An Explanation of the WW Excess at the LHC by Jet-Veto Resummation

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Work with *Prerit Jaiswal* (Syracuse)

For details and references see
arXiv:1407.4537
(published in PRD)

More WW pairs than expected?

Process of interest

Inclusive WW production:
(so they think)

$$\mathrm{p} + \mathrm{p} \longrightarrow \underbrace{\mathrm{W}^+ + \mathrm{W}^-}_{\text{leptonic}} + \sum \text{all jets}$$

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$\sqrt{s}$	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	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$	$57.25^{+2.35+1.09}_{-1.60-0.80}$

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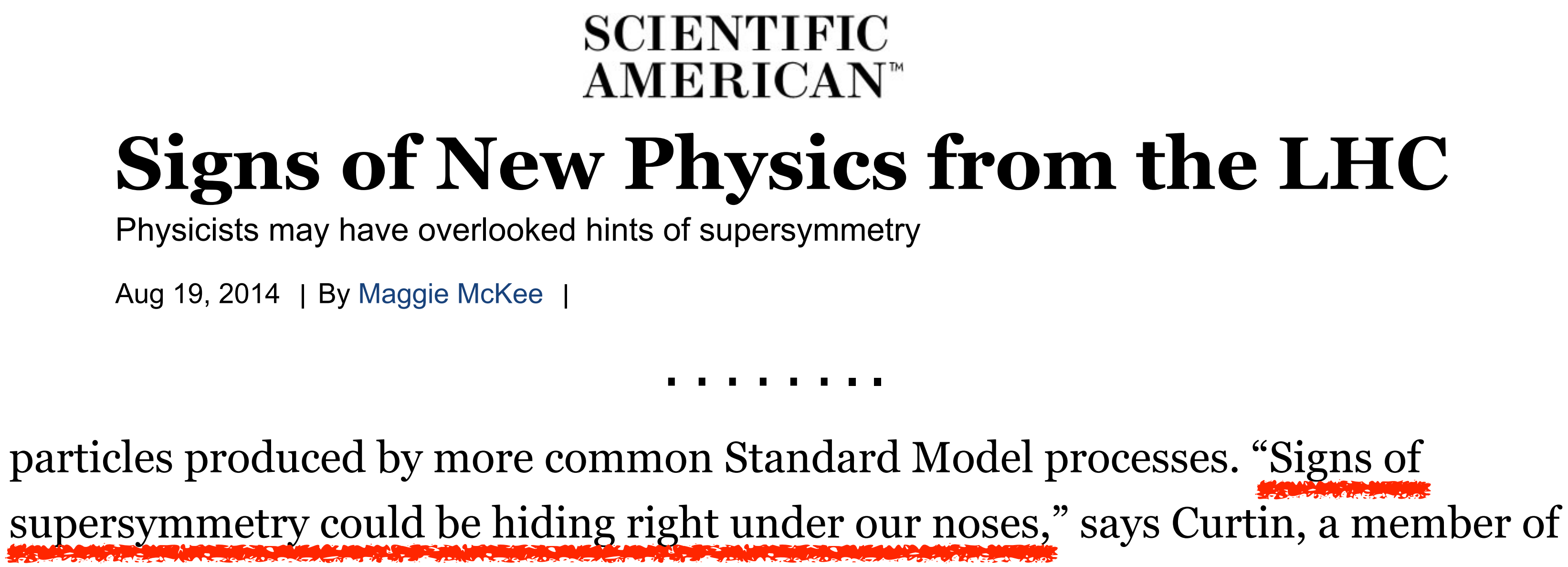
A mild, but persistent excess.

Two experiments more consistent with each other than with theory.

Perhaps new physics?

(with dilepton + MET signature)

Perhaps SUSY?


SCIENTIFIC AMERICAN™

Signs of New Physics from the LHC

Physicists may have overlooked hints of supersymmetry

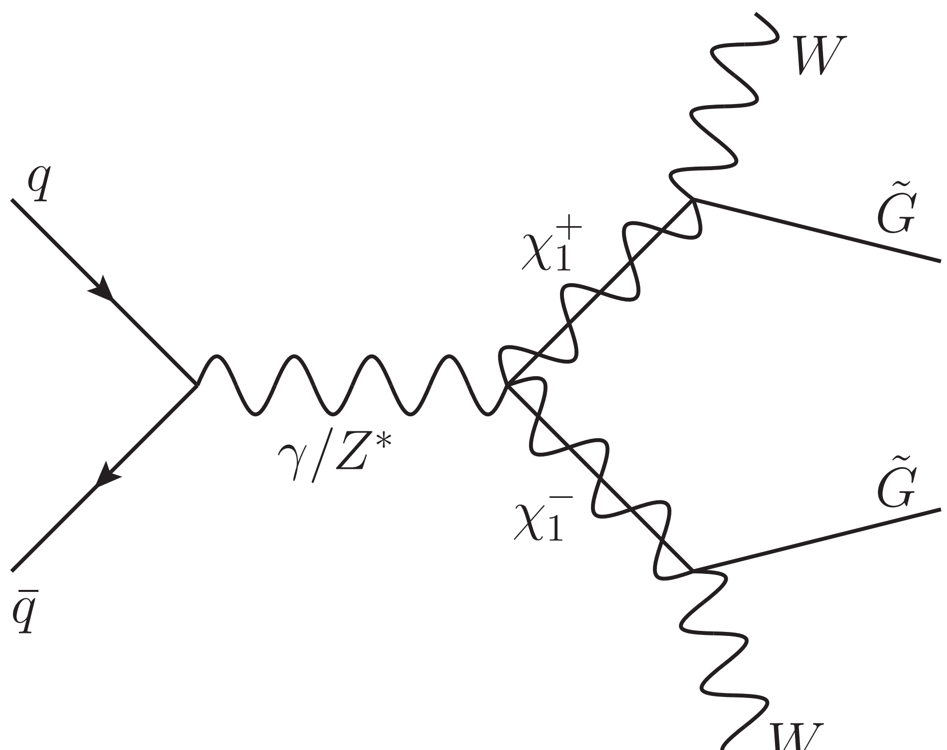
Aug 19, 2014 | By Maggie McKee |

....

particles produced by more common Standard Model processes. "Signs of supersymmetry could be hiding right under our noses," says Curtin, a member of

....

e.g.



From Curtin, Jaiswal & Meade, 1206.6888

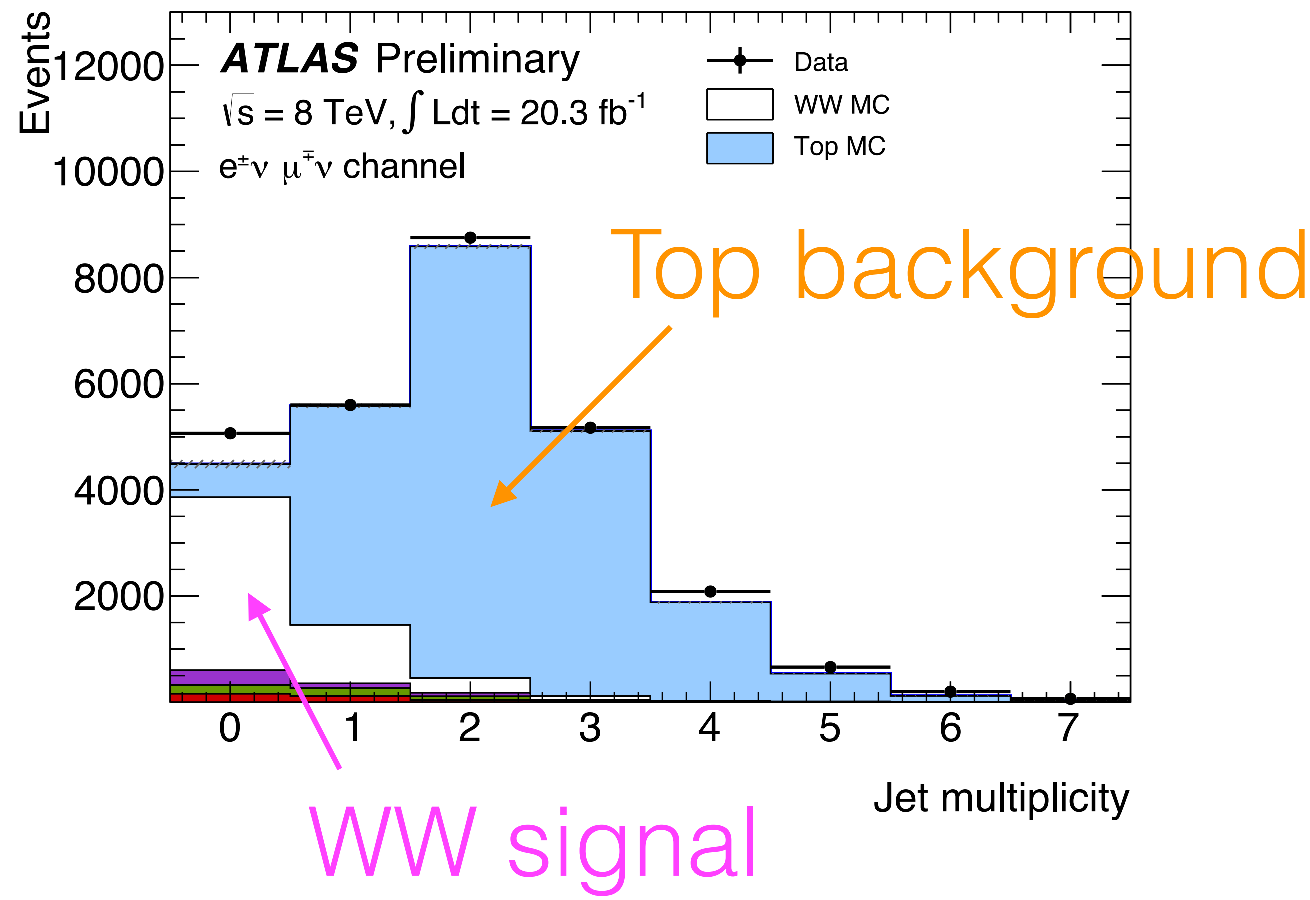
Or perhaps not ...

Subtlety: Experiments actually only measure

$$\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{W}^+ + \mathrm{W}^- + \sum \text{~~all~~ jets}$$

some

From **ATLAS-CONF-2014-033**



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Use only 0-jet bin, i.e., impose *Jet Veto:*

No jet with $p_\mathrm{T} > p_\mathrm{T}^\mathrm{veto}$

$p_\mathrm{T}^\mathrm{veto} = 25\ \mathrm{GeV}$ (ATLAS)
$p_\mathrm{T}^\mathrm{veto} = 30\ \mathrm{GeV}$ (CMS)

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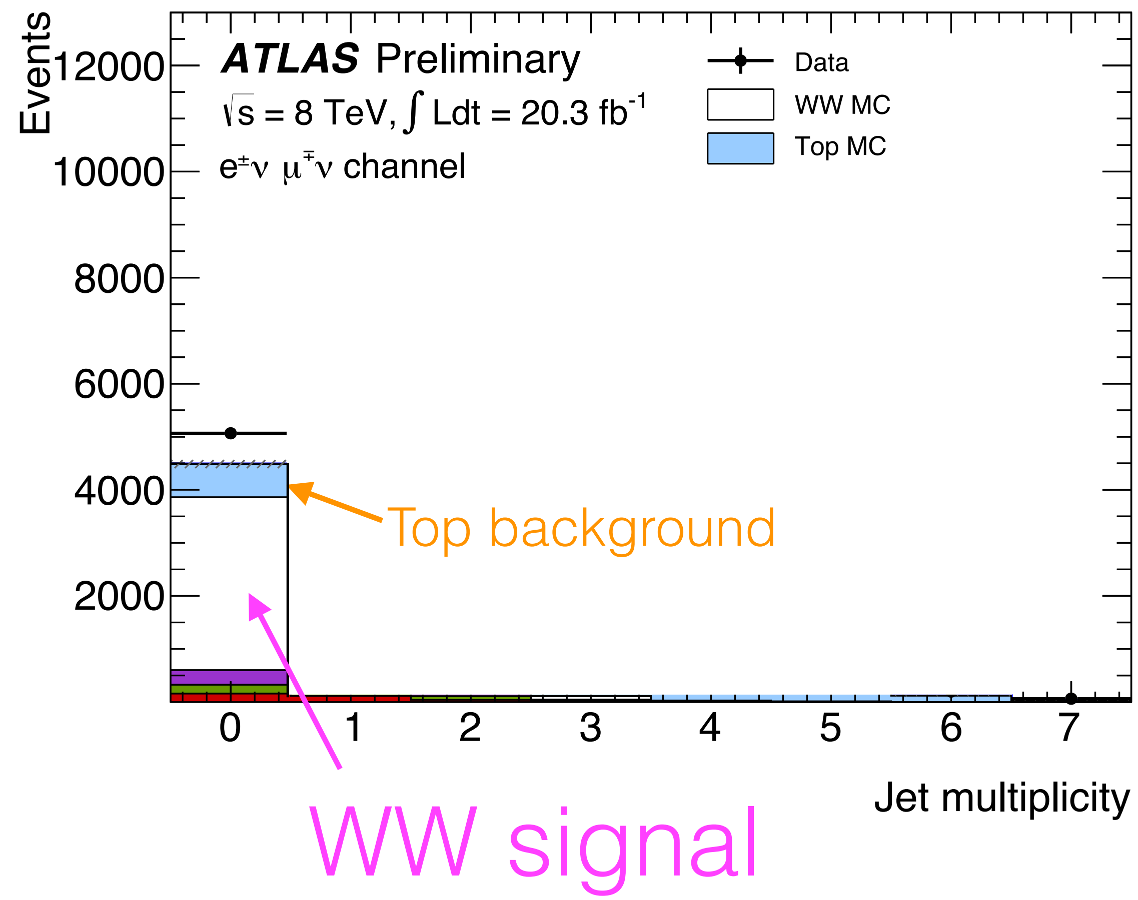

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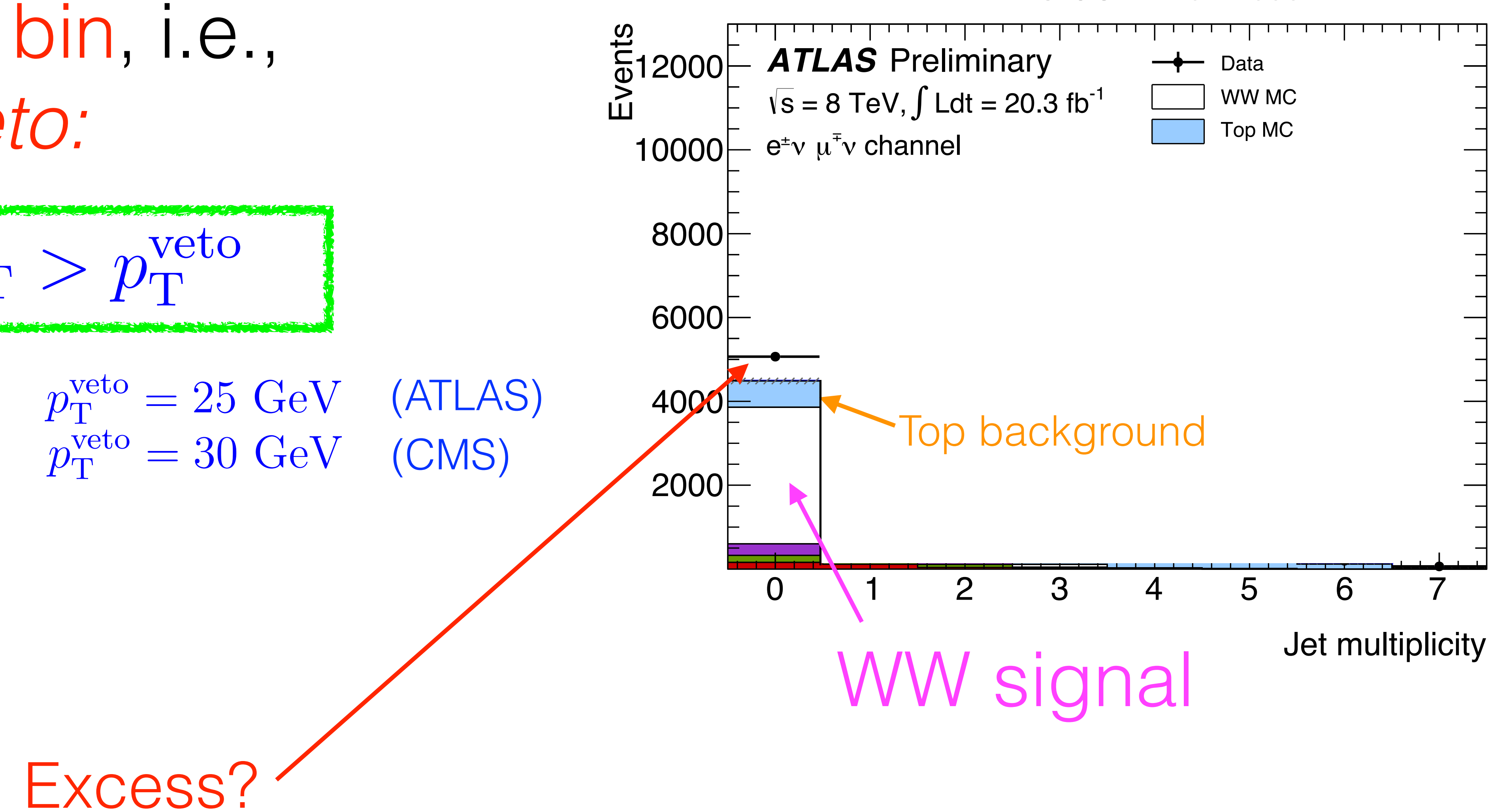

Or can theory be subtle with jet veto?

Yes, it's subtle!

Inclusive case:

$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}M_{\mathrm{WW}}} = \int \mathrm{d}(\cos\theta)\,\mathrm{d}\eta \cdots$$

Orientation of WW system

Rapidity of WW system

Invariant mass of WW system

= a function of only one mass scale M_{WW}

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Rapidity of WW system (η)

Invariant mass of WW system (M_{WW})

= a function of only one mass scale M_{WW}

Loop integrals ⟶ Series in $\log\frac{M_{\mathrm{WW}}}{\mu}$

Log can be minimized by $\mu \sim M_{\mathrm{WW}}$

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Jet-veto case:

$$\frac{d\sigma_{\rm veto}}{dM_{\rm WW}} = \int d(\cos\theta)\, d\eta \cdots$$

= a function of two scales $M_{\rm WW},\ p_{\rm T}^{\rm veto}$

Loop integrals ⟶ $\log \frac{M_{\rm WW}}{\mu}\,,\ \ \log \frac{p_{\rm T}^{\rm veto}}{\mu}$

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$$\frac{d\sigma_{\text{veto}}}{dM_{\text{WW}}} = \int d(\cos\theta)\, d\eta \cdots$$

= a function of two scales $M_{\text{WW}}, \ p_T^{\text{veto}}$

Loop integrals ⟶ $\log \frac{M_{\text{WW}}}{\mu}, \ \log \frac{p_T^{\text{veto}}}{\mu}$

Can't minimize **both** logs! Left with series in $\log \frac{M_{\text{WW}}}{p_T^{\text{veto}}}$.

Do the logs matter?

Biggest log at 1-loop ~ $\alpha_s \left[\log \frac{M_{WW}^2}{(p_T^{veto})^2}\right]^2$

e.g. $p_T^{veto} = 30\,\mathrm{GeV},\ M_{WW} = 300\,\mathrm{GeV}$ ⟶ $(\log 100)^2 \sim 20$

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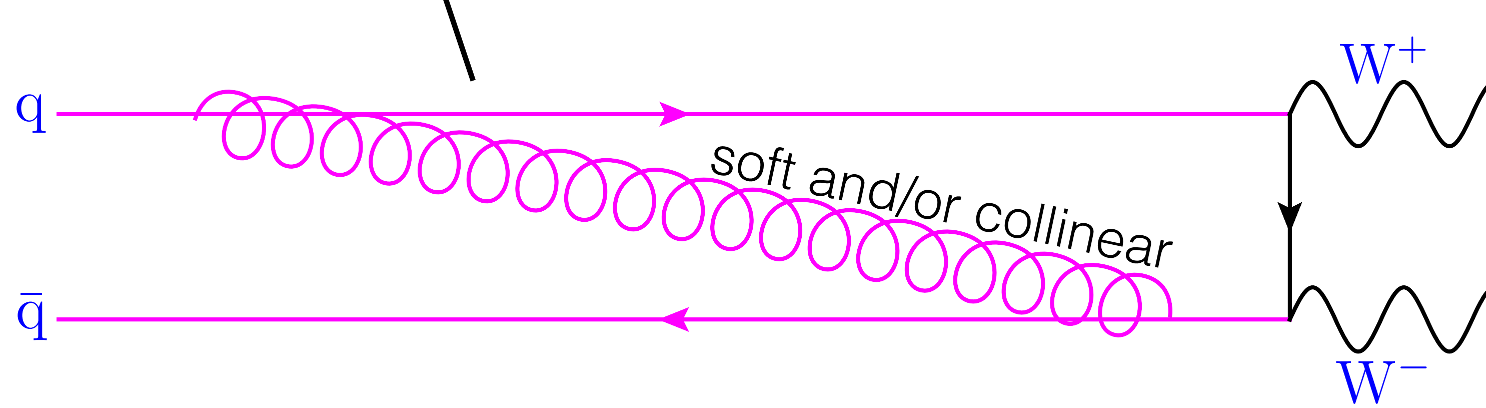
Actually, **worse** than this because

$\log \frac{M_{WW}^2}{(p_T^{veto})^2}$'s are from **IR** divergences from **initial states**

(soft and/or collinear)



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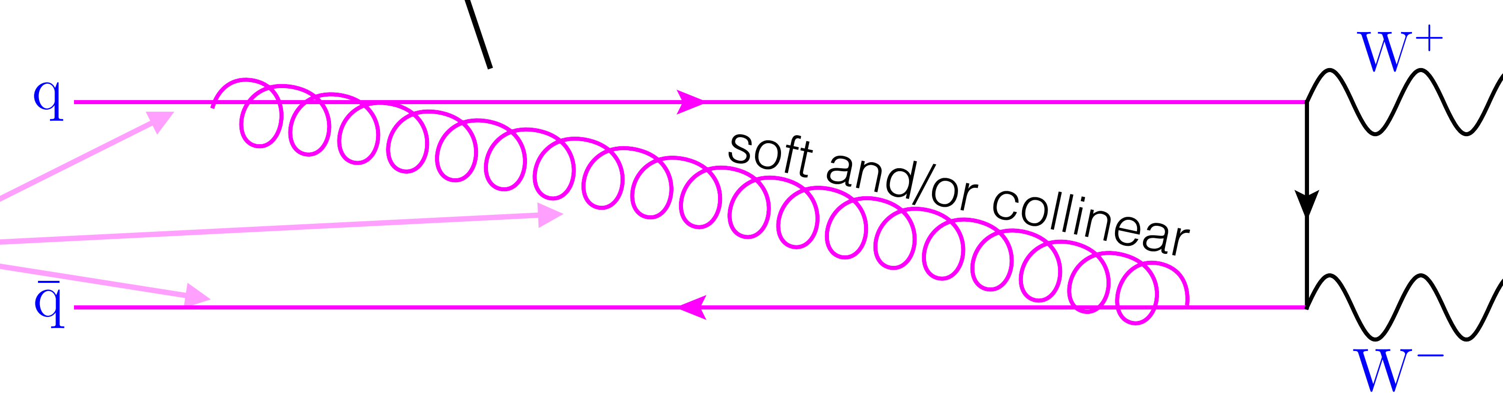
i.e., M_{WW}^2, not $\hat{t}$.



"$\log \frac{M_{WW}^2}{(p_T^{veto})^2}$" is actually $\log \frac{-\hat{s} - i0^+}{(p_T^{veto})^2} = \log \frac{M_{WW}^2}{(p_T^{veto})^2} - i\pi$

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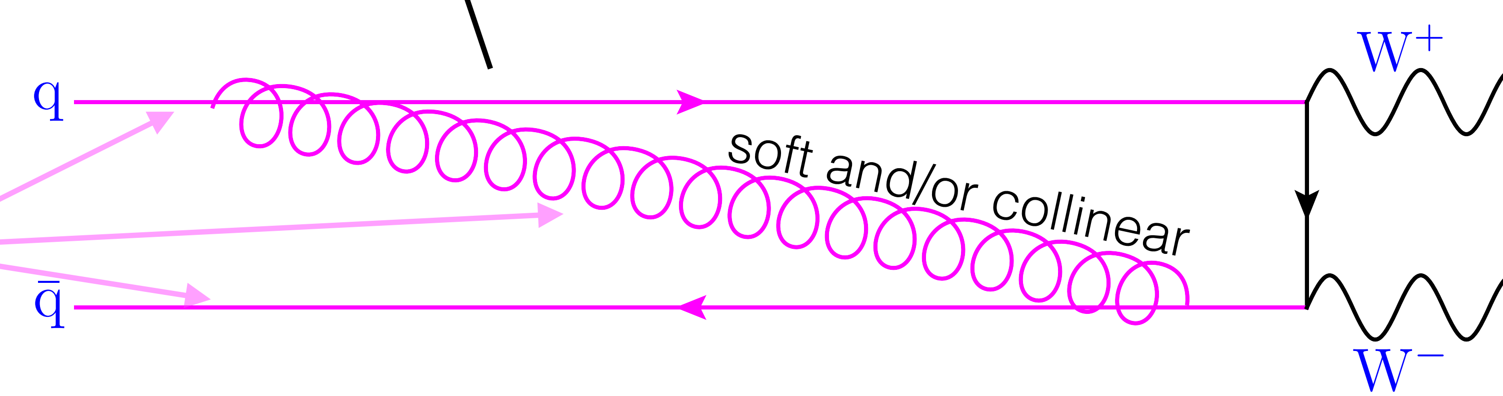

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from $\alpha_s \log^2$

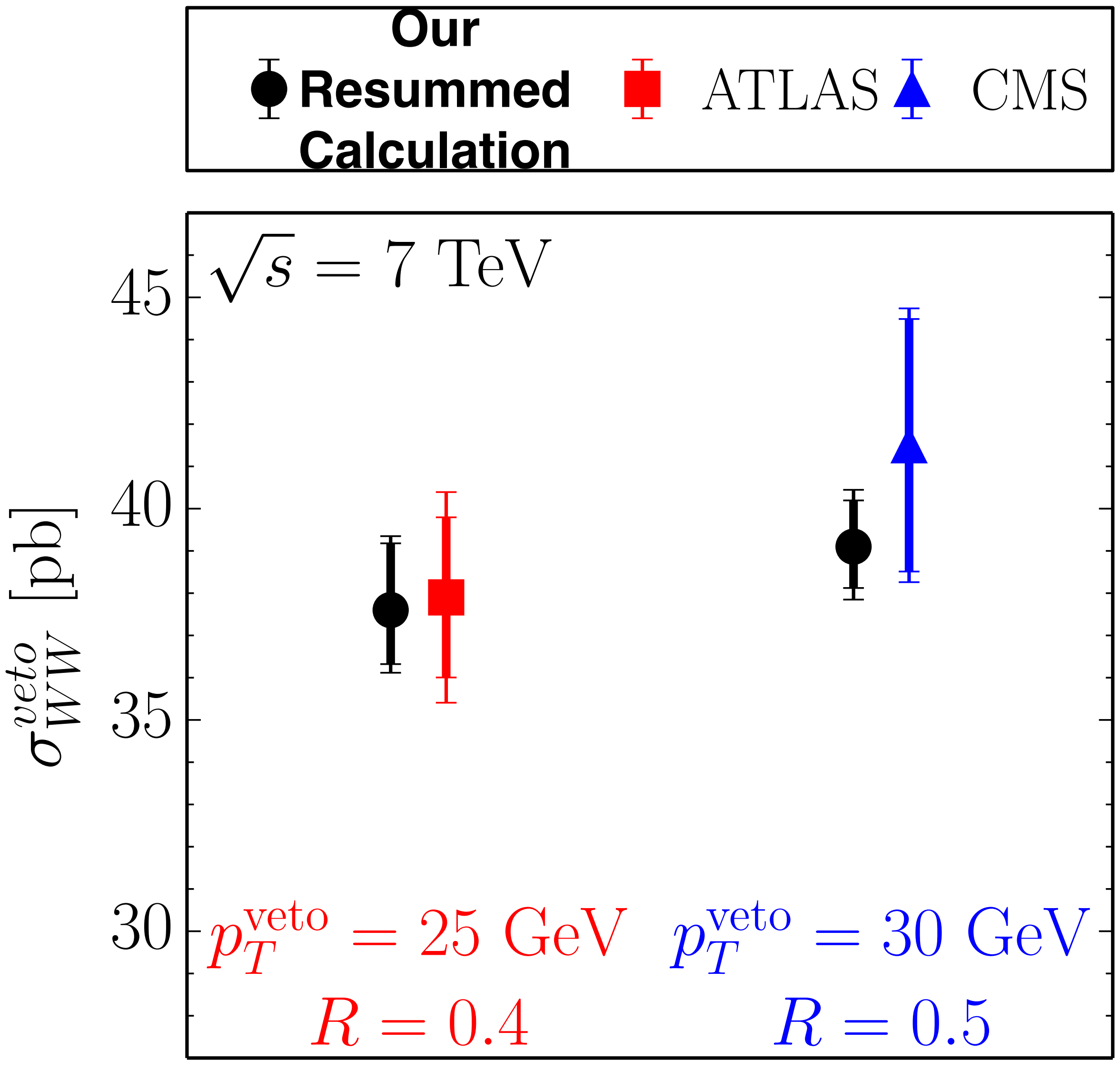
$\pi^2 \sim 10$

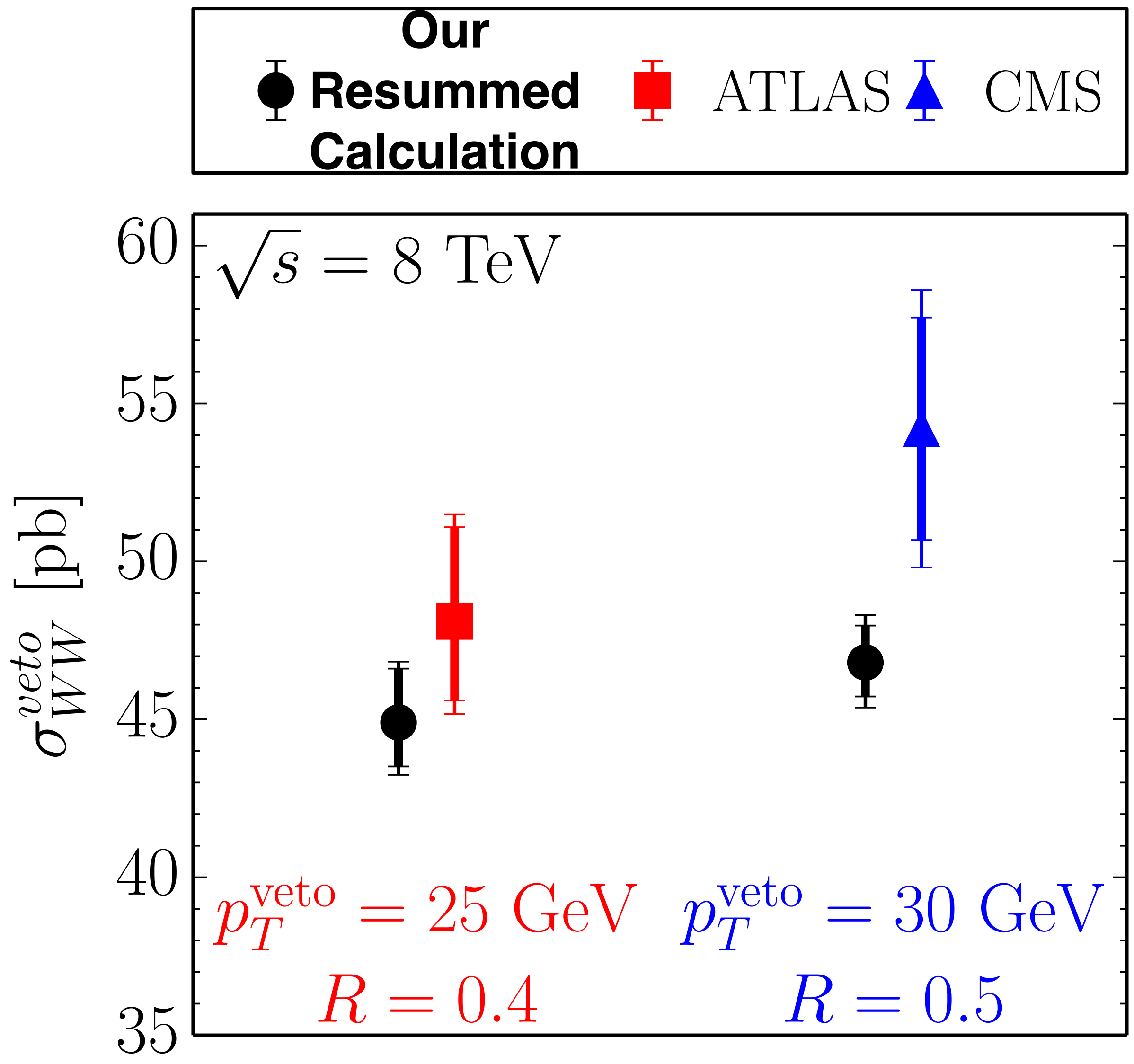
Big!

Must resume the whole $\log \frac{-M_{WW}^2 - i0^+}{(p_T^{veto})^2}$ **!!**

So we did.

Comparing *jet-veto* cross-sections directly:





Nicely compatible!

How did we do it?

Resummation automatic if "right viewpoint" adopted.

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Vertices — Easy.

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We should use a **maximally vertices-like** lagrangian,
(for the processes in question)
aka an effective field theory!

In “familiar” EFTs (to BSM model builders) e.g. Fermi theory

Particles

- *Guaranteed-off-shell* particles — e.g. $Z, W^{\pm}$
- *Can-be-on-shell* particles — e.g. q, γ

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used in this work

In more general EFTs (e.g. HQET, NRQED, **SCET**)

Do the same thing **mode-by-mode**

(a la Wilson, except in Minkowski instead of Euclidean space)

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Fourier modes

Guaranteed-off-shell modes

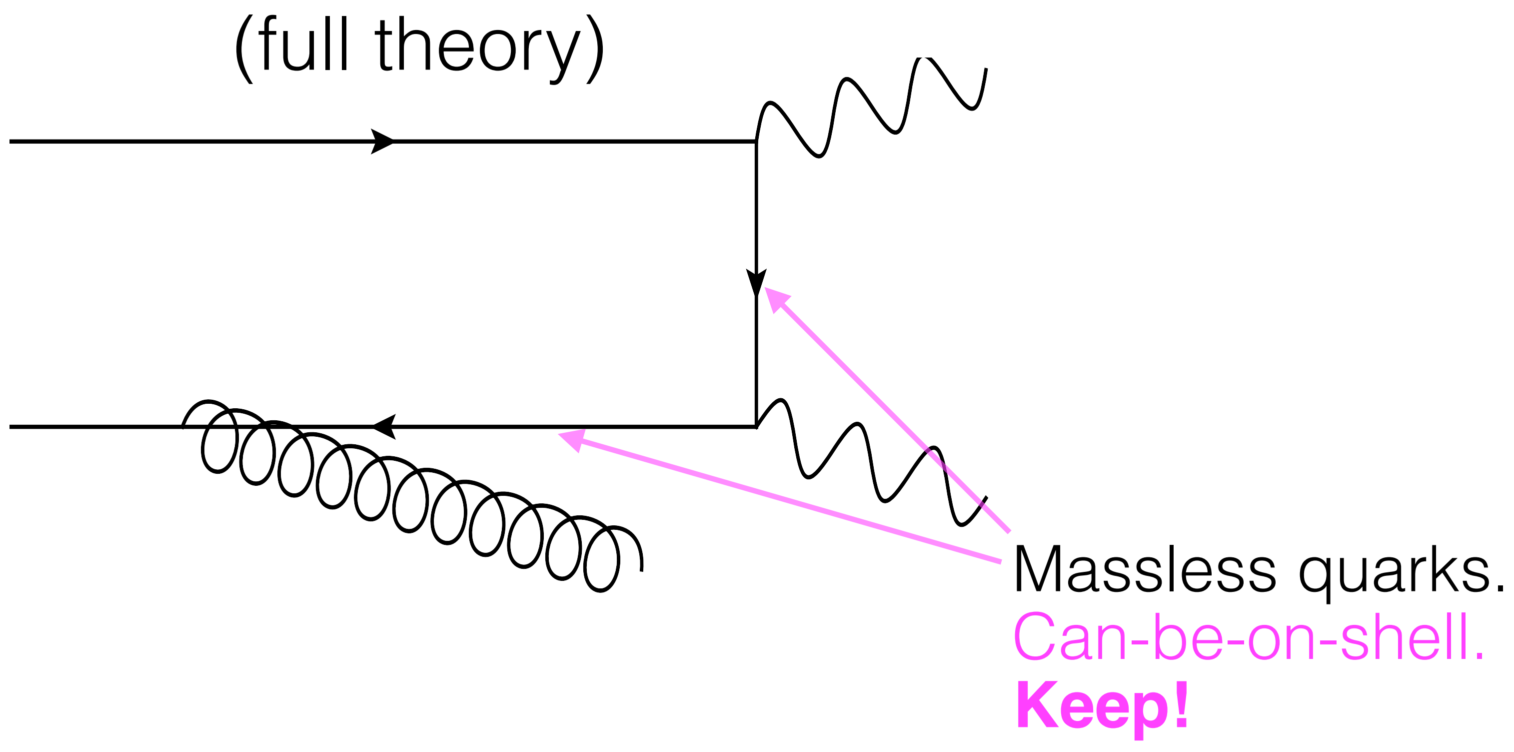
Can-be-on-shell modes

Convert propagators to vertices

Keep propagators as they are

What's the difference?

In familiar EFTs:



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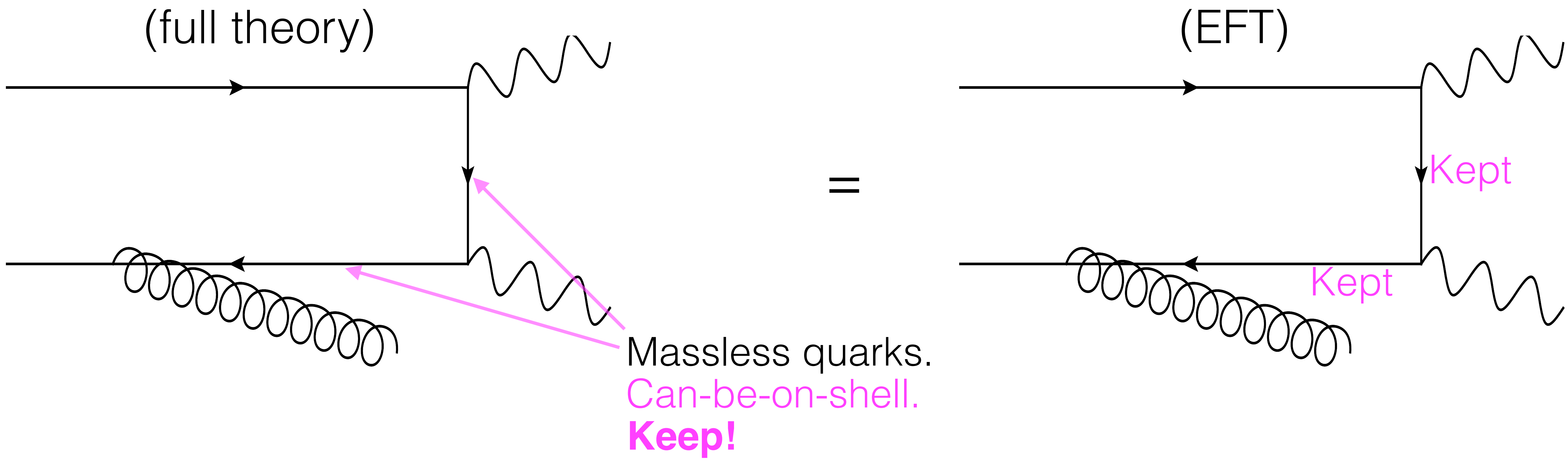

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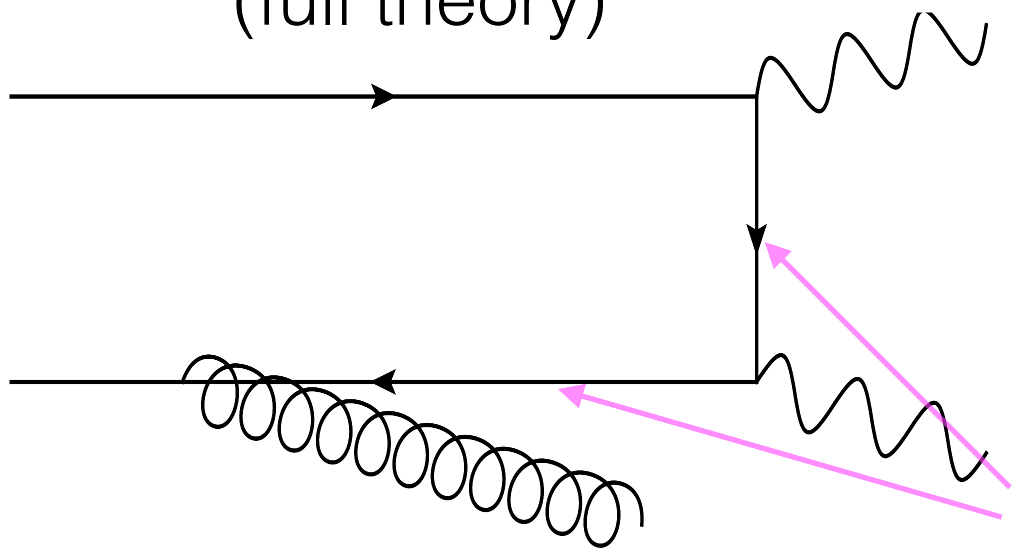
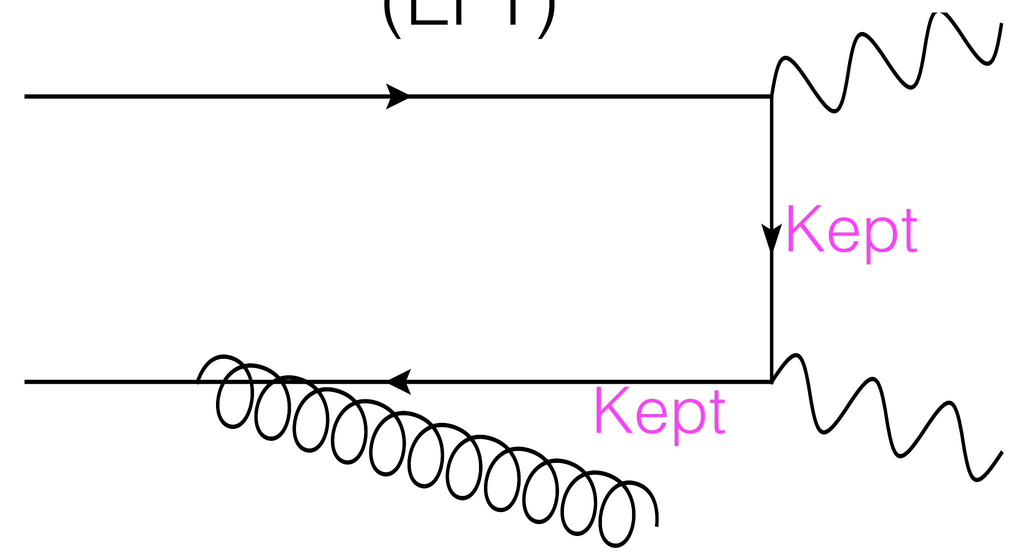


Massless quarks.
Can-be-on-shell.
Keep!

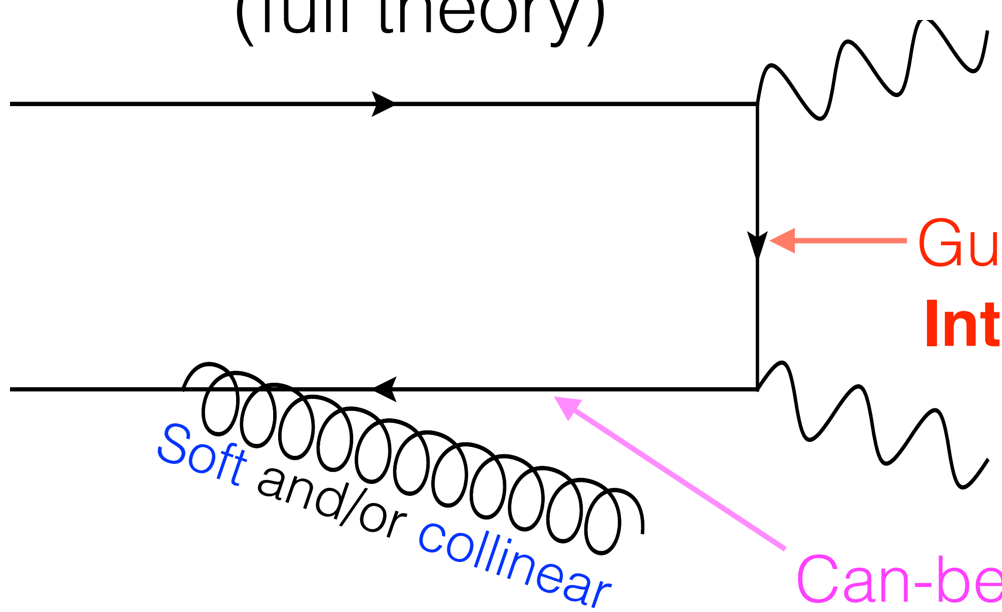
=

(EFT)



In SCET:

(full theory)



Guaranteed-off-shell.
Integrate out!

Can-be-on-shell.
Keep!

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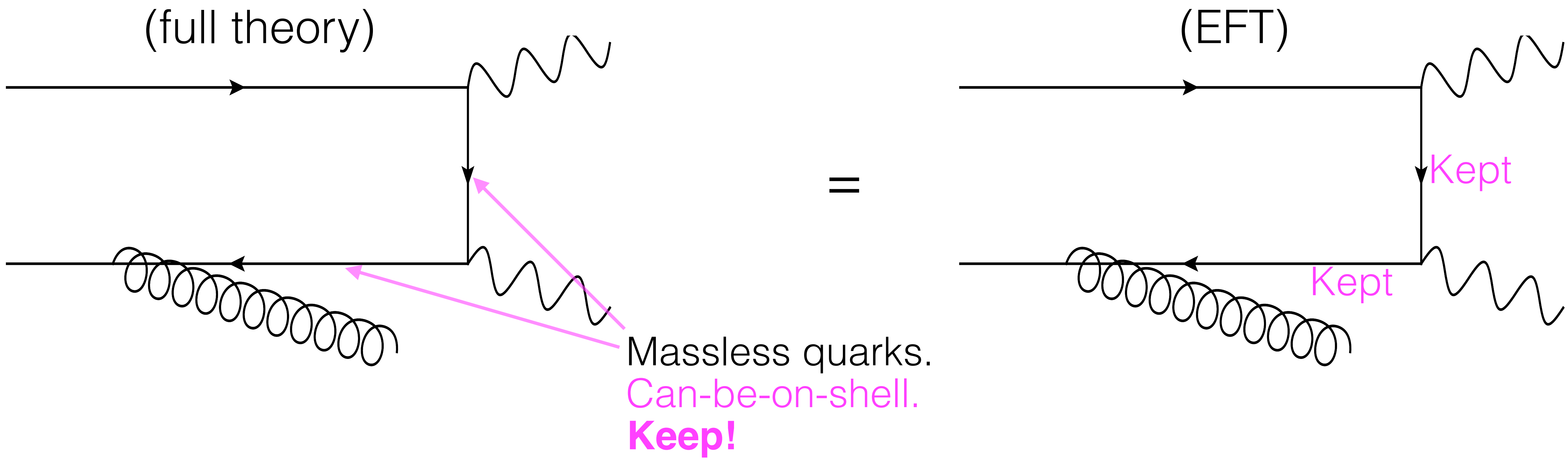

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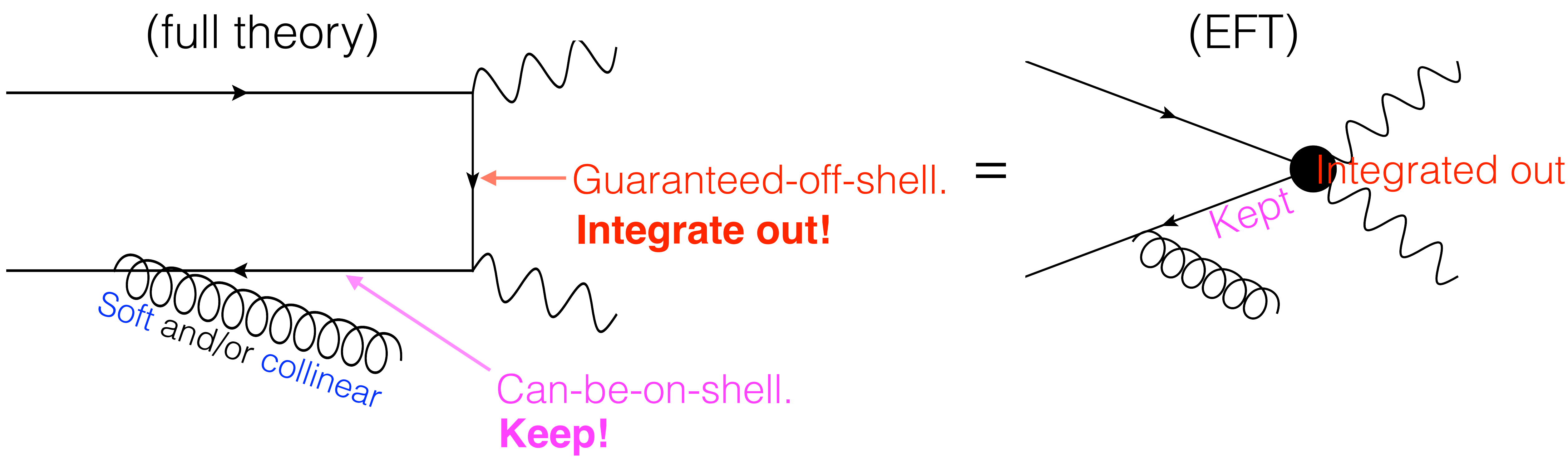
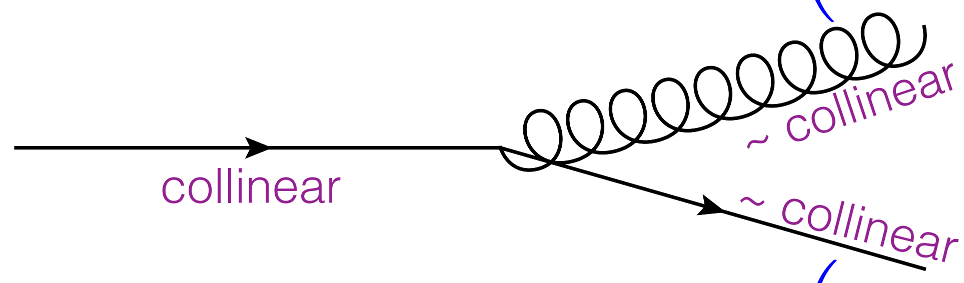


Can-be-on-shell modes may be divided further

$$k = \Big(zE,\ 0,\ p_{\rm T},\ zE + \mathcal{O}(p_{\rm T}^2/E)\Big)$$

$$p = (E,\ 0,\ 0,\ E)$$



$$q = \Big((1-z)E,\ 0,\ -p_{\rm T},\ (1-z)E - \mathcal{O}(p_{\rm T}^2/E)\Big)$$

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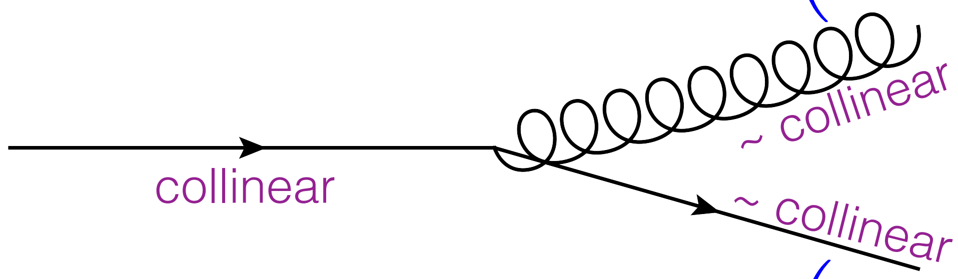

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Collinear can-be-on-shell modes have large positive rapidity:

$$\eta = \frac{1}{2}\log\frac{k^0+k^3}{k^0-k^3} \sim \log\frac{E}{p_{\rm T}^2/E} \sim \log\frac{E}{p_{\rm T}} \gg 1$$

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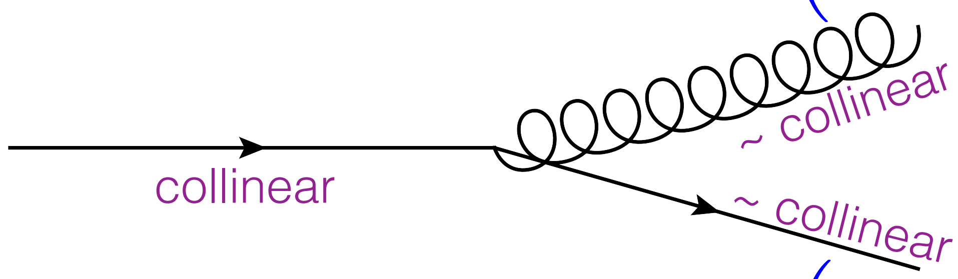

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Anticollinear modes have large negative rapidity:

$$\eta \sim \log\frac{p_{\mathrm{T}}^2/E}{E} \sim -\log\frac{E}{p_{\mathrm{T}}} \ll -1$$

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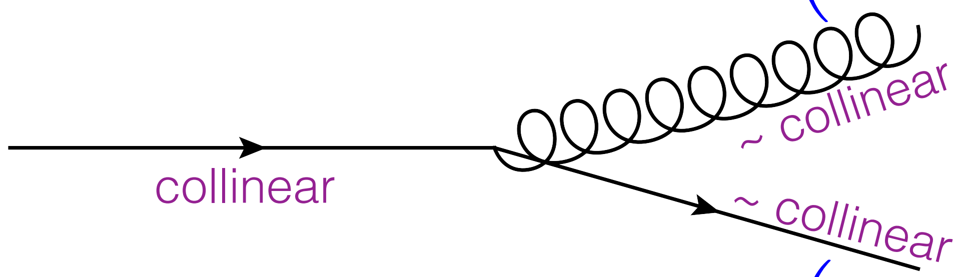

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Collinear/anticollinear modes obey **different scaling laws:**

Their $k^0 \pm k^3$ components scale oppositely in $\dfrac{E}{p_{\rm T}}$.
Their virtualities are the same, $k^2 \sim p_{\rm T}^2$.

Multiple cutoffs in EFT

Artificial boundaries to separate different groups of modes

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All EFTs have a "UV" cutoff Λ:

$$\begin{cases} |p^2 - m^2| > \Lambda^2 & \text{Guaranteed-off-shell. Integrate it out!} \\ |p^2 - m^2| < \Lambda^2 & \text{Can-be-on-shell. Keep it!} \end{cases}$$

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We also need a *rapidity cutoff* $\eta_{\mathrm{c}} \gg 1$:

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We have TWO cutoffs! (Boundaries b/w on- vs off-shell modes & b/w collinear vs anticollinear modes)

Multiple Renormalization Groups

Cutoffs are **artificial** mode boundaries.

Physical observables should be

Λ independent

η_c independent

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Λ independent $\longrightarrow$ $\Lambda \frac{\partial}{\partial \Lambda} \cdots = \cdots$ Familiar RGEs (Virtuality)

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(We only like $\pm\infty$ for limits of integration!)

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(ii) (Re)regulate integrals by "unbounded" regulators.

Dim reg for divergences from $\Lambda \to \infty$: ~~Λ~~ ⟶ $1/\epsilon\,,\ \mu$

Analytic reg for divergences from $\eta_c \to 0$: ~~η_c~~ ⟶ $1/\alpha\,,\ \nu$

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$\longrightarrow$ Divergences!

(ii) (Re)regulate integrals by "unbounded" regulators.

Dim reg for divergences from $\Lambda \to \infty$: ~~Λ~~ $\longrightarrow$ $1/\epsilon\,,\ \mu$

Analytic reg for divergences from $\eta_c \to 0$: ~~η_c~~ $\longrightarrow$ $1/\alpha\,,\ \nu$

(iii) Correct "mistakes" by renormalization.

Multiple Renormalization Groups

Cutoffs are **artificial** mode boundaries.

Physical observables should be

Λ independent ⟶ $\Lambda \frac{\partial}{\partial \Lambda} \cdots = \cdots$ Familiar RGEs (Virtuality)

η_{c} independent ⟶ $\eta_{\mathrm{c}} \frac{\partial}{\partial \eta_{\mathrm{c}}} \cdots = \cdots$ *Rapidity* RGEs!

In practice, sharp boundaries are cumbersome.

(We only like $\pm\infty$ for limits of integration!)

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Then,

Virtuality RGEs: $\mu \frac{\partial}{\partial \mu} \cdots = \cdots$ Rapidity RGEs: $\nu \frac{\partial}{\partial \nu} \cdots = \cdots$

The Strategy

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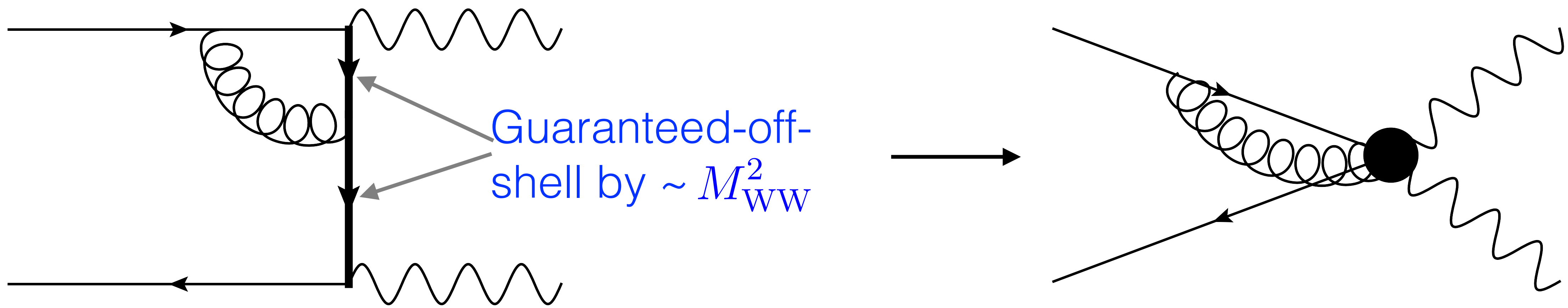
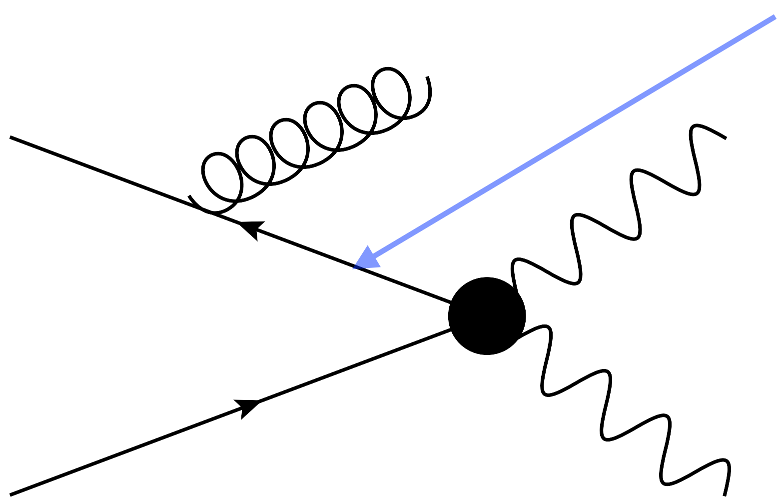


At this point,



Allowed virtuality ~ $O(M_{\mathrm{WW}}^2)$

i.e. $p \sim (E, 0, p_{\mathrm{T}}, E)$

where $p^2 \sim p_{\mathrm{T}}^2$ can be $O(M_{\mathrm{WW}}^2)$

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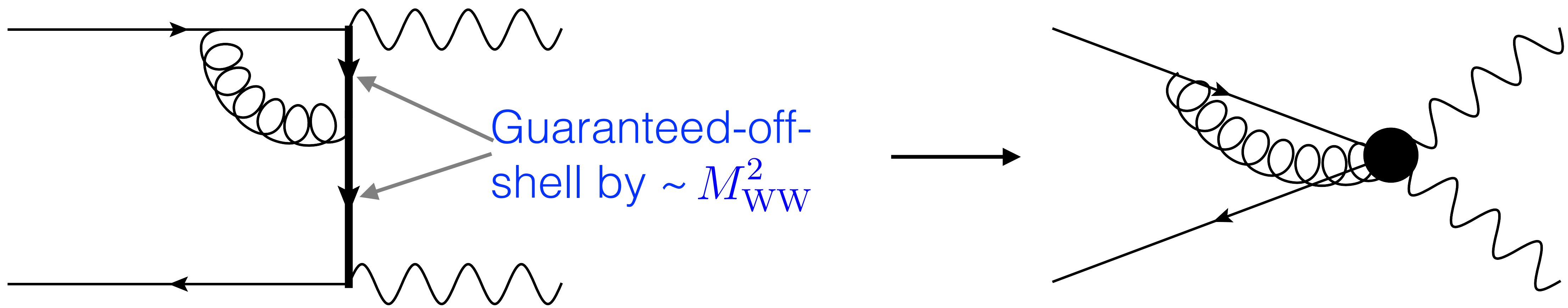

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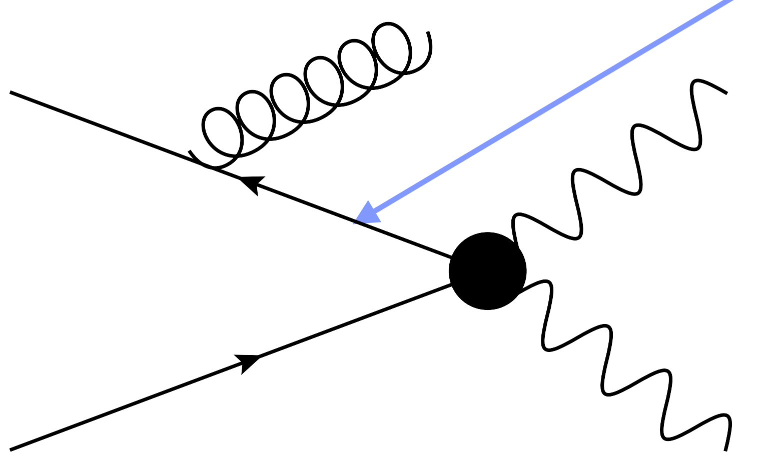

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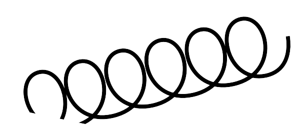
But this $p_{\rm T}$ = $p_{\rm T}$ of  .

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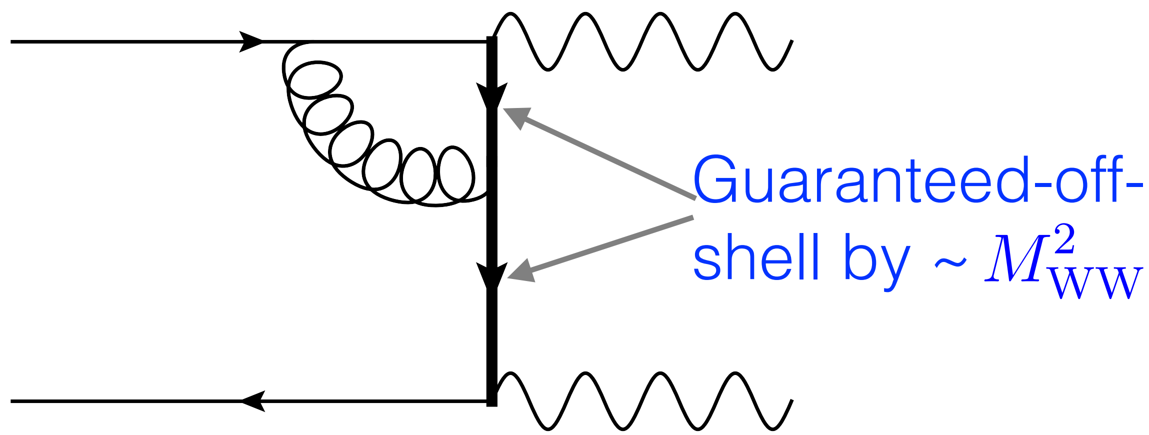
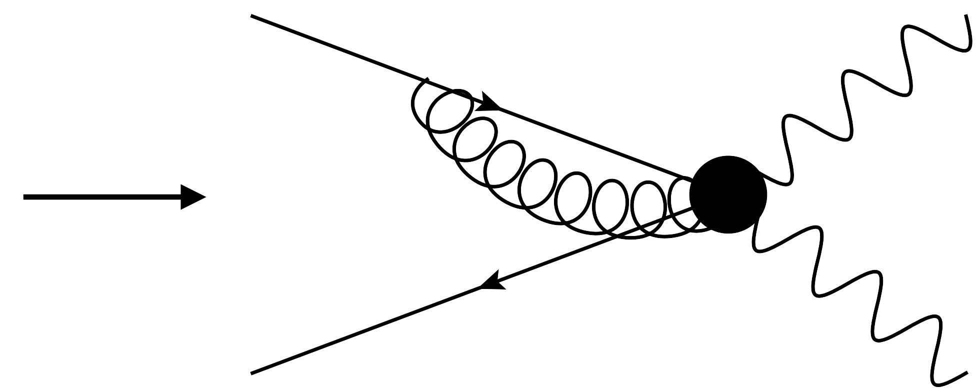
e.g. 



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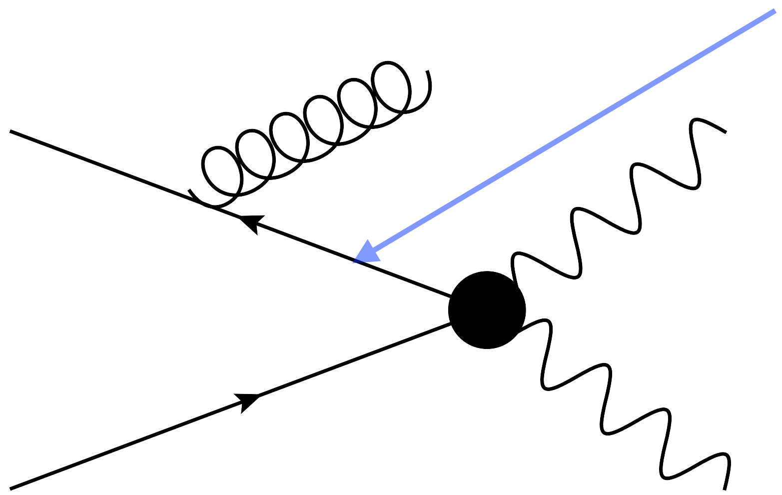

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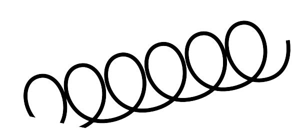
But this $p_{\rm T}$ = $p_{\rm T}$ of  .

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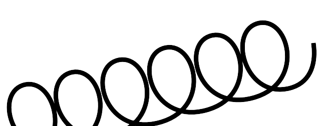
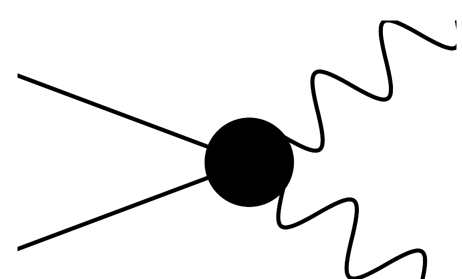
Don't attach  **to**  **yet!**

The Strategy

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(3) Run p_T RGE to lower allowed virtuality from $\mu \sim M_\mathrm{WW}$ to $\mu \sim p_\mathrm{T}^\mathrm{veto}$.

No large logs, b/c it's just matching EFT at μ onto EFT at $\mu - \mathrm{d}\mu$.

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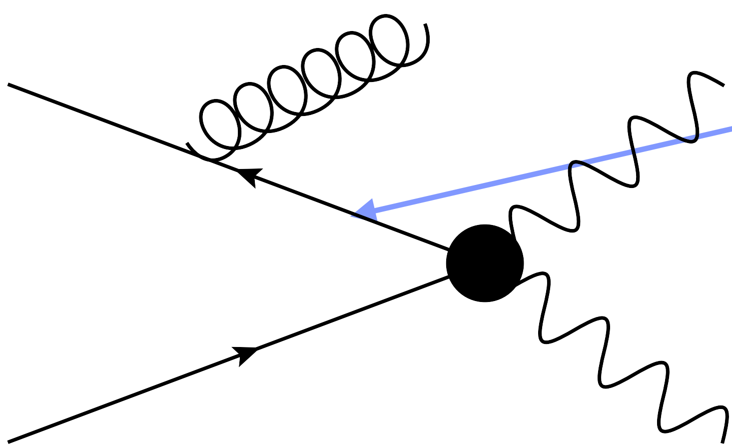
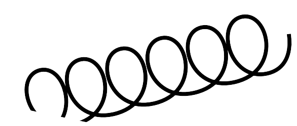


Allowed virtuality ~ $p_{\mathrm{T}}^{\mathrm{veto}}$

→ p_{T} of  is at most ~ $p_{\mathrm{T}}^{\mathrm{veto}}$

Consistent with jet veto!

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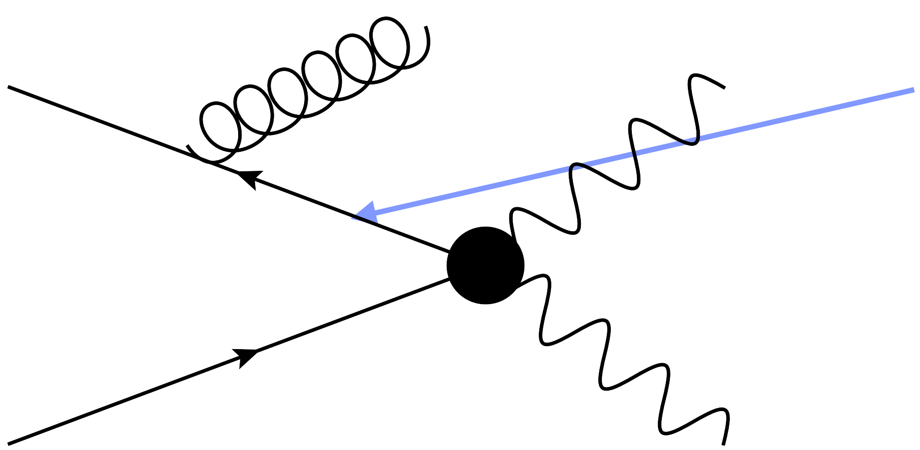

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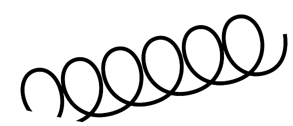
→ p_{T} of  is at most ~ $p_{\mathrm{T}}^{\mathrm{veto}}$

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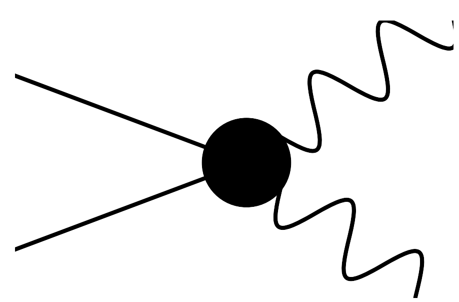
(4) Attach real gluons to . **No large logs** since $\frac{\mu}{p_{\mathrm{T}}^{\mathrm{veto}}} \sim 1\,!$

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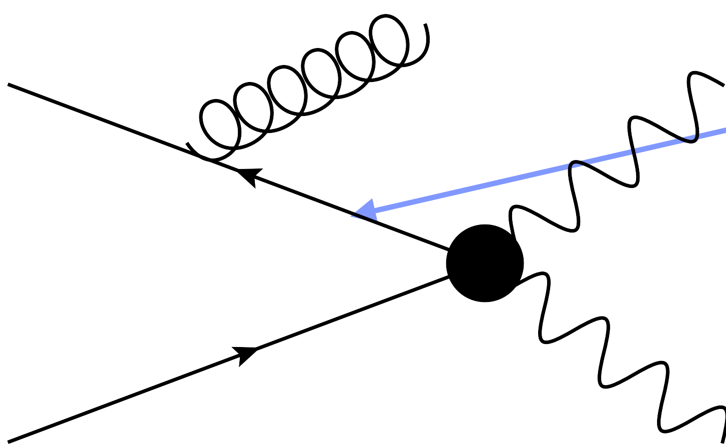

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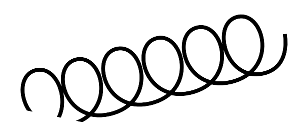
→ $p_{\rm T}$ of  is at most ~ $p_{\rm T}^{\rm veto}$

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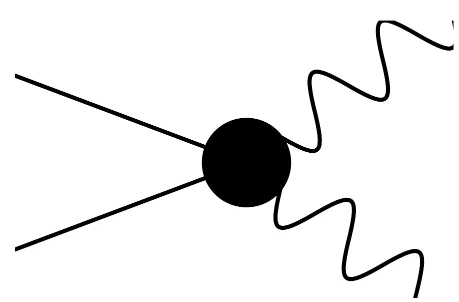
(4) Attach real gluons to . **No large logs** since $\frac{\mu}{p_{\rm T}^{\rm veto}} \sim 1$!

(5) Perform jet-clustering and impose jet veto.

(N.B.) In steps (1) & (3), take $\mu^2 < 0$ to also resum π^2 terms.

Other building blocks:

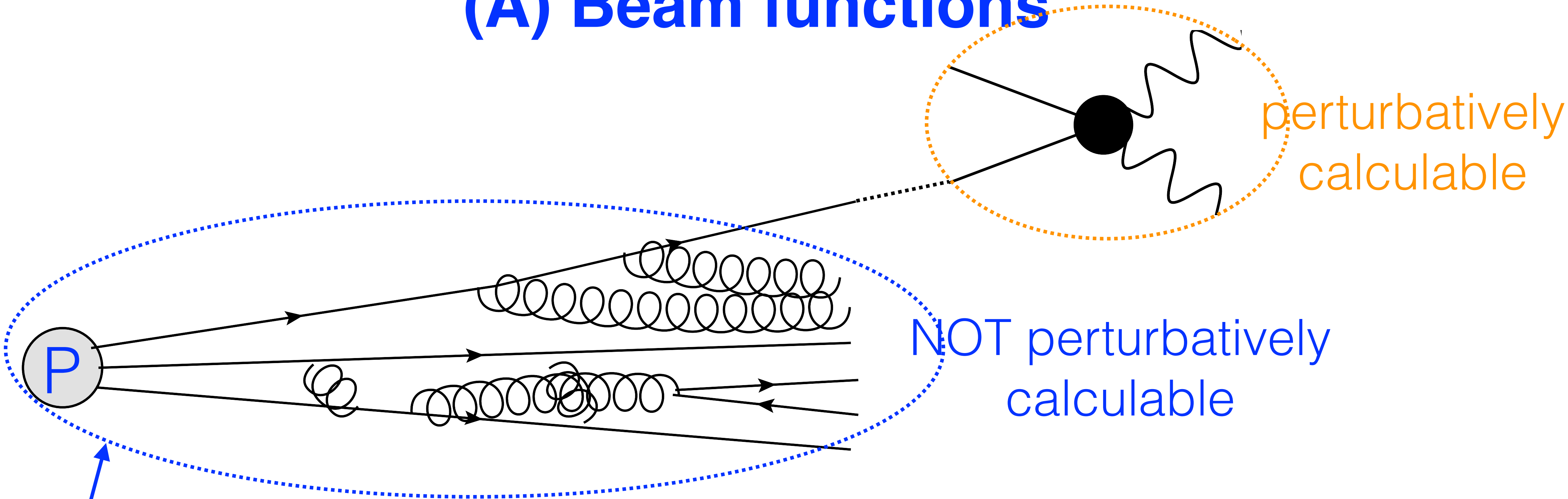
(A) Beam functions

(B) Nonlocality

(C) Multiple $\mathrm{SU}(3)_{\mathrm{C}}$ gauge groups

(D) Wilson lines

(A) Beam functions



Isn't it just described by PDFs?

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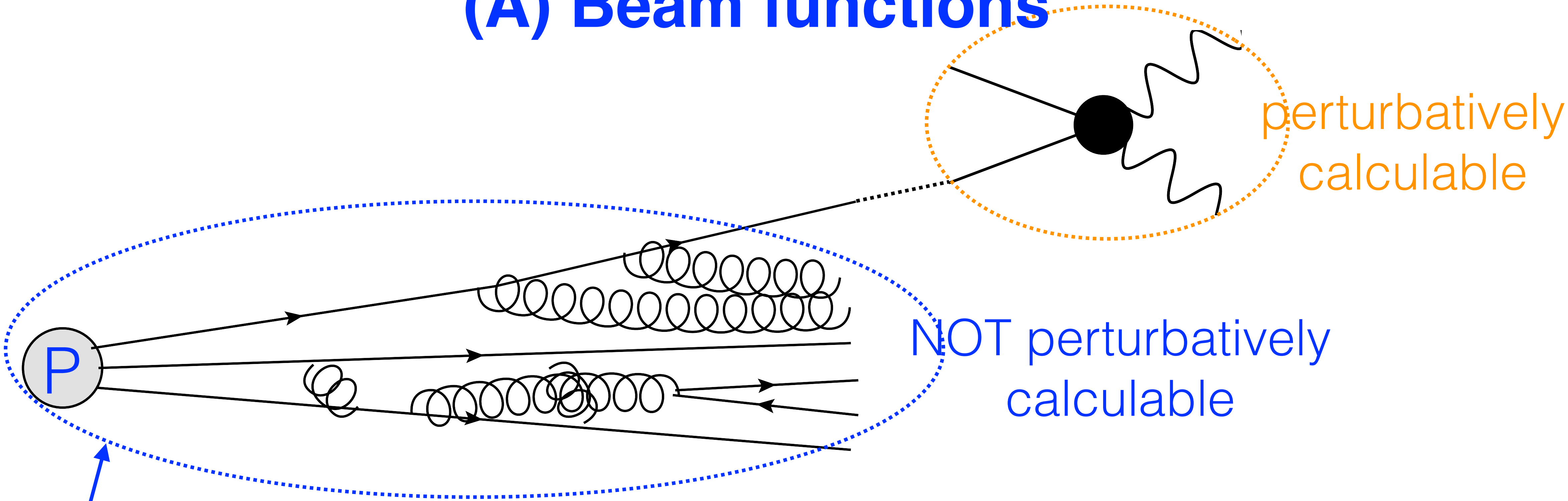

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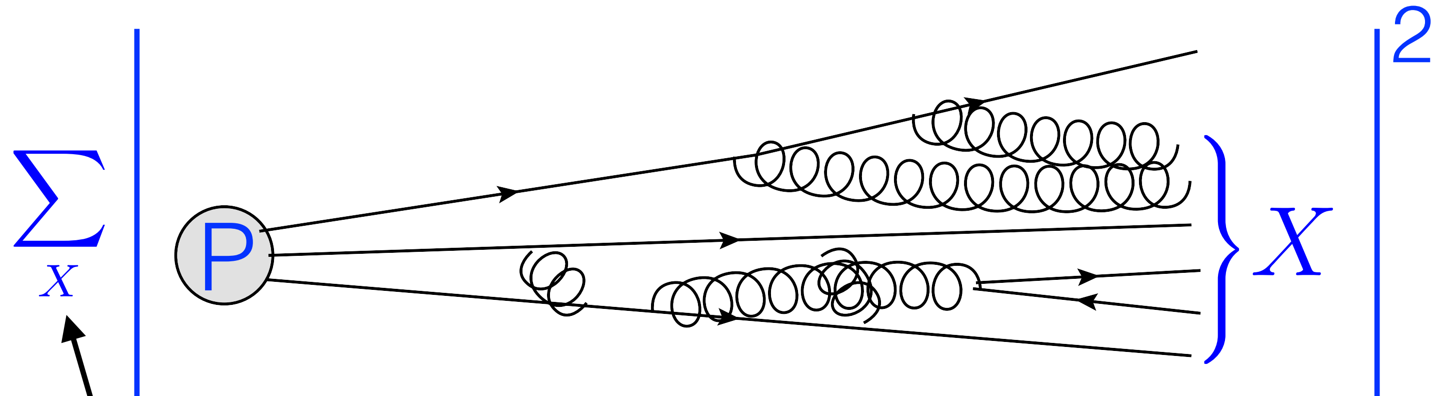
PDF =



over all X

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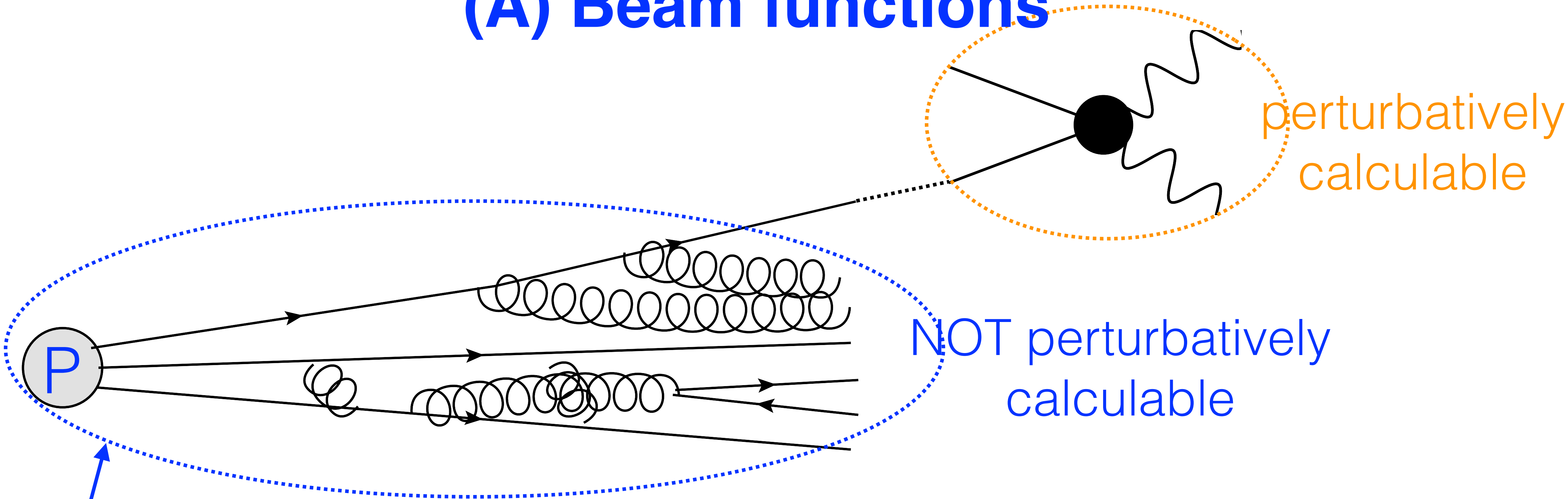

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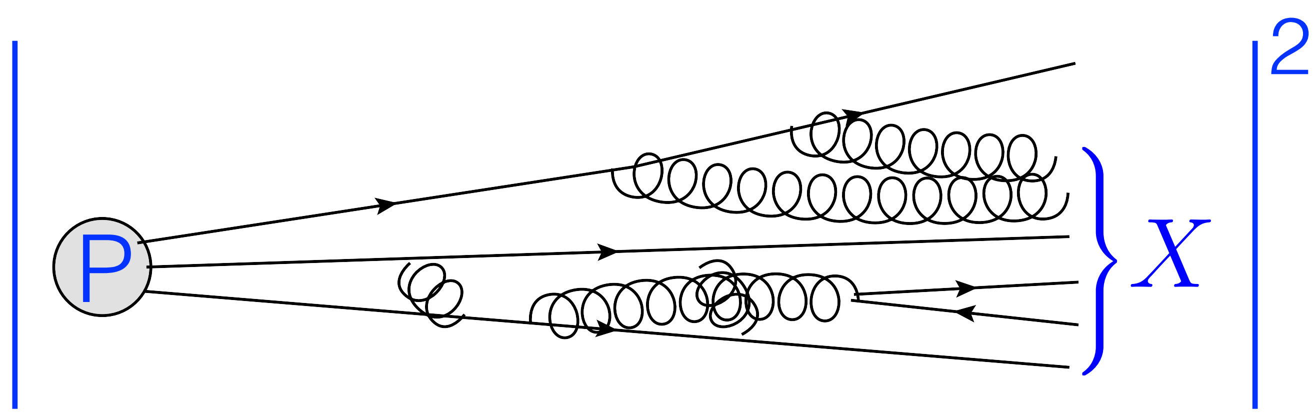
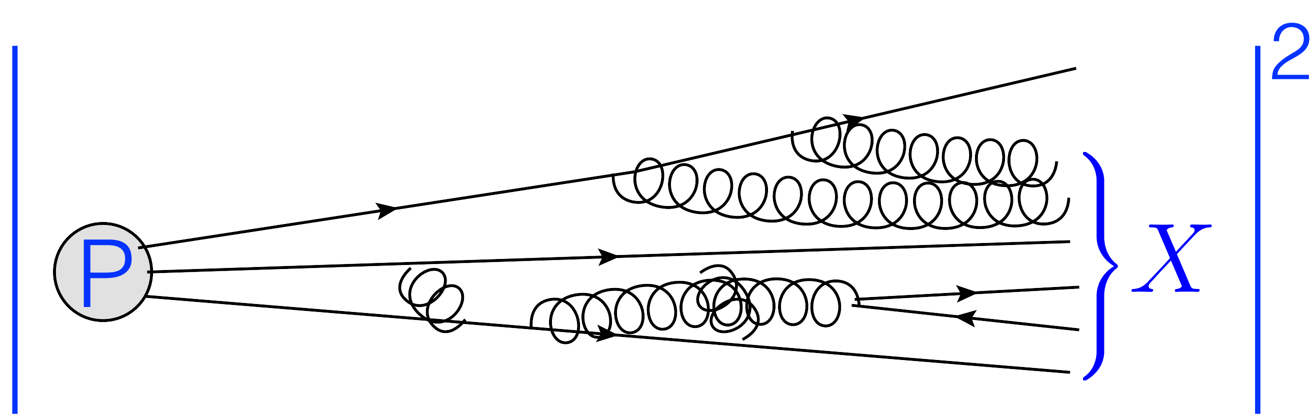
PDF = $\sum_X$



over all X

But we want $\sum_X$



= Beam function

over all X passing jet veto

(B) Nonlocality

In "familiar" EFTs:

Lagrangians are expanded in $\frac{\partial_\mu}{\Lambda}$ which is $\ll 1$ for all μ

⟶ Isotropically local lagrangians

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In our SCET:

Collinear momenta = $\left\{ \begin{array}{rcl} p^{1,2} & \sim & \epsilon M_{\mathrm{WW}} \\ p^0 - p^3 & \sim & \epsilon^2 M_{\mathrm{WW}} \\ p^0 + p^3 & \sim & M_{\mathrm{WW}} \end{array} \right.$ with $\epsilon \equiv \frac{p_{\mathrm{T}}^{\mathrm{veto}}}{M_{\mathrm{WW}}} \ll 1$

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locality in $x_0 - x_3$

Expansion in $\partial^0 + \partial^3$ cannot be truncated!

Collinear sector is NON-local in $x_0 + x_3$!

Similarly, anticollinear sector is non-local in $x_0 - x_3$.

(C) Multiple $\mathrm{SU}(3)_{\mathrm{C}}$ gauge groups

Global $\mathrm{SU}(3)_{\mathrm{C}}$ — a **real** symmetry in full theory, a **real** symmetry in EFT.

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<u>In full theory</u>

Only one gluon field with all possible Fourier modes

⟶ Need $\mathrm{SU}(3)_\mathrm{C}$ gauge transformations with all possible modes

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So, we need **two** sets of gauge transformations:

Collinear $\mathrm{SU}(3)_C$ = gauge transformations w/ collinear modes only

q = triplet $\bar{\mathrm{q}}$ = singlet

Anticoll. $\mathrm{SU}(3)_C$ = gauge transformations w/ anticoll. modes only

q = singlet $\bar{\mathrm{q}}$ = triplet

(D) Wilson lines

But, wait! Under $\mathrm{SU(3)_{coll}} \times \mathrm{SU(3)_{anti\text{-}coll}}$, WW production vertex

$$W_\mu^+ W_\nu^- \bar{q} \Gamma^{\mu\nu} q$$ is NOT invariant! (It's still invariant under $\mathrm{SU(3)_{global}}$.)

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What should we do? Exploit the nonlocality!

Define a *collinear Wilson line:*

$$W_{\mathrm{c}} = \hat{\mathcal{P}} \exp\left[-\mathrm{i} g_{\mathrm{c}} \int_{\mathcal{P}} \mathrm{d}x \cdot G_{\mathrm{c}}\right]$$

G_{c}: Collinear gluon

$\mathcal{P}$: Straight path in $x_0 + x_3$ direction

Allowed nonlocal direction for collinear fields

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$x_0 + x_3$ direction: Allowed nonlocal direction for collinear fields

Then, $\chi = W_{\mathrm{c}}^\dagger q$ is $\mathrm{SU}(3)_{\mathrm{coll}}$ invariant!

(Do the analogous thing in anticollinear sector.)

Differences from pT resummation

(P. Meade et al., arXiv:1407.4481)

(1) Jet-algorithm dependence

In Jet-veto resummation, $p_{\mathrm{T}} < p_{\mathrm{T}}^{\mathrm{veto}}$ jet-by-jet

In pT resummation, p_{T} = p_{T} of WW = p_{T} of all jets

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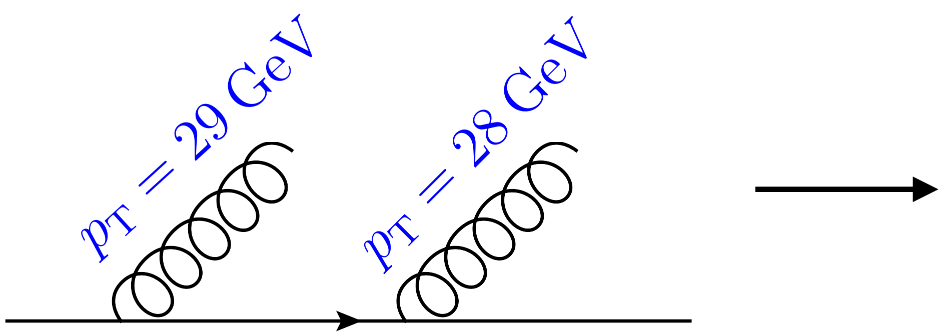

Passes jet veto with $p_{\rm T}^{\rm veto} = 30$ GeV if reconstructed as 2-jet event.

Don’t pass if deemed 1-jet event.

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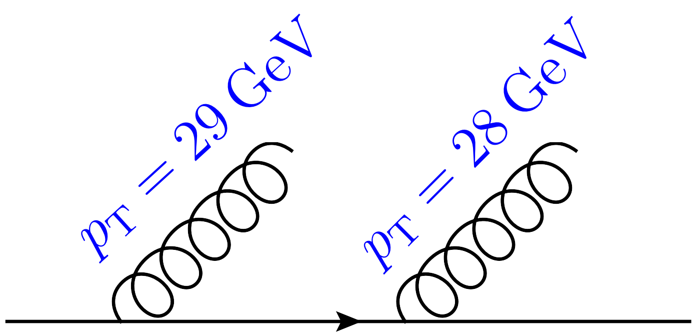

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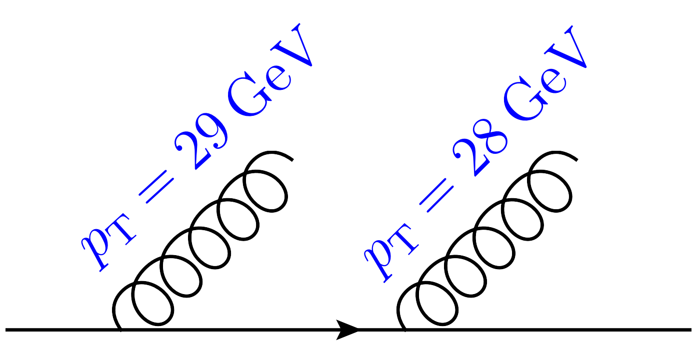

→ Always goes into the $57\text{-}\mathrm{GeV}$ bin.

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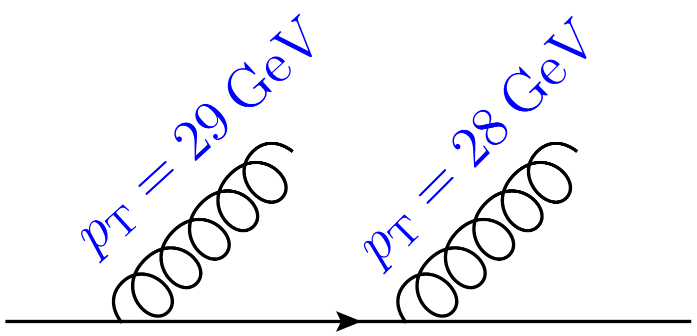

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Jet-veto cross-section depends on jet radius R at $O(\alpha_s^2)$

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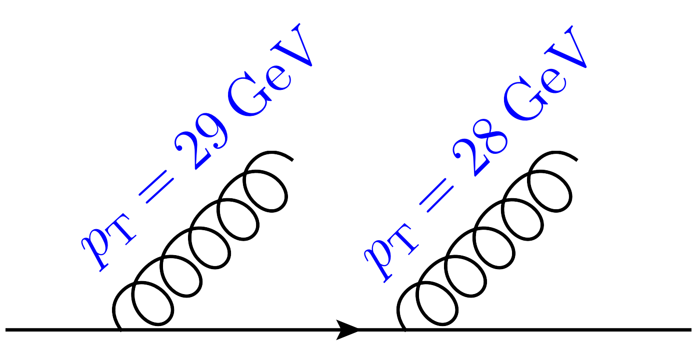

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No dependence on R!

Differences from pT resummation

(P. Meade et al., arXiv:1407.4481)

(2) π^2 resummation

We did.

The logs come as $\log\frac{-M_{\mathrm{WW}}^2-\mathrm{i}0^+}{\mu^2}=\log\frac{M_{\mathrm{WW}}^2}{\mu^2}-\mathrm{i}\pi$.

Unnatural (though possible) to resum only $\log\frac{M_{\mathrm{WW}}^2}{\mu^2}$ but not $\mathrm{i}\pi$.

They didn't.

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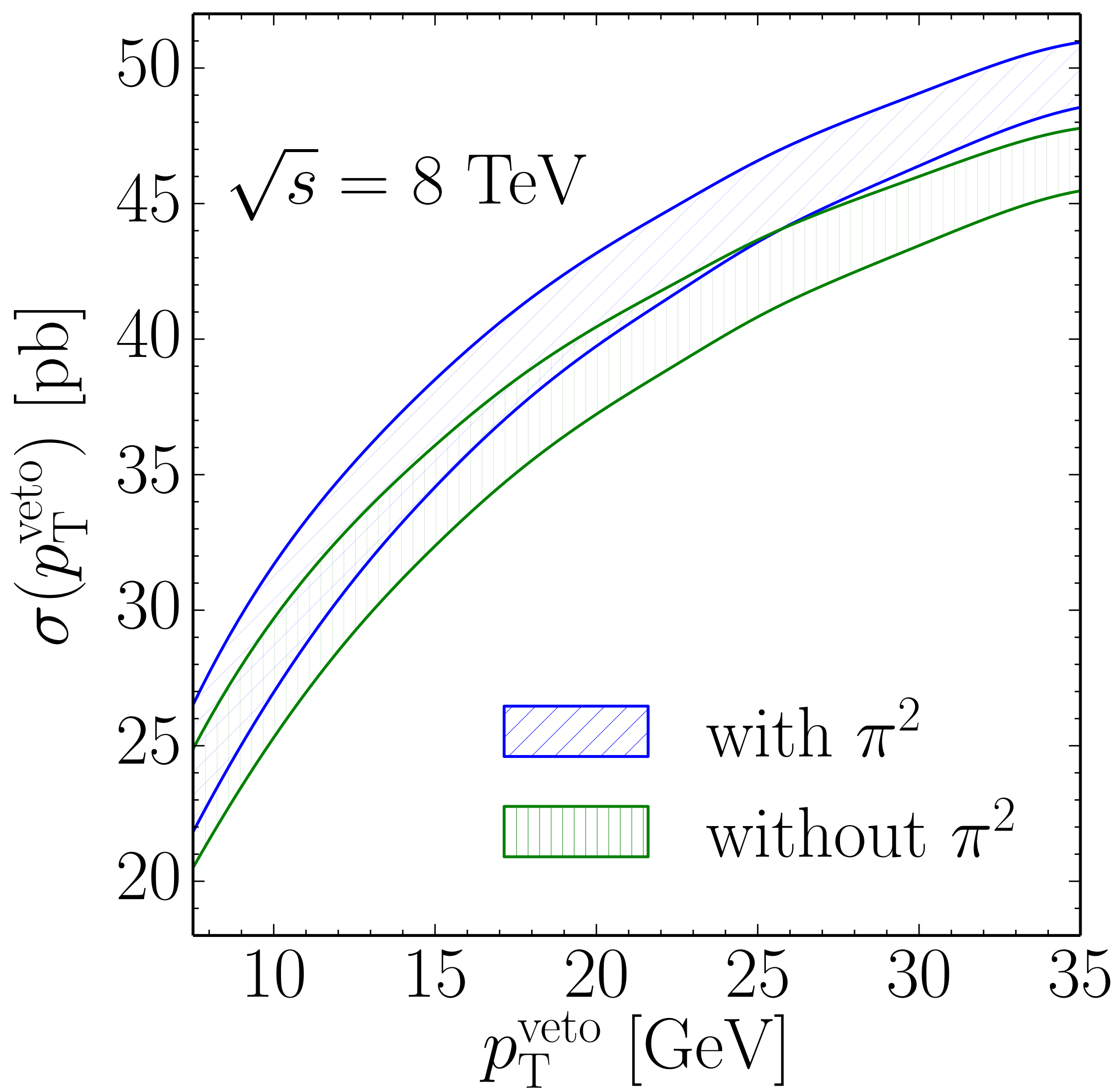
They didn't. Does it matter?



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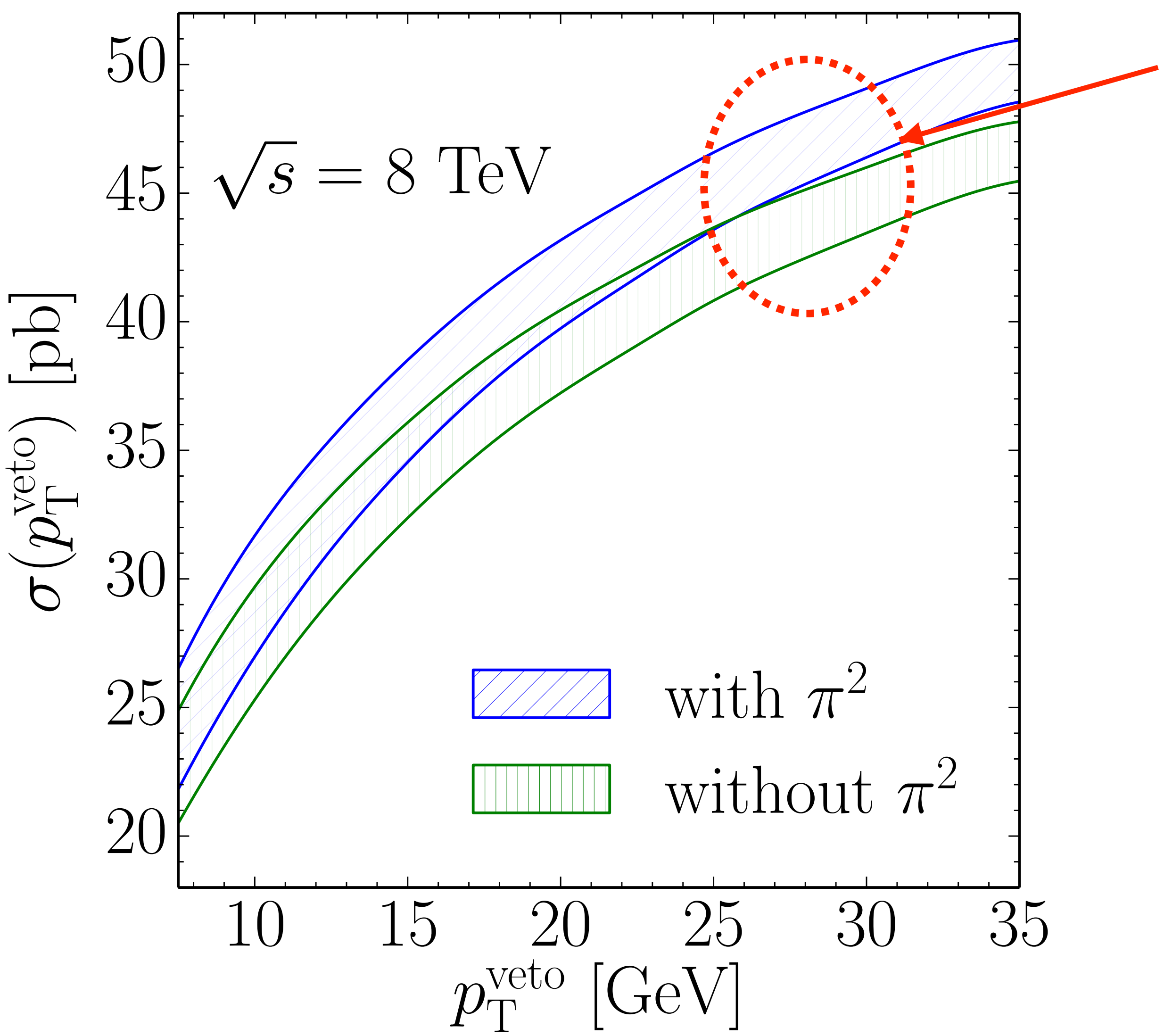
We did.

The logs come as $\log \frac{-M_{\rm WW}^2 - {\rm i}0^+}{\mu^2} = \log \frac{M_{\rm WW}^2}{\mu^2} - {\rm i}\pi$.

Unnatural (though possible) to resum only $\log \frac{M_{\rm WW}^2}{\mu^2}$ but not ${\rm i}\pi$.

They didn't. Does it matter?



Difference ~ 10% for $p_{\rm T}^{\rm veto} \sim 25$–$30$ GeV

Can explain difference b/w our and their results!

Differences from pT resummation

(P. Meade et al., arXiv:1407.4481)

(2) π^2 resummation

We did.

The logs come as $\log \frac{-M_{\rm WW}^2 - {\rm i}0^+}{\mu^2} = \log \frac{M_{\rm WW}^2}{\mu^2} - {\rm i}\pi$.

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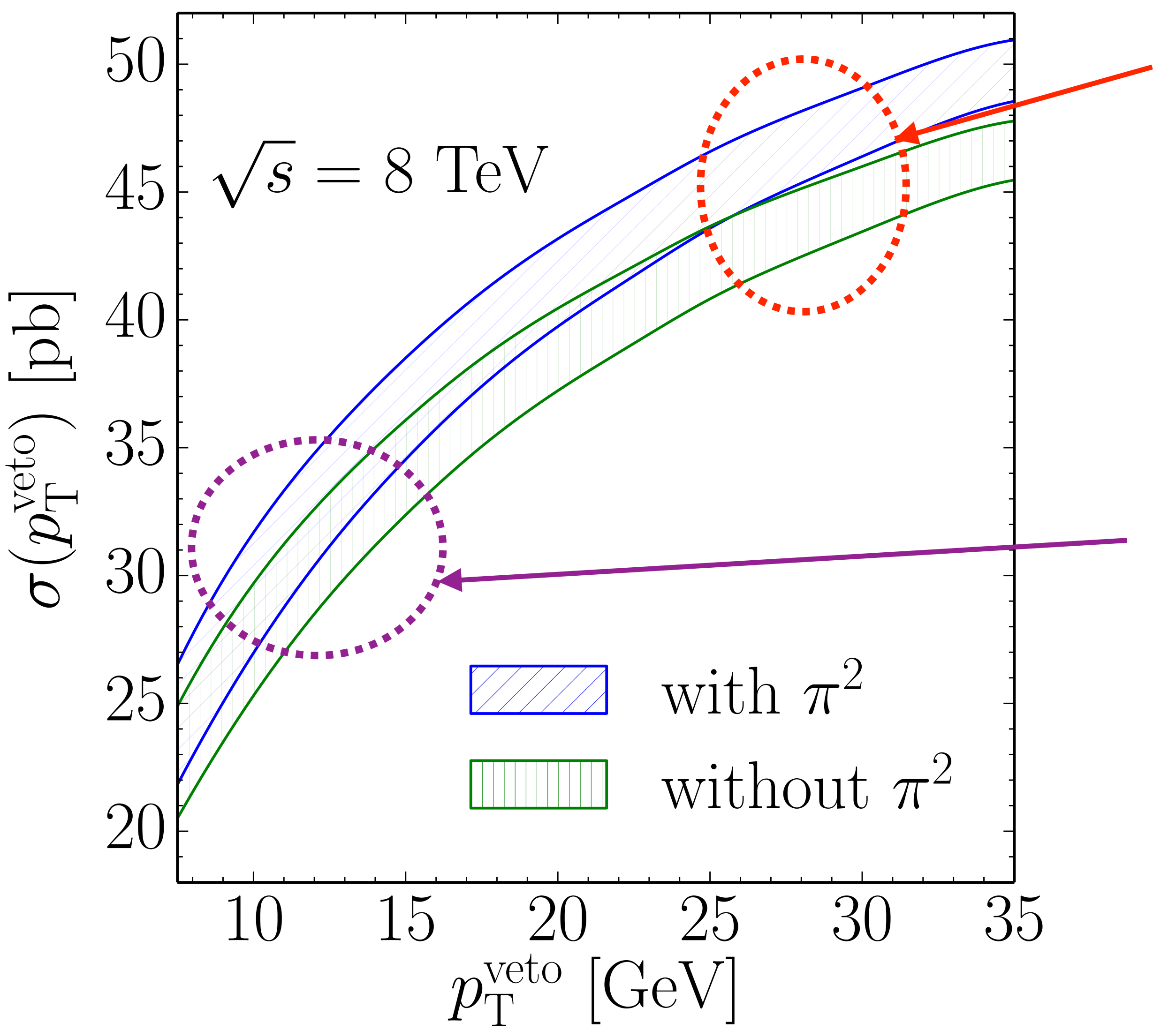


Difference ~ 10%
for $p_T^{\rm veto} \sim 25$–30 GeV

Can explain difference b/w our and their results!

Larger logs tend to cancel with π^2:

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

~10

Our results

Our results

Cross-sections

with π^2 | without π^2

Total:

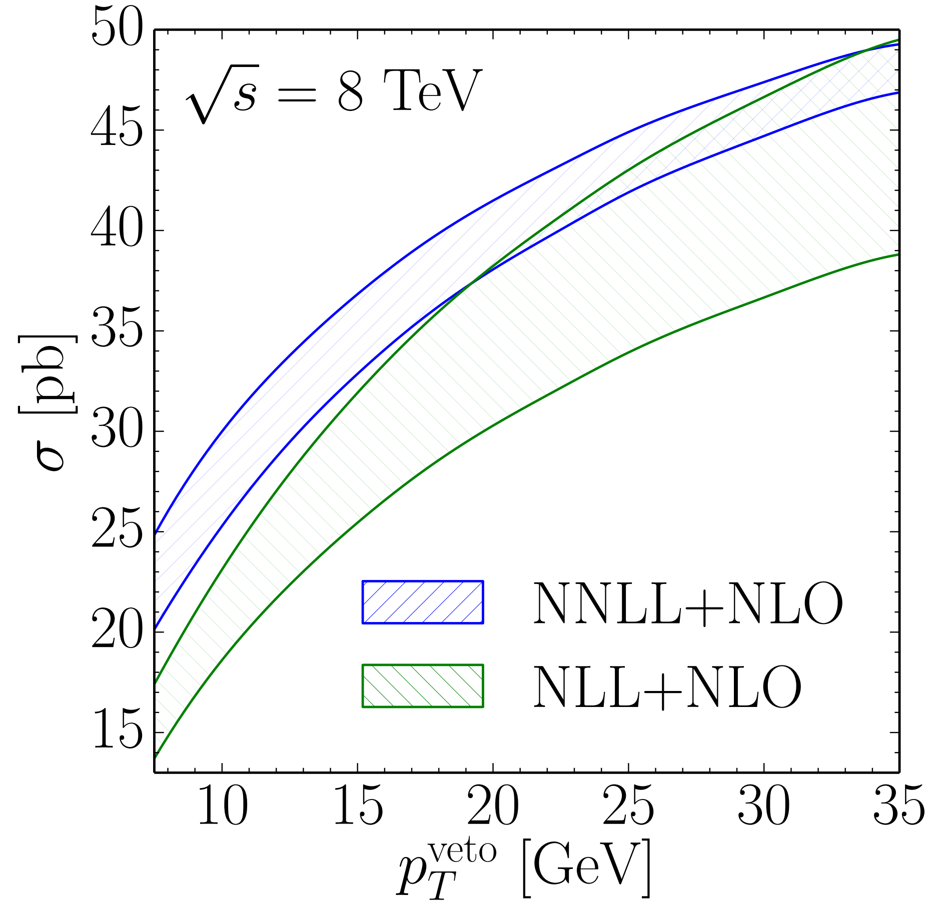
Differential:

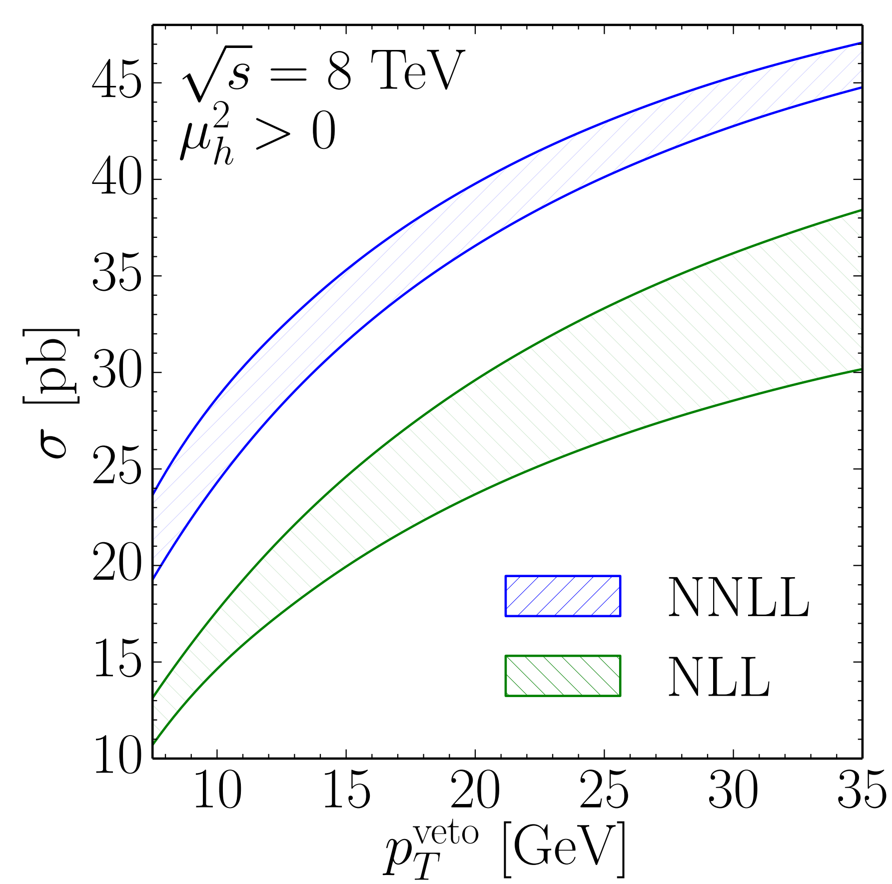
Our results

Cross-sections

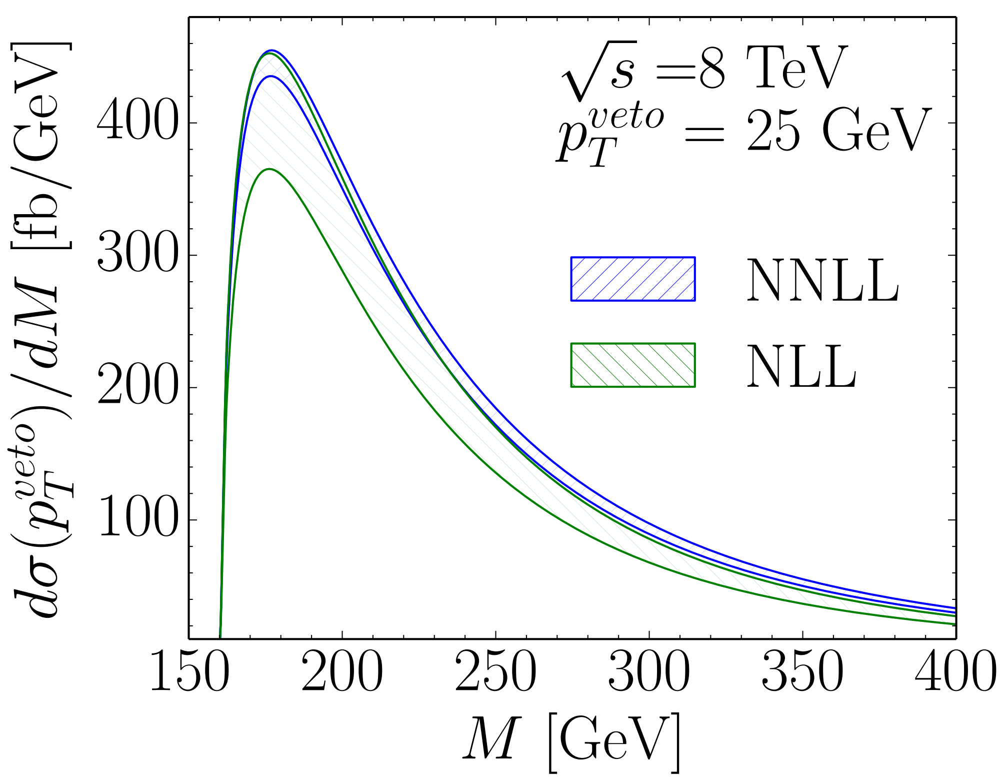
with π^2 | without π^2

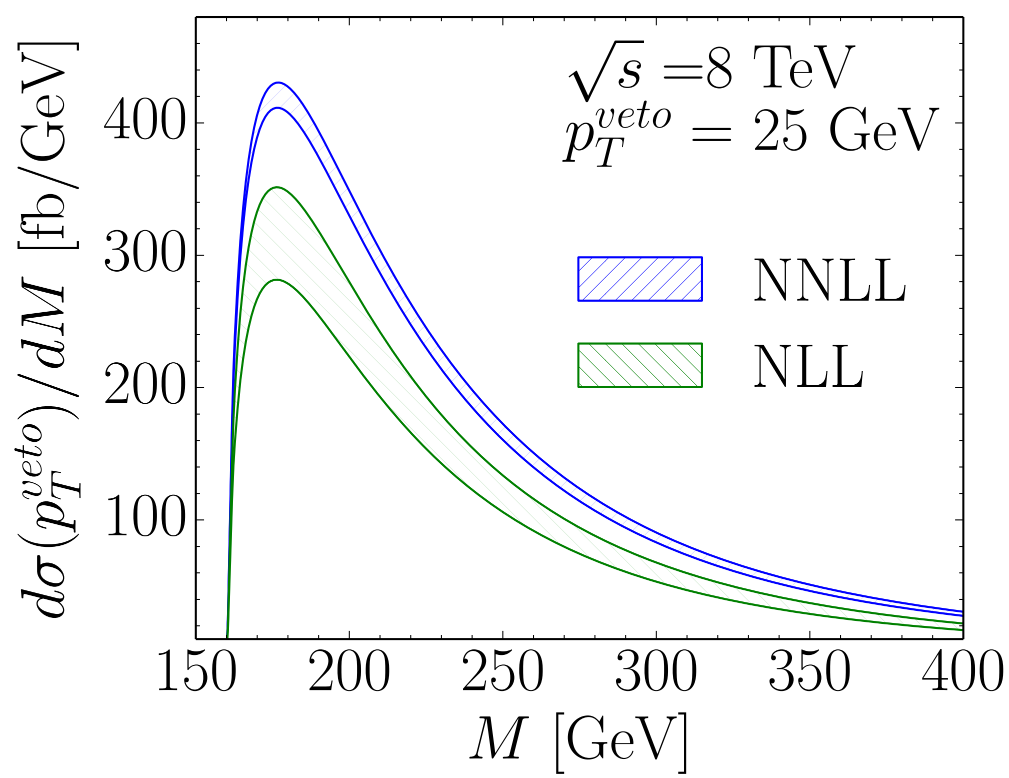
Total:





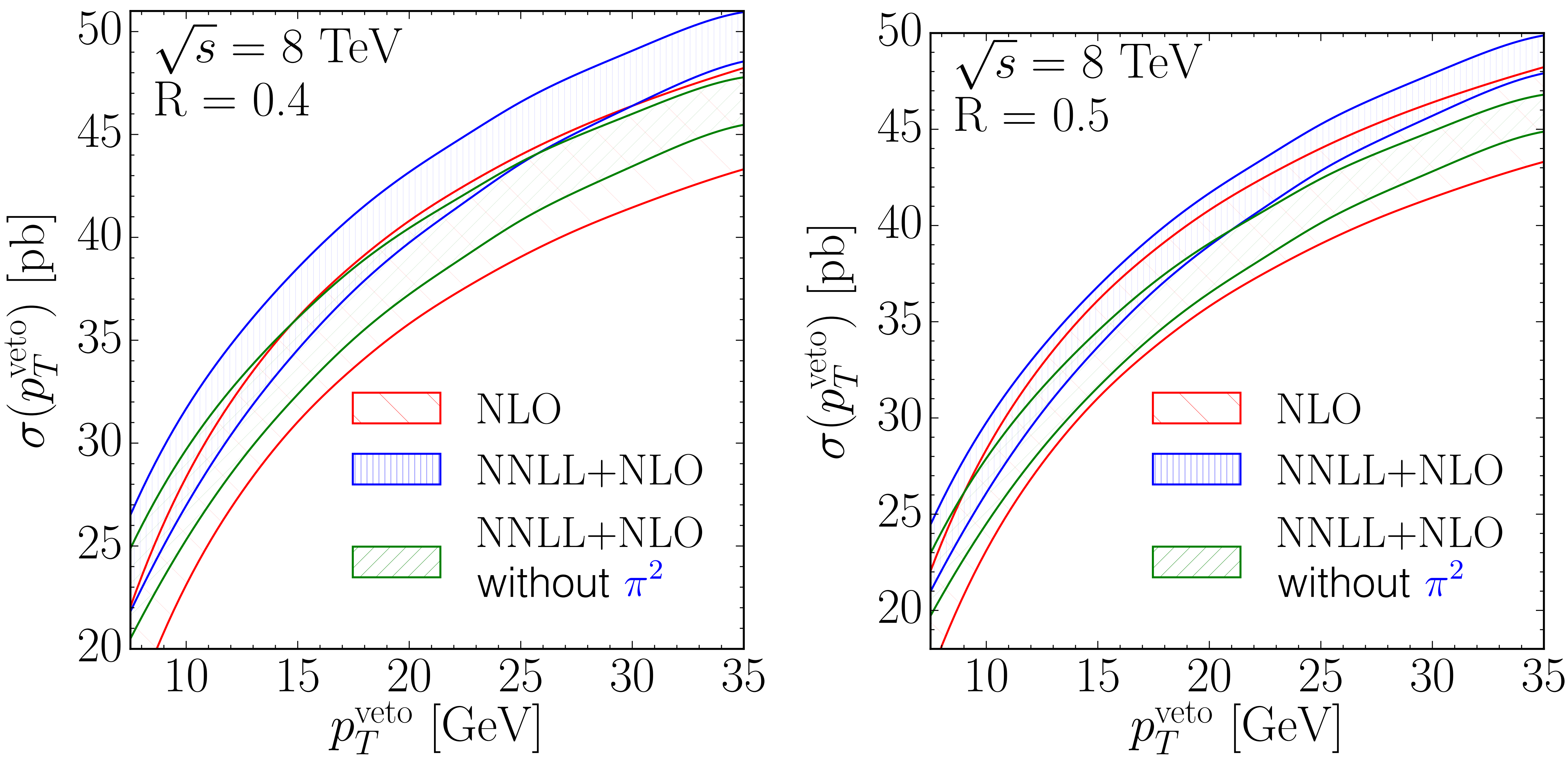
Differential:





Our results

Comparison with fixed-order NLO (MCFM)



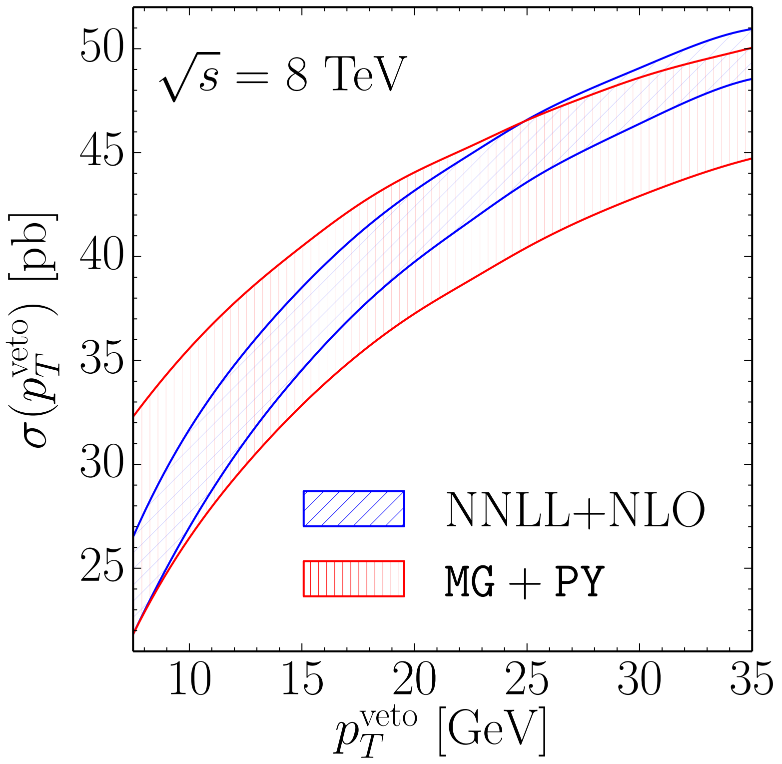
Our results

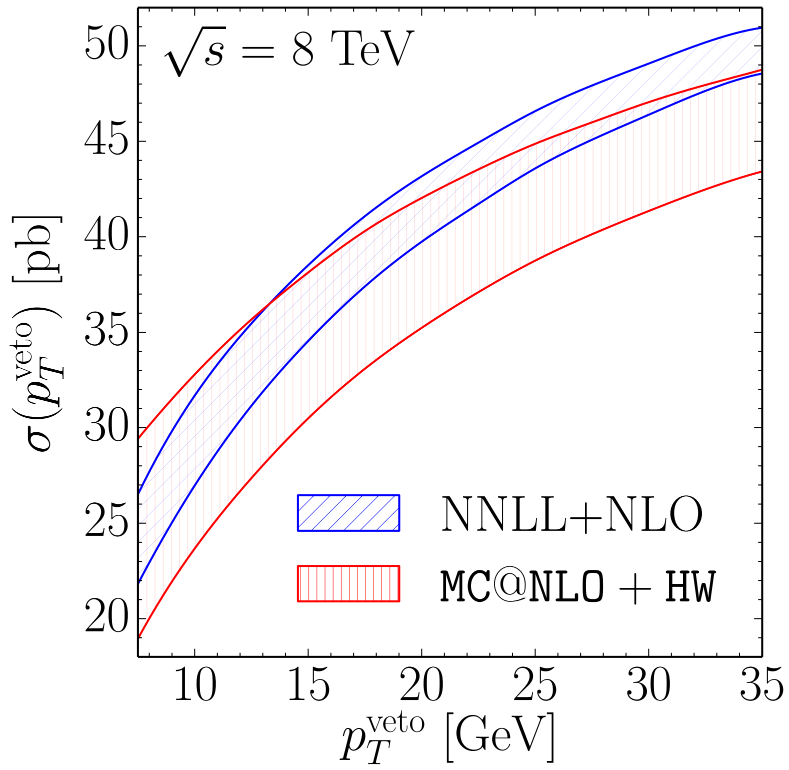
NNLL+NLO: Our result
(with power corrections)

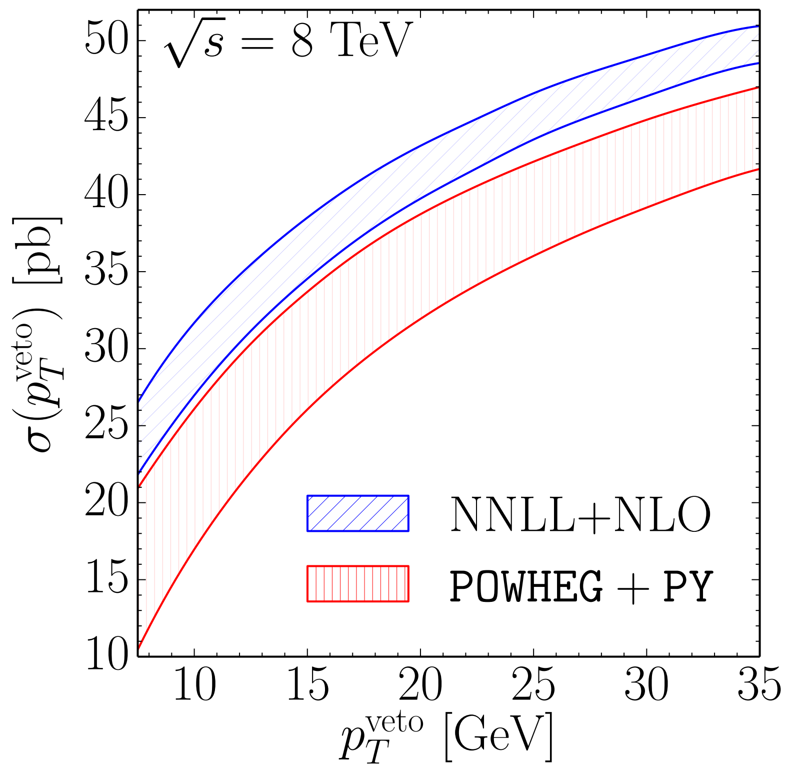
MG: Madgraph5

PY: Pythia6 HW: Herwig6

Comparison with Monte Carlo + Parton Shower







Our results

Comparison with Monte Carlo + Parton Shower

NNLL+NLO: Our result (with power corrections)

MG: Madgraph5

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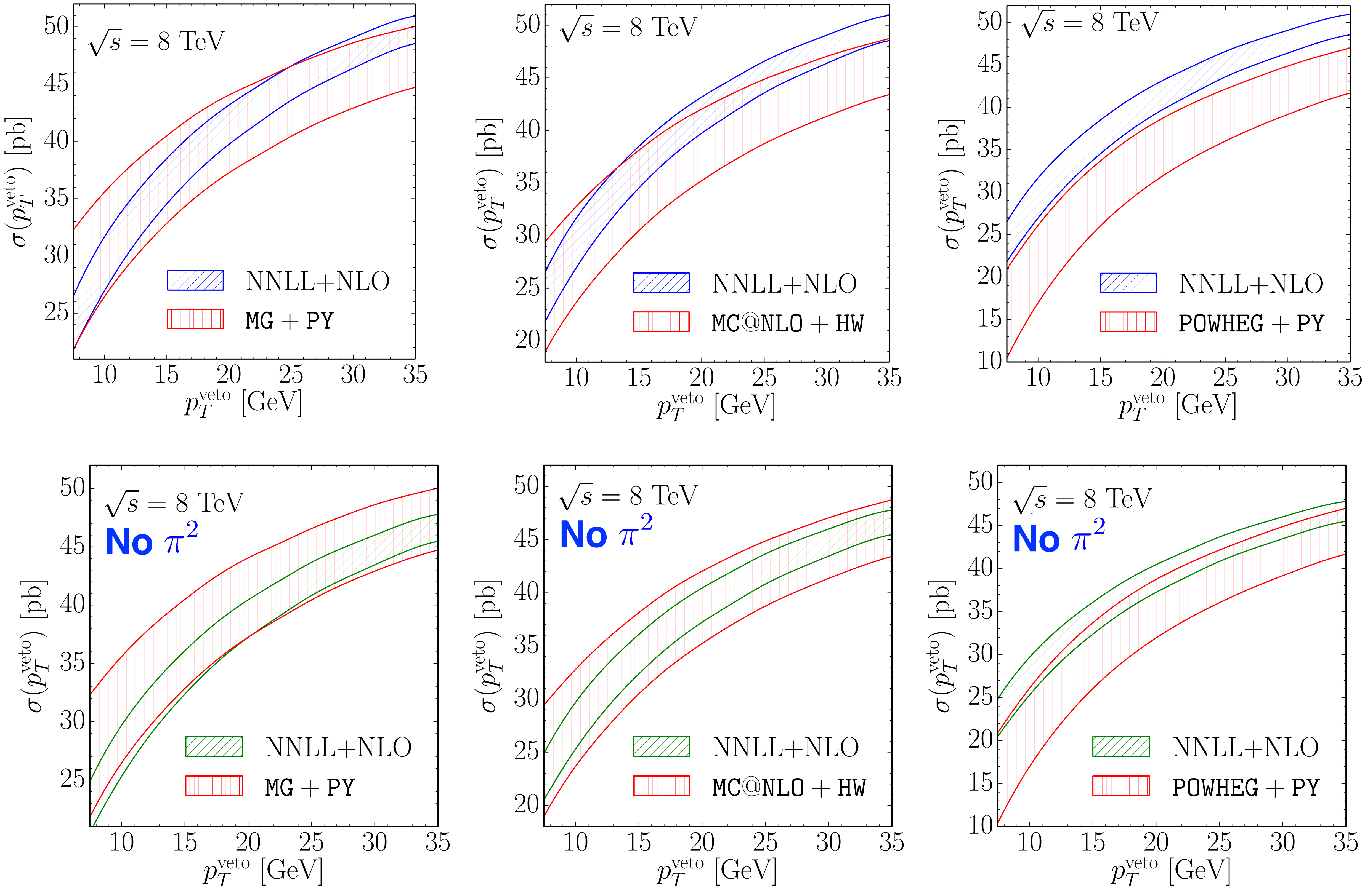
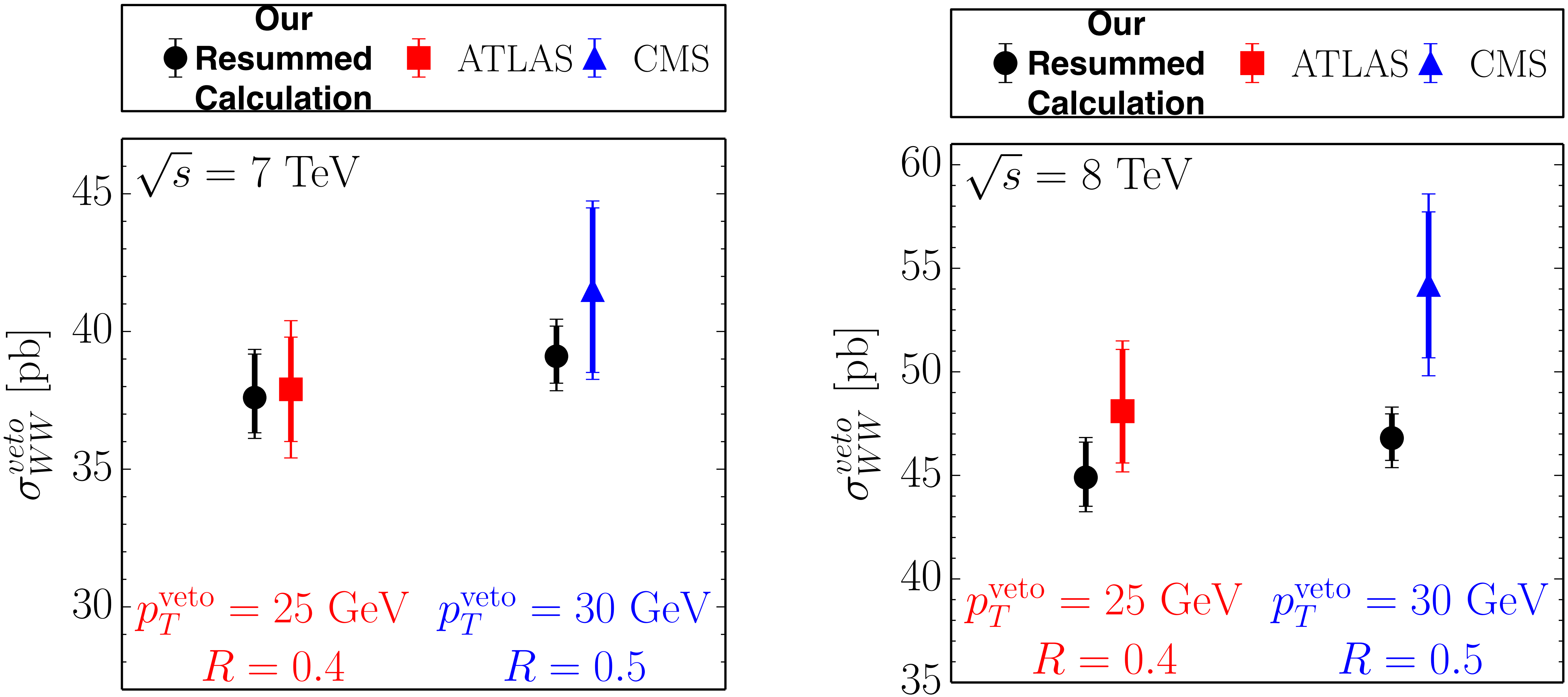


Our results

Comparison with Experimental Data



Thank you!