# Particle Physics
# The Standard Model
## Charmonium - DIS with neutrinos - Spin crisis

Frédéric Machefert

frederic@cern.ch
Laboratoire de l'accélérateur linéaire (CNRS)

Cours de l'École Normale Supérieure
24, rue Lhomond, Paris

March 14th, 2019

# Part VIII

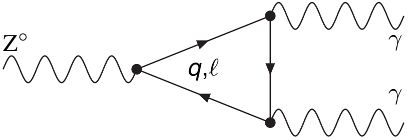
## Charmonium - DIS with neutrinos - Spin crisis

- The $J/psi$
  - GIM
  - Discovery and Properties
- DIS with neutrinos
  - $F_2$
  - Cross Section
- Spin Crisis

## Properties of the c

$$
\begin{aligned}
m_0 &= 1.27\text{GeV} \\
\tau &= (1.040 \cdot 10^{-12})\text{s} \quad c\bar{d} \\
c\tau &= 311.8\mu\text{m} \\
C &= +\tfrac{2}{3}
\end{aligned}
$$

Theoretically predicted before its discovery in 1974 by Glashow, Iliopoulos and Maiani (GIM)!




Triangle Anomaly if

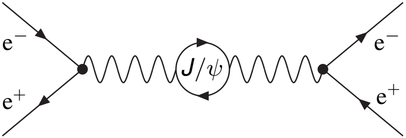
$$\sum_i c_A^f (q_i)^2 N_C \neq 0$$

u, d, s, e:

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

$$+3\cdot(-1/2)(-\frac{1}{3})^2 = 0 \neq 0$$

Complete families (charged) to avoid triangle anomalies




## Production

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

- $e^+e^-$: hit the resonance ($R \sim N_C q^2$ helps)
- $pp$: find a needle ($e^+e^-$) in a haystack (QCD)

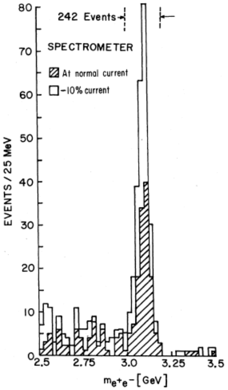
## Spin

- $= S_\gamma$ (by production)

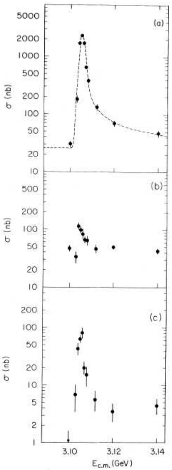
## Decay

- $J/\psi \to e^+e^-$
- $J/\psi \to \mu^+\mu^-$
- hadronic decays: vector mesons ($\gamma^\star \to \rho = u\bar{u}$)
- gluons

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:

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

- dominated by $\sigma_{exp}$
- need to know $\sigma_{exp}$ at per mil!

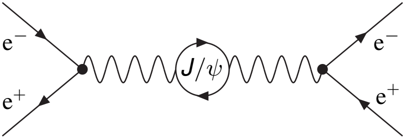
## Width via lifetime?

$J/\psi$ lifetime shorter than for charmed mesons: EM decay

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

NO WAY to get $\gamma$ (boost) high enough

ENS

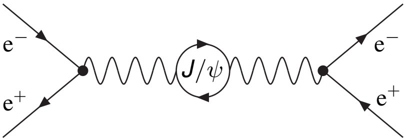



$$\begin{aligned}\sigma &\sim \Gamma_{ee}\Gamma_X \frac{1}{(s-m_{J/\psi}^2)^2+m_{J/\psi}^2\Gamma^2} \\ &= \Gamma_{ee}\Gamma_X \frac{\pi}{m_{J/\psi}\Gamma}\delta(s-m_{J/\psi}^2) \\ &\sim \Gamma_{ee}\mathcal{B}(J/psi \to X)\end{aligned}$$

## Cross section measurement

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

- valid only on the resonance, i.e. $\sqrt{s} = m_{J/\psi}$
- cross section = counting experiment $\Delta \sim 1/\sqrt{N}$
- $\mathcal{B}(J/\psi \to ee) = 7\%$




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

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 unknowns
Measure the cross sections to 1%:

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

## $J/\psi$ to quarks and leptons

EM interactions ($\gamma^\star$)

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

This means:

$$\begin{aligned} \Gamma &= \Gamma_{ggg} + \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{had} \\ &= \Gamma_{ggg} + \Gamma_{ee} + \Gamma_{ee} + 2\Gamma_{ee} \\ &= \Gamma_{ggg} + 4\Gamma_{ee} \end{aligned}$$

## $J/\psi \to ggg$

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

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

## $\alpha_S$

$$\begin{aligned} \frac{\Gamma_{ggg}}{\Gamma_{ee}} &= \frac{1 - 4\mathcal{B}_{ee}}{\mathcal{B}_{ee}} \qquad (B_{ee} = 7\%) \\ &= \frac{10(\pi^2 - 9)\alpha_S^3}{81\pi\alpha^2 q_c^2} \end{aligned}$$

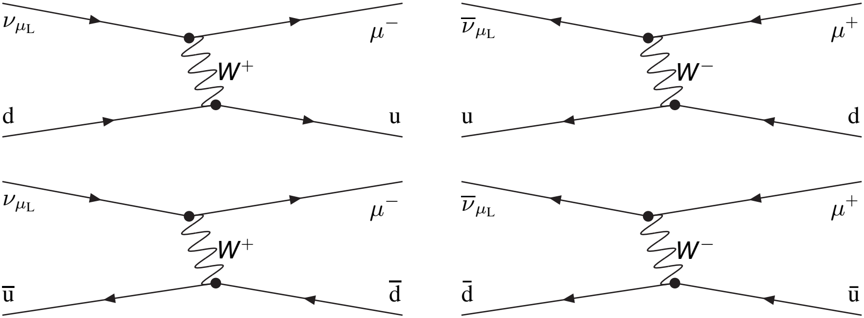
$\alpha_S(c\bar{c}) = 0.19$
$\alpha_S(b\bar{b}) = 0.16$
RUNS

## DIS

- electrons/muons
  - point-like probe
  - target with structure
  - EM interaction $Q^2$
  - non-fixed target possible
- neutrinos
  - point-like probe
  - target with structure
  - Weak interaction $Q^2$
  - non-fixed target impossible

## DIS

- $\nu_{\mu_{\rm L}}, \overline{\nu}_{\mu_{\rm L}}$
- produce pions with protons
- pions decay to $\nu_{\mu_{\rm L}} \mu$
- sign of $\mu$ defines (anti-)particle
- CC: detect the muon (low background)




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

$\gamma \to \mathrm{W}^{\pm}$: $\frac{\alpha}{Q^2} \to \frac{G}{2\pi\sqrt{2}}$

forbidden: $\overline{\nu}_{\mu_L} + \mathrm{d} \to \mu^+ \mathrm{u}$

$\nu_{\mu_L}$ and $\overline{\nu}_{\mu_L}$ probe different partons....

## Bjorken approach

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

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

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

## QPM

relationship with QPM ($F_2 = 2xF_1$)

$$\begin{array}{lcccl} MW_1^{\bar{\nu}} & \rightarrow & F_1^{\bar{\nu}} & = & f_u(x) + f_{\bar{d}}(x) \\ MW_1^{\nu} & \rightarrow & F_1^{\nu} & = & f_d(x) + f_{\bar{u}}(x) \\ \nu W_3^{\bar{\nu}} & \rightarrow & F_3^{\bar{\nu}} & = & -2f_u(x) + 2f_{\bar{d}}(x) \\ \nu W_3^{\nu} & \rightarrow & F_3^{\nu} & = & -2f_d(x) + 2f_{\bar{u}}(x) \end{array}$$

# Predict: $F_2^{\nu N}$ and $F_2^{\mathrm{e}N}$

- nucleon $N_{protons} = N_{neutrons}$, $N_{sea} = 0$
- EM interaction
- Strong Isospin: $f_{\mathrm{u}}^{p} = f_{\mathrm{d}}^{n}$
- Ansatz neutrino scattering
- Strong Isospin

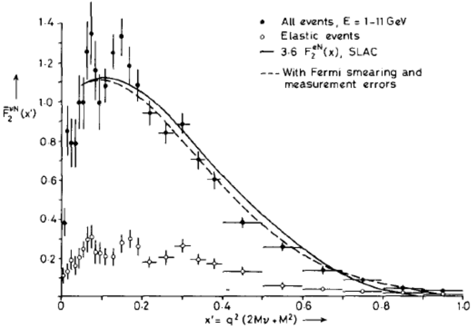
$$
\begin{aligned}
F_2^{\mathrm{e}N} &= \tfrac{1}{2}(F_2^{ep} + F_2^{en}) \\
&= \tfrac{1}{2}x(\tfrac{4}{9}f_{\mathrm{u}}^{p} + \tfrac{1}{9}f_{\mathrm{d}}^{p} + \tfrac{4}{9}f_{\mathrm{u}}^{n} + \tfrac{1}{9}f_{\mathrm{d}}^{n}) \\
&= \tfrac{1}{2}x(\tfrac{5}{9}f_{\mathrm{u}}^{p} + \tfrac{5}{9}f_{\mathrm{d}}^{p}) \\
&= \tfrac{5}{18}x(f_{\mathrm{u}}^{p} + f_{\mathrm{d}}^{p})
\end{aligned}
$$

$$
\begin{aligned}
F_2^{\nu N} &= \tfrac{1}{2}(F_2^{\nu p} + F_2^{\nu n}) \\
&= \tfrac{1}{2}x(2f_{\mathrm{d}}^{p} + 2f_{\mathrm{d}}^{n}) \\
&= x(f_{\mathrm{d}}^{p} + f_{\mathrm{u}}^{p})
\end{aligned}
$$

ENS

## 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!

Neutrinos:


$J_z = 0$: isotropic


$J_z = 1$: non-isotropic

Anti-Neutrinos:


$J_z = 1$: non-isotropic


$J_z = 0$: isotropic

**Reminder**

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

- $\nu_{\mu_L} + Fe \rightarrow \mu + X$
- $N_n \approx N_p$: isoscalar target
- $M$: target mass
- $y[0,1] = \frac{p \cdot q}{E} = \frac{E - E'}{E}$
- EM $Q^4$ from $\gamma$-propagator replaced by $\mathrm{W}^{\pm}$ propagator $\rightarrow$ const.
- isotropic and non-isotropic initial state encoded in $y \sim q$

## Differential cross section

$$\frac{\partial \sigma^{(\nu,\bar{\nu})N}}{\partial x \partial y} = \frac{G^2 ME}{\pi}\left[\frac{F_2^{\nu N}}{2}(1 - y + y^2/2) \mp x\frac{F_3^{\nu N}}{2}(y - y^2/2)\right]$$

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

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

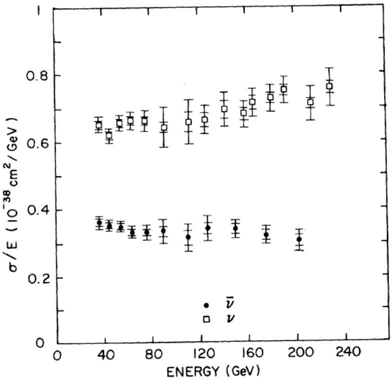
- integrate over $x$ :
  $< q >= \int_0^1 x(f_u + f_d)$,
  $< \bar{q} >= \int_0^1 x(f_{\bar{u}} + f_{\bar{d}})$
- integrate over $y$: $\int_0^1 (1-y)^2 = \frac{1}{3}$
- calculate ratio for valence

$$\sigma^{\nu N} = \frac{G^2 ME}{\pi}[< q > + < \bar{q} > \frac{1}{3}]$$

$$\sigma^{\bar{\nu} N} = \frac{G^2 ME}{\pi}[< q > \frac{1}{3} + < \bar{q} >]$$

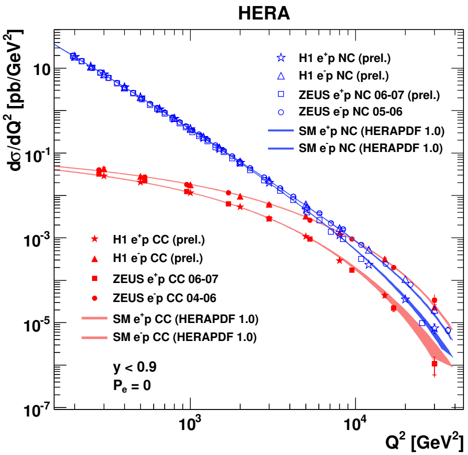
$$\frac{\sigma^{\nu N}}{\sigma^{\bar{\nu} N}} \approx 3$$

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




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

# Unifying EM and EW




- CC ($\mathrm{W}^{\pm}$): $\mathrm{e}p \to \nu_{\mathrm{e_L}} + X$
- NC ($\gamma$,$\mathrm{Z}^{\circ}$): $\mathrm{e}p \to \mathrm{e} + X$
- EM $Q^{-4}$
- Fermi (flat) until $m^2_{\mathrm{W}\pm}$
- at $Q^2 = m^2_{\mathrm{W}\pm}$: unification

All is well?

## Sum Rules

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

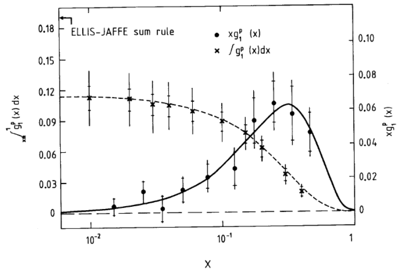
## Experimental Approach

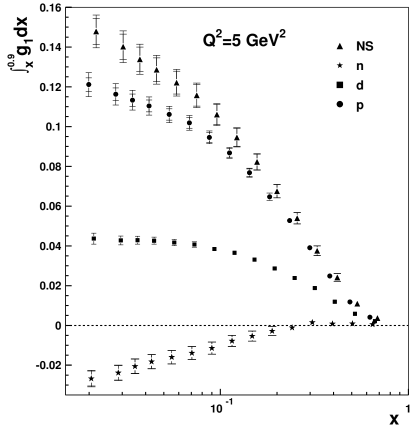
Polarize proton and measure asymmetry:

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

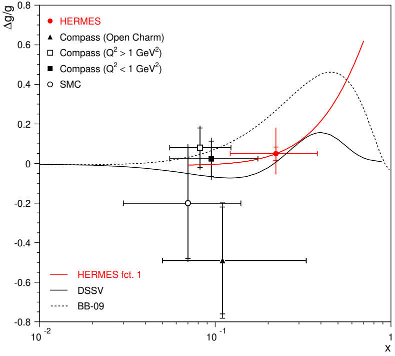
Probe: Polarized muon from pion decay (remember parity violation)

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




- 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