Jet-Veto Resummation

A case study for WW Production

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References :

arXiv:1407.4537 : PJ and Takemichi Okui

arXiv:1411.0677 : PJ

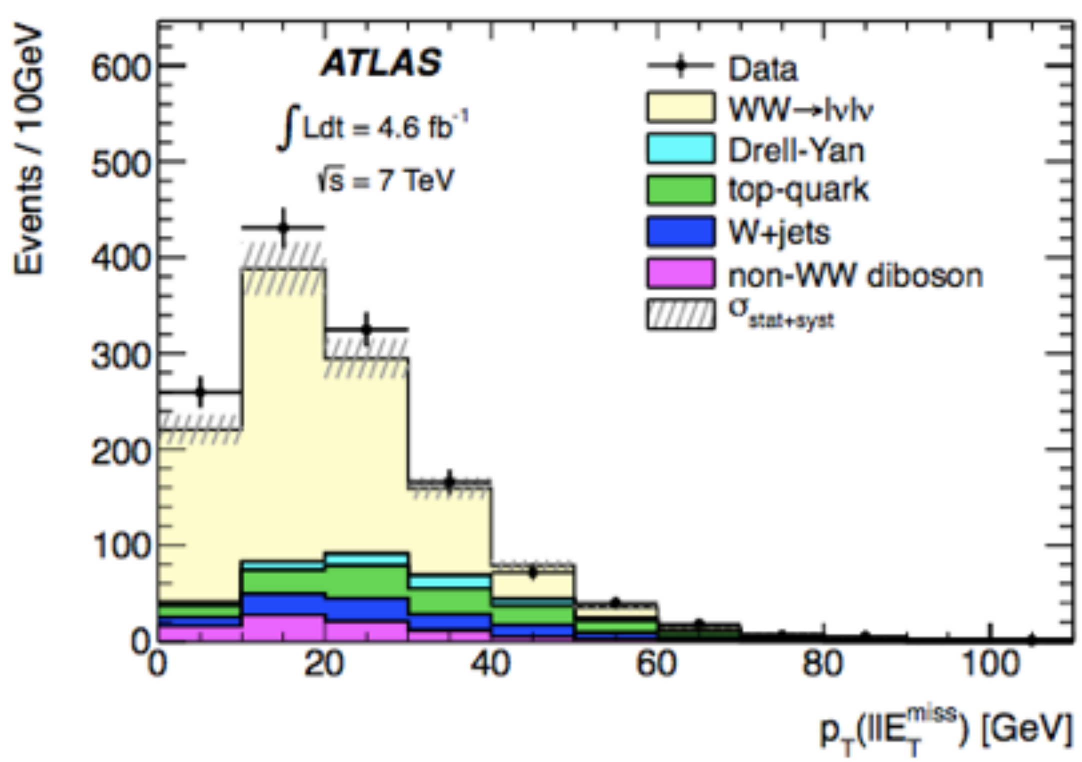
arXiv:1506.xxxx : PJ and Takemichi Okui

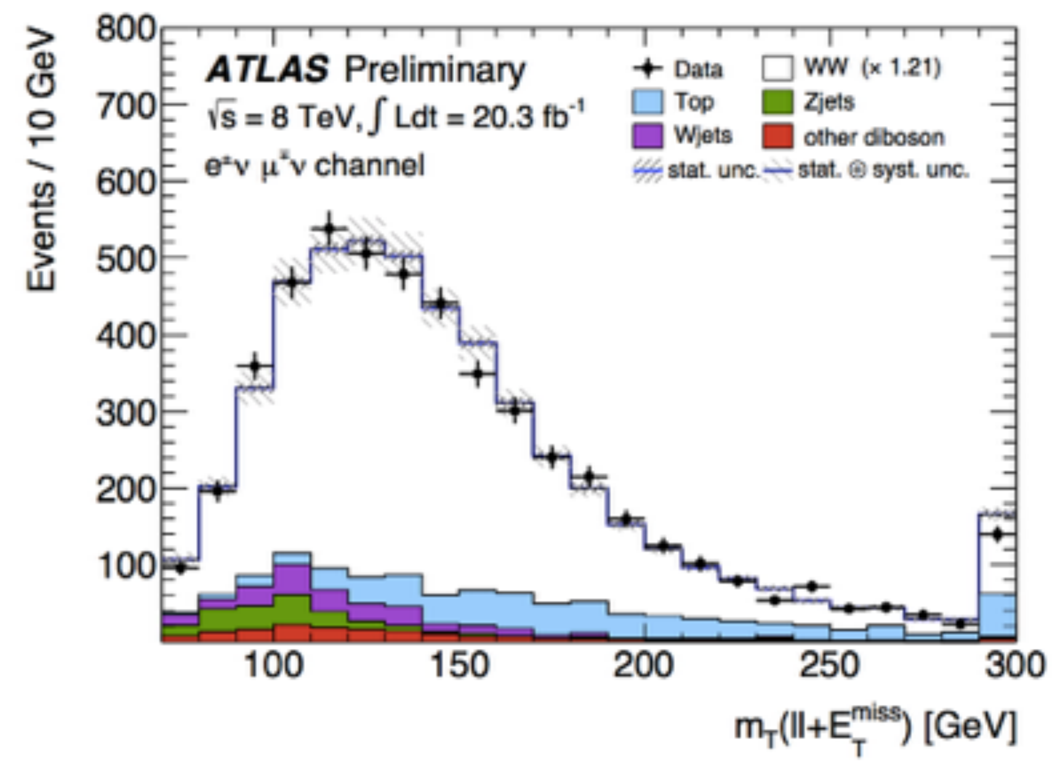
A tale of two Ws

- Process : p p → W W → ℓ ν ℓ ν
- Mild excesses reported by ATLAS <u>and</u> CMS at 7 <u>and</u> 8 TeV measurements. *[before 2014]*

$\sqrt{s}$	ATLAS σ [pb]	CMS σ [pb]	Theory (MCFM) σ [pb]
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]	$47.04^{+2.02+0.90}_{-1.51-0.66}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$ [16]	$57.25^{+2.35+1.09}_{-1.60-0.80}$

$\boxed{\text{NLO}}$





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NLO

NNLO : 1408.5243 Gehrmann et al.

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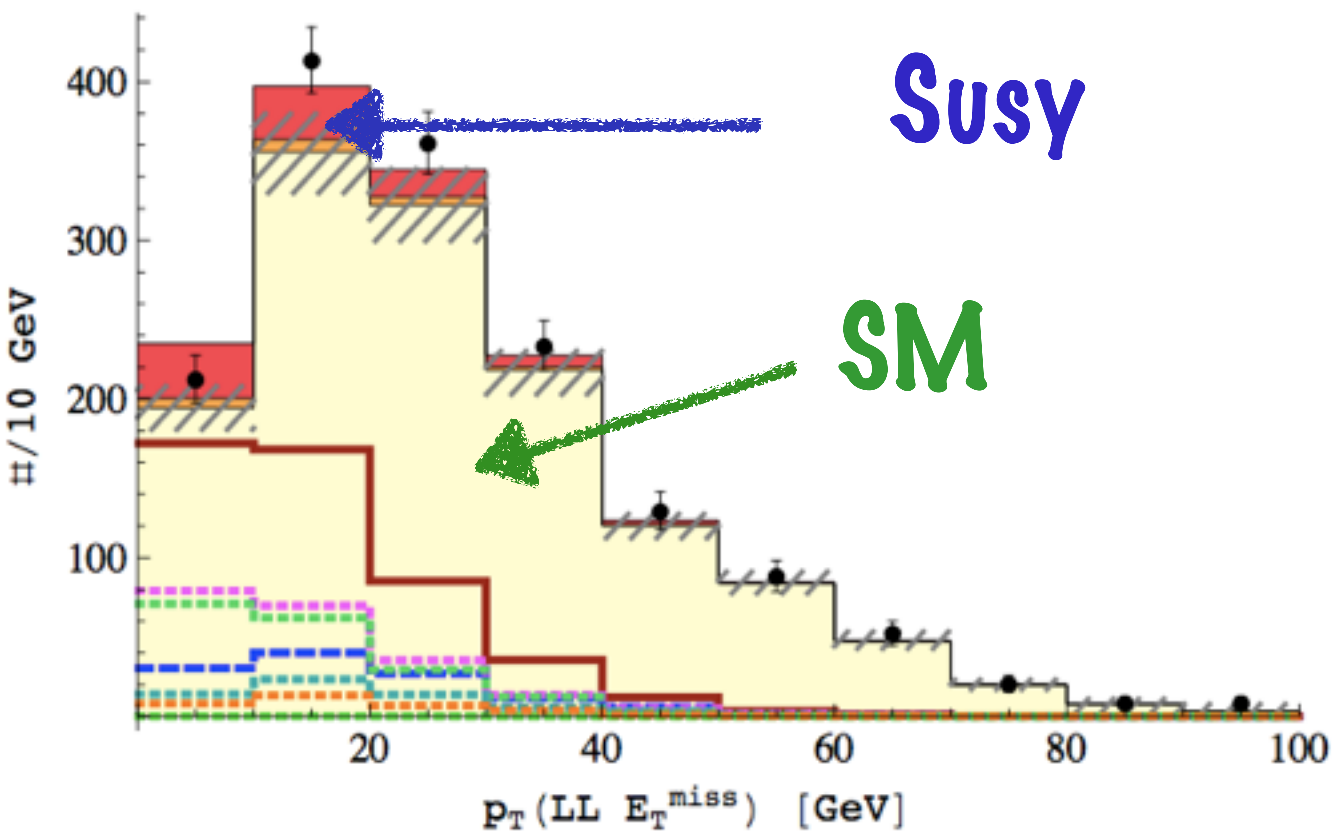
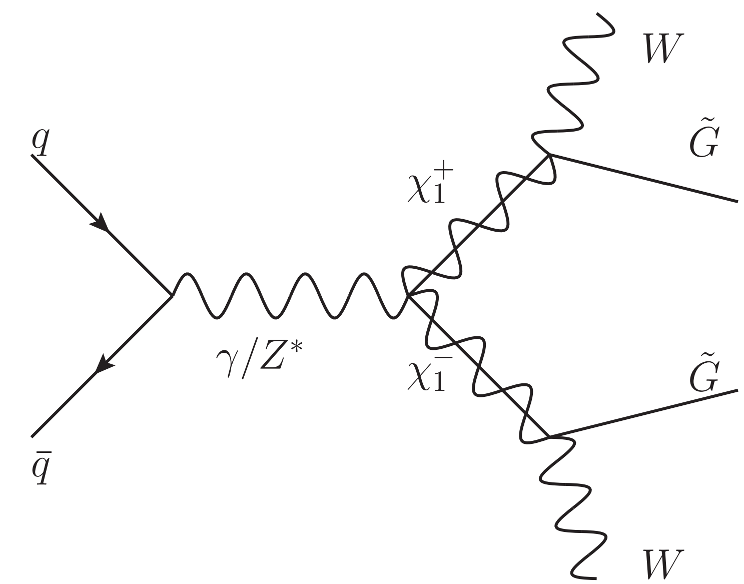
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]	$47.04^{+2.02+0.90}_{-1.51-0.66}$	$49.04^{+2.1\%}_{-1.8\%}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$ [16]	$57.25^{+2.35+1.09}_{-1.60-0.80}$	$59.84^{+2.2\%}_{-1.9\%}$

- Discrepancy reduces slightly at NNLO but does not go away.
- Perhaps not so surprising since MCFM includes gg → W W contribution (formally NNLO)

A tale of two Ws

- New physics hiding in plain sight? (ℓ ℓ + MET final state)
- *Could it be SUSY?*





110 GeV charginos
D. Curtin, PJ, and P. Meade,
Charginos hiding in plain sight
[arXiv:1206.6888]

- Any new physics charged under electroweak gauge group could possibly lead to such signatures. Other proposed explanations for the WW excess include sleptons and stops.

A tale of two Ws

- *Could the WW excess have a more subtle explanation?*
- Cross-section reported : p p → W W + X

  X are <u>all</u> hadronic final states i.e. inclusive measurement

- Actual measurement : p p → W W + X'

  X' are <u>some</u> hadronic final states that pass jet-veto condition.

Jet-veto : No <u>jets</u> in an event

ATLAS :
$p_T >$ 25 GeV
anti-k_T jets with R=0.4

CMS :
$p_T >$ 30 GeV
anti-kT jets with R=0.5

A tale of two Ws

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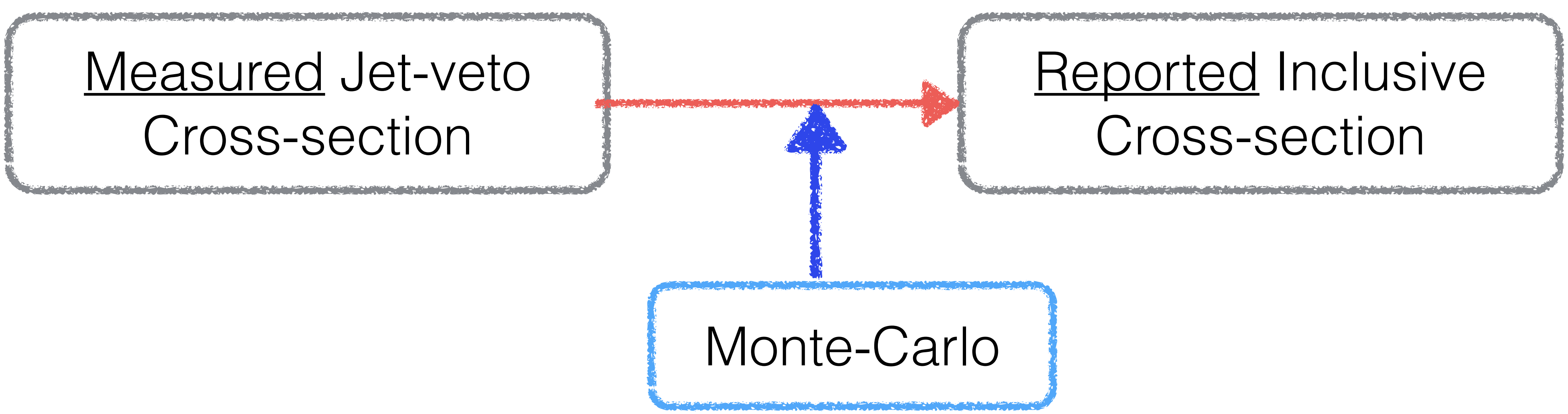
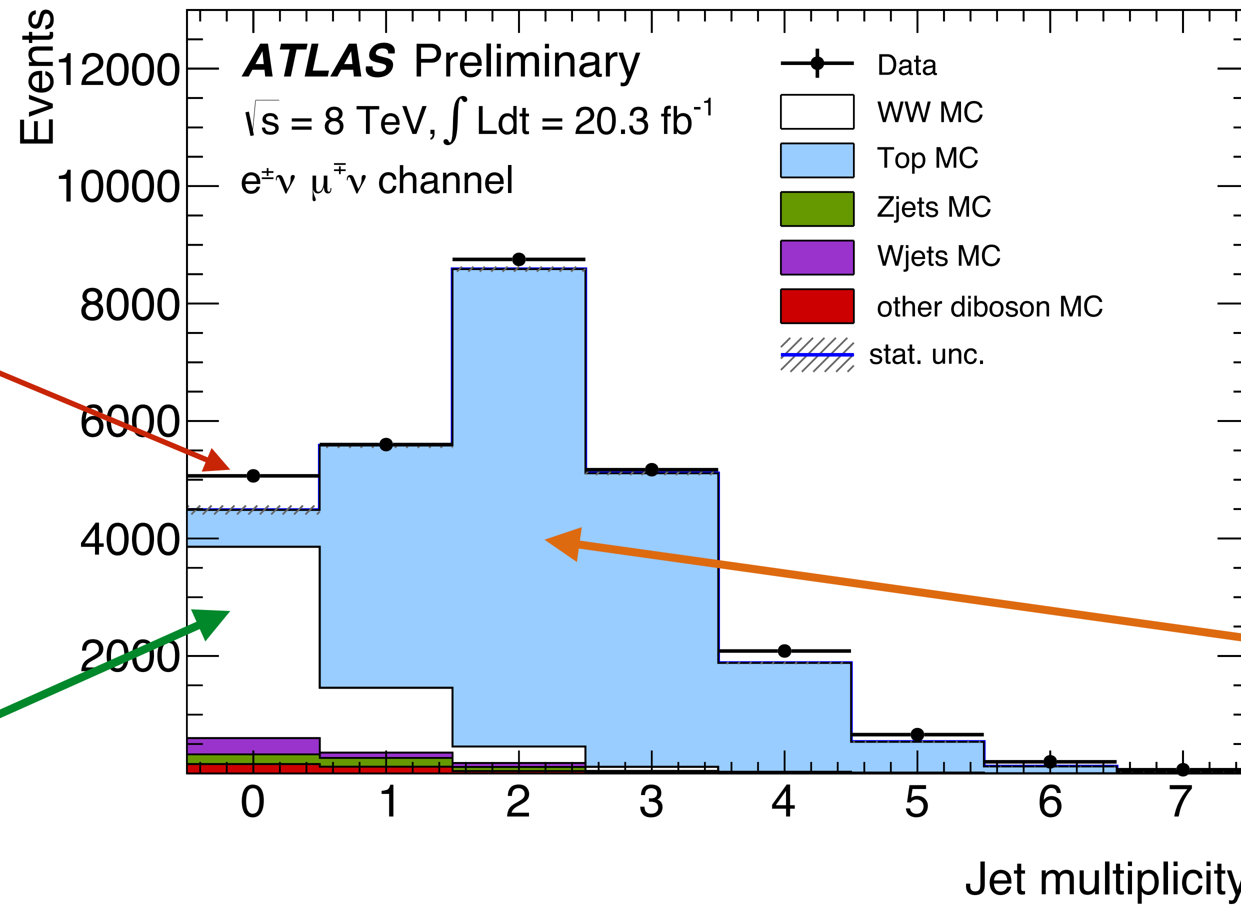


Do we have a good theoretical understanding of MC?

A tale of two Ws

Disagreement in the 0-jet bin



Top background

WW signal

<u>Measured</u> Jet-veto Cross-section

<u>Reported</u> Inclusive Cross-section

Monte-Carlo

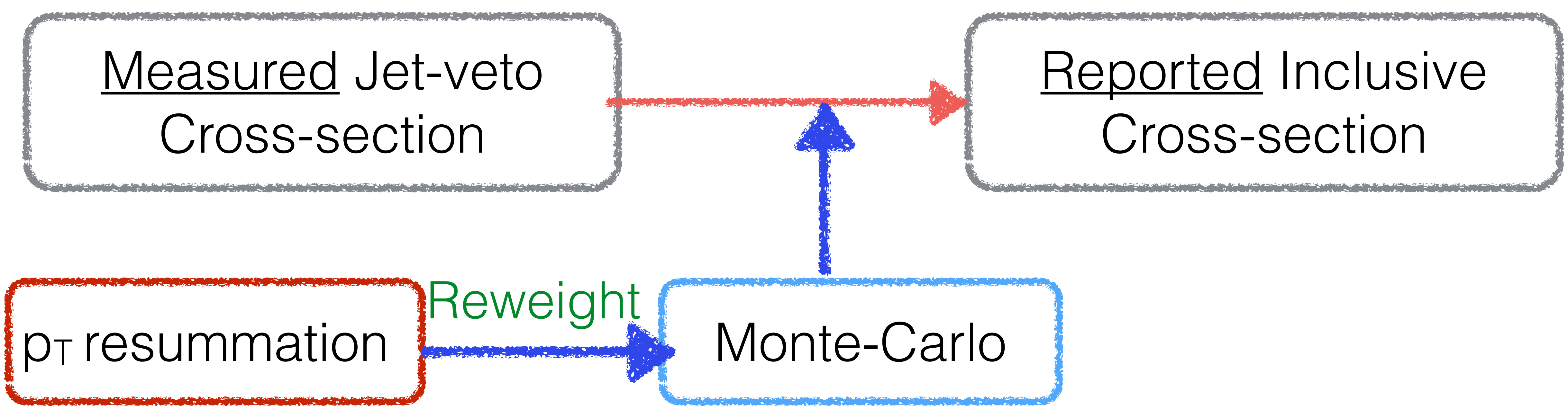
Do we have a good theoretical understanding of MC?

A tale of two Ws

- Discrepancy between p_T distribution shapes from NNLL resummation and MC *[arXiv:1407.4481, P. Meade et al.]*
- **New CMS 8 TeV analysis** *[CMS-PAS-SMP-14-016]* reweights MC to correct for the p_T distribution.

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

Theory : $59.8^{+1.3}_{-1.1}\,\text{pb}$



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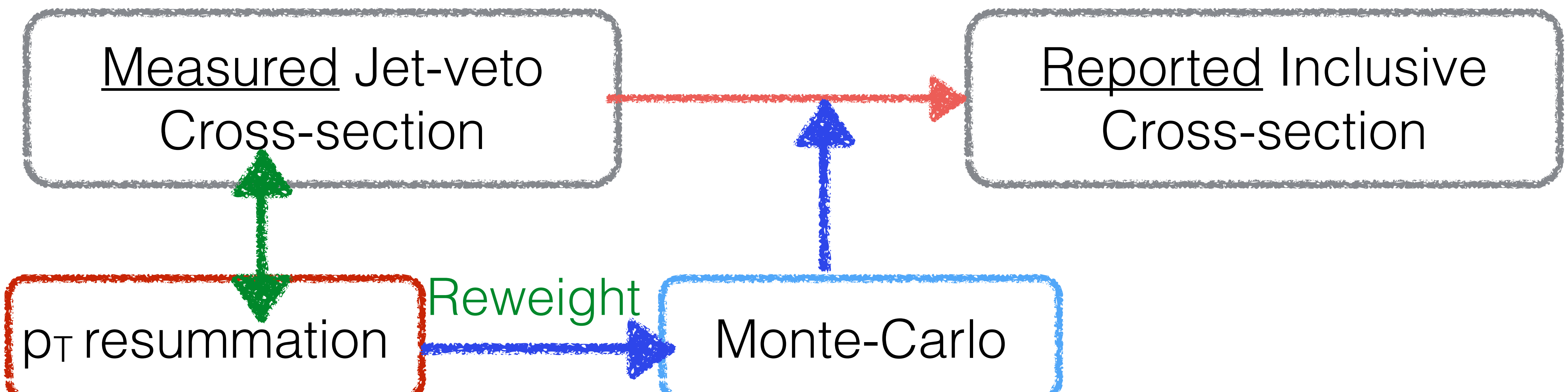
- Some correlations between jet-veto and pT of the WW system captured by p_T reweighting technique.



Do we have a good theoretical understanding of MC?

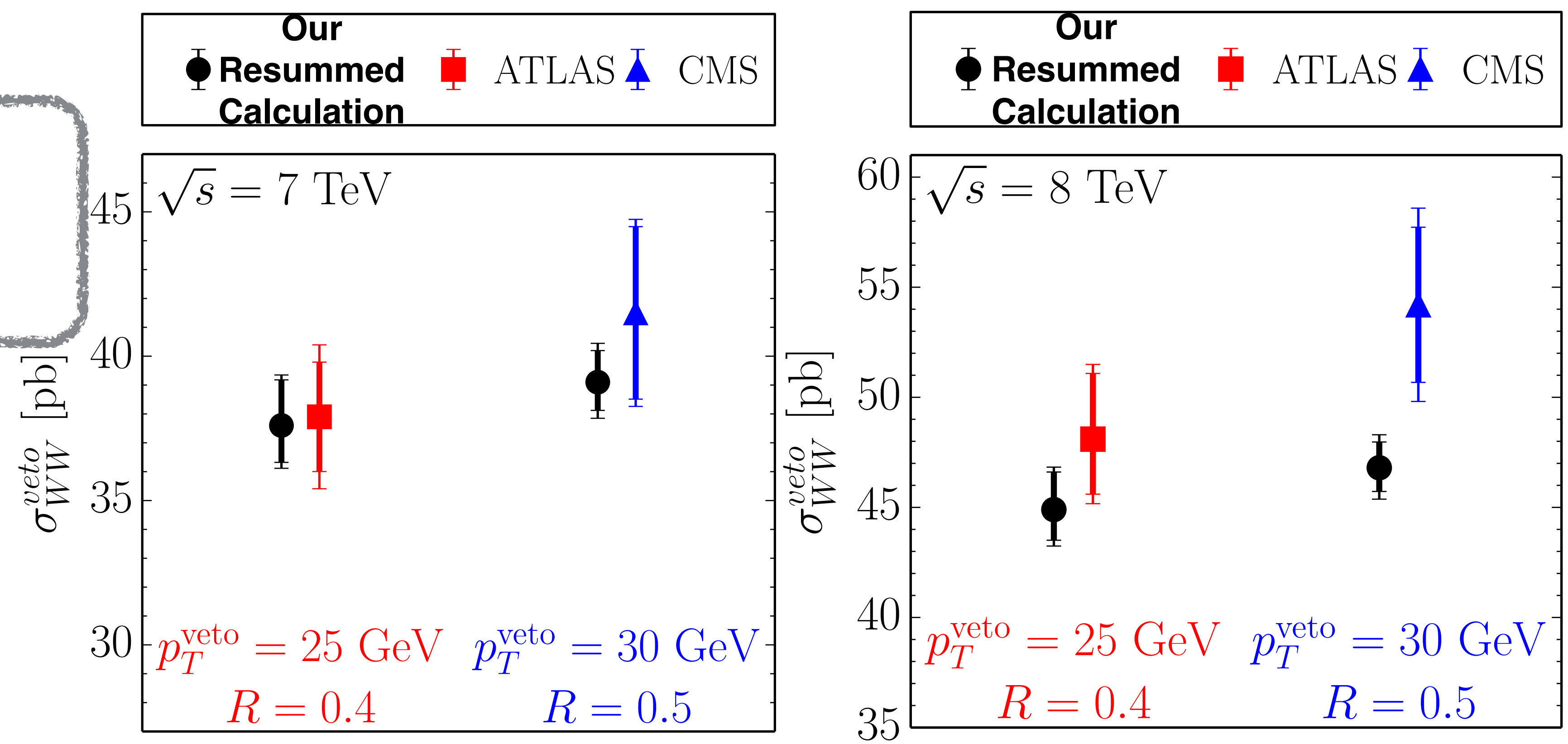
A tale of two Ws

- Our approach : Calculate jet-veto cross-section analytically by resummation at NNLL without relying on MC.

PJ and T. Okui, *An Explanation of the WW Excess at the LHC by Jet-Veto Resummation*, [arXiv:1407.4537].

Measured Jet-veto Cross-section

Comparison of our results with experimental data



Outline

1. Large logs and their resummation

2. Rapidity Renormalization Group

3. Applications to WW + 0 jets

Part 1

Large logs and their resummation

Origin of large logs

- Higher order calculations in perturbation theory often involve logarithmic terms which under certain situations can be large.
- Such large logs can spoil perturbative convergence and need to be resummed to all orders.
- Origin of such large logs is usually the presence of multiple scales in the problem.

Origin of large logs

Example : p p → W W

	Inclusive	Jet-veto
Scales in the problem	M_{WW}	p_T^{veto}, M_{WW}
Logs at higher orders	$\log(M_{WW}/\mu)$	$\log(M_{WW}/\mu)$ $\log(p_T^{veto}/\mu)$
Choice of μ to minimize logs	$\mu \sim M_{WW}$	<u>No choice of μ</u> Large logs of the form $\log(p_T^{veto}/M_{WW})$ remain

Origin of large logs

- Structure of IR logs in perturbation theory is

$$1+\alpha_s(L^2+L+1)+\alpha_s^2(L^4+L^3+L^2+L+1)+\ldots$$

where

$$L=\log\left[\frac{-M_{WW}^2-i\epsilon}{(p_T^{veto})^2}\right]=\log\left[\frac{M_{WW}^2}{(p_T^{veto})^2}\right]-i\pi$$

- At each order in perturbation theory, leading log term enters as powers of $\alpha_s L^2$
- Consider WW production at LHC, for M_{WW} ~ 250 GeV and p_T^{veto} ~ 25 GeV,

$$\log^2\left[\frac{M_{WW}^2}{(p_T^{veto})^2}\right]\sim 20$$

- Also, π^2 terms can be sizable.

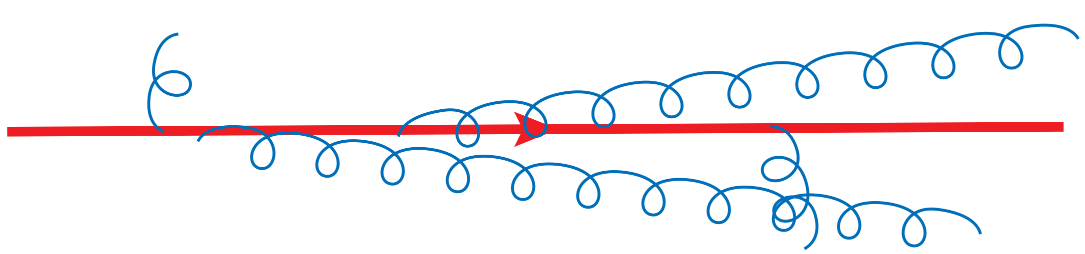
SCET

- We will use EFT to resum large logs, specifically Soft-Collinear Effective Theory (SCET).

<u>Degrees of Freedom and power counting</u>:

Unlike usual EFTs, power counting is not in the mass scale. Instead, power counting is in the <u>virtuality</u>.

- 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 : $(p_+, p_-, p_\perp) \sim (\lambda, \lambda, \lambda) M$



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

SCET : Parallels with generic EFTs

EFT (Fermi's theory)

- Integrate out heavy modes ($\sim m_W$) and keep only the light modes ($\sim m_f$) in EFT.
- Information about heavy modes encoded in Wilson coefficients by matching to full theory at high scale.
- Wilson coefficient is run down to a low mass scale where computations are performed. The RG running effective resums large logs $\sim \log(m_W/m_f)$

SCET (WW jet-veto)

- Integrate out high virtualities (or highly off-shell modes ~ M_{WW}) and keep only almost on-shell modes ($\sim p_T^{veto}$) in SCET.
- Information about highly off-shell modes encoded in Wilson coefficients by matching to full theory (i.e. QCD) at high scale.
- Wilson coefficient is run down to a low virtuality scale where computations are performed. The RG running effective resums large logs $\sim \log(M_{WW}/p_T^{veto})$

Peculiar features of SCET

- Non-locality of SCET operators

From the power scaling of momentum components

$$\partial_+\phi_{\rm c} \sim M\phi_{\rm c}\,, \quad \partial_-\phi_{\rm c} \sim \lambda^2 M\phi_{\rm c}\,, \quad \partial_\perp\phi_{\rm c} \sim \lambda M\phi_{\rm c}$$

Derivatives along x+ direction unsuppressed.

Example :

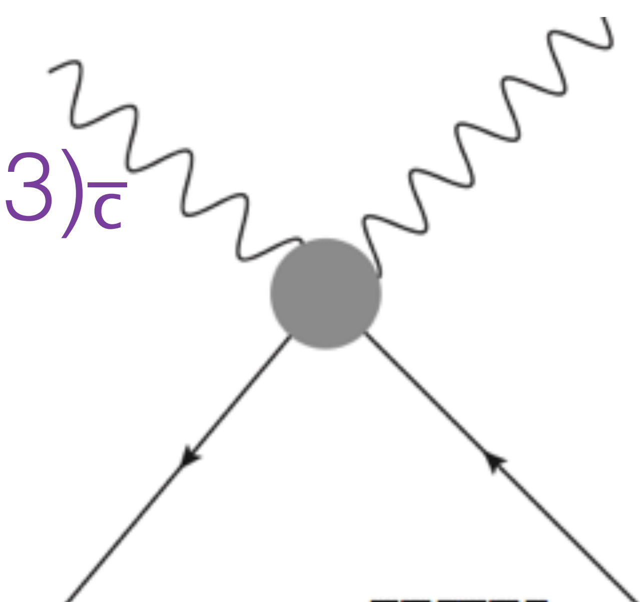
$$\int dt\;\; C(t,\ldots)\;\; \phi_c(x_+ + t, x_-, x_\perp)\ldots$$

Peculiar features of SCET

Gauge symmetry for each sector

- Multiple copies of SU(3), one for each sector.
- i.e. Collinear modes transform under $SU(3)_c$ but singlet under $SU(3)_{\bar{c}}$ $\phi_c(x) \xmapsto{U_c} \phi'_c(x) = U_c(x)\,\phi_c(x)$
- Anti-Collinear modes transform under $SU(3)_{\bar{c}}$ but singlet under $SU(3)_c$
- Unlike QCD, following operator not gauge invariant under $SU(3)_c$ x $SU(3)_{\bar{c}}$

$$W_\mu W_\nu \bar{q}\,\Gamma^{\mu\nu} q$$



$q\,\bar{q} \rightarrow WW$

Peculiar features of SCET

Wilson lines

- Wilson lines for each sector.

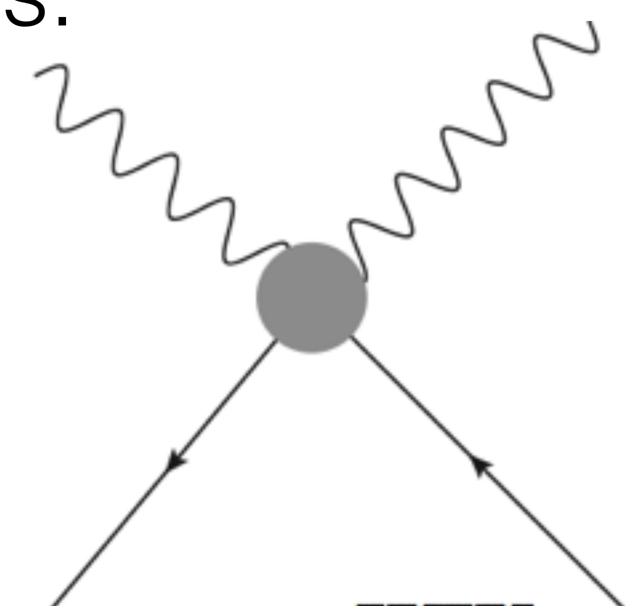
$$W_{\mathrm{c}}(x) \equiv \mathcal{P}_s \exp\left[-\mathrm{i}g_{\mathrm{c}} \int_{-\infty}^{0} \mathrm{d}s\, G_{\mathrm{c}+}(z(s))\right]$$

$$z^+(s) = x^+ + s\,, \quad z^-(s) = x^-\,, \quad \vec{z}_\perp(s) = \vec{x}_\perp$$

- Wilson lines are not only allowed in SCET due to non-locality of operators but also essential for constructing gauge-invariant operators.

$$W_\mu W_\nu \bar{q}\, W_{\bar{c}}\, \Gamma^{\mu\nu} W_c^{+} q$$

Gauge invariant under $SU(3)_c$ x $SU(3)_{\bar{c}}$

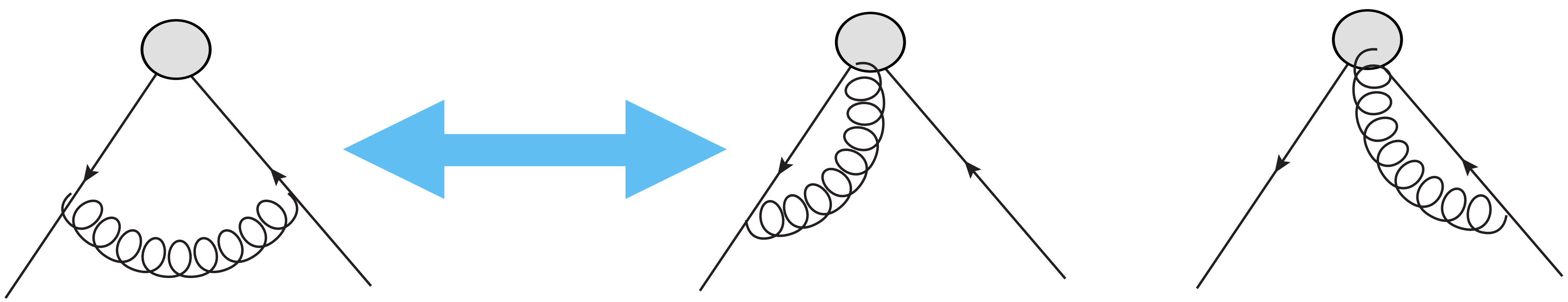


$q\,\bar{q} \to WW$

SCET : Jet-veto calculations

- Scaling of the WW system momentum ~ M (1, 1, λ)
- Scaling of x ~ 1/M (1, 1, 1/λ)
- Keeping leading order terms in λ (SCET power counting parameter) in SCET Lagrangian and allowing for non-locality i.e. multipole expansion

$$\chi_{\bar{c}}^{i\alpha}(x^- + t_2, \vec{x}_\perp)\,\Gamma_\alpha^{\ \beta}\,\chi_{c i\beta}(x^+ + t_1, \vec{x}_\perp) \qquad \chi_c(x) \equiv W_c^\dagger(x)\,\xi_c(x)$$



QCD

No UV poles
IR poles : ε^{-2} , ε^{-1}

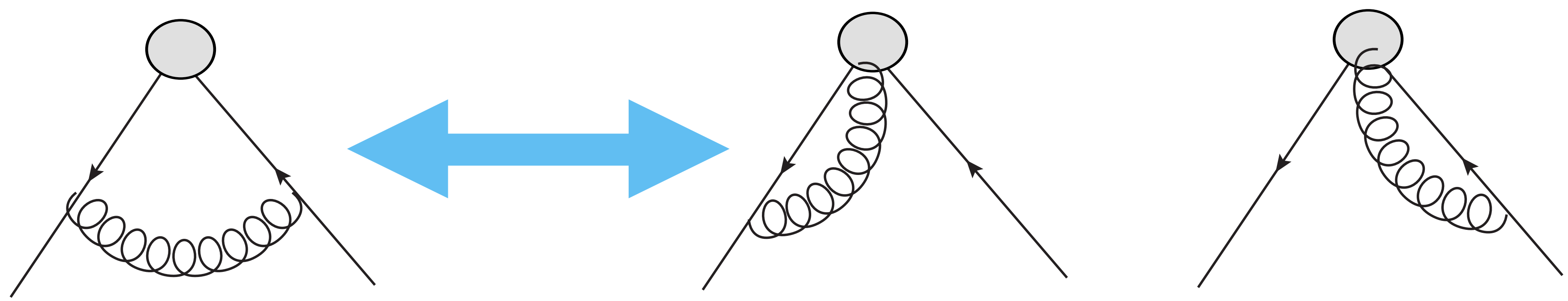
SCET

Scaleless integrals ⇒ 0
UV poles = IR poles : ε^{-2} , ε^{-1}

SCET : Jet-veto calculations

- Match SCET to full theory (QCD) at $\mu \sim M_{WW}$
- Run down the Wilson coefficient from last step down to $\mu \sim p_T^{veto}$

$$\chi_{\bar{c}}^{i\alpha}(x^- + t_2, \vec{x}_\perp)\, \Gamma_\alpha^{\ \beta}\, \chi_{c\, i\beta}(x^+ + t_1, \vec{x}_\perp) \qquad \chi_c(x) \equiv W_c^\dagger(x)\, \xi_c(x)$$



QCD

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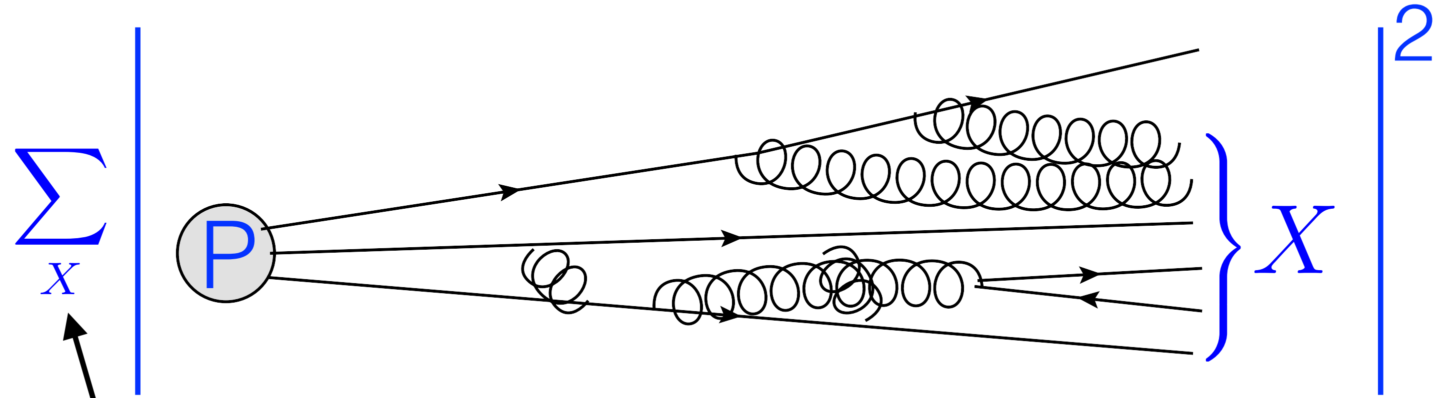
SCET

Scaleless integrals ⇒ 0

UV poles = IR poles : ε^{-2} , ε^{-1}

SCET : Jet-veto calculations

- What remains is the matrix elements of SCET operators between initial proton states and final hadronic states, called Beam Functions

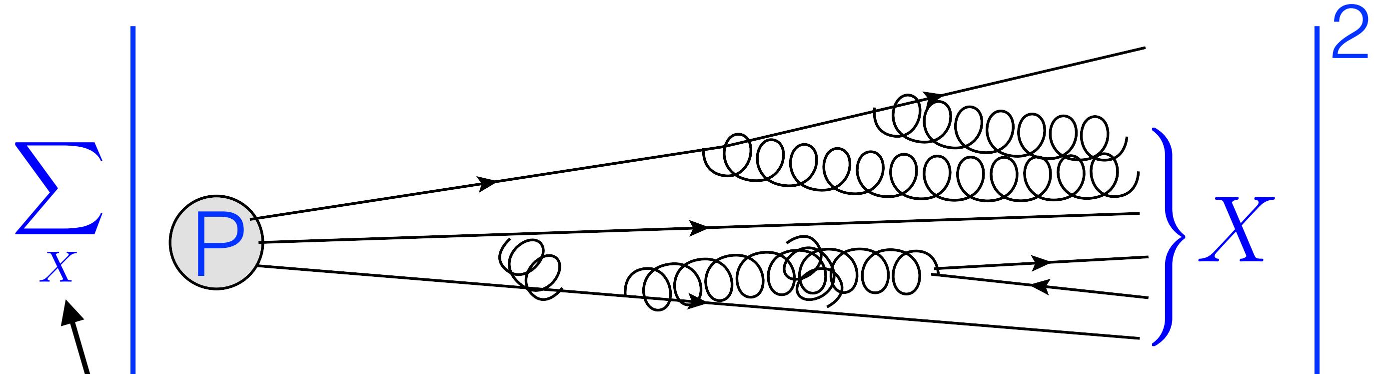


= Beam function

over all X passing jet veto

- Beam Functions are generalization of PDFs

PDF =

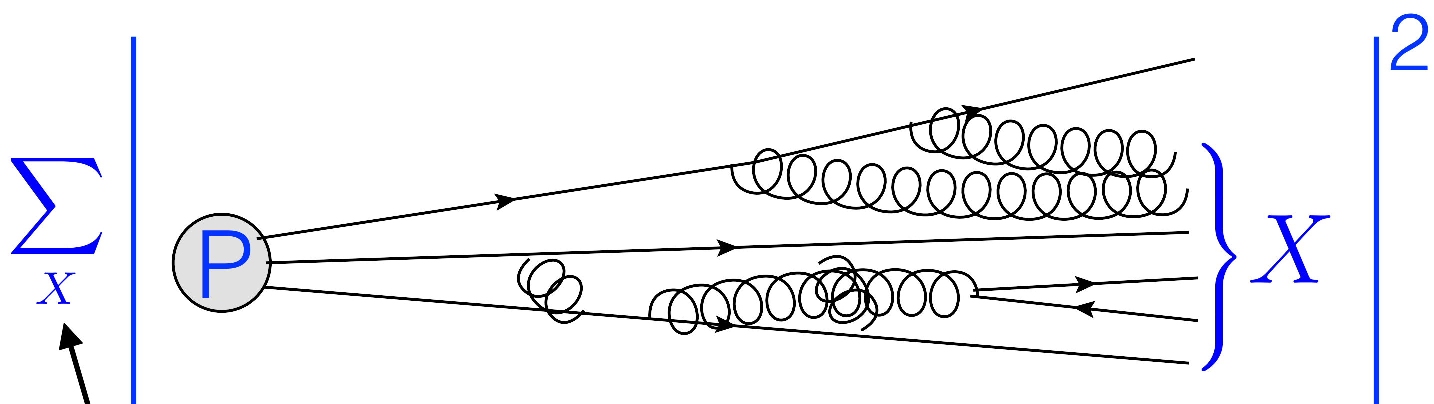


over all X

- Evaluate Beam Functions as OPE on to PDFs.

SCET : Jet-veto calculations

- What remains is the matrix elements of SCET operators between initial proton states and final hadronic states, called Beam Functions



= Beam function

over all X passing jet veto

- One final complication : Beam functions have divergences which are <u>not</u> regulated by dimensional regularization!

- The additional singularities go by the name of rapidity divergences

Part 2
Rapidity Renormalization Group

Origin of rapidity divergences

Recall :

- 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 : $(p_+, p_-, p_\perp) \sim (\lambda, \lambda, \lambda)M$

- In the usual EFTs, divergences arise when EFT is run into UV and such divergences need to be regulated.
- Similarly in SCET, UV divergences arise when we let the theory run into high virtuality regime (or highly off-shell regime). Such divergences are regulated by DR.
- What happens when collinear mode runs into anti-collinear mode? Or soft mode into collinear mode?

Origin of rapidity divergences

Recall :

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

- What happens when collinear mode runs into anti-collinear mode? Or soft mode into collinear mode?
- By the same logic as before, we expect divergences.
- DR does not regulate such divergences because all the modes have the same virtuality ~ $(M\ \lambda)^2$.
- Need a regulator that separates these modes.

Origin of rapidity divergences

Recall :

- 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 : $(p_+, p_-, p_\perp) \sim (\lambda, \lambda, \lambda)M$

- Need a regulator that separates these modes.
- Rapidity of these modes are vastly different : logλ, -logλ, 1
- Need rapidity regulator to separate modes. Corresponding to rapidity regulator exists a rapidity renormalization group (RRG) equations, just as there exists RG equations corresponding to dim reg regulator μ.

Rapidity Regulator

- Vast literature in SCET on rapidity regulators. We choose to work with analytic rapidity regulator, similar to one used by Becher et al. for Drell-Yan pT resummation *[arXiv:1007.4005]* . **Analytic rapidity regulators in SCET have been used before as well.*

- However, formulation of RRG with analytic regulator had been missing. We address this issue *[arXiv:1506.xxxx : PJ and Takemichi Okui]*.

- We introduce the following analytic regulator

$$\left(\frac{\nu}{k_+}\right)^{\alpha}\theta(k_+ - k_-) + \left(\frac{\bar{\nu}}{k_-}\right)^{\bar{\alpha}}\theta(k_- - k_+)$$

Splits the phase space integrals into regions of different rapidities

- The light-cone divergences in the beam function are now regulated at the expense of introducing regulator scales ν and $\bar{\nu}$, which play role analogous to μ in DR. Correspondingly, the role of ε is played by α and $\bar{\alpha}$.

Rapidity RG (RRG)

- With the regulators in place, factorized cross-section takes the form :

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M} \sim H(\mu)\, Z_{\mathrm{S}}(\mu, \nu, \bar{\nu})\, B(\mu, \nu)\, \bar{B}(\mu, \bar{\nu})$$

- The hard function H(μ) is the squared Wilson coefficient RG evolved from $\mu \sim M_{WW}$ to $\mu \sim p_T^{veto}$.
- B(μ, ν) is the regulated beam function.
- To cancel divergences from the beam functions, a renormalization constant Z_S has to introduced. Alternatively, Z_S can be interpreted as soft function which is matrix element consisting of states with soft modes.
- Requiring cross-section to be independent of the scale ν gives RRG.
- We benefit from the condition that RG evolution is independent of the path in (μ, ν) parameter space.

Rapidity RG (RRG)

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$$\frac{\mathrm{d}\sigma}{\mathrm{d}M} \sim H(\mu)\, Z_{\mathrm{s}}(\mu,\nu,\bar{\nu})\, B(\mu,\nu)\, \bar{B}(\mu,\bar{\nu})$$

- Just as the initial condition for RG of the Wilson coefficient is chosen to be μ~M_{WW} to minimize logs, similarly, initial conditions for rapidity scales are chosen to minimize logs.

- Just as truncation in perturbation series leads to scale uncertainty associated with μ, there are scale uncertainties associated with rapidity scales.

- While the source of μ scale uncertainty can be traced to strong coupling running, the source of v scale uncertainty are logs of the form log(μ/v) i.e. μ uncertainty feeds into v uncertainty.

Rapidity RG (RRG)

Scale uncertainties from RRG

- Our all-order factorization formula is identical to Becher et al, there is no dependence on rapidity scales. So, naively there is no rapidity scale to vary that may lead to scale uncertainty.
- However, at a given order in resummed perturbation theory, dependence on rapidity scale reappears which is a source of additional scale uncertainties.

arXiv:1506.xxxx : PJ and Takemichi Okui

Part 3

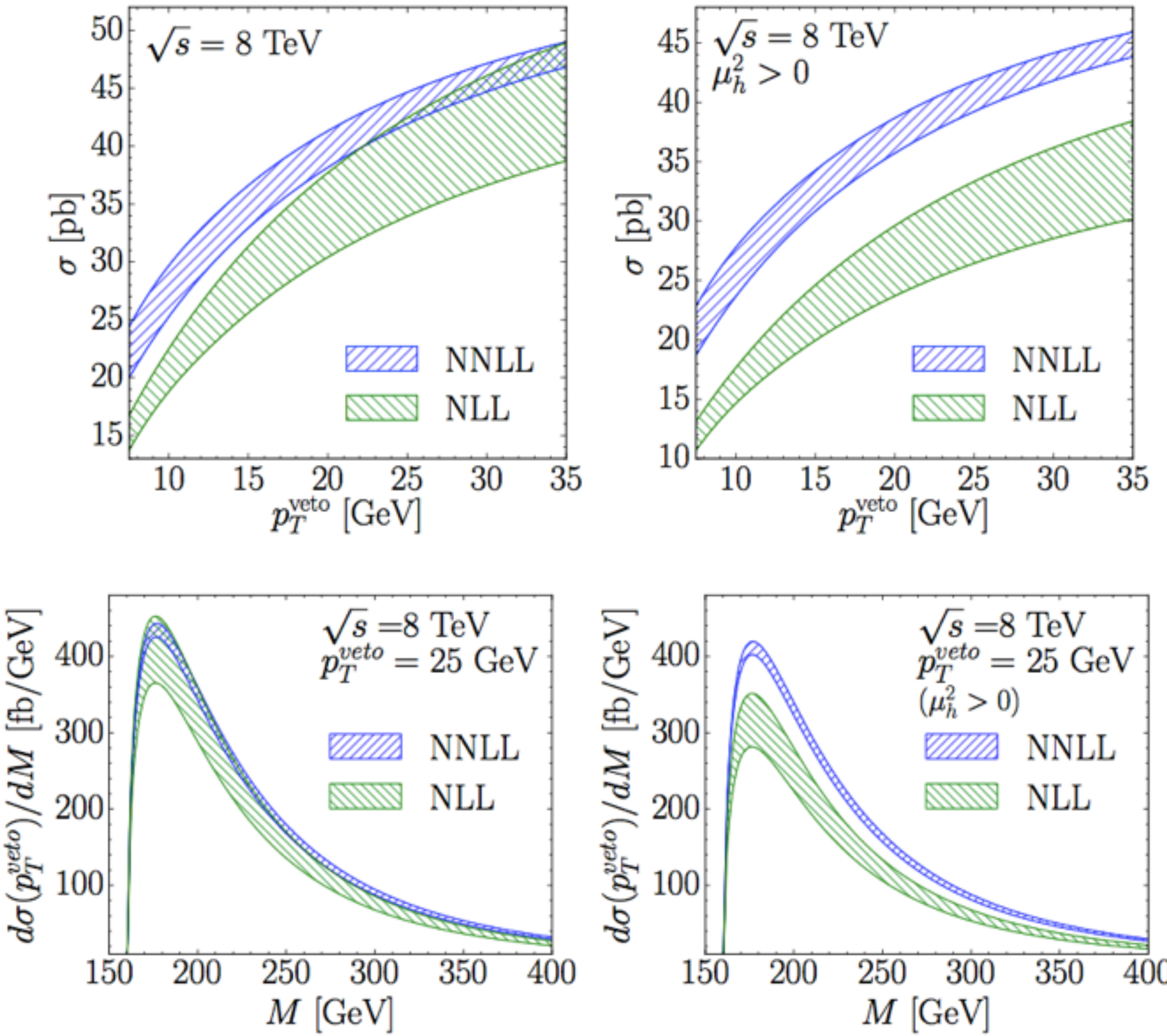
Applications to WW + 0 jets

Counting

- We work at leading order in SCET
  i.e. consider terms that are singular in $\lambda = p_T^{veto}/M_{WW}$
- Higher order corrections are suppressed by powers of λ,
  they are called power corrections.
- Counting large logs as $1/\alpha_s$,
  - NLL : Keep terms up to $\mathcal{O}(1)$
  - NNLL : Keep terms up to $\mathcal{O}(\alpha_s)$

Results

With π^2 | Without π^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 :

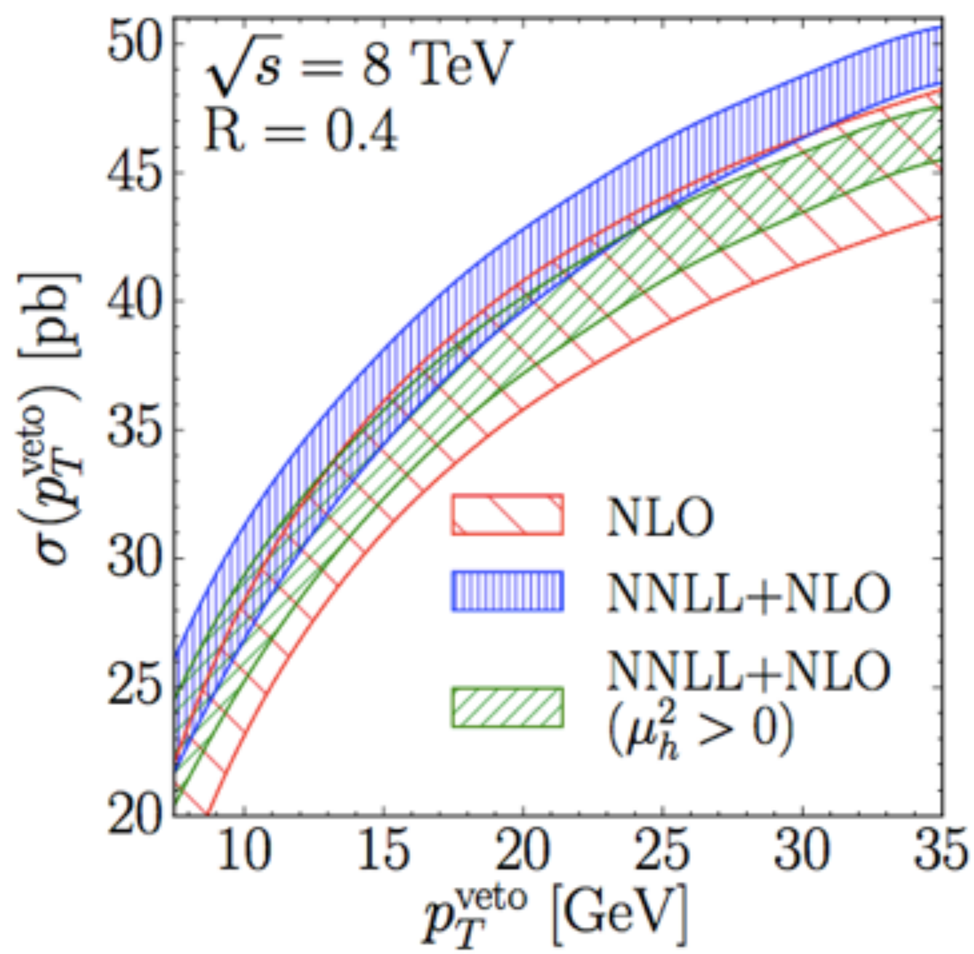
$\log[-M^2/\mu_h^2]$ give factors of π^2 when squared if $\mu_h^2 > 0$.

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

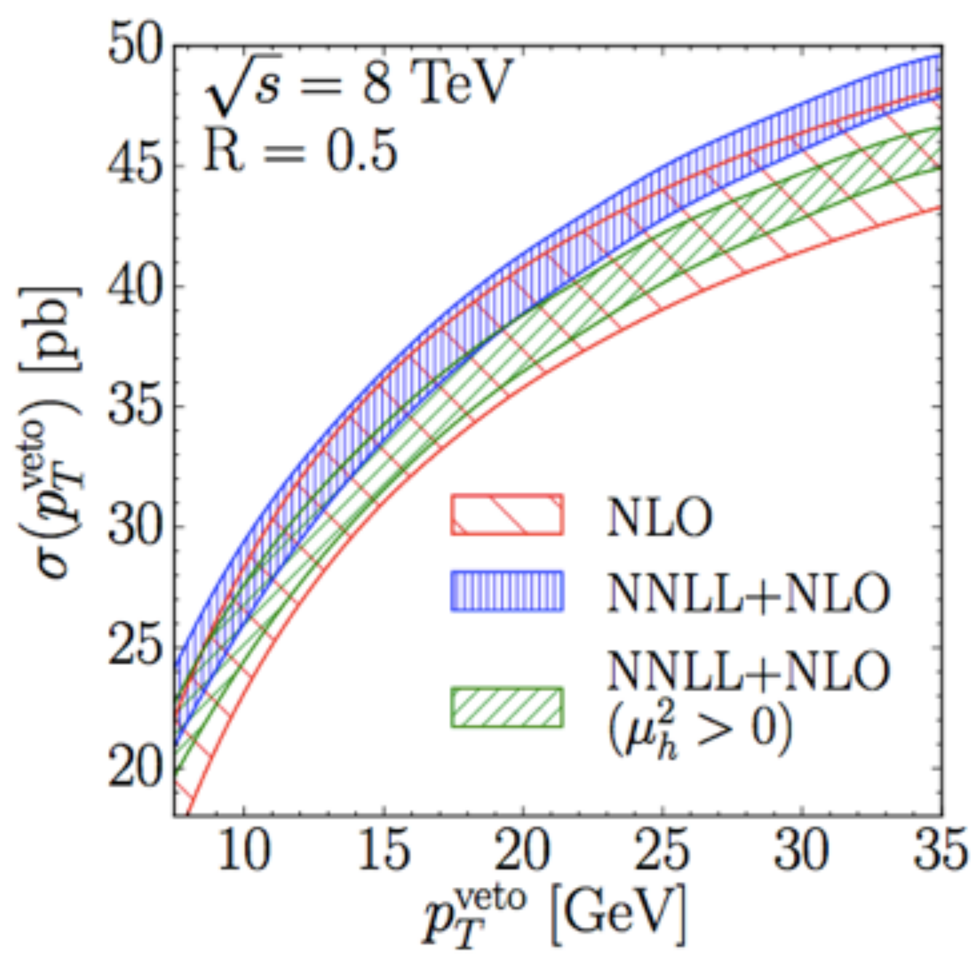
Results

- Comparison with fixed order

R=0.4



R=0.5



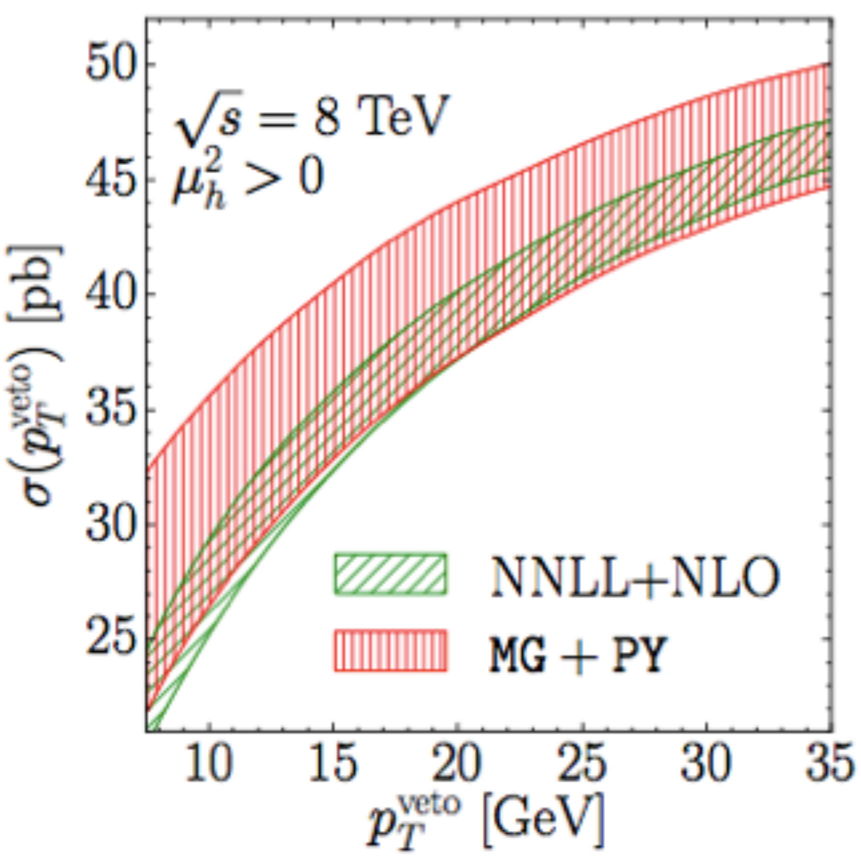
R dependence through log(R) terms at NNLO

NNLL+NLO means power corrections included (which are < 1%)

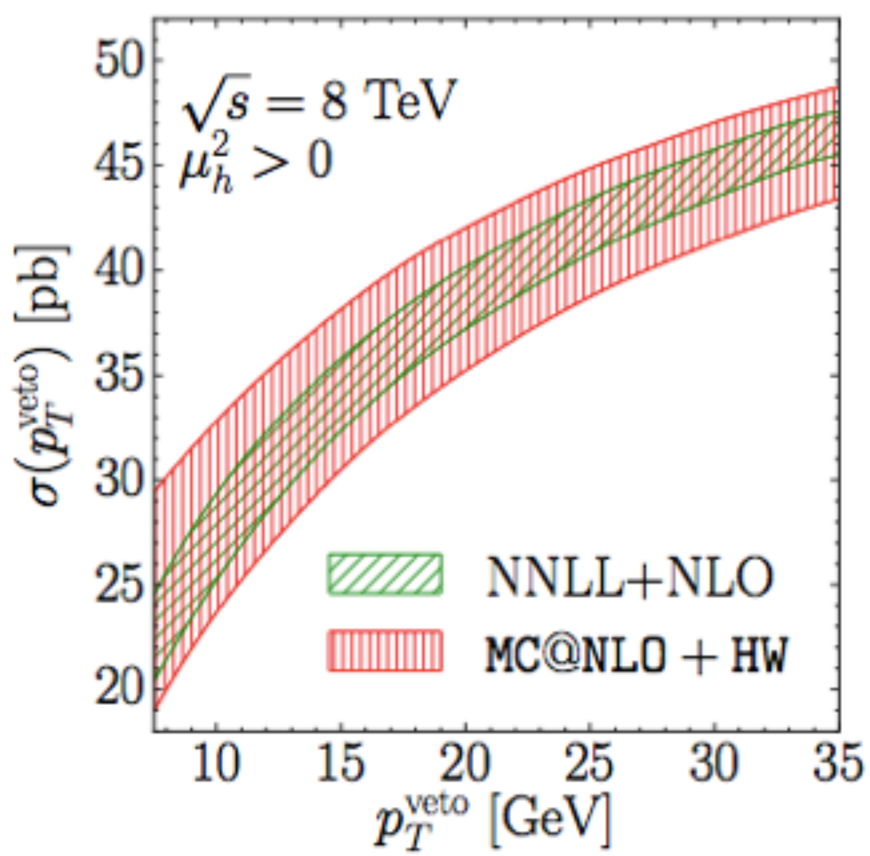
Results

- Comparison with MC+Parton shower

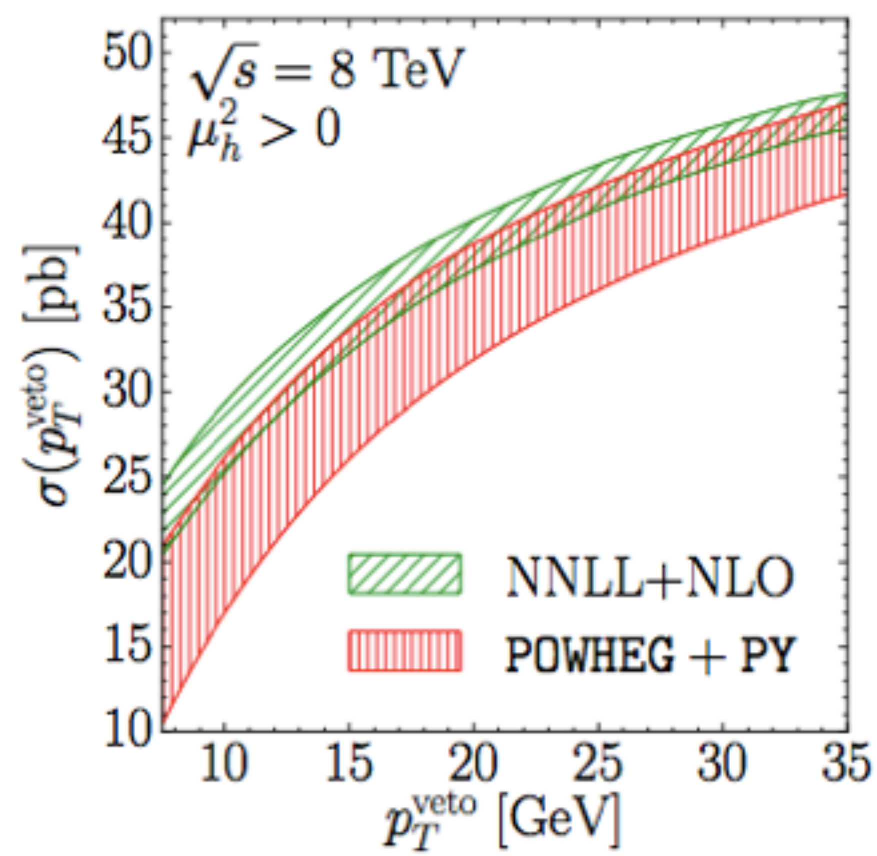
Madgraph
+Pythia



MC@NLO
+Herwig



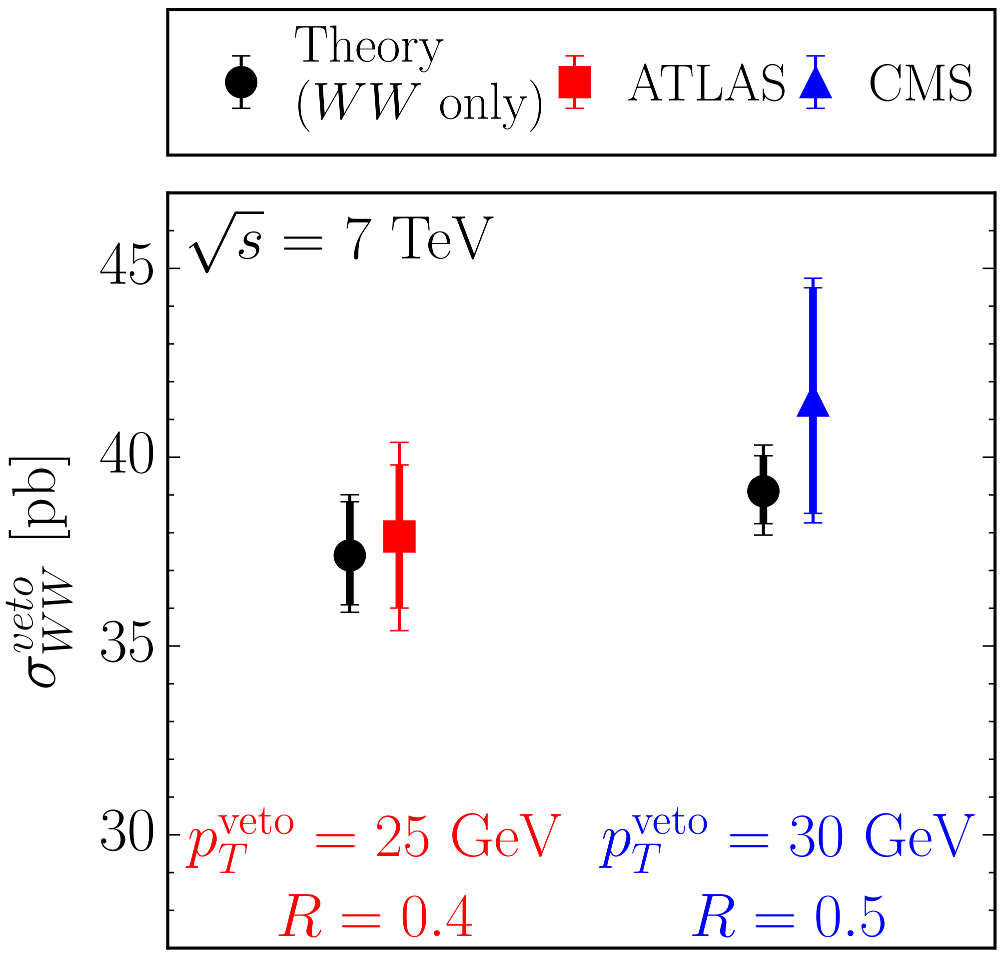
Powheg
+Pythia



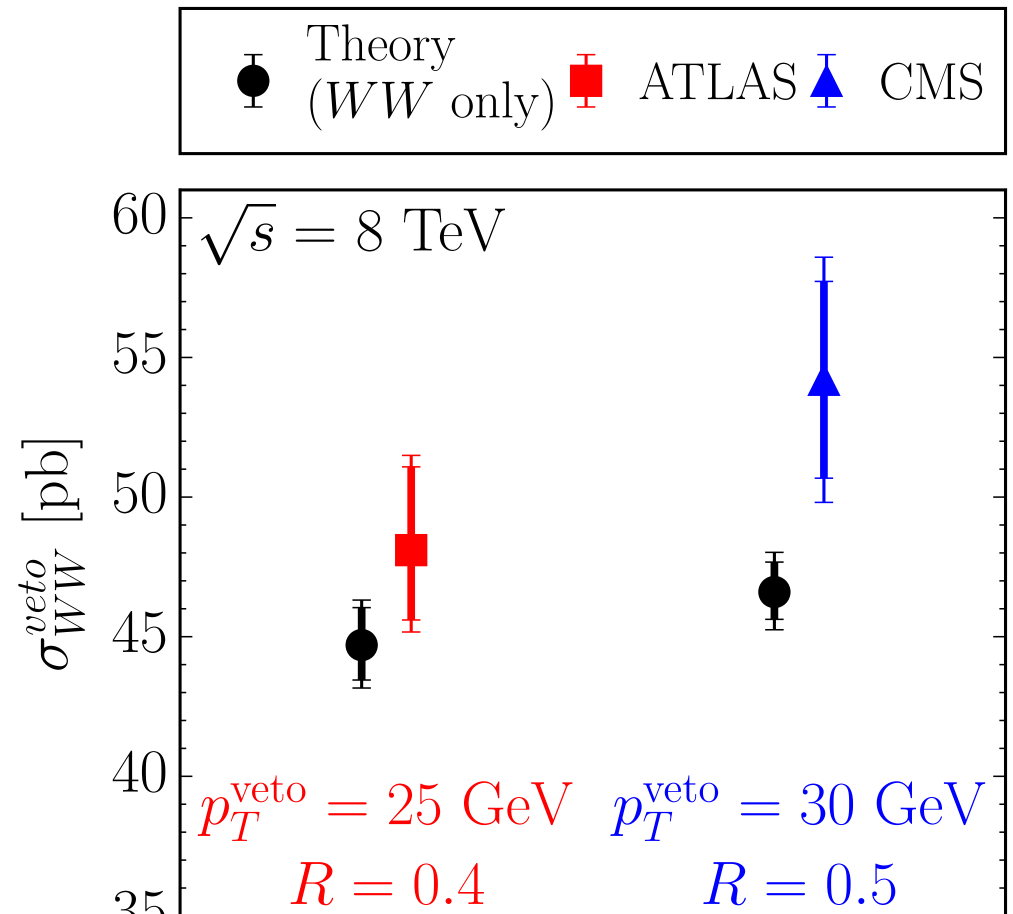
Without π^2 Resummation

Results

7 TeV



8 TeV



With π^2 Resummation

To π^2 or not to π^2

- Logarithms in the Wilson coefficient of the form

$$\log\left[\frac{-M_{WW}^2 - i\epsilon}{\mu^2}\right]$$

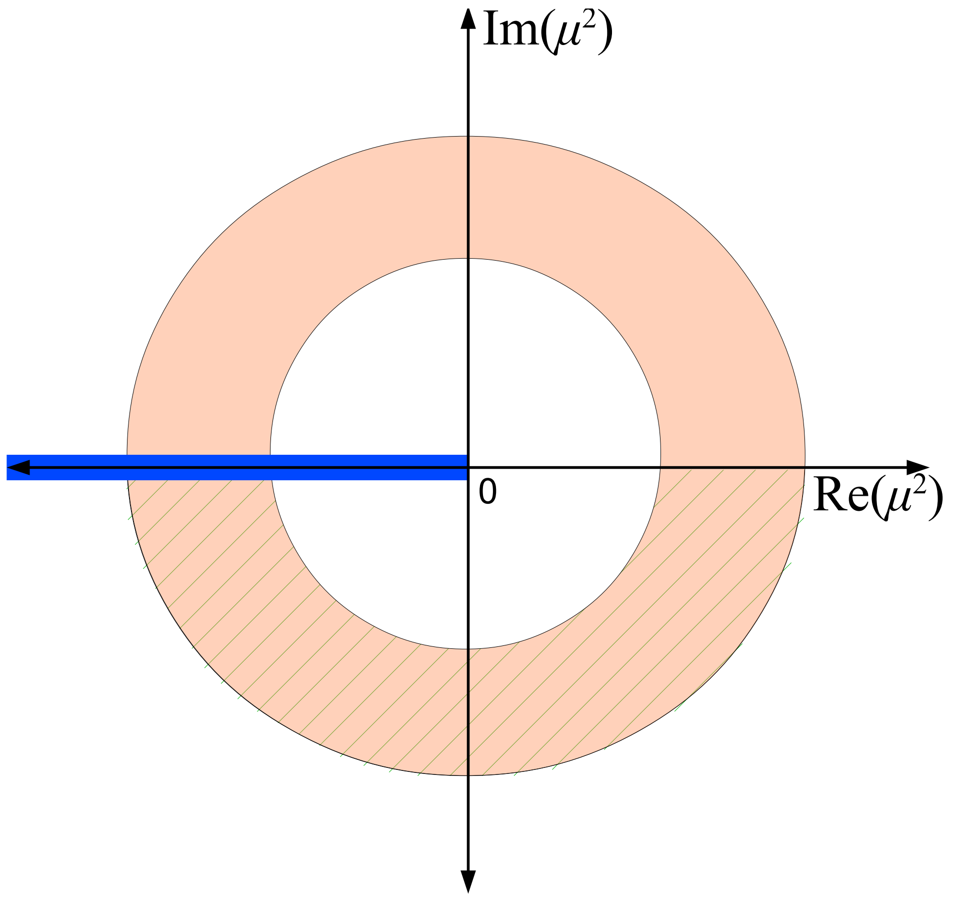
- Matching SCET to QCD should be performed at a scale μ_h so as to minimize logs.
- Naive choice of $\mu_h = M_{WW}$ leads to factors of $i\pi$ which on squaring can give large contributions of $\sim \pi^2$.
- On the other hand, $\mu_h^2 = -(M_{WW})^2$ gives no π^2 terms.
- In general, μ_h is complex while the RG equation runs down to factorization scale which is real.
- The complex phase of μ_h^2 is associated with large perturbative corrections which can be resummed in SCET. The RGE for the Wilson coefficient, be it real or complex, is already known.

To π^2 or not to π^2

- Logarithms in the Wilson coefficient of the form

$$\log\left[\frac{-M_{WW}^2 - i\epsilon}{\mu^2}\right]$$

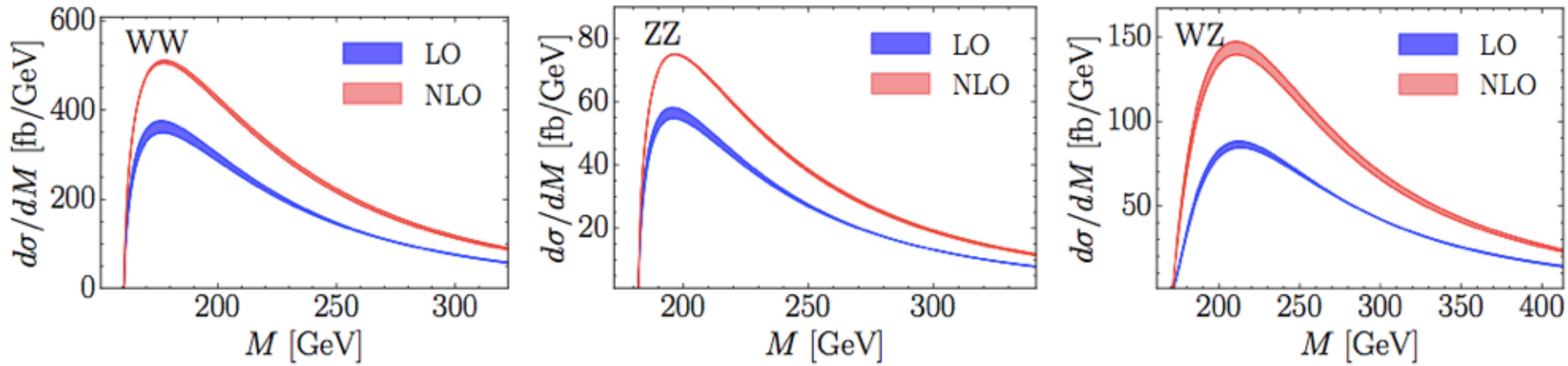
- $\mathrm{Arg}[\mu_h^2] = \theta$, we want to resum θ^2 terms.
- If logs are the only source of π^2 terms, obvious choice is $|\theta| = \pi$
- If not, need to vary θ in analogy with varying scales by factors of 1/2 and 2.



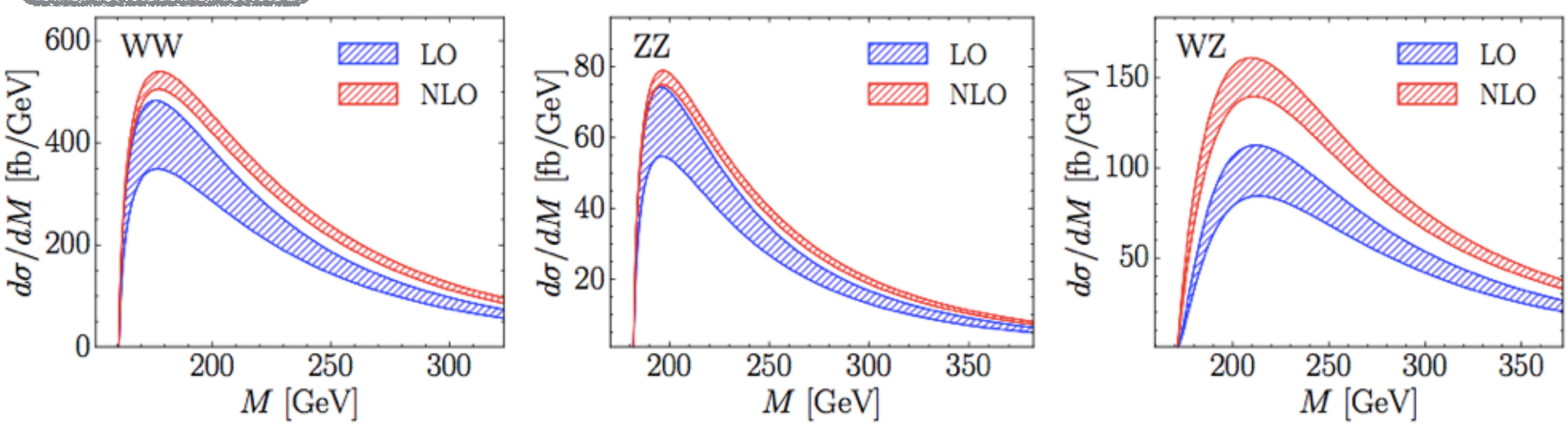
To π^2 or not to π^2

Before

arXiv:1411.0677 : PJ



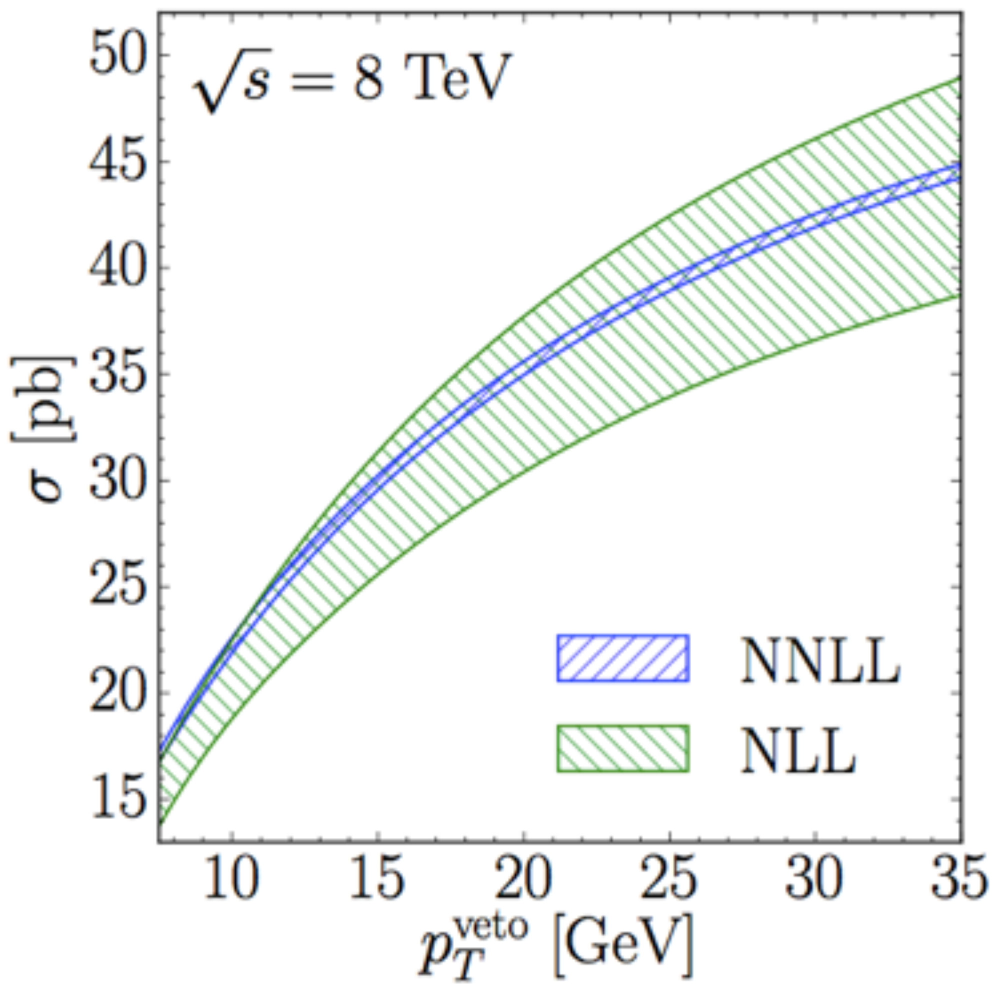
After



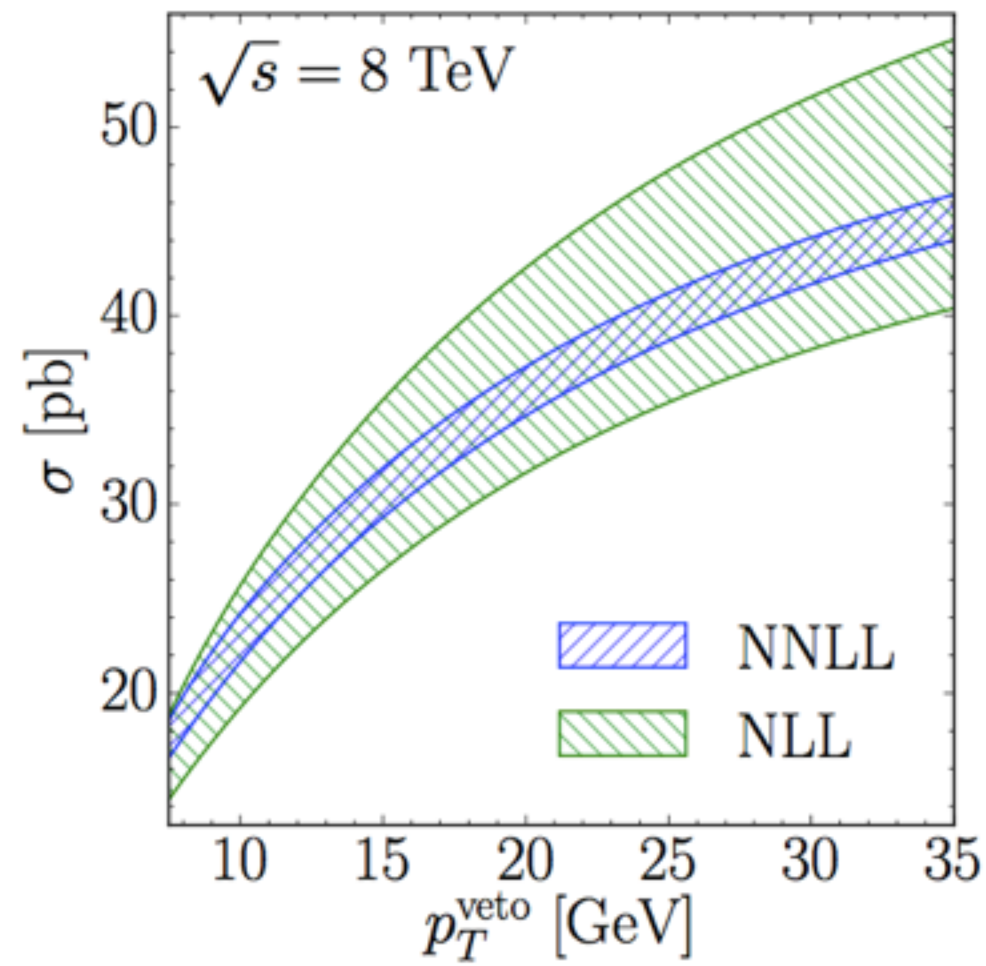
Impact of RRG

Jet-parameter R=1

Before RRG



After RRG



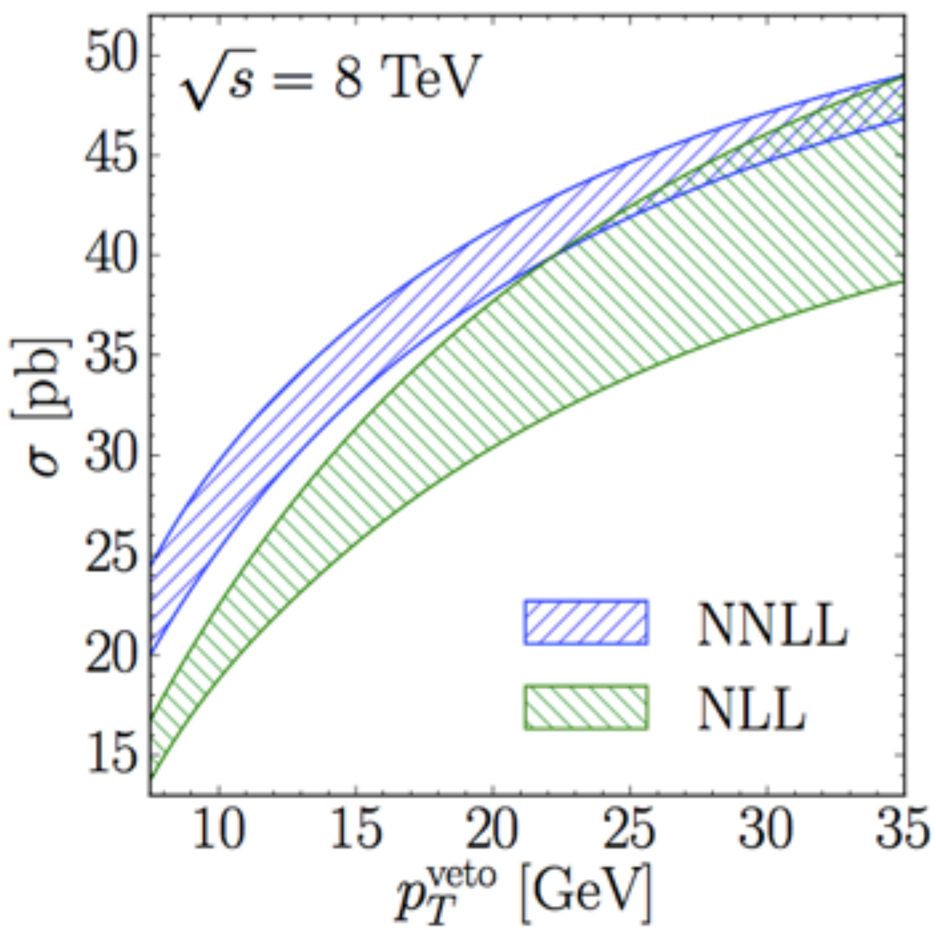
- Scale uncertainty before RRG ~ 1% (can’t be right)
- Scale uncertainty after RRG ~ 5%

Impact of RRG

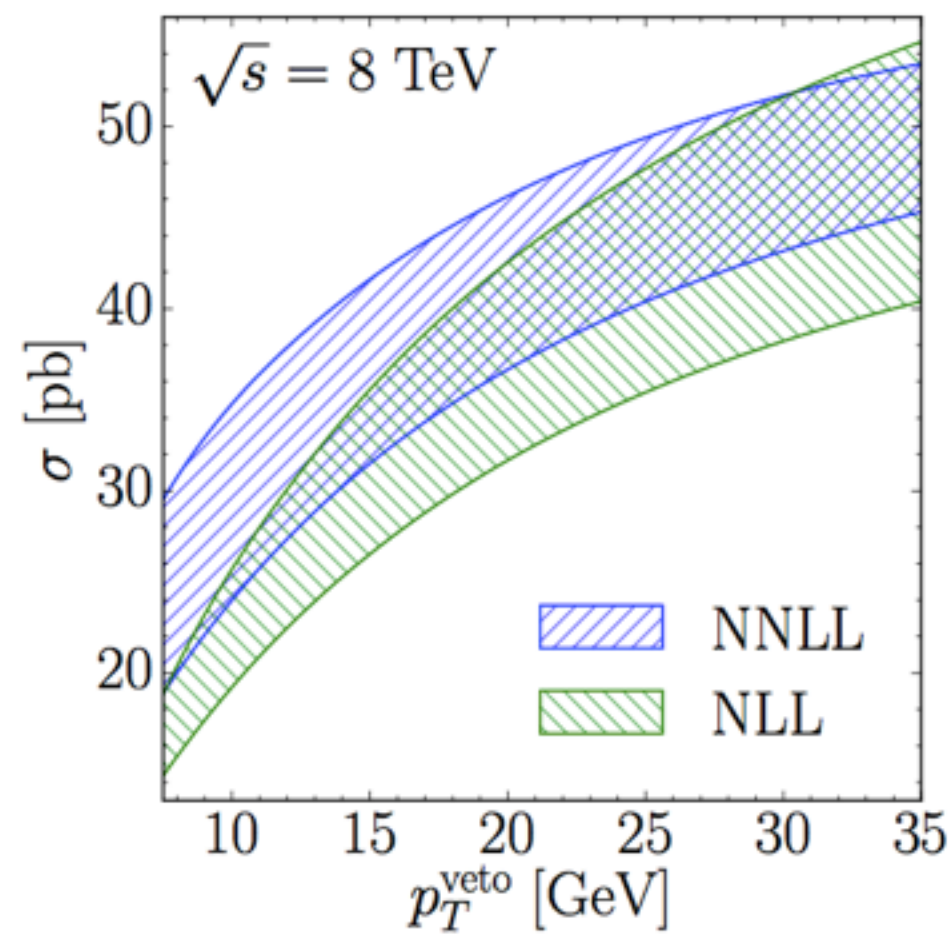
Jet-parameter R=0.4

Used by LHC experiments

Before RRG



After RRG



arXiv:1506.xxxx : PJ and Takemichi Okui

- Scale uncertainty after RRG more than 10% !!
- Reason for large NNLL uncertainty is large log(R) terms which arise at NNLO and resummation of which is currently an open problem.

Future directions

- Understand correlations between pT resummation and jet-veto resummation [work in progress with P. Meade and H. Ramani]
- Calculation of fully differential beam function, which would allow us to get pT distributions in the 0-jet bin [work in progress with T. Okui]
- How to resum log(R) terms.