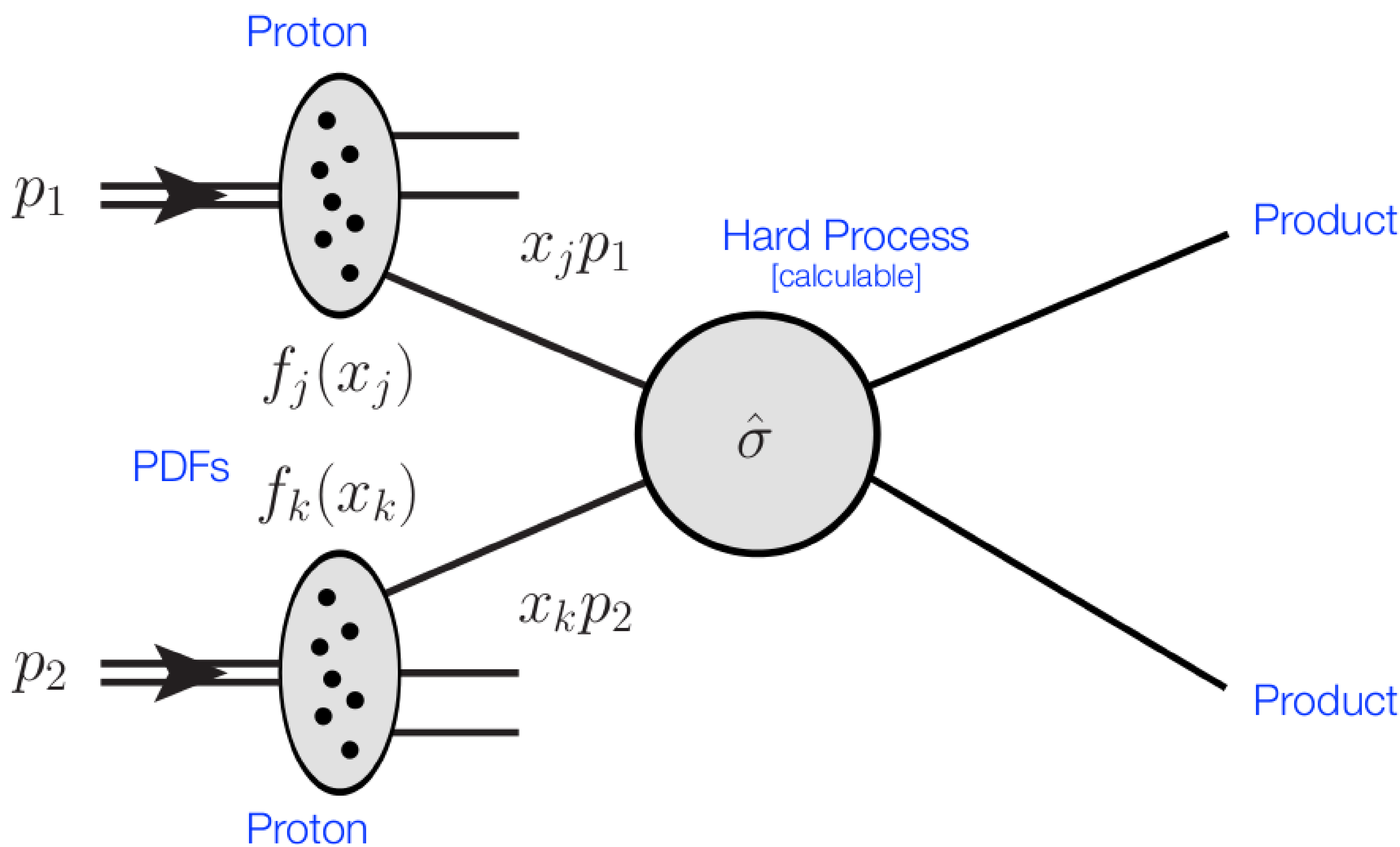
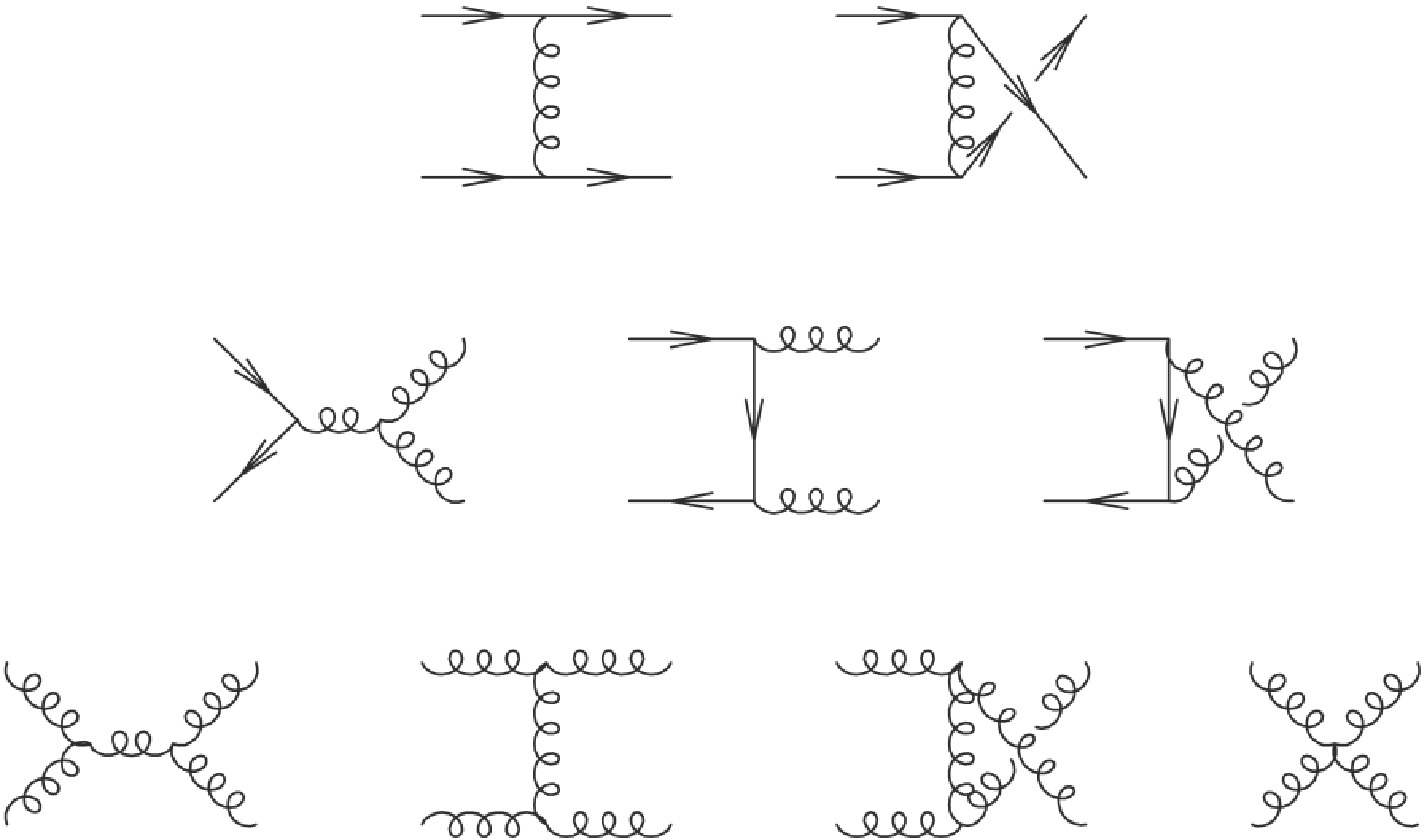
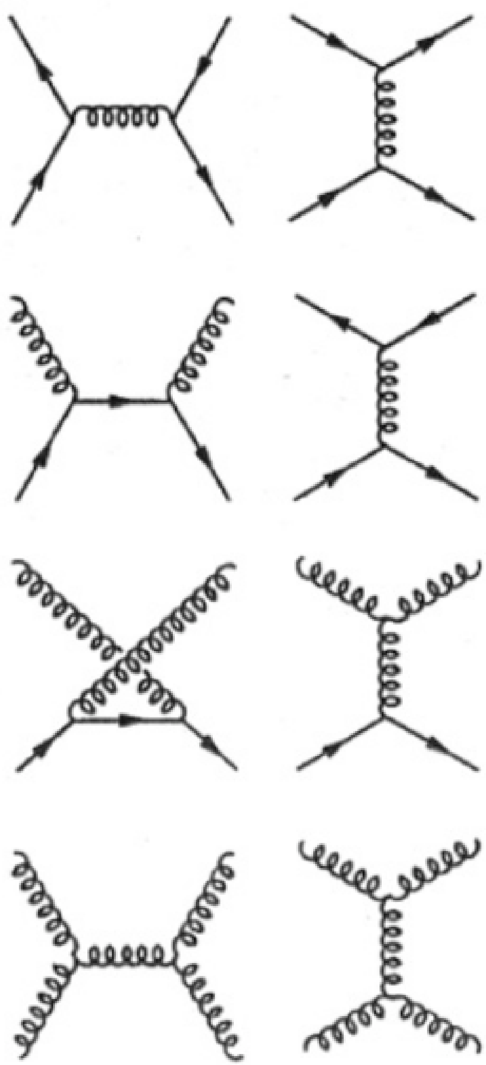
Proton-Proton Scattering @ LHC



Some Hard Processes ...

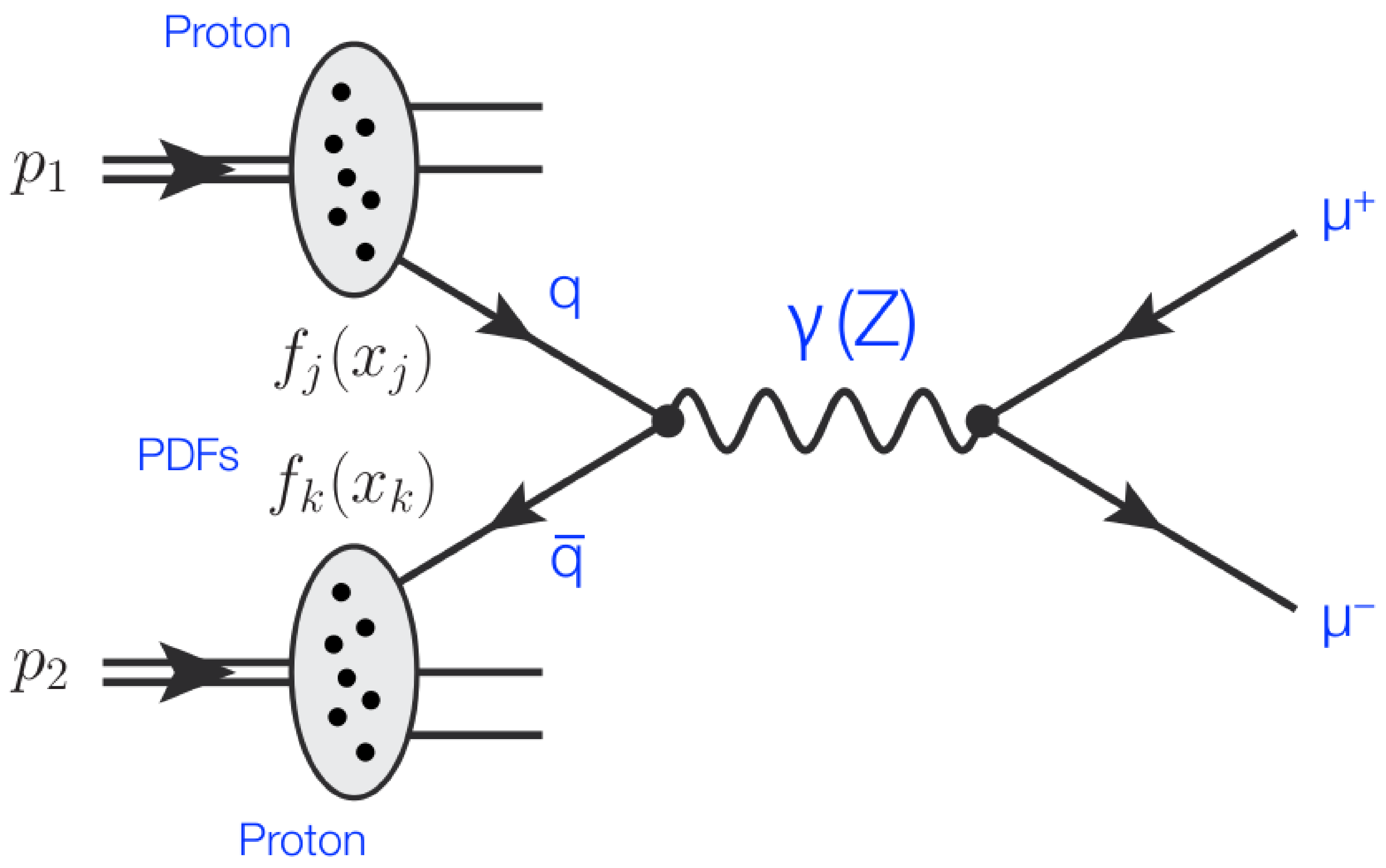


QCD Matrix Elements

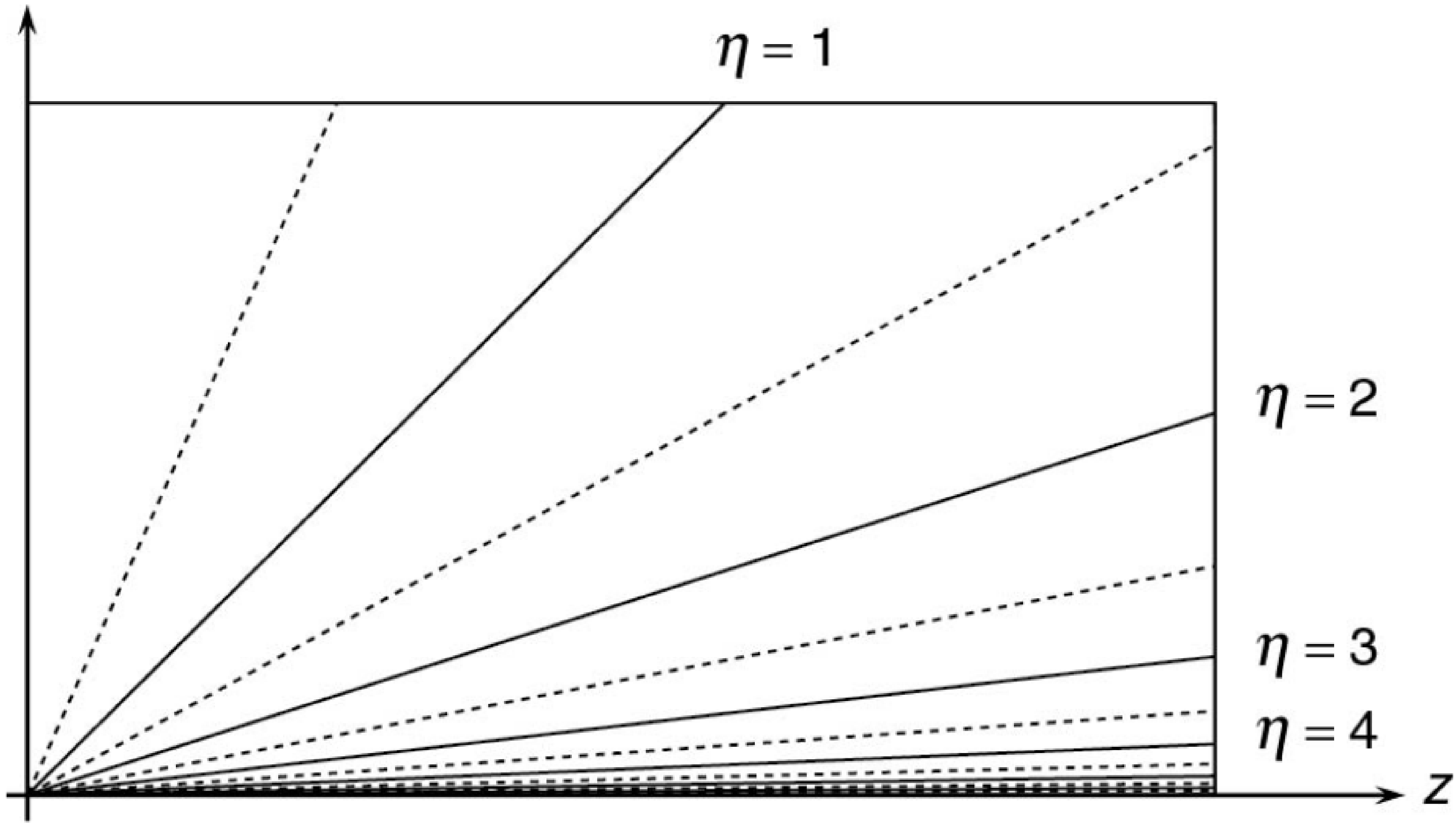


Subprocess	$\lvert\mathcal{M}\rvert^2/g_s^4$	$\lvert\mathcal{M}(90°)\rvert^2/g_s^4$
$qq' \to qq'$, $q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.2
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.6
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{8}{3}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	1.0
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{3}{8}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	0.1
$qg \to qg$	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \to gg$	$\frac{9}{4}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}+\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}+3\right)$	30.4

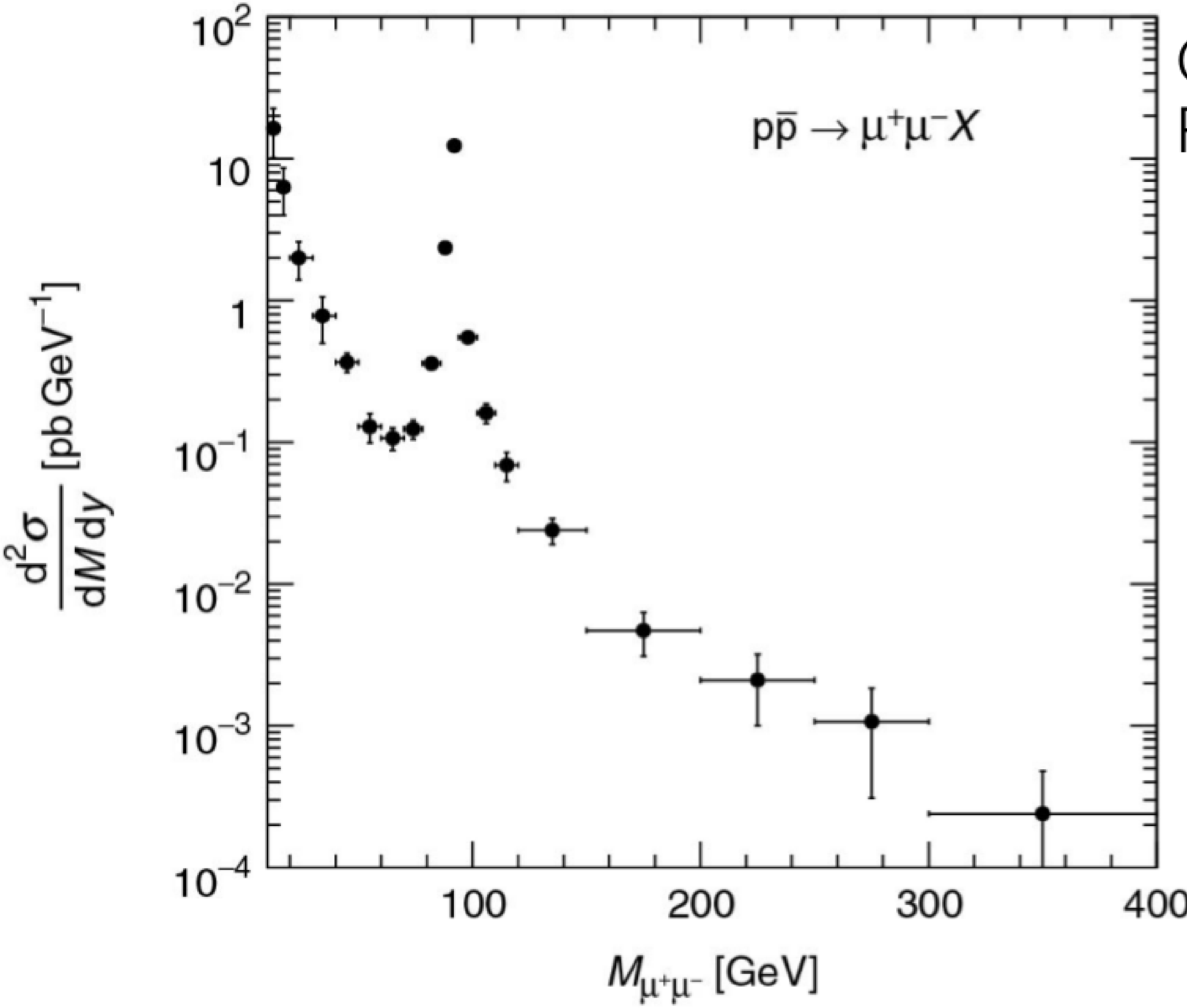
Example: Drell-Yan Process



Pseudorapidity Regions

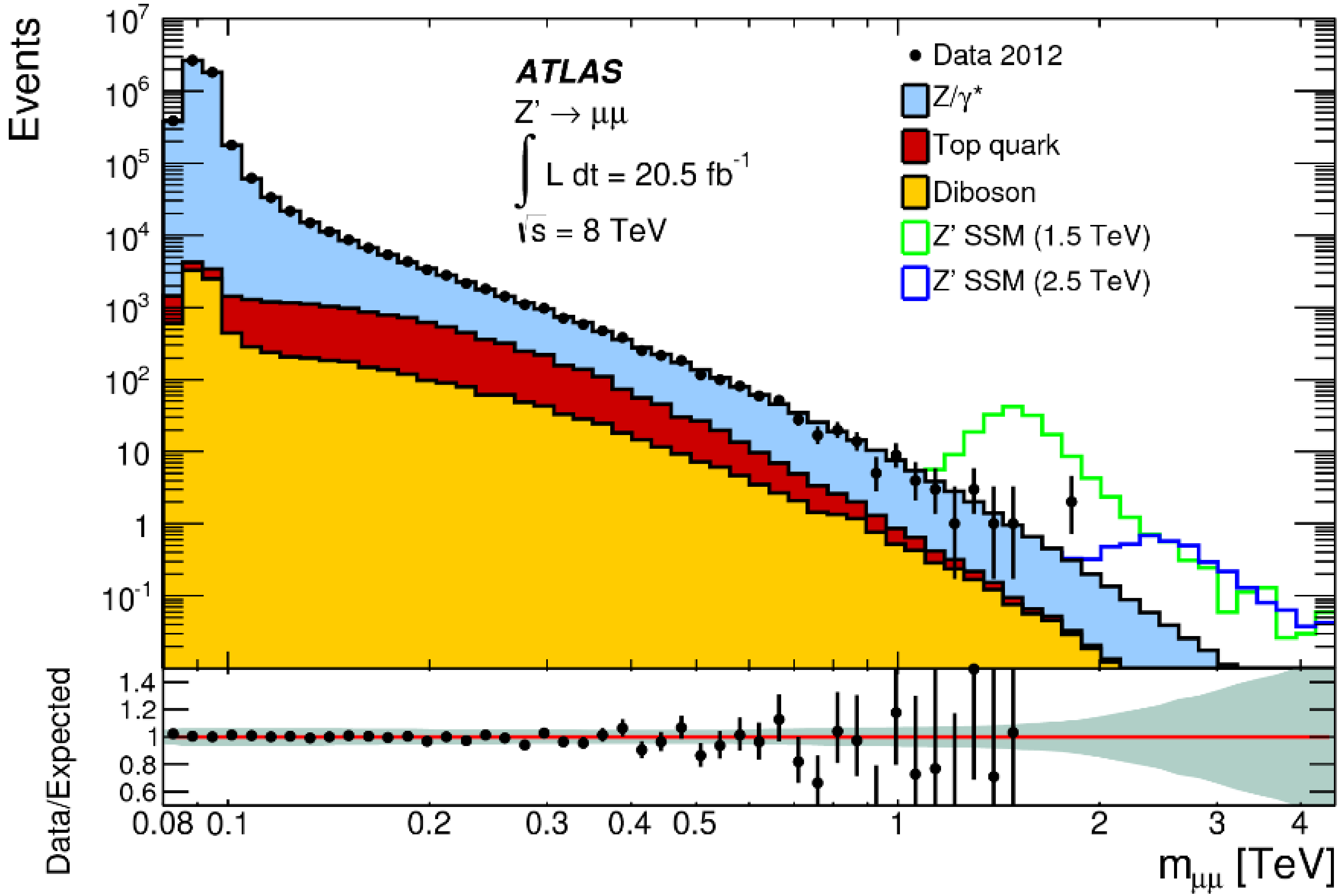


CDF Result

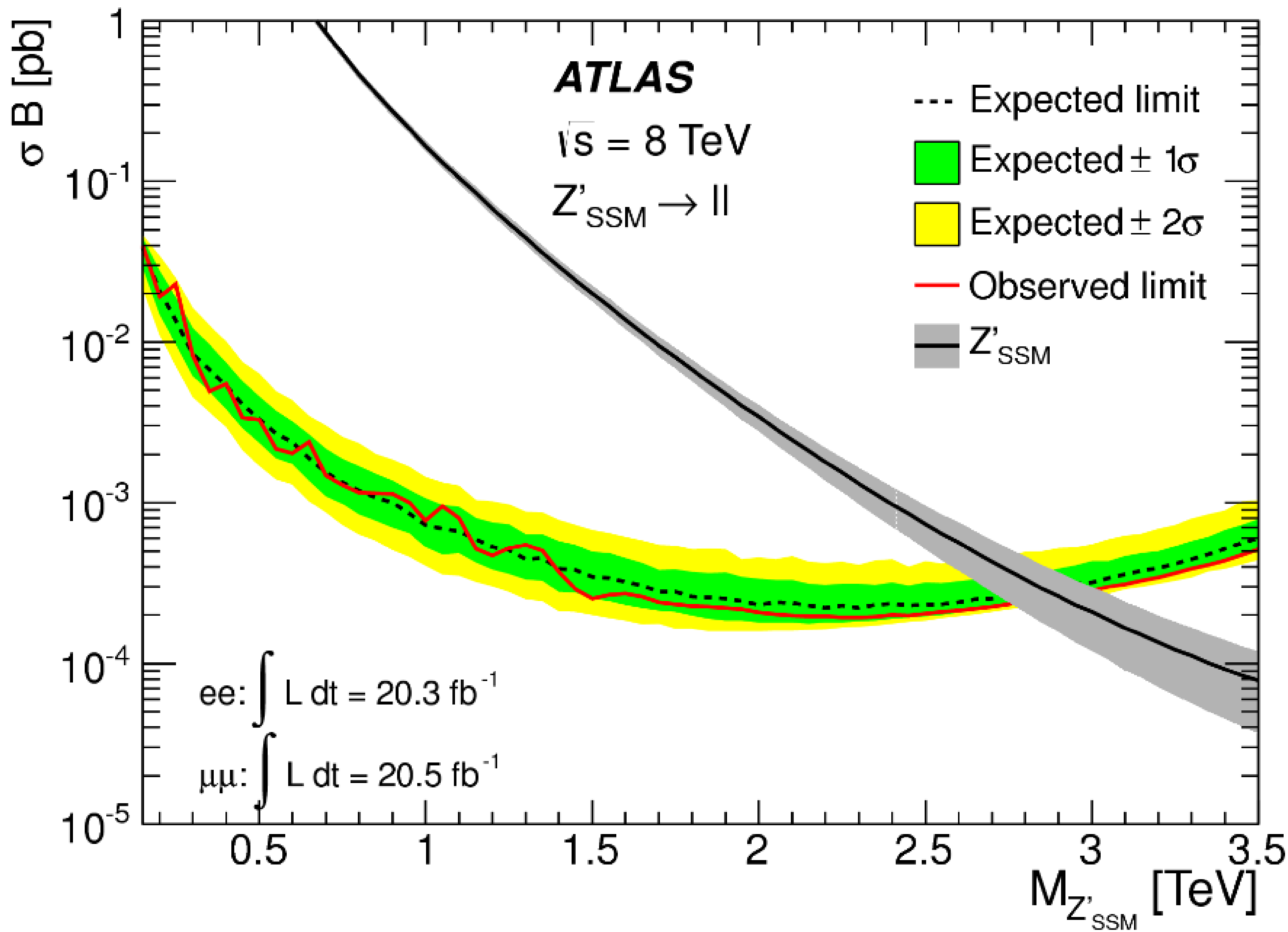


$p\bar{p} \to \mu^+\mu^- X$
$\frac{d^2\sigma}{dM\,dy}$ [pb GeV^{-1}]
$M_{\mu^+\mu^-}$ [GeV]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
200
300
400

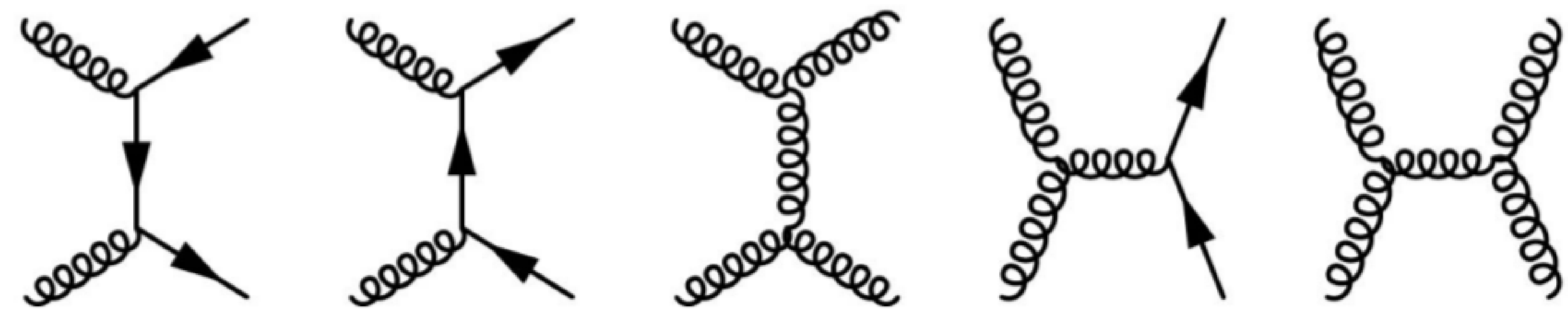
ATLAS Z' Search Result



ATLAS Z' Search Result

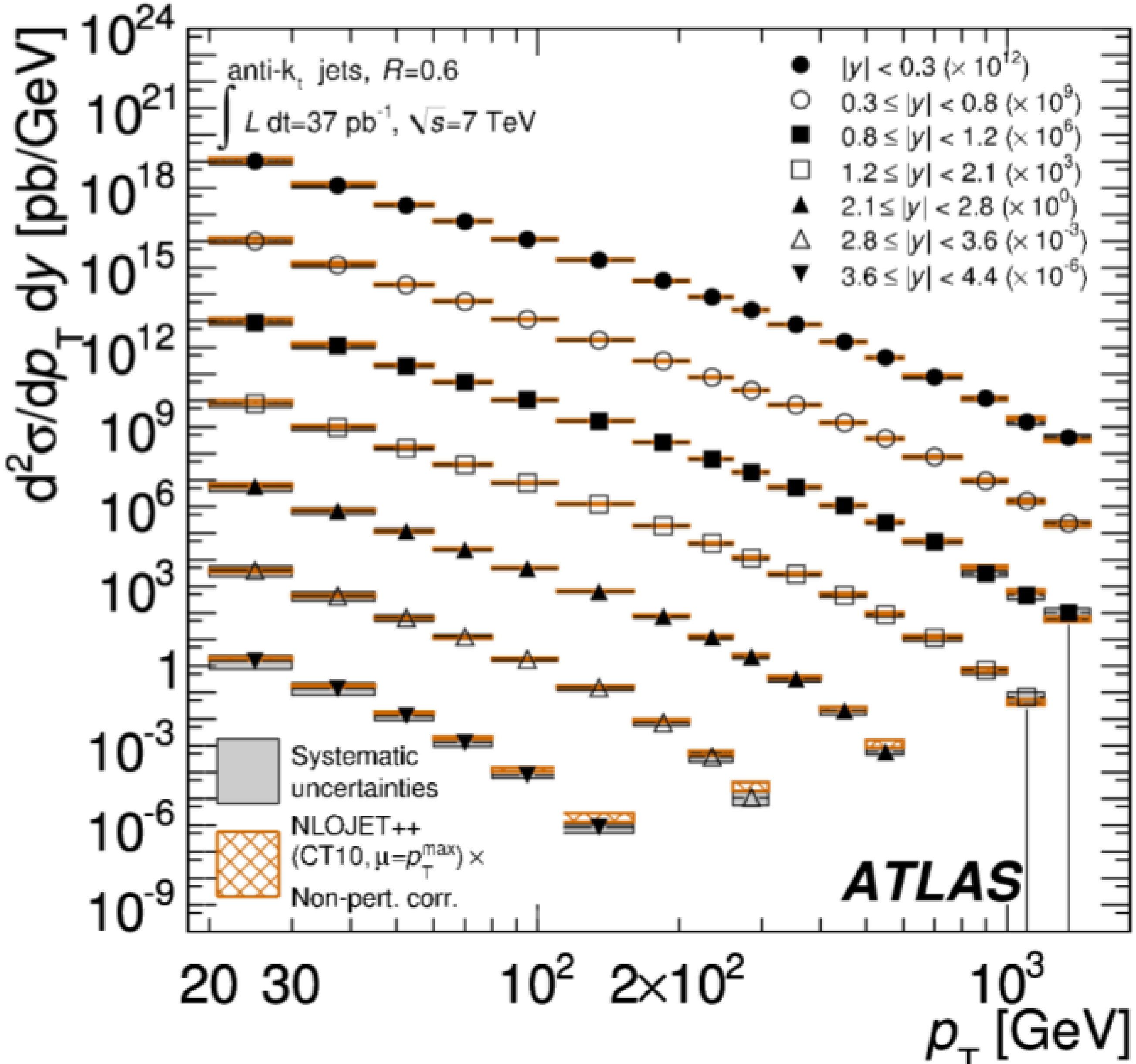


QCD Dijet-Production

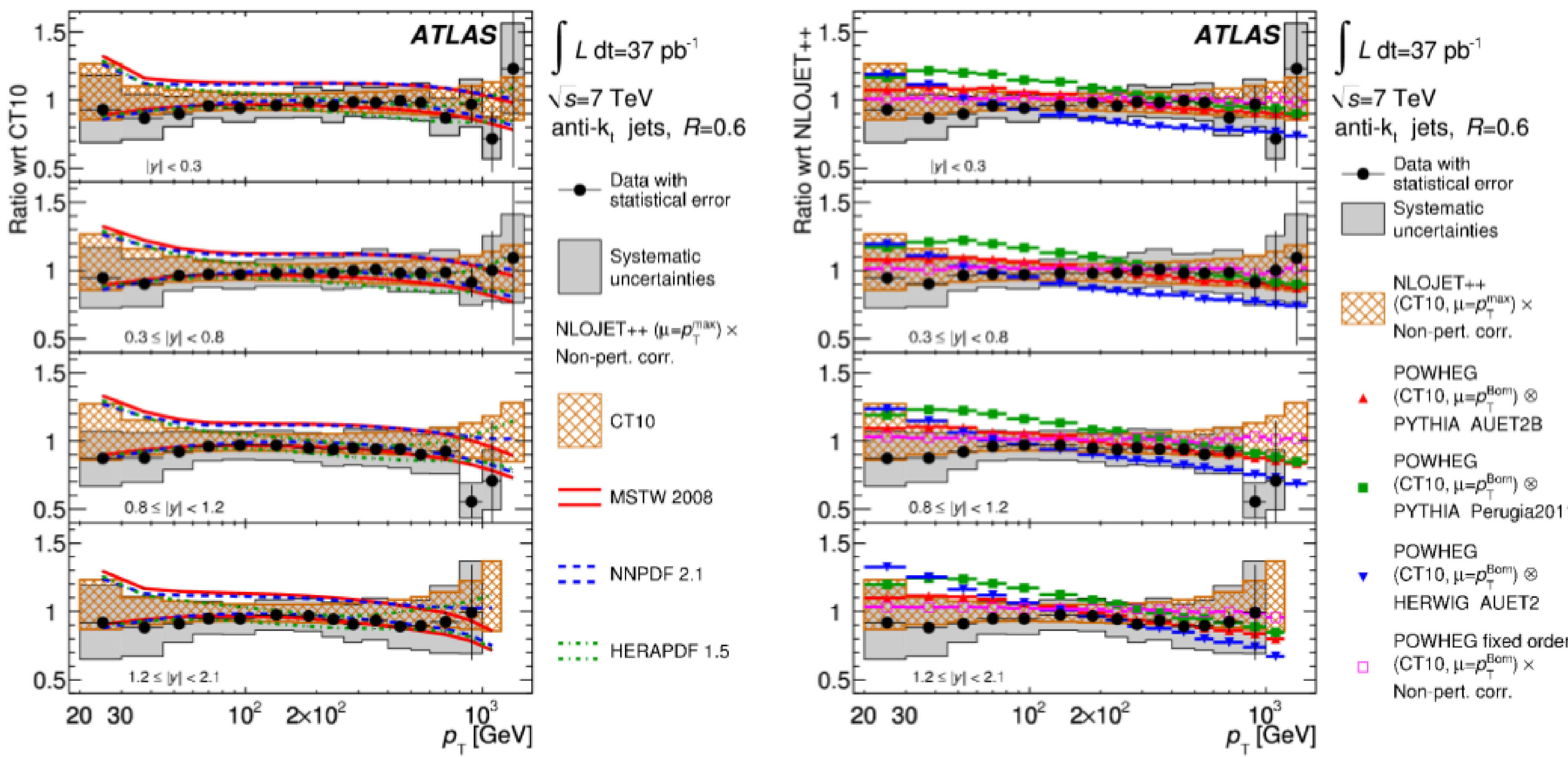


M. Thomson, Modern Particle Physics

Inclusive Jet Cross Section



Inclusive Jet Cross Section



Reminder of Parity

particle solution $\Psi_i = u_i(E,\vec{p})\; e^{i(\vec{p}\vec{x}-Et)}$

$$u_1 = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ \frac{p_z}{E+m} \\ \frac{p_x+ip_y}{E+m} \end{pmatrix} \qquad u_2 = \sqrt{E+m}\begin{pmatrix} 0 \\ 1 \\ \frac{p_x-ip_y}{E+m} \\ \frac{-p_z}{E+m} \end{pmatrix}$$

antiparticle solution $\Psi_i = v_i(E,\vec{p})\, e^{-i(\vec{p}\vec{x}-Et)}$

$$v_1 = \sqrt{E+m}\begin{pmatrix} \frac{p_x-ip_y}{E+m} \\ \frac{-p_z}{E+m} \\ 1 \\ 0 \end{pmatrix} \qquad v_2 = \sqrt{E+m}\begin{pmatrix} \frac{p_z}{E+m} \\ \frac{p_x+ip_y}{E+m} \\ 0 \\ 1 \end{pmatrix}$$

These solutions have positive energies.

Partity operator P:

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Spin ½ particles AT REST have intrinsic partiy P = +1

Spin ½ particles AT REST have intrinsic parity P=-1

Historical Θ/τ

In 1956, parity conservation as well as T and C symmetry was a "dogma"

$\longrightarrow$ very little experimental tests done

θ/τ puzzle:

$\theta \longrightarrow \pi^+\pi^0$; P($\pi^+\pi^0$) = +1

$\tau \longrightarrow \pi^+\pi^+\pi^-$; P($\pi^+\pi^+\pi^-$) = -1

P(q) = 1; P($\bar{q}$) = -1;

P(meson) = $P_q P_{\bar{q}}(-1)^L$;

lowest energy, $S = 0$

P=-1

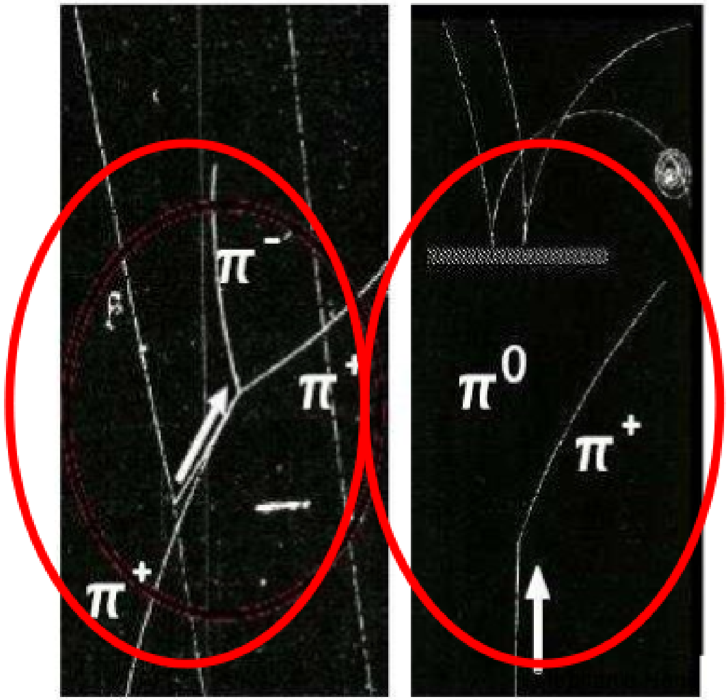
θ, τ have same mass, same lifetime, however different parity ...

Yang, Lee:

$\longrightarrow \theta = \tau = K^+$

weak interaction violates parity

proposed a set of measurements which test parity

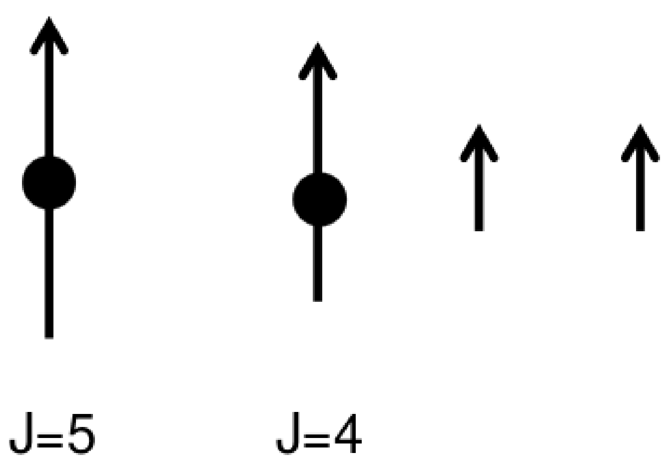


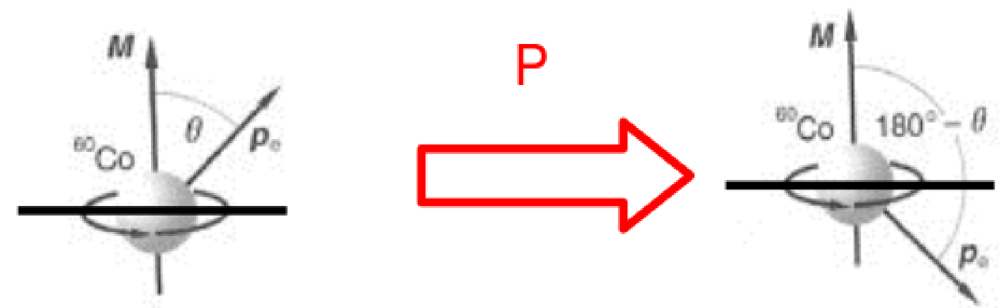
Wu-Experiment

Partiy conservation: physics stays invariant under parity conservation

Idea: Check that number of electrons emitted in direction of spin ($\vec{J}$) of ^{60}Co and in opposite direction (-$\vec{J}$) are the same.

$$^{60}Co \rightarrow ^{60} Ni^{*} + e^{-} + \overline{\nu_e}$$





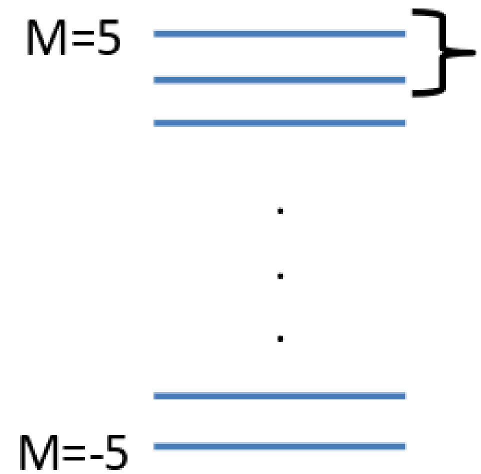
Experiment: Invert polarization of ^{60}Co and compare electron rate in same angle Θ

$$Ni^{*} \rightarrow Ni + \gamma$$

photons are preferentially emitted in direction of spin. Use photon distribution to test polarization of ^{60}Co. (elm IA conserves parity)

MAIN CHALLENGE: Polarization of ^{60}C0

Spin of ^{60}Co: J=5 → M = -5,-4, …., 4, 5



$\Delta E = g\,\mu_K\,B$

$\mu_K \sim 5.05 \times 10^{-27}$ J/T

Population of energy levels follows Boltzmann distribution:

$$e^{-\frac{E}{k_B T}}$$

for $\Delta E >> k_B T$ only lowest energy level is populated, however for given B field in experiment (2.3 T) very low temperatures needed

g factor depends on gitter structure

Example: g= 7.5 (^{60}Co), B = 2.3 T, T = 0.003 K

$$\frac{P(m=-4)}{P(m=-5)} = e^{-\frac{\Delta E}{k_B T}} = 0.074$$ → 92% polarized ^{60}Co

Solution Part-I: embedding ^{60}C0 in a paramagnetic material ($B \sim \mu_r$; $\mu_r \sim 3$-4)
still temepratures of T=0.01K needed

Adiabatic Colling

1926 von Debye proposed method to create low temperature

Fundamental relation of thermodynamics: $dU = T\,dS - p\,dV$

1. Step: isotherm magnetisation
   - paramagnetic material in helium gas is put into magnetic field
   - energy levels are split up, only lower once are populated
   - entropy gets smaller: $dS < 0 \rightarrow dU < 0$, helium gas absorbes heat

2. Step: helium gas removed → thermal isolation of nitrit

3. Step: adiabatic cooling
   - magnetic field is slowly switched off
   - split off of energy levels get smaller
   - system likes to polpulate higher states, however $dU = const$ due to isolation
   - dS gets larger thus T gets smaller

↔ Caveat: need magnetic field to get polarized ^{60}Co

How to combine Cooling and Polarization?

Two competing effects needed in the nitrit-crystal to get high degree of ploarization

1) Need high B field and low temperature to get polarization
2) Switch off B field to lower temperature via adiabatical cooling
   B field on → warm up, B field off → cool down

How does this work?

Solution: Some paramagnetic material have large anisotropic distribution of g-factors
(artefact of crystal structure, different binding mechanisms)

B field for adiabatic cooling in direction with high g-factor
Thus large split up of energy levels, thus large cooling effect

B field for polarization in direction of low g-factor, thus only little warm up

Wu-Experiment

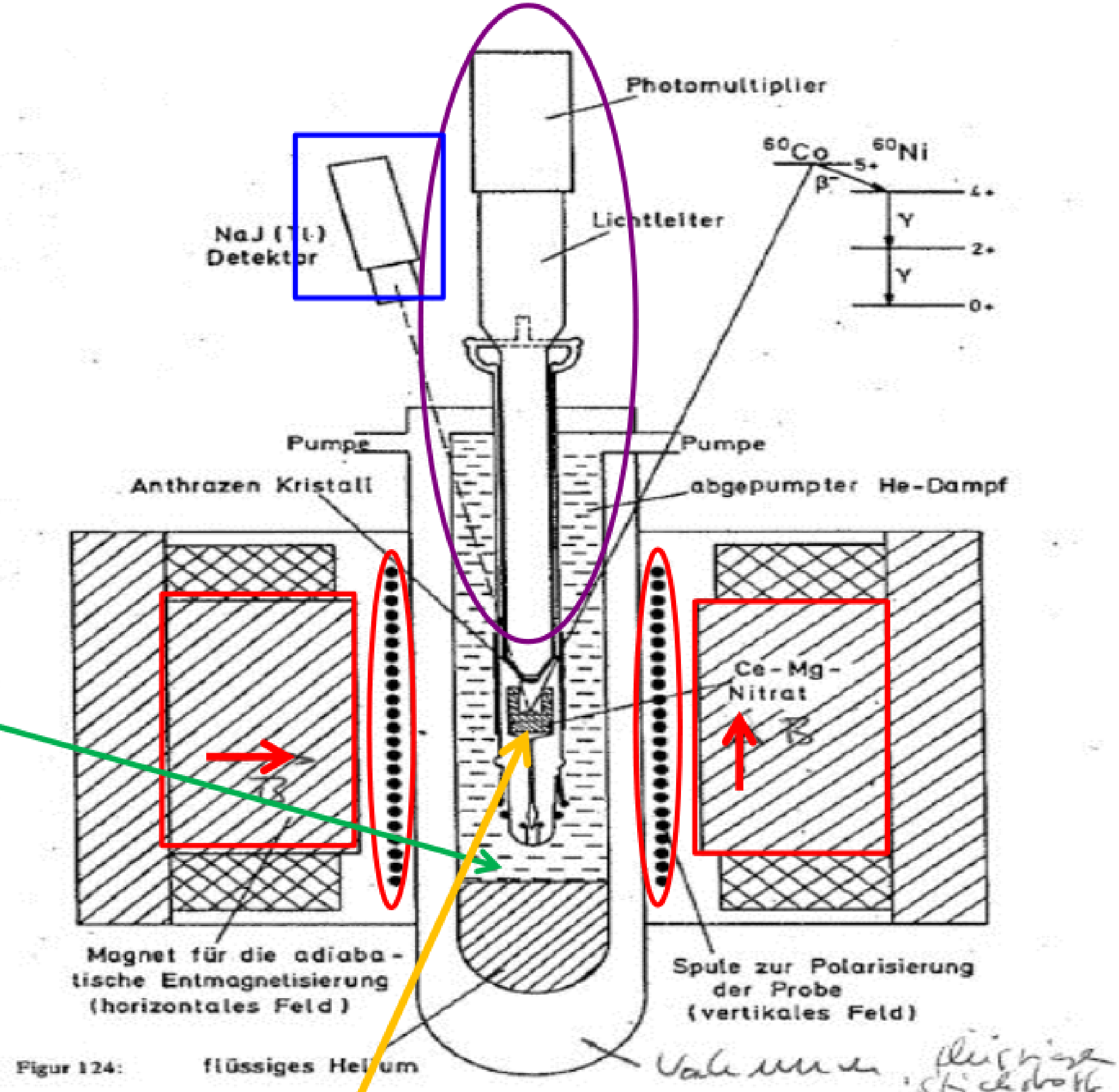
Requirements:

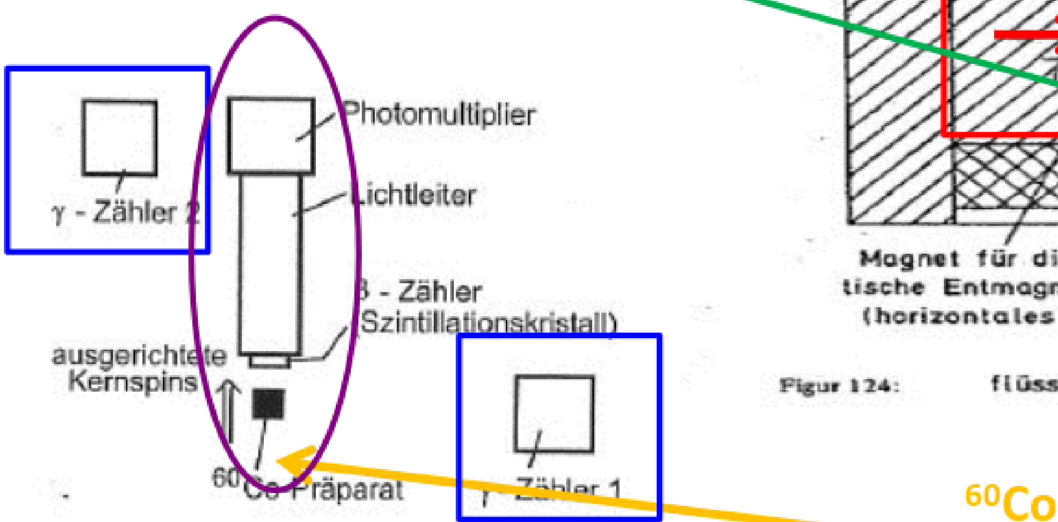
- 2 B fields in orthogonal directions

- detection of emitted electron
  (cover a small opening angle Θ)

- detection of emitted gamma
  (to test polarization of ^{60}Co)

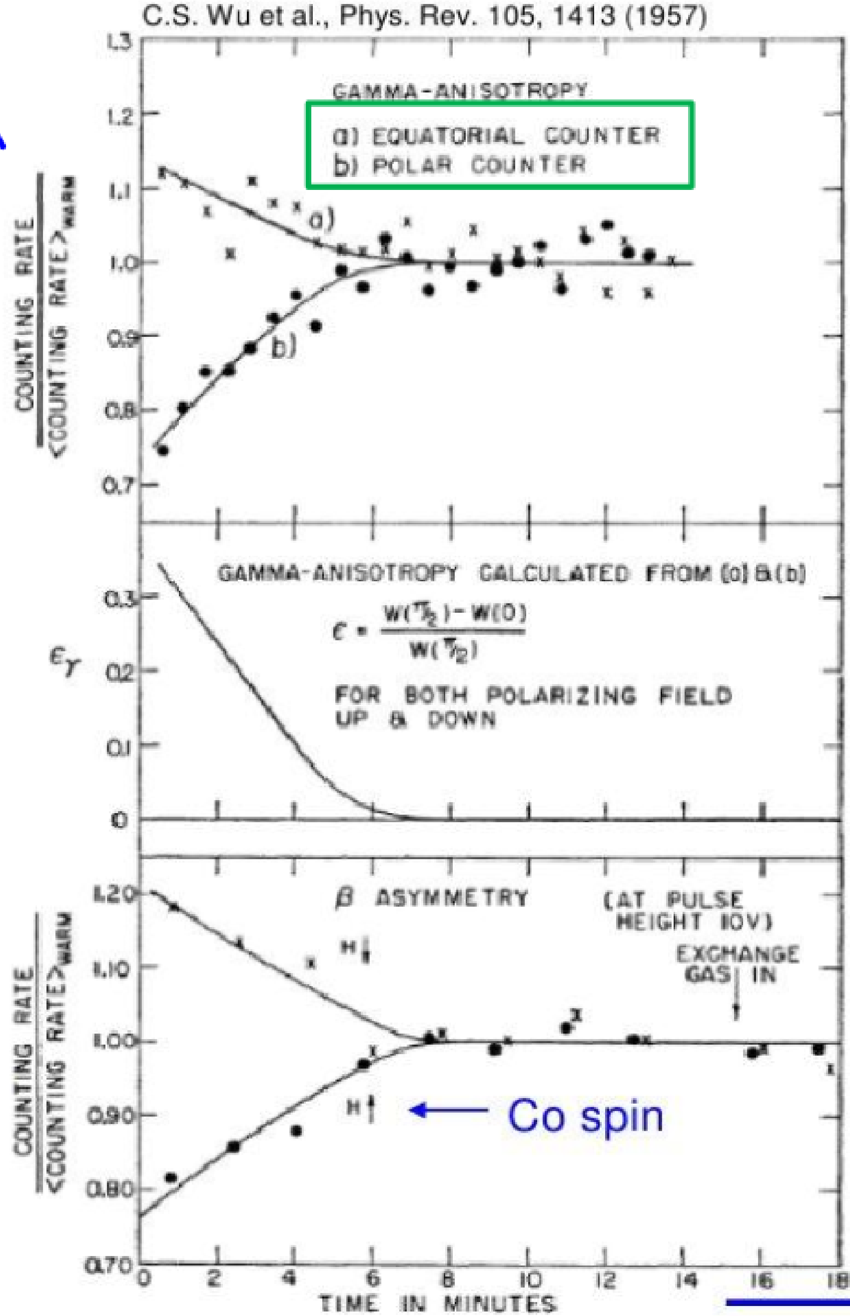
- crystal needs to be located
  in helium bath first than in vacuum





Wu-Experiment: Results

counting rate relative to warm (unpolarized) rate



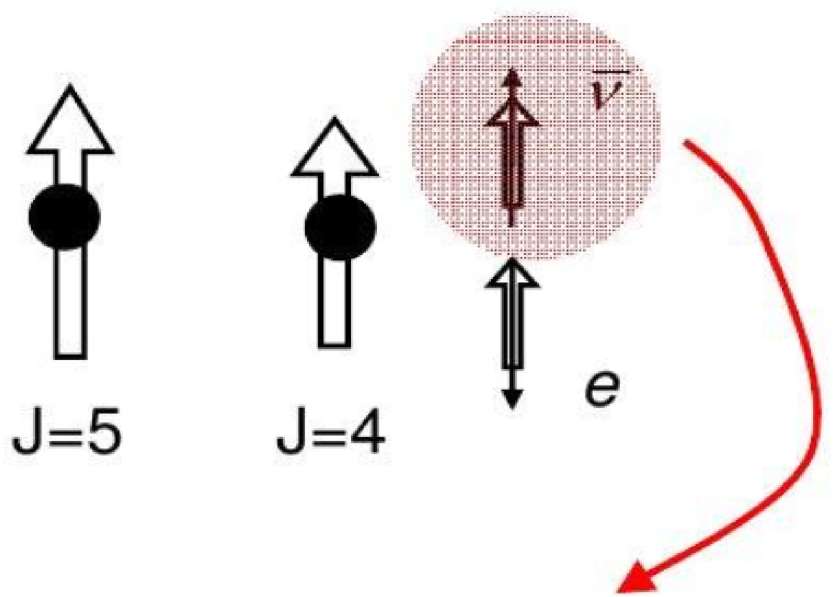
measure photon anisotropy, to determine degree of polarization

electron rates are different depending on the polarization!

warm up with time

parity violation

Qualitative Explanation



Consequence of existence of only left-handed (LH) neutrinos (RH anti-neutrinos)

Wu experiment established P violation!

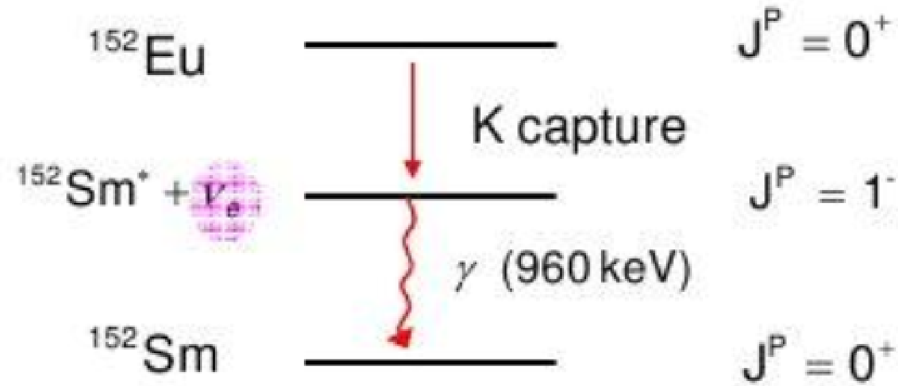
It was however not precise enough to measure helicity of neutrino
H ~ 0.7 ± large uncertainties

→ Goldhaber experiment

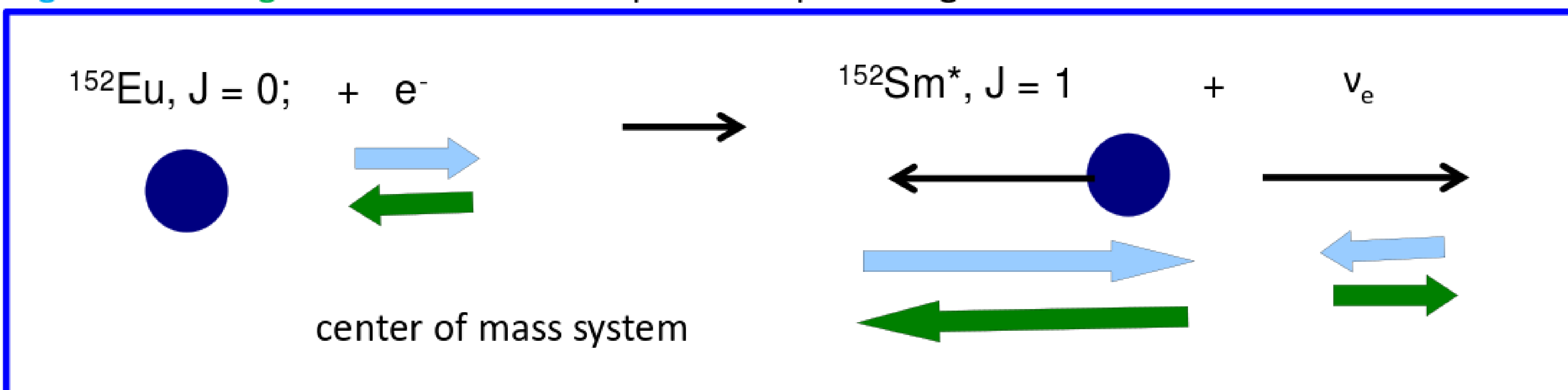
Goldhaber Experiment

$^{152}Eu + e^- \rightarrow {}^{152}Sm^* + \nu_e$

$\quad\quad \hookrightarrow {}^{152}Sm + \gamma$



Light blue and green arrows indicate possible spin configurations

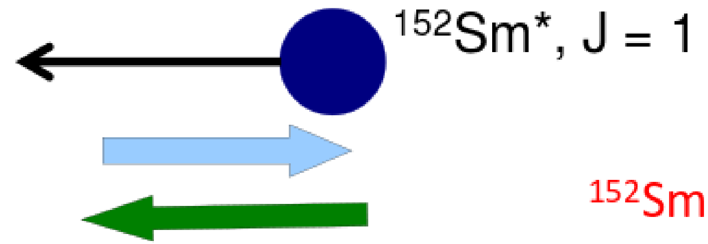


spin of neutrino is in opposite direction than the one of $^{152}Sm^*$,
momentum of is in opposite direction than the one of $^{152}Sm^*$

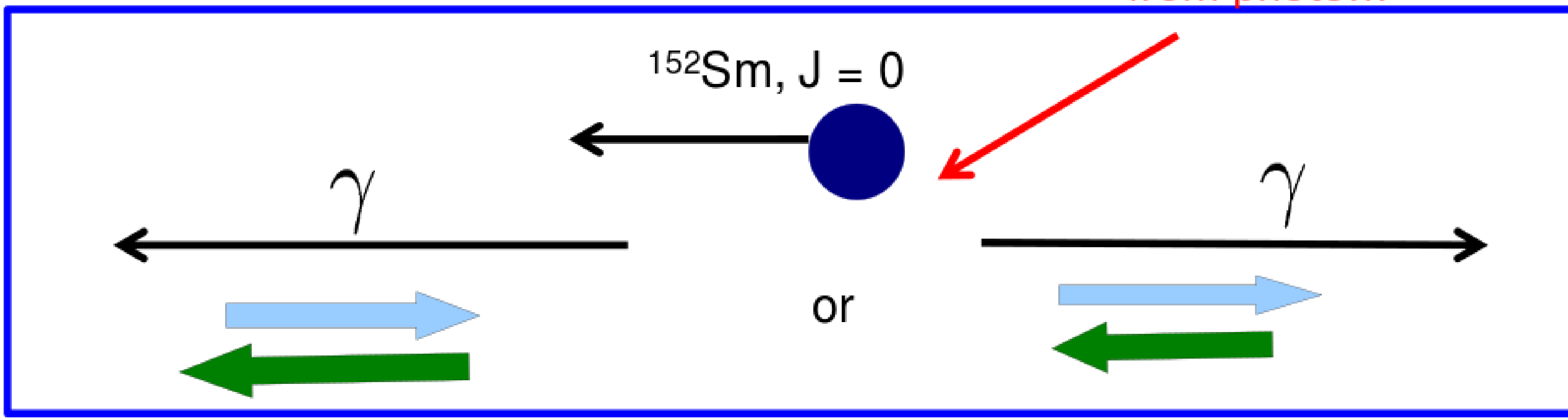
Goldhaber Experiment

$^{152}Eu + e^- \rightarrow {}^{152}Sm^* + \nu_e$

$\quad\quad\quad\quad\quad\quad\quad \hookrightarrow {}^{152}Sm + \gamma$



^{152}Sm get's small recoil from photon!



direction of spin of photon is opposite of neutrino

emitted in direction of Sm*

$$h(\gamma) = h(\nu_e)$$

emitted in opposite direction of Sm*

$$h(\gamma) = -h(\nu_e)$$

Two open question: 1) What is the direction of emission of the photon?
2) What is the polarization of the photon?

Resonant Scattering

To compensate the nuclear recoil, the photon energy must be slightly larger than 960 keV.

This is the case for photons which have been emitted in the direction of the Eu→Sm recoil (Doppler-effect).

Resonant scattering only possible for "forward" emitted photons, which carry the polarization of the Sm* and thus the polarization of the neutrinos.

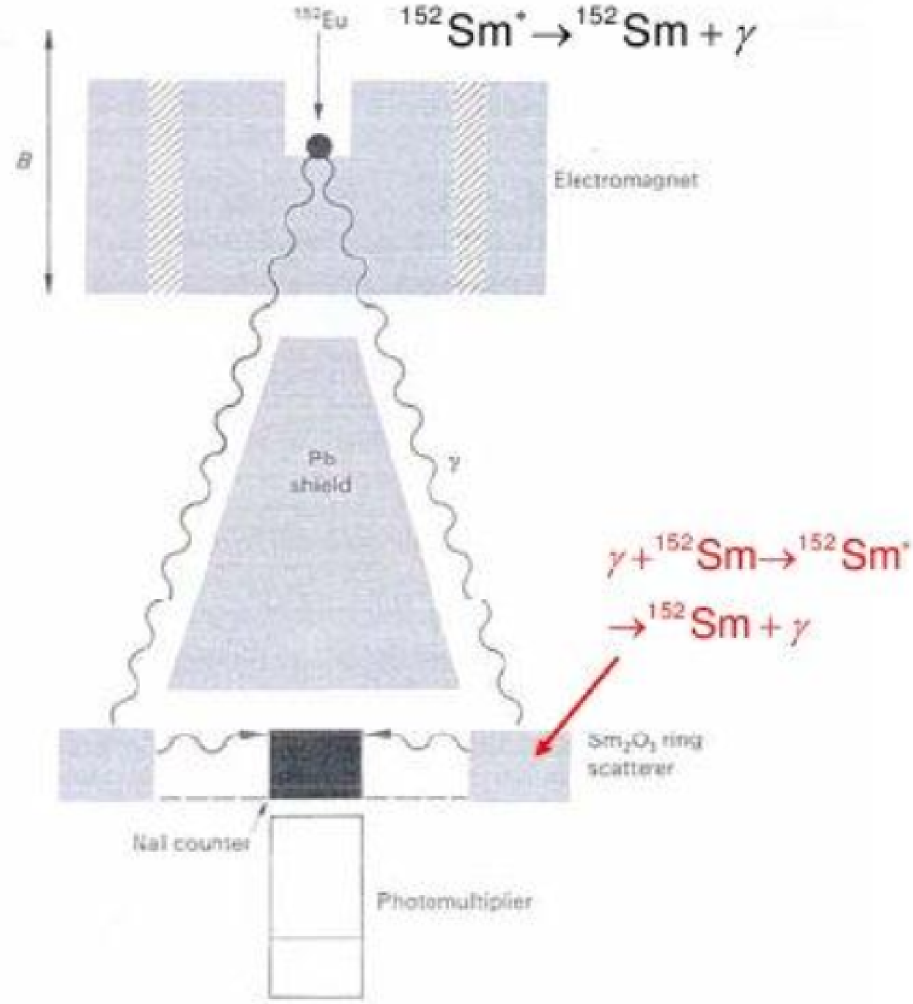


Fig. 7.8. Schematic diagram of the apparatus used by Goldhaber *et al.*, in which γ-rays from the decay of $^{152}Sm^*$, produced following K-capture in ^{152}Eu, undergo resonance scattering in Sm_2O_3 and are recorded by a sodium iodide scintillator and photomultiplier. The transmission of photons through the iron surrounding the source depends on their helicity and the direction of the magnetic field **B**.

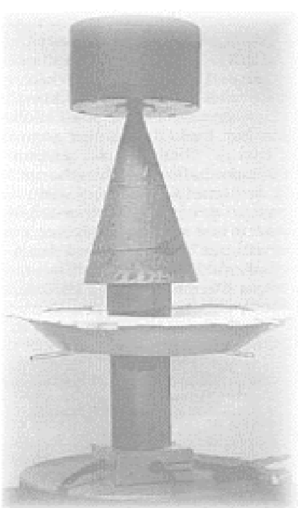
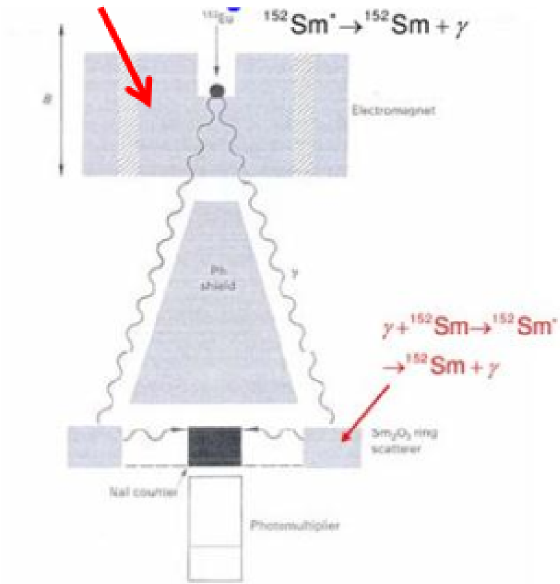


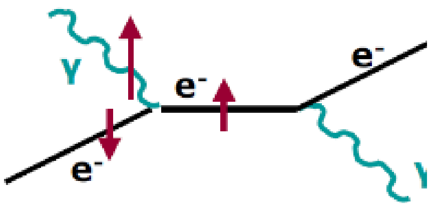
foto of exeperiment

Measurement of Polarization of Photon

Exploit that the transmission index through magnetized iron is polarization dependent: Compton scattering in magnetized iror

iron in B field





γ	γ
.H	RH
$\vec{B}$	$\vec{B}$
Polarization of electrons in iron	Polarization of electrons in iron
(... minimize pot. energy)	Absorption leads to spin flip
LH photons cannot be absorbed: Good transmission	RH photons undergo Compton scattering: Bad transmission

Photons w/ polarization anti-parallel to magnetization undergo less absorption

Goldhaber Experiment: Result

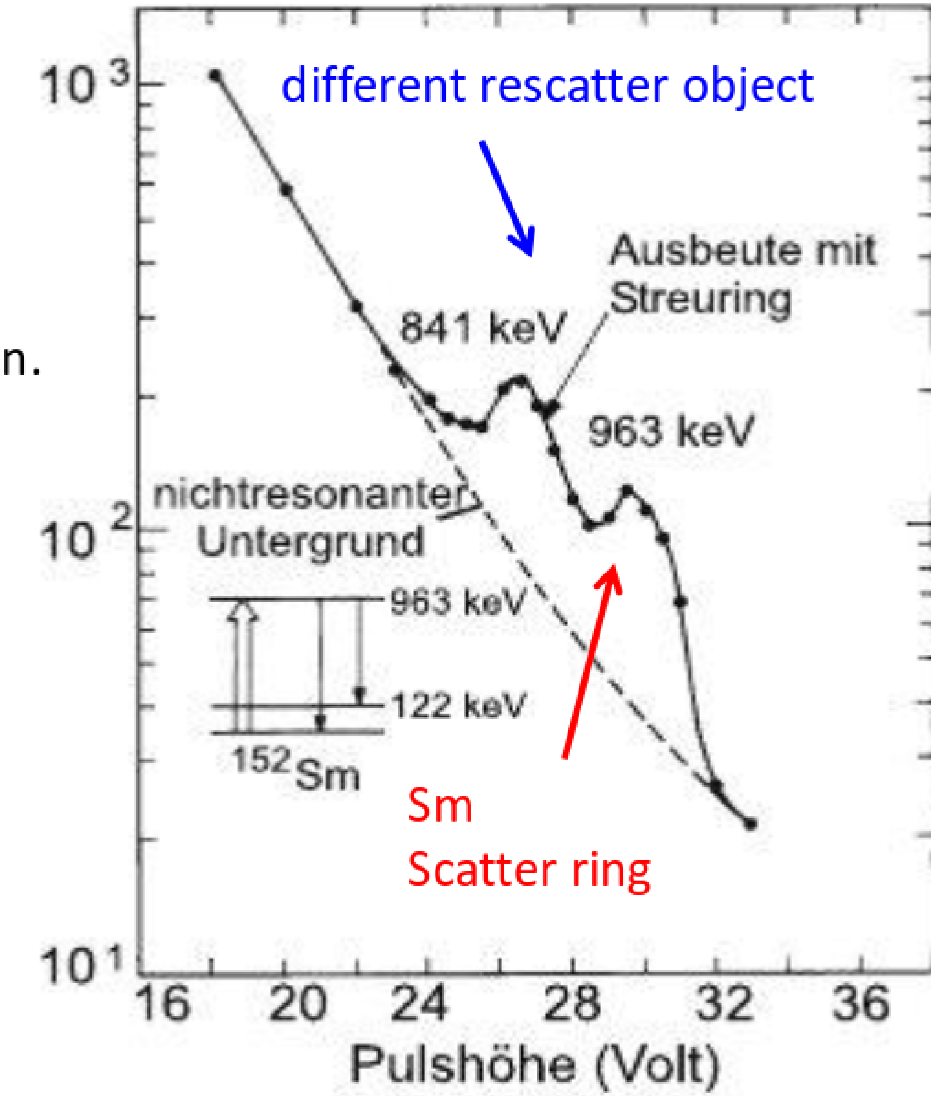
- Due to geometry of experiment, only resonant scattered photons are detected
  Helicity of detected photons identical to helicity of neutrino.

- Detect photons which pass trough magnetized iron.

B field points in flight direction of photons
→ measure fraction of (mainly) LH photons

B field points in opposit direction
→ measure fraction of (mainly) RH photons

$$\delta = \frac{N_- - N_+}{0.5(N_- + N_+)} = 0.017 \pm 0.003$$



N_ : counting rate with magentic field down
N_+: counting rate with magnetic field up

Goldhaber-Experiment: Result

Result: $\delta = +0.017 \pm 0.003$

Theoretical expectation (for 100% polarized photons)

$$\delta = \pm 0.025 \quad \begin{cases} \text{„-“ for } h > 0 \\ \text{„+“ for } h < 0 \end{cases}$$

Only 5-8% of electrons in iron are polarized, thus asymmetry of scattering for LH and RH photons is very small, thus heavily wash out the asymmetry.

Due to background effects (thermal movements inside the source, polarisation can depend on angle, …) expect for pure LH neutrios 75% polarized photons

Measured photo polarisation: 66 ± 15%, consistent with 75%

➡ **Neutrino are left handed particles**