Progress in FDC project

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Outline

Brief Introduction to FDC package

Feynman Diagram Calculation(FDC).
This first version of FDC was presented at AIHENP93 workshp,1993.

FDC Homepage::
http://www.ihep.ac.cn/lunwen/wjx/public_html/index.html

FDC-LOOP
FDC-PWA
FDC-EMT

FDC-SM-and-Many-Extensions
FDC-NRQCD
FDC-MSSM

→ **Written in REDUCE, RLISP,C++. To generate Fortran**

→ **Event Generator**

FDC System

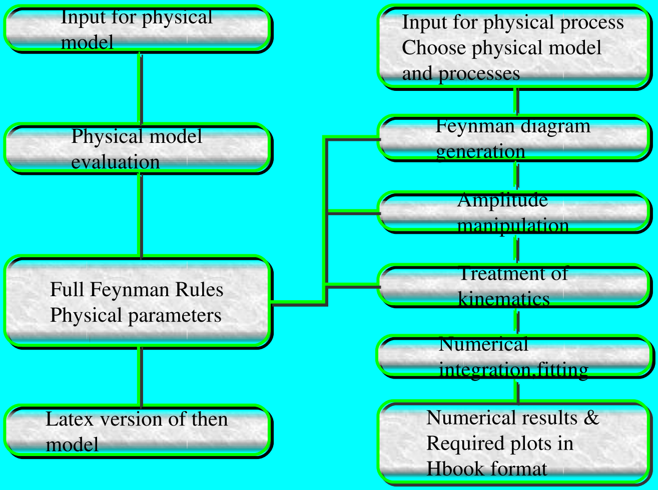


FIG.1: FDC system flow chart

To prepare first principle model

Input the description of the first principle model:
Standard model and its extensions
Supersymmetry model and its extensions

Construct the Lagrangian accroding to the following conditions:
Gauge invariance, global symmetry, supersymmetry,
Yukawa coupling, H†=H
and then deduce Feynman rules, mixing of particles, ...

The generated physical model for system use include FORTAN77 source to calculate mixing matrices if needed

To prepare phenomenological model

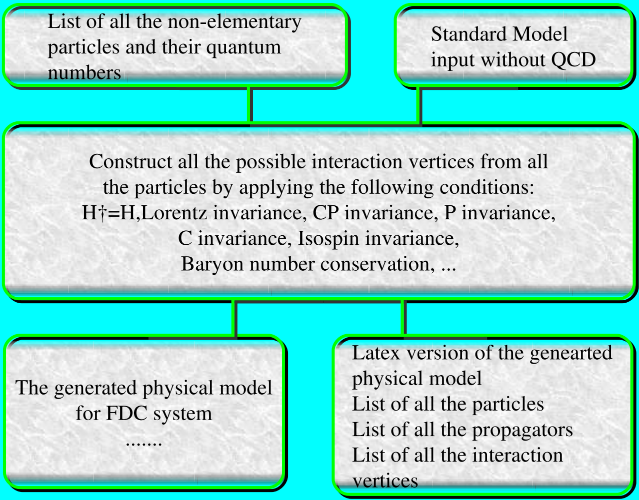
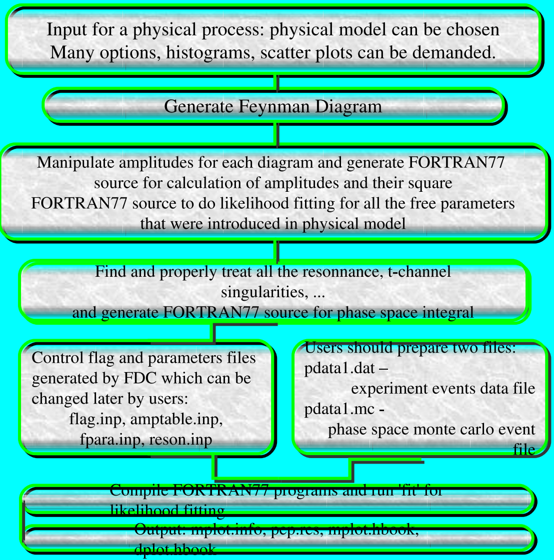


FIG.3: System flow chart for physical process

Physical Process



To automatically construct the Lagrangian and deduce the Feynman rules for SM, MSSM

From a simple and easy understanding input. Input and Output can be viewed on
http://www.ihep.ac.cn/lunwen/wjx/public_html/model/mssm2a/index.ht

Advantages:

Easy to change soft-breaking terms ....
Easy to change globel symmetry
Easy to add more matter fields
Easy to switch to different gauge
Easy to chose different parameterization scheme

Automatically phase space treatment

It was presented at AIHENP96 and many improvements had been made

The program do analysis each Feynman diagram and look for:

t-channel peaks (calculate t_min, t_max)
s-channel peaks (calculate s_min, s_max)
sub-kinematics arrangement,
next sub-kinematics, ...

To generate Fortran source for these arrangement, and each sub-kinematics located in a sub-range. Sub-range divided by behave of Denominator of each diagram.

FDC-PWA: Powerful Tool

- To work with high spin states (0, 1/2, 1, 3/2, 2, 5/2, 3 , 7/2, 4, 9/2) and to construct effective Lagrangians.
- The expression of the effective interaction vertices and the propagators for the high spin states are quite lengthy.
- The related amplitudes and amplitude squares are complicated.
- There are many free parameters in the effective Lagrangian and these parameters will be fixed when the generated program is used to do Likelihood fitting of experimental data.
- To generate a complete set of the Fortran sources to do the partial wave analysis on experimental data.

To do Partial Wave Analysis by using FDC-PWA

To use following command in FDC-PWA to do the job

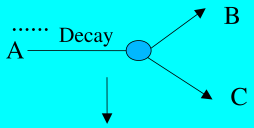
- gmodel
- diag
- amp
- kine
- cd fort
- make
- fit

2.The Rule to Construct Effective Lagrangian For PWA

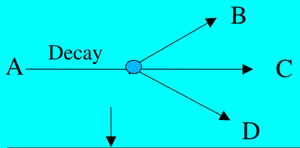
- Lorentz Invariance
- C-parity conservation
- P-parity conservation
- CP conservation
- H=H
- ……

The Input is a list of all related particles.

The output is all interaction vertices



The coefficients of all the independent terms are constant



The coefficients of all the indepent terms depend on two varibales

Each Coefficient has independent phase factor

Each Propagator has suppression factor

FDC-NRQCD

The method to calculate heavy quarkonium production and decay has been built in FDC

SM+heavy-quarkonium

http://www.ihep.ac.cn/lunwen/wjx/public_html/index.html

FDC-MSSM

MSSM has been buit in FDC and all the possible two particle decay channels of all the possible particles are calculated.
http://www.ihep.ac.cn/lunwen/wjx/public_html/index.html

The calculations by using FDC-loop in last three years

- Our work concentrate on QCD correction to heavy quarkonium production in B-factory, z boson decay, Υ decay, HERA, Tevatron, LHC.
- It is found that that QCD corrections to these processes are very important.
- There are six-point, five-point, ... Feynamn diagrams are accounted in the calculations. In many case, five-point scalar integral can not be decomposed into four-point ones due to special kinematic range in bound state related problem.

$e^+e^- \to J/\psi + \eta_c$

Experimantal Data

BELLE: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (25.6 \pm 2.8 \pm 3.4)$ fb
BARAR: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (17.6 \pm 2.8^{+1.5}_{-2.1})$ fb
[?, ?, ?]

LO NRQCD Predictions

$2.3 \sim 5.5$ fb
[?, ?, ?]

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[?, ?, ?]

LO NRQCD Predictions

$2.3 \sim 5.5$ fb
[?, ?, ?]

NLO QCD corrections

$K \equiv \sigma^{NLO}/\sigma^{LO} \sim 2$
First given in PRL96, (2006) Y. J. Zhang, Y. J. Gao and K. T. Chao
Confirmed by the analytic result in PRD77, (2008), B. Gong and J. X. Wang

$e^+e^- \to J/\psi + J/\psi$

Problem

LO NRQCD prediction indicates that the cross section of this process is large than that of $J/\psi + \eta_c$ production by a factor of 1.8, but no evidence for this process was found at the B factories.
PRL90, (2003) G. T. Bodwin, E. Braaten and J. Lee
PRD70, (2004), K. Abe, et al

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NLO QCD corrections

- Greatly decreased, with a K factor ranging from $-0.31 \sim 0.25$ depending on the renormalization scale.
- Might explain the situation.

PRL100, (2008) B. Gong and J. X. Wang

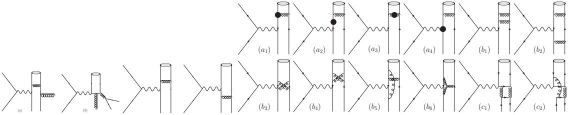
Cross section at NLO for $e^+e^- \to J/\psi + gg$

$$\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[a(\hat{s}) + \beta_0 \ln \left(\frac{\mu}{2m_c} \right) \right] \right\}$$

m_c(GeV)	$\alpha_s(\mu)$	$\sigma^{(0)}$(pb)	$a(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$
1.4	0.267	0.341	2.35	0.409	1.20
1.5	0.259	0.308	2.57	0.373	1.21
1.6	0.252	0.279	2.89	0.344	1.23

PRL102, (2009) B. Gong and J. X. Wang

$e^+e^- \to J/\psi + c\bar{c}$

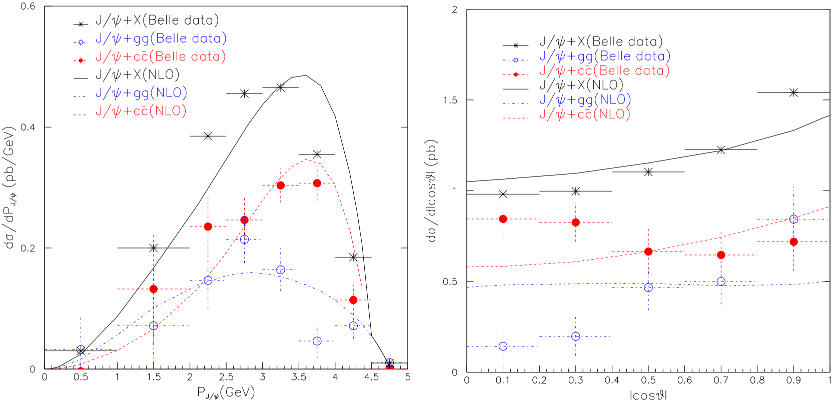


$$\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[a(\hat{s}) + \beta_0 \ln\left(\frac{\mu}{2m_c}\right) \right] \right\}$$

m_c(GeV)	$\alpha_s(\mu)$	$\sigma^{(0)}$(pb)	$a(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$
1.4	0.267	0.224	8.19	0.380	1.70
1.5	0.259	0.171	8.94	0.298	1.74
1.6	0.252	0.129	9.74	0.230	1.78

Cross sections with different charm quark mass m_c with the renormalization scale $\mu = 2m_c$ and $\sqrt{s} = 10.6$ GeV.

PRD80, (2009) B. Gong and J. X. Wang



Momentum distribution of inclusive J/ψ production with $\mu = \mu^*$ and $m_c = 1.4$ GeV is taken for the $J/\psi cc$ channel. The contribution from the feed-down of ψ' has been added to all curves by multiplying a factor of 1.29.

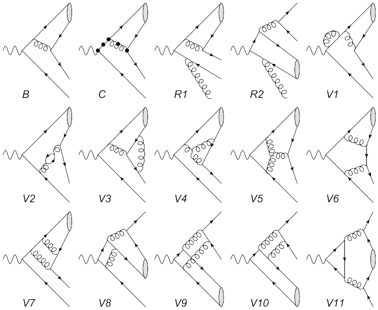
- Experimental and Leading-order Theoretical Results.[Acciarri:1998]

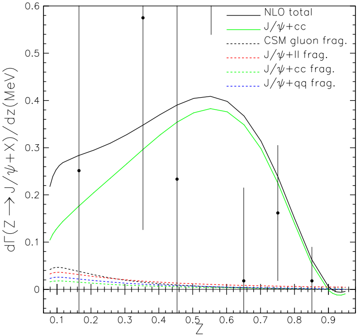
$$Br(Z \to J/\psi_{prompt} + X) = (2.1^{+1.4}_{-1.2}) \times 10^{-4}$$

Dominant process: $Z \to J/\psi + c\bar{c} + X$, and the total decay width is presented as

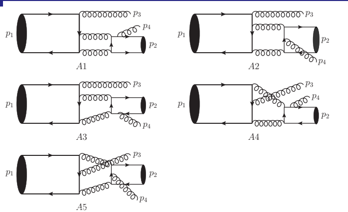
$$\Gamma^{NLO}(\mu) = \Gamma^{LO}(\mu)[1 + \frac{\alpha_s(\mu)}{\pi}(A + \beta_0 ln\frac{\mu}{2m_Q} + Bn_f)]. \quad (1)$$

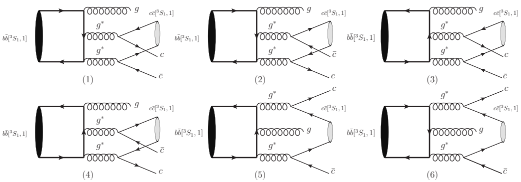
$$Br^{total} = (7.3 \sim 10) \times 10^{-5}$$





The result is presented in: PRD82, (2010), Li and J. X. Wang.





Experimental Data for $Br(\Upsilon \to J/\psi + X)$:

CLEO$(11 \pm 4 \pm 2) \times 10^{-4}$ *Phys. Lett. B* **224**, 445
ARGUS $< 6.8 \times 10^{-4}$ *Z. Phys. C***55**, 25(1992)
CLEO$(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$ *Phys. Rev. D***70**, 072001(2004)

The situation is quite strange ????

The correct leading order prediction is

$$\mathcal{B}_{\text{Direct}}(\Upsilon \to J/\psi + c\bar{c}g) = 3.9 \times 10^{-5}.$$

Z. G. He and J. X. Wang, Phys.Rev.D81:054030,2010.

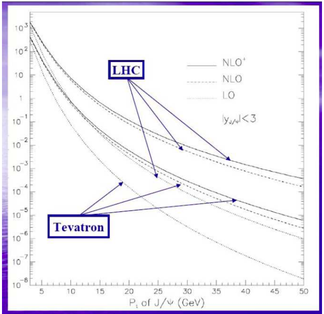
Part of NLO prediction from $\Upsilon \to J/\psi + gg$ is

$$\mathcal{B}_{\text{Direct}}(\Upsilon \to J/\psi + gg) = 3.1 \times 10^{-5}.$$

Z. G. He and J. X. Wang, arXiv:1009.1563[hep-ph]].

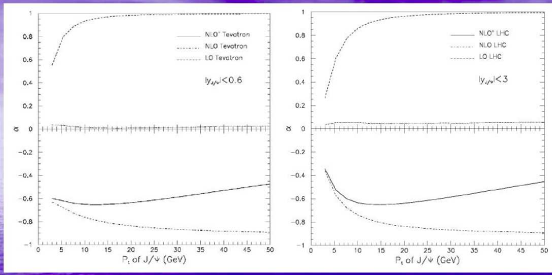
The full QCD correction for the inclusive J/ψ production in Υ decay would be a very interesting and challenge work for explaining the experimental data.

QCD Correction to color-singlet J/ψ production



Transverse momentum distribution of J/ψ production

NLO⁺ : contribution from $J/\psi + c\bar{c}$ is included



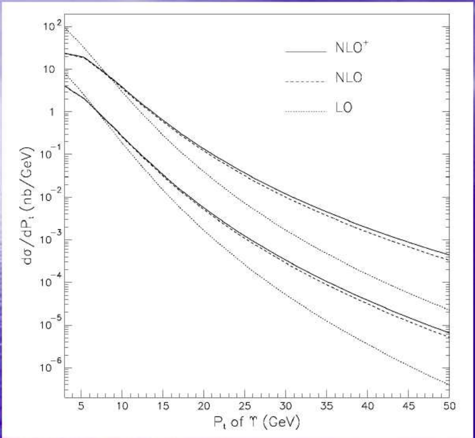
Transverse momentum distribution of J/ψ polarization parameter α

J/ψ polarization status drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO

Some technique problems must be solved to calculate J/ψ polarization

P_t distribution of J/ψ polarization at QCD NLO was calculated in PRL100,232001 (2008), B. Gong and J. X. Wang

NLO QCD Correction to Υ Production and Polarization



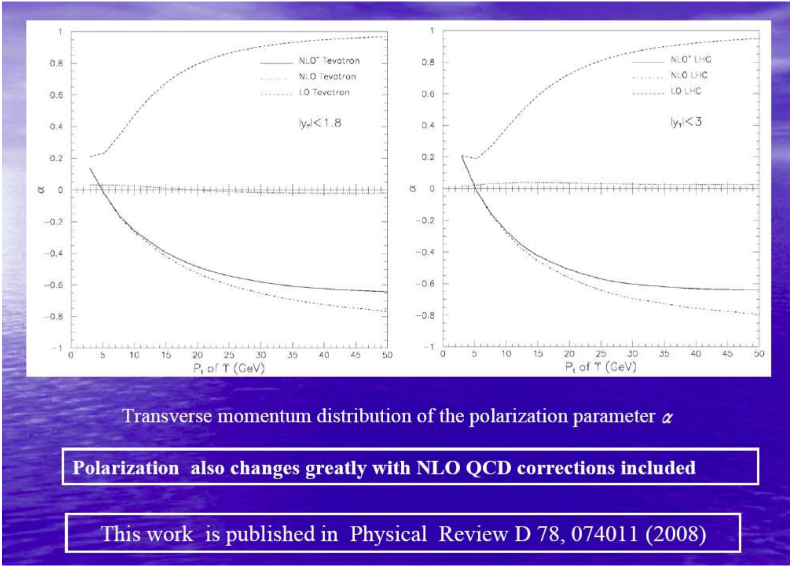
Transverse momentum distribution of Υ production

NLO^{+} : contribution from $\Upsilon + b\bar{b}$ is included

$$m_c \leftrightarrow m_b$$
$$M_{J/\psi} \leftrightarrow M_{\Upsilon}$$
$$R_s(0)^{J/\psi} \leftrightarrow R_s(0)^{\Upsilon}$$
$$n_f = 3 \leftrightarrow n_f = 4$$

Upper: LHC
Lower: Tevatron

$$|R_s^{\Upsilon}(0)|^2 = 0.479\ \mathrm{GeV}^3$$
$$m_b = 4.75\ \mathrm{GeV}$$
$$\mu_r = \mu_f = \sqrt{(2m_b)^2 + p_t^2}$$
$$|y_{\Upsilon}|_{\mathrm{Tevatron}} < 1.8$$
$$|y_{\Upsilon}|_{\mathrm{LHC}} < 3$$


NLO* Tevatron
NLO Tevatron
LO Tevatron
$|y_\Upsilon| < 1.8$
α
P_t of Υ (GeV)
NLO* LHC
NLO LHC
LO LHC
$|y_\Upsilon| < 3$
α
P_t of Υ (GeV)
Transverse momentum distribution of the polarization parameter α
Polarization also changes greatly with NLO QCD corrections included
This work is published in Physical Review D 78, 074011 (2008)

NLO QCD corrections to J/ψ production via S-wave color octet states

3 tree processes at LO — **At NLO**

$$g(p_1) + g(p_2) \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right](p_3) + g(p_4), \qquad (267, 413)$$

$$g(p_1) + q(p_2) \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right](p_3) + q(p_4), \qquad (49, 111)$$

$$q(p_1) + \bar{q}(p_2) \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right](p_3) + g(p_4). \qquad (49, 111)$$

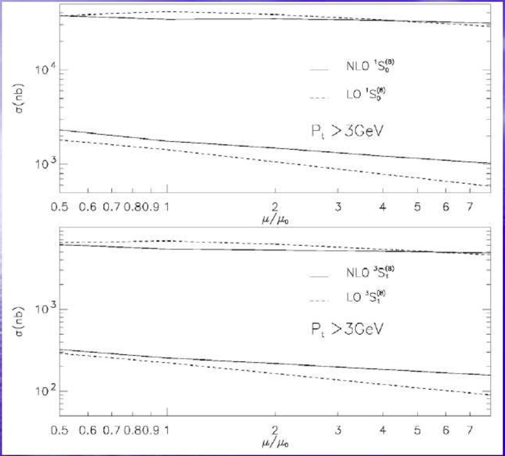
Real Correction (8 processes at NLO)

$$gg \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]gg, \quad gg \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]q\bar{q},$$

$$gq \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]gq, \quad q\bar{q} \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]gg,$$

$$q\bar{q} \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]q\bar{q}, \quad q\bar{q} \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]q'\bar{q}',$$

$$qq \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]qq, \quad qq' \rightarrow J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]qq',$$



Total cross section of J/ψ production as function of the renormalization and factorization scale via S-wave color octet states

Upper curves: LHC
Lower curves: Tevatron

$$\mu_r = \mu_f = \mu$$

$$\mu_0 = \sqrt{(2m_c)^2 + p_t^2}$$

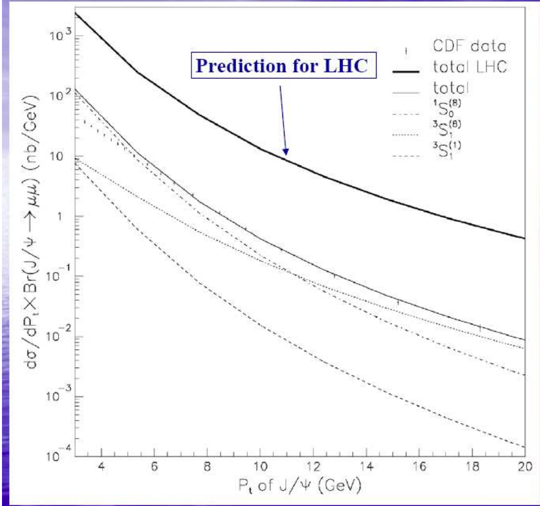
$$|y_{J/\psi}|_{\text{Tevatron}} < 0.6$$

$$|y_{J/\psi}|_{\text{LHC}} < 3$$

K factors at $\mu = \mu_0$:

	Tevatron	LHC
$^1S_0^{(8)}$	1.235	0.826
$^3S_1^{(8)}$	1.119	0.800

The NLO QCD corrections don't change the total cross section very much.



$$\mu_r = \mu_f = \sqrt{(2m_c)^2 + p_t^2}$$

$$|y_{J/\psi}|_{\text{Tevatron}} < 0.6$$

$$|y_{J/\psi}|_{\text{LHC}} < 3$$

Our fitted matrix elements:

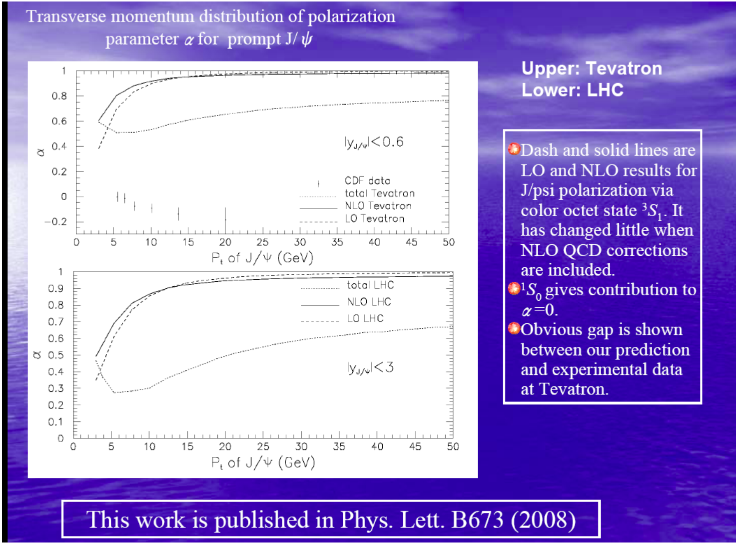
$$\langle \mathcal{O}_8^\psi(^3S_1)\rangle = 0.0045\ \text{GeV}^3$$

$$\langle \mathcal{O}_8^\psi(^1S_0)\rangle = 0.0760\ \text{GeV}^3$$

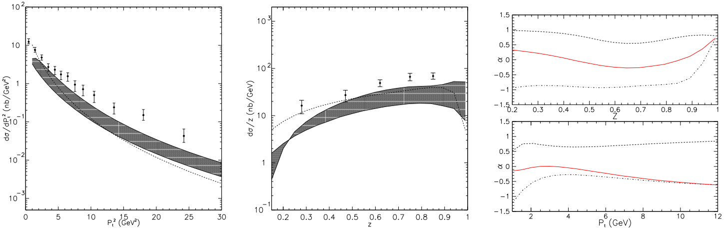
Notes in fitting

- Experimental data with p_t<6 GeV has been abandoned
- Feed down from ψ' has been included by multiplying a factor of $B(\psi' \to J/\psi + X) \times \langle \mathcal{O}_n^{\psi'}\rangle / \langle \mathcal{O}_n^{\psi}\rangle$
- Contribution via P-wave has not been included

Transverse momentum distribution of prompt J/ψ production


Transverse momentum distribution of polarization parameter α for prompt J/ψ
|y_J/ψ|<0.6
CDF data
total Tevatron
NLO Tevatron
LO Tevatron
P_t of J/Ψ (GeV)
α
total LHC
NLO LHC
LO LHC
|y_J/ψ|<3
P_t of J/Ψ (GeV)
α
Upper: Tevatron
Lower: LHC
Dash and solid lines are LO and NLO results for J/psi polarization via color octet state ³S₁. It has changed little when NLO QCD corrections are included.
¹S₀ gives contribution to α=0.
Obvious gap is shown between our prediction and experimental data at Tevatron.
This work is published in Phys. Lett. B673 (2008)

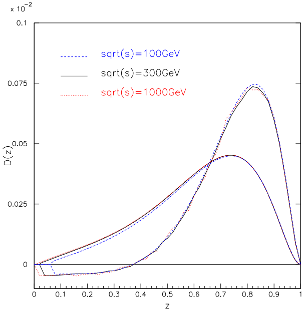
QCD Correction to color-singlet J/ψ production at HERA.



P_t distribution of production and different scheme of polarization for J/ψ (color-singlet) at QCD NLO was calculated in C. H. Chang, R. Li, J. X. Wang, PRD80,034020 (2009).

New Progress

Fragmentation function of $c \to J/\psi$ at QCD NLO was calculated by B. Gong and J. X. Wang, in prepare



The way to manipulate the amplitude

Two way for amplitude square calculation:
One is directly amplitude square.
the other is numerical amplitude and the square.

For higher order tree part (real gluon or photon emition)

It usually contains soft and collinear divergence and can not be calculated numerically. two-cutoff method in phase space (B. W. Harris and J. F. Owens, Phys. Rev. D65, 094032 (2002)) are realized in our program.

- Parton distribution functions are proper used in the program.
- The higher-order tree are divided into two part. The part with soft or/and collinear divergence is plused into virtual correction part. And the other part is calculated numerically.
- this method is realized in FDC.

Scalar Integral

- For the scalar integral in one-loop calculation, we choose to perform the integration analytically in N-dimension regularization.
- It is hard to find a general way to perform scalar integration in N-dimension for 4-point, or, 5-point, ... scalar integrals.
- We need a general way to realize in computer program.

General way

A scalar N-point function in D-dimension can be defined as

$$T_0^{(N)}(p_1,\ldots,p_{N-1},m_0,m_1,\ldots,m_{N-1}) = \mu^{4-D}\int\frac{\mathrm{d}^Dq}{(2\pi)^D}\frac{1}{N_0\ldots N_{N-1}},$$

where $N_n = (q+p_n)^2 - m_n^2 + i\epsilon, \quad n = 0,\ldots,N-1,$
According to S. Dittmaier: Nucl. Phys. B675,447 (2003) , the IR singularities part can be expressed as sum of a few 3-point with IRS

$$T_0|_{\mathrm{sing}}^{(N)} = \sum_{n=0}^{N-1}\sum_{\substack{k=0\\k\neq n,n+1}}^{N-1} A_{nk}\,C_0(p_0,\ldots,p_k,m_n,m_{n+1},m_k).$$

We can evaluate the scalar integral by

$$T_0^D = T_0^\epsilon - T_0|_{\mathrm{sing}}^\epsilon + T_0|_{\mathrm{sing}}^D. \qquad (2)$$

Where T_0^ϵ, $T_0|_{\mathrm{sing}}^\epsilon$ means to us $i\epsilon$ in the propagators to regularize singularities

$i\epsilon$-regularization

- Let the N-dimension back to 4-dimension.
- to keep $i\epsilon$ in the propagators make the scalar integrals well defined.
- Standard way given by t'hooft and Veltman in Nucl. Phys. B153, 365 (1979) can be applied.
- to do expansion on $i\epsilon$ in the final results will give an analytic expression of the result.
- This way is suitable to program and we realized it in FDC package.

Summary

- New Progress, ...

Thank you!