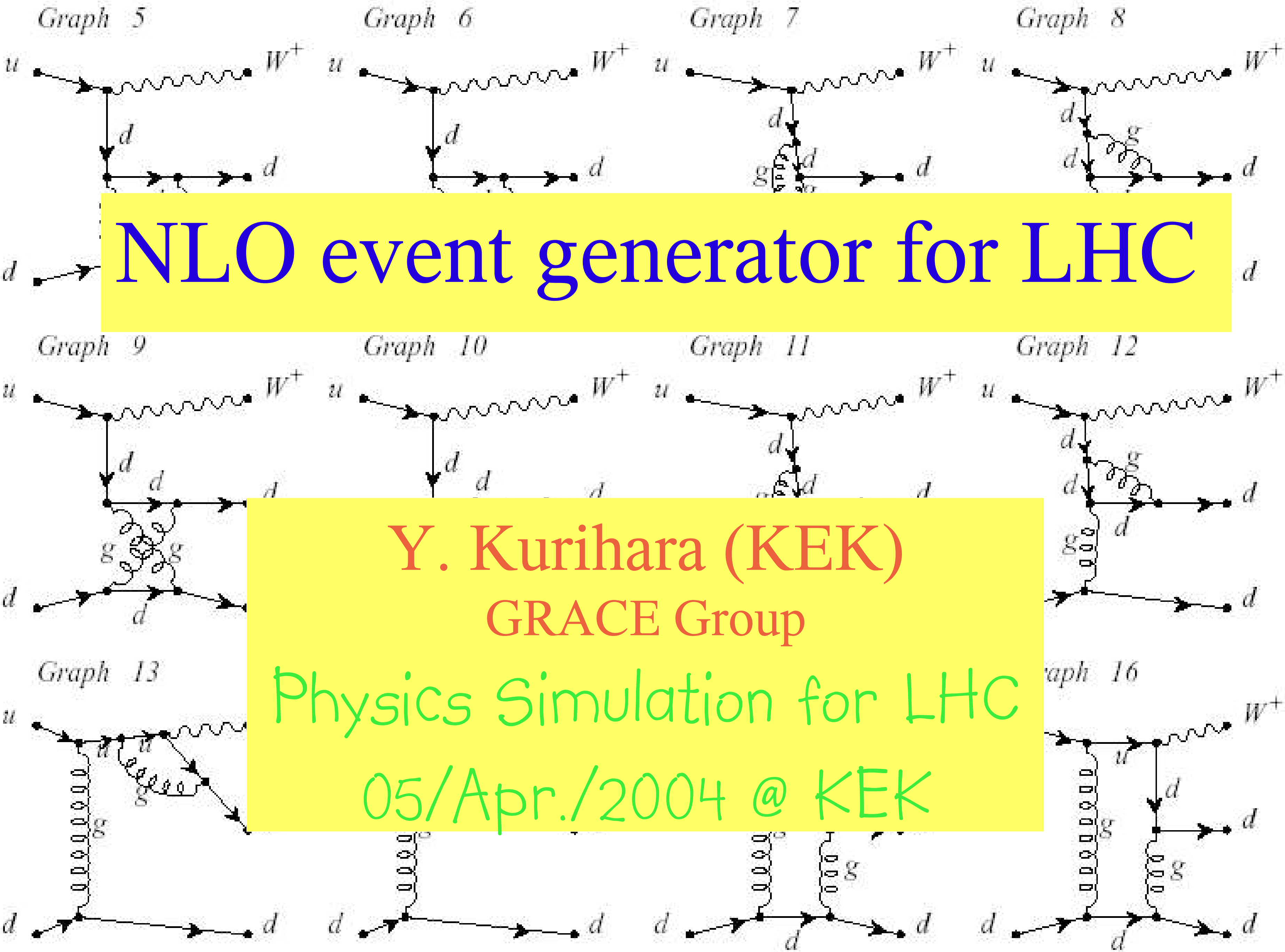


NLO event generator for LHC

Y. Kurihara (KEK)
GRACE Group

Physics Simulation for LHC

05/Apr./2004 @ KEK

Motivation

- LHC Experimental requirement

New Particle Search/Precision Measurement

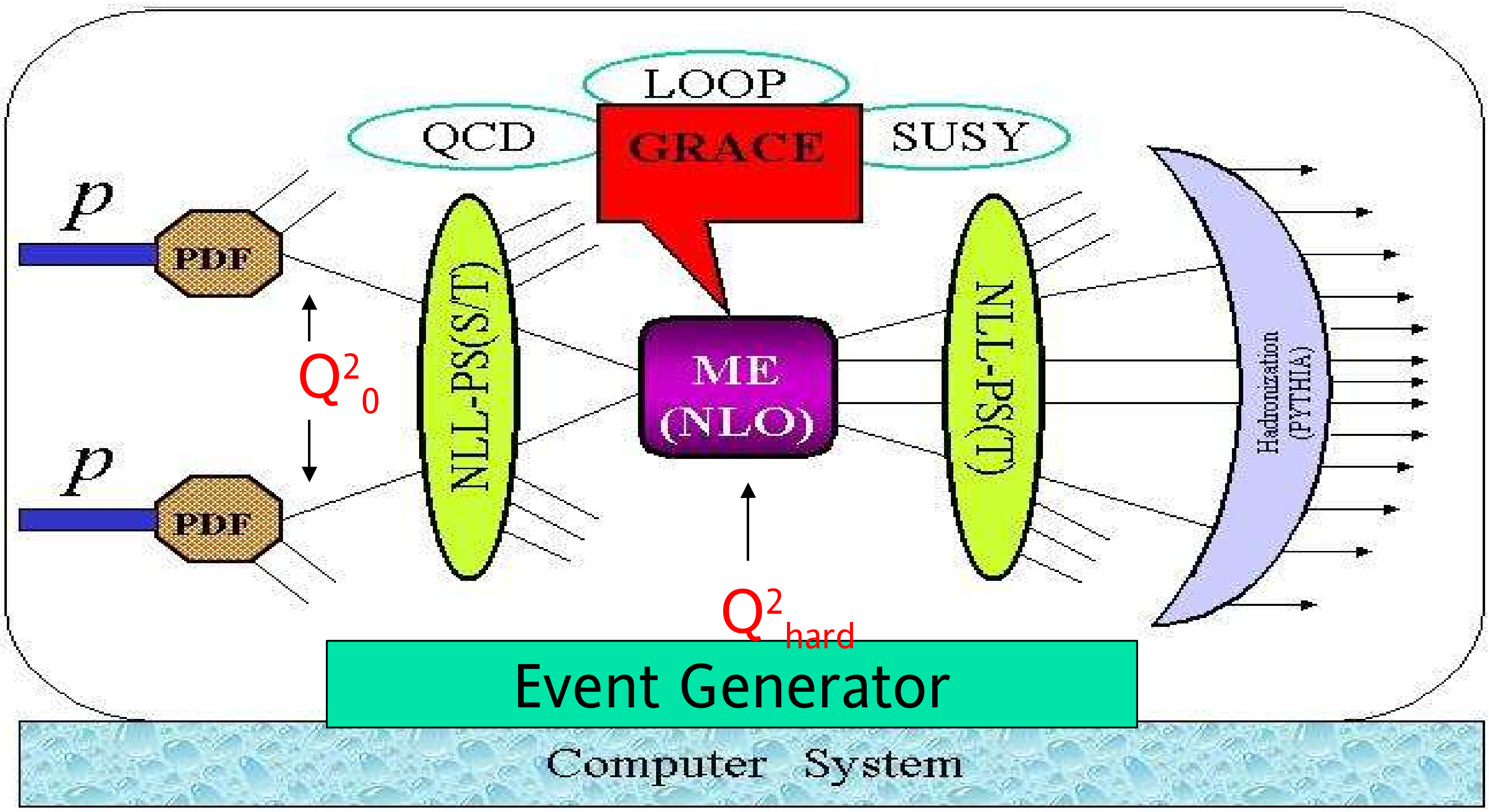
LO-QCD Event generator+K-factor

↓

Obviously not enough!

We need
NLO Event generator!

Grand Design



Difficulties → Solutions

- Large number of diagrams → **GRACE**
- Numerical instability due to a collinear singularity
- Double counting between ME and PDF/PS

→ **LL-subtraction + Parton Shower**

- Negative weight → **Improved SPRING**

NLO matrix elements

- 2→2 processes
  - Drell-Yan process — G. Altalelli et al. (1979)
  - Two-jet production — (1986~1992)
  - Prompt photon production — P. Aurenche et al. (1988)
  - Z-pair procudtion — B. Mele et al. (1991)
  - Heavy quark production — M.L. Mangano et al. (1992)
  - W-pair production — S. Frixione et al. (1993)
  - V + jet — W.T. Giele et al. (1993)
- 2→3 processes
  - Three jets — Z. Bern et al. (1993)
  - V+two-jet — J. Campbell et al. (2003)

$$pp \to W + 3\text{jets}$$

31 processes (initial 1 generation, final 2 generations)

Tree 730 Feynman Graphs

1 loop 20915 Feynman Graphs

$$pp \to W + 4\text{jets}$$

96 processes (initial 1 generation, final 2 generations)

Tree 9716 Feynman Graphs

1 loop 414906 Feynman Graphs

Automatic calculation by GRACE

GRACE author list

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d)Kogakuin University, Nishi-Shinjuku 1-24, Shinjuku, Tokyo 163-8677, Japan

e)Seikei University, Musashino, Tokyo 180-8633, Japan

f)Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan

GRACE Family

- GRACE/SM

  Tree diagrams/Standard Model

  T. Ishikawa, et al., **GRACE manual (v1.0)**, KEK Report 92-19

  F. Yuasa, et al., Prog. Theor. Phys. (Suppl.) **138** (2000) 18

- GRACE/SUSY (v2.2.0)

  Tree diagrams/MSSM

  M. Kuroda, hep-ph/9902349

  J. Fujimoto, et al., Compt. Phys. Commun. **153** (2003) 106

Programs are avairable from
http://minami-home.kek.jp

- GRACE-loop

  1-loop diagrams/Standard Model (w/ NLG)

  $e^+e^- \to \nu\nu h$: G. Belanger, et al., Phys. Lett. B **559** (2003) 252

  NLG : G. Belanger, et al., hep-ph/9907406

  $e^+e^- \to tth$, Zhh (G. Belanger's talk)

- GRACE/SUSY-loop

  1-loop diagrams/MSSM(w/ NLG)

  Under development

  $e^+e^- \to \chi_1^+\chi_1^-$: T. Kon, et al., LoopFest II, 15/May/2003 @ BNL

- GRACE/NLO-QCD

  1-loop diagrams/QCD

  Under development

  Y. Kurihara, et al., Nucl. Phys. B **654** (2003) 301

Parton Shower

➢PYTHIA/HERWIG

Q2 evolution/x-distribution → PDF(Parton distribution function)

Soft-Collinear jets → (backward) Parton Shower

PS is used as a model to geneate jets

➢ Our strategy

Q^2 evolution/x-distribution/Soft-Collinear jets

→ LL/NLL Parton Shower (forward)

PS is legitimate child of pQCD
(no tunable parameters)

Parton Shower

DGLAP Equation

Splitting function ← pQCD

$$\frac{dD(x,Q^2)}{d\ln Q^2}=\frac{\alpha}{2\pi}\int_x^1\frac{dy}{y}P_+(x/y)D(y,Q^2)$$

↓

$$D(x,Q^2)=\Pi(Q^2,Q_s{}^2)D(x,Q_s{}^2)+\frac{\alpha}{2\pi}\int_{Q_s{}^2}^{Q^2}\frac{dK^2}{K^2}\Pi(Q^2,K^2)\int_x^{1-\epsilon}\frac{dy}{y}P(y)D(x/y,K^2)$$

$$\Pi(Q^2,Q'^2)=\exp\left(-\frac{\alpha}{2\pi}\int_{Q'^2}^{Q^2}\frac{dK^2}{K^2}\int_0^{1-\epsilon}dxP(x)\right)$$

Sudakov Factor

↓

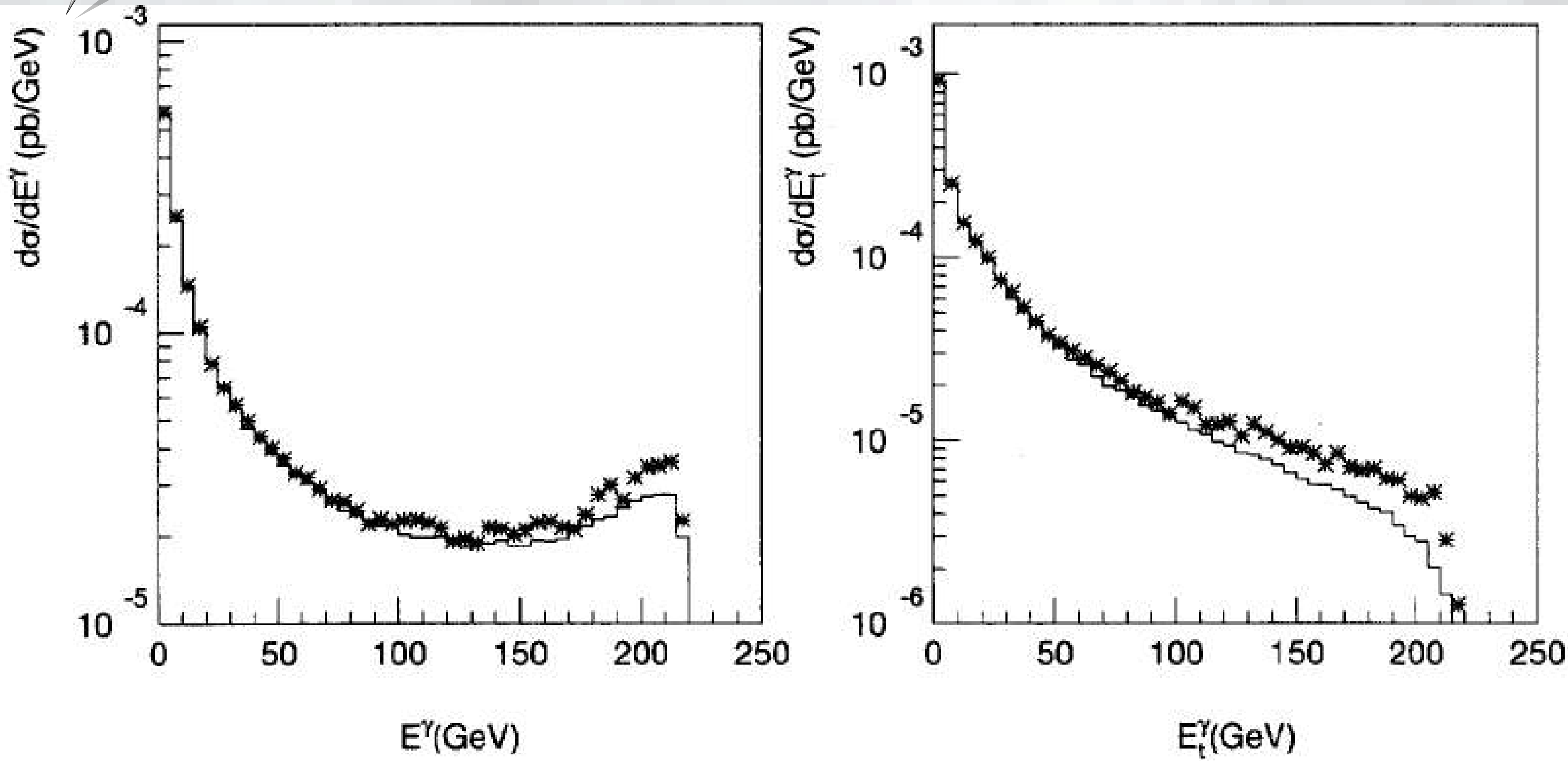
non-branch provability

Example in QED (annihilation)

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

Zhγ ME

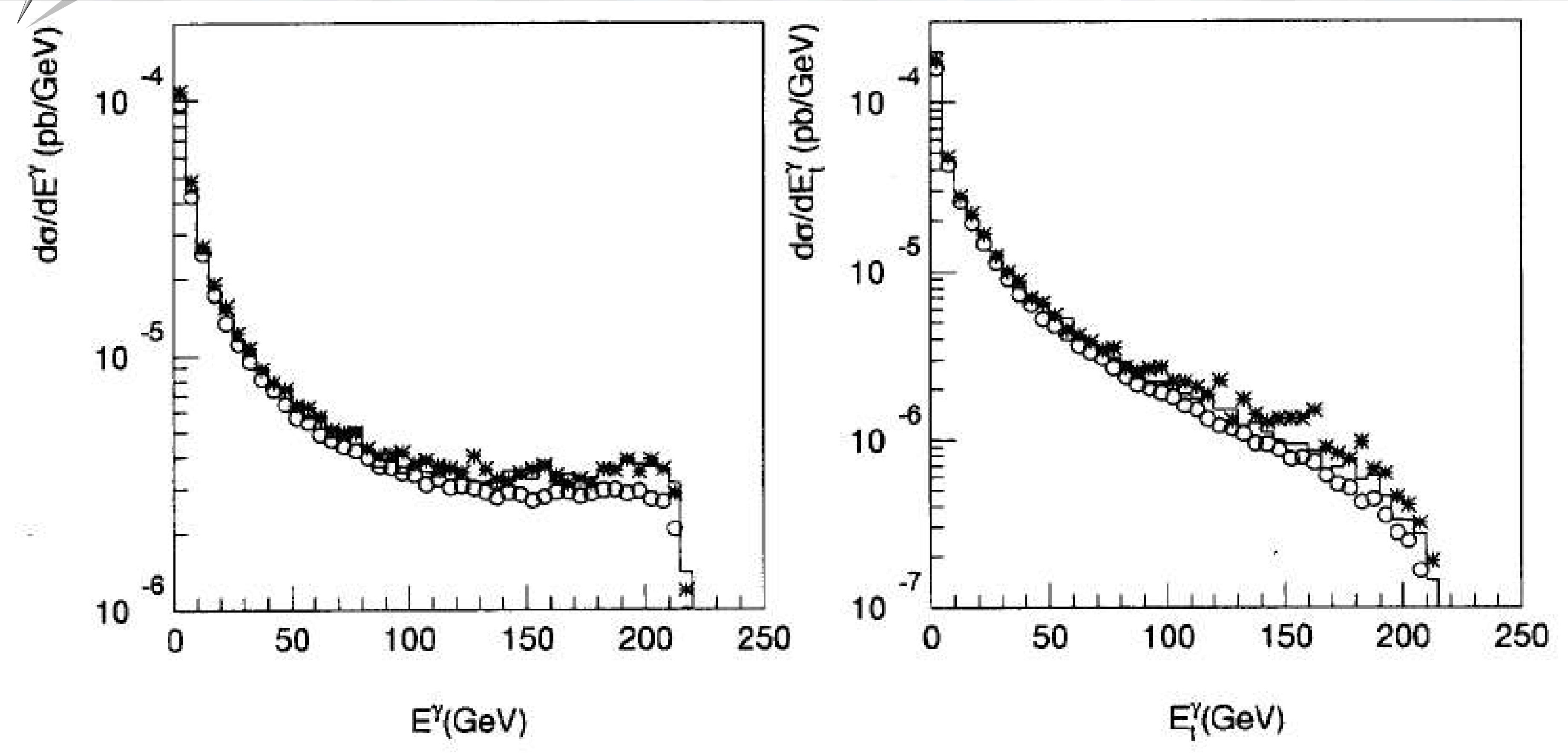
* ZH ME + γPS



Example in QED (annihilation)

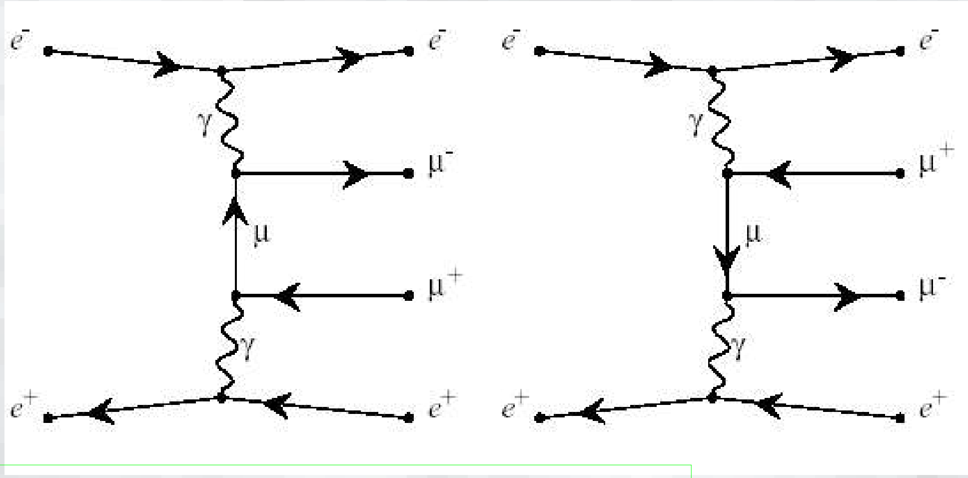
$e^+e^- \to ZH + \gamma\gamma$

Zhγγ ME
∗ ZH ME + γγPS
○ Zhγγ ME+PS(soft)



Example in QED (fusion)

$e^+e^- \to e^+e^-\mu^+\mu^-$



Soft correction formula

$$\sigma_{\rm soft} = \sigma_0(s)\left\{1 + \frac{\alpha}{\pi}\left[-2l(L-1) + \frac{3}{2}(L-1)\right]\right\}$$

O(α) correction

$$2{\rm Re}F_1 + \delta_s \to \frac{\alpha}{\pi}\left(-2l(L_t-1) + \frac{3}{2}L_t - 2\right)$$

$$L_t = \ln(-t/m_e^2)$$

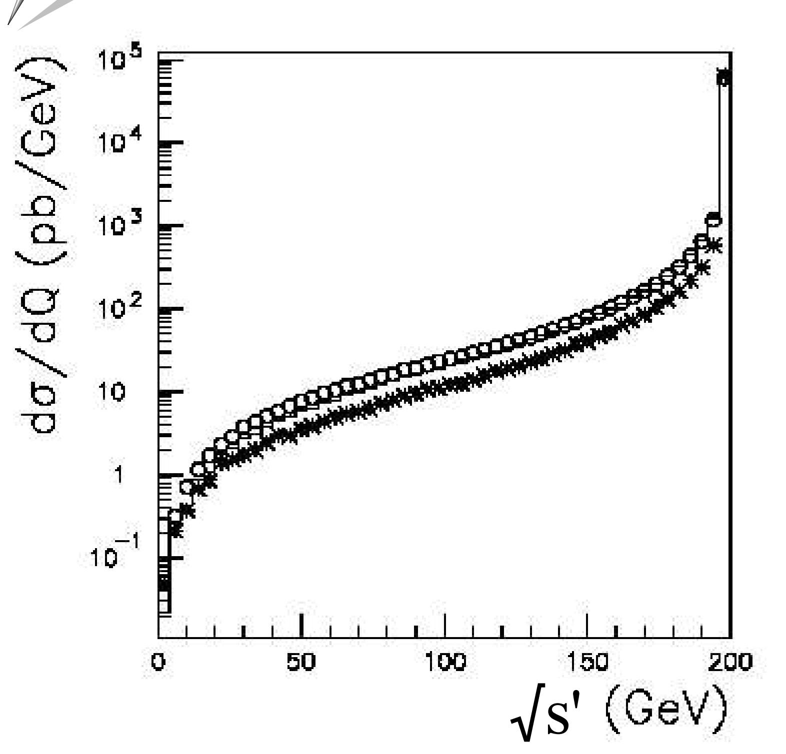
Factrization energy scale

F. A. Berends, P. H. Daverveldt and R. Kleiss, Nucl. Phys. **B253** (1985), 412.

$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$:Total cross sections

E_{CM} (GeV)	σ_0 (nb)	σ_{sf} (nb)	σ_{QEDPS} (nb)	σ_{BDK} (nb)
20	97.0(1)	96.3(1)	96.0(2)	96.0(1)
40	137.5(3)	136.3(1)	135.9(3)	135.9(1)
100	202.8(4)	201.0(2)	200.5(4)	200.5(2)
200	262.0(6)	259.8(3)	259.1(6)	258.8(2)

F. A. Berends, P. H. Daverveldt and R. Kleiss, Nucl. Phys. **B253** (1985), 412.



□ GRACE+PS

* GRACE+SF

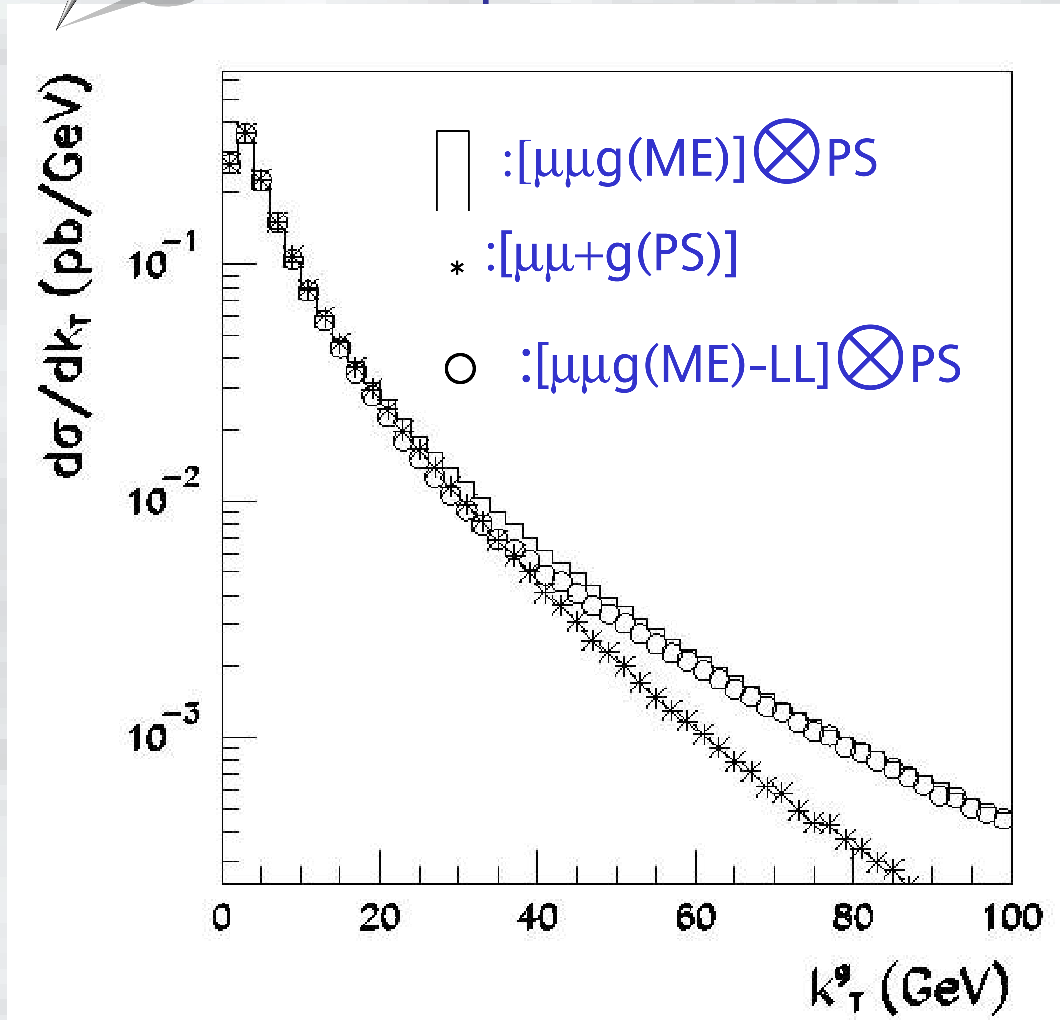
○ BDK

Y. Kurihara, J. Fujimoto, Y. Shimizu, K. Kato, K. Tobimatsu, T. Munehisa, Prog. Theor. Phys. **103**, 1199 (2000)

Drell-Yan process

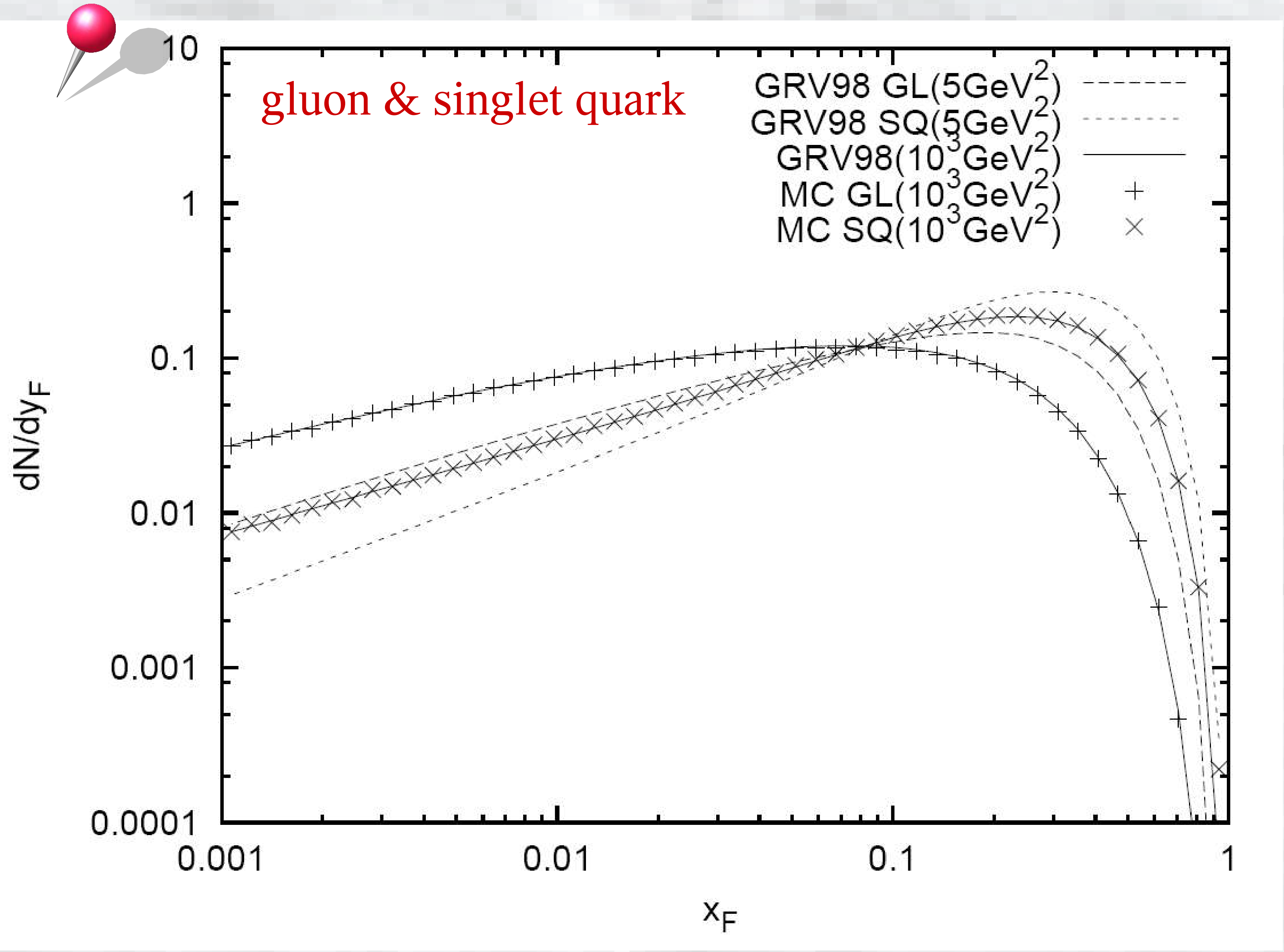
- Process : $u\bar{u} \rightarrow \mu^+\mu^-$(+gluon) in $p\bar{p}$ collision
- Cuts: $\sqrt{s_{\mu\mu}}$>40GeV, k_T^g> 1 GeV

k^g_T Test

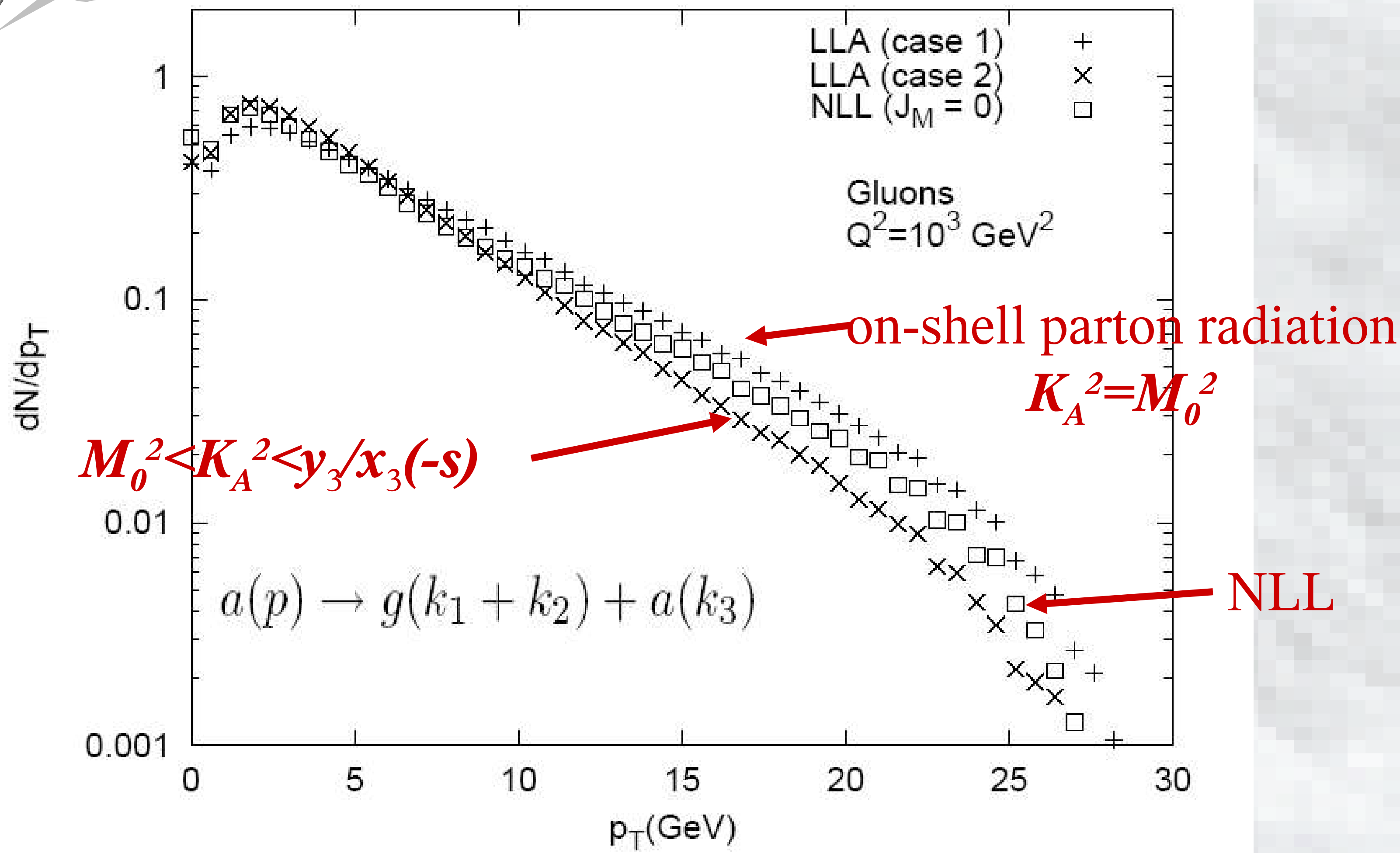


✓NLL Parton Shower

H. Tanaka, PTP **110** (2003) 963.



p_T distribution Gluon



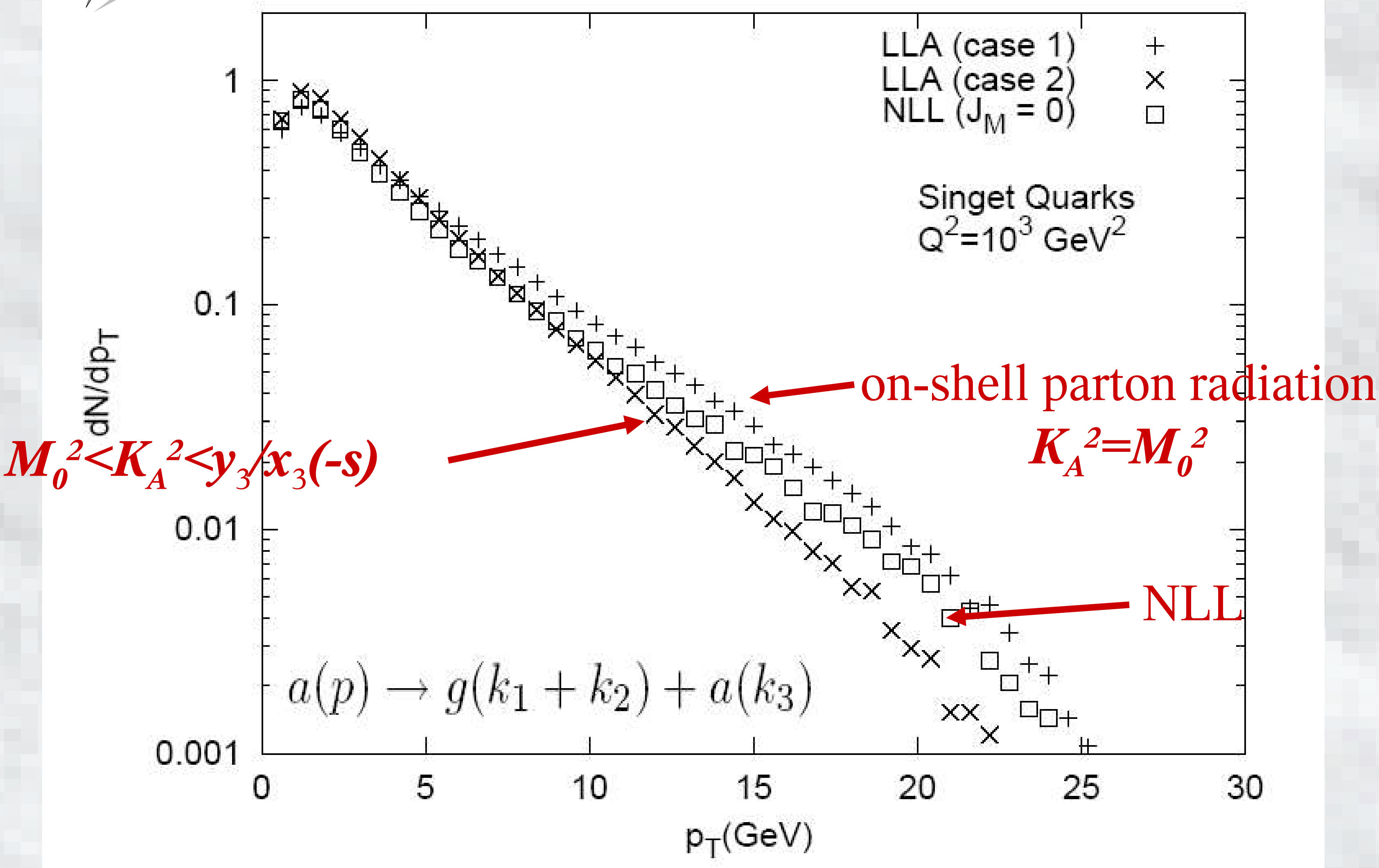
$$p_T^2 = x_3 y_3 \left[p^2 + \frac{-s}{x_3} - \frac{K_A^2}{y_3} \right]$$

$K_A^2 = (k_1 + k_2)^2$, $s = k_3^2$ and $p_T^2 = \vec{k}_{3T}^2$

$y_3 = 1 - x_3$

H. Tanaka, PTP **110** (2003) 963.

p_T distribution : singlet quarks



H. Tanaka, PTP **110** (2003) 963.

Double Countiong

No IR-divergence

$$\sigma_{NLO}=[\sigma_{tree}(1 + \delta_V + \delta_{s/c})+\sigma_{vis}]\otimes \text{PDF/PS}$$

$1/\varepsilon^2_{IR}, 1/\varepsilon_{IR}$ cancellation

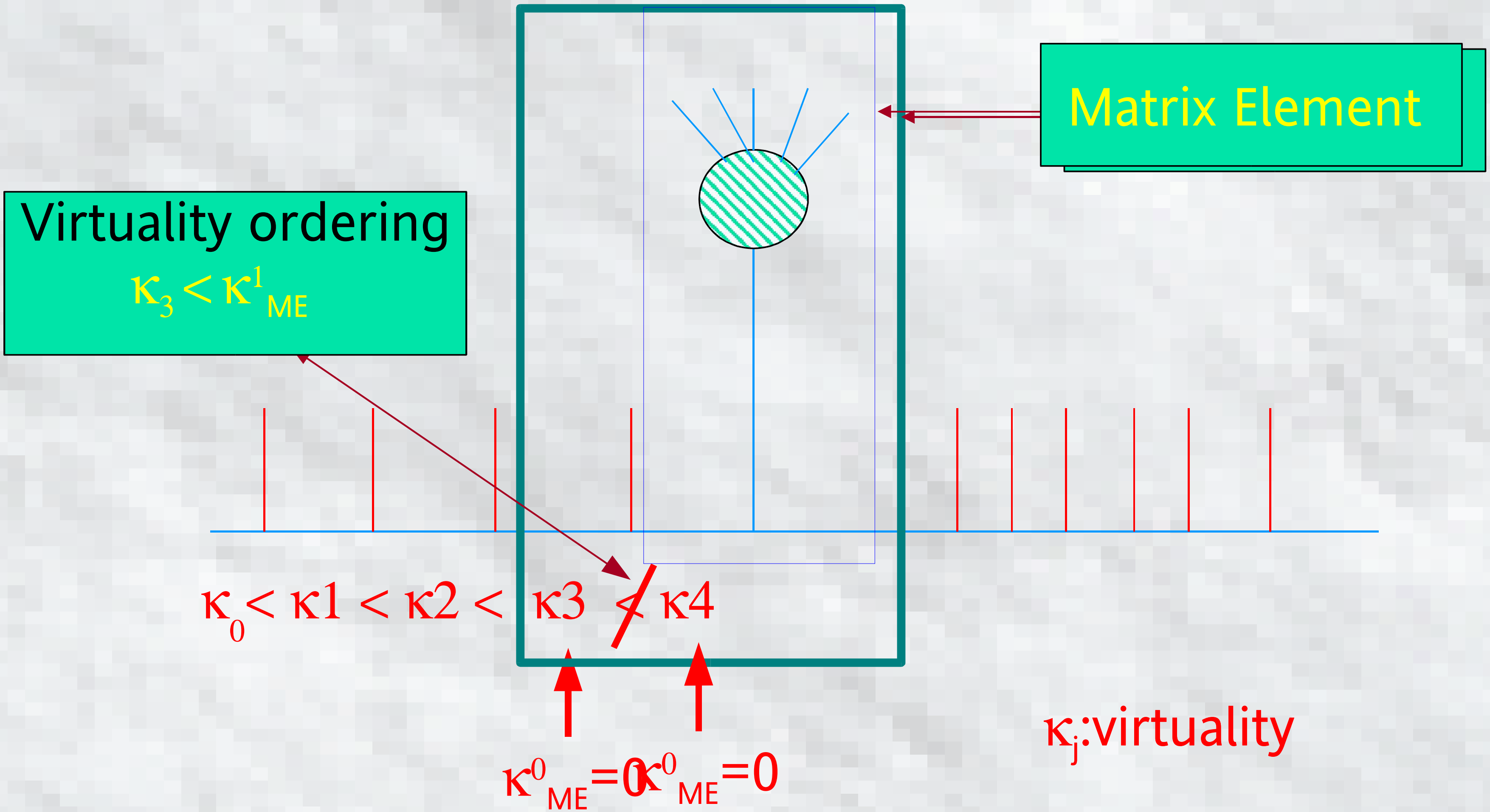
PDF/Parton Shower

$$\frac{1}{\varepsilon_{IR}} f_c \frac{\alpha_s}{2\pi} \mathrm{P}(x)$$

P(x) : Splitting function

Space/time dimension : $d=4+2\varepsilon_{IR}$

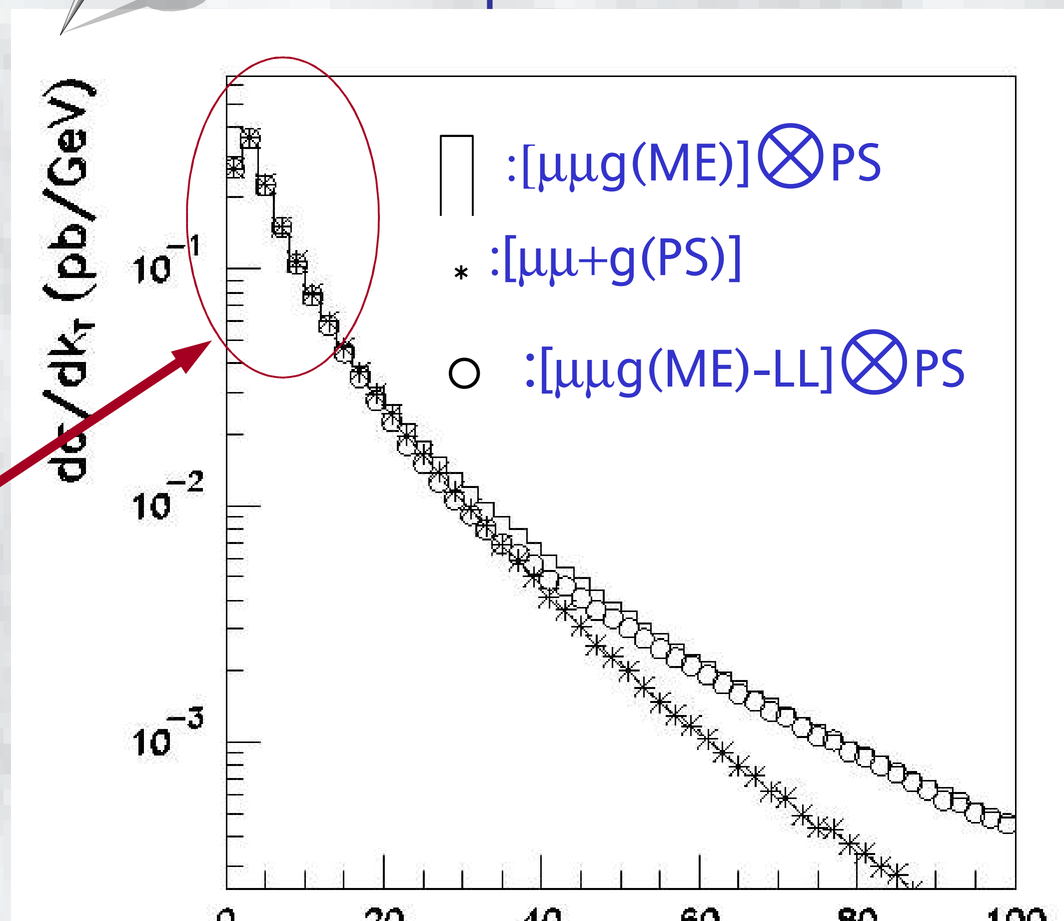
Double Counting Rejection

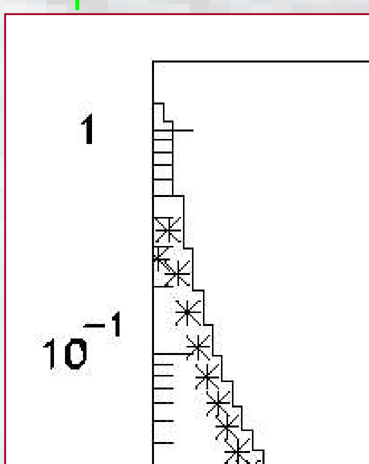


Drell-Yan process

k^g_T Test

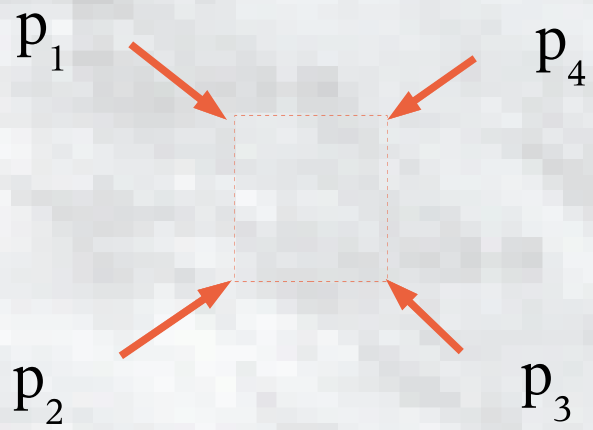
- Process : $u\bar{u} \to \mu^+\mu^-$(+gluon) in $p\bar{p}$ collision
- Cuts:
  - $\sqrt{s}_{\mu\mu}$>40GeV
  - k_T^g> 1 GeV





w/o virtuality ordering

Box Integral



$$J_{(4)}(s,t;p_1^2,p_2^2,p_3^2,p_4^2;n_x,n_y,n_z) = \frac{\Gamma(2-\varepsilon_{IR})}{(4\pi)^2\left(4\pi\mu_R^2\right)^{\varepsilon_{IR}}} \int_0^1 dx \int_0^{1-x} dy \int_0^{1-x-y} dz \frac{x^{n_x} y^{n_y} z^{n_z}}{D^{2-\varepsilon_{IR}}},$$

$$\begin{aligned}
D &= -s\,xz - t\,yw - p_1^2\,xy - p_2^2\,yz - p_3^2\,zw - p_4^2\,xw - i0, \\
w &= 1 - x - y - z, \\
s &= (p_1 + p_2)^2, \\
t &= (p_1 + p_4)^2.
\end{aligned}$$

All on-shell (massless) external legs

$$J_4(s,t;0,0,0,0;n_x,n_y,n_z) = \frac{1}{(4\pi)^2 s\, t} B(n_x+\varepsilon_{IR}, n_y+n_z+\varepsilon_{IR}) n_x! \Gamma(\varepsilon_{IR})\Gamma(1-\varepsilon_{IR})$$

$$\times \left[\left(\frac{-\tilde{t}}{4\pi\mu_R^2}\right)^{\varepsilon_{IR}} \left(\frac{-t}{s}\right)^{n_x} \frac{B(1+n_z, n_x+n_y+\varepsilon_{IR})}{\Gamma(n_x+\varepsilon_{IR})}\right.$$

$$\times\ {}_2F_1\left(1+n_x, n_x+n_y+\varepsilon_{IR}, 1+n_x+n_y+n_z+\varepsilon_{IR}, -\frac{\tilde{u}}{\tilde{s}}\right)$$

$$+ \left(\frac{-\tilde{s}}{4\pi\mu_R^2}\right)^{\varepsilon_{IR}} \sum_{l=0}^{n_x} \left(\frac{-s}{t}\right)^{l} \frac{(-1)^l}{\Gamma(l+\varepsilon_{IR})(n_x-l)!} B(1+n_y, l+n_z+\varepsilon_{IR})$$

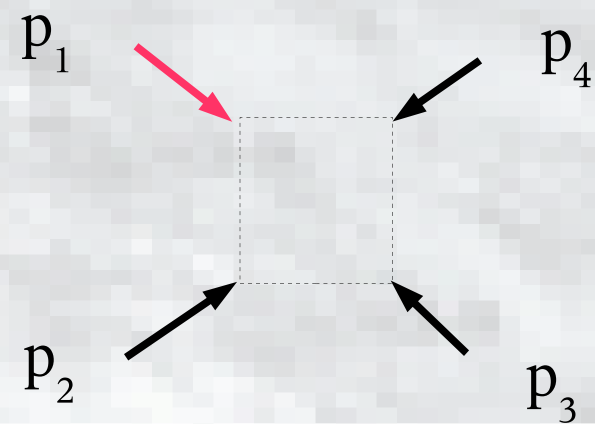
$$\left.\times\ {}_2F_1\left(1+l, l+n_z+\varepsilon_{IR}, 1+l+n_y+n_z+\varepsilon_{IR}, -\frac{\tilde{u}}{\tilde{t}}\right)\right].$$

Scalar Integral

$$J_{(4)}(s,t;0,0,0,0;0,0,0) = \frac{1}{(4\pi)^2 s\, t} \frac{B(\varepsilon_{IR},\varepsilon_{IR})\Gamma(1-\varepsilon_{IR})}{\varepsilon_{IR}}$$

$$\times \left[\left(\frac{-\tilde{s}}{4\pi\mu_R^2}\right)^{\varepsilon_{IR}} {}_2F_1\left(1,\varepsilon_{IR}, 1+\varepsilon_{IR}, -\frac{\tilde{u}}{\tilde{t}}\right) + \left(\frac{-\tilde{t}}{4\pi\mu_R^2}\right)^{\varepsilon_{IR}} {}_2F_1\left(1,\varepsilon_{IR}, 1+\varepsilon_{IR}, -\frac{\tilde{u}}{\tilde{s}}\right)\right]$$

One off-shell box integral



$$J_4(s,t;p_1^2,0,0,0;n_x,n_y,n_z) =$$

$$\frac{\Gamma(2-\varepsilon_{IR})}{(4\pi)^2\left(4\pi\mu_R^2\right)^{\varepsilon_{IR}}}\int_0^1 dx\int_0^{1-x} dy\int_0^{1-x-y} dz\frac{x^{n_x}y^{n_y}z^{n_z}}{\left(-xzs-y(1-x-y-z)t-p_1^2xy-i0\right)^{2-\varepsilon_{IR}}}$$

$$= \quad \frac{1}{(4\pi)^2 s\ t}B(n_x+\varepsilon_{IR},n_y+n_z+\varepsilon_{IR})n_x!\Gamma(\varepsilon_{IR})\Gamma(1-\varepsilon_{IR})$$

$$\times \quad \left[\left(\frac{-\tilde{t}}{4\pi\mu_R^2}\right)^{\varepsilon_{IR}}\left(\frac{-t}{s}\right)^{n_x}\frac{B(1+n_z,n_x+n_y+\varepsilon_{IR})}{\Gamma(n_x+\varepsilon_{IR})}\mathcal{I}^{(1)}\right.$$

$$+ \quad \left.\left(\frac{-\tilde{s}}{4\pi\mu_R^2}\right)^{\varepsilon_{IR}}\sum_{l=0}^{n_x}\frac{(-1)^l B(1+n_y,l+n_z+\varepsilon_{IR})}{\Gamma(l+\varepsilon_{IR})(n_x-l)!}\mathcal{I}_l^{(2)}\right]$$

$u=-s-t+p_1^{\,2}$

$$\mathcal{I}^{(1)} = B(1+n_z, n_x+n_y+\varepsilon_{IR})\ {}_2F_1\left(1+n_x, n_x+n_y+\varepsilon_{IR}, 1+n_x+n_y+n_z+\varepsilon_{IR}, -\frac{\tilde{u}}{\tilde{s}}\right)$$

$$\begin{aligned}
\mathcal{I}_l^{(2)} &= \sum_{k_1=0}^{n_z} {}_{n_z}C_{k_1} \left(\frac{s}{p_1^2-s}\right)^{n_y+k_1} \sum_{k_2=0}^{n_y+k_1} {}_{n_y+k_1}C_k\ (-1)^{n_y+k_2} \left(\frac{-t}{s}\right) \\
&\times \int_0^1 dw \left(1+\frac{\tilde{u}}{\tilde{s}}w\right)^{-(l+1)} \left(1+\frac{\tilde{t}+\tilde{u}}{\tilde{s}}w\right)^{k_2+l-1+\varepsilon_{IR}} \\
&= \sum_{k_1=0}^{n_z} \sum_{k_2=0}^{n_y+k_1} {}_{n_z}C_{k_1}\ {}_{n_y+k_1}C_k\ (-1)^{k_1+k_2} \left(\frac{s}{p_1^2-s}\right)^{n_y+k_1} \frac{1}{l+k_2+\varepsilon_{IR}} \left(1+\frac{u}{t}\right)^l \\
&\times \left[{}_2F_1\left(1+l, l+k_2+\varepsilon_{IR}, 1+l+k_2+\varepsilon_{IR}, -\frac{\tilde{u}}{\tilde{t}}\right)\right. \\
&- \left.\left(\frac{\tilde{p_1}^2}{\tilde{s}}\right)^{l+k_2+\varepsilon_{IR}} {}_2F_1\left(1+l, l+k_2+\varepsilon_{IR}, 1+l+k_2+\varepsilon_{IR}, -\frac{\tilde{u}\tilde{p_1}^2}{\tilde{t}\tilde{s}}\right)\right],
\end{aligned}$$

Status of GRACE NLO Generator

Already tested

- Drell-Yan process
- W production

Under development

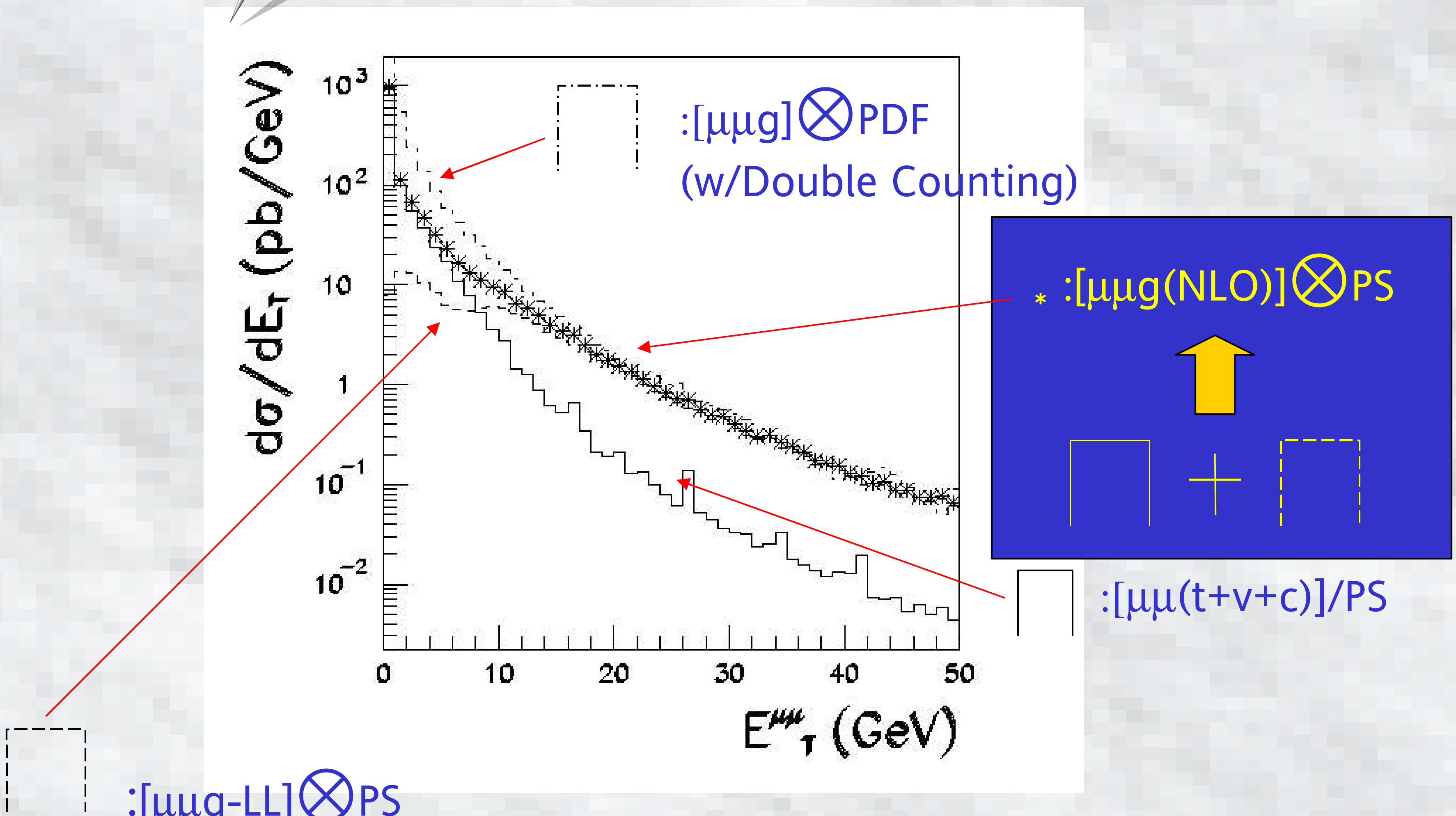
- Prompt photon
- V+1 jet

Future plan

- V+2 jets,.....

Drell-Yan Process @ NLO

E_T of μ-pair system



Summary

(1) Matrix Elements
- Automatic generation by GRACE

(2) Parton Shower
- x-deterministic PS at LL
- NLL-PS is avairable

(3) Soft/Collinear treatment
- (N)LL-subtraction method

(4) Application
- Drell-Yan process/w production
- V+1jet,2jet