Recent Progress of GRACE Development

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GRACE Author list

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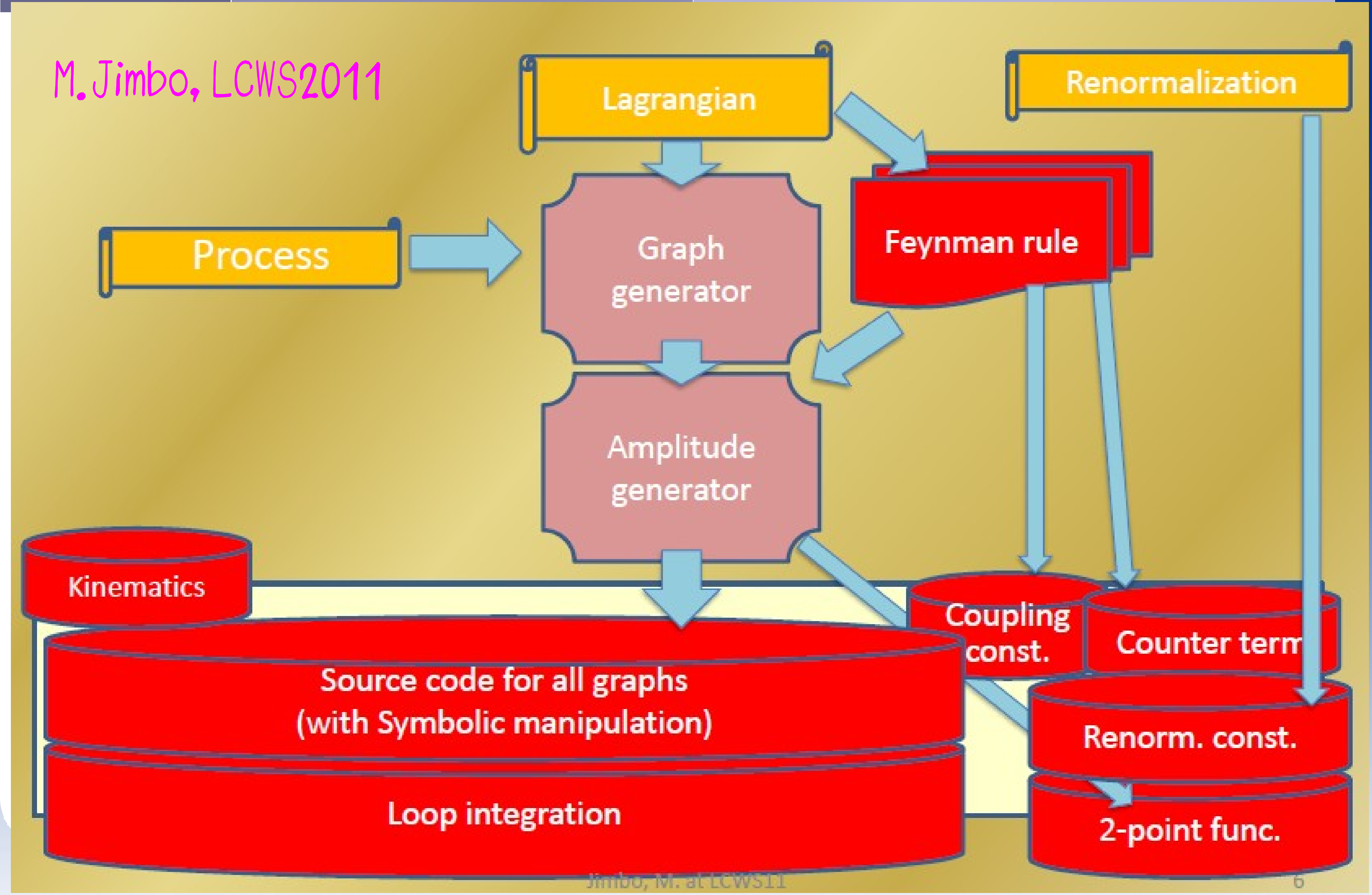
Special thanks : S. Odaka, E. de Doncker

Outline

- Introduction : What is GRACE ?
- Recent Developments:
    - GRACE for SUSY Processes
    - LO/NLO QCD Event-Generators for LHC
    - Multi-Loop Calculation
- Summary

What is GRACE ?

What is GRACE? : Structure



What is GRACE? : Input File

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Model="sm.mdl";
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Process;
  ELWK={2,2};
  QCD={3,1};
  Initial={u u-bar};
  Final  ={gluon, w-plus, w-minus};
  Expand=Yes;
  Block=No;
  AnyCT=Yes;
  Kinem="2301";
Pend;
```

Name of model file

loop order

tree order

Order of α

Order of α_s

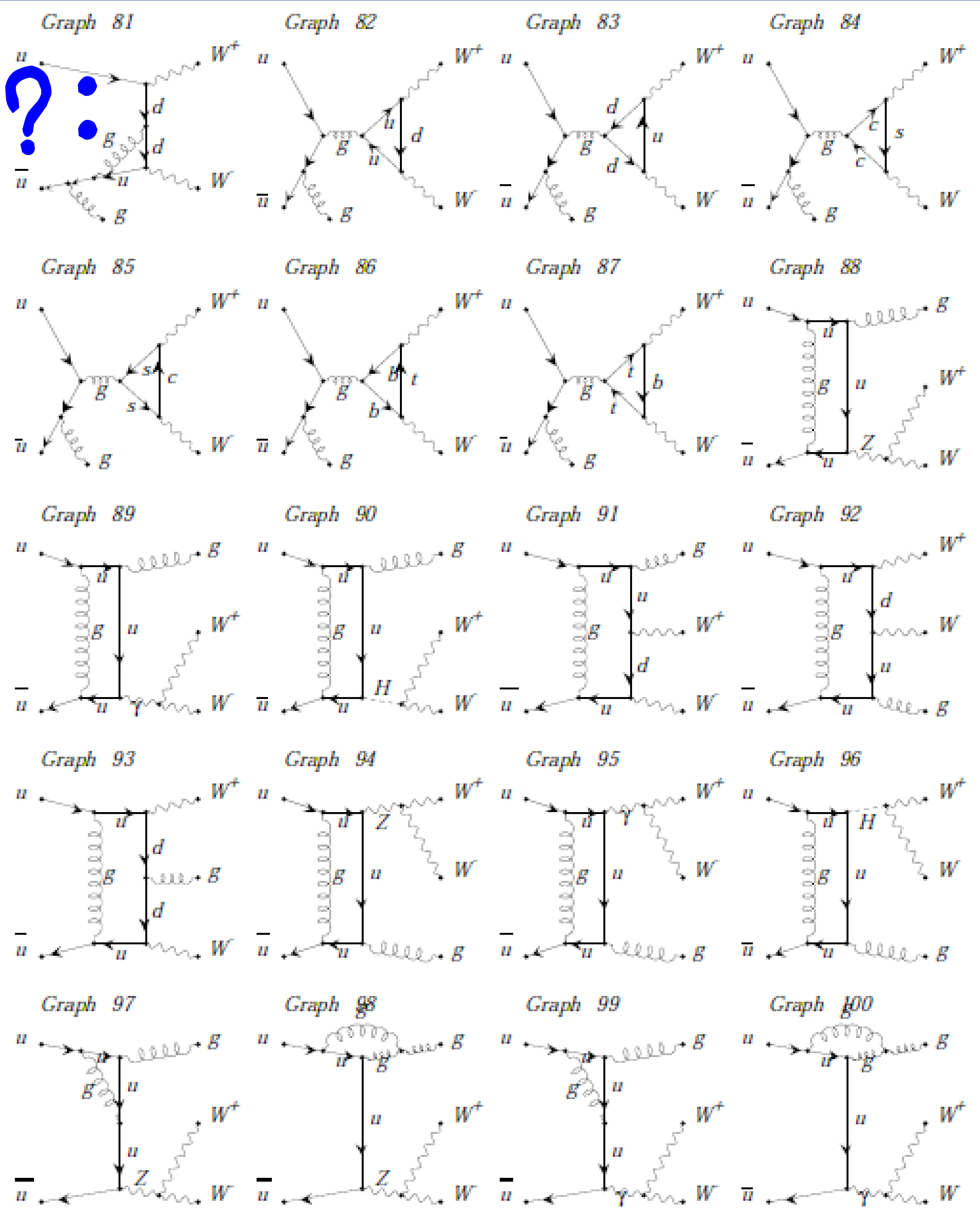
initial state particles

final state particles

kinematics number

What is GRACE? :

Diagrams



What is GRACE? :

FORTRAN Code

```
      subroutine atrg2
      implicit real*8(a-h,o-z)

      include 'inclrl.h'
      include 'inclk.h'
      include 'inclrp.h'
*-----------------------------------------------------------------------
      common /amwork/cftrl3q,av4,av5,extrl3q,pttrl3q
      common /amwori/lt4,lt5
*     880 (880) + 32 (32) bytes used

      integer     lt4(0:3),lt5(0:3)
      real*8      extrl3q(2),pttrl3q(4,3)
      complex*16  cftrl3q(2,4)
      complex*16  av4(lextrn*lintrn*lepexa)
      complex*16  av5(lintrn*lextrn*lepexv)
      complex*16  atmp
      real*8      cwgt(0:1)

*-----------------------------------------------------------------------

* Denominators of propagators
      aprop = 1.0d0
      call snprpd(pphase,aprop,vntrl3,
     &       amuq**2,0.0d0)

* Internal momenta
      call smintf(amuq,pftrl3,vntrl3,extrl3q,pttrl3q,cftrl3q)

* Vertices (6)
      call smffv(lextrn,lintrn,lepexa,extr2q,extrl3q,amuq,amuq,cguq,
     &           cftr2q,cftrl3q,pttr2q,pttrl3q,eqtrl4e,lt4,av4)
      call smffv(lintrn,lextrn,lepexv,extrl3q,extr4t,amuq,amdq,cwuq,
     &           cftrl3q,cftr4t,pttrl3q,pttr4t,eqtr9b,lt5,av5)

      call smconf(lt4,lt5,2,1,extrl3q,av4,av5,lt,av)

      sym = - 1.0d0
      aprop          = sym/aprop

      indexg(1) = 1
      indexg(2) = 4
      indexg(3) = 2
      indexg(4) = 3

      if(jcpol(4).ne.0) call smcpol(2, lt, av)

      call atmpord(lt, av, indexg, agcwrk)

      ancp(jgraph) = 0.0d0
*     nbase = 2
      do 500 ih = 0 , ltrag-1
         atmp        = agcwrk(ih)*aprop
         agc(ih,0) = agc(ih,0) + (-1/6.d0)*atmp
         agc(ih,1) = agc(ih,1) + (1/2.d0)*atmp
         ancp(jgraph) = ancp(jgraph) + atmp*conjg(atmp)
  500 continue

      return
      end
```

What is GRACE? : Integration

Integration Result of BASES

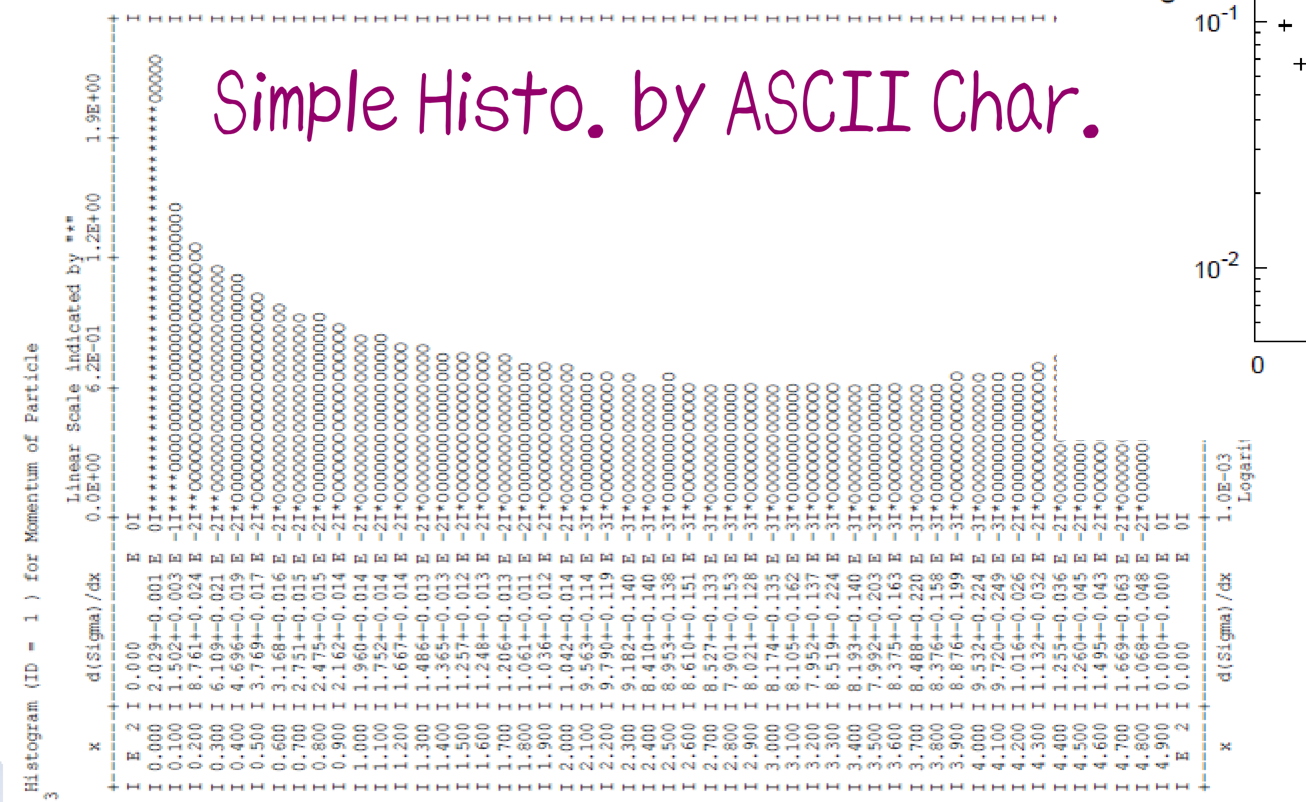
```
                                                     Date: 10/ 9/10   01:24
                 Convergency Behavior for the Grid Optimization Step
 ------------------------------------------------------------------------------
 <- Result of  each iteration ->  <-     Cumulative Result     -> < CPU  time >
  IT Eff R_Neg   Estimate  Acc %  Estimate(+- Error )order  Acc % ( H: M: Sec )
 ------------------------------------------------------------------------------
   1 100   0.00  2.775E+01  3.440  2.775262(+-0.095475)E 01  3.440   0: 0:30.33
   2 100   0.00  2.975E+01  1.021  2.956613(+-0.028933)E 01  0.979   0: 1: 0.51
   3 100   0.00  2.939E+01  0.278  2.939853(+-0.007866)E 01  0.268   0: 1:30.66
   4 100   0.00  2.934E+01  0.134  2.935474(+-0.003522)E 01  0.120   0: 2: 0.77
 ------------------------------------------------------------------------------

                                                     Date: 10/ 9/10   01:24
                 Convergency Behavior for the Integration Step
 ------------------------------------------------------------------------------
 <- Result of  each iteration ->  <-     Cumulative Result     -> < CPU  time >
  IT Eff R_Neg   Estimate  Acc %  Estimate(+- Error )order  Acc % ( H: M: Sec )
 ------------------------------------------------------------------------------
   1 100   0.00  2.939E+01  0.115  2.939291(+-0.003370)E 01  0.115   0: 2:30.75
   2 100   0.00  2.941E+01  0.111  2.940266(+-0.002348)E 01  0.080   0: 3: 0.92
   3 100   0.00  2.941E+01  0.109  2.940542(+-0.001896)E 01  0.064   0: 3:31.04
   4 100   0.00  2.936E+01  0.104  2.939294(+-0.001611)E 01  0.055   0: 4: 1.32
   5 100   0.00  2.940E+01  0.112  2.939457(+-0.001447)E 01  0.049   0: 4:31.54
 ------------------------------------------------------------------------------
```

Integration Result (pb)

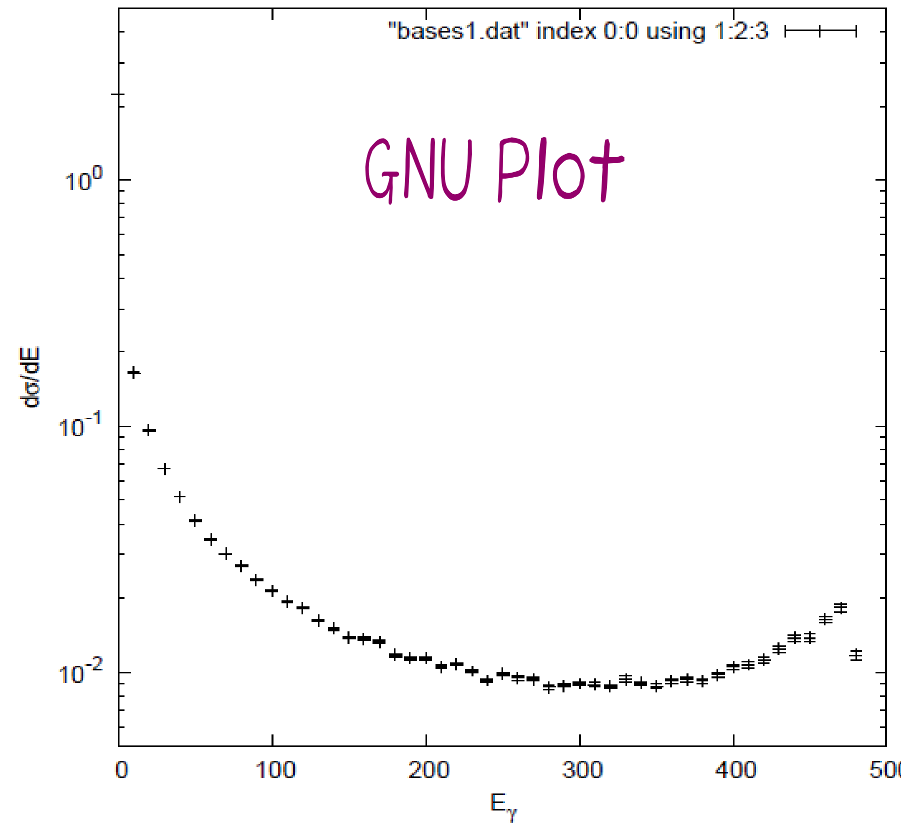
Accuracy (%)

What is GRACE? : Distributions

Energy Distribution



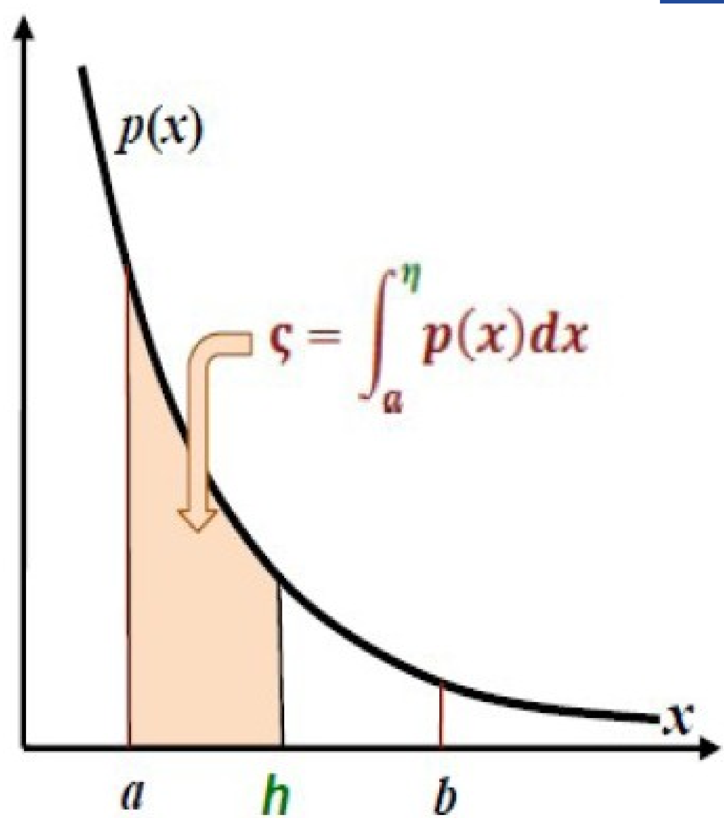
Simple Histo. by ASCII Char.



GNU Plot

What is GRACE? : Event Generation

- Numerical Integration by BASES
  - Probability Density Matrix



  - Event Generation w/ unit Weight
  - LHAccord Interface

S. Kwabata

GRACE for SUSY

GRACE for SUSY : Gauge Fixing

- Full Lagrangean of MSSM
  - $\mathscr{L} = \mathscr{L}_{\text{MSSM}} + \mathscr{L}_{\text{GF-V}} + \mathscr{L}_{\text{GF-S}} + \mathscr{L}_{\text{CT}}$
- Non-linear Gauge Fixing : Gauge bosons
  - $\mathscr{L}_{\text{GF-V}} = -|F_W|^2/\xi_W + F_Z^2/(2\xi_Z) + F_\gamma^2/(2\xi_\gamma)$

$$F_{W^\pm} = (\partial_\mu \pm ie\tilde{\alpha}A_\mu \pm igc_W\tilde{\beta}Z_\mu)W^{\pm\mu}$$
$$\pm i\xi_W \frac{g}{2}(v + \tilde{\delta}_h h^0 + \tilde{\delta}_H H^0 \pm i\tilde{\kappa}G^0)G^\pm$$

$$F_Z = \partial_\mu Z^\mu + \xi_Z \frac{g_Z}{2}(v + \tilde{\varepsilon}_h h^0 + \tilde{\varepsilon}_H H^0)G^0$$

$$F_\gamma = \partial_\mu A^\mu$$

J.Fujimoto et al., Phys.Rev.D75, 113002('07)

GRACE for SUSY : System Check

- Non-linear Gauge Check (One Phase Point)
  - Ex. for $\tilde{t}_1 \to b\tilde{\chi}_1^+$ One-Loop
  - NLG Parameters : $(\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}_h, \tilde{\delta}_H, \tilde{\kappa}, \tilde{\varepsilon}_h, \tilde{\varepsilon}_H)$

Case 1 : (0,0,0,0,0,0,0)

Ans = 0.15117115752797127186610833503954323

Case 2 : (1000,2000,3000,4000,5000,6000,7000)

Ans = 0.15117115752797127186610833480863836

Unit(GeV)

K.Iizuka, et al, POS(RADCOR2009)068[hep-ph/1001.2800]

GRACE for SUSY : System Check

- Ex. for $\tilde{t}_1 \to b\tilde{\chi}_1^+$ One-Loop (One Phase Point)
  - UV-Cancellation Check

Case 1 : (Cuv=1/ε=0)
Ans = 0.15117115752797127186610833503954323
Case 2 : (Cuv=1000)
Ans = 0.15117115752797127186596180279397801

  - IR-Cancellation Check

Case 1 : ($\lambda=10^{-24}$)
Ans = 0.15117115752797127186610833503954323
Case 2 : ($\lambda=10^{-27}$)
Ans = 0.15117115752797127186610833519983020

K.Iizuka, et al, POS(RADCOR2009)068[hep-ph/1001.2800]

GRACE for SUSY : Results

- **Two scenarios:**

  Scenario 1. Large slepton masses

  $\tilde{t}_1 \to b W^+ \tilde{\chi}_1^0$ ⇨ **major decay mode (BR ~ 100%)**

  1-loop correction: Ref. Iizuka, K. et al., PoS(RADCOR2009)068, (2010).

  Scenario 2. Small slepton masses

  'Semi-Leptonic' decay modes dominate ⇦ We focus on

  $\tilde{t}_1 \to b l^+ \tilde{\nu}_l$ $\tilde{t}_1 \to b \tilde{l}^+ \nu_l$

T.Inoue,M.Jimbo, LCWS2011

GRACE for SUSY : Results(parameters)

Scenario 1

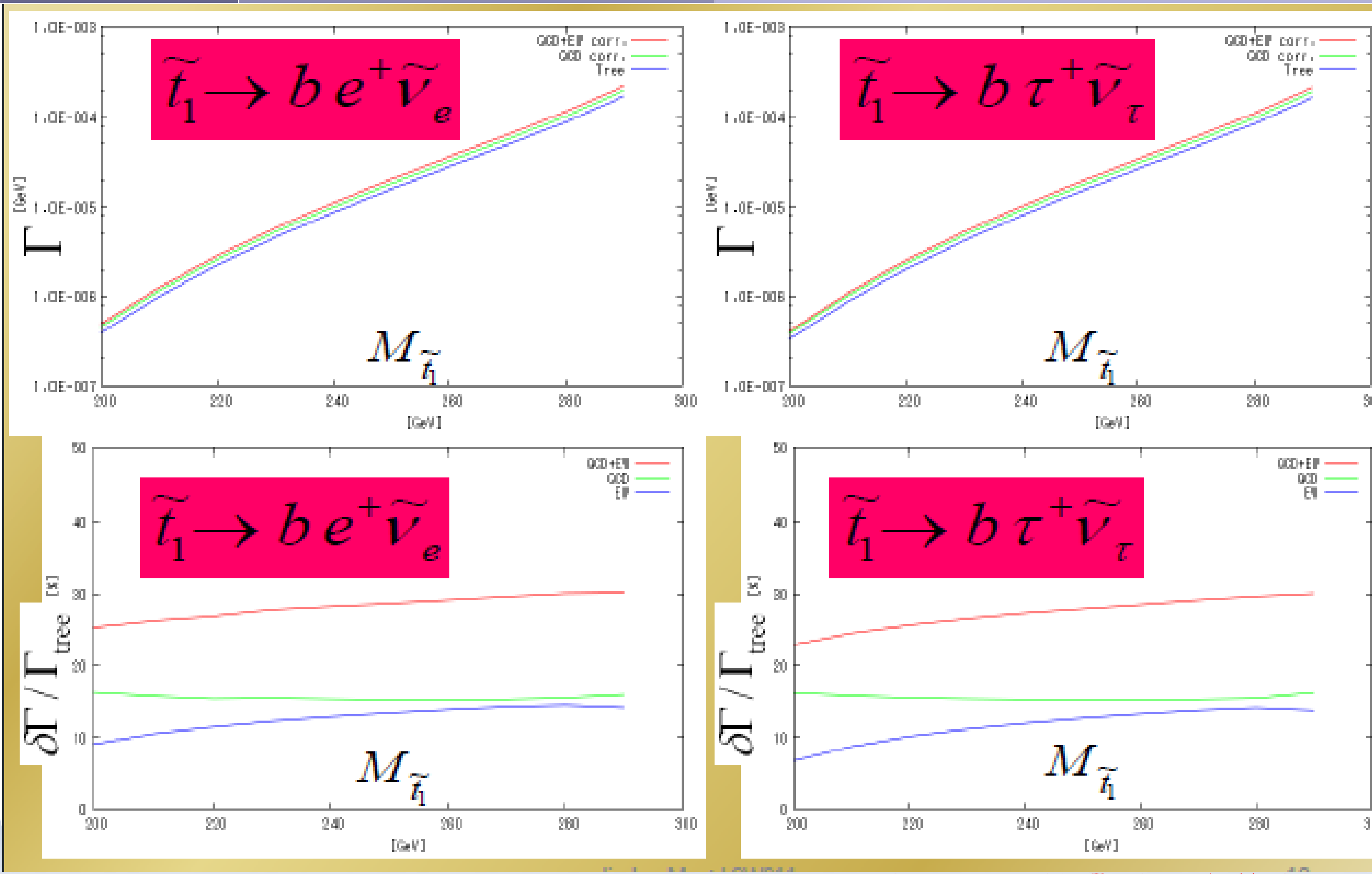
$\tan\beta$	10	$m_{\tilde b_1}$	330GeV
μ	-750GeV	$\theta_{\tilde b}$	0.6π
M_2	400GeV	m_A	525GeV
$m_{\tilde\ell_1^\pm}$	325GeV	$m_{\tilde g}$	1389GeV
$m_{\tilde\ell_2^\pm}$	370GeV	$m_{\tilde\chi_1^0}$	194GeV
$\theta_{e,\mu}$	0.05π	$m_{\tilde\chi_1^+}$	396GeV
θ_τ	0.2π		
$m_{\tilde\nu_{e,\mu}}$	316GeV		
$m_{\tilde\nu_\tau}$	328GeV		
$m_{\tilde t_2}$	480GeV		
θ_t	0.8π		

Scenario 2

$\tan\beta$	7	$m_{\tilde b_1}$	330GeV
μ	-500GeV	$\theta_{\tilde b}$	0.6π
M_2	300GeV	m_A	300GeV
$m_{\tilde\ell_1^\pm}$	170GeV	$m_{\tilde g}$	1042GeV
$m_{\tilde\ell_2^\pm}$	175GeV	$m_{\tilde\chi_1^0}$	146GeV
$\theta_{e,\mu}$	0.01π	$m_{\tilde\chi_1^+}$	294GeV
θ_τ	0.2π		
$m_{\tilde\nu_{e,\mu}}$	151GeV		
$m_{\tilde\nu_\tau}$	152GeV		
$m_{\tilde t_2}$	600GeV		
θ_t	0.8π		

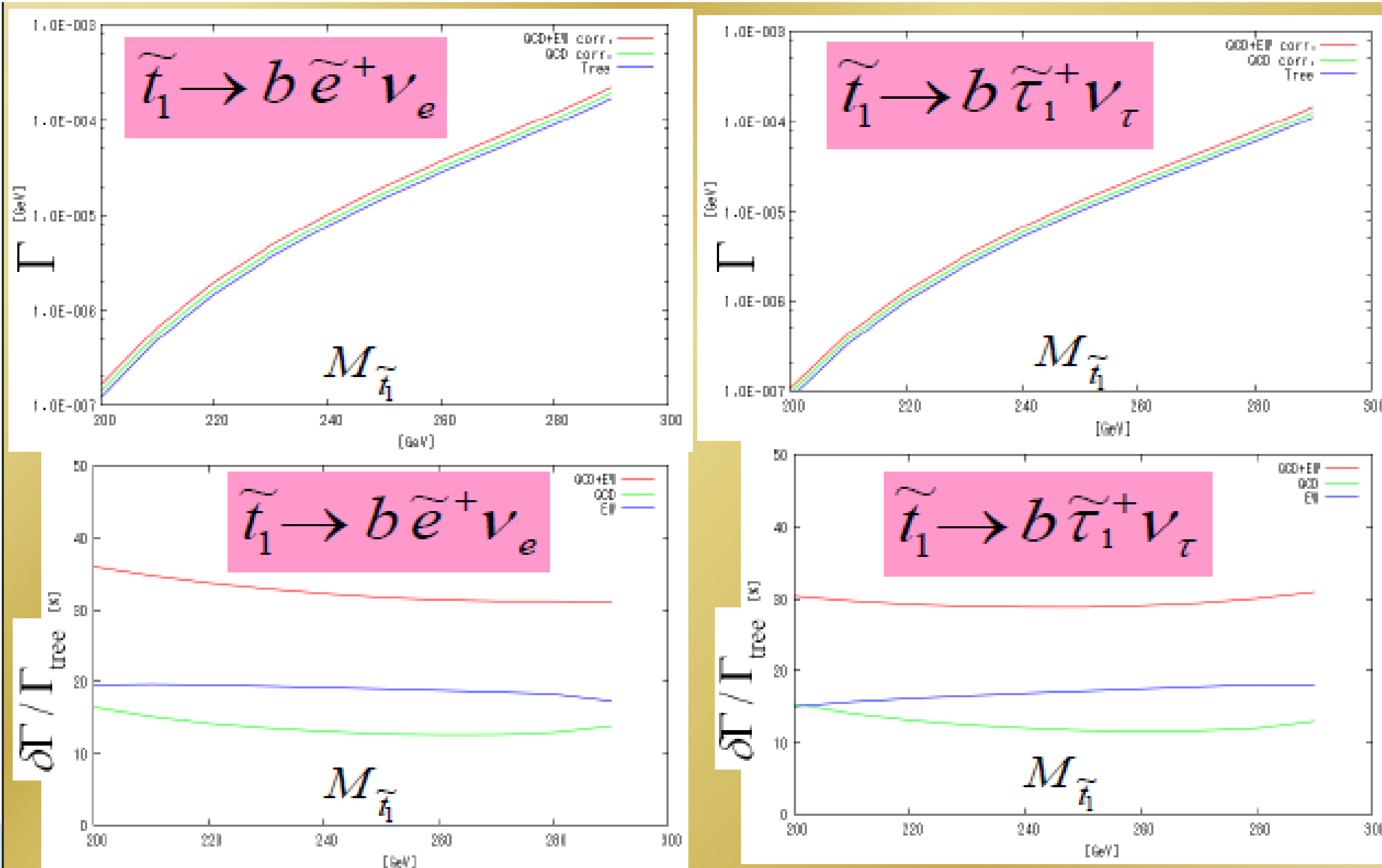
T.Inoue,M.Jimbo, LCWS2011

GRACE for SUSY : Results(stop decay)



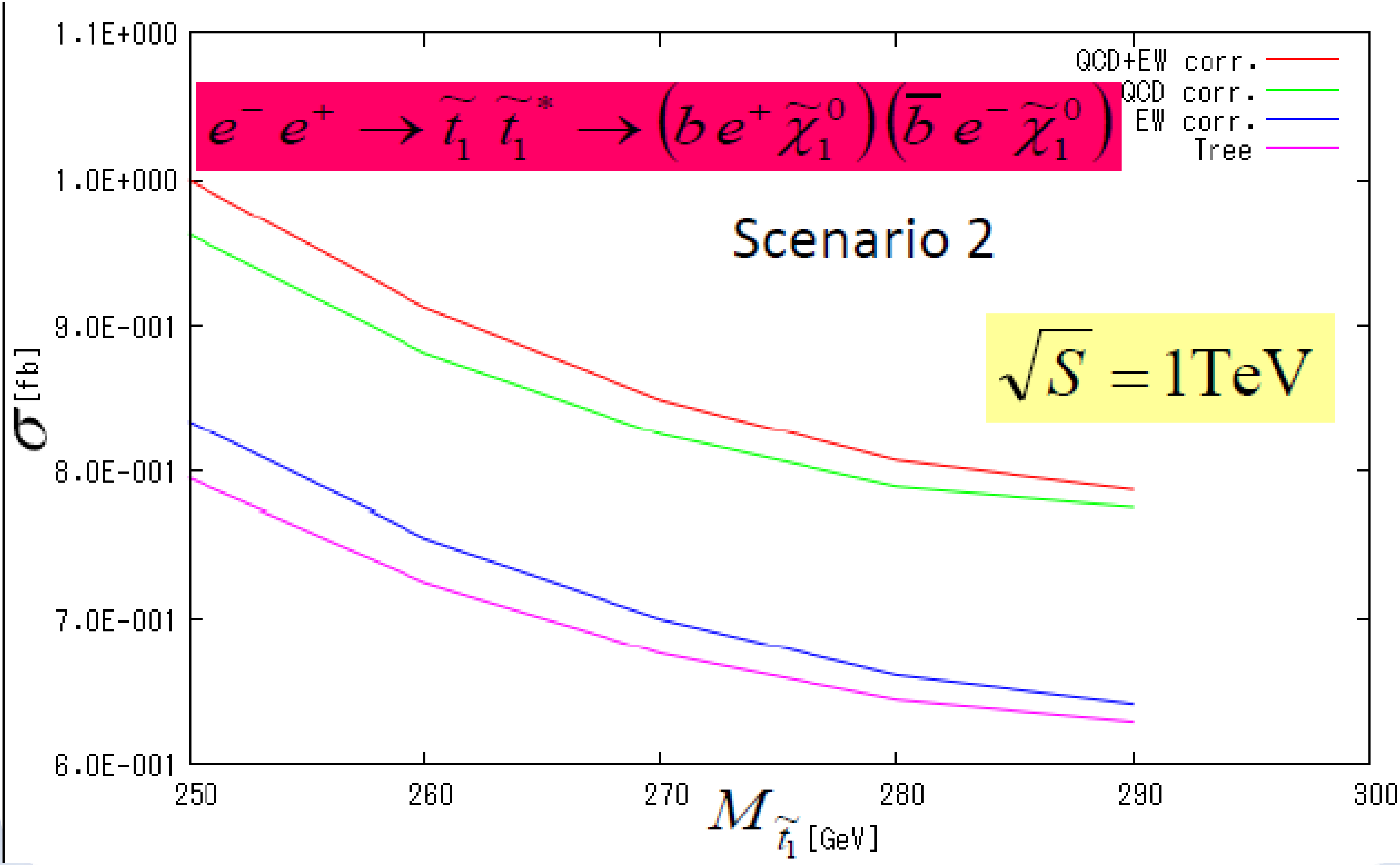
T.Inoue,M.Jimbo, LCWS2011

GRACE for SUSY : Results(stop decay)



T.Inoue,M.Jimbo, LCWS2011

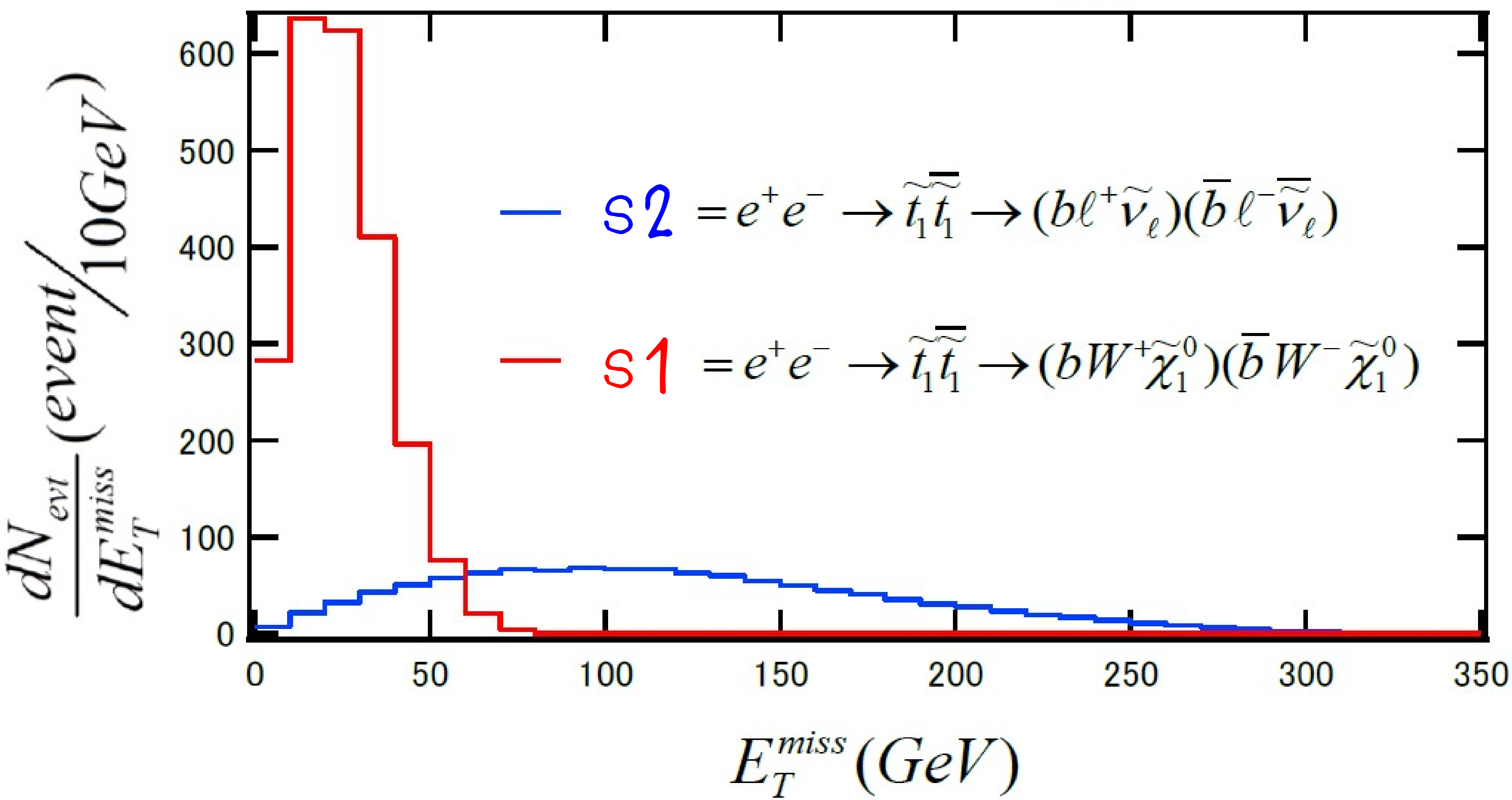
GRACE for SUSY : Results(Prod./Decay)



T.Inoue,M.Jimbo, LCWS2011

GRACE for SUSY : Results(Prod./Decay)

$m_{\tilde{t}_1}$ =285 GeV 100 fb^{-1} $\sqrt{s} = 1\text{TeV}$



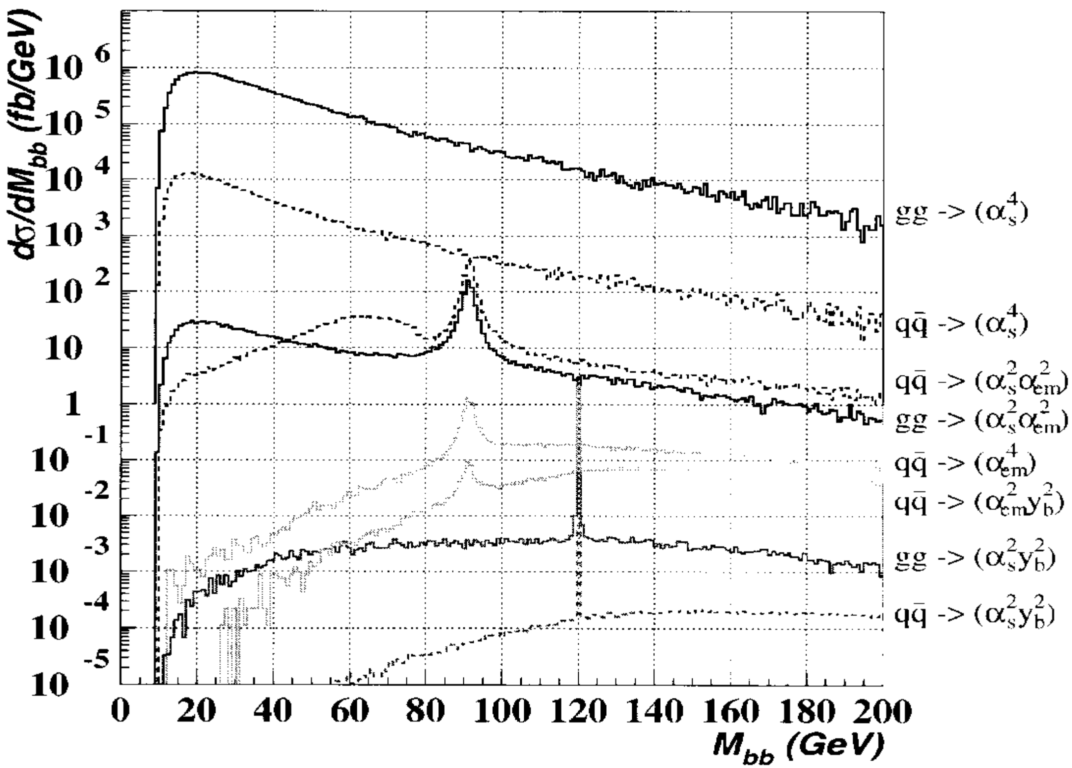
T.Inoue,M.Jimbo, LCWS2011

GRACE for LHC

Tree-Level Event Generator GR@PPA 2.8

GRACE for LHC : GR@PPA 2.7

- W + jets (up to 3 jets) with the subsequent W decay
- Z + jets (up to 2 jets) with the subsequent Z decay
- Four bottom quarks
- top-quark pair with the subsequent decay
- di-boson (WW, WZ and ZZ) with the subsequent W/Z decay



GRACE for LHC : GR@PPA 2.8

New features of GR@PPA 2.8

- ME-PS matching in the generation of W, Z, W^+W^-, ZW, ZZ production processes at hadron collisions
  - LLL subtraction & custom LL PS
  - Forward evolution PS in the initial state (QCDPS)
  - Backward evolution PS (QCDPSb) available as well
  - Final-state PS (QCDPSf) also implemented as well as initial-state radiations.

GRACE for LHC : GR@PPA 2.8

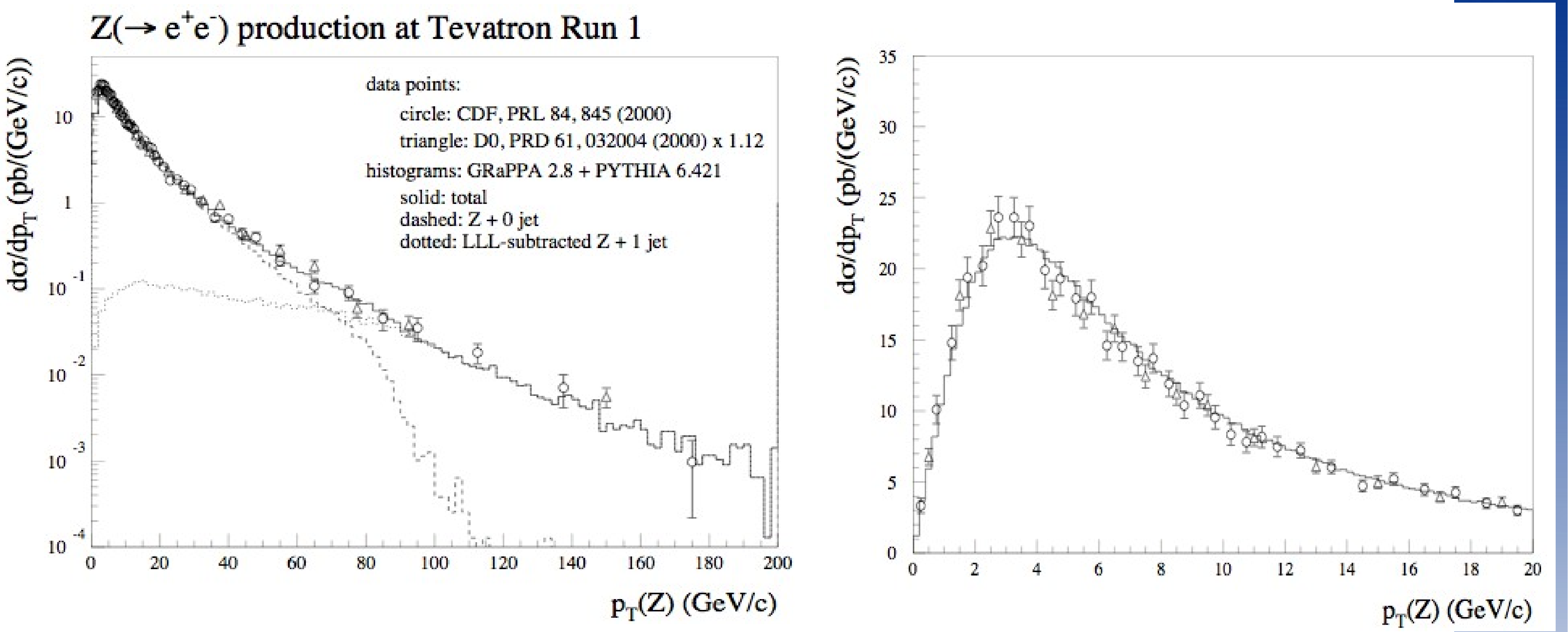
- Additional features
  - *W* and *Z* decays in the matrix elements
  - Exact spin, phase-space and off-shell effects at the tree level
  - PDG values for the decay widths and branching ratios of *W* and *Z*
  - Generated events can be passed to PYTHIA to proceed the simulation : hadronization and decays
  - Still at LO : Please wait GR@PPA 3.0

It can be downloaded from:

http://atlas.kek.jp/physics/nlo-wg/grappa.html

GRACE for LHC : GR@PPA 2.8

Z-boson production



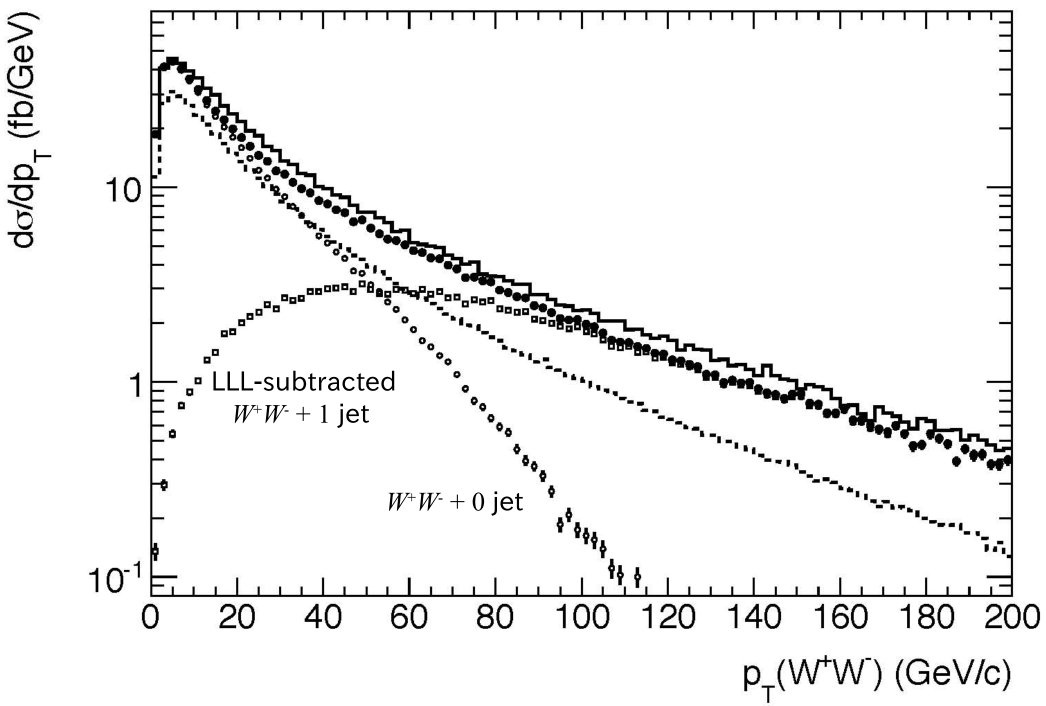
The D0 data and the simulation are normalized to the CDF cross section.

GRACE for LHC : GR@PPA 2.8

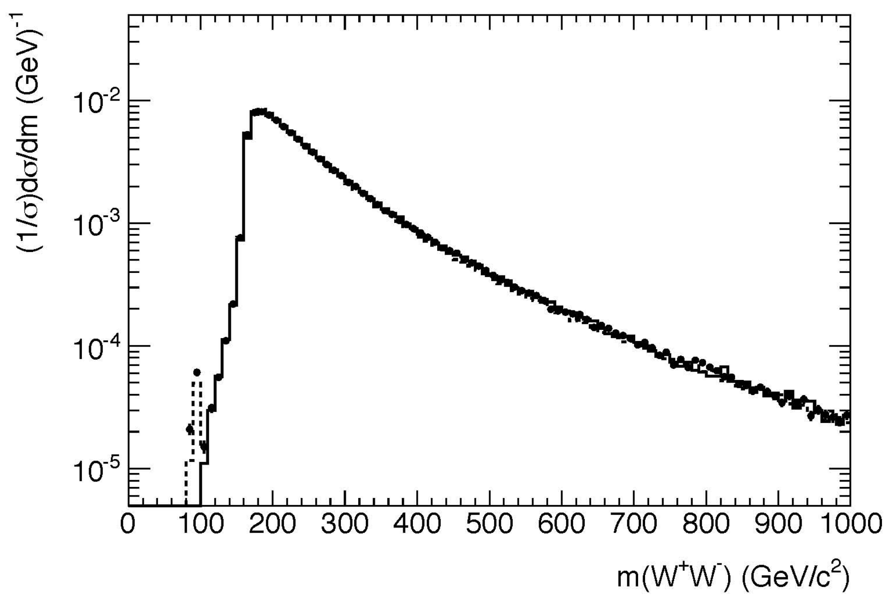
W+W- production at LHC

Plot: GR@PPA 2.8 + PYTHIA 6.4

Histograms
solid: MC@NLO (IL1 = IL2 = 1)
+ HERWIG
dashed: PYTHIA 6.4 (new PS)



No significant difference between the three simulations in the W^+W^- invariant mass spectrum, except for a small Z peak



Prepared by S. Odaka

GRACE for LHC : GR@PPA 2.8

$\gamma\gamma$ production at LHC

Reasonable agreement with ResBos

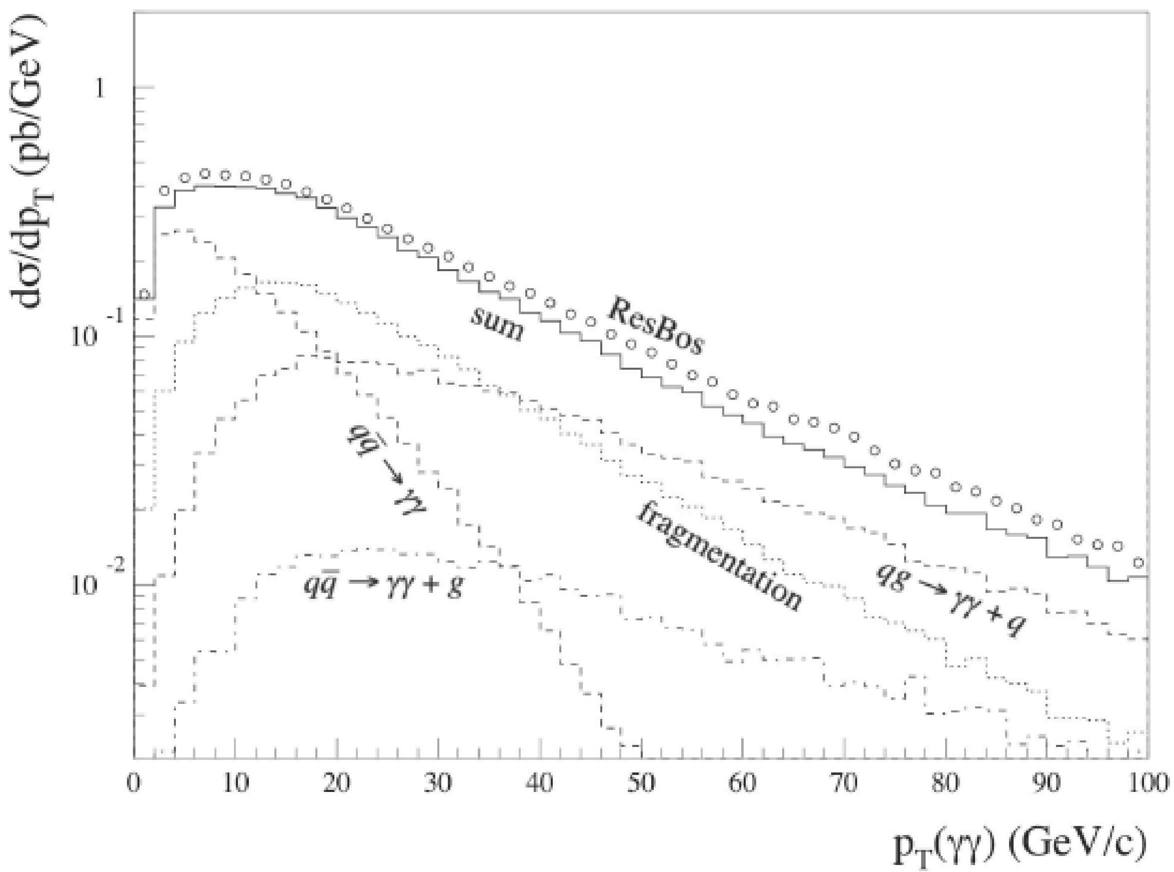
ResBos: resummed NLO calculation.
Here, $gg \to \gamma\gamma$ is not included.

ResBos: 15.5 pb
GR@PPA + PYTHIA: 13.7 pb

$q\bar{q} \to \gamma\gamma$ is less than 1/3 of the sum.

$q\bar{q} \to \gamma\gamma$:	4.1 pb (30%)
fragmentation:	5.1 pb (37%)
$qg \to \gamma\gamma + q$:	3.7 pb (27%)
$q\bar{q} \to \gamma\gamma + g$:	0.8 pb (11%)

This separation is not physical, but is a result when we separate soft/hard radiations at $\mu_F = p_T$ of $q\bar{q} \to \gamma\gamma$ or $qg \to \gamma q$.

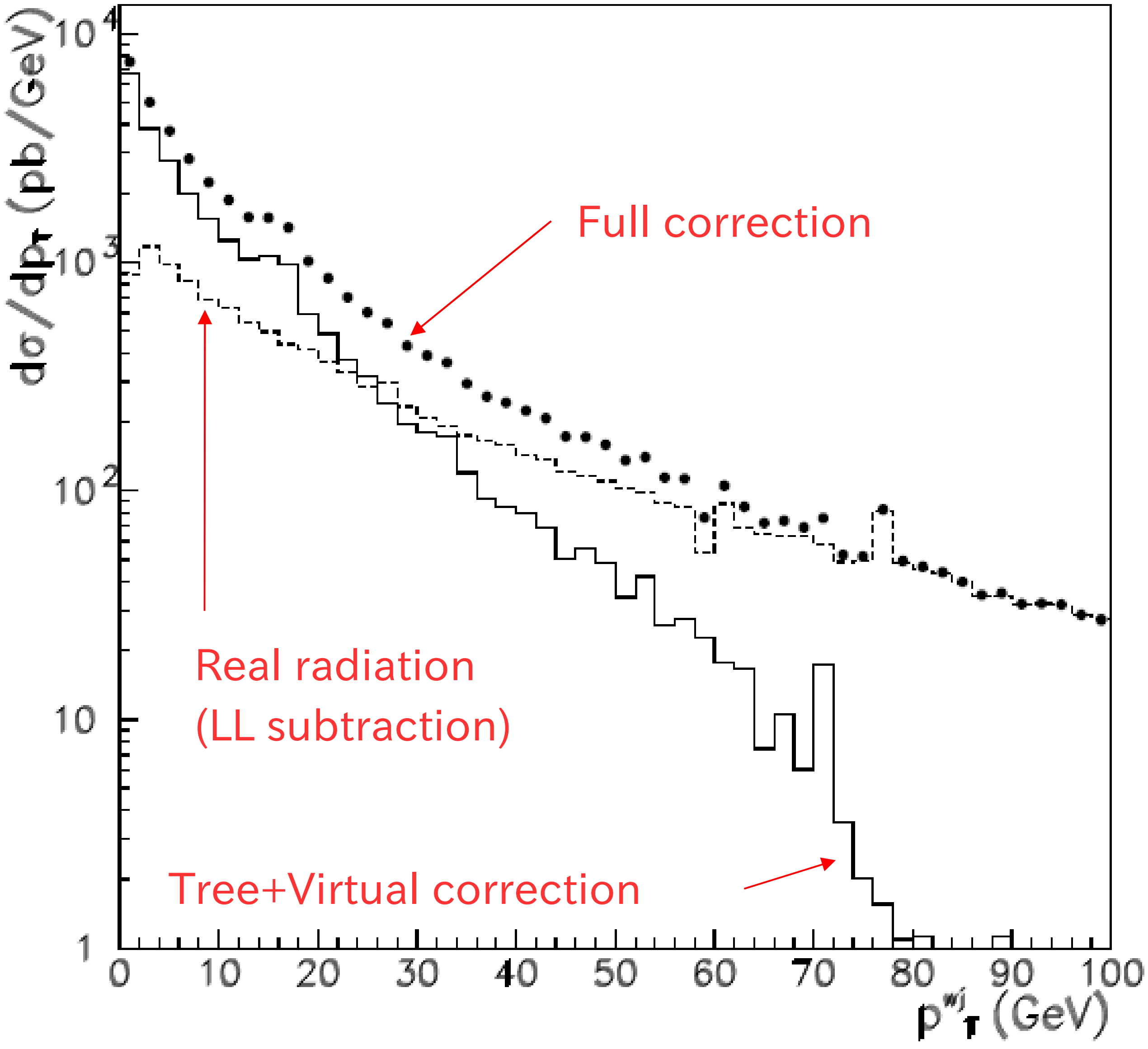


NLO/QCD EG

GR@PPA 3.0

GRACE for LHC : NLO Generator

Transverse momentum distribution of W-jet



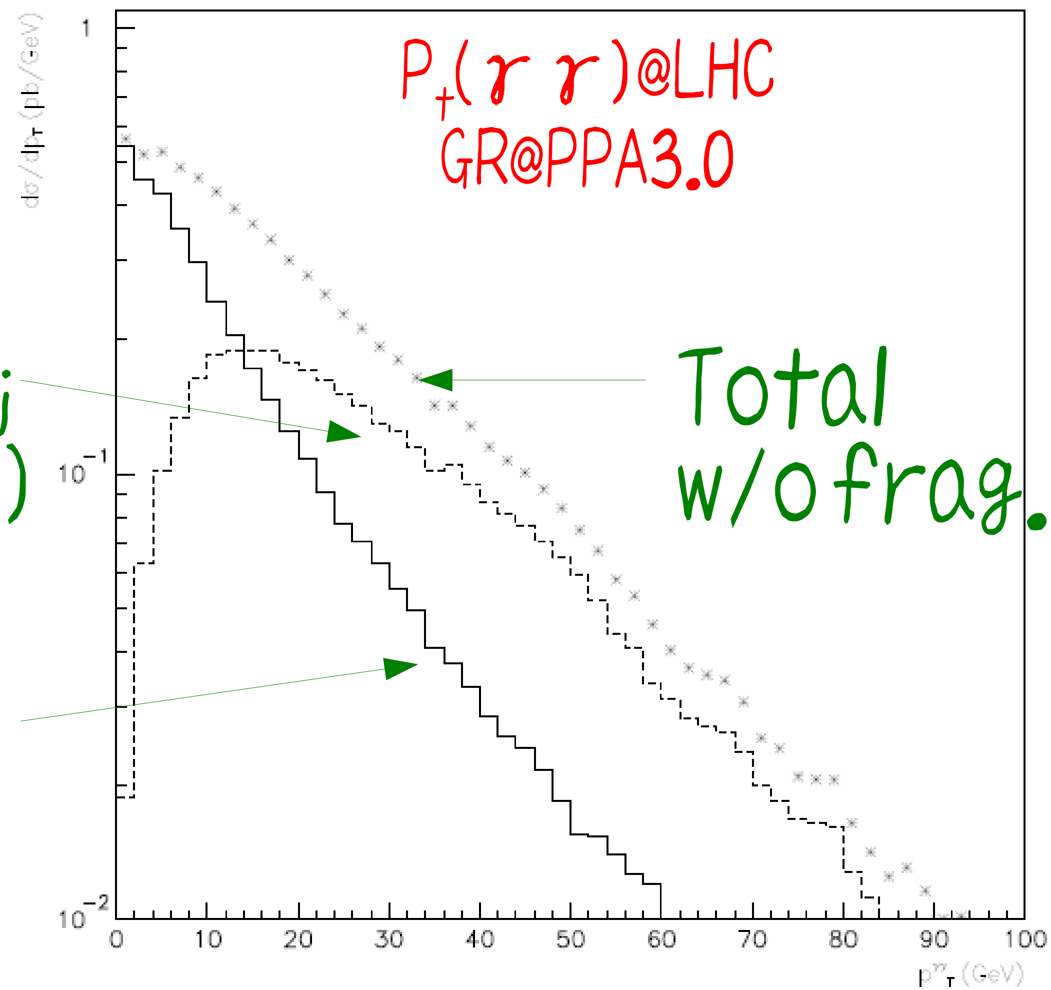
GRACE for LHC : NLO Generator

Transverse momentum distribution of γγ

K-factor=2.3
(2.4 by DIPHOX)

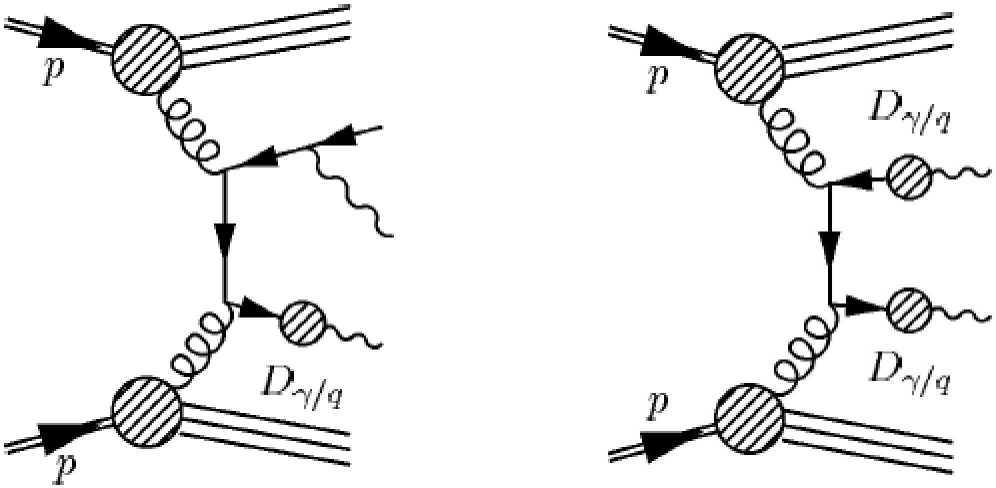
$q\bar{q} \to \gamma\gamma j$
(LLL-Sub.)

$q\bar{q} \to \gamma\gamma$
(NLO)



GRACE for LHC : NLO Generator

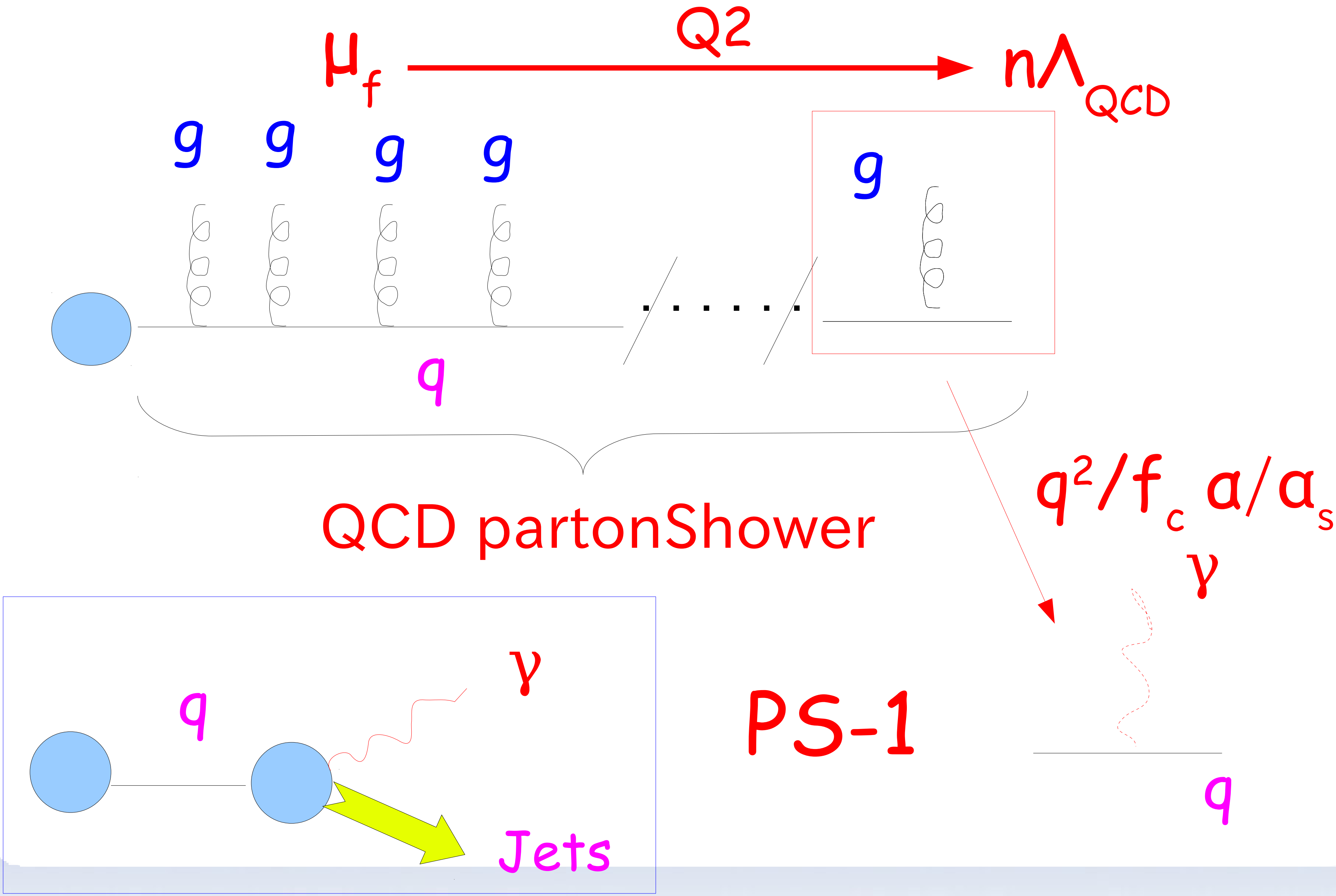
Fragmentation Processes



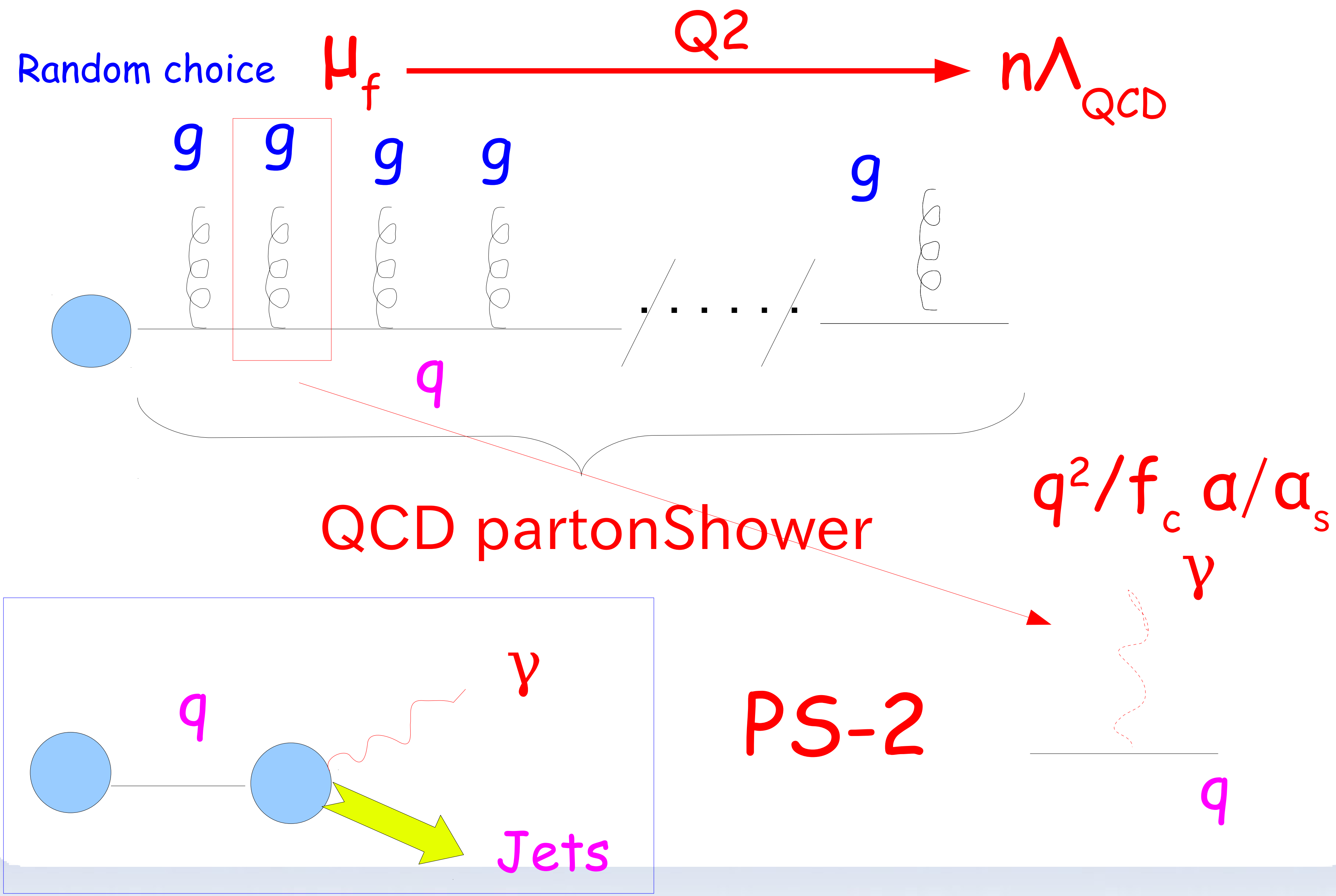
single fragmentation double fragmentation

- DIPHOX
  - Fragmentation Function
  - Inclusive Jet → No Event-Generation
- GR@PPA
  - Parton Shower (QCD/QED Mixed)
  - Fully Exclusive→Event-Generation

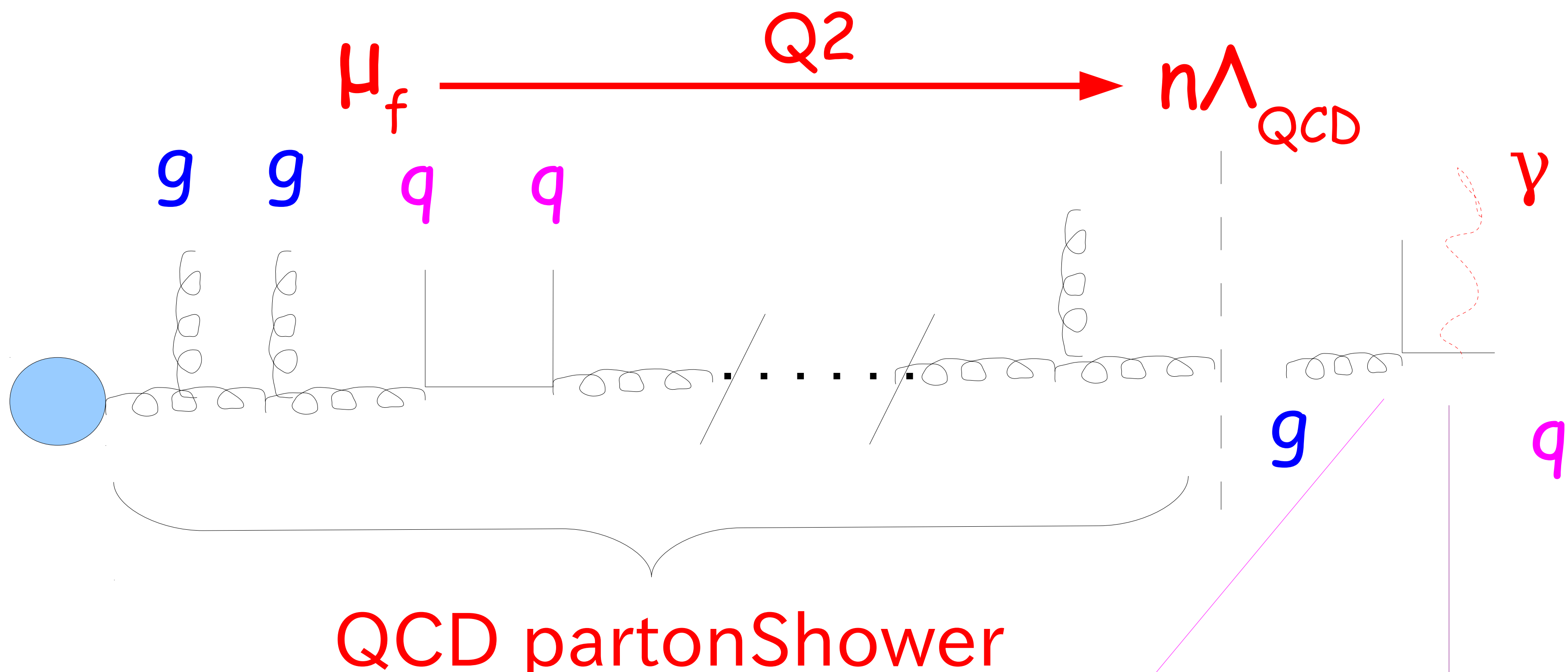
GRACE for LHC : QCED PS

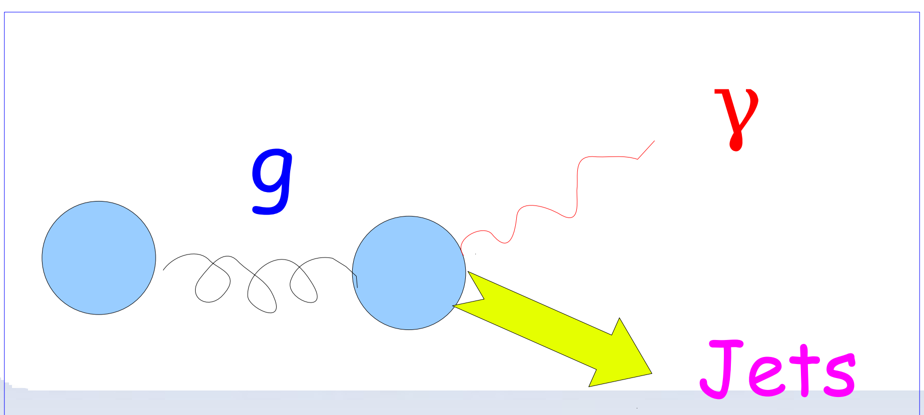


GRACE for LHC : QCED PS



GRACE for LHC : QCED PS





4%

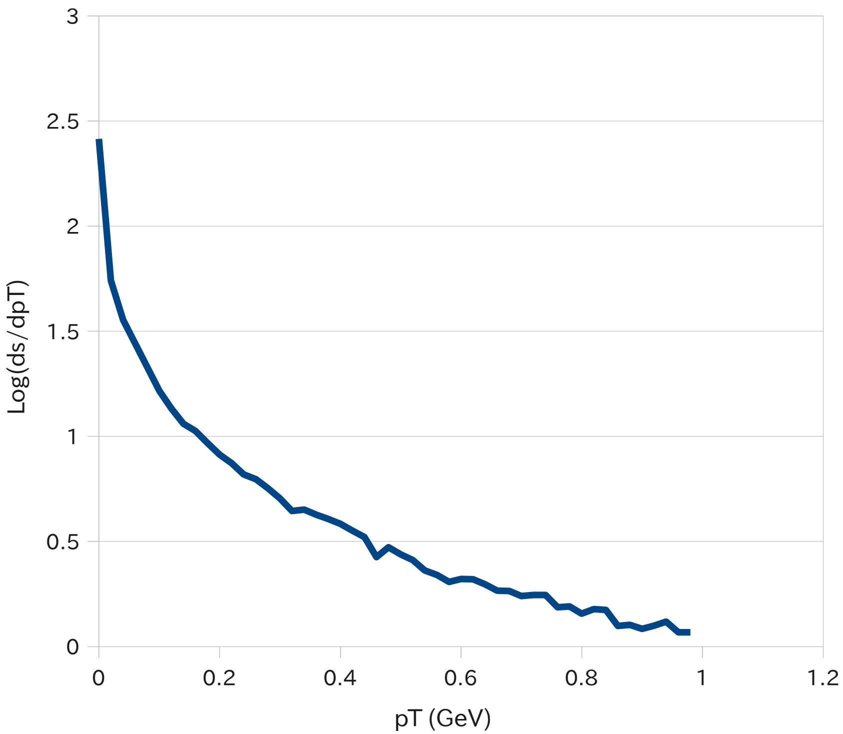
g→qq

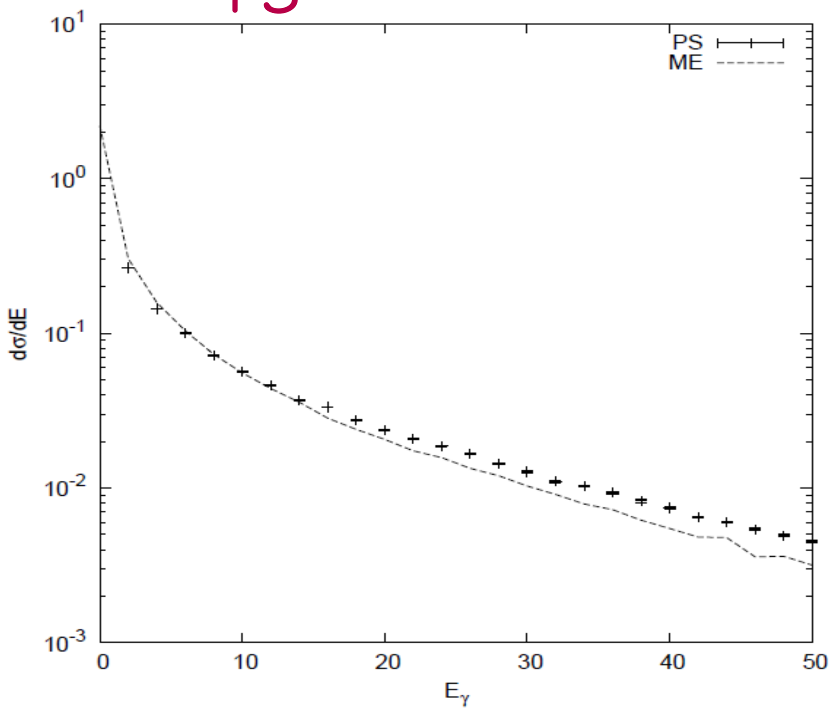
$$\frac{\alpha}{2\pi}\frac{1}{k_T^2}\frac{1+x^2}{1-x}$$

GRACE for LHC : QCED PS

$Q2=(50\ GeV)\sim(5\Lambda_{QCD})$, E_{gluon} = 100GeV

PS ME calc. uu →g* → dd γ
* PS



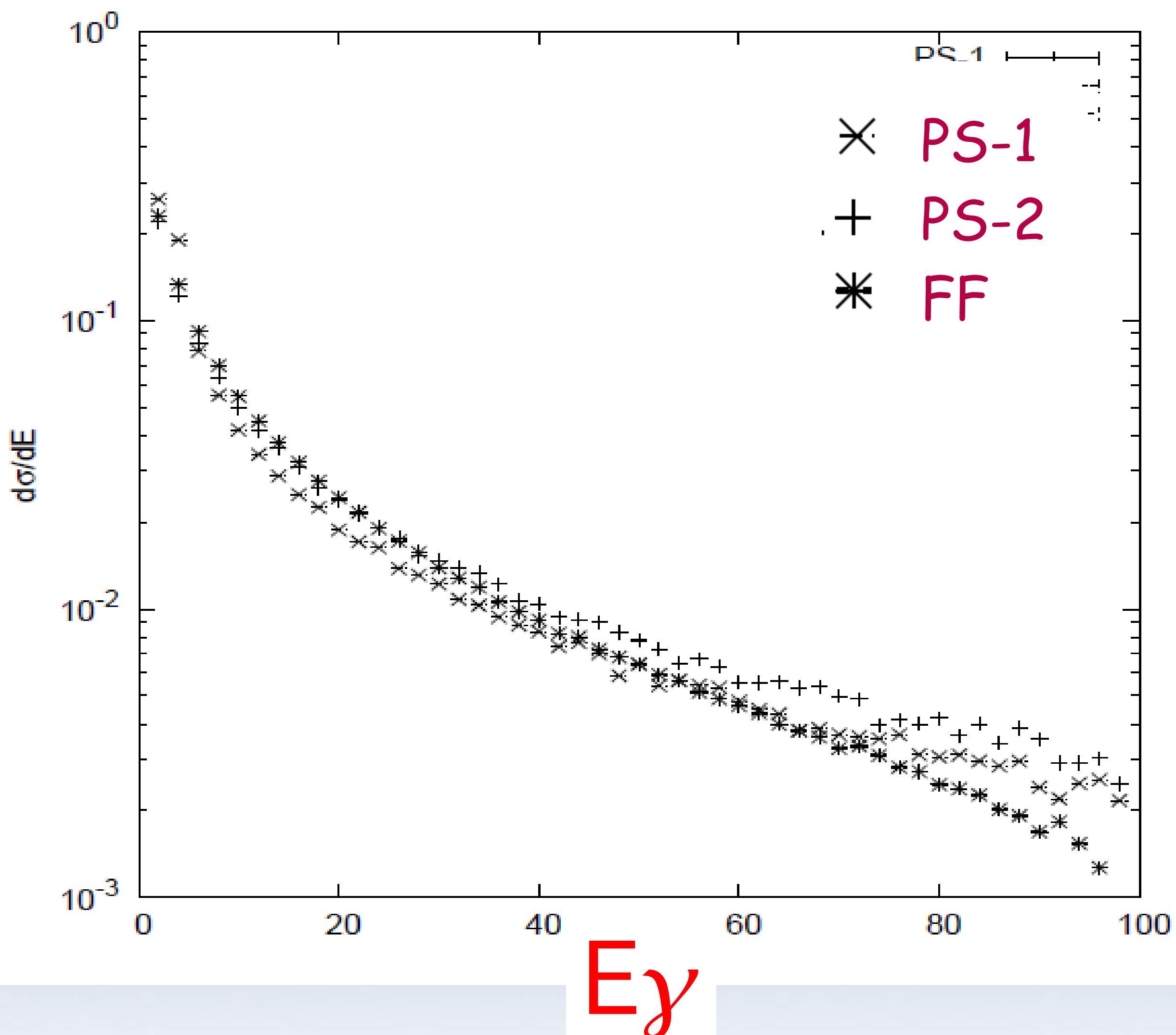


jet pT γ energy

GRACE for LHC : QCED PS

Comparison w/ Fragmentation Function Method

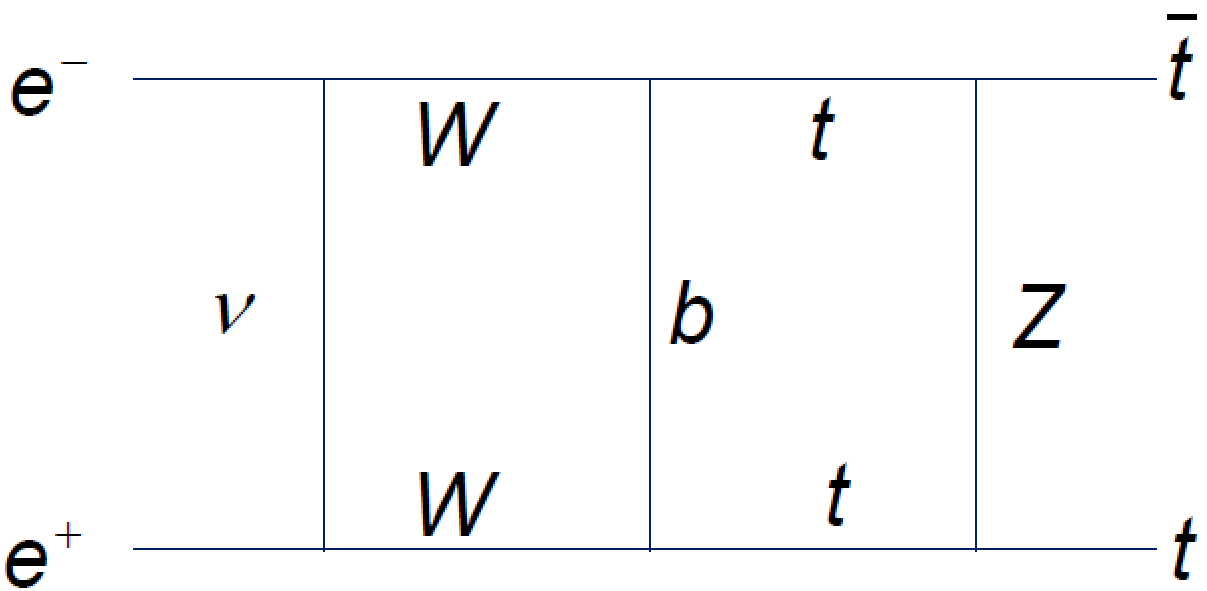
γ energy



Multi-Loop Integration

Multi-Loop : DCM

Formulae for 2-loop integrals are given for many cases: However, it seems to be difficult to write ‘general solution’ .



K. Kato, QFTHEP2011

Multi-Loop : DCM

example

$$\int_0^1 \frac{dx}{m^2 - sx(1-x) - i\varepsilon}$$

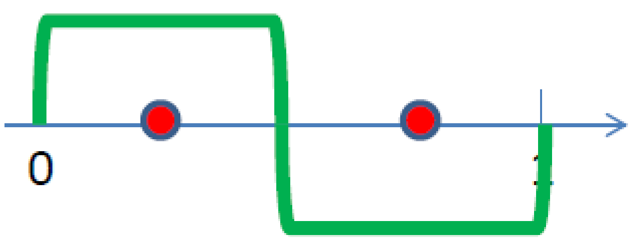
Analytic

$$\left.\frac{1}{z - i\varepsilon}\right|_{\varepsilon \to +0} = \mathrm{P}\frac{1}{z} + i\pi\delta(z)$$

Numerical

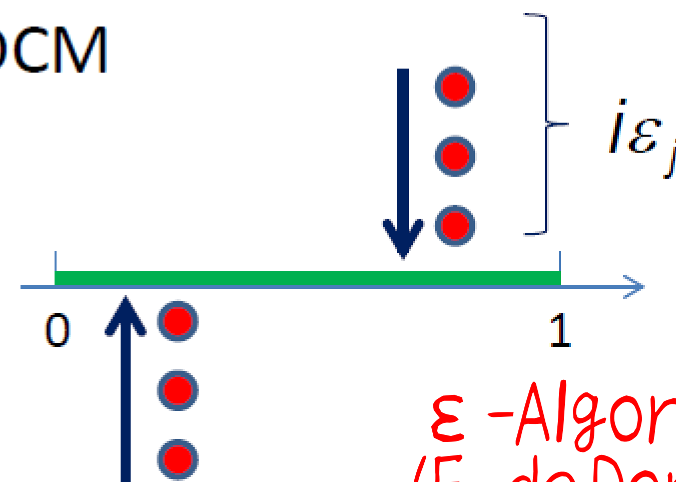
$$\varepsilon_j = \frac{\varepsilon_0}{A_c^j}$$

Contour deformation



would be hard for multi-x case

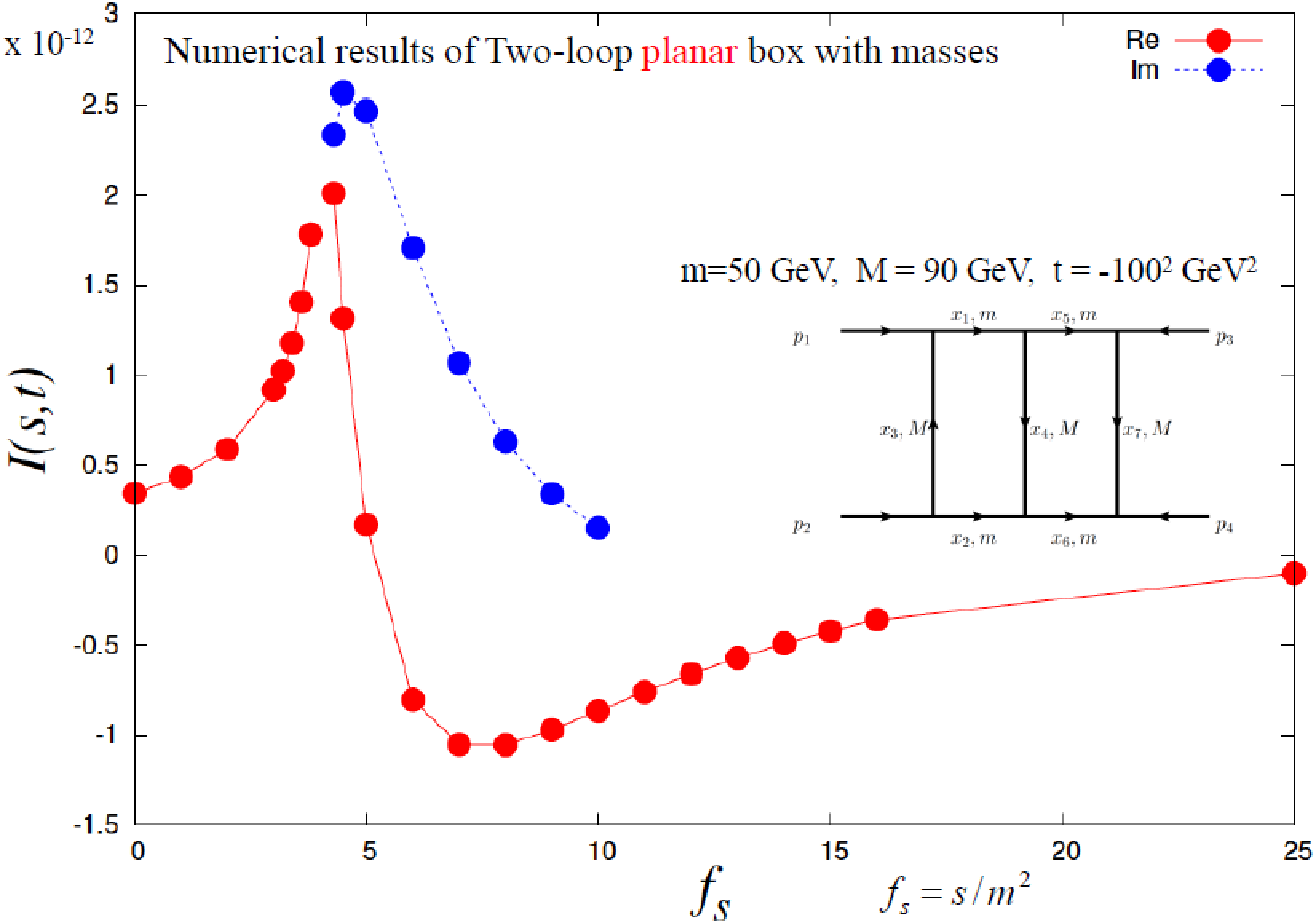
DCM



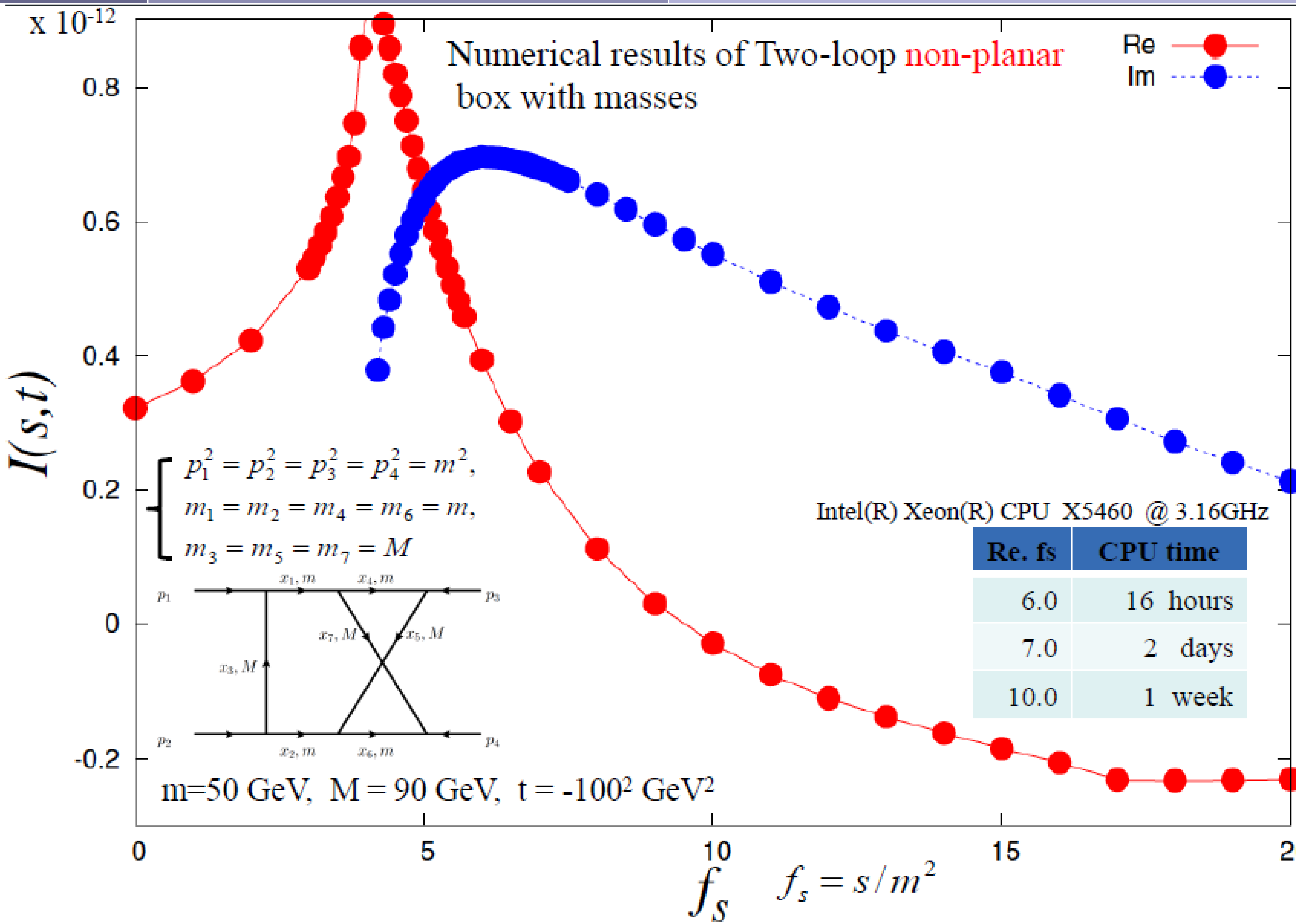
ε -Algorithm
(E. de Doncker)

K. Kato, QFTHEP2011

Multi-Loop : DCM



Multi-Loop : DCM



Re. fs	CPU time
6.0	16 hours
7.0	2 days
10.0	1 week

Summary

- GRACE is a Automatic Generator of Generators
- Electro-weak SM, QCD, MSSM @ 1-Loop order
- GR@PPA 2.8
  - Full Exclusive unweighted Hadron Event Generator w/ ME⇔PS Matching @ Tree Level
  - 2.8 → 3.0 : NLO +QECD PS Full Exclusive unweighted Event Generator
- Direct Computation Method (DCM)
  - Unique numerical method for loop integeations
  - General masses & momenta
  - Any polynomials of Feynman-parameters on numerator