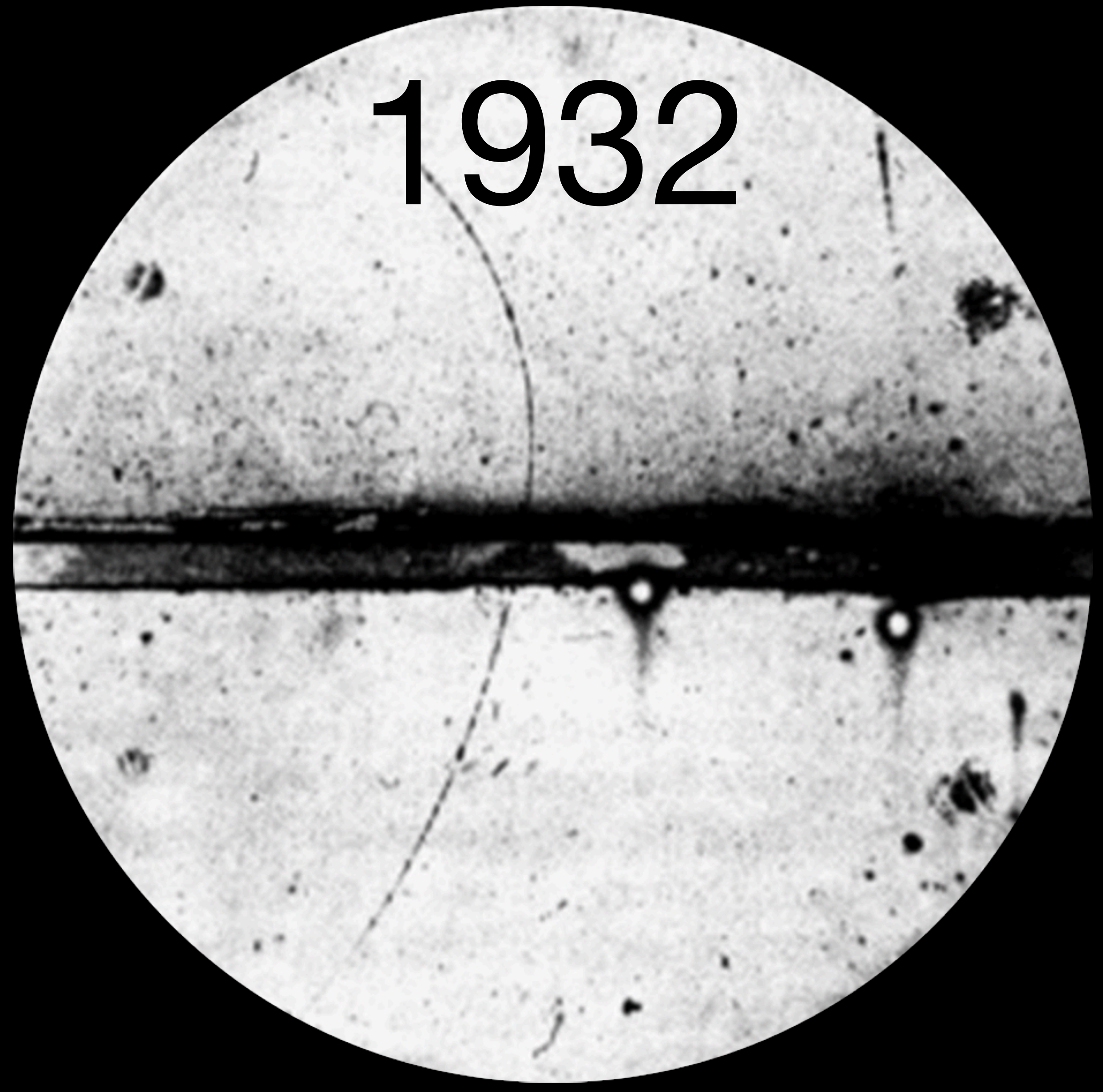
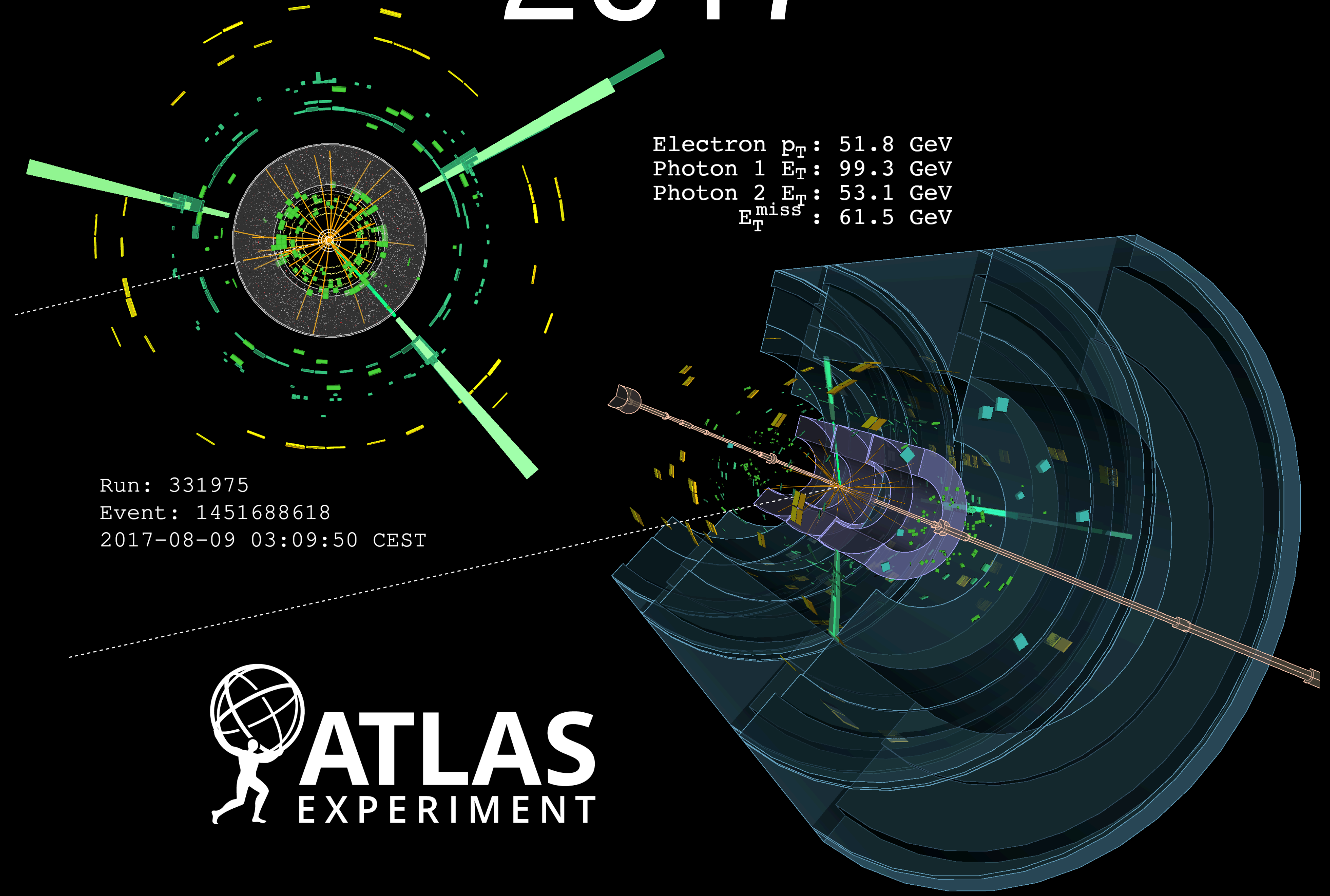
PHYS 7363 - Experimental Particle Detection and Detectors I



Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we "see" subatomic particles, this course is for you!

2017



Detect Identify Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

Multiboson group at SMU

- I joined Southern Methodist University as an Assistant Professor in the fall of 2024
- My research interests lie in multiboson physics, polarization measurements and effective field theories
- I am interested in studying event generators on GPUs and contributing to ATLAS upgrades

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
August	18	19	20	21	22	23	24
	25	26	27	28	29	30	31
September	1	2	3	4	5	6	7
	8	9	10	11	12	13	14
	15	16	17	18	19	20	21
	22	23	24	25	26	27	28
October	29	30	1	2	3	4	5

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	**21**	22	23	24	25	26
	27	28	29	30	31	1	2
November	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	**25**	**26**	**27**	**28**	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

Key dates

- Weeks 1-4: Particle interaction with matter
  - Interaction of charged and neutral particles
  - Particle showers
- Weeks 5-9: Detector technologies:
  - Tracking detectors (gaseous detectors, semiconductor detectors)
  - Particle detection with photons (scintillators, Cherenkov detectors)
  - Calorimetry (electromagnetic and hadronic calorimeters)
- Weeks 10-12: Large and small scale experiments:
  - Triggering and data acquisition
  - Tracking
  - Full reconstruction (particle flow)
- Week 13-15: Preparation for final project:
  - FCC-ee: https://indico.fnal.gov/event/67484/contributions/314057/attachments/187076/257915/US%20FCC%20Tutorial_FullSim.pdf
  - Muon collider: https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/

Resources

- PDG review: Passage of particles through matter
  - https://pdg.lbl.gov/2020/reviews/rpp2020-rev-passage-particles-matter.pdf
- N. Wermes / H. Kolanoski, “Particle Detectors”, Oxford University Press, 2020
- Georg Viehhauser/Tony Weinberg, “Detectors in Particle Physics: A Modern Introduction”, CRC Press, Taylor and Francis Group
- C. Grupen / B. Schwartz, “Particle Detectors”, Cambridge University Press, 2011
- F. Hartmann, “Evolution of Silicon Sensor Technology in Particle Physics”
- A. Strandlie, R. Frühwirth, Pattern Recognition, Tracking and Vertex Reconstruction in Particle Detectors
- LHC experiment design: https://www.nature.com/articles/nature06078

Homework

- Do some literature survey
  - Find the “detector papers” for each of these experiments (ATLAS, CMS, LHCb, Alice)
  - Read the foundational choices made in detector design: why are we building this detector
  - What is the physics motivation
  - Let’s have a 5 min/person discussion on the physics motivation next week
  - For astro-particle, pick one experiment

- Electron-volt (eV) is a unit of energy equal to the amount of kinetic energy gained by a single electron when it's accelerated through an electric potential difference of one volt
- In traditional units = 1.602 X 10^{-19} Joules

Continuing from last time…

How to use magnets to bend beams and collide?

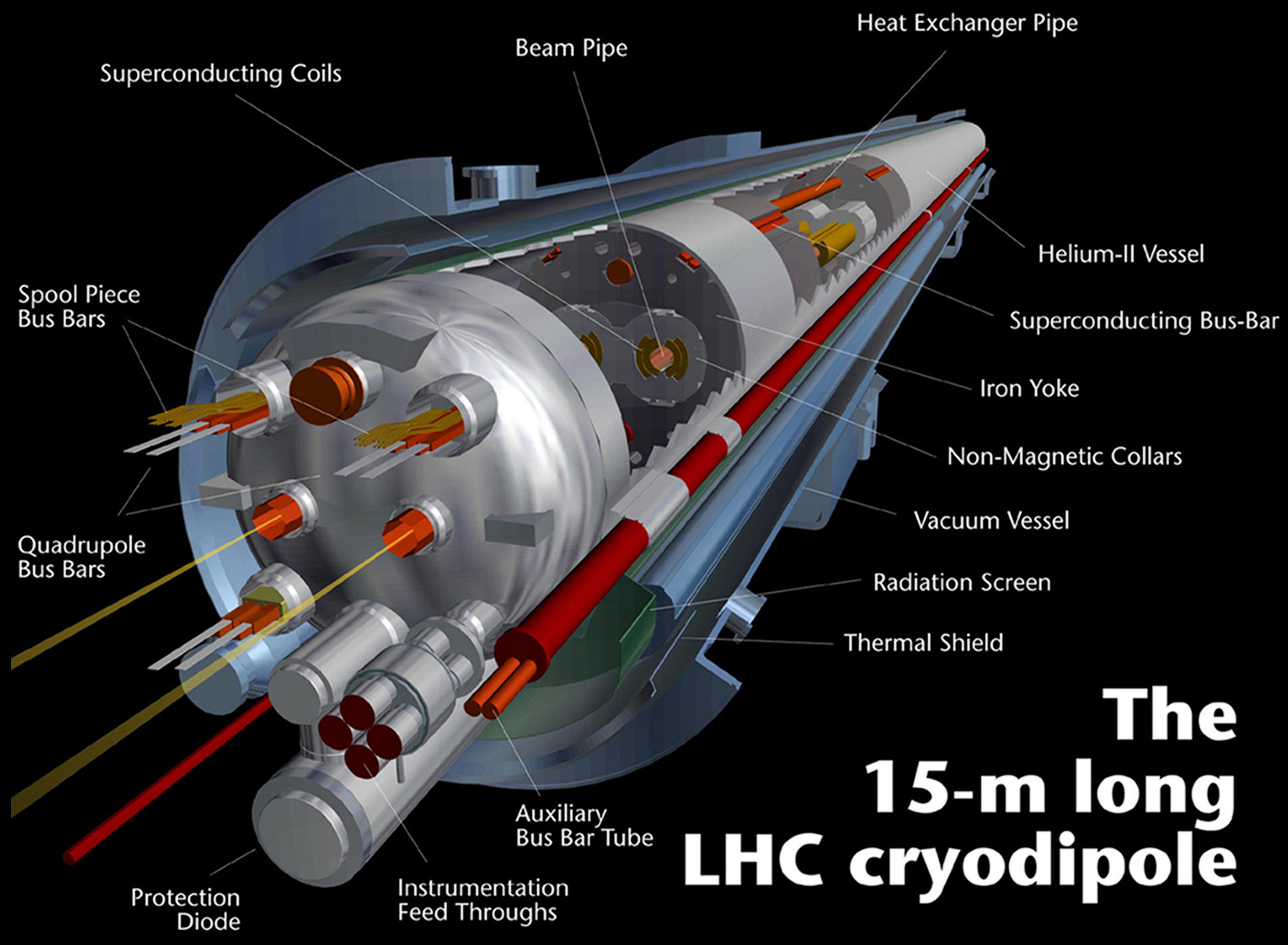
- Dipole magnets are used to bend the paths of the protons around the 27 km ring

- Squeezed for collision into a space narrower than human hair

- Require huge forces to control them

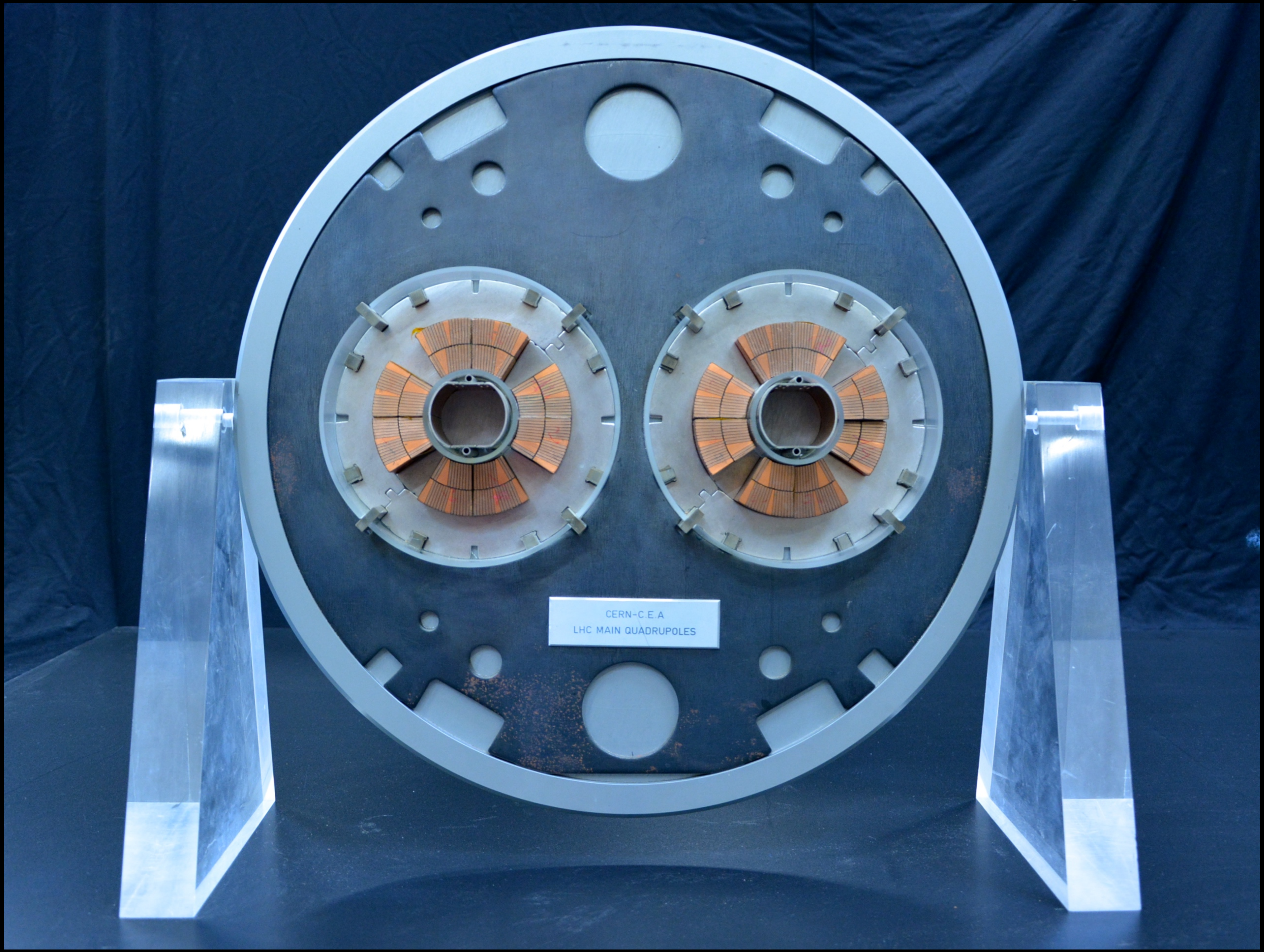
  - Computer-generated image of an LHC dipole magnet

  - Magnets must be cooled to 1.9 K (less than –270.3°C) → superconducting coils can produce the required 8 T magnetic field strength



The 15-m long LHC cryodipole

LHC magnets



A quadrupole focusing magnet

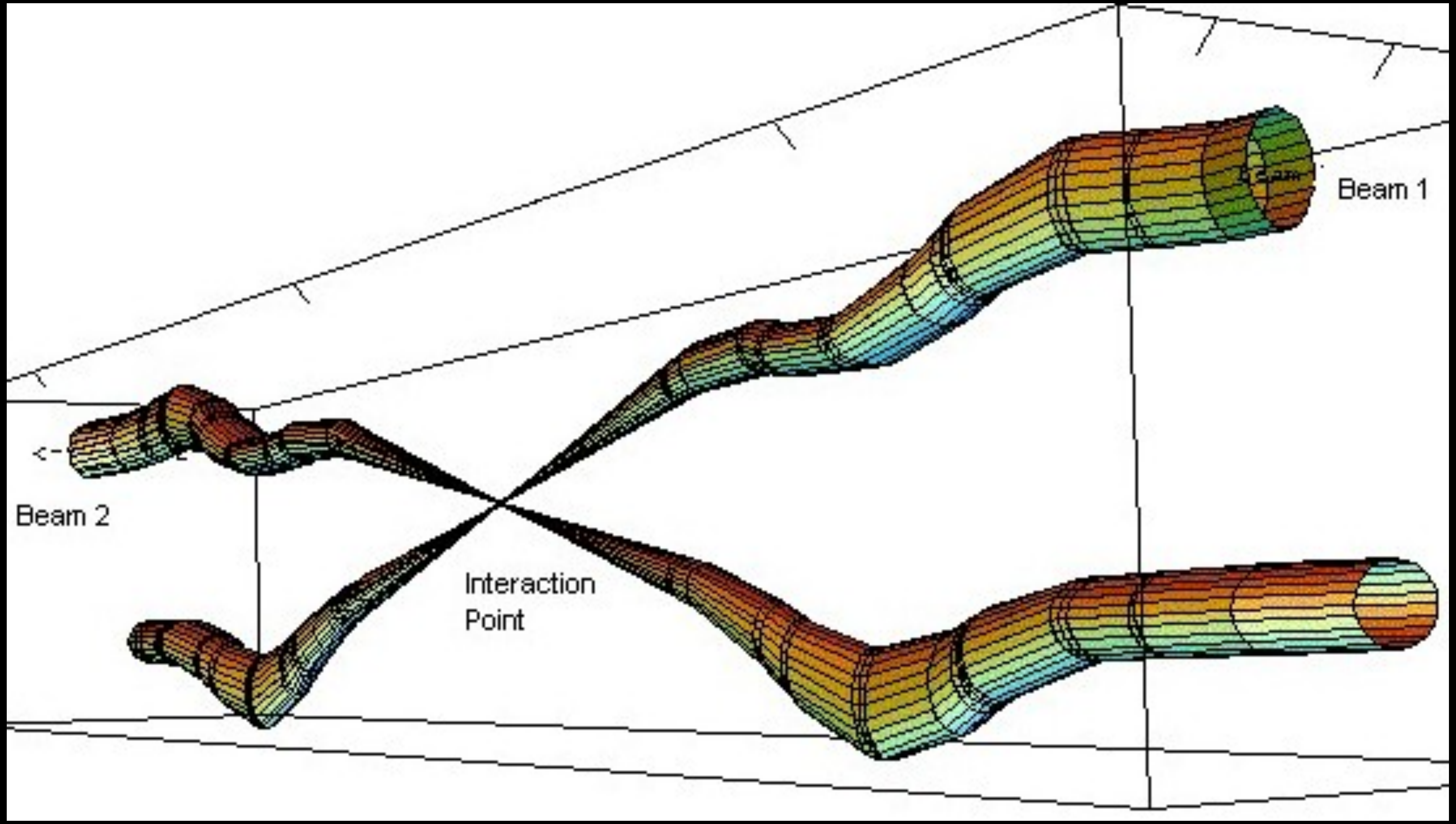
- Use a quadrupole magnet to focus beams
- Quadrupole magnets focus the proton beams
  - Squeeze them so that more particles collide when the beams cross paths
- Precision needed analogous to colliding two knitting needles launched from either side of the Atlantic Ocean

To recapitulate…

- Two kinds of magnets needed

🧲

1. Dipole magnets to bend the beams of protons
2. Quadrupole magnets to focus the proton beams at the detectors



Magnets are key

- LHC uses the tunnel built for a previous generation of experiment
- Often referred to as a “poisoned gift” as obvious way to increase energy = construct a bigger tunnel
- Build stronger magnets!
- Not so easy! Increasing magnetic field by factors of two is highly non-trivial
- Need magnetic fields stronger six times stronger than an MRI machine

Magnets are key

- In 1986, when R&D on the LHC started, three key issues needed to be addressed:
    - High field
    - Superfluid He
    - Two-in-one design
- Revolutionary two-in-one design used → perfect for usage in small tunnels
- Two magnetic channels are hosted in the iron yoke → can be housed with a small cryogenic module
- Originally developed at Brookhaven National Lab but deemed unnecessary at the time → we will build a big tunnel for the Superconducting Super Collider
- Huge win for the LHC when a field of 9 T at 1.8 K was reached in 1987 → most critical milestone

Large Hadron Collider (LHC) timeline

Key Date	Event
March 1984	Should we build a Large Hadron Collider (LHC) in the preexisting tunnel?
January 1987	President Reagan announces support for the Superconducting Super Collider - a circular accelerator with an 87 km circumference — smash particles at 40 TeV. Still need the LHC?
October 1992	The two multipurpose experiments at the LHC publish letters of intent. Specialized experiment (ALICE) follows suit.
October 1993	Superconducting Super Collider project canceled
April 1994	Magnet prototype built and achieves 8.73 T
December 1994	LHC construction is approved by the CERN Council

Large Hadron Collider (LHC) timeline

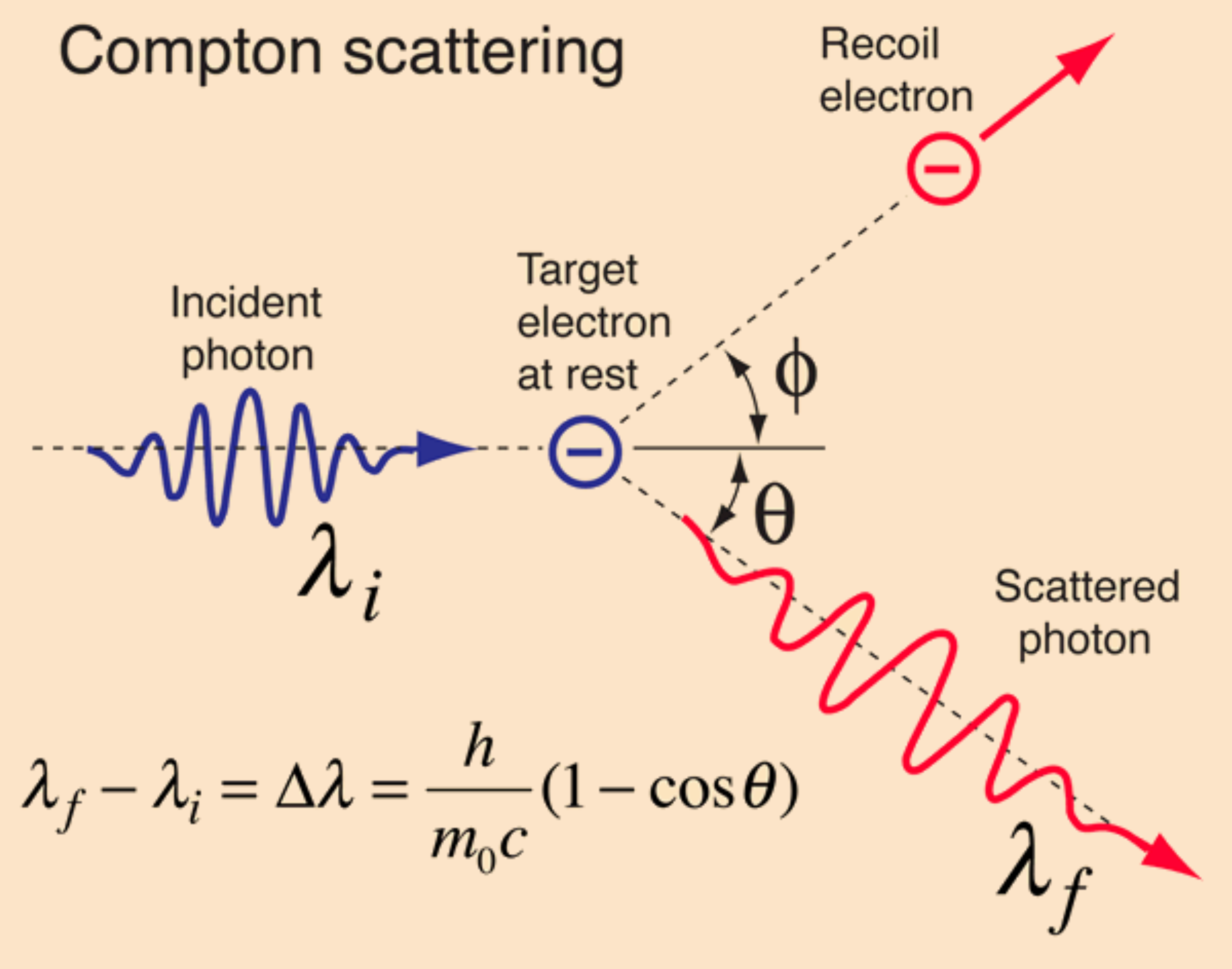
Key Date	Event
October 1995	LHC conceptual design report published
January 1997	CMS and ATLAS experiments approved. Other specialized experiments approved.
December 1997	United States admitted as CERN observer state
July 1998	Gallo-Roman ruins discovered at the CMS site — 6 month delay
May 2002-February 2005	ATLAS and CMS caverns excavated, reinforced and inaugurated
April 2007	The last LHC dipole magnet goes underground
September 10 2008	The LHC starts up

- Where the Superconducting Super Collider was going to be built
- Even the tunnel was partially dug

Particle interaction with matter

Particle detection through interaction

- Particles can be detected by their interaction with matter. Detectors typically use the following processes:
  - Ionization and excitation of atoms in media by charged particles
  - bremsstrahlung: photon radiation emitted by charged particles in the fields of atomic nuclei
  - photon scattering and photon absorption
  - Cherenkov (charged particle traveling faster than speed of light in a medium) and transition radiation
  - nuclear reactions: hadrons (p, n, π, α) with nuclear matter
  - weak interactions constituting the only possibility to detect neutrinos



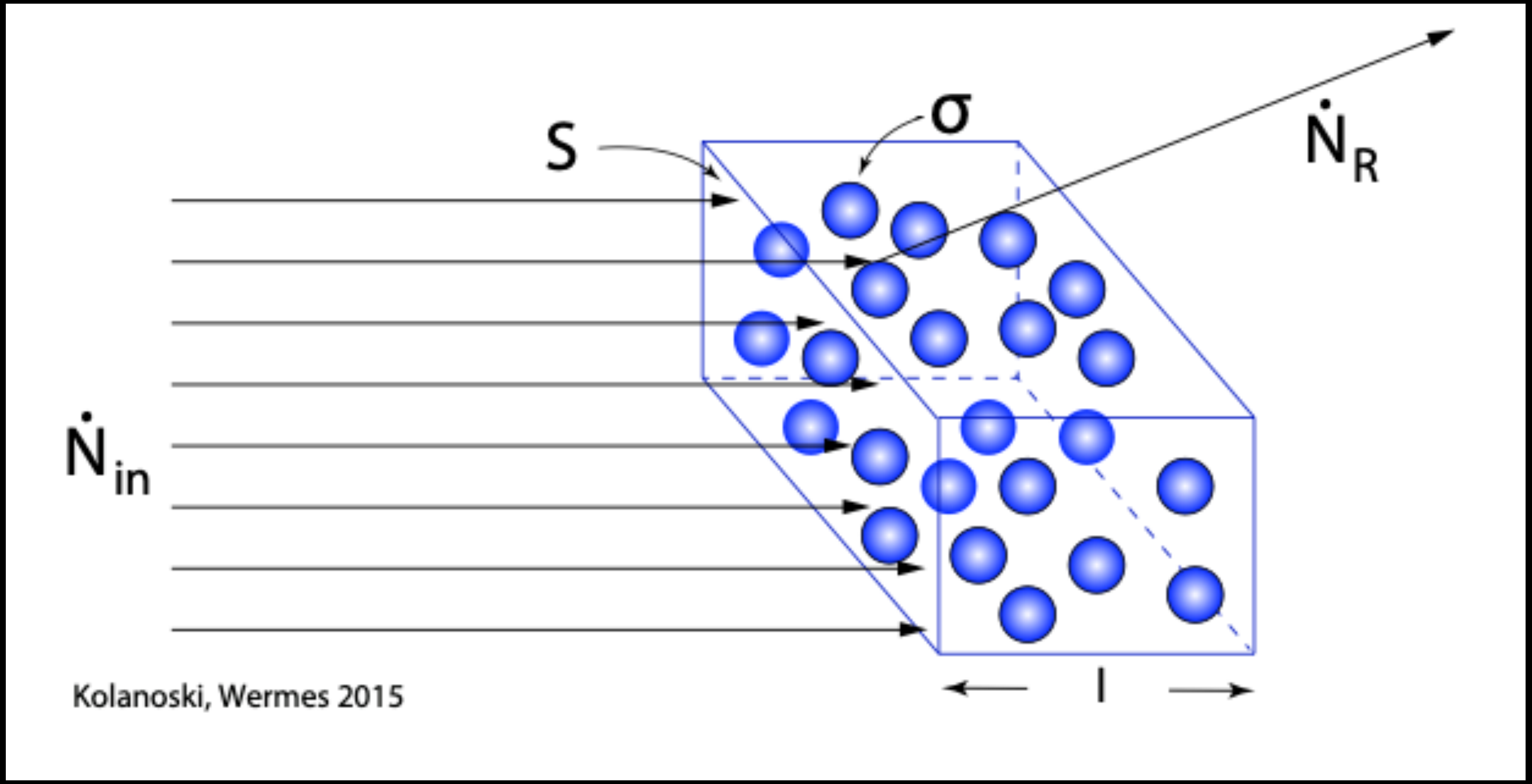
$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

Particle detection through interaction

- Generally, a particle will undergo more than just one interaction process on its path through matter if it is not absorbed in its first interaction. For example, charged particles usually lose energy in a large number of subsequent ionization and excitation interactions with atoms of the medium they pass through.
- The probability that a particle interacts with the atoms of a medium is defined by the cross section of a reaction. The definition of the cross section and related terms will be given in the following section.

Particle detection through interaction: cross sections

- The cross section is a measure of the probability of a particle reaction
- Depends on the kind and strength of the interactions between particles
- Represented by an effective area
- The cross section σ represents the effective area of the target particle as seen by an incoming beam
- Assume beam has no spatial extent



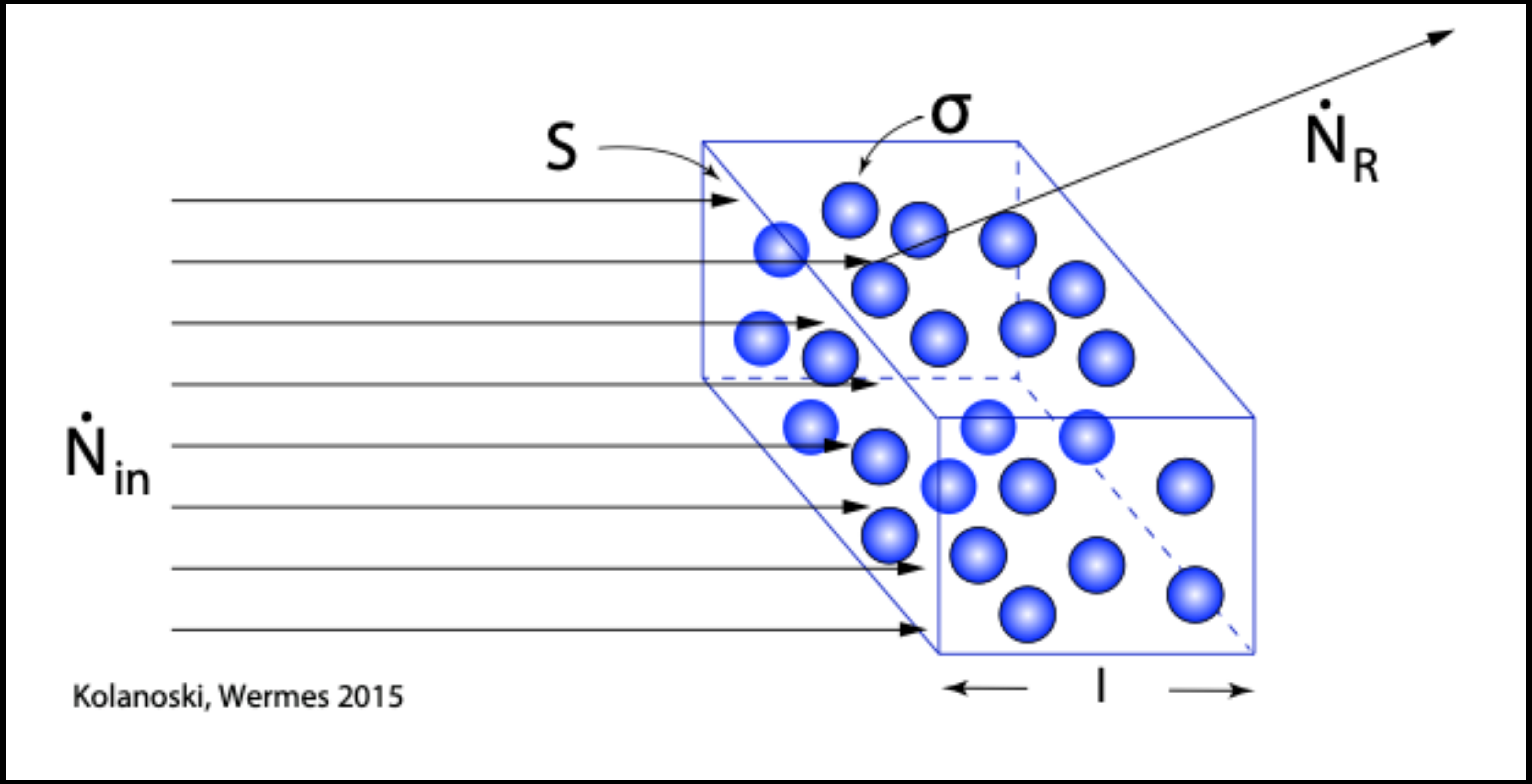
Kolanoski, Wermes 2015

$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_{\text{R}}$: incoming reaction rate

Particle detection through interaction: cross sections

- Beam enters target area with rate $\dot{N}_{\text{in}}$
- There are the following number of particles in the target volume:
  - $N_T = \frac{\rho V}{A} N_A$
  - Target volume, $V = Sl$
  - Target mass density, ρ
  - Atomic mass per mole of the target particles, A
  - $N_A = 6.02214076 \times 10^{23}$/mol



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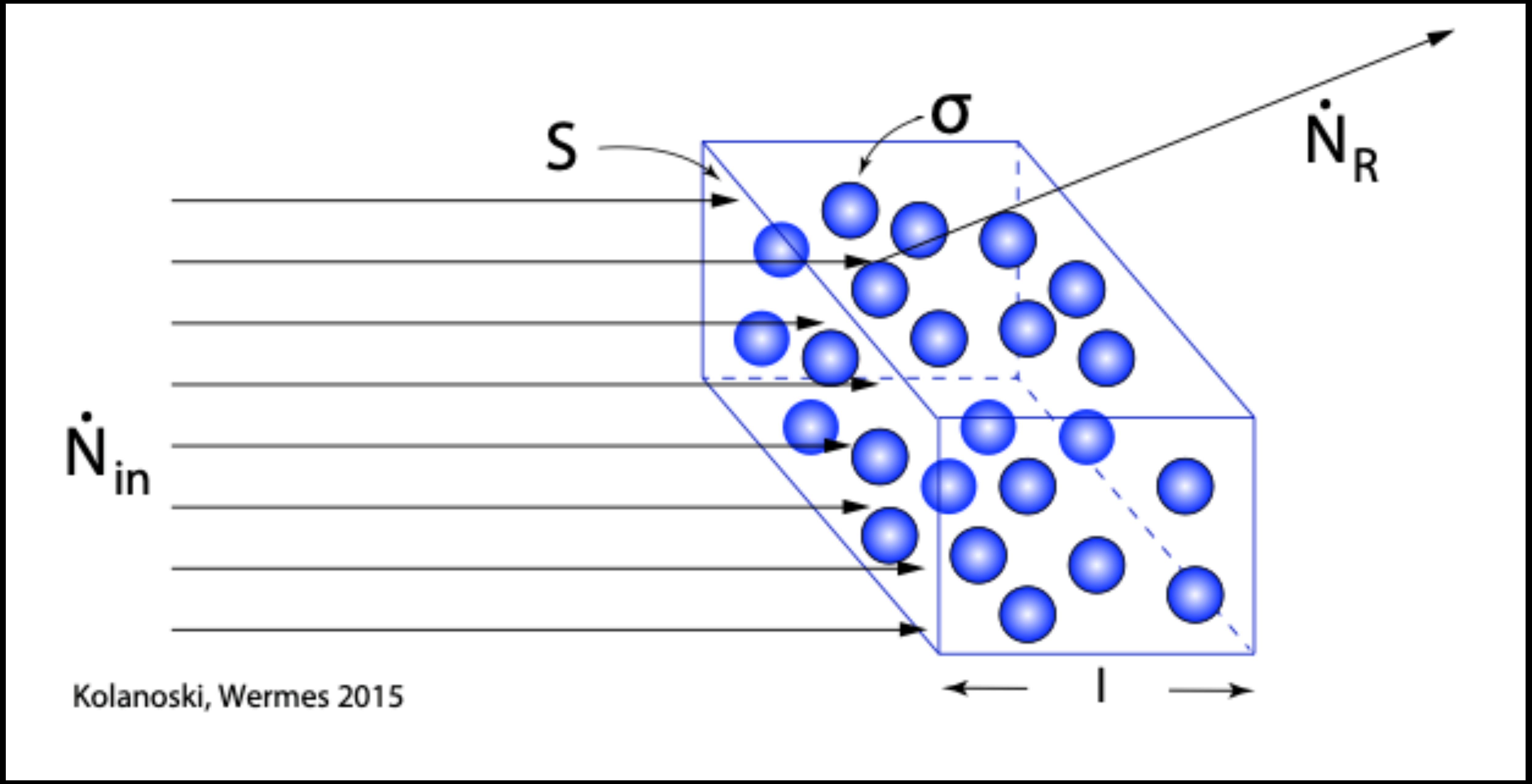
Particle detection through interaction: cross sections

  - $N_A = 6.02214076 \times 10^{23}$/mol is Avogadro's number
  - Used to define mole since 2019
- Target can be any type of particle (atom, molecule, electron)
- Number density given by
  - $n = \dfrac{N_T}{V} = \dfrac{\rho}{A} N_A$
- The incoming beam "sees" a total area:
  - $N_T \sigma$ of target particles
- Probability to hit a particle target
  - $P = N_T \sigma / S$
  - This probability can be expressed by the scattering or reaction rate ($\dot{N}_R$) relative to the rate of incoming beam particles ($\dot{N}_{\text{in}}$)



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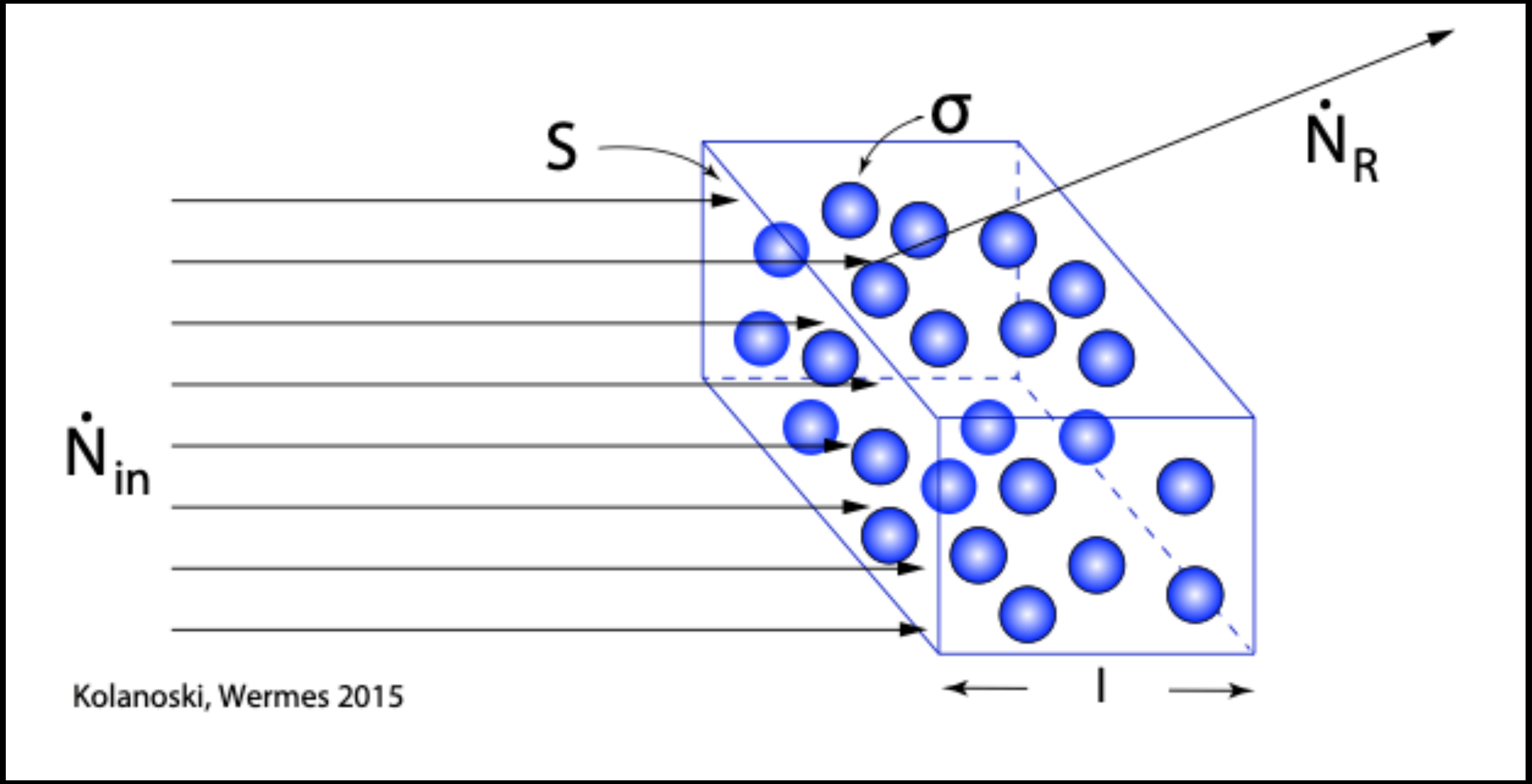
$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_{\text{R}}$: incoming reaction rate

Particle detection through interaction: cross sections

- This probability can be expressed by the scattering or reaction rate ($\dot{N}_R$) relative to the rate of incoming beam particles ($\dot{N}_{\text{in}}$)
  - $P = \dfrac{\dot{N}_R}{\dot{N}_{\text{in}}} = \dfrac{N_T\sigma}{S} = n\sigma l$
  - The cross section (σ) can be expressed as:
    - $\sigma = \dfrac{\dot{N}_R}{\dot{N}_{\text{in}}}\dfrac{1}{nl}$
    - Reaction rate is proportional to the cross section, proportionality constant is L
    - $\dot{N}_R = \sigma L,\ L = \dot{N}_{\text{in}}\ nl$



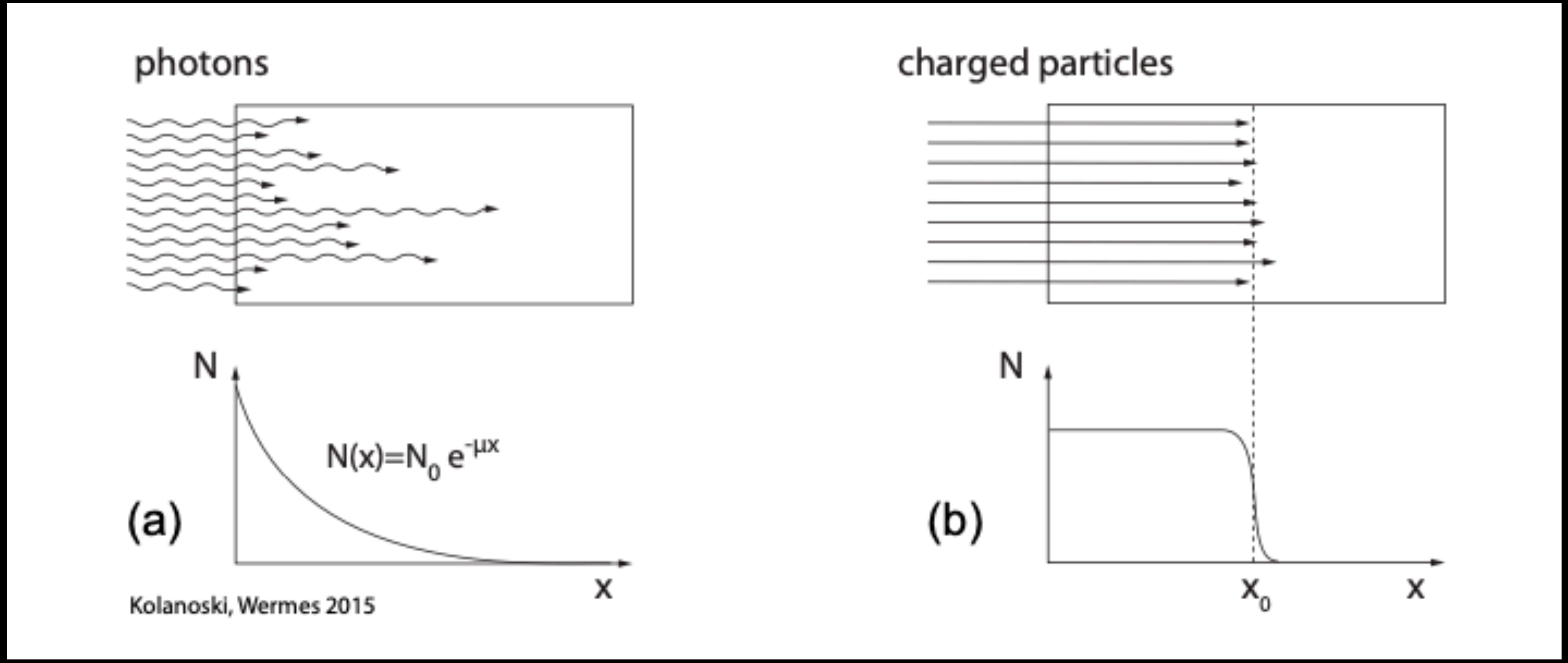
Kolanoski, Wermes 2015

$\dot{N}_{\text{in}}$: incoming particle rate

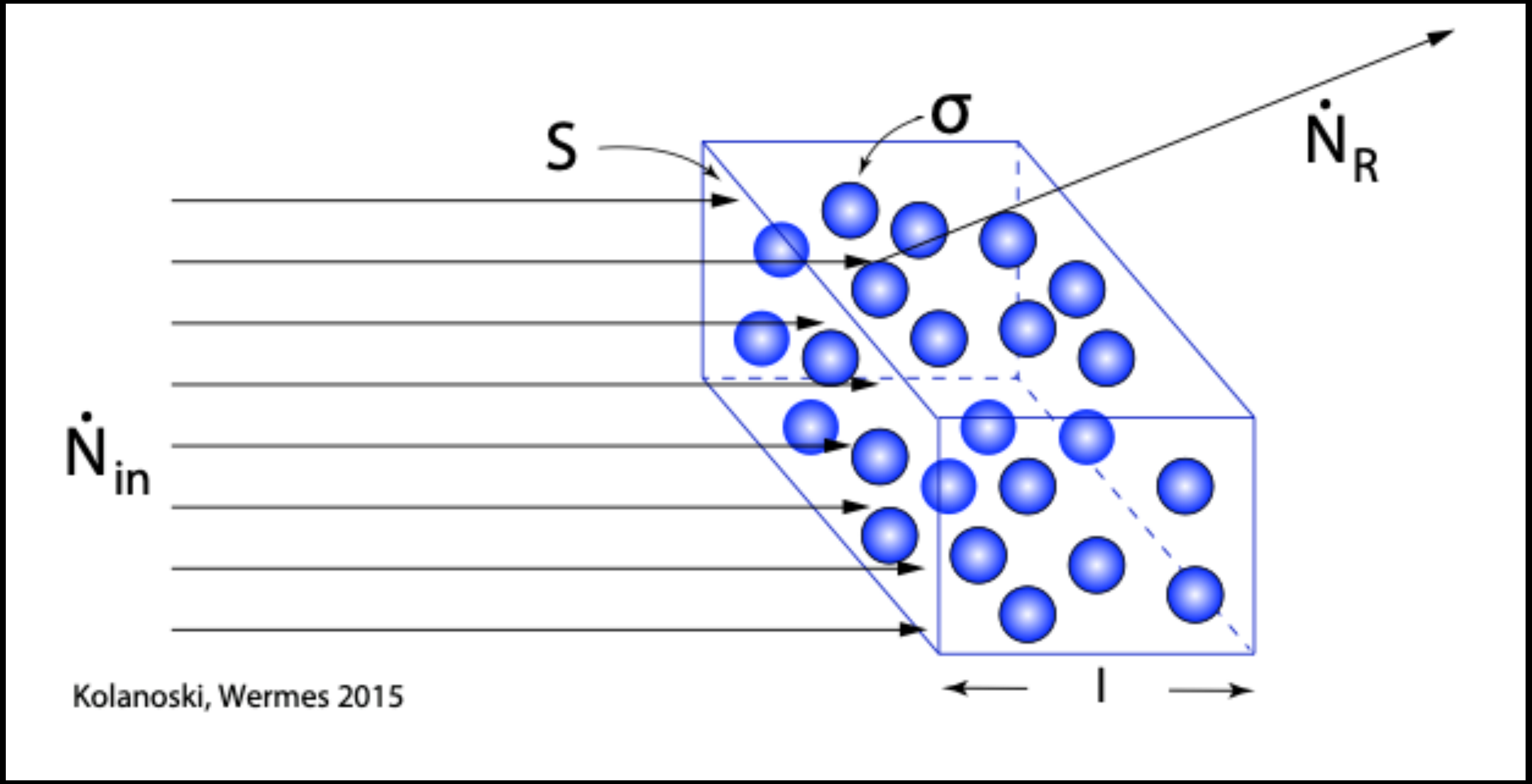
$\dot{N}_R$: incoming reaction rate

Particle detection through interaction: cross sections

- The term luminosity defined here for fixed target experiments is used for collider experiments
- If the target is not sufficiently thin:



Kolanoski, Wermes 2015



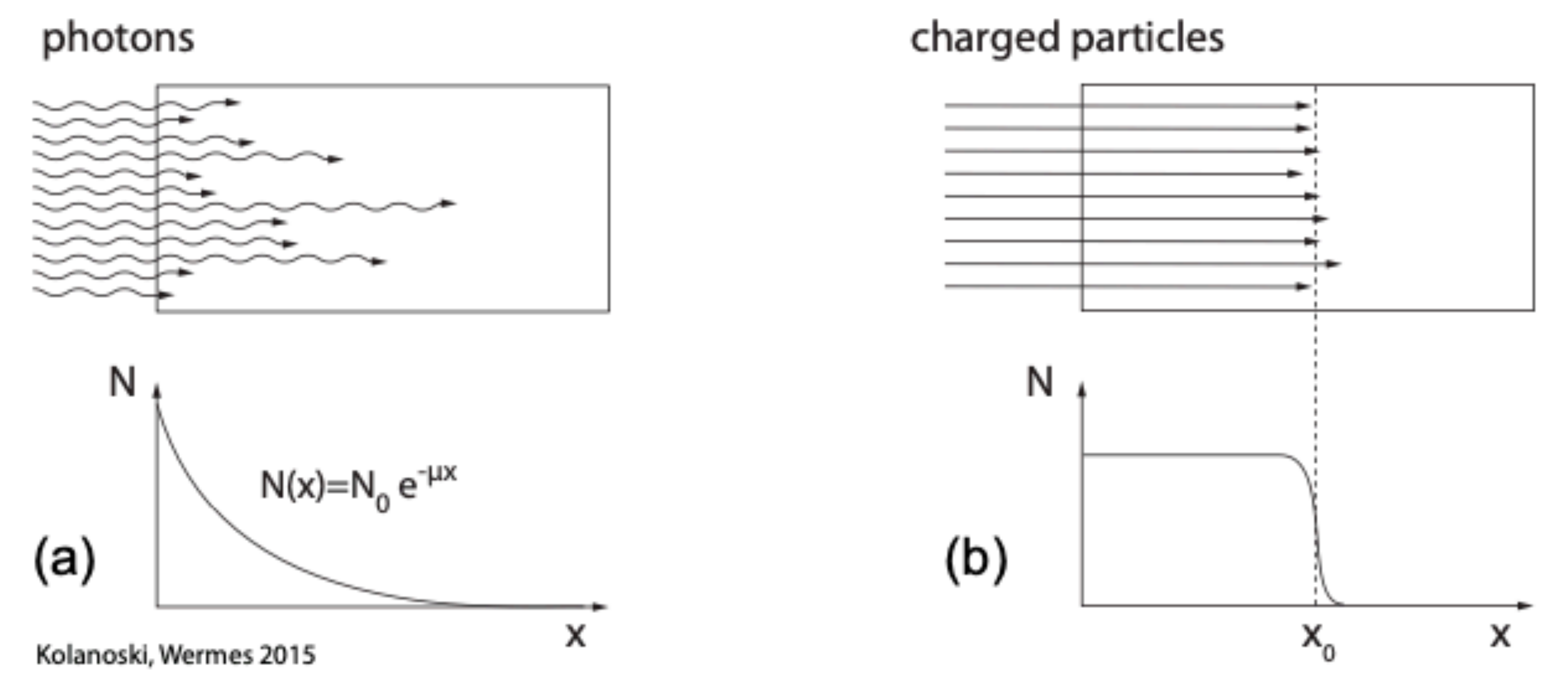
Kolanoski, Wermes 2015

$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_R$: incoming reaction rate

Particle detection through interaction: interaction depth

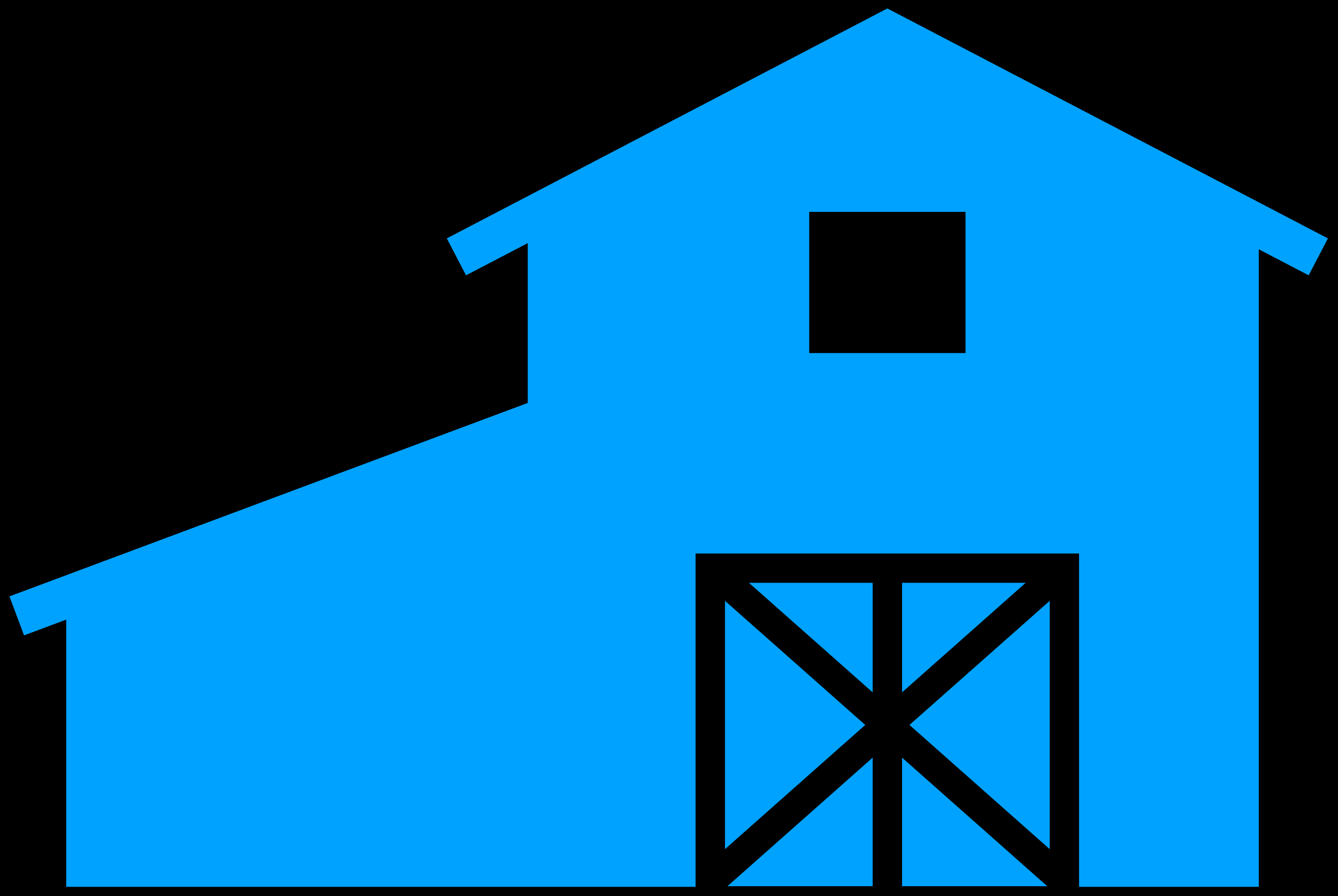
- If the assumption of a thin target is no longer valid
  - Take into account the number of particles $N(x)$ that have thus far not interacted with the target decreases exponentially with the depth x
    - $\dfrac{dN}{N} = -n\sigma\, dx$
    - $N(x) = N_0 e^{-\mu x},\ \mu = n\sigma,\ N_0$ = original number of particles
    - Mean free path: $\lambda = \dfrac{1}{\mu} = \dfrac{1}{n\sigma}$



Kolanoski, Wermes 2015

Particle detection through interaction: units

- The cross section has dimensions of area, units: barn
    - 1 barn = 1 b = 10^{-24} cm^2
- The name originated during the Manhattan Project, where colliding large nuclei was considered as easy as “hitting the side of a barn”



Energy loss of charged particles by ionization

- When penetrating a medium, charged particles lose energy by ionisation and excitation of the medium's atoms
- The energy loss per path length is described by the Bethe-Bloch formula
- Energy loss of a particle passing through matter arises from a sequence of individual stochastic processes
- The average energy loss per path length depends on the properties of the medium a, mass of the particle M and the velocity of the particle, β
  - $$-\left\langle \frac{dE}{dx} \right\rangle = n \int_{T_{min}}^{T_{max}} T \frac{d\sigma_a}{dT}(M, \beta, T)\ dT$$
  - Here n is the target number density and $d\sigma_a/dT$ (differential cross section for a loss of kinematic energy T in the collision)
  - The integral from T_{min} to T_{max} comprises the region of all possible energy transfers