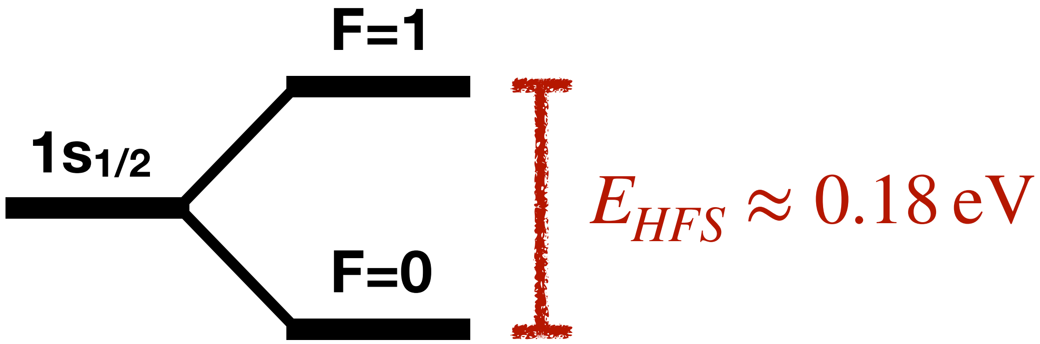
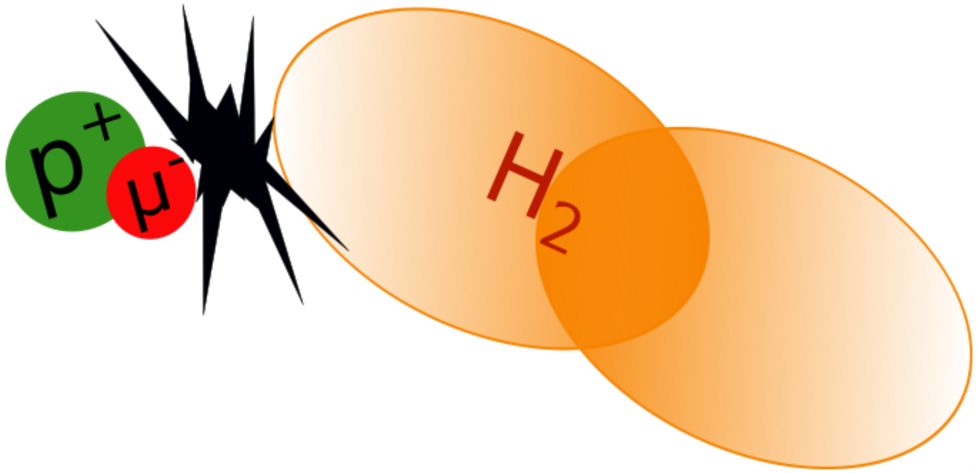
Simulation of μp diffusion in the HyperMu target

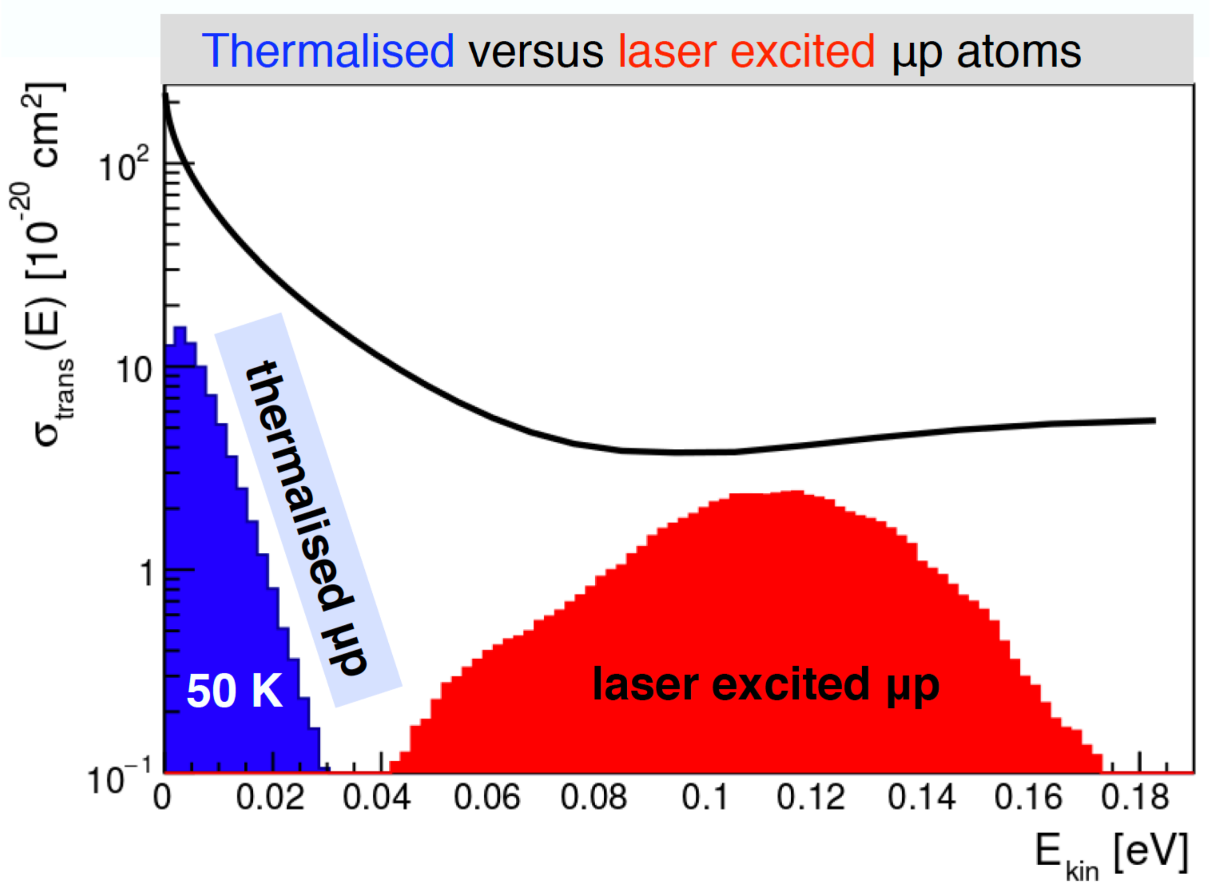
LTP Seminar 28 October 2019

Jonas Nuber





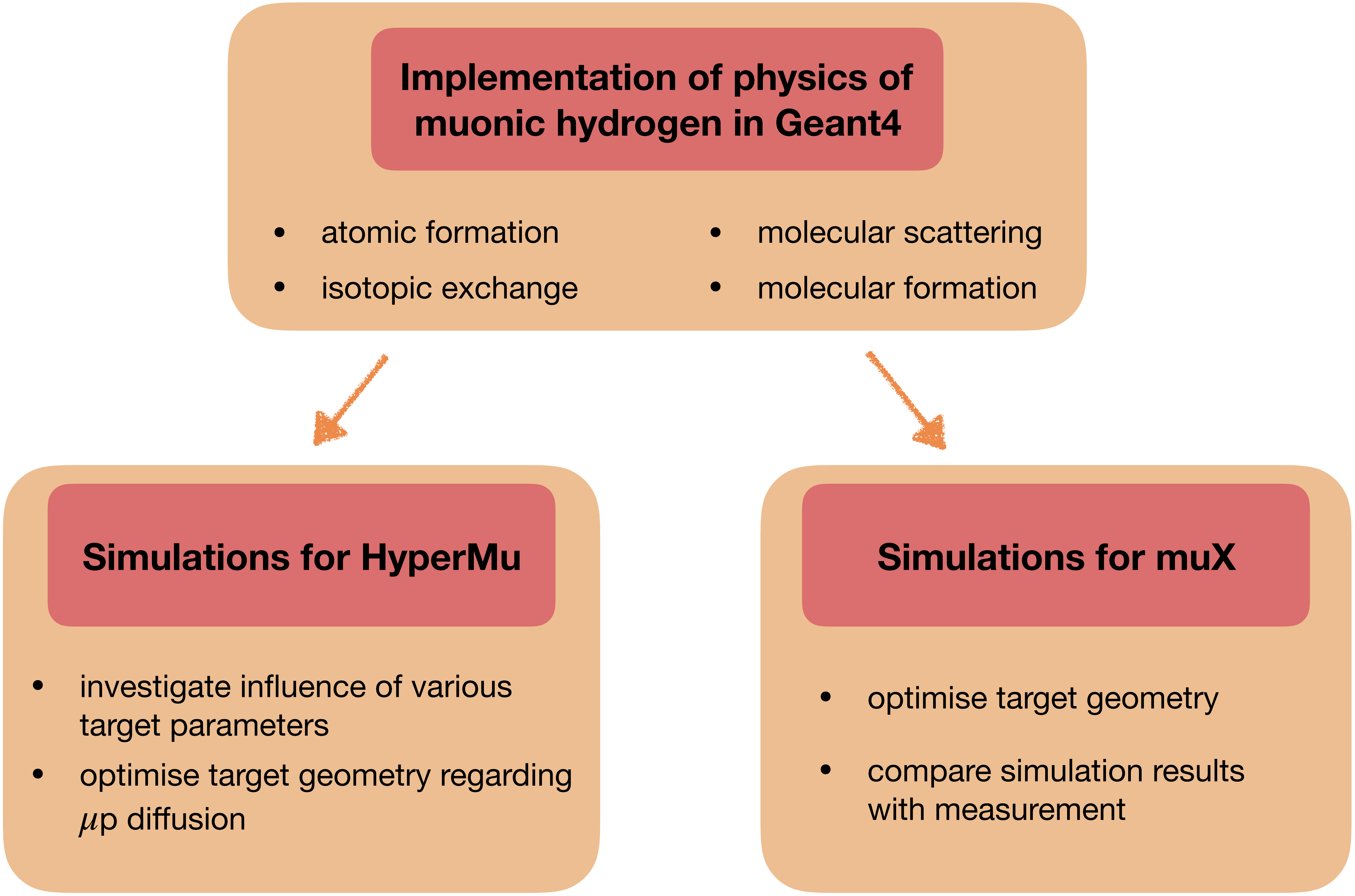
- Collisional quenching (F=1→F=0) of μp in H_2 is crucial part of measurement



- Energy kick of ~0.1 eV distinguishes excited from non-excited μp atoms

Diffusion of μp atoms in H_2 gas is central for the measurement

The μp / μd diffusion project



Implementation of physics of muonic hydrogen in Geant4

- atomic formation
- isotopic exchange
- molecular scattering
- molecular formation

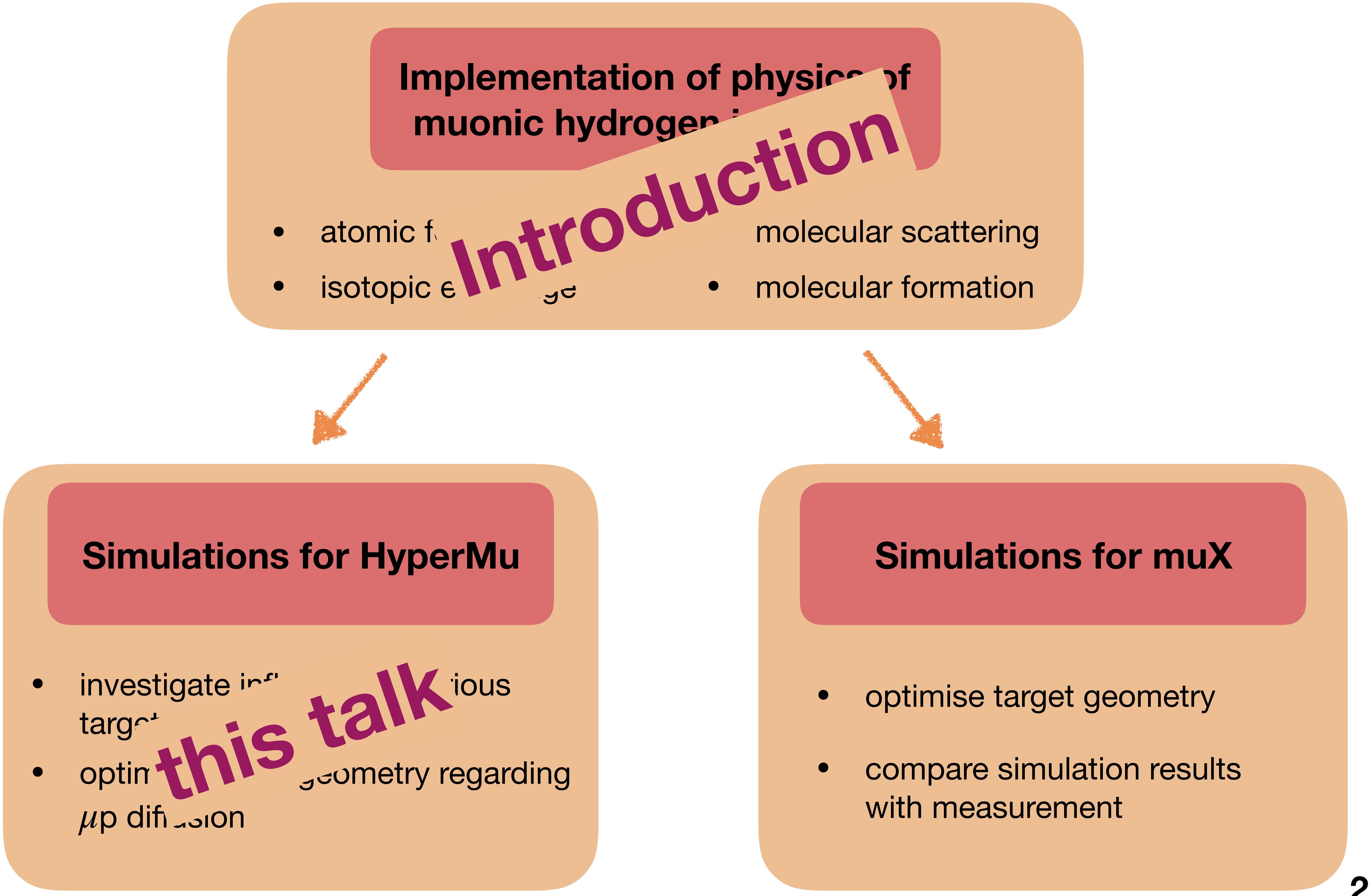
Simulations for HyperMu

- investigate influence of various target parameters
- optimise target geometry regarding μp diffusion

Simulations for muX

- optimise target geometry
- compare simulation results with measurement

The μp / μd diffusion project



Implementation of physic of muonic hydrogen i

Introduction

- atomic f
- isotopic e ge
- molecular scattering
- molecular formation

Simulations for HyperMu

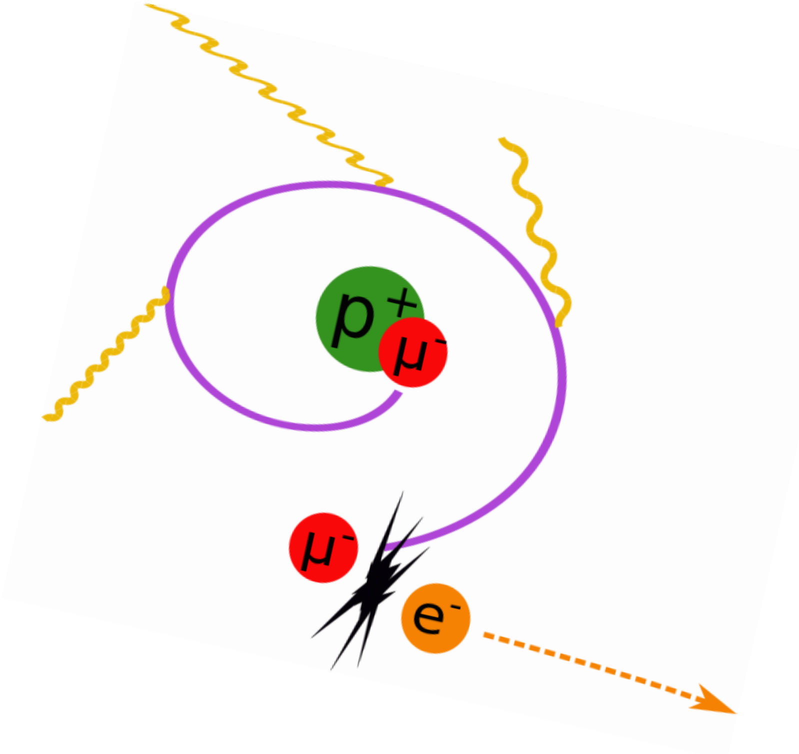
this talk

- investigate in ious targ
- optim geometry regarding μp dif sion

Simulations for muX

- optimise target geometry
- compare simulation results with measurement

Negative muons in hydrogen gas



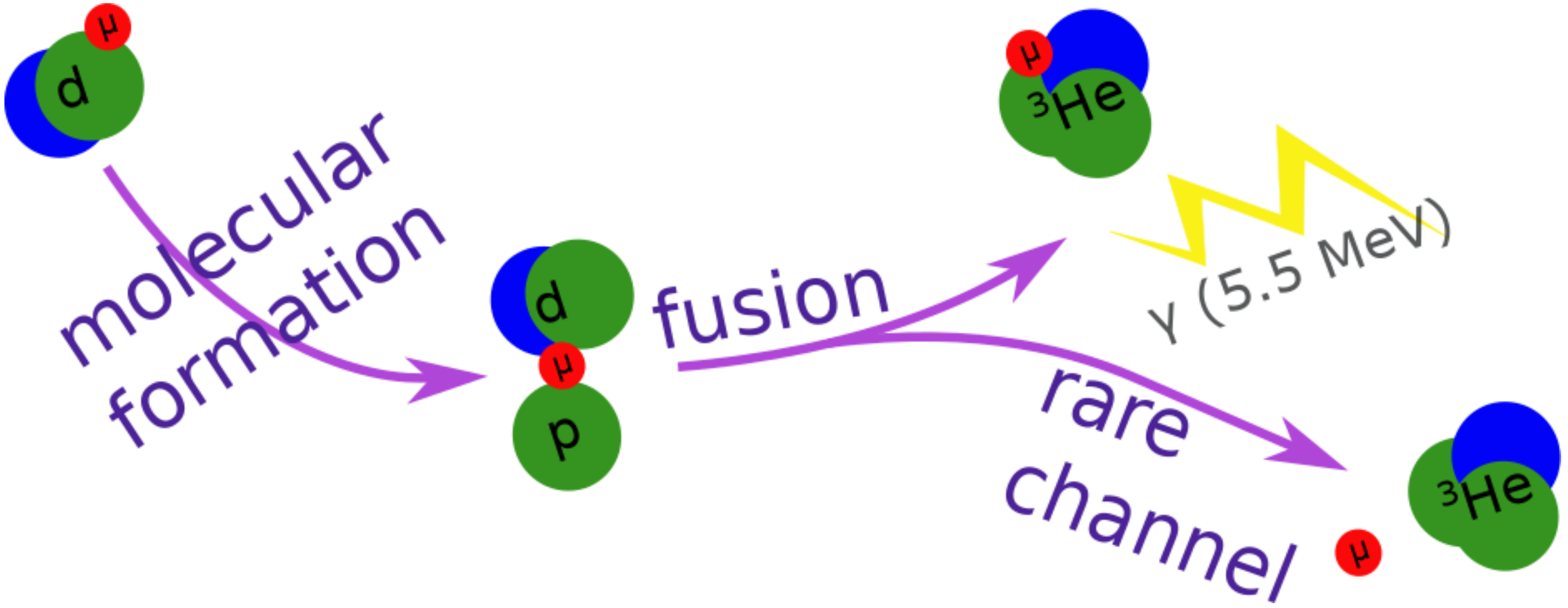
- Atomic capture after muon stopping:
  - De-excitation cascade (external Auger, radiative, Coulomb collisions)
  - Initial energy of μp: meV to several eV, high energy μp up to over 100 eV

- Molecular scattering: $\mu p + XY \rightarrow \mu p + XY$

- Isotopic exchange: $\mu p + d \rightarrow \mu d + p + 135\ \mathrm{eV}$

- Transfer to heavy nuclei: $\mu p \rightarrow (\mu Z)^*$

Molecular formation and muon-catalyzed fusion



Rates for molecular formation at liquid hydrogen density:

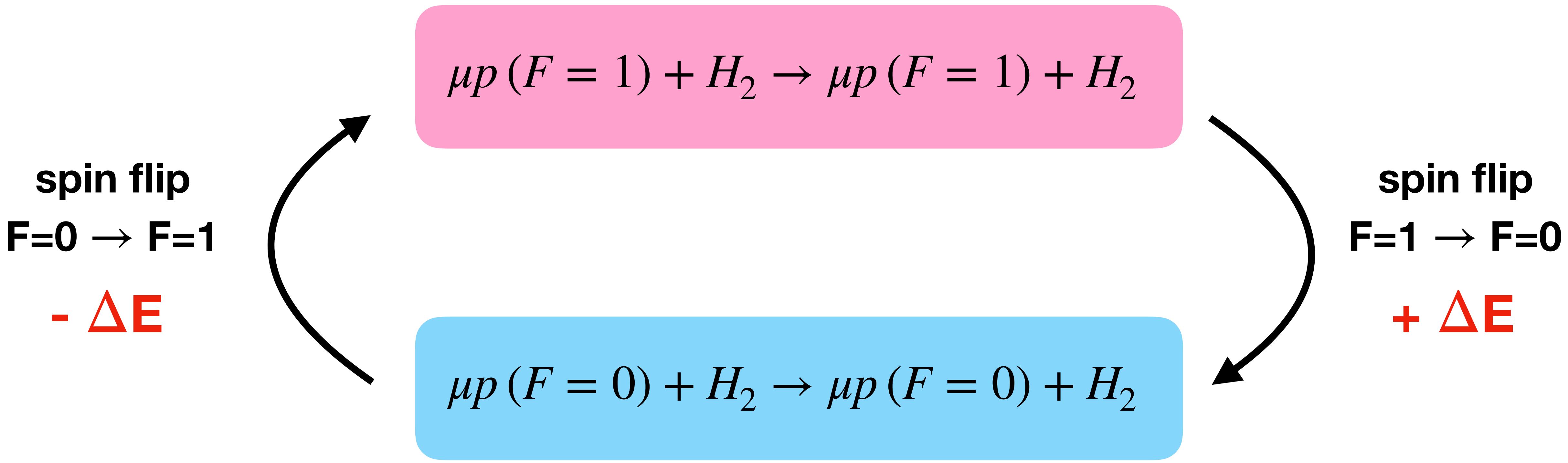
$$\lambda_{p\mu p} = 1.89 \cdot 10^6 \ \frac{1}{s} \qquad \lambda_{p\mu d} = 5.80 \cdot 10^6 \ \frac{1}{s}$$

[Bleser et al., Phys. Rev. 132:2679, 1963]

Let’s talk about HyperMu

μp diffusion in HyperMu

- Molecular scattering:



$$\mu p\,(F=1)+H_2 \rightarrow \mu p\,(F=1)+H_2$$

spin flip
F=1 → F=0
+ ΔE

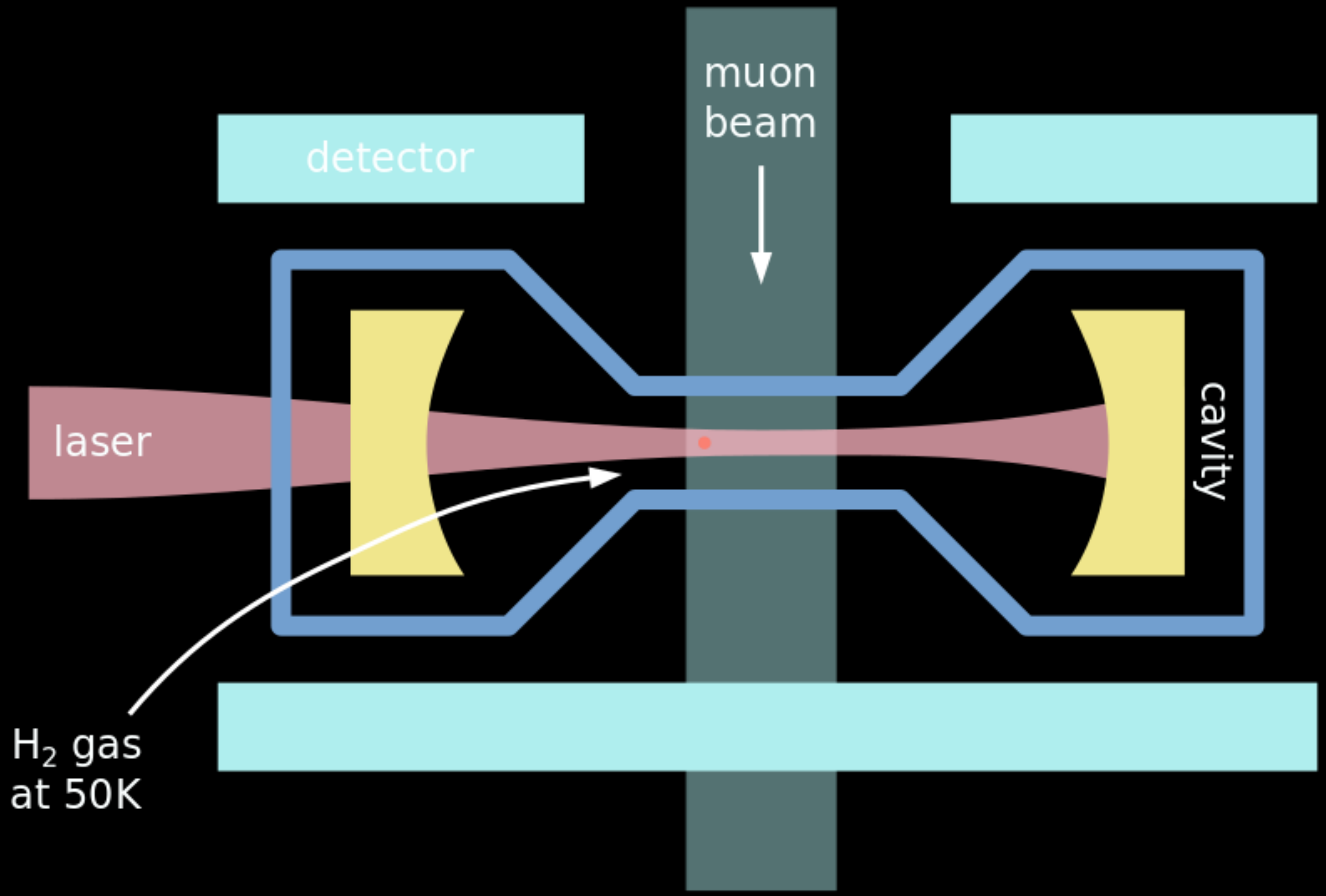
$$\mu p\,(F=0)+H_2 \rightarrow \mu p\,(F=0)+H_2$$

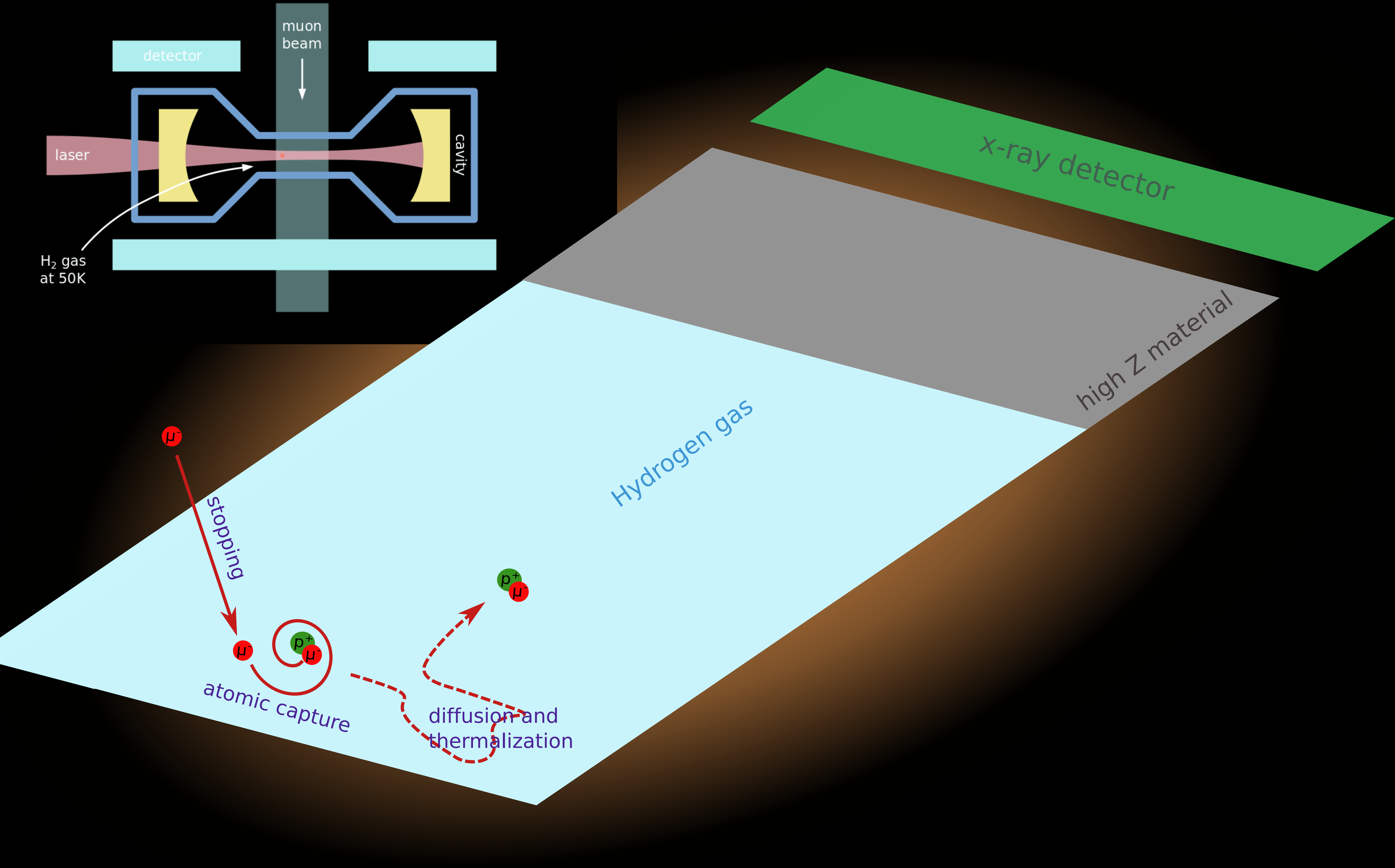
spin flip
F=0 → F=1
- ΔE

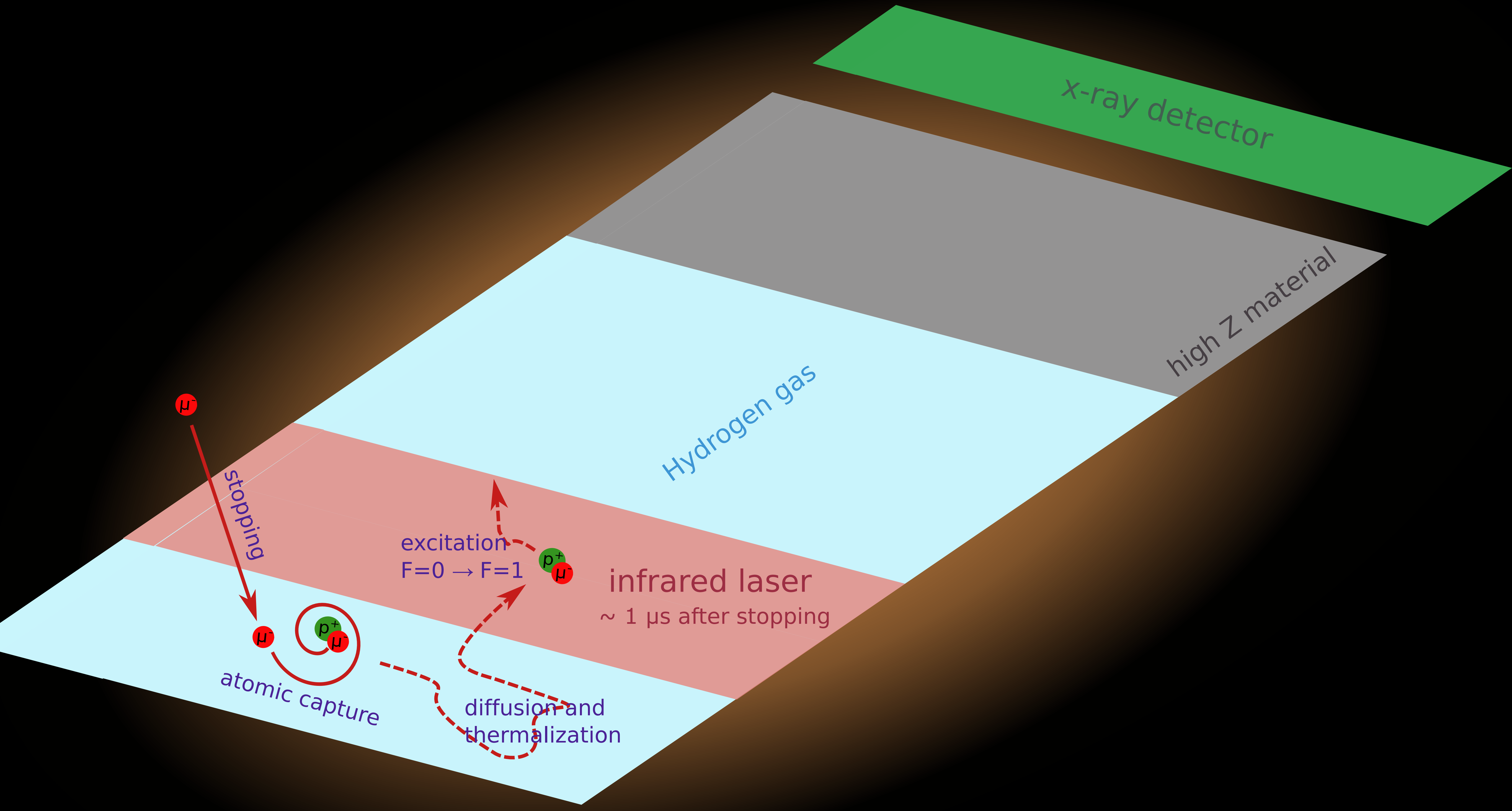
differential cross sections calculated by A. Adamczak

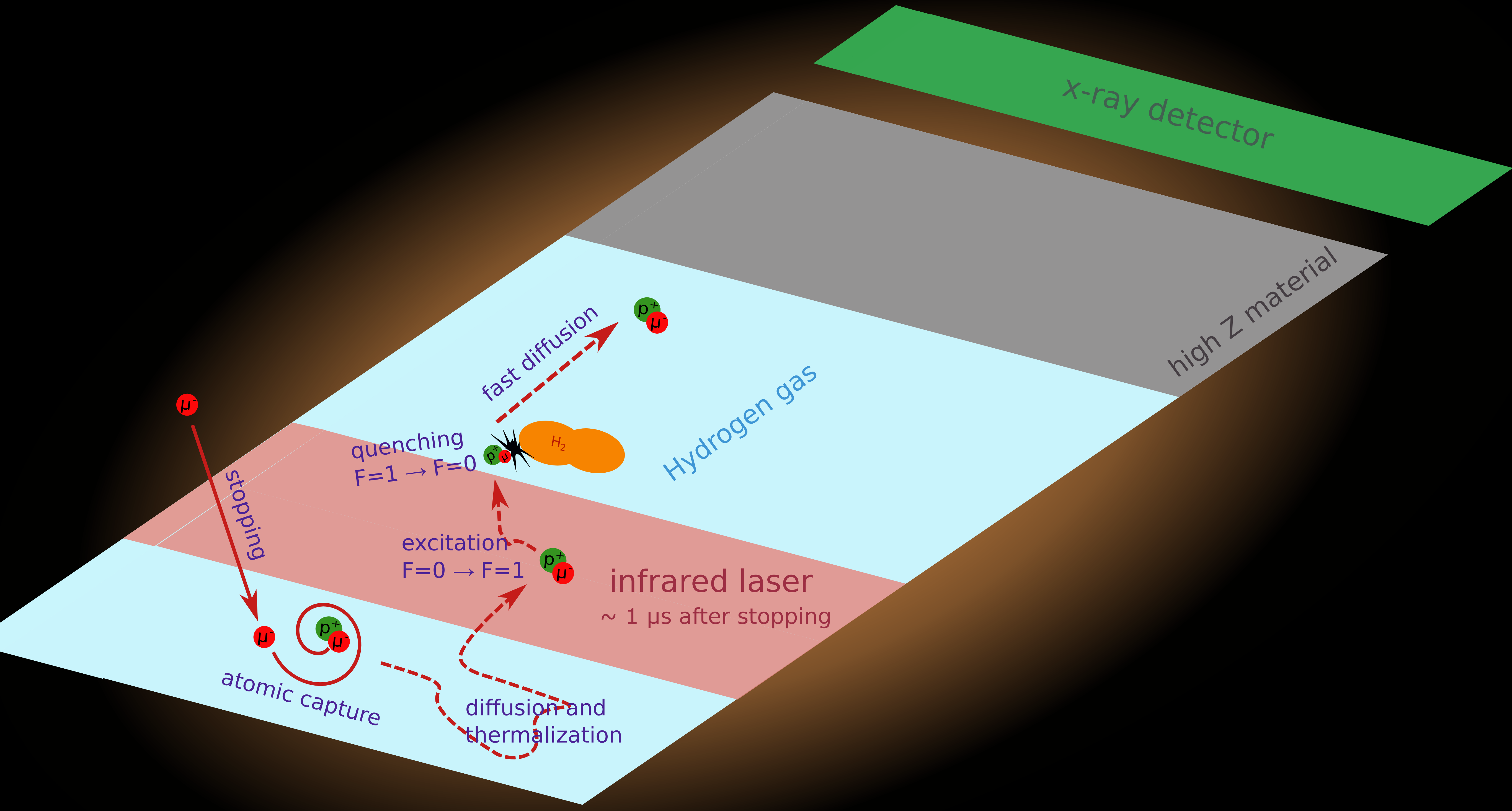
- pμp formation:

  only small contribution in HyperMu due to low H_2 density


muon
beam
detector
laser
cavity
H_2 gas
at 50K


detector
muon beam
laser
cavity
H_2 gas at 50K
x-ray detector
high Z material
Hydrogen gas
μ^-
stopping
μ^-
p^+
μ^-
atomic capture
diffusion and thermalization
p^+
μ^-


x-ray detector
high Z material
Hydrogen gas
μ^-
stopping
μ^-
p^+
μ^-
atomic capture
diffusion and
thermalization
excitation
F=0 → F=1
p^+
μ^-
infrared laser
~ 1 μs after stopping



x-ray detector

high Z material

Hydrogen gas

fast diffusion

quenching
F=1 → F=0

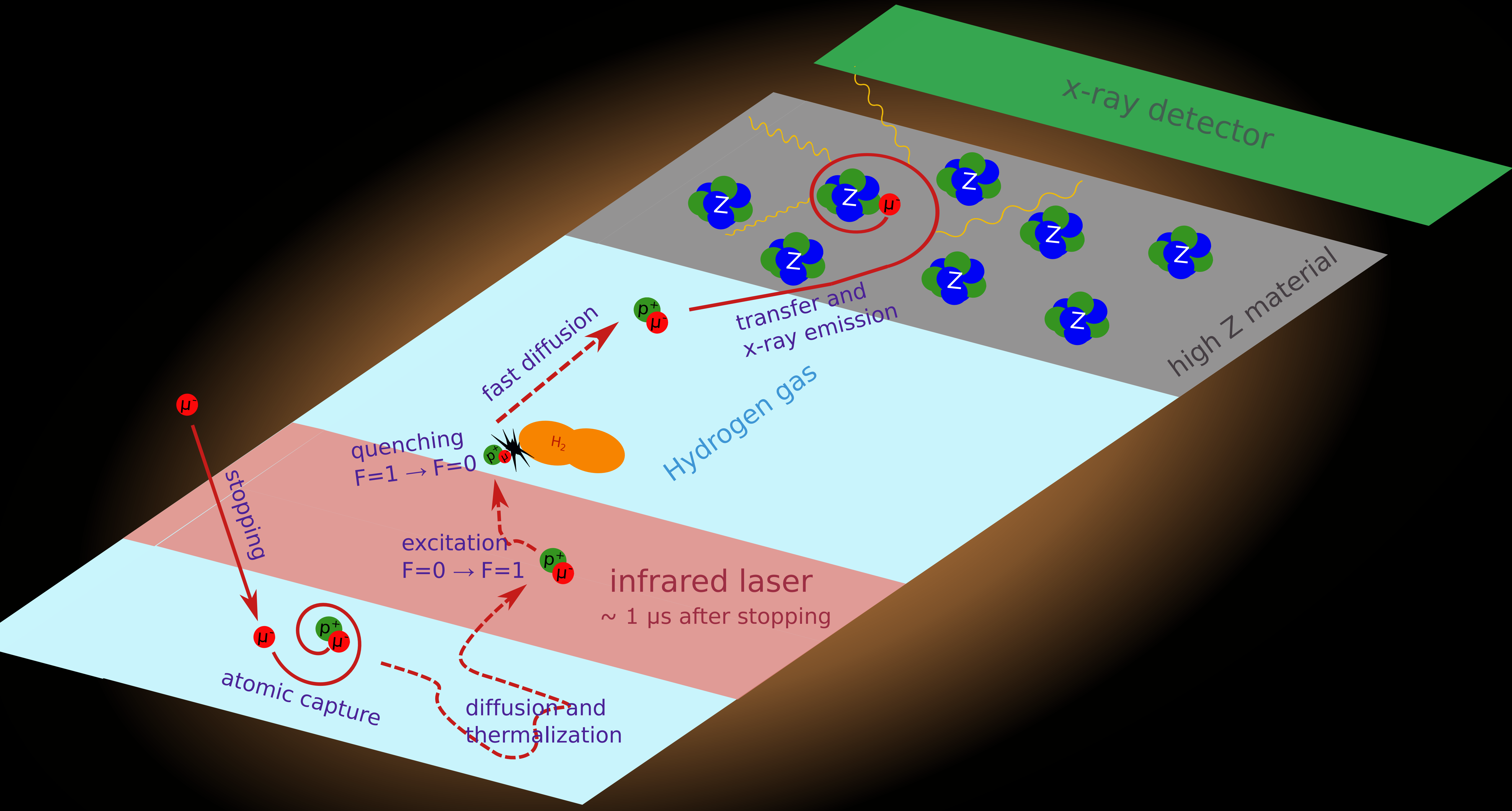
stopping

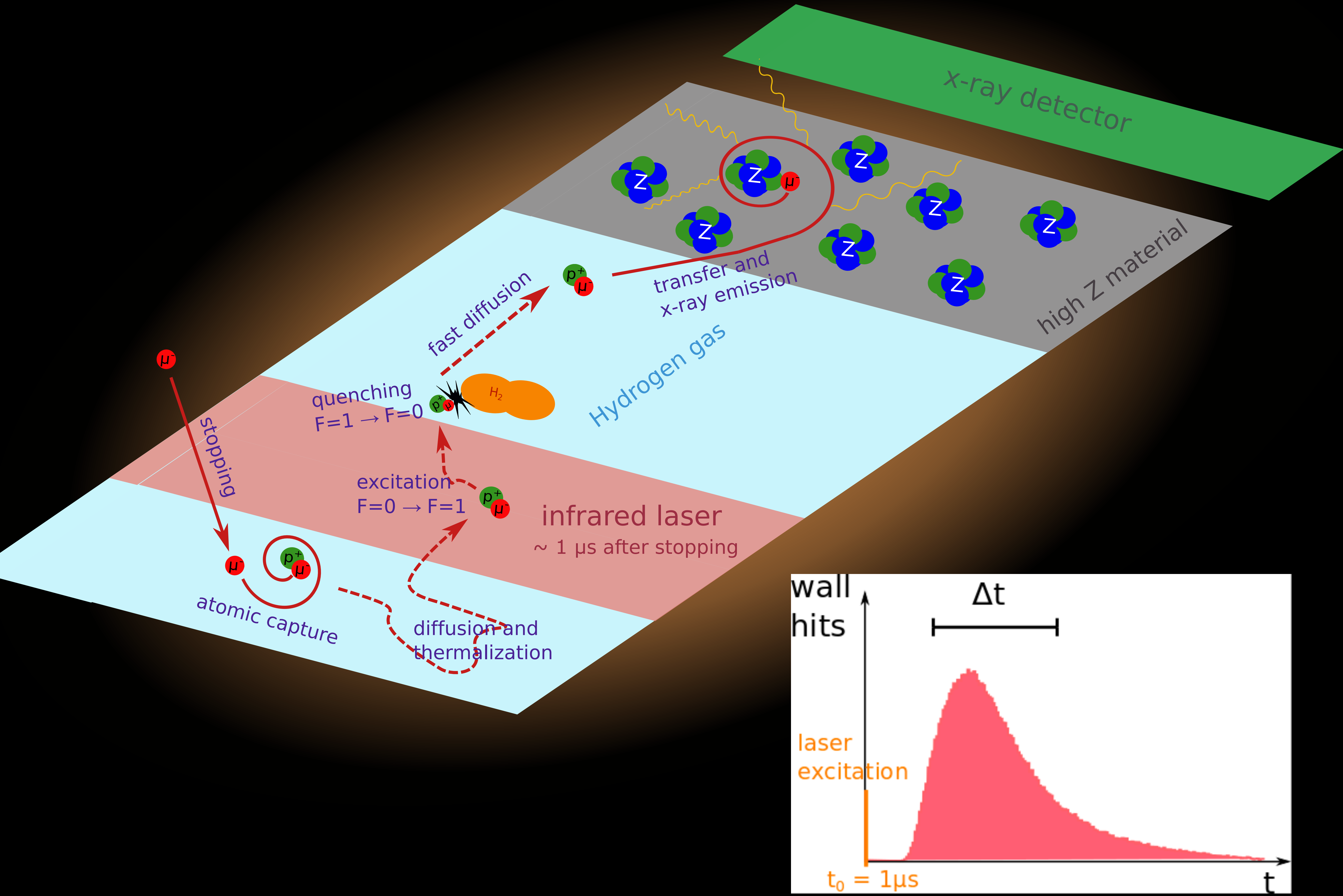
excitation
F=0 → F=1

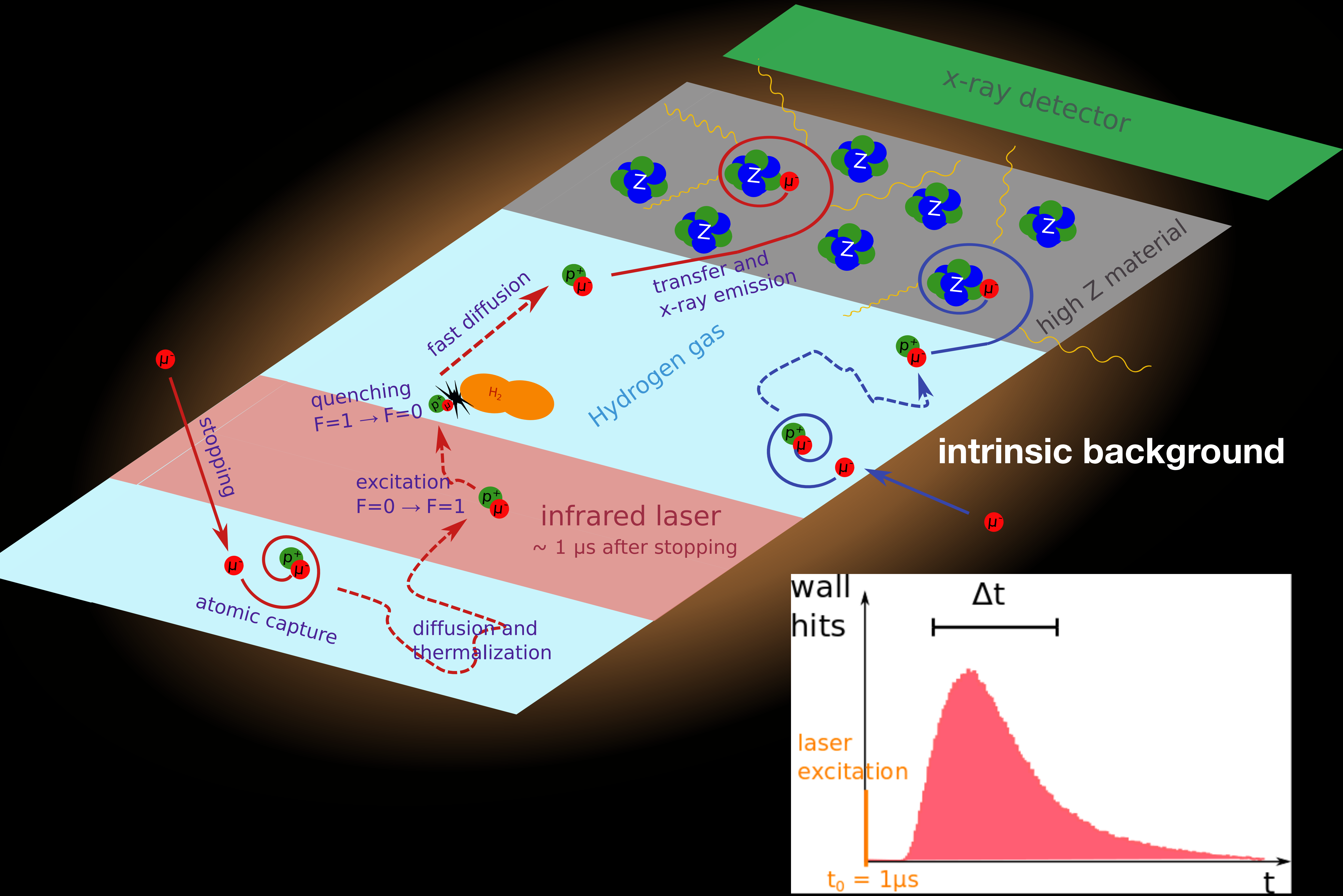
infrared laser
~ 1 μs after stopping

atomic capture

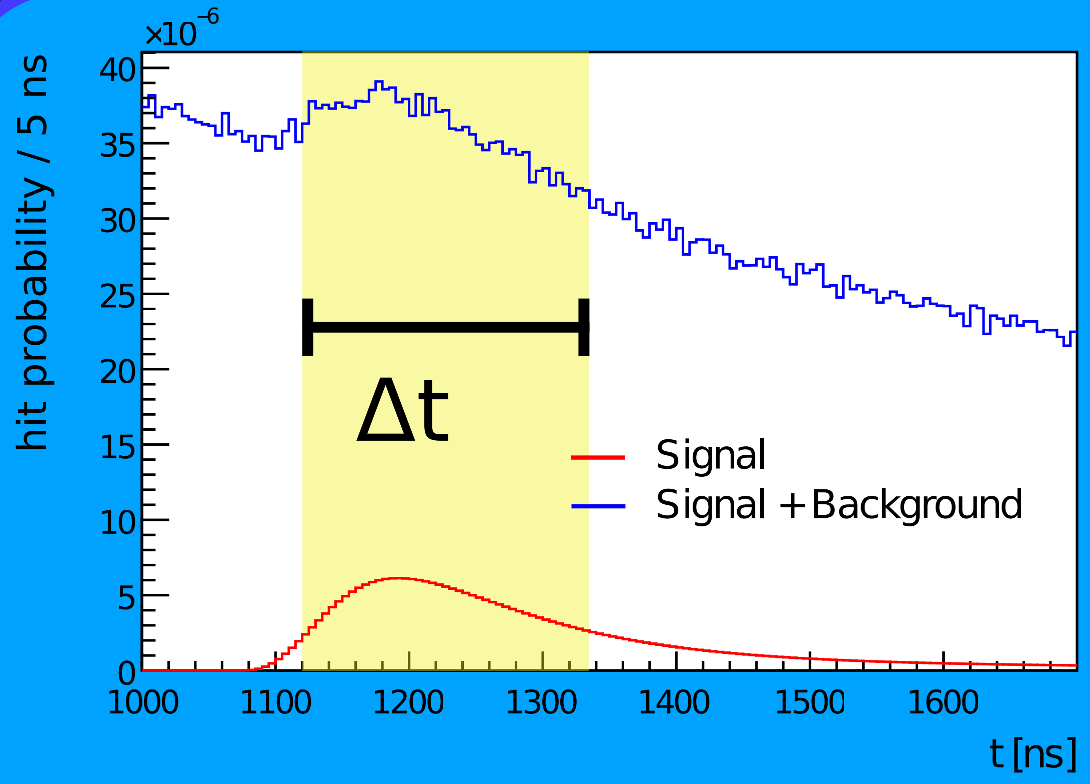
diffusion and
thermalization


x-ray detector
high Z material
Z
μ
transfer and
x-ray emission
p+
μ-
fast diffusion
Hydrogen gas
quenching
F=1 → F=0
H2
μ-
stopping
excitation
F=0 → F=1
infrared laser
~ 1 μs after stopping
atomic capture
diffusion and
thermalization

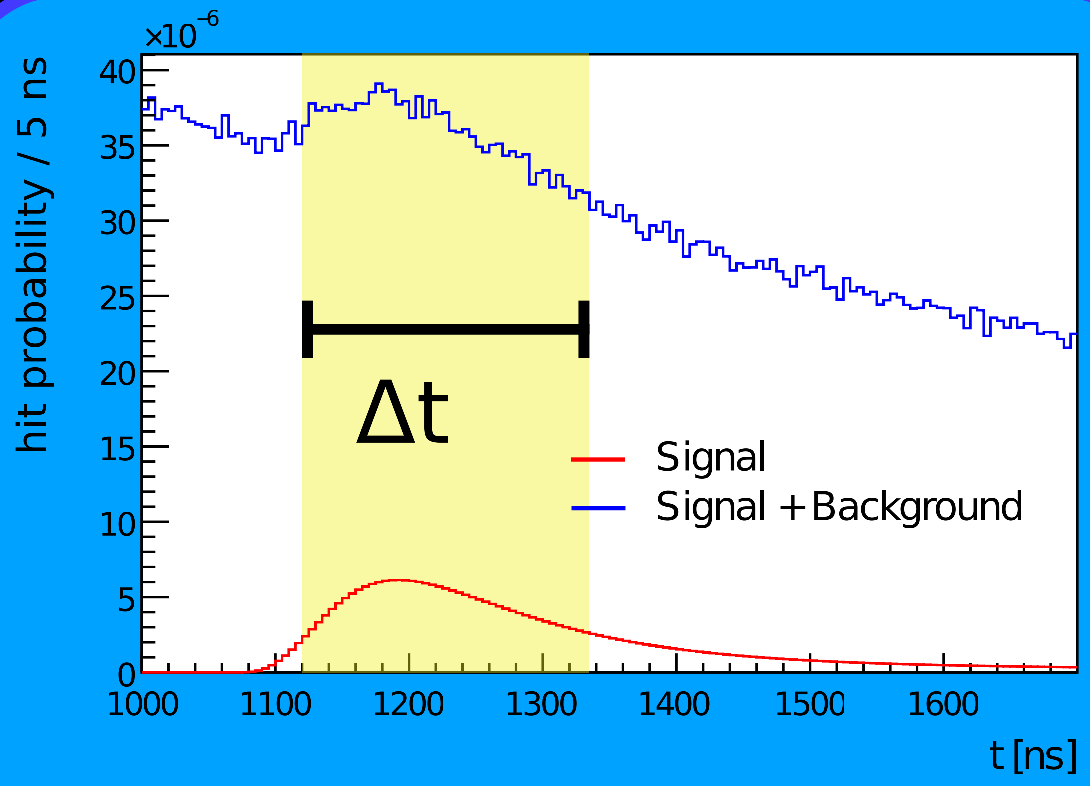

x-ray detector
high Z material
Z
μ^-
transfer and
x-ray emission
p^+
fast diffusion
Hydrogen gas
quenching
F=1 → F=0
H_2
stopping
excitation
F=0 → F=1
infrared laser
~ 1 µs after stopping
atomic capture
diffusion and
thermalization
wall
hits
Δt
laser
excitation
t_0 = 1µs
t



intrinsic background

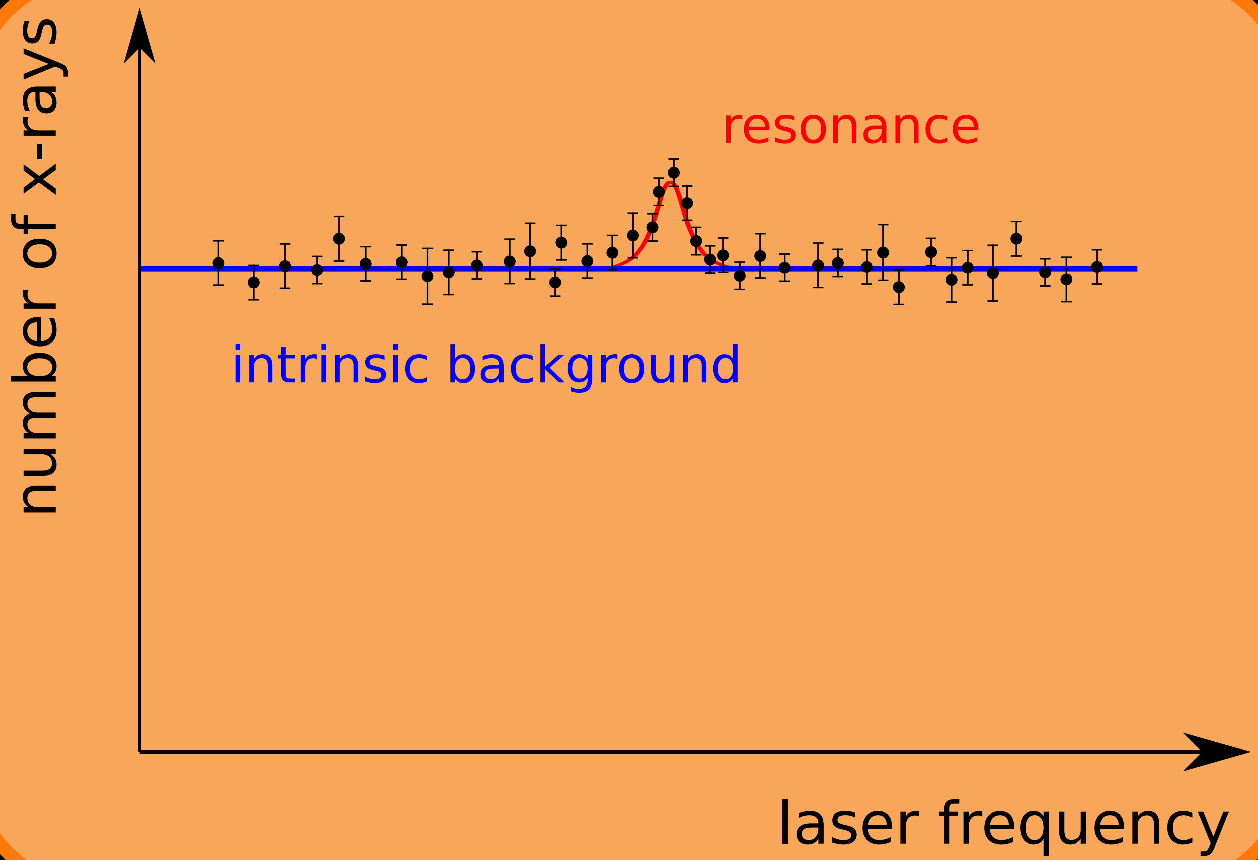


Signal peak only existing when laser is on resonance!



Signal peak only existing when laser is on resonance!

resonance curve



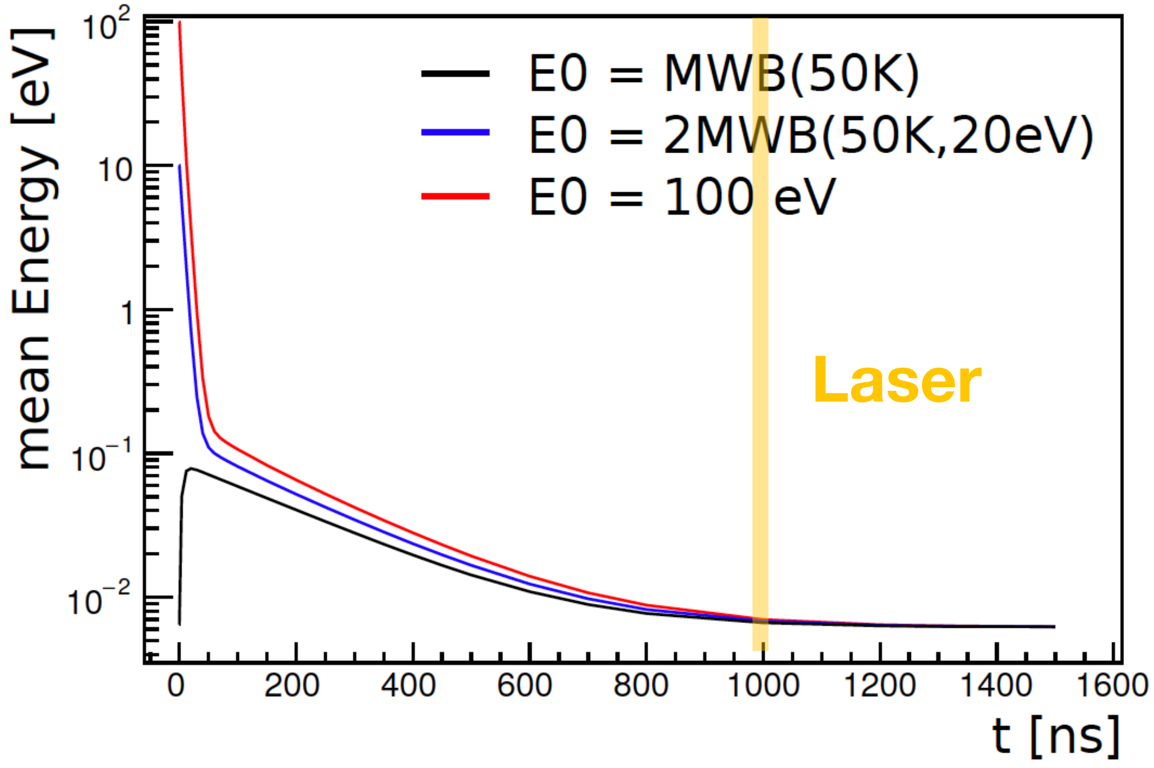
Simulations for HyperMu

Diffusion and thermalisation before laser enters cavity

Diffusion of laser-excited μp atoms

Combined simulation of signal and background

Thermalisation after μp formation

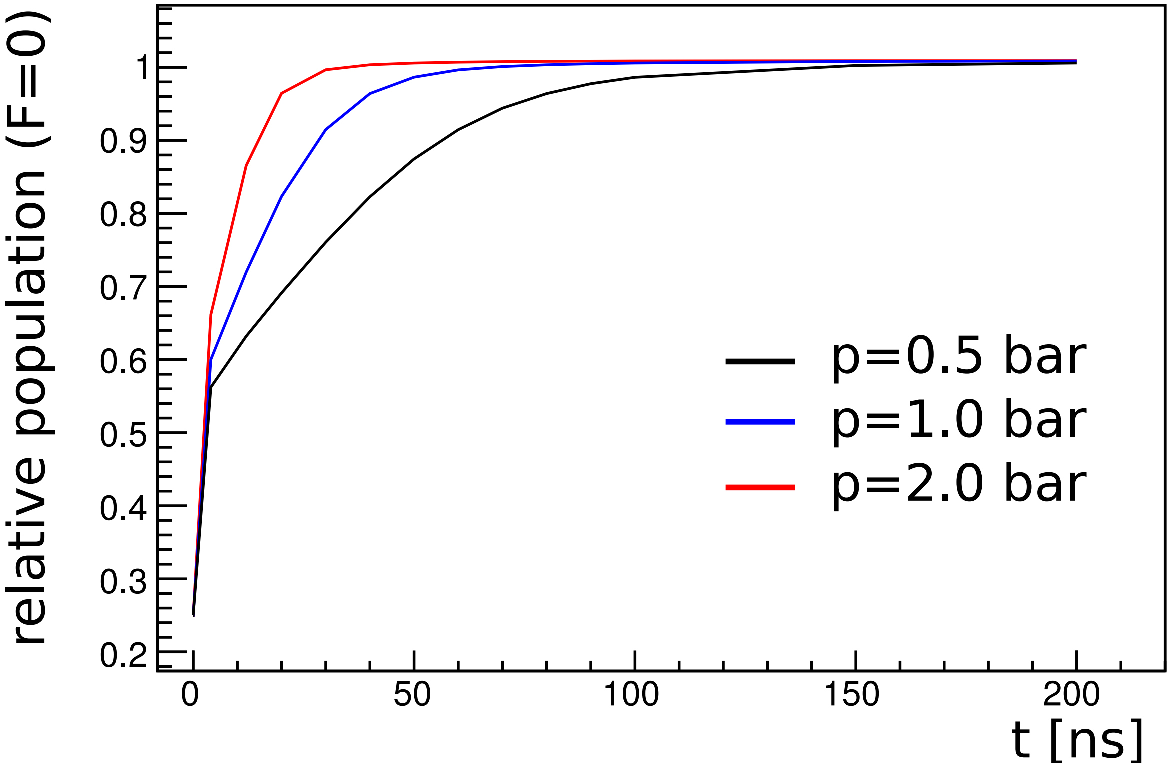


- Time for thermalisation: ~ 1 μs (d = 1 mm, p = 1 bar)

→ independent of initial energy

- After cascade, statistical distribution over hyperfine states:
75% (F=1), 25% (F=0)

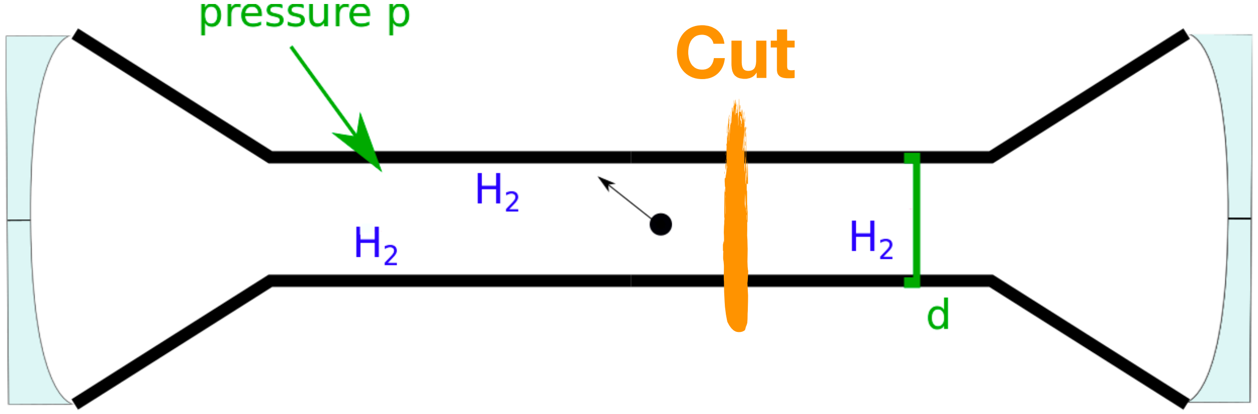
- μp are quenched and thermalised in collisions with H_2 molecules



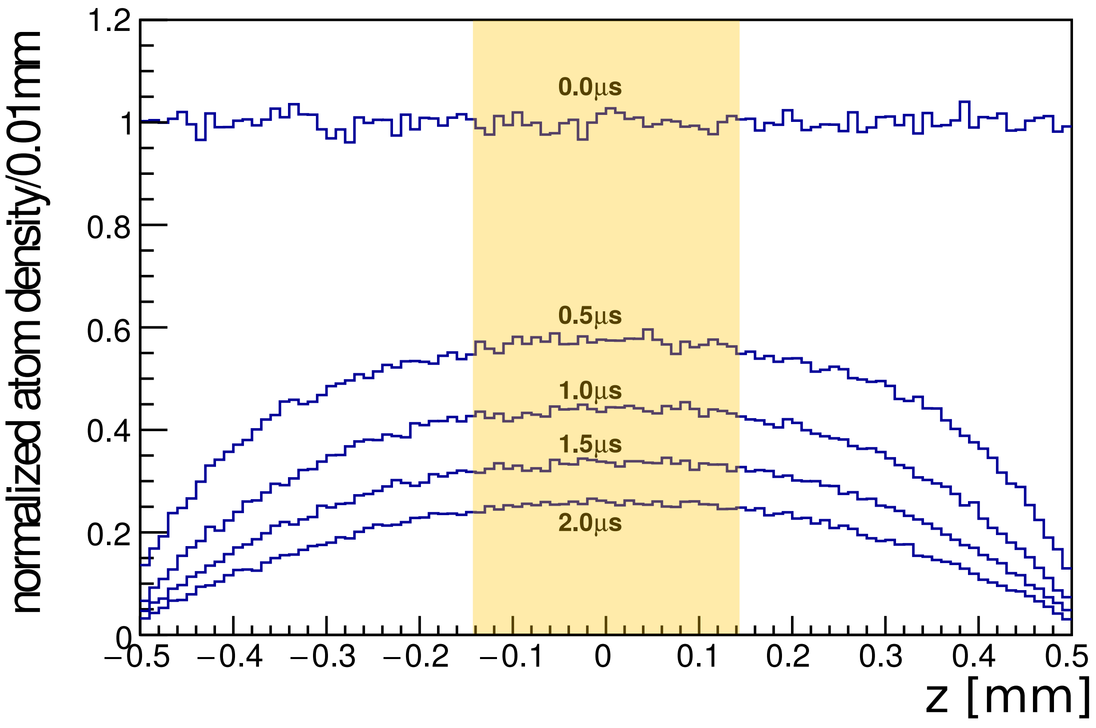
μp diffusion to wall before laser

- During thermalisation, some μp diffuse to wall or decay

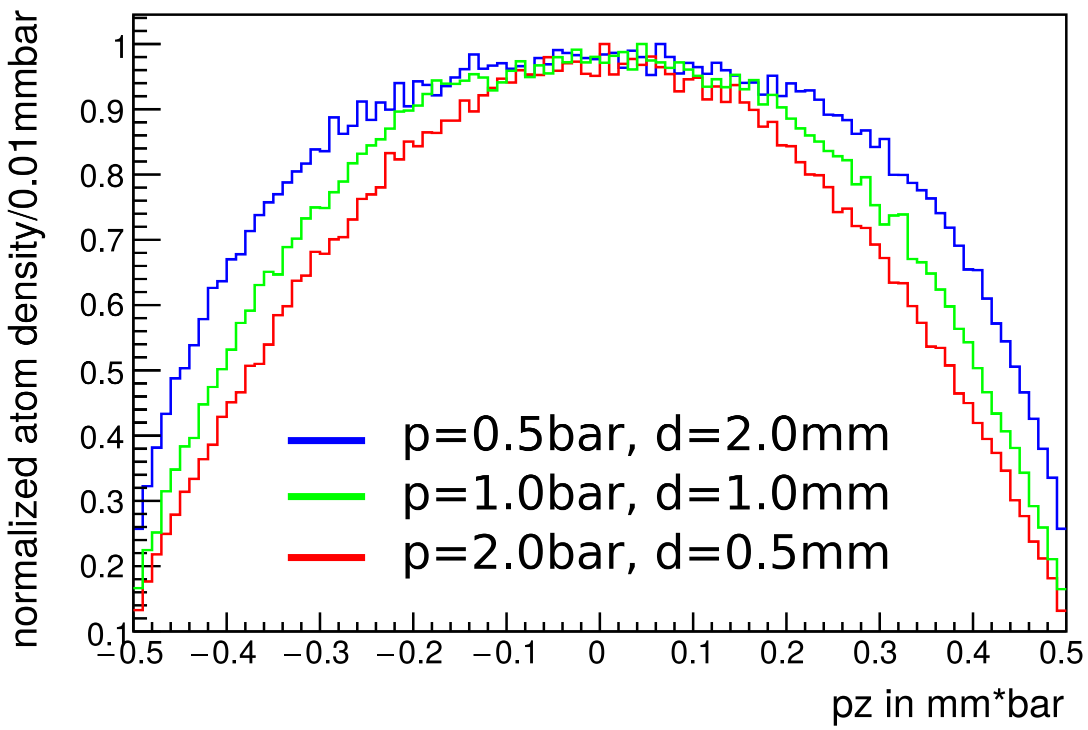
- Uniform stopping distribution is assumed (low pressure, short distance)



- Strong peak in center is good for signal-to-background ratio

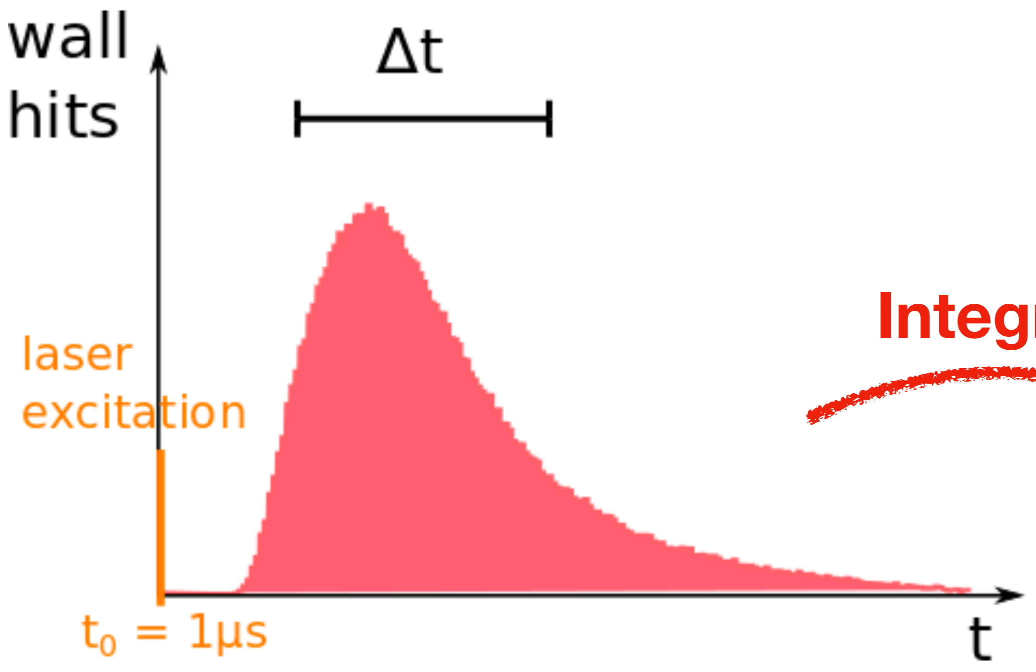


p = 1.5 bar, with decay



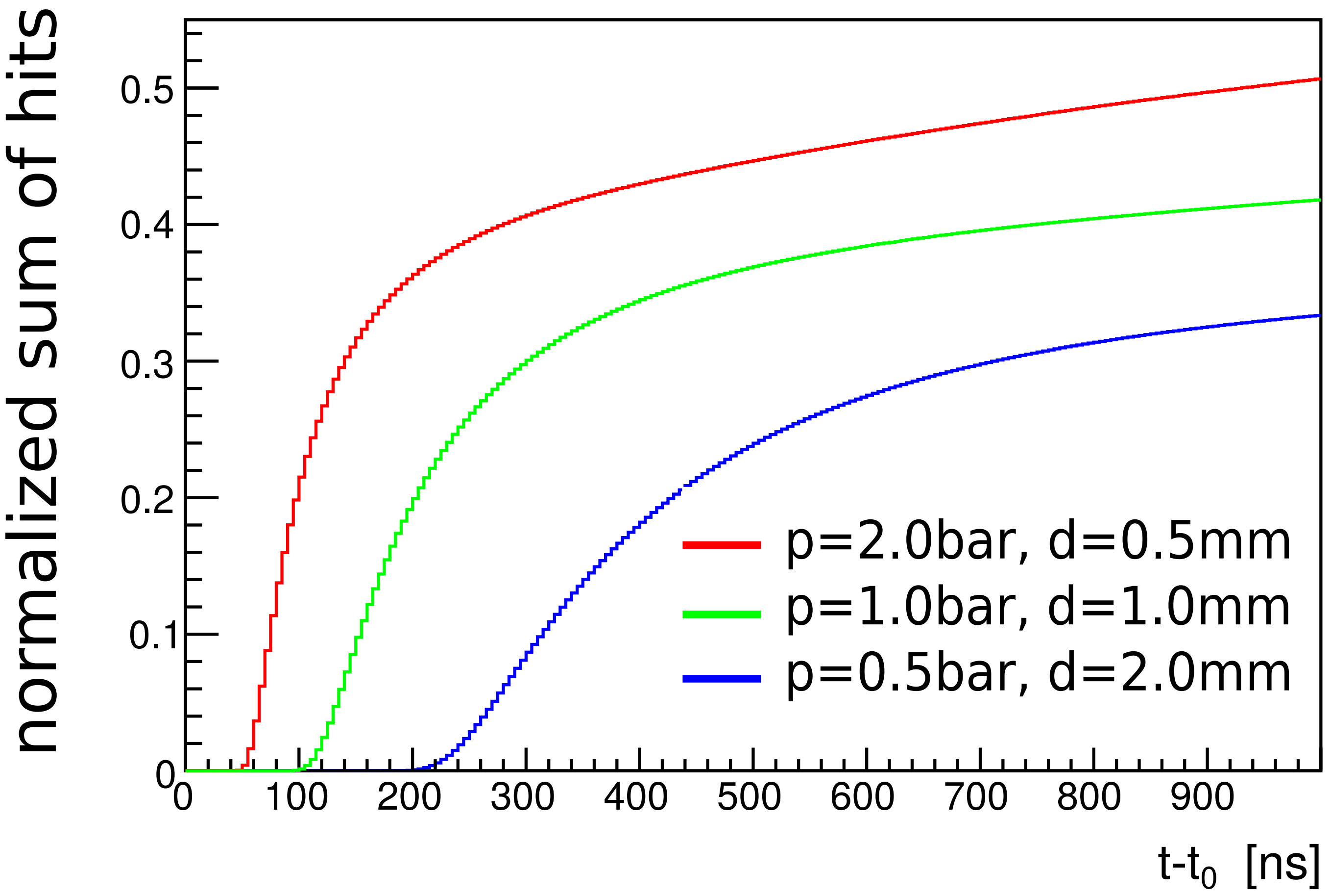
normalised to maximum

Diffusion after laser excitation



Integration

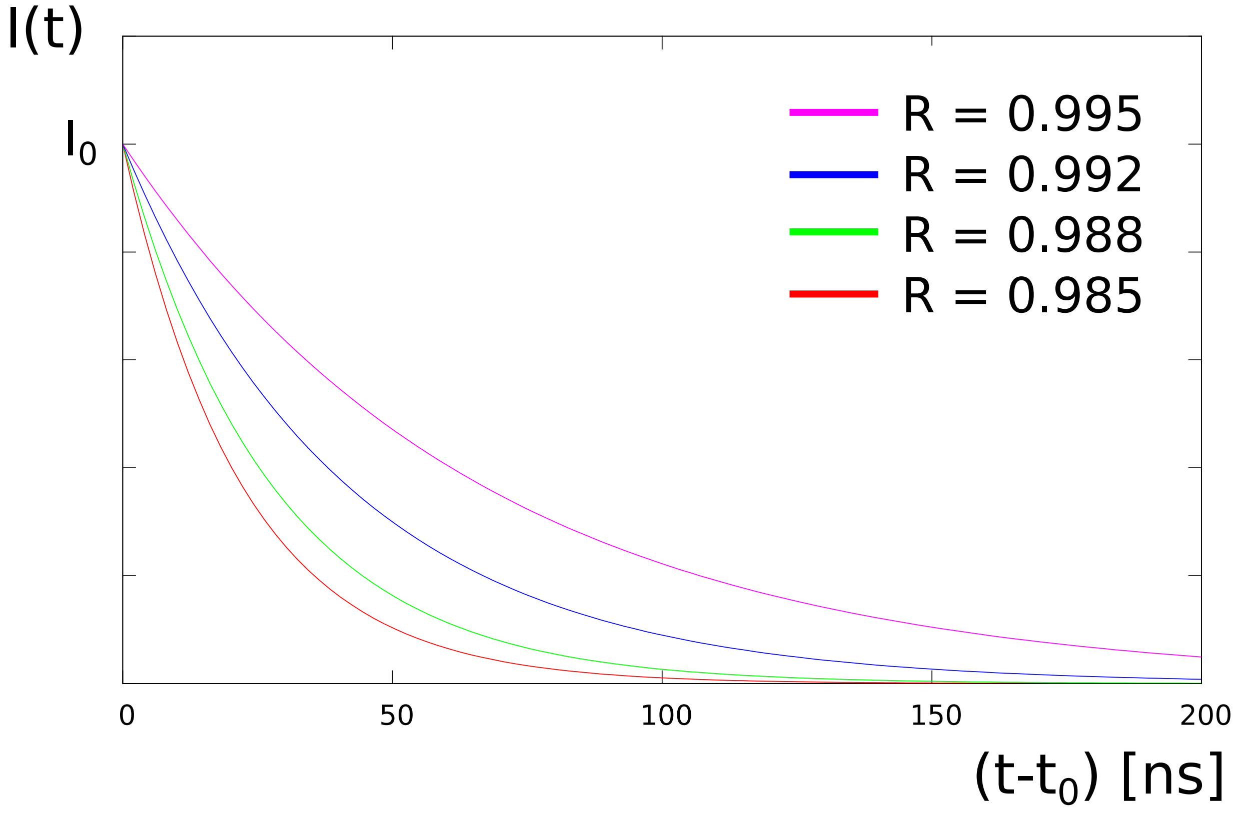
Study optimal conditions for signal in simulations of laser-excited μp atoms



Plot on the right:

- Excitation in target center, decay included
- Comparison of targets with equal stopping properties

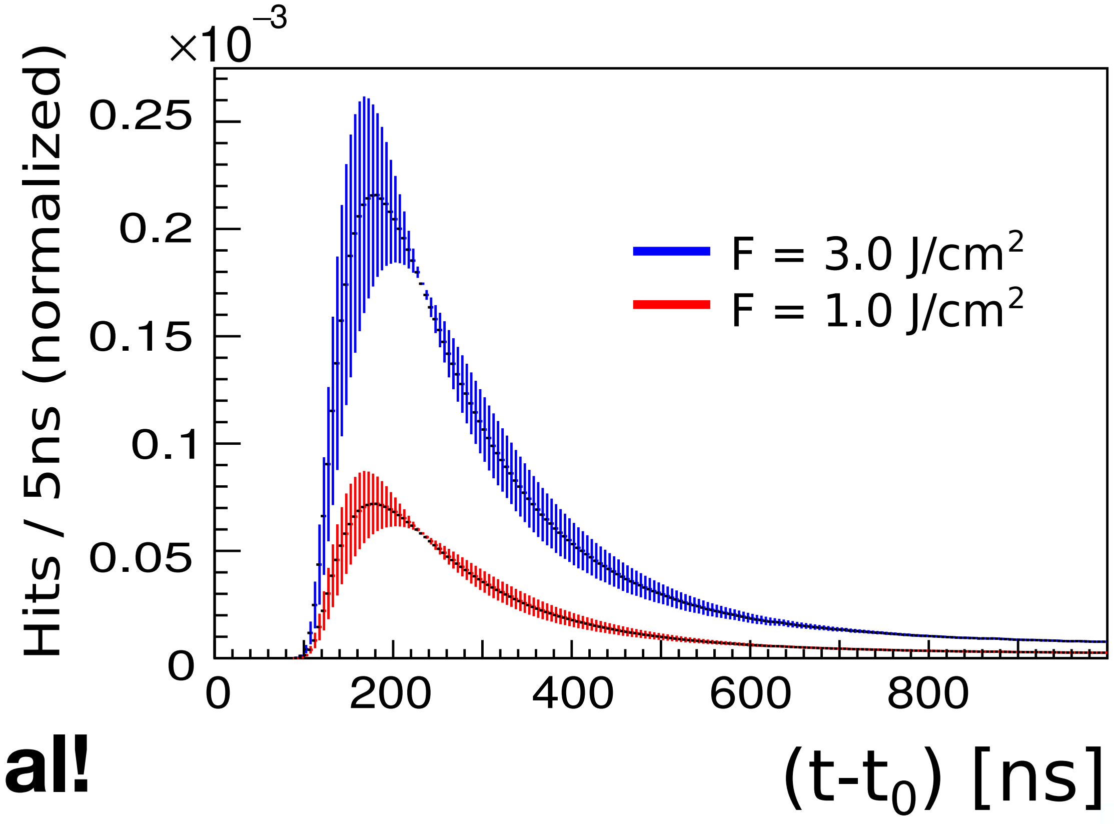
Fluence and excitation probability



Probability of excitation of a μp is determined by laser fluence

$$F \sim \frac{E_{laser}}{1-R}$$

$$p_{ex} = 1 - \exp\left(-\frac{F}{F_s}\right)$$

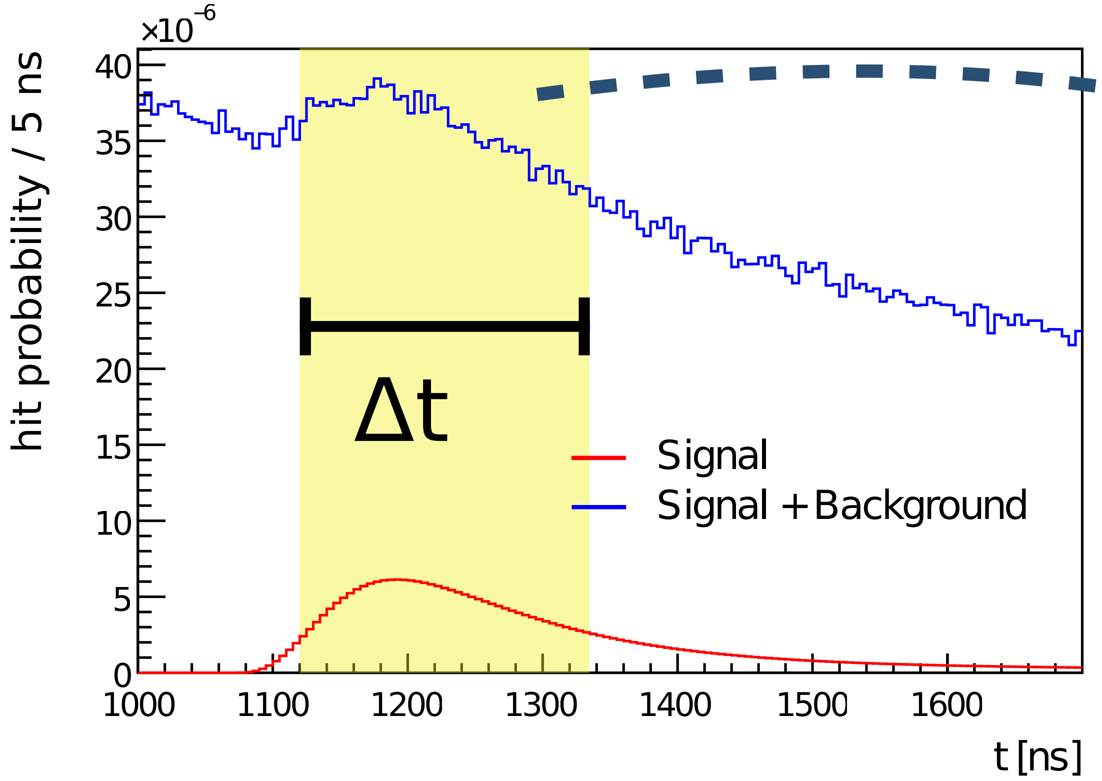


Far from saturation, number of laser-excited μp reaching the wall grows linearly with fluence

Performance of laser system is crucial!

Figure of merit for signal over background

probability per muon to produce wall hit



How quickly will the resonance peak grow?

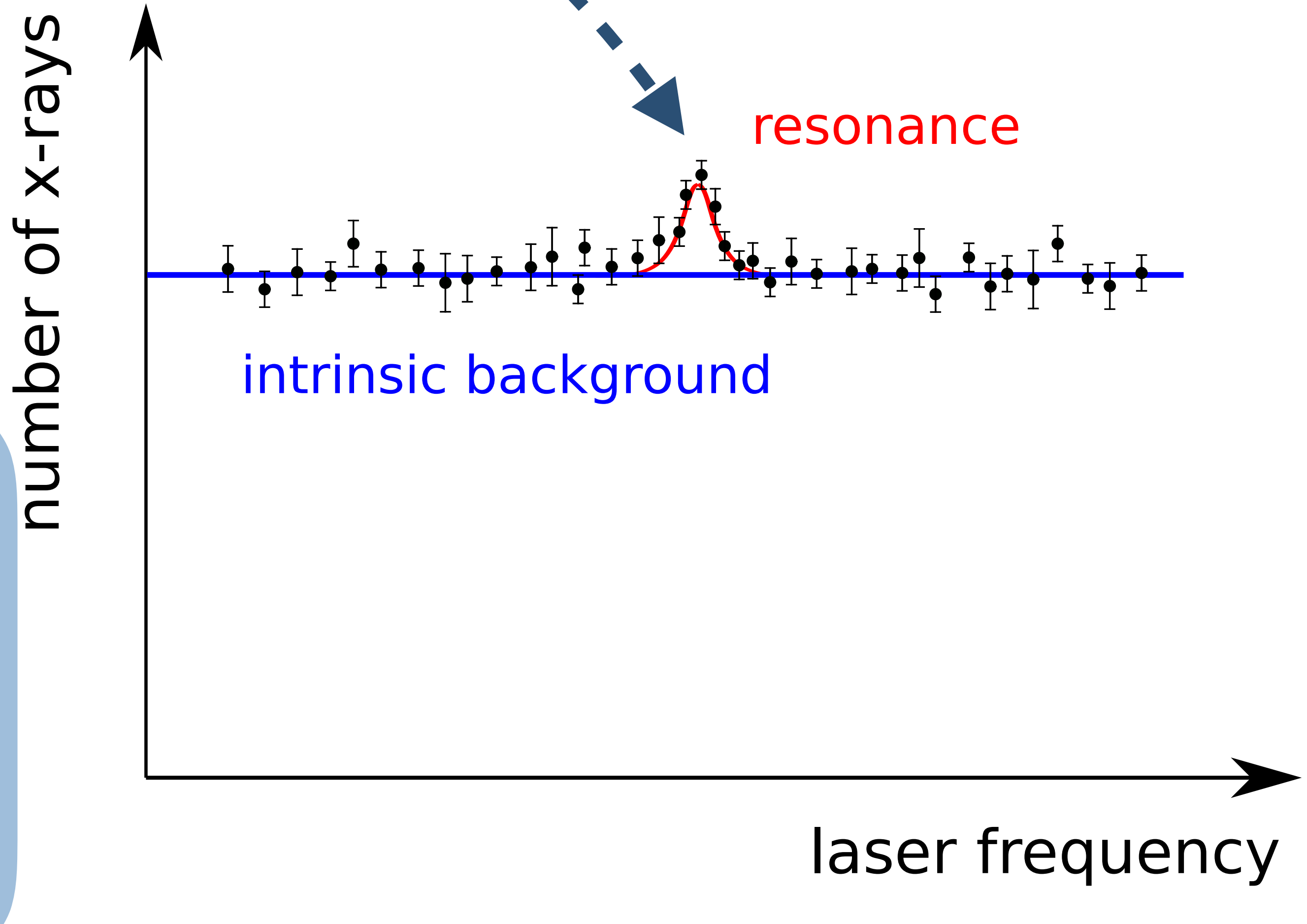


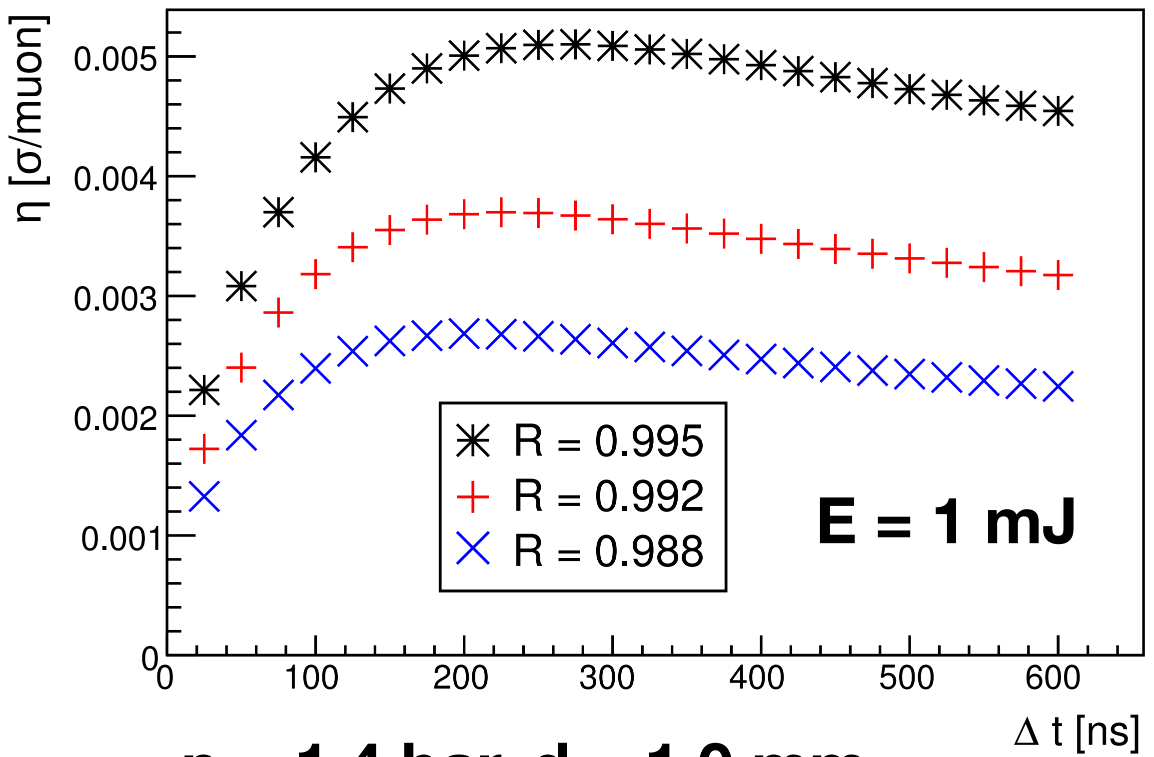
Figure of merit:

$$\eta = \frac{S}{\sqrt{S+BG}}$$

$$S = \int_{\Delta t} \text{Signal}\ \mathrm{d}t \qquad BG = \int_{\Delta t} \text{Background}\ \mathrm{d}t$$

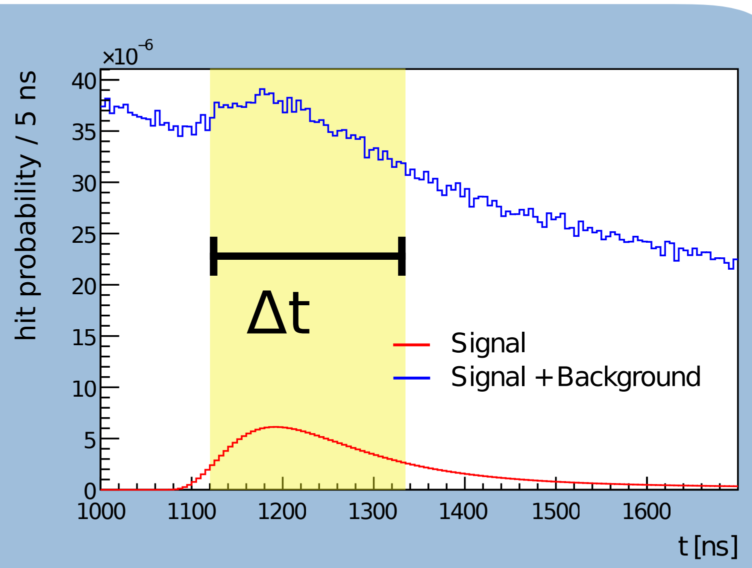
“Statistical significance per muon event”

Results of combined simulations

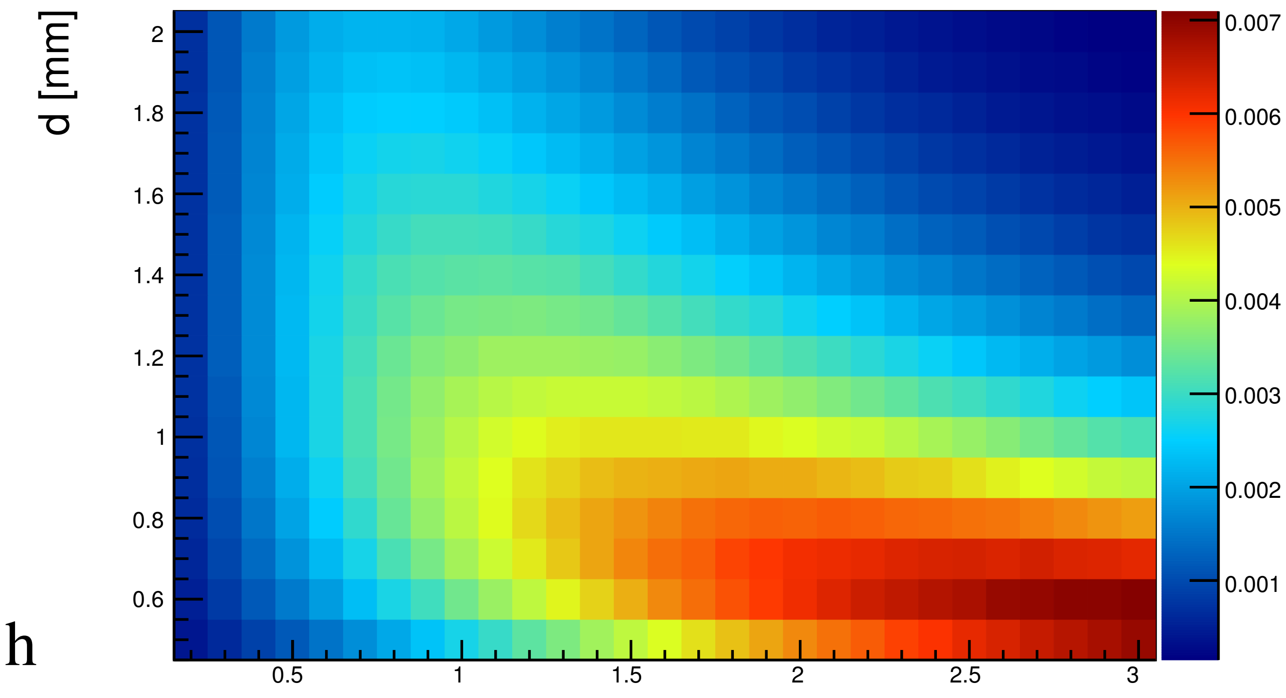


p = 1.4 bar, d = 1.0 mm

reminder



$$\eta = \frac{S}{\sqrt{S+BG}}$$

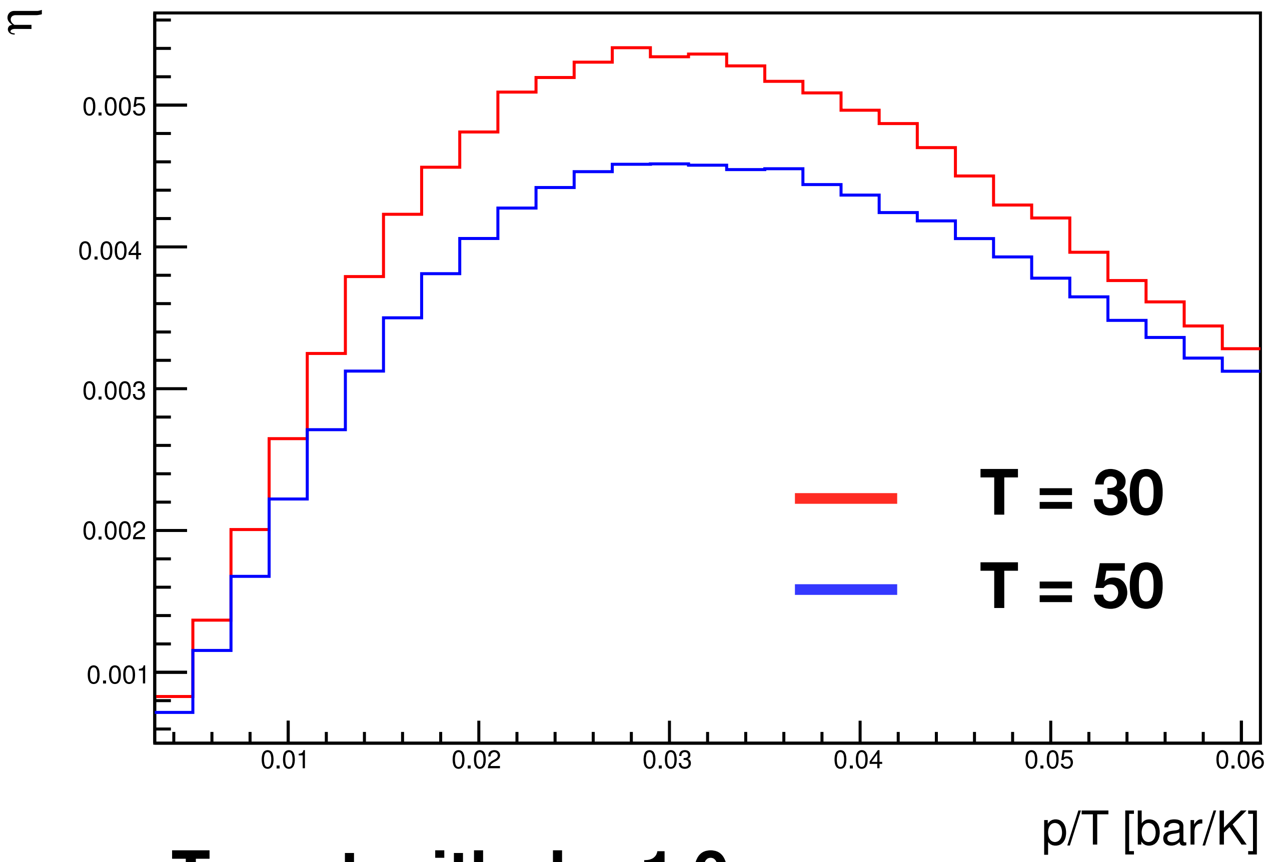


F = 1.9 J/cm²

- Identify optimal geometry by parameter scans
- Results can be used to estimate measurement time

e.g. for 4σ : $t_{point} = \left(\frac{4}{0.005}\right)^2 \cdot \frac{1}{R_\mu} \cdot \frac{1}{\epsilon_{tot}} \approx 3\ \mathrm{h}$

30 K → 50 K

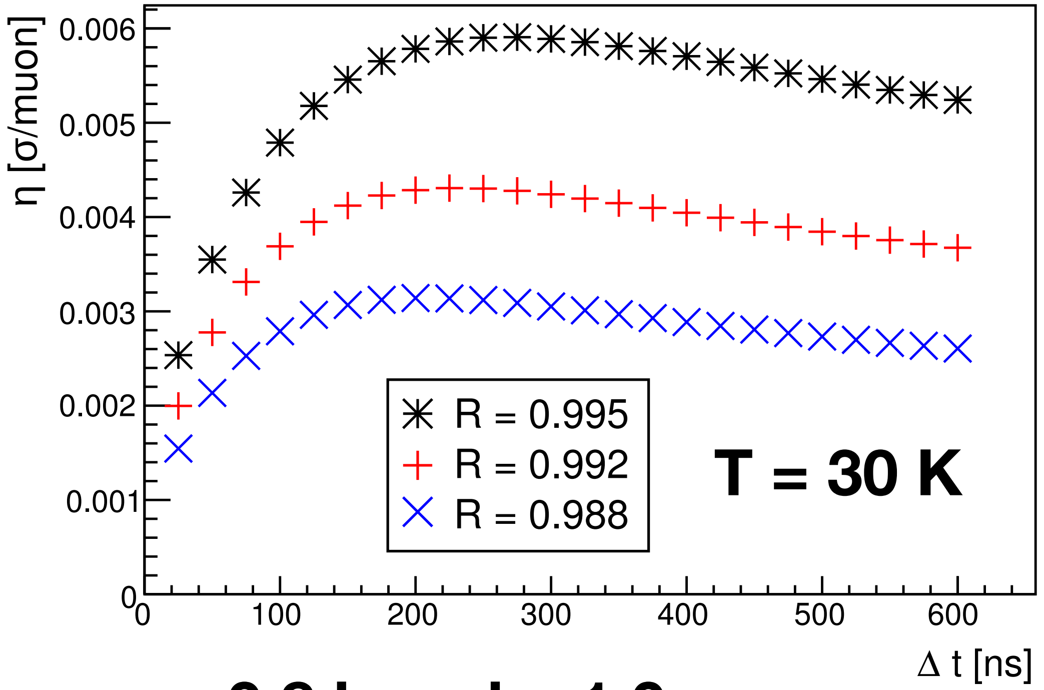


Target with d = 1.0 mm,
F = 1.9 J/cm²

$$\eta = \frac{S}{\sqrt{S+BG}}$$

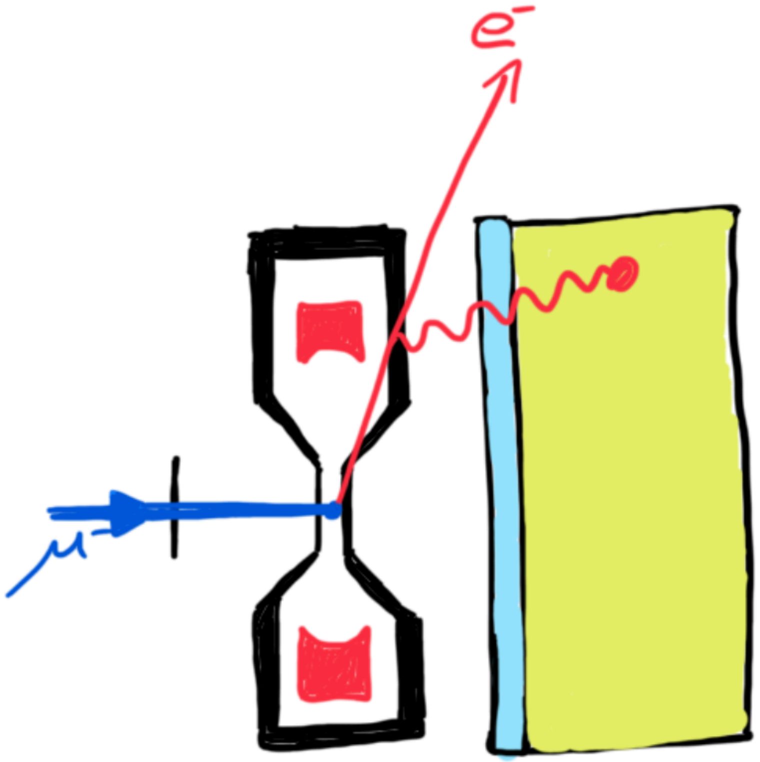
Thermalised μp atoms move slower in H_2 gas at T = 30 K

→ reduction of intrinsic background



p = 0.8 bar, d = 1.0 mm

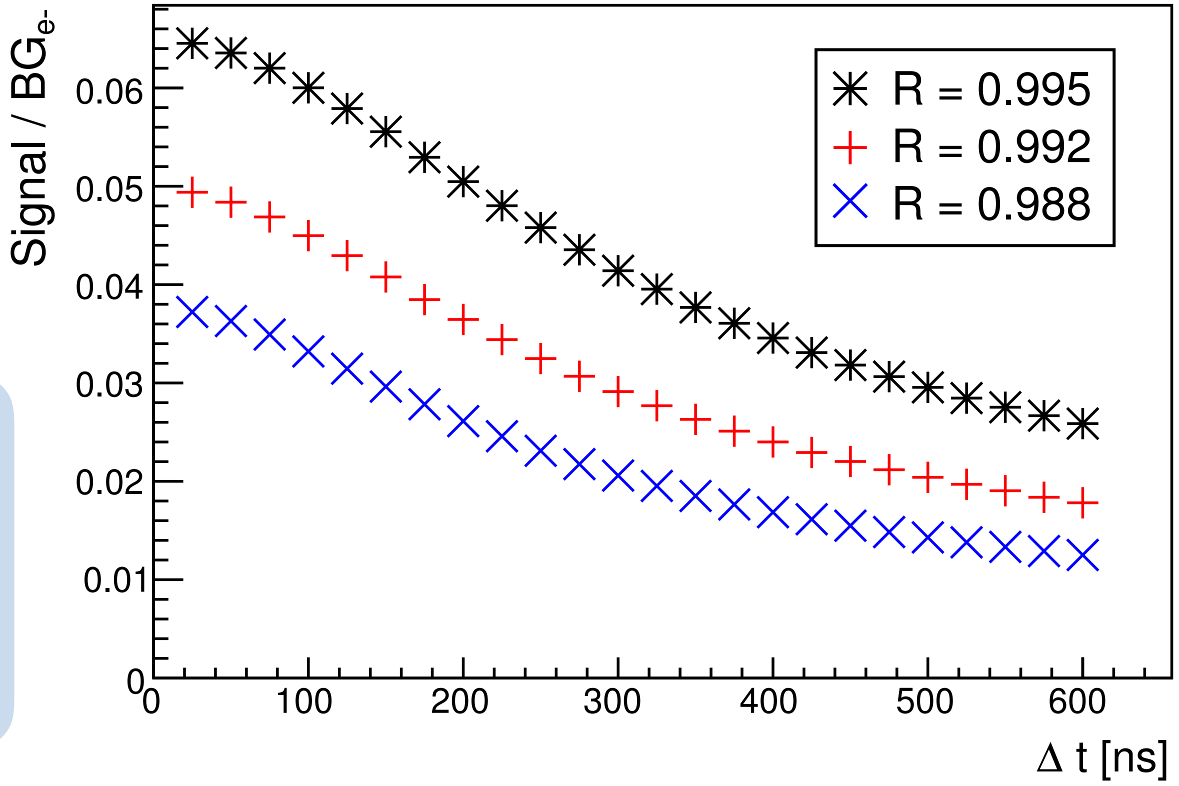
Background II: Muon decay



Bremsstrahlung

- Misinterpreted muon decays produce additional source of background
- Below: Ratio between number of signal hits within time interval Δt and number of decays of muons which are still present in the target

$$\frac{\int_{\Delta t} \text{Signal } dt}{N_{\Delta t}(e^-)}$$



Filigran target geometry needed to reduce bremsstrahlung

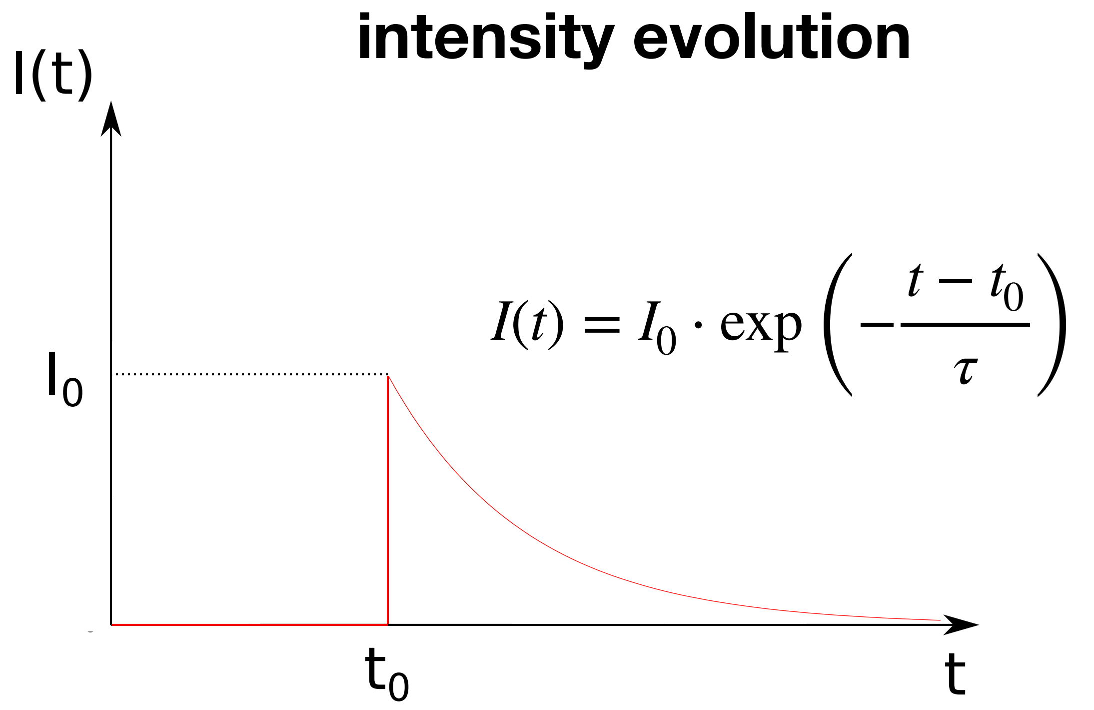
→ tested in few weeks

Summary

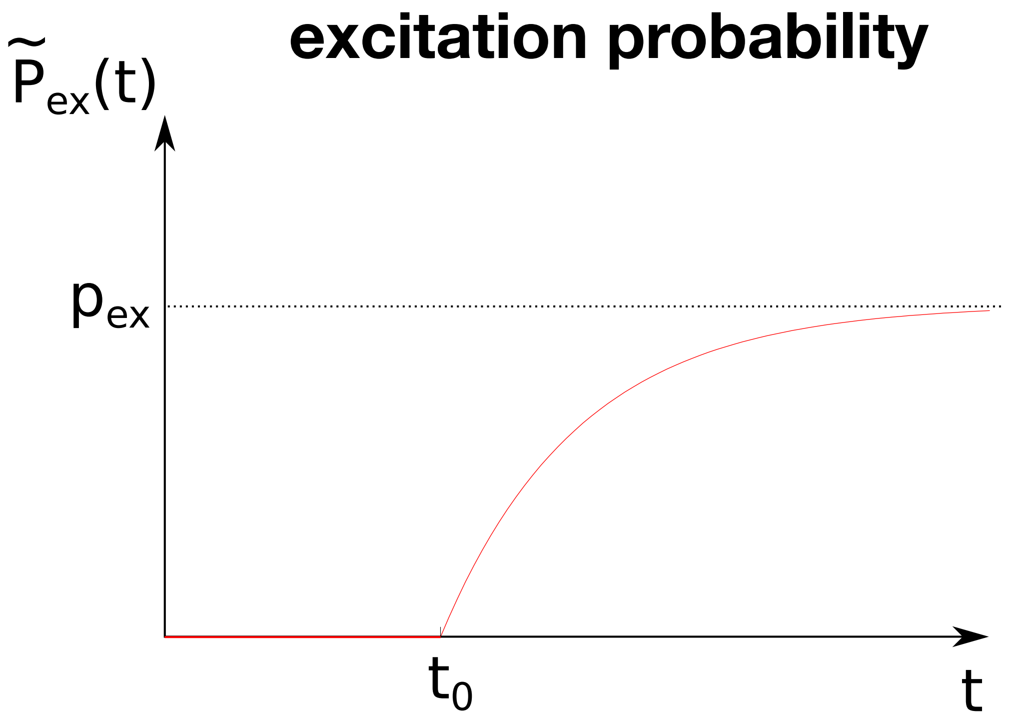
- Diffusion of μp atoms is central in the HyperMu experiment
    - Signal: diffusion of laser-excited μp atoms to walls
    - Irreducible background: diffusion of thermal μp atoms to walls
- Monte Carlo simulations of μp diffusion help to design the target and to estimate the measurement time
- HyperMu is a challenging experiment with strong constrains on target geometry, laser system and detector system
    - filigran and short gas cell
    - high fluence is crucial (laser system + cavity)
- Next beam time in two weeks !!

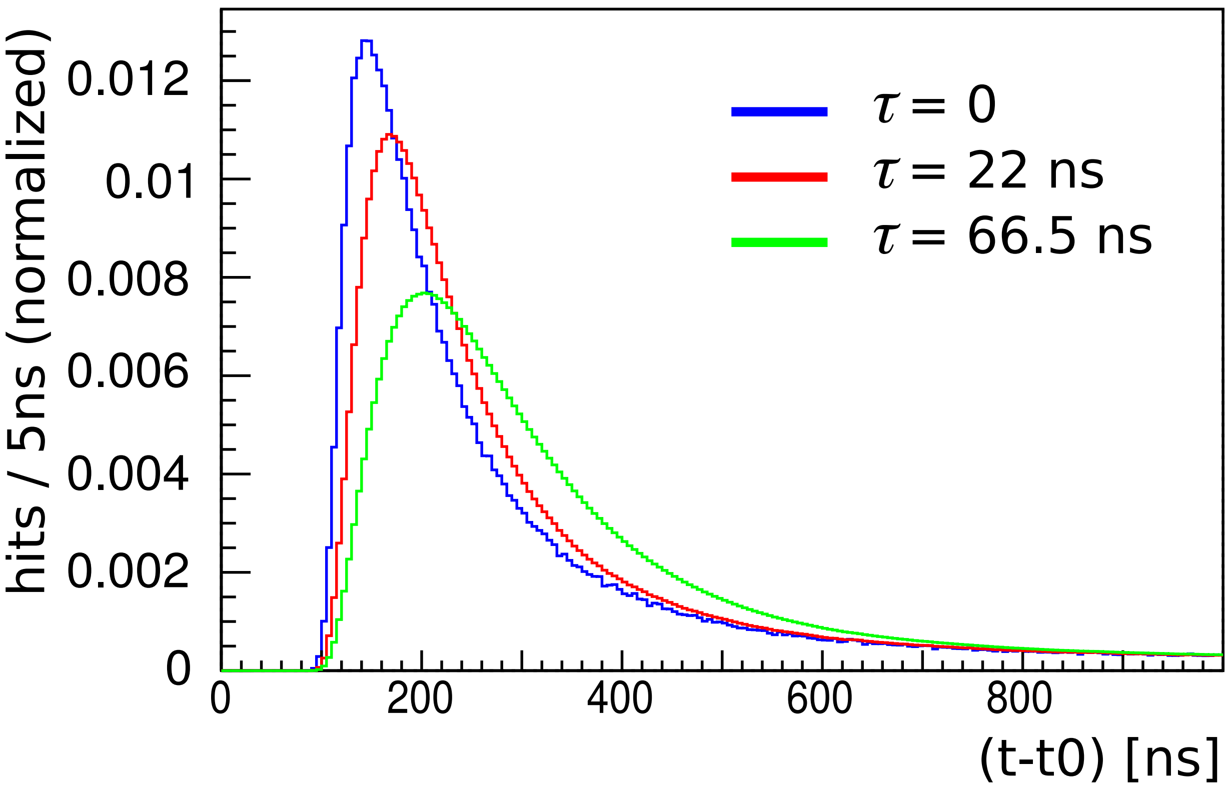
Backup slides

Impact of the cavity lifetime


intensity evolution

$$I(t) = I_0 \cdot \exp\left(-\frac{t-t_0}{\tau}\right)$$


excitation probability



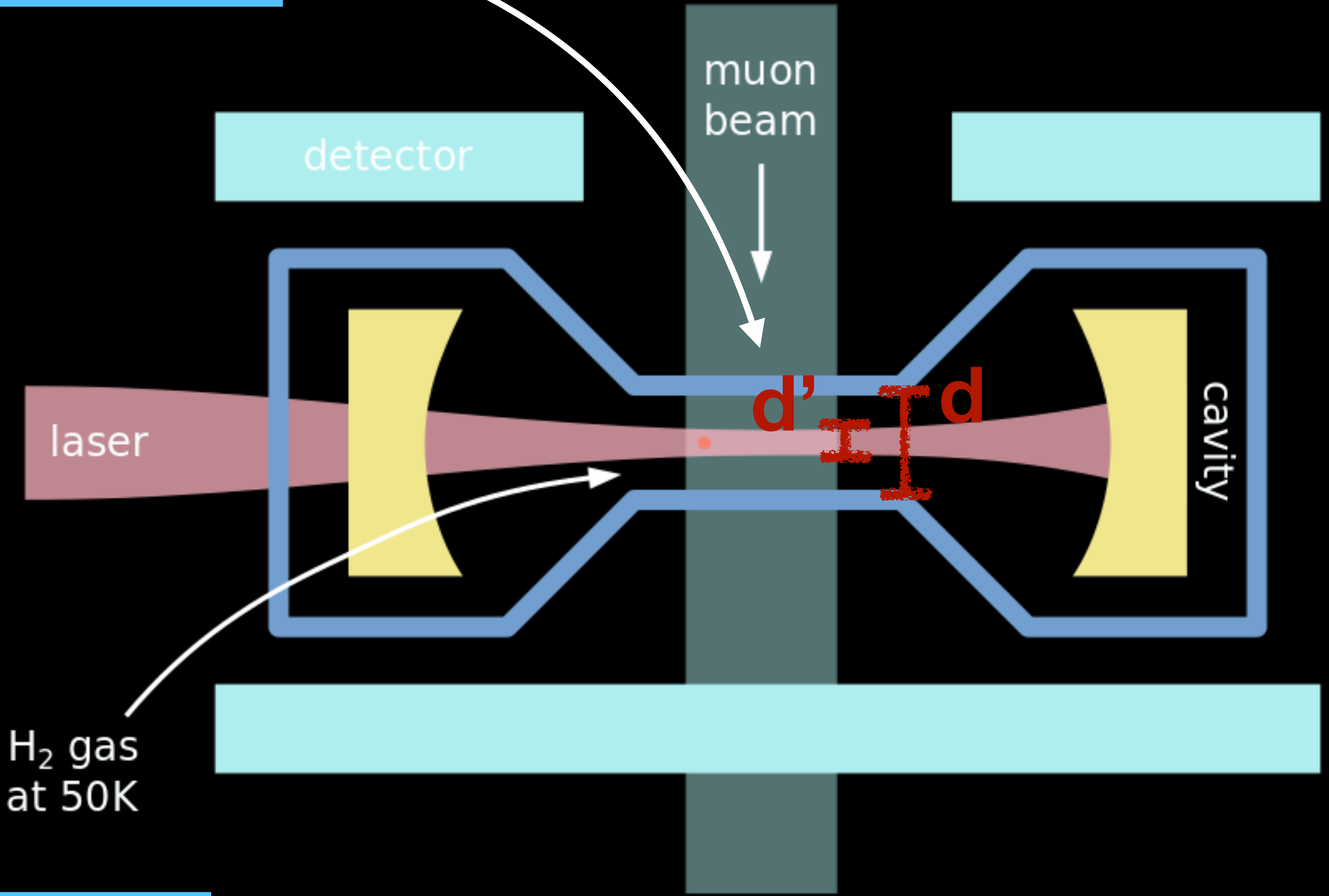
- Limited reflectivity of mirrors leads to exponential decrease of laser intensity
- Convolution of signal histogram with intensity profile smears peak to higher t

(input) parameters of the simulation

target length d

laser spread d’

~ 1 mm



gas pressure

gas temperature

~ 1 bar

~ 50 K

reflectivity of cavity

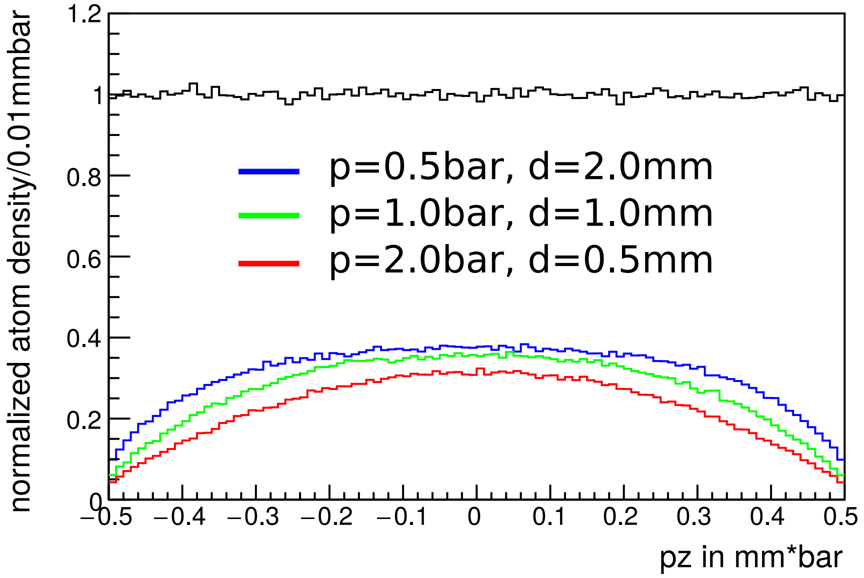
↓

Fluence F

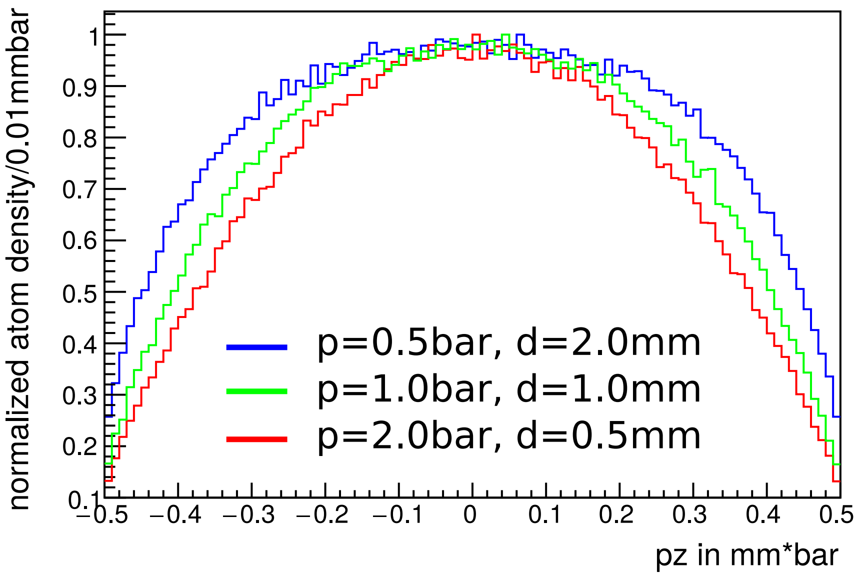
↑

total energy of laser pulse

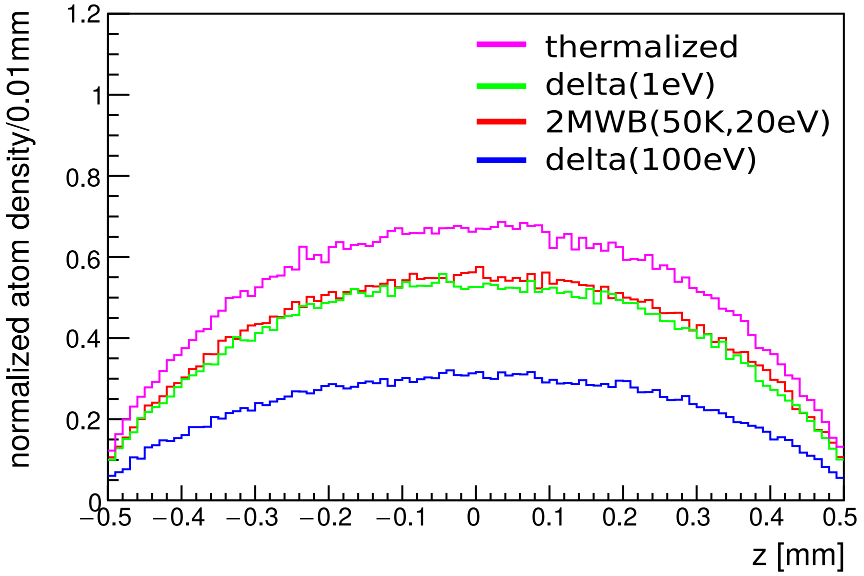
Diffusion before laser



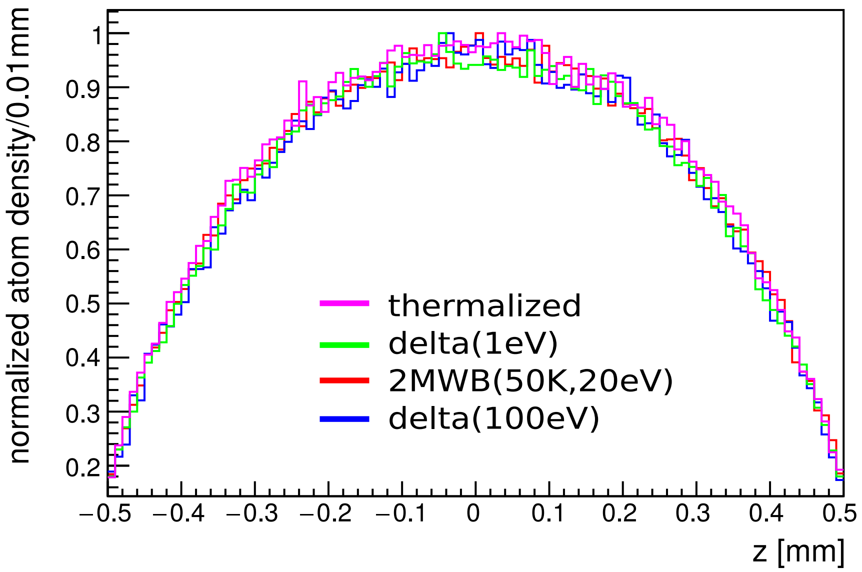
a) normalized to 1



b) normalized to maximum

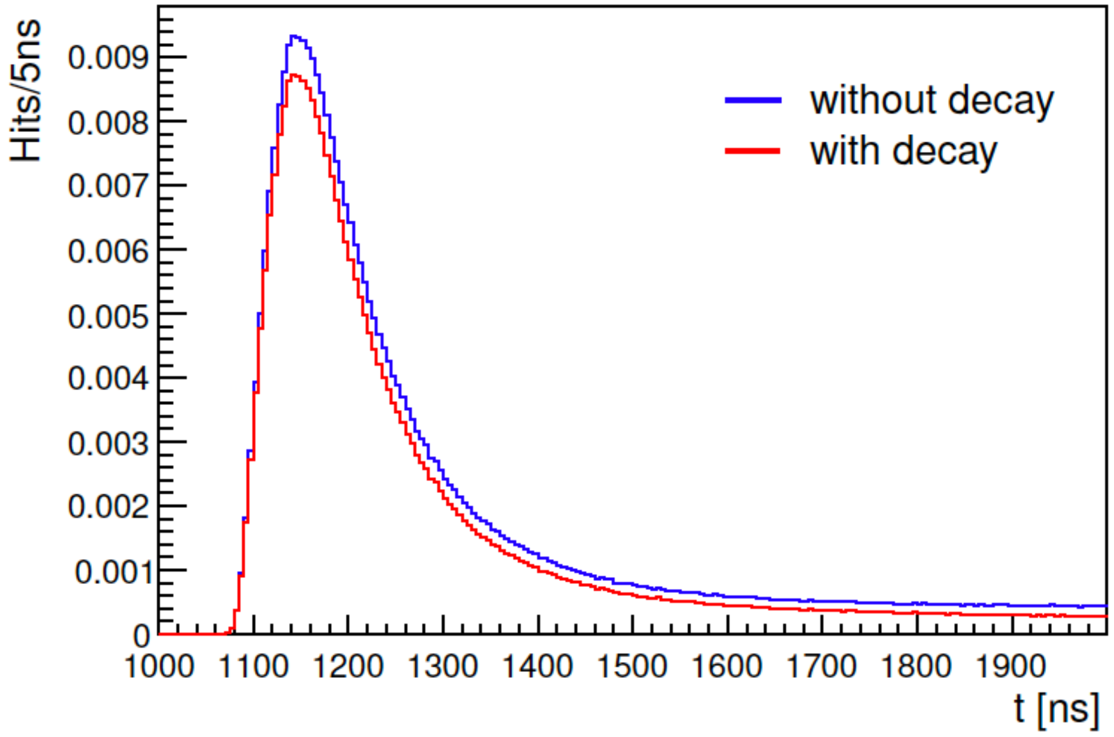


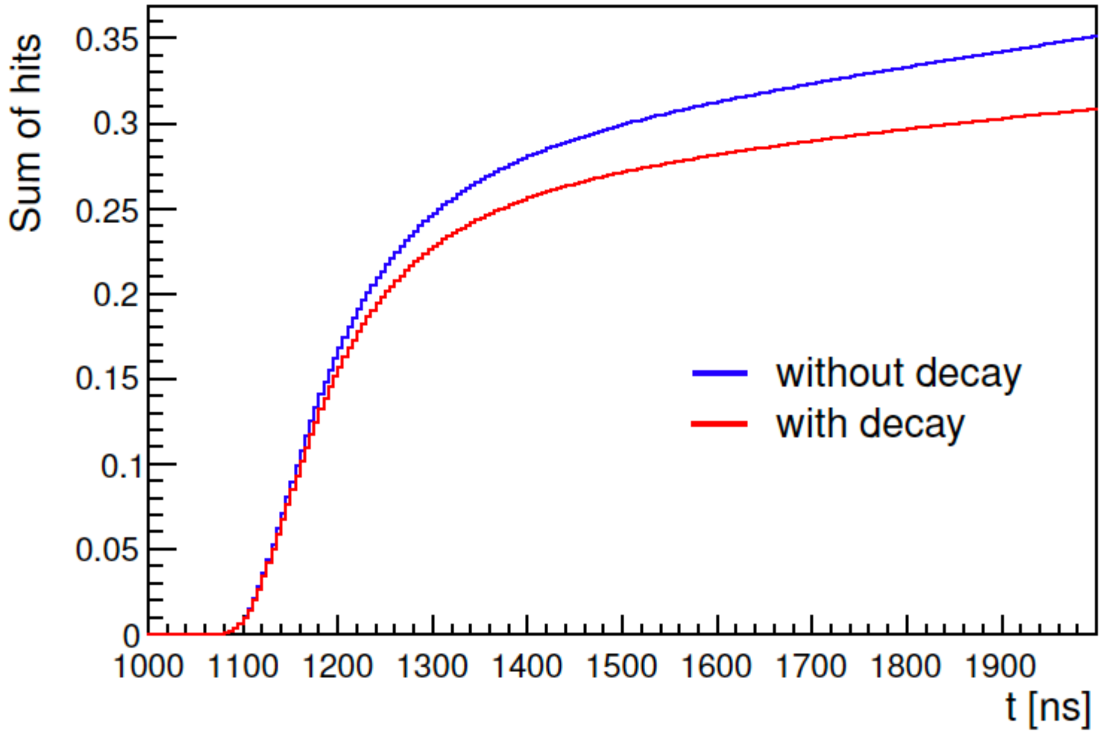
a) normalized to 1



b) normalized to maximum

Hits with / without decay

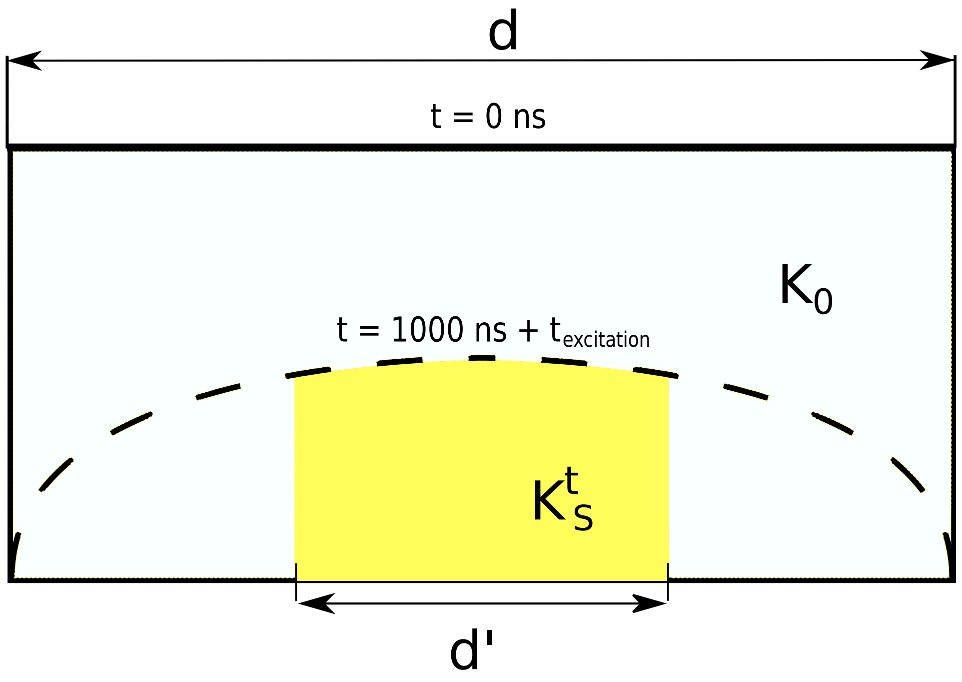




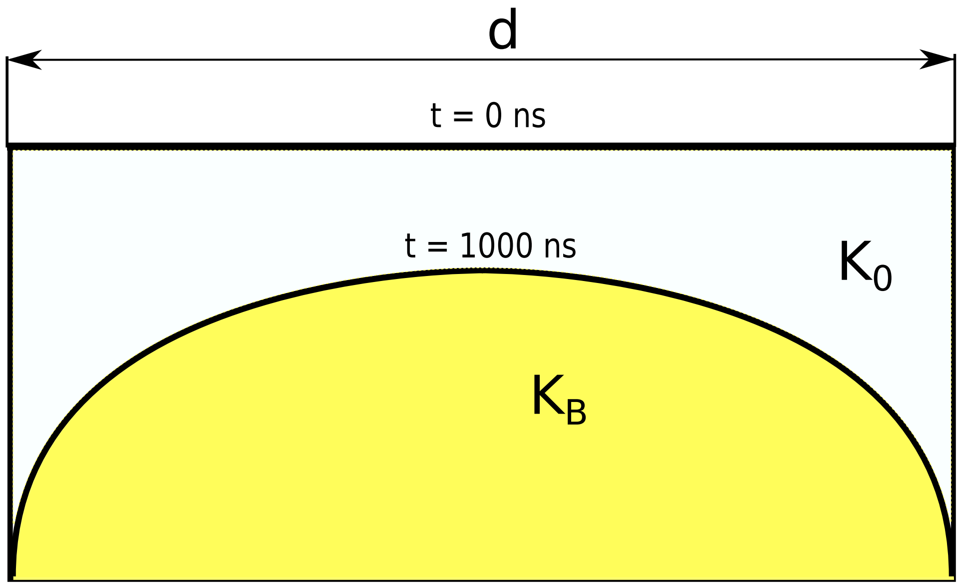
Combined signal and background simulation

pre-laser diffusion

Signal



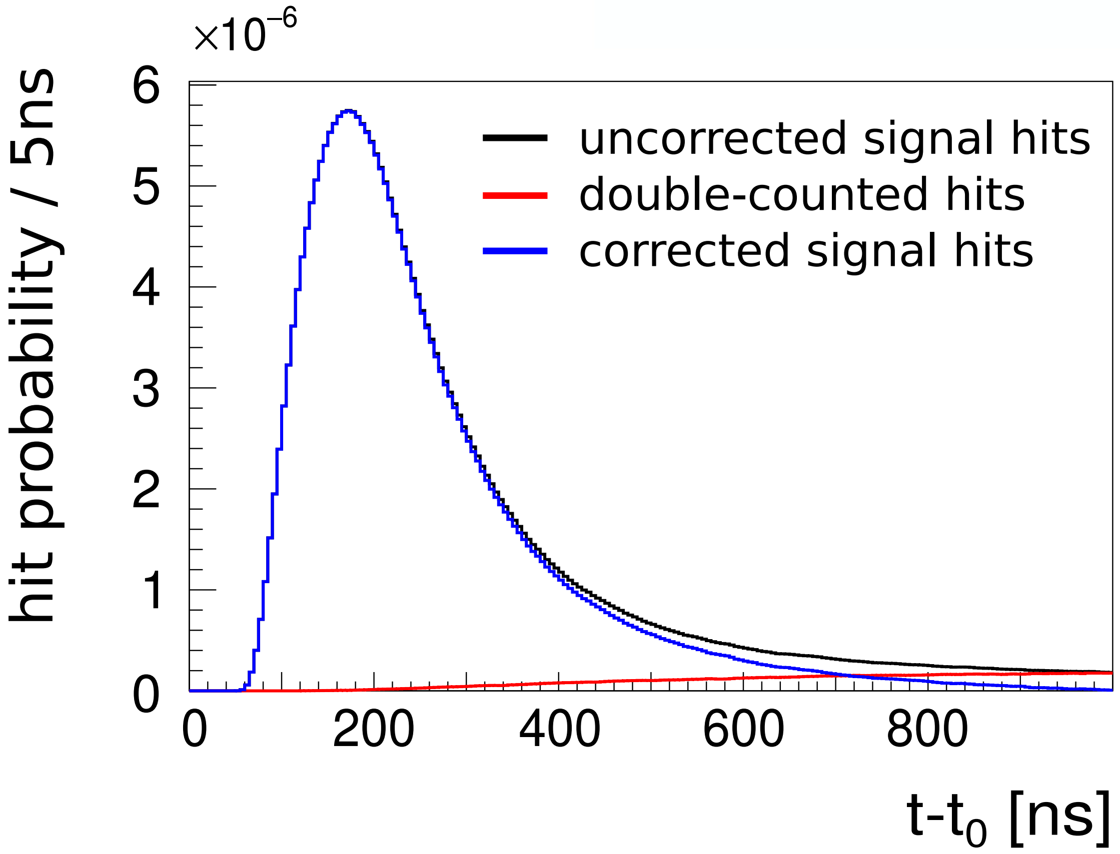
Background

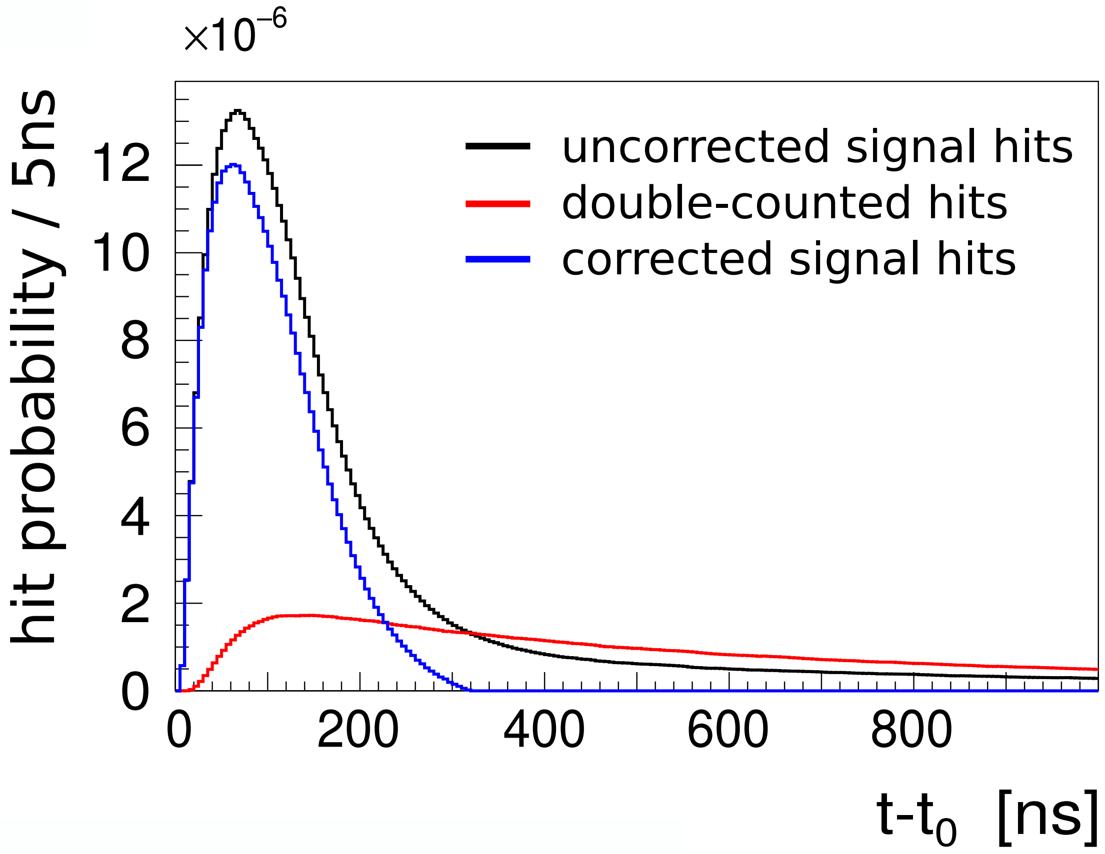


x excitation probability

- double-counted signal

double counts





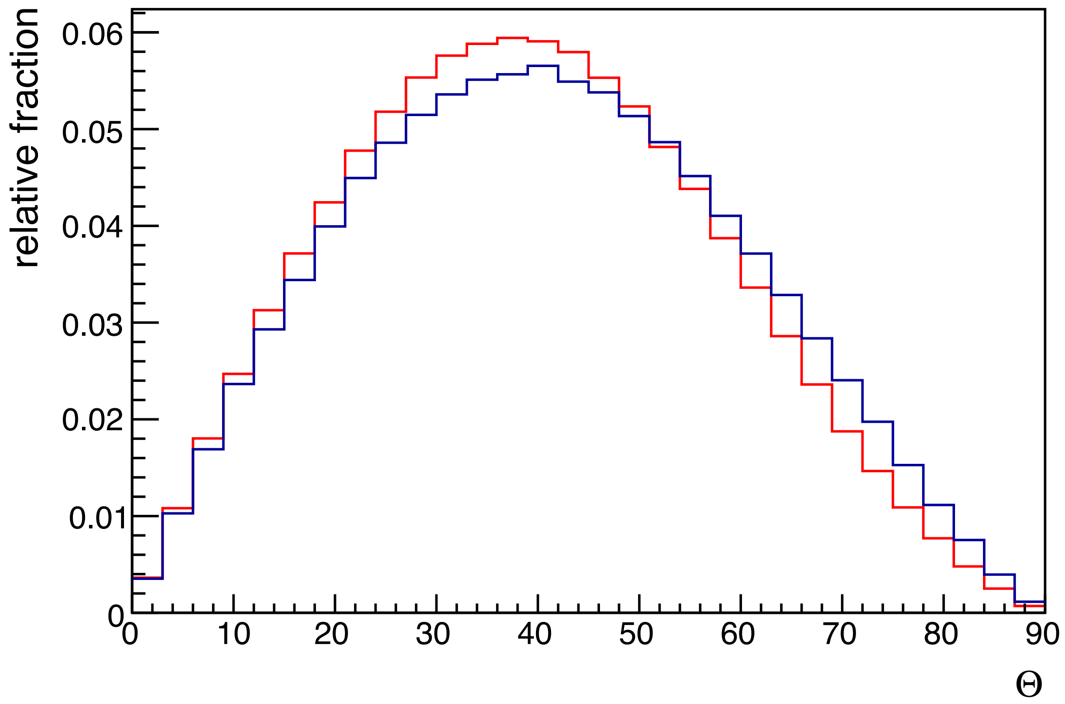
p = 1.0 bar, d = 1.0 mm

p = 2.0 bar, d = 0.5 mm

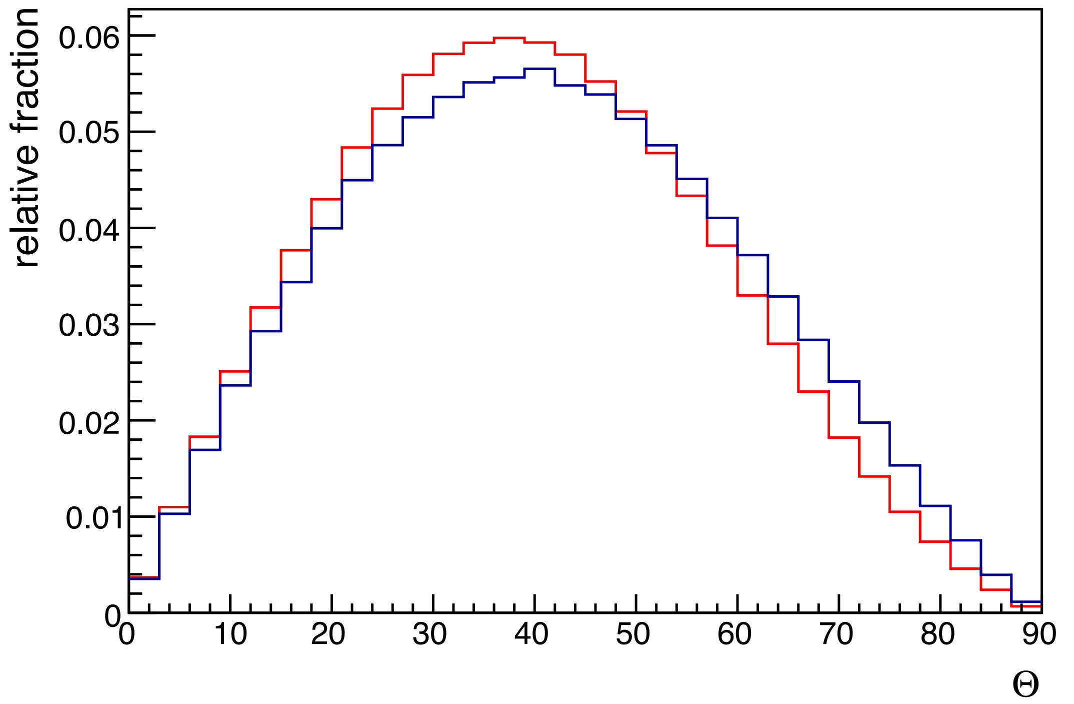
d’ = 0.45 mm

Angle of hits

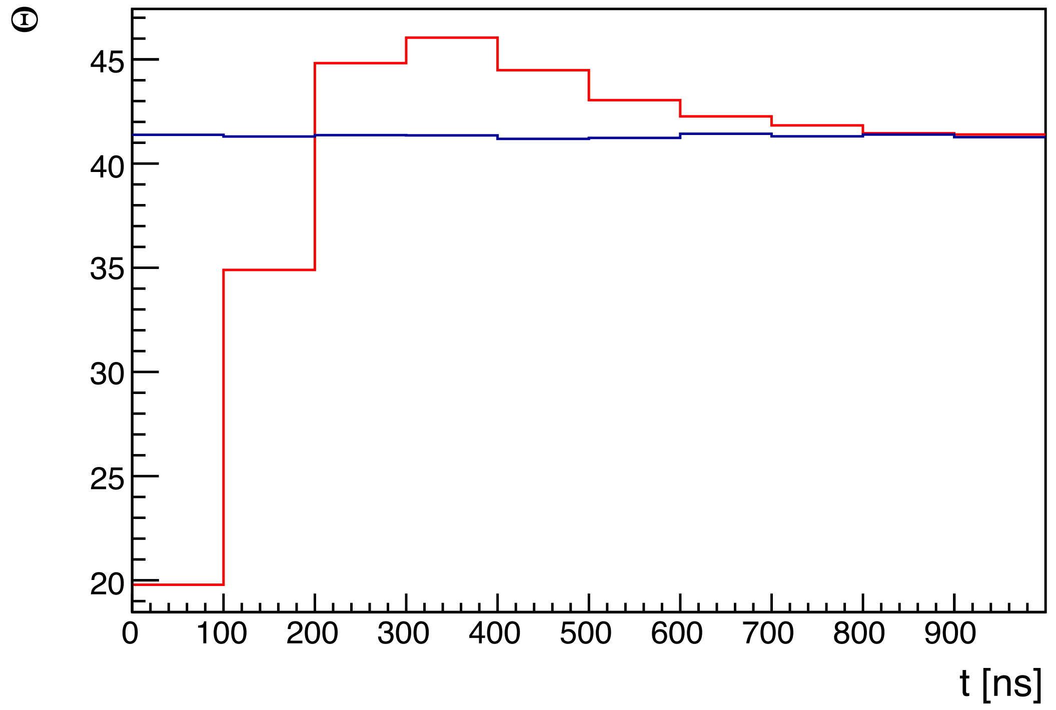
Θ for BG (blue) and Signal (red)



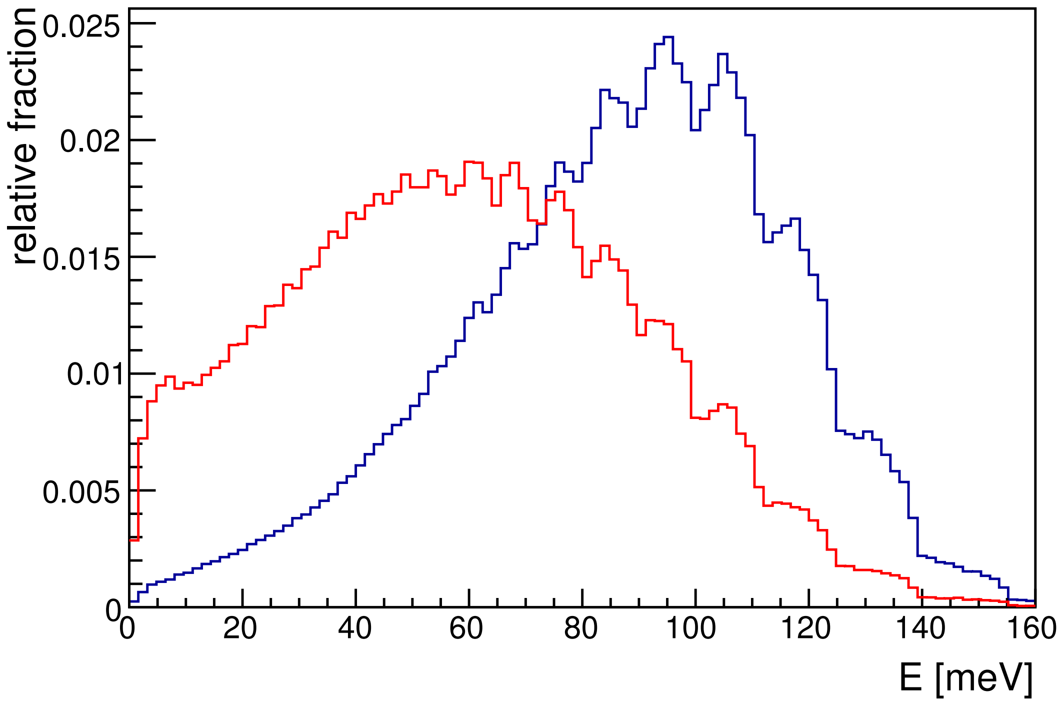
Θ for BG (blue) and Signal (red) including decay

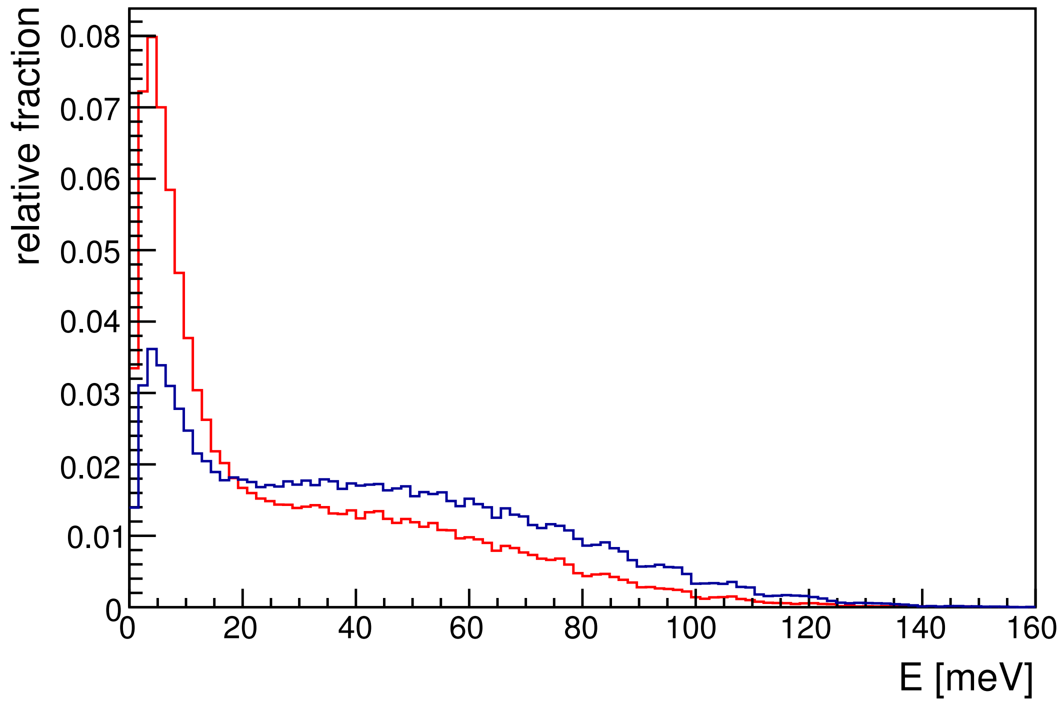


mean angle in interval t1-t2 for BG (blue) and Signal (red)



Energy of hits

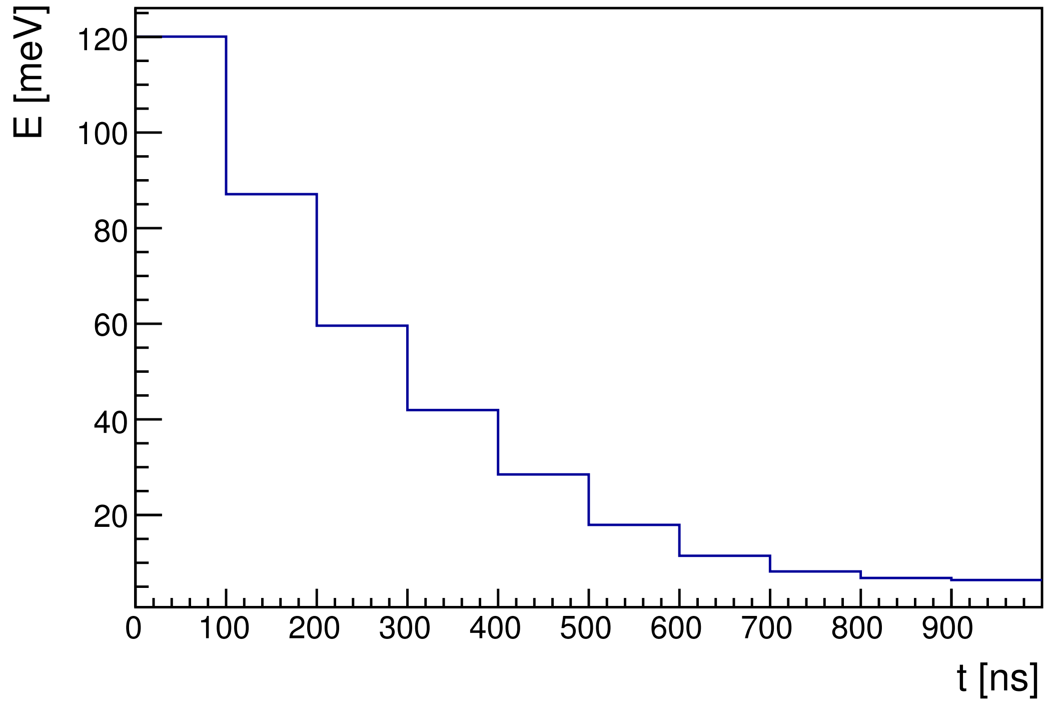

Energy of laser-excited mup hitting wall in time windows [100-200]ns(blue) and [200-300]ns(red)


Energy of laser-excited mup hitting wall in time windows [300-400]ns(blue) and [400-500]ns(red)

p = 0.8 bar
d = 1.0 mm

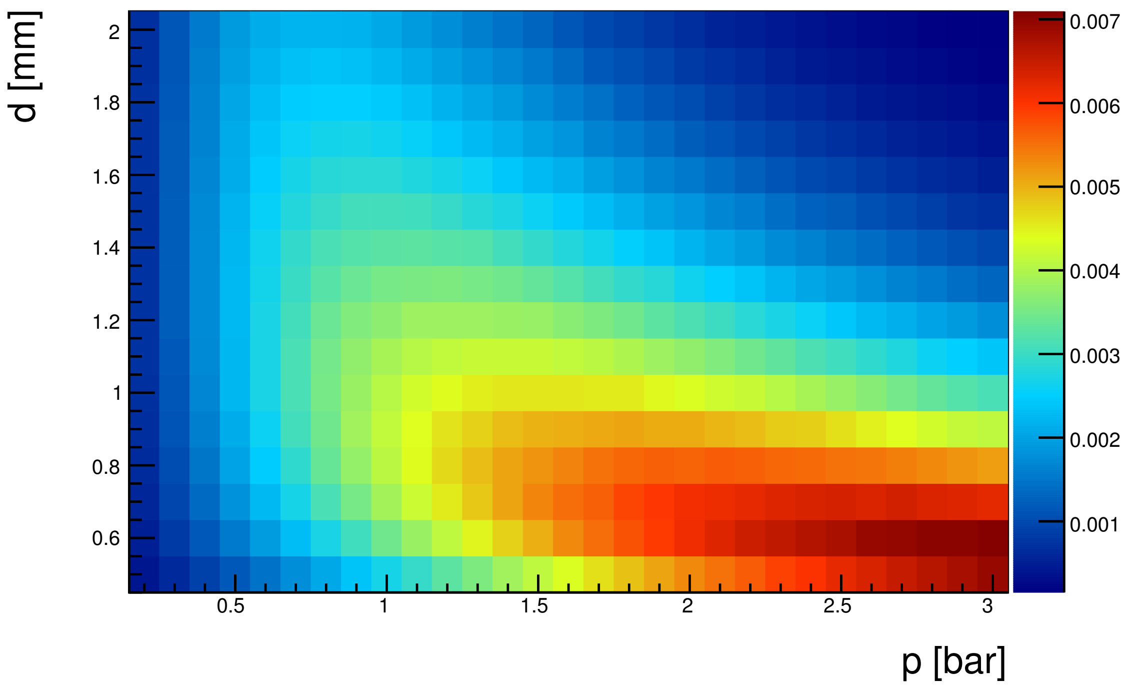
T = 30 K
Only laser excited atoms

d' = 0.25 mm

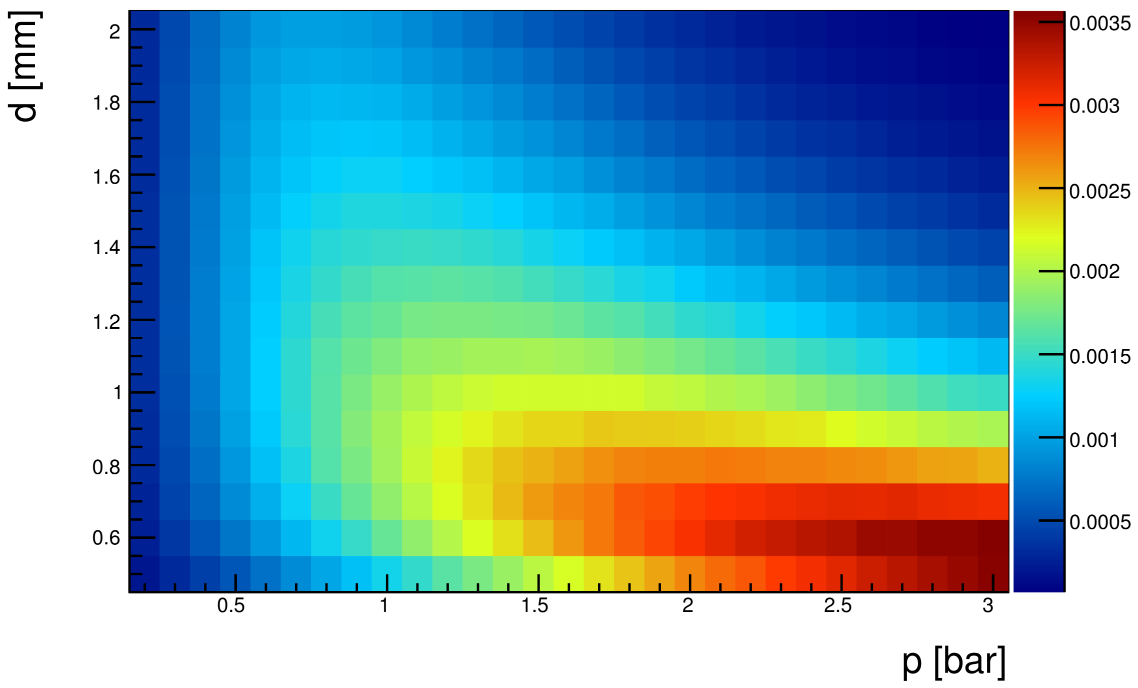

mean Energy in interval t1-t2 for Signal hits

E_0 = 2MWB (50 K, 20 eV)

F=1.9 J/cm2, R=0.995

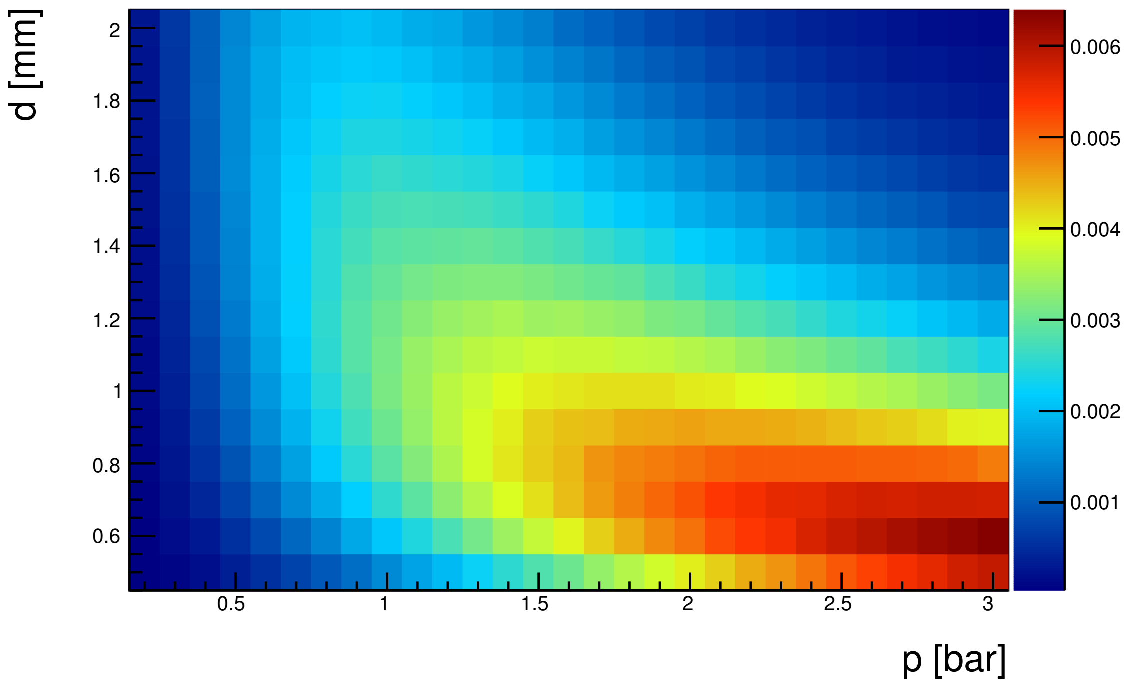


F=0.8 J/cm2, R=0.988



E_0 = delta(100 eV)

F=1.9 J/cm2, R=0.995



F=0.8 J/cm2, R=0.988