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Trapezoid optimizations and performance studies

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Trapezoid algorithms

- The trapezoid has 6 planar faces:
- two faces are perpendicular to z-axis at +/-fDz → trivial normals are (0,0,+/-1) like for the box)
- four side planes (non-trivial normals)
- Distances are calculated based on 2 dot products perf face, between face normals and positions or directions
- In order to save dot product calculations, add inside/outside checks and try to return early
- Two trap configurations: PLANESHELL=ON/OFF

Box algorithms are very simple

- Guilherme Amadio has improved box algorithms into just a few lines, thanks to trivial box normals

```
template <typename Real_v>
VECGEOM_FORCE_INLINE
VECGEOM_CUDA_HEADER_BOTH
static Vector3D<Real_v> HalfSize(const UnplacedStruct_t &box)
{
  return Vector3D<Real_v>(box.fDimensions[0], box.fDimensions[1], box.fDimensions[2]);
}

template <typename Real_v, typename Bool_v>
VECGEOM_FORCE_INLINE
VECGEOM_CUDA_HEADER_BOTH
static void Contains(UnplacedStruct_t const &box, Vector3D<Real_v> const &point, Bool_v &inside)
{
  inside = (point.Abs() - HalfSize<Real_v>(box)).Max() < Real_v(0.0);
}

template <typename Real_v, typename Inside_v>
VECGEOM_FORCE_INLINE
VECGEOM_CUDA_HEADER_BOTH
static void Inside(UnplacedStruct_t const &box, Vector3D<Real_v> const &point, Inside_v &inside)
{
  Real_v dist = (point.Abs() - HalfSize<Real_v>(box)).Max();

  inside = vecCore::Blend(dist < Real_v(0.0), Inside_v(kInside), Inside_v(kOutside));
  vecCore__MaskedAssignFunc(inside, Abs(dist) < Real_v(kTolerance), Inside_v(kSurface));
}
```

Box algorithms are very simple

```
template <typename Real_v>
VECGEOM_FORCE_INLINE
VECGEOM_CUDA_HEADER_BOTH
static void DistanceToOut(UnplacedStruct_t const &box, Vector3D<Real_v> const &point,
                          Vector3D<Real_v> const &direction, Real_v const & /* stepMax */, Real_v &distance)
{
  const Vector3D<Real_v> invDir(Real_v(1.0) / NonZero(direction[0]), Real_v(1.0) / NonZero(direction[1]),
                                Real_v(1.0) / NonZero(direction[2]));

  const Real_v distIn = Max((-Sign(invDir[0]) * box.fDimensions[0] - point[0]) * invDir[0],
                            (-Sign(invDir[1]) * box.fDimensions[1] - point[1]) * invDir[1],
                            (-Sign(invDir[2]) * box.fDimensions[2] - point[2]) * invDir[2]);

  const Real_v distOut = Min((Sign(invDir[0]) * box.fDimensions[0] - point[0]) * invDir[0],
                             (Sign(invDir[1]) * box.fDimensions[1] - point[1]) * invDir[1],
                             (Sign(invDir[2]) * box.fDimensions[2] - point[2]) * invDir[2]);

  distance = vecCore::Blend(distIn > distOut || distIn > Real_v(kTolerance), Real_v(-1.0), distOut);
}

template <typename Real_v>
VECGEOM_FORCE_INLINE
VECGEOM_CUDA_HEADER_BOTH
static void SafetyToIn(UnplacedStruct_t const &box, Vector3D<Real_v> const &point, Real_v &safety)
{
  safety = (point.Abs() - HalfSize<Real_v>(box)).Max();
}
```

Can we simplify trapezoid algorithms, inspired on the box ones?

Simpler trapezoid algorithms?

- Think of extensions from box algorithms

```
template <typename Real_v>
VECGEOM_FORCE_INLINE
VECGEOM_CUDA_HEADER_BOTH
static void DistanceToOut(UnplacedStruct_t const &unplaced, Vector3D<Real_v> const &point,
                          Vector3D<Real_v> const &dir, Real_v const &stepMax, Real_v &distance)
{
  (void)stepMax;
  using Bool_v = vecCore::Mask_v<Real_v>;

  // step 0: if point is outside any plane --> return -1, otherwise initialize at Infinity
  Bool_v outside = Abs(point.z()) > MakePlusTolerant<true>(unplaced.fDz);
  distance       = vecCore::Blend(outside, Real_v(-1.0), InfinityLength<Real_v>());
  Bool_v done(outside);
  if (vecCore::EarlyReturnAllowedAt<Real_v>(EARLYRETURNTHR) && vecCore::MaskFull(done)) return;

  //
  // Step 1: find range of distances along dir between Z-planes (smin, smax)
  //

  Real_v distz = (Sign(dir.z()) * unplaced.fDz - point.z()) / NonZero(dir.z());
  vecCore__MaskedAssignFunc(distance, !done && dir.z() != Real_v(0.), distz);

//
// Step 2: find distances for intersections with side planes.
//

#ifndef VECGEOM_PLANESHELL_DISABLE
    Real_v disttoplanes = unplaced.GetPlanes()->DistanceToOut(point, dir);
    vecCore::MaskedAssign(distance, disttoplanes < distance, disttoplanes);

#else
    //=== Here for VECGEOM_PLANESHELL_DISABLE

    // loop over side planes - find pdist,Proj for each side plane
    Real_v pdist[4], proj[4], vdist[4];
```

Still to be dropped?!

This is much simpler than before!

See next page…

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Simpler trapezoid algorithms?

```
#else
    //=== Here for VECGEOM_PLANESHELL_DISABLE

    // loop over side planes - find pdist,Proj for each side plane
    Real_v pdist[4], proj[4], vdist[4];
    // Real_v dist1(distance);
    // EvaluateTrack<Real_v>(unplaced, point, dir, pdist, proj, vdist);

    TrapSidePlane const *fPlanes = unplaced.GetPlanes();
    for (unsigned int i = 0; i < 4; ++i) {
      // Note: normal vector is pointing outside the volume (convention), therefore
      // pdist>0 if point is outside  and  pdist<0 means inside
      pdist[i] = fPlanes[i].fA * point.x() + fPlanes[i].fB * point.y() + fPlanes[i].fC * point.z() + fPlanes[i].fD;

      // Proj is projection of dir over the normal vector of side plane, hence
      // Proj > 0 if pointing ~same direction as normal and Proj<0 if pointing ~opposite to normal
      proj[i] = fPlanes[i].fA * dir.x() + fPlanes[i].fB * dir.y() + fPlanes[i].fC * dir.z();

      vdist[i] = -pdist[i] / NonZero(proj[i]);
    }

    // early return if point is outside of plane
    // for (unsigned int i = 0; i < 4; ++i) {
    //   done = done || (pdist[i] > MakePlusTolerant<true>(0.));
    // }
    // vecCore::MaskedAssign(dist1, done, Real_v(-1.0));
    // if (vecCore::EarlyReturnAllowedAt<Real_v>(EARLYRETURNTHR) && vecCore::MaskFull(done)) return;

    for (unsigned int i = 0; i < 4; ++i) {
      // if track is pointing towards plane and vdist<distance, then distance=vdist
      // vecCore__MaskedAssignFunc(dist1, !done && proj[i] > 0.0 && vdist[i] < dist1, vdist[i]);
      vecCore__MaskedAssignFunc(distance, pdist[i] > MakePlusTolerant<true>(0.), Real_v(-1.0));
      vecCore__MaskedAssignFunc(distance, proj[i] > 0.0 && -Sign(pdist[i]) * vdist[i] < distance,
                                -Sign(pdist[i]) * vdist[i]);
    }
#endif
  }
```

Considering EvaluateTrack<>() function to replace a whole loop

Block was replaced with 1 line

Performance comparisons

Five commits are compared:

**** 68c48276** – tag v0.3.rc*

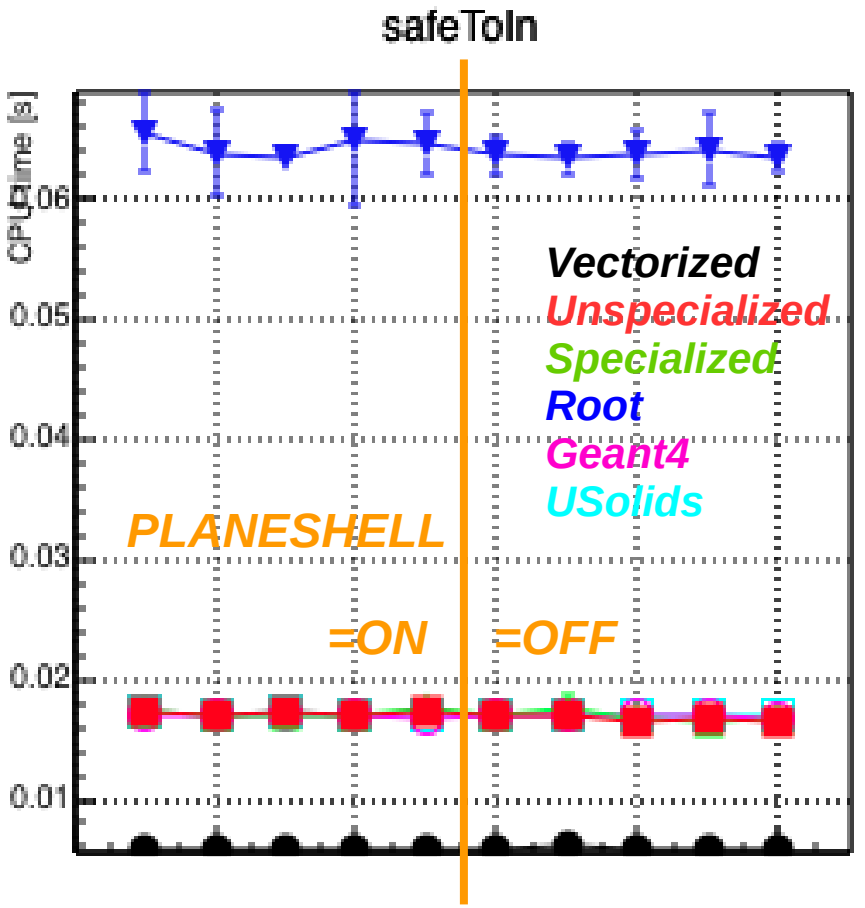
**** 4e5928c1** – tag v00.03.00*

**** 019d29a0** – DistToIn( ) and DistToOut( ) improvements (merge request #384)*

**** b356bad1** – improvs to NormalKernel( ) (merge request #415)*

**** 2c007289** – Improvs to Contains( ), Inside( ) and SafetyToOut( )*

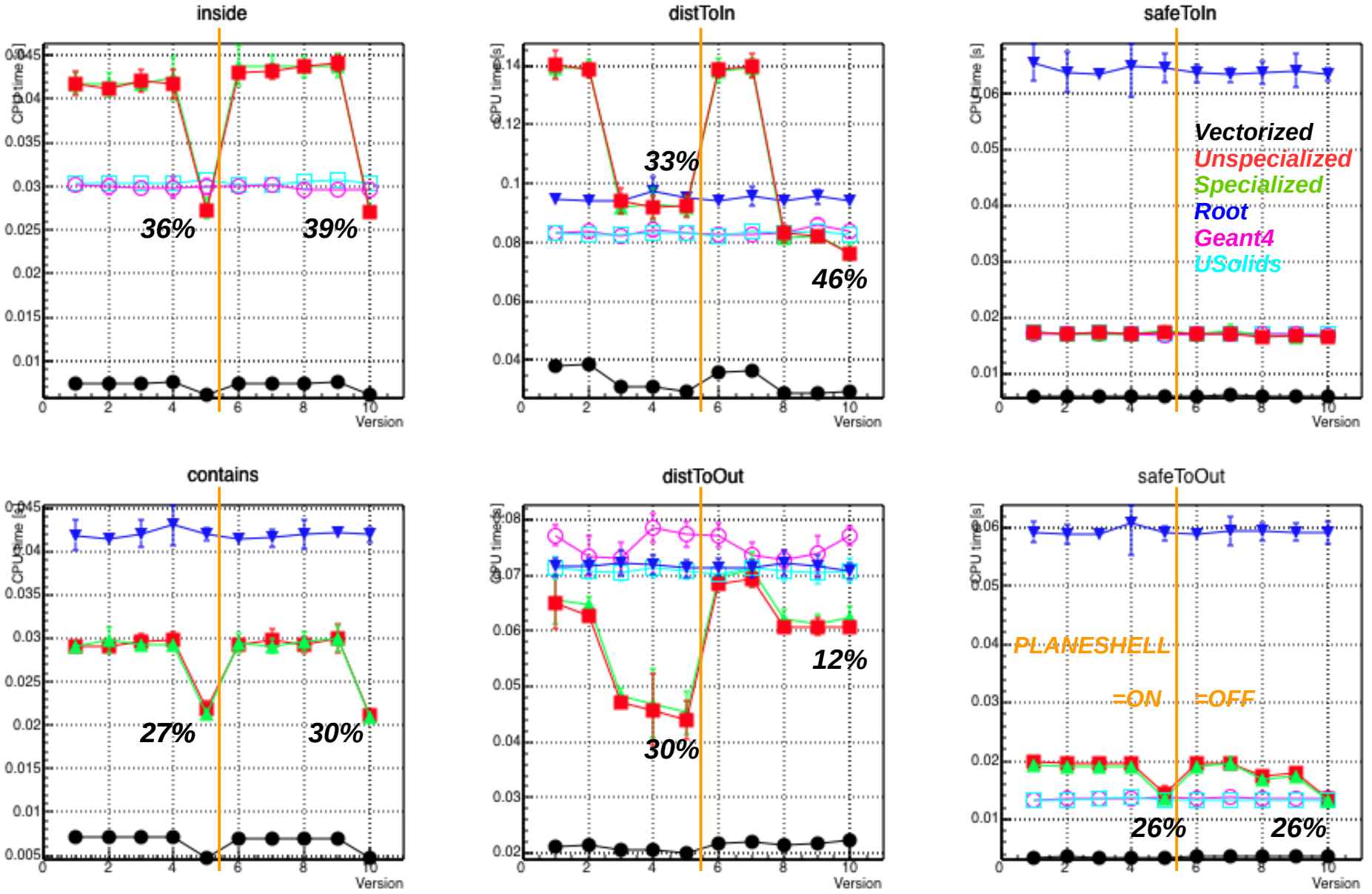
Measurements taken on my MacBook Pro, with most programs disabled.



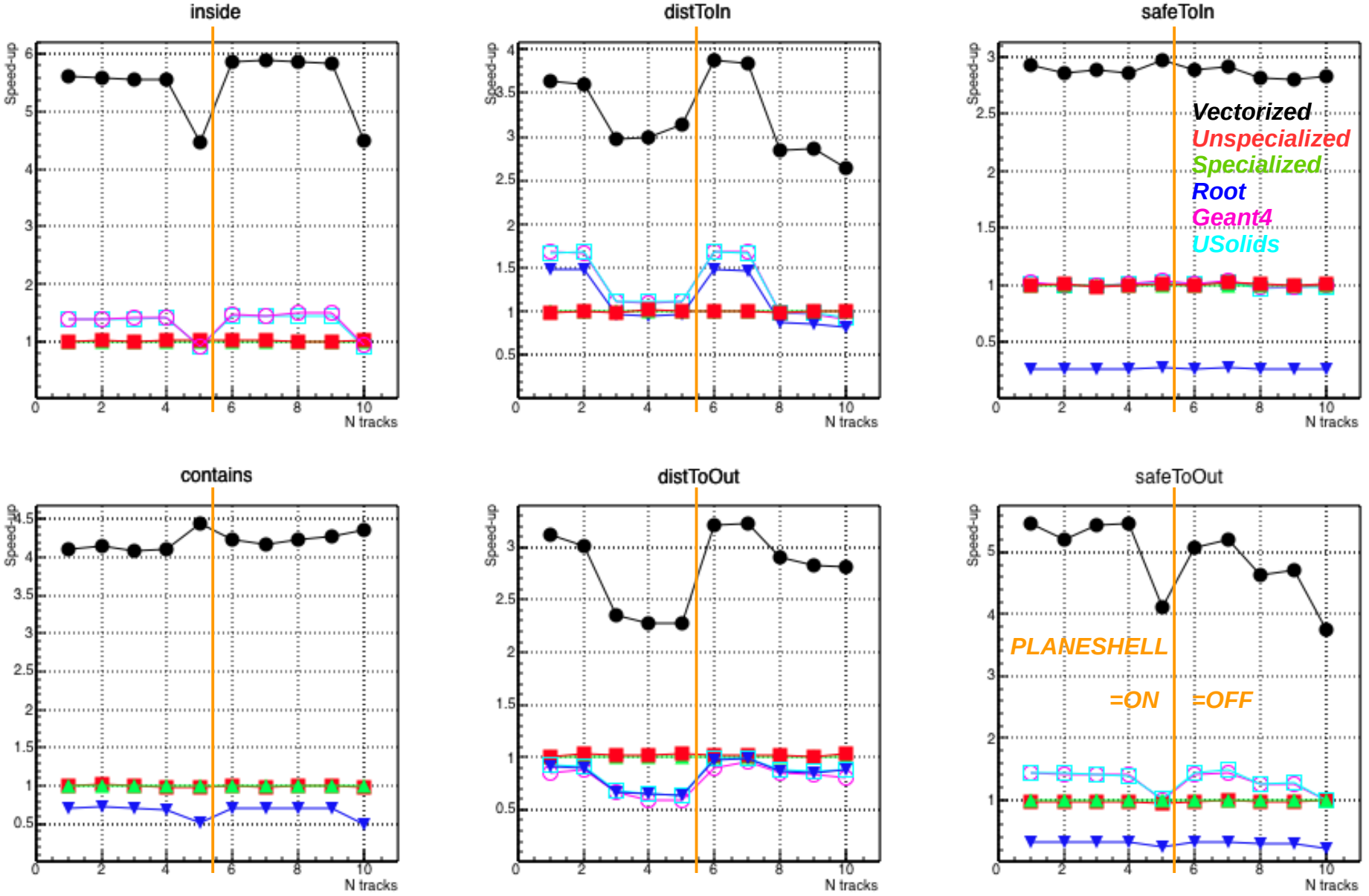
Speedups defined w.r.to Specialized algorithm, e.g. speedup = Vect.time / Spec.time

Each data point define as an average of slowest 20 / 21 data points (largest measurement is discarded in averaging). Error bars represent standard deviations.

Performance comparisons: CPU times



Performance comparisons: speedups



Note that improvements to scalar algorithm brought speedups down to ~4x (expected for AVX)

Performance improvement summary

- Significant performance improvements achieved by simplifying trapezoid algorithms as expanded box algorithms
- Vectorized speedups significantly above expected value (e.g. 4 for AVX) probably mean that scalar algorithms have room for optimization
- Some improvements come from careful use of early returns (see next section!)

Performance effects of early returns

- VecCore::EarlyReturnAllowed() is defined as
  always true for CPUs vs. always false for GPUs
- My previous experience (poorly documented) was that such definition introduces opposing effects on scalar and vectorized algorithms.
- To document this effect, a new templated earlyReturn function is defined (e.g. for T=Real_v):

```
template <typename T>
VECCORE_FORCE_INLINE
VECCORE_ATT_HOST_DEVICE
constexpr Bool_s EarlyReturnAllowedAt(size_t vecSize)
{
#ifdef VECCORE_CUDA_DEVICE_COMPILATION
  return false;
#else
  return vecCore::VectorSize<T>() <= vecSize;
#endif
}

#define EARLYRETURNTHR 1
```

Performance effects of early returns

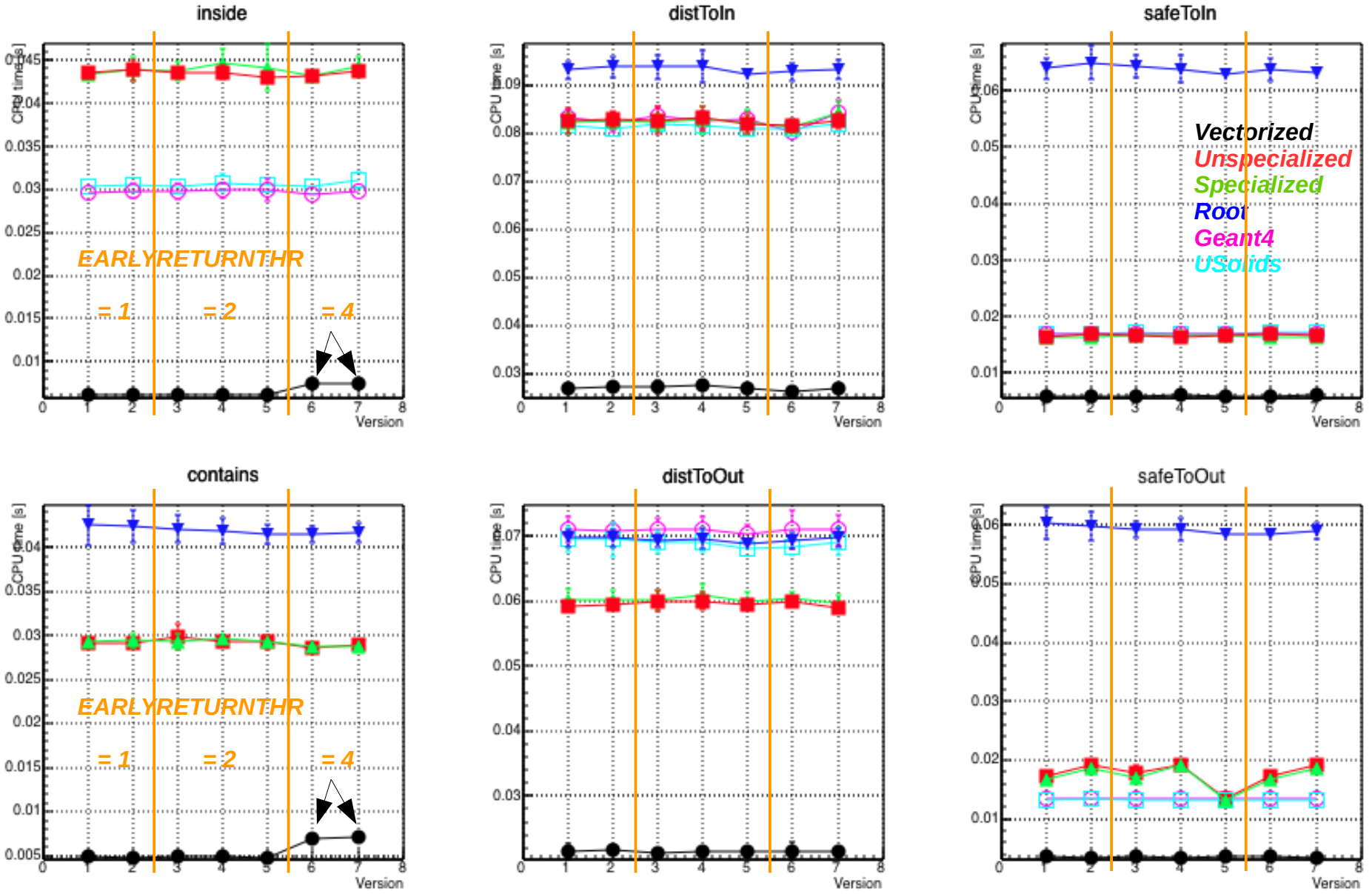
- Look at trapezoid's GenKernelForContainsAndInside():

```
  template <typename Real_v, typename Bool_v, bool ForInside>
  VECGEOM_FORCE_INLINE
  VECGEOM_CUDA_HEADER_BOTH
  static void GenericKernelForContainsAndInside(UnplacedStruct_t const &unplaced, Vector3D<Real_v> const &point,
                                                Bool_v &completelyInside, Bool_v &completelyOutside)
  {
    // z-region
    completelyOutside = Abs(point[2]) > MakePlusTolerant<ForInside>(unplaced.fDz);
    if (vecCore::EarlyReturnAllowedAt<Real_v>(EARLYRETURNTHR) && vecCore::MaskFull(completelyOutside)) {
      return;
    }
    if (ForInside) {
      completelyInside = Abs(point[2]) < MakeMinusTolerant<ForInside>(unplaced.fDz);
    }

#ifndef VECGEOM_PLANESHELL_DISABLE
    unplaced.GetPlanes()->GenericKernelForContainsAndInside<Real_v, ForInside>(point, completelyInside,
                                                                               completelyOutside);
#else
    // here for PLANESHELL=OFF (disabled)
    TrapSidePlane const *fPlanes = unplaced.GetPlanes();
    Real_v dist[4];
    for (unsigned int i = 0; i < 4; ++i) {
      dist[i] = fPlanes[i].fA * point.x() + fPlanes[i].fB * point.y() + fPlanes[i].fC * point.z() + fPlanes[i].fD;
    }

    for (unsigned int i = 0; i < 4; ++i) {
      // is it outside of this side plane?
      completelyOutside = completelyOutside || dist[i] > MakePlusTolerant<ForInside>(0.);
      if (ForInside) {
        completelyInside = completelyInside && dist[i] < MakeMinusTolerant<ForInside>(0.);
      }
      if (vecCore::EarlyReturnAllowedAt<Real_v>(EARLYRETURNTHR) && vecCore::MaskFull(completelyOutside)) return;
    }
#endif

    return;
  }
```

→ *Look at how performance varies with EARLYRETURNTHR value*

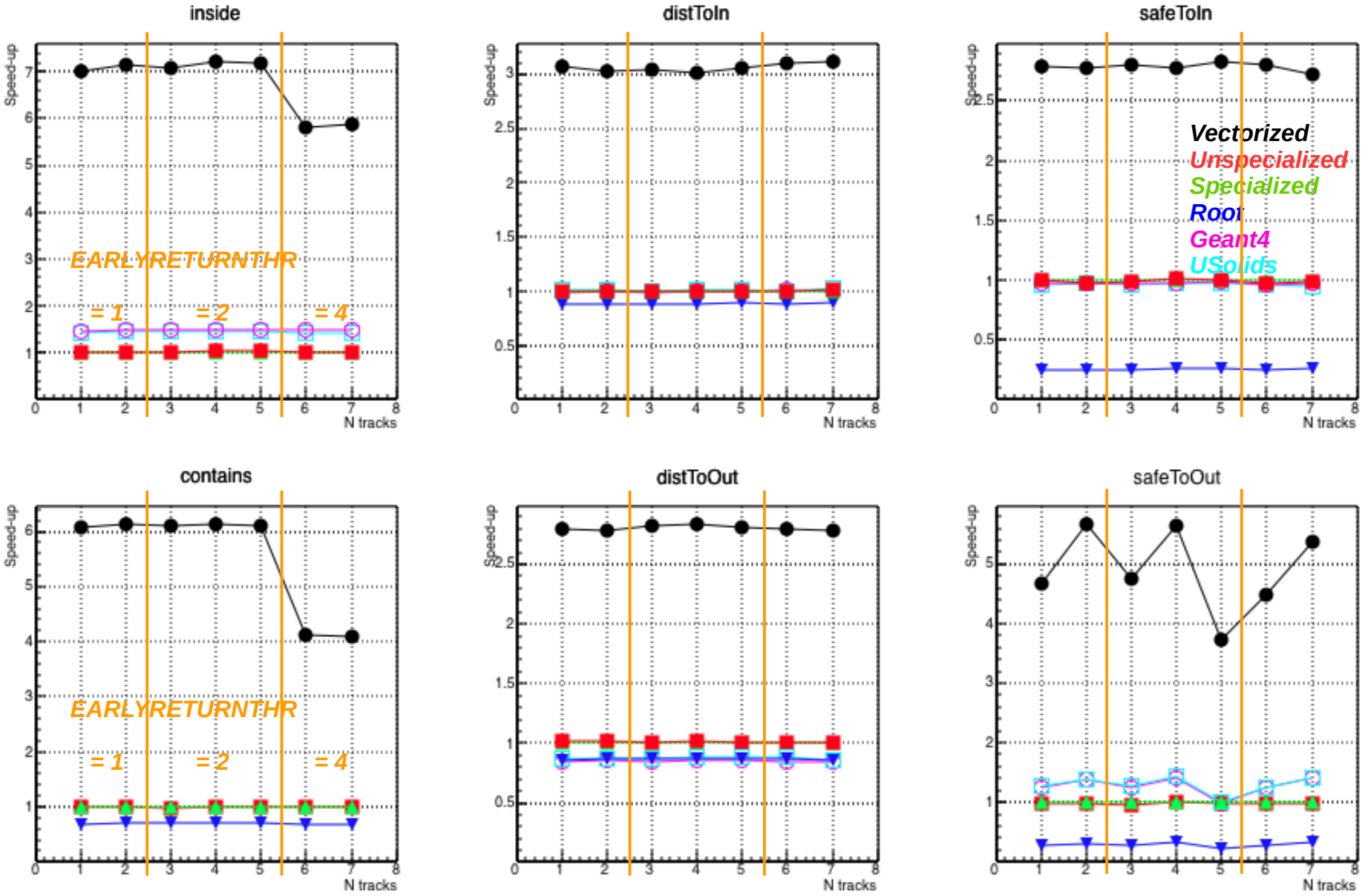
Performance comparisons: CPU times

PLANESHELL=OFF



Performance comparisons: speedups

PLANESHELL=OFF



Suggestions about early returns

- The last two plots show significant overheads from just checking for the conditions for early returns
- Hence the use of early returns should be avoided for very simple functions, like Contains(), Inside() and SafetyToIn,Out() in very simple shapes, as even small overheads produce significant performance degradation.
- Early return checks should be used **very sparingly in vector mode**, unless the checks are true for a significant fractions of the function calls.
- For more complex functions like DistanceToIn,Out(), the overheads can probably be considered small
- The overheads from early return checks in vectorized mode can be minimized (if not completely eliminated) with a smart definition of EarlyReturnAllowed() functions, e.g. always true for scalars, always false for vectors (in CPUs)