Particle Physics: The Standard Model

Dirk Zerwas

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April 25 and May 16, 2013

Properties of the c

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\begin{aligned}
m_0 &= 1.27\,\mathrm{GeV} \\
\tau &= (1.040 \cdot 10^{-12})\,\mathrm{s} \quad c\bar{d} \\
c\tau &= 311.8\,\mu\mathrm{m} \\
C &= +\tfrac{2}{3}
\end{aligned}
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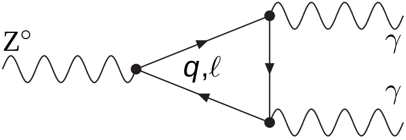
Theoretically predicted before its discovery in 1974 by Glashow, Iliopoulos and Maiani (GIM)!



($\gamma \perp Z°$) Triangle Anomaly if

$$\sum q_i N_C \neq 0$$

u, d, s, e:

$$3 \cdot \frac{2}{3} + 3 \cdot (-\frac{1}{3}) - 1 + 3 \cdot (-\frac{1}{3}) 0$$

Complete families (charged) to avoid triangle anomalies

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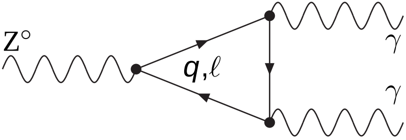

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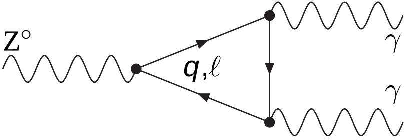

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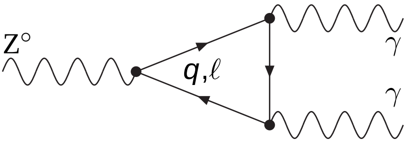

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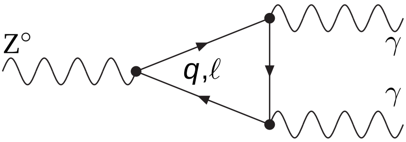

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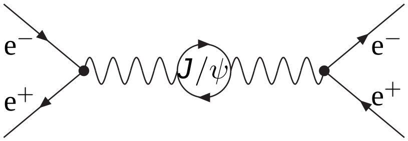

Production

- Richter $e^+e^- \to \psi$
- Ting: $pp \sim u_V \bar{u}_S \to J$

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- $= S_\gamma$ (by production)

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- $J/\psi \to e^+e^-$
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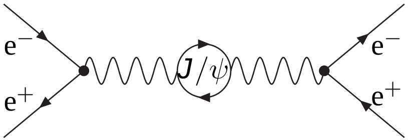
- No charmed mesons possible!



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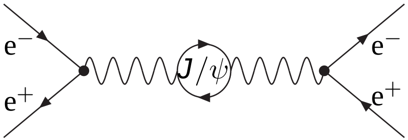

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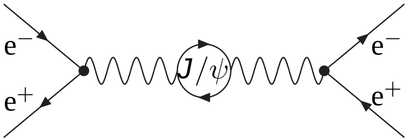

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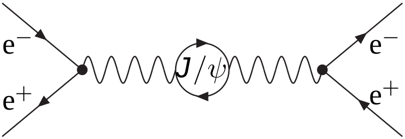

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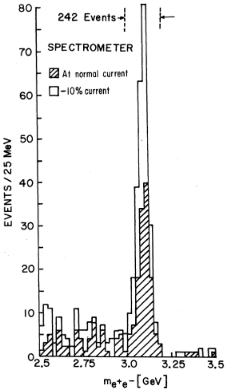
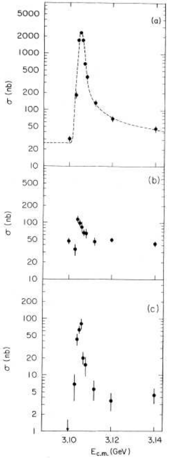
30 GeV protons on fixed Target (BNL AGS):



e^+e^- SLAC SPEAR LAB=CM hadrons, electrons, muons



Width

$$\Gamma = 93.4keV = 0.093 \cdot 10^{-3} GeV$$

Measure invariant mass:

$$\begin{aligned} m(e^+e^-) &= m_\psi \\ \Gamma_{exp} &= \sqrt{\Gamma^2 + \sigma_{exp}^2} \\ \sigma_{exp} &\sim 1\% = 30MeV \\ \Gamma_{ee} &\sim 5keV \end{aligned}$$

- dominated by σ_{exp}
- need to know σ_{exp} at per mil!

Width via lifetime?

J/ψ lifetime shorter than for charmed mesons: EM decay

$$\begin{aligned} & \beta\gamma c\tau \\ = & \beta\gamma c\hbar\Gamma^{-1} \\ = & 1 \cdot \gamma \cdot 0.2GeV \cdot fm \\ & \cdot (0.093 \cdot 10^{-3} GeV)^{-1} \\ \sim & \gamma \cdot 2 \cdot 10^3 fm \end{aligned}$$

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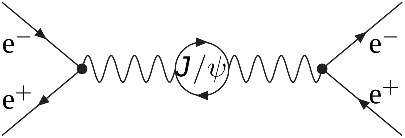

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Cross section measurement

- Describe the resonance with a Breit-Wigner: on-shell particle with lifetime (looks like a propagator)
- decay to final state X
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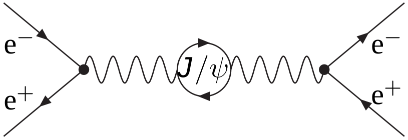

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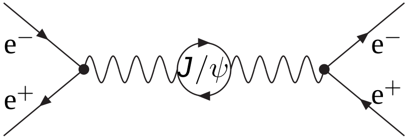

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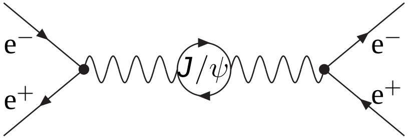

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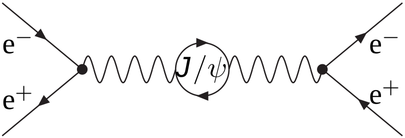

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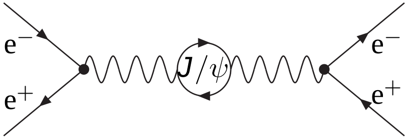

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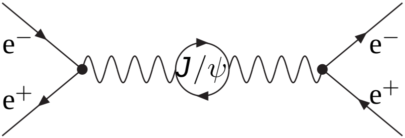

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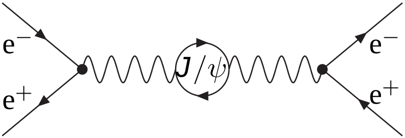

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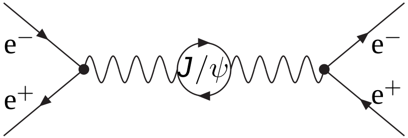

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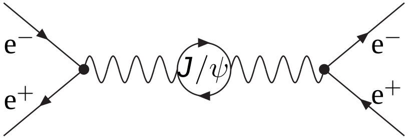

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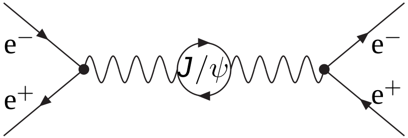

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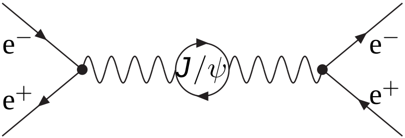


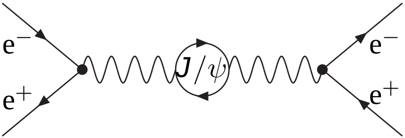
$$\sigma_{ee} \sim \Gamma_{ee}\frac{\Gamma_{ee}}{\Gamma}$$
$$\sigma_{\mu\mu} \sim \Gamma_{ee}\frac{\Gamma_{\mu\mu}}{\Gamma}$$
$$\sigma_{had} \sim \Gamma_{ee}\frac{\Gamma_{had}}{\Gamma}$$

Hypothesis: completeness!

$$\Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{had} = \Gamma$$
$$\sigma_{ee} + \sigma_{\mu\mu} + \sigma_{had} = \frac{12\pi}{m^2_{J/\psi}}\Gamma_{ee}$$

3 measurements 3 unkowns
Measure the cross sections to 1%:

$$\Delta\Gamma_{ee} = \sqrt{3}\cdot 1\% \approx 1.7\% \sim 0.1 keV$$



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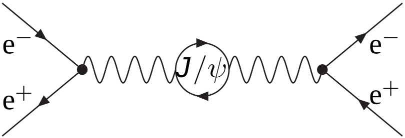

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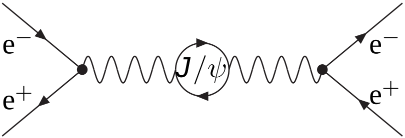

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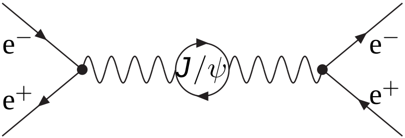

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J/ψ to quarks and leptons

EM interactions ($\gamma^\star$)

$$\frac{\Gamma(J/\psi \to had)}{\Gamma(J/\psi \to e^+e^-)} = N_C \sum q_i^2 = 3 \cdot [(\tfrac{2}{3})^2 + (\tfrac{1}{3})^2 + (\tfrac{1}{3})^2] = 2$$

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$J/\psi \to ggg$

Landau-Yang: Spin-1 cannot decay to 2 massless spin-1

$$\Gamma(J/\psi \to ggg) \sim \frac{160}{81}(\pi^2 - 9)\alpha_S^3$$

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  - target with structure
  - EM interaction Q^2
  - non-fixed target possible
- neutrinos
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  - Weak interaction Q^2
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- pions decay to $\nu_{\mu_L}\mu$
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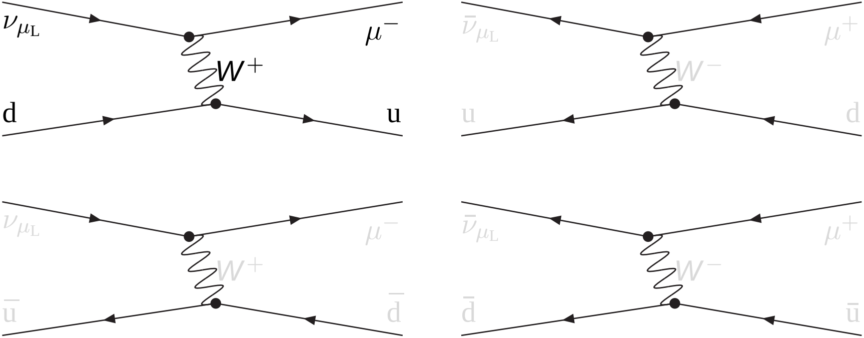

forbidden: $\nu_{\mu_L} + \mathrm{u} \rightarrow \mu^- \mathrm{d}$

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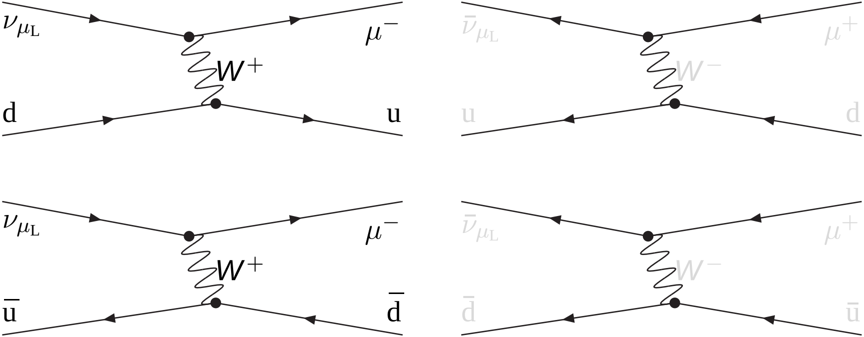
ν_{μ_L} and $\bar{\nu}_{\mu_L}$ probe different partons....



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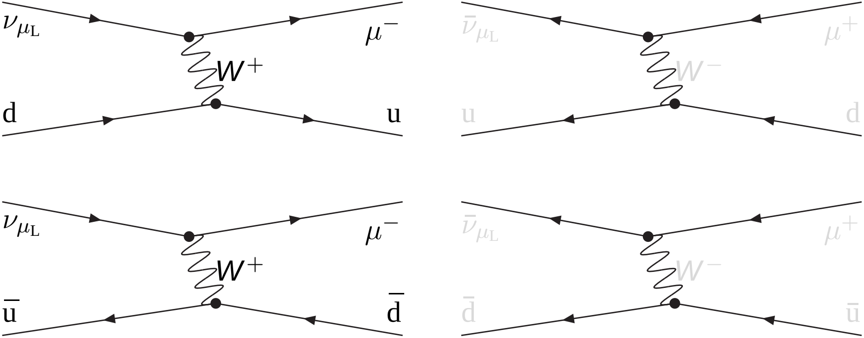

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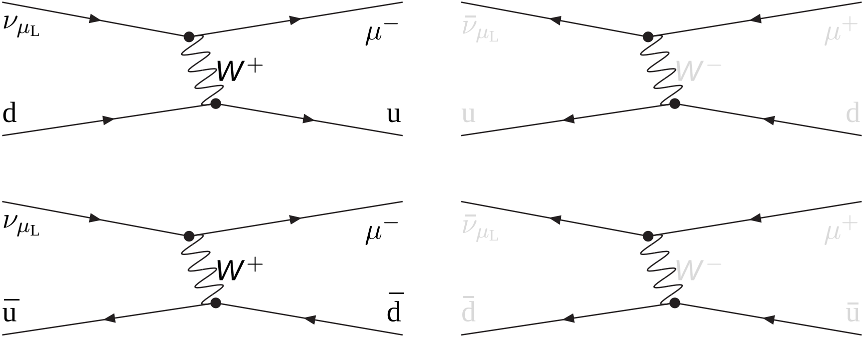

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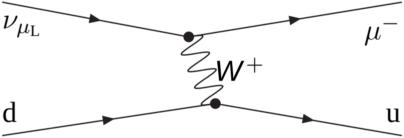

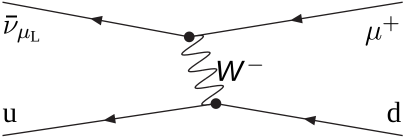

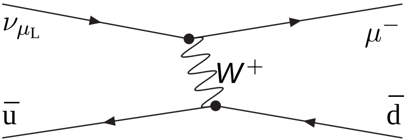

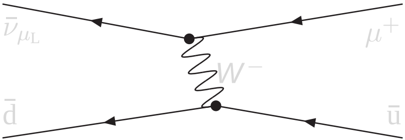

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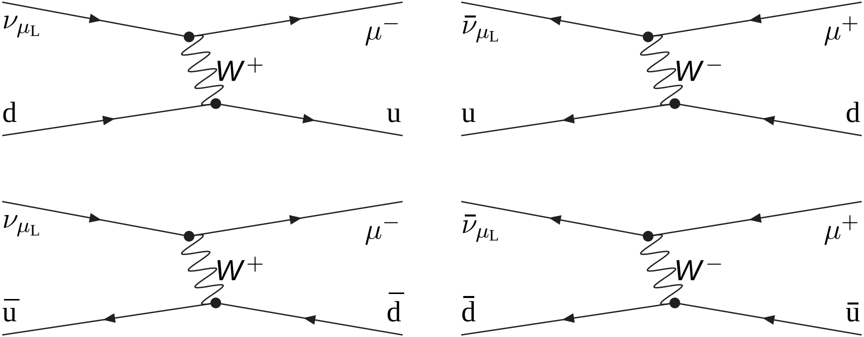

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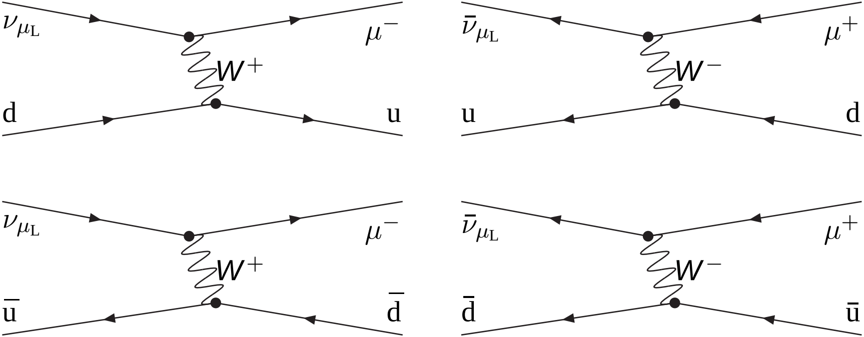

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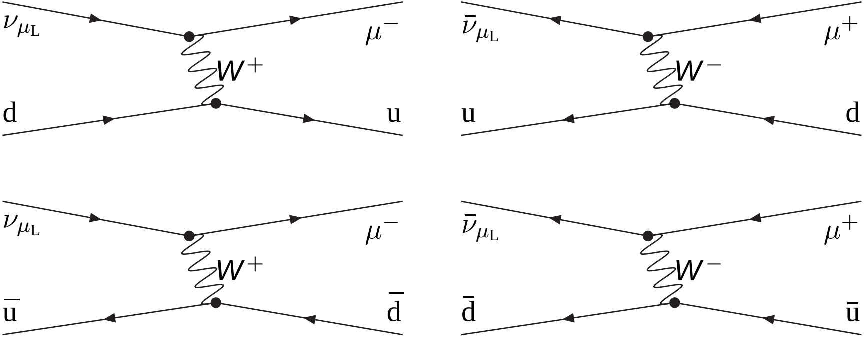

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Bjorken approach

$$\nu = \frac{E-E'}{M}$$

$$\frac{\partial^2\sigma}{\partial E'\partial\Omega'} = \frac{G^2}{2\pi^2}E'^2[2W_1^{(\nu,\bar{\nu})}(\nu,Q^2)\sin^2\frac{\theta}{2} + W_2^{(\nu,\bar{\nu})}(\nu,Q^2)\cos^2\frac{\theta}{2} \mp W_3^{(\nu,\bar{\nu})}(\nu,Q^2)\sin^2\frac{\theta}{2}]$$

- W_3: no conserved current in EW interactions (QED!)

QPM

relationship with QPM ($F_2 = xF_1$)

$$\begin{aligned}
2MW_1^{\bar{\nu}} &\rightarrow F_1^{\bar{\nu}} = 2f_{\mathrm{u}}(x) + 2f_{\bar{\mathrm{d}}}(x) \\
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Predict: $F_2^{\nu N}$ and F_2^{eN}

- nucleon $N_{protons} = N_{neutrons}, N_{sea} = 0$
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- Strong Isospin: $f_u^p = f_d^n$
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\begin{aligned}
F_2^{eN} &= \frac{1}{2}(F_2^{ep} + F_2^{en}) \\
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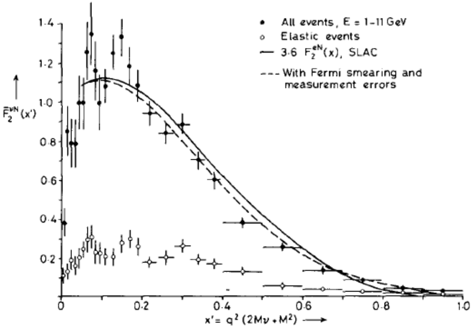
Prediction

$$\frac{F_2^{\nu N}}{F_2^{eN}} = \frac{18}{5} \approx 3.6$$



Conclusion

Prediction from electron DIS QPM-scaled agrees with neutrino-DIS measurement!

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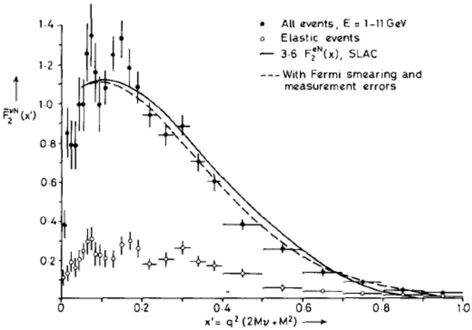

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Prediction from electron DIS QPM-scaled agrees with neutrino-DIS measurement!

Neutrinos:

$J_z = 0$: isotropic

$J_z = 1$: non-isotropic

Anti-Neutrinos:

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Reminder

$1 - \gamma_5$: left-particle, right-anti-particle

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- isotropic and non-isotropic initial state encoded in $y \sim q$

Differential cross section

$$\frac{\partial \sigma^{\nu N}}{\partial x \partial y} = \frac{G^2 ME}{\pi}[x(f_\mathrm{u} + f_\mathrm{d}) + x(f_{\bar{\mathrm{u}}} + f_{\bar{\mathrm{d}}})(1-y)^2]$$

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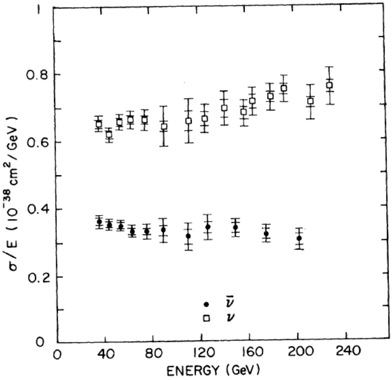
Scaling $\frac{\sigma}{E}$



Scaling ok, Ratio$\sim$ 2, $\rightarrow$ sea and gluons count

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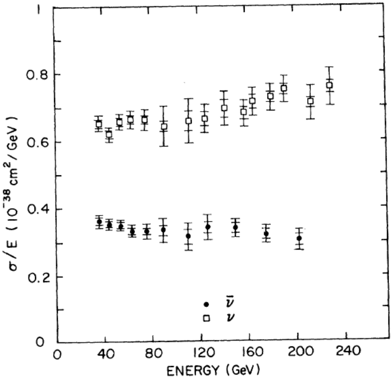

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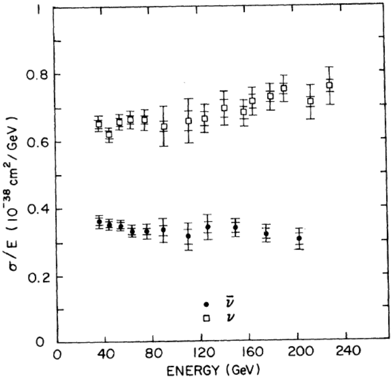

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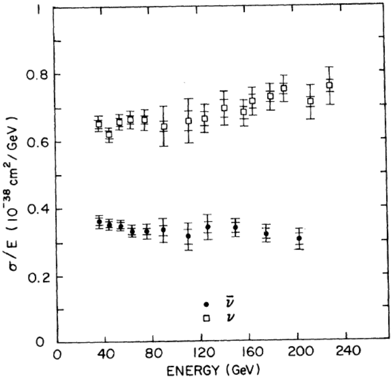

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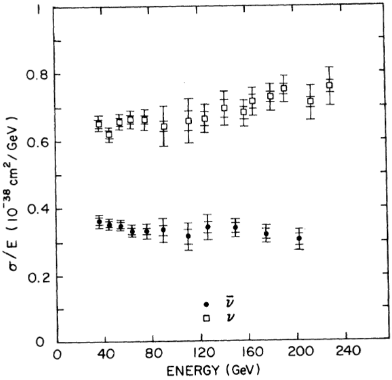

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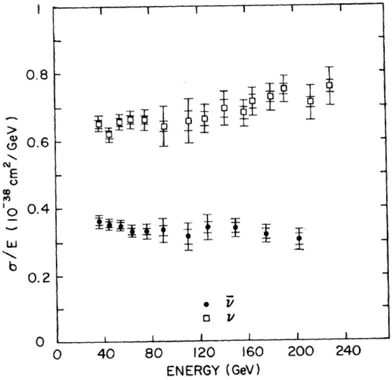

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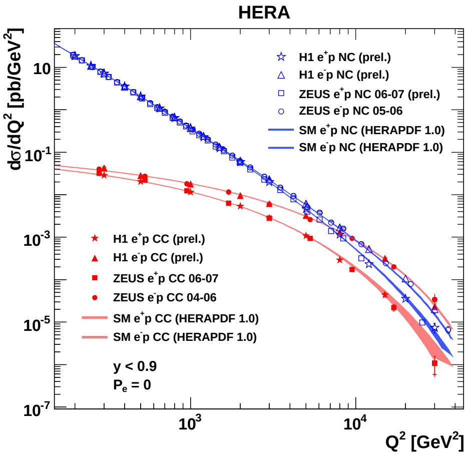
Unifying EM and EW



- CC ($W^{\pm}$): $ep \longrightarrow \nu_{e_L} + X$
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- at $Q^2 = m^2_{W^{\pm}}$: unification

All is well?

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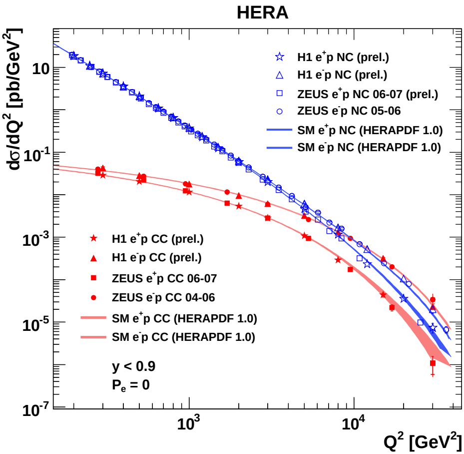

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All is well?

Sum Rules

- Baryon number: OK
- Charge: OK
- Momentum: 50% gluons OK
- Spin?

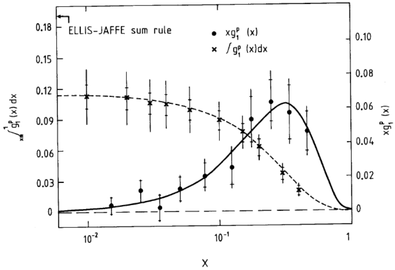
Experimental Approach

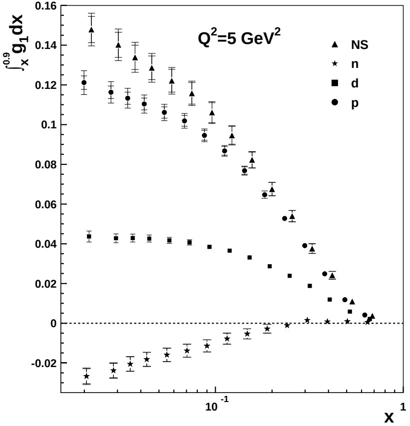
Polarize proton and measure asymmetry:

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{||}}{\sigma^{\uparrow\downarrow} + \sigma^{||}}$$

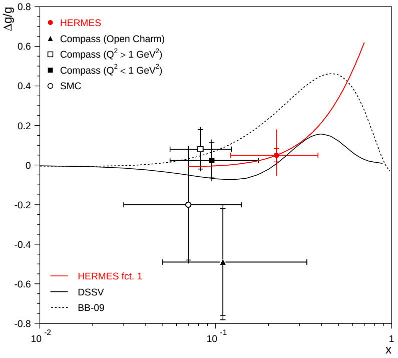
Probe: Polarized muon from pion decay (remember parity violation)

$$g_1 = \frac{1}{2}\sum q_i^2 (N^{||} - N^{\uparrow\downarrow})$$





- roughly 30% ????
- difficult integration
- HERMES (HERA) confirms!



Spin Crisis

- Low Q^2:
  - consistent picture (Problem Solving)
- High Q^2:
  - quark spin insufficient
  - gluon spin not sufficient
  - the solution today is unknown