## Particle Physics: The Standard Model

### **Dirk Zerwas**

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Dirk Zerwas Particle Physics: The Standard Model

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GIM Discovery and Properties

### Properties of the c

$$\begin{array}{rcl} m_{0} & = & 1.27 {\rm GeV} \\ \tau & = & (1.040 \cdot 10^{-12}) {\rm s} & c \bar{d} \\ c \tau & = & 311.8 \mu {\rm m} \\ C & = & +\frac{2}{3} \end{array}$$

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



( $\gamma \perp Z^{\circ}$ ) Triangle Anomaly if

 $\sum q_i N_C \neq 0$ 

u, d, s, e:

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

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### Production

• Richter  $e^+e^- \rightarrow \psi$ 

• Ting:  $pp \sim u_V \bar{u}_S \rightarrow J$ 

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

#### Spin

• =  $S_{\gamma}$  (by production)

#### Decay

•  $J/\psi \rightarrow e^+e^-$ 

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- hadronic decays: vector mesons (γ<sup>\*</sup> → ρ = uū)
- gluons
- No charmed mesons possible!

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GIM Discovery and Properties

## 30 GeV protons on fixed Target (BNL AGS):



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



GIM Discovery and Properties

#### Width

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

### Measure invariant mass:

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

• dominated by  $\sigma_{exp}$ 

 need to know σ<sub>exp</sub> at per mil!

### Width via lifetime?

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

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

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

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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
- decay to initial state (t inverted)

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

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

#### 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.  $\sqrt{s} = m_{J/\psi}$
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GIM Discovery and Properties



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The J/psi DIS with neutrinos Spin Crisis GIM Discovery and Properties



$$\begin{array}{lll} \sigma_{\rm ee} & \sim & \Gamma_{\rm ee} \frac{\Gamma_{\rm ee}}{\Gamma} \\ \sigma_{\mu\mu} & \sim & \Gamma_{\rm ee} \frac{\Gamma_{\mu\mu}}{\Gamma} \\ \sigma_{had} & \sim & \Gamma_{\rm ee} \frac{\Gamma_{had}}{\Gamma} \end{array}$$

Hypothesis: completeness!

$$\begin{aligned} \Gamma_{\rm ee} + \Gamma_{\mu\mu} + \Gamma_{had} &= \Gamma \\ \sigma_{\rm ee} + \sigma_{\mu\mu} + \sigma_{had} &= \frac{12\pi}{m_{J/\psi}^2} \Gamma_{\rm ee} \end{aligned}$$

Three measurements three unkowns Measure the cross sections to 1%:

$$\begin{array}{rcl} \Delta \Gamma_{ce} & = & \sqrt{3} \cdot 1\% \\ & \approx & 1.7\% \\ & \sim & 0.1 \mbox{keV} \end{array}$$

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The J/psi DIS with neutrinos Spin Crisis GIM Discovery and Properties



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The J/psi OIS with neutrinos Spin Crisis GIM Discovery and Properties



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GIM Discovery and Properties

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

EM interactions ( $\gamma^{\star}$ )

$$\frac{\Gamma(J/\psi \rightarrow had)}{\Gamma(J/\psi \rightarrow e^+e^-)}$$

$$= N_C \sum q_i^2$$

$$= 3 \cdot \left[ \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 \right] \\ = 2$$

### This means:

$$\Gamma = \Gamma_{ggg} + \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{had}$$
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### $J/\psi ightarrow ggg$

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

$$\Gamma(J/\psi 
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m S}^3$$

 $\alpha_{\rm S}$ 

$$= \frac{1-4\mathcal{B}_{ee}}{\mathcal{B}_{ee}}$$
$$= \frac{10(\pi^2 - 9)\alpha_1^2}{81\pi \alpha^2 \sigma^2}$$

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 $lpha_S(car c) = 0.19$  $lpha_S(bar b) = 0.16$ RUNS

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## DIS

## electrons/muons

- point-like probe
- target with structure
- EM interaction Q<sup>2</sup>
- non-fixed target possible

## neutrinos

- point-like probe
- target with structure
- Weak interaction Q<sup>2</sup>
- non-fixed target impossible

### DIS

# • $u_{\mu_{\mathrm{L}}}, \, \bar{ u}_{\mu_{\mathrm{L}}}$

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

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### F<sub>2</sub> Cross Section

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F<sub>2</sub> Cross Section









forbidden:  $\nu_{\mu_{\rm L}} + \mathbf{u} \to \mu^- \mathbf{d}$  $\gamma \to \mathrm{W}^{\pm}: \frac{\alpha}{Q^2} \to \frac{G}{2\pi\sqrt{2}}$ 

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F<sub>2</sub> Cross Section









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F<sub>2</sub> Cross Section

 $\bar{\nu}_{\mu_{\mathrm{L}}}$ 





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F<sub>2</sub> Cross Section









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F₂ Cross Section







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Cross Section

 $\bar{\nu}_{\mu_{\mathrm{L}}}$ 





u d

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### Bjorken approach

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

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

## • W<sub>3</sub>: no conserved current in EW interactions (QED!)

### QPM

relationship with QPM ( $F_2 = xF_1$ )

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F<sub>2</sub> Cross Section

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

- nucleon  $N_{protons} = N_{neutrons}$ ,  $N_{sea} = 0$
- EM interaction
- Strong Isospin:  $f_{\rm u}^{p} = f_{\rm d}^{n}$
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$$F_{2}^{eN} = \frac{1}{2}(F_{2}^{ep} + F_{2}^{eN}) \qquad F_{2}^{\nu N} = \frac{1}{2}(F_{2}^{\nu p} + F_{2}^{\nu n}) \\ = \frac{1}{2}x(\frac{4}{9}f_{u}^{p} + \frac{1}{9}f_{d}^{p} + \frac{4}{9}f_{u}^{n} + \frac{1}{9}f_{d}^{n}) \qquad = \frac{1}{2}x(2f_{d}^{p} + 2f_{d}^{n}) \\ = \frac{1}{2}x(\frac{5}{9}f_{u}^{p} + \frac{5}{9}f_{d}^{p}) \qquad = x(f_{d}^{p} + f_{u}^{p}) \\ = \frac{5}{18}x(f_{u}^{p} + f_{d}^{p})$$

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The J/psi DIS with neutrinos

F<sub>2</sub> Cross Sectio

### Prediction

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



### Conclusion

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

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The J/psi DIS with neutrinos

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$$\nu_{\mu_{\rm L}} + Fe \rightarrow \mu + X$$

- $N_n \approx N_p$ : isoscalar target
- M: target mass
- $y[0,1] = \frac{p \cdot q}{E} = \frac{E E'}{E}$
- EM Q<sup>4</sup> from  $\gamma$ -propagator replaced by W<sup>±</sup> propagator  $\rightarrow$  const.
- isotropic and non-isotropic initial state encoded in  $y \sim q$

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

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**Cross Section** 



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F<sub>2</sub> Cross Section

• 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
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 $rac{\sigma^{
u N}}{\sigma^{ar{
u} N}}~pprox$  3

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



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

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F<sub>2</sub> Cross Section

- 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 w
- integrate over y:  $\int_0^1 (1-y)^2 = \frac{1}{3}$
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Scaling 🖁



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F<sub>2</sub> Cross Section

- integrate over *x* :
   < *q* >= ∫<sub>0</sub><sup>1</sup> *x*(*f*<sub>u</sub> + *f*<sub>d</sub>),
   < *q* >= ∫<sub>0</sub><sup>1</sup> *x*(*f*<sub>ū</sub> + *f*<sub>d</sub>)
   integrate over *y*:
  - $\int_0^1 (1 y)^2 = \frac{1}{3}$
- calculate ratio for valence  $\sigma^{\nu N} = \frac{G^2 M E}{\pi} [\langle q \rangle + \langle \bar{q} \rangle \frac{1}{3}]$   $\sigma^{\bar{\nu}N} = \frac{G^2 M E}{\pi} [\langle q \rangle \frac{1}{3} + \langle \bar{q} \rangle]$   $\frac{\sigma^{\nu N}}{\sigma^{\bar{\nu}N}} \approx 3$

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



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F<sub>2</sub> Cross Section

## Unifying EM and EW



- CC (W<sup>±</sup>):
  - $e p 
    ightarrow 
    u_{e_{
    m L}} + X$
- NC  $(\gamma, Z^{\circ})$ : ep  $\rightarrow$  e + X
- EM Q<sup>-4</sup>
- Fermi (flat) until  $m^2_{
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• at 
$$Q^2 = m_{W^{\pm}}^2$$
:  
unification

All is well?

F<sub>2</sub> Cross Section

## Unifying EM and EW



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- at  $Q^2 = m_{W^{\pm}}^2$ : unification

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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:

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

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

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

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



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#### Spin Crisis

- Low Q<sup>2</sup>:
  - consistent picture (Problem Solving)

## • High Q<sup>2</sup>:

- quark spin insufficient
- gluon spin not sufficient

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 the solution today is unknown