Phenomenology
Before & After the Higgs Boson

Phenomenology Before & After the Standard Model: a symposium in honor of Vernon Barger

June 5, 2025

Tao Han, University of Pittsburgh

Forty years ago, I took my first flight ride

Beijing PEK → SFO → ORD → MSN

a place I lived longer than any other places

A Prime Time for HEP: The SSC Era

One of my 1st papers:

University of Wisconsin - Madison

MAD/PH/324
January 1987

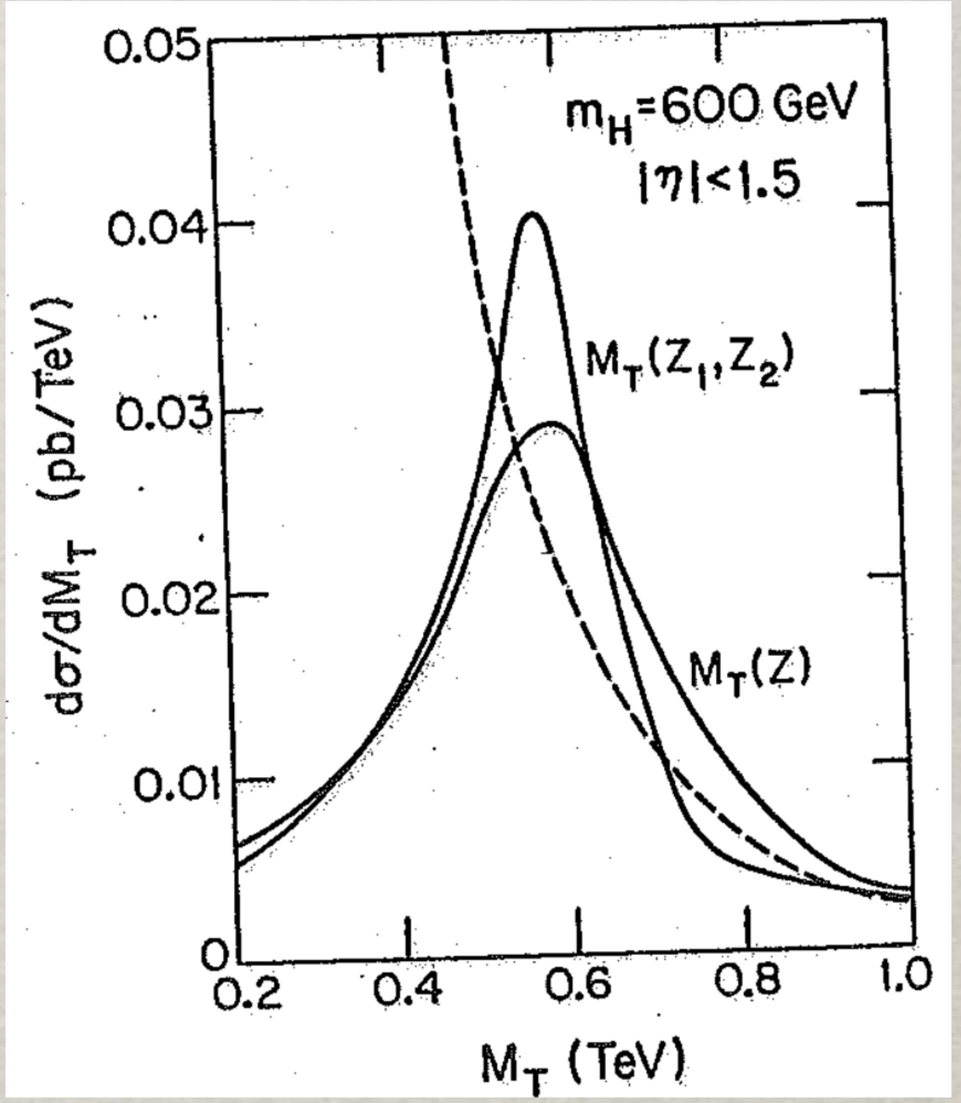
Improved Transverse-Mass Variable for Detecting Higgs-Boson Decays into Z Pairs

V. BARGER AND T. HAN
Physics Department, University of Wisconsin, Madison, Wisconsin 53706 USA

R. J. N. PHILLIPS
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

ABSTRACT

A promising decay mode for detecting heavy Higgs bosons at a supercollider is $H \to ZZ \to (\ell^+\ell^-)(\nu\bar{\nu})$, with one Z detected by e^+e^- or $\mu^+\mu^-$ decay and the other decaying to undetected neutrinos. Such events peak versus the transverse mass of the detected Z. We show there is an even sharper peak versus the two-body transverse mass, incorporating the missing transverse momentum carried by the second Z-boson.



$$M_T(Z) = 2(p_T^2 + M_Z^2)^{1/2}$$

The "cluster transverse mass" was introduced

$$[M_T(Z_1, Z_2)]^2 = \left[(p_T^2 + M_Z^2)^{1/2} + (\not{p}_T^2 + M_Z^2)^{1/2}\right]^2$$

From kinematics to dynamics

University of Wisconsin - Madison

受入
87-9-501
高工研図書室

MAD/PH/368
September 1987

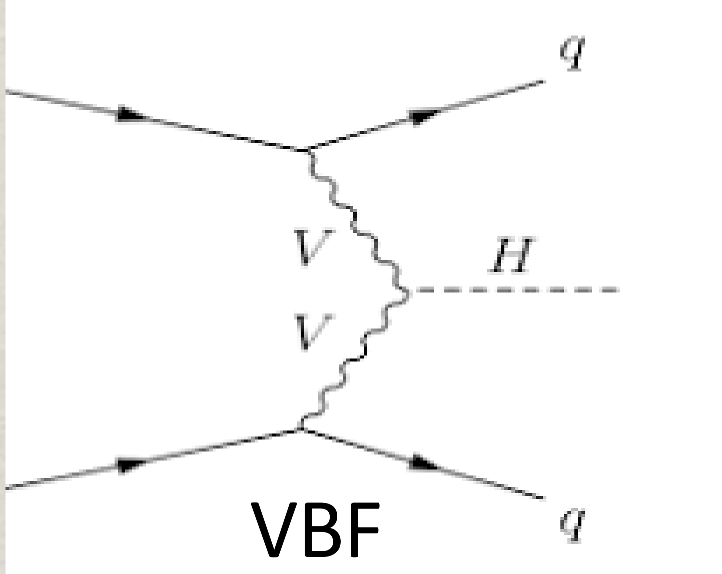
RESCUING THE HEAVY HIGGS SIGNAL

V. BARGER and T. HAN
Physics Department, University of Wisconsin, Madison, WI 53706, USA

R. J. N. PHILLIPS
Rutherford Appleton Laboratory, Chilton, Didcot,

ABSTRACT

If the Higgs scalar boson H^0 has mass greater than 600 Ge
have been foreseen in identifying it in pp collisions at the SSC. We show that the $H^0 \to ZZ$ signal, with one $Z \to \ell^+\ell^-$ and one $Z \to \nu\bar{\nu}$ decay, can be separated from background by selecting events with $\ell^+\ell^-$ at the Z mass plus large missing p_T plus two jets. This signal is enhanced by using an improved transverse-mass variable.



"forward jet-tagging"

Improving the Heavy Higgs Four Charged Lepton Signature

Vernon D. Barger (Wisconsin U., Madison), Tao Han (Wisconsin U., Madison), Phillips (Rutherford) (Dec, 1987)

Published in: *Phys.Lett.B* 206 (1988) 339-342

Improving the Heavy Higgs Boson Two Charged Lepton - Two Neutrino Signal

Vernon D. Barger (Wisconsin U., Madison), Tao Han (Wisconsin U., Madison), R.J.N. Phillips (Rutherford) (1988)

Published in: *Phys.Rev.D* 37 (1988) 2005-2008

STANDARD MODEL HIGGS BOSON STUDIES FOR SUPERCOLLIDERS

by

TAO HAN

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

(Physics)

at the

UNIVERSITY OF WISCONSIN–MADISON

1990

ACKNOWLEDGEMENTS

First of all, I would like to thank my advisor, Professor Vernon Barger, for his support and invaluable guidance throughtout my graduate career. His extensive knowledge and experience were crucial to the progress made in my research. I am deeply indebted to him for making this thesis possible.

I would like to thank Dr. Roger J. N. Phillips for guidance and many collaborations; his keen insight and experience were crucial to the success of my research.

I am grateful to Drs. Ulrich Baur, Manuel Drees, Kaoru Hagiwara, Francis Halzen, JoAnne Hewett, Wai-Yee Keung, Duncan Morris, Martin Olsson, Tom Rizzo, Scott Willenbrock, and Dieter Zeppenfeld who have been always available for discussions and help. Many thanks also go to Linda Dolan, Bill Long, and Brenda Sprecher for technical assistance.

I also want to thank some of my fellow graduate students from whom I have been benefited: Drs. C. S. Kim, Jim Ohnemus, and H. Pi; as well as Gour Bhattacharya, Kingman Cheung, Bob Fletcher, Dan LaCourse, Y. B. Pan, and Alan Stange.


FRONTIERS IN PHYSICS
Collider Physics
Vernon D. Barger
Roger J. N. Phillips

(~1989)

More on the Transverse Mass: kinematics vs dynamics

Heavy leptons at hadron supercolliders

V. Barger, T. Han, and J. Ohnemus

Show more

Phys. Rev. D **37**, 1174 – **Published 1 March, 1988**

DOI: https://doi.org/10.1103/PhysRevD.37.1174

Am score 0

Citations 46

Abstract

The production, decay, and detection of a fourth-generation charged heavy lepton L at r… hadron supercolliders is discussed for masses $m_L > M_W$ and $m_{\nu_L} \cong 0$. The leptonic and hadr… signals for single L production and $L\bar{L}$ pair production are evaluated. In all channels exa… heavy-lepton signal is smaller than backgrounds from single and pair production of $W^\pm$ bosons. However, it may still be possible to detect a heavy lepton from its contribution t… 4 jets events where the Z(→νν¯)+jets background may be determined from measuremen… (Z→ll¯)+jets events.

$$M_T(\ell\bar{\ell}', \not{p}_T) = \left[\left\{p_T^2(\ell\bar{\ell}') + m^2(\ell\bar{\ell}')\right\}^{1/2} + |\not{p}_T|\right]^2 - |p_T(\ell\bar{\ell}') + \not{p}_T|^2$$

University of Wisconsin - Madison

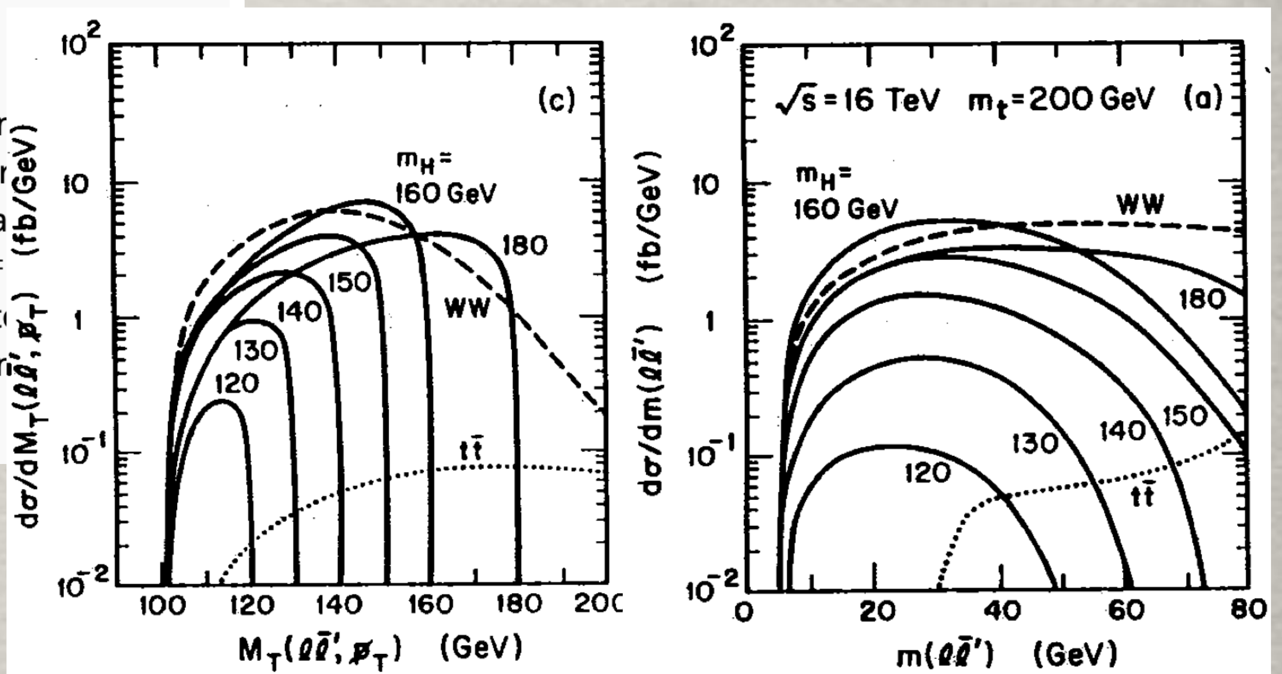
MAD/PH/571
August 1990

受入
90-9-22
高エ研図書室

INTERMEDIATE MASS HIGGS BOSON AT HADRON SUPERCOLLIDERS

V. Barger, G. Bhattacharya, T. Han, and B. A. Kniehl

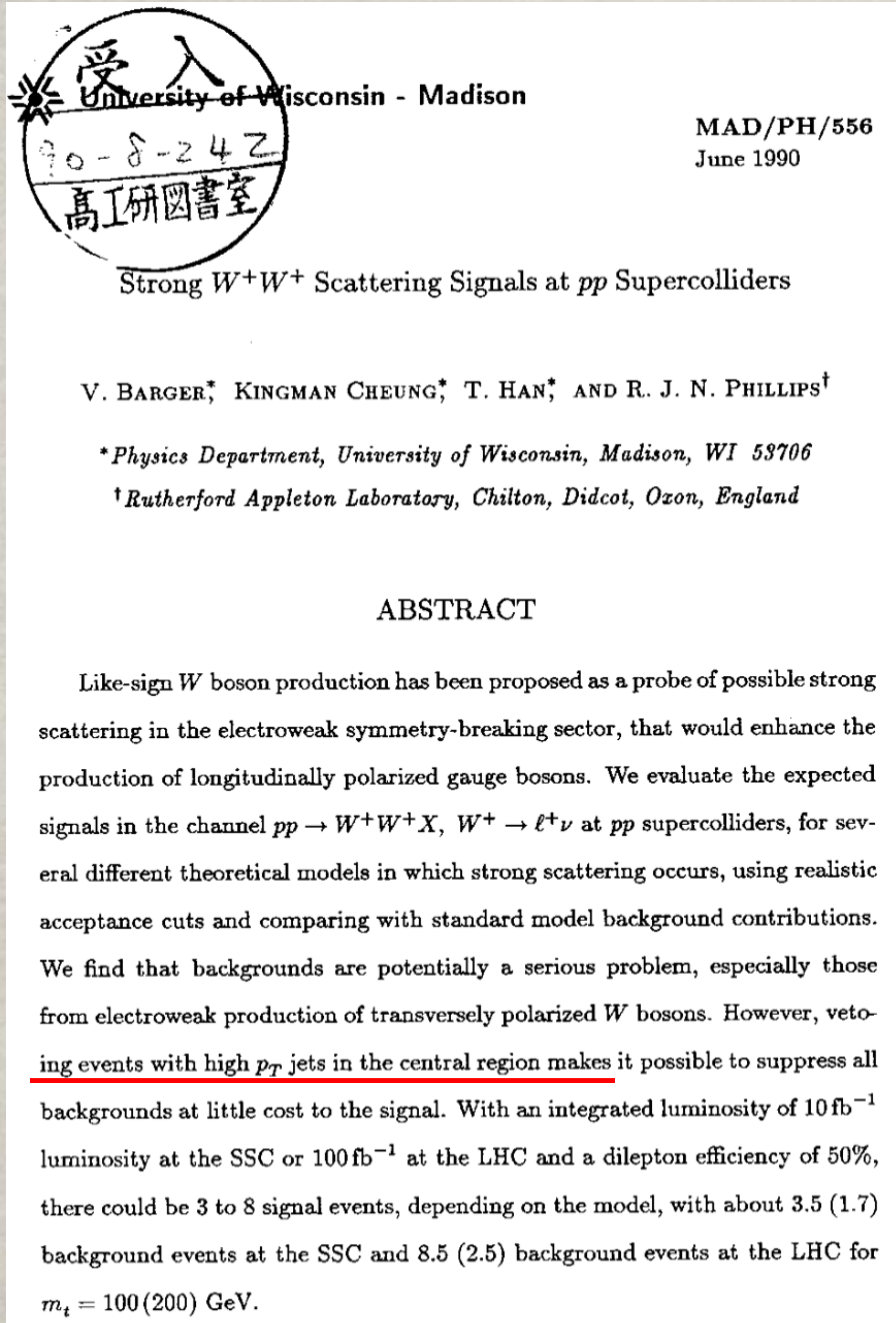
Physics Department, University of Wisconsin, Madison, WI 53706, USA



N. Glover, J. Ohnemus, S. Willenbrock: PDR 37 (1988) 3193:
Higgs Boson Decay to One Real and One Virtual *WW* Boson

M_T broad! M(ll) → spin correlation

Forward-Jet Tagging & Central-jet Vetoing



受入 90-8-24 高工研図書室

University of Wisconsin - Madison

MAD/PH/556
June 1990

Strong W^+W^+ Scattering Signals at pp Supercolliders

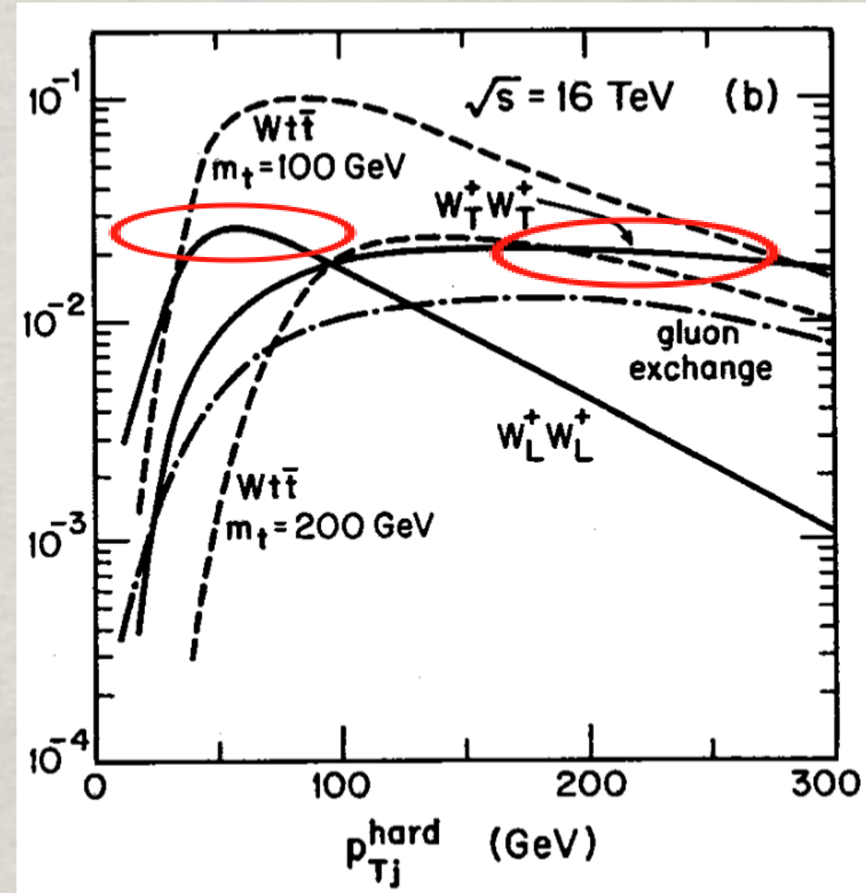
V. BARGER*, KINGMAN CHEUNG*, T. HAN*, AND R. J. N. PHILLIPS†

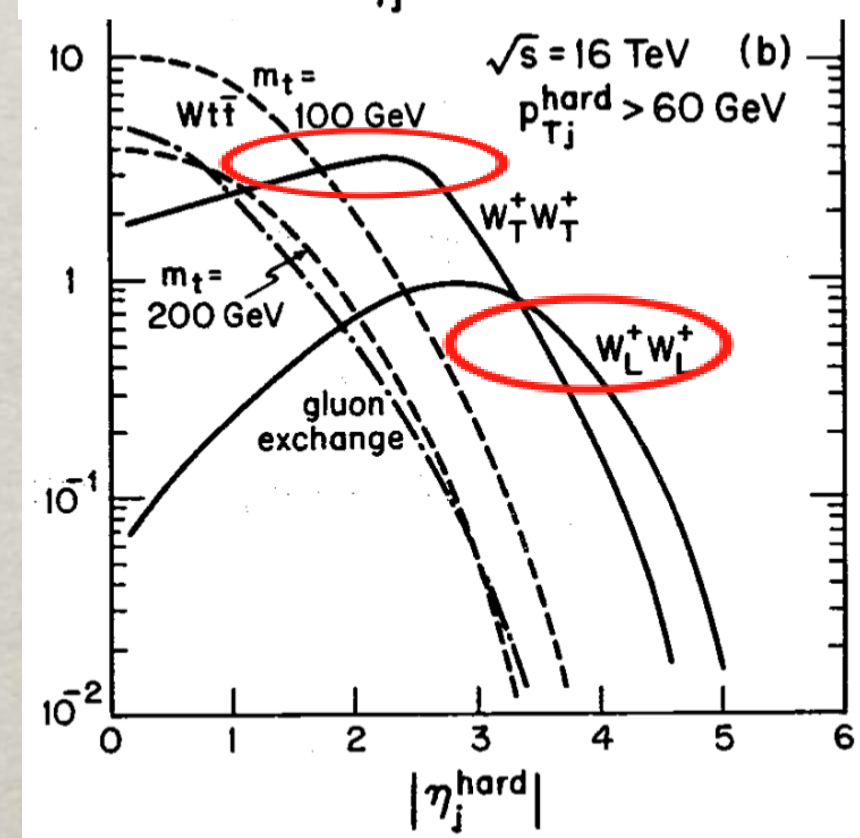
*Physics Department, University of Wisconsin, Madison, WI 53706

†Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

ABSTRACT

Like-sign W boson production has been proposed as a probe of possible strong scattering in the electroweak symmetry-breaking sector, that would enhance the production of longitudinally polarized gauge bosons. We evaluate the expected signals in the channel $pp \to W^+W^+X$, $W^+ \to \ell^+\nu$ at pp supercolliders, for several different theoretical models in which strong scattering occurs, using realistic acceptance cuts and comparing with standard model background contributions. We find that backgrounds are potentially a serious problem, especially those from electroweak production of transversely polarized W bosons. However, vetoing events with high p_T jets in the central region makes it possible to suppress all backgrounds at little cost to the signal. With an integrated luminosity of $10\,\text{fb}^{-1}$ luminosity at the SSC or $100\,\text{fb}^{-1}$ at the LHC and a dilepton efficiency of 50%, there could be 3 to 8 signal events, depending on the model, with about 3.5 (1.7) background events at the SSC and 8.5 (2.5) background events at the LHC for $m_t = 100\,(200)$ GeV.





University of Wisconsin - Madison

受入
91-4-4
高工研図書室

MAD/PH/638
FERMILAB-PUB-91/76-T
FSU-HEP-910404
April 1991

A Comparative Study of the Benefits of Forward Jet Tagging in Heavy Higgs Production at the SSC

V. Barger,[1] Kingman Cheung,[1] T. Han,[2] J. Ohnemus,[3] D. Zeppenfeld[1]

Fermi National Accelerator Laboratory

Single Forward Jet-Tagging and Central Jet-Vetoing to Identify the Leptonic WW Decay Mode of a Heavy Higgs Boson

V. Barger,[1] Kingman Cheung,[1] T. Han,[2] D. Zeppenfeld[1]

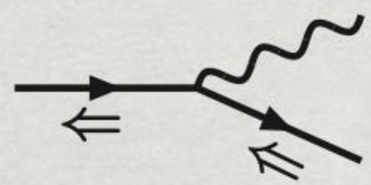
[1] *Department of Physics, University of Wisconsin, Madison, WI 53706*

[2] *Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510*

EW Splitting: Kinematics & Dynamics

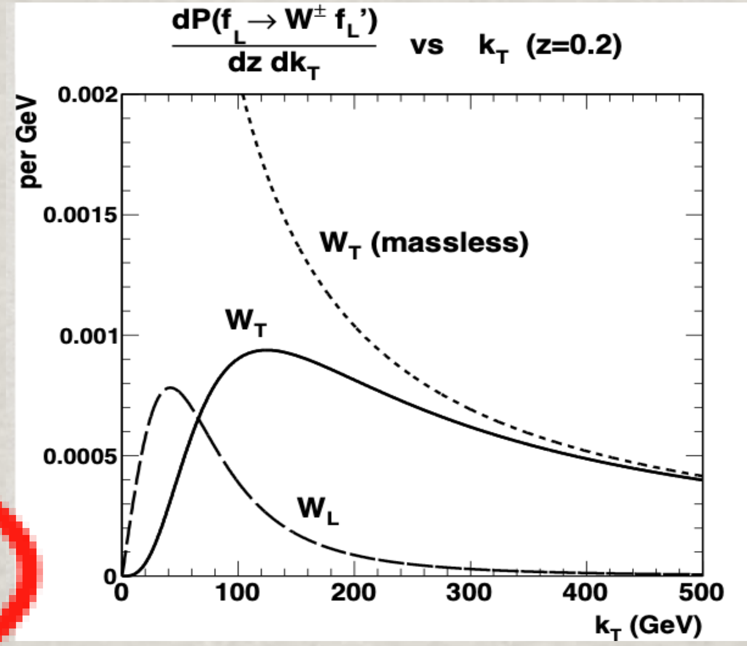
In the unbroken phase

f → f V_T



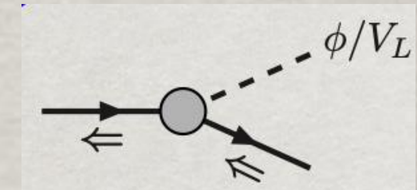
$$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1+\bar{z}^2}{z}\right)$$

$$P_{q\to qV_T} = (g_V^2 + g_A^2)\,\frac{\alpha_2}{2\pi}\,\frac{1+(1-x)^2}{x}\ln\frac{Q^2}{\Lambda^2}$$



In the broken phase

f → f V_L



$$\frac{v^2}{k_T^2}\;\frac{dk_T^2}{k_T^2} \sim (1-\frac{v^2}{Q^2})$$

$$P_{q\to qV_L} = (g_V^2 + g_A^2)\,\frac{\alpha_2}{\pi}\,\frac{1-x}{x}$$

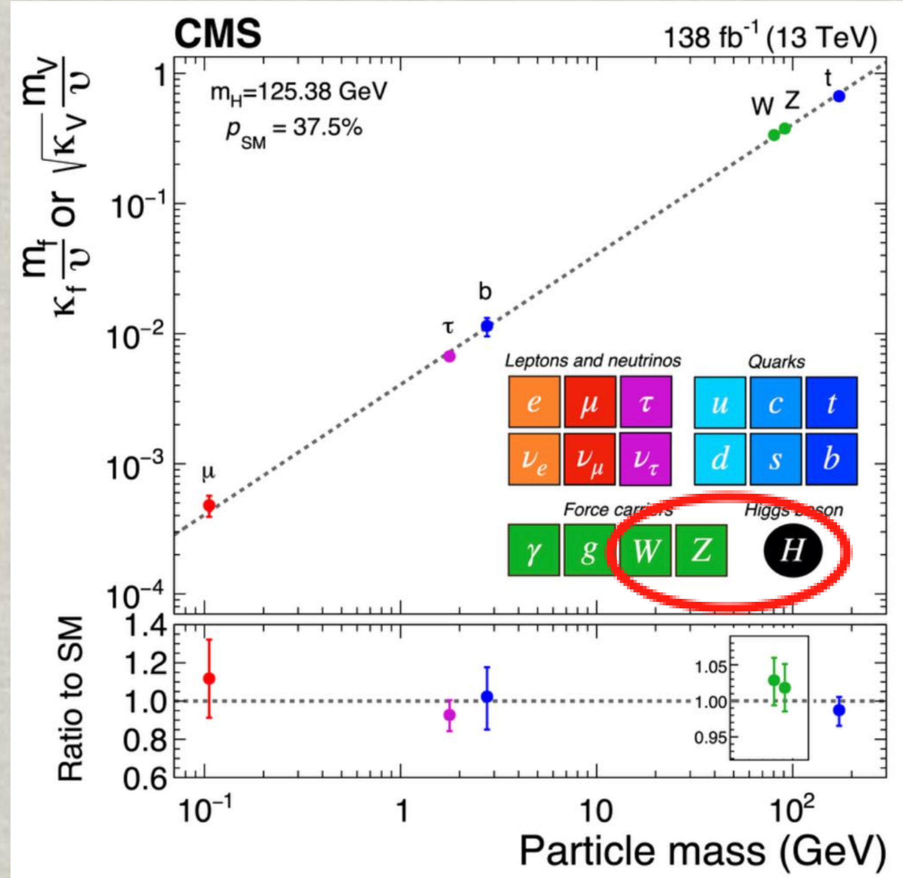
For a longitudinal vector: $\epsilon(k)_L^\mu = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W}$ + O(M_W/E)

trivial "scalarization" EW symmetry breaking

- Broken phase ~v^2/Q^2 → higher-twist effects like Λ^2_{QCD}/Q^2.
- The PDFs for V_L:
  - no $\log(Q^2/M^2)$ → "Bjorken scaling" restoration
  - Goldstone Boson Equivalence Theorem violation!
- Kinematic basis "forward jet-tagging, central jet-vetoing"!

Ciafaloni et al., Hep-ph/0505047; J.M. Chen, TH & B. Tweedie, arXiv:1611.00788.

Higgs on trial @ High Energies



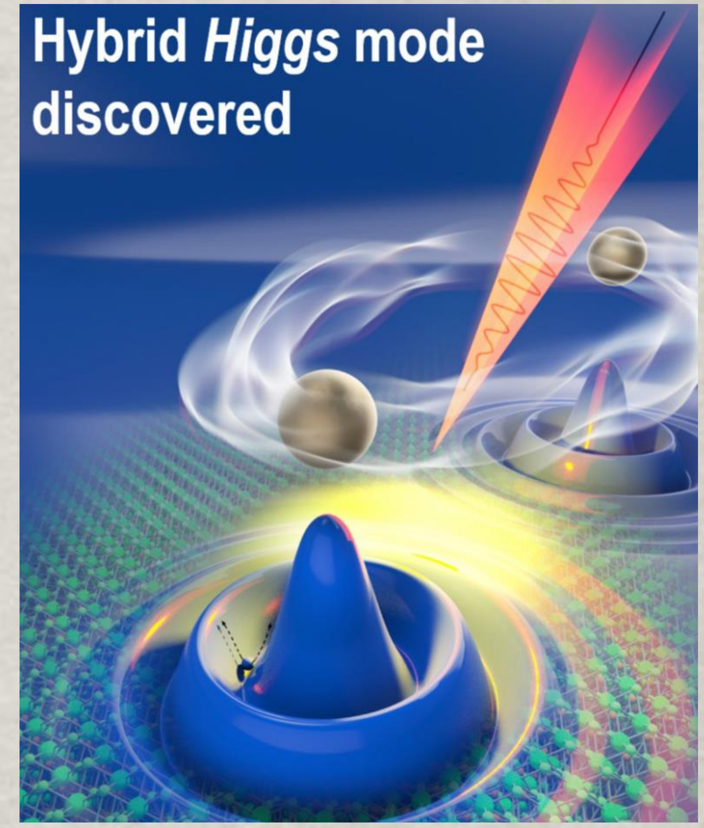
$$\Phi = \begin{pmatrix} w_1 \\ w_2 \\ z \\ h \end{pmatrix}$$

or $U = \exp\{i\omega^i\tau^i/v\}$

← CERN LHC

Laser @ 10^{12} Hz

(2021, Ames Lab)→



EW Symmetry Restoration (EWSR)

$$\frac{v}{E}: \frac{v\ (250\ \text{GeV})}{10\ \text{TeV}} \approx \frac{\Lambda_{QCD}\ (300\ \text{MeV})}{10\ \text{GeV}} \qquad v/E,\ m_t/E,\ M_W/E \to 0!$$

(*i*) the physics of the transverse gauge bosons ($W_T^\pm, Z_T, \gamma$) and fermions is described by a massless theory in the unbroken phase;

(*ii*) the longitudinal gauge bosons ($W_L^\pm Z_L$) are scalarized as Goldstone bosons ($\omega^\pm, \omega^0$), and join the Higgs boson to restore the unbroken $O(4)$ symmetry ($\omega^\pm, \omega^0, H$) in the Higgs sector.

parametrically: $\delta = \frac{M_W}{2E_W}$

R. Capdevilla, TH, arXiv:2412.12336

Test EWSR @ LHC / muon Collider

Huang, Lewis, Lane, Liu, arXiv:2009.09429; R. Capdevilla, TH, arXiv:2412.12336.

Massless gauge sector & Higgs sector:

$$r_{Z\gamma} = \frac{\sigma(WZ)}{\sigma(W\gamma)}\,, \quad r_{ZH} = \frac{\sigma(WZ)}{\sigma(WH)}$$

For **δ** = $M_W/2E \ll 1$:

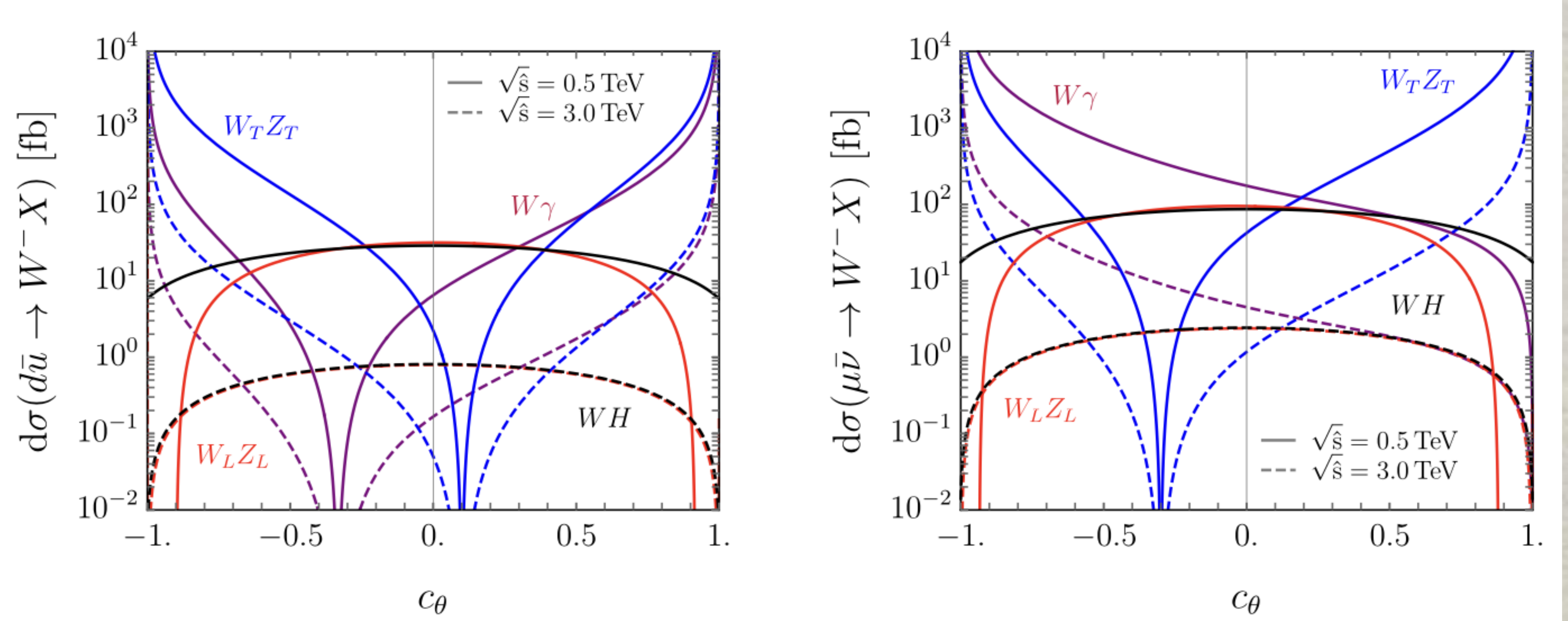
$$\frac{\sigma(W_T Z_T)}{\sigma(W_T\gamma)} \approx \frac{g_z^2}{e^2}\,\frac{(g_-^{f_1})^2 + (g_-^{f_2})^2}{Q_1^2 + Q_2^2}$$

$$\sigma(W_L^{\pm} Z_L) \sim \sigma(W_L^{\pm} H),$$
$$\text{or } \sigma(\omega^{\pm}\omega^0) \sim \sigma(\omega^{\pm} H)$$

Utilizing the "Radiation Amplitude Zeros" (RAZs)

$$c_\theta^{W^-\gamma} = \frac{Q_d + Q_u}{Q_d - Q_u} \qquad\qquad c_\theta^{W^- Z_T} = \frac{g_-^d + g_-^u}{g_-^d - g_-^u}$$

Mikaelian, Samual PRL (1979) U. Baur, TH, Jim Ohnemus, PRL (1994)



$$\delta \approx M_W/2\ \text{TeV} < 5\%$$

What do we learn in testing EWSR?

"endlessly confirm the correctness of SM" ?!

- Carlo Rubia

SMEFT BSM vs. HEFT BSM

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + H + i\phi^0 \end{pmatrix},$$

$$\mathcal{L}_{\mathrm{SMEFT},\mu\phi} = -\sum_{n=1}^{\infty} \frac{c_{\varphi}^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^{n+2}$$

$$U = e^{2i\phi^a T_a/v} \quad \text{with} \quad \phi^a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix},$$

$$\mathcal{L}_{Uh} = \frac{v^2}{4} \mathrm{tr}[D_\mu U^\dagger D^\mu U] F_U(H) + \frac{1}{2} \partial_\mu H \partial^\mu H - V(H)$$

weakly coupled (SUSY) strongly coupled (composite)

new scale ~ **Λ** nearby scale ~ **4π υ**

At the LHC: Higgs coupling SM-like ~ 10%

(light) Fermion Yukawa's wide open:

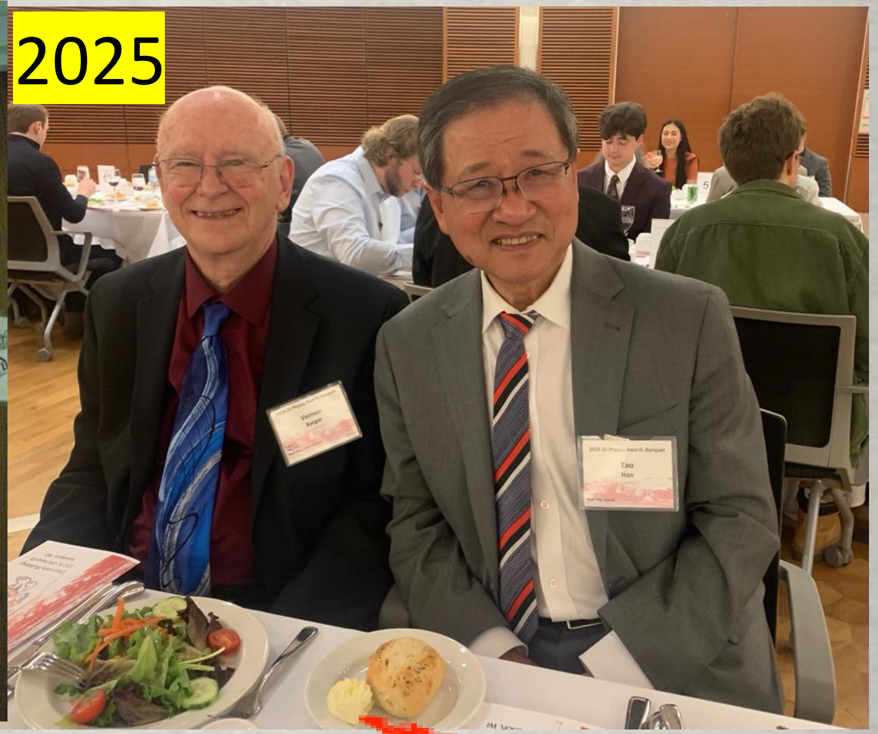
$$-\sum_{n=1}^{\infty} \frac{c_{\ell\varphi}^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^n (\bar{\ell}_L \varphi \mu_R + \mathrm{h.c.})$$

$$-\frac{v}{\sqrt{2}} \left[\bar{\ell}_L Y_\ell(H) U P_- \ell_R + \mathrm{h.\,c.} \right]$$

$$Y_\ell(H) = \frac{\sqrt{2} m_\mu}{v} + \sum_{k \geq 1} y_{\ell,k} \left(\frac{H}{v} \right)^k$$

E. Celada, TH et al., arXiv:2312.13082

Journey in phenomenology before & after the Higgs boson



Congratulations Vernon

for the 2021 APS Sakurai Prize!

Pheno family tree

Name	Year	C[urrent position]
George Wojcik	2021-2024	C
Nicholas Orlofsky	2017-2020	P
Joshua Berger	2015-2018	A
Ran Lu	2013-2016	P
Jordi Salvado	2013-2015	P
Gabe Shaughnessy	2011-2014	S
Maike Trenkel	2009-2011	R
Pavel Fileviez Perez	2010-2011	A
Sogee Spinner	2008-2011	S
Ian-Woo Kim	2007-2010	S
Tom McElmurry	2007-2009	A
Kathryn Zurek	2006-2008	P
Devin Walker	2006-2007	A
Patrick Huber	2004-2007	P
Hooman Davoudiasl	2004-2006	F
Heather Logan	2002-2005	P
Cheng-Wei Chiang	2003-2004	P
Lian-Tao Wang	2002-2004	P
Graham Kribs	2000-2003	P
Tilman Plehn	1998-2002	P
Carlo Oleari	2000-2002	P
Michal Brhlik	2000-2001	S
Stefan Hesselbach	2000-2001	T
Jaime Alvarez	1999-2000	P
Ren-Jie Zhang	1998-2000	I
Mauricio Magro	1998-2000	P
Toby Falk	1997-2000	L
Chung Kao	1996-2000	P
Gustavo Burdman	1996-1999	P
James Kelly	1996-1998	A
Laura Reina	1997-1998	Professor, Florida State University
Sean Fleming	1995-1997	Professor, University of Arizona
James Amundson	1994-1996	Fermilab Computing Division
Youichi Yamada	1995-1996	Professor, Tohoku U.
Erwin Mirkes	1993-1995	Analyst, Deutsche Bank
David Summers	1993-1995	Space Division, SEA
Brian Wright	1992-1995	Deceased (formerly UCSF, physiology)
Maria Concepcion Gonzalez-Garcia	1991-1994	Professor, SUNY Stony Brook and Professor, University of Barcelona

Michael Berger	1991-1994	Professor, University of Indiana
Michael Doncheski	1990-1993	Director of Academic Affairs, Penn State Mont A
Mihiko Nojiri	1992-1993	Professor, KEK
Ted Allen	1991-1997	Assoc. Professor, Hobart & William Sm
Gye (Tai) Park	1991-1992	Professor, Yonsei University
Roxanne Springer	1990-1992	Professor, Duke University
Enrique Zas	1990-1991	Professor, University of San
Ulrich Baur	1989-1991	Deceased (formerly prof. at SU
Berndt Kniehl	1989-1991	Professor, University of Hambur
Robert Foot	1989-1990	Academic Staff, University of Mel
Oscar Hernandez	1988-1991	Professor, Marianopolis College
JoAnne Hewett	1988-1991	Professor, SLAC
David B. Reiss	1988-1989	Consultant, Scientific Arts, Wolfram Sol
Duncan Morris	1987-1990	Financial Industry (Canada/stock trading)
Dieter Zeppenfeld	1986-1989	Professor, University of Karlsruhe
Manuel Drees	1986-1988	Professor, University of Bonn
Kari Enqvist	1986-1987	Professor, University of Helsinki
Sumathi Rao	1986-1987	Professor, Harish-Chandra Research Institute
Scott Willenbrock	1986-1988	Professor, University of Illinois
Xerxes Tata	1986-1988	Professor, University of Hawaii
Kenichi Hikasa	1984-1986	Professor, Tohoku University
Alexander Jourjine	1984-1986	MPI for Physics of Complex Systems, Dresden
Paul Stevenson	1983-1984	Professor (emeritus), Rice University
M. Teresa Thomaz	1982-1983	Professor, Univ. Federal Fluminense, Brazil
Kaoru Hagiwara	1981-1984	Professor (emeritus), KEK
J. L. Cortes	1981-1983	Professor, University of Zaragoza
Cosmas Zachos	1979-1981	Professor, Argonne National Laboratory
Jacques Leveille	1978-1980	Amerada Hess, Houston (geophysics)
David Scott	1977-1980	Lecturer, Cambridge University, Chem. Engineering
Benedikt Humpert	1977-1978	Swiss Business School, Zurich
Julio Abad	1976-1978	Deceased (Formerly Professor, University of Zaragoza)
Dimitri Nanopoulos	1976-1977	Professor, Texas A&M University
Mark Singer	1975-1977	Boeing Advanced Technology
Ronald McElhaney	1973-1975	Chief Technology Officer, Siebel Systems (Oracle)
Edward Osypowski	1970-1971	Senior Lecturer (emeritus), University of Wisconsin, Marathon Co.
Chris Michael	1969-1969	Professor (emeritus), University of Liverpool
Miguel Virasoro	1968-1970	Professor (emeritus), Abdus Salam Institute for Theoretical Physics
Keiji Kikkawa	1968-1969	Professor (emeritus), Kanagawa U., Dept. of Information Science
Paul Fishbane	1967-1969	Professor (emeritus), University of Virginia
L. M. Simmons	1967-1969	Co-founder, Santa Fe Center for Emergent Strategies and President, Aspen Center for Physics (1985-88)

Name	PhD	Advisor	Current Position
Stephen McKay		Barger (w/ A. Barger)	Current student
Kairui Zhang	2024	Barger	Current student
Andrea Peterson	2014	Barger	Science Policy Analyst, FYI: Science Policy News, AIP
Tien-Tien Yu	2013	Barger	Associate Professor, University of Oregon
Peisi Huang	2013	Barger	Associate Professor, University of Nebraska
Brian Yencho	2011	Barger	Software Developer, Livefront
Ian Lewis	2011	T. Han (w/ Barger)	Associate Professor, University of Kansas
Mat McCaskey	2010	Barger	Software engineer, Vantage Partners
Yu Gao	2010	Barger	Scientist, Beijing Institute of HEP
Gabe Shaughnessy	2007	Barger	Senior data scientist, Jungle Scout
Adam Tregre	2007	Barger	Actuarial analyst, QBE North America
Hye-Sung Lee	2005	Barger	Professor, Institute for Basic Science, Daejon, Korea
Benjamin Wood	2002	Barger	Military systems analyst
Young-Jae Kim	2002	T. Han (w/Barger)	Scientific consultant, KhiMetrics
Danny Marfatia	2001	T. Han (w/Barger)	Professor, University of Hawaii
Tianjun Li	2000	Barger	Professor, UESTC, Chengdu
Hong Pi	1989	L. Durand (w/ Barger)	Ocwen Financial Corporation
John Beacom	1997	Balantekin (w/Barger)	Professor, The Ohio State University
Pedro Mercadante	1997	Barger	Professor, U. Federal do ABC, Brazil
Paul Ohmann	1994	Barger	Assoc. Professor, University of St. Thomas
Gour Bhattacharya	1992	Barger	Professor, Taki Govt. College, India
Kingman Cheung	1992	Barger	Professor, Tsing Hua University
Alan Stange	1992	Barger	Financial analyst, Renaissance Technologies
Tao Han	1990	Barger	Professor, University of Pittsburgh
William Putikka	1989	R. Joynt (w/ Barger)	Assoc. Professor, Ohio State U. at Mansfield
William Long	1988	Barger	Senior Engineer (Sept 09), Cray Inc.
Jorge Lopez	1987	L. Durand (w/Barger)	Shell E&P
James Ohnemus	1987	Barger	Quantitative analyst, Iberdrola Renewables
Howard Baer	1984	Barger	Professor, University of Oklahoma

Kerry Whisnant	1982	Barger	Professor, Iowa State University
Wai-Yee Keung	1980	Barger	Professor (emeritus), UIC
Thomas Gottschalk	1978	Barger	Comp science, Caltech
Thomas Weiler	1976	Barger	Deceased (Formerly Professor, Vanderbilt University)
John Luthe	1975	Barger	Assoc. Professor, Comp Sci and Engineering, Mississippi State University
Kevin Geer	1973	Barger	Technical analyst, Santa Barbara
Penny Estabrooks	1972	Barger	Professor (emeritus), Carleton University
Peter Weiler	1971	Barger	Computer specialist, UW-Madison (retired)
K.V. L. Sarma	1969	Barger	Deceased (Formerly Professor, Tata Institute)

Back up slides

Radiation Amplitude Zeros (RAZs)

VOLUME 43, NUMBER 11 PHYSICAL REVIEW LETTERS 10 SEPTEMBER 1979

Magnetic Moment of Weak Bosons Produced in pp and $p\bar{p}$ Collisions

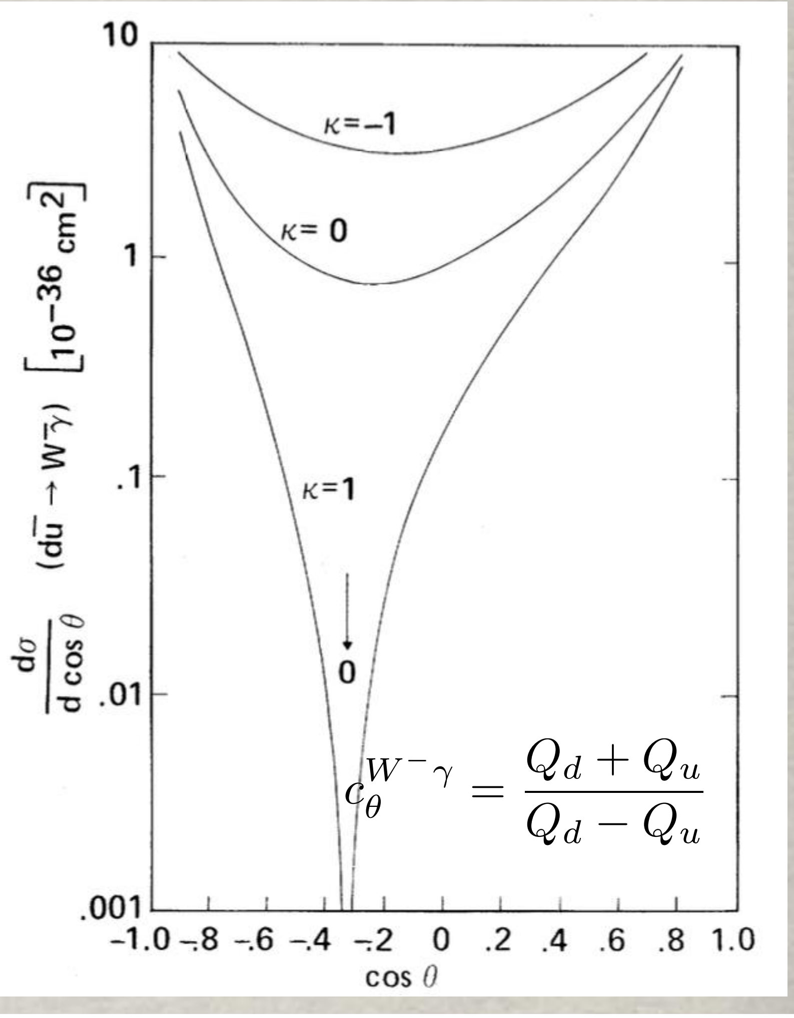
K. O. Mikaelian and M. A. Samuel
Physics Department, Oklahoma State University, Stillwater, Oklahoma 74074

and

D. Sahdev
Physics Department, Case Western Reserve University, Cleveland, Ohio 44106

(Received 5 June 1979)

We suggest that the reactions $pp \to W^{\pm}\gamma X$ and $p\bar{p} \to W^{\pm}\gamma X$ are good candidates for measuring the magnetic moment parameter κ in $\mu_W = (e/2M_W)(1+\kappa)$. The angular distribution of the W bosons in $p\bar{p} \to W^{\pm}\gamma X$ is particularly sensitive to this parameter. For the gauge-theory value of $\kappa = 1$, we have found a peculiar zero in $d\sigma(d\bar{u} \to W^-\gamma)/d\cos\theta$ at $\cos\theta = -\frac{1}{3}$, the location of this zero depending on the quark charge through $\cos\theta = -(1+2Q_d)$. A similar zero occurs in $d\sigma(u\bar{d} \to W^+\gamma)/d\cos\theta$. We can offer no explanation for this behavior.



VOLUME 72, NUMBER 25 PHYSICAL REVIEW LETTERS 20 JUNE 1994

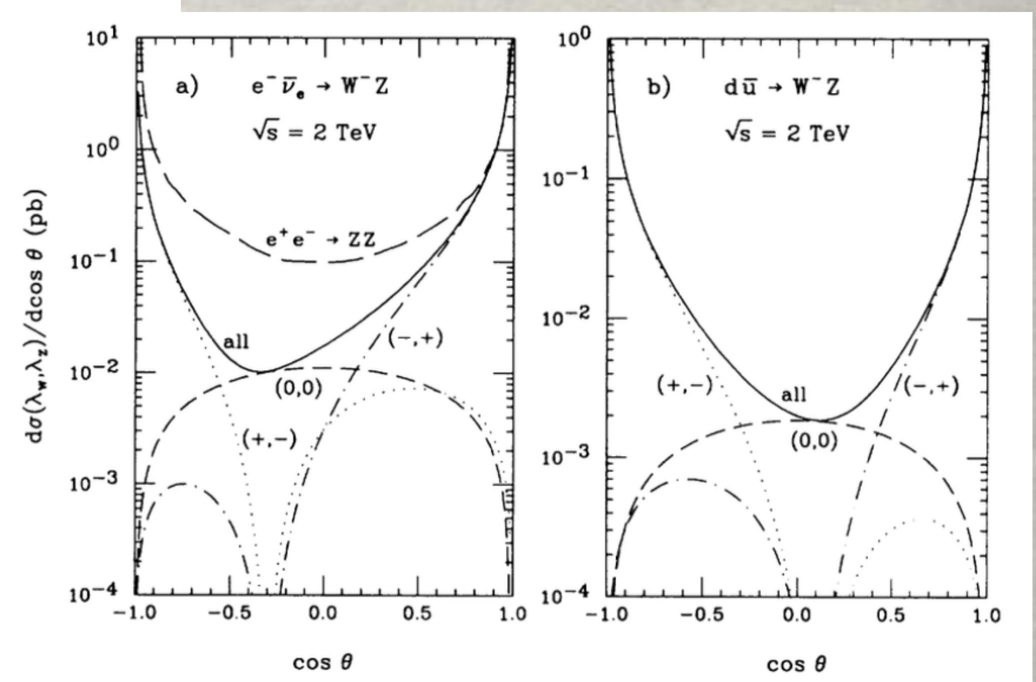
Amplitude Zeros in $W^{\pm}Z$ Production

U. Baur
Department of Physics, Florida State University, Tallahassee, Forida 32306

T. Han and J. Ohnemus
Department of Physics, University of California, Davis, California 95616

(Received 9 March 1994)

We demonstrate that the standard model amplitude for $f_1\bar{f}_2 \to W^{\pm}Z$ at the Born level exhibits an approximate zero located at $\cos\theta = (g_-^{f_1} + g_-^{f_2})/(g_-^{f_1} - g_-^{f_2})$ at high energies, where the $g_-^{f_i}$ $(i = 1, 2)$ are the left-handed couplings of the Z boson to fermions and θ is the center of mass scattering angle of the W boson. The approximate zero is the combined result of an exact zero in the dominant helicity amplitudes $\mathcal{M}(\pm, \mp)$ and strong gauge cancellations in the remaining amplitudes. For nonstandard WWZ couplings these cancellations no longer occur and the approximate amplitude zero is eliminated.



$$c_\theta^{W^- Z_T} = \frac{g_-^d + g_-^u}{g_-^d - g_-^u}$$

Test EWSR @ LHC / muon Collider

Huang, Lewis, Lane, Liu, arXiv:2009.09429; R. Capdevilla, TH, arXiv:2412.12336.

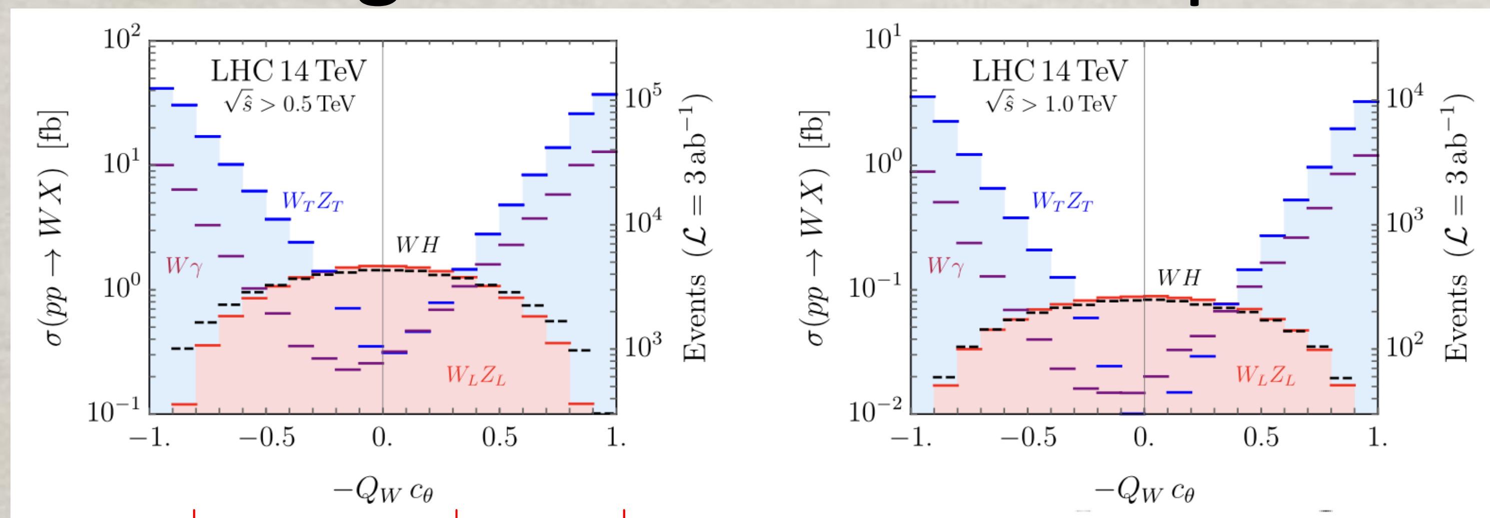
Massless gauge sector & Higgs sector:

$$r_{Z\gamma} = \frac{\sigma(WZ)}{\sigma(W\gamma)}, \quad r_{ZH} = \frac{\sigma(WZ)}{\sigma(WH)}$$

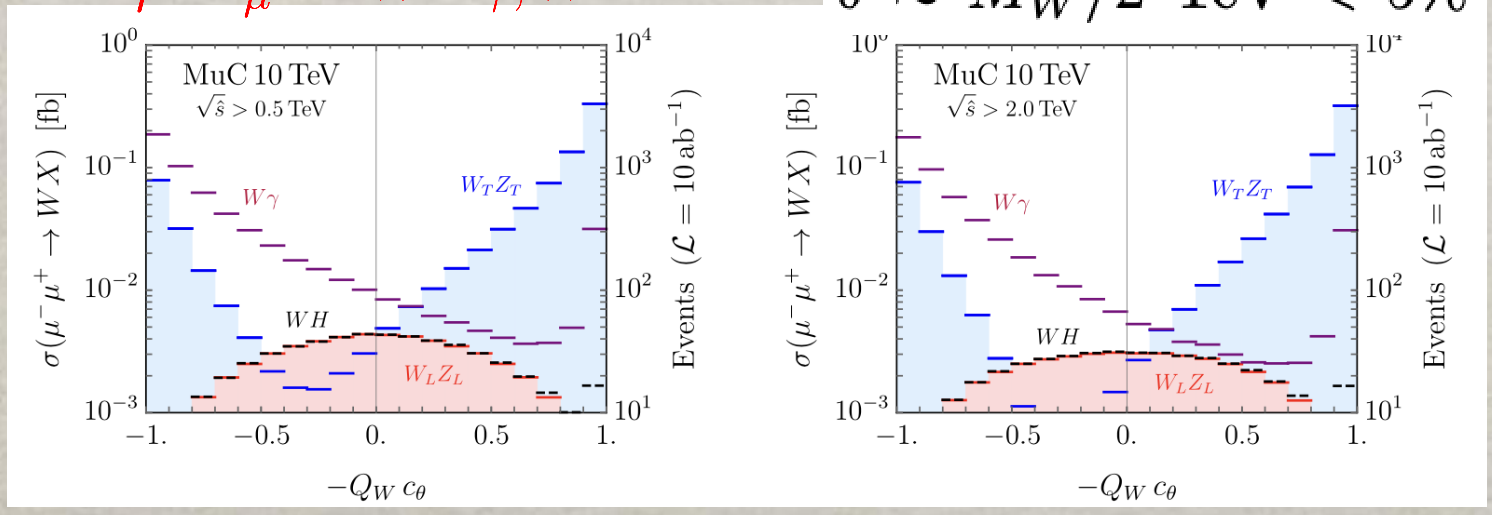
For $\boldsymbol{\delta} = M_W/2E \ll 1$:
$$\frac{\sigma(W_T Z_T)}{\sigma(W_T\gamma)} \approx \frac{g_z^2}{e^2}\frac{(g_-^{f_1})^2 + (g_-^{f_2})^2}{Q_1^2 + Q_2^2}$$

$$\sigma(W_L^\pm Z_L) \sim \sigma(W_L^\pm H),$$
$$\text{or } \sigma(\omega^\pm\omega^0) \sim \sigma(\omega^\pm H)$$

Utilizing the "Radiation Amplitude Zeros" (RAZs)



$\mu^\pm \nu_\mu \to W^\pm\gamma, W^\pm Z$ $\delta \approx M_W/2$ TeV $< 5\%$



$$c_\theta^{W^-\gamma} = \frac{Q_d + Q_u}{Q_d - Q_u}$$

$$c_\theta^{W^- Z_T} = \frac{g_-^d + g_-^u}{g_-^d - g_-^u}$$

U. Baur, TH, Jim Ohnemus, PRL (1994)

Gauge / scalar separation:

R. Capdevilla, TH, arXiv:2412.12336

$$f_1\bar{f}_2 \to W^\pm\gamma,$$
$$f_1\bar{f}_2 \to W^\pm Z,$$
$$f_1\bar{f}_2 \to W^\pm H.$$

$$\mathcal{M}^{W\gamma}_{\pm\mp} \approx -\frac{geV_{12}}{\sqrt{2}}\frac{(\lambda_{\rm w}-c_\theta)}{s_\theta}\left[Q_{(1-2)}c_\theta - Q_{(1+2)}\right],$$
$$\mathcal{M}^{WZ}_{\pm\mp} \approx \frac{gg_zV_{12}}{\sqrt{2}}\frac{(\lambda_{\rm w}-c_\theta)}{s_\theta}\left[g_-^{(1-2)}c_\theta - g_-^{(1+2)}\right],$$
$$\mathcal{M}^{WZ}_{00} \approx -\frac{g_z^2V_{12}}{2\sqrt{2}}s_\theta g_-^{(1-2)} = \frac{g^2V_{12}}{2\sqrt{2}}s_\theta,$$
$$\mathcal{M}^{WH}_{0} \approx \frac{g^2V_{12}}{2\sqrt{2}}s_\theta,$$

- Gauge sector: Radiation Amplitude Zeros (RAZs)

EM: $c_\theta^{W^-\gamma} = \dfrac{Q_d+Q_u}{Q_d-Q_u}$ EW (transverse): $c_\theta^{W^-Z_T} = \dfrac{g_-^d+g_-^u}{g_-^d-g_-^u}$

Mikaelian, Samual (1979)

$$c_{\theta_0} = \begin{cases} -1/3\ (\approx 0.1) & \text{for } d\bar{u} \to W_T^-\gamma\ (W_T^-Z_T), \\ 1\ (\approx -0.3) & \text{for } \ell^-\bar{\nu} \to W_T^-\gamma\ (W_T^-Z_T), \end{cases}$$

U. Baur, TH, JO, (1994)

- Higgs scalar sector: $\mathcal{M}^{W_LZ_L}(\delta \ll 1) \approx \mathcal{M}^{W_Lh}(\delta \ll 1)$