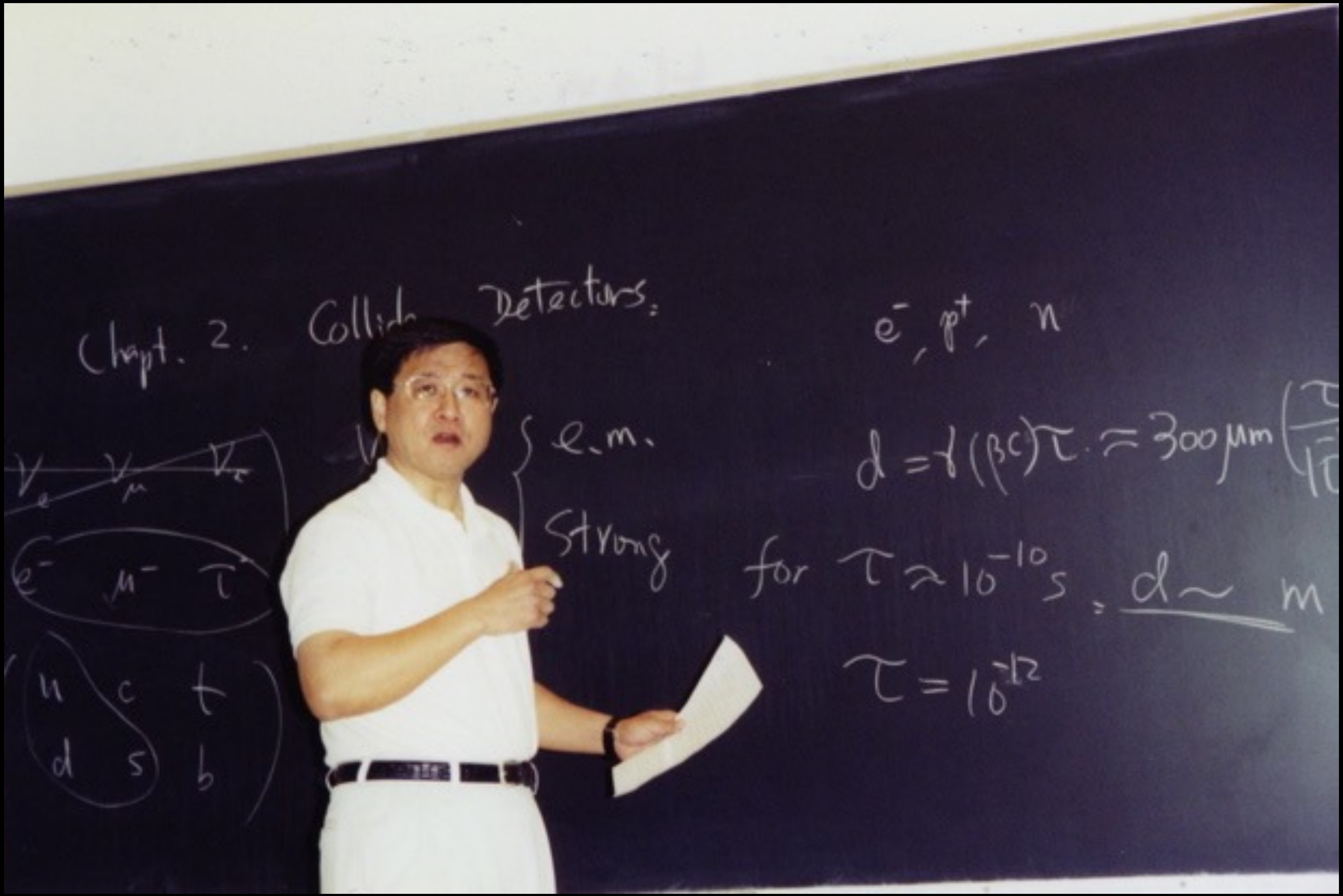
From TASI to the CSM

Neil Christensen
Illinois State University

TASI 2004

TASI 2004



Chapt. 2.
Detectors.
e.m.
Strong
e^-, p^+, n
$d = \gamma(\beta c)\tau \simeq 300\,\mu m$
for $\tau \approx 10^{-10}$ s, $d \sim$ m
$\tau = 10^{-12}$

TASI 2004

COLLIDER PHENOMENOLOGY

Basic Knowledge and Techniques*

Tao Han[1,†]

FeynRules 2008


FeynRules - Feynman rules made easy

Neil D. Christensen [a], Claude Duhr [b]

LHC-TI 2009

Theoretical High Energy Physics: Phenomenology
The Institute For Elementary Particle Physics

Research Seminars Symposia Personnel Contact

Phenomenology @ UW

LHC-TI: UW-Madison 2009-2011

Testing CP Violation in ZZH Interactions at the LHC

Neil D. Christensen, Tao Han, and Yingchuan Li*

Discovery in Drell-Yan Processes at the LHC

Cheng-Wei Chiang[1,2,3,4], Neil D. Christensen[4,5], Gui-Jun Ding[6], and Tao Han[4,5]

Pheno 2010-2011

Phenomenology 2010 Symposium

May 10, 2010, 7:30 AM → May 12, 2010, 12:30 PM America/Chicago

University of Wisconsin, Madison, Wisconsin, USA

Description The 2010 Phenomenology Symposium was held May 10-12, 2010 at the University of Wisconsin-Madison.
PHENO 10 covered the latest topics in particle phenomenology and theory plus related issues in astrophysics and cosmology.
Now that the LHC has begun its historic mission, we are all excited about the prospect of new discoveries.

PHENO 10 Organizers: Vernon Barger, Neil Christensen, Linda Dolan, Lisa Everett, Francis Halzen, Tao Han (chair), Ian-Woo Kim, Frank Petriello, Sogee Spinner, Xerxes Tata and Maike Trenkel.

PITT-PACC 2011-2014

University of Pittsburgh

Pittsburgh Particle Physics Astrophysics and Cosmology Center

Phenomenology 2012 Symposium

May 7 – 9, 2012
University of Pittsburgh
US/Eastern timezone

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LHC Lights the Way to New Physics

The 2012 Phenomenology Symposium will be held May 7-9, 2012 at the University of Pitt
It will cover the latest topics in particle phenomenology and theory plus related issues in
and cosmology. Now that the LHC has begun its historic mission, we are all excited abou
of new discoveries!

Symposium registration closes April 29.

Pheno 2012-2014

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PITT-PACC 2011-2014

MSSM Higgs Bosons at The LHC

Neil Christensen[a], Tao Han[a], and Shufang Su[b]

Low-Mass Higgs Bosons in the NMSSM and Their LHC Implications

Neil Christensen,[a] Tao Han,[a] Zhen Liu[a] and Shufang Su[b]

Pair Production of MSSM Higgs Bosons in the Non-decoupling Region at the LHC

Neil D. Christensen[a], Tao Han[a], and Tong Li[b,c]

Determining the Dark Matter Particle Mass through Antler Topology Processes at Lepton Colliders

Neil D. Christensen[1,2], Tao Han[2,3], Zhuoni Qian[2], Josh Sayre[2], Jeonghyeon Song[4], and Stefanus[2]

FeynRules 2.0 & CalcHEP 3.4

FeynRules 2.0- A complete toolbox for tree-level phenomenology

Adam Alloul [a], Neil D. Christensen [b], Céline Degrande [c,d], Claude Duhr [d], Benjamin Fuks [e,f]

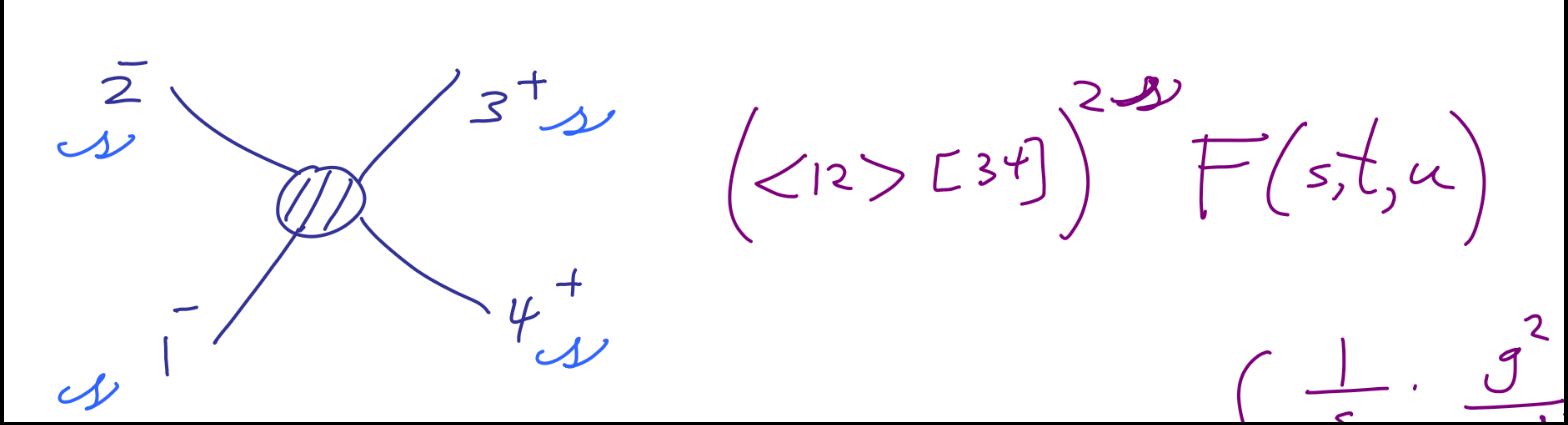
CalcHEP 3.4 for collider physics within and beyond the Standard Model

Alexander Belyaev[1,2], Neil D. Christensen[3], Alexander Pukhov[4]

Pheno 2011 & 2014

12:10 - 12:45
Nima Arkani-Hamed (IAS)
HEP in the New Era

1:00 - 1:30
Nima Arkani-Hamed (IAS)
Future perspectives



Parke-Taylor (1986)

$$|\mathcal{M}_n(--+++\ldots)|^2 = c_n(g,N)\left[(1\cdot 2)^4 \sum_P \frac{1}{(1\cdot 2)(2\cdot 3)(3\cdot 4)\ldots(n\cdot 1)} + O(N^{-2}) + O(g^2)\right] \quad (3)$$

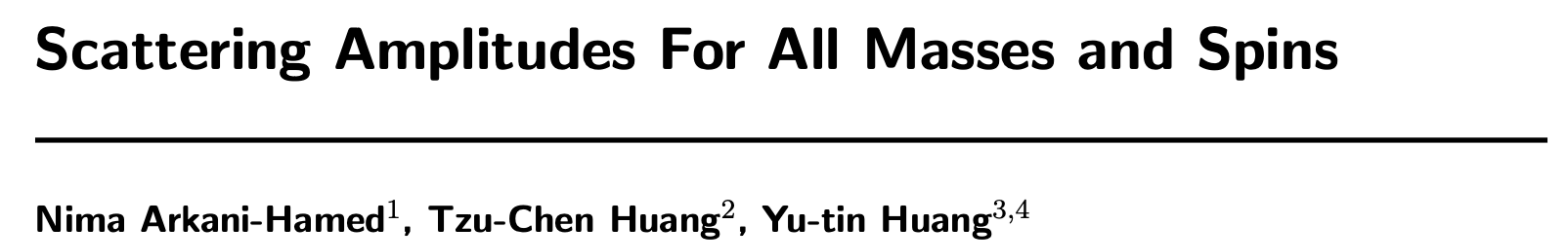
$$\mathcal{M}_n(--+++\ldots) \propto \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\cdots\langle n1\rangle}$$

BCFW 2005

Direct Proof Of Tree-Level Recursion Relation In Yang-Mills Theory

Ruth Britto, Freddy Cachazo, Bo Feng, and Edward Witten

AHH (Sep 2017)


Scattering Amplitudes For All Masses and Spins

Nima Arkani-Hamed[1], Tzu-Chen Huang[2], Yu-tin Huang[3,4]

Constructive Standard Model (CSM) (Feb 2018)

The Constructive Standard Model: Part I

Neil Christensen[1,*] and Bryan Field[2,†]

Particles	Coupling	Vertex
$\nu^-\bar{\nu}^+Z$	$-\frac{i\sqrt{2}\,e}{\sin 2\theta_w}$	$\frac{\langle\mathbf{31}\rangle[\mathbf{23}]}{M_Z}$
$f\bar{f}Z$	$-\frac{i\sqrt{2}\,e}{\sin 2\theta_w}$	$\frac{g_L\langle\mathbf{31}\rangle[\mathbf{23}]+g_R[\mathbf{31}]\langle\mathbf{23}\rangle}{M_Z}$
$l\bar{\nu}_l^+W$	$\frac{ie}{\sin\theta_w}$	$\frac{\langle\mathbf{31}\rangle[\mathbf{23}]}{M_W}$
$\bar{l}\nu_l^-\bar{W}$	$\frac{ie}{\sin\theta_w}$	$\frac{[\mathbf{31}]\langle\mathbf{23}\rangle}{M_W}$
$f_i\bar{f}_jW$	$\frac{ie}{\sin\theta_w}V_{ij}$	$\frac{\langle\mathbf{31}\rangle[\mathbf{23}]}{M_W}$
$\bar{f}_if_j\overline{W}$	$\frac{ie}{\sin\theta_w}V_{ij}^*$	$\frac{[\mathbf{31}]\langle\mathbf{23}\rangle}{M_W}$

Constructive Standard Model (CSM)

2-, 3- and 4-Body Decays in the Constructive Standard Model

Neil Christensen,[1,*] Bryan Field,[2,†] Annie Moore,[1] and Santiago Pinto[1]

$$\mathcal{M} = g_{Wff}^2 \frac{2M_W^2[\mathbf{23}]\langle\mathbf{14}\rangle - m_\mu m_e[\mathbf{12}]\langle\mathbf{3}4\rangle}{2M_W^2((p_1+p_2)^2 - M_W^2)}.$$

Constructive QED

Challenges with Internal Photons in Constructive QED

Neil Christensen,[1,*] Harold Diaz-Quiroz,[1] Bryan Field,[2,†] Justin Hayward,[1] and John Miles[1]

$$\mathcal{M} = \frac{e^2}{s}\left(\langle\mathbf{13}\rangle[\mathbf{24}] + [\mathbf{13}]\langle\mathbf{24}\rangle + [\mathbf{14}]\langle\mathbf{23}\rangle + \langle\mathbf{14}\rangle[\mathbf{23}]\right)$$

Constructive QED

Challenges with Internal Photons in Constructive QED

Neil Christensen,[1,*] Harold Diaz-Quiroz,[1] Bryan Field,[2,†] Justin Hayward,[1] and John Miles[1]

The Constructive Method for Massive Particles in QED

Hsing-Yi Lai,[a] **Da Liu,**[a,b] and **John Terning**[a]

Momentum shift and on-shell recursion relation for electroweak theory

Yohei Ema,[1,2,a] Ting Gao,[1,b] Wenqi Ke,[1,2,c] Zhen Liu,[1,d]
Kun-Feng Lyu,[1,e] Ishmam Mahbub[1,f]

Momentum shift and on-shell constructible massive amplitudes

Yohei Ema,[1,2,a] Ting Gao,[1,b] Wenqi Ke,[1,2,c] Zhen Liu,[1,d]
Kun-Feng Lyu,[1,e] Ishmam Mahbub[1,f]

Perturbative Unitarity in the CSM

Perturbative Unitarity and the 4-Point Vertices in the Constructive Standard Model

Neil Christensen[1,*]

CSM 4-Point Vertices

Particles	Coupling	Vertex
$hhhh$	$-i\frac{3e^2 m_h^2}{4M_W^2 s_W^2}$	1
$hhZZ$	$i\frac{e^2}{2M_W^2 s_W^2}$	$[\mathbf{34}]\langle\mathbf{34}\rangle$
$hhW\bar{W}$	$i\frac{e^2}{2M_W^2 s_W^2}$	$[\mathbf{34}]\langle\mathbf{34}\rangle$

A Complete Set of 4-Point Amplitudes in the Constructive Standard Model

Neil Christensen[1,*]

SPINAS: Spinor Amplitude Subroutines for Constructive Diagram Evaluations

Neil Christensen[1,*]

$q,\bar{q}\to q,\bar{q}$ Neutral		
$q,\bar{q}\to l,\bar{l}$ Neutral		
$e,e\to\mu,\mu$	$e,\mu\to e,\mu$	
$e,\bar{e}\to e,\bar{e}$	$e,e\to e,e$	
$e,\bar{e}\to\nu_\mu,\bar{\nu}_\mu$	$e,\nu_\mu\to e,\nu_\mu$	
$e,\bar{e}\to\nu_e,\bar{\nu}_e$	$e,\nu_e\to\nu_e,e$	
$\nu_e,\bar{\nu}_e\to\nu_\mu,\bar{\nu}_\mu$	$\nu_e,\nu_\mu\to\nu_e,\nu_\mu$	
$\nu_e,\bar{\nu}_e\to\nu_e,\bar{\nu}_e$	$\nu_e,\nu_e\to\nu_e,\nu_e$	
$f,\bar{f}\to f,\bar{f}$ Charged		
$u,\bar{d}\to t,\bar{b}$	$u,b\to d,t$	
$u,\bar{d}\to\nu_\tau,\bar{\tau}$	$u,\tau\to\nu_\tau,d$	
$\mu,\bar{e}\to\bar{\nu}_e,\nu_\mu$	$\mu,\nu_e\to e,\nu_\mu$	
$l,\bar{l}\to b,\bar{b}$ Neutral		
$e,\bar{e}\to h,h$	$e,h\to e,h$	
$e,\bar{e}\to\gamma,h$	$e,\gamma\to e,h$	
$e,\bar{e}\to Z,h$	$e,Z\to e,h$	
$e,\bar{e}\to\gamma,\gamma$	$e,\gamma\to\gamma,e$	$\gamma,\gamma\to e,\bar{e}$
$\gamma,Z\to\bar{e},e$	$\gamma,e\to Z,e$	
$e,\bar{e}\to Z,Z$	$e,Z\to Z,e$	
$e,\bar{e}\to W,\bar{W}$	$e,W\to W,e$	
$\nu_e,\bar{\nu}_e\to Z,h$	$\nu_e,Z\to\nu_e,h$	
$\nu_e,\bar{\nu}_e\to Z,Z$	$\nu_e,Z\to Z,\nu_e$	
$\nu_e,\bar{\nu}_e\to W,\bar{W}$	$\nu_e,W\to W,\nu_e$	
$q,\bar{q}\to b,\bar{b}$ Neutral without g		
$u,\bar{u}\to h,h$	$u,h\to u,h$	
$u,\bar{u}\to\gamma,h$	$u,\gamma\to u,h$	
$u,\bar{u}\to Z,h$	$u,Z\to u,h$	
$u,\bar{u}\to\gamma,\gamma$	$\gamma,\gamma\to u,\bar{u}$	$u,\gamma\to\gamma,u$
$\gamma,Z\to u,\bar{u}$	$\gamma,u\to Z,u$	

$q,\bar{q}\to b,\bar{b}$ Neutral without g Continued		
		$d,\gamma\to\gamma,d$
$\gamma,Z\to d,\bar{d}$	$\gamma,d\to Z,d$	
$g,\gamma\to u,u$	$g,u\to\gamma,u$	
$g,g\to u,\bar{u}$	$g,u\to g,u$	
$d,g\to d,h$	$h,g\to d,\bar{d}$	
$g,Z\to d,\bar{d}$	$g,d\to Z,d$	
$g,\gamma\to d,\bar{d}$	$d,\gamma\to g,d$	
$g,g\to d,\bar{d}$	$\bar{d},g\to g,\bar{d}$	
$f,\bar{f}\to b,\bar{b}$ Charged		
$\bar{e},\nu_e\to W,h$	$h,\nu_e\to W,e$	
$\bar{e},\nu_e\to\gamma,W$	$\gamma,\nu_e\to W,e$	
$\bar{e},\nu_e\to Z,W$	$Z,\nu_e\to W,e$	
$u,\bar{d}\to W,h$	$u,h\to W,d$	
$\bar{u},d\to\gamma,\bar{W}$	$\gamma,W\to u,\bar{d}$	
$d,W\to g,u$	$g,W\to u,\bar{d}$	
$\bar{u},d\to Z,\bar{W}$	$W,d\to Z,u$	
$b,\bar{b}\to b,\bar{b}$		
$h,h\to h,h$		
$h,h\to Z,Z$	$h,Z\to Z,h$	
$h,h\to W,\bar{W}$	$h,W\to W,h$	
$\gamma,h\to W,\bar{W}$	$\gamma,W\to W,h$	
$Z,h\to W,\bar{W}$	$Z,W\to W,h$	
$\gamma,\gamma\to W,\bar{W}$	$\gamma,W\to\gamma,W$	
$\gamma,Z\to W,\bar{W}$	$\gamma,W\to Z,W$	
$Z,Z\to Z,Z$		
$Z,Z\to W,\bar{W}$	$Z,W\to Z,W$	
$W,W\to W,W$	$W,\bar{W}\to W,\bar{W}$	
$g,g\to g,g$		

A Field-Theory Action for the Constructive Standard Model

Neil Christensen[1,*]

$$\mathcal{S}_{free} = \int \frac{d^4p_1 d^4p_2}{(2\pi)^4}\delta^4(p_1+p_2)\left[p_1^2 A^+(p_1)A^-(p_2) + \left(p_1^2 - m_e^2\right)\bar{e}_{\mathrm{I}}(p_1)e^{\mathrm{I}}(p_2)\right]$$

$$\mathcal{S}_{int} = \int \frac{d^4p_1 d^4p_2 d^4p_3}{(2\pi)^8}\delta^4(p_1+p_2+p_3)\Big[q_e\bar{e}_{\mathrm{I}}(p_1)\left[\tilde{x}_{31}[\mathbf{31}]^{JI}A^+(p_2) + x_{31}\langle\mathbf{31}\rangle^{JI}A^-(p_2)\right]e_{\mathrm{I}}(p_3)\Big]$$

The Scattering Algebra of Physical Space: Squared Massive Constructive Amplitudes

Moab Croft and Neil Christensen

Object	**Traditional**	**Relation**	**SA/APS**
Right-Angle Spinor	$\vert\mathbf{j}\rangle_\alpha^{\ \mathrm{J}}$	$\equiv$	$\lambda = \sqrt{mc}R_pL_a$
Left-Angle Spinor (Transpose)	$\left(\langle\mathbf{j}\vert^{\alpha\mathrm{J}}\right)^T$	$\equiv$	$\hat{B}\widetilde{\lambda}$
Right-Square Spinor	$\vert\mathbf{j}]^{\dot{\beta}}_{\ \mathrm{J}}$	$\equiv$	$\lambda^-\hat{B}^\dagger$
Left-Square Spinor (Transpose)	$\left([\mathbf{j}\vert_{\dot{\beta}\mathrm{J}}\right)^T$	$\equiv$	$\lambda^\dagger$
(Raising) Epsilon Tensor	ϵ^{JK}	$=$	$\left[\hat{B}^\dagger\right]^{\mathrm{JK}}$
(Lowering) Epsilon Tensor	ϵ_{JK}	$=$	$\left[\hat{B}\right]_{\mathrm{JK}}$
(Left) Lorentz Product	$\langle\mathbf{j}\vert^{\alpha\mathrm{J}}\vert\mathbf{k}\rangle_\alpha^{\ \mathrm{K}}$	$=$	$\left[\hat{B}\widetilde{\lambda}_j\lambda_k\right]^{\mathrm{JK}}$
(Right) Lorentz Product	$[\mathbf{j}\vert_{\dot{\beta}}^{\ \mathrm{J}}\vert\mathbf{k}]^{\dot{\beta}\mathrm{K}}$	$=$	$\left[\hat{B}^\dagger\lambda_j^\dagger\lambda_k^-\right]^{\mathrm{JK}}$
(First) Momentum Insertion	$[\mathbf{j}\vert_{\dot{\beta}}^{\ \mathrm{J}}p_l^{\dot{\beta}\alpha}\vert\mathbf{k}\rangle_\alpha^{\ \mathrm{K}}$	$=$	$\left[\hat{B}\lambda_j^\dagger p_l^-\lambda_k\right]^{\mathrm{JK}}$
(Second) Momentum Insertion	$\langle\mathbf{j}\vert^{\alpha\mathrm{J}}p_{l,\alpha\dot{\beta}}\vert\mathbf{k}]^{\dot{\beta}\mathrm{K}}$	$=$	$\left[\hat{B}^\dagger\widetilde{\lambda}_j p_l\lambda_k^-\right]^{\mathrm{JK}}$

Thank you Tao!

- Partially supported by NSF Grant No PHY-2411482.