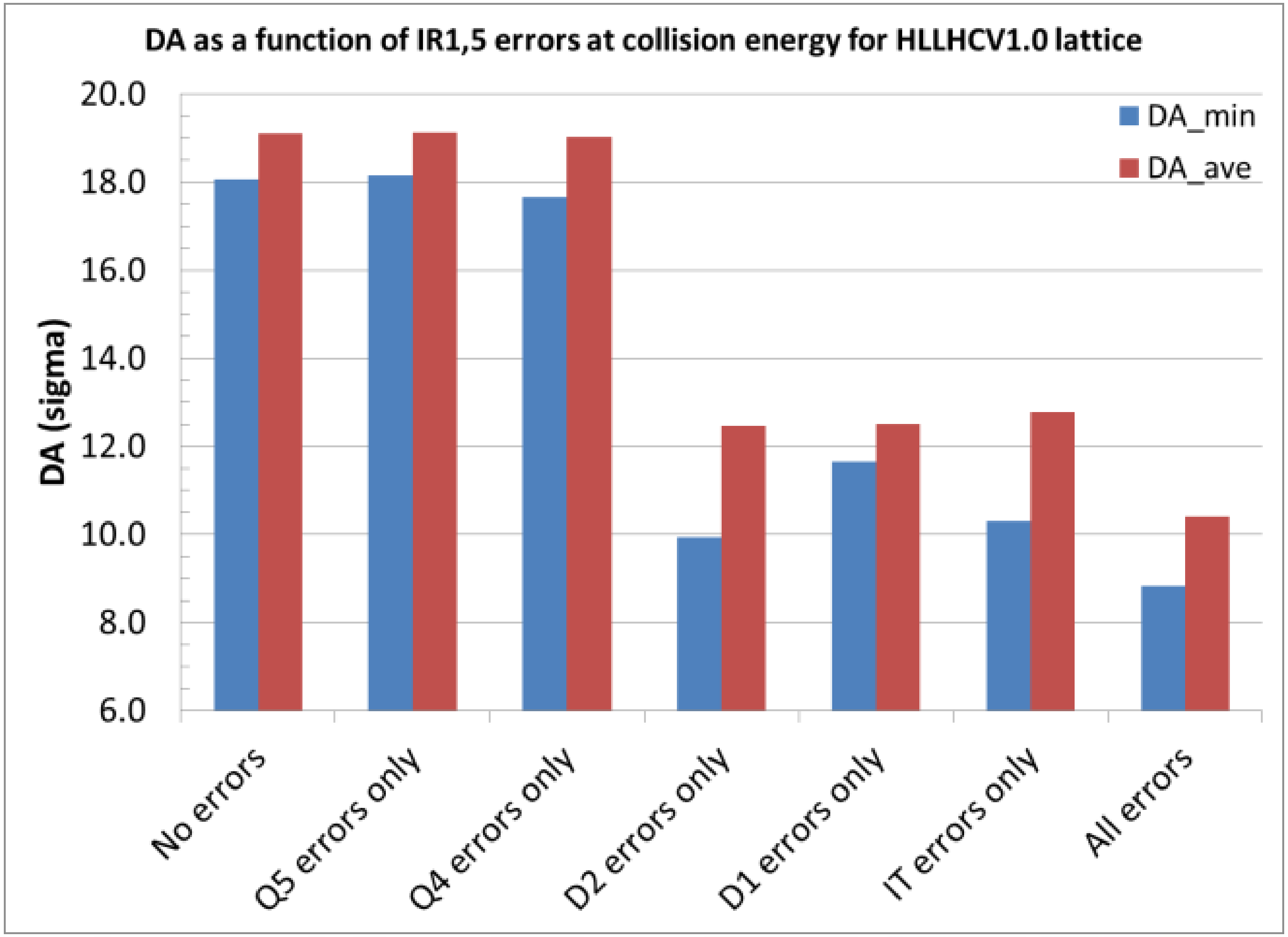
When D1, D2, Q4, Q5 errors are off, the effect of IT field errors in HLLHCV1.0 lattice at collision energy is about 0.5σ smaller DA relative to SLHCV3.1b lattice.



DA sensitivity to IR magnet errors in HLLHCV1.0 lattice at collision energy

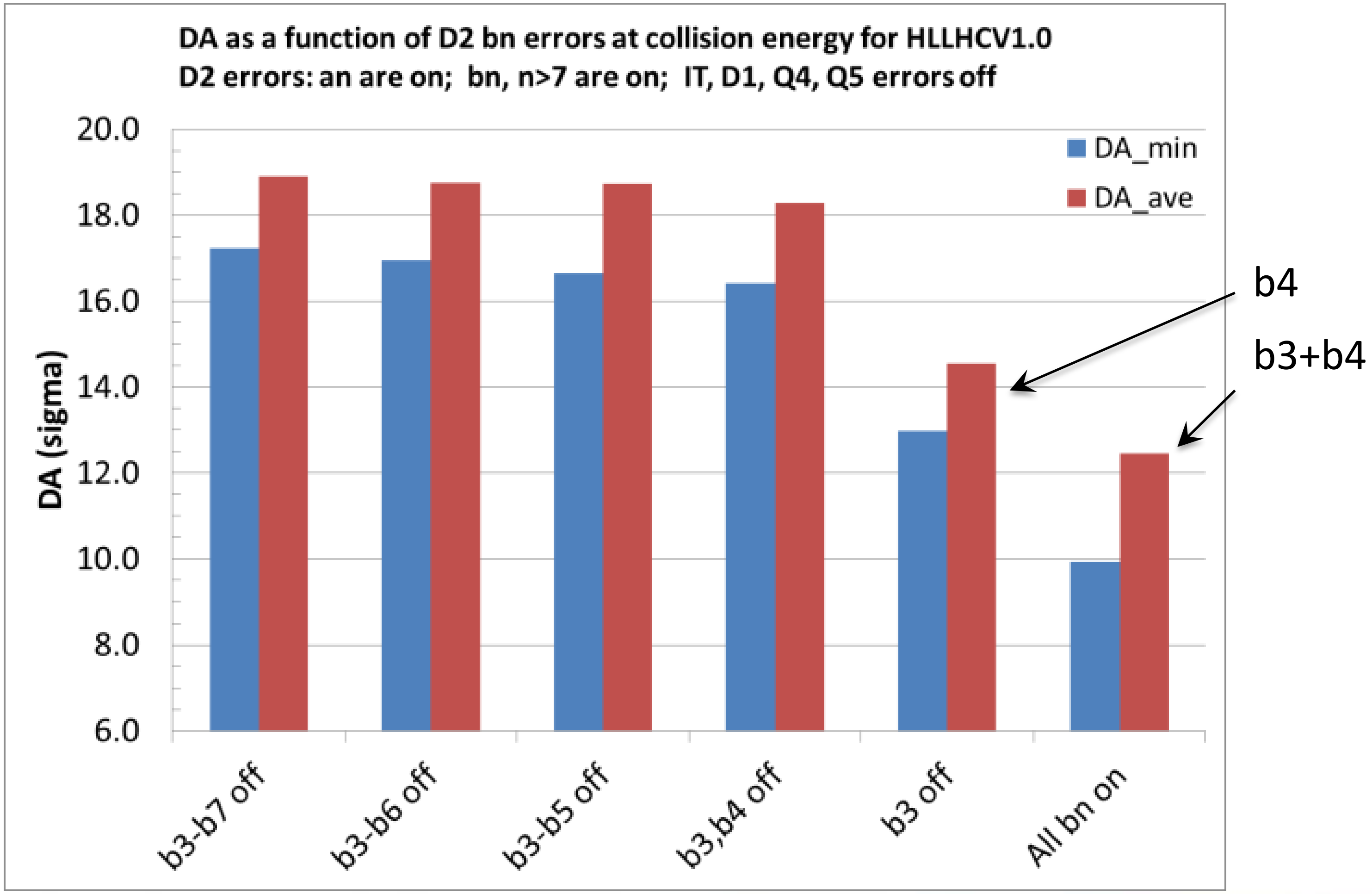
Arc errors and standard corrections are always included.

Errors in the D2 separation dipoles and the IT cause the most reduction of the DA.

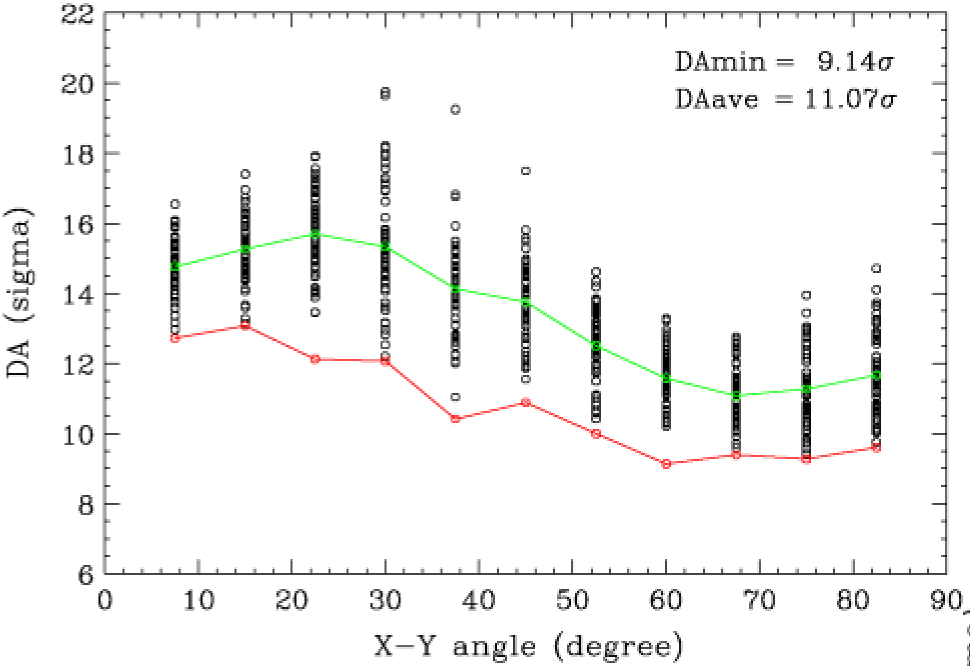


DA sensitivity to low order b_n terms of D2 error field for HLLHCV1.0 lattice at collision energy

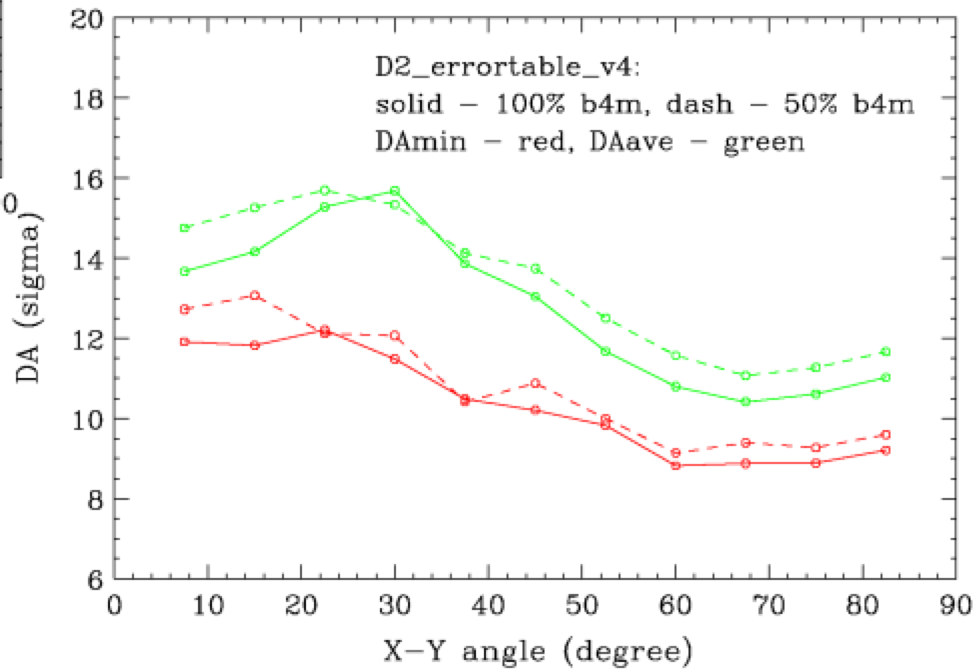
The b3 and b4 terms of the D2 error field make the most impact on the DA. This effect is likely amplified by the sextupole resonances near the nominal tune.



DA of HLLHCV1.0 lattice at collision energy when b4m of D2 error field is reduced to 50%

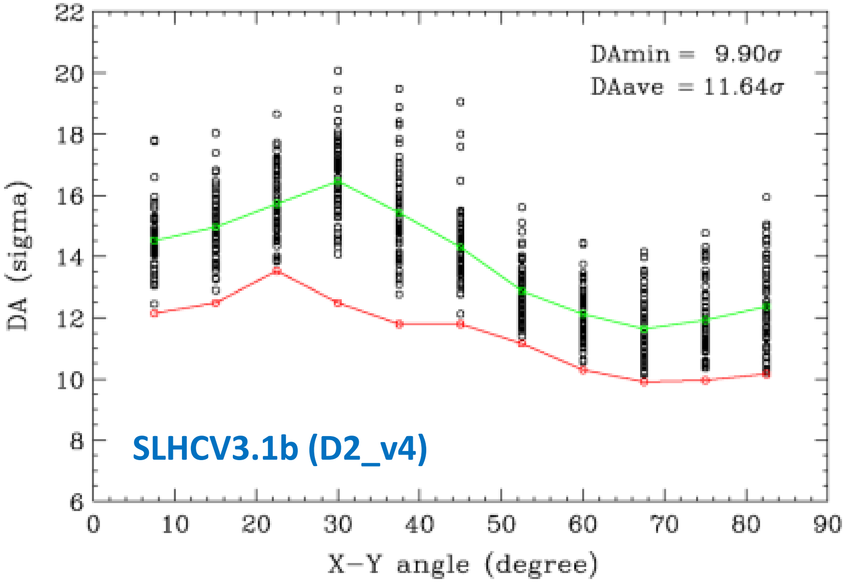


Since b3m in D2 is already optimized (reduced), the next step could be reduction of b4m by 50%.
This improves the average DA by ~0.5σ.
Still, more improvements are needed for reaching 10σ of minimum DA.

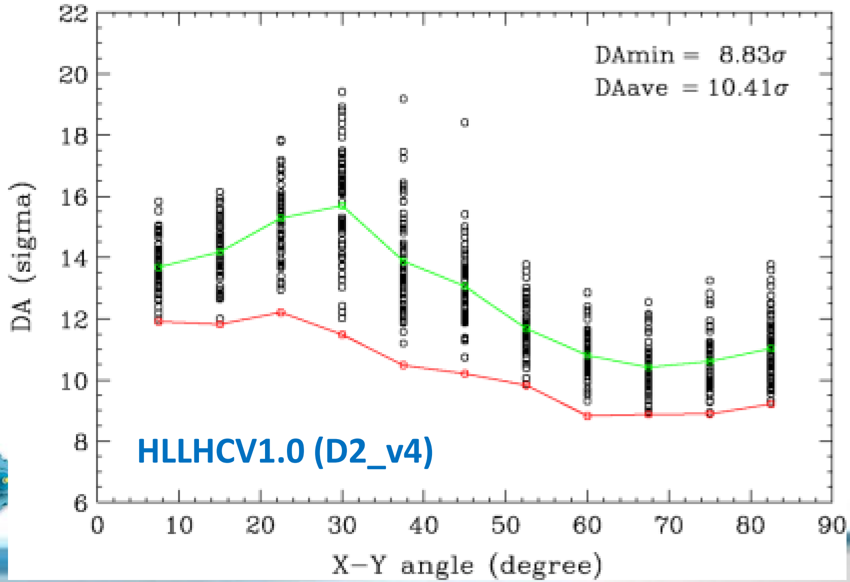


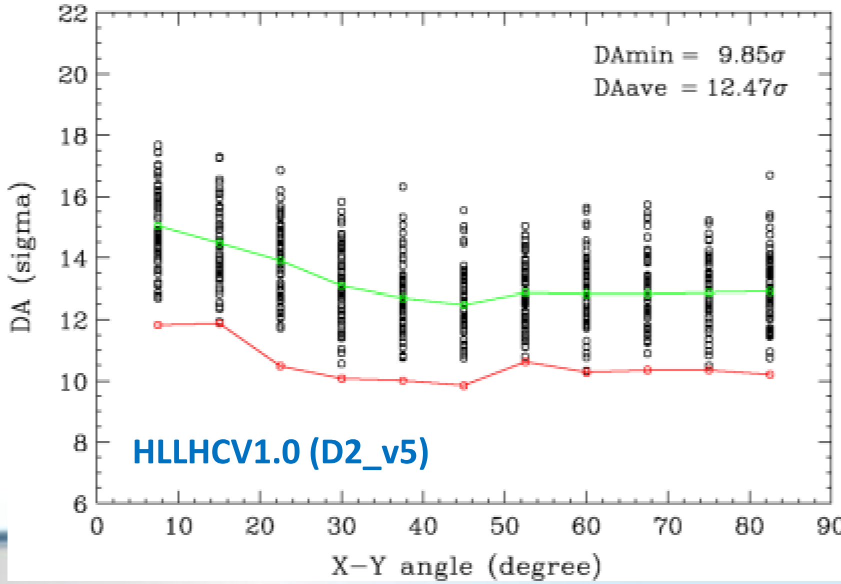
In next slides the impact of an improved FQ will be studied.

DA with all errors at collision energy for SLHCV3.1b and HLLHCV1.0 and D2 error tables v4 and v5

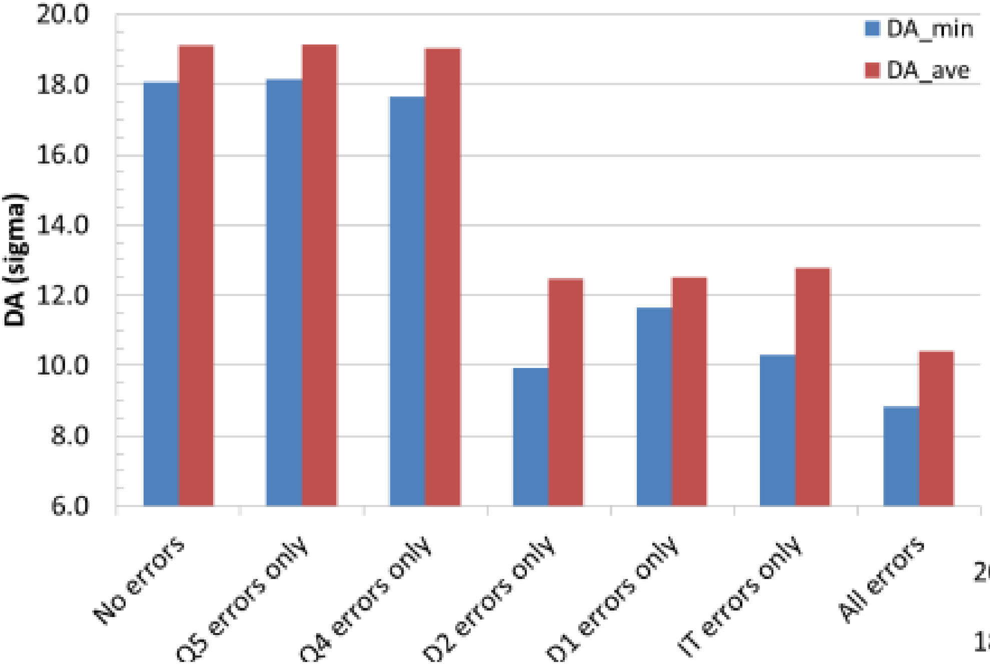


The DA of HLLHCV1.0 with the latest D2_errortable_v5 errors is significantly improved compared to DA with optimized D2_errortable_v4 (b3m at 50%) – compare two lower plots.
It also has comparable DA_min and better DA_ave as compared to SLHCV3.1b with D2_errortable_v4 (b3m at 50%) – compare diagonal plots -> **hints for compensation between FQ of different magnet families**.



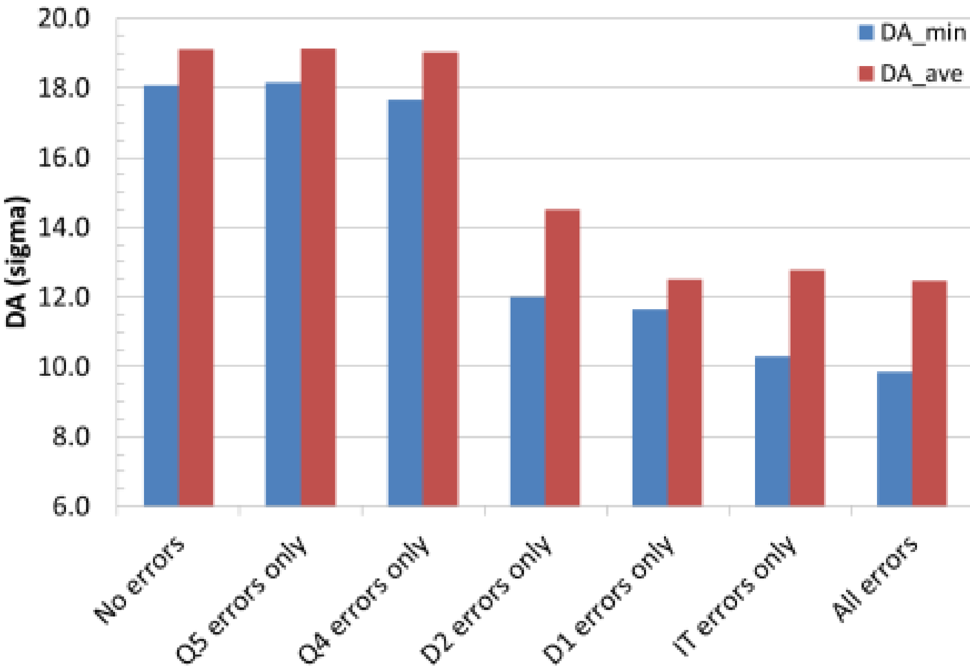


DA sensitivity to IR errors for HLLHCV1.0 at collision energy for D2 field error tables v4 and v5



D2_errortable_v4 (b3m at 50%)

D2_errortable_v5



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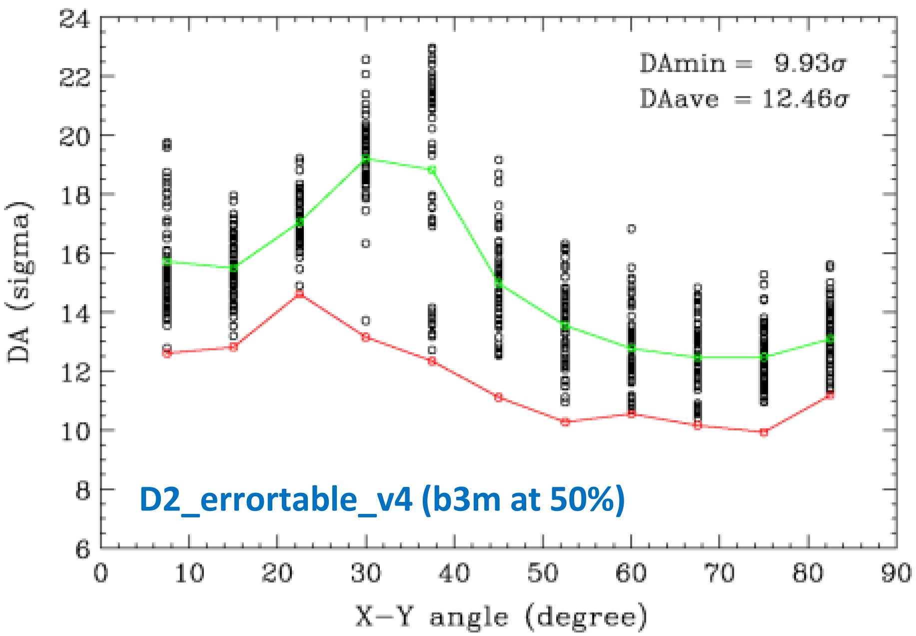
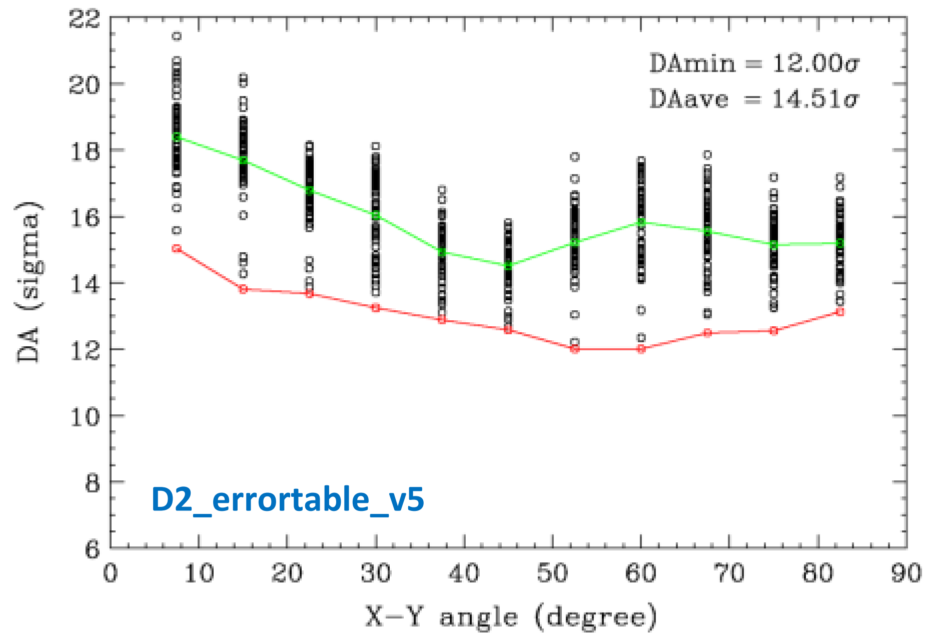
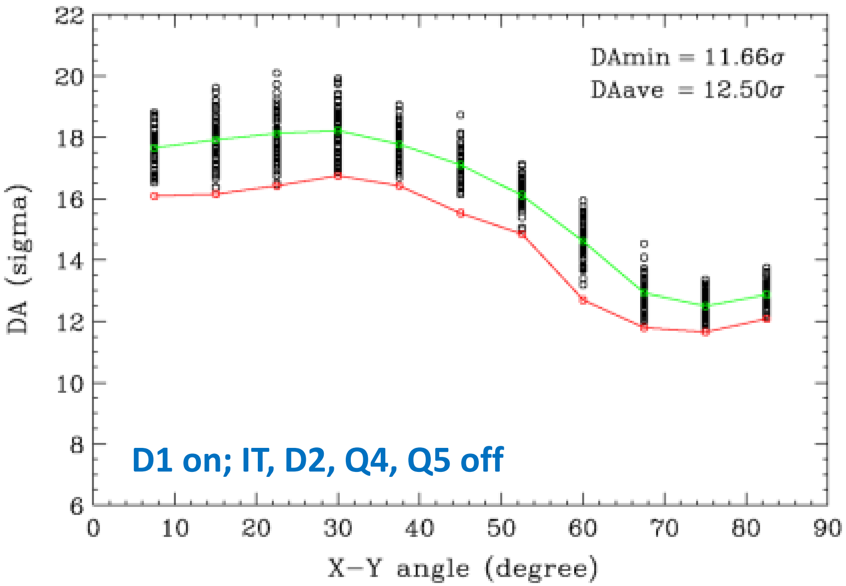
DA of HLLHCV1.0 with D2 errors ON and IT, D1, Q4, Q5 errors OFF

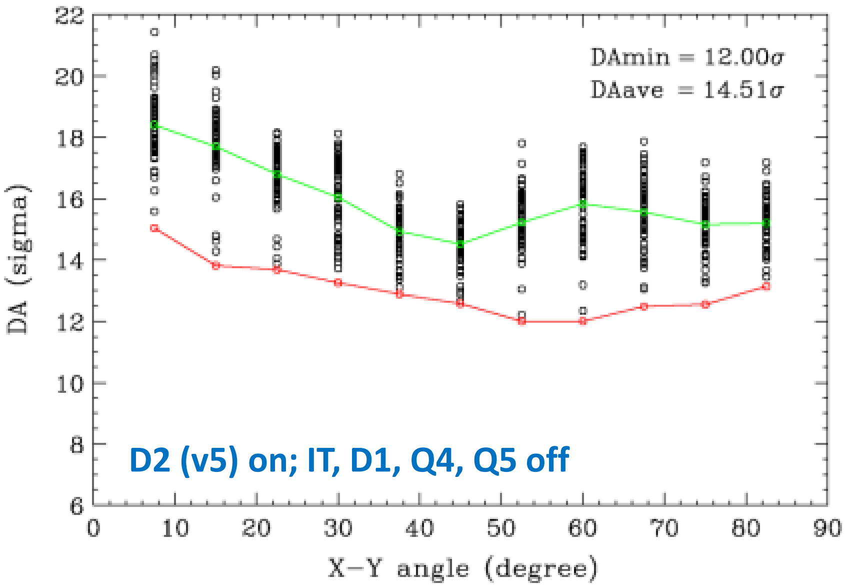
When IT, D1, Q4, Q5 errors are off, the D2_errortable_v5 improves DA of HLLHCV1.0 by about 2 sigma relative to optimized D2_errortable_v4 (b3m at 50%).



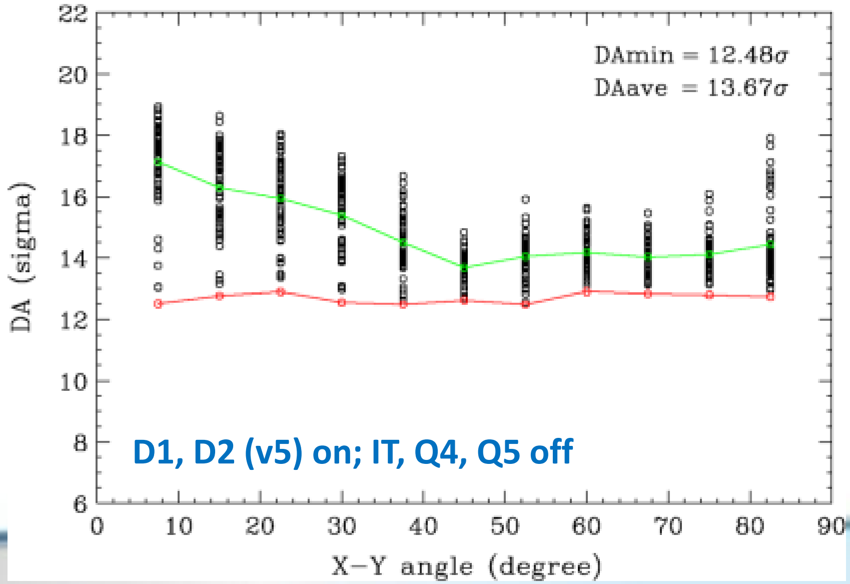


Effects of D1, D2 (v5) errors when IT, Q4, Q5 errors are OFF





With the other IR errors off, the D1 errors mostly reduce vertical DA (see above). When D1 and D2 (v5) errors are applied together, they seem to result in some error cancellation properties which improve DA_min relative to cases where D1 or D2 errors are applied separately.



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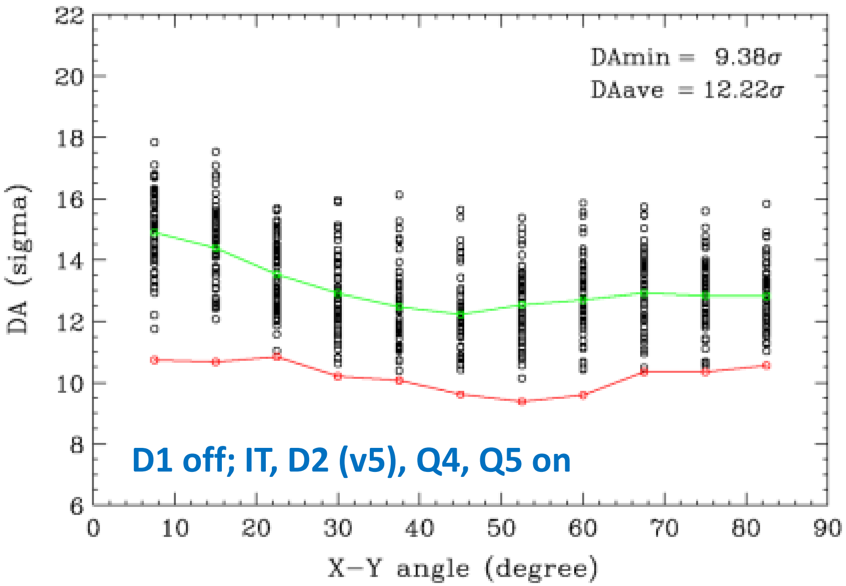
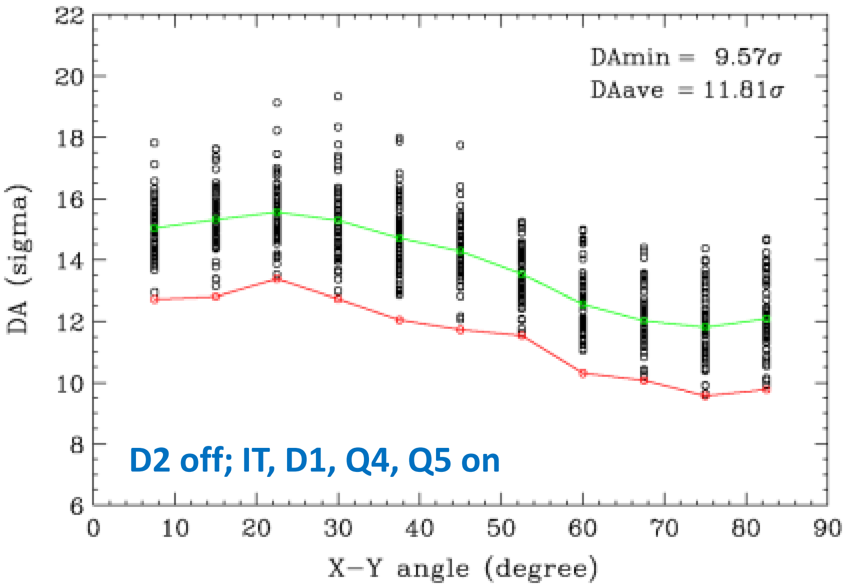
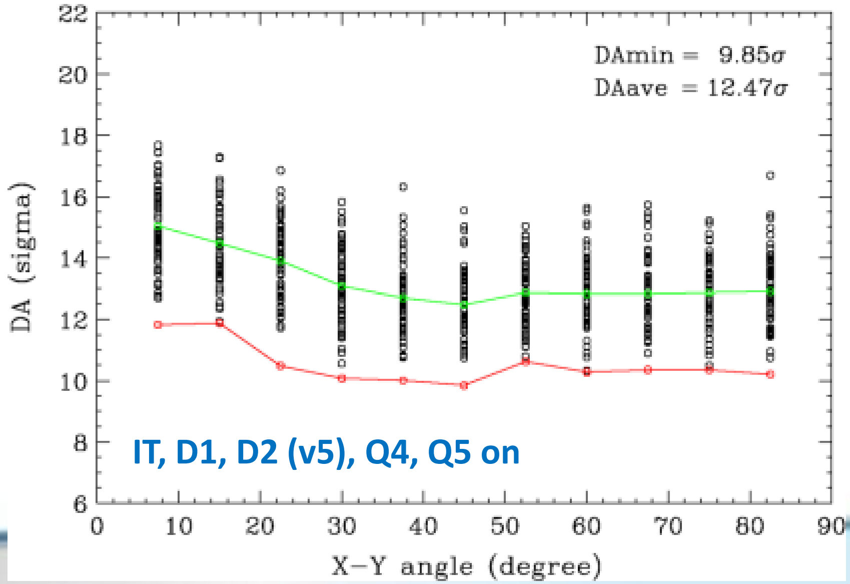
Effects of D1, D2 (v5) errors when IT, Q4, Q5 errors are ON





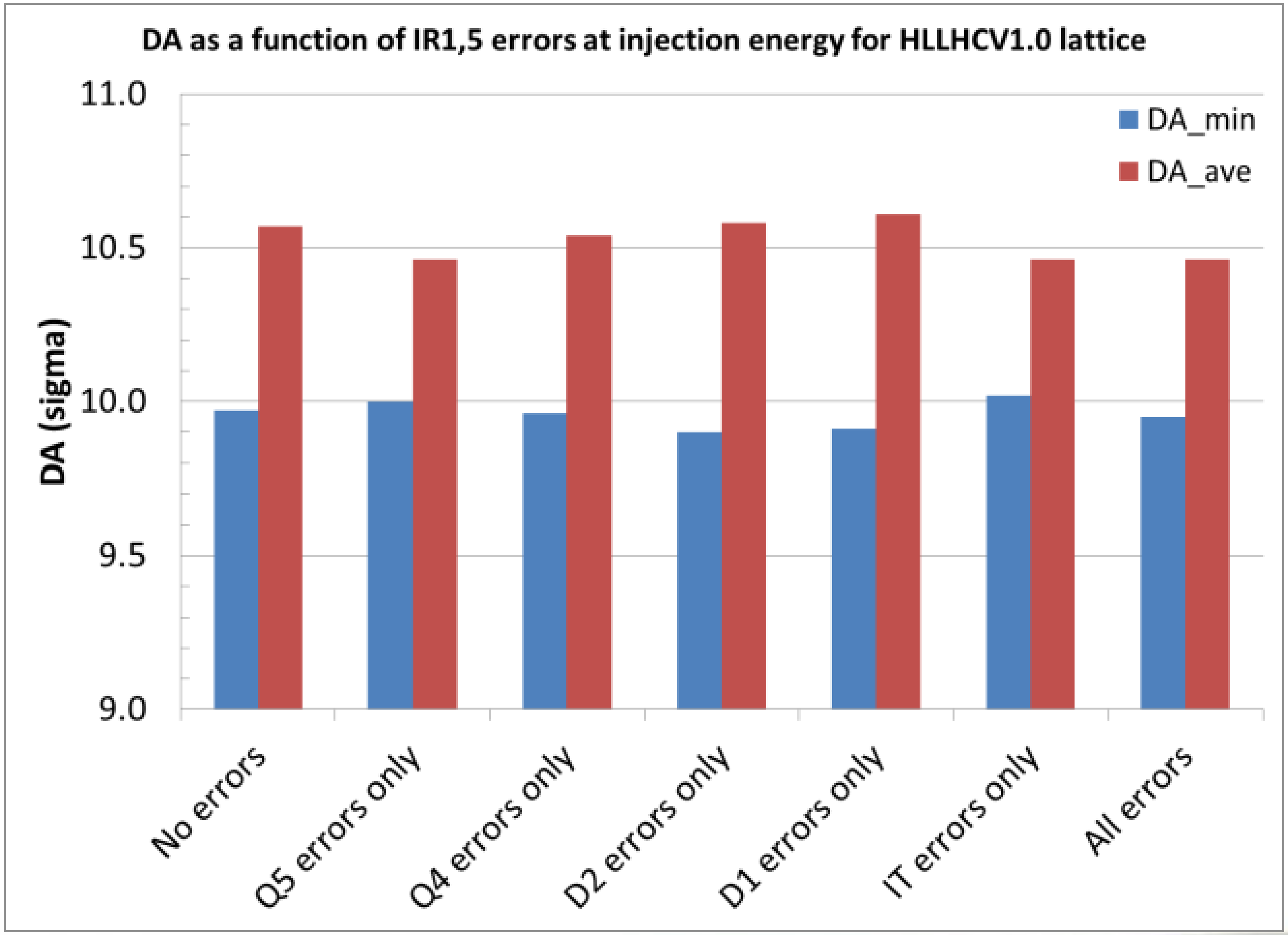
Similar conclusion as on the previous page, when the IT, Q4, Q5 errors are turned on: there is some improvement when the D1 and D2 (v5) errors are applied together, resulting in better DA, compared to cases when D1, D2 errors are applied separately.

It appears that there may be compensation between b3m terms of D1 and D2 reducing the impact of the nearby 3rd order resonance.



HLHCV1.0 lattice at injection energy: DA sensitivity to IR magnet errors

Arc errors and standard corrections are always included. Injection lattice with β^* = 5.5 m at IP1,5. Similar to SLHCV3.1b lattice, there is no impact from the IR magnet errors on DA of HLLHCV1.0 lattice at injection energy.



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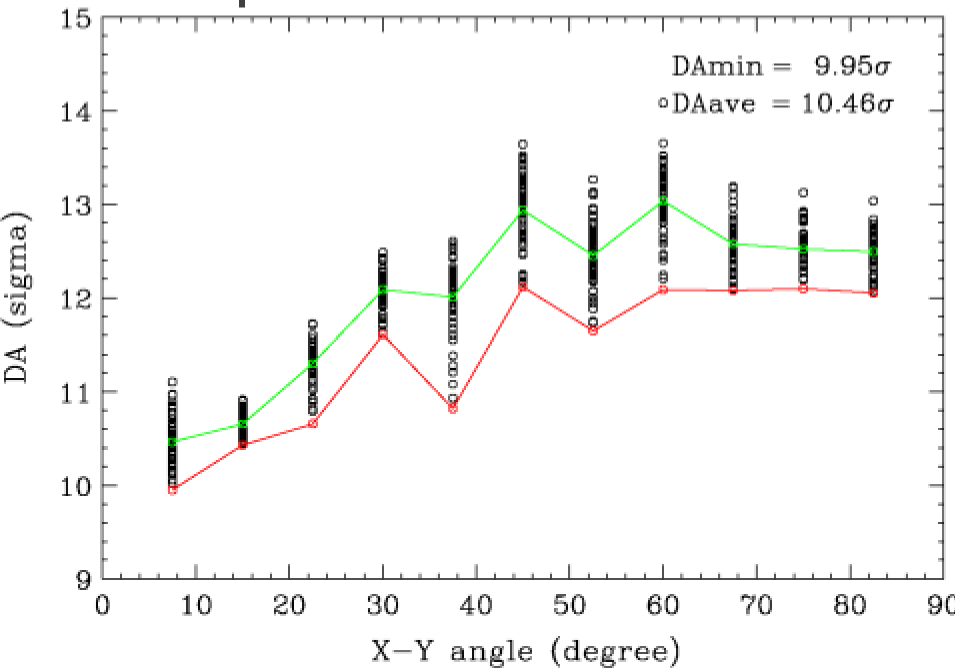
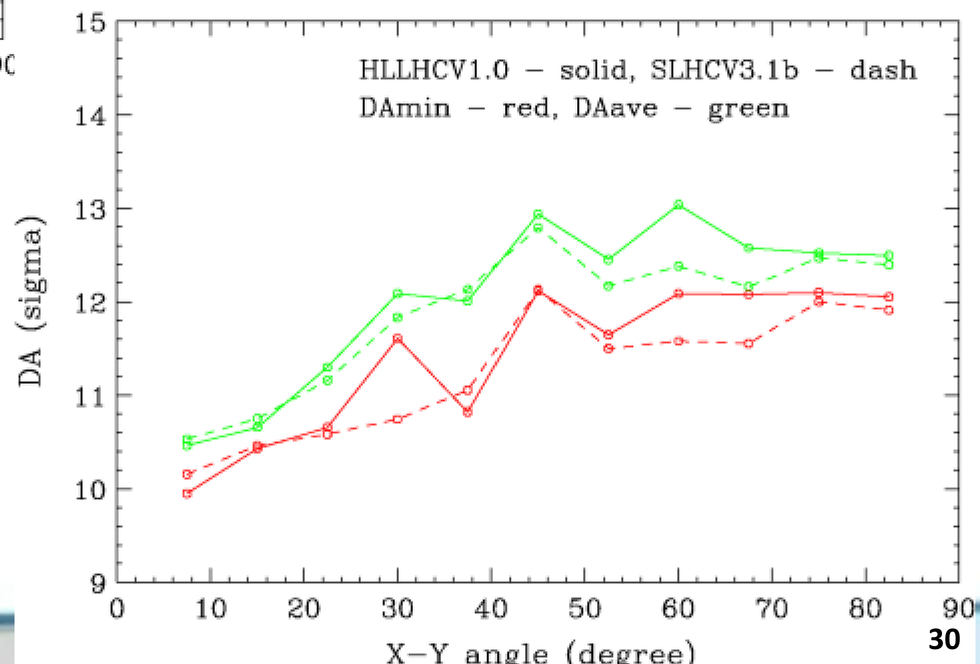
DA of HLLHCV1.0 lattice at injection energy and comparison to SLHCV3.1b



The DA of HLLHCV1.0 and SLHCV3.1b lattices at injection energy are comparable and acceptable.
However, it is 1σ below the DA of the nominal LHC. Hence, further improvements (e.g. tune adjustment) may need to be considered.



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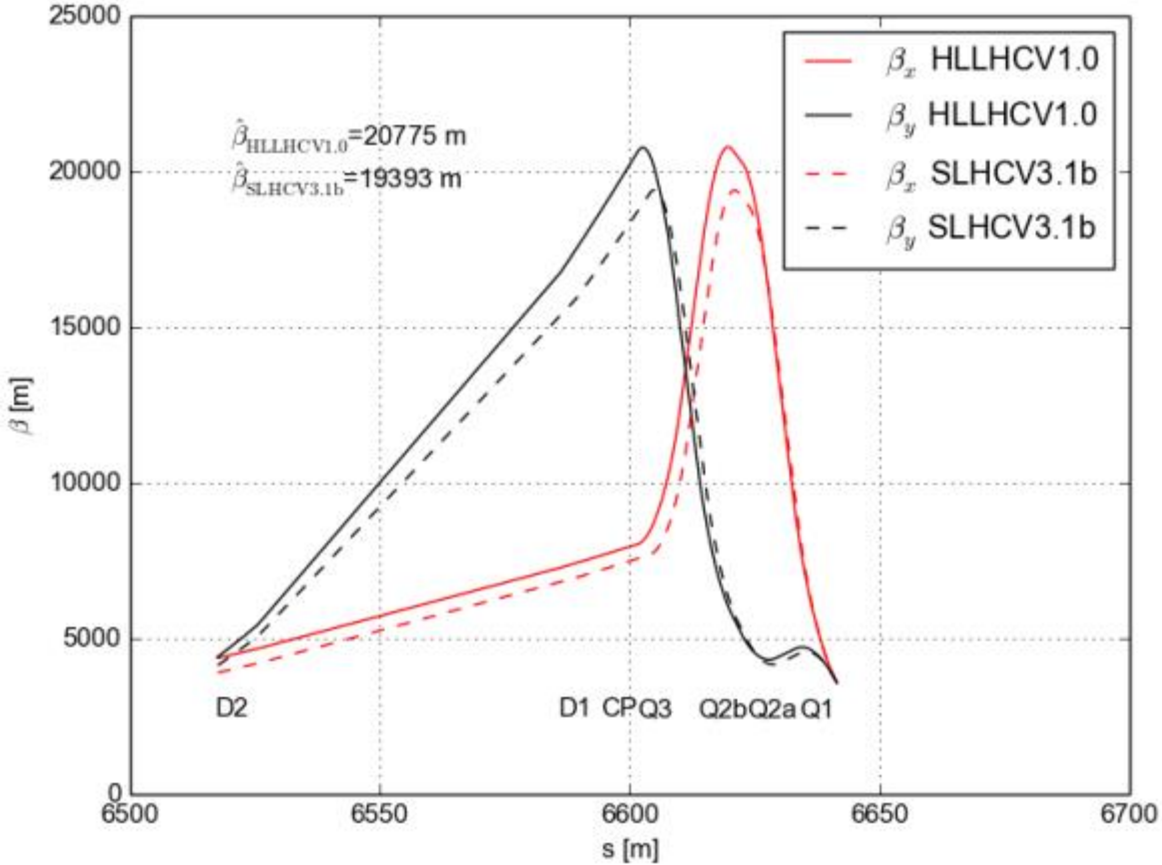
Intermediate summary

- DA situation for HLLHCV1.0
  - Collision:
    - Minimum DA (35 angles): **8.8 σ (but the latest D2 FQ improves it)**
    - FQ: **that determined with SLHCV3.1b is still suitable**
    - **Strong impact of D2 FQ: optimisation in progress**
  - Injection:
    - Minimum DA (11 angles): **9.9 σ**
    - FQ: **acceptable**

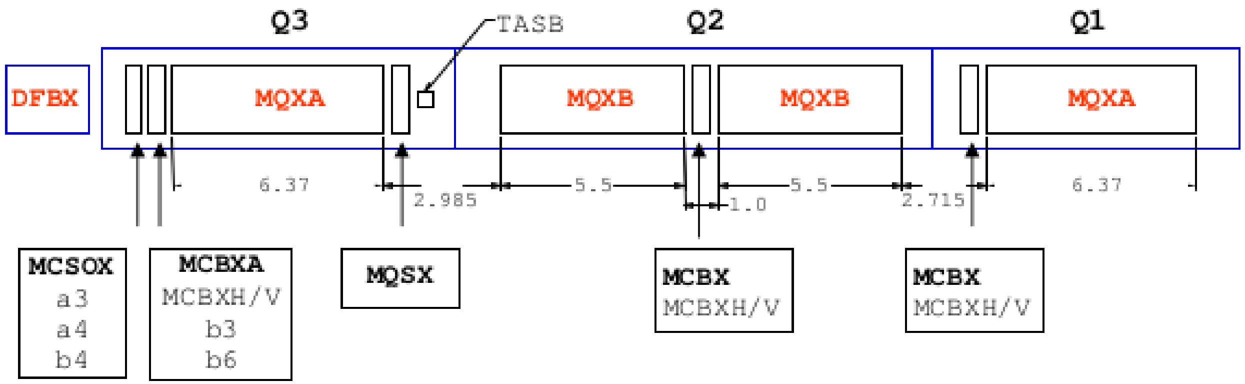
Comparison SLHCV3.1b – HLLHCV1.0

- Larger β_{max} (7%) due to smaller gradient and Q1-Q3 split (50 cm additional drift). Therefore:
  - Larger driving terms and main sextupole strengths.
- Different quadrupoles orientation w.r.t the IP.
- Different IP1/5 phase advance.
- Different correctors position.

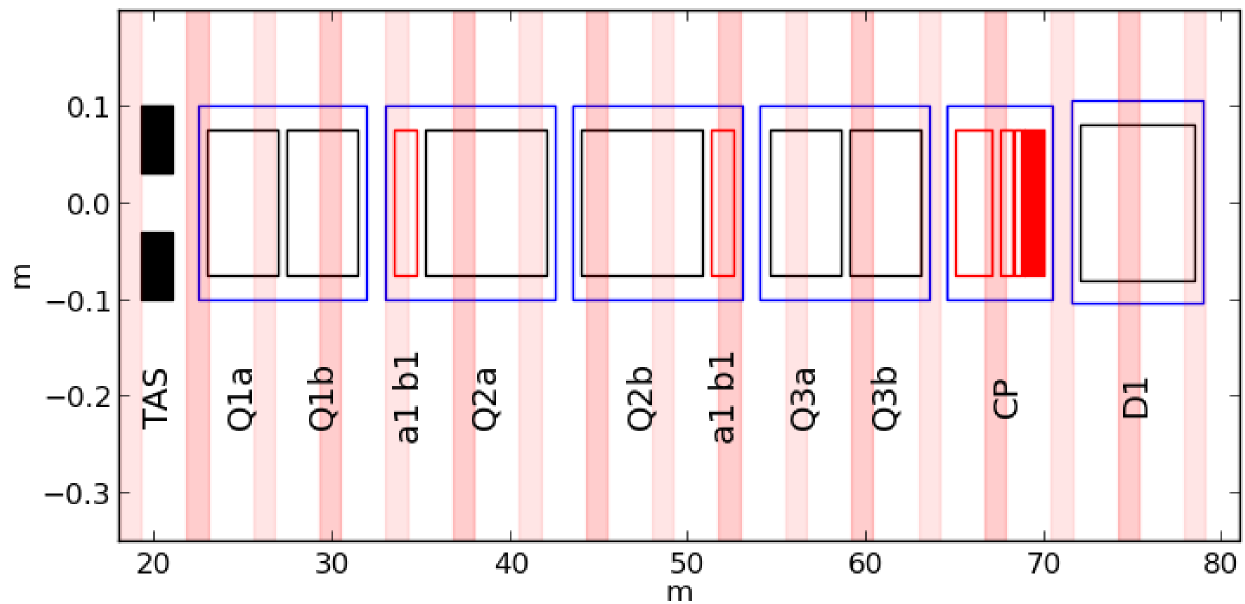


High Luminosity LHC

HL-LHC V1.0 layout



LHC nominal layout



HLLHC V1.0 layout

Triplet layout and orientations

- SLHCV3.1b:

a) IP |Q1= |Q2a= |Q2b= |Q3=

- HLLHCV1.0:

a) IP =Q1a||Q1b= =Q2a| |Q2b= =Q3a||Q3b=

b) IP |Q1a=|Q1b= |Q2a= |Q2b= |Q3a=|Q3b=

c) IP =Q1a||Q1b= |Q2a= =Q2b| =Q3a||Q3b=

Left side mirror symmetric.

= lead end side; | non lead end side;

SLHCV3.1b: side cancellation between Q1-Q3 and Q2

HLLHCV1.0a: Local cancellation between quads, preferred orientation from hardware integration

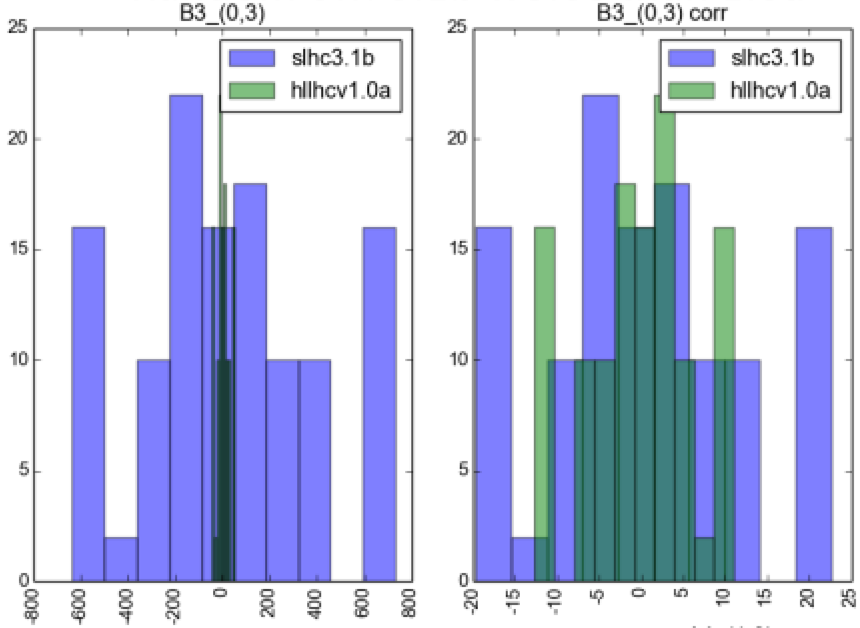
HLLHCV1.0b: Mimic closely 3.1b

HLLHCV1.0c: Reverses Q2 to better cancel Q1b with Q2a

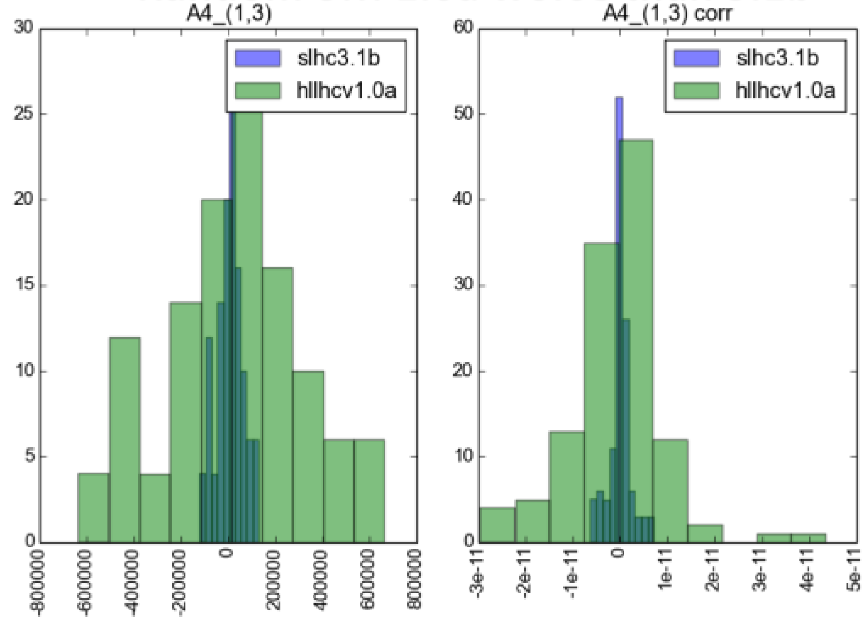
Other orientations with the same degree of symmetries tested without qualitative differences, options without symmetries not pursued.

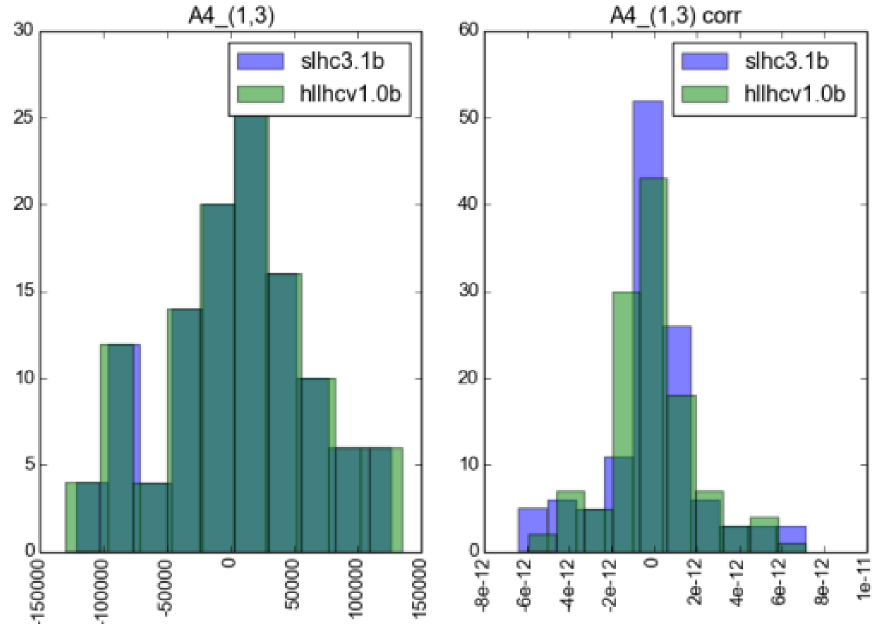
Driving term and corrector strength

Random off: 3.1b worse than 1.0a



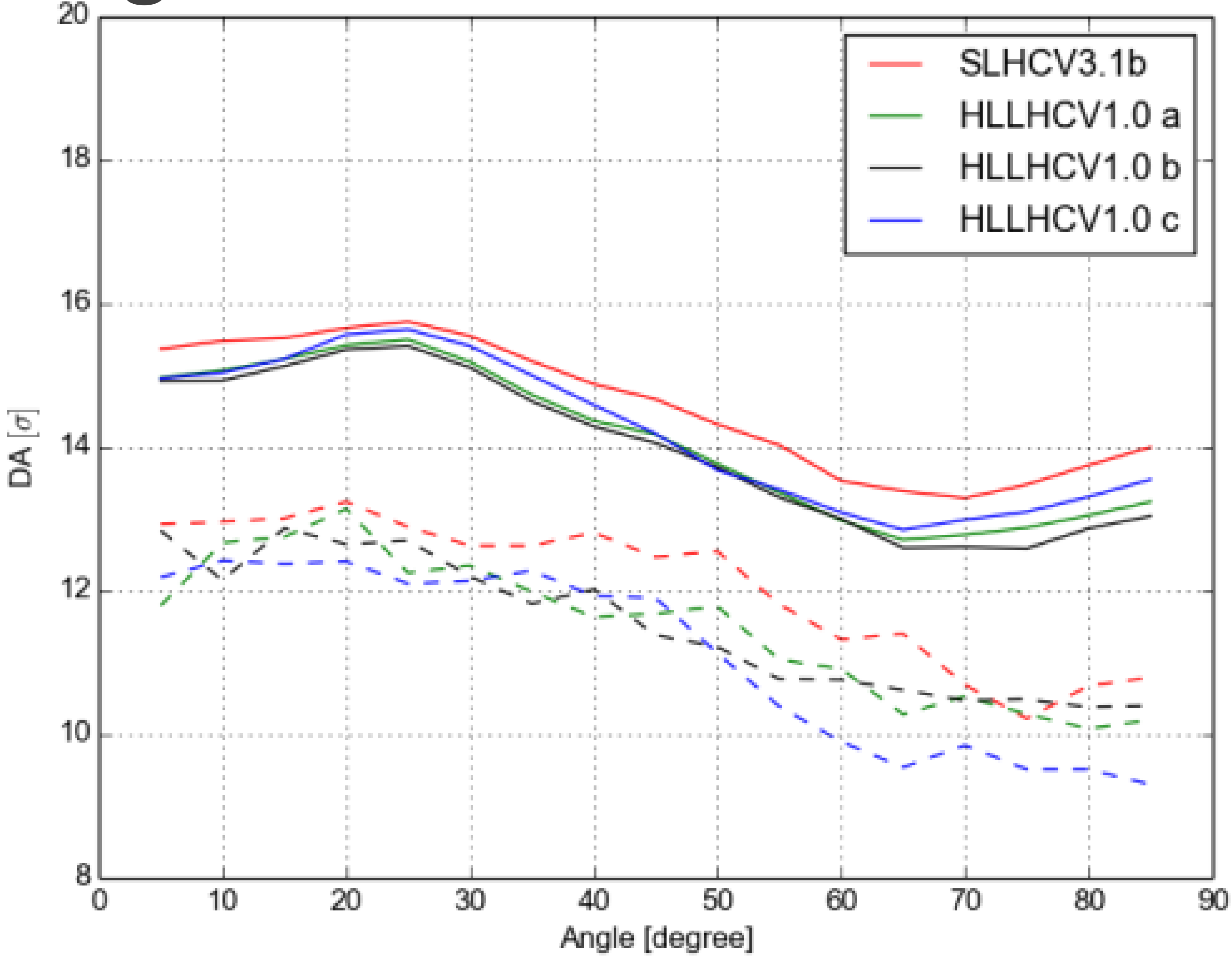
Random off: 1.0a worse than 3.1b





Random off: 1.0b very similar to 3.1b.

Tracking results



No obvious choice of reorientation.

Outlook

- Further optimisation of D2 FQ (discussions at US-LARP) -> collision.
- Impact of reviewed IT FQ (outcome of US-LARP meeting) -> injection and collision.
- Start considering the FQ of Q4 (input from WP3) -> injection and collision.
- DA vs. IP1/5 phase advance -> injection and collision.
- Further studies of DA at injection.
- Selection of IT orientation.

High Luminosity LHC