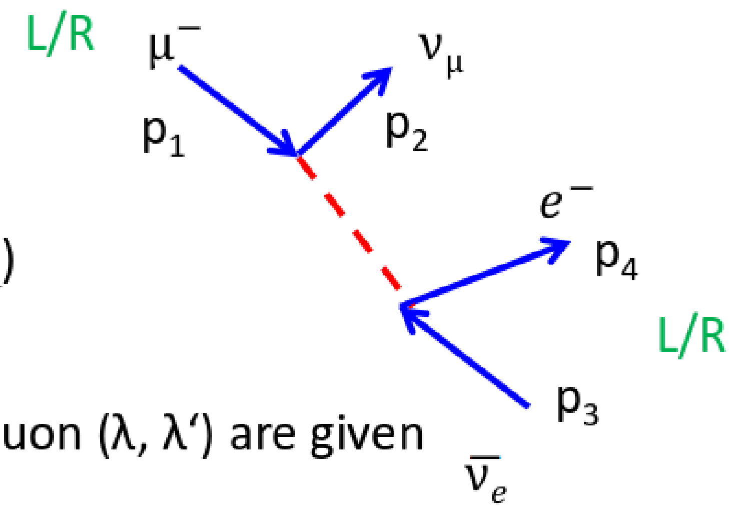
Experimental Probe of V-A structure

Most general form of matrix element, include scalar (S), vector (V) and tensor (T) currents.

$$M = \frac{G_F}{\sqrt{2}} \sum_{\substack{i=S,V,T \\ \lambda,\lambda'=R,L}} g^i_{\lambda\lambda'} \left(\overline{u(p_4)_{\lambda'}}\ \Gamma^i\ v(p_3)_m\right) \left(\overline{u(p_2)_n}\ \Gamma^i\ u(p_1)_\lambda\right)$$

n,m = R/L given if coupling i and handiness of electron and muon (λ, λ') are given



Possible current-current couplings

i / λλ'	RR	RL	LR	LL
S	x	x	x	x
V	x	x	x	x
T		x	x	

There are in general 10 complex amplitudes $g^i_{\lambda\lambda'}$

pure V-A couling: $g^V_{LL} = 1$,
all others 0

Experimental idea: measure polarization of electron for a given polarization of initial state.
Determine energy and angular distribution of electron.

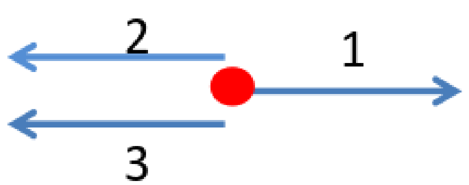
Note: in the notation of the Experimental data on the next Slide V stands for vector and axial vector coupling and accordingly S for scalar an pseudo-scalar

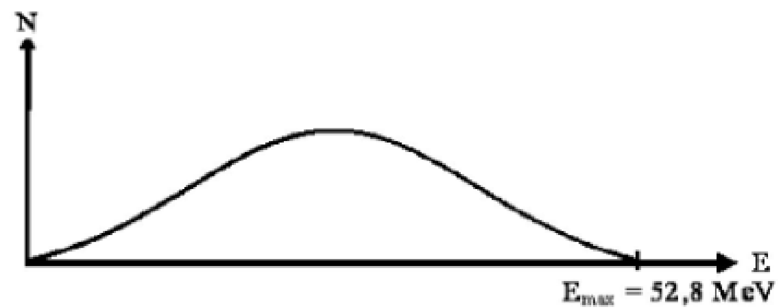
Experimental Probe of V-A structure: Muon Decay

Experimental idea: measure polarization of electron for a given polarization of initial state.
Determine energy and angular distribution of electron.

Consider muon rest system: m(μ) ~ 105 MeV; m(e)~m(ν)~0

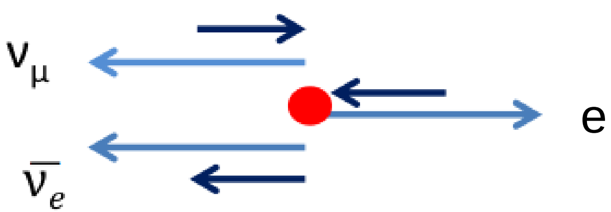
Maximum energy (m(μ)/2) of particle 1, if particle 2, 3 fly in opposite direction in muon CMS.





pure kinematics

E.g. V-A theory



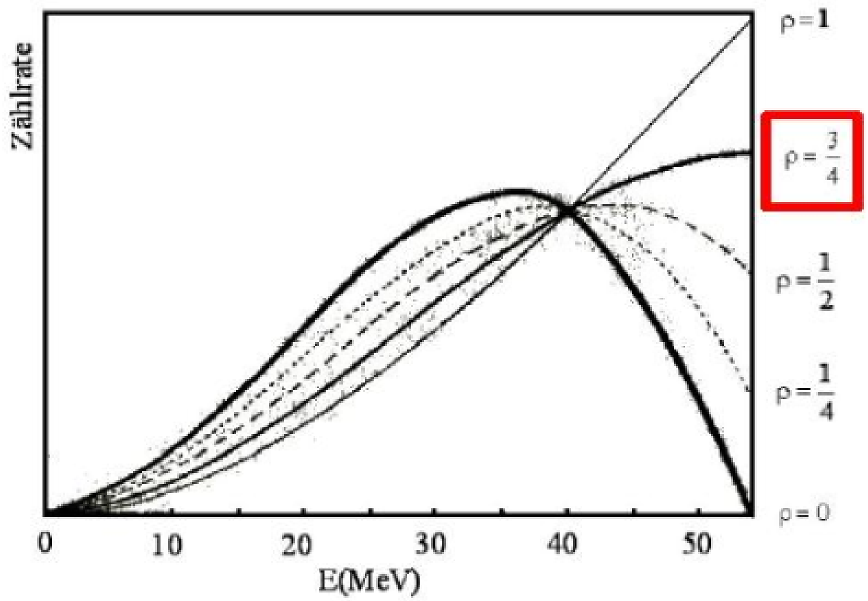
in approximation of zero mass, this is only possible configuration (despite it is kinematically unlikely)

Experimental Probe of V-A structure: Muon Decay

Energy spectrum of emitted electron:

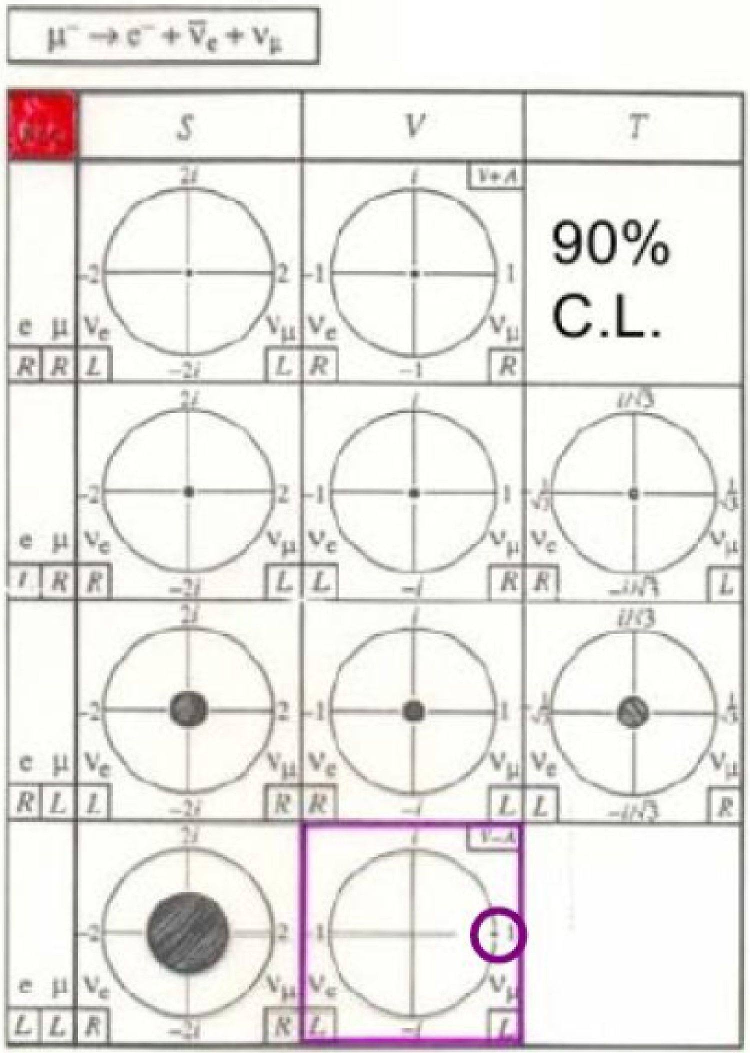
$$dN(E) = \frac{4E^2 dE}{\tau_\mu} [3(1\text{-}E) + \frac{2}{3}\rho\,(4E - 3)]$$

Michelparameter: ρ



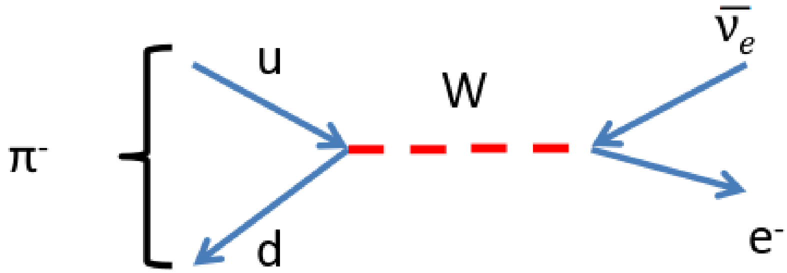
V-A theory: ρ = 0.75

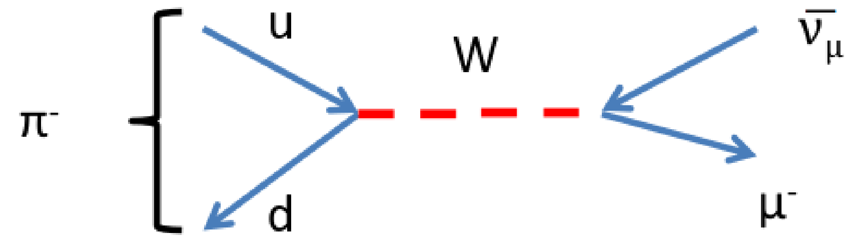
Couplings in muon decay



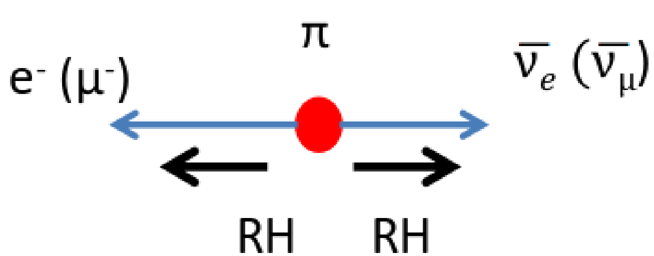
V-A theory is confirmed

Experimental Probe of V-A structure: Pion Decay





momentum and angular momentum conservation (pion CMS):



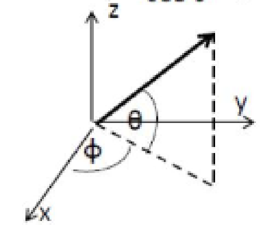
Phase space favors electron channel: m(π) ~140 MeV, m(μ)~105 MeV, m(e) ~ 511 keV

However:
Since anti-neutrino is (almost) massless, CC weak ineraction can only occur in RH state, t
electron/muon has to be in RH helicity state as well.

Weak IA cuples to LH chirality component of RH helicity state.

Definition of Polarization

$$\vec{p} = |\vec{p}|\begin{pmatrix}\sin\theta\cos\varphi \\ \sin\theta\sin\varphi \\ \cos\theta\end{pmatrix}$$



Right handed helicity spinor: $u_{h=+1} = N\begin{pmatrix}\cos\Theta/2 \\ e^{i\varphi}\sin\Theta/2 \\ \frac{|\vec{p}|}{E+m}\cos\Theta/2 \\ \frac{|\vec{p}|}{E+m}e^{i\varphi}\sin\Theta/2\end{pmatrix}$

projector on left handed chirality: $P_L = \frac{1}{2}(1-\gamma^5) = \frac{1}{2}\begin{pmatrix}+1 & 0 & -1 & 0 \\ 0 & +1 & 0 & -1 \\ -1 & 0 & +1 & 0 \\ 0 & -1 & 0 & +1\end{pmatrix}$

$$P_L\, u_{h=+1} = \frac{1}{2} N\left(1-\frac{|\vec{p}|}{E+m}\right)\begin{pmatrix}\cos\Theta/2 \\ e^{i\varphi}\sin\Theta/2 \\ -\cos\Theta/2 \\ -e^{i\varphi}\sin\Theta/2\end{pmatrix}$$

Right handed helicity spinor has left handed chirality component.

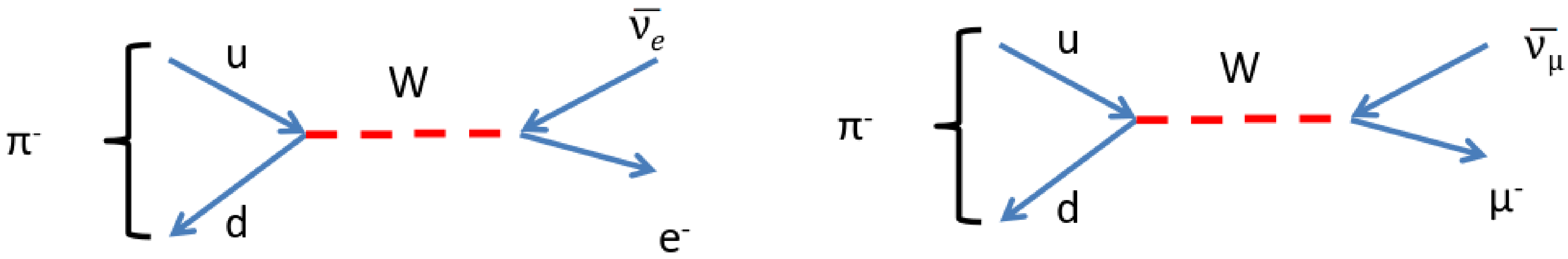
$$u_{h=+1} = P_R\, u_{h=+1} + P_L\, u_{h=+1} = \frac{1}{2} N\left(1+\frac{|\vec{p}|}{E+m}\right) u_R + \frac{1}{2} N\left(1-\frac{|\vec{p}|}{E+m}\right) u_L$$

right handed helicity — right handed chirality — left handed chirality

$$\text{Pol} = \frac{<P_R> - <P_L>}{<P_R> + <P_L>} = -\beta \left(= -\frac{v}{c}\right)$$

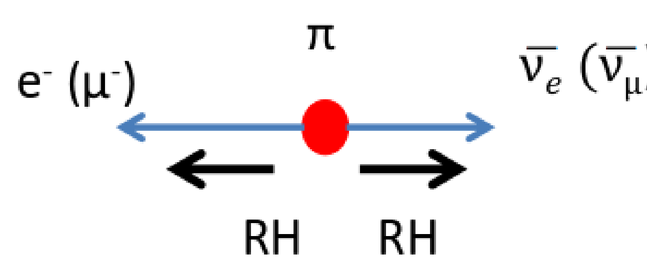
for lighter particles left handed chirality component is smaller!

Experimental Probe of V-A structure: Pion Decay



Measurement :

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} = (1.230 \pm 0.004)\ 10^{-4}$$



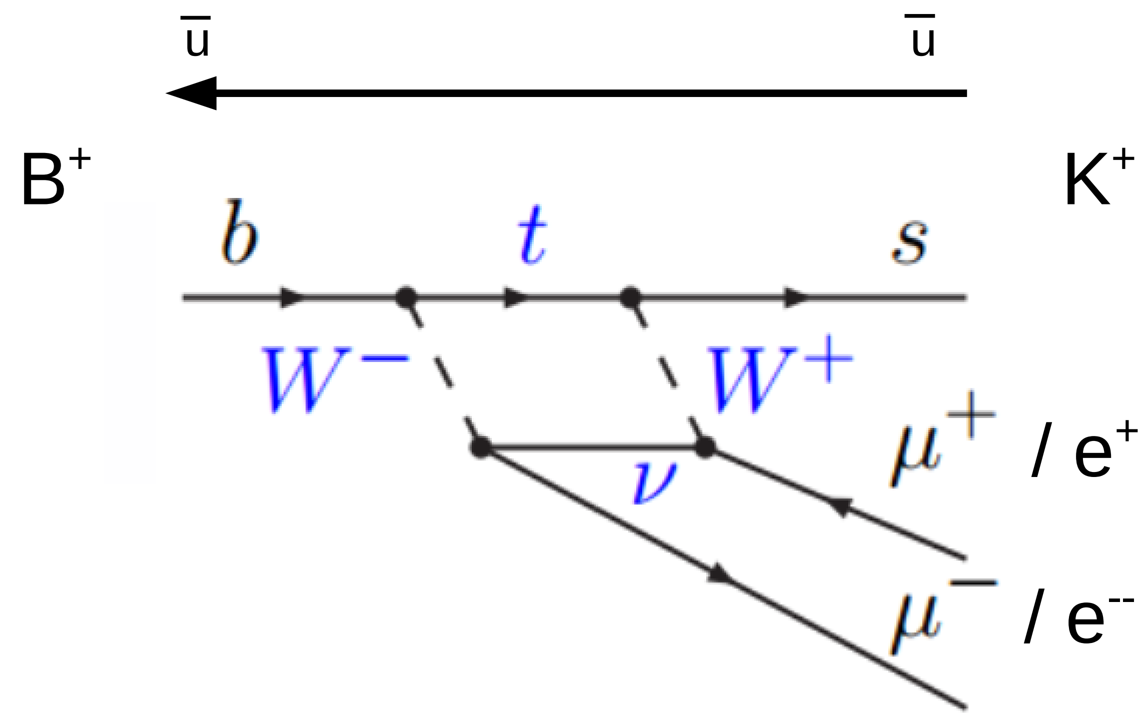
Electron decay is strong helicity suppressed.
Force the lepton in the „wrong“ helicity state, suppressed by v/c.

(For complete derivation of relative production rate, see homeworks):

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} = \left(\frac{m_e^2}{m_\mu^2}\right)\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right) = 1.275\ 10^{-4}$$

excellent agreement with experiment

Test of Lepton Universality at LHCb



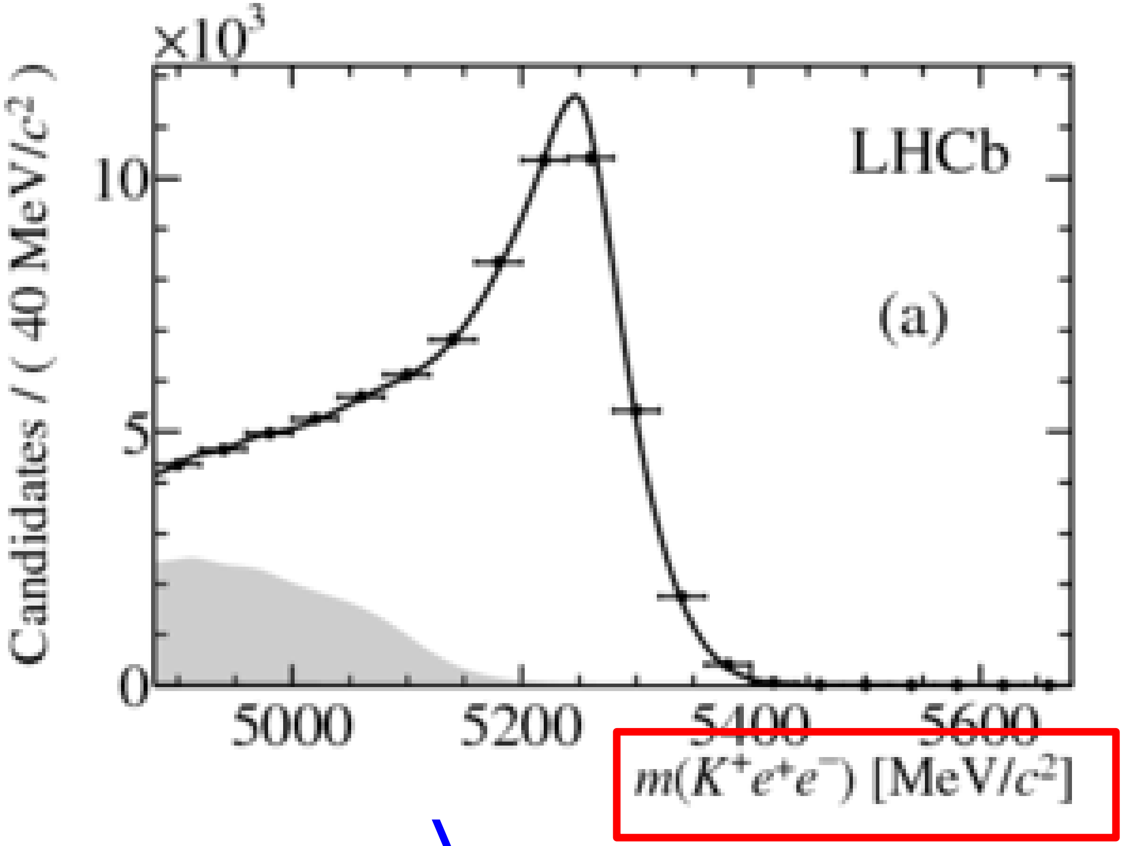
theory prediction:

$$R_K = \frac{\int_{q^2=1\ \mathrm{GeV}^2/c^4}^{q^2=6\ \mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2)\mathrm{d}q^2}{\int_{q^2=1\ \mathrm{GeV}^2/c^4}^{q^2=6\ \mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+e^+e^-]/\mathrm{d}q^2)\mathrm{d}q^2} = \boxed{1 \pm \mathcal{O}(10^{-3})}$$

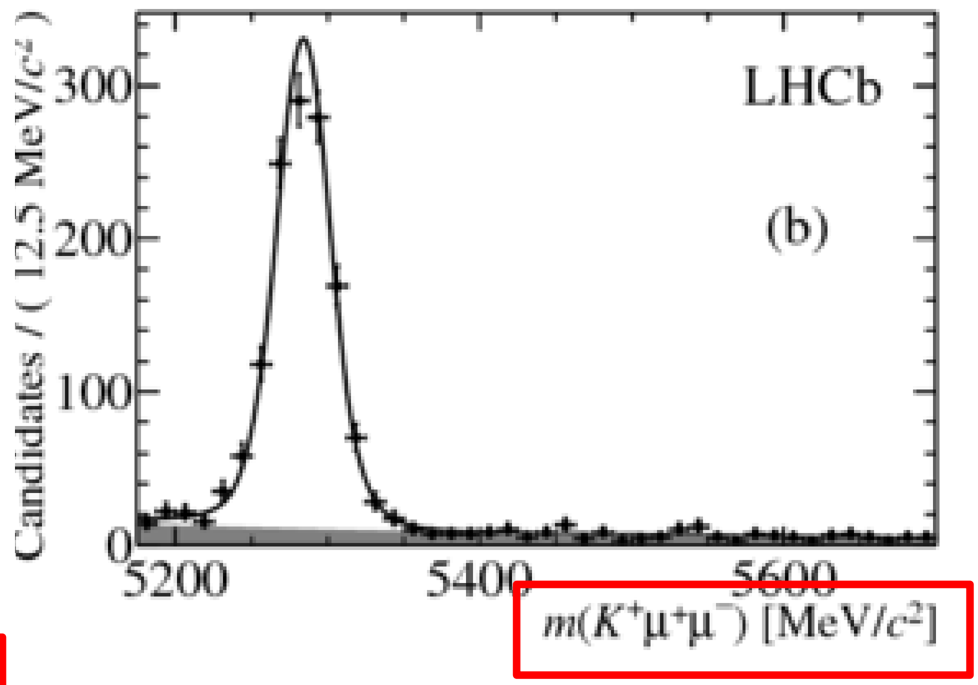
extremly clean prediction as the hadronic part is the same for both decays

If we see significant deviation from 1 it is clear sign of physics beyond the standard model!

in one q^2 bin

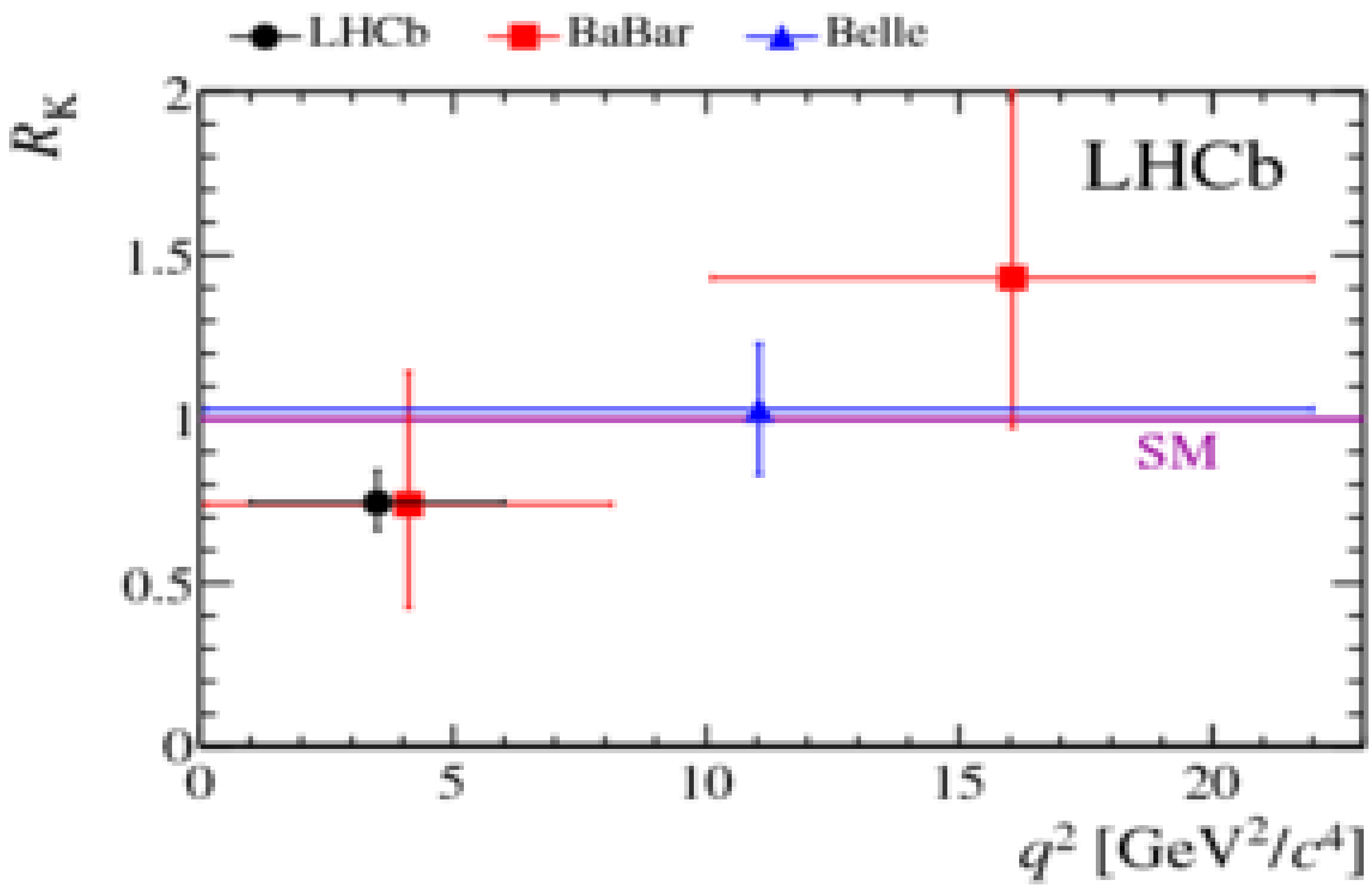


all events



Momentum of rather low momentum electrons/positrons (several 100 MeV) hard to precisely measure due to **Bremsstrahlung**.

Muon signal significantly cleaner.



$$R_K = 0.745\,^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.36\,(\text{syst})$$

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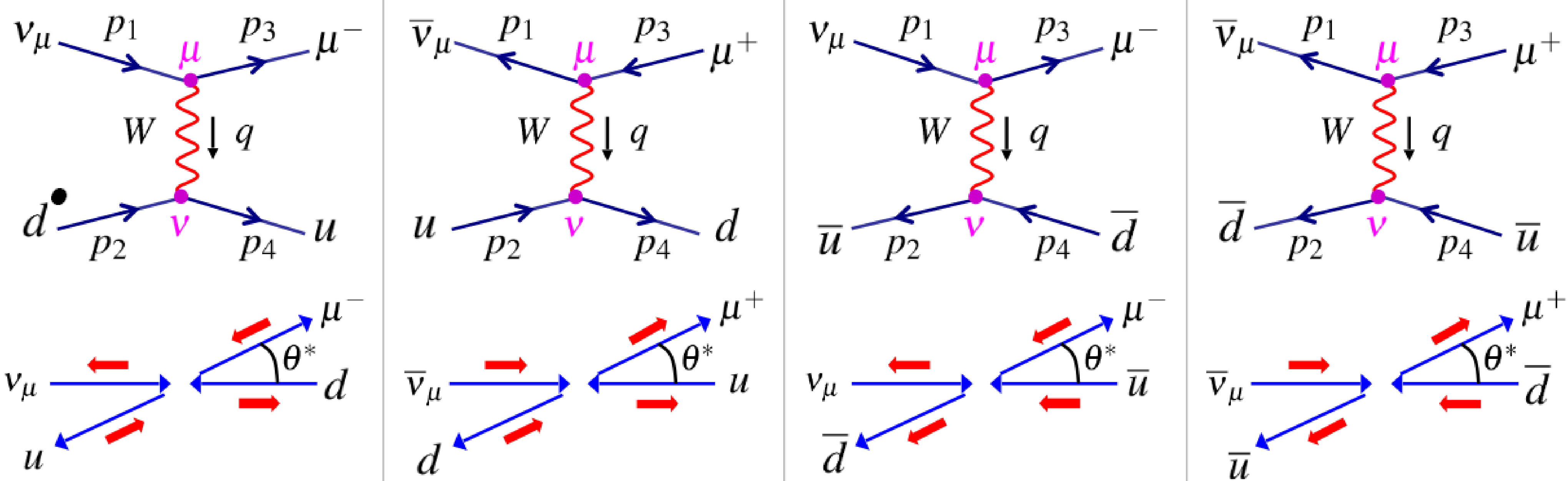
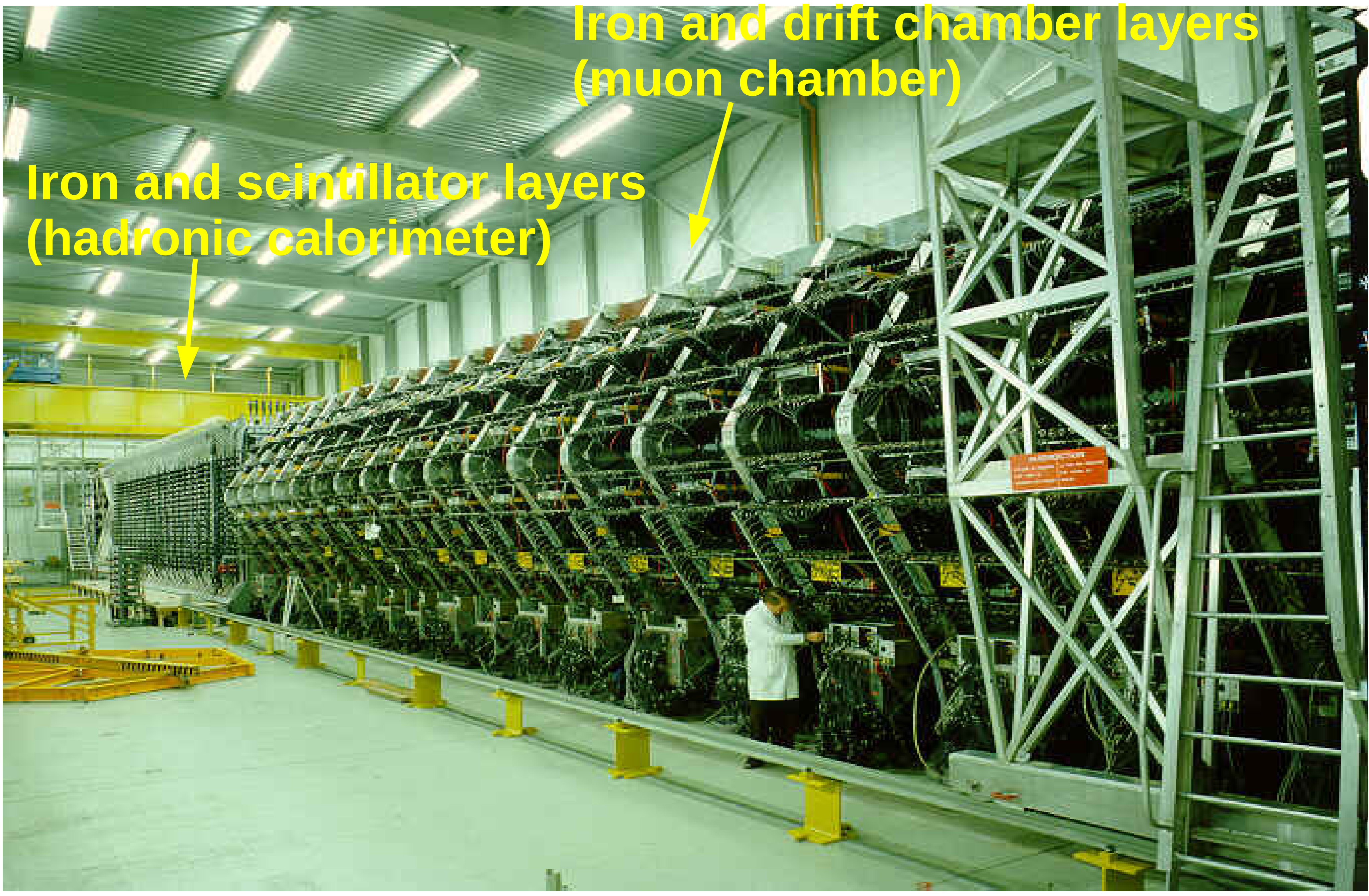
2.6 σ away from SM predictions …. waiting for analysis of new data!

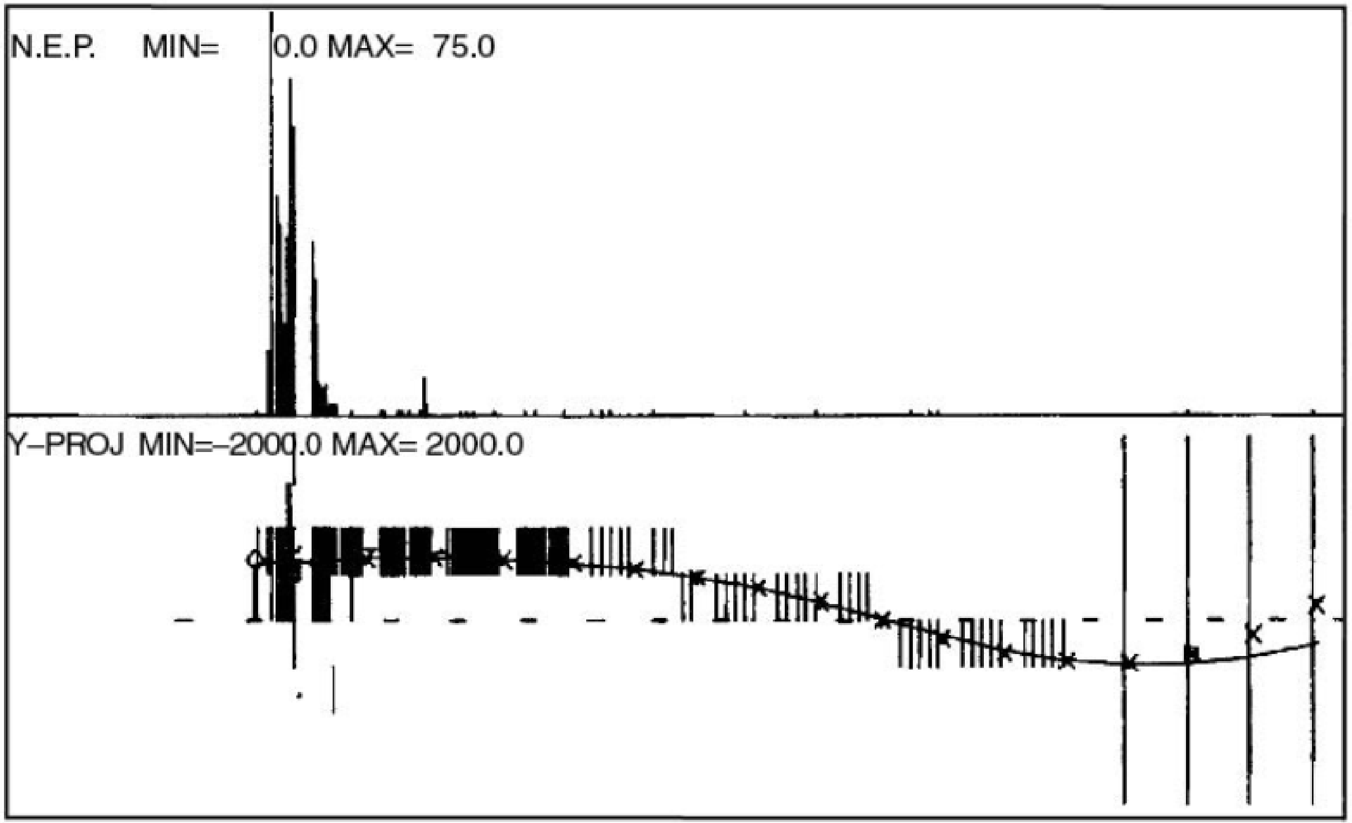


$S_z = 0$	$S_z = +1$	$S_z = -1$	$S_z = 0$
$\frac{d\sigma_{\nu q}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$	$\frac{d\sigma_{\overline{\nu} q}}{d\Omega^*} = \frac{G_F^2}{16\pi^2}(1+\cos\theta^*)^2\hat{s}$	$\frac{d\sigma_{\nu \overline{q}}}{d\Omega^*} = \frac{G_F^2}{16\pi^2}(1+\cos\theta^*)^2\hat{s}$	$\frac{d\sigma_{\overline{\nu}\overline{q}}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$
$\sigma_{\nu q} = \frac{G_F^2\hat{s}}{\pi}$	$\sigma_{\overline{\nu} q} = \frac{G_F^2\hat{s}}{3\pi}$	$\sigma_{\nu\overline{q}} = \frac{G_F^2\hat{s}}{3\pi}$	$\sigma_{\overline{\nu}\overline{q}} = \frac{G_F^2\hat{s}}{\pi}$

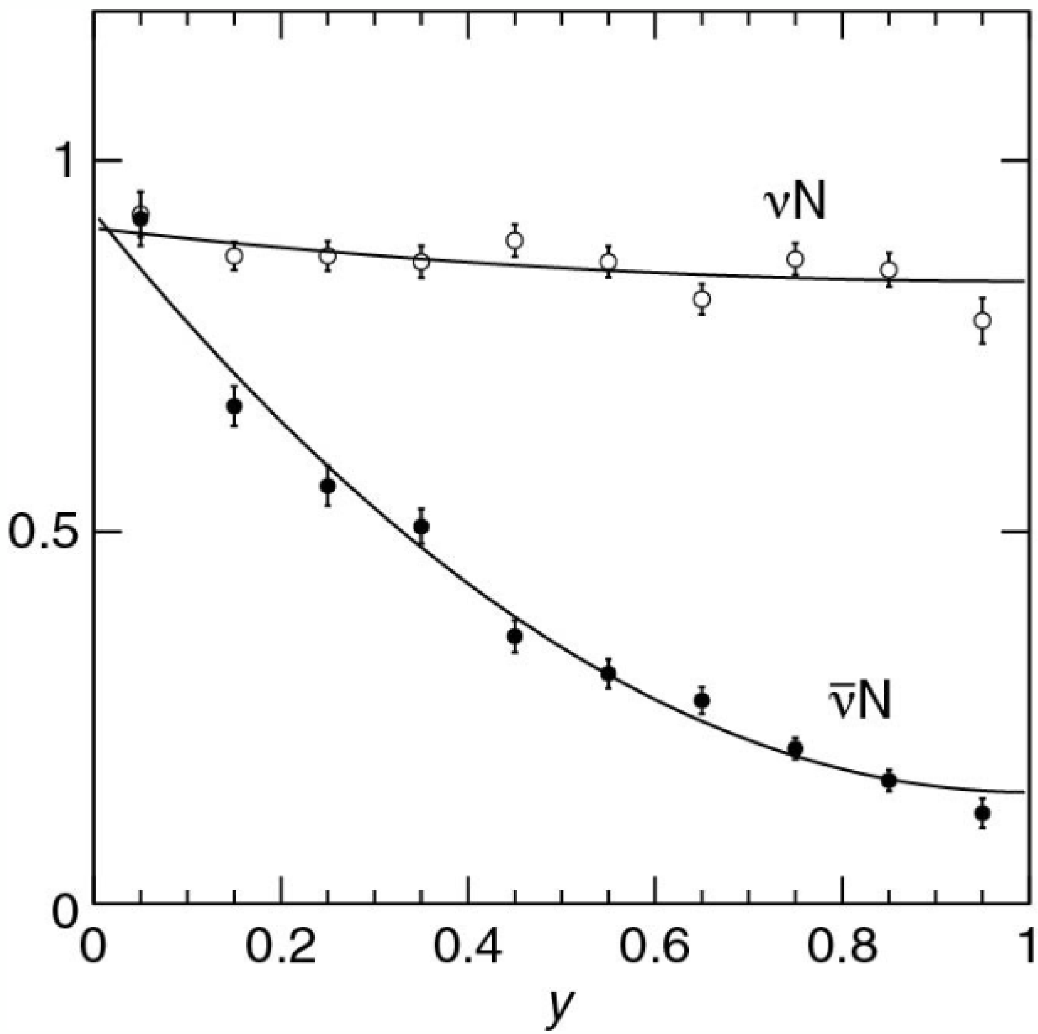
CDHS – CERN-Dortmund-Heidelberg-Saclay Experiment

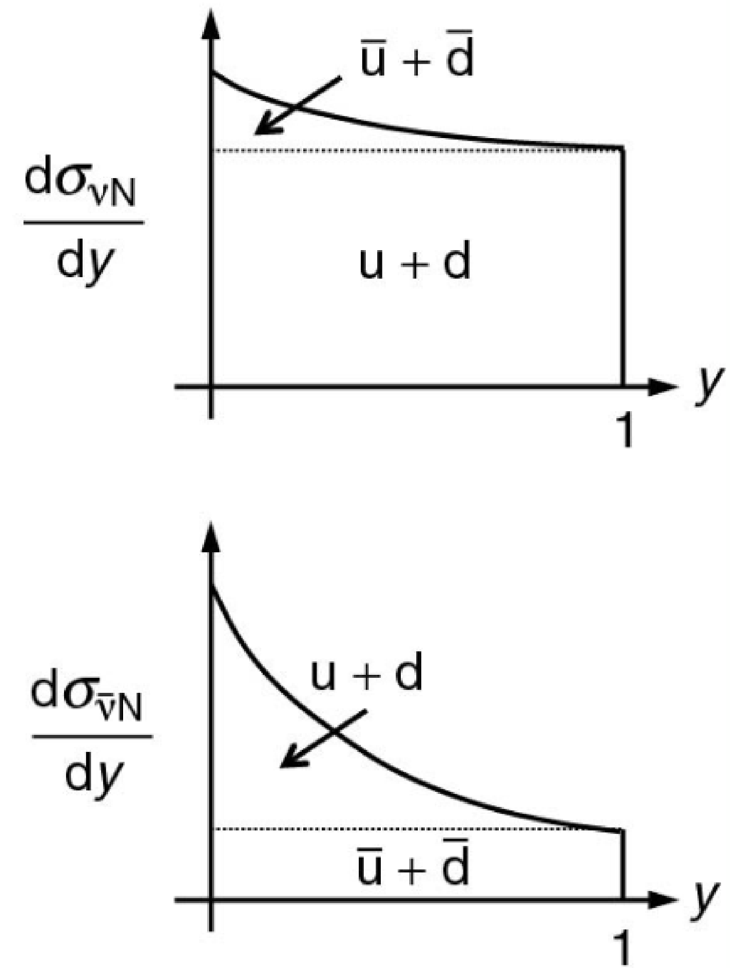


Deep-Inelastic Neutrino Interaction in CDHS



Neutrino-Nukleon Differential Cross Section





M. Thomson, Modern Particle Physics
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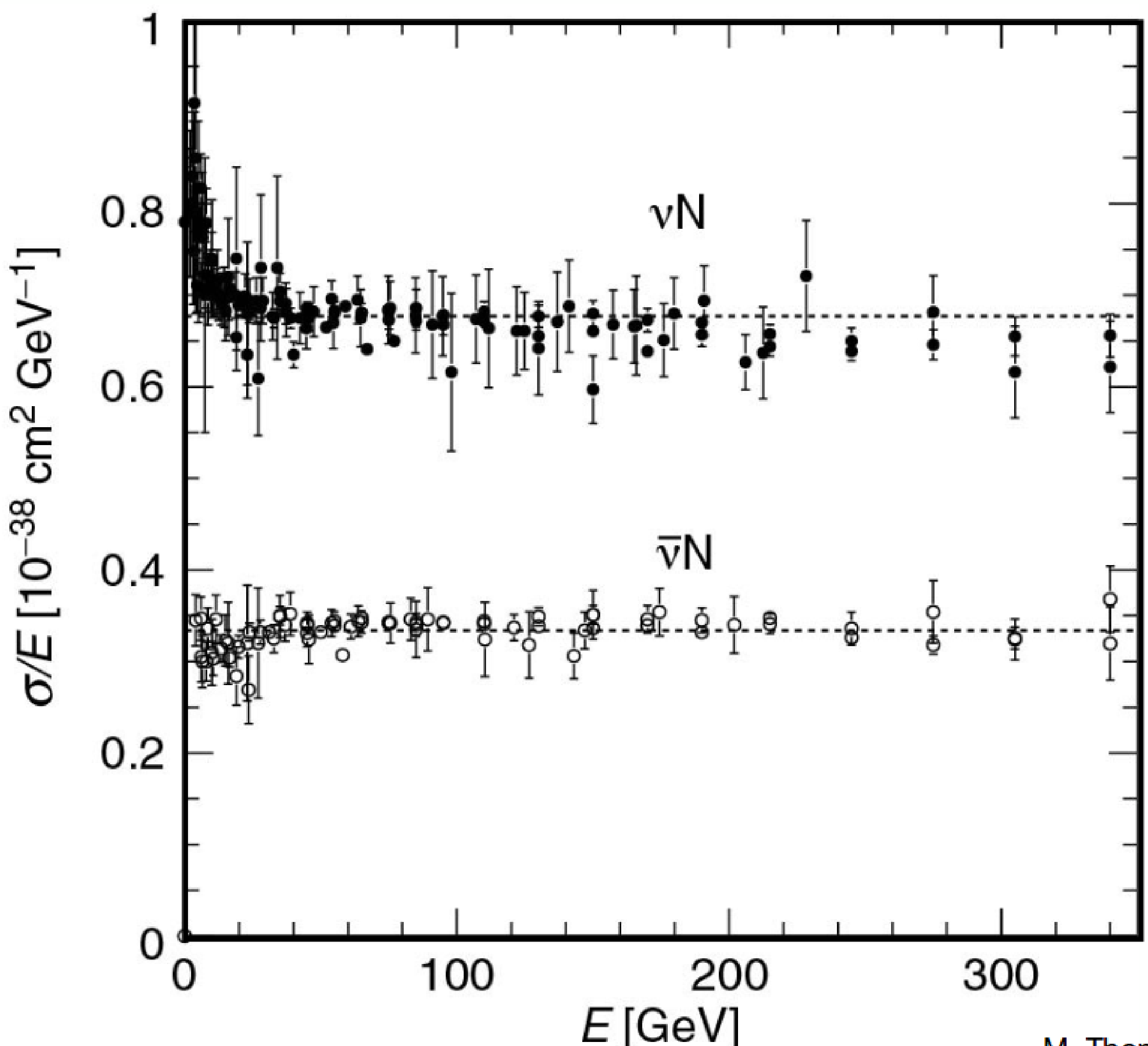
Neutrino-Nukleon Total Cross Section



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