Precision physics with dibosons at hadron colliders

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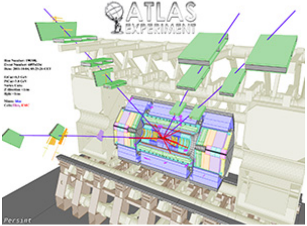

MF, Chris Frye, Jakub Scholtz, Matt Strassler
JHEP 1603, 171 [arXiv:1510.08451], ...

Why precision? Why dibosons?

- in the era of precision Higgs physics
- ...but not all EW physics easy to tie to Higgs measurements
  - BSM might not be easy to connect either
- non-Higgs precision measurements are the next frontier
- large part of this effort hinges on precision calculations
  q.v. T. Neumann's talk
- but clever choices of observables can also help
  cf. hadronic or Higgs decay ratios
- diboson rates related by $SU(2)_L \times U(1)_Y$ relations
  also custodial $SU(2)$
  - broken at low energies, but restored above the EW scale
  - is there any way to take advantage of this?

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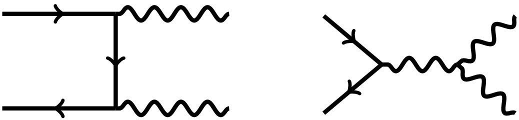
Plan

- Leading order
  - Structure of partonic cross sections
  - Ratio observables
- Prospects for measurement
- Next-to-leading order
  - NLO corrections for $\sigma(\gamma\gamma)$, $\sigma(Z\gamma)$, $\sigma(ZZ)$
  - Other higher-order issues
  - Photon isolation
- Theoretical uncertainties
- Summary and outlook

(Nearly) massless gauge bosons at high $\sqrt{s}$

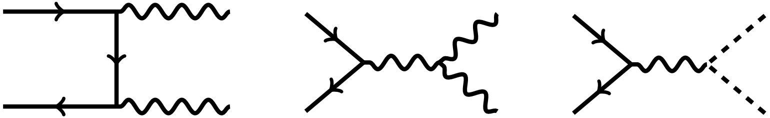
expand around unbroken $SU(2)_L \times U(1)_Y$ (gauge bosons: w^a, b)

- corrections at $(m_{W,Z}/E)^2$



$$
\begin{aligned}
bb_{\mathbf{1}} \equiv bb: &\quad |bb\rangle \\
wb_{\mathbf{3}} \equiv wb: &\quad \{|w^+b\rangle\,,\ |w^3b\rangle\,,\ |w^-b\rangle\} \\
ww_{\mathbf{1}}: &\quad |w^-w^+\rangle + |w^-w^+\rangle - |w^3w^3\rangle \\
ww_{\mathbf{3}}: &\quad \{|w^+w^3\rangle - |w^3w^+\rangle\,,\ |w^+w^-\rangle - |w^-w^+\rangle\,, \\
&\qquad |w^3w^-\rangle - |w^-w^3\rangle\}
\end{aligned}
$$

Amplitudes



(1) (2) (3)

schematically define coupling-stripped amplitudes:

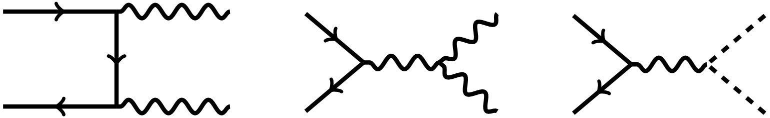
ϕ^a goldstones to unitarize $a_{1,3}$ once $m_V \neq 0$

$$a_1 = (1), \quad a_3 = (1) + (2), \quad a_L = (3)$$

matrix elements of interest:

$$a_1 \sim \mathcal{M}(bb) \qquad \sim \mathcal{M}(ww_{\mathbf{1}}) \qquad \propto t\text{-}, u\text{-channel}$$
$$a_3 \sim \mathcal{M}(ww_{\mathbf{3}}) \qquad \propto s\text{-}, t\text{-}, u\text{-channel}$$

Amplitudes



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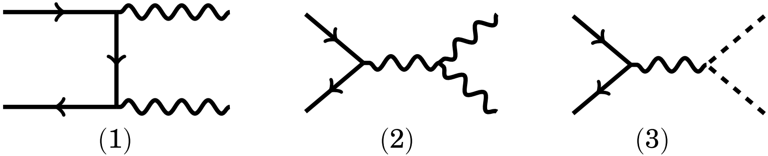

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$$a_L \sim \mathcal{M}(\phi\phi) \qquad \propto s\text{-channel}$$

Amplitudes
at high energies

boson statistics fix amplitudes under $\hat{t} \leftrightarrow \hat{u}$

- a_1, a_L symmetric
- a_3 antisymmetric

$\Longrightarrow a_3$ vanishes at threshold, $\mathrm{Re}(a_1^\dagger a_3)$ vanishes in asymmetries

$$|a_1|^2 = \frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}}$$

$$2\mathrm{Re}(a_1^\dagger a_3) = \frac{\hat{t} - \hat{u}}{2\hat{s}} + \frac{1}{4}\left(\frac{\hat{t}}{\hat{u}} - \frac{\hat{u}}{\hat{t}}\right)$$

$$|a_3|^2 = \frac{\hat{u}\hat{t}}{4\hat{s}^2} - \frac{1}{8} + \frac{1}{32}\left(\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}}\right)$$

$$|a_L|^2 = \frac{\hat{u}\hat{t}}{4\hat{s}^2}$$

Amplitudes

with mass corrections

boson statistics fix amplitudes under $\hat{t} \leftrightarrow \hat{u}$

- a_1, a_L symmetric
- a_3 antisymmetric

$\Longrightarrow a_3$ vanishes at threshold, $\mathrm{Re}(a_1^\dagger a_3)$ vanishes in asymmetries

$$|A_1|^2 = (\hat{t}\hat{u} - m_1^2 m_2^2)\left(\frac{1}{\hat{t}^2} + \frac{1}{\hat{u}^2}\right) + \frac{2\hat{s}(m_1^2 + m_2^2)}{\hat{t}\hat{u}}$$

$$\mathrm{Re}(A_1^\dagger A_3) = P_s\left(\hat{t}\hat{u} - m_1^2 m_2^2 - \hat{s}(m_1^2 + m_2^2)\right)\left(\frac{1}{\hat{u}} - \frac{1}{\hat{t}}\right) + \frac{1}{4}(\hat{t}\hat{u} - m_1^2 m_2^2)\left(\frac{1}{\hat{u}^2} - \frac{1}{\hat{t}^2}\right)$$

$$|A_3|^2 = \cdots$$

$$|A_L|^2 = P_s^2\left(\hat{t}\hat{u} - m_1^2 m_2^2 + 2\hat{s}(m_1^2 + m_2^2)\right)$$

finite m effects have uniform structure

$\gamma\gamma, Z\gamma, ZZ$
Partonic rates

electroweak symmetry breaking

$$\gamma = c_W\, b + s_W\, w^3, \quad Z = c_W\, w^3 - s_W b$$

neutral boson pairs built from bb, wb, $ww_{\mathbf{1}}$.
partonic rates all proportional:

$$\frac{d\hat{\sigma}_{q\bar{q}\to 12}}{d\hat{t}} = \frac{C_{q\bar{q}\to 12}}{\hat{s}^2}|A_1|^2$$

where

$$C_{q\bar{q}\to\gamma\gamma} = \frac{1}{2}\frac{\pi\alpha_2^2 s_W^4}{N_c}\,(Q^4 + Q^4)$$

$$C_{q\bar{q}\to Z\gamma} = \frac{\pi\alpha_2^2 s_W^2 c_W^2}{N_c}(L^2Q^2 + R^2Q^2)$$

$$C_{q\bar{q}\to ZZ} = \frac{1}{2}\frac{\pi\alpha_2^2 c_W^4}{N_c}\,(L^4 + R^4)$$

$$L = T_3 - Y_L t_W^2$$

$$R = -Y_R t_W^2$$

$\gamma\gamma, Z\gamma, ZZ$
PDF convolution

$$\frac{d\sigma_{pp\to V_0^1 V_0^2}}{d\mathcal{O}} = \sum_q \int dx_1\, dx_2\, f_q(x_1) f_{\bar{q}}(x_2) \frac{d\hat{\sigma}_{q\bar{q}\to V_0^1 V_0^2}}{d\mathcal{O}} + (x_1 \leftrightarrow x_2)$$

change to more natural variables $(\hat{s}, y, m_T)$

$$\sigma_{pp\to V_0^1 V_0^2} = \sum_q \int \frac{d\hat{s}}{s} \int dm_T \frac{d\hat{\sigma}_{q\bar{q}\to V_0^1 V_0^2}}{dm_T} \int dy\, f_q f_{\bar{q}}$$

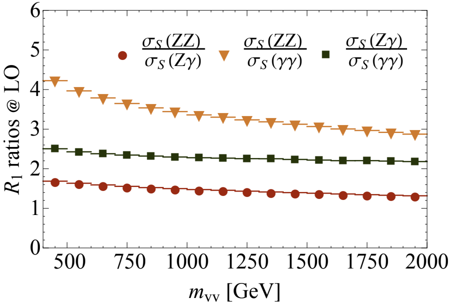
grouping couplings with PDFs into weighted parton luminosities

$$\frac{d\sigma_{pp\to V_0^1 V_0^2}}{dm_T} = \frac{1}{s} \int d\hat{s} \left| \frac{d\hat{t}}{dm_T} \right| \frac{|A_1|^2}{\hat{s}^2} \underbrace{\sum_q C_{q\bar{q}\to V_0^1 V_0^2} \int dy\, f_q f_{\bar{q}}}_{\mathcal{L}_{12}(\hat{s})}$$

$\gamma\gamma, Z\gamma, ZZ$
Ratio observables

ratios of σs determined primarily by parton luminosities

$$\left[\frac{d\sigma_{pp\to Z\gamma}}{d\sigma_{pp\to\gamma\gamma}}\right]_{\hat{s}} = \frac{\mathcal{L}_{Z\gamma}(\hat{s})}{\mathcal{L}_{\gamma\gamma}(\hat{s})}\left(1 + \frac{m_Z^2}{\hat{s}} + \cdots\right)$$



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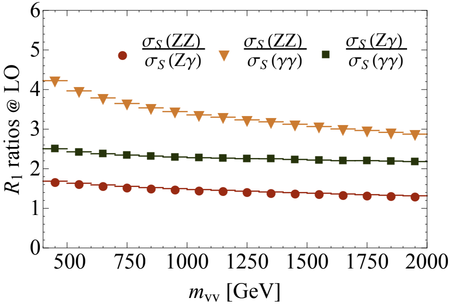
$V_1^0 V_2^0$	$C_{12}^u \cdot 10^5$	$C_{12}^d \cdot 10^5$
$\gamma\gamma$	1.2	0.07
$Z\gamma$	2.2	0.7
ZZ	1.6	3.3



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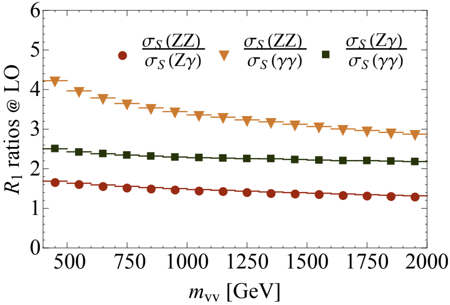
$u\bar{u}$ dominates – PDFs mostly cancel



$W^\pm\gamma$, $W^\pm Z$ at LO

$W^\pm\gamma$ and $W^\pm Z$ built from wb and $ww_\mathbf{3}$ $\Longrightarrow$ Need A_1 and A_3.

Also A_L for $\phi^\pm\phi^3$ component of $W^\pm Z$.

$$\frac{d\hat{\sigma}_{u\bar{d}\to W^\pm\gamma}}{d\hat{t}} = \frac{\pi|V_{ud}|^2\alpha_2^2 s_W^2}{N_c\hat{s}^2}\left(\frac{Y_L^2}{2}|A_1|^2 \pm 2Y_L\mathrm{Re}(A_1^\dagger A_3) + |A_3|^2\right)$$

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$$\left. + 4c_W^2|A_3|^2 + \frac{1}{2}|A_L|^2\right)$$

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numerically small

$\Longrightarrow W\gamma/WZ \sim \tan^2\theta_W$

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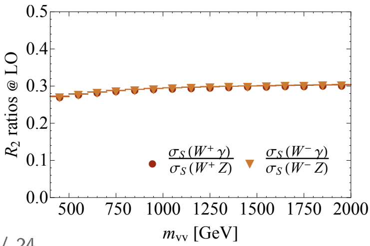
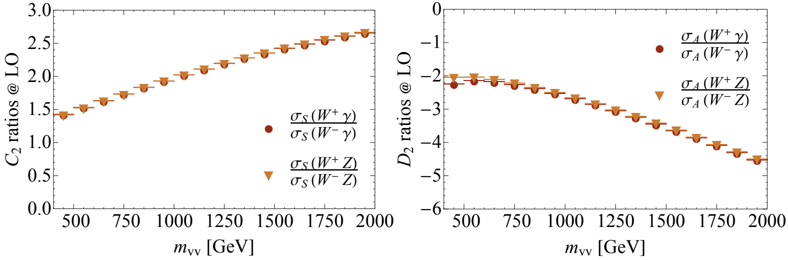
numerically small
$\Longrightarrow W\gamma/WZ \sim \tan^2\theta_W$
rad. zero at threshold
$\Longrightarrow W\gamma/WZ \sim 0.19$



$W^{\pm}\gamma$, $W^{\pm}Z$
ratio observables

CP symmetry controls $W^{-}V^{0}$ rates:

$$d\hat{\sigma}_S(u\bar{d} \to W^{+}V^{0}) = d\hat{\sigma}_S(d\bar{u} \to W^{-}V^{0})$$
$$d\hat{\sigma}_A(u\bar{d} \to W^{+}V^{0}) = -d\hat{\sigma}_A(d\bar{u} \to W^{-}V^{0})$$

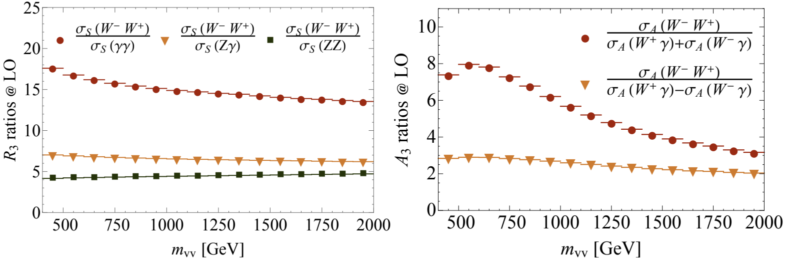


ratios roughly $\sim f_u/f_d$

W^+W^-
partonic rate

W^+W^- built from $ww_{\mathbf{1}}$, $ww_{\mathbf{3}}$, $\phi^+\phi^-$.
Very similar to $W^\pm\gamma$.

$$\frac{\sigma_A(W^+W^-)}{a\sigma_A(W^+\gamma)+b\sigma_A(W^-\gamma)} \sim \frac{\mathcal{L}^A_{u\bar{u}} - \mathcal{L}^A_{d\bar{d}}}{4|V_{ud}|^2 s_W^2 Y_L (a\mathcal{L}^A_{u\bar{d}} - b\mathcal{L}^A_{d\bar{u}})}$$



Full family of ratio observables

- $R_{1a} = \frac{\sigma_S(Z\gamma)}{\sigma_S(\gamma\gamma)}, \quad R_{1b} = \frac{\sigma_S(ZZ)}{\sigma_S(\gamma\gamma)}, \quad R_{1c} = \frac{\sigma_S(ZZ)}{\sigma_S(Z\gamma)},$
- $C_{2a} = \frac{\sigma_S(W^+\gamma)}{\sigma_S(W^-\gamma)}, \quad C_{2b} = \frac{\sigma_S(W^+Z)}{\sigma_S(W^-Z)},$

  $D_{2a} = \frac{\sigma_A(W^+\gamma)}{\sigma_A(W^-\gamma)}, \quad D_{2b} = \frac{\sigma_A(W^+Z)}{\sigma_A(W^-Z)},$

  $R_2^{\pm} = \frac{\sigma_S(W^{\pm}Z)}{\sigma_S(W^{\pm}\gamma)}, \quad A_2^{\pm} = \frac{\sigma_A(W^{\pm}Z)}{\sigma_A(W^{\pm}\gamma)},$
- $R_3 = \frac{\sigma_S(W^+W^-)}{\sigma_S(V_1^0 V_2^0)}, \quad A_3 = \frac{\sigma_A(W^+W^-)}{\sigma_A(WV^0)},$

For rest of the talk focus on R_1 family

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Experimental issues

some issues cancel...

- luminosity
- jet energy scale

dominant part of exp. systematics

...some don't

- $Z \to$ leptons $\Rightarrow$ Z need additional cuts
  or $Z \to \nu\bar{\nu}$ — has it's own issues
  - some Zs lost when leptons escape detection
  - losses decrease at higher p_T
- Finite m_Z window: $|m_{\ell\ell} - m_Z| < 25$ GeV
  - some admixture of γ^* in Z sample
  - small effect
- small $O(5\%)$ shift, calculable with negligible uncertainties

Variable bin widths

problem: very few Z decays to leptons

V_1V_2	$N_f + N_b$	$N_f - N_b$
$\gamma\gamma$	12 000	0
$Z\gamma$	2000	0
ZZ	220	0
$W^+\gamma$	3300	-500
$W^-\gamma$	2100	220
W^+Z	790	33
W^-Z	520	-16
W^-W^+	9500	-430

choose bin widths for 5% statistical uncertainty.
$R_{1a} = \sigma_S(Z\gamma)/\sigma_S(\gamma\gamma)$ not statistics limited with 300 fb^{-1}

C_{2a}, D_{2a}, R_3 too, but wait for next paper...

others will have to wait until 3000 fb^{-1}

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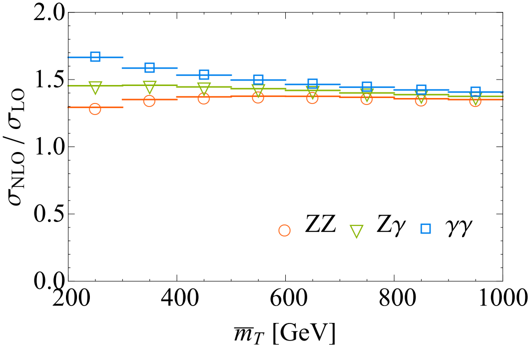
NLO corrections to diboson production

EW processes at LHC typically have large $O(\alpha_s)$ corrections

$qg \to V_1 V_2 q$ appears at $O(\alpha_s)$, and $f_g \gg f_{\bar{q}}$

large uncertainties if $d\sigma$ "effectively LO" somewhere in PS

$$\bar{m}_T = \frac{1}{2}(m_{T1} + m_{T2}) = \text{min. } E \text{ at } \theta_{CM} = \pi/2$$



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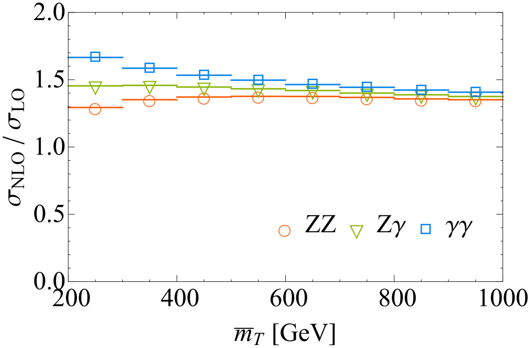
radiation can never reduce this variable



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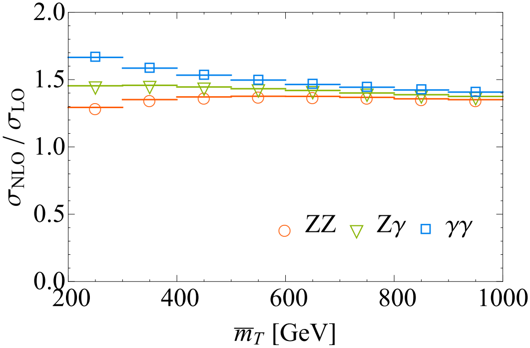
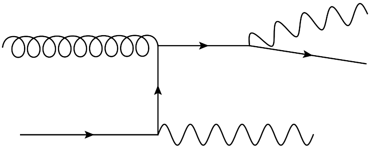
Choose cuts to avoid measurements with large kinematic logs

$$H_T < \frac{1}{2} p^V_{T,\min}, \quad p^V_{T,\min} > \frac{1}{2} p^V_{T,\max}$$

Fixed order calculation reliable



Photon IR divergences



divergence in qg process when $q\gamma$ are collinear
without photon isolation, configuration will dominate
will introduce sensitivity to NP IR physics if not careful

Smooth-cone isolation

The theorist's solution

eliminate collinear singularity using "smooth cone" isolation

[Frixione, 1998]

choose parameters ϵ and δ and require

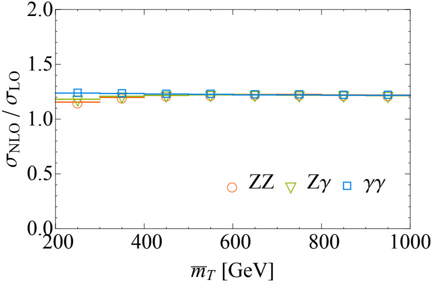
$$\sum_{h\in(\theta<\delta)} p_T^h < \epsilon p_T^\gamma \left(\frac{1-\cos\theta}{1-\cos\delta}\right)$$

no partons allowed with $\theta = 0 \implies$ no collinear singularity

but, enhancement at small θ for γ, "dead cone" around Z: $\theta_{\mathrm{dc}} \approx \frac{m_Z}{m_{VV}}$

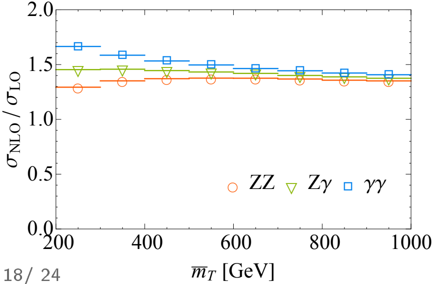
…and requires infinite resolution

Collinear qV region



$(\delta, \epsilon) = (\mathbf{1.2}, \mathbf{0.2})$

$(\delta, \epsilon) = (\mathbf{0.4}, \mathbf{0.5})$

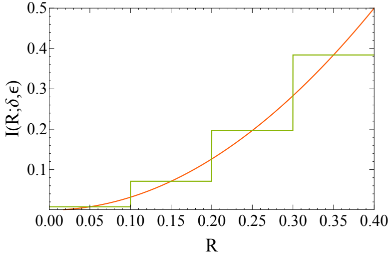


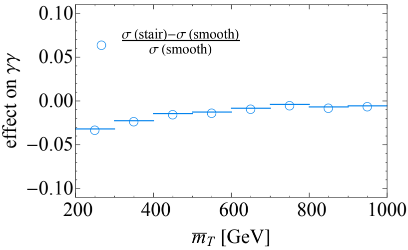
Staircase isolation

"practical" smooth-come isolation:

- stairs of width $\Delta R = 0.1$
- heights match smooth cone at midpoint
- never take heights below 25 GeV (pileup/resolution)

minimize sensitivity to frag. functions & large $\log(\epsilon)$
experimentally viable





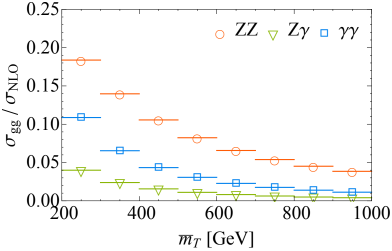
gg initial states at NNLO

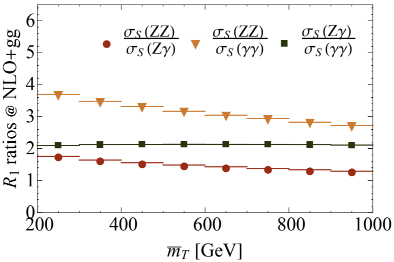
$gg \to V_1 V_2$

- formally NNLO
- numerically important because of large f_g
- finite, so can be included without full $O(\alpha_s^2)$ correction

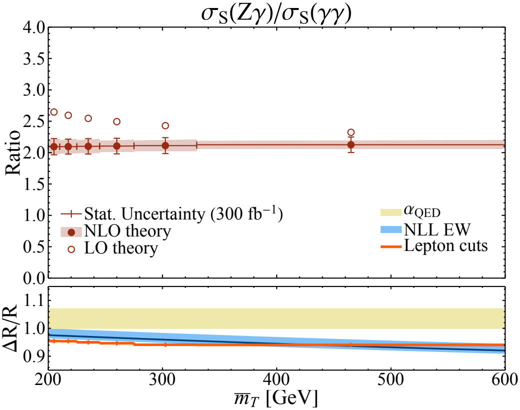
smaller enhancement for $gg \to Z\gamma$ due to vanishing of $gg \to w^3 b$

$gg \to \gamma\gamma$ at 2-loop publicly available
can be used to set scales in $gg \to Z\gamma, ZZ$

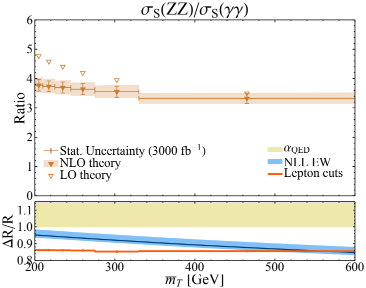


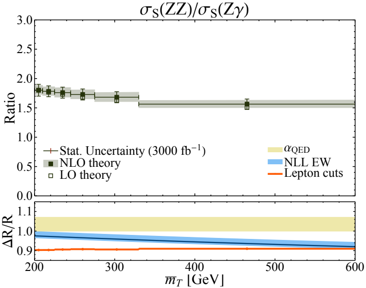


Predicted ratios



Predicted ratios





Plan

- Leading order
  - Structure of partonic cross sections
  - Ratio observables
- Prospects for measurement
- Next-to-leading order
  - NLO corrections for $\sigma(\gamma\gamma)$, $\sigma(Z\gamma)$, $\sigma(ZZ)$
  - Other higher-order issues
  - Photon isolation
- **Theoretical uncertainties**
- Summary and outlook

Uncertainty budget

Effect	R_{1a} $(Z\gamma/\gamma\gamma)$	R_{1b} $(ZZ/\gamma\gamma)$	R_{1c} $(ZZ/Z\gamma)$	Comments
$qq \to VVqq$	2–3%	3–3.5%	1.5–2.5%	extrapolating $p^j_{T,\min} \to 0$
μ_R, μ_F (gg)	0.5–1%	1%	1–2%	uses NLO $gg \to \gamma\gamma$
μ_R, μ_F (NLO)	0.5–1%	1.5–2.5%	1–1.5%	varied independently
PDF	0.5%	1–1.5%	0.5–1%	MSTW2008 using MCFM
γ isolation	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	Uncertainty in frag. fun.
α_{QED}	7%	14%	7%	Fully correlated
EW (LL)	$^{+2\%}_{-1\%}$	$^{+3\%}_{-1\%}$	$^{+2\%}_{-1\%}$	EFT scale uncertainty

Plan

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Summary & outlook

$SU(2)_L \times U(1)_Y$ structure of diboson rates at LO suggests organizing data in cross section ratios

observables based on this structure:
- low uncertainties, small QCD corrections
- candidates for (even) high(er)-precision calculation

certainly useful as check that we understand SM backgrounds

how to best use this for new physics?
- reliable characterization of new resonances?
- increased sensitivity to non-resonant effects?
- can anything be done with less luminosity?

Thank you!