Status of GRACE Development

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Outline

- Introduction
- What is GRACE ?
- GRACE for SUSY Processes
- QCD Event-Generators for LHC
- Summary

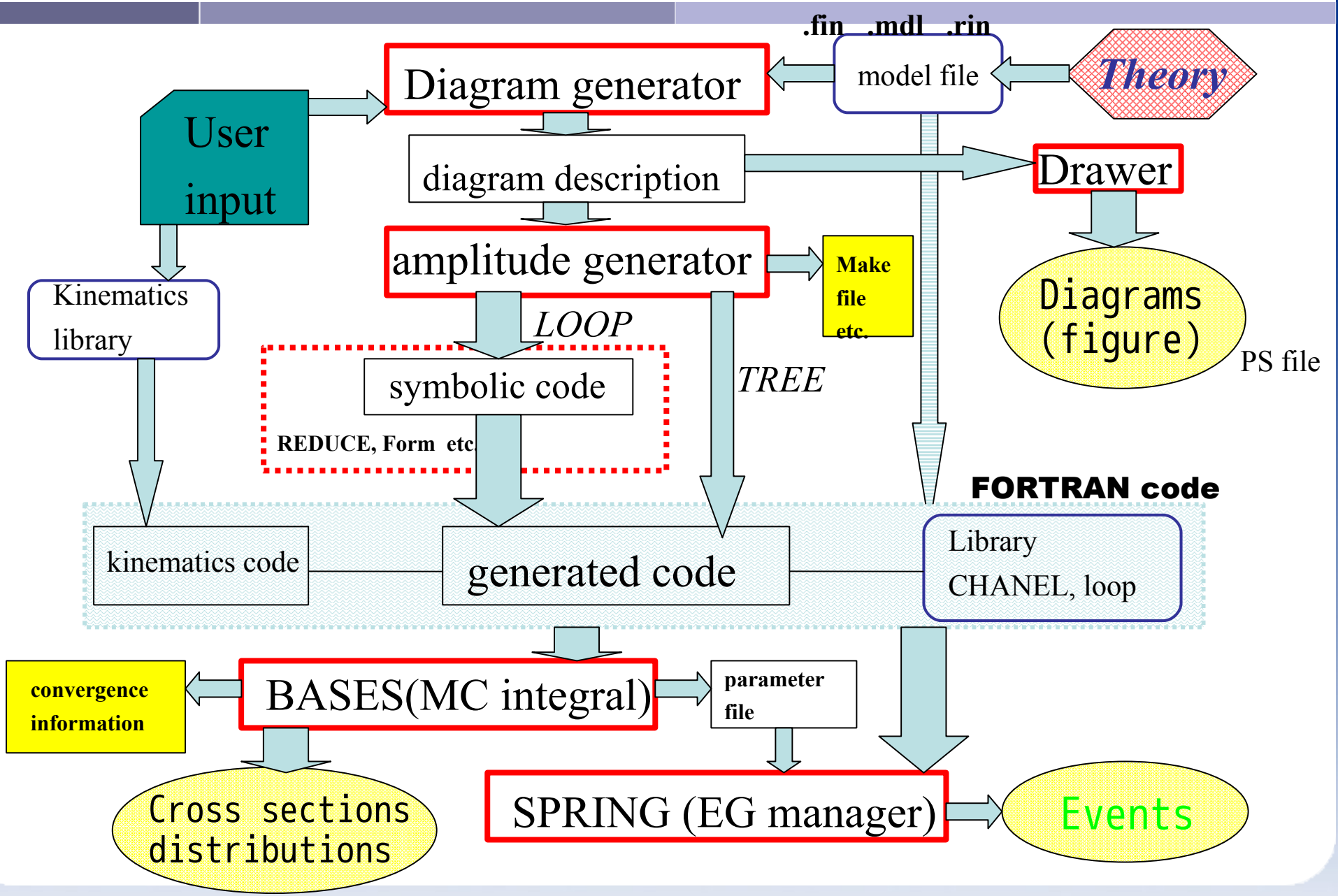
Introduction

- Automatic Calculation Systems
  - This year is 20's Anniversary!
  - GRACE meets CompHEP at AIHENP1990@Lyon
  - Battle Field of "LEP-II War" @1995
  - Tree to Loop
  - Leptons to Quarks
  - SM to BSM

No ACS, No Physics!

What is GRACE ?

What is GRACE? : Structure



What is GRACE? : Model File 1

```
%=======================================
% gauge bosons
%---------------------------------------
 Particle=W-plus["W+"]; Antiparticle=W-minus["W-"];
     Gname={"W", "W^+", "W^-"};
     PType=Vector; Charge=1; Color=1; Mass=amw; Width=agw;
     PCode=2; KFCode=24; Gauge="wb";
 Pend;
%
 Particle=Z["Z0"];       Antiparticle=Particle;
     Gname={"Z^0"};
     PType=Vector; Charge=0; Color=1; Mass=amz; Width=agz;
     PCode=4; KFCode=23; Gauge="zb";
 Pend;
%
 Particle=photon["A"];    Antiparticle=Particle;
     Gname={"\gamma"};
     PType=Vector; Charge=0; Color=1; Mass=ama; Width=0;
     PCode=1; Massless; KFCode=22; Gauge="ab";
 Pend;
%
 Particle=gluon["g"]; Antiparticle=Particle;
     Gname={"g"};
     PType=Vector; Charge=0; Color=8; Mass=amg; Width=0;
     PCode=8; Massless; KFCode=21;
     Gauge="gl"; PSelect="gluon";
 Pend;
```

What is GRACE? : Model File 2

```
 Vertex={u-bar, u, Z}; ELWK=1; FName=czuu(2,1/3);
          Vend;
 Vertex={c-bar, c, Z}; ELWK=1; FName=czuu(2,2/3);
          Vend;
 Vertex={t-bar, t, Z}; ELWK=1; FName=czuu(2,3/3);
          Vend;
 Vertex={d-bar, d, Z}; ELWK=1; FName=czdd(2,1/3);
          Vend;
 Vertex={s-bar, s, Z}; ELWK=1; FName=czdd(2,2/3);
          Vend;
 Vertex={b-bar, b, Z}; ELWK=1; FName=czdd(2,3/3);
          Vend;
%-------------------------------------
% FFV (FFg)
%-------------------------------------
 Vertex={u-bar, u, gluon}; QCD=1; FName=cguu(2,1/3);
          FType="V"; Vend;
 Vertex={d-bar, d, gluon}; QCD=1; FName=cgdd(2,1/3);
          FType="V"; Vend;
 Vertex={c-bar, c, gluon}; QCD=1; FName=cguu(2,2/3);
          FType="V"; Vend;
 Vertex={s-bar, s, gluon}; QCD=1; FName=cgdd(2,2/3);
          FType="V"; Vend;
 Vertex={b-bar, b, gluon}; QCD=1; FName=cguu(2,3/3);
          FType="V"; Vend;
 Vertex={t-bar, t, gluon}; QCD=1; FName=cgdd(2,3/3);
          FType="V"; Vend;
```

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

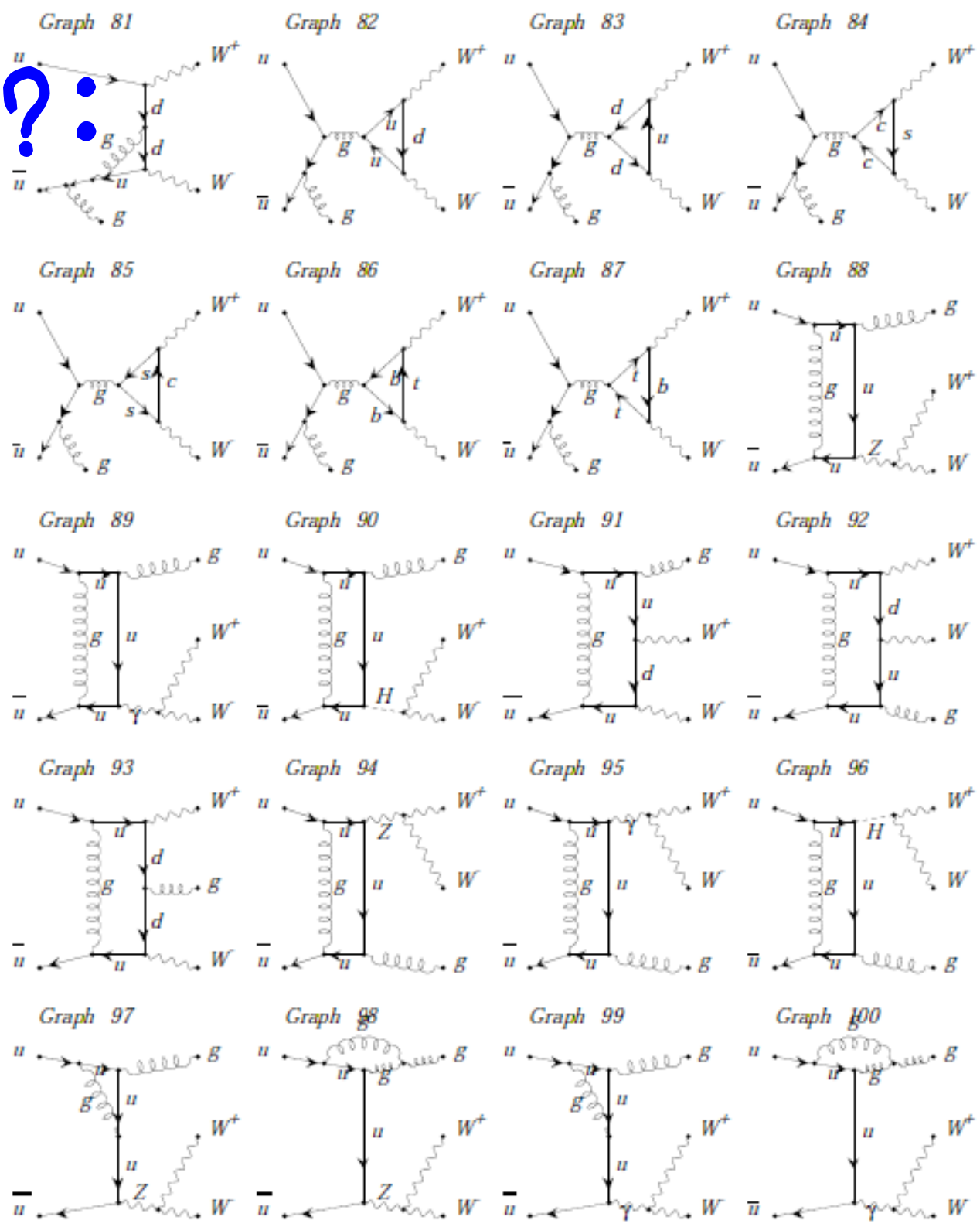
initial state particles

final state particles

kinematics number

What is GRACE? :

Diagrams



What is GRACE? :

FORTRAN Code

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

      include 'inctrl.h'
      include 'inclk.h'
      include 'inctrp.h'
*-----------------------------------------------------------------------
      common /amwork/cftr13q,av4,av5,extr13q,pttr13q
      common /amwori/lt4,lt5
*     880 (880) + 32 (32) bytes used

      integer     lt4(0:3),lt5(0:3)
      real*8      extr13q(2),pttr13q(4,3)
      complex*16 cftr13q(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 smprpd(pphase,aprop,vntr13,
     &      amuq**2,0.0d0)

* Internal momenta
      call smintf(amuq,pftr13,vntr13,extr13q,pttr13q,cftr13q)

* Vertices (6)
      call smffv(lextrn,lintrn,lepexa,extr2q,extr13q,amuq,amuq,cguq,
     &           cftr2q,cftr13q,pttr2q,pttr13q,eqtr14e,lt4,av4)
      call smffv(lintrn,lextrn,lepexv,extr13q,extr4t,amuq,amdq,cwuq,
     &           cftr13q,cftr4t,pttr13q,pttr4t,eqtr9b,lt5,av5)

      call smconf(lt4,lt5,2,1,extr13q,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 atrmpord(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

Date: 10/ 9/10 01:24

Convergency Behavior for the Grid Optimization Step

<- Result of IT	Eff	R_Neg	each iteration -> Estimate	Acc %	<- Cumulative Result Estimate(+- Error)order	Acc %	-> < CPU time > (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

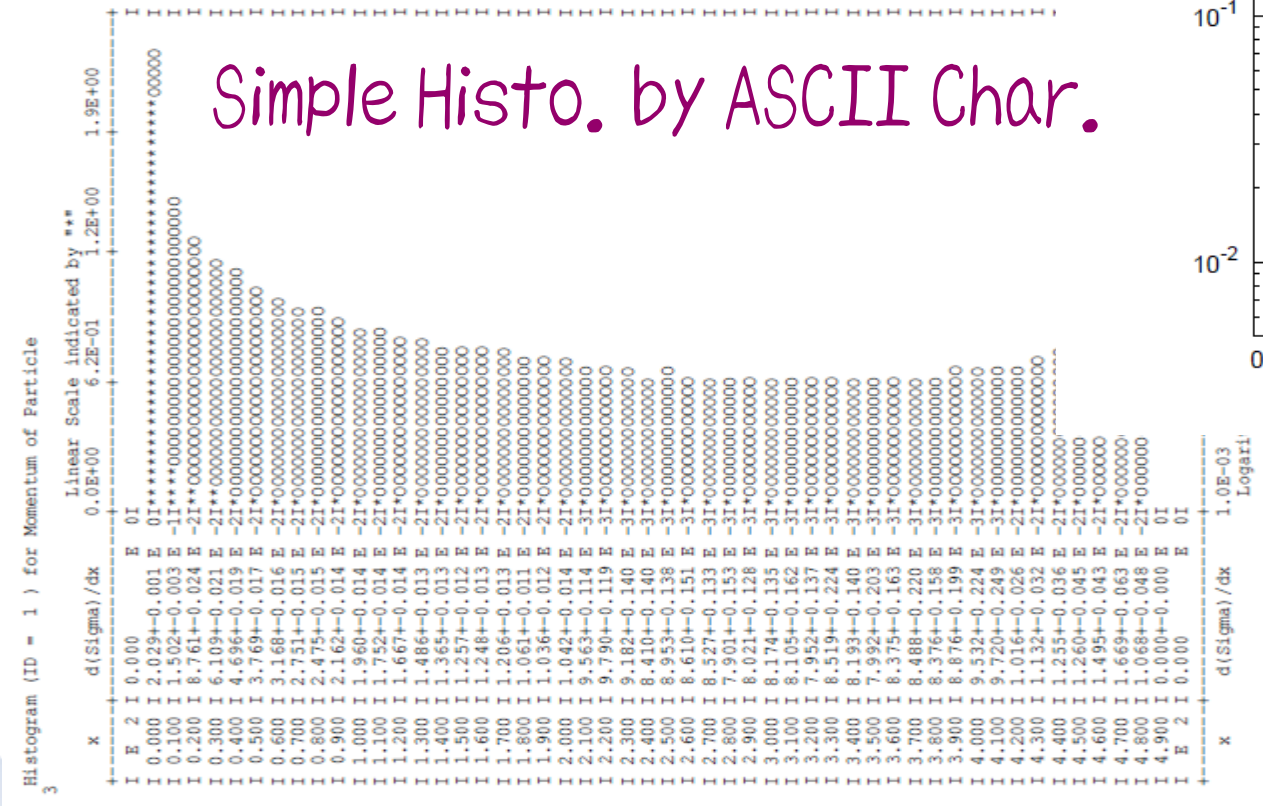
<- Result of IT	Eff	R_Neg	each iteration -> Estimate	Acc %	<- Cumulative Result Estimate(+- Error)order	Acc %	-> < CPU time > (H: M: Sec)
1	100	0.00	2.939E+01	0.115	2.939291(+-0.003370)E 01	0.115	0: 2:30.75
2	100	0.00	2.941E+01	0.111	2.940266(+-0.002348)E 01	0.080	0: 3: 0.92
3	100	0.00	2.941E+01	0.109	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

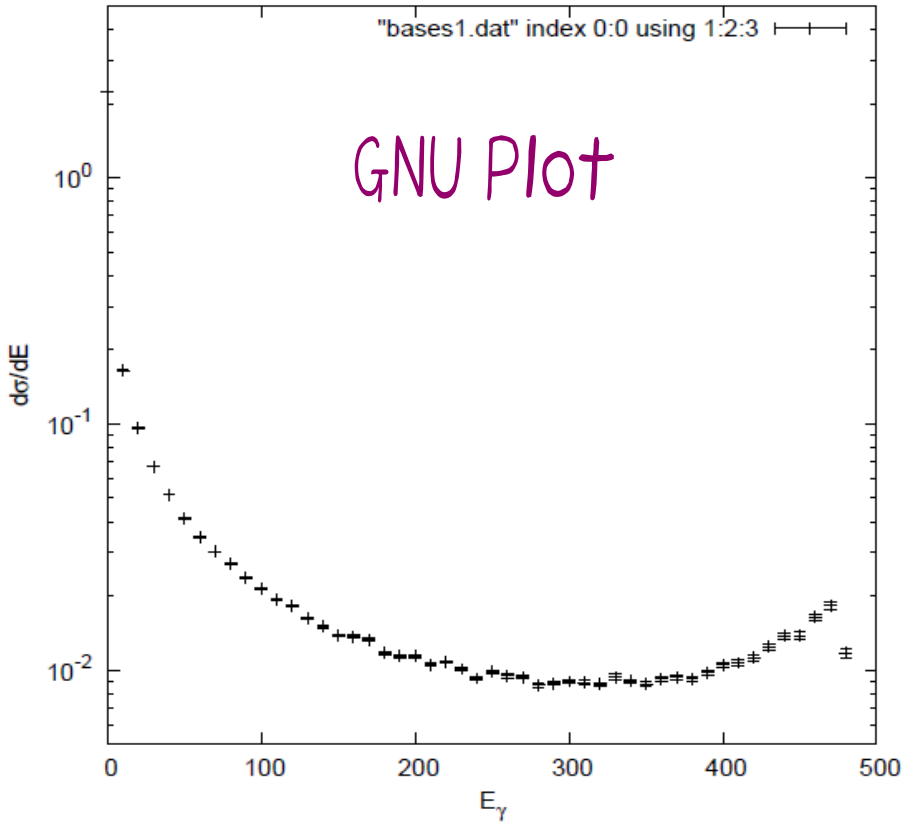
Integration Result (pb)

Accuracy (%)

What is GRACE? : Distributions

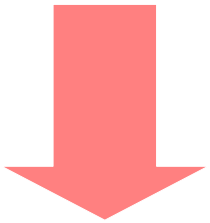
Energy Distribution





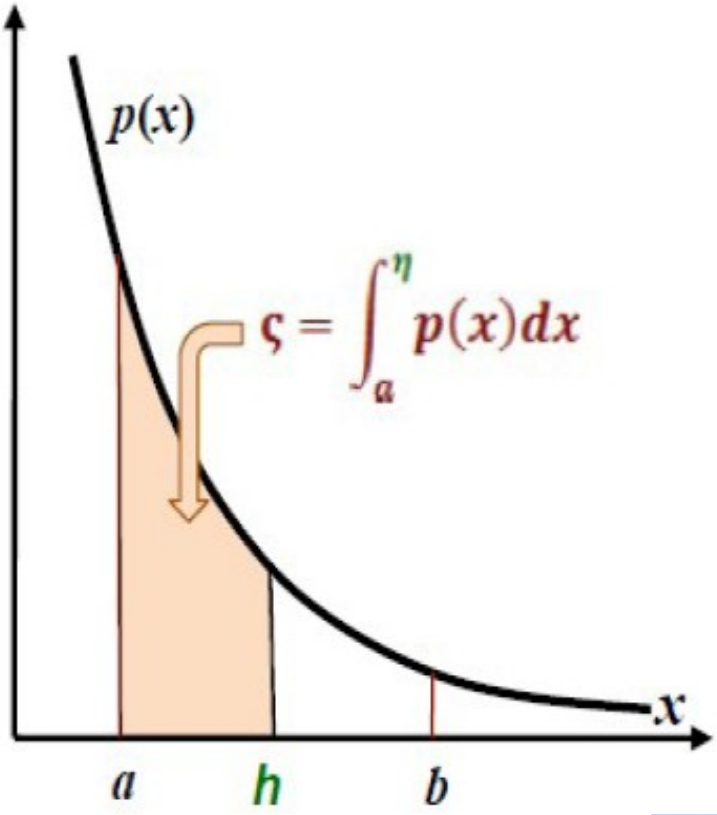
What is GRACE? : Event Generation

- Numerical Integration by BASES
  - Probability Density Matrix



  - Event Generation

    W/ unit Weight
  - LHAccord Interface



GRACE for SUSY

GRACE for SUSY : Gauge Fixing

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

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

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

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

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

GRACE for SUSY : Gauge Fixing

- Non-linear Gauge Fixing : S-leptons
  - $\mathscr{L}_{\text{GF-S}} =$

$$
\begin{aligned}
&+ig\left[\sum_{ij}\left\{\tilde{c}_{ij}^{du}\left(\tilde{d}_i^*\tilde{u}_j\right)+\tilde{c}_{ij}^{sc}\left(\tilde{s}_i^*\tilde{c}_j\right)+\tilde{c}_{ij}^{bt}\left(\tilde{b}_i^*\tilde{t}_j\right)\right\}+\sum_i\left\{\tilde{c}_i^{e}\left(\tilde{e}_i^*\tilde{\nu}_e\right)+\tilde{c}_i^{\mu}\left(\tilde{\mu}_i^*\tilde{\nu}_\mu\right)+\tilde{c}_i^{\tau}\left(\tilde{\tau}_i^*\tilde{\nu}_\tau\right)\right\}\right]\\
&-ig\left[\sum_{ij}\left\{\tilde{c}_{ij}^{ud}\left(\tilde{u}_i^*\tilde{d}_j\right)+\tilde{c}_{ij}^{cs}\left(\tilde{c}_i^*\tilde{s}_j\right)+\tilde{c}_{ij}^{tb}\left(\tilde{t}_i^*\tilde{b}_j\right)\right\}+\sum_i\left\{\tilde{c}_i^{e}\left(\tilde{\nu}_e^*\tilde{e}_i\right)+\tilde{c}_i^{\mu}\left(\tilde{\nu}_\mu^*\tilde{\mu}_i\right)+\tilde{c}_i^{\tau}\left(\tilde{\nu}_\tau^*\tilde{\tau}_i\right)\right\}\right]\\
&+g_Z\left[\sum_{ij}\left\{\tilde{c}_{ij}^{uu}\left(\tilde{u}_i^*\tilde{u}_j\right)+\tilde{c}_{ij}^{dd}\left(\tilde{d}_i^*\tilde{d}_j\right)+\tilde{c}_{ij}^{cc}\left(\tilde{c}_i^*\tilde{c}_j\right)+\tilde{c}_{ij}^{ss}\left(\tilde{s}_i^*\tilde{s}_j\right)+\tilde{c}_{ij}^{tt}\left(\tilde{t}_i^*\tilde{t}_j\right)+\tilde{c}_{ij}^{bb}\left(\tilde{b}_i^*\tilde{b}_j\right)\right\}\right.\\
&\left.+\tilde{c}^{\nu_e\nu_e}\left(\tilde{\nu}_e^*\tilde{\nu}_e\right)+\tilde{c}^{\nu_\mu\nu_\mu}\left(\tilde{\nu}_\mu^*\tilde{\nu}_\mu\right)+\tilde{c}^{\nu_\tau\nu_\tau}\left(\tilde{\nu}_\tau^*\tilde{\nu}_\tau\right)+\sum_{ij}\left\{\tilde{c}_{ij}^{ee}\left(\tilde{e}_i^*\tilde{e}_j\right)+\tilde{c}_{ij}^{\mu\mu}\left(\tilde{\mu}_i^*\tilde{\mu}_j\right)+\tilde{c}_{ij}^{\tau\tau}\left(\tilde{\tau}_i^*\tilde{\tau}_j\right)\right\}\right]
\end{aligned}
$$

GRACE for SUSY : Renomarization

- Electro-weak corrections
  - On-Mass-Shell scheme

    → mass shifts for h^0, $H^{\pm}$, $\chi^0_{2,3,4}$ only
  - Sfermion sector

→ residue conditions: $\delta Z_{\tilde{f}\tilde{f}} = \frac{\partial}{\partial q^2}\Sigma(q^2)\Big|_{q^2\to m^2_{\tilde{f}}} \equiv \Sigma'(m^2_{\tilde{f}})$

$\tilde{f}_1 - \tilde{f}_2$ decoupling conditions:

$$\frac{1}{2}\delta Z_{\tilde{f}_i\tilde{f}_j} = -\frac{\Sigma_{\tilde{f}_i\tilde{f}_j}(m^2_{\tilde{f}_j})}{m^2_{\tilde{f}_i} - m^2_{\tilde{f}_j}}, \quad i \neq j$$

external wave function: $\delta Z^{ext}_{\tilde{t}_2\tilde{t}_2} \neq 0,\ \delta Z^{ext}_{\tilde{b}_2\tilde{b}_2} \neq 0$

GRACE for SUSY : Renomarization

- QCD corrections

  * light quarks(u,d,c,s) and gluon
    $\Rightarrow$DR-bar scheme
    $\rightarrow$ PDF, parton-shower, …

  * massive quarks(b,t), squark and gluino
    $\Rightarrow$On-Mass-Shell scheme

  * IR regularization… $1/\bar{\varepsilon}$ (Dimensional)

    $d = 4 - 2\varepsilon = 4 + 2\bar{\varepsilon}$

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 = 0.151171157527971271866108335039543 23

Case 2 : (Cuv=1000)

Ans = 0.151171157527971271865961802793978 01

  - IR-Cancellation Check

Case 1 : (λ =10^{-24})

Ans = 0.151171157527971271866108335039543 23

Case 2 : (λ =10^{-27})

Ans = 0.151171157527971271866108335199830 20

GRACE for SUSY : System Check

- Ex. for $\tilde{t}_1 \to b\tilde{\chi}_1^+$ One-Loop : (After Integration)
  - Electro-weak correction

Cuv	0	1000	0	0
λ (GeV)	10^{-24}	10^{-24}	10^{-27}	10^{-24}
kc (GeV)	10^{-3}	10^{-3}	10^{-3}	10^{-5}
loop	-0.06256	-0.06256	-0.09364	-0.06256
soft	0.21373	0.21373	0.24481	0.19301
hard	0.04849	0.04849	0.04849	0.06921
sum	0.19966	0.19966	0.19966	0.19966
correction	13.9%	13.9%	13.9%	13.9%

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 : (After Integration)
  - QCD Correction

Cuv	0	1	0
Cir	0	0	1
loop	-1.254	-1.254	-1.479
soft	-3.752	-3.752	-3.527
hard	4.905	4.905	4.905
sum	-0.100	-0.100	-0.100
correction	-7.1%	-7.1%	-7.1%

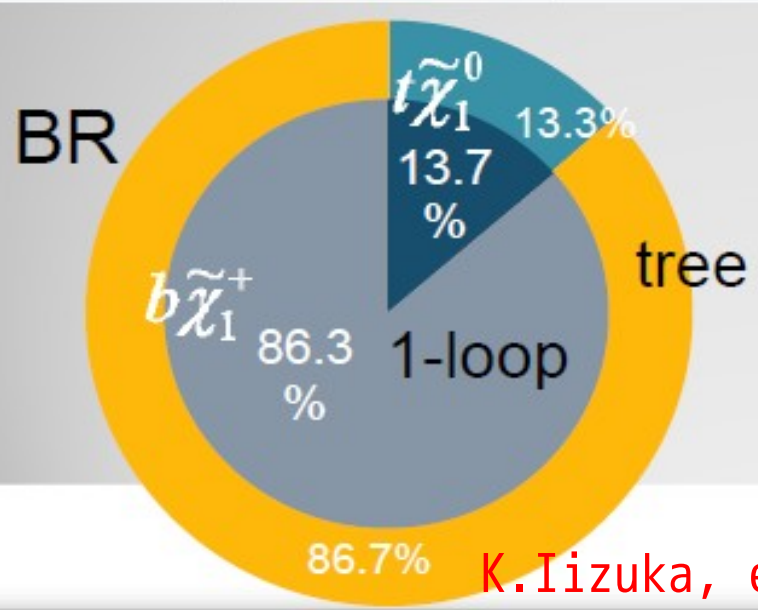
K.Iizuka, et al, POS(RADCOR2009)068[hep-ph/1001.2800]

GRACE for SUSY : Example

Summary of stop1 decay

Table4: summary of stop1 decay unit : [GeV]

	tree	δΓ (QCD) δΓ (ELWK)	δΓ/tree(QCD) δΓ/tree(ELWK)	total
$\tilde{t}_1 \to b\tilde{\chi}_1^+$	1.43267	-0.104 0.200	-7.1% 13.9%	6.8%
$\tilde{t}_1 \to t\tilde{\chi}_1^0$	0.22067	0.00461 0.01681	2.1% 7.6%	9.7%

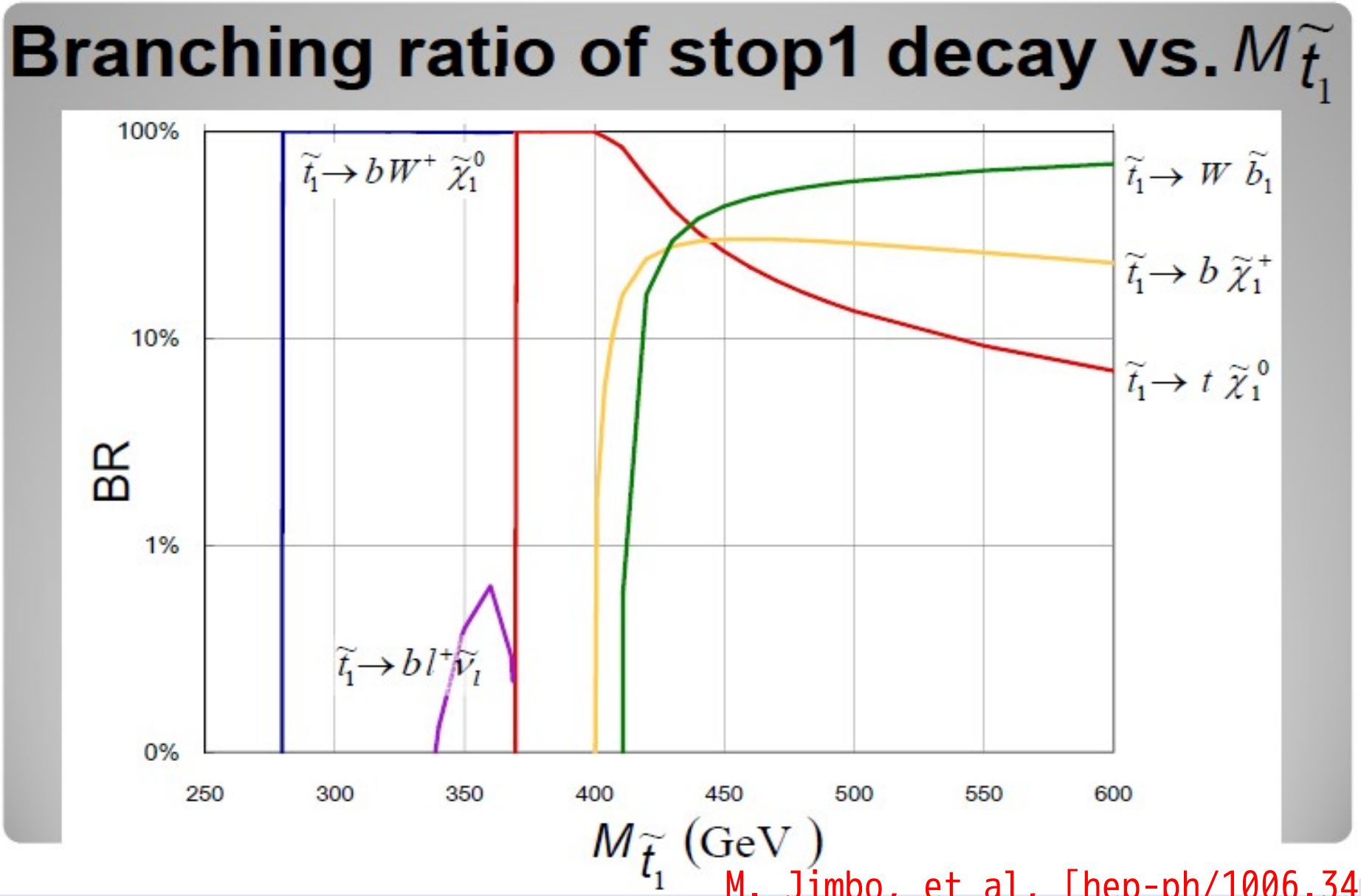


total decay width

Γ(tree) : 1.65 [GeV]
Γ(QCD) : 1.55 [GeV]
Γ(Electroweak) : 1.87 [GeV]
Γ(1-loop) : 1.77 [GeV]

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

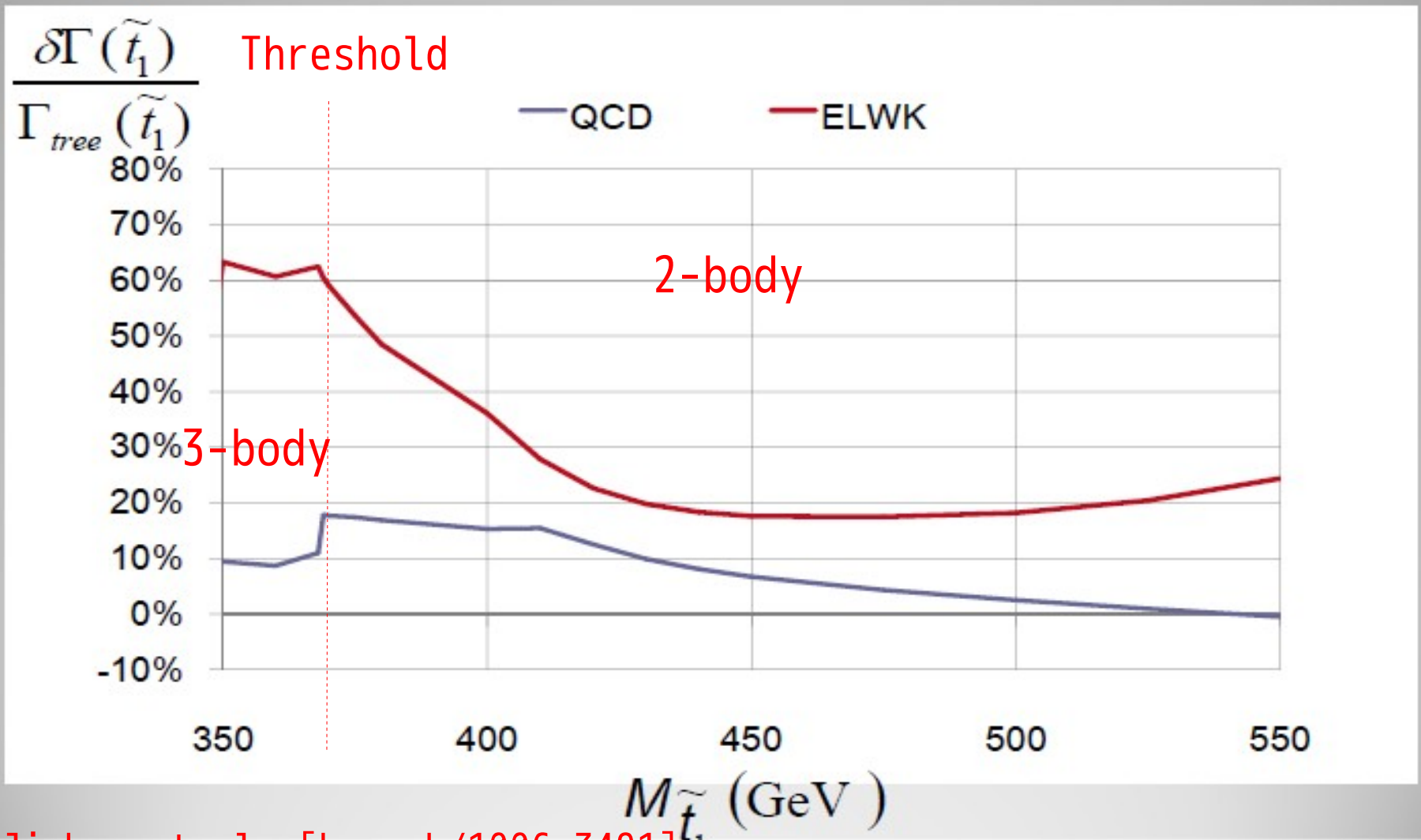
GRACE for SUSY : Example



M. Jimbo, et al, [hep-ph/1006.3491]

GRACE for SUSY : Example

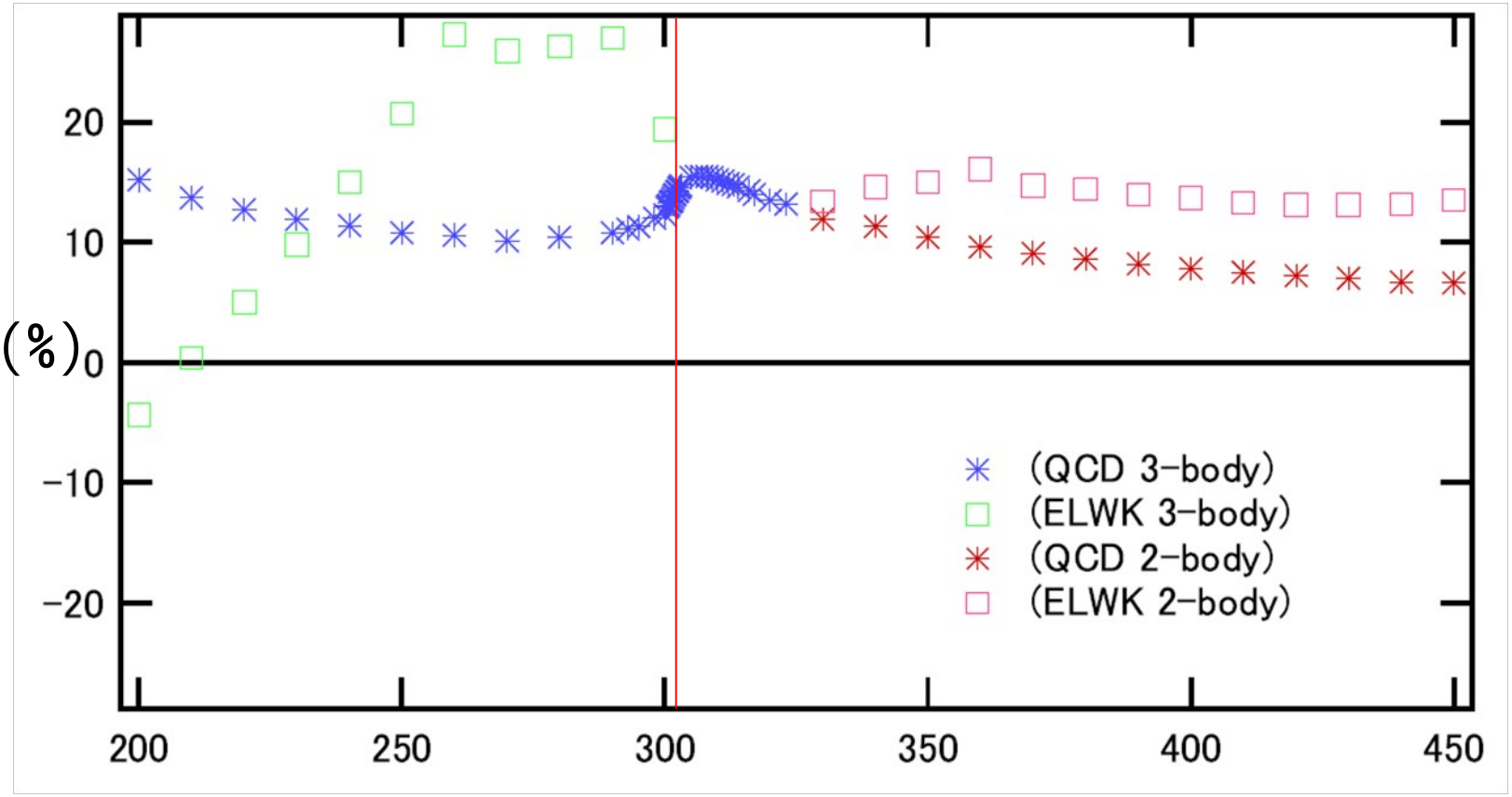
1-loop corrections for total width of stop1 vs. $M_{\tilde{t}_1}$



M. Jimbo, et al, [hep-ph/1006.3491]

GRACE for SUSY : Example

$\tilde{t}_1 \to b\nu_\tau\tilde{\tau}_1^+$



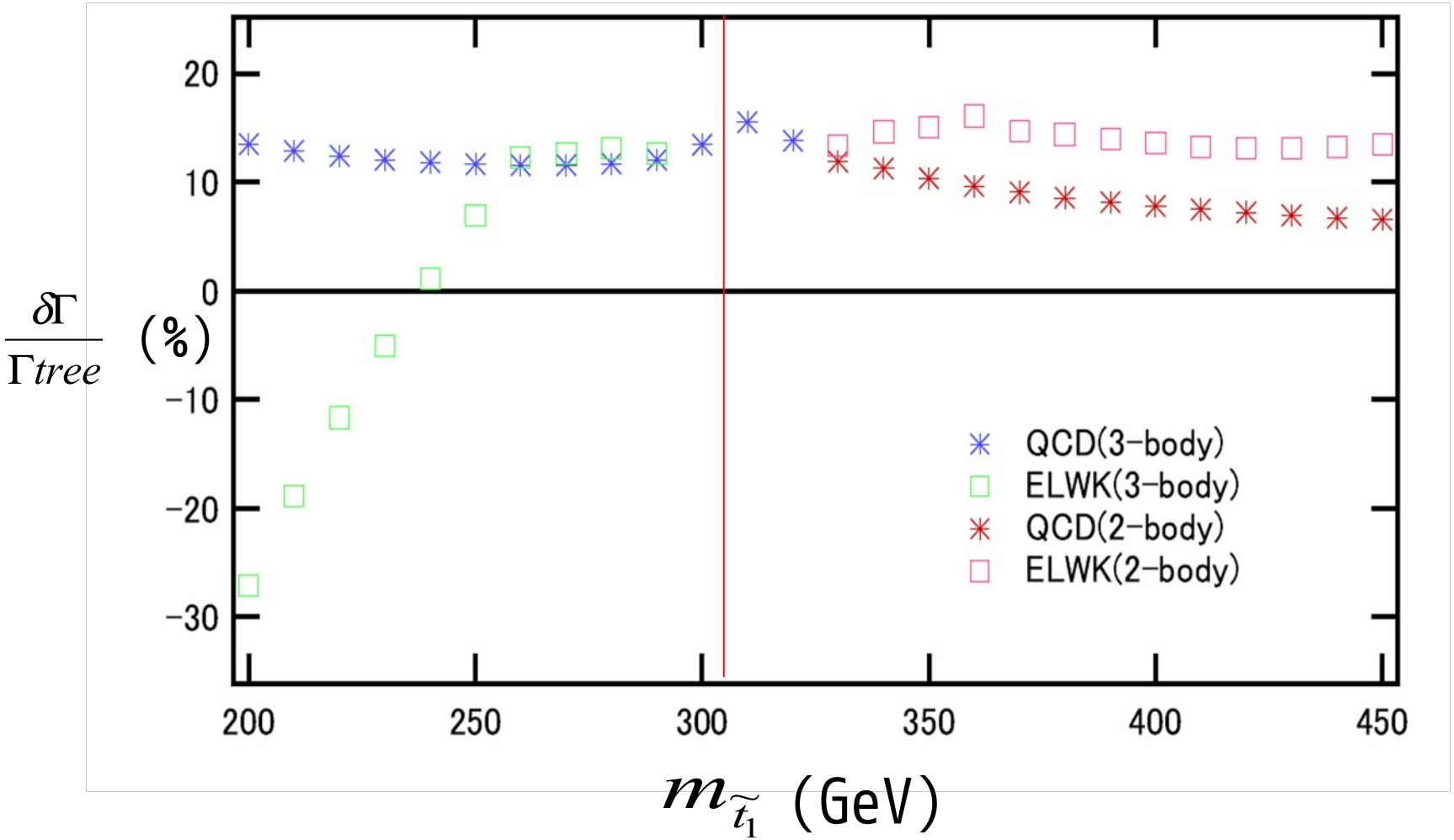
$\frac{\delta\Gamma}{\Gamma tree}$ (%)

$m_{\tilde{t}_1}$ (GeV)

T. Koike, et al, [JPS Meeting 2010/09/12]

GRACE for SUSY : Example

$\tilde{t}_1 \to b\tilde{\chi}_1^+$

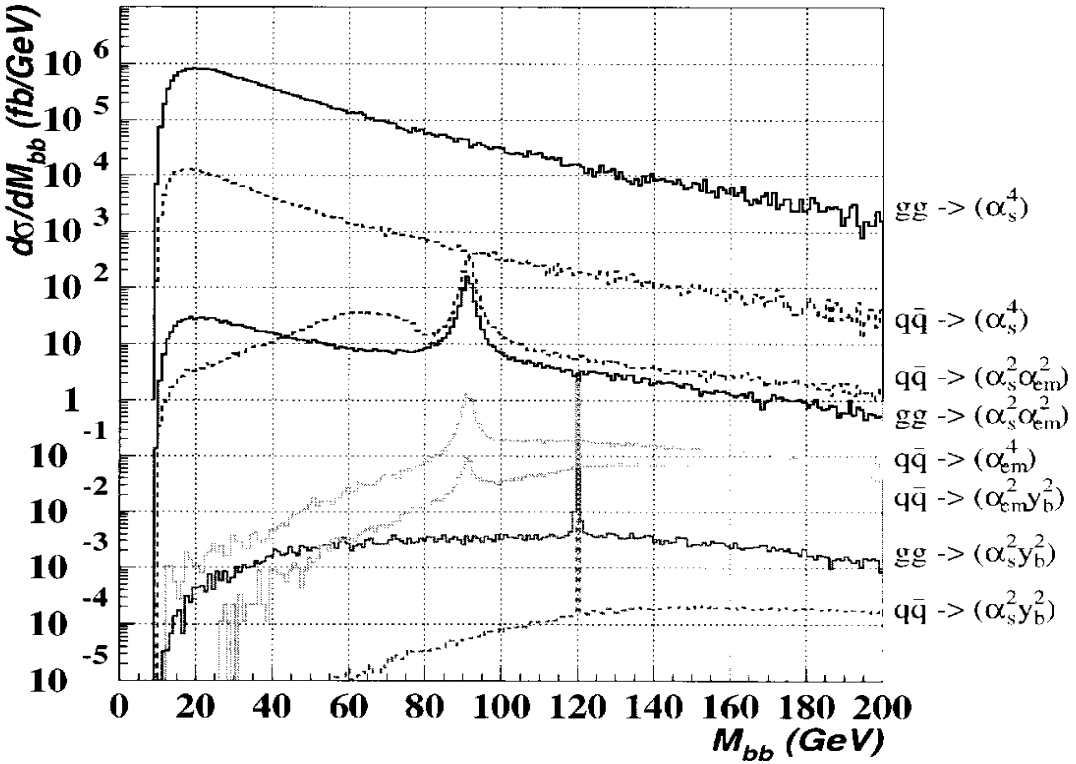


T. Koike, et al, [JPS Meeting 2010/09/12]

GRACE for LHC

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 LLPS
  - 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.

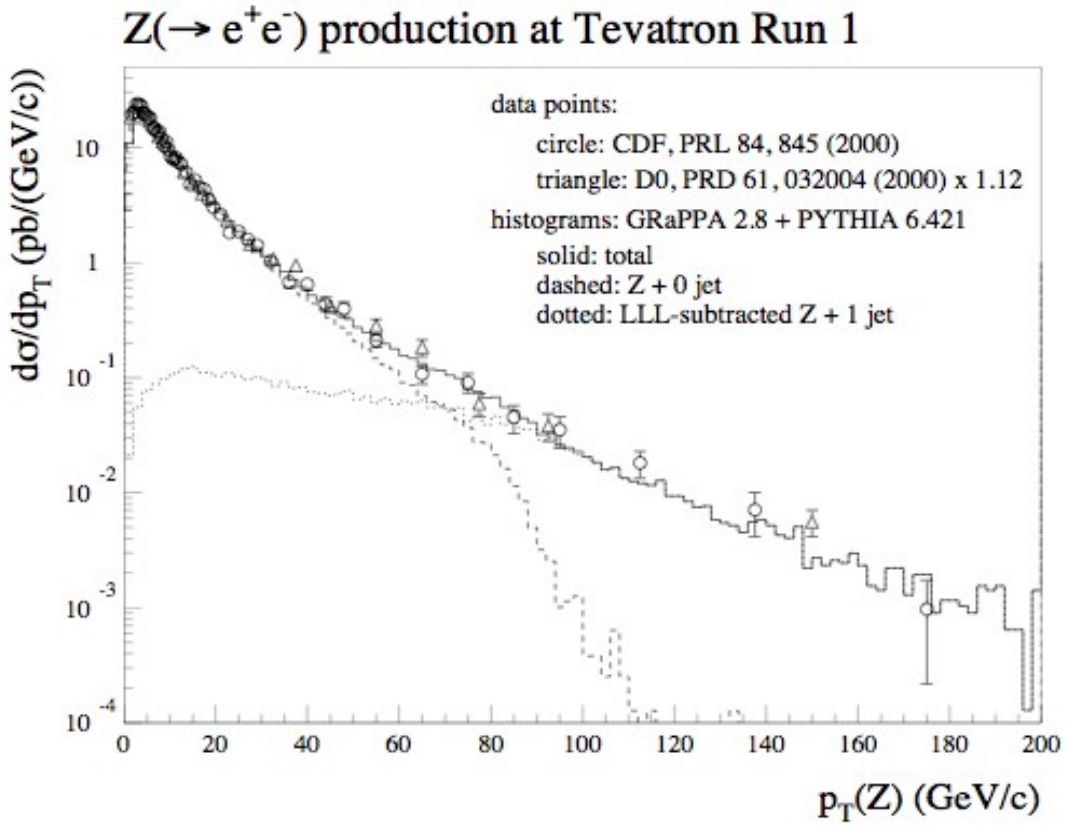
GRACE for LHC : GR@PPA 2.8

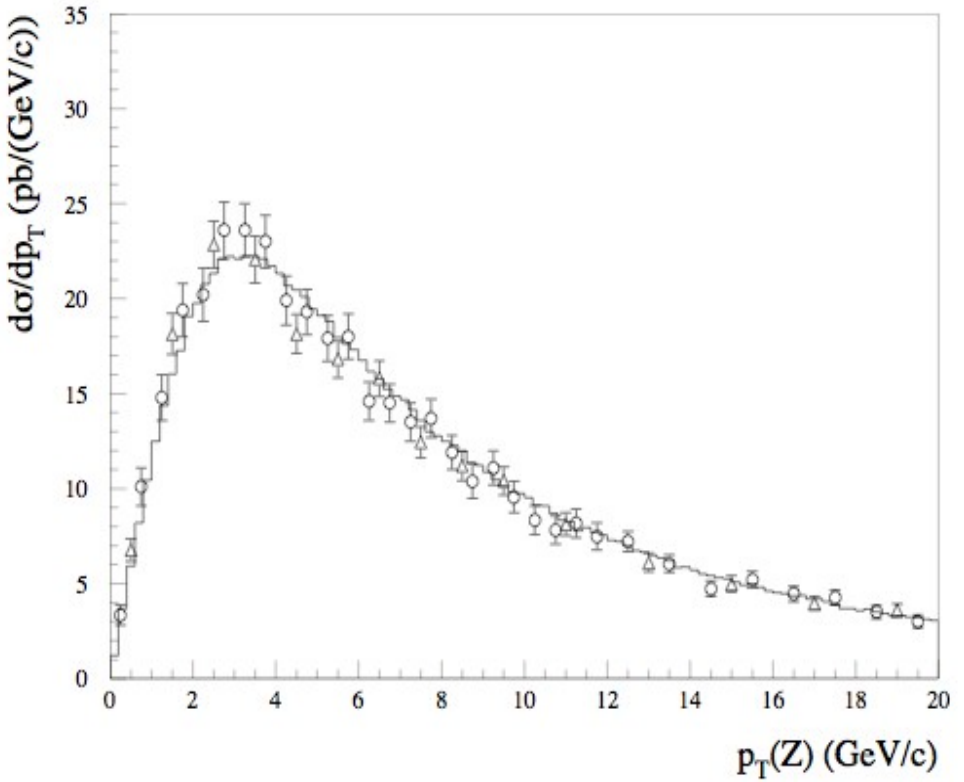
- Additional features
  - W and Z decays in the matrix elements
  - Exact spin, phase-space and off-shell effects at the tree level
  - PDG values for the decay widths and branching ratios of W and Z
  - Generated events can be passed to PYTHIA to proceed the simulation : hadronization and decays
  -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

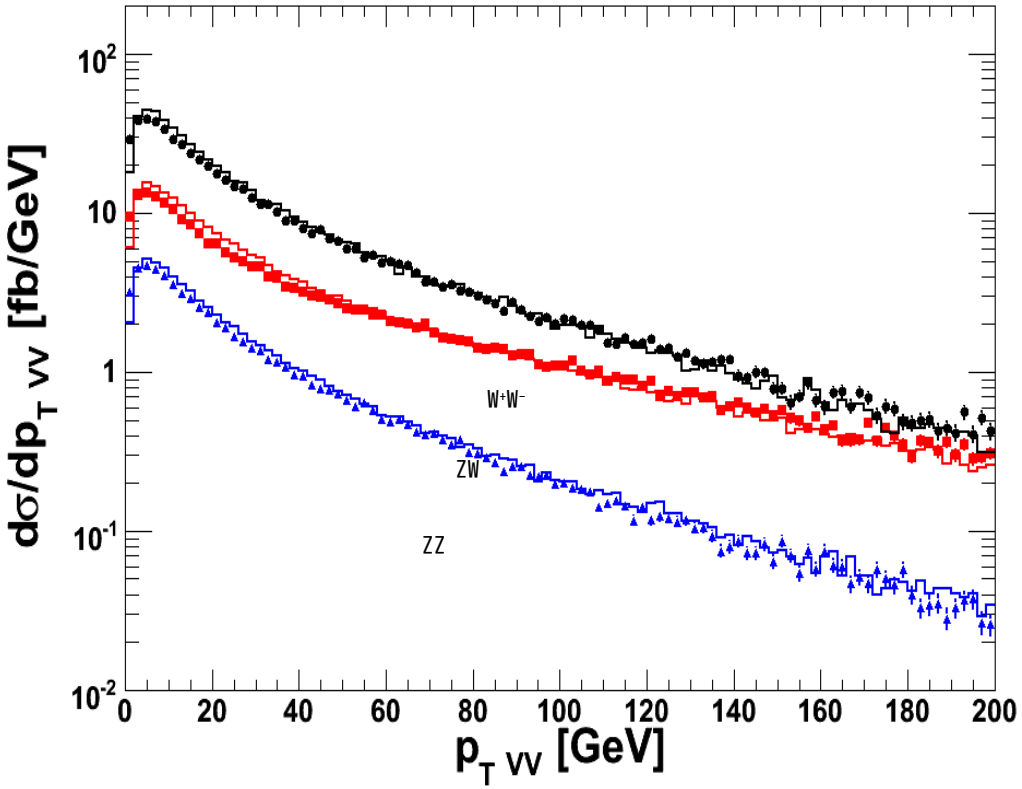


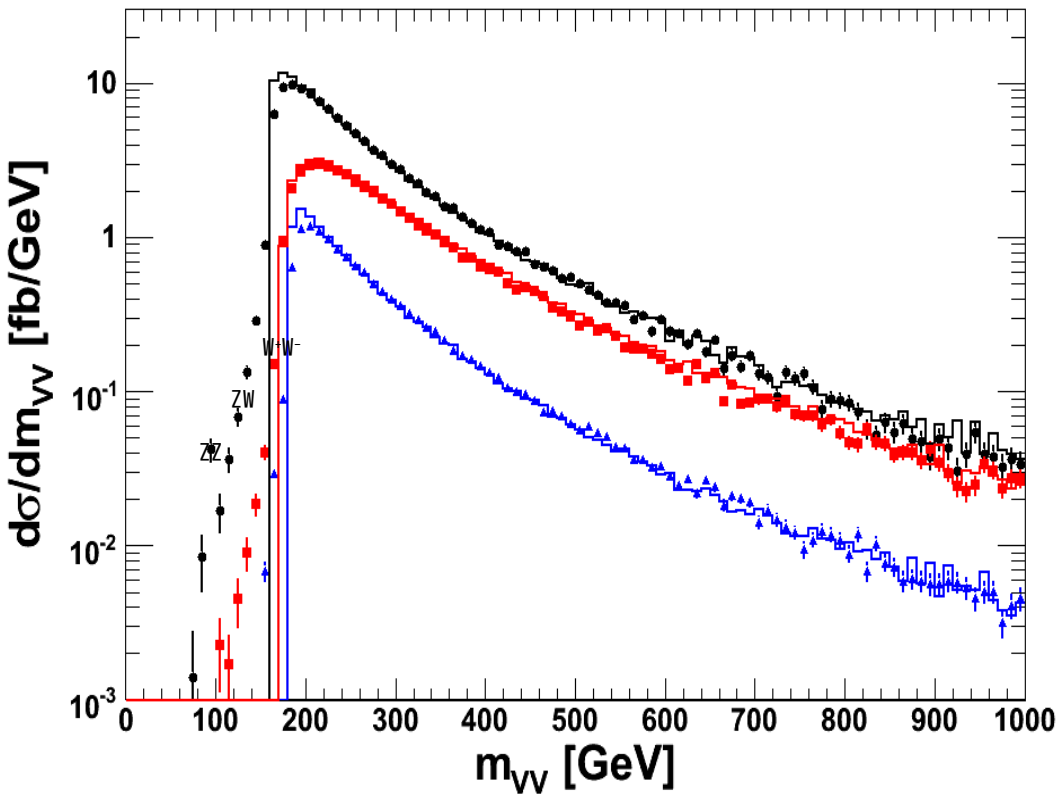


The D0 data and the simulation are normalized to the CDF cross section.

GRACE for LHC : GR@PPA 2.8

Di-boson production@LHC : GR@PPA v.s. MC@NLO





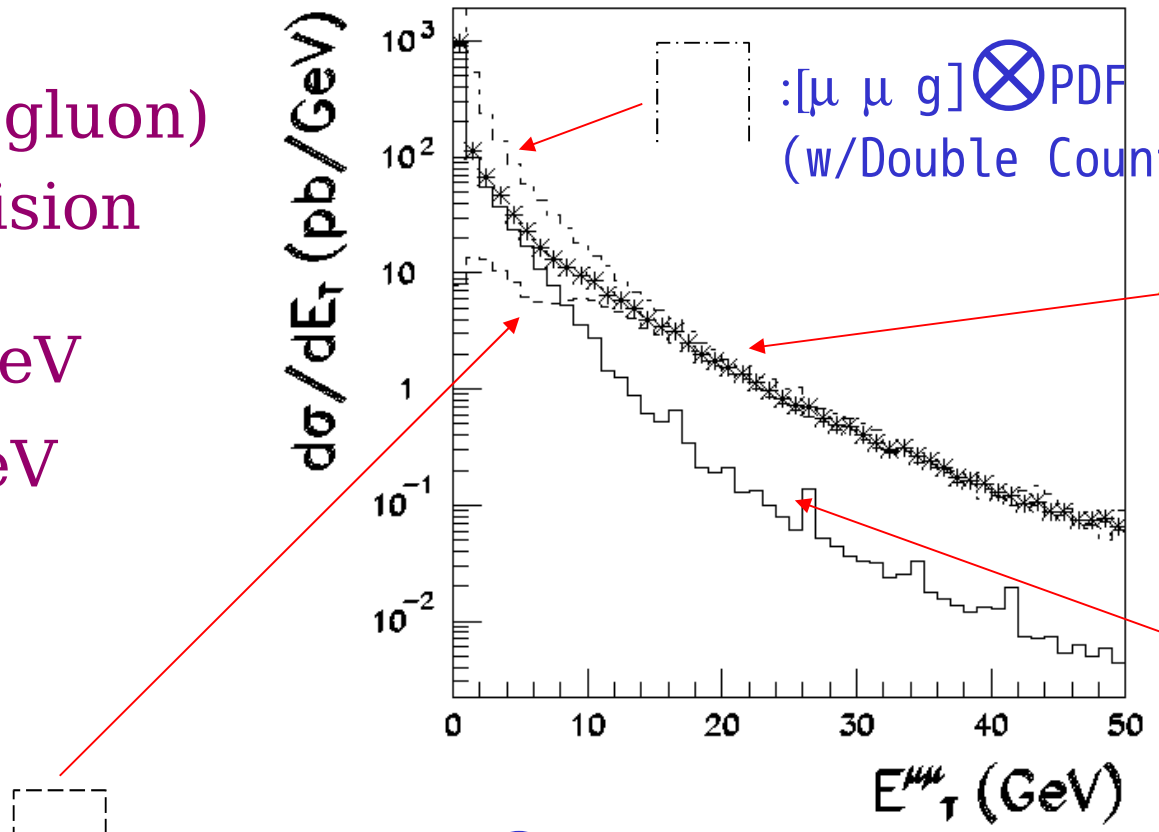
Plots: GR@PPA 2.8 + PYTHIA 6.419

Solid lines : MC@NLO3.31+Herwig6.510.3+Jimmy4.31.3

GRACE for LHC : NLO Generator

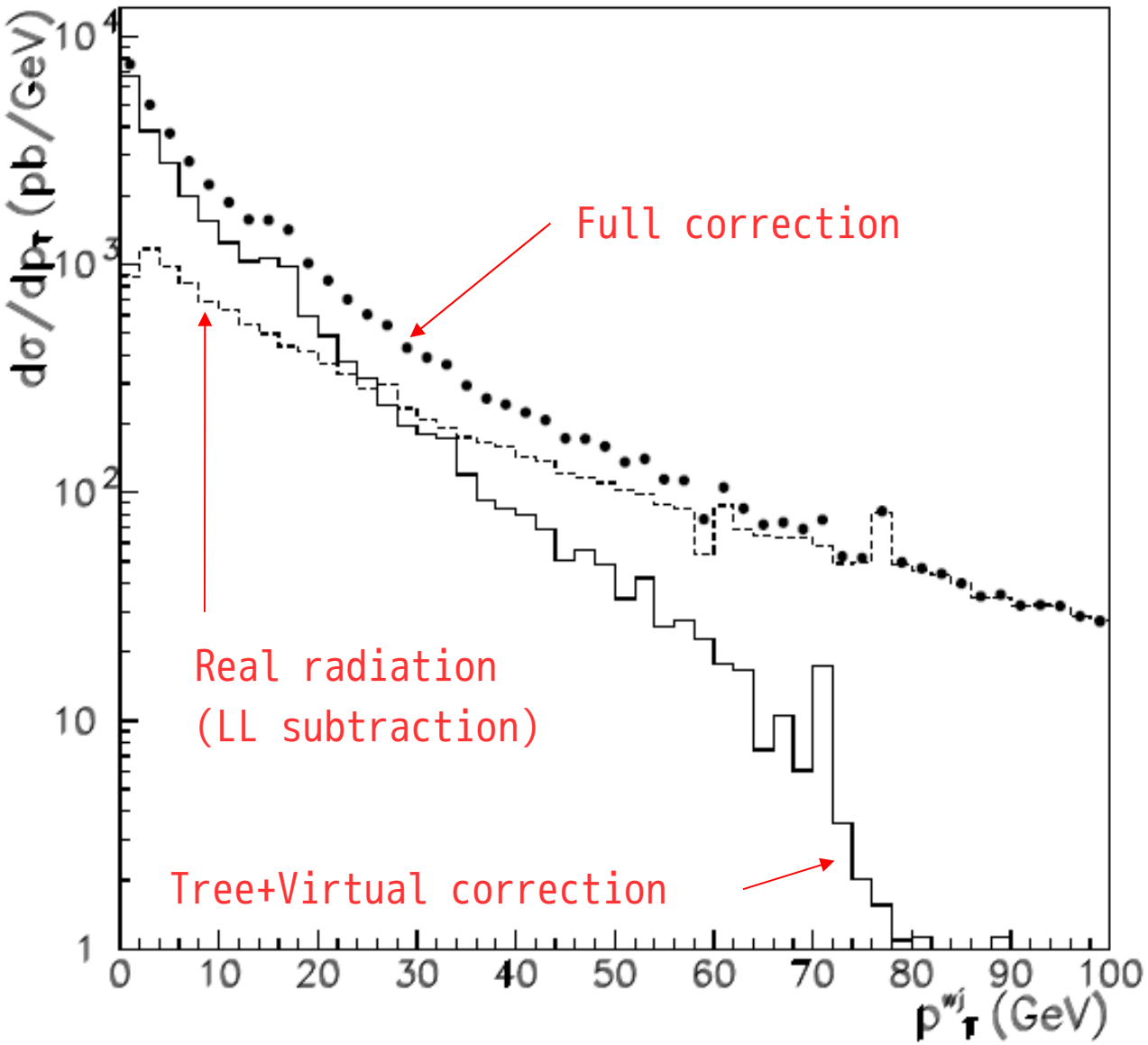
ME⇔PS Matching @ NLO

- Process :
  $uu \to \mu^+\mu^-(+\text{gluon})$
  in pp collision
  Cuts:
  . $\sqrt{s_{\mu\mu}} > 40\text{GeV}$
  $k_T^g > 1$ GeV



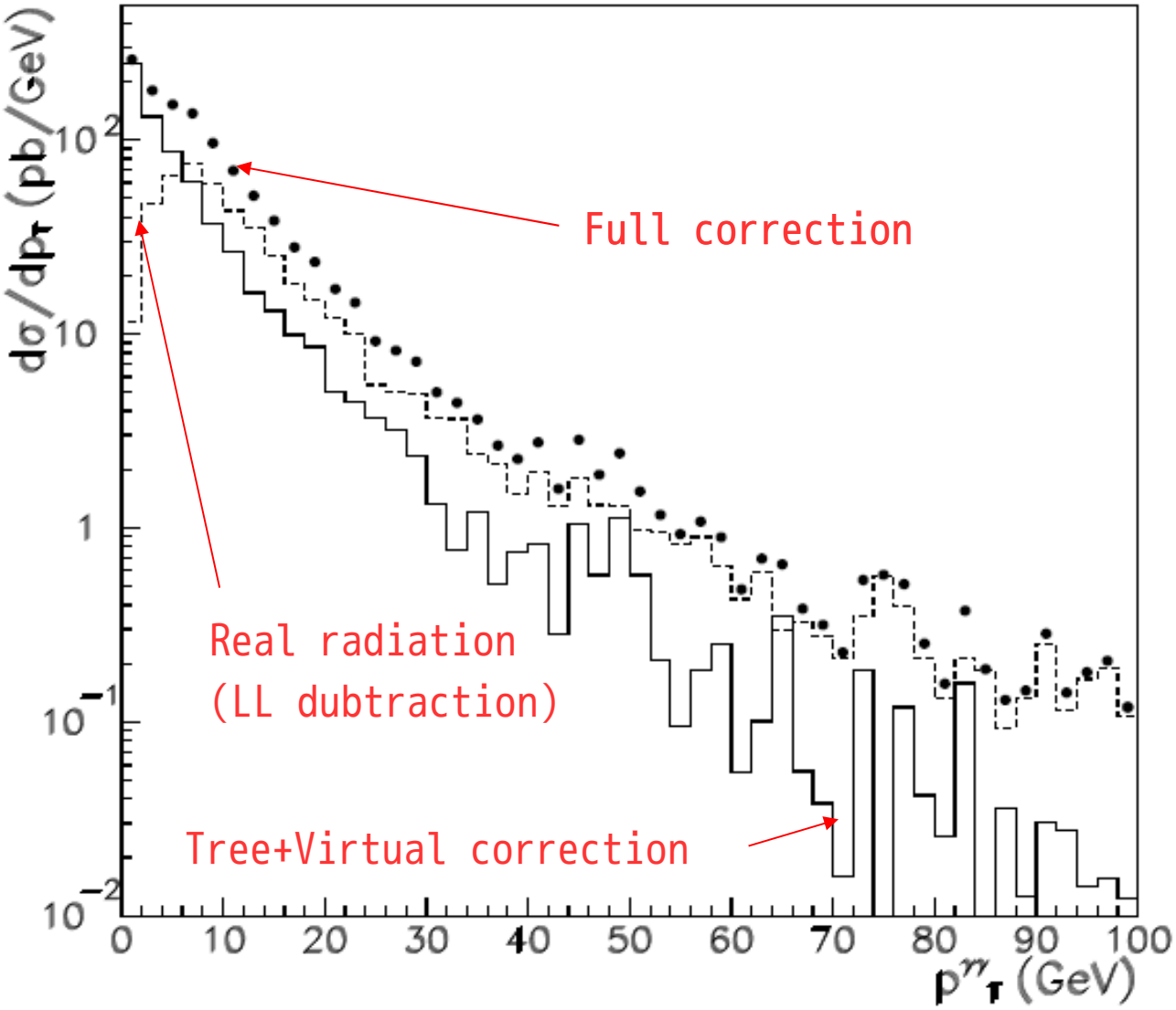
GRACE for LHC : NLO Generator

Transverse momentum distribution of W-jet



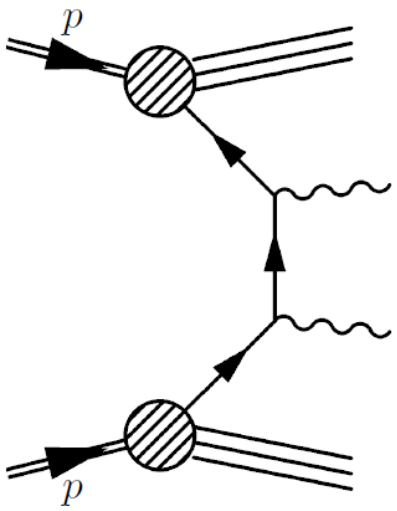
GRACE for LHC : NLO Generator

Transverse momentum distribution of $\gamma\gamma$

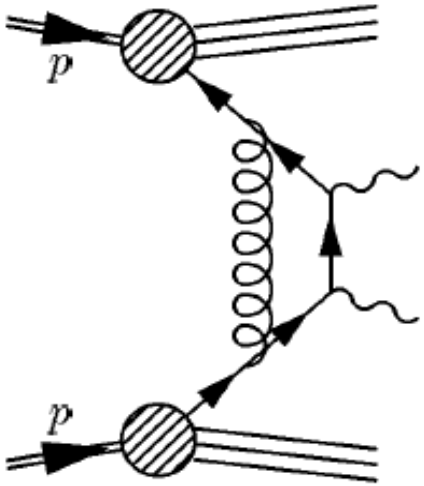


GRACE for LHC : NLO Generator

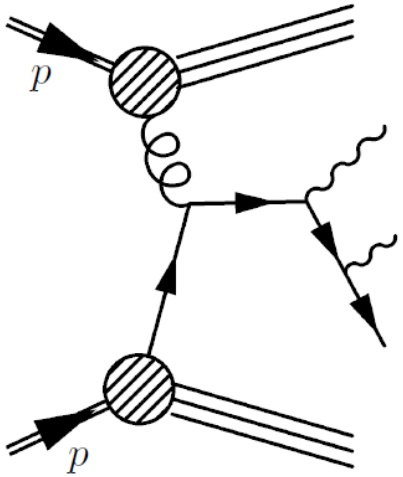
Direct Processes



Lowest Process



Loop Correction

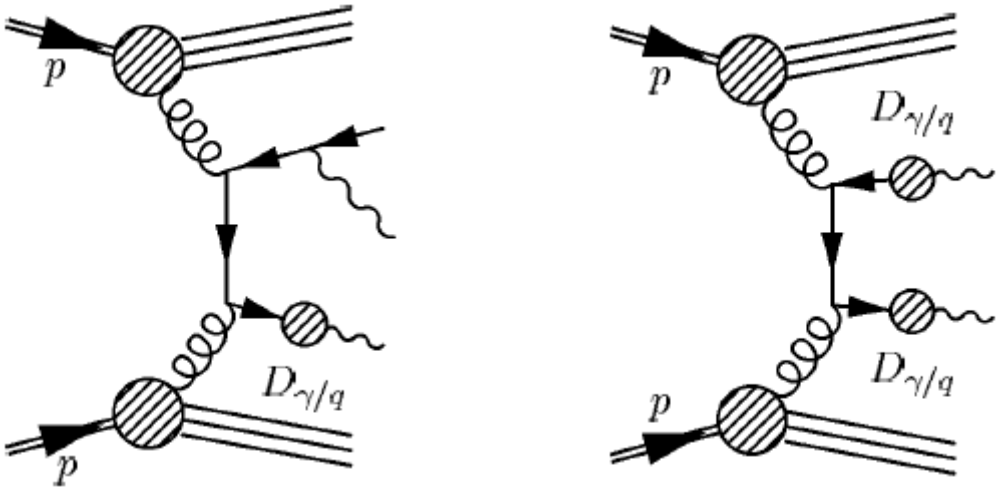


Real Radiation

- Diphox
  - T.Binoth, J.Ph.Guillet, E.Pilon, M.Werlen
  - Eur.Phys.J.C16,311(2000)

GRACE for LHC : NLO Generator

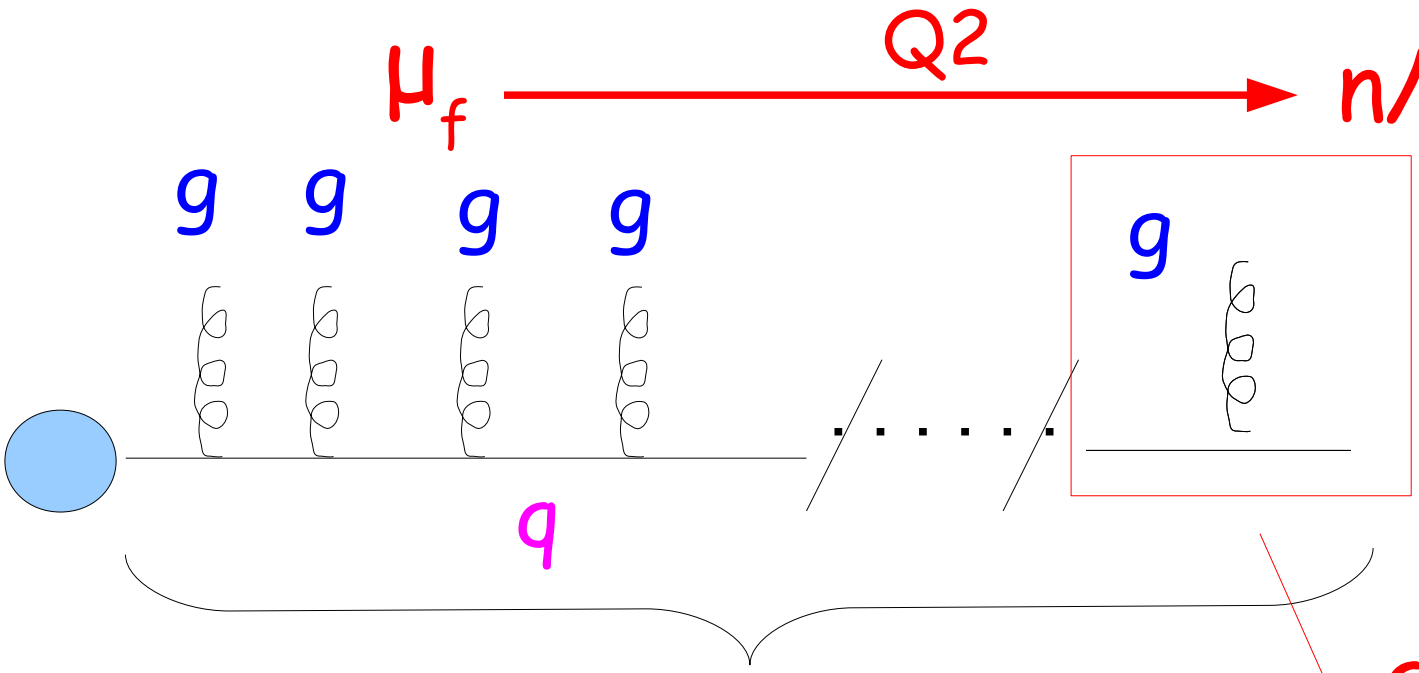
Fragmentation Processes



single fragmentation double fragmentation

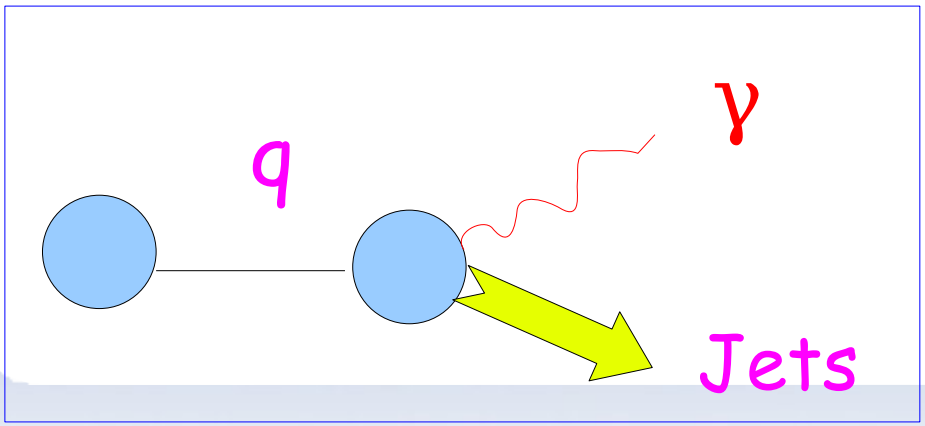
- DIPHOX
  - Fragmentation Function
  - Inclusive Jet → No Event-Generation
- GR@PPA
  - Parton Shower (QCD/QED)
  - Event-Generation

GRACE for LHC : QCED PS

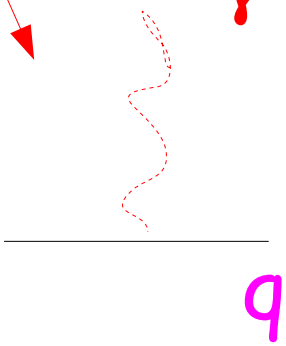


QCD partonShower

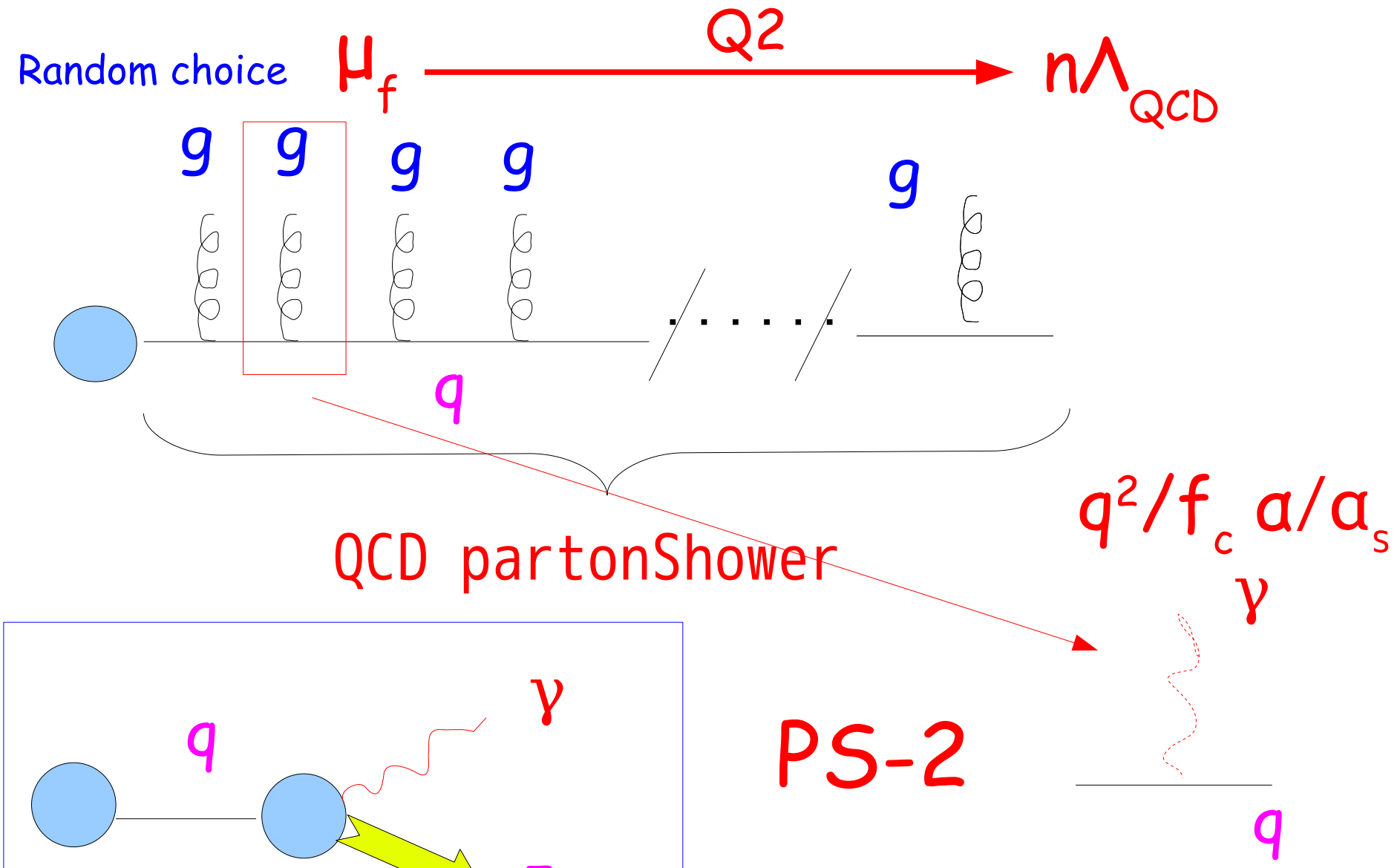
$q^2/f_c\ \alpha/\alpha_s$



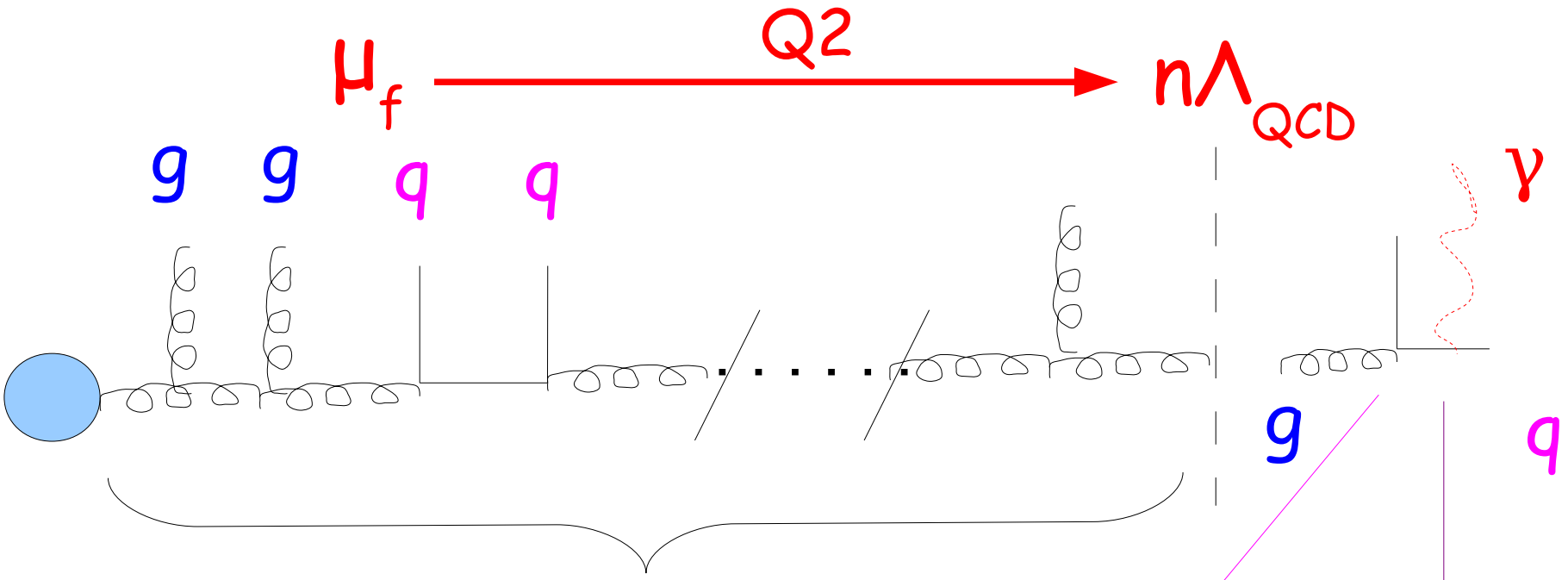
PS-1



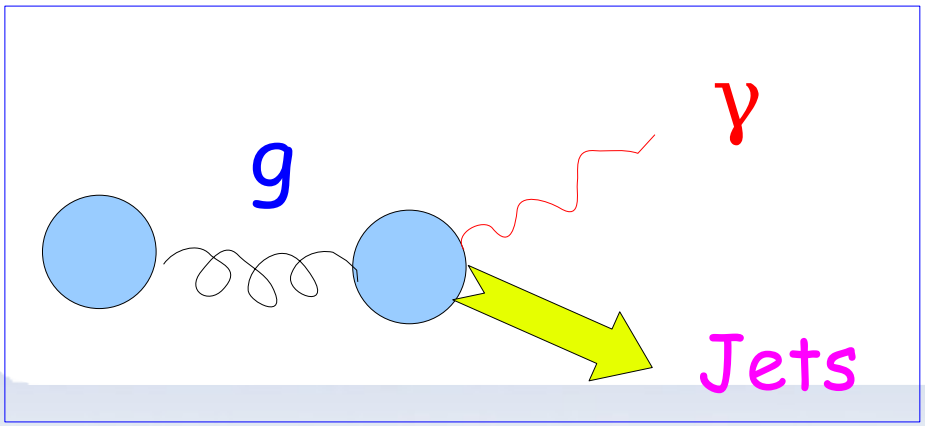
GRACE for LHC : QCED PS



GRACE for LHC : QCED PS



QCD partonShower



4%

$g \rightarrow qq$

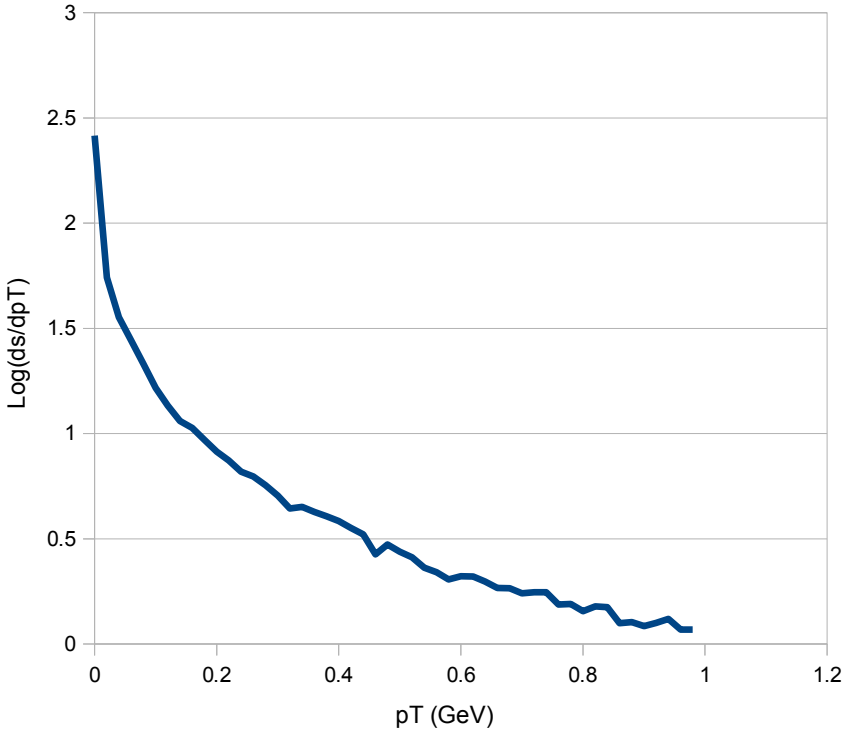
$$\frac{\alpha}{2\pi}\frac{1}{k_T^2}\frac{1+x^2}{1-x}$$

GRACE for LHC : QCED PS

Q2=(50 GeV)~($5\Lambda_{QCD}$) , Egluon = 100GeV

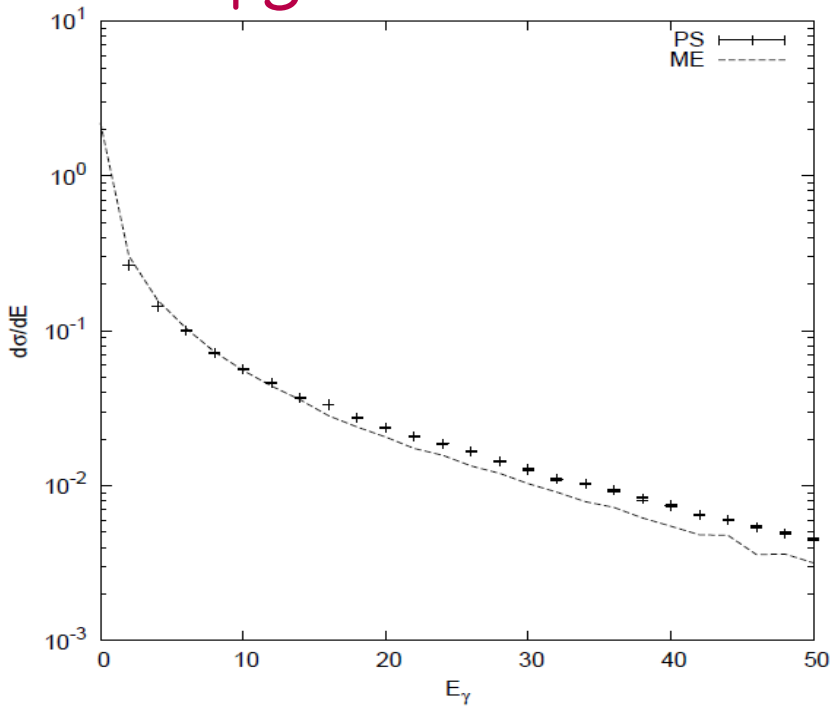
—— PS

—— ME calc. uu →g* → dd γ



jet pT

* PS

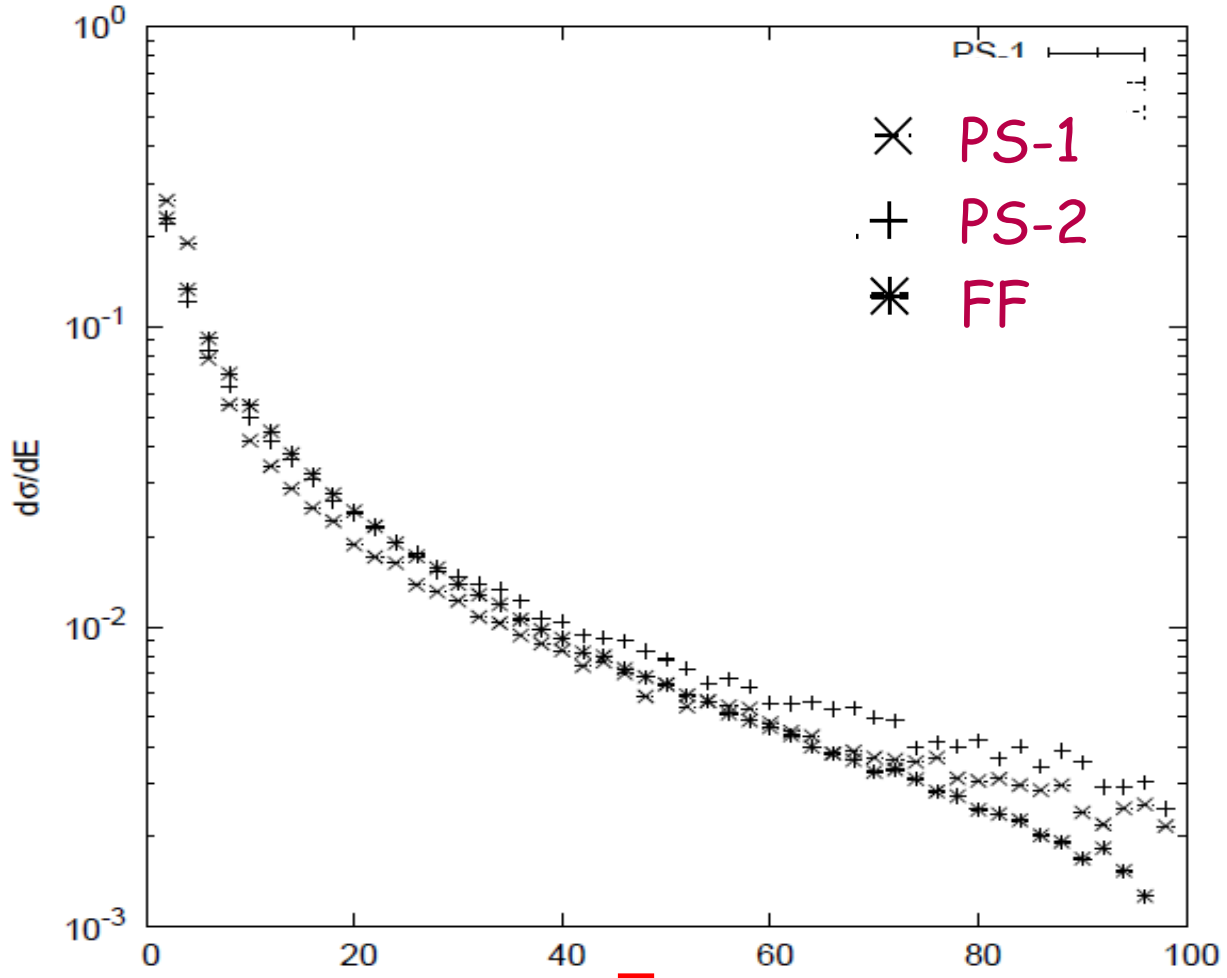


γ energy

GRACE for LHC : QCED PS

Q2=(50 GeV)~(5Λ_{QCD}) , Equark = 100GeV

γ energy



Summary

- GRACE is a Automatic Generator of Generators
- QED, Electro-weak SM, QCD, MSSM @ 1-Loop order
- GR@PPA 2.8
  - Full Exclusive unweighted Hadron Event Generator w/ ME⇔PS Matching
  - 2.8→3.0: NLO+QECD PS Full Exclusive unweighted Event Generator