物理事例产生器

平荣刚

中国科学院高能物理研究所
(pingrg@ihep.ac.cn)

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1. 引言

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事例产生子

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事例产生子是MC模拟的一个重要组成部分，它为探测器的事例模拟提供各条径迹的动量、顶点和粒子种类的信息

高能物理实验中为什么需要事例产生子？

- **高精度产生子模型是获得探测器效率可靠地保证**

  探测器在各个方向上的粒子探测效率不是完全相同的，探测器的空间覆盖也不是全空间的，如果事例产生器提供的粒子在空间分布和种类与真实的物理过程不一致，可能导致探测效率的偏差。

- **产生器为物理分析提供精确的截面**

  在物理分析中，需要产生子计算精确的截面。如在测量数据的积分亮度(L)实验中，对于正负电子对撞机，常常采用Babha过程($e^+e^- \to e^+e^-$)和双光子过程($e^+e^- \to \gamma\gamma$)，测量L的精度，与产生子计算的这两个过程的截面精度有关。

$$L = \frac{N^{sig}}{\sigma\ \varepsilon},$$

这里，σ 是产生子计算的包括辐射修正的截面，ε是探测器效率。

- **实验要求产生器为不稳定粒子的衰变分支比提供精确的计算**

  对粒子衰变的事例形状、带点径迹多重数、粒子产额的总数测量实验中，如果粒子的各个遍举衰变衰变分支比不能准确计算，不可能给出可靠的探测效率。对高能粒子过程，有的产生子对截面的计算可以到达NNL精度，对于部分子的强子化过程，通常采用唯象参数调节的办法，通过匹配数据的各种分布，来达到实验精度要求。

- **对于R–值测量实验和遍举过程的强子截面测量，产生子要精确地计算初态辐射因子。**

  在正负电子对撞机实验中，测量遍举强子产生的Born截面，需要产生器计算相应的初态辐射因子，才能求得Born截面。

  $$\sigma_{Born}=\frac{N^{sig}}{L\varepsilon f_{ISR}},$$ 这里，L是数据的积分亮度，

  ε是探测器效率，f_{ISR}是初态辐射修正因子。

事例产生器

事例产生子是基于Monte-Carlo方法，根据特定的概率模型，通过合理、高效的方法抽样生成物理事例软件包/库。它是探测器模拟的事例源，为探测器模拟提供各种粒子的四动量。

❖对事例产生子的性能有哪些要求？

a.高精度的理论计算模型

Beyond leading order: QED过程，ISR过程，高能QCD过程→精确的截面，参数，合理的event shape和单粒子的分布

b.模型具有很好的扩展性，参数便于优化

c.高效的事例抽样效率

一些极端的分布, 如Bhabha角分布，质量分布中的窄共振态等，合理的抽样方案可提高单个事例的CPU利用率。

d. 软件的开放性，可移植性，详细的用户手册

例： 在$J/\psi \to e^+e^-$衰变中，电子的角分布满足$1+\cos^2\theta$, θ是电子的极角。

事例产生步骤:

a. 用相空间模型(仅满足衰变初末态的能动量守恒)，抽取末态电子的四动量。

b. 用舍选抽样方法，选出末态电子角分布符合$1+\cos^2\theta$的事例。即：产生一个随机数ξ，如果满足$\xi < (1+\cos^2\theta)/2$, 接受这个事例；否则，不接受这个事例，回到a.

BESIII上的物理目标和产生子

Charm physics :

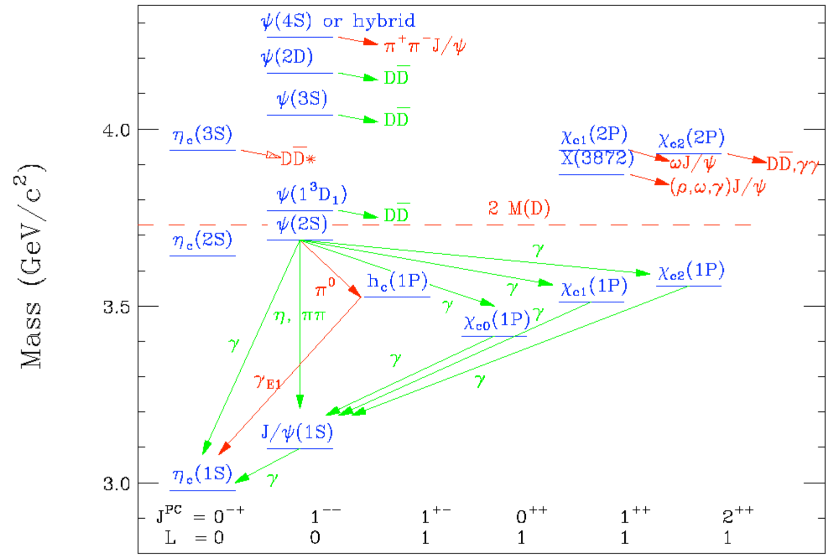
$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$

Charmonium physics and light hadron physics

$e^+e^- \rightarrow \psi(2S),\ J/\psi\ (\chi_{cJ}, \eta_c, \ldots)$

τ & QCD physics

$e^+e^- \rightarrow \tau\tau$, light hadrons



Precision : reson. Para. & Br. 1% or more

$\delta m_\tau \sim 0.09\text{MeV}$

Challenge: precision (syst. Error dominant)

High precision event generators: KKMC, EvtGen, Bhlumi, Bhwide .....

2.1 相空间的产生

考虑粒子衰变的情况：

- 两体衰变相空间：$P(M) \rightarrow p_1(m_1) + p_2(m_2)$

$$d\Phi_2 = \delta^4(P - p_1 - p_2)\frac{d^3\vec{p}_1}{(2\pi)^3 2E_1}\frac{d^3\vec{p}_2}{(2\pi)^3 2E_2}$$

$$= \frac{1}{4}\frac{1}{(2\pi)^6}\frac{|\vec{p}_1|}{M}d\phi_1 d(\cos\theta_1),$$

where

$$|\vec{p}_1| = \frac{\sqrt{[M^2 - (m_1 + m_2)^2][M^2 - (m_1 - m_2)^2]}}{2M}$$

$\phi_1, \cos\theta_1$ 可以按均匀分布抽样产生

-Weight events

-Un-weight events

多体衰变的相空间：$P(M) \to p_1(m_1) + \ldots + p_n(m_n)$

约定：省略(2π)的常数因子

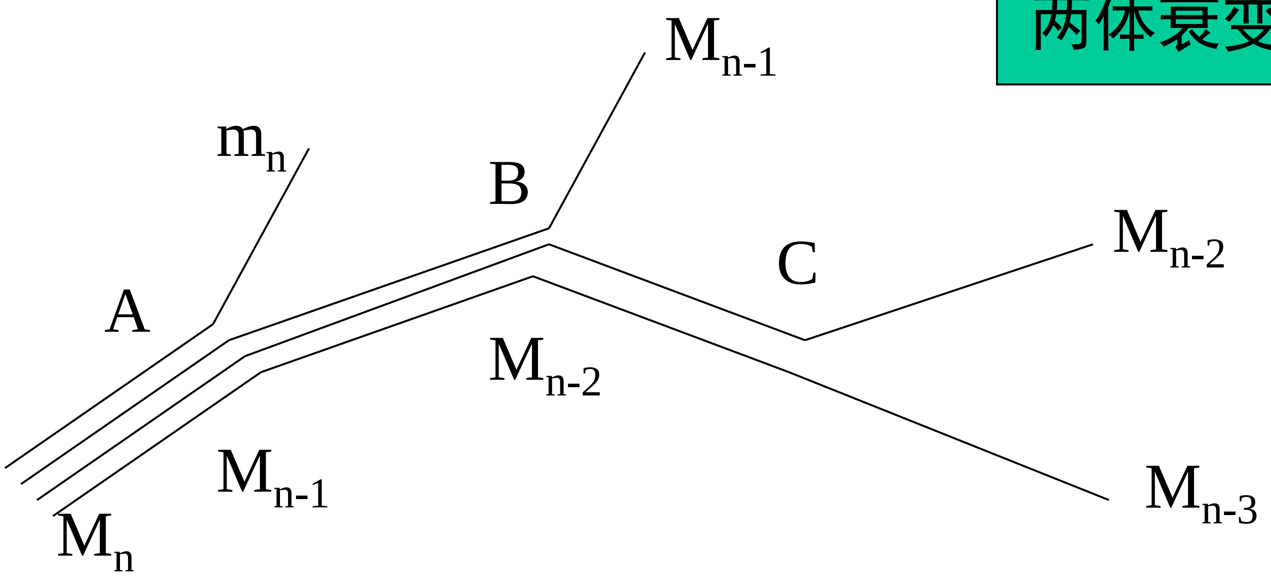
能动量守恒

在壳条件

$$R_n(P;m_1,m_2\ldots m_n) = \int \delta^4\left(\sum_{i=1}^{n} p_i - P\right)\prod_{j=1}^{n}\delta(p_j^2 - m_j^2)\,d^4p_j$$

$$R_n = \frac{1}{m_1}\iint\prod_{i=1}^{n-1}\left\{2M_i R_2(M_{i+1};M_i,m_{i+1})\right\}dM_{n-1}\ldots dM_2$$

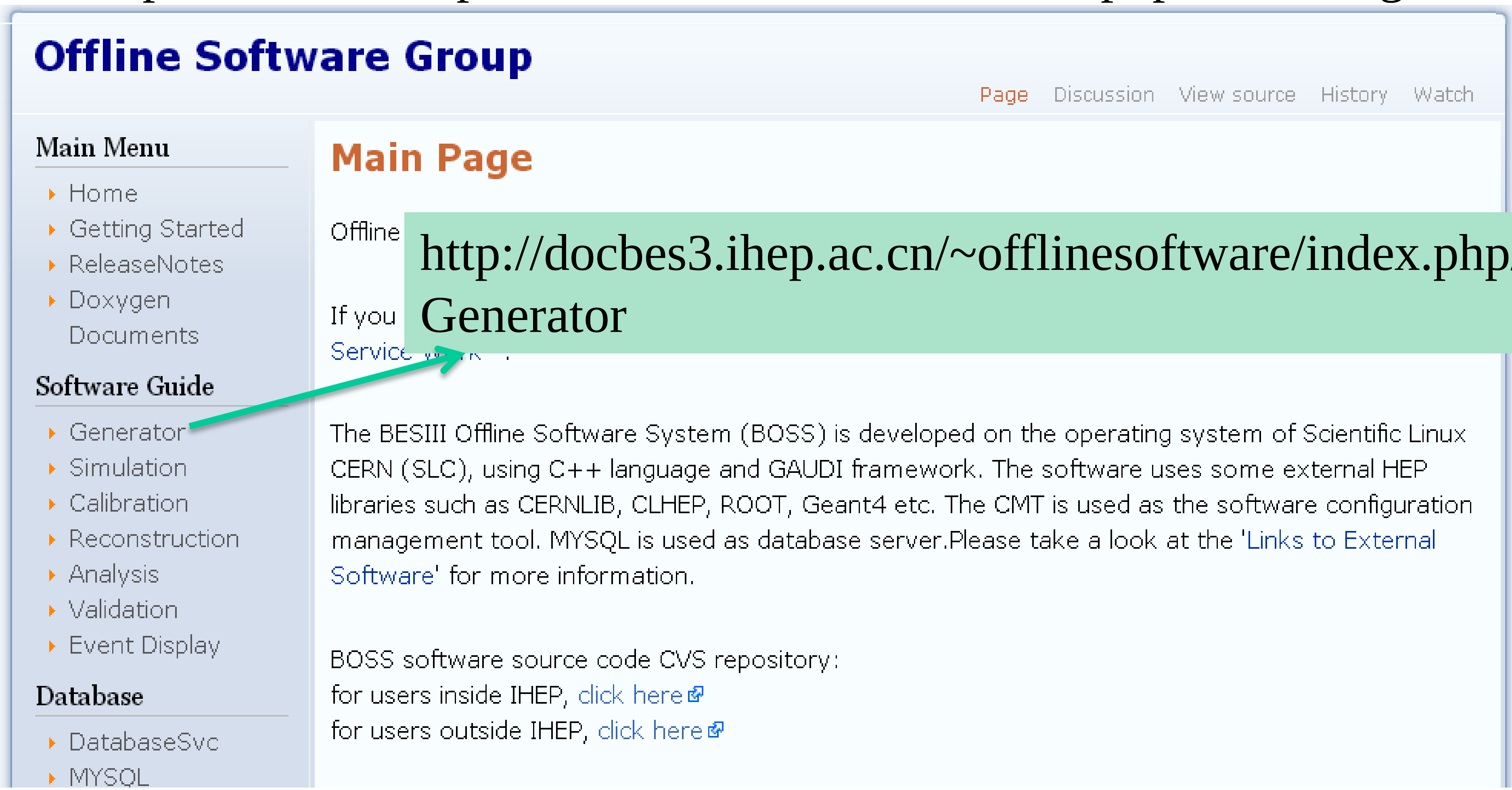
两体衰变相空间



3. BESIII产生子简介

在哪里可以获得有关BESIII产生子的信息或资料？

http://docbes3.ihep.ac.cn/~offlinesoftware/index.php/Main_Page



Offline Software Group

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Main Page

Offline

If you

Service

The BESIII Offline Software System (BOSS) is developed on the operating system of Scientific Linux CERN (SLC), using C++ language and GAUDI framework. The software uses some external HEP libraries such as CERNLIB, CLHEP, ROOT, Geant4 etc. The CMT is used as the software configuration management tool. MYSQL is used as database server.Please take a look at the 'Links to External Software' for more information.

BOSS software source code CVS repository:
for users inside IHEP, click here
for users outside IHEP, click here

http://docbes3.ihep.ac.cn/~offlinesoftware/index.php/Generator

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Generator

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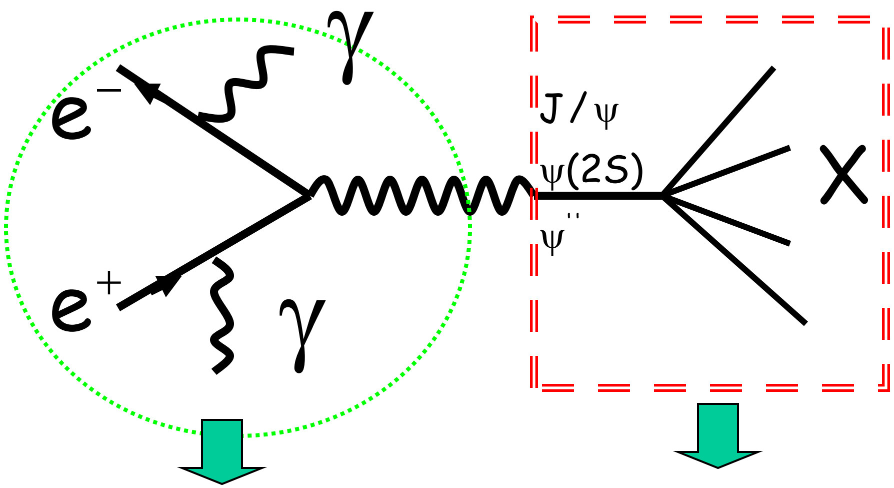
粲夸克衰变的产生子框架(official)

KKMC+BesEvtGen

KKMC(ISR) + BesEvtGen(FSR)



$e^+e^- \to (n\gamma)\gamma^*$

$(n\gamma)J/\psi$

$(n\gamma)\psi''$

$J/\psi \to X$

$\psi(2S) \to X$

$\psi'' \to X$

CMS ➔ Lab.
Syst. (Yan Ye)

G4

Both for exclusive and inclusive decays

GenBes: obsolete

Not recommend to use

下面具体介绍：

- KKMC
- BesEvtGen
- Bhlumi/Bhwide
- Babayaga
- Phokhara
- PYTHIA
- Lundcharm
- Two-gamma

参考文献：

KKMC

1.S. Jadach, B.F.L. Ward, Z. Was, Computer Physics Communications 130(2000) 260-325

2. S. Jadach, B.F.L. Ward, Z. Was, Physical Review D63 (2001) 113009

BesEvtGen:

1.David J. Lane, Nucl.Instrum.Meth.A462:152-155,2001

2.http://bes3.ihep.ac.cn/group/offline/SofPro/generator/docments/guide_EvtGen.pdf

3. Guide for BesEvtGen

Babayaga

1. G. Galossini, Nucl. Phys. B758(2006) 227-253

2. http://www.pv.infn.it/hepcomplex/babayaga.html

Phokhara:

1. http://ific.uv.es/~rodrigo/phokhara/

Cosmic Ray

1. Allkofer et al, Phys. Lett. 36B (1971), 425;

2. A.Dar, Phys. Rev. Lett. 51 (1983), 227

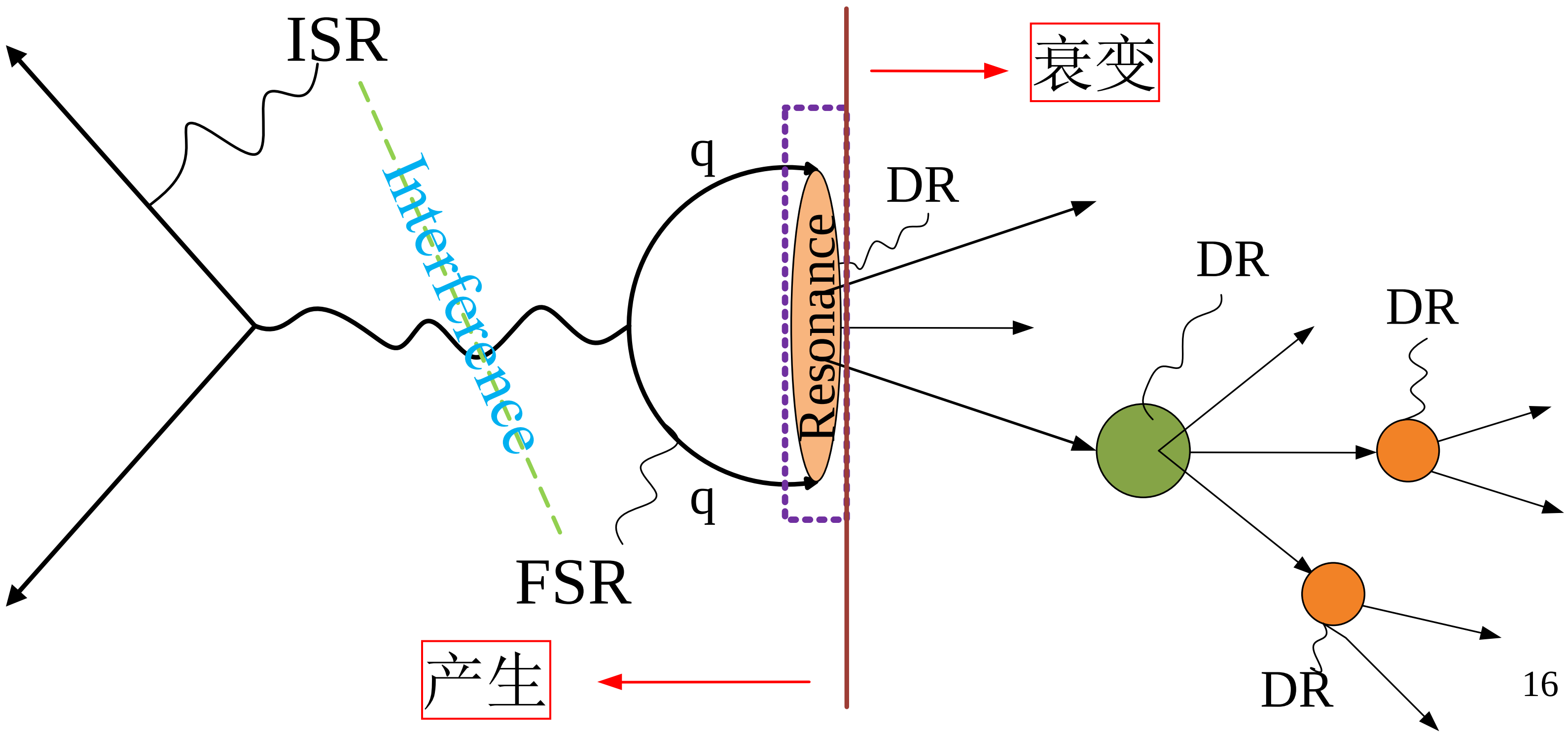
KKMC

- ✓物理过程：$e^+e^- \to f\bar{f} + n\gamma$, **f**=$\mu,\tau$,**d,u,s,c,b**. $E_{cm} \in [m_\tau, 1\text{TeV}]$ 这个产生子基于**Electroweak Standard Model** 对这个过程的精确计算结果。
- ✓早期用于：**LEP, SLC**；未来：**Linear Colliders, b, c,** t-工厂.
- ✓技术特点：
  - ✓考虑了束流的初态辐射(ISR)和出射费米子的末态辐射效应(FSR)，QED计算到达二级精度,计算采用 **Coherent Exclusive Exponentiation (CEEX)** 方案，并考虑可能的干涉效应。
  - ✓夸克的强子化采用强子簇射模型(PYTHIA)，tau-轻子的衰变调用TAUOLA库，并考虑了自旋极化效应。
  - ✓支持共振态衰变：$J/\psi, \psi(2S), \psi(3770), \psi(4030), \psi(4160), \psi(4415), \rho, \rho', \rho'', \omega, \omega', \phi, \phi'$
  - ✓末态粒子的辐射修正：PHOTOS

KKMC 的辐射修正

CEEX(Coherent Exclusive Exponentiation)

- 包含ISR和FSR效应及其干涉效应
- 末态带电粒子的辐射修正调用PHOTOS



BESIII上的KKMC支持以下事例的产生：

- $e^+e^- \to \mathrm{Resonance} + n\gamma(\mathrm{ISR/FSR})$

  $\mathrm{Resonance}: J/\psi, \psi(2S), \psi(3770), \psi(4030),$

  $\psi(4160), \psi(4415), \rho, \rho', \rho'', \omega, \omega', \phi, \phi',$ Y family

- $e^+e^- \to \mathrm{lepton\ \ pair} + n\gamma(\mathrm{ISR/FSR})$

- $e^+e^- \to q\bar{q} + n\gamma(\mathrm{ISR/FSR}),\ \ q = \mathrm{quark}$

用户选项：

束流的质心能量、束流能散、共振态名称、共振态质量、随机数种子、联结BesEvtGen的开关。

BesEvtGen

✓BesEvtGen是基于EvtGen产生子发展的tau-粲能区的产生子，在EvtGen的模型基础上，添加了更多的tau-粲物理的模型

✓EvtGen产生子是BaBar和CLEO合作组联合发展的、为研究B物理而研制的产生子

✓EvtGen平台具有强大的功能，不仅支持粲夸克偶素的遍举衰变模型，也提供了连结其它产生子的接口，如PYTHIA，PHOTOS等。

✓BesEvtGen大多属于动力学产生子，实现的算法采用基于衰变的振幅概率的舍选抽样，对于级联式衰变，EvtGen平台能够自动计算各级衰变的自旋密度矩阵，并把它们关联起来。

EvtGen的算法

- Selection Algorithm: (sequential sampling)
  Consider the example:

$$B \to D^* \quad \tau\bar{\nu}$$
$$\hookrightarrow D\pi \quad \hookrightarrow \pi\nu$$

振幅可以通过协变张量振幅或者螺旋度振幅构建

  - Generate the $B \to D^*\tau\nu$ decay:

$$P = \sum_{\lambda_{D*}\lambda_\tau} |A^{B\to D^*\tau\nu}_{\lambda_{D*}\lambda_\tau}|^2$$

  - Average over τ spin and calculate the D^* spine density matrix

$$\rho^{D^*}_{\lambda_{D*}\lambda'_{D*}} = A^{B\to D^*\tau\nu}_{\lambda_{D*}\lambda_\tau}(A^{B\to D^*\tau\nu}_{\lambda'_{D*}\lambda_\tau})^*$$

  - Generate the $D^* \to D\pi$ decay

$$P = \sum_{\lambda_{D*}\lambda'_{D*}} = \rho^{D^*}_{\lambda_{D*}\lambda'_{D*}} A^{D^*\to D\pi}_{\lambda_{D*}}(A^{D^*\to D\pi}_{\lambda'_{D*}})^*$$

- selection algorithm (cont.)
  - Calculate spin density matrix for the τ:

$$\rho^{\tau}_{\lambda_\tau \lambda'_\tau} = \sum_{\lambda_{D^*} \lambda'_{D^*}} \hat{\rho}^{D^*}_{\lambda_{D^*} \lambda'_{D^*}} A^{B \to D^* \tau \nu}_{\lambda_{D^*} \lambda'_\tau} (A^{B \to D^* \tau \nu}_{\lambda'_{D^*} \lambda'_\tau})^*$$

with

$$\hat{\rho}^{D^*}_{\lambda_{D^*} \lambda'_{D^*}} \equiv A^{D^* \to D\pi}_{\lambda_{D^*}} (A^{D^* \to D\pi}_{\lambda'_{D^*}})^*$$

  - Generate the $\tau \to \pi\nu$ decay

$$P = \sum_{\lambda_\tau \lambda'_\tau} \rho^{\tau}_{\lambda_\tau \lambda'_\tau} A^{\tau \to \pi\nu}_{\lambda_\tau} (A^{\tau \to \pi\nu}_{\lambda'_\tau})^*$$

  - These steps allow us to generate each mode the decay chain independently.
  - Generalize to arbitrarily long decay chains.
  - Calculation of probabilities and spin density matrices are done by the framework.

BesEvtGen中的衰变模型

✓在EvtGen中，每一级衰变可以用一个模型来描述，例如：

$\psi(2S) \to \pi^+\pi^- J/\psi$, **then** $J/\psi \to e^+e^-$

Model： VVPIPI VLL

✓级联式衰变，用户可以通过单级衰变模型的组装来实现.

$\psi(2S) \to \pi^+\pi^- J/\psi \to \pi^+\pi^- e^+e^-$

衰变卡片：

```
Decay psi(2S)
1.0 J/psi pi+ pi- VVPIPI;
Enddecay
Decay J/psi
1.0 e+ e- VLL;
Enddecay
End
```

✓EvtGen模型的创建：用户可以根据需求在EvtGen平台下创建自己的模型。在EvtGen中，可用于tau-粲物理的模型有20个左右，在BesEvtGen中，增添了30多个模型。关于这些模型的具体使用规则，用户需要参考EvtGen/BesEvtGen手册。

http://bes3.ihep.ac.cn/group/offline/SofPro/generator/docments/guide_EvtGen.pdf

http://bes3.ihep.ac.cn/group/offline/SofPro/generator/docments/guide_BesEvtGen.pdf

✓用户填写衰变卡片的规则

-粒子的名称必须按照pdt.table文件中的定义填写

pdt.table @BossCvs /Generator/ BesEvtGen / share

--EvtGen允许用户定义新粒子态

pdt.table

注意：用户添加的粒子，指定的ID号不允许与现有的ID号重叠！

```
*      type        name                  id  mass/GeV width/GeV max_Dm/GeV 3*charge 2*spin lifetime*c/mm Lund-KC
add  p Parton       d                     1  0.0099         0        0       -1       1       0 1
*
* Dummy particles for users to change properties & simulate new particles.
* Convention for the numbers after the "dummy": charge spin_serial
*
add  p Meson        dummy00_1                51  1            0.1       1.0    0       0       0 0


*      |           |                    |  |             |       |       |       |       | + KC=Lund internal code
*      |           |                    |  |             |       |       |       |       + T=c*lifetime (mm, alternative to W)
*      |           |                    |  |             |       |       |       + S=2*spin
*      |           |                    |  |             |       |       + Q=3*charge
*      |           |                    |  |             |       + WM=max deviation from mass
*      |           |                    |  |             + W=width in GeV
*      |           |                    |  + M=mass in GeV
*      |           |                    + ID=STDHEP-ID
*      |           + NAME=name to be used in printout or as char string to identify particle
*      + TYPE
```

--模型的书写规则必需按照参考手册的要求填写

4.17 JPE

Author: Rong-Gang Ping

Usage:
BrFr gamma pseudoscalar JPE;

BesEvtGen guide

Explanation:

This model is constructed for a vector decays into a photon plus a pseudoscalar, e.g. $J/\psi \to \gamma\eta_c$

Example:

Decay J/psi
1.000 gamma eta_c JPE;
Enddecay

注意： gamma eta_c的顺序不能改变，模型后面的分号不能缺少！

Notes:

Helicity amplitude used.

-- Decay 卡的结构

对应于一级衰变

下一级衰变

Decay 母粒子的名称

Br x_1 x_2 . . x_n 衰变模型（参数）;

Enddecay

……

End

--几点说明

1. 如果衰变链中某一级的衰变没有指定分支比和模型，EvtGen将会按照一个内置的衰变卡进行衰变，衰变模式是按照粒子表中现有的衰变道抽样。

2. 如果某个母粒子的衰变道分支比之和大于或者小于1，EvtGen平台将会对这些道的分支比重新归一。

3. 对于$\psi(3770) \rightarrow D\bar{D}$ ，$D\bar{D}$ 阈值需要再KKMC中设置：

KKMC. ThresholdCut=3.7;

4. EvtGen平台能够自动过滤掉遍举衰变模型(如：Lundcharm) 产生的、与Decay卡中单举衰变道重叠的道。

Bhlumi/Bhwide

✓适用于Bhabha过程：$e^+e^- \rightarrow e^+e^- + n\gamma(ISR/FSR)$

Bhlumi适用于小角Bhabha（ $\theta < 6^o$ ）

Bhwide适用于大角Bhabha（ $\theta > 6^o$ ）

✓早期用于LEP1/SLC实验，以及后来的LEP2实验。

✓精度：Bhlumi，0.11%(@LEP1能区)，0.25%(@LEP2能区)

Bhwide,0.3%(@Z-boson peak), 1.5%(@ LEP2能区)

➢ Babayaga

– 在e^+e^-对撞机上测量R值

$$R = \frac{\sigma(e^+e^- \to 强子)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

– 量度测量：

需要高精度的产生子：$e^+e^- \to e^+e^-, \mu^+\mu^-, \gamma\gamma$

– $BESII: e^+e^- \to (\gamma)e^+e^-(RADEE), (\gamma)\mu^+\mu^-(MUGEN)(\sim \alpha^3)$

– **Babayaga :**

利用强子簇射算法求解Lipatov – Altarelli – Parisi 方程

(Ref: G.Galossini, Nucl. Phys. B758(2006) 227-253)

Babayaga 3.5:

http://www.pv.infn.it/hepcomplex/babayaga.html

-- BESIII发布版本：

产生子名称：Babayaga

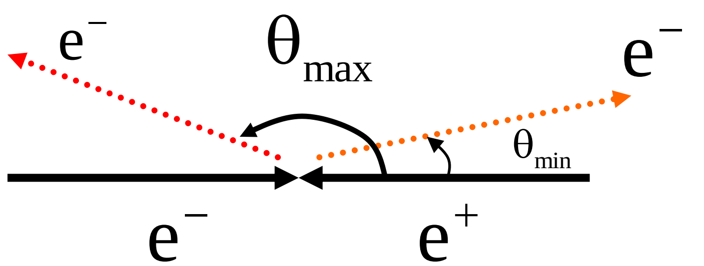
--用户选项:

过程： 1:$e^+e^- \to (n\gamma)e^+e^-$

2:$e^+e^- \to (n\gamma)\mu^+\mu^-$

3:$e^+e^- \to (n\gamma)\gamma\gamma$

4:$e^+e^- \to (n\gamma)\pi^+\pi^-$



质心能量= 2* E_{beam}

Running α ： 0=off, 1=on

FSR switch (for ICH=2): 0=off,1=on

---cuts:

charged particles: E_{min}(MinimumEnergy),

θ_{min}(MinThetaAngle),

θ_{max}(MaxThetaAngle)

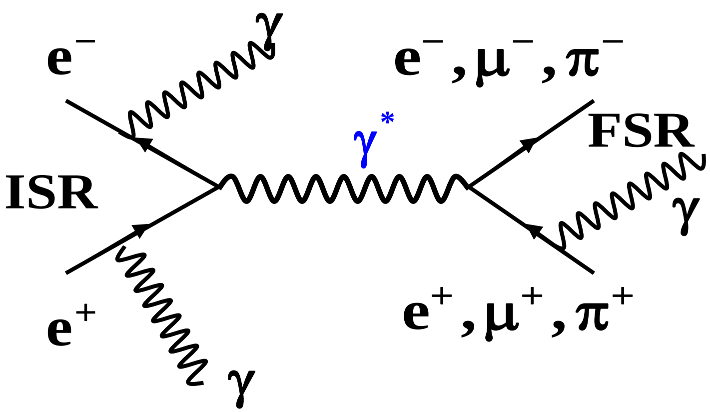
MaximumAcollinearity

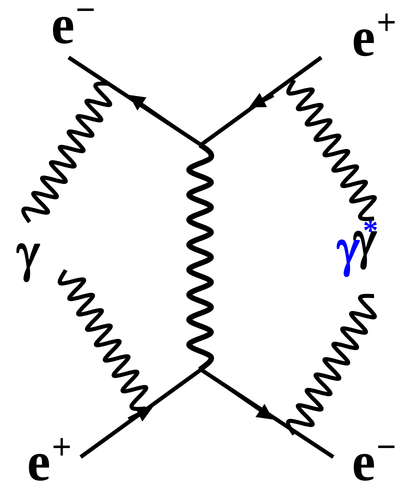
photons : MinEnergyCutG

MinAngCutG

MaxAngCutG

-技术细节：





采用结构函数方法计算截面：

$$\sigma(s) = \int dx_1 dx_2 dy_1 dy_2 \int d\Omega D(x_1, Q^2) D(x_2, Q^2) \times D(y_1, Q^2) D(y_2, Q^2) \frac{d\sigma_0(x_1 x_2 s)}{d\Omega} \Theta(cuts)$$

结构函数

Born-like XS

1。原则上，ISR和FSR可以考虑到任意阶，并考虑了它们的干涉效应。

2. Babaaya采用强子簇射算法，光子可以具有横动量

3. 初、末态粒子的辐射光子考虑到10个，一共40个，但最多只输出两个硬光子

4. 强子道没有FSR，理论误差为0.5%

Phokhara

Phokhara 6.0 (realsed at Dec. 2006)

Source: http://ific.uv.es/~rodrigo/phokhara/

Fixed order radiative corrections: NLO accuracy

Leptonic channel: $\mu^+\mu^-$

Hadronic channels:

$\pi^+\pi^-$

$2\pi^0\pi^+\pi^-, 2\pi^+2\pi^-$

$p\bar{p}, n\bar{n}, \Lambda\bar{\Lambda}$

$\pi^0\pi^+\pi^-$, K^+K^-, $K^0\bar{K}^0$

Tagged or untagged photons

Modular structure: easy replacement of hadronic form factor

Physics and techniques

□ radiative return method:

$$e^+ + e^- \rightarrow \gamma + \gamma^*, \gamma^* \rightarrow \text{hadrons}$$

To measure σ_{had} over a wide range of energies

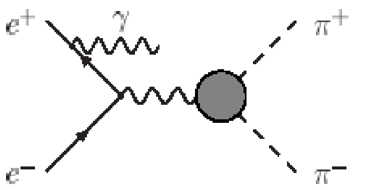
□ Initial state radiation (ISR) to NLO

$$e^+(p_1) + e^-(p_2) \rightarrow \gamma^*(Q) + \gamma(k_1)$$

$$d\sigma = \frac{1}{2s} L_{\mu\nu} H^{\mu\nu} d\Phi_2(p_1, p_2; Q, k) d\Phi_n(Q, q_1 \ldots q_n) \frac{dQ_2}{2\pi}$$

$L_{\mu\nu}$: leptonic tensor to NLO

$H^{\mu\nu}$: hadronic tensor, model dependent



FSI for

$e^+e^- \rightarrow \gamma\pi^+\pi^-$

EPJC24,71

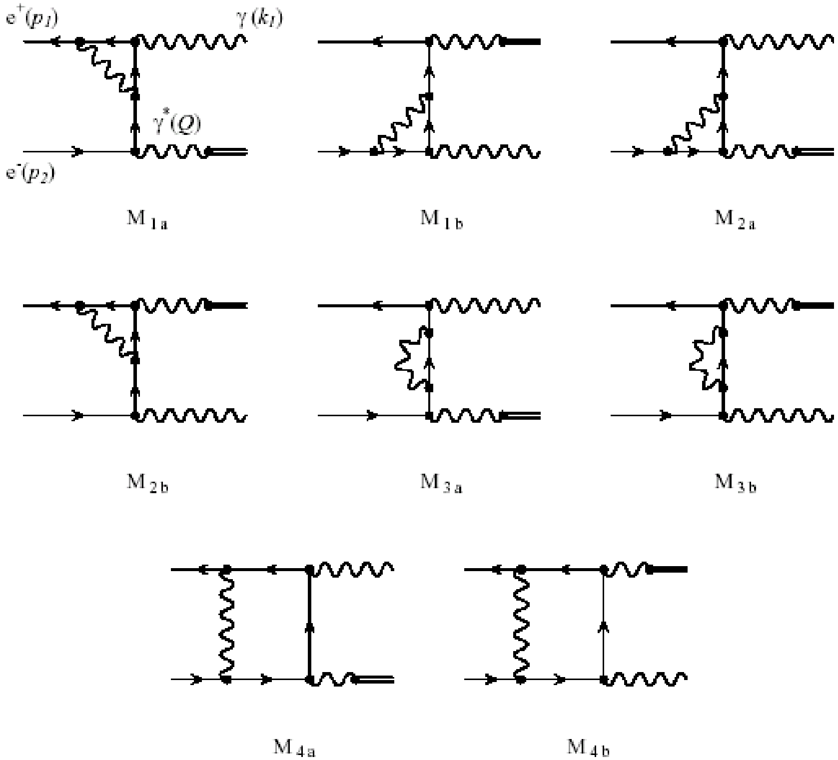


Fig. 1. One-loop corrections to initial state radiation in $e^+e^- \to \gamma + \text{hadrons}$

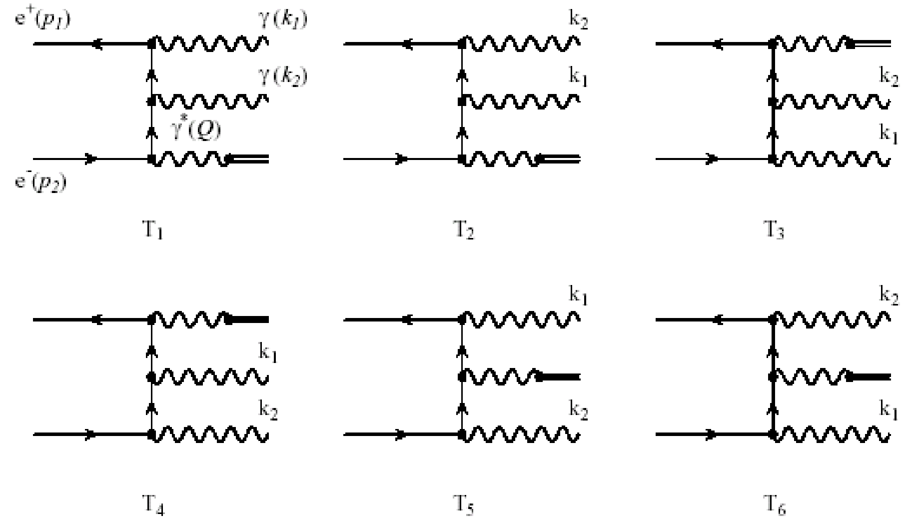


Fig. 2. Emission of two real photons from the initial state in e^+e^- annihilation into hadrons

The one-loop matrix elements contain infrared divergences.

These are canceled by adding the diagram with the two photons.

☐ Final state radiation (FSI) to NLO

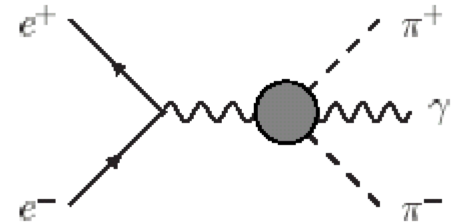
$d\sigma = d\sigma_{ISR} + d\sigma_{FSR} + d\sigma_{INT}$

ISR : dominated by photons collinear to beams

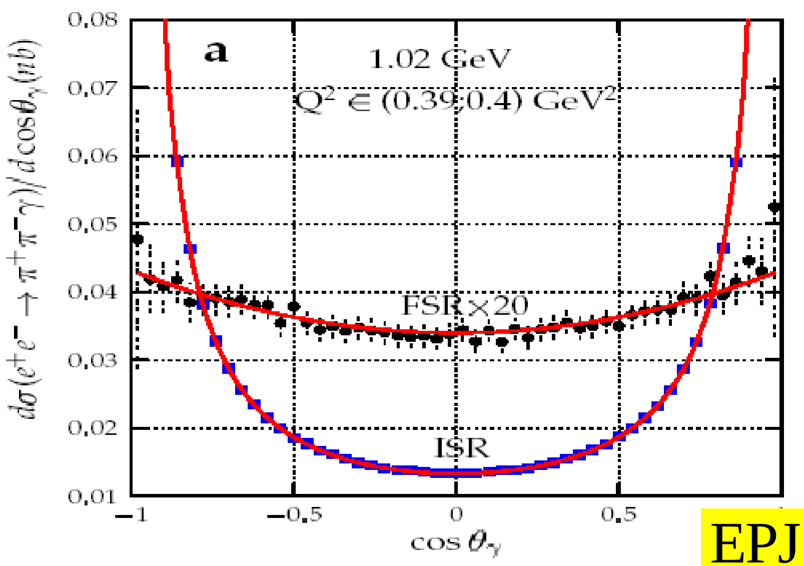
FSR : dominated by photons collinear to hadrons

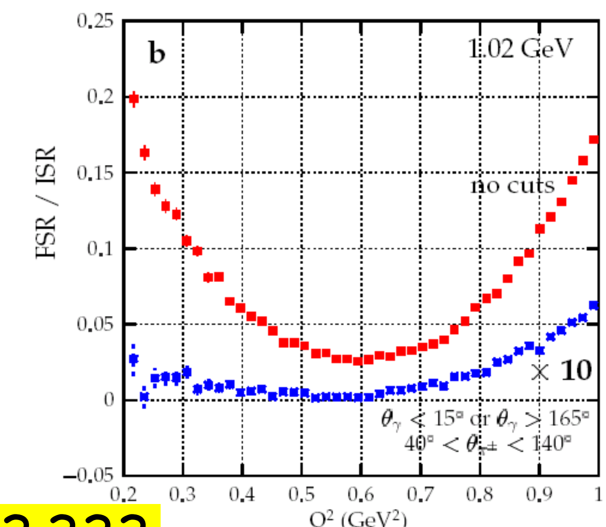
INT : asymmetry, used to test the FSR model

recipe: ISR and FSR can be distangled by properly setting angular cuts



FSR for $e^+e^- \to \gamma\pi^+\pi^-$

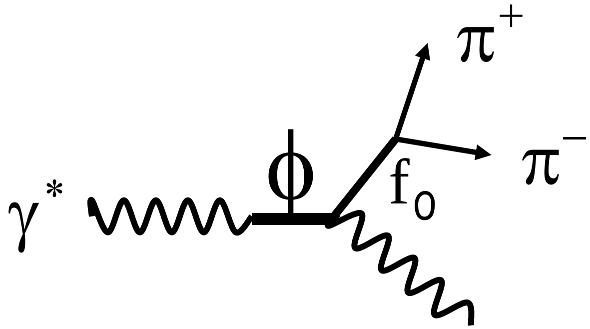


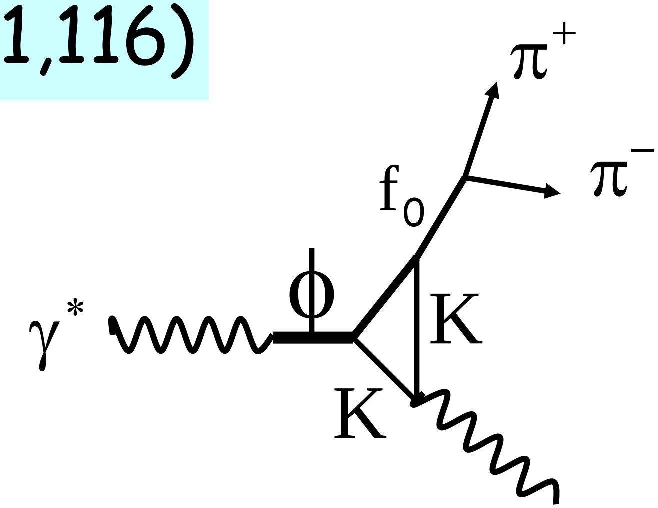


EPJC33,333

□ Hadronic tensors :

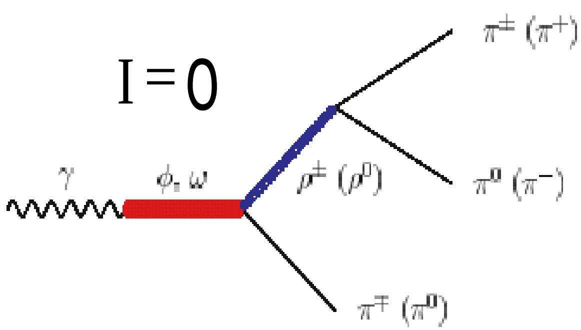
$\gamma^* \to \pi^+\pi^-$ (Phys. Lett. B611,116)

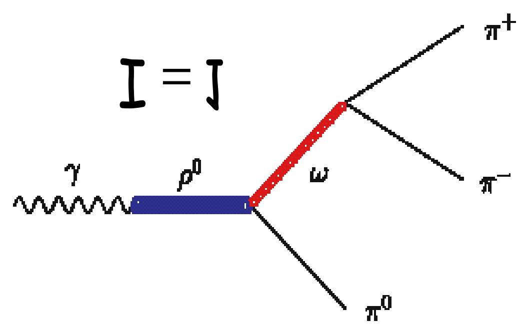




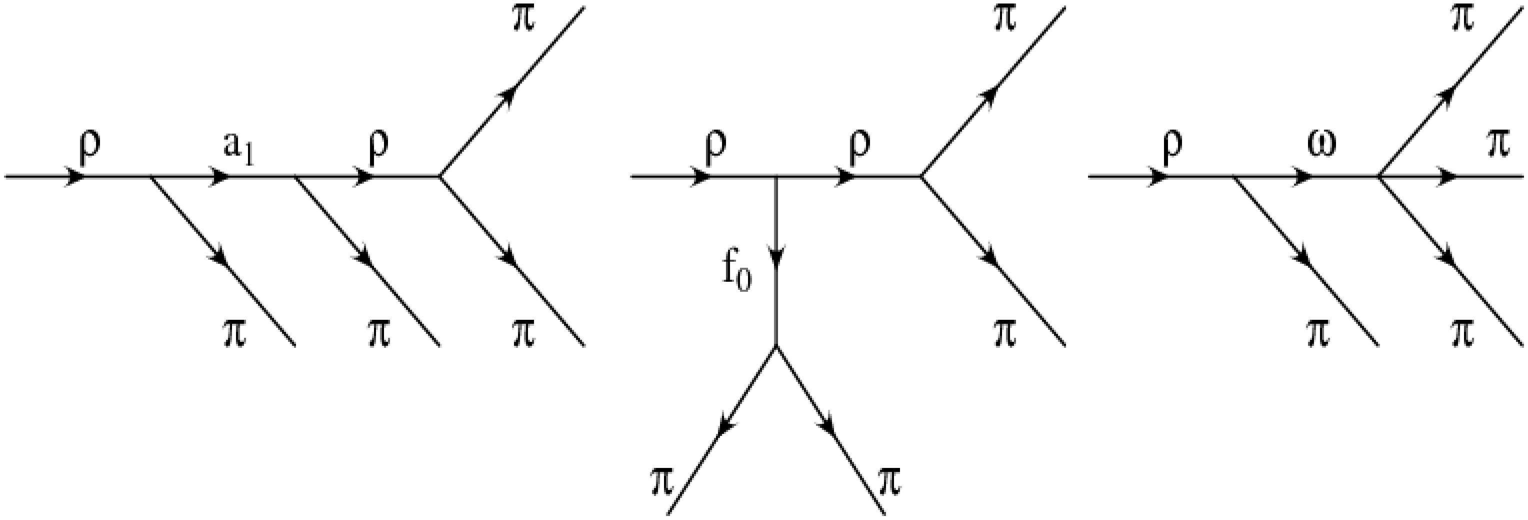
Switches in program: f0_model

$\gamma^* \to \pi^0\pi^+\pi^-$ (EPJC47,617)





$\gamma^* \rightarrow 4\pi$



Eur.Phys.J .C18 : 497(hep - ph/0008262)

Nucl. Phys. B (proc. Suppl.)98,289

$$\gamma^* \to p\bar{p},\ n\bar{n},\ \Lambda\bar{\Lambda}$$

EPJC35,527

PRD75,074026

Pauli and Dirac form factor :

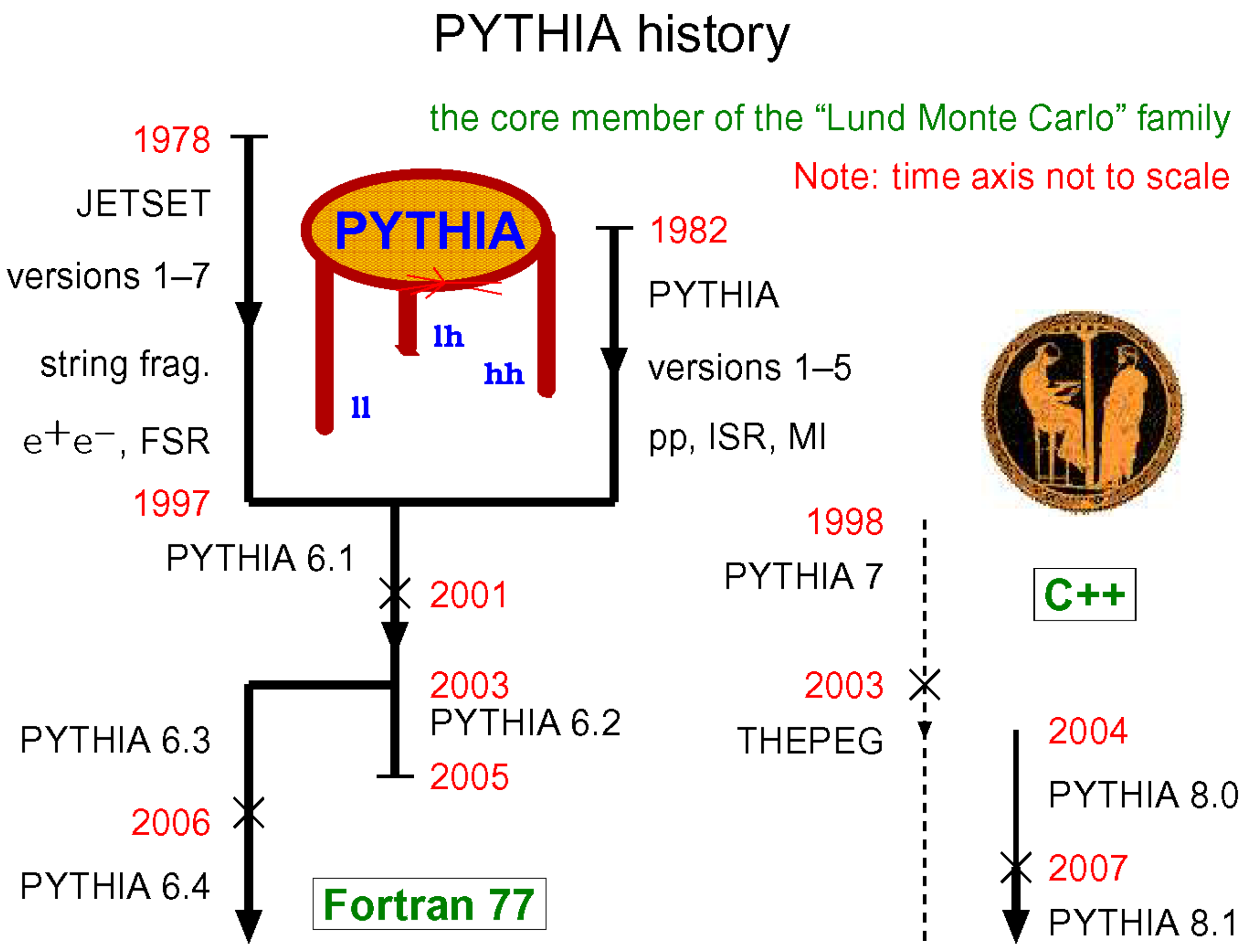
$$J_\mu = -ie\bar{u}(q_2)\left(F_1^N(Q^2)\gamma_\mu - \frac{F_2^N(Q^2)}{4m_N}[\gamma_\mu, \not{Q}]\right)v(q_1)$$

$$H_{\mu\nu} = J_\mu J_\nu^+$$

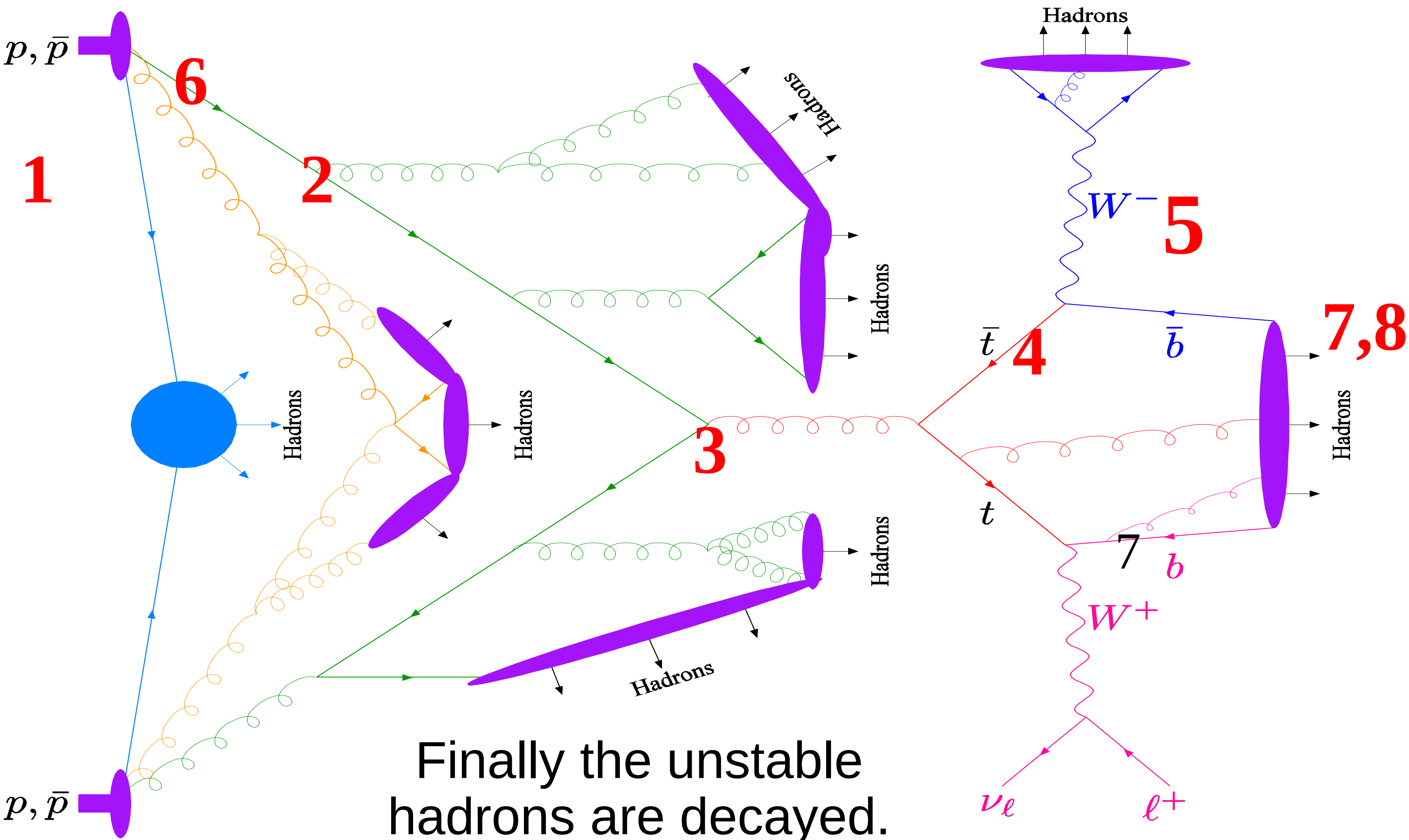
Nucleon form factors are determined by fitting exp. data

PYTHIA

高能对撞机上非常流行的事例产生子



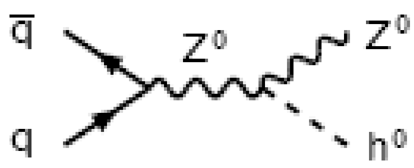
例:核子对撞的事例产生及演化



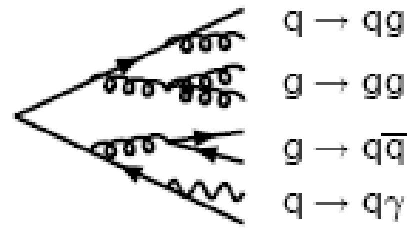
Finally the unstable hadrons are decayed.

PYTHIA 中的物理过程（Lund模型）

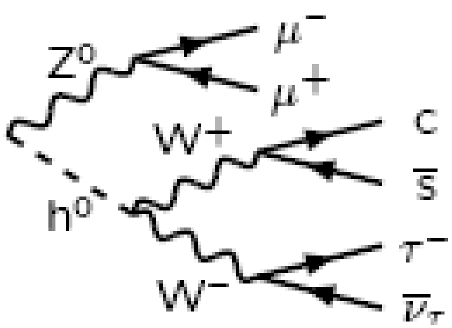
1. 硬过程：|M|², Breit-Wigner



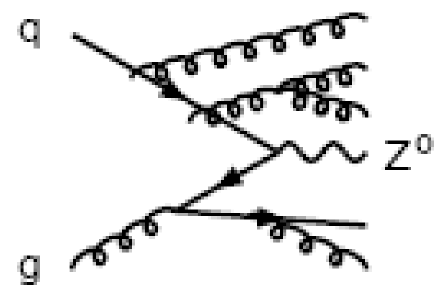
3. 末态部分子簇射



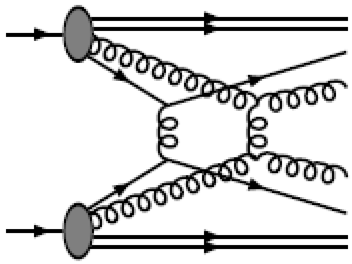
2. 共振态衰变



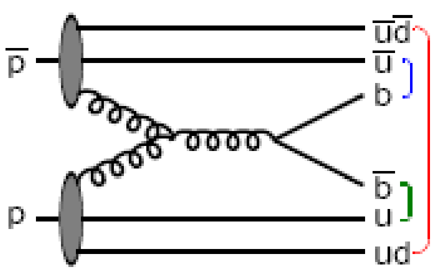
4. 初态部分子簇射



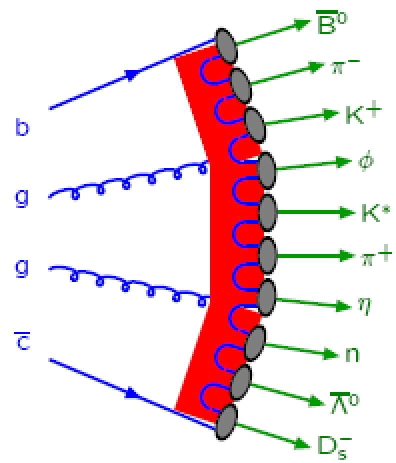
5. 部分子—部分子的多体相互作用



6. 束流残余



7. 强子化过程



8. 常规衰变

等等…

BESII: J/ψ, ψ(2S), ψ(3770)

⇒ **Lundcharm model**

PYTHIA Process Library

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g \gamma^*_T \to f_i \bar{f}_i$
136	$g \gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

No.	Subprocess
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to g G^*$
394	$qg \to q G^*$
395	$gg \to g G^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}^*_\ell$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$b q_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$b q_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$b q_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b \bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b \bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b \bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

PYTHIA 在EvtGen中的调用

Decay Parent_particle_name
Br. X_1 x_2… PYTHIA mode;
Enddecay

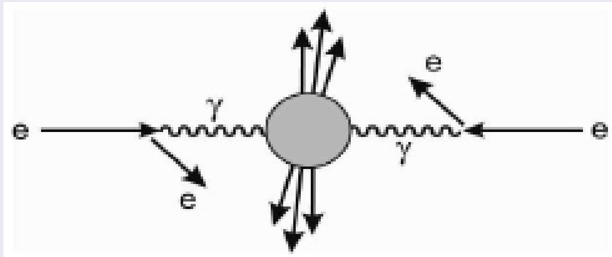
QED的强子过程： $e^+e^- \to \gamma^* / Z \to \text{light hadrons}$

Decay vpho
1.000 PYCONT;
Enddecay

TWO GAMMA

✓过程：$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-X(\pi\pi, KK, p\bar{p}, \eta, \eta' \ldots)$

✓用于研究两光子物理或其它过程的本底



✓说明：截面计算由两部分构成：

两光子的量度函数和$\gamma^*\gamma^* \to$ hadrons

过程的截面。

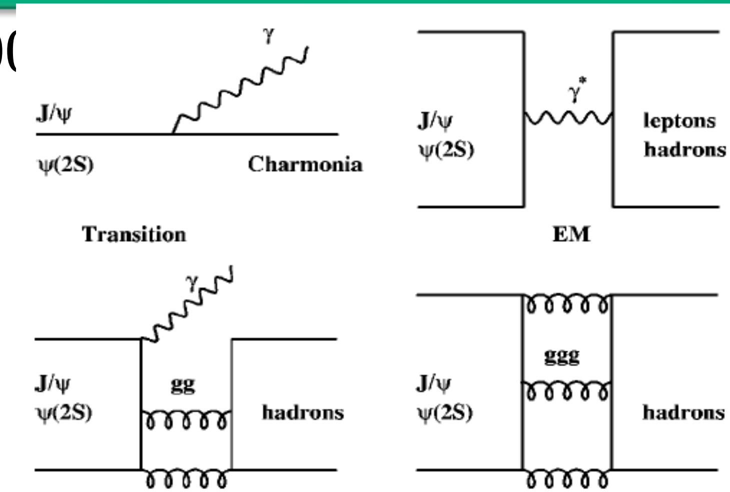
✓强子化过程采用Lund模型，共振态采用相对论形式，

PQCD:采用手征微扰方案(ChPT).

在tau—粲能区的精度为10%左右

4. Lundcharm

Phys. Rev.D, 62, 034003(200(



- 粲夸克偶素的单举衰变产生子 **(BESII)**

- **基于JETSET7.4的参数表**

TABLE I. Parameters of JETSET7.4 tuned in the charmonium generator.

Dynamic parameter				Particle ratio			
Parameter	Def	Tuned	Description	Parameter	Def	Tuned	Description
$PARJ(21)$	0.36	0.5	σ, width of Gaussian	$parj(11)$	0.5	0.60	V/P ratio of $u\&d$
$PARJ(33)$	0.8	0.6	diquark minium mass	$parj(12)$	0.6	0.66	V/P ratio of s
$parj(126)$	2 GeV	1 GeV	gg minimum mass	$parj(14)$	0	0.62	axial Vector ratio
$parj(25)$	1.0	0.5	η extra suppression	$parj(15)$	0	0.12	scalar meson ratio
				$parj(16)$	0	0.12	another axial Vector
				$parj(17)$	0	0.10	tensor meson
				$parj(1)$	0.1	0.09	$p(qq)/p(q)$
				$parj(2)$	0.3	0.4	$p(ss)/p(uu)$

Lundcharm 模型的参数优化

- **参数响应函数方法**

CHIN. PHYS. LETT. 31, 061301 (2014)

产生子参数调节软件：Professon, Rivet,

Exp. : TASSO, ALEPH, DELPHI, LHC

$$f(\boldsymbol{p}_0 + \delta\boldsymbol{p}, x) = a_0^{(0)}(x) + \sum_{i=1}^{n} a_i^{(1)}(x)\delta p_i + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}^{(2)}(x)\delta p_i \delta p_j \approx MC(\boldsymbol{p}_0 + \delta\boldsymbol{p}, x),$$

参数　　观测量

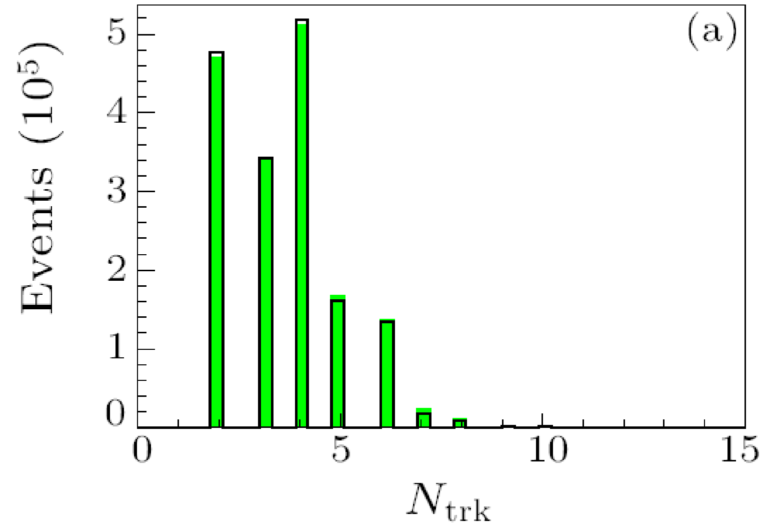
参数对观测量分布的敏感度检验

$$S_i(x) = \frac{\delta MC(x)}{MC(x)} \Big/ \frac{\delta p_i}{p_i} \approx \frac{\partial \ln MC(x)}{\partial \ln |p_i|}\Big|_{p_i},$$

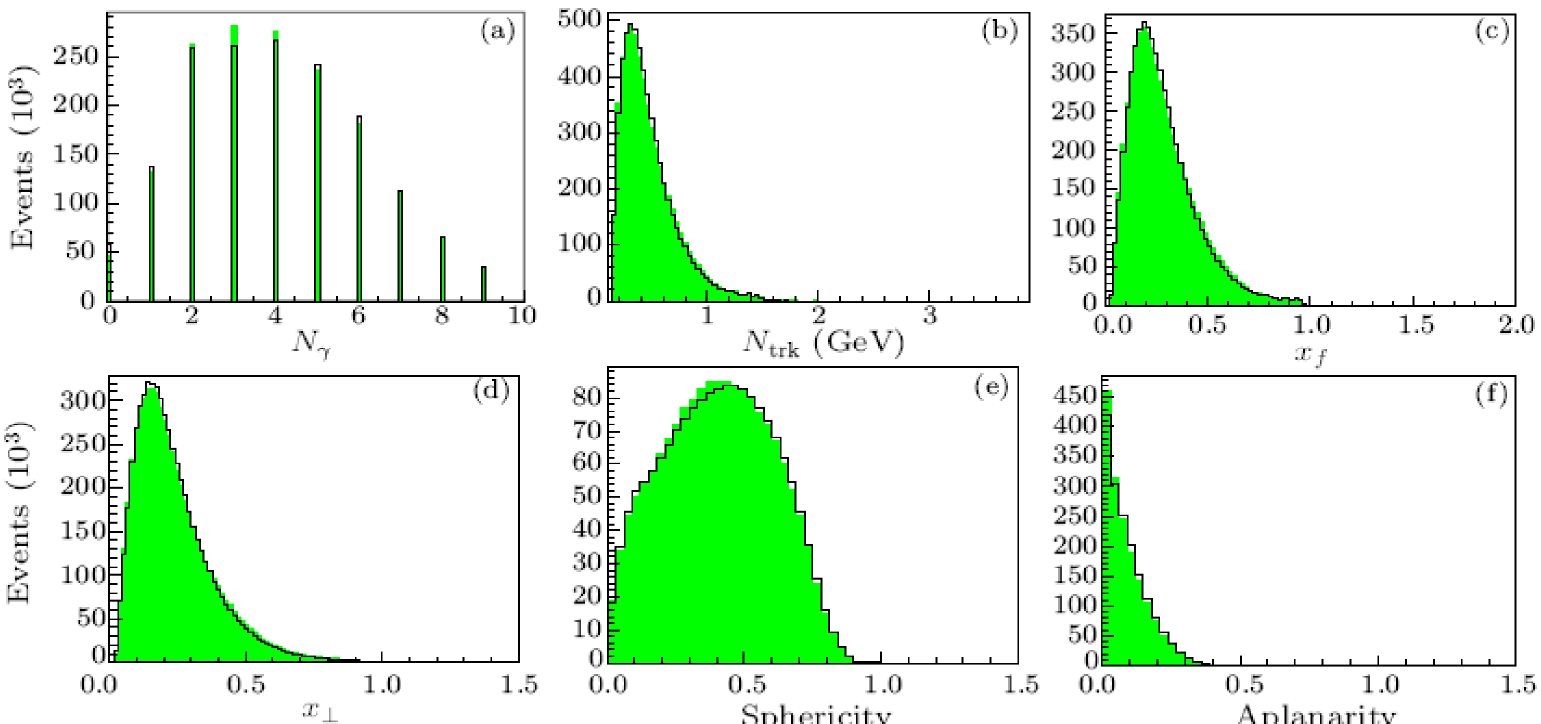
$J/\psi \rightarrow$ light hadrons

Table 1. List of tuned parameters and their definitions. The default values are taken from JETSET.[4]

Parameters	Default	Tuned	Description
PARJ(1)	0.1	0.071 ± 0.000	$P(qq)/P(q)$
PARJ(2)	0.3	0.490 ± 0.002	$P(ss)/P(uu)$
PARJ(11)	0.5	0.100 ± 0.001	V/P ratio of u- and d-quarks
PARJ(12)	0.6	0.928 ± 0.003	V/P ratio of s-quark
PARJ(14)	0.0	0.645 ± 0.001	axial vector meson ratio
PARJ(15)	0.0	0.016 ± 0.000	scalar meson ratio
PARJ(16)	0.0	0.026 ± 0.001	another axial vector meson
PARJ(17)	0.0	0.156 ± 0.001	tensor meson
PARJ(21)	0.36	0.427 ± 0.001	σ, width of Gaussian
PARJ(25)	1.0	0.366 ± 0.001	η extra suppression
PARJ(33)	0.8	0.338 ± 0.002	diquark minimum mass
PARJ(126)	2	0.813 ± 0.001	gg minimum mass



CHIN. PHYS. LETT. 31, 061301 (2014)



习题一：取A=137,C=187,M=256和$X0$=1,用线性同余法产生3维随机数和2维随机数，然后分别绘出其3维和2维分布图。

习题二：证明Breit-Wigner分布 $f(x) = \frac{\Gamma}{\pi}\frac{1}{(x-x_0)^2+\Gamma^2}$ **可以通过抽样)抽样** $x_i = x_0 + \Gamma\cot(\pi\xi_i)$**得到，其中，**$\xi_i$ **是在(0,1)区间的均匀分布随机数。**

习题三：如果ξ_1, ξ_2 **是(0,1)之间均匀分布的随机数子样，试推导出以下随机变量的密度分布函数：**

$1.\ X_1 = \xi_1^2$，　$2.\ X_2 = \xi_1 * \xi_2$，　$3.\ X_3 = \xi_1/\xi_2$，

并用蒙特卡罗方法检验你的密度分布函数的正确性。

习题四：在$J/\psi \to e^+e^-$**衰变中，电子的极角余弦**$x = cos\,\theta$**的分布密度函数为**$f(x) = \frac{3}{8}(1 + x^2)$**，给出三种随机变量**$x$**的不同蒙特卡洛抽样算法。**

5. 总 结

- 事例产生器是物理分析当中不可或缺的工具
  - ➢ 它在物理分析
  - ➢ 探测器效率的确定
  - ➢ 亮度测量
  - ➢ 初态辐射修正因子计算方面发挥着不可替代的作用
- 也是物理分析当中一个重要的组成部分。