

An Explanation of the WW excess at the LHC by Jet-veto resummation

Prerit Jaiswal Syracuse University

SCET 2015, Santa Fe 26th March, 2015

$p p \rightarrow W W$: The WW excess'

A mild excess, 1.5 - 2 σ over NLO theory prediction

- Excess at both 7 and 8 TeV, experiments more consistent * with each other than the theory prediction.
- Significance of excess higher (3 σ) when considering bin- $*$ by-bin analysis.

\rightarrow W W : `The WW excess'

New Physics Hiding in Plain Sight?

 B. Feigl, H. Rzehak, and D. Zeppenfeld, New physics backgrounds to the $H \rightarrow W W$

search at the LHC?, LarXiv: 1205.34681.

- D. Curtin, P. Jaiswal, and P. Meade, Charginos hiding in plain sight, [arXiv: 1206.6888].
- P. Jaiswal, K. Kopp, and T. Okui, Higgs \ast production amidst the LHC detector, [arXiv:1303.1181].
- K. Rolbiecki and K. Sakurai, Light stops $*$ emerging in WW cross section measurements?, [arXiv:1303.5696].
- D. Curtin, P. Jaiswal, P. Meade, and P.-J. \ast Tien, Casting light on BSM physics with SM standard candles, [arXiv: 1304.7011].
- D. Curtin, P. Meade, and P.-J. Tien, Natural $*$ SUSY in Plain Sight, [arXiv:1406.0848].
- J.S. Kim, K. Rolbiecki, K. Sakurai and J. $\frac{1}{2}$ Tattersall, Stop that ambulance! New physics at the LHC?, [arXiv: 1406.0858] .

An explanation of the WW excess with 110 GeV charginos

Or simply a QCD effect?

Both ATLAS and CMS experiments impose jet-veto in their analysis

Need a better understanding of jet-veto. P. Jaiswal and T. Okui, An Explanation of the WW Excess at the LHC by Jet-Veto Resummation, [arXiv:1407.4537].

Jet-veto example : no `jets' with pT > 25 GeV allowed \ast Jet-veto \implies Many scales \implies Large Logs Jet-Veto : Origin of Large Logs Minimize logs from virtual diagrams. Minimize logs from real diagrams. WW + 0 jet measurement : Two scales appear : Mww and pr^{veto} ω 2 possible choices : μ = Mww or μ = pτ^{νετο}?? Inclusive WW measurement : Only one scale appears : Mww ☛ Obvious scale choice : μ ≈ MWW . [μ= μf= μr]

Jet-Veto and Large Logs: The problem of many scales

- A well known and understood problem in EFTs (Effective Field Theories)
- SCET can provide answers on how to resum the large logs.

Soft Collinear Effective Theory (SCET) Degrees of Freedom and power counting: mode should not be in the e↵ective theory.) This determines that *^p* ⇠ *^O*(2*M*). Therefore, the components of the initial quark must have the following parametric scaling parameters of the following parameter of *M* and : 0_a *<u><i>p* **111601** \boldsymbol{y} **10** *p* **111601** \boldsymbol{y} **10** *p* **111601** \boldsymbol{y} **111601** \boldsymbol{y} </u> *,*)*M .* (2.9) *^a·^b* ⌘ *^a*+*b*⁺ ⁺ *^ab* ⁺ *^a*? *·b*? = 2(*ab*⁺ ⁺ *^a*+*b*) + *^a*? *·b*? mode should not be in the e↵ective theory.) This determines that *^p* ⇠ *^O*(2*M*). Therefore, the components of the initial quark must have the following parametric scaling parameters of the following parameter Soft Collinear Effective Theory (SCET) $\textbf{\textit{R}}$ Degrees of Freedom and power-counting $\textbf{\textit{R}}$

Collinear Modes : $(p_+, p_-, p_\perp) \sim (1, \lambda^2, \lambda) M$ ω reference to the initial ω , the *p* of the initial ω , the initial ω should scale as p (*p*+*, p*₋*, p*₁) ~ $(1, \lambda^2, \lambda)M$ are only a finite number of \sim $(1 \t1 \t12 \t1)$ \sim contract tytous. This is independent to \sim

- Anti-collinear Modes : * Anti-collinear Modes: $(p_+, p_-, p_\perp) \sim (\lambda^2, 1, \lambda) M$ $(p_1, p_2, p_3) \approx (1^2 + 1) M$ $\left(\frac{p}{\mu}, \frac{p}{\mu}, \frac{p}{\mu}\right) \sim (\lambda, 1, \lambda)$ *W* $\lim_{m \to \infty} \frac{1}{m}$ scaling behavior $(n - m - n)$, $(1^2 + 1)M$ **8 By Letting all operate by collinear and and anticollinear fields without including the so-called so-called so-called** (r, r, r, \ldots)
	- Soft Modes: $(p_+, p_-, p_\perp) \sim (\lambda, \lambda, \lambda)$ *,* 1*,*)*M ,* (2.10) * Soft Modes: $(p_+, p_-, p_\perp) \sim (\lambda, \lambda, \lambda)M$

Regulators :

- * Separation of off-shell and on-shell modes : DR **greater than Λ. component with 4-momentum** *qreater than Λ. component* **with 4-momentum** *p***, where the virtuality** Λ **.** At cut-off scale A, integrate out modes with off-s mode should not be in the e↵ective theory.) This determines that *^p* ⇠ *^O*(2*M*). Therefore, the component must of the initial quark must have the following parameter of the following parameter in terms of the
In the following parameter in the following parameter in the following parameter in the following parameter of *M* and : At cut-off scale Λ, integrate out modes with off-shellness and on-shell modes . DR which is the scale in the size of the virtuality of the virtual
The size of the virtuality of the virt of collinear and anticollinear modes are given by their *p*T. ⁹ Strictly speaking, we also have *^m^W* and *^m^Z* . For parametrics/scaling discussions, we treat them as ⇠ *^O*(*M*).
- x Separation of collinear/anti-collinear modes : DR not sufficient. * Separation of collinear/anti-collinear modes : collinear quark with 4-momentum *quark with 4-momentum a* gluon with 4-momentum *quark with a gluon with a gluon with a* gluon with α . We will be written to find the set of th

SCET to regulate rapidity divergences, which amounts to modifying the integration measure d*p*⁺ in P $\mathcal{X}=\mathcal{X$ \overline{A} discussed in Section 2.1.3, the beam functions have rapid types that arise from artificial arise from artificially separating collinear and anticollinear modes for the purpose of well-defined power counting.

<u>ingar</u> *p*⁺ Separation of collinear/anti-collinear modes : The divergences in the beam functions arise from the d*p*⁺ and d*p* integrations implicit in ^P *X X*^opectivity, *v respectively, in the factorization (2.68).* We examine the factorization (2.68).

Analytic / Rapidity Regulators to regulate rapidity divergences, which are integrated the integration of the integration measure dependence of the integration of the integration measure dependence of the integration measure of the integration measure de

 $\overline{}$ Analogous to DR : take α \rightarrow 0 limit in the end.

- Collit $\frac{1}{2}$ Collinear Anomaly :
	- *p p* Dependence of amplitudes on ν.
	- Physical observables do not depend on regulator \Rightarrow RGE in v

Analogous to μ dependence in DR

SCET: Calculations $f(x) = f(x) + f(x) + f(x)$ $\mathcal{L}_{\text{hard}} =$ 1 $\frac{1}{M} \epsilon^*_{\mu}(p_3,s_3) \epsilon^*_{\nu}(p_4,s_4) e^{\mathrm{i}(p_3+p_4)\cdot x} \mathcal{J}^{\mu\nu}(x)$ \mathfrak{p}_3 **+** \mathfrak{p}_4 **j** = **(1, 1,** λ **)** \Rightarrow **x** = **(1, 1, 1/** λ **)** * SCET Current $J_X^{\mu\nu}(x,P_1,P_2,p_3,p_4) \equiv \left\langle X \middle| \mathcal{J}^{\mu\nu}(x) \middle| \text{p}(P_1) \text{p}(P_2) \right\rangle$ $J_X^{\mu\nu}(x, P_1, P_2, p_3, p_4)$ $\int \frac{d\alpha_1 d\alpha_2}{\alpha_1}$ (c), c₂, P₃₊₄||, P₃₋₄, P₁) $\frac{d\alpha_1}{\alpha_2}$ ($\frac{d\alpha_2}{\alpha_3}$ ($\frac{d\alpha_3}{\alpha_4}$) $\frac{d\alpha_4}{\alpha_5}$ ($\frac{d\alpha_4}{\alpha_6}$ ($\frac{d\alpha_5}{\alpha_7}$) $\frac{d\alpha_7}{\alpha_8}$ ($\frac{d\alpha_8}{\alpha_7}$) $\frac{d\alpha_1}{\alpha_7}$ (**Consistent power counting** \Rightarrow **Multipole expansion** $\lambda_1, \lambda_2, \lambda_3$ in the leading order in $(1, \lambda^2, \lambda)$ \mathbf{y} **C**ross-section $\boldsymbol{\sigma} \propto \mathbf{I}(\mathbf{y})$ $\mathbf{I}(\mathbf{0})$ $\mathbf{a}^{j}(\mathbf{p}_{\boldsymbol{\sigma}}+\mathbf{p}_{\boldsymbol{\sigma}})$, footorizes $\tau = |\hat{C}(u, u)|^2 \otimes B(u, u) \otimes B(u, u) \otimes A(v^{veto}, u)$ **where** *p***3**≠4 **p**3 **p**3 *p*⁴, while *a* and *i*⁴ Wilson Coefficients Beam functions collinear anomaly \star **SCET Lagrangian**: $p(P_1) + p(P_2) \rightarrow W^+(p_3, s_3) + W^-(p_4, s_4) + X$ need to evaluate the matrix element $\int_{0}^{\infty} M^{(p)}(P^{(p)}(P^{(p)}) \circ \phi(P^{(p)}(P^{(p)})))$ $(p_3 + p_4) = (1, 1, \lambda) \implies x = (1, 1, 1/\lambda)$ vanishing component of is picking up the on-shell, physical polarizations of the initial collinear and anticollinear quarks. The remaining polarizations are always o↵-shell and hence do not appear in the SCET. $\mathcal{C}_1 = \frac{1}{\epsilon^* (n_2 - \epsilon_2)} \epsilon^* (n_1 - \epsilon_1) \frac{\mathrm{i} (p_3 + p_4) \cdot x}{\mathrm{i} (p_3 + p_4)}$ 2.3.1 Factorization of Matrix Elements and Matrix Elements and Matrix Elements and To calculate the cross section for the process p(*P*1) + p(*P*2) ! *^W*+(*p*3*, s*3) + *^W*(*p*4*, s*4) + *^X*, we 18 where dependence on the proton spins are instructed to proton spins and the fields inside the fields inside th = Z $\mathrm{d} t_1\, \mathrm{d} t_2\, C^{\mu\nu}(t_1,t_2,p_{3+4\parallel},p_{3-4},\mu_{\mathrm f}) \, \big\langle X \big| \chi^{i\alpha}_{\mathrm{\bar c}}(x^-+t_2,\vec{x}_\perp) \; \Gamma_{\alpha}^{\;\;\beta} \, \chi_{\mathrm{c}\:\!i\beta}(x^+ + t_1,\vec{x}_\perp) \big| \mathrm{p}(P_1) \, \mathrm{p}(P_2) \big\rangle$ where the Wilson coefficing coefficient coefficient **C**_{*n*} $\frac{1}{2}$ **is now evaluated at the scale of** $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $(s_+, s_-, s_+)= (1, \lambda^2, \lambda)$ ***** Cross-section **σ** ∝ J(x) J(0) e^{i(p₃+p₄).x} factorizes \sim $\sqrt{2}$ collinear states, i.e., i.e. $P_2(\mu_s, \mu) \propto A_c(P_T, \mu)$ where *X*^c ↵ consists only of collinear particles, and **collinear anomaly** Wilson Coefficients Beam functions collinear anomaly 2

SCET : Calculations Wilson Coefficients *^J ^µ*⌫(*x*) are time-ordered and that *^Jµ*⌫ *^X* is only the connected part of the matrix element. Substi-**VIISON GOETHERNTS**

Matching full theory (QCD) to SCET operators at a hard scale μ_h

 poles interpreted as UV poles Choose μ_h² = M² to minimize log[M²/μ_h²] at matching. connecting c and α , because c collinear and α on linear gluons and α on linear gluons, and α as they are charged under separate gauge gauge gauge gauge groups we have a section 2.1.5. Therefore, we have $\frac{1}{2}$ *.* (2.52)

Then use RGE to run to a low energy scale μ . = ⌦ *X*¯c *i*↵ ¯c (*x* + *t*2*,* ~ *x*?) p(*P*2) ↵ *X*^c c*i*(*x*⁺ ⁺ *^t*1*,* ~ *x*?) Using the momentum operator to a low end y your point **x**,

• SCET : Calculations

Beam Functions Without all use the participant to the parton model description, we give the operator definition, we give the o which in the SCET formalism (which is literally identical to the QCD operator in the QCD operator α

Generalization of PDFs for less inclusive observables like jet-veto \ast

- $\phi_n^{q/N}(\xi,\mu) = \frac{1}{2\pi}$ 2π Z $dt e^{-i \xi t \bar{n} \cdot P}$ *Xn* $\langle N(P)|\bar{\chi}^{(0)I}(t\bar{n})|X_n\rangle$ $\rlap{/}~\,$ $\frac{\partial}{\partial x} \langle X_n | \chi^{(0)I}(0) | N(P) \rangle$
- where the sum is over the collinear states *|Xn*i and (*x*) = *W†* (*x*) ⁴ (*x*) (1.2) satisfying jet-veto condition Jet-veto beam functions : X_n is all collinear final states PDF : X_n is all collinear final states
- λ Renormalization of PDFs :
	- literature but wish to but wish to scaleless integrals in DR
		- IN the above experience in the above expression in a possible in the spin averaging is implicitly under the spin and the spin and the spin averaging is in the spin and the spin averaging is in the spin averaging in the spi If writes gone in arres gone in terms operators in terms of contraction \Rightarrow UV divergence = IR divergence (DGLAP=splitting functions)
- Renormalization of Beam functions : \ast
	- operator evaluated between the nucleonic states, with the nucleonic states, with the transverse momenta of the ope on to PDFs the interpretation of probability density density of probability density of probability density of probability density density of probability density density density of probability density density of probabi
	- DR not sufficient : need rapidity regulators
	- $\overline{}$ $Dependence on v \Rightarrow Collinear anomaly term$

Results for WW+0 jet production at the LHC

P. J. and T. Okui, An Explanation of the WW Excess at the LHC by Jet-Veto Resummation, LarXiv:1407.45371.

How to count

- Power Counting parameter in SCEI : λ = preto/M
	- All calculations at LO in SCET power counting.
	- * SCET resums pieces singular in the $\lambda \rightarrow 0$ limit (i.e. logⁿ λ)
	- Corrections beyond the singular pieces : Power Corrections ☛ Add them at the end if the full NLO result is known. ☛ (Power Corrections) = NLO - (Singular pieces of NLO)

$$
\sigma_{tot} = \sigma_{resum} + (\sigma_{N''LO} - \sigma_{resum}^{[N''LO expansion]})
$$

Power Corrections

All ingredients already known in the literature.

NLL and NNLL Results for $q\overline{q}$ \rightarrow WW+0 jet

Consistency Checks and Power Corrections

- Recall : SCET resums terms singular in p_T veto/ $M \rightarrow 0$
- Power corrections suppressed by powers of pr^{veto}/M. Found to be less than 1%.
- Consistency Check : For small pr^{veto}, NNLL cross-section expanded to O(αs) should match fixed-order NLO calculations.

✔ Good agreement between our resummed results expanded to O(α_s) and MCFM for $q\overline{q} \rightarrow WW$ at NLO in the 0-jet bin for small pr^{veto}.

NNLL+NLO Results

Beyond NLO : Besides logarithm terms e.g. α_s^2 L⁴, jet-clustering dependence :

$$
\left(P_T^{veto}/M \right)^{\alpha_s^2 \left[1 + \log R + R^2 + R^4 + \dots \right]}
$$

Comparison with MC+Parton Showers

(Includes LO gg contribution assuming 100% of them pass jet-veto)

WW+0/1/2 jet matched : LO Madgraph5 + Pythia6

MC@NLO + Herwig6

Powheg v1 + Pythia6

Jet algorithm : anti- k_T , $k=0.4$ CTEQ6L for LO MC, CT10nlo for NLO MC, MSTW08nnlo for NNLL+NLO

Comparison with LHC data

Similar Calculations * LarXiv:1407.44811 Transverse momentum resummation for WW : Patrick Meade, Harikrishnan Ramani, Mao Zeng

- 3-7% reduction in discrepancy. (similar to our results without T^2 resummation)
- * LarXiv:1410.47451 NNLL+NNLO extrapolation from Drell-Yan Pier Francesco Monni, Giulia Zanderighi
- * LarXiv:1412.84081 Automated NNLL+NLO : T. Becher, R. Frederix, M. Neubert and L. Rothenier
	- * Consistent with our result (without π^2 resummation)
- * LarXiv:1408.52431 NNLO for WW: Gehrmann et al
	- $*$ Increase of 7% consistent (NNLO effects accounted by π^2 resummation)

New CMS 8 TeV result with full data set Figure City of 101 For The experimental and the event with the event selection as well as well as

- Reweighted MC using the `correct' pT distribution of the W-pair. [following procedure outlined in arXiv:1407.4481] channels as shown in Table 4. *s*W+W = 60.1 *±* 0.9 (stat.) *±* 3.2 (exp.) *±* 3.1 (th.) *±* 1.6 (lum.) pb. (2) x Reweighted MC using the correct' of distribution of * Keweighted MC using the correct p1 distribution of
- * Theory NNLO prediction: $59.8^{+1.3}_{-1.1}$ pb on the integrated luminosity are reported separately. The combined result is measured to be:
	- Observed :

 $\sigma_{W^+W^-} = 60.1 \pm 0.9$ (stat.) ± 3.2 (exp.) ± 3.1 (th.) ± 1.6 (lum.) pb.

Complex scales and scale uncertainties

P. J., A New Perspective on Scale Uncertainties, [arXiv:1411.0677].

Origin of Complex Scales Logarithms in Wilson coefficient, C(μ) : son pair-production channels, *W*+*W*, *ZZ* and *W±Z*, owing to their similar kinematics. The cross-sections $n - n$ orations in these channels at p*s* = 7 TeV and 8 TeV LHC **ractori** laborations. The discrepancy in the *WW* channel is par-Logarithme in Wilson coefficient C(U). evgar
 physics could be hiding in the *W*⁺*W* measurements $*$ Mate \mathbf{F} derstanding of the higher-order corrections to the SM T^2 duction has a long history, with the first NLO QCD corand *ZZ* production with one jet have been computed in [41–43] and [44], respectively, while *W*+*W* + 2 jets calculations were considered in [45, 46]. Transverse mo $pp \rightarrow V V'$, where $V \in \{ W, Z \}$ $\mathbf{r}^{\mathbf{z}}$ $\frac{1}{50}$ $\sigma = C(\mu) \otimes f(\mu) \otimes f(\mu) \otimes S(\mu)$ [51, 52]. Finally, the NNLO QCD corrections to *W*⁺*W* **Roofficiel PDFs** Cofficientials above includes powers of above increasing powers powers and the form $\log \left[(-M^2 - i0^+)\right]$ / μ^2 ^T the diboson system and *µ* is the factorization scale, which j or scale to guv at μ = μ _h μ_1 μ_2 μ_3 = M minimizes lons trolled by the logarithmic terms, $\mathbf{y} = \mathbf{y} \mathbf{y} \mathbf{y}$ and $\mathbf{y} = \mathbf{y} \mathbf{$except that branch cut \Rightarrow - i π factors so that double logs produce rections. Further, given that physical observables are \mathcal{P} independent, one can estimate scale uncertainty in the scale un Matching of SCET to QCD at μ = μ^h Choice of μ_h ? μ_h = M minimizes logs.... π^2 factors. Factorized cross sections : Wilson Coefficient PDFs Soft Function

***** Motivates choice of μ_h in the complex μ^2 -plane, e.g. $\mu_h^2 \approx -M^2$ boson invariant mass distribution in variable to the LO and NLO shown in the LO and NLO shown in the NLO shown in

Large logs from Complex Scales Logarithms in Wilson coefficient, C(μ) : ticularly compelling given that both ATLAS and CMS **Logal** physics could be hiding in the *W*+*W* measurements $\frac{1}{2}$ $\frac{1}{\sqrt{2}}$ and **Languis Computer Computer** $\mathbf{E} = \mathbf{E} \mathbf$ above in the form coefficient, α iparithms of α $\log \left[(-M^2 - i0^+) / \mu^2 \right]$ Matching scale μ_h² complex-valued. is a little start of the school in the scale at which are real \cdot , \cdot , and \cdot that **indicated and the control of the cross-section** indicated the control of the cont But PDFs evaluated at factorization scales which are real : μ f² = M^2

- $\frac{1}{2}$ High Hierarchy of scales in the complex μ² -plane
	- problem: the hard scale, *µ*^h and the factorization scale, 100 S 100 (μ _h / μ _f / \Rightarrow $-a$
- step process, *C*(*µ*h) ! *C*(*|µ*h*|*) ! *C*(*µ*f). In this pa- u per, we will consider it inclusive consider it is so that \star Ph: rections to *W*⁺*W*, *ZZ* and *W±Z* channels computed in Phase of μ^h 2 : Θ
- is reasonable to set *µ*^f = *|µ*h*|* ⌘ *µ*. For less inclusive measurements, such as in positive jet-veto [50], we have the such as in positive \sim $log(\mu_h^2/\mu_f^2) = i \Theta$ $log(\mu_h^2)$
	- $C = C \cdot C \cdot C$ $M = \pm T$ be trivially extended to less-inclusive measurements. If Logs dominant : Θ = ±π

- Let us define ^µ ⌘ *^µ*^f ⁼ *[|]µ*h*[|]* and *^µ*² ^h ⁼ ^µ²*eⁱ*⇥, where ⇥ ² lf non-Log terms dominant, no preferred value of Θ. we showed that the logarithms *LM*(*µ*h) present in the
- hard matching coecient are minimized for µ = *M* and $F_1(x)$ 2: $\frac{1}{2}$ is shown the scale in the complex i RG equation for C(μ) known \Rightarrow Evolve from $\mu_h^2 \rightarrow \mu_f^2 \Rightarrow$ Resum Θ terms. \ast H tor $\mathbb{G}(\mu)$ known \Rightarrow Evolve the choice of the hard matching scale to be the scale of orange shaded region satisfies *M/*2 *< |µ*h*| <* 2*M* but only the
- associated with the choice of the hard scale parameters, $-T \in \mathbb{R}$ and $T \in \mathbb{R}$ similar to $M/Z \in \mathbb{R}$ \cdots \cdots ^F is the cusp-anomalous dimension which re-Vary : -π < Θ < π similar to M/2 < |μh| < 2 M

Scale Uncertainty

3-4 % increase in central value prediction w.r.t NLO (dynamic scale). \ast

Better estimate of scale uncertainty. \ast

Work in progress

- pT resummation : allows to get distributions but misses jetclustering dependence
- Jet-veto resummation : allows precise calculation of crosssection in 0-jet bin but not the distributions.

- * Detailed comparison of pT resummation vs jet-veto resummation (with P. Meade and H. Ramani)
- Differential pT distributions in the zero-jet bin (with T. Okui)