Recent progress of automatic computation in HEP

Kiyoshi KATO (Kogakuin Univ.) and GRACE collaboration
June 28, 2013
The XXI International Workshop
High Energy Physics and Quantum Field Theory
Saint Petersburg Area, Russia

Automatic computation

- A software system to perform perturbative computation in Quantum Field Theory which is an important tool for High Energy Physics (→ QFTHEP)
- A solution to large scale computaion which is beyond man-power calculation
  - multi-body final states
  - higher-order radiative corrections

systems

- Full systems or tools(e.g., LanHEP: from Lagrangian to Feyman rules, QGRAF:diagram generation)
- Tree level or loop level(radiative correction)
- Diagramers vs. Unitarian
  Use/Not use Feynman diagrams

Automatic computations and event generators, tree level

From Lagrangian to Feynman rules

- LanHEP (native symbolic language)
- FeynRules (Mathematica)

Tree level hard process integrand generator

- CompHEP,(Squared amplitude, many models including MSSM), CalcHEP (SM, MSSM, + many)
- Grace (Helicity amplitudes, SM),
- FDC (Wang)
- COMIX (multi-leg tree level event generator, color reccursive relation, many legs)
- AMEGIC++ (parton level generator)
- HELAC/Phegas (dyson-schwinger)
- O'Mega (alpha algorithm)

General purpose mainly tree level (all decay, 2->2, 2->3, some 2->4, ISR, PS and Hadronisation)

- Pythia++, Ariadne, MC++
- Herwig++
- Isajet

General purpose event generators based on automatic integrand callculations

- Whizard (O'Mega)
- Sherpa (using Comix and AMEGIC++, CKKW, Pythia (or Pythia like)
- Madgraph, MadEvent
- Graceful (based on Grace, interfaced to Pythia) in progress …

Specific set of event generators

- Gr@ppa (Grace for matrix elements and Pythia/Herwig for parton shower/Hadronization)
- AlpGen (multi parton generation)

Parton shower matching

- CKKW, POWHEG, MLM, Subtraction method (matrix element matching with shower MC)

Event database:

- MC database (CompHEP)
- JETWEB

Automatic computations and event generators, NLO,…

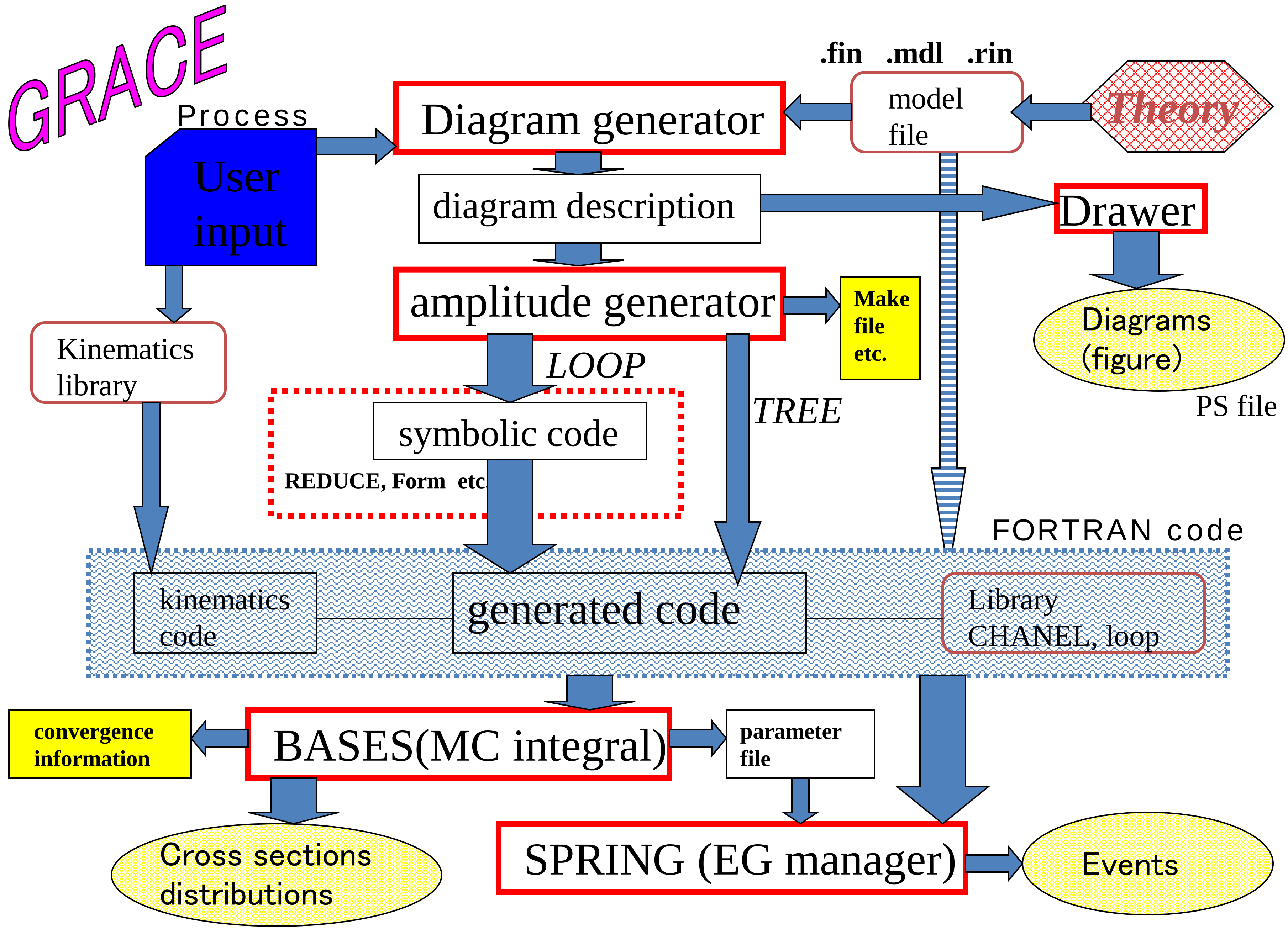
- RESBOS (Q_t resummation NLO/NNLO, no parton shower necessary) lepton distributions in Drell-Yan-like processes); inclusive with respect to hadronic radiation

NLO hard process
NLO event generators (specific processes)

- MC@NLO (Herwig + Subtraction methods: H, single Boson, single top, lepton pairs, H +W/Z, …)
- MCFM (full spin correlation, Wbb, …)
- BlackHat (one-loop, W/Z+3,4 jets)
- NLOjet++ (Catani-Seymour dipole subtraction method)
- Rocket (N-gluon amplitude, 2-q +N-g, W +2-q + N-g, W +4 q +Ng… N> 20)
- CutTools (one-loop amplitudes at integrand level)
- JETRAD (inclusive 1 and 2 jet production)
- JETI
- FeynCalc (Mathematica/Form Passarino-Veltman reduction of one-loop amplitudes to standard scalar integrals) FeynArt, FeynRules, …
- Grace one-loop
- FDC (loop)
- Golem (one-loop amplitude up-to six legs)
- Phox family JetPhox (inclusive γ/hadron+jet, Diphox (hadron production of 2γ, hadron+γ, hadron+hadron)

GRACE system

- Tree and 1-loop, SM and MSSM (and some extension)
  Public version(in Web page) : tree-only
- Components:
  - diagram generator
  - amplitude/matrix element generator
  - libraries for kinematics, color, loop-integrals
  - Monte-Carlo integration in phase space
  - efficient event generation
- This talk : Recent results by GRACE group



GRACE
Process
User input
Diagram generator
.fin .mdl .rin
model file
Theory
diagram description
Drawer
amplitude generator
Make file etc.
Diagrams (figure)
PS file
Kinematics library
LOOP
TREE
symbolic code
REDUCE, Form etc
FORTRAN code
kinematics code
generated code
Library CHANEL, loop
convergence information
BASES(MC integral)
parameter file
Cross sections distributions
SPRING (EG manager)
Events

How do you believe the results?

System diagnosis

- Cancelation on UV divergence ($\frac{1}{\varepsilon}$ is kept as a variable in the code)
- Cancelation of IR divergence (λ regularization)
- Cancelation of soft-photon cut k_C
- Non-linear gauge invariance

Change numerical precision

Analytical calculation(e.g., QED part)

Comparison with other study(*if any*)

non-Linear gauge

Gauge invariance check --- Powerful diagnosis

Loop integral --- numerator structure --- $\xi = 1$ (Feynman gauge) favorable

$$g^{\mu\nu} - (1-\xi)\frac{p^\mu p^\nu}{p^2 - \xi M^2 + i\varepsilon}$$

Non-linear gauge fixing ---- $\xi = 1$ and free gauge parameters

$$L_{GF} = -\frac{1}{\xi_W} F^+ F^- - \frac{1}{2\xi_Z}\left(F^Z\right)^2 - \frac{1}{2\xi}\left(F^A\right)^2$$

$$F^{\pm} = \left(\partial^\mu \mp ie\tilde{\alpha}A^\mu \mp i\frac{ec_W}{s_W}\tilde{\beta}Z^\mu\right)W^{\pm}_\mu$$

$$+\xi_W\left(M_W\chi^{\pm} + \frac{e}{2s_W}\tilde{\delta}H\chi^{\pm} \pm i\frac{e}{2s_W}\tilde{\kappa}\chi_3\chi^{\pm}\right)$$

$$F^Z = \partial^\mu Z_\mu + \xi_Z\left(M_W\chi_3 + \frac{e}{2s_W c_W}\tilde{\varepsilon}H\chi_3\right)$$

$$F^A = \partial^\mu A_\mu$$

$$\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}, \tilde{\varepsilon}, \tilde{\kappa}$$

5 gauge parameters appear in vertices

$$e^+e^- \to t\bar{t}\gamma \qquad e^+e^- \to e^+e^-\gamma$$

P.H. Khiem , J. Fujimoto, T. Ishikawa, T. Kaneko, K. Kato,
Y. Kurihara, Y. Shimizu, T. Ueda, J.A.M. Vermaseren, Y. Yasui
K.Tobimatsu, M.Igarashi, N.Nakazawa

Study for ILC ; top physics, background for new physics, Luminocity study, …

Full electroweak 1-loop radiative correction

process $e^+e^- \to t\bar{t}\gamma$

$e^+e^- \to t\bar{t}$

J. Fujimoto and Y. Shimizu et al.,
Mod. Phys. Lett. 3A, 581 (1988).
J. Fleischer, A. Leike, T. Riemann et al.,
Eur. Phys. J. C 31, 37 (2003).

P. H. Khiem et al.,
Eur. Phys. J. C73, 2400(2013)

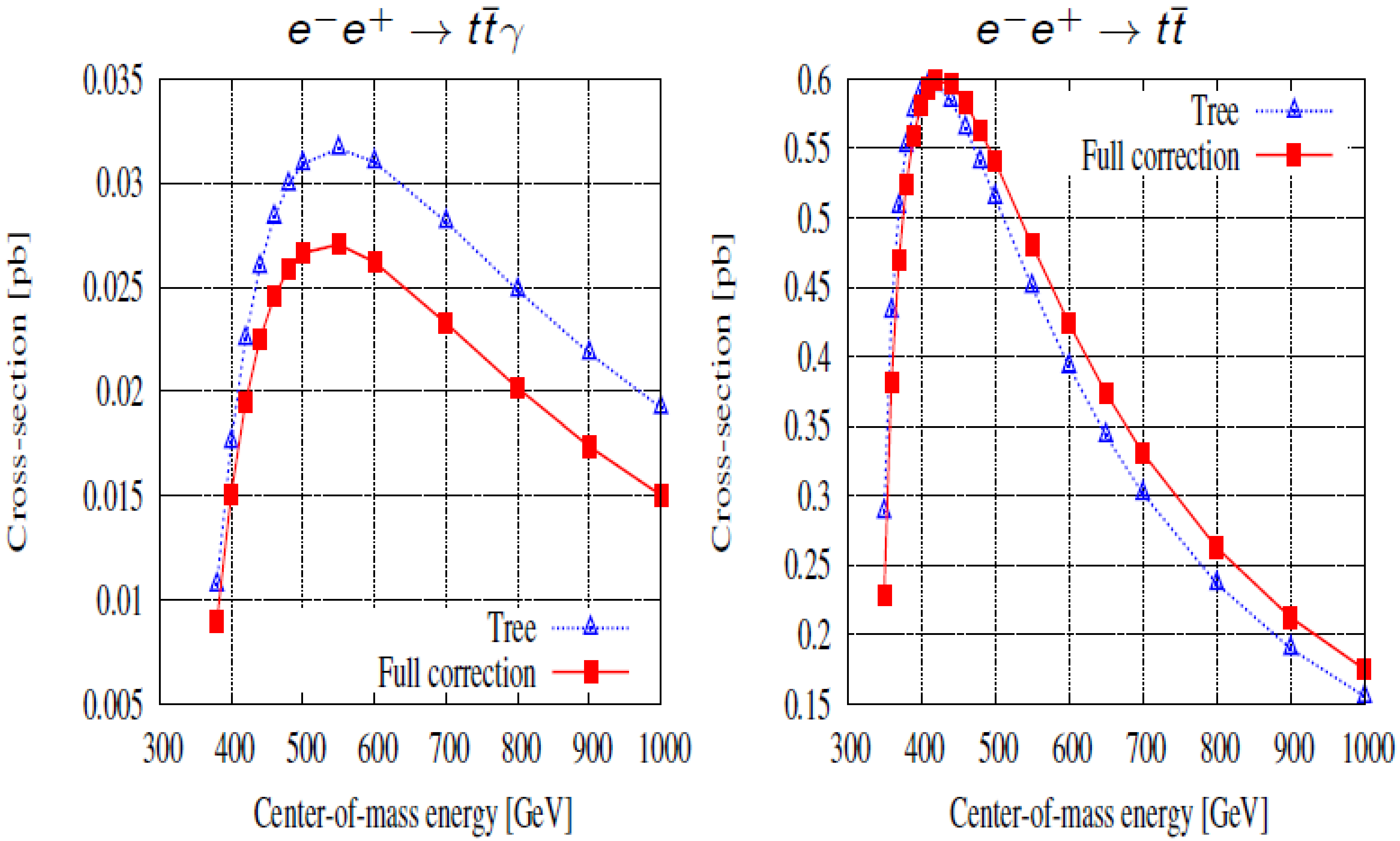
Confirmed the results
for $e^+e^- \to t\bar{t}$ also

$$E_\gamma > 10\mathrm{GeV}, \quad 10^\circ < \theta_\gamma < 170^\circ$$

No. of graphs	tree	1-loop
$e^+e^- \to t\bar{t}$	4	150
$e^+e^- \to t\bar{t}\gamma$	16	1814
$e^+e^- \to t\bar{t}\gamma\gamma$	80	

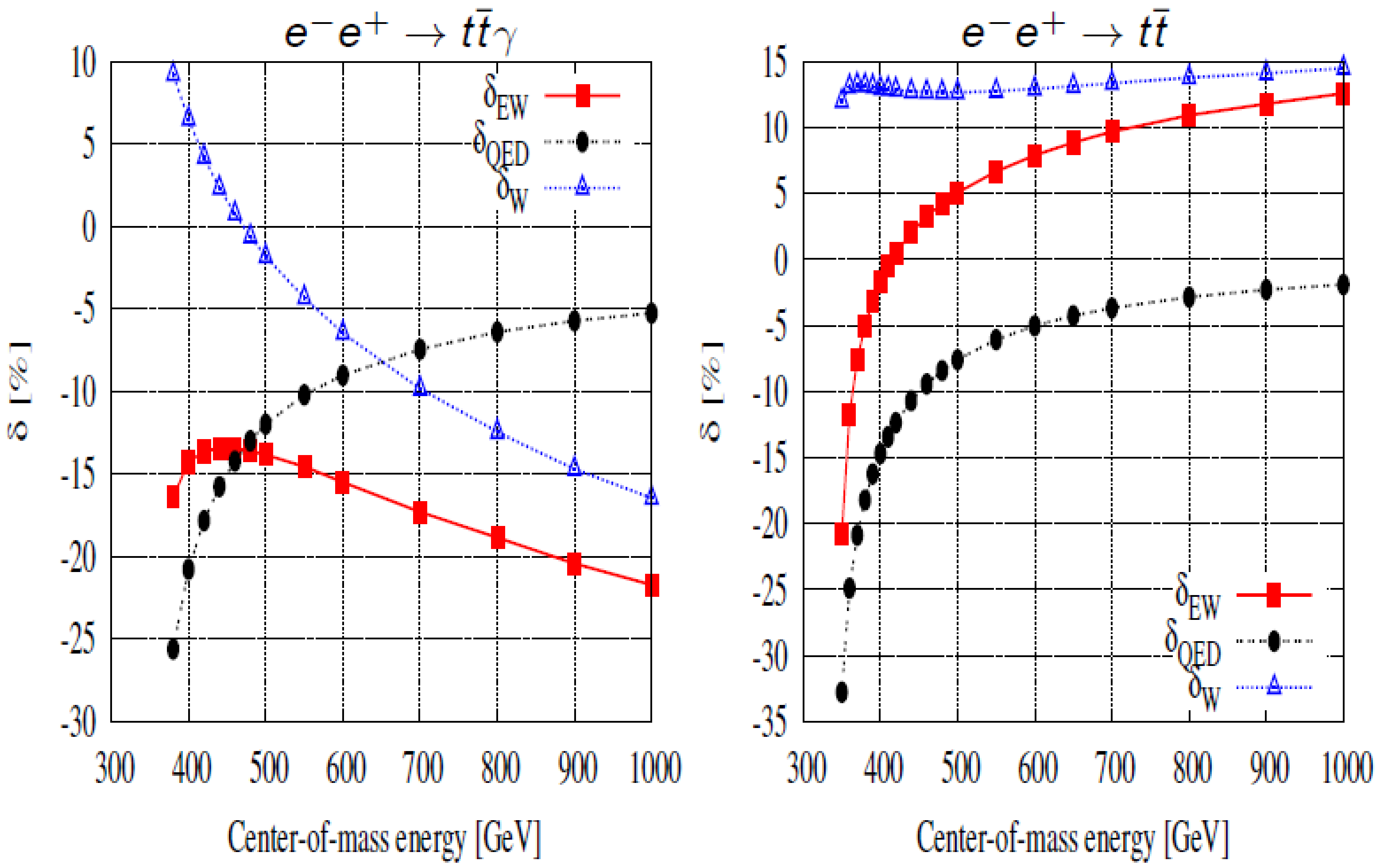
Numbers are in non-linear gauge fixing model.

Total cross section



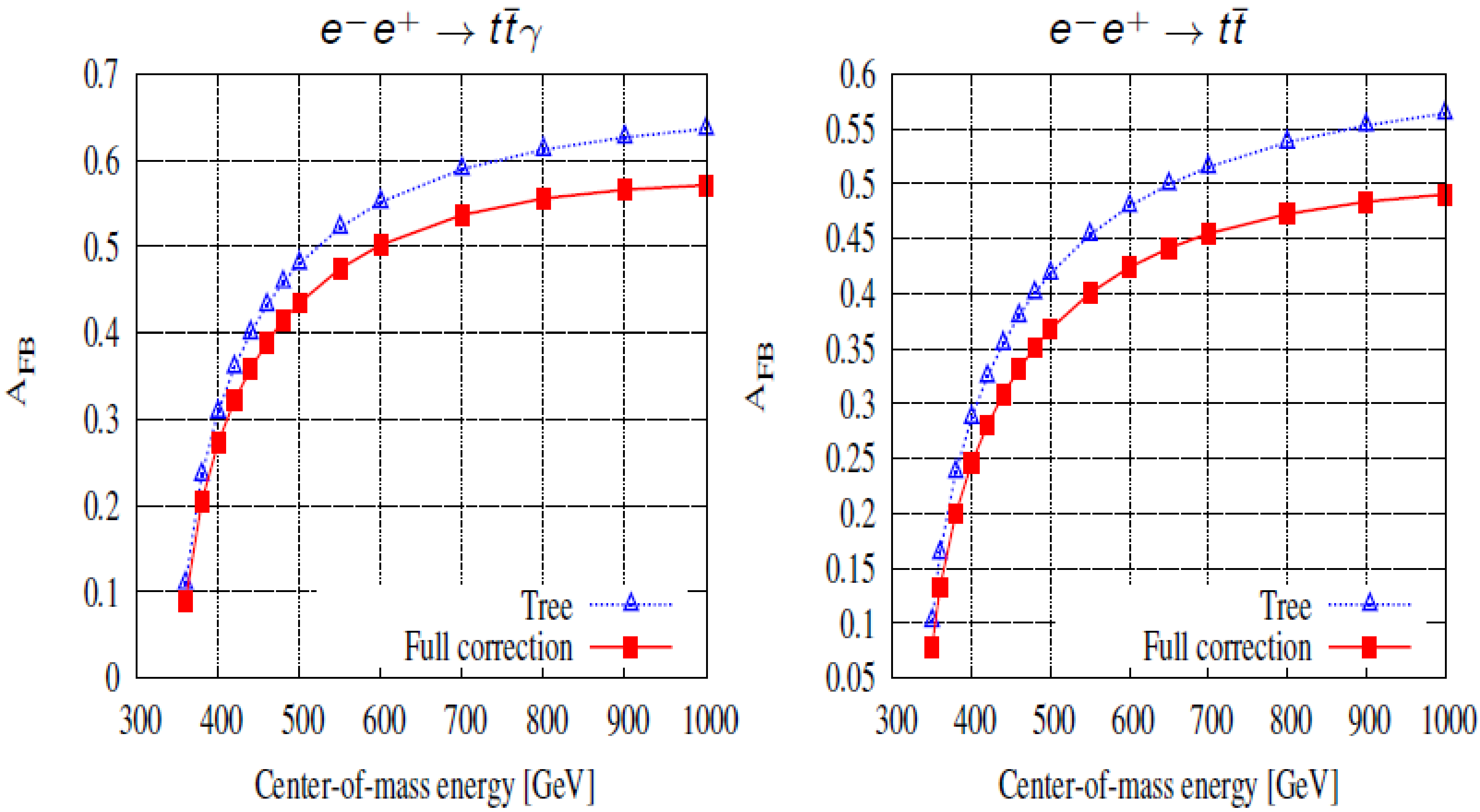
$$E_\gamma > 10\text{GeV},\ \ 10^\circ < \theta_\gamma < 170^\circ$$

Radiative corrections



Forward-backward asymmetry of t

$$A_{FB} = \frac{\sigma(0^0 \leq \theta_t \leq 90^0) - \sigma(90^0 \leq \theta_t \leq 180^0)}{\sigma(0^0 \leq \theta_t \leq 90^0) + \sigma(90^0 \leq \theta_t \leq 180^0)}$$



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

One-loop electroweak corrections to *e+e−* → *e+e−* :

J. Fujimoto et al., *Prog. Theor. Phys. Supplement (1990) 100.*

M. Bohm et al., *Nuclear Physics B304 (1988) 687-711*

Tree level calculation of *e+e−* → *e+e−γ* :

Y. Shimizu et al., *Comp.Phys. Commun. 55, 337-385(1989).*

Two-loop QED correction to *e+e−* → *e+e−* :

A.A. Penin: Phys.Rev. D72 (2005) 051301; Phys. Rev. D74 (2006) 019901.

One-loop electroweak correction to $e^+e^- \to e^+e^-\gamma$

P. H. Khiem et al.,
2013, JPS meeting (Hiroshima)

Tree 32
1-loop 3456

Calculation

Against numerical instability and large scale computation …
Use LoopTools for evaluating scalar one-loop integrals.
Heavy computation… 5,6-point functions with reduction
Use MPI(parallel computing) in quadruple precision calculation.
Use dynamic link method with ifort.

Cuts

$e^+, e^-, \gamma \quad E > 10\mathrm{GeV} \quad 10^\circ < \theta_{\mathrm{Beam}} < 170^\circ$

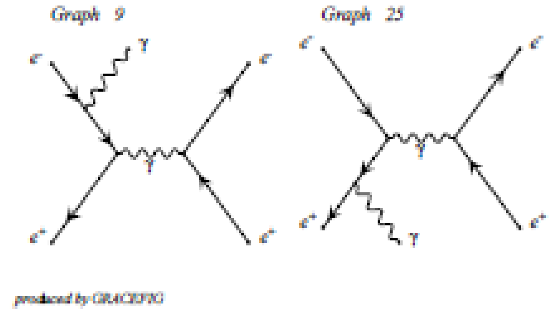
$\angle(e^+, e^-) > 10^\circ$ Can be relaxed

$\angle(\gamma, e^+), \angle(\gamma, e^-) > 10^\circ$

Large cancelation

External photon
Polarization sum

M_1 M_2



(1) $< \varepsilon^{\mu} \varepsilon^{\nu} >= -g^{\mu\nu}$

(2) $< \varepsilon^{\mu} \varepsilon^{\nu} >= -g^{\mu\nu} + \dfrac{q^{\mu} n^{\nu} + n^{\mu} q^{\nu}}{qn} - n^2 \dfrac{q^{\mu} q^{\nu}}{(qn)^2}$

Code : lengthy
Calculation: stable

	(1)	(2)
$\mathcal{M}_1^2 + \mathcal{M}_2^2$	$0.1116212357E^{+13}$	$0.3644158264E^{+02}$
$2\mathcal{M}_1^* \mathcal{M}_2$	$-0.1116212356E^{+13}$	$0.1546482734E^{+03}$
$\lvert\mathcal{M}_1 + \mathcal{M}_2\rvert^2$	$0.1910871582E^{+03}$	$0.1910898560E^{+03}$

Diagnosis(1) UV divergence

At a phase space point

1. C_{UV} **independence of the result.**

C_{UV}	$2\mathcal{R}(\mathcal{M}^{+}_{Tree}\mathcal{M}_{Loop})+$ soft contribution.
0	$-0.39263556486314591354656968784977 0$
10^2	$-0.39263556486314591354656968784975 2$
10^4	$-0.3926355648631459135465696878495 29$

Diagnosis(2) IR divergence

2. λ **independence of the result.**

λ [GeV]	$2\mathcal{R}(\mathcal{M}^{+}_{Tree}\mathcal{M}_{Loop})+$ soft contribution.
10^{-17}	$-0.392635564863145965951753297380674$
10^{-19}	$-0.3926355648631459104963726372876 57$
10^{-21}	$-0.39263556486314591354656968784977 0$
10^{-23}	$-0.3926355648631459171818206686217 04$
10^{-25}	$-0.392635564863145920823132105718981$

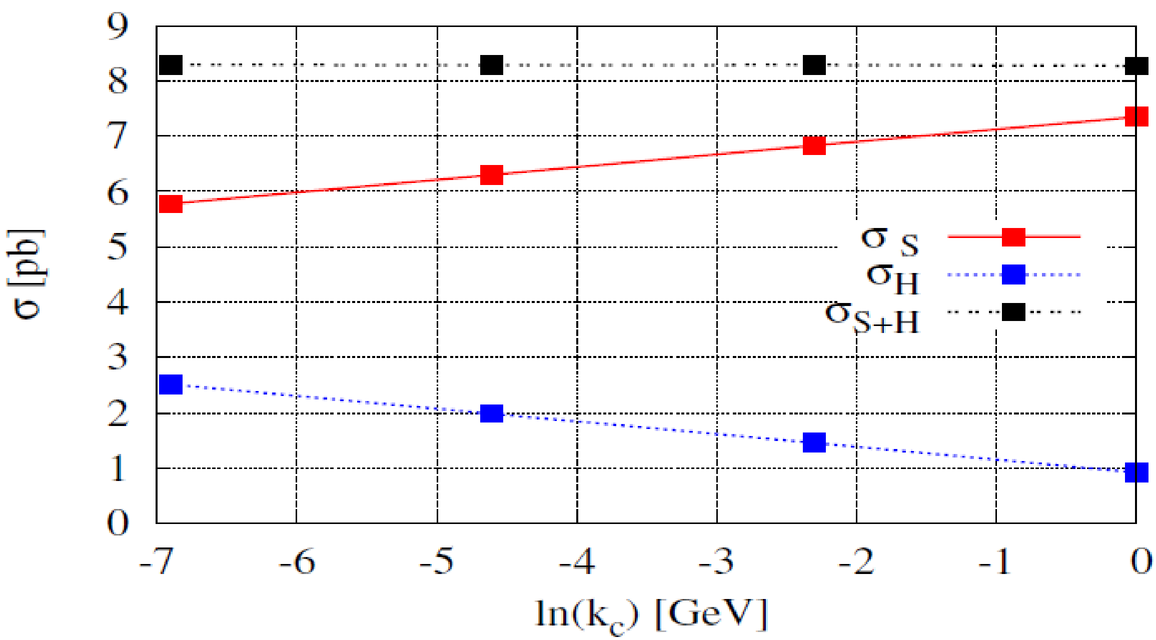
Diagnosis(3) non-linear gauge invariance

At a phase space point

3. Gauge invariance of the result.

$(\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}, \tilde{\varepsilon}, \tilde{\kappa})$	$2\mathcal{R}(\mathcal{M}^{+}_{Tree}\mathcal{M}_{Loop})+$ soft contribution.
$(1,2,3,4,5)\times 10^{-1}$	−0.392635564863145913554033322734
$(1,2,3,4,5)\times 10^{-2}$	−0.392635564863145913547492915486
$(1,2,3,4,5)\times 10^{-3}$	−0.392635564863145913546838874761
$(1,2,3,4,5)\times 10^{-4}$	−0.392635564863145913546773470689
$(0,0,0,0,0)\times 10^{0}$	−0.392635564863145913546569687849

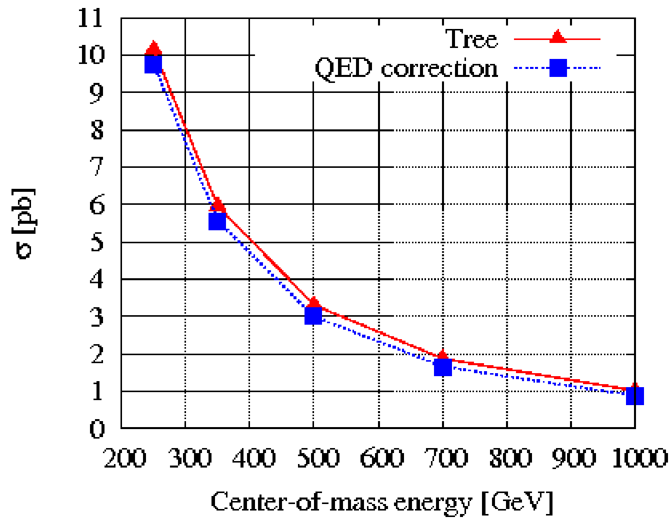
Diagnosis(4) k_c independence

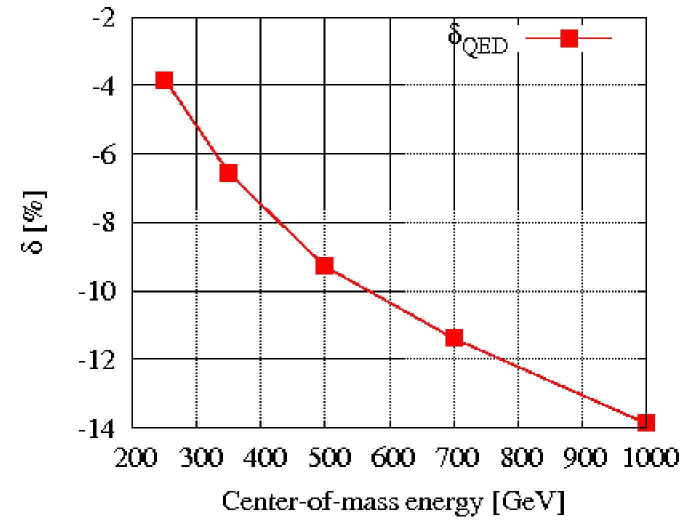


Integrated in phase space

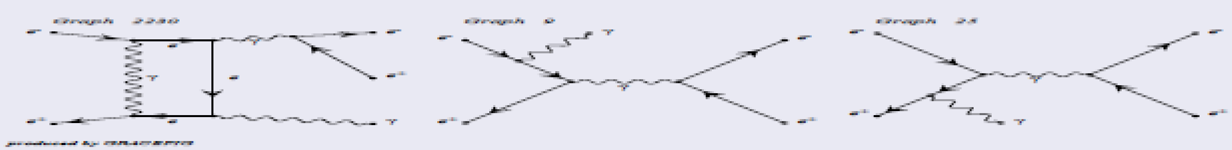
FULL QED corrections

partial comparison with analytical formula(Igarashi, Tobimatsu)



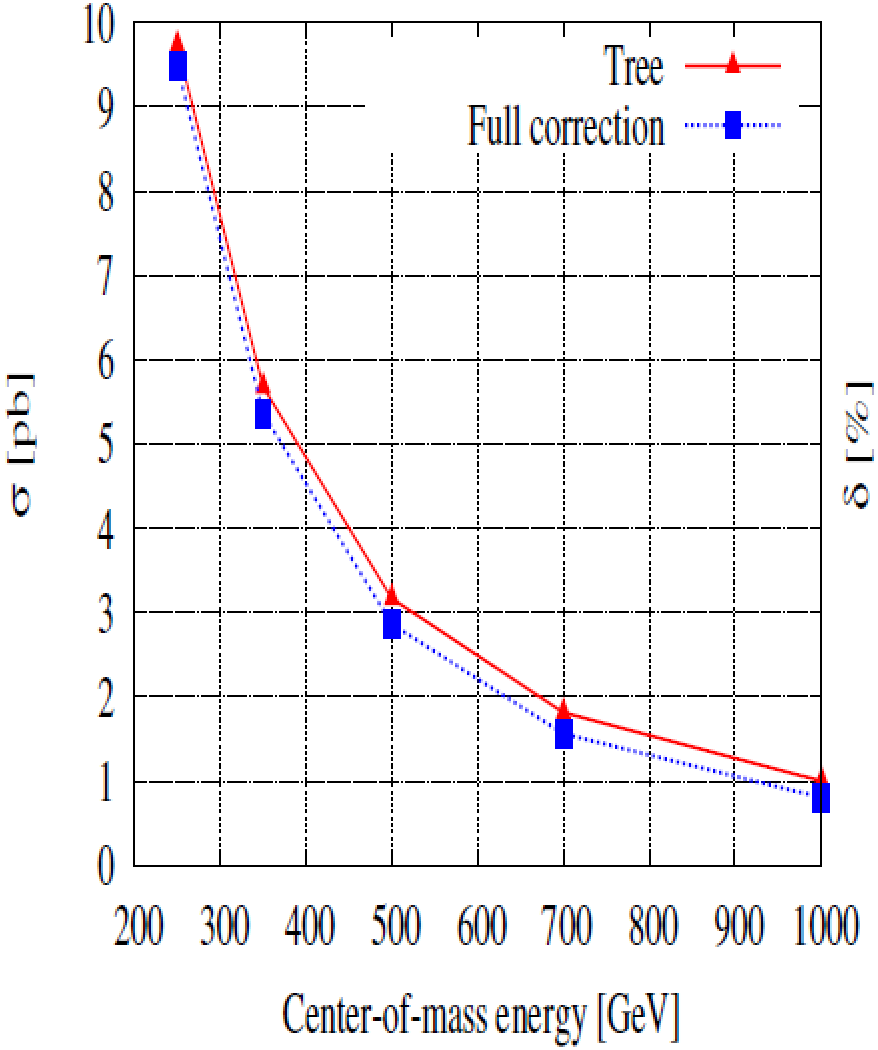


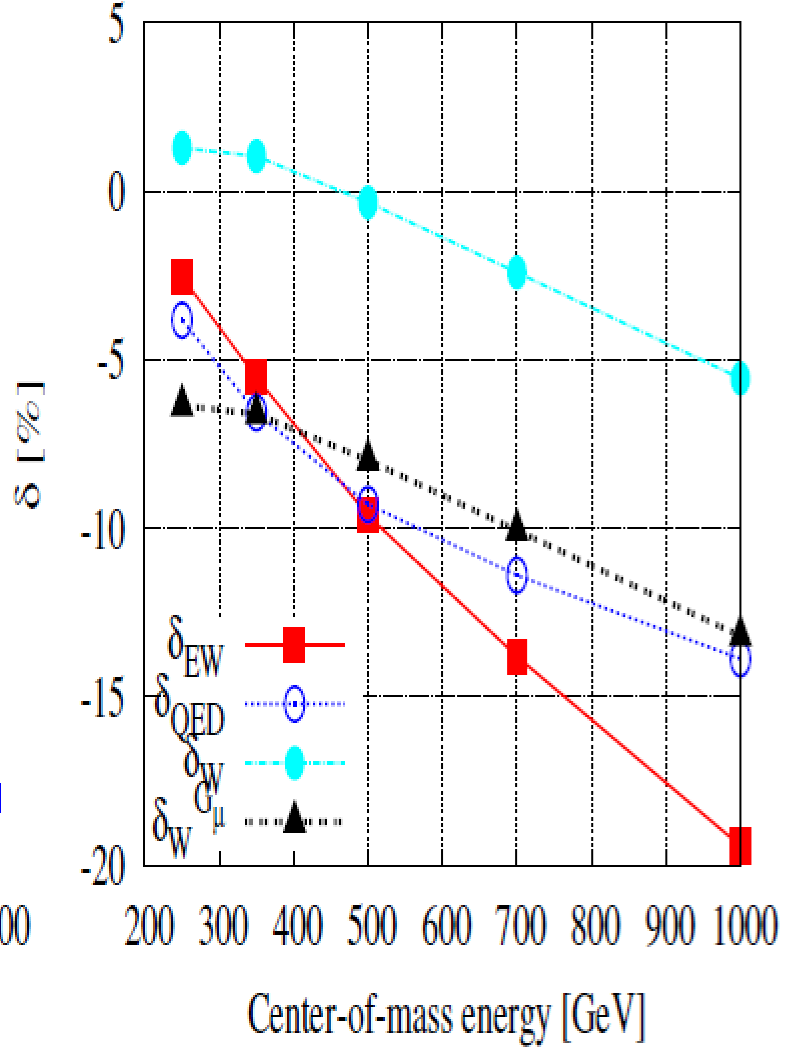
Amplitude	GRACE-Loop	IGARASHI et al
$2\mathcal{R}(\mathcal{M}^{+}_{Tree}\mathcal{M}_{Loop})$	6.400328327×10^3	6.400328334×10^3



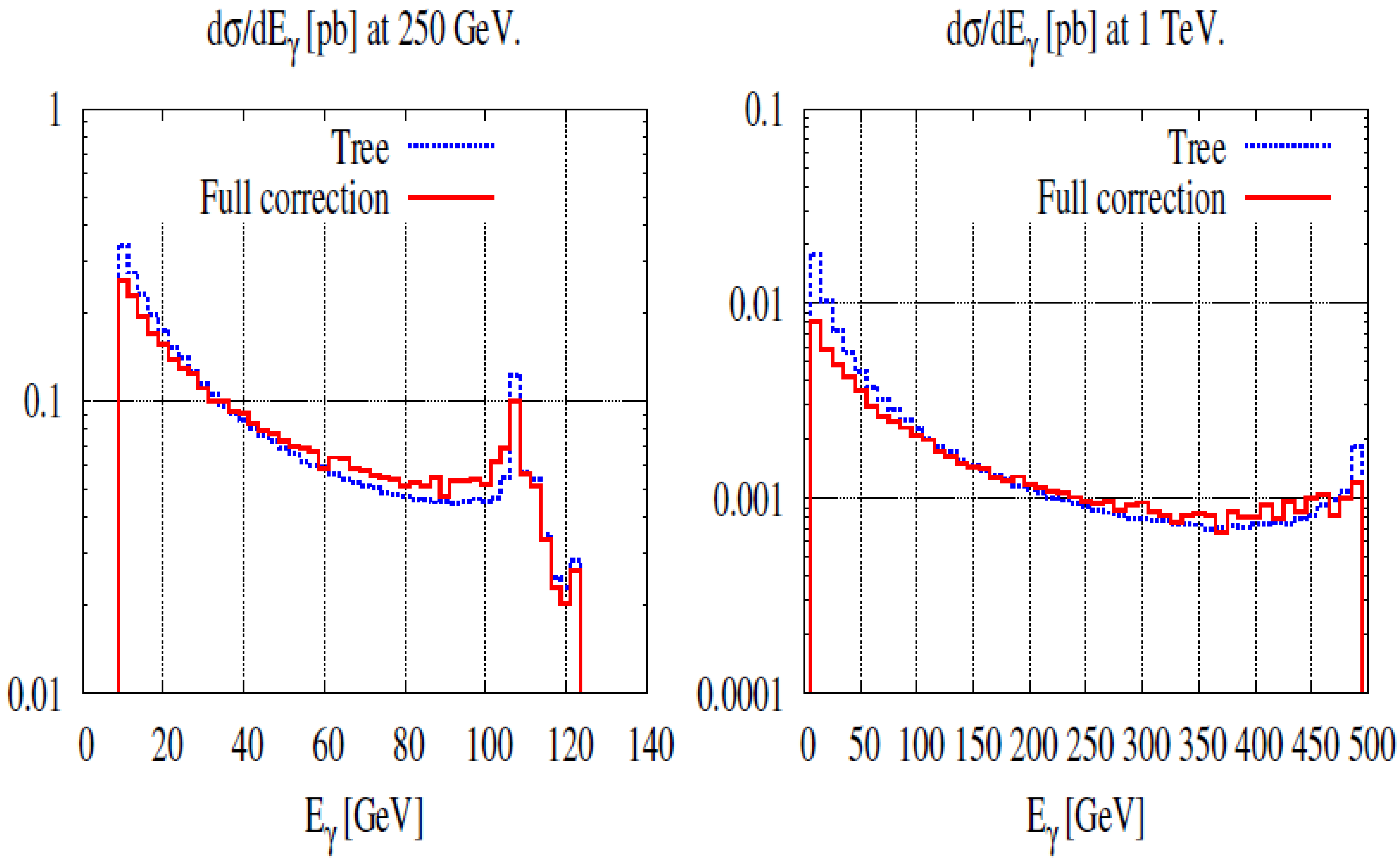
Analytic formula for full QED correction … in progress
Compact and efficient code can be developed.

Full EW corrections

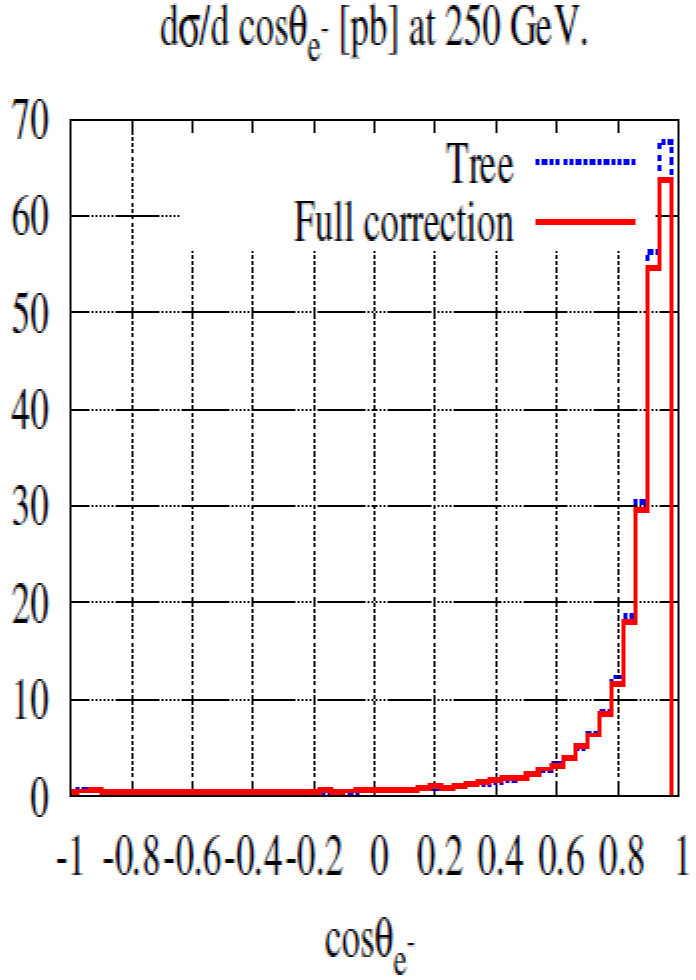


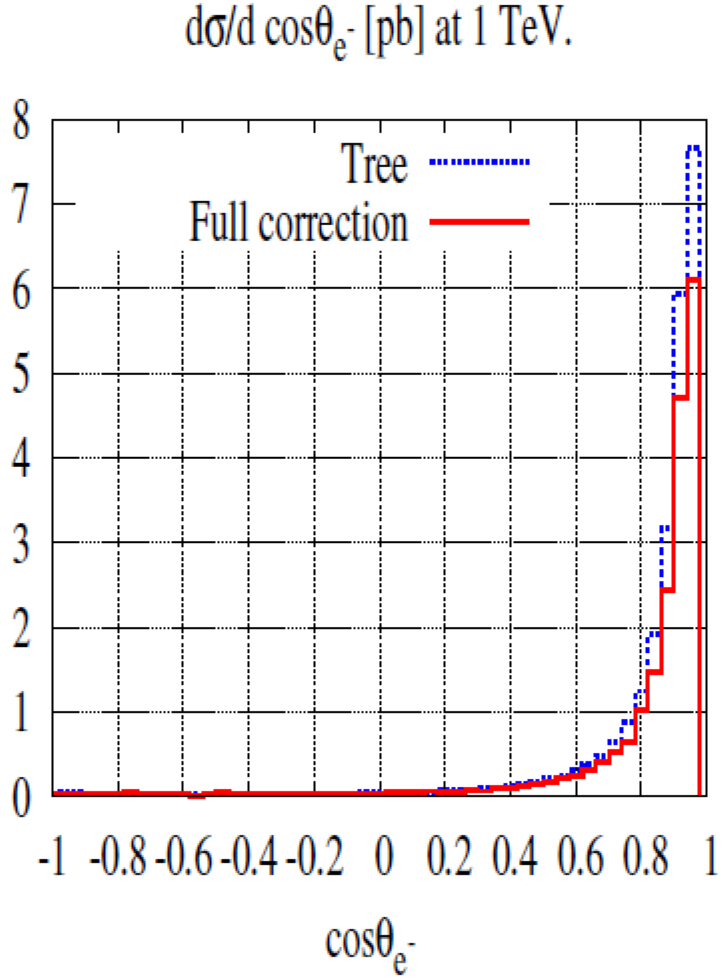


photon energy distribution



electron angular distribution





muon g-2, 2-loop EW

N.Nakazawa, T.Ishikawa, Y.Yasui

Toward 2-loop automation

- System development → started complete 2-loop EW muon g-2 project
- 2-loop integrals ・・・ DCM (QFTHEP Sochi, 2011)

Present Status of the Experiment and Theory

BNL E821 (2002,2004,2006)

a_exp(μ+) = 11 659 204(6)(5) × 10^{-10}

a_exp(μ−) = 11 659 215(8)(3) × 10^{-10}

Assuming CPT –invariance,

a_exp(μ) = 11 659 208.9(5.4)(3.3) × 10^{-10}

first error --- statistical
second error --- systematic

T. Gribouk and A. Czarnecki, Phys. Rev. D 72, 053016 (2005)

S. Heinemeyer, D. Stöckinger, G. Weiglein, Nucl. Phys. B 699 (2004) 103–123

QED-Theory : a_QED(μ) = 11 658 471.809(0.015) x 10^{-10} up to 5-th loop

ELWK-theory: a_ELWK(μ) = 19.48 x 10^{-10} - 4.07(0.1)(0.18) x10^{-10}
1-loop 2-loop
= 15.4(0.1)(0.2)x10^{-10}

Hadronic: a_(HAD) (μ) = [701.5(4.2)(1.9)(0.3)+0.7(2.6)] x 10^{-10}

Total(SM): a_(SM)(μ) = 11 659 180.2(0.2)4.2)(2.6) x 10^{-10}

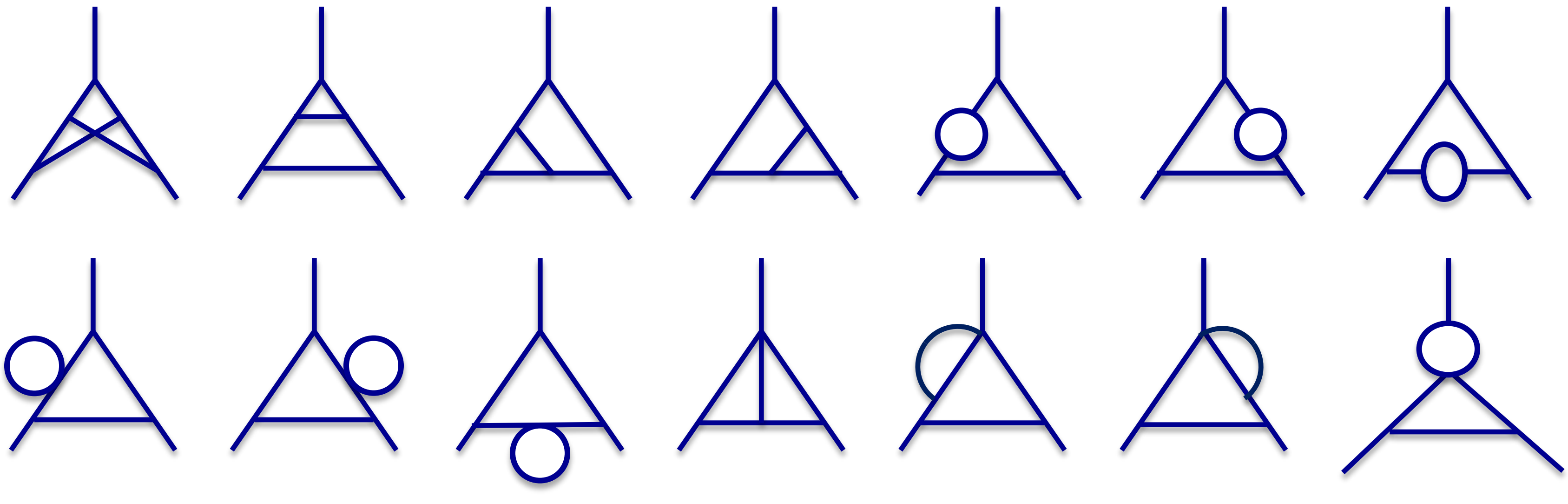
Δ=(exp)-(SM)

=28.7 x10^{-10}

strategy

1. Draw the diagrams and Corresponding Feynman Amplitudes (in Non-linear gauge)
   1780 : 2-loop proper diagrams
   70 : 1-loop proper diagrams with a 1-loop counter term

2. Classify the diagrams according to Topology types
   14 types for 2-loop proper diagrams
   6 types for diagrams with 1-loop C.T.



calculation

denominator

$$\prod_{j=1}^{6}\frac{1}{(p_j^2-m_j^2)}=\Gamma(6)\int\prod_{j=1}^{6}\frac{\delta(1-\sum z)dz_j}{[z_j(p_j^2-m_j^2)]^6},\qquad p_j=\sum_{s=1}^{2}\eta_j(s)\ell_s+q_j$$

After loop integral $$F=\int\prod dz_j\frac{1}{(4\pi)^n}\frac{\Gamma(6-n)}{(\det U)^{n/2}}\frac{1}{(V-i\varepsilon)^{6-n}}$$

numerator

$$\frac{p_j^\mu}{(p_j^2-m_j^2)}=D_j^\mu\frac{1}{(p_j^2-m_j^2)}=\frac{1}{2}\int_{m_j^2}^{\infty}dm_j^2\frac{\partial}{\partial q_j^\mu}\frac{1}{(p_j^2-m_j^2)}$$

g-2 projection operation

$$\mathrm{Proj}(\mu)=\frac{1}{4}(\gamma\cdot p-\frac{1}{2}\gamma\cdot q+m)(m\gamma_\mu\cdot p^2-(m^2+\frac{q^2}{2})p_\mu)(\gamma\cdot p+\frac{1}{2}\gamma\cdot q+m)$$

$$F_2^{(4)}(0)=\lim_{q^2\to 0}\frac{m}{p^4q^2}\mathrm{Tr}(\Gamma_\mu\cdot\mathrm{Proj}(\mu))$$

$q_\mu \Rightarrow$ photon momentum

$(\mathrm{p}-\mathrm{q}/2)_\mu \Rightarrow \mu^-$ momentum

$(\mathrm{p}+\mathrm{q}/2)_\mu \Rightarrow \mu^+$ momentum

Ultraviolet divergence appear as $\frac{1}{\varepsilon}$ pole

Infrared singularity is regularized by fictitious mass λ

To get the Fortran Source, all the symbolic manipulations are done by FORM

To get the numerical value, we use the adoptive MC system BASES

Status

UV cancelation OK

Non-linear gauge invariance … in progress

Final results … to appear soon.

Radiative corrections for MSSM

- GRACE includes MSSM model.
- Study decay channels, production processes

After LHC search and 'Higgs' discovery, window for MSSM turns narrower.

Relatively light stop scenario still seems to work.

T.Kon, Y.Kouda, M.Jimbo, T.Ishikawa, Y.Kurihara. M.Kuroda, K.Kato

Renormalization, Nonlinear gauge extension

T.Kon, M.Jimbo, T.Ishikawa, M.Kuroda

light $\tilde{t}_1$ scenario

MSSM 126GeV Higgs ----- Sparticles are heavy? O(1TeV)

300 GeV stop ----- possibly observable in LHC/ILC

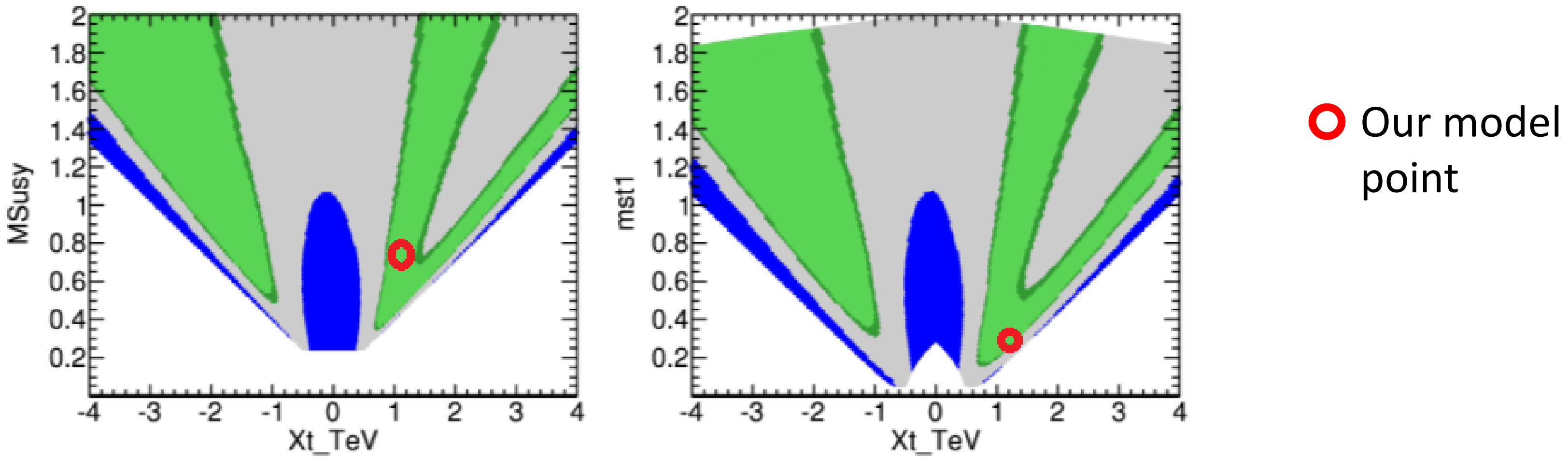
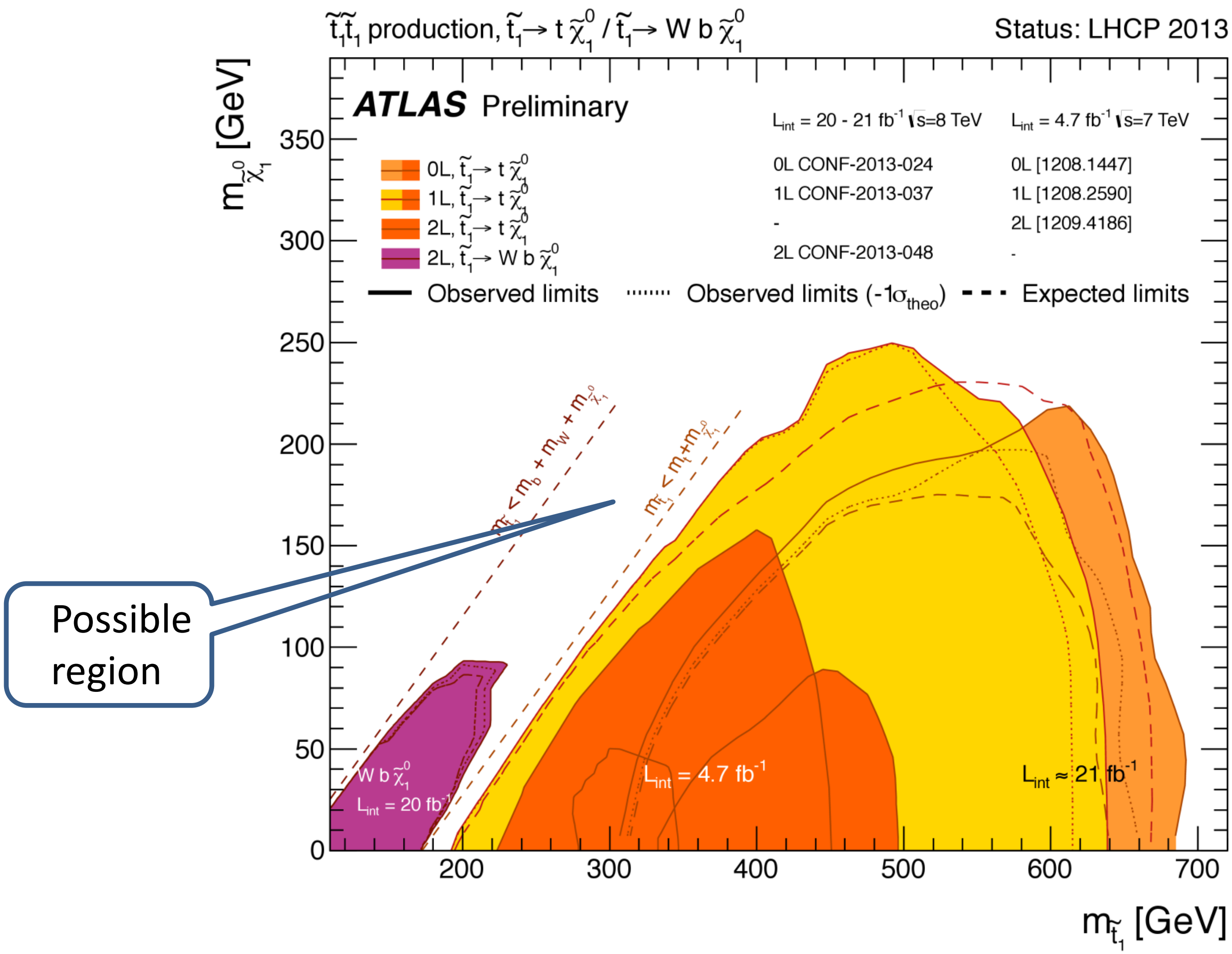


Fig. 15 Scalar top masses in the m_h^{max} scenario (with M_{SUSY} and X_t free) that yield $M_h \sim$ 125.5 GeV (green area), LEP excluded regions are shown in blue. Left: X_t-M_{SUSY} plane, right: X_t-$m_{\tilde{t}_1}$ plane [7].

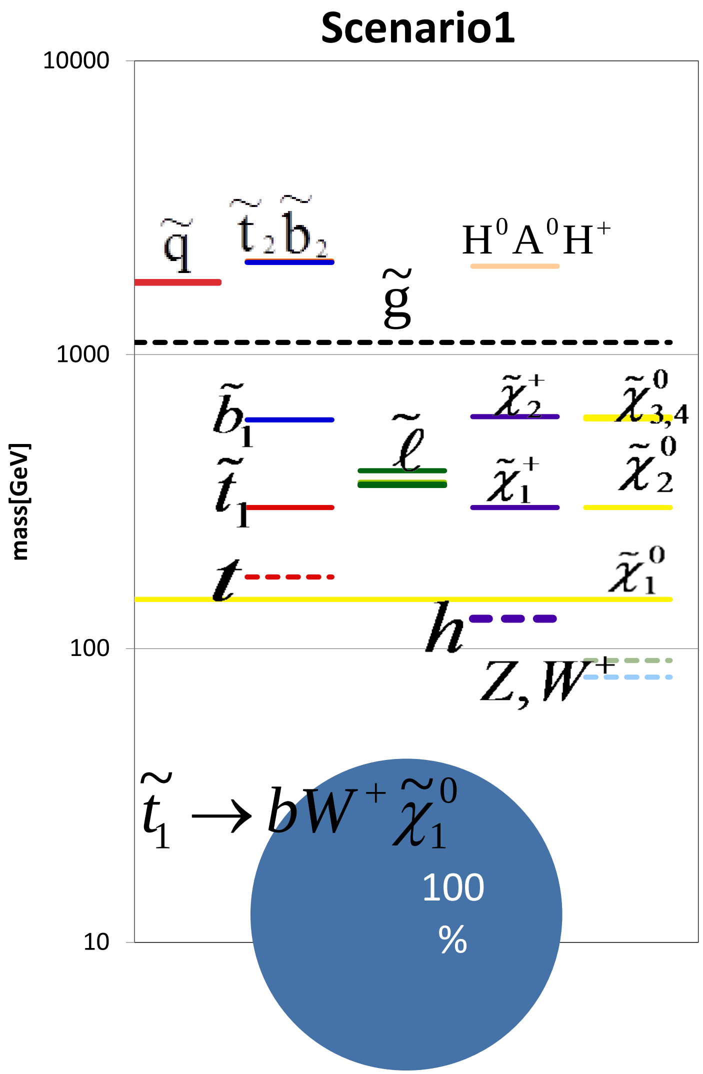
(7)S. Heinemeyer, O. St° al and G. Weiglein, *Phys. Lett.* **B 710** (2012) 201 [arXiv:1112.302[hep-ph]];

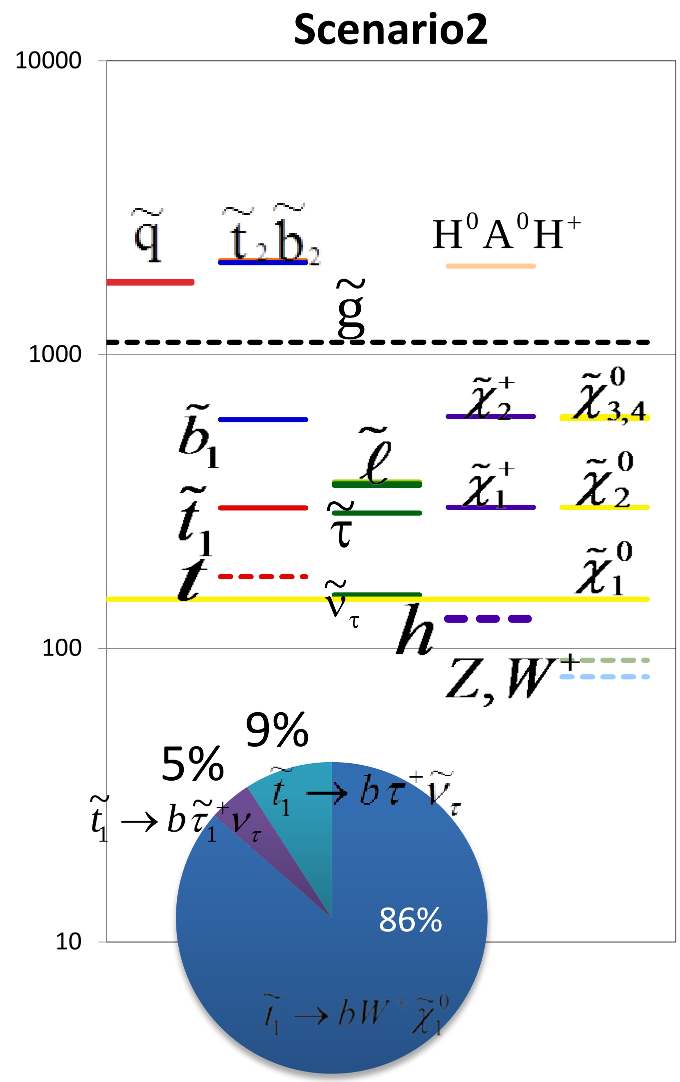
Recent Results of Light Stop Search at ATLAS



ATLAS-CONF-2013-024
ATLAS-CONF-2013-048
ATLAS-CONF-2013-053

Light stop models



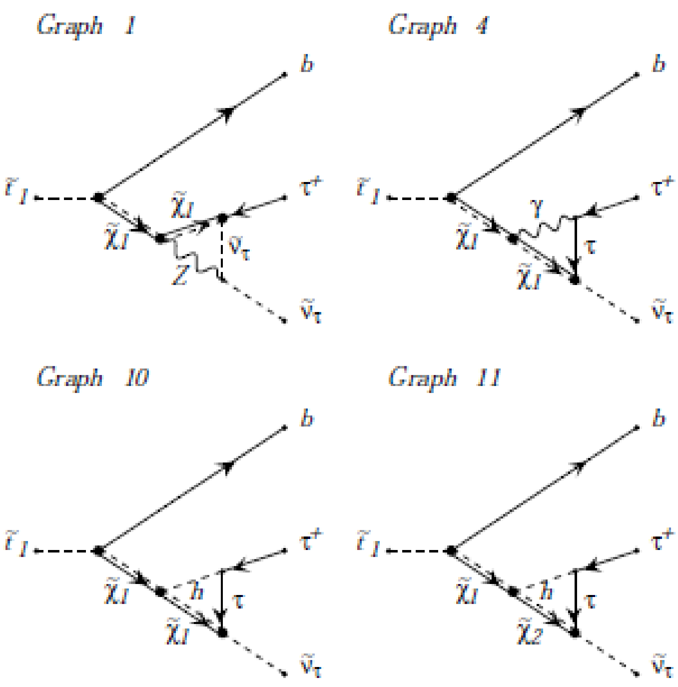


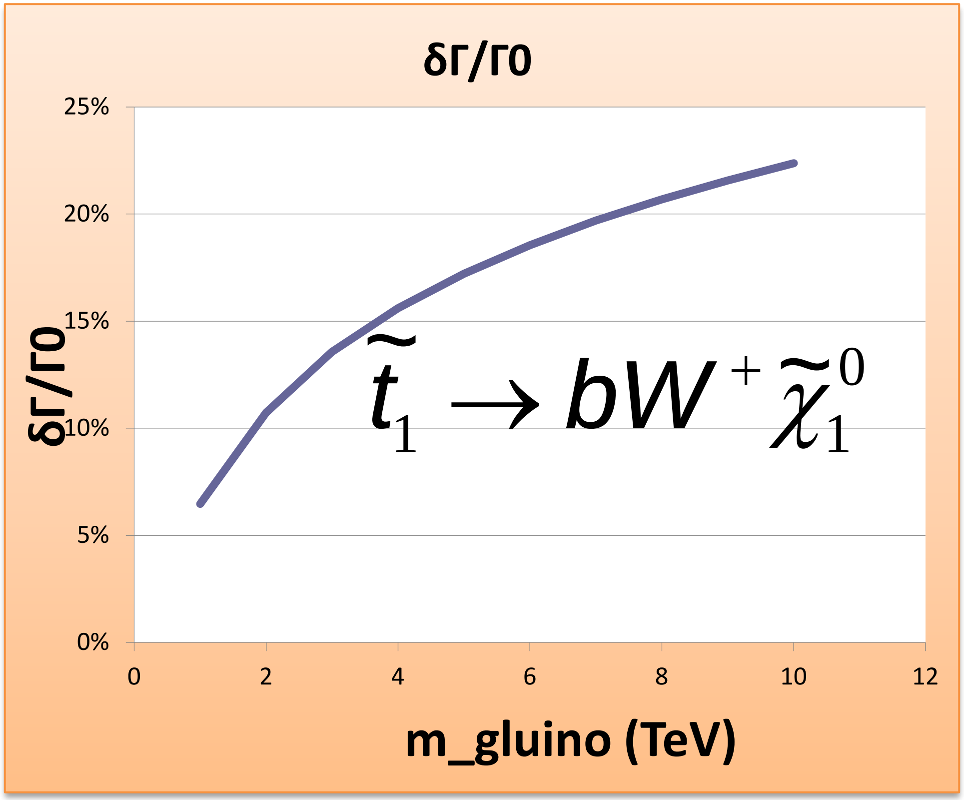
scenario1,2 : tanβ=30 μ=600GeV

1-loop R.C. to stop-1 decay

$$\widetilde{t}_1 \to b\tau^+\widetilde{\nu}_\tau$$

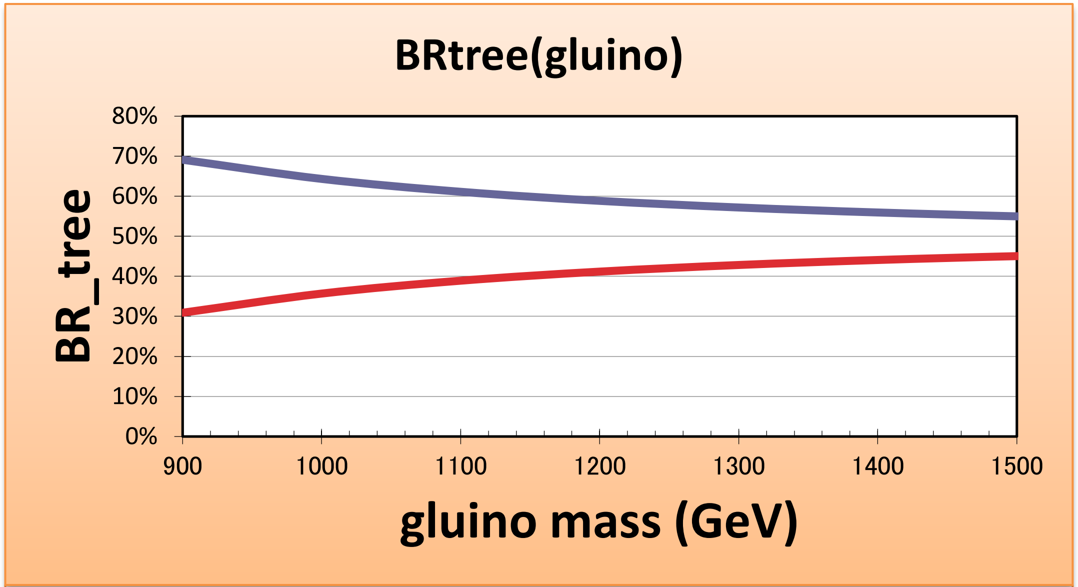
tree 2 diagrams
QCD 1-loop 12 diagrams
ELW 1-loop 490 diagrams





gluino mass vs gluino decay width

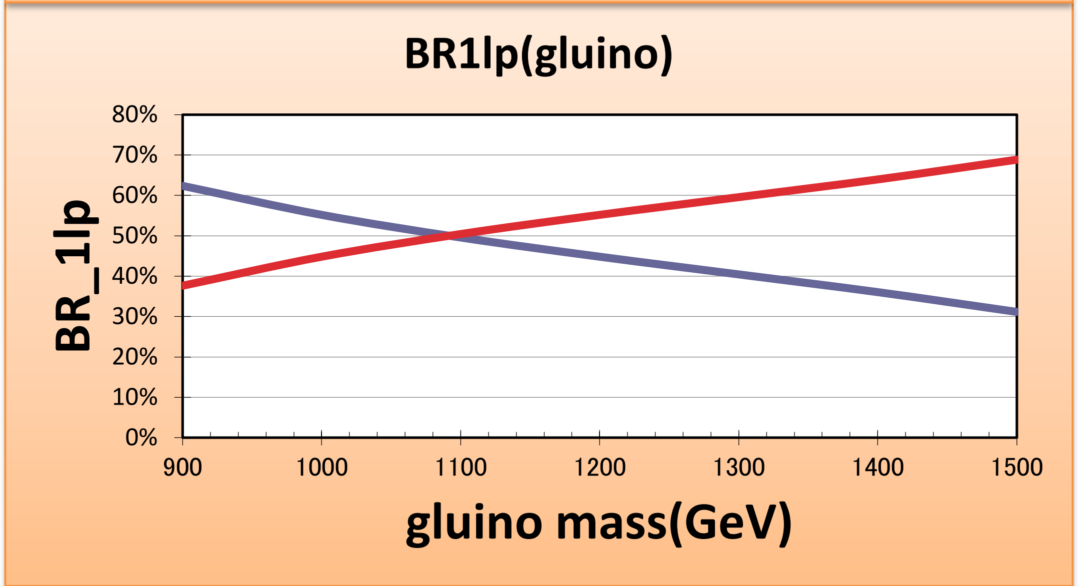
Tree



$t\tilde{t}_1$

$b\tilde{b}_1$

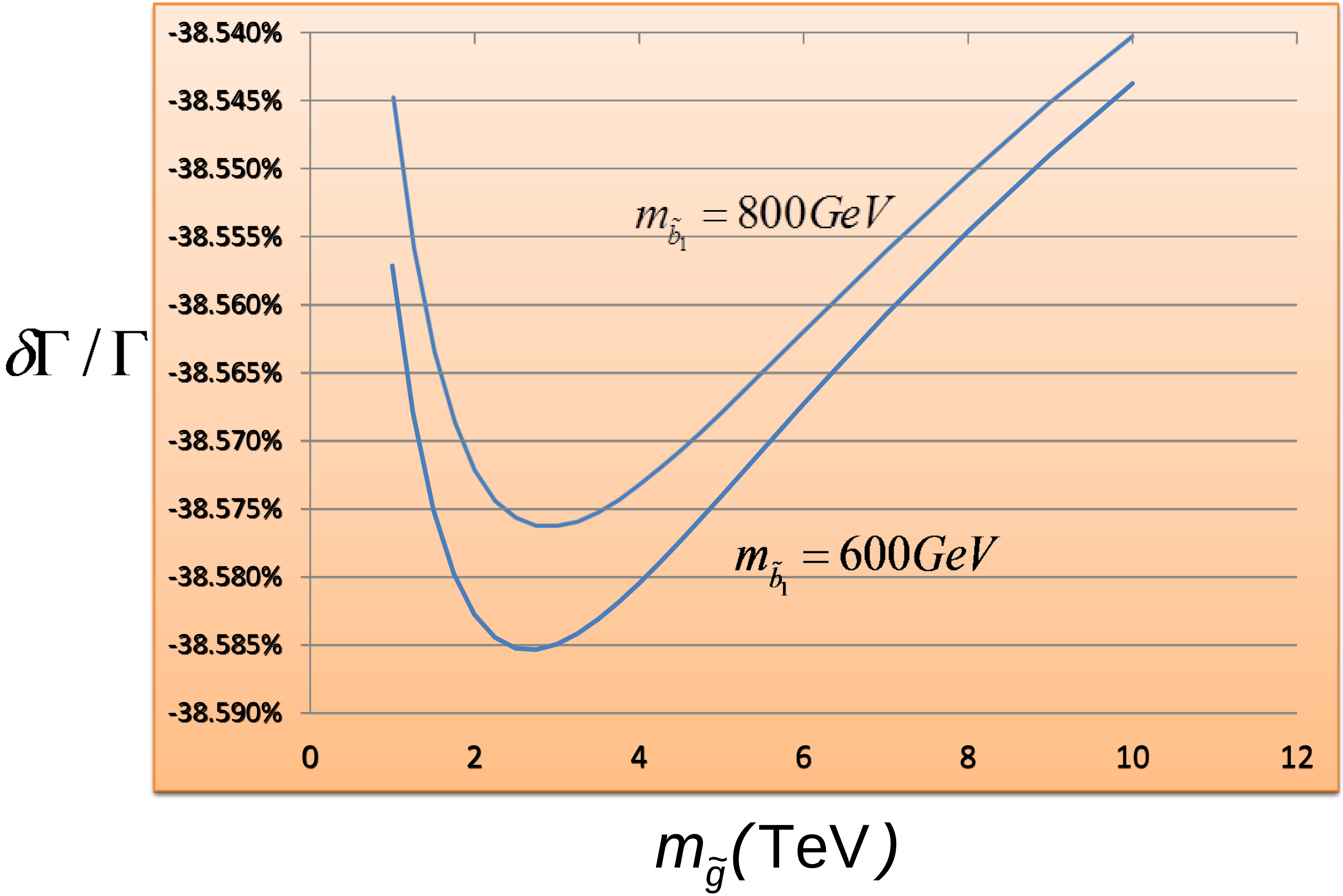
1Loop



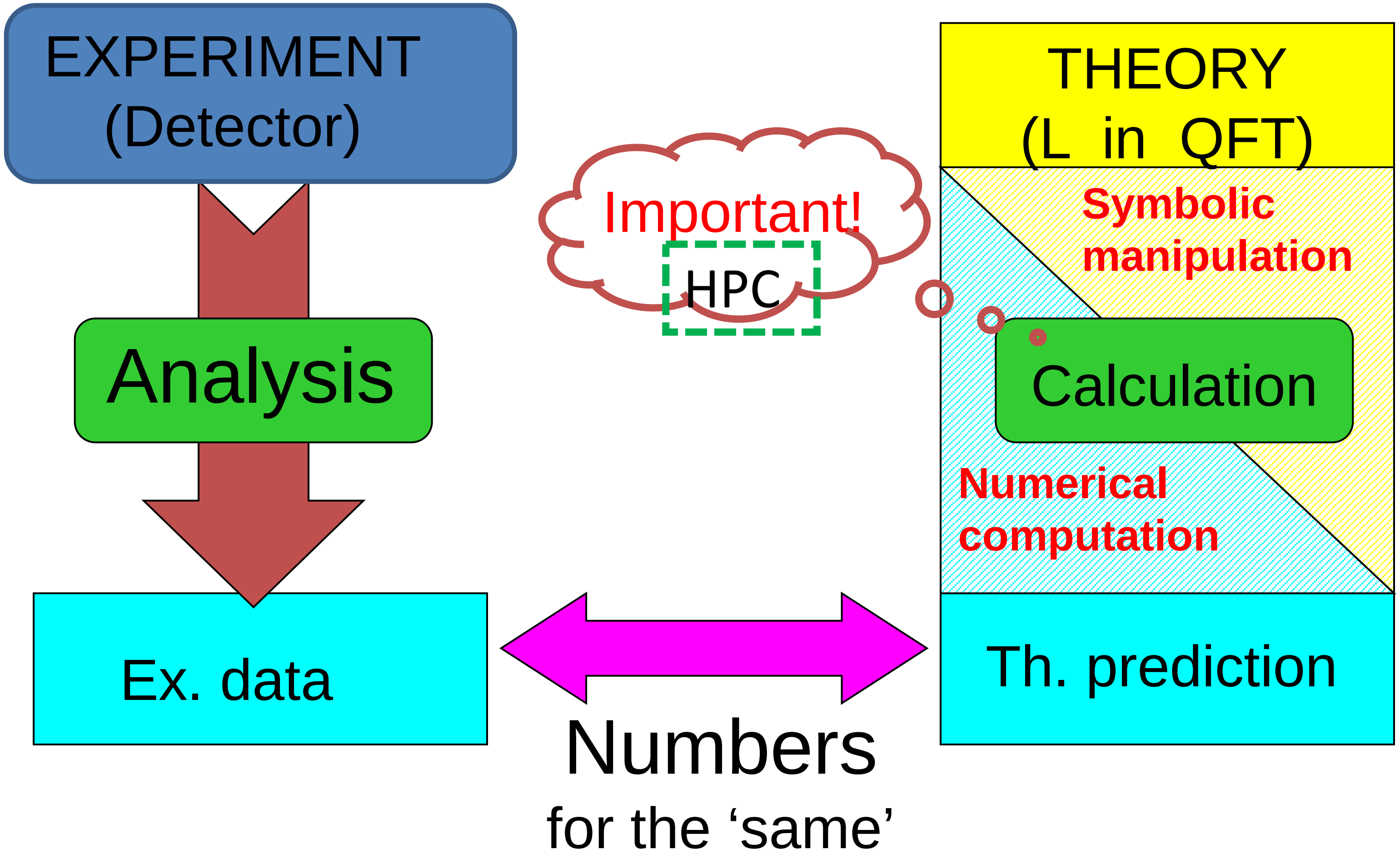
$b\tilde{b}_1$

$t\tilde{t}_1$

H→bb mode, gluino mass dep.



Summary


EXPERIMENT
(Detector)
Analysis
Ex. data
Important!
HPC
THEORY
(L in QFT)
Symbolic
manipulation
Calculation
Numerical
computation
Th. prediction
Numbers
for the ‘same’

GRACE system is developed to perform large scale calculation in HEP automatically.

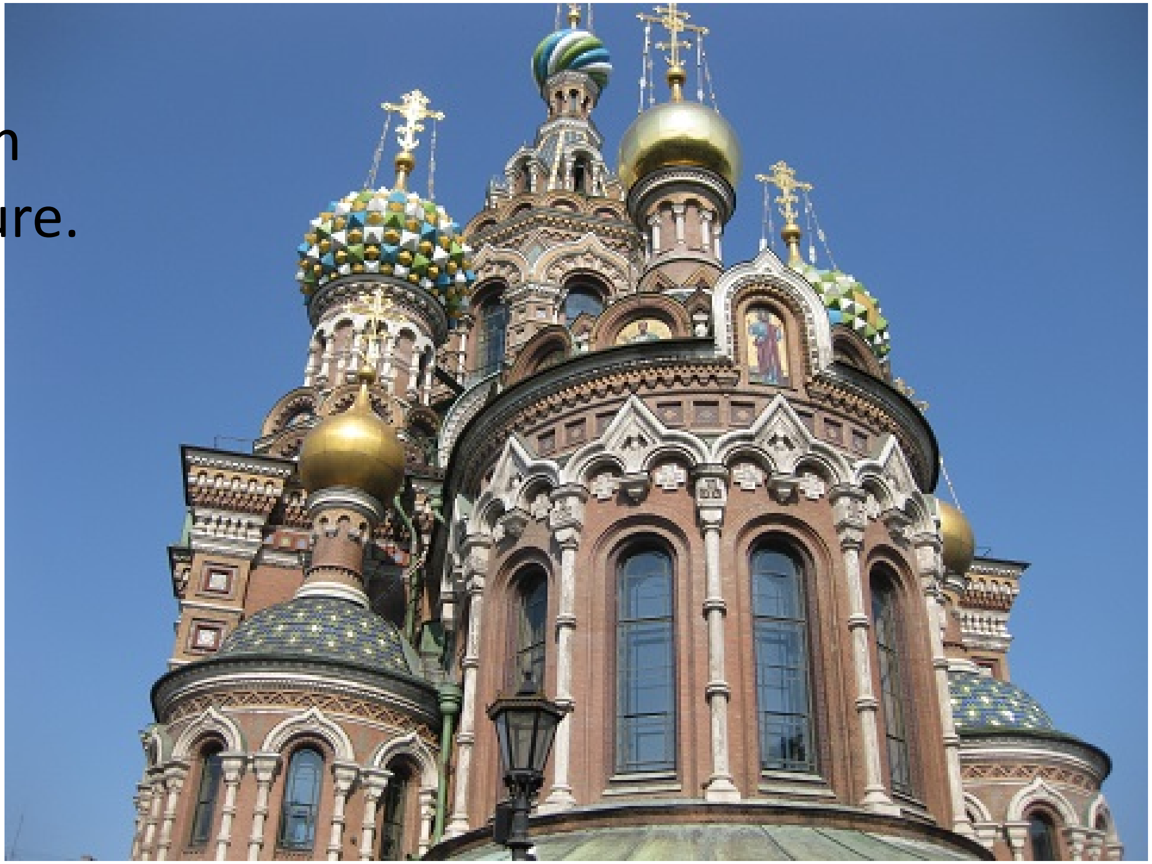
It successfully calculates

$e^+e^- \to t\bar{t}\gamma, e^+e^-\gamma$

radiative corrections to MSSM particles

and extends its capability further.

2-loop automation can be possible in the future.



THANK YOU !