HELAS, Toponium and the ILC

Kaoru Hagiwara (KEK)

Hitoshi Fest @ Kavli IPMU
2024.12.20

① Jun 1989

MULTIPLE WEAK BOSON PRODUCTION VIA GLUON FUSION #1

Kaoru Hagiwara (Durham U.), Hitoshi Murayama (Tokyo U.) (Jun, 1989)

Published in: *Phys.Rev.D* 41 (1990) 1001

pdf DOI cite claim reference search 14 citations

SSC

② Apr 1990

SUPERSYMMETRIC CONTRIBUTIONS TO GAMMA ($Z \to$ HADRONS) #2

Kaoru Hagiwara (KEK, Tsukuba), Hitoshi Murayama (Tokyo U.) (Apr, 1990)

Published in: *Phys.Lett.B* 246 (1990) 533-536

DOI cite claim reference search 22 citations

LEP

③ Oct 1990

Search for the Yukawa interaction in the process e+ e- ---> t anti-t Z at TeV linear colliders #3

Kaoru Hagiwara (KEK, Tsukuba), H. Murayama (Tokyo U.), I. Watanabe (Hiroshima U.) (Oct, 1990)

Published in: *Nucl.Phys.B* 367 (1991) 257-286

DOI cite claim reference search 83 citations

④ Dec 1990

Single weak boson production at TeV e+ e- colliders #4

Kaoru Hagiwara (Durham U. and KEK, Tsukuba), H. Iwasaki (Hiroshima U.), A. Miyamoto (KEK, Tsukuba), H. Murayama (Tokyo U.), D. Zeppenfeld (Wisconsin U., Madison) (Dec, 1990)

Published in: *Nucl.Phys.B* 365 (1991) 544-596

DOI cite claim reference search 55 citations

⑤ Nov 1990

JLC physics #23

H. Murayama (Tokyo U.) (1990)

Contribution to: 2nd Workshop on Japan Linear Collider (JLC), 135-149

cite reference search 0 citations

⑥ Jan 1992

HELAS: HELicity amplitude subroutines for Feynman diagram evaluations #6

H. Murayama (Tohoku U.), I. Watanabe (Hiroshima U.), Kaoru Hagiwara (KEK, Tsukuba) (Jan, 1992)

pdf cite claim reference search 71 citations

HELAS (③–⑥)

⑦ Mar 1992

Top quark pair production near threshold #7

Y. Sumino (Tokyo U.), K. Fujii (KEK, Tsukuba), Kaoru Hagiwara (KEK, Tsukuba and Durham U.), H. Murayama (Tohoku U.), C.K. Ng (SLAC) (Mar, 1992)

Published in: *Phys.Rev.D* 47 (1993) 56-81

pdf links DOI cite claim reference search 149 citations

JLC (③–⑦)

1987	M2	I gave weekly lectures @UTokyo (Hitoshi was a M2 student)	
1988	D1	Oct 8-19 I meet Hitoshi @UTokyo.	I was in
1989	D2	• paper ①	Durham
1990	D3	Mar 2-16 Pheno school @KEK with K.Hikasa • papes ②, ③, ④ Many projects @KEK • JLC WS2 ⑤	
1991	Ph.D. Tohoku U	• HELS manual ⑥	Durham
1992		• Toponium paper with J.Sumino ⑦ Tim Stelzer visited KEK & learned HELAS ⇒ MadGraph (1994).	

Multiple weak-boson production via gluon fusion

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(Received 25 September 1989)

We note here that this chiral transformation produces no anomaly for a degenerate quark doublet in the QCD sector. The resulting Yukawa Lagrangian is simply

$$\mathcal{L}_{\mathrm{Yukawa}} = -f\frac{1}{\sqrt{2}}\sqrt{(v+H)^2+(\chi^3)^2+2\chi^+\chi^-} \times (\bar{U},\bar{D})\begin{pmatrix} U \\ D \end{pmatrix} . \quad (3)$$

This form exhibits explicitly the SO(4) symmetry of the fields $(v+H,\chi^1,\chi^2,\chi^3)$ where $\chi^{\pm}=(\chi^1 \pm i\chi^2)/\sqrt{2}$. This symmetry is a reflection of the $SU(2)_L \times SU(2)_R$ symme-

$$\mathcal{L}_{\mathrm{eff}} = \frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{a\mu\nu} \ln\left[\left(1+\frac{H}{v}\right)^2 + 2\frac{\chi^+\chi^-}{v^2} + \frac{(\chi^3)^2}{v^2}\right] . \quad (4)$$

This is our main result.

The "Feynman rules" for $gg \to$ multiple W and Z bosons are obtained by expanding the effective action (4). From its form, we see immediately that only even numbers of W/Z are produced, which is analogous to the G-parity selection rule for the pions. The vertex for $2n$ W/Z's which contain m pairs of W^+W^- and $(2n-2m)$ Z's is

$$\frac{\alpha_s}{3\pi}\delta^{ab}[k_2^\mu k_1^\nu - (k_1\cdot k_2)g^{\mu\nu}]\frac{1}{v^{2n}}\frac{(-1)^{n-1}}{n}2^m(2n-2m)!m!m!{}_nC_m , \quad (5)$$

where the colors of gluons are denoted by a,b, and their four-momenta by k_1^μ, k_2^ν. These "vertices" correspond to the infinitely-heavy-quark loop with Goldstone-boson legs [we call these direct amplitudes; see Fig. 1(a)]. The cross sections averaged over colors and helicities of two gluons are

$$\sigma(gg \to (W^+W^-)^m Z^{2n-2m}) = \frac{1}{2}\frac{1}{8}\frac{\alpha_s^2}{9\pi^2}\frac{\hat{s}}{8}(2n-2m)!\left(\frac{2^m n!}{nv^{2n}(n-m)!}\right)^2 V_{\mathrm{ph}} , \quad (6)$$

Supersymmetric contributions to $\Gamma(Z \rightarrow \text{hadrons})$

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and

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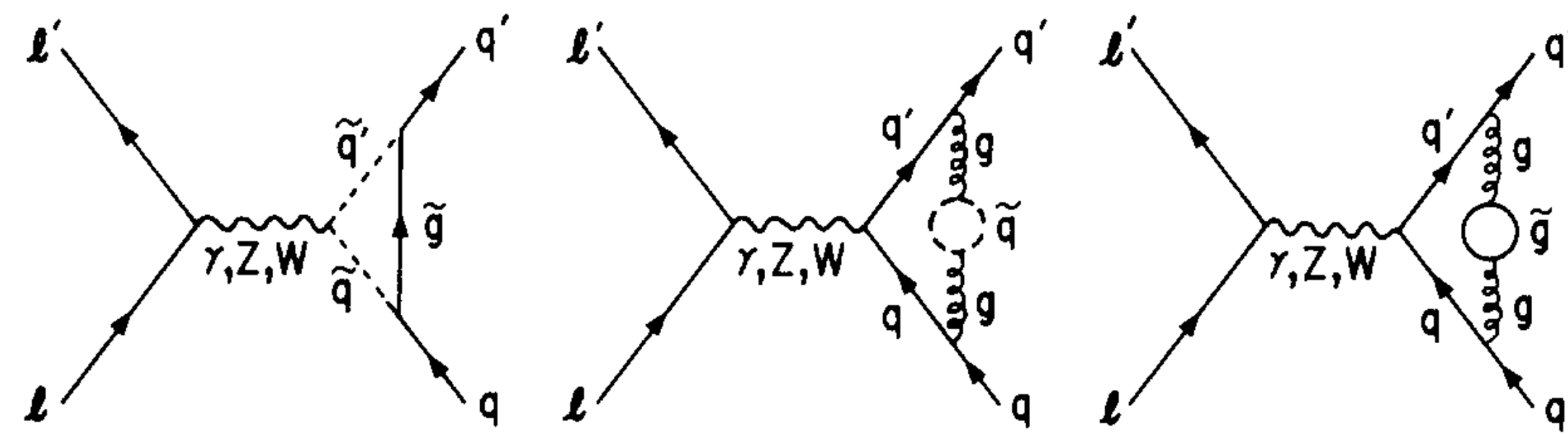
Received 27 May 1990



Search for the Yukawa interaction in the process $e^+e^- \to t\bar{t}Z$ at TeV linear colliders

K. Hagiwara [1], H. Murayama [2,*] and I. Watanabe [3]

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Received 29 October 1990

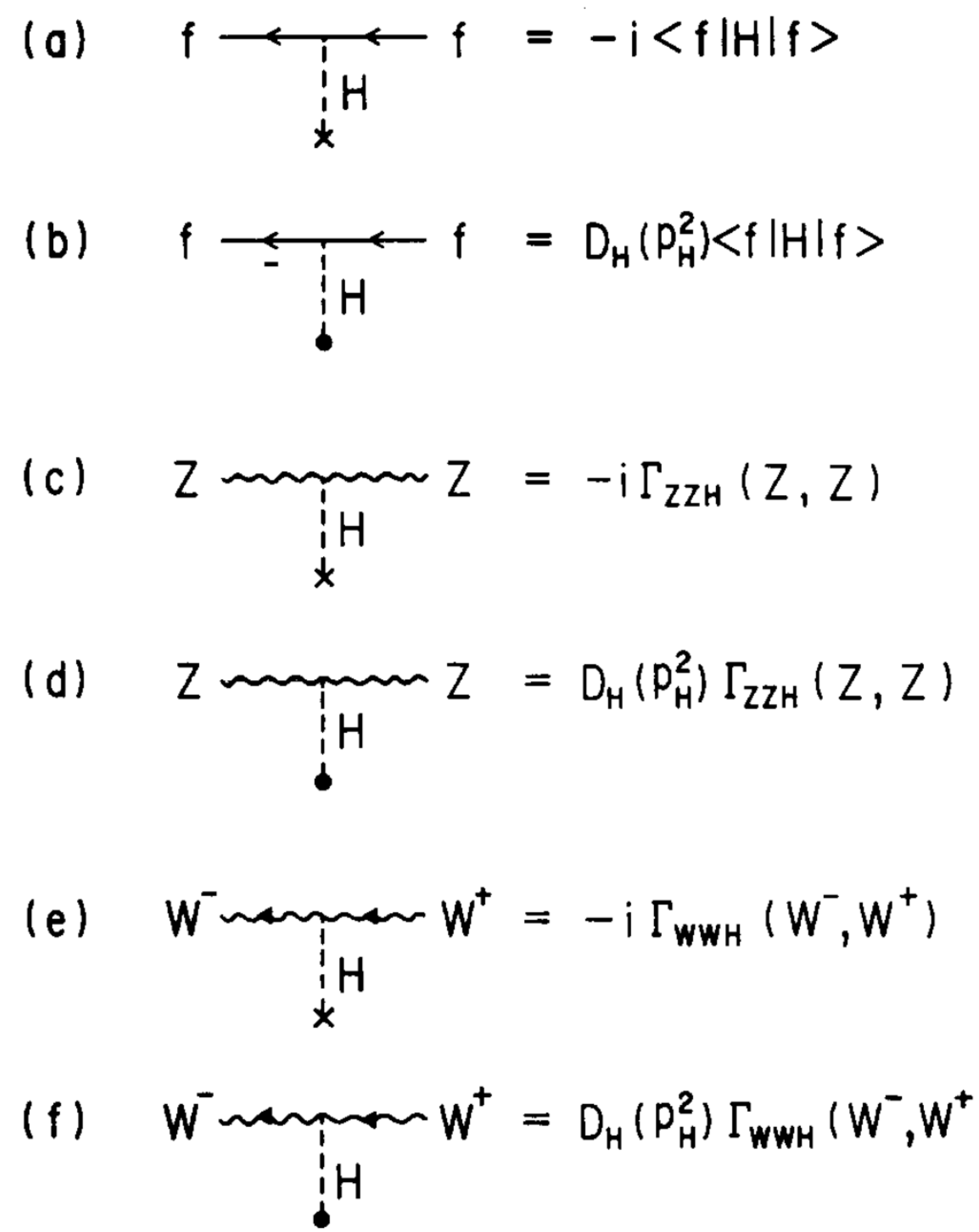

Fig. 3. Additional HELAS Feynman rules including a Higgs boson which is represented by a dashed line.

SINGLE WEAK BOSON PRODUCTION AT TeV e^+e^- COLLIDERS

K. HAGIWARA[1,2], H. IWASAKI[3], A. MIYAMOTO[2], H. MURAYAMA[4] and D. ZEPPENFELD[5]

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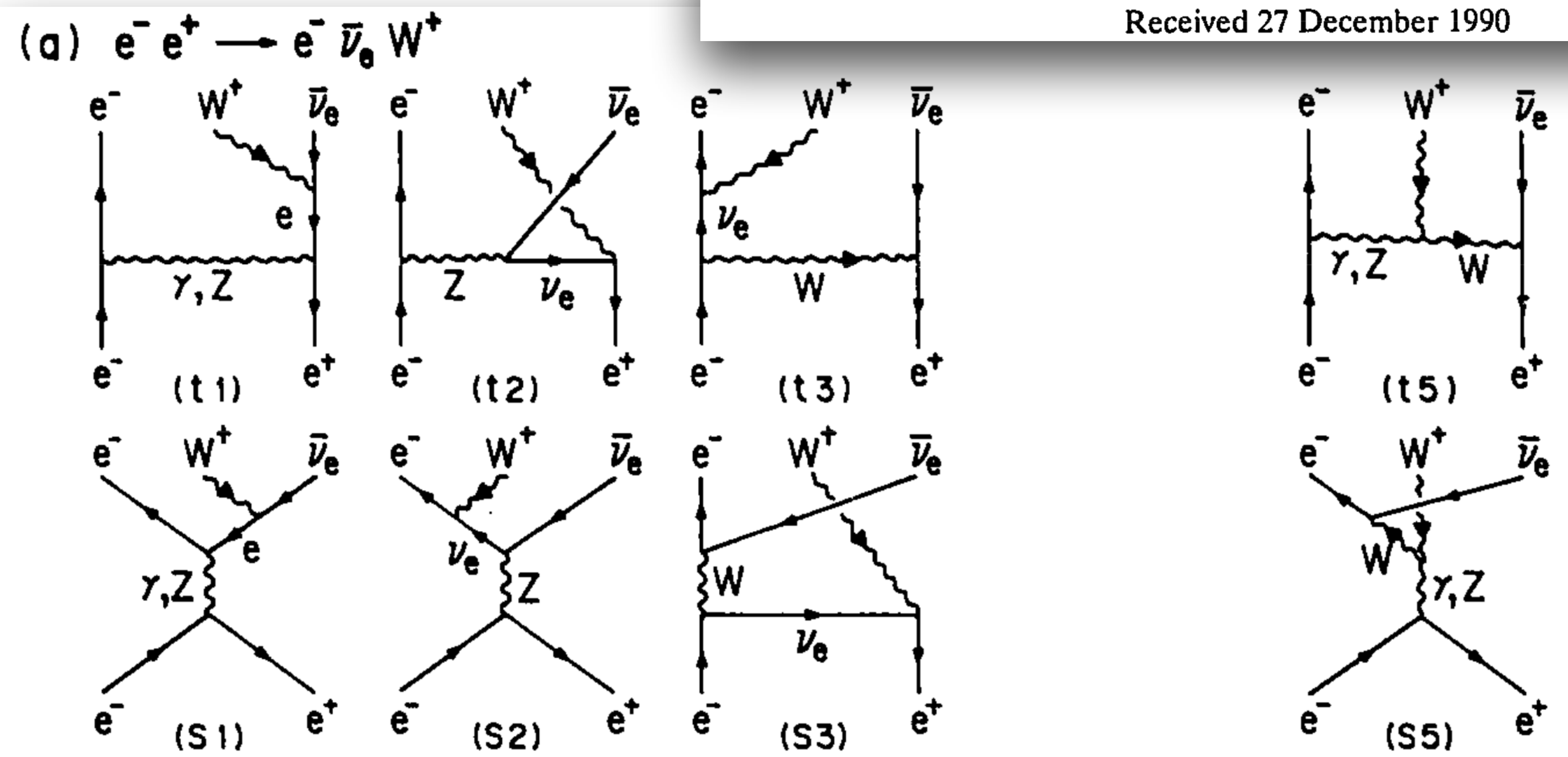
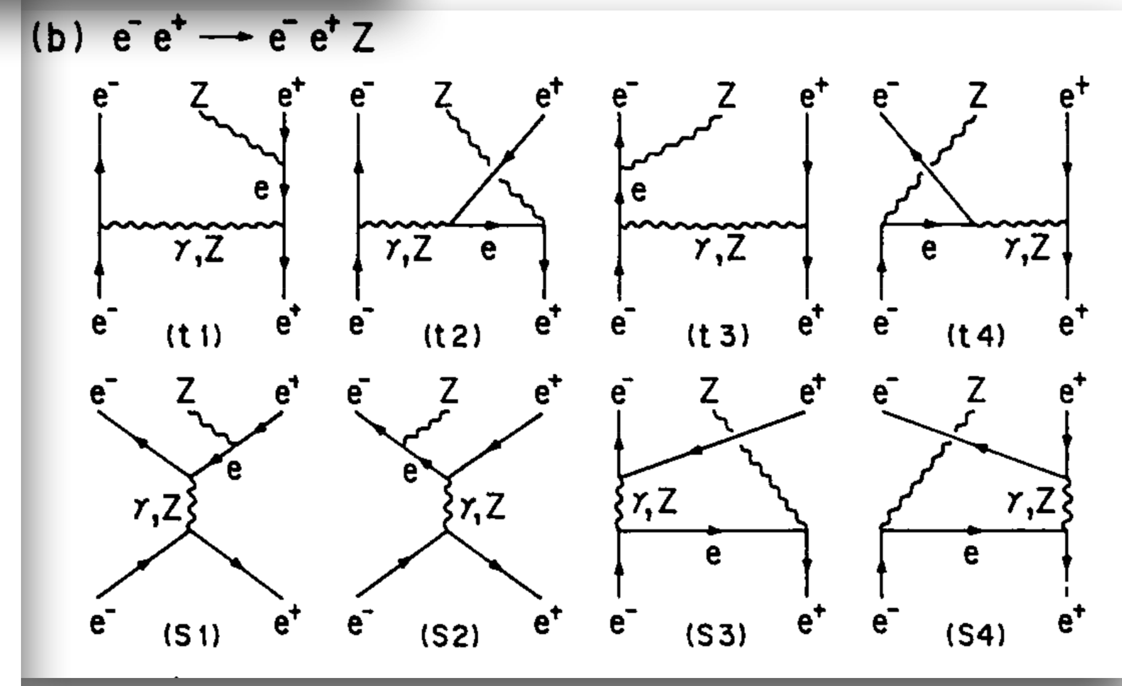
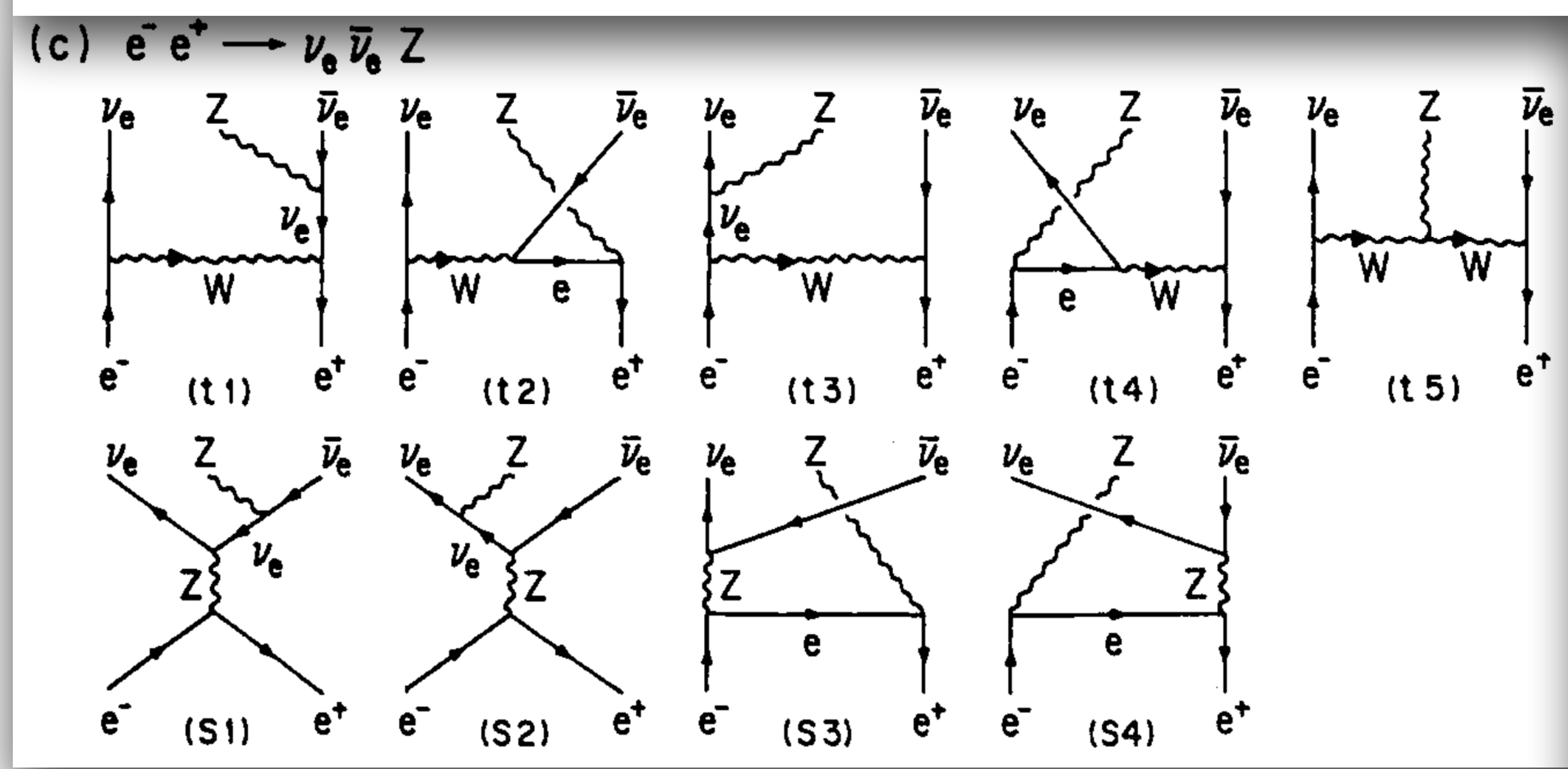
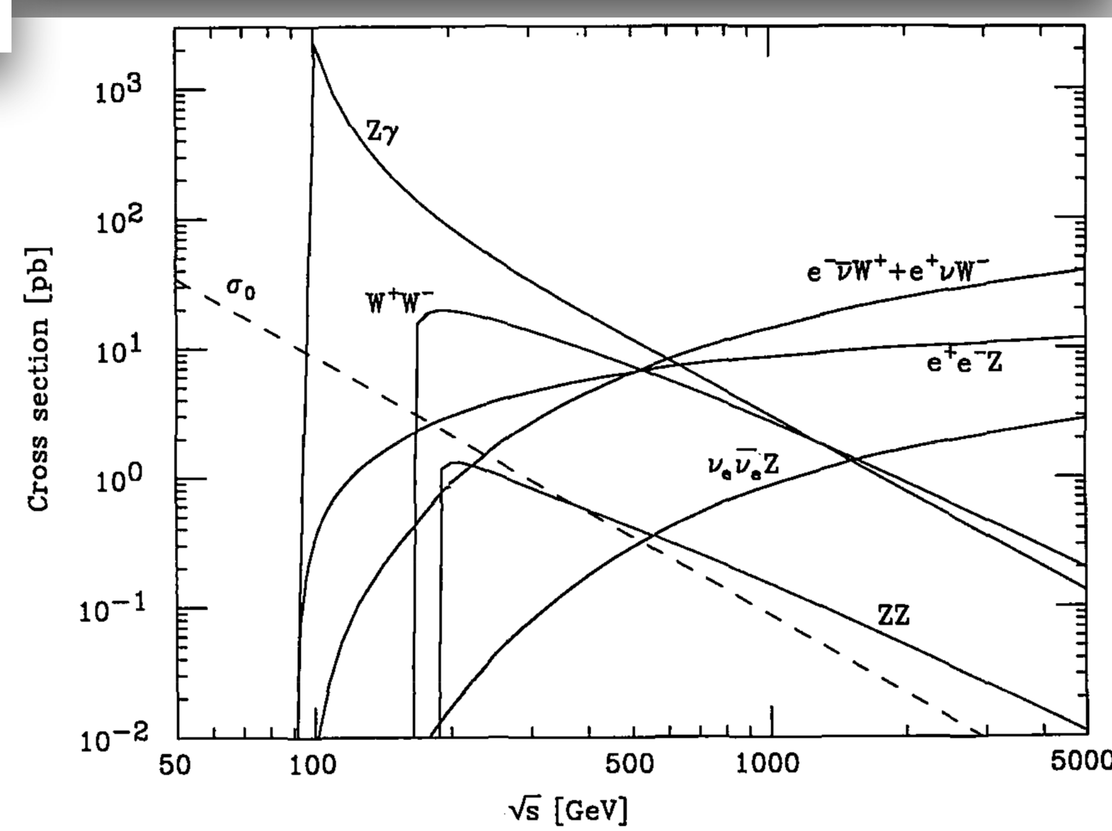
Received 27 December 1990









KEK Report 91-11
January 1992
H

HELAS: HELicity Amplitude Subroutines for Feynman Diagram Evaluations

H. MURAYAMA, I. WATANABE and K. HAGIWARA

Chapter 2

How to use HELAS

2.1 Basic Idea

The basic idea of HELAS is to begin with the external lines by creating the wavefunctions explicitly using a fixed notation, and to give rules to join the lines. You may suppose that there are too many possibilities for a complete set of joining rules but in fact they can all be classified into a finite set in renormalizable theories. We will show all the possible rules of renormalizable theories in Table 2.1.

Vertex	interaction
FFV	vector or axial vector couplings
FFS	Yukawa couplings
VVV	Yang-Mills couplings
VVS	Higgs interaction
SSV	scalar gauge couplings
SSS	scalar self-couplings
VVVV	Yang-Mills couplings
VVSS	scalar gauge couplings (seagull)
SSSS	scalar self-couplings

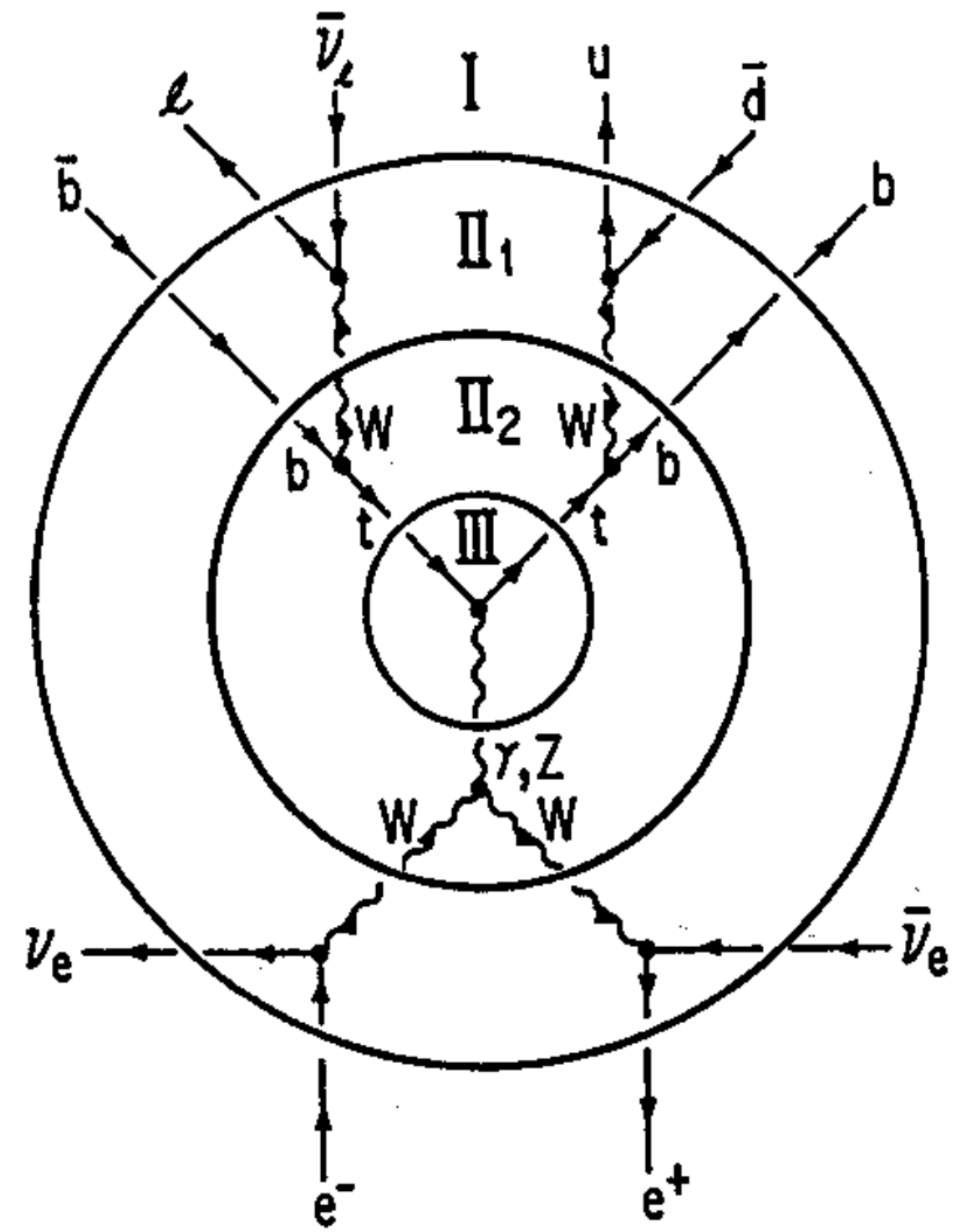


Figure 5: The steps you follow when coding with HELAS . The shown example is an extended version of Fig. 4(a), where the final W^+ decays into $u\bar{d}$, and W^- into $l\bar{\nu}_l$.

2.9.3 Goldstone bosons and the BRS invariance tests

What we find most efficient in testing the helicity amplitudes with one or more external vector bosons is the BRS identity [4]

$$\langle phys;\,\mathrm{out}|\,(\partial^\mu V_\mu - \xi_V m_V \chi_V)\,|phys;\,\mathrm{in}\rangle = 0, \qquad (2.35)$$

where ξ_V is the covariant R_ξ gauge parameter and χ_V the Goldstone mode associated with the vector boson V. The states $\langle phys;\,\mathrm{out}|$ and $|phys;\,\mathrm{in}\rangle$ are arbitrary physical states of on-shell external particles. By using the reduction formula, the identity (2.35) leads to an exact relationship between the S-matrix elements of the four-divergence of the vector boson and those of the associated Goldstone boson

$$\langle phys,\,V_S;\,\mathrm{out}|phys;\,\mathrm{in}\rangle \;=\; -\langle phys,\,\chi_V;\,\mathrm{out},|phys;\,\mathrm{in}\rangle, \qquad (2.36)$$

where V_S denotes the 'scalar' component of the vector boson. Eq. (2.36)

A.4 Collinear Singularities

The output of the JEEXXX is simply

$$\hat{J}^{\mu}_{A}(\langle e'|, |e\rangle) = (-e)\bar{u}(p,\sigma')\gamma^{\mu}u(k,\sigma), \tag{A.24}$$

for the t-channel photon emission from the electron current. Since the problem is

For the helicity non-flip case $\sigma = \sigma'$, the truncated current reads

$$\hat{J}^{\mu}_{A} = (-e)\sqrt{x}(2E)\left(\cos\frac{\theta}{2},\ \sin\frac{\theta}{2}e^{-i\sigma\phi},\ i\sigma\sin\frac{\theta}{2}e^{-i\sigma\phi},\ \cos\frac{\theta}{2}\right), \tag{A.27}$$

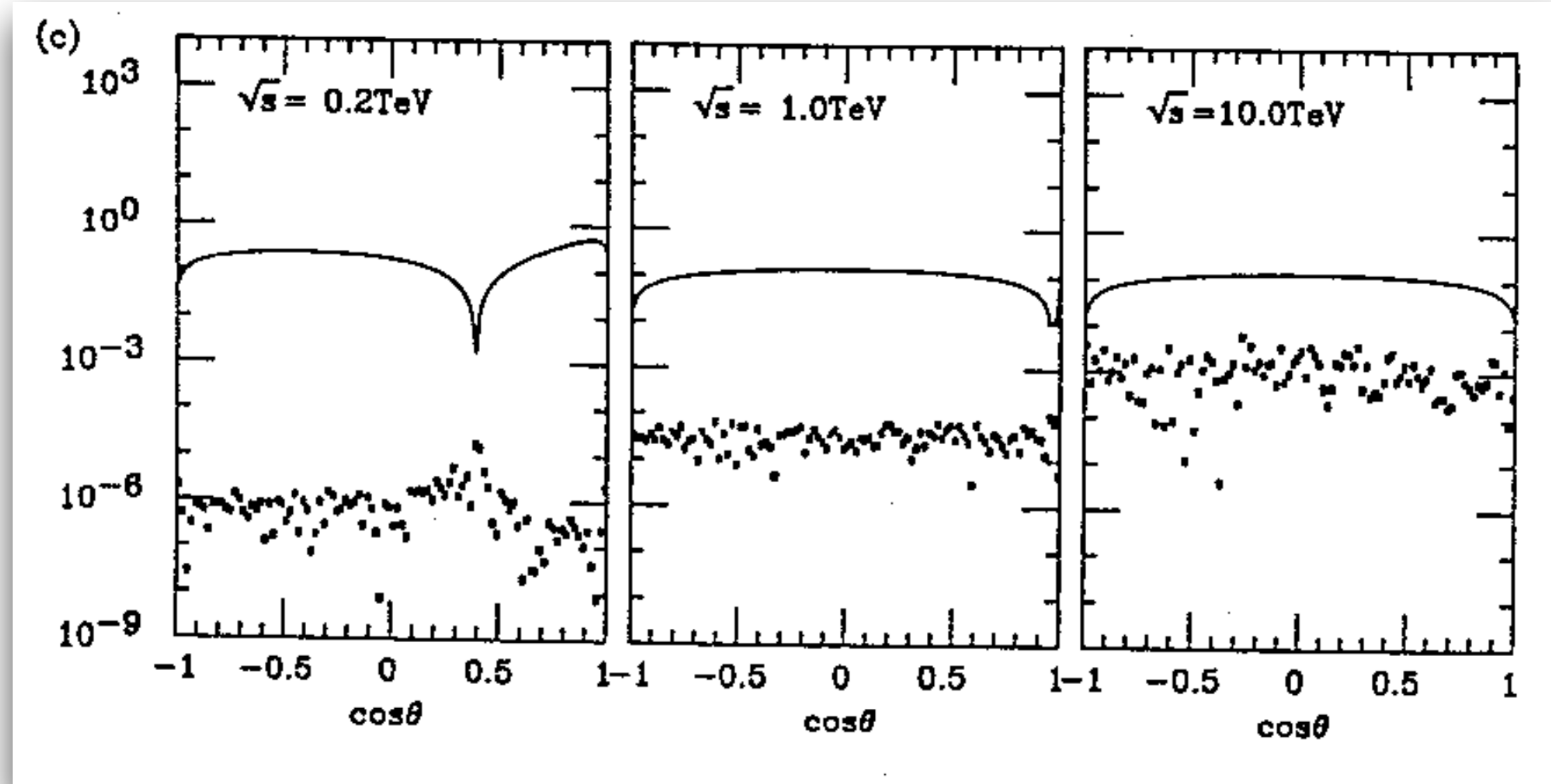
where the terms of order $O(m_e^2/E^2)$ are neglected. One can check the conservation of the current by contracting with the four-momentum of the photon

$$\begin{aligned} p^{\mu}_{A} &= k^{\mu} - p^{\mu} \\ &= E(1-x,\ -x\beta'\sin\theta\cos\phi,\ -x\beta'\sin\theta\sin\phi,\ \beta - x\beta'\cos\theta) \\ &= E(1-x,\ -x\sin\theta\cos\phi,\ -x\sin\theta\sin\phi,\ 1-x\cos\theta) + O\left(\frac{m_e^2}{E}\right), \end{aligned} \tag{A.28}$$

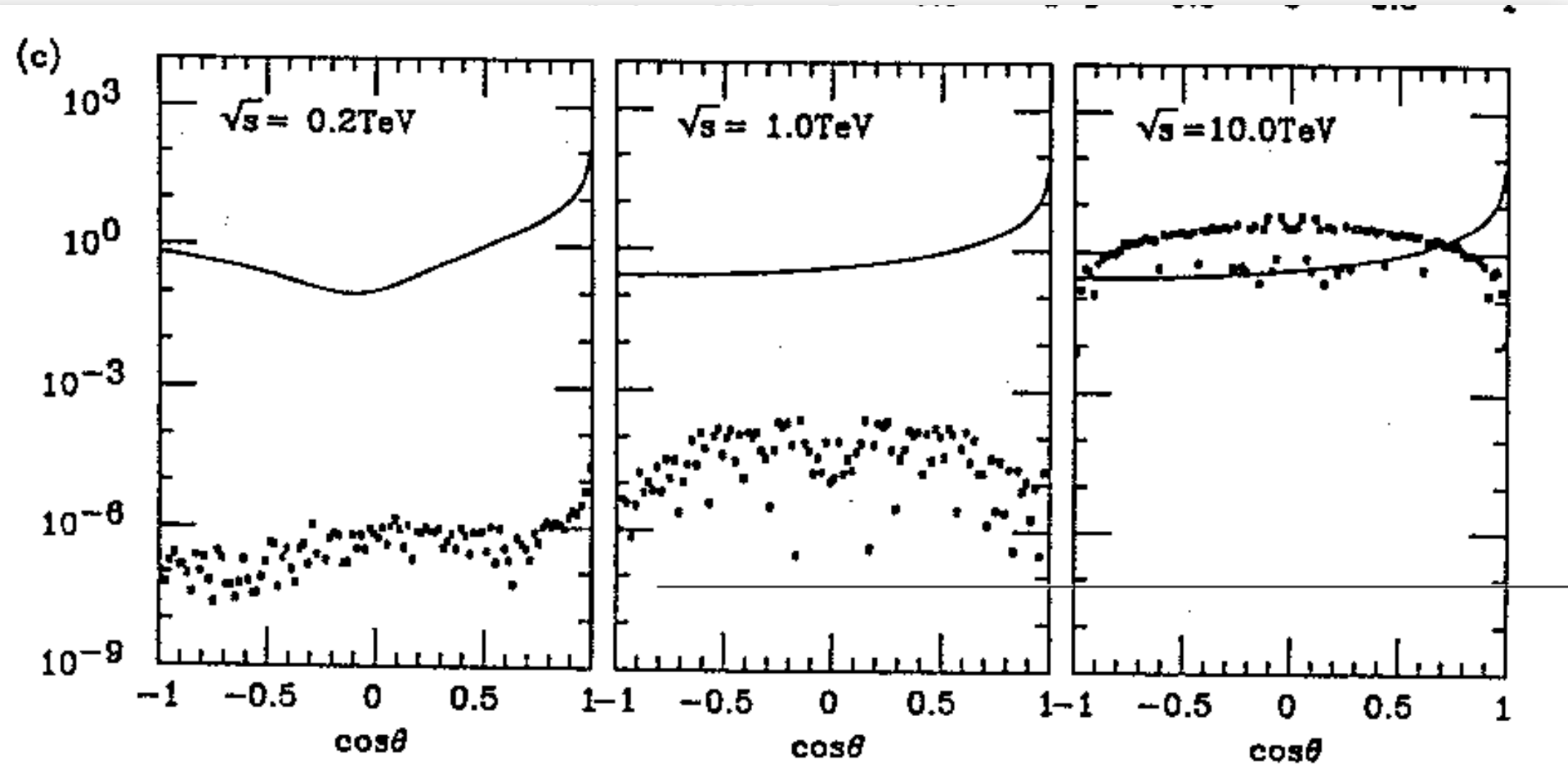
Since the problem lies in the collinear limit $\cos\theta \to 1$, it is instructive to give the expression in the limit,

$$\begin{aligned} \hat{J}^{\mu}_{A} &= \sqrt{x}(2E)(1,\ 0,\ 0,\ 1), \\ p^{\mu}_{A} &= E(1-x,\ 0,\ 0,\ 1-x). \end{aligned} \tag{A.29}$$

$$\begin{aligned} \hat{J}^{\mu}_{A} - \hat{J}^{0}_{A}\frac{p^{\mu}_{A}}{p^{0}_{A}} = (-e)\sqrt{x}(2E)\sin\frac{\theta}{2}\Bigg(0,\ & e^{-i\sigma\phi} + \frac{2x}{1-x}\cos^2\frac{\theta}{2}\cos\phi, \\ & i\sigma e^{-i\sigma\phi} + \frac{2x}{1-x}\cos^2\frac{\theta}{2}\sin\phi,\ -\frac{2x}{1-x}\cos\frac{\theta}{2}\sin\frac{\theta}{2}\Bigg), \end{aligned} \tag{A.30}$$

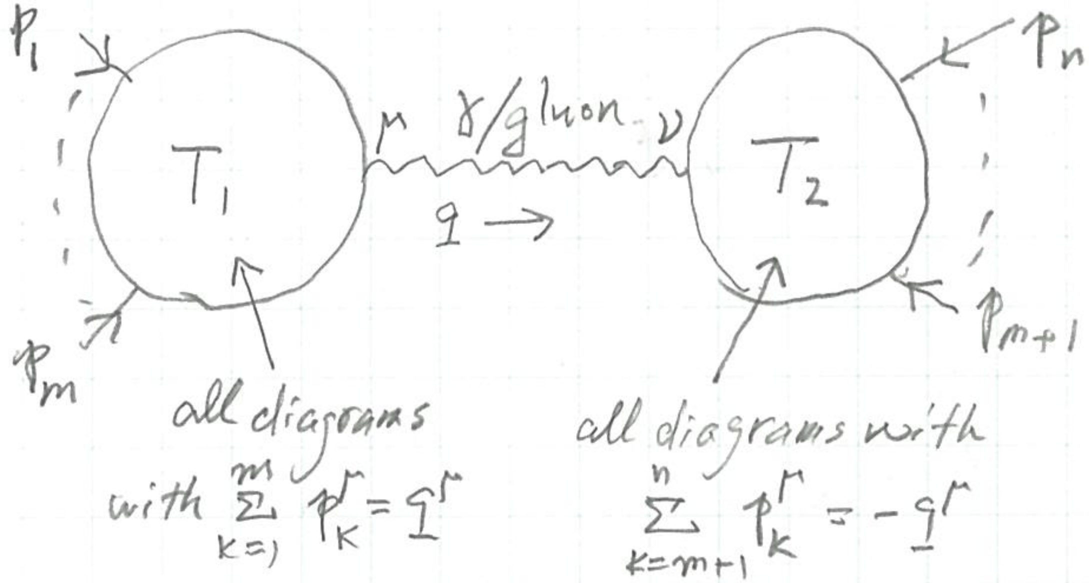


$$e_L^- e_R^+ \to W_L^- W_L^+$$


(c)
$\sqrt{s}$ = 0.2TeV
$\sqrt{s}$ = 1.0TeV
$\sqrt{s}$ =10.0TeV
10^3
10^0
10^-3
10^-6
10^-9
−1 −0.5 0 0.5 1
cosθ

$$W_L^- W_L^+ \to W_L^- W_L^+$$

QED & QCD : Feynman gauge ⇒ FD gauge   2003.03003 (KH-Kanzaki-Mawatari)



$$= T(p_1,\cdots,p_n) = T_1^\mu(p_1,\cdots,p_m)\,\frac{P^{\xi}_{\mu\nu}(q)}{q^2+i\epsilon}\,T_2^\nu(p_{m+1},\cdots,p_n)$$

$$P^{\xi}_{\mu\nu}(q) = -g_{\mu\nu} + (1-\xi)\frac{q_\mu q_\nu}{q^2}$$

$$\underbrace{q_\mu T_1^\mu = q_\nu T_2^\nu = 0}_{\text{(BRST)}} \Rightarrow \xi\text{-independence of } T.$$

$$P^{\xi}_{\mu\nu}(q) = -g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2} - \xi\frac{q_\mu q_\nu}{q^2}$$

$$q^\mu = (q^0, 0, 0, |\vec{q}|)$$

$$= \sum_{h=\pm1} \epsilon^*_\mu(q,h)\epsilon_\nu(q,h) + \mathrm{sgn}(q^2)\,\epsilon^*_\mu(q,0)\epsilon_\nu(q,0) - \xi\frac{q_\mu q_\nu}{q^2}$$

$$q^0 > 0,\quad Q = \sqrt{|q^2|}$$

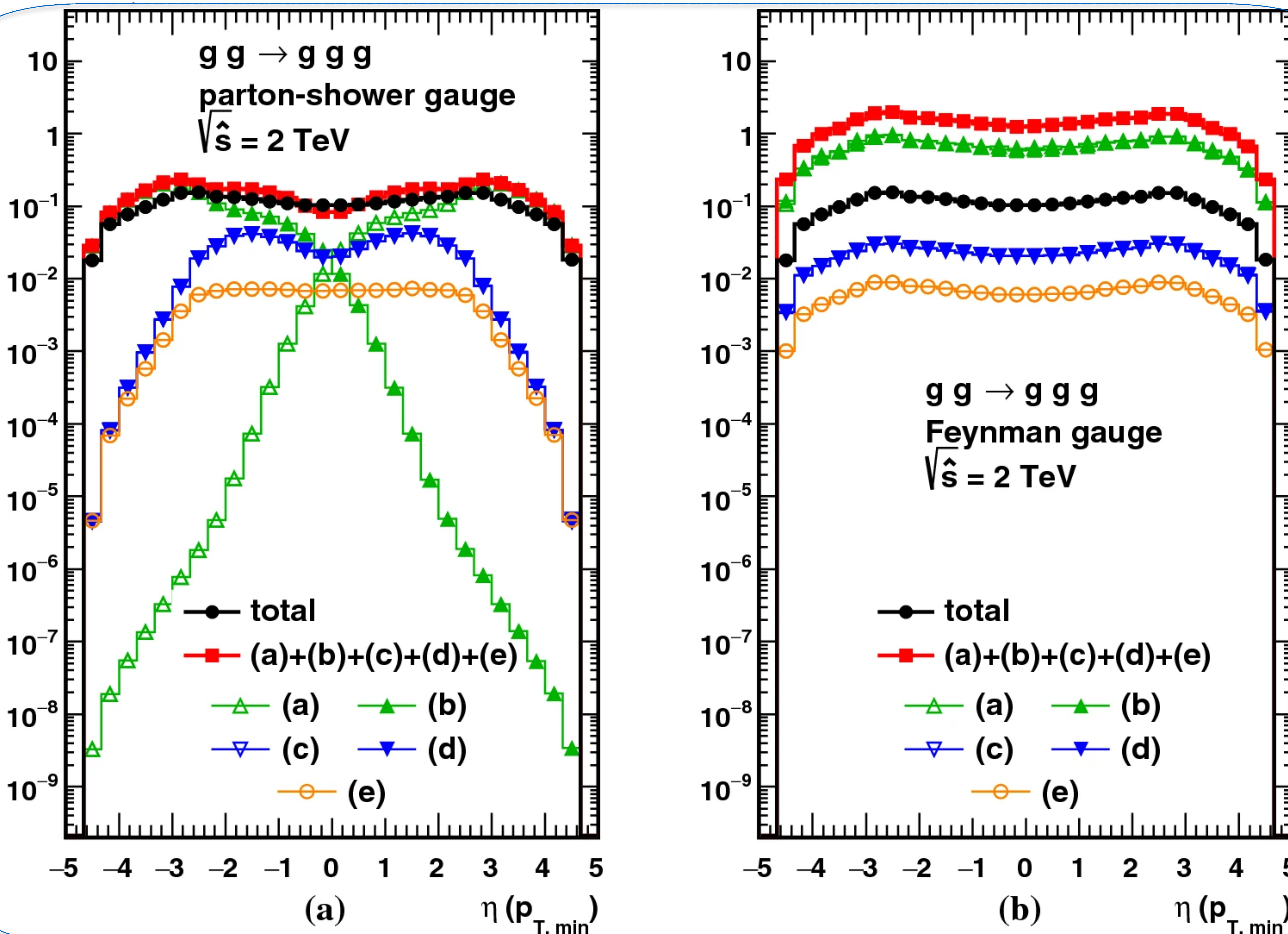
$$\epsilon^\mu(q,\pm1) = \frac{1}{\sqrt{2}}(0, 1, \pm i, 0)$$

$$\epsilon^\mu(q,0) = \begin{cases} (\sinh y, 0, 0, \cosh y) & \text{when } q^2>0 \;:\; q^\mu = Q(\cosh y, 0, 0, \sinh y) \\ (\cosh y, 0, 0, \sinh y) & \text{when } q^2<0 \;:\; q^\mu = Q(\sinh y, 0, 0, \cosh y) \end{cases}$$

We introduce $\tilde{\epsilon}^\mu(q,0) = \epsilon^\mu(q,0) - \frac{q^\mu}{Q} = \begin{cases} e^{-y}(-1,0,0,1) \\ e^{-y}(1,0,0,-1) \end{cases} = -\mathrm{sgn}(q^2)\frac{Q\,n^\mu}{n\cdot q}$ when $q^0>0$

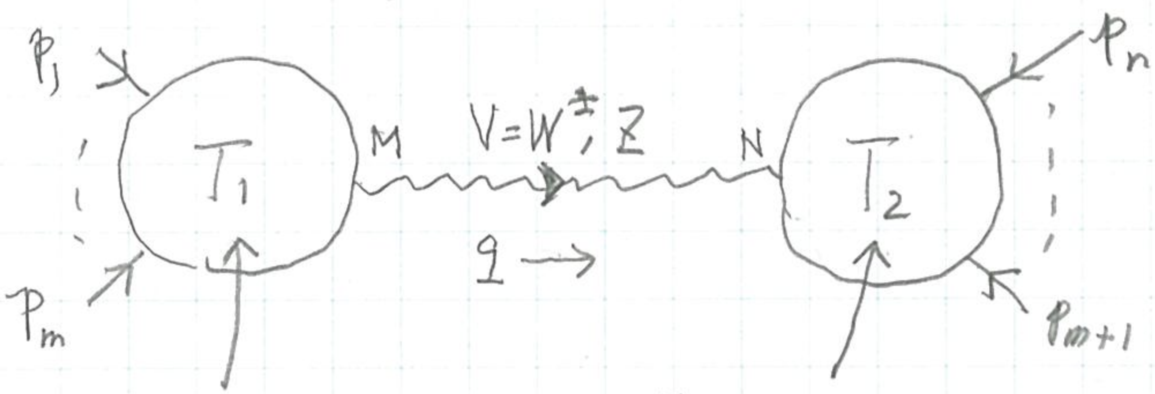
and define

$$P^{FD}_{\mu\nu}(q) = \sum_{h=\pm1} \epsilon^*_\mu(q,h)\epsilon_\nu(q,h) + \underbrace{\mathrm{sgn}(q^2)\,\tilde{\epsilon}_\mu(q,0)\tilde{\epsilon}_\nu(q,0)}_{= q^2 n^\mu n^\nu/(n\cdot q)^2} = -g_{\mu\nu} + \frac{q_\mu n_\nu + n_\mu q_\nu}{n\cdot q} \quad \text{with } n^\mu = \left(\mathrm{sgn}(q^0), -\frac{\vec{q}}{|\vec{q}|}\right)$$



Distributions of pseudorapidity of the final-state particle with minimum transverse momentum for the process $gg \to ggg$ in the PS gauge (**A**) and in the Feynman gauge (**B**). A line with filled circles denotes the total distribution, while lines with triangles (a–d) and open circles (e) show the distribution of the squared amplitudes of each type of the Feynman diagrams depicted in Fig. 4. A line with filled squares presents the distribution of the sum of the squared amplitudes of each diagram **[arXiv:2003.03003, EPJC2020, KH, Kanzaki & Mawatari]**

EW ($W^\pm$ & Z of the SM): U gauge ⇒ FD gauge [2203.10440] Chen-KH-Kanzaki-Mawatari



all diagrams with $\sum_{k=1}^{m} p_k^\mu = q^\mu$ all diagrams with $\sum_{k=m+1}^{n} p_k^\mu = -q^\mu$

$$= T(p_1,\cdots,p_n) = T_1^M \frac{P_V^U(q)_{MN}}{q^2-m_V^2} T_2^N \qquad M=\mu,4 \quad N=\nu,4$$

$$P_V^U(q)_{\mu\nu} = -g_{\mu\nu} + \frac{q_\mu q_\nu}{m_V^2} \;;\; P_V^U(q)_{\mu 4} = P_V^U(q)_{4\nu} = P_V^U(q)_{44} = 0$$

$$\text{BRST}: \begin{cases} q_\mu T_1^\mu = i m_V T_1^{\pi_V} \\ q_\nu T_2^\nu = -i m_V T_2^{\pi_V} \end{cases} \quad \text{when } q^0>0$$

$$P_V^U(q)_{\mu\nu} = -g_{\mu\nu} + \frac{q_\mu q_\nu}{m_V^2}$$

$$= -g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2} + \left(\frac{1}{m_V^2} - \frac{1}{q^2}\right) q_\mu q_\nu$$

$$= \sum_{h=\pm1} \epsilon_\mu^*(q,h)\epsilon_\nu(q,h) + \mathrm{sgn}(q^2)\,\epsilon_\mu^*(q,0)\epsilon_\nu(q,0) + \frac{q^2-m_V^2}{m_V^2}\frac{q_\mu q_\nu}{q^2}$$

$$= \sum_{h=\pm1} \epsilon_\mu^*(q,h)\epsilon_\nu(q,h) + \mathrm{sgn}(q^2)\left[\left(\tilde\epsilon_\mu(q,0) + \frac{q_\mu}{Q}\right)\left(\tilde\epsilon_\nu(q,0) + \frac{q_\nu}{Q}\right) + \frac{q^2-m_V^2}{m_V^2}\frac{q_\mu q_\nu}{Q^2}\right]$$

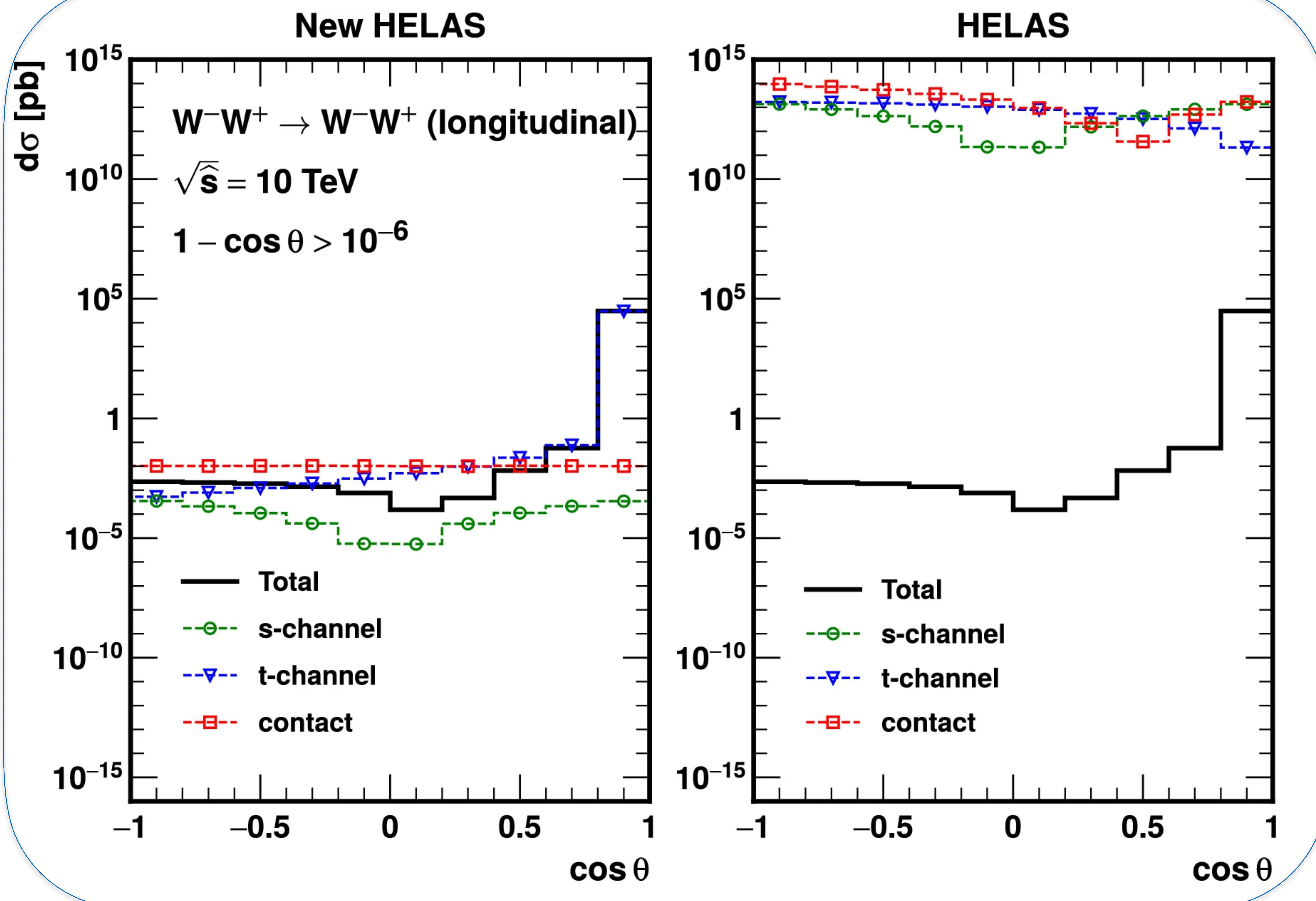
Apply BRST identities ↓ The same as QED & QCD ⇓ mixing ↙

$$T = T_1^\mu \frac{P_V^U(q)_{\mu\nu}}{q^2-m_V^2+i\epsilon} T_2^\nu = T_1^M \frac{P_V^{FD}(q)_{MN}}{q^2-m_V^2+i\epsilon} T_2^N \; : \; (T_1^\mu, T_1^4)\begin{pmatrix} -g_{\mu\nu} + \frac{q_\mu n_\nu + n_\mu q_\nu}{n\cdot q} & i m_V \frac{n_\mu}{n\cdot q} \\ -i m_V \frac{n_\nu}{n\cdot q} & 1 \end{pmatrix}\begin{pmatrix} T_2^\nu \\ T_2^4 \end{pmatrix}$$

$T_1^4 = T_1^{\pi_V}$

$T_2^4 = T_2^{\pi_V}$

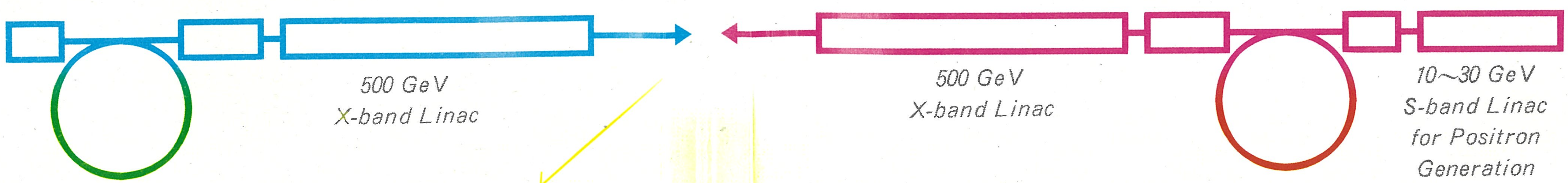
↑ mixing ↑ G.B. (π_V)



[arXiv:2203.10440, EPJC2023,Chen, KH, Kanzaki & Mawatari]

Proceedings of the Second Workshop on Japan Linear Collider (JLC)

KEK, November 6 - 8, 1990



NATIONAL LABORATORY FOR HIGH ENERGY PHYSICS, KEK

The Second Workshop JLC

JLC Physics

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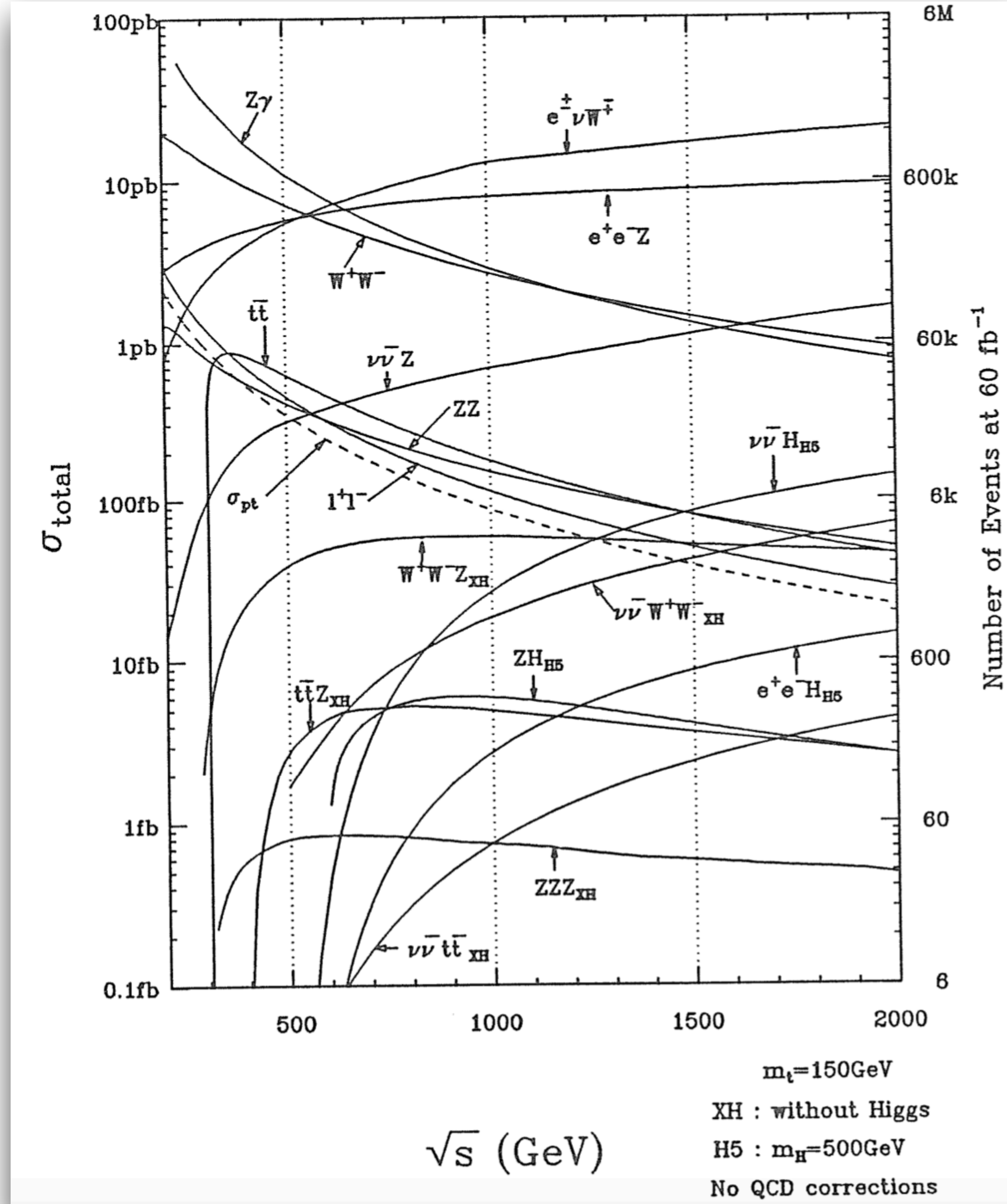
Abstract

We discuss what will be the physics goal of JLC. We briefly summarize our status of electroweak physics. Possible scenarios at and beyond Fermi scale are listed, one is the $SU(2)_L \times U(1)_Y$ gauge theory and the other is the composite scenario. The experimental consequences of each scenarios are discussed. Some suggestions on minimal requirements on the detector and the accelerator to achieve the physics goals are given.

1 Introduction

To my understanding, the aim of this workshop is to discuss the following three points.

1. How we can build JLC.
2. What we can do at JLC.
3. What the *goal* of JLC is.



100pb
10pb
1pb
100fb
10fb
1fb
0.1fb
σ total
6M
600k
60k
6k
600
60
6
Number of Events at 60 fb⁻¹
500
1000
1500
2000
√s (GeV)
Zγ
e± ν W∓
e⁺e⁻Z
W⁺W⁻
tt̄
νν̄ Z
ZZ
σpt
l⁺l⁻
νν̄ H_H5
W⁺W⁻Z_XH
νν̄ W⁺W⁻_XH
ZH_H5
e⁺e⁻H_H5
tt̄Z_XH
ZZZ_XH
νν̄ tt̄_XH
m_t=150GeV
XH : without Higgs
H5 : m_H=500GeV
No QCD corrections

Top-quark pair production near threshold

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K. Hagiwara

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H. Murayama

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SLAC, Stanford University, Stanford, California 94309
(Received 15 April 1992)

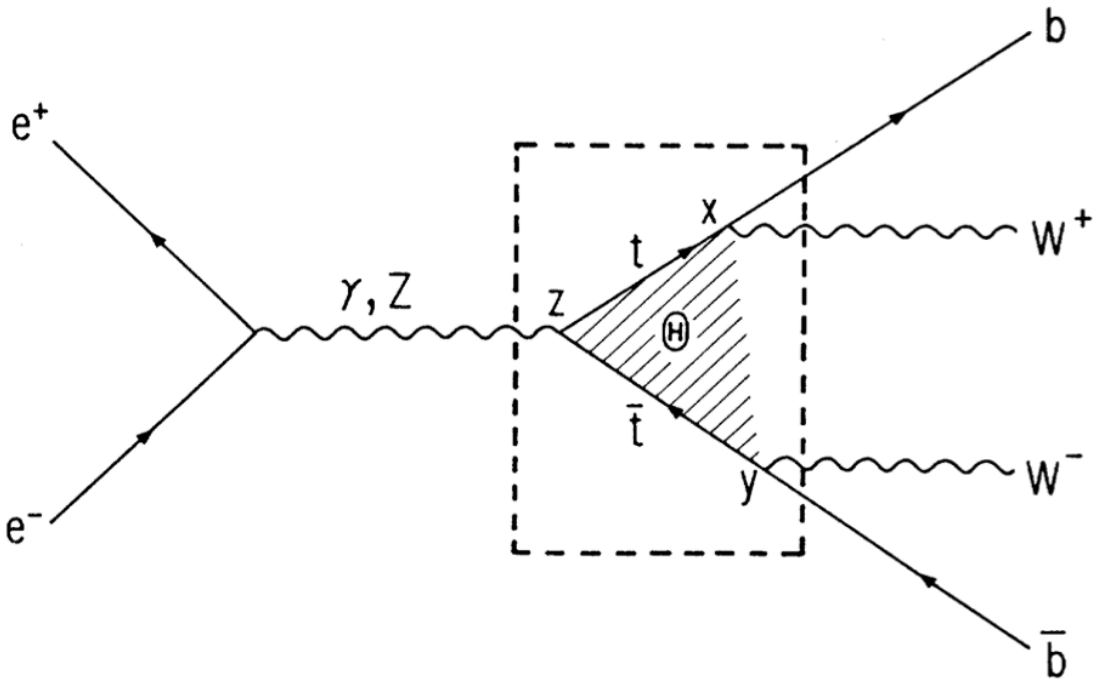


FIG. 1. The diagram for the $t\bar{t}$ pair production process and their subsequent decays into bW's. The box with the dashed line shows the three-point function $K(x,y,z)$ that carries the information of the toponium resonance.

The nontrivial and interesting part of the process is contained in the three-point Green's function

$$K(x,y,z)_{\alpha\gamma,\delta\beta}=\langle 0|Tt_\alpha(x)\bar{t}_\beta(y){:}\bar{t}_\gamma(z)t_\delta(z){:}|0\rangle \ , \quad (2.6)$$

which expresses the amplitude where a $t\bar{t}$ pair is created at a space-time point z and the $t(\bar{t})$ quark decays at another point $x(y)$, see Fig. 1. This three-point function contains the effect of full QCD interactions, in the ab-

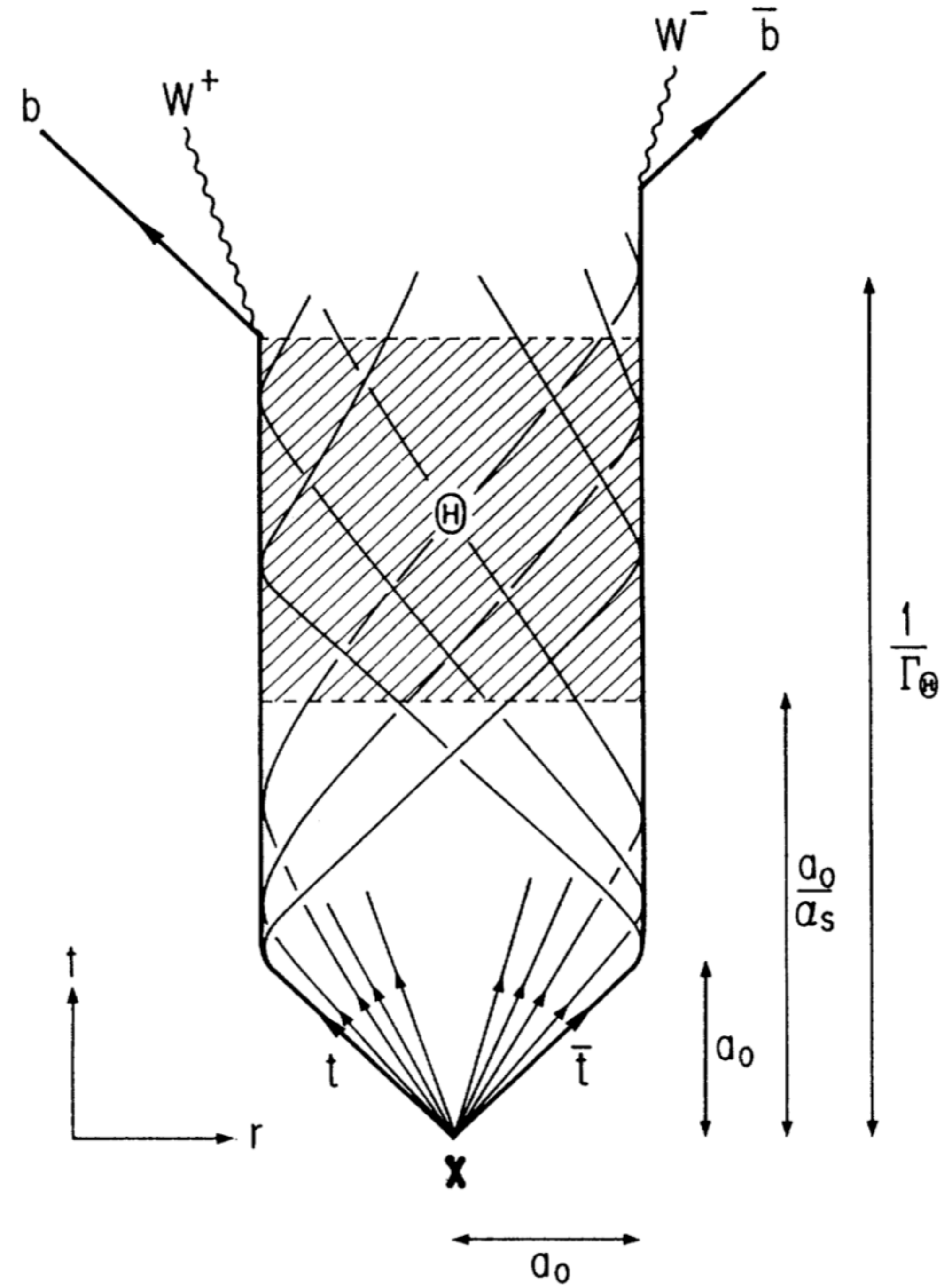
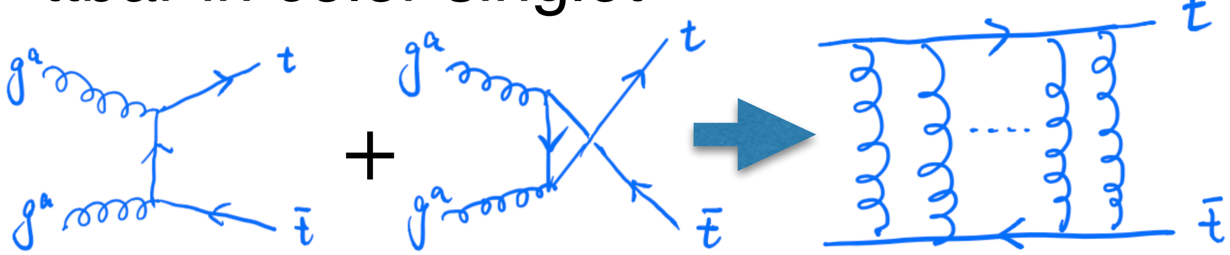


FIG. 2. A figure that shows the time evolution of the non-relativistic $t\bar{t}$ system.

Toponium formation

Production at the LHC

- ttbar in color singlet



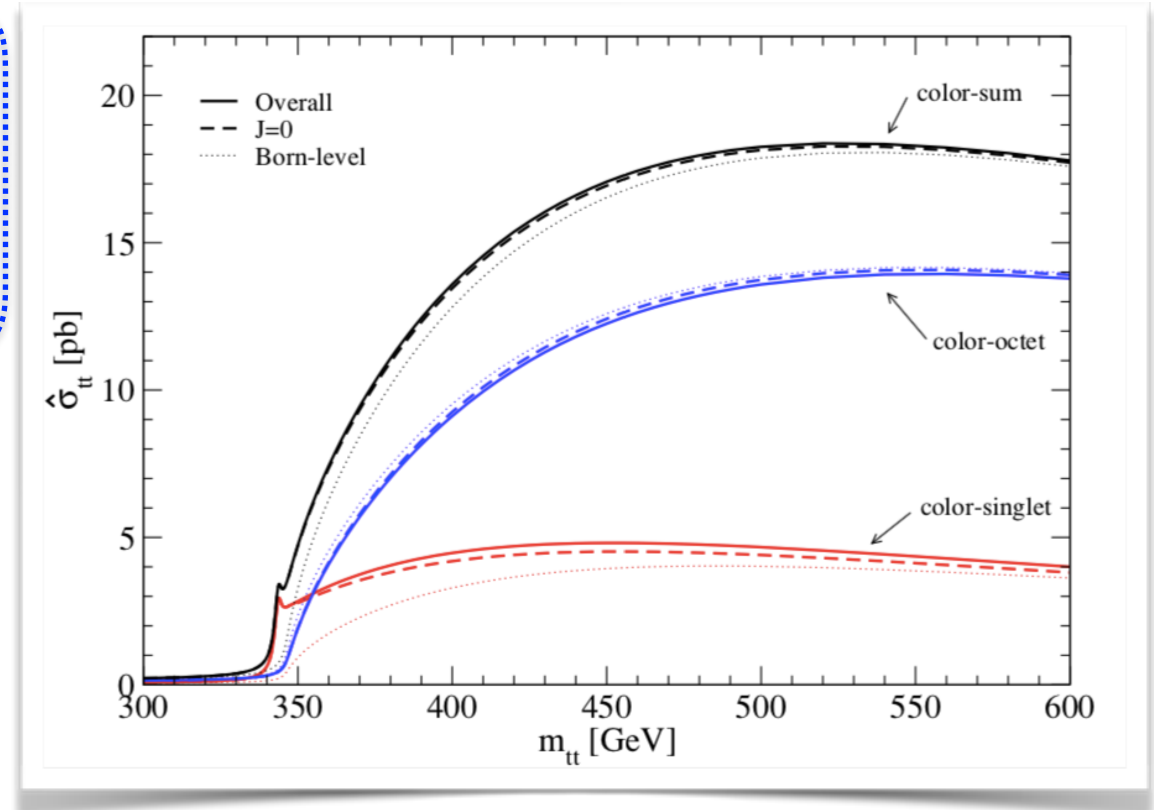
Toponium

η_t

✤ The colour-singlet dominates at the threshold
   - the gg-singlet channel dominates

✤ The J=0 state dominates
   - L=S=0

✤ The toponium η_t couples to 2 gluons (C=+) .



Y.Sumino and H.Yokoya. JHEP 2010

toponium formation　　　top decay　　　hadronization

Bohr model

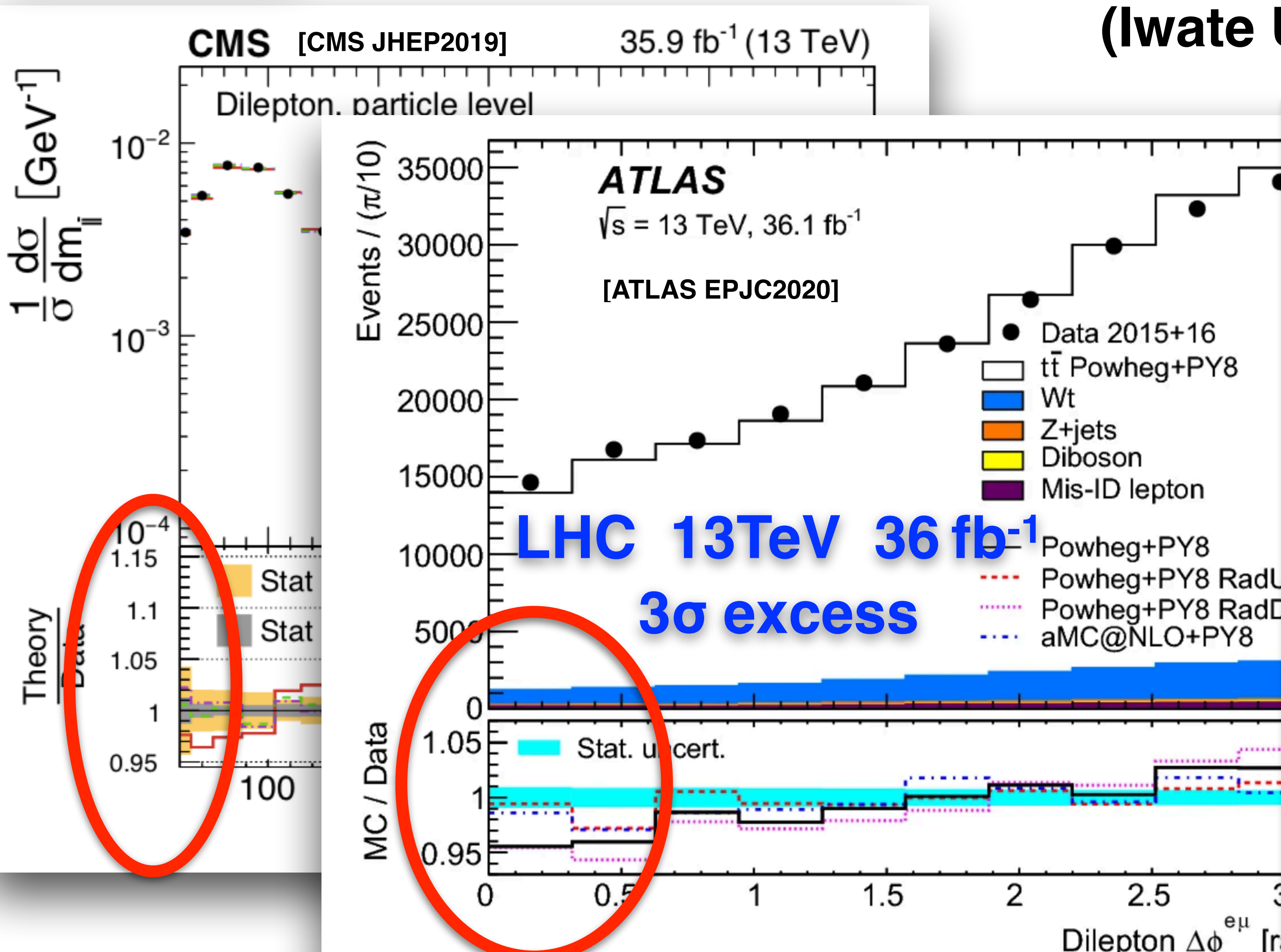
$$\frac{1}{C_F \cdot \alpha_S \cdot m_t/2} \sim \frac{1}{20\,\mathrm{GeV}} \ll \frac{1}{\Gamma_t} \sim \frac{1}{1.5\,\mathrm{GeV}} \ll 1\,\mathrm{fm} \sim \frac{1}{0.2\,\mathrm{GeV}}$$

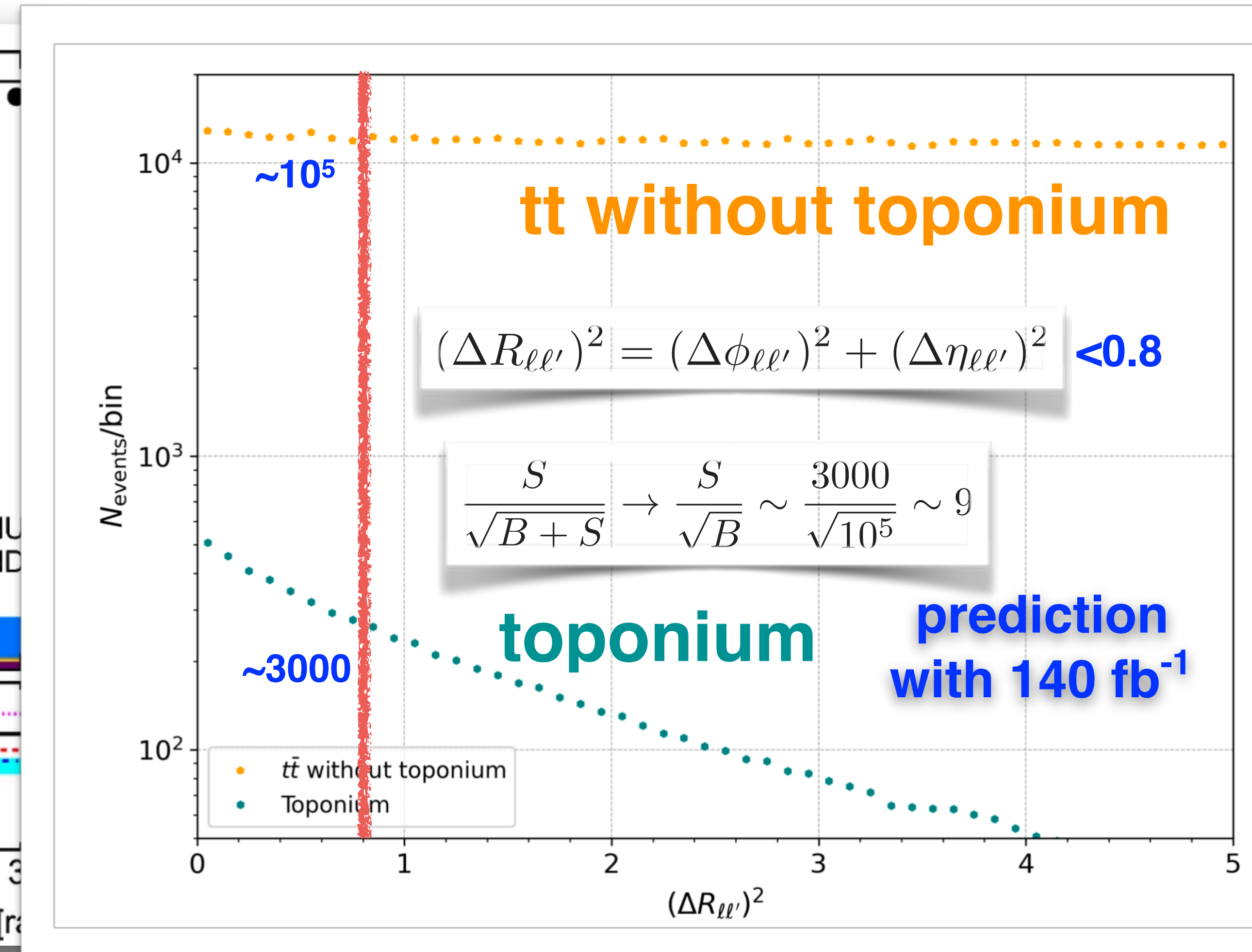
✦ Top quark decays before hadronization

✦ Toponium forms before top decay

Toponium at the LHC

Ya-Juan Zheng
(Iwate University)





- In the ttbar cross section measurement, both ATLAS and CMS observed excess of Data over the 'SM' prediction at low phi(ll'), m(ll') bins.
  - This may suggest that either ttbar production MC underestimates dileptons in small angle region, or new physics.
  - The standard ttbar MC does not have toponium.
- We include the toponium effect in the simulation, in the small separation region between the two final state leptons, 9 sigma significance is expected with integrated luminosity 140/fb.

Workshop for Tera-Scale Physics and Beyond, KEK, December 18, 2024

Based on
[1] Benjamin Fuks, Kaoru Hagiwara, Kai Ma and YJZ, 'Signatures of toponium formation in LHC run 2 data', Phys. Rev.D 104 (2021) 3, 034023.
[2] Benjamin Fuks, Kaoru Hagiwara, Kai Ma and YJZ, 'Simulating toponium formation signals at the LHC', arXiv:2411.18962.

Excavating the Road to the ILC

A decade ago, our goal was to have the ILC running concurrently with the LHC. Today, I think we need to uncover hints of new physics within the LHC data that could guide future explorations at the ILC.

A Lesson from the Toponium 'Discovery' at the LHC

New physics can easily be obscured by subtle adjustments to SM event simulation programs, particularly if we assume that "nothing beyond the SM is within reach."

Instead, we should adopt the opposite bias: assume that new physics is hiding within the data—from the LHC, flavor physics experiments, and precision measurements—and actively seek evidence for it.

The key question is: **How do we look for this evidence?**

It may be our imagination that paves the way to the ILC.