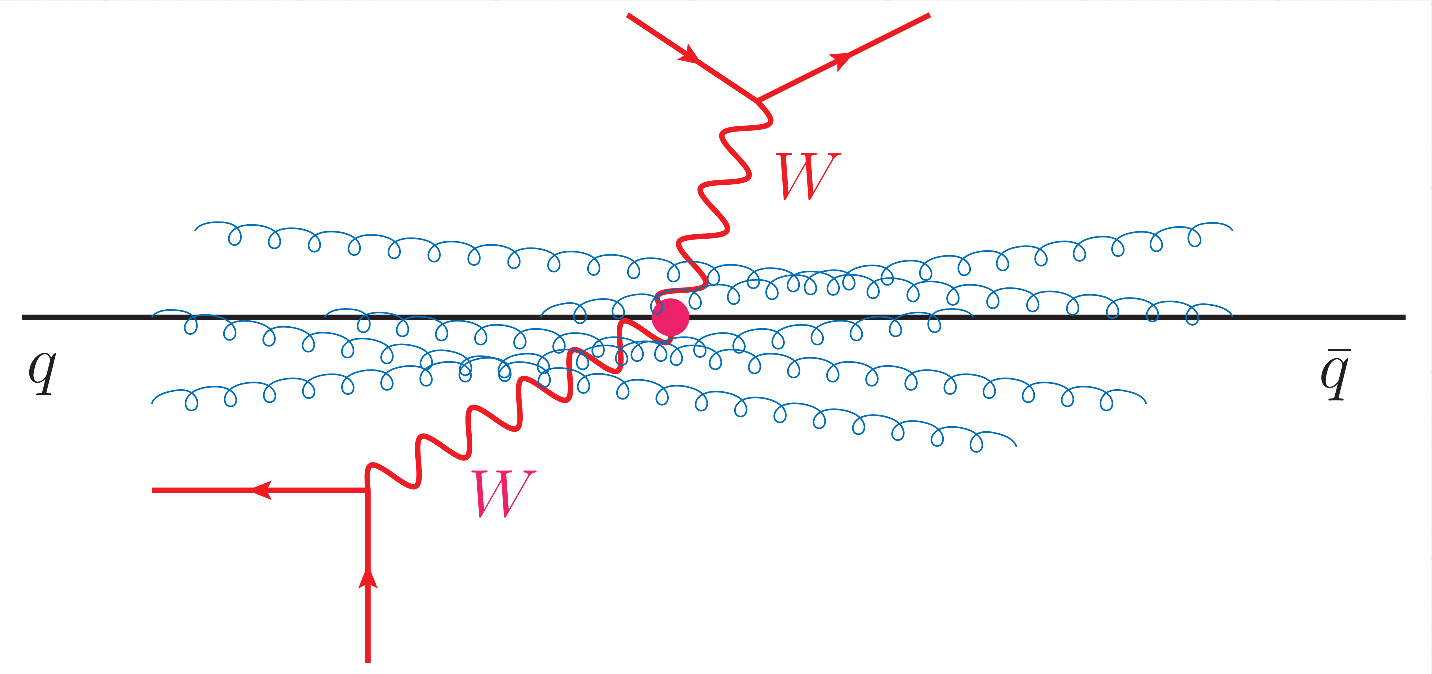
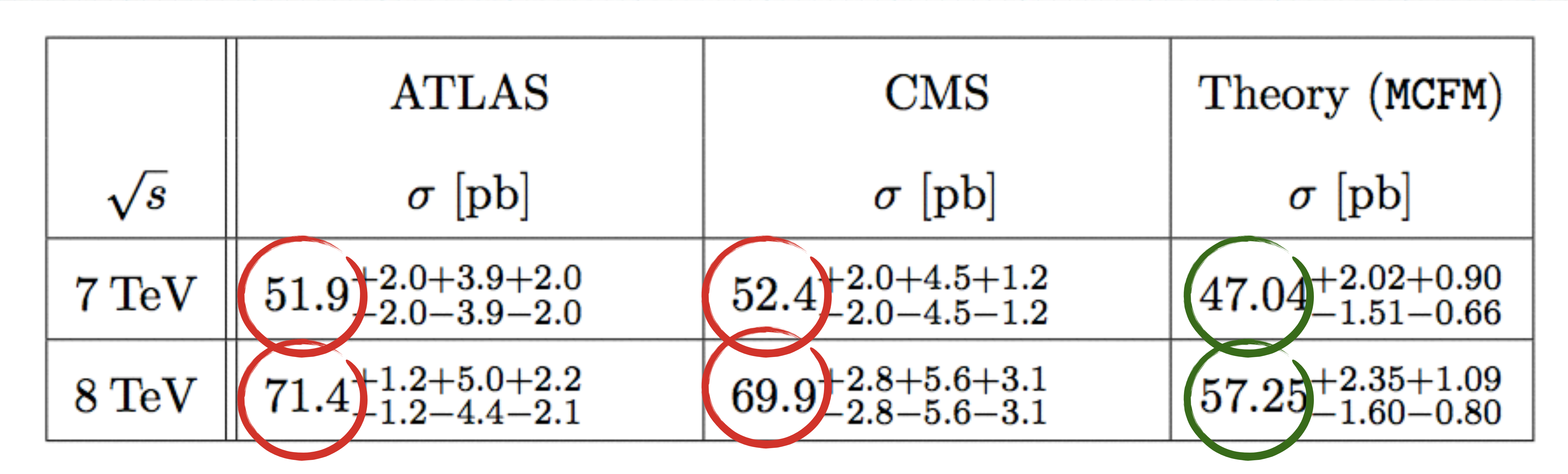


An Explanation of the WW excess at the LHC by Jet-veto resummation

Prerit Jaiswal
Syracuse University

SCET 2015, Santa Fe
26th March, 2015

$p\,p \rightarrow W\,W$: `The WW excess´



$\sqrt{s}$	ATLAS σ [pb]	CMS σ [pb]	Theory (MCFM) σ [pb]
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$	$47.04^{+2.02+0.90}_{-1.51-0.66}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$	$57.25^{+2.35+1.09}_{-1.60-0.80}$

- 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.

p p → W W : `The WW excess'

$\sqrt{s}$	ATLAS σ [pb]	CMS σ [pb]	Theory (MCFM) σ [pb]
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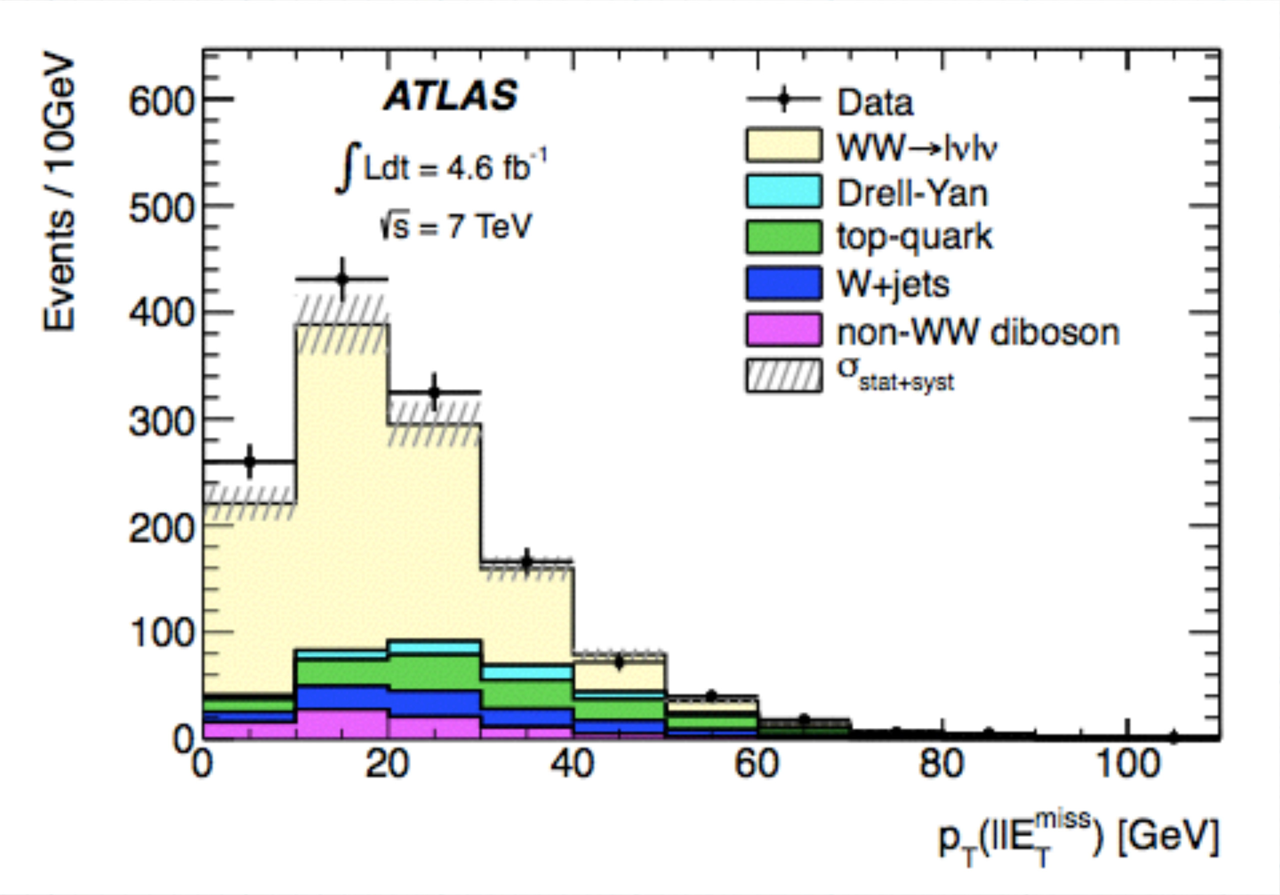
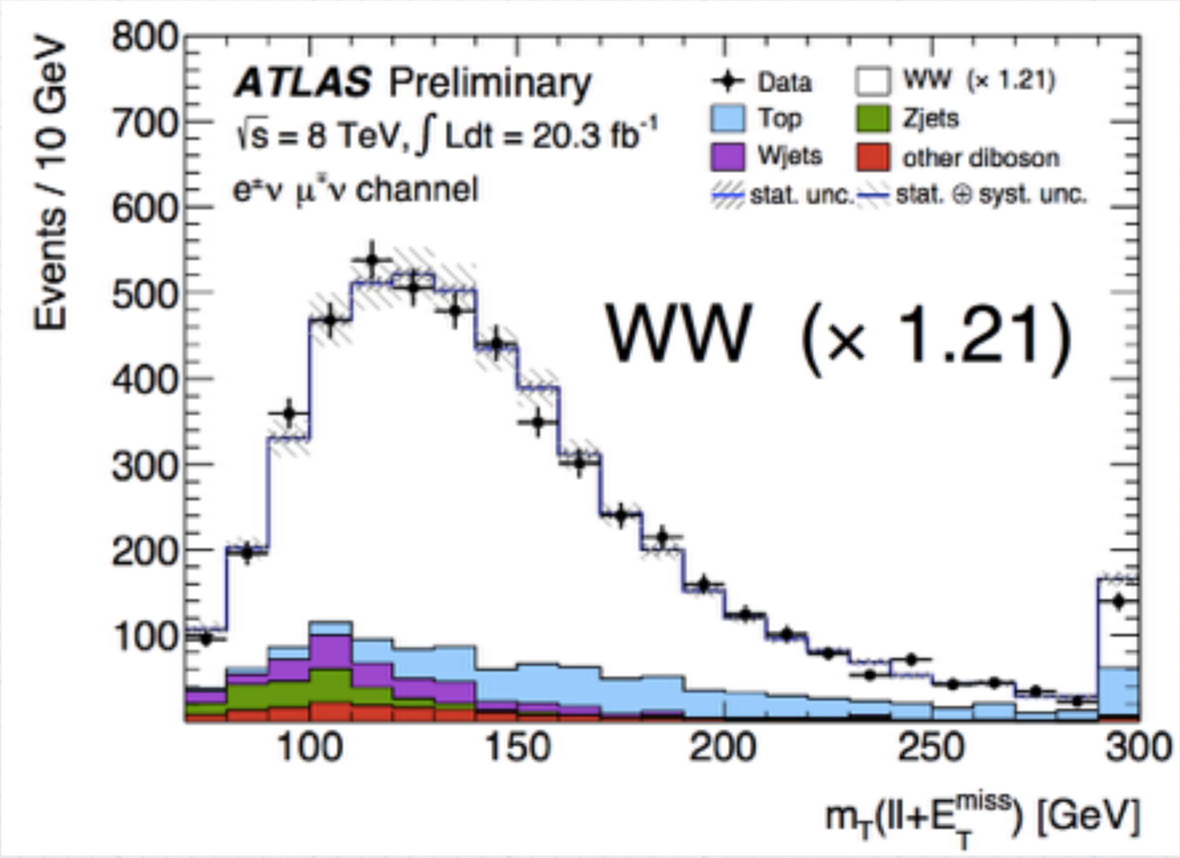
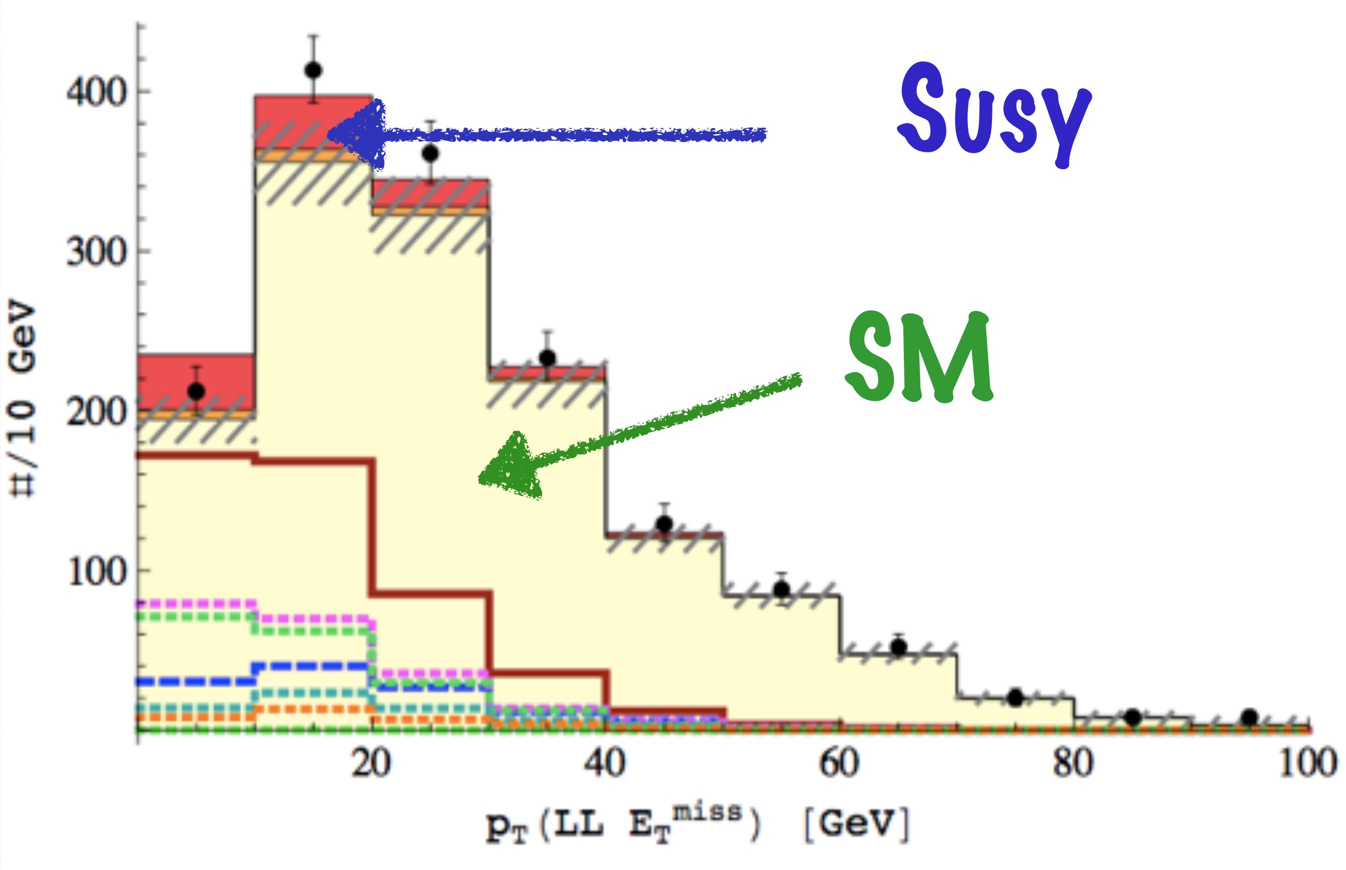


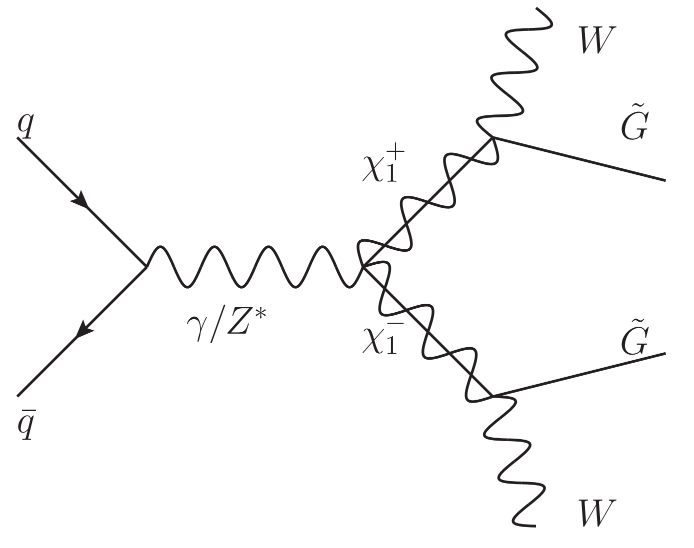


New Physics Hiding in Plain Sight?

- B. Feigl, H. Rzehak, and D. Zeppenfeld, **New physics backgrounds to the H → W W search at the LHC?**,[arXiv:1205.3468].
- D. Curtin, P. Jaiswal, and P. Meade, **Charginos hiding in plain sight**, [arXiv:1206.6888].
- P. Jaiswal, K. Kopp, and T. Okui, **Higgs 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. 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. Tattersall, **Stop that ambulance! New physics at the LHC?**, [arXiv:1406.0858] .

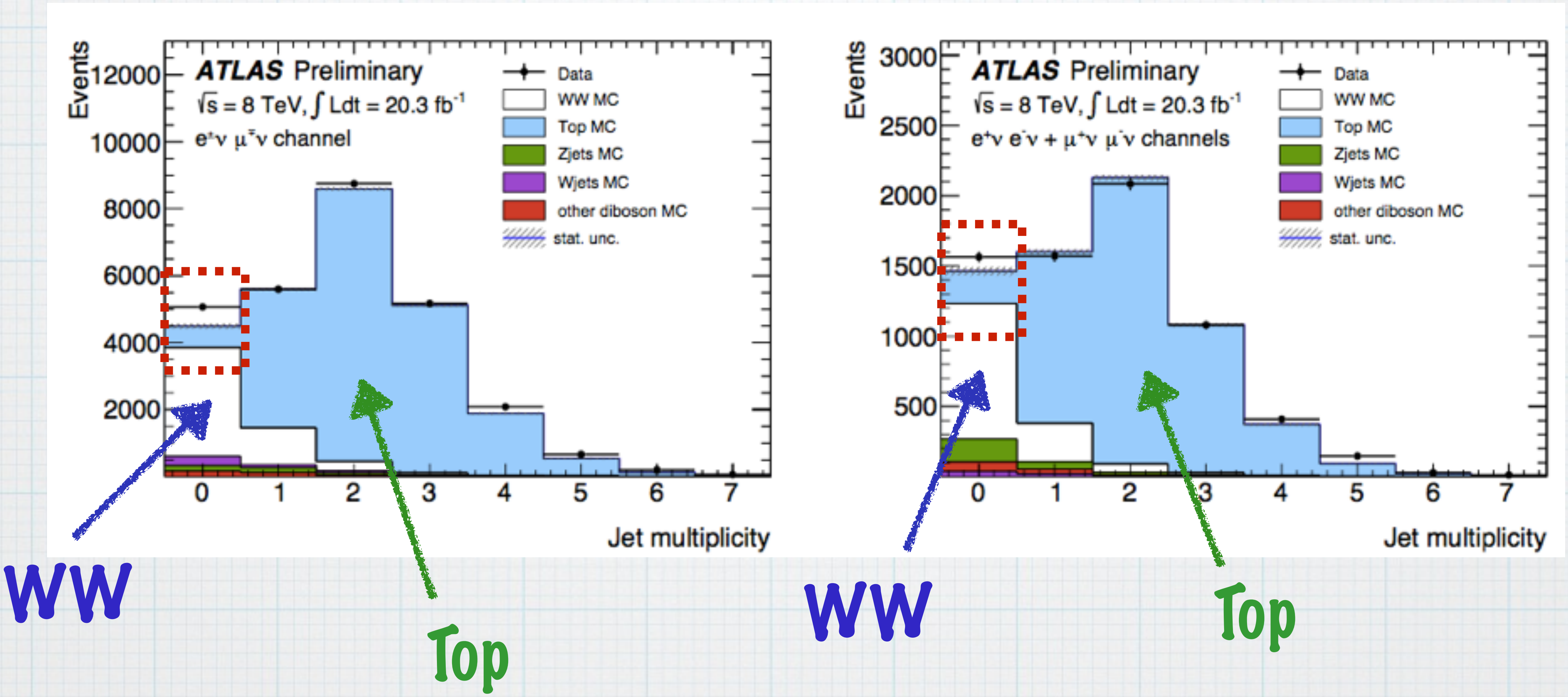


An explanation of the WW excess with 110 GeV charginos



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 : Origin of Large Logs

- Jet-veto example : no `jets' with $p_T > 25$ GeV allowed
- Jet-veto $\Longrightarrow$ Many scales $\Longrightarrow$ Large Logs
  - Inclusive WW measurement :
    Only one scale appears : M_{WW}
    ☛ Obvious scale choice : $\mu \approx M_{WW}$. [$\mu = \mu_f = \mu_r$]
  - WW + 0 jet measurement :
    Two scales appear : M_{WW} and p_T^{veto}
    ☛ 2 possible choices : $\mu \approx M_{WW}$ or $\mu \approx p_T^{veto}$??

Minimize logs from virtual diagrams.

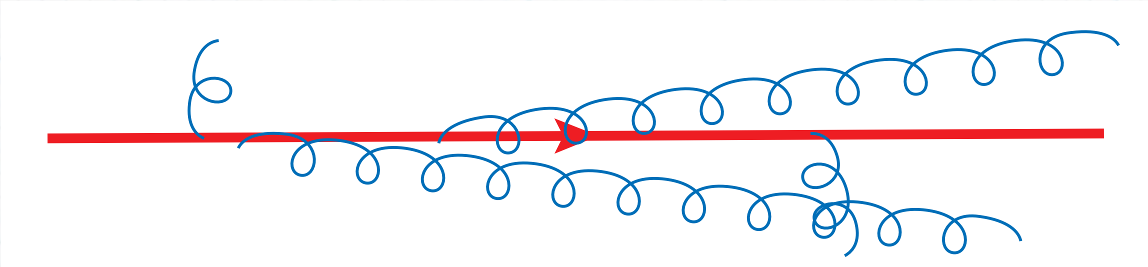
Minimize logs from real diagrams.

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:
  - Collinear Modes : $(p_+, p_-, p_\perp) \sim (1, \lambda^2, \lambda)M$
  - Anti-collinear Modes : $(p_+, p_-, p_\perp) \sim (\lambda^2, 1, \lambda)M$
  - Soft Modes : $(p_+, p_-, p_\perp) \sim (\lambda, \lambda, \lambda)M$



$$\lambda \equiv p_{\mathrm{T}}^{\mathrm{veto}}/M$$

- Regulators :
  - Separation of off-shell and on-shell modes : DR
    At cut-off scale Λ, integrate out modes with off-shellness greater than Λ.
  - Separation of collinear/anti-collinear modes :
    DR not sufficient.

SCET

- Separation of collinear/anti-collinear modes :
  - Analytic / Rapidity Regulators

$$\int \frac{\mathrm{d}p_+}{p_+} \quad \Longrightarrow \quad \int \frac{\mathrm{d}p_+}{p_+}\left(\frac{\nu}{p_+}\right)^{\alpha} \qquad\qquad \int \frac{\mathrm{d}p_-}{p_-} \quad \Longrightarrow \quad \int \frac{\mathrm{d}p_-}{p_-}\left(\frac{\nu}{p_+}\right)^{\alpha}$$

Analogous to DR : take α→0 limit in the end.

- Collinear Anomaly :
  - Dependence of amplitudes on ν.
  - Physical observables do not depend on regulator
    ⇒ RGE in ν
  - Analogous to μ dependence in DR

SCET : Calculations

- **SCET Lagrangian :** $\mathrm{p}(P_1) + \mathrm{p}(P_2) \to W^+(p_3, s_3) + W^-(p_4, s_4) + X$

$$\mathcal{L}_{\text{hard}} = \frac{1}{M}\, \epsilon^*_\mu(p_3, s_3)\, \epsilon^*_\nu(p_4, s_4)\, \mathrm{e}^{\mathrm{i}(p_3+p_4)\cdot x}\, \mathcal{J}^{\mu\nu}(x)$$

$(p_3 + p_4) \approx (1, 1, \lambda) \quad \Rightarrow \quad x \approx (1, 1, 1/\lambda)$

- **SCET Current**

$$J^{\mu\nu}_X(x, P_1, P_2, p_3, p_4) \equiv \langle X | \mathcal{J}^{\mu\nu}(x) | \mathrm{p}(P_1)\, \mathrm{p}(P_2) \rangle$$

$$J^{\mu\nu}_X(x, P_1, P_2, p_3, p_4)$$
$$= \int \mathrm{d}t_1\, \mathrm{d}t_2\, C^{\mu\nu}(t_1, t_2, p_{3+4\|}, p_{3-4}, \mu_{\mathrm{f}})\, \langle X | \chi^{i\alpha}_{\bar{\mathrm{c}}}(x^- + t_2, \vec{x}_\perp)\, \Gamma_\alpha^{\ \beta}\, \chi_{\mathrm{c}i\beta}(x^+ + t_1, \vec{x}_\perp) | \mathrm{p}(P_1)\, \mathrm{p}(P_2) \rangle$$

Consistent power counting ⇒ Multipole expansion

$(\partial_+, \partial_-, \partial_\perp) \approx (1, \lambda^2, \lambda)$

- **Cross-section** $\sigma \propto J(x)\, J(0)\, e^{i(p_3+p_4).x}$ factorizes

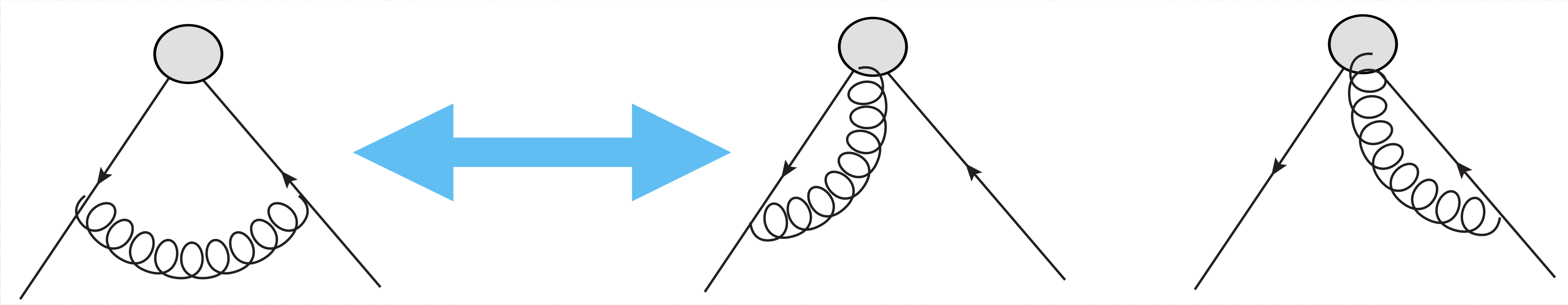
$$\sigma = \underbrace{\left|\hat{C}(\mu_h, \mu)\right|^2}_{\text{Wilson Coefficients}} \otimes \underbrace{B_1(\mu_s, \mu) \otimes B_2(\mu_s, \mu)}_{\text{Beam functions}} \otimes \underbrace{A_c(p_T^{veto}, \mu)}_{\text{collinear anomaly}}$$

SCET : Calculations

Wilson Coefficients

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

$$\chi^{i\alpha}_{\bar{c}}(x^- + t_2, \vec{x}_\perp)\,\Gamma_\alpha^{\ \beta}\,\chi_{ci\beta}(x^+ + t_1, \vec{x}_\perp)$$



QCD

No UV poles

IR poles : ε^{-2} , ε^{-1}

SCET

Scaleless integrals $\Rightarrow$ 0

UV poles = IR poles : ε^{-2} , ε^{-1}

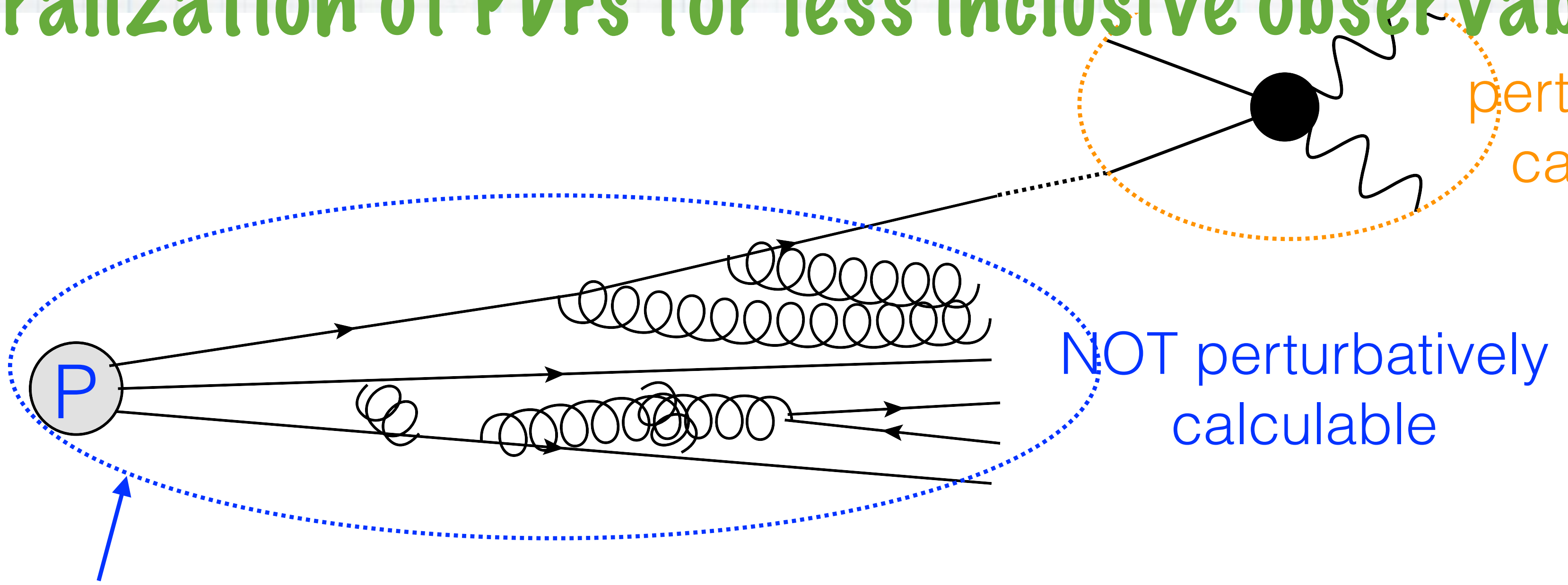
One loop Wilson coefficients $\Longrightarrow$ Full QCD diagrams with IR poles interpreted as UV poles

- Choose $\mu_h^2 \approx M^2$ to minimize $\log[M^2/\mu_h^2]$ at matching.
- Then use RGE to run to a low energy scale μ .

SCET : Calculations

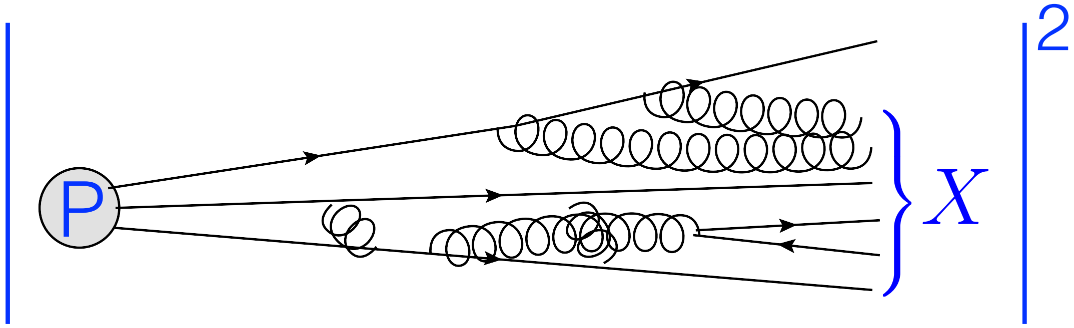
Beam Functions

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



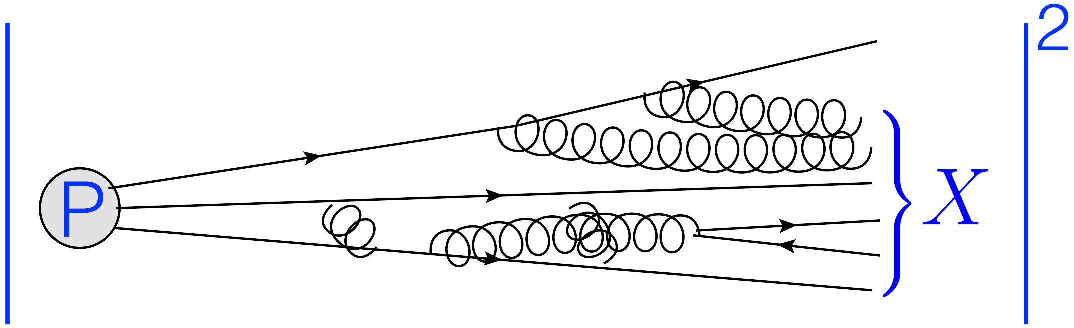
Isn't it just described by PDFs? No! Because

PDF = $\sum_X$



over all X

But we want $\sum_X$



= Beam function

over all X passing jet veto

SCET : Calculations

Beam Functions

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

$$\phi_n^{q/N}(\xi,\mu) = \frac{1}{2\pi}\int \mathrm{d}t\, e^{-i\xi t\bar{n}\cdot P} \sum_{X_n} \langle N(P)|\,\bar{\chi}^{(0)I}(t\bar{n})\,|X_n\rangle\, \frac{\bar{\not{n}}}{2}\, \langle X_n|\,\chi^{(0)I}(0)\,|N(P)\rangle$$

PDF : X_n is all collinear final states

Jet-veto beam functions : X_n is all collinear final states satisfying jet-veto condition

- Renormalization of PDFs :
  - Scaleless integrals in DR
    $\Rightarrow$ UV divergence = IR divergence (DGLAP=splitting functions)
- Renormalization of Beam functions :
  - OPE on to PDFs
  - DR not sufficient : need rapidity regulators
  - Dependence on $\nu \Rightarrow$ 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, [arXiv:1407.4537].

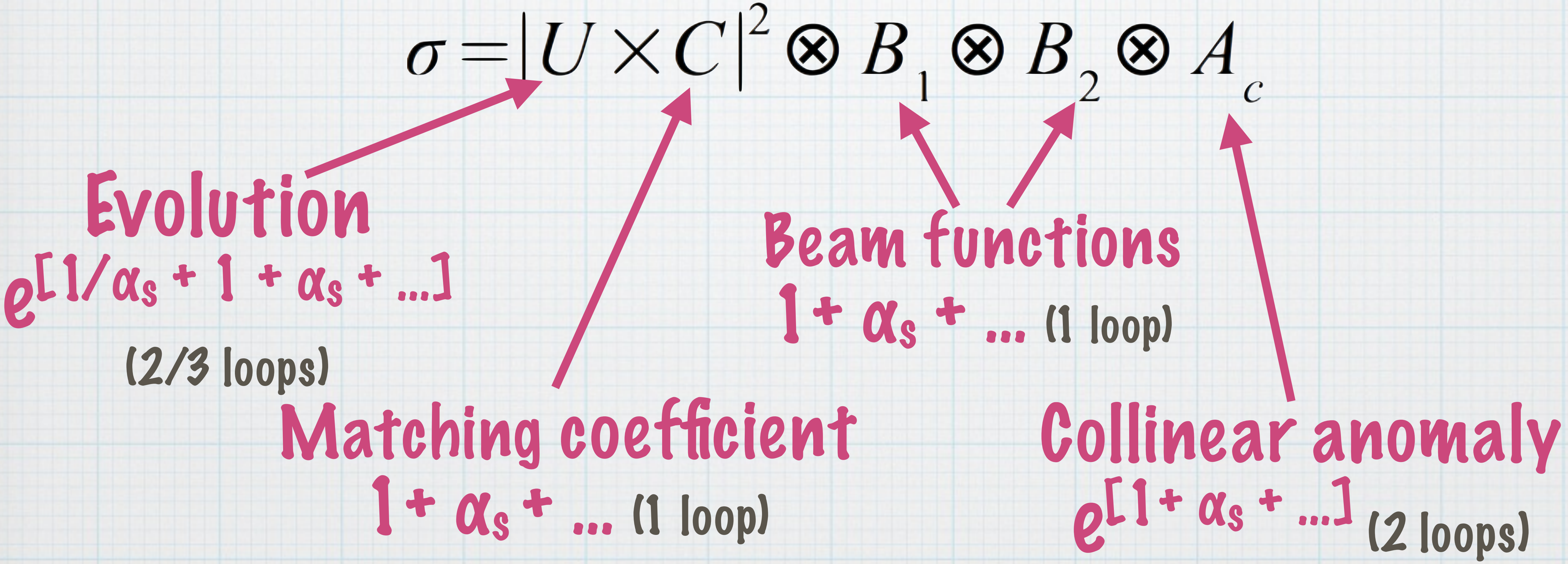
How to count

- Power Counting parameter in SCET : $\lambda = p_T^{veto}/M$
  - All calculations at LO in SCET power counting.
  - SCET resums pieces singular in the $\lambda \rightarrow 0$ limit (i.e. $\log^n \lambda$)
  - 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)

$$\sigma_{tot} = \sigma_{resum} + \underbrace{\left(\sigma_{N^n LO} - \sigma_{resum}^{[N^n LO\, expansion]}\right)}_{\text{Power Corrections}}$$

How to count

- α_s Counting in Resummed Perturbation Theory
  - Count log[$(p_T^{veto})^2/M^2$] as $1/\alpha_s$
  - NLL : Keep terms up to $\mathcal{O}(1)$
    NNLL : Keep terms up to $\mathcal{O}(\alpha_s)$



$$\sigma = |U \times C|^2 \otimes B_1 \otimes B_2 \otimes A_c$$

Evolution

$e^{[1/\alpha_s + 1 + \alpha_s + \dots]}$

(2/3 loops)

Beam functions

$1 + \alpha_s + \dots$ (1 loop)

Matching coefficient

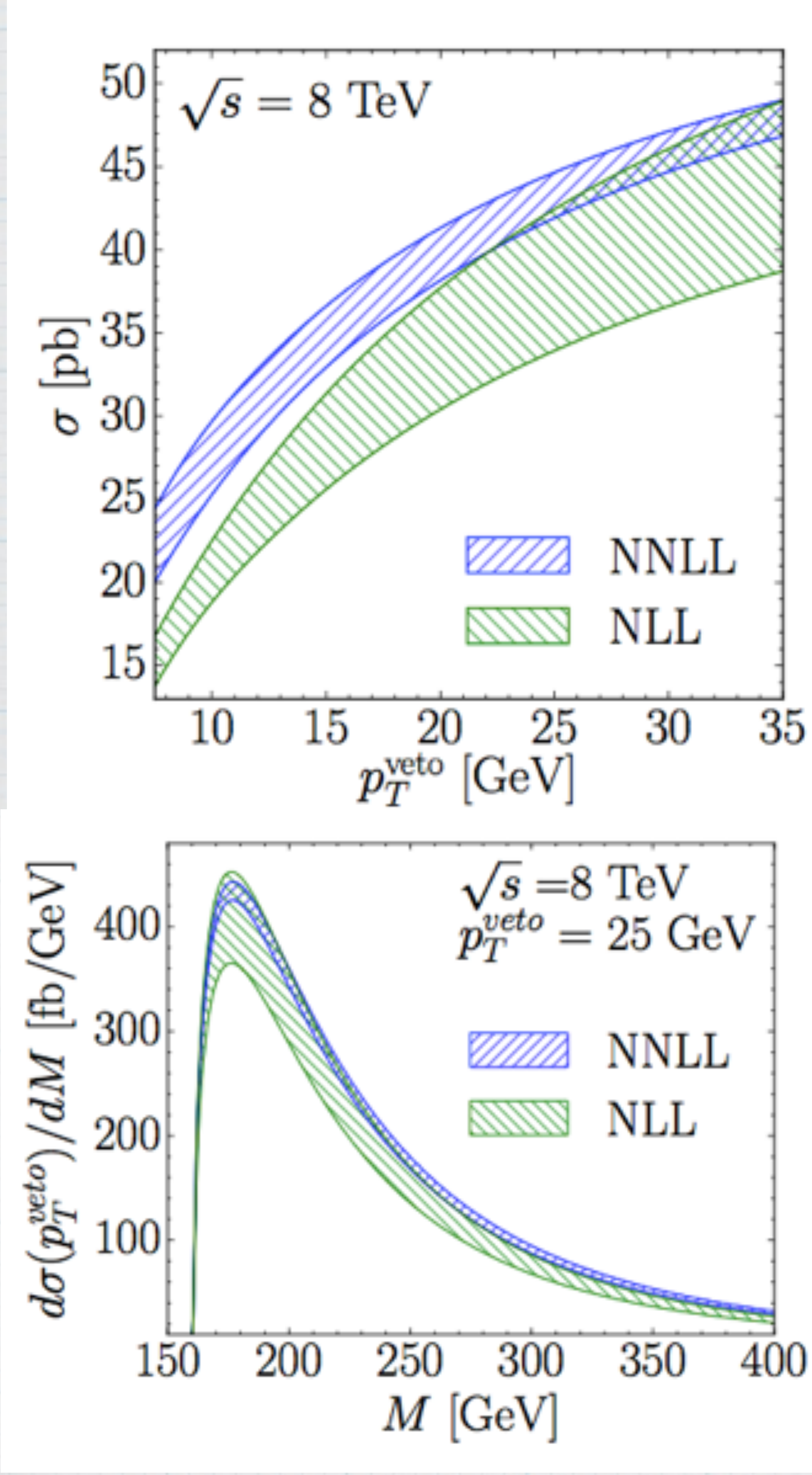
$1 + \alpha_s + \dots$ (1 loop)

Collinear anomaly

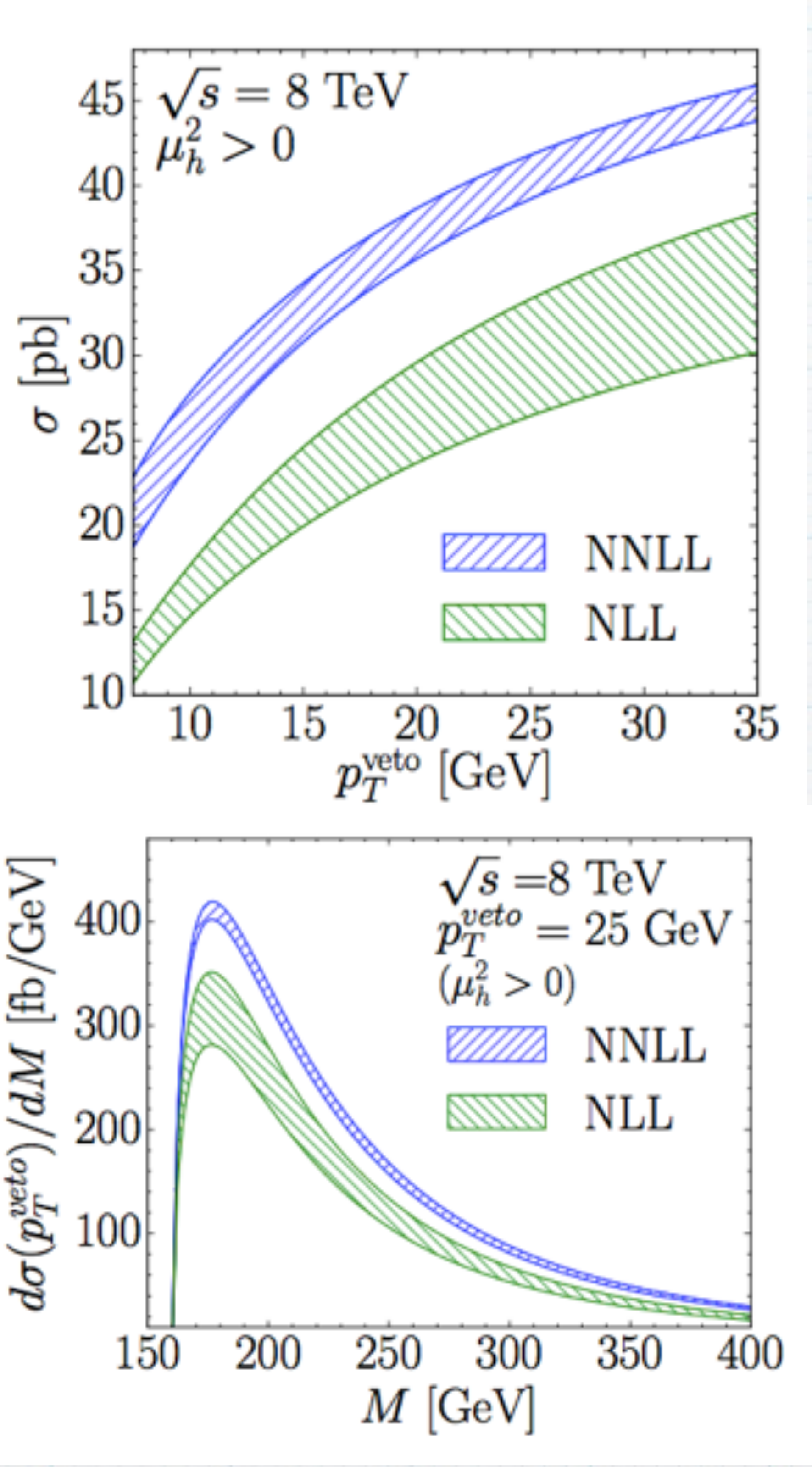
$e^{[1 + \alpha_s + \dots]}$ (2 loops)

All ingredients already known in the literature.

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



$\mu_h^2 \approx -M^2$



$\mu_h^2 \approx M^2$

- $\mu_f \approx p_T^{\text{veto}}$
- Scale uncertainty : Vary μ_f and μ_h by factors of 1/2 and 2.
- anti-k_T jets (R=0.4)

π^2 Resummation :

$\log[-M^2/\mu_h^2]$ give factors of π^2 when squared if $\mu_h^2 > 0$.

Better choice : $\mu_h^2 \approx -M^2$

Consistency Checks and Power Corrections

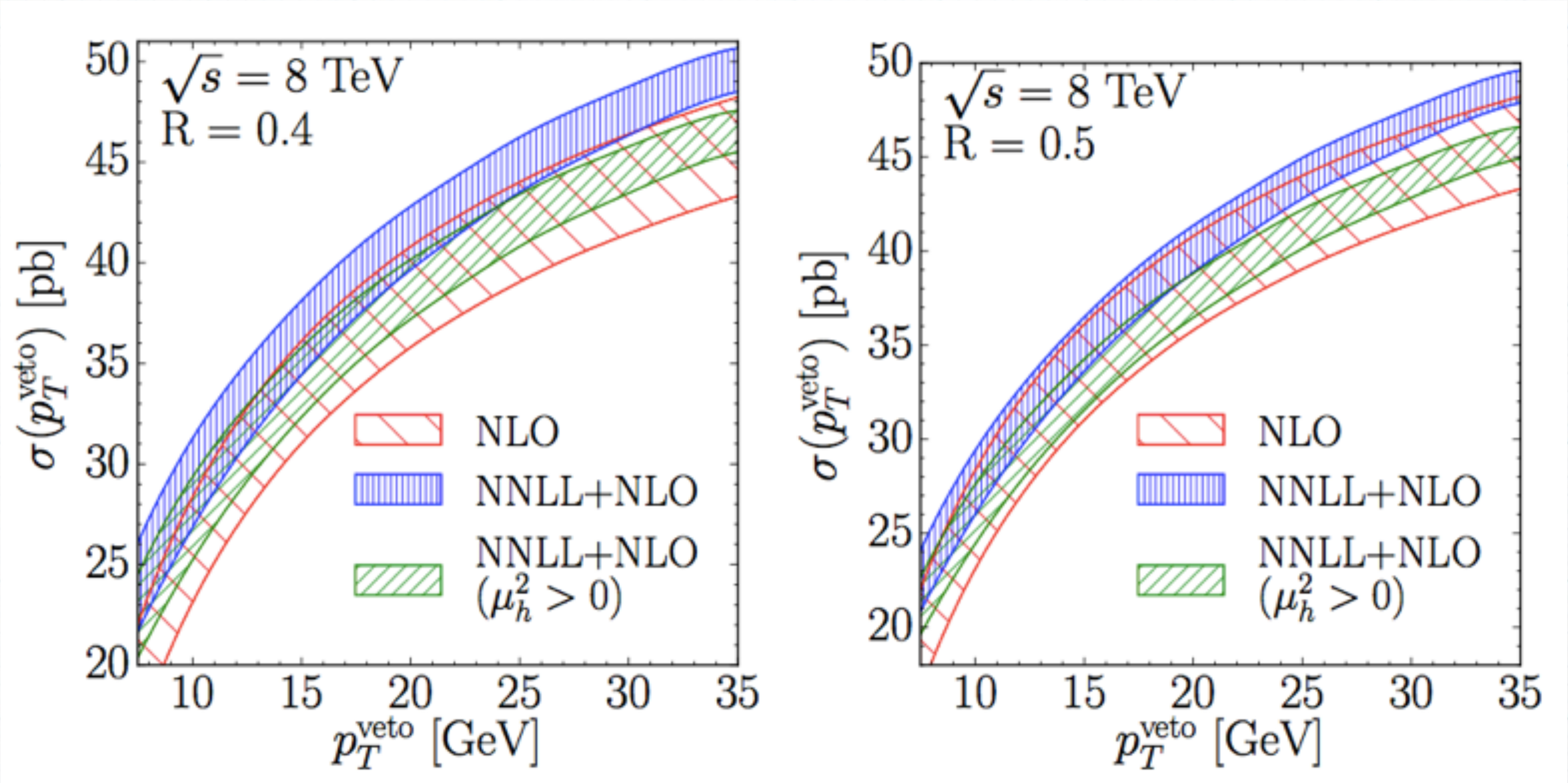
- Recall : SCET resums terms singular in $p_T^{veto}/M \rightarrow 0$

- Power corrections suppressed by powers of p_T^{veto}/M. Found to be less than 1%.

- Consistency Check : For small p_T^{veto}, NNLL cross-section expanded to $\mathcal{O}(\alpha_s)$ should match fixed-order NLO calculations.

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

NNLL+NLO Results

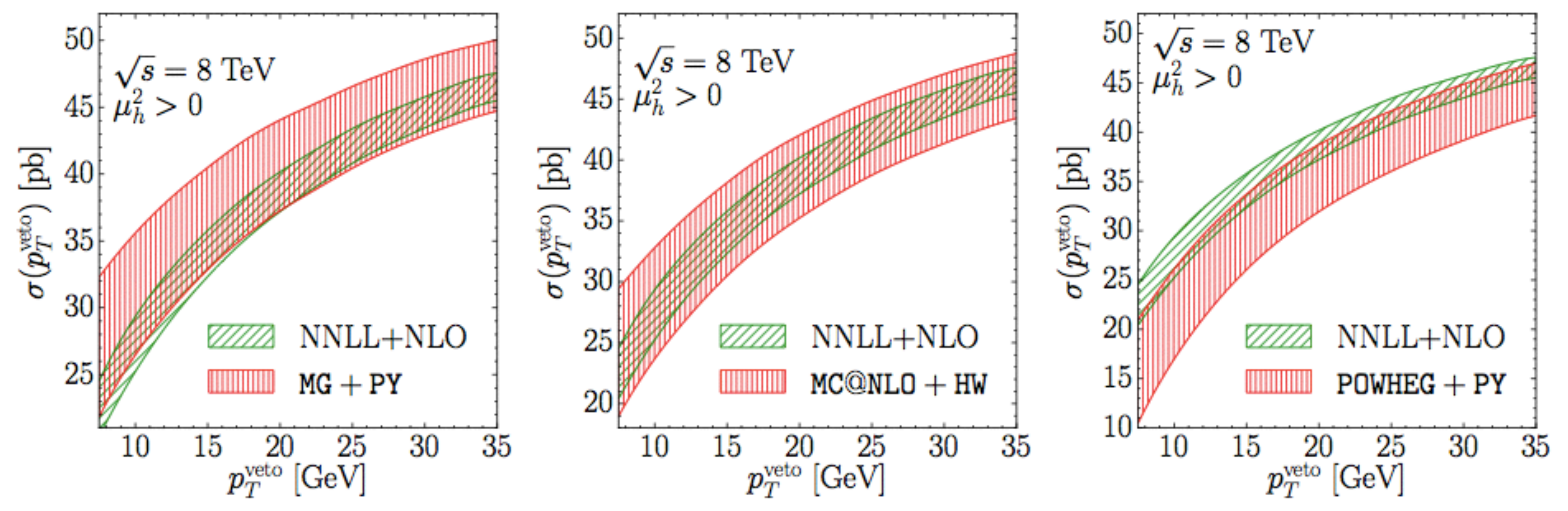


- Beyond NLO : Besides logarithm terms e.g. $\alpha_s^2 L^4$, jet-clustering dependence :

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

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

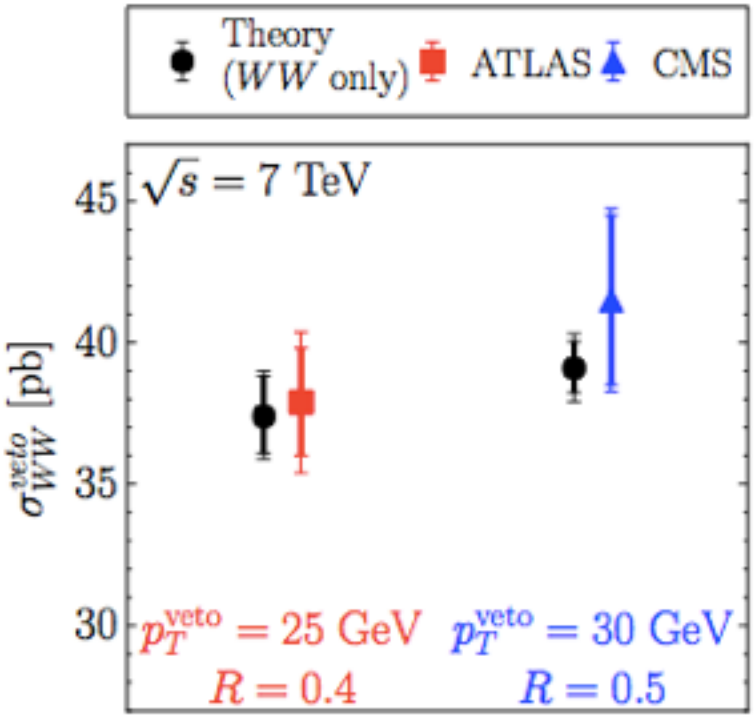
MC@NLO +
Herwig6

Powheg v1 +
Pythia6

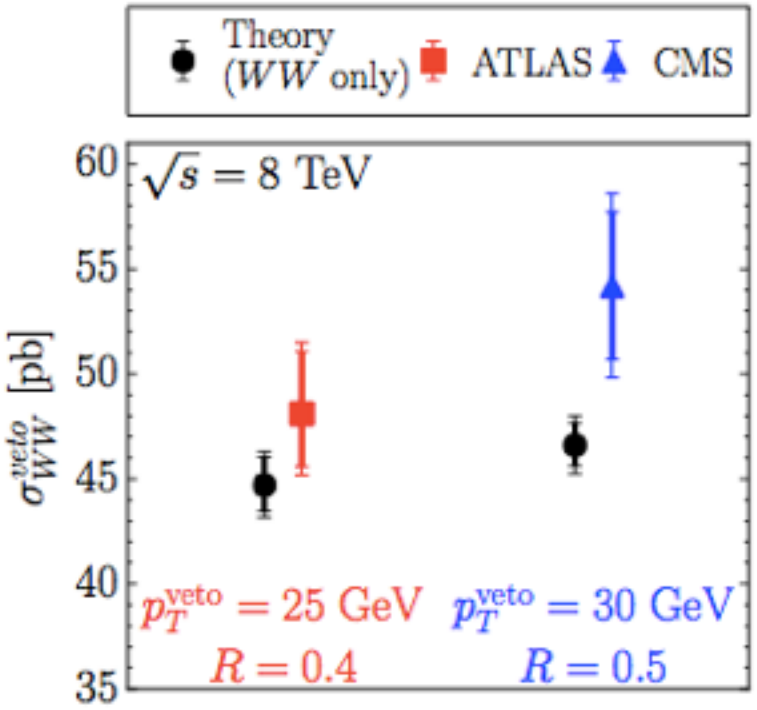
Jet algorithm : anti-k_T, R=0.4
CTEQ6L for LO MC, CT10nlo for NLO MC,
MSTW08nnlo for NNLL+NLO

Comparison with LHC data

	$\sqrt{s} = 7$ TeV	
	$R = 0.4$ $p_{\mathrm{T}}^{\text{veto}} = 25$ GeV	$R = 0.5$ $p_{\mathrm{T}}^{\text{veto}} = 30$ GeV
ATLAS $\sigma_{WW}^{\text{veto}}$ [pb]	$37.9^{+3.8\%+5.0\%+3.8\%}_{-3.8\%-5.0\%-3.8\%}$	–
CMS $\sigma_{WW}^{\text{veto}}$ [pb]	–	$41.5^{+3.8\%+7.2\%+2.3\%}_{-3.8\%-7.2\%-2.3\%}$
Theory $\sigma_{WW}^{\text{veto}}$ [pb]	$37.4^{+3.8\%}_{-3.0\%}$	$39.0^{+2.4\%}_{-2.3\%}$
Theory $\sigma_{h\to WW}^{\text{veto}}$ [pb]	$2.1^{+13.5\%}_{-11.4\%}$	$2.3^{+11.5\%}_{-10.6\%}$



	$\sqrt{s} = 8$ TeV	
	$R = 0.4$ $p_{\mathrm{T}}^{\text{veto}} = 25$ GeV	$R = 0.5$ $p_{\mathrm{T}}^{\text{veto}} = 30$ GeV
ATLAS $\sigma_{WW}^{\text{veto}}$ [pb]	$48.1^{+1.7\%+6.2\%+3.1\%}_{-1.7\%-5.2\%-2.9\%}$	–
CMS $\sigma_{WW}^{\text{veto}}$ [pb]	–	$54.2^{+4.0\%+6.5\%+4.4\%}_{-4.0\%-6.5\%-4.4\%}$
Theory $\sigma_{WW}^{\text{veto}}$ [pb]	$44.7^{+3.5\%}_{-2.8\%}$	$46.6^{+2.2\%}_{-2.1\%}$
Theory $\sigma_{h\to WW}^{\text{veto}}$ [pb]	$2.6^{+13.3\%}_{-11.7\%}$	$2.9^{+11.5\%}_{-11.5\%}$



Similar Calculations

- [arXiv:1407.4481] **Transverse momentum resummation for WW** : Patrick Meade, Harikrishnan Ramani, Mao Zeng
  - 3-7% reduction in discrepancy. (similar to our results without π^2 resummation)
- [arXiv:1410.4745] **NNLL+NNLO extrapolation from Drell-Yan** Pier Francesco Monni, Giulia Zanderighi
- [arXiv:1412.8408] **Automated NNLL+NLO** : T. Becher, R. Frederix, M. Neubert and L. Rothenier
  - Consistent with our result (without π^2 resummation)
- [arXiv:1408.5243] **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

- Reweighted MC using the `correct' pT distribution of the W-pair. [following procedure outlined in arXiv:1407.4481]
- Theory NNLO prediction : $59.8^{+1.3}_{-1.1}\,\mathrm{pb}$
- Observed :

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

Complex scales
and
scale uncertainties

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

Origin of Complex Scales

$p\,p \to V\,V'$, where $V \in \{W, Z\}$

Factorized cross sections :

$$\sigma = \underbrace{C(\mu)}_{\text{Wilson Coefficient}} \otimes \underbrace{f_1(\mu) \otimes f_2(\mu)}_{\text{PDFs}} \otimes \underbrace{S(\mu)}_{\text{Soft Function}}$$

Logarithms in Wilson coefficient, $C(\mu)$:

$$\log\left[(-M^2 - i0^+)/\mu^2\right]$$

- Matching of SCET to QCD at $\mu = \mu_h$
- Choice of μ_h? $\mu_h = M$ minimizes logs....
- ....except that branch cut ⇒ $- i\pi$ factors so that double logs produce π^2 factors.
- Motivates choice of μ_h in the complex μ^2-plane, e.g. $\mu_h^2 \approx -M^2$

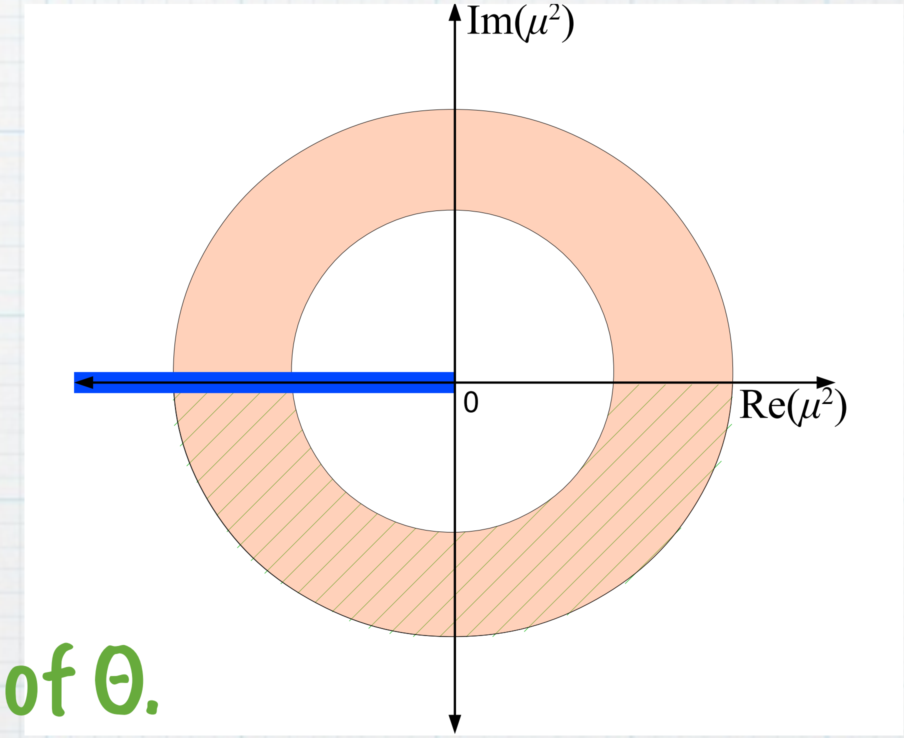
Large logs from Complex Scales

Logarithms in Wilson coefficient, C(μ) :

$$\log\left[(-M^2 - i0^+)/\mu^2\right]$$

- Matching scale μ_h^2 complex-valued.
- But PDFs evaluated at factorization scales which are real : $\mu_f^2 \approx M^2$
- Hierarchy of scales in the complex μ^2-plane

⇒ Large Logs $\log(\mu_h^2/\mu_f^2)$



- Phase of μ_h^2 : Θ

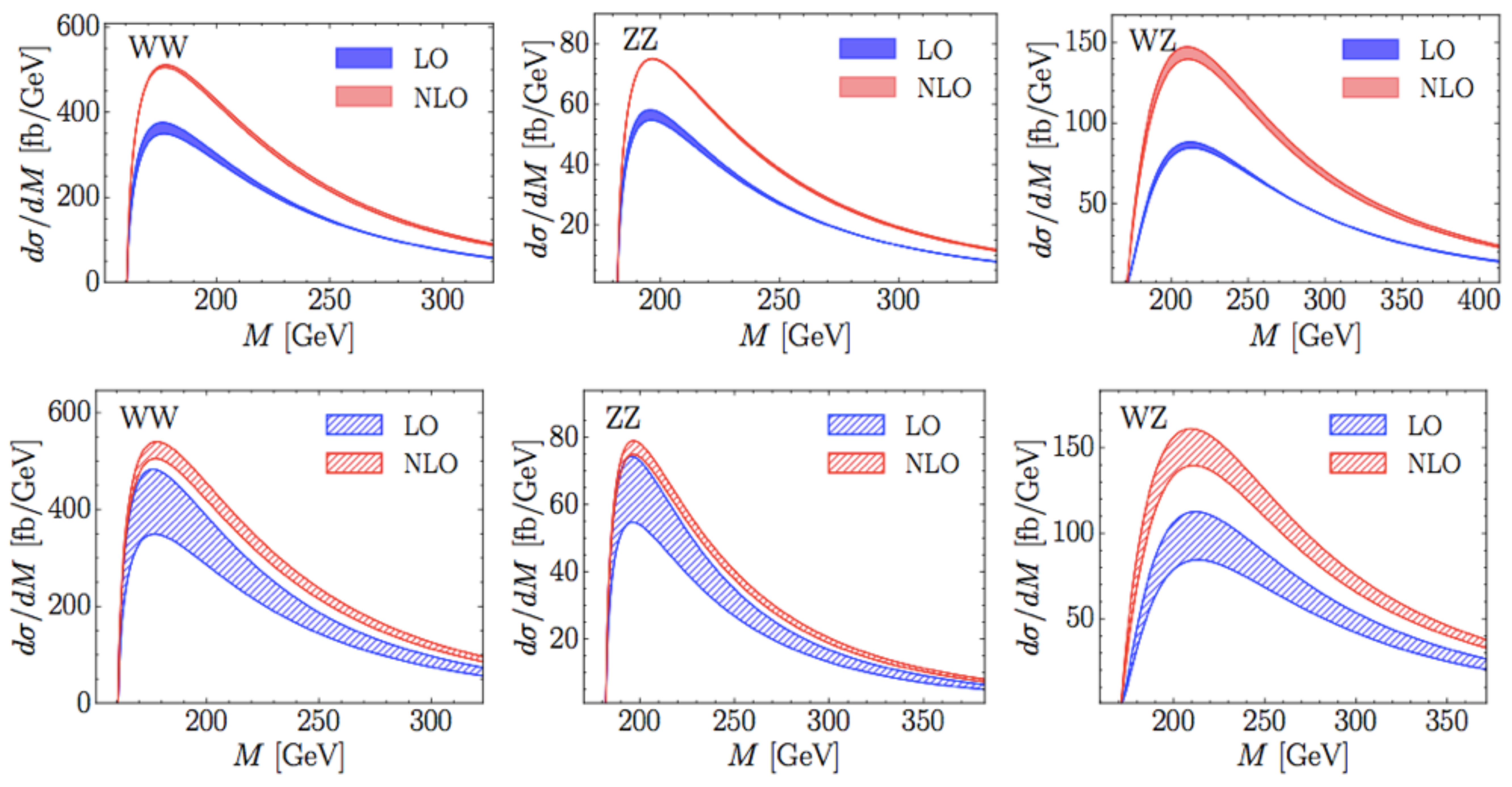
$\log(\mu_h^2/\mu_f^2) = i\,\Theta$

If Logs dominant : $\Theta = \pm\pi$

If non-Log terms dominant, no preferred value of Θ.

- RG equation for C(μ) known ⇒ Evolve from $\mu_h^2 \rightarrow \mu_f^2$ ⇒ Resum Θ terms.
- Vary : $-\pi < \Theta < \pi$ similar to $M/2 < |\mu_h| < 2M$

Scale Uncertainty



- 3-4 % increase in central value prediction w.r.t NLO (dynamic scale).
- Better estimate of scale uncertainty.

Work in progress

- pT resummation : allows to get distributions but misses jet-clustering dependence
- Jet-veto resummation : allows precise calculation of cross-section 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)