

Simulation of photon propagation generated by a particle traversing a crystal of arbitrary shape

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Special thanks

- Dr. Tomáš Sýkora, Faculty of Mathematics and Physics, Charles University, Institute of Particle and Nuclear Physics, SFG committee



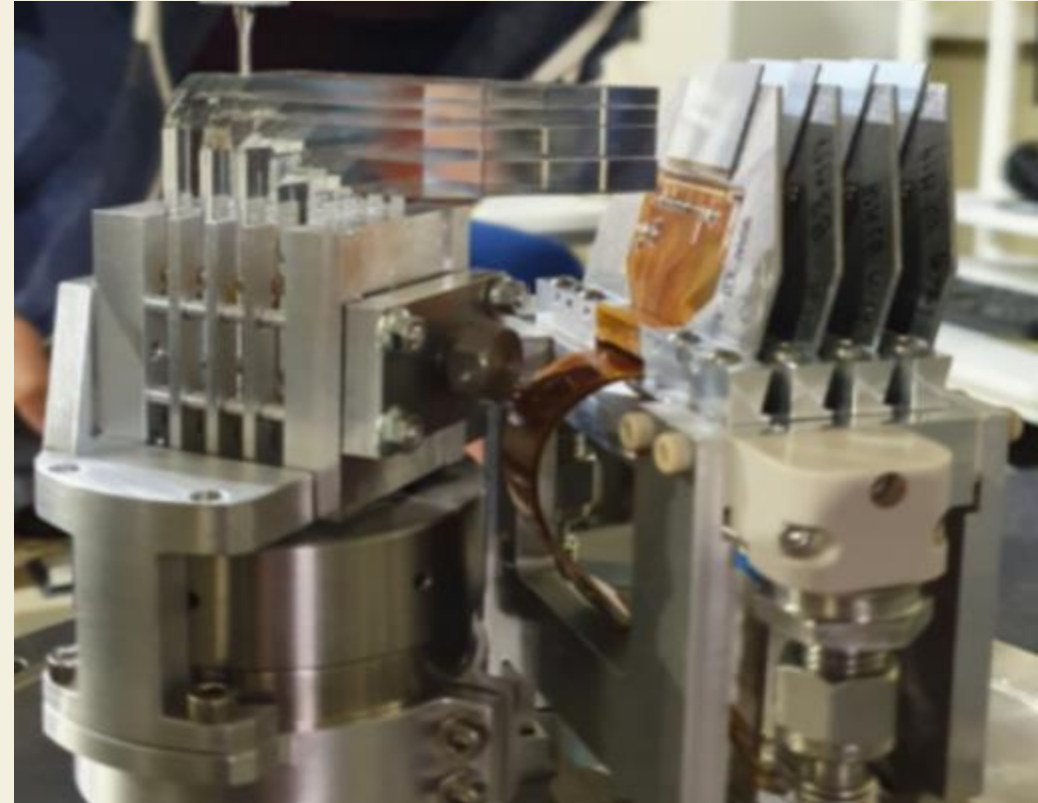
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Introduction of experiment status and goals

- **SFG project:** We are following up on previous works, see citations. Currently, we have managed to simulate a cuboid and a cuboid with a bottom cut-edge. And we have built a simulation macro which evaluates our results for different rotations of the crystal and sizes of the cut angle.

Goals: The original goal of the SFG project was the creation of a simulation for an arbitrary shape of the crystal. We have not reached this point yet, but an attempt to achieve this goal will take place in the near future.

The second, so far unsolved goal is the inclusion of the scintillation process into the simulation. The status is similar as with the simulation of an arbitrary shape.



What I built: a photon tracer for a bar with any end cut



Physics in

120 GeV proton $\rightarrow$ Cherenkov photons:
Frank–Tamm spectrum, Sellmeier $n(\lambda)$, 180–
650 nm, ≈ 100 photons per mm of track.



Transport

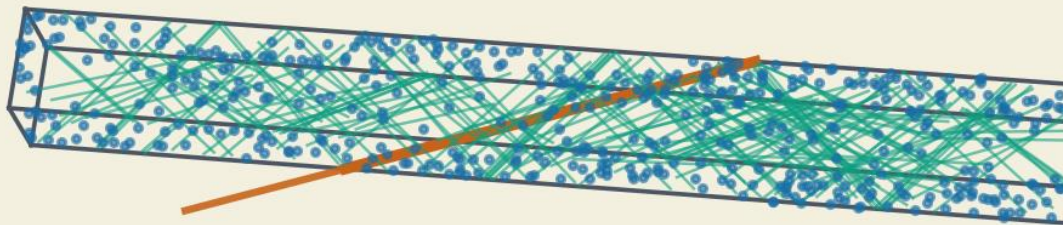
Reflection by reflection: every face tested for
total internal reflection; at the readout an exit
test plus Fresnel transmission; optional
surface loss and bulk absorption.



Out

Fate, arrival time and number of reflections
of every photon; scans over the proton
angle θ and the cut angle θ_F ; a 3-D event
display.

- bar edges
- proton
- photon first legs
- reflection points



*One proton through the bar ($\theta \approx 14^\circ$): the first legs of ≈ 170 photons
and 500 reflection points, drawn from the 3-D export of my event
display.*

Python / NumPy, vectorised over photons: ≈ 0.2 s per proton, ≈ 1 s per (θ ,
 θ_F) point.

Built on the supervisor's August tracer and corrected in three rounds:
exit test at the readout, Fresnel transmission, proton mass.

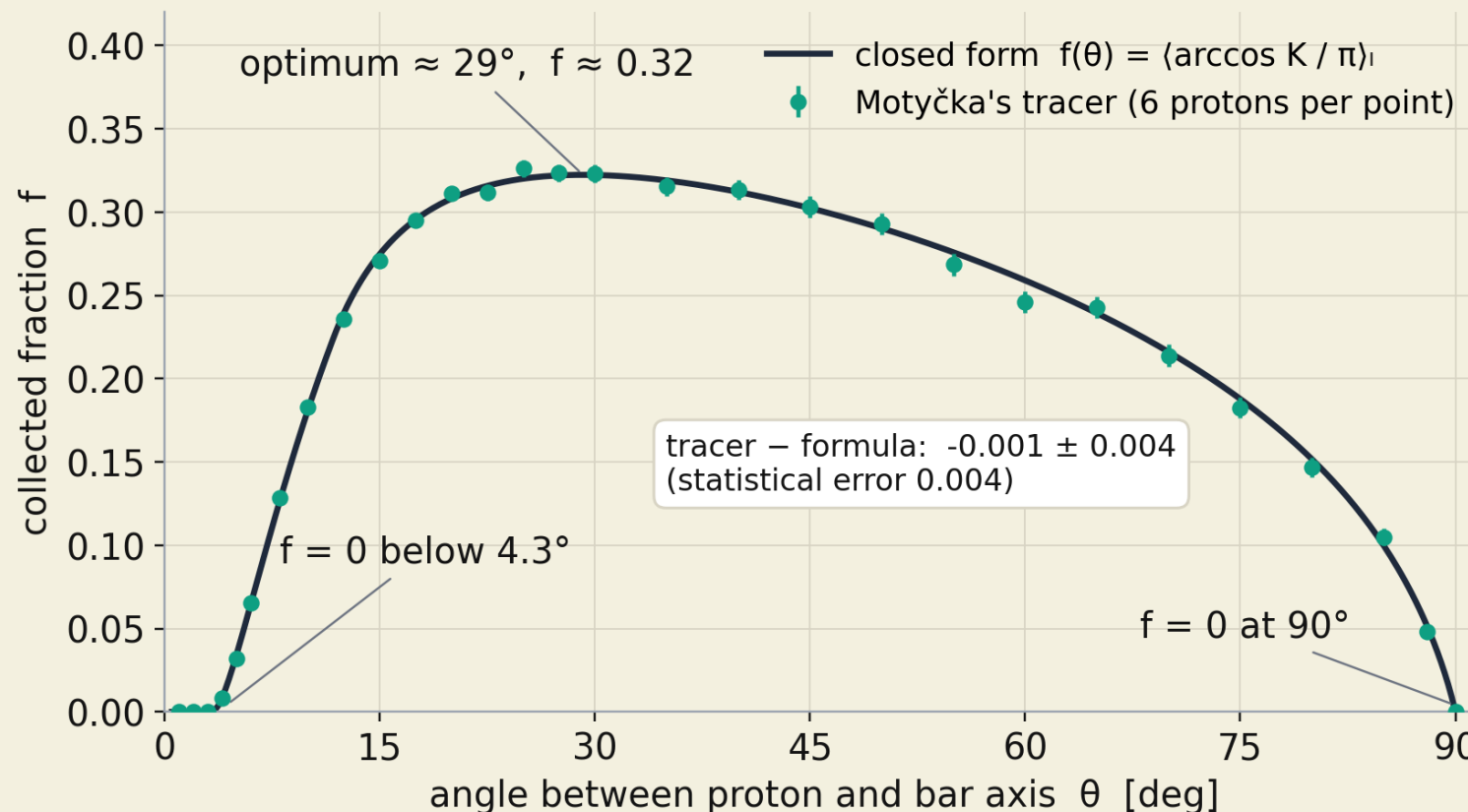
A general, fast tool — checked against two independent calculations on the next slides.

Check 1 — plain bar: tracer vs closed formula

$$\cos \theta_c = 1/n, \quad \sin \theta_{\text{crit}} = 1/n$$
$$\theta_c + \theta_{\text{crit}} = 90^\circ$$

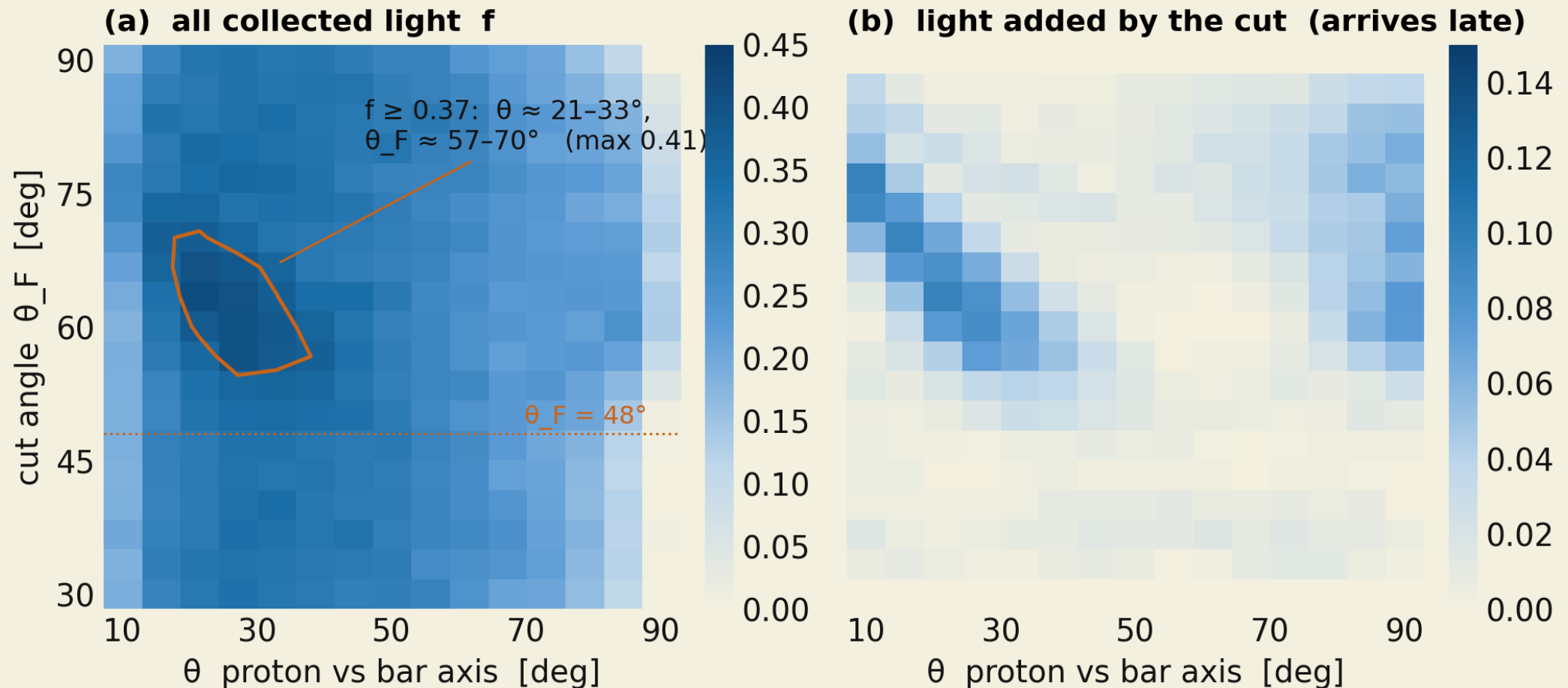
For fused silica $n > \sqrt{2}$. A photon from a proton along the bar meets the end face exactly at θ_c — beyond the critical angle. With an air gap at the readout it never leaves: the bar is blind on-axis.

The supervisor derived a closed formula for the collected fraction $f(\theta)$ of a plain bar. I ran my tracer at 29 angles, 6 protons each, without looking at the formula first.



Agreement -0.001 ± 0.004 — pure statistics. The plain bar collects nothing below 4° or at 90° ; best at $\theta \approx 29^\circ$, $f \approx 0.32$.

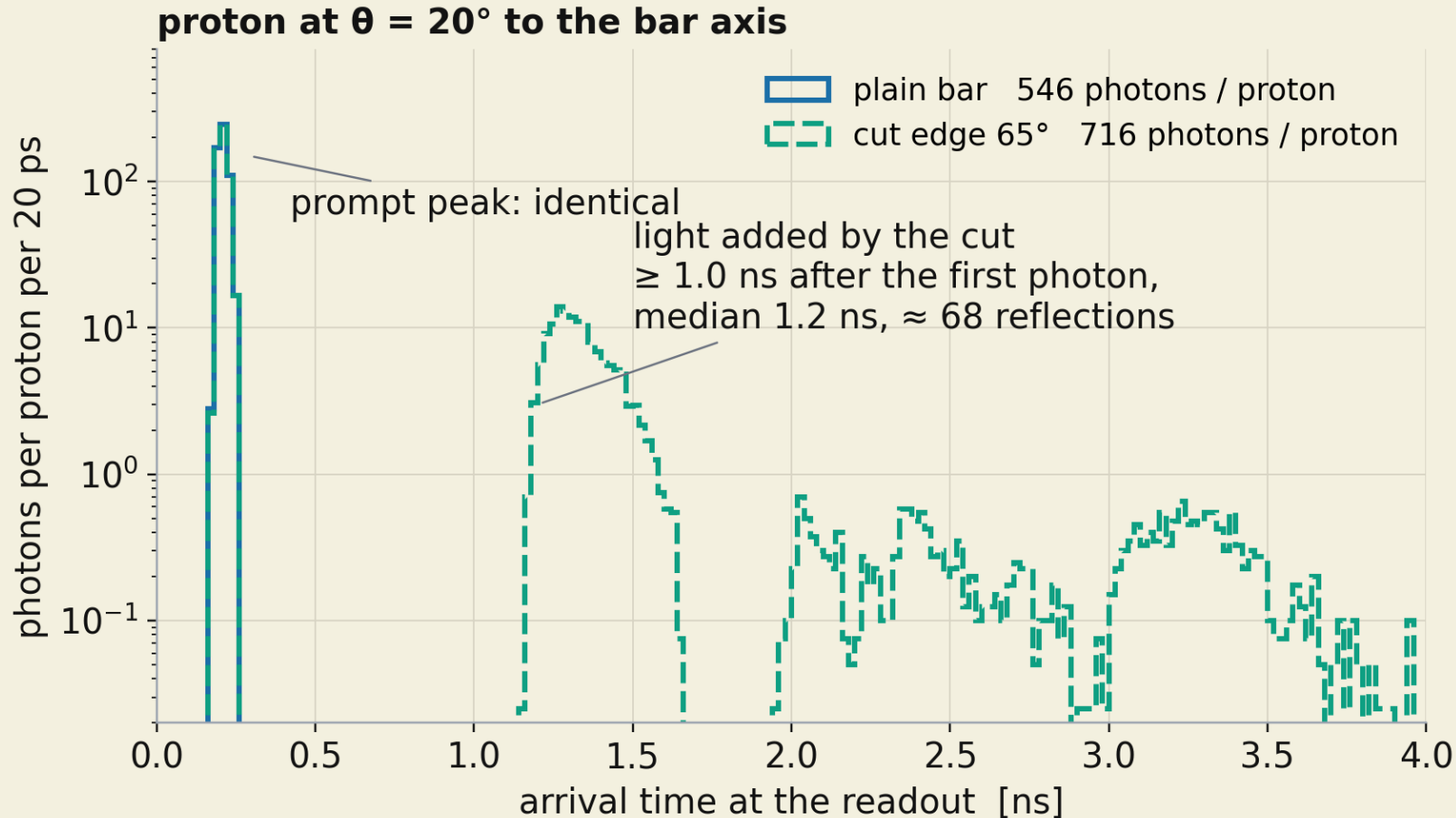
Cut end: where does it help?



285 (θ , θ_F) points $\times$ 4 protons, my tracer. Supervisor's independent deterministic scan – my map: mean +0.000, rms 0.007 = statistics.

Best: $\theta_F \approx 57-70^\circ$ for $\theta \approx 21-33^\circ$: $f = 0.41$ vs 0.32 for the plain bar (+30 %). A cut at the Cherenkov angle, 48° , adds nothing.

...but when does the added light arrive?



+31 %

photons per proton: 546 $\rightarrow$ 716 ($\theta = 20^\circ$, cut 65°)

≥ 1.0 ns late

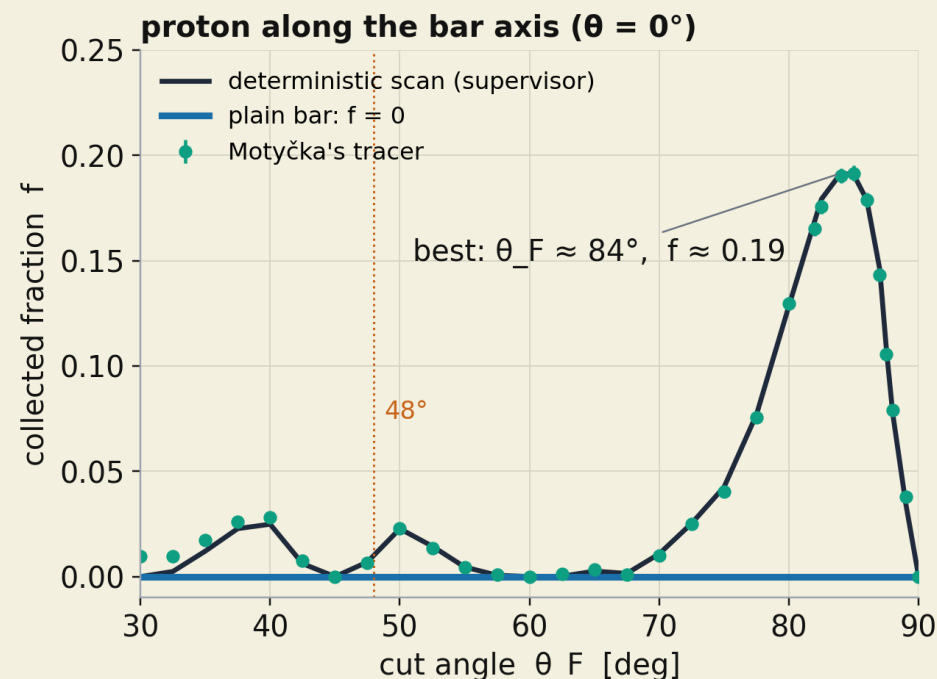
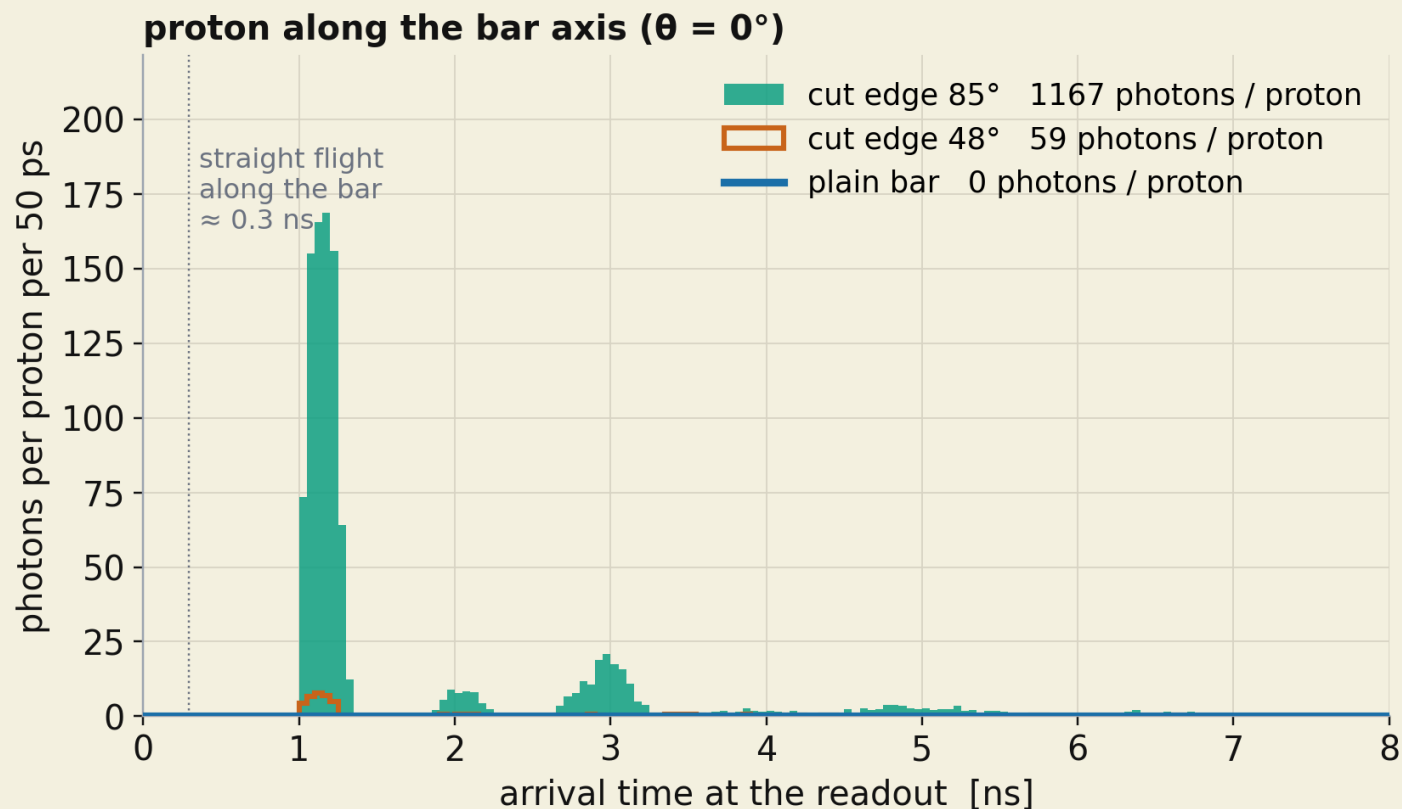
every added photon arrives ≥ 1.0 ns
after the first one (median 1.2 ns)

≈ 68 reflections

for the added light — versus ≈ 4 for the
prompt light

The cut does not touch the leading edge — it adds a late tail. For time-of-flight: no gain. For charge: +30 %.

Proton along the bar: only the cut sees it



Plain bar: 0 of 6100 photons. Shallow cut 85° : 1167 photons per proton — all ≥ 1 ns late, after ≈ 88 reflections. Cut at 48° : 59.

Cut-angle scan at $\theta = 0^\circ$: my tracer and the deterministic scan agree to 0.003. The zeros at 45° and 60° are geometry: at 45° the fold only swaps the two trapped velocity components; at 60° every photon that would be folded steeply enough leaves through the cut face instead.

Take-home



A plain bar can be blind

$\theta_C + \theta_{\text{crit}} = 90^\circ$: with an air-gap readout, light from an on-axis proton is trapped for ever. Best proton angle $\approx 30^\circ$, $f \approx 0.32$. Tracer = formula to 0.004.



The right cut is not θ_C

Cut at $\approx 65^\circ$ for protons at $20\text{--}30^\circ$ ($\approx 85^\circ$ on-axis) adds up to +30 % light; a cut at 48° adds nothing. Independent deterministic scan agrees to 0.007.



All added light is late

≥ 1 ns after the prompt peak, after 70–90 reflections. More charge, not better timing — and it dies quickly with any loss per reflection (1 % loss $\rightarrow$ half of it gone).

Next: the real readout coupling and photodetector efficiency, pitch–yaw maps with the corrected tracer, timing resolution with a realistic photodetector pulse, and an arbitrary convex shape.

Thank you. — Backup slides: parameters, validation details, full maps, sensitivity, code.

Sources

- [1] Dyndal, M., Schoeffel, L., & Sykora, T. (2017). Fast Cherenkov model of optical photons generation and transportation. ATLAS NOTE (ATL-SOFT-PUB-2017-001). CERN.
- [2] Rousselle, O. (2019). Fast simulation of the ATLAS Forward Proton detector. CERN Summer student report. CERN.

Image sources

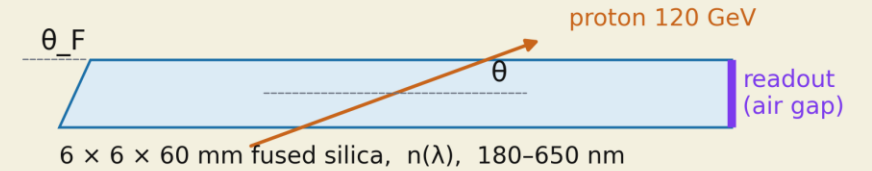
- [1] Charles University, Faculty of Mathematics and Physics. "Logo of the Faculty of Mathematics and Physics." Charles University. <https://www.mff.cuni.cz/> (accessed Sep. 10, 2026).
- [2] ATLAS Collaboration, "ATLAS Forward Proton Time-of-Flight detector performance," CERN, Geneva, Switzerland, Rep. ATL-FWD-PROC-2023-004, 2023. [Online]. Available: <https://cds.cern.ch/record/2880100/files/ATL-FWD-PROC-2023-004.pdf>

Backup

parameters · validation details · full maps · sensitivity · what is in the code

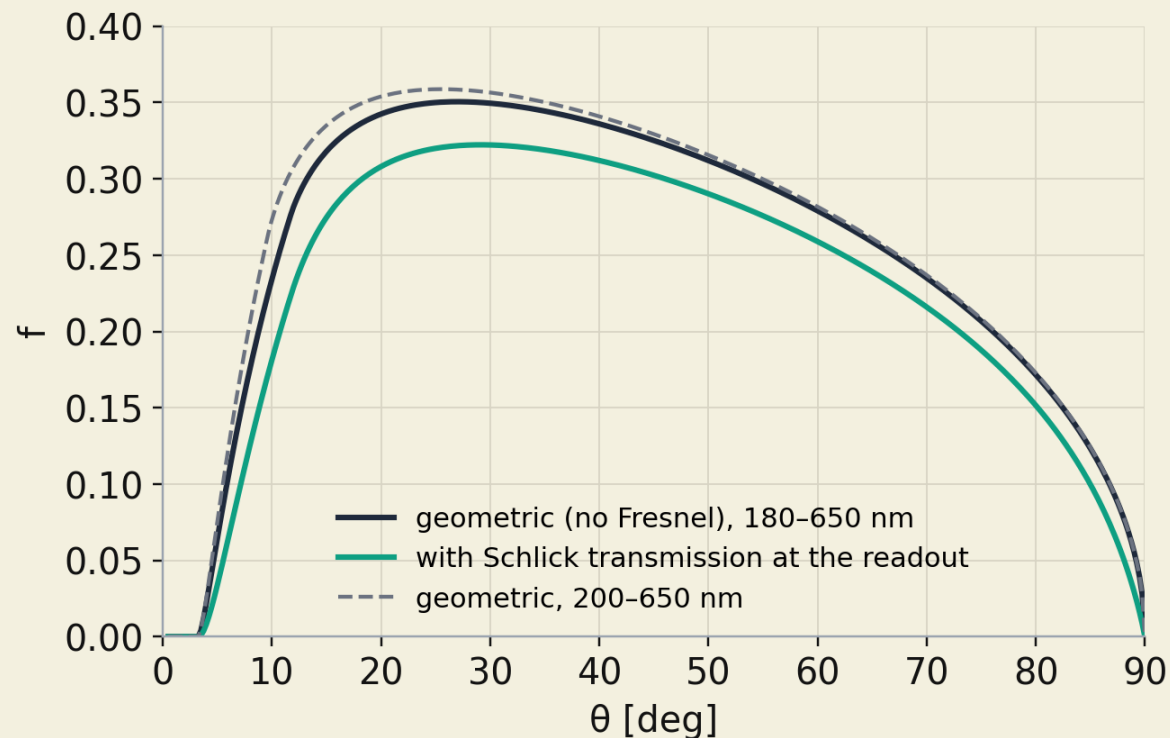
B1 · Parameters and definitions

Radiator	6 × 6 × 60 mm fused silica (amorphous), $n(\lambda)$ from the Sellmeier fit of Malitson
Photons	Frank–Tamm spectrum, 180–650 nm: ≈ 102 photons per mm of track (6 150 for the 60 mm axial chord)
Proton	120 GeV ($\beta = 0.99997$), straight line through the bar centre in the y – z plane, angle θ to the bar axis
Cut	plane at the far end, angle θ_F between the cut face and the bar axis; $\theta_F = 90^\circ$ is the plain bar
Readout	the + z end face, air gap ($n = 1$): a photon leaves only if its incidence is below $\theta_{\text{crit}} \approx 43^\circ$, with Schlick–Fresnel transmission; otherwise it is reflected back
Side walls & cut	ideal: total internal reflection above θ_{crit} , escape below (no Fresnel reflection)
Losses	surface reflectivity $R = 1$ (0.99 in B4), bulk absorption length 10 m, bounce limit 400 (1 000 for the axial runs)
f	detected / generated photons per proton, including the Fresnel transmission; direct = detected without any reflection at the readout face
Statistics	4–6 protons per point (1 800–6 000 photons each): binomial error 0.004–0.010 on f



Sketch to scale (cut drawn at $\theta_F = 65^\circ$). The cut removes the far corner on the side towards which the proton moves.

B2 · Validation details



Unit tests

$f = 0.0000$ at $\theta = 1^\circ, 2^\circ, 3^\circ$ and at 90° (36 000 photons each) — the two blind spots of the plain bar.

Closed form (supervisor)

For $n > \sqrt{2}$ a photon is collected iff $|v_z| > \cos \theta_{\text{crit}} = \sin \theta_C$, so per wavelength $f(\theta) = \arccos(K)/\pi$ with $K = (\sin \theta_C - \cos \theta \cos \theta_C)/(\sin \theta \sin \theta_C)$, then averaged over the Frank–Tamm spectrum. Monochromatic 400 nm: optimum 21.9° , $f = 0.379$. Band 200–650 nm: 25° , 0.359. With Schlick transmission (as in the tracer): 29° , 0.32.

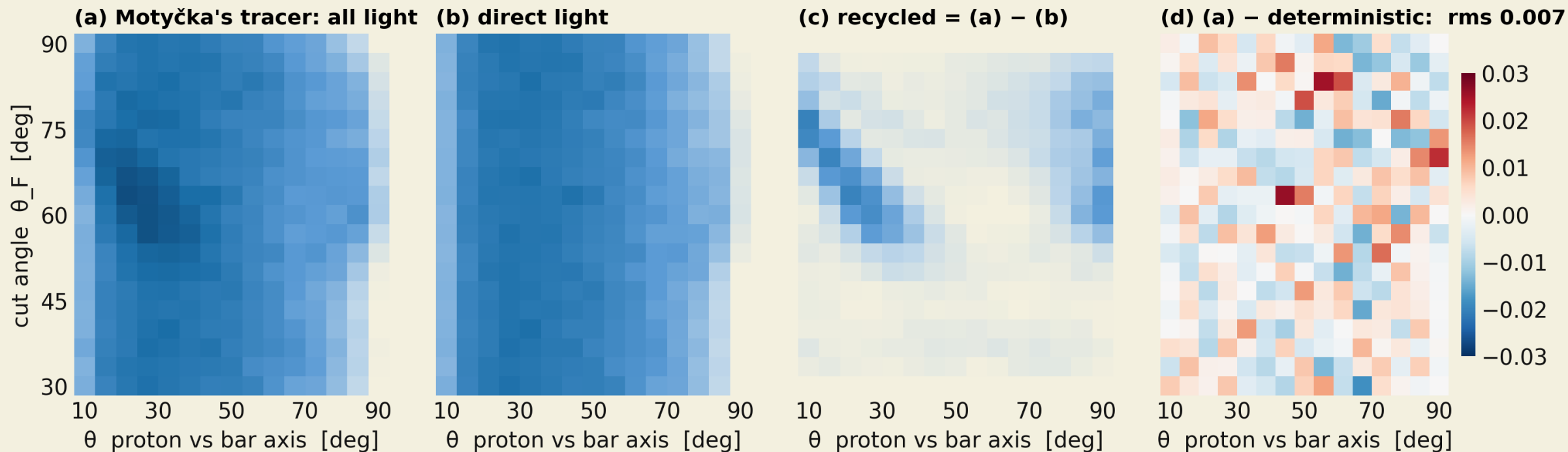
Tracer – formula

29 angles $\times$ 6 protons: mean -0.001 , rms 0.004, statistical error 0.004.
Geometric (Fresnel off): mean -0.001 , rms 0.004.

Deterministic scan (supervisor)

Same physics, no random numbers: rays on an (s, φ, λ) grid of $8 \times 240 \times 16$ per point, weights carried exactly (transmitted part counted, reflected part continues). Independent code.

B3 · Full map and the difference to the deterministic scan



(b) is θ_F -independent up to $\theta \approx 65^\circ$ and equals the plain bar there — all θ_F structure in (a) is recycled light. (d): mean +0.000, rms 0.007, largest |difference| 0.026 over 285 points; the statistical error of one point is 0.007. Grid: $\theta = 10 \dots 90^\circ$ in 15 steps, $\theta_F = 30 \dots 90^\circ$ in 19 steps, 4 protons per point.

B4 · Sensitivity: surface loss, and what is approximated

configuration	R = 1	R = 0.99 per reflection
$\theta = 20^\circ$, cut 65° : f (all)	0.398	0.343
$\theta = 20^\circ$, cut 65° : prompt part	0.304	0.291
$\theta = 20^\circ$, cut 65° : added (late) part	0.094	0.052
$\theta = 0^\circ$, cut 85° : f (all late)	0.189	0.106
$\theta = 0^\circ$, cut 85° : photons per proton	1167	656

Why it matters

The prompt light makes ≈ 4 reflections, the recycled light 70–90: a 1 % loss per reflection costs 4 % of the prompt signal but about half of the recycled one. The gain from the cut is therefore an upper limit until the real surface quality is known.

Approximations in the tracer

- Fresnel at the readout in Schlick's form with the refracted angle (exact limit $R \rightarrow 1$ at θ_{crit} ; the exact unpolarised average is a 4-line change).
- Arrival times use the phase velocity c/n ; the group velocity is 3–5 % lower (0.01–0.05 ns on the times shown).
- Malitson's Sellmeier fit is extrapolated from 210 nm down to 180 nm.
- No photodetector efficiency, no real coupling medium yet — a glued readout ($n \approx 1.5$) would remove the on-axis trap entirely.

Bulk absorption (10 m) is negligible for these path lengths; the bounce limit (400 / 1 000) is reached only by trapped photons.

B5 · What is in the code



cherenkov_sim.py (v05)

sellmeier(λ) · local_planes(a, b, c, θ_F) — six outward planes, cut included · ProtonTrack — chord, β from $E = \sqrt{p^2 + m^2}$ · PhotonGenerator — Frank–Tamm yield, $1/\lambda^2$ sampling, cone around the track · RayTracer.trace — vectorised over photons: nearest plane, TIR test, readout exit test + Fresnel, surface loss, absorption, bounce limit · per-photon table (fate, t_arrival, reflections).



Scans and figures

mc_tools.py — configuration for (θ , θ_F), N protons, counter of readout-face reflections (prompt / late split) · run_all.py — plain-bar scan, 15×19 map, axial θ_F scan, arrival-time runs · make_figs.py — every figure in this talk · ref_tools.py — the supervisor's closed form and deterministic scan used as the reference.



What changed since v04

v04 (August): closed-form transport with three geometry errors — half the light lost, cuboid vs cut inverted. v05: explicit tracer; exit test at the readout (SFG review, September) — without it the axial plain bar gave 70–90 % instead of 0; Fresnel; proton mass; all results reproducible from config + scripts.

Reproduce: `python run_all.py → data/*.csv` (≈ 6 min on 2 cores) · `python make_figs.py → figs/*.png` · `node build.js → this deck`. Motyčka's `cherenkov_sim.py` is imported unchanged.