NLO corrections to tri-boson production in the WZjj channel

Based on a work done by
A. Denner, DL, S. L. P. Chavez and G. Pelliccioli
(arxiv:2407.21558)

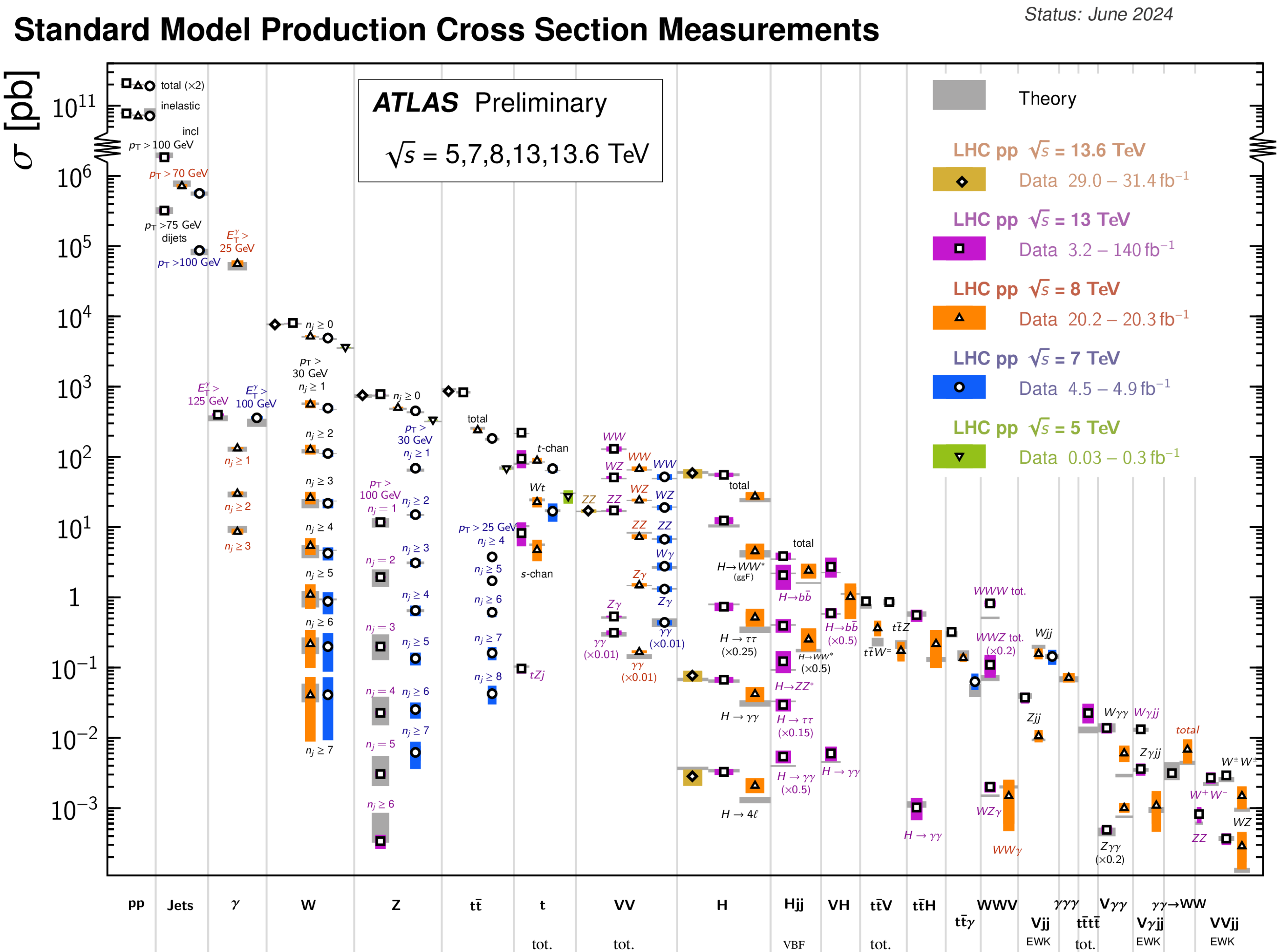
Presented by
Daniele Lombardi

HP² Workshop 2024 (University of Turin and INFN)
Parallel Session: EW and Higgs Physics, EFT and BSM
September 12th, 2024

Probing the SM EW Sector

Despite many confirmations, some parts of the Standard-Model (SM) EW sector are still poorly constrained:

- Triple and quartic vector-boson couplings
- Symmetry-breaking mechanism



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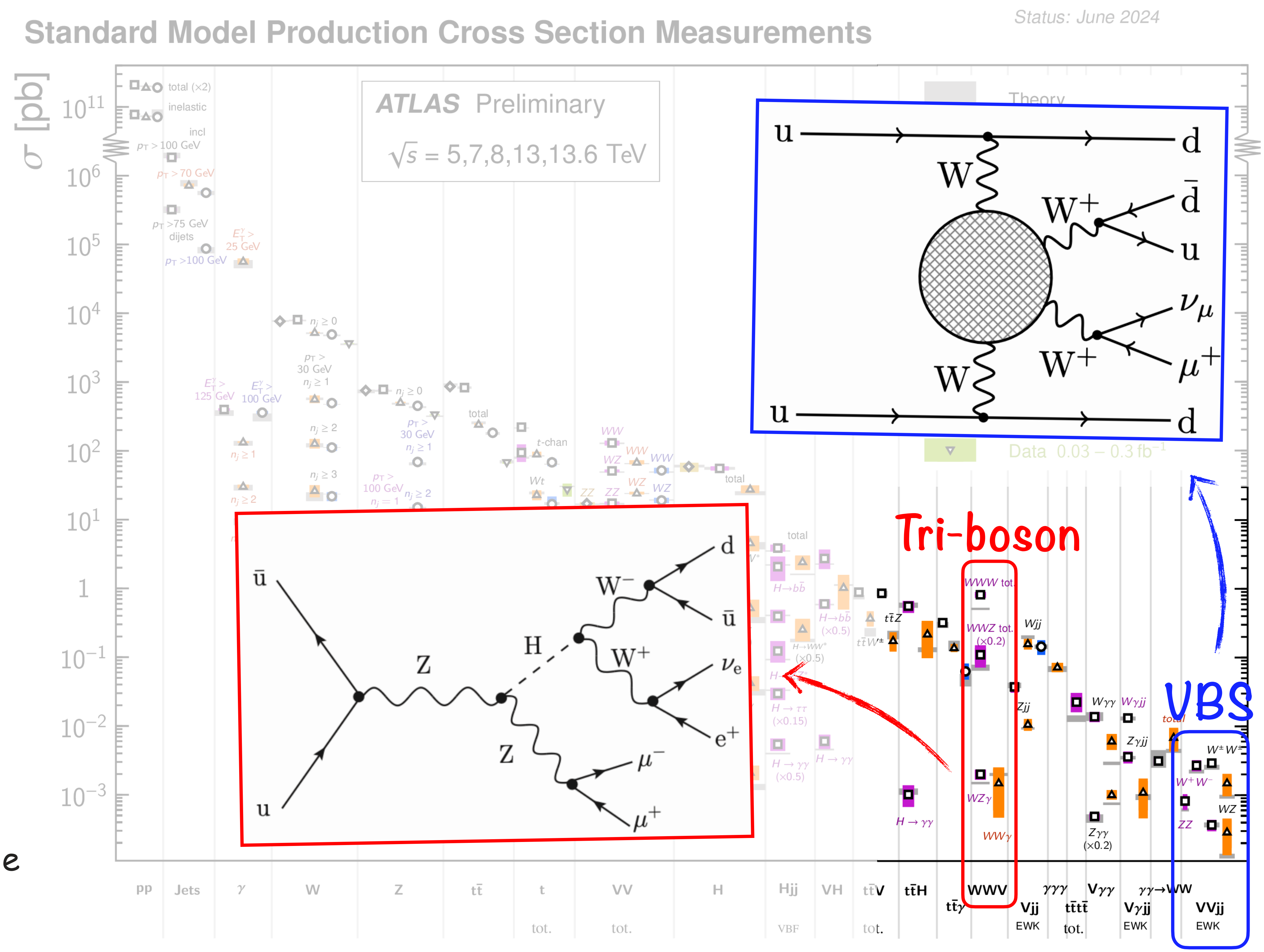
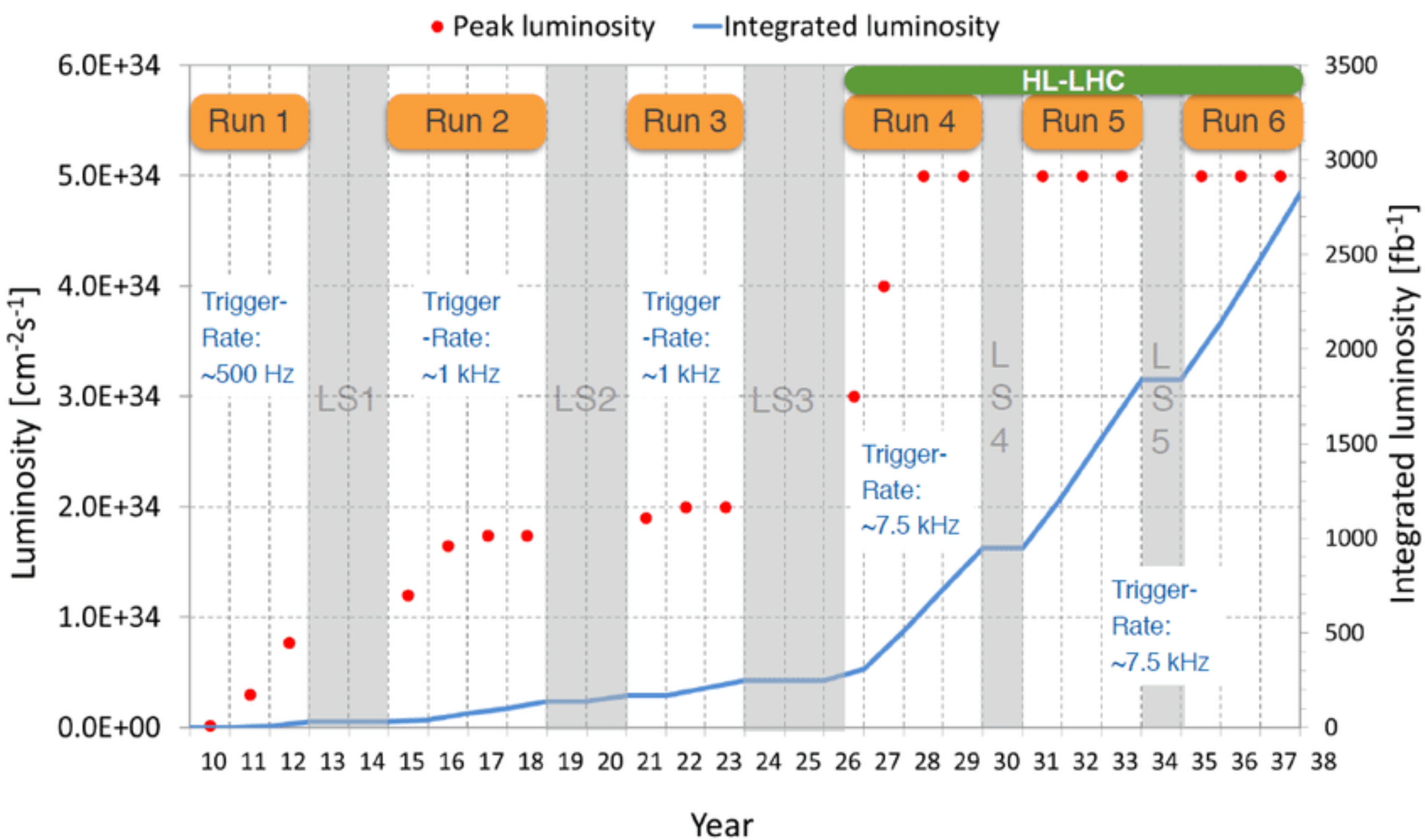
↓

Tri-boson production and VBS are golden channels to probe these sectors of the SM!



What experiments can do ...

Tri-boson-production measurements are affected by large background and small cross sections



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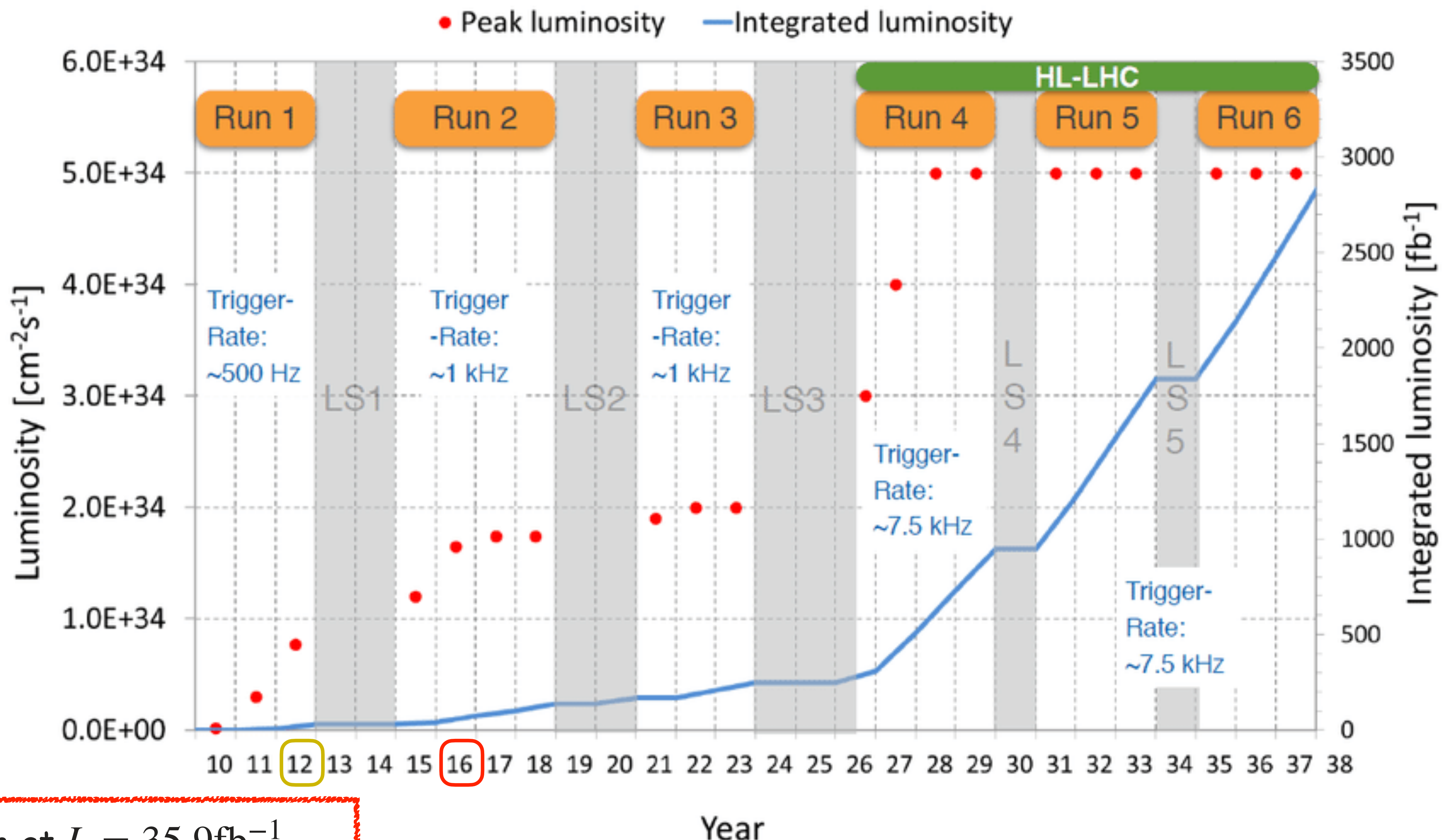

ATLAS search at $L = 20.3\text{fb}^{-1}$ and $\sqrt{s} = 8\text{TeV}$

CMS search at $L = 35.9\text{fb}^{-1}$ and $\sqrt{s} = 13\text{TeV}$

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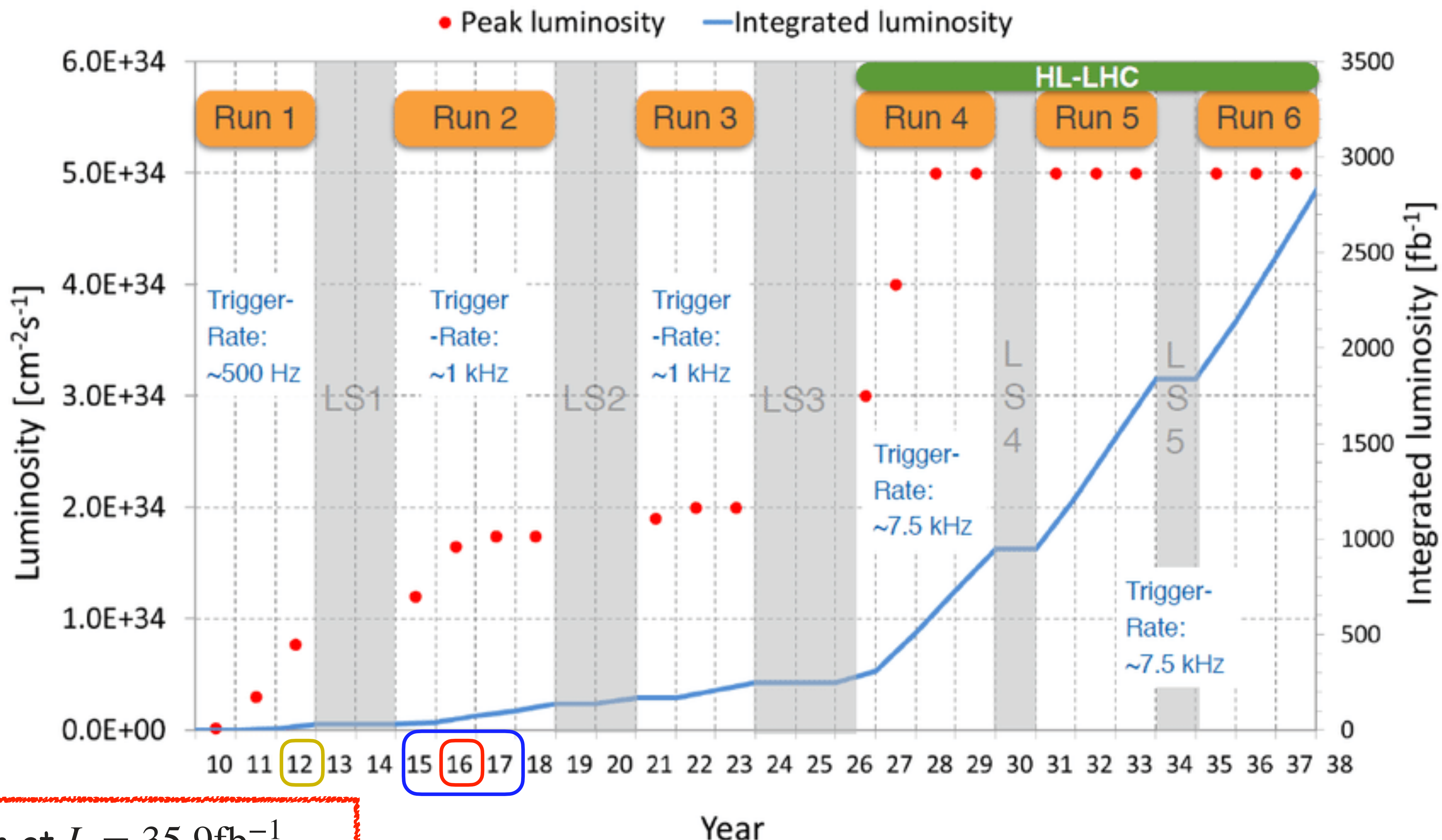

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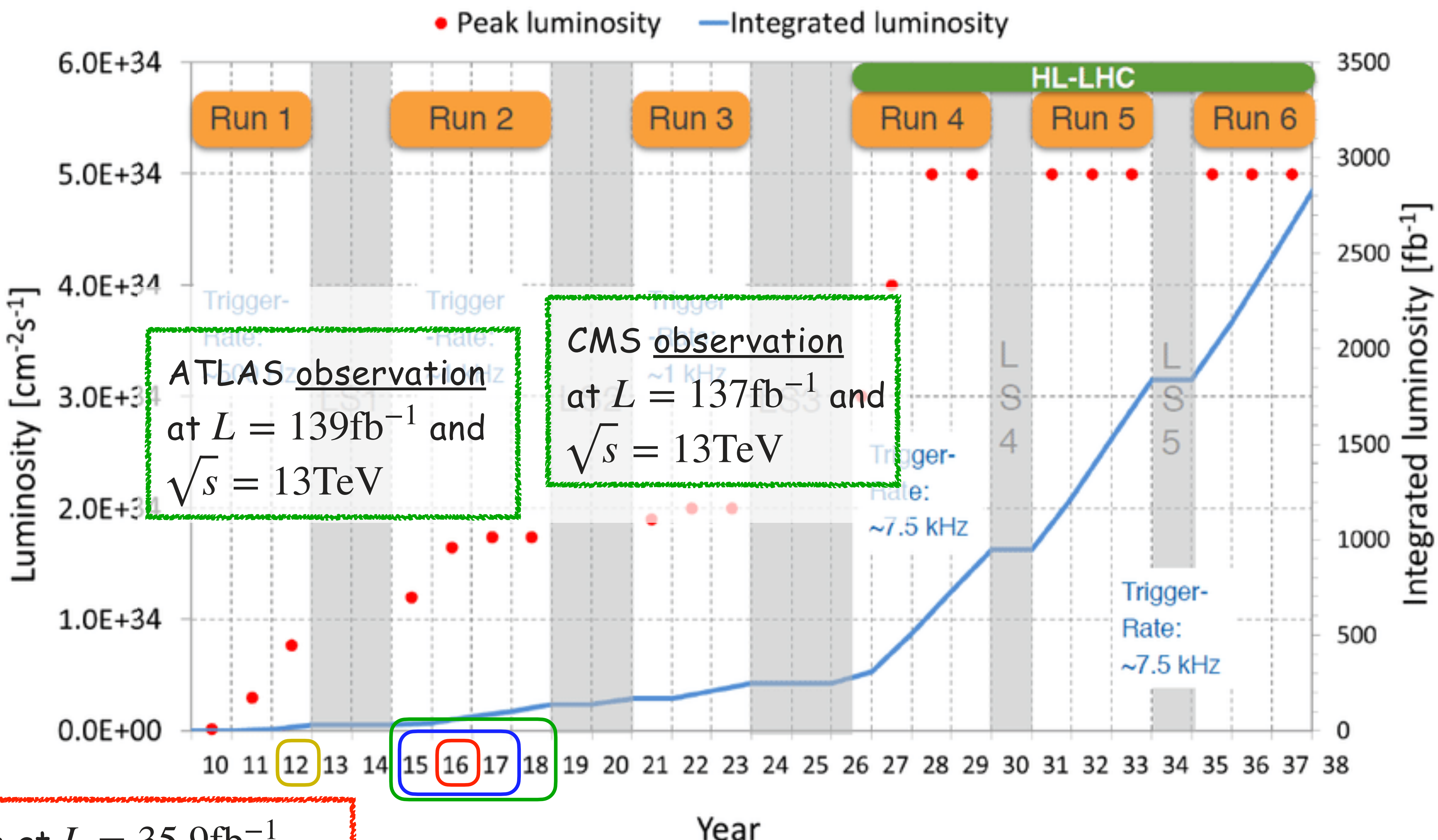

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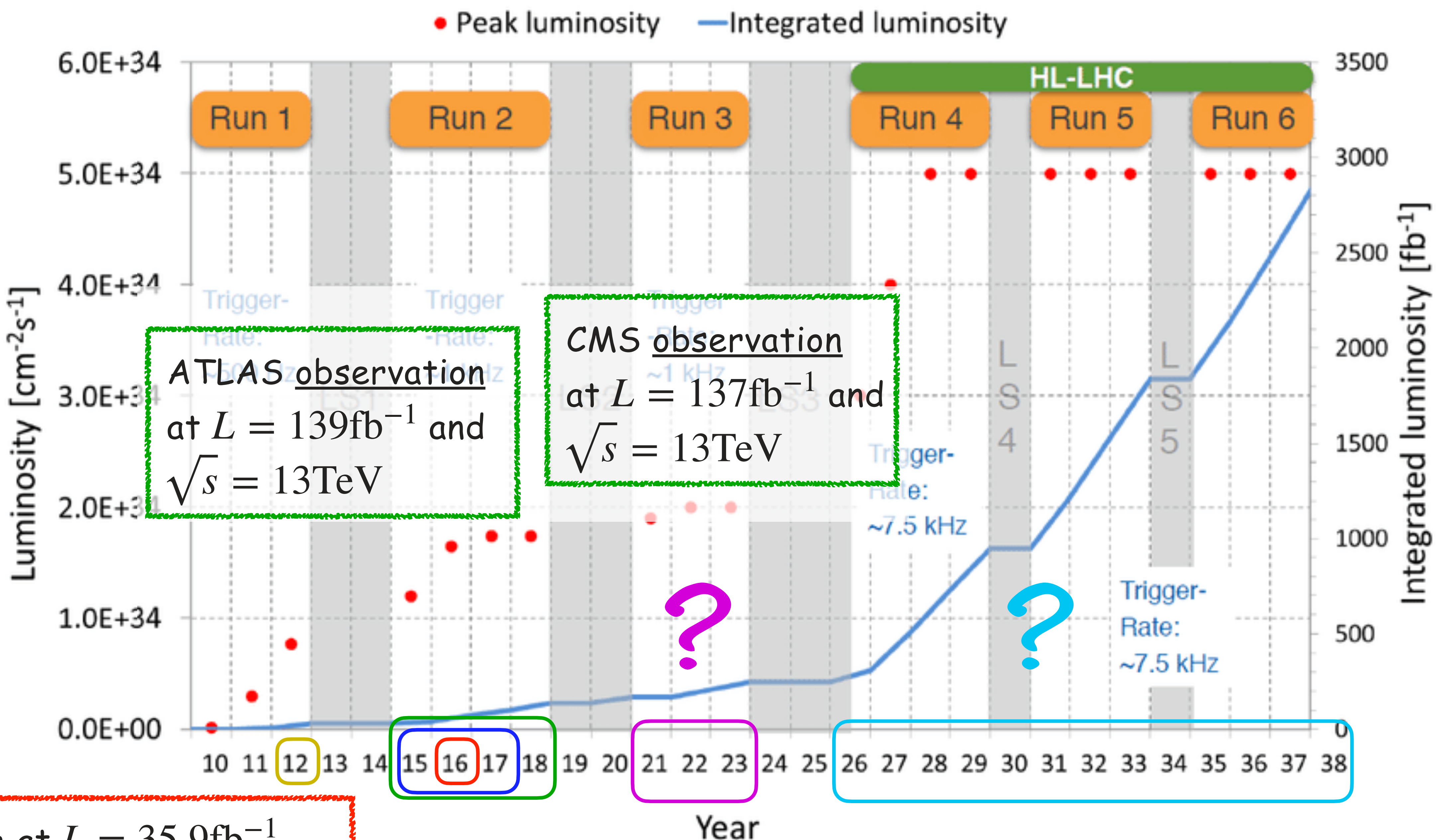

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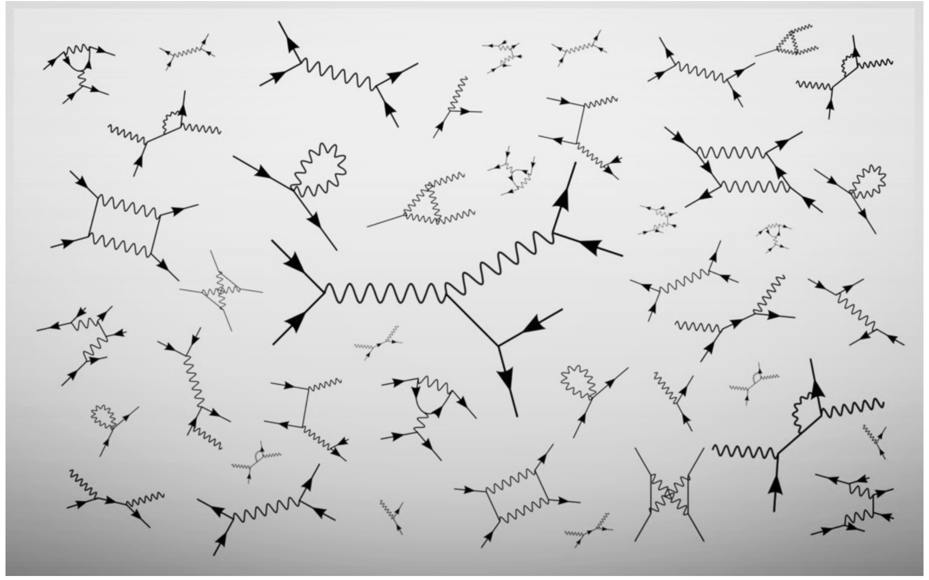
... and what theory can do



- ☑ **NLO QCD on-shell** predictions for all tri-boson processes [arXiv:hep-ph/0703273, arXiv:0804.0350].
- ☑ **NLO QCD+EW on-shell** predictions for WWW and WWZ [arXiv:1307.7403, arXiv:1705.03722].
  - ➡ Fully-leptonic decay included at LO with narrow-width approximation for WZZ and WWW [arXiv:1507.03693, arXiv:1605.00554].
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} Fully-leptonically decaying vector bosons

- ☑ **NLO QCD+EW off-shell** calculation matched to **PS** for tri-boson in the W^+W^+jj channel [arXiv:2406.11516].
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} One hadronically-decaying vector boson

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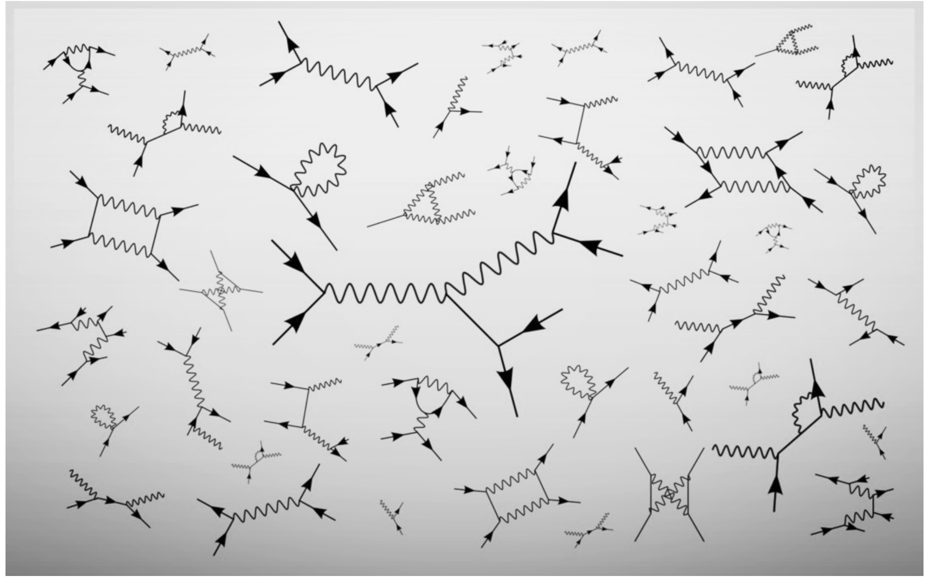

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This Talk!

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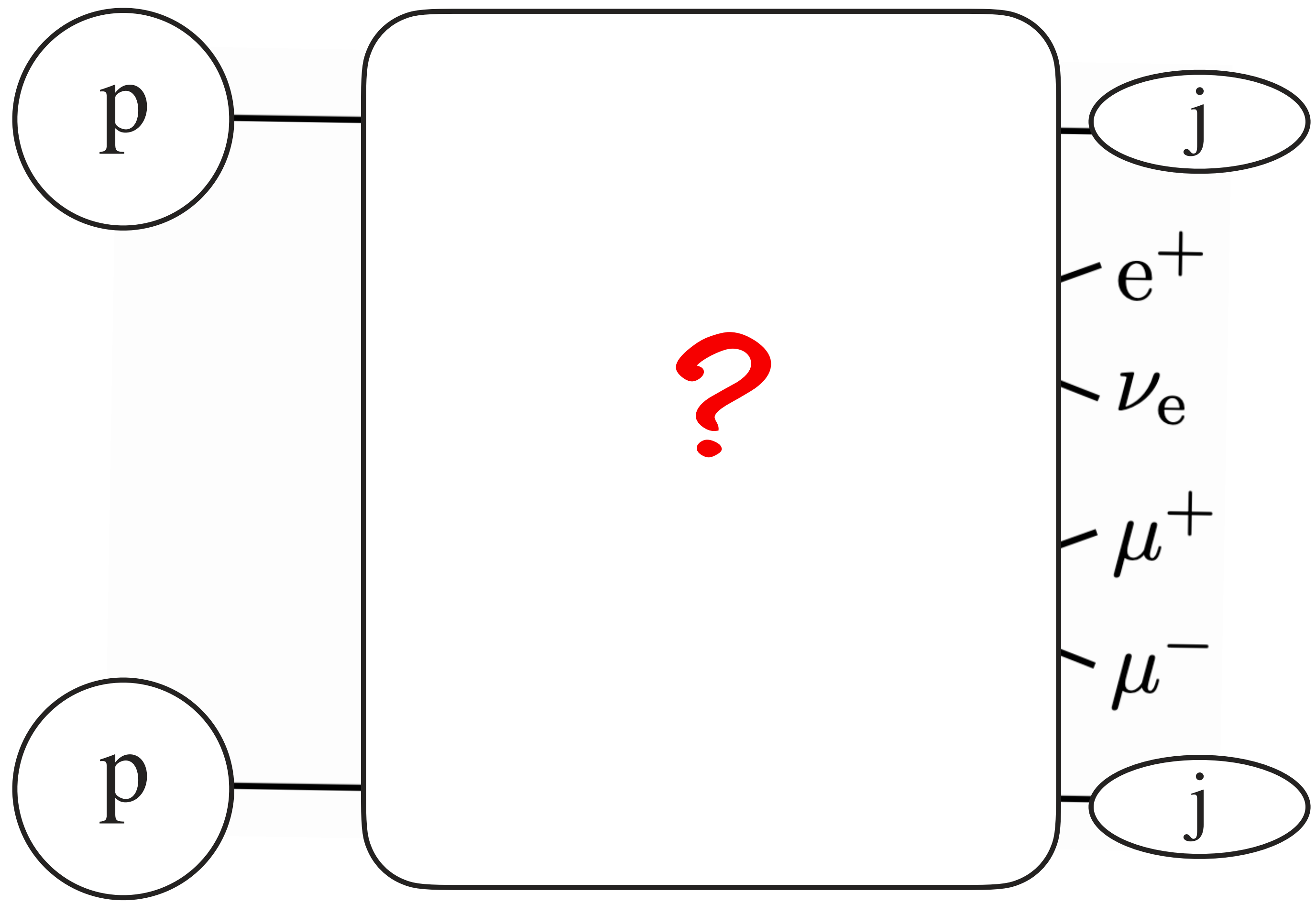
Off-shell calculations just look at the final states

➡ Overlap of VBS and tri-boson production



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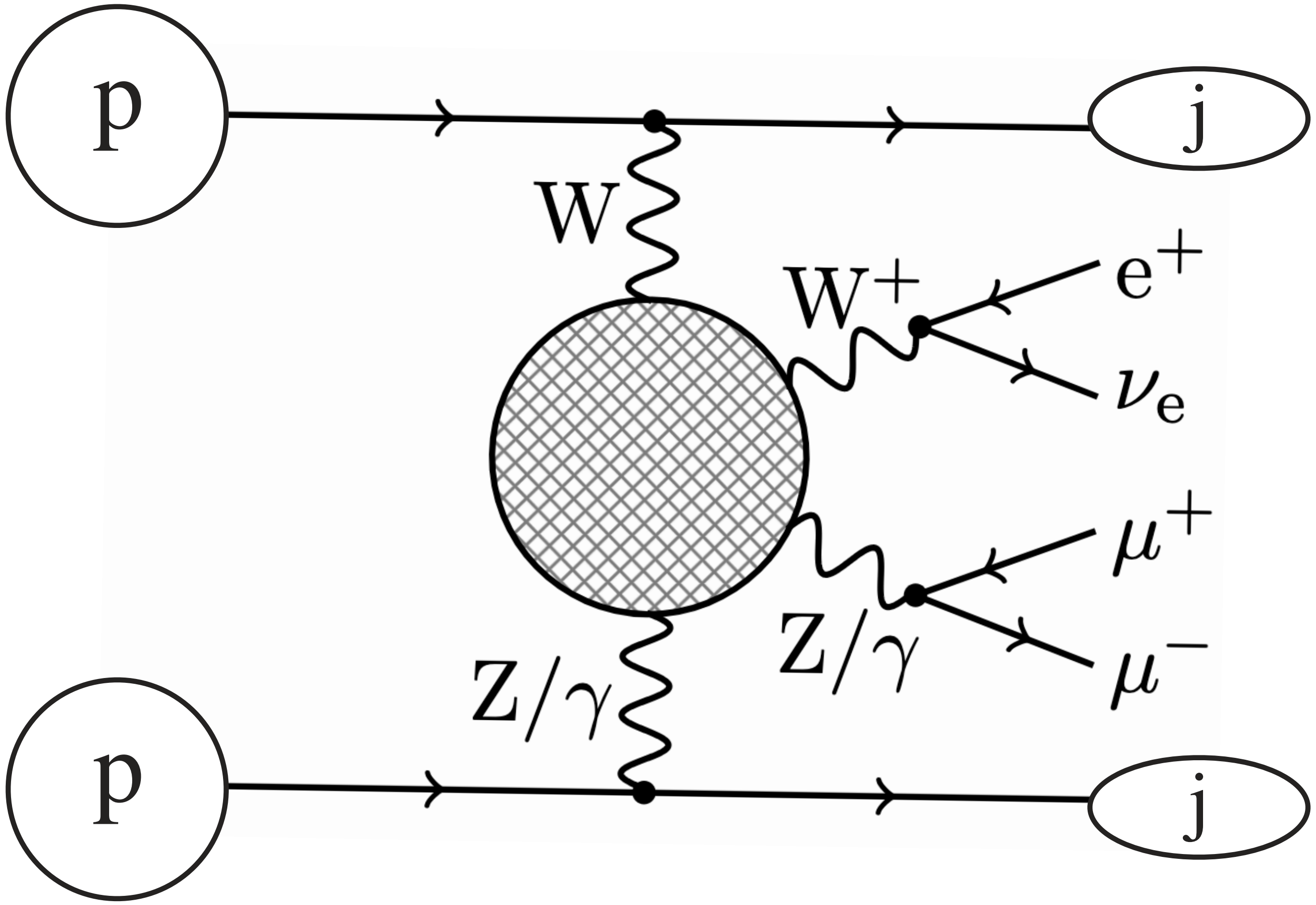

VBS

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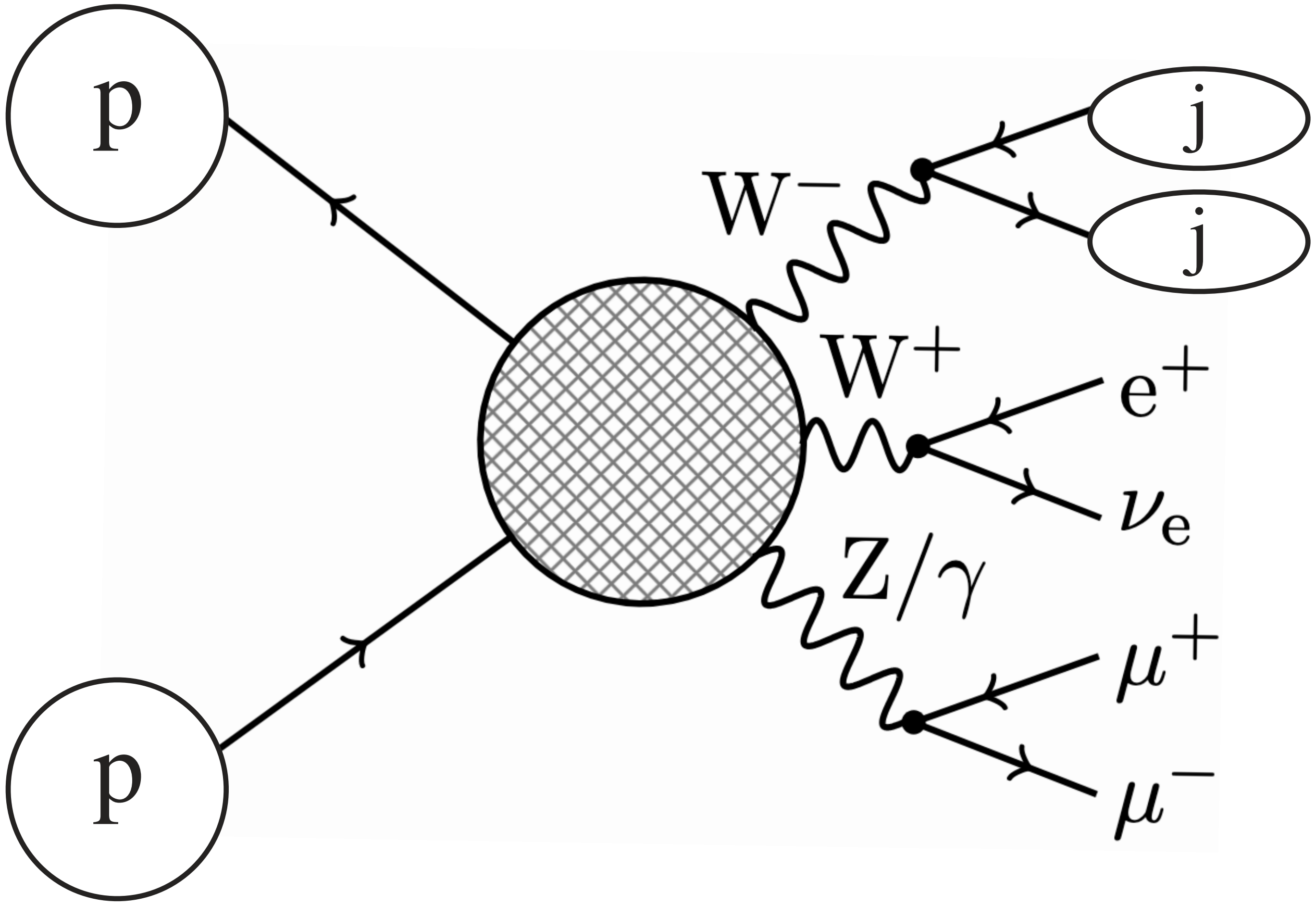

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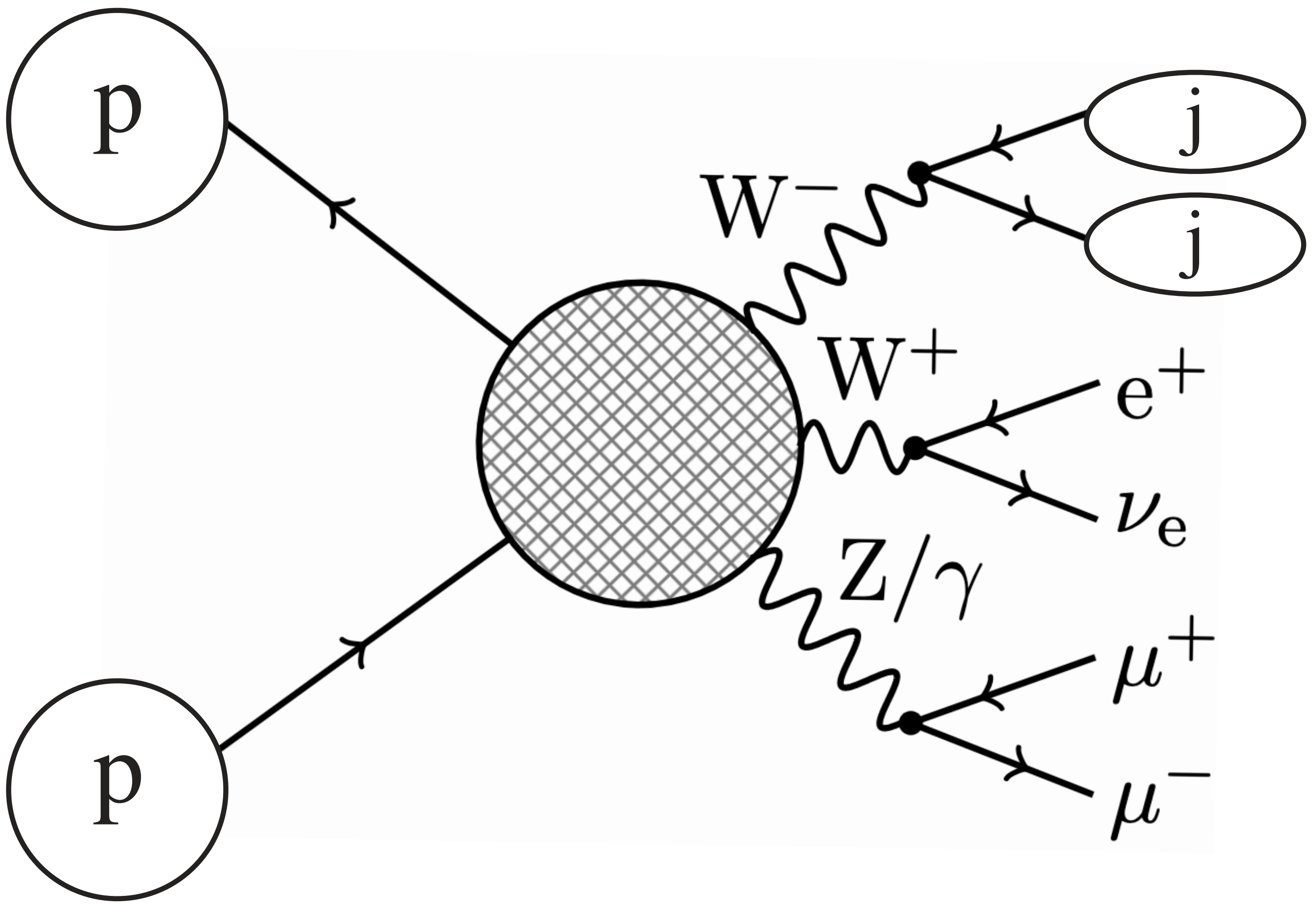
The two processes are experimentally defined on different fiducial phase spaces !



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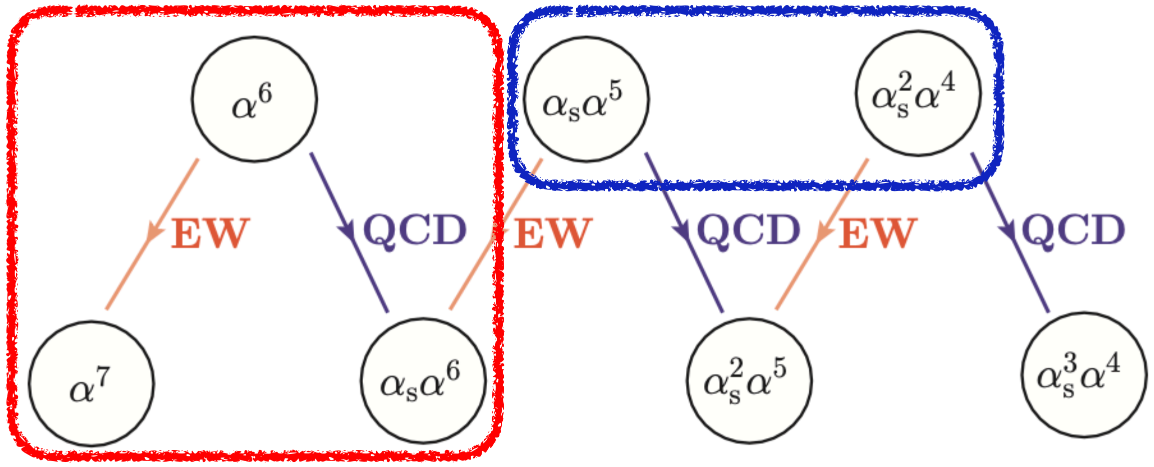
Structure of the calculation

A. Denner, DL, SLP. Chavez and G. Pelliccioli [arXiv:2407.21558]

NLO QCD and NLO EW corrections to fully off-shell

$$pp \to e^+\nu_e\mu^+\mu^- jj$$

in a phase space which enhances the tri-boson signal.



- Calculation performed with the in-house MOCANLO program:
  - SM amplitudes computed with RECOLA (CKM matrix set to identity matrix);
  - Tensor reduction and evaluation of 1-loop integrals with COLLIER library.

- All relevant partonic channels included: light-quark and photon induced, together with $\bar{b}b$ initiated (5-flavour scheme).

- **Signal**: $\mathcal{O}(\alpha^6)$ (LO) + $\mathcal{O}(\alpha^7)$ (NLO$_{\text{EW}}$) + $\mathcal{O}(\alpha_s\alpha^6)$ (NLO$_{\text{QCD}}$)

- **Background** assessment:
  - Channels with at least one final-state bottom quark → top-enhanced contributions;
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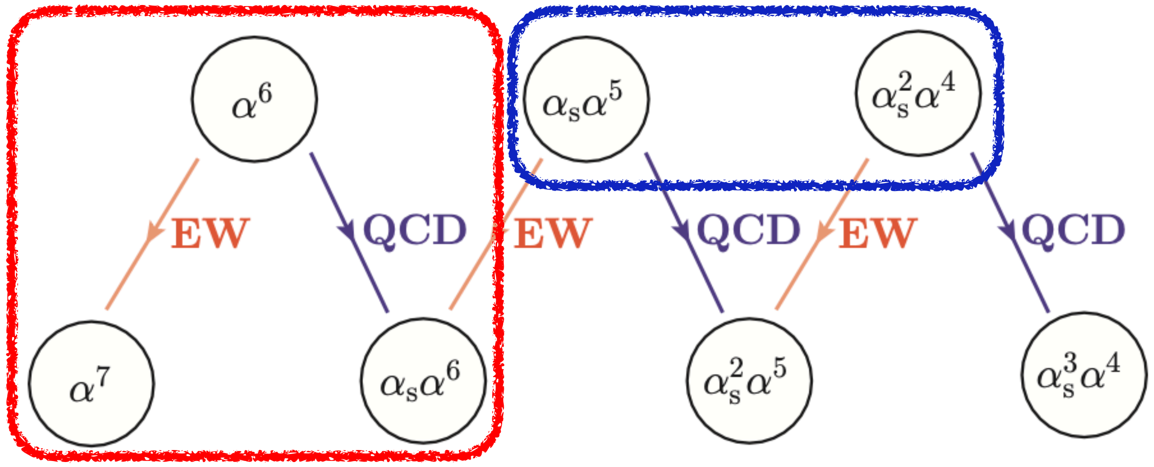

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Definition of phase space

Inspired by HL LHC studies by ATLAS [ATL-PHYS-PUB-2018-030]

$$p\,p \;\rightarrow\; e^+\nu_e\mu^+\mu^-\,j\,j \;\;@\,13.6\,TeV$$

- QCD partons with $|\eta| < 5$ are clustered into jets with anti-k_t clustering ($R = 0.4$).
  - Photon never reconstructed as jets + perfect b-jet tagging and veto
  - Exactly two tagged jets satisfying: $p_{T,j_{1/2}} > 40\,GeV,\quad |y_{j_{1/2}}| < 3$ → VETO on additional radiation
  - Invariant-mass cut on tagged jets: $50\,GeV < M_{j_1j_2} < 100\,GeV$

Hadronically-decaying vector boson

- Leptons/quarks are dressed with anti-k_t clustering ($R = 0.1$):
  - Common rapidity cut for all leptons: $|y_{\ell_i}| < 4$.
  - Transverse-momentum cuts on p_T-ordered leptons $p_{T,\ell_1} > 50\,GeV,\; p_{T,\ell_2} > 40\,GeV,\; p_{T,\ell_3} > 20\,GeV$.
  - Cuts tuned to leptonically-decaying vector bosons:

- Z boson: $76\,GeV < M_{\mu^+\mu^-} < 106\,GeV$
- W^+ boson: $M_{\mathrm{T},W^+} = \sqrt{2p_{\mathrm{T},e^+}p_{\mathrm{T},\nu_e}(1-\cos(\phi_{e^+}-\phi_{\nu_e}))} > 20\,GeV$

Leptonically-decaying vector bosons

Structure of the calculation: $\mathcal{O}(\alpha^6)$

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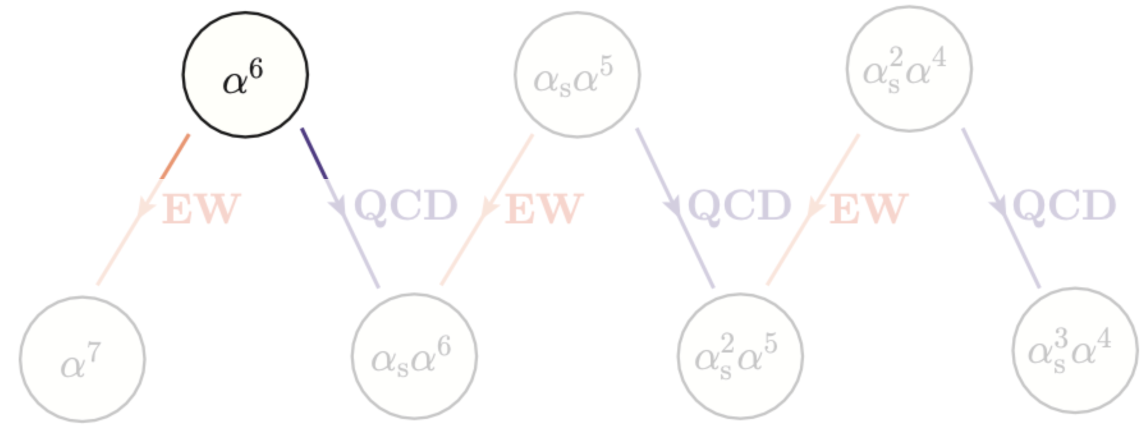
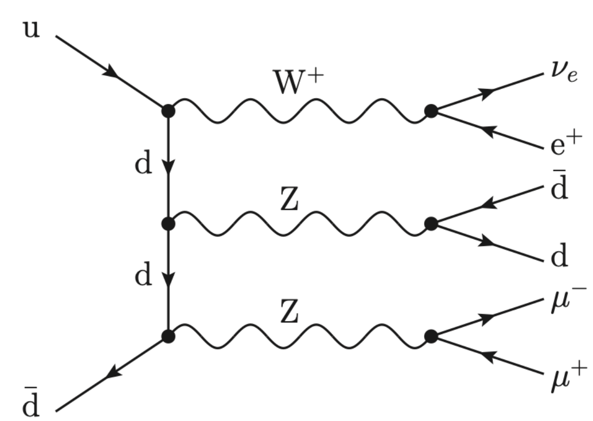
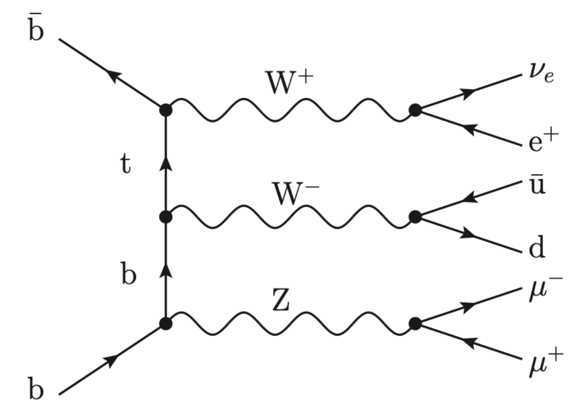
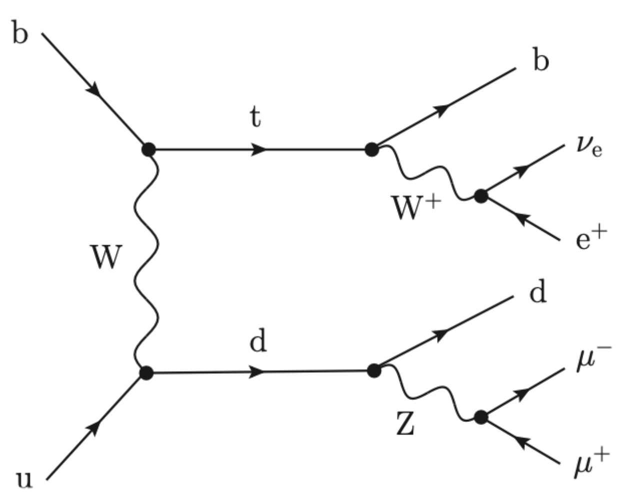


Signal contributions are triply resonant

- $q_1\bar{q}_2$ channels, with q_1 and $\bar{q}_2$ belonging to same generation and such that $Q(q_1)+Q(\bar{q}_2)\in\{-1,0\}$
- $\gamma\gamma$ and $b\bar{b}$ channels

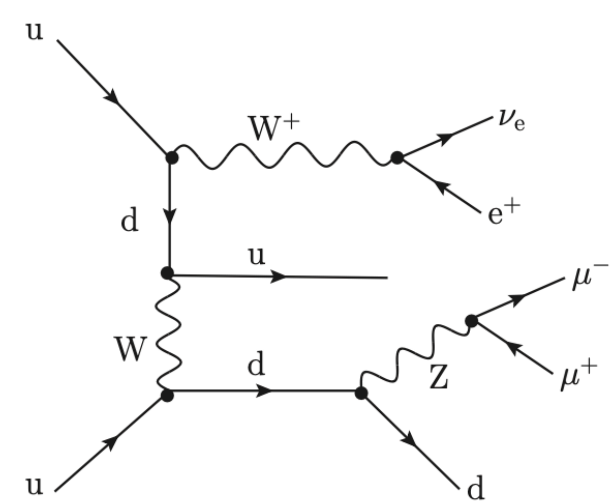






Background (at most doubly resonant)

- $q_1\bar{q}_2'$ channels, suppressed by phase-space cuts
- Channels with at least one b quark in the final state (contributions to tZj production) $\rightarrow$ assuming perfect b-jet veto

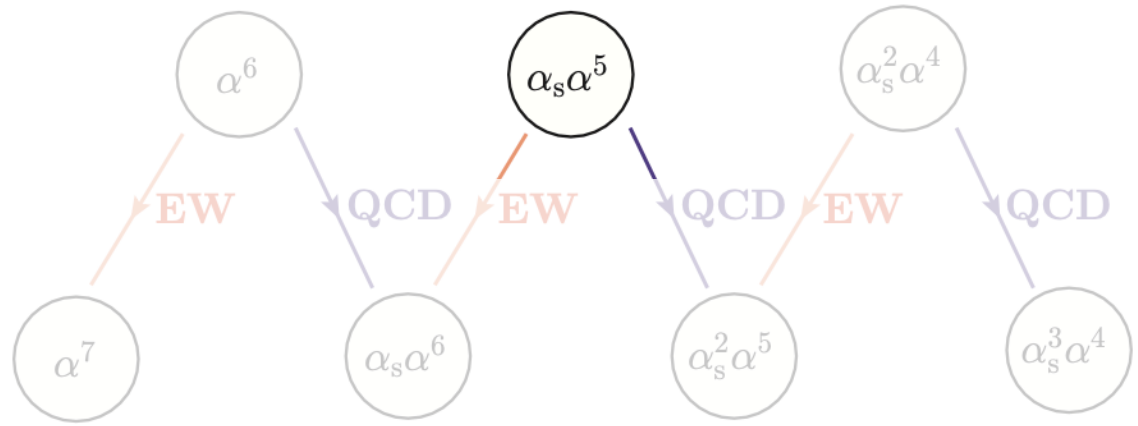


Structure of the calculation: $\mathcal{O}(\alpha_s \alpha^5)$

NLO QCD and NLO EW corrections to fully off-shell:

$$p\,p \;\to\; e^+ \nu_e \mu^+ \mu^- j\,j$$

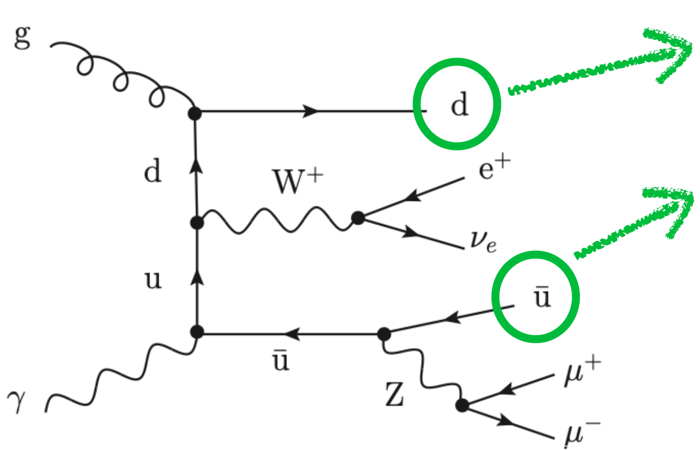
in a phase space which enhances the tri-boson signal.



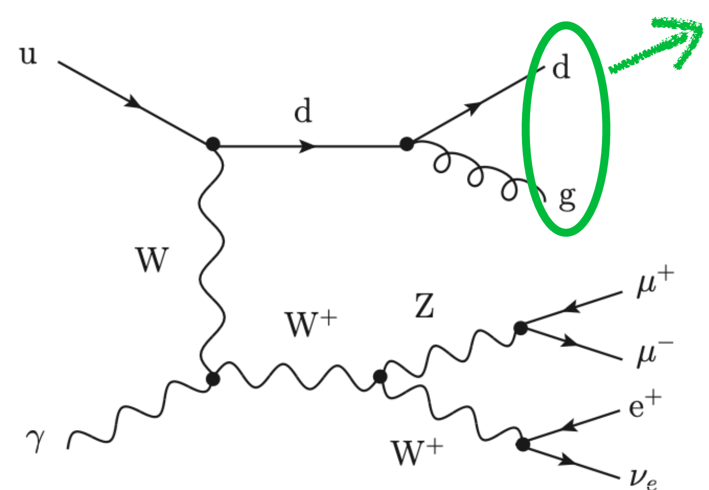
Background arising from

- Interferences of $\mathcal{O}(g^6)$ and $\mathcal{O}(g_s^2 g^4)$ amplitudes allowed by colour algebra
- Squares of $\mathcal{O}(g_s g^5)$ amplitudes from γg and γq channels

$$50\,GeV < M_{j_1 j_2} < 100\,GeV = M_{jj}^{\text{cut}}$$



Typically large invariant mass ($M_{j_1 j_2} > M_{jj}^{\text{cut}}$)



$M_{j_1 j_2} \lesssim M_{jj}^{\text{cut}}$: misidentified hadronically-decaying boson

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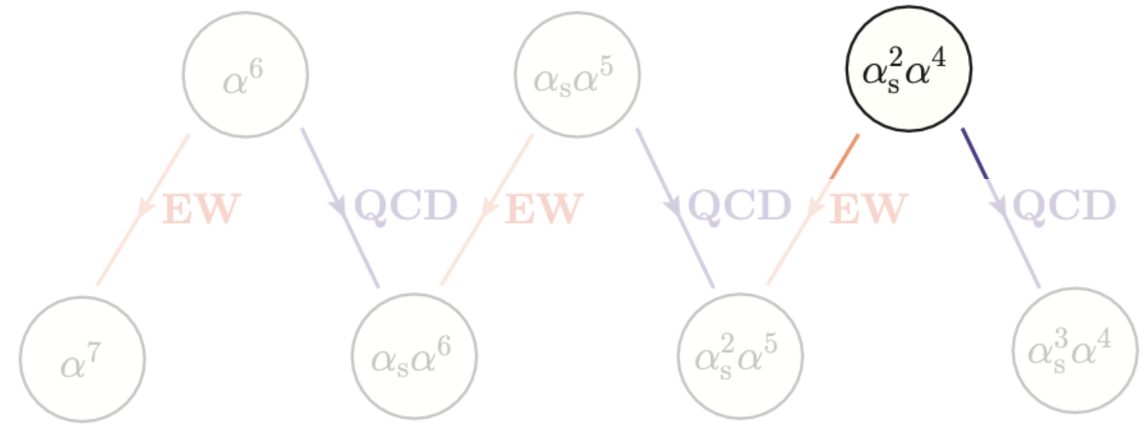
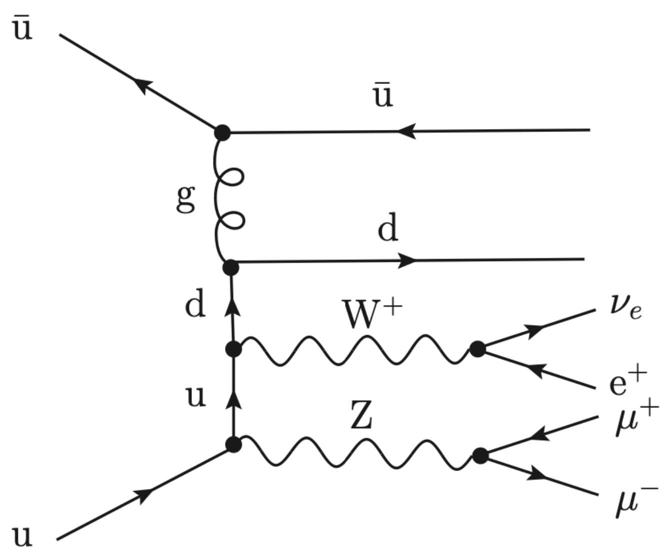
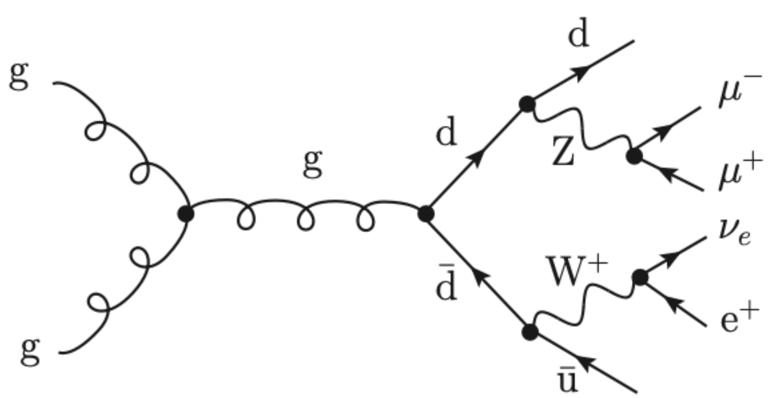
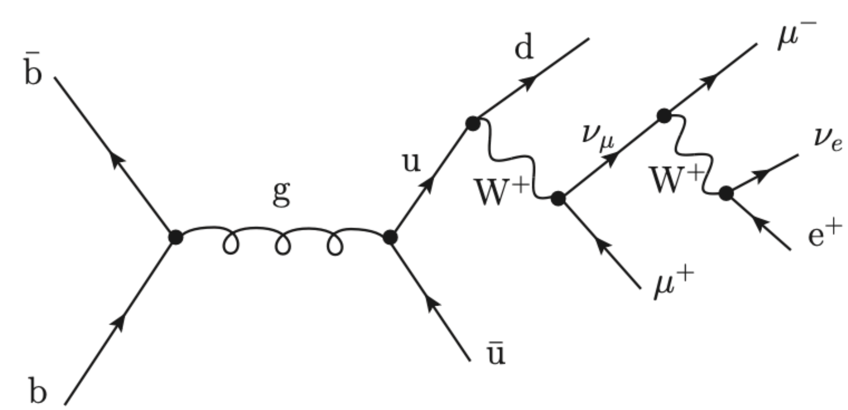


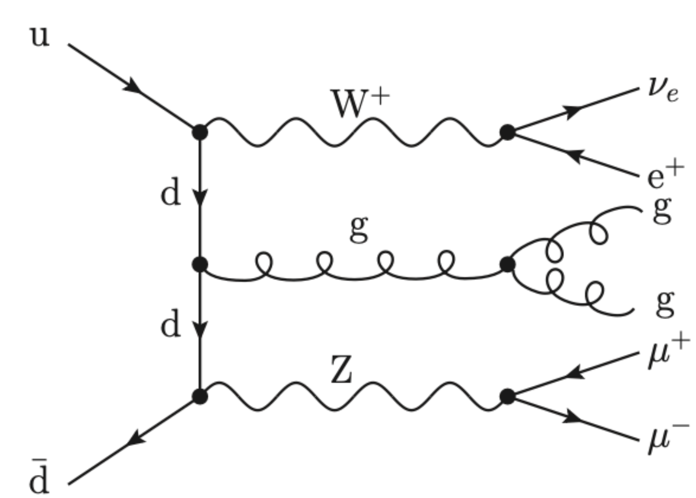




Background arising from

- Diagrams with only an internal gluon propagator
- Diagrams with two external gluons, either as initial or as final states → overwhelming background source





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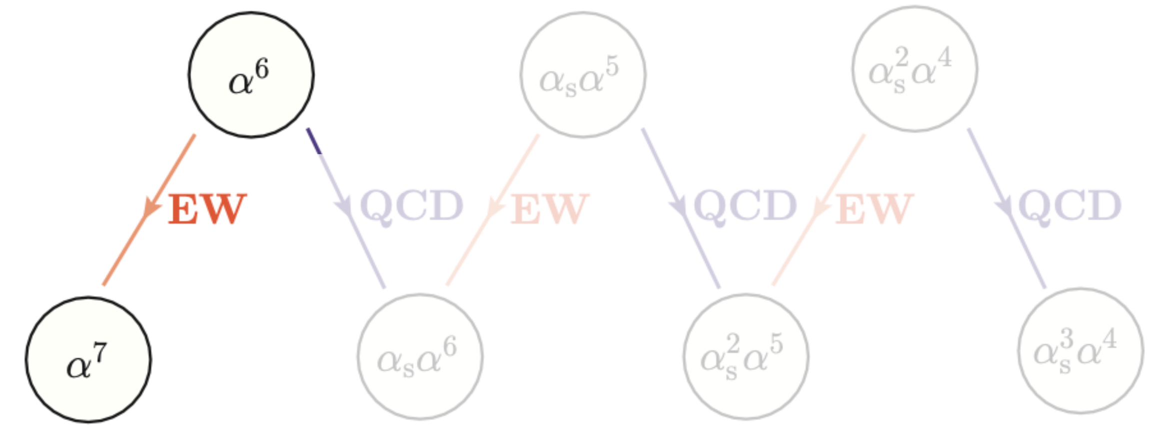
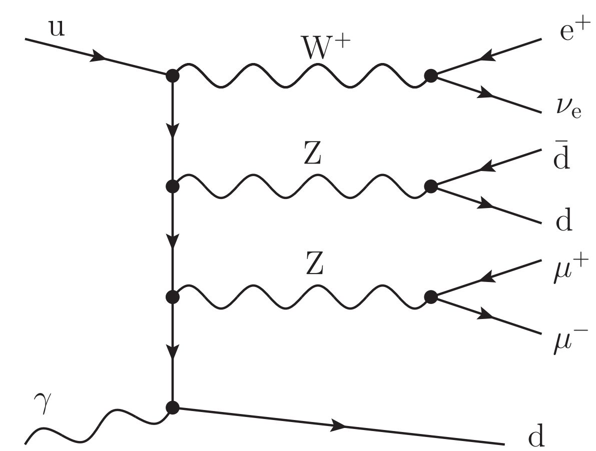
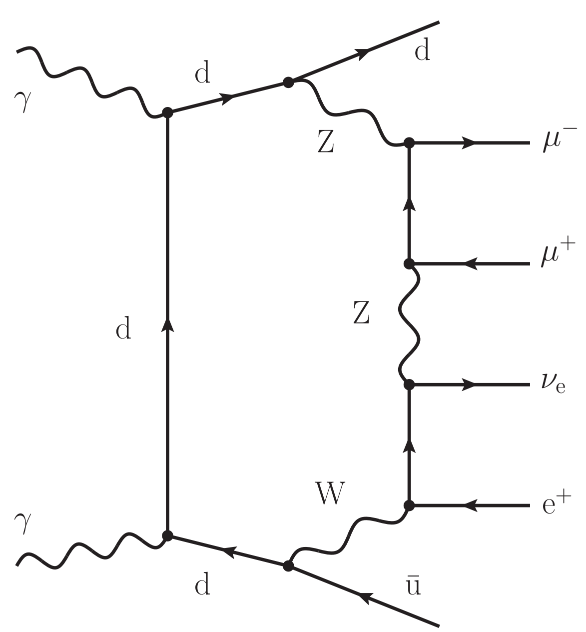
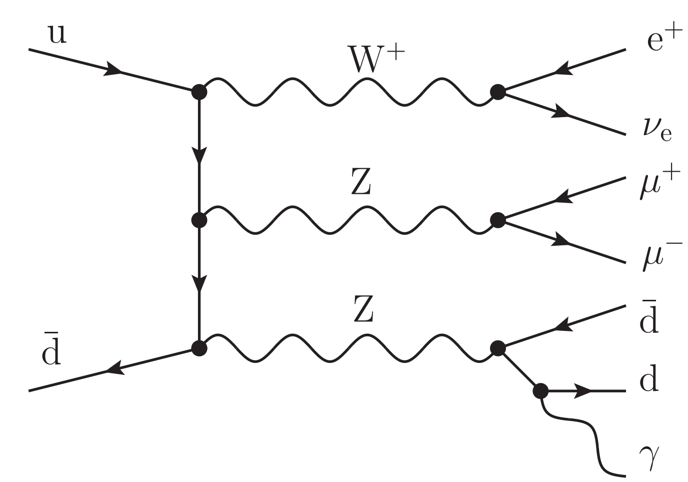




1. γq channels open up at $\mathcal{O}(\alpha^7)$ (absent at $\mathcal{O}(\alpha^6)$)
   $\rightarrow$ only initial-state singularities



2. Real and virtual corrections
   to channels at $\mathcal{O}(\alpha^6)$



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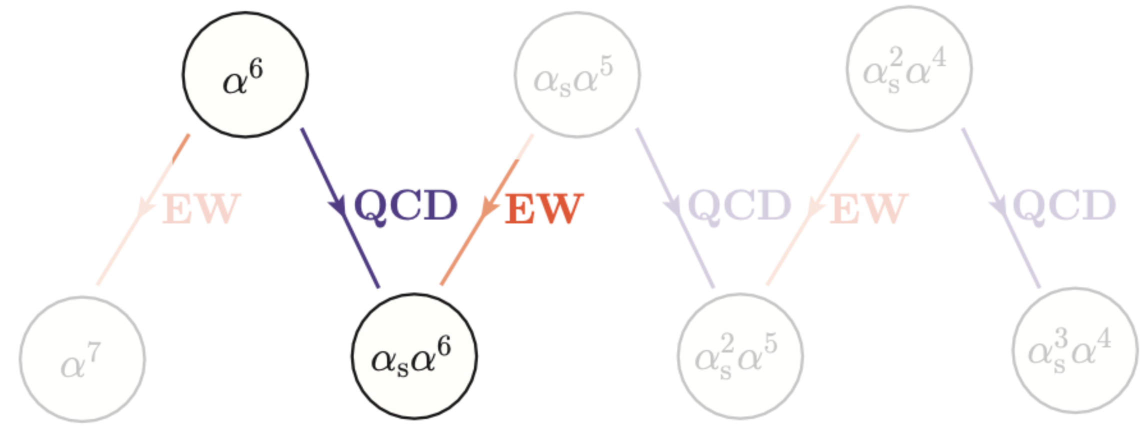
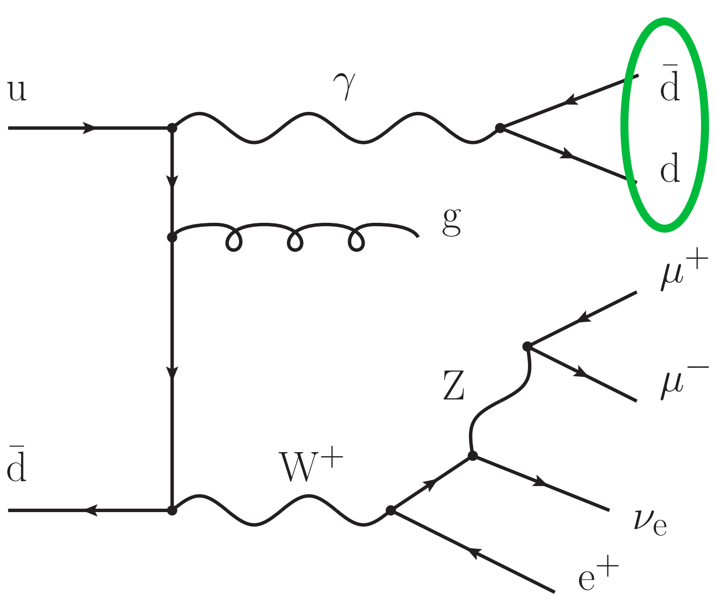


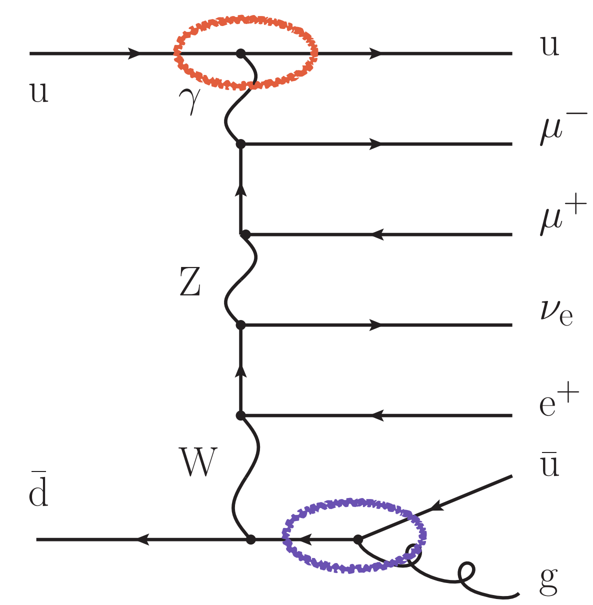
QCD corrections to $\mathcal{O}(\alpha^6)$

- Both QCD and QED Catani-Seymour dipoles required
- Unsubtracted singularities due to jet definition



Configurations where a clustering of collinear quark pair from $\gamma^\star \to q\bar{q}$ splitting occurs are not compensated by virtual corrections

→ Photon-to-jet conversion function [arXiv:1907.02366]



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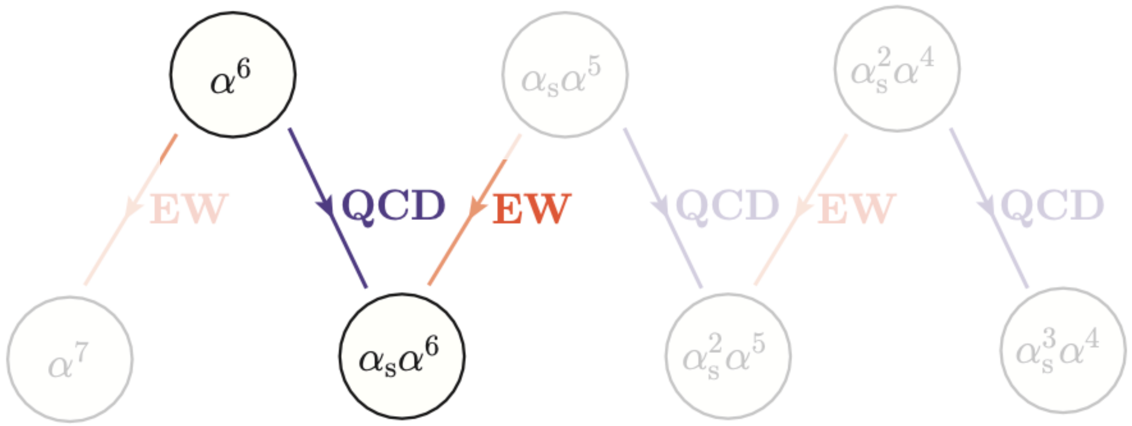

EW corrections to $\mathcal{O}(\alpha_s\alpha^5)$

- QED Catani-Seymour dipoles suffice to subtract all IR singularities (due to jet selection cuts)
- Unsubtracted soft-gluon singularities for $q\gamma$ channels

$$\gamma q_1 \to \mu^+\mu^- e^+\nu_e q_2 \, \gamma g$$

Soft gluon can be clustered with a hard photon

$$\gamma q_1 \to \mu^+\mu^- e^+\nu_e q_2 \quad \gamma$$

Virtual QCD corrections

- Modified jet algorithm: Discard all events where jets are recombination of a parton and a photon whose energies exceed $E_\gamma/(E_p + E_\gamma) > z_{\text{cut}} = 0.7$ [arXiv:1411.0916]
- Events with collinear pairs (q_2, γ) partially cut away: Absorb new divergences in photon fragmentation function

$\mu_0 = M_Z^{OS}$

Fiducial cross sections at LO

Subprocess	$\mathcal{O}(\alpha^6)$ [ab]	$\mathcal{O}(\alpha_s\alpha^5)$ [ab]	$\mathcal{O}(\alpha_s^2\alpha^4)$ [ab]
$q\bar{q} \to q\bar{q}$	47.616(2)	−0.4524(2)	39.1(1)
b	12.3879(6)	–	7.628(2)
$qq/\bar{q}\bar{q}$	1.04105(5)	−1.9664(4)	20.05(7)
$\gamma\gamma$	0.8592(1)	–	–
$\mathrm{b\bar{b}}$	0.7137(1)	–	0.0034516(7)
$\gamma q/\gamma\bar{q}$	–	9.617(2)	–
$\mathrm{g}\gamma$	–	0.9460(4)	–
gg	–	–	17.5(1)
$\mathrm{g}q/\mathrm{g}\bar{q}$	–	–	608.8(3)
$q\bar{q} \to \mathrm{gg}$	–	–	162.0(1)
total	62.618(2)	8.144(2)	855.3(5)

Fiducial cross sections at LO

$\mu_0 = M_Z^{OS}$

$\sigma_{LO}^{sig} = 50.230(2)$ ab

97% of LO signal arises from $q\bar{q}$ channel

Subprocess	$\mathcal{O}(\alpha^6)$ [ab]	$\mathcal{O}(\alpha_s\alpha^5)$ [ab]	$\mathcal{O}(\alpha_s^2\alpha^4)$ [ab]
$q\bar{q} \to q\bar{q}$	47.616(2)	−0.4524(2)	39.1(1)
b	12.3879(6)	–	7.628(2)
$qq/\bar{q}\bar{q}$	1.04105(5)	−1.9664(4)	20.05(7)
$\gamma\gamma$	0.8592(1)	–	–
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Background

Channels with one or two b quarks in the finale state: isolated assuming perfect b-jet veto

Fiducial cross sections at LO

$\mu_0 = M_Z^{OS}$

Background

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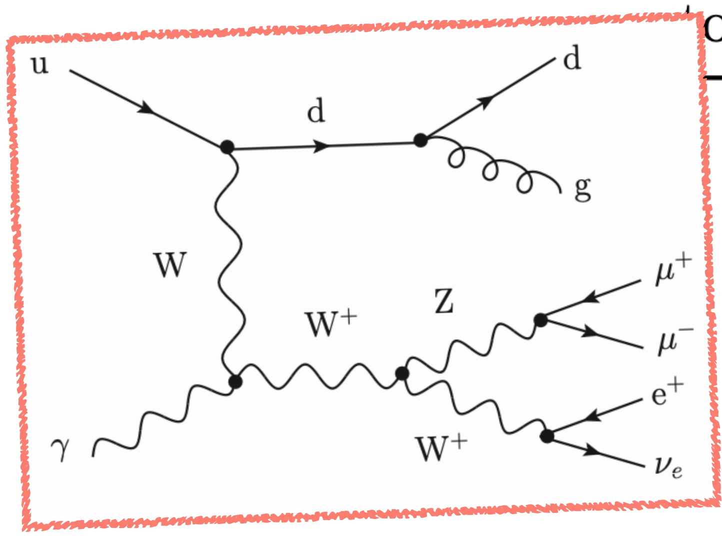
Channels with one or two b quarks in the finale state: isolated assuming perfect b-jet veto



Dominance of squared-diagram contributions from γq channels

$\mu_0 = M_Z^{OS}$

Fiducial cross sections at LO

Subprocess	$\mathcal{O}(\alpha^6)$ [ab]	$\mathcal{O}(\alpha_s\alpha^5)$ [ab]	$\mathcal{O}(\alpha_s^2\alpha^4)$ [ab]
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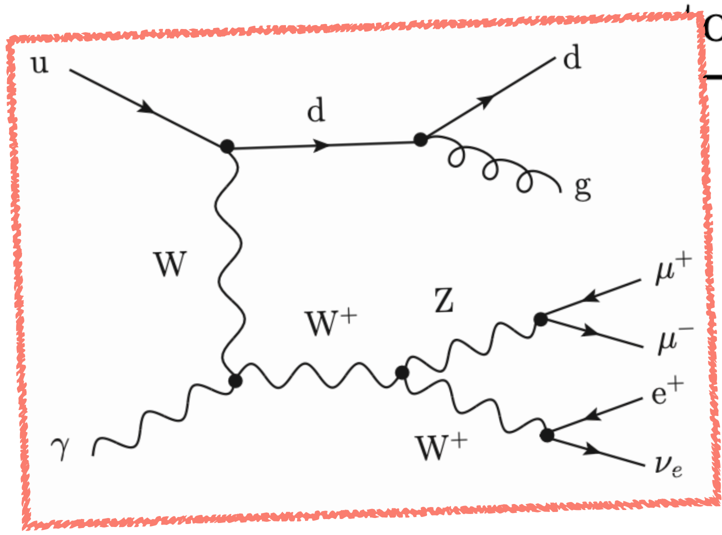
Background

Channels with one or two b quarks in the finale state: isolated assuming perfect b-jet veto



Dominance of squared-diagram contributions from γq channels

Channels with external gluons completely overwhelm the signal

Fiducial cross sections at NLO

$\mu_0 = M_Z^{OS}$

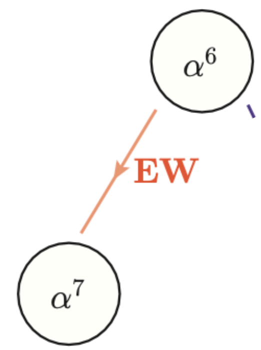
$\Delta^{(i)}_{\alpha^6}$: ratio of NLO correction and corresponding $\mathcal{O}(\alpha^6)$ contribution

Subprocess	$\mathcal{O}(\alpha^6)$ [ab]	$\mathcal{O}(\alpha^7)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]	$\mathcal{O}(\alpha_s\alpha^6)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]
$q\bar{q} \to q\bar{q}$	47.616(2)	−7.81(5)	−16.4	−6.83(6)	−14.3
$qq/\bar{q}\bar{q}$	1.04105(5)	−0.1156(3)	−11.1	4.19(1)	402.5
$\gamma\gamma$	0.8592(1)	−0.1045(6)	−12.1	−0.1341(4)	−15.6
$\mathrm{b}\bar{\mathrm{b}}$	0.7137(1)	−0.0836(4)	−11.7	−0.2195(5)	−30.7
$\gamma q/\gamma\bar{q}$	–	0.9175(2)	–	−0.593(6)	–
$\mathrm{g}\gamma$	–	–	–	0.0053(7)	–
$\mathrm{g}q/\mathrm{g}\bar{q}$	–	–	–	5.766(3)	–
total	50.230(2)	−7.20(5)	−14.3	2.17(6)	4.3

Fiducial cross sections at NLO

$\mu_0 = M_Z^{OS}$

$\Delta^{(i)}_{\alpha^6}$: ratio of NLO correction and corresponding $\mathcal{O}(\alpha^6)$ contribution



Subprocess	$\mathcal{O}(\alpha^6)$ [ab]	$\mathcal{O}(\alpha^7)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]	$\mathcal{O}(\alpha_s\alpha^6)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]
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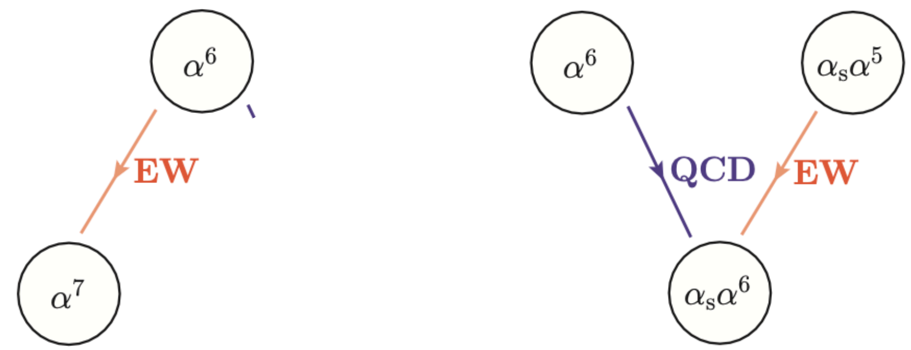
Large NLO EW correction of -14.3%, due to missing cancellation between $q\bar{q}$ and γq channels

→ large EW Sudakov logarithms induced by $\langle\sqrt{s}\rangle \sim 750\,GeV$

Fiducial cross sections at NLO

$\mu_0 = M_Z^{OS}$

$\Delta^{(i)}_{\alpha^6}$: ratio of NLO correction and corresponding $\mathcal{O}(\alpha^6)$ contribution



Subprocess	$\mathcal{O}(\alpha^6)$ [ab]	$\mathcal{O}(\alpha^7)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]	$\mathcal{O}(\alpha_s\alpha^6)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]
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Large NLO EW correction of -14.3%, due to missing cancellation between $q\bar{q}$ and γq channels

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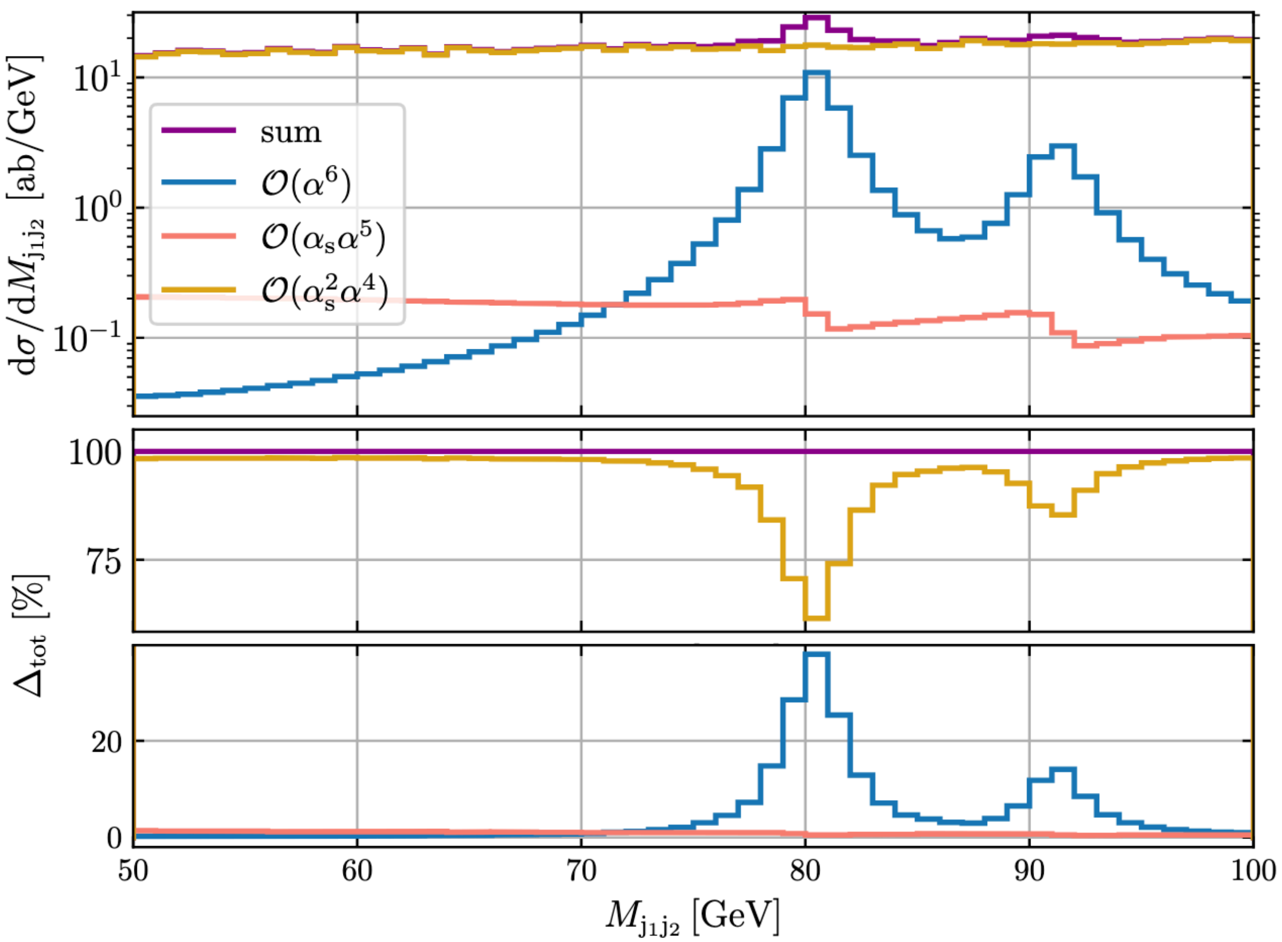
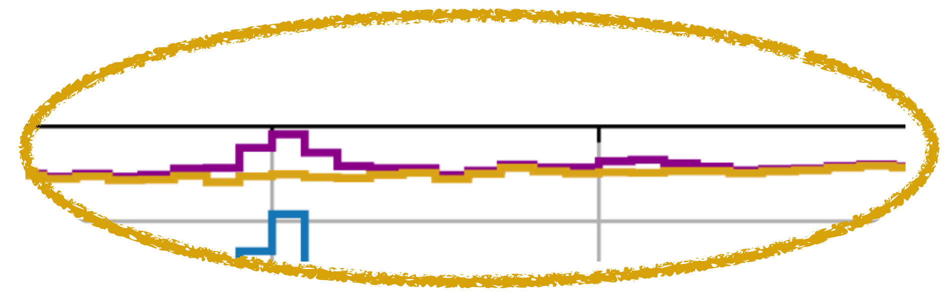
Large cancellations among different channels

Differential cross sections: $M_{j_1 j_2}$



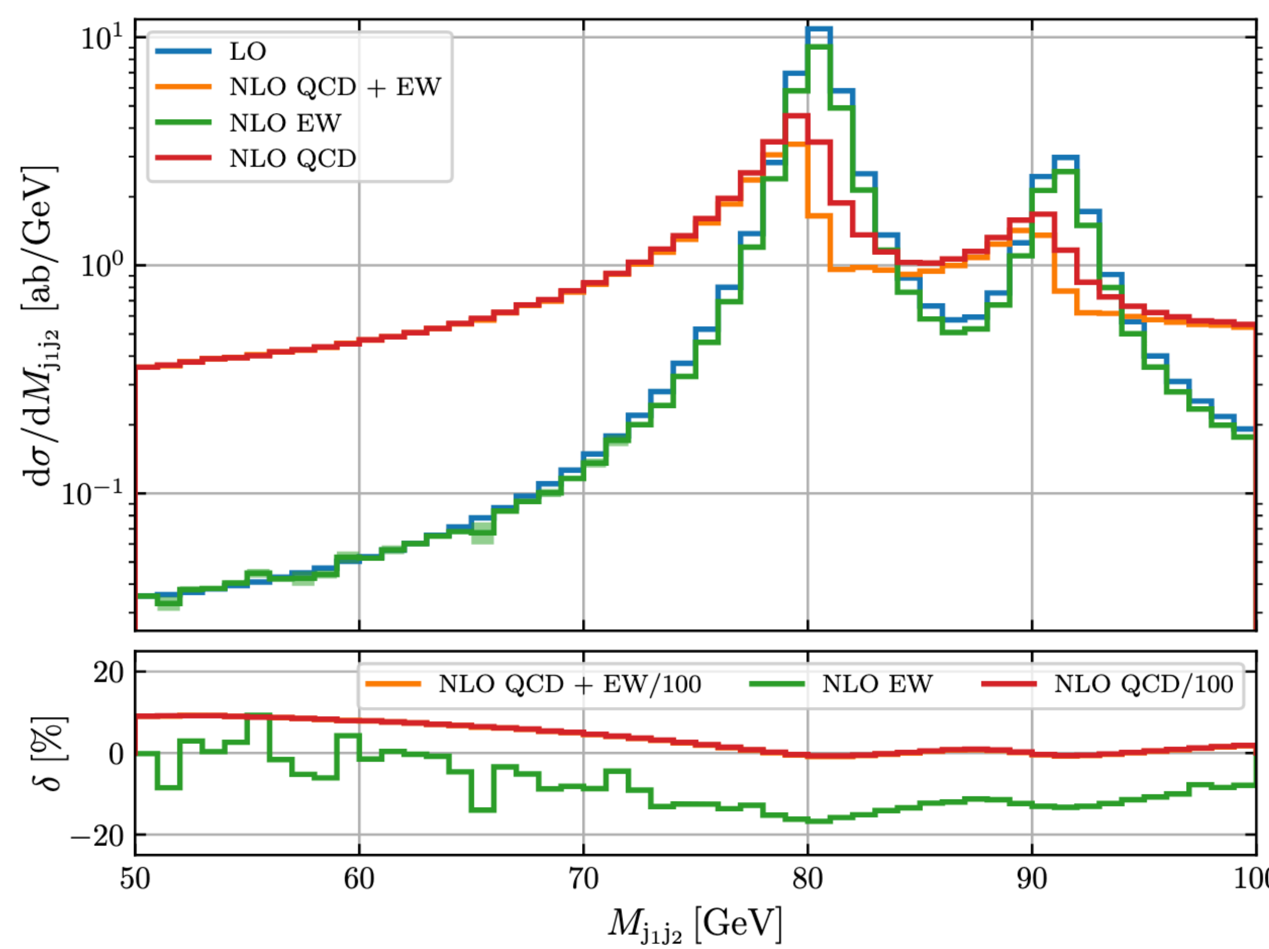
LO QCD background



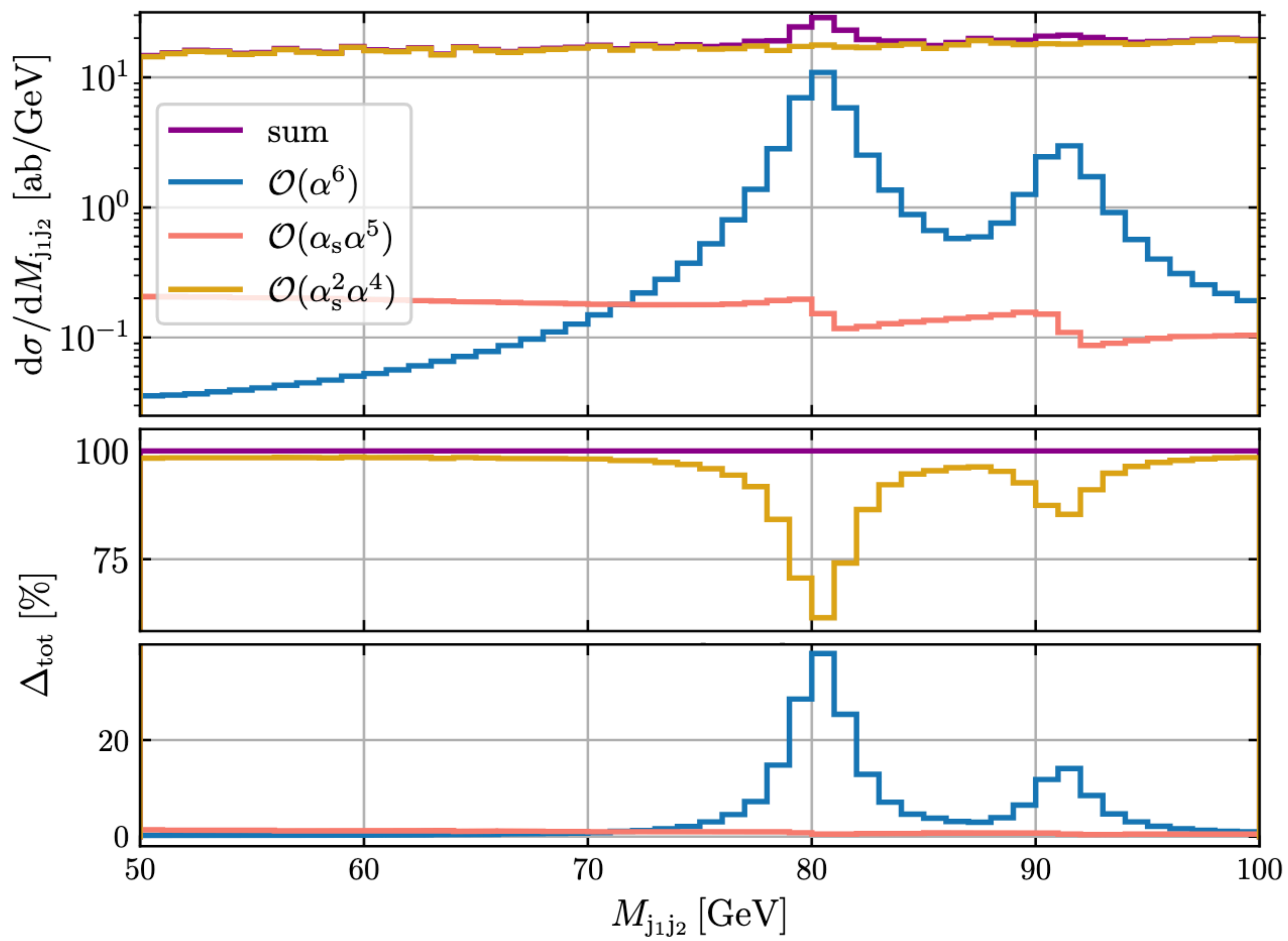
$\mathcal{O}(\alpha_s\alpha^5)$ background

Signal LO

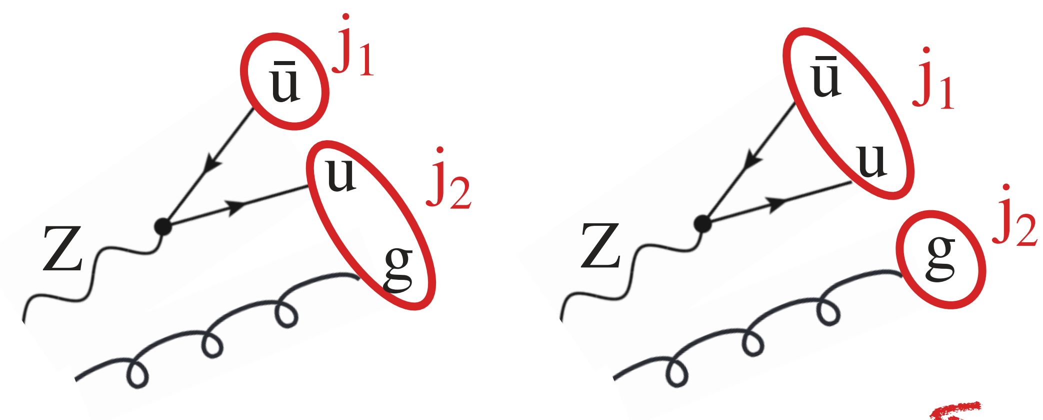
- It amounts to 38% at $M_{j_1j_2} \sim M_W$ and 14% at $M_{j_1j_2} \sim M_Z$ of the sum of the three LO contributions

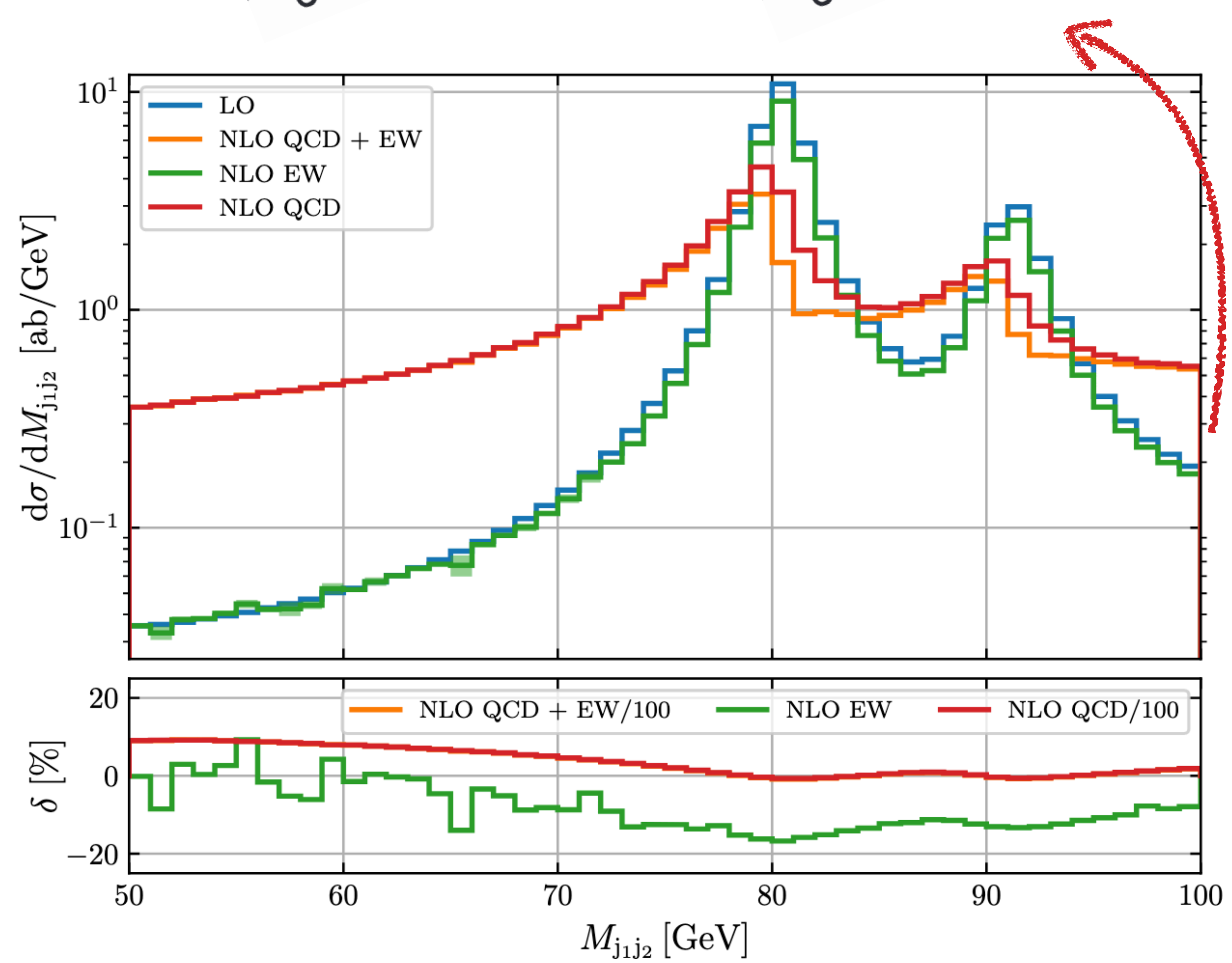


Differential cross sections: $M_{j_1 j_2}$



NLO QCD + EW	=	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7) + \mathcal{O}(\alpha_s\alpha^6)$
NLO EW	=	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7)$
NLO QCD	=	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha_s\alpha^6)$





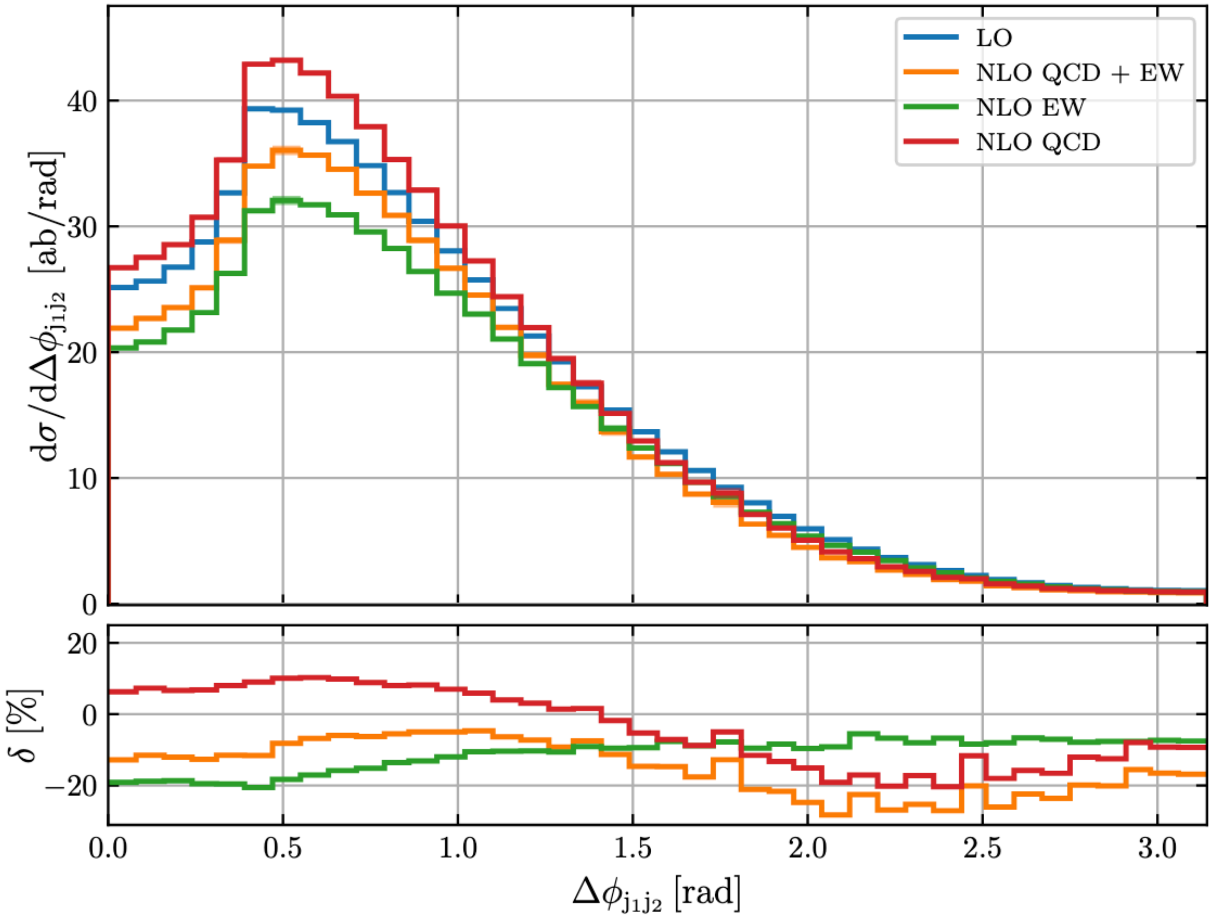
QCD corrections

- Large radiative-return effects (left sides of peaks)
- Real-radiation effects on right side of Z-peak

EW corrections

- Tiny radiative-return effects
- Largest corrections of -17% on W peak

Differential cross sections: $\Delta\phi_{j_1 j_2}$ and p_{T,μ^+}



NLO QCD + EW	=	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7) + \mathcal{O}(\alpha_s\alpha^6)$
NLO EW	=	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7)$
NLO QCD	=	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha_s\alpha^6)$

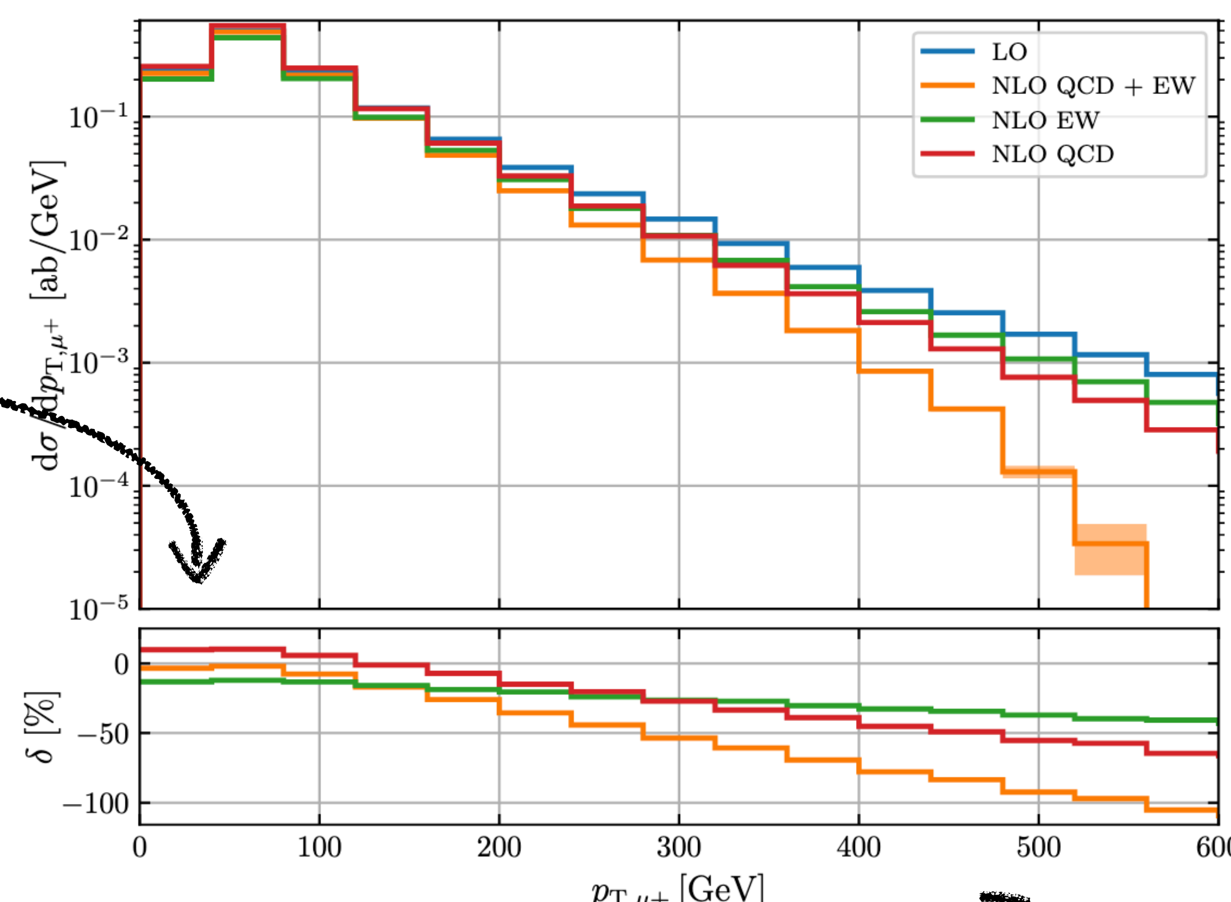
- Dominance of EW corrections where bulk of the cross section resides
- Negative corrections in the tail

Bulk

- EW and QCD corrections of similar size but opposite sign

Tails

- EW Sudakov logarithms generate large negative corrections
- Negative QCD corrections due to scale choice



Summary

- Tri-boson production plays a crucial role in improving our understanding of the standard model → it is worth investigating it in all its decay modes!
- We computed for the first time the NLO corrections to triple vector-boson production in the WZjj channel:
  - At the inclusive level, EW corrections amount to -14% → large compared to previous results available in the literature;
  - At the differential level, EW and QCD corrections show a non-trivial interplay for many leptonic and hadronic observables → relevant shape effects

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  - At the differential level, EW and QCD corrections show a non-trivial interplay for many leptonic and hadronic observables → relevant shape effects

Thank you for your attention

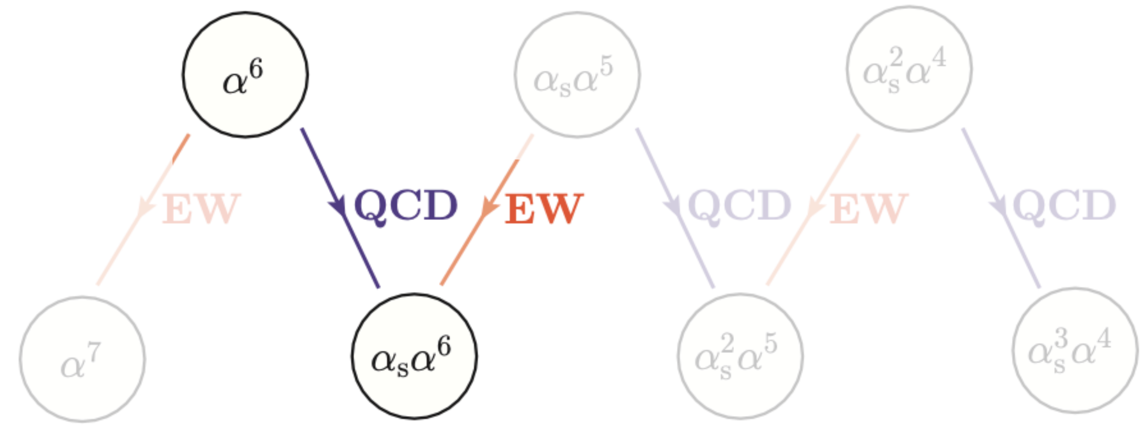
Backup

Structure of the calculation: $\mathcal{O}(\alpha_s\alpha^6)$

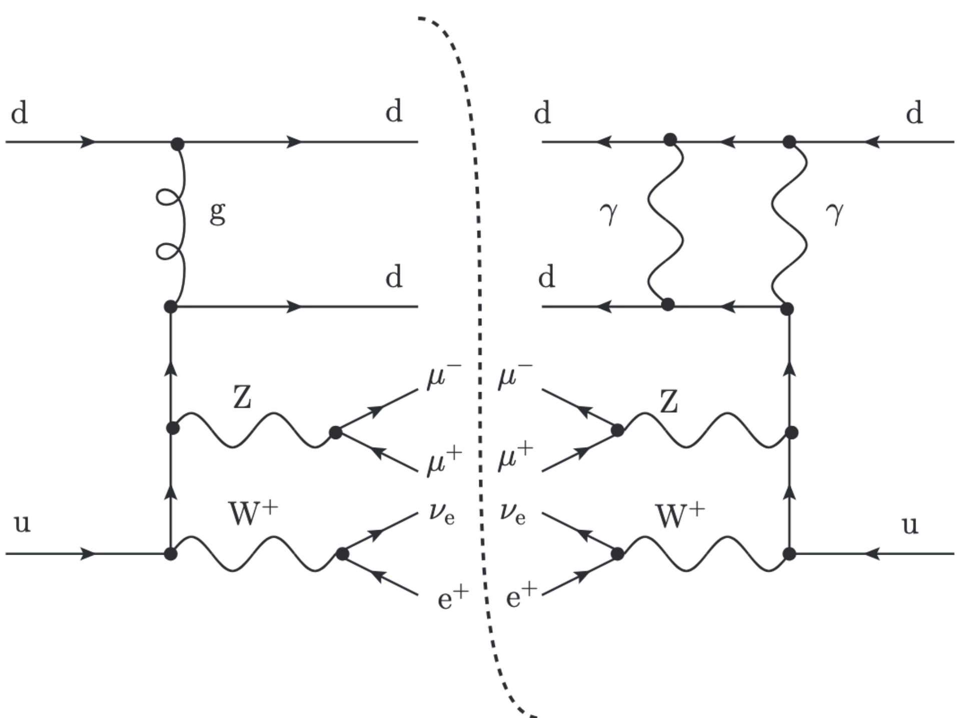
NLO QCD and NLO EW corrections to fully off-shell:

$$pp \rightarrow e^+\nu_e\mu^+\mu^- jj$$

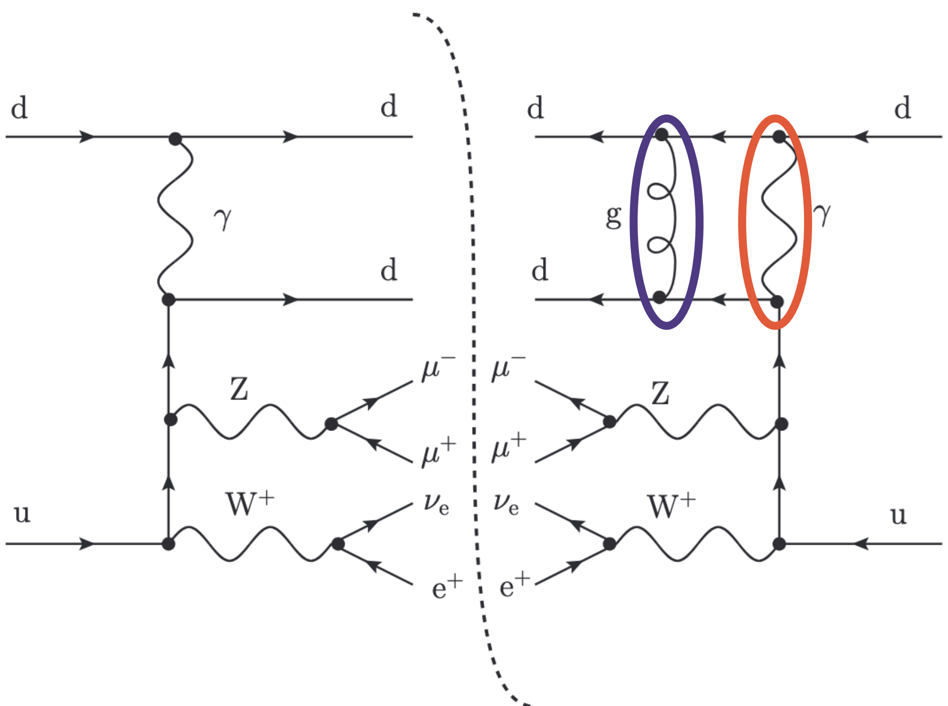
in a phase space which enhances the tri-boson signal.



Virtual contributions can not be unambiguously attributed to one of the two corrections



EW correction to $\mathcal{O}(\alpha_s\alpha^5)$



QCD correction to $\mathcal{O}(\alpha^6)$

or

EW correction to $\mathcal{O}(\alpha_s\alpha^5)$

Fiducial cross sections at LO

LO containing the signal

QCD background

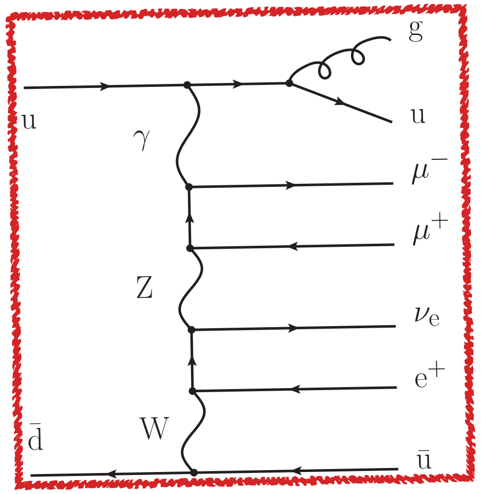
Contributions with two external gluons

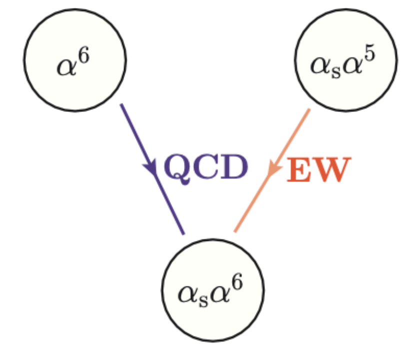
	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	sum
σ_{LO} [ab]	50.230(2)	8.144(2)	847.7(5)	906.0(5)
Δ_{tot} [%]	5.54	0.90	93.56	100.00

Subprocess	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	sum
$\sigma_{\mathrm{LO}}^{qq/\bar{q}\bar{q}/q\bar{q}}$ [ab]	48.657(2)	$-2.4189(5)$	59.2(1)	105.4(1)
Δ_{α^6} [%]	96.87	-4.82	117.92	209.98
$\sigma_{\mathrm{LO}}^{\gamma}$ [ab]	0.8592(1)	10.563(2)	–	11.422(2)
Δ_{α^6} [%]	1.71	21.03	–	22.74
$\sigma_{\mathrm{LO}}^{\mathrm{b\bar{b}}}$ [ab]	0.7137(1)	–	0.0034516(7)	0.7171(1)
Δ_{α^6} [%]	1.42	–	0.01	1.43
$\sigma_{\mathrm{LO}}^{\mathrm{b/\bar{b}}}$ [ab]	12.3879(6)	–	7.628(2)	20.016(2)
Δ_{α^6} [%]	24.66	–	15.19	39.85

Top enhanced contributions

Fiducial cross sections at NLO





Subprocess	$\mathcal{O}(\alpha^6)$ [ab]	$\mathcal{O}(\alpha^7)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]	$\mathcal{O}(\alpha_s\alpha^6)$ [ab]	$\Delta^{(i)}_{\alpha^6}$ [%]
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$g\gamma$	–	–	–	0.0053(7)	–
$gq/g\bar{q}$	–	–	–	5.766(3)	–
total	50.230(2)	−7.20(5)	−14.3	2.17(6)	4.3

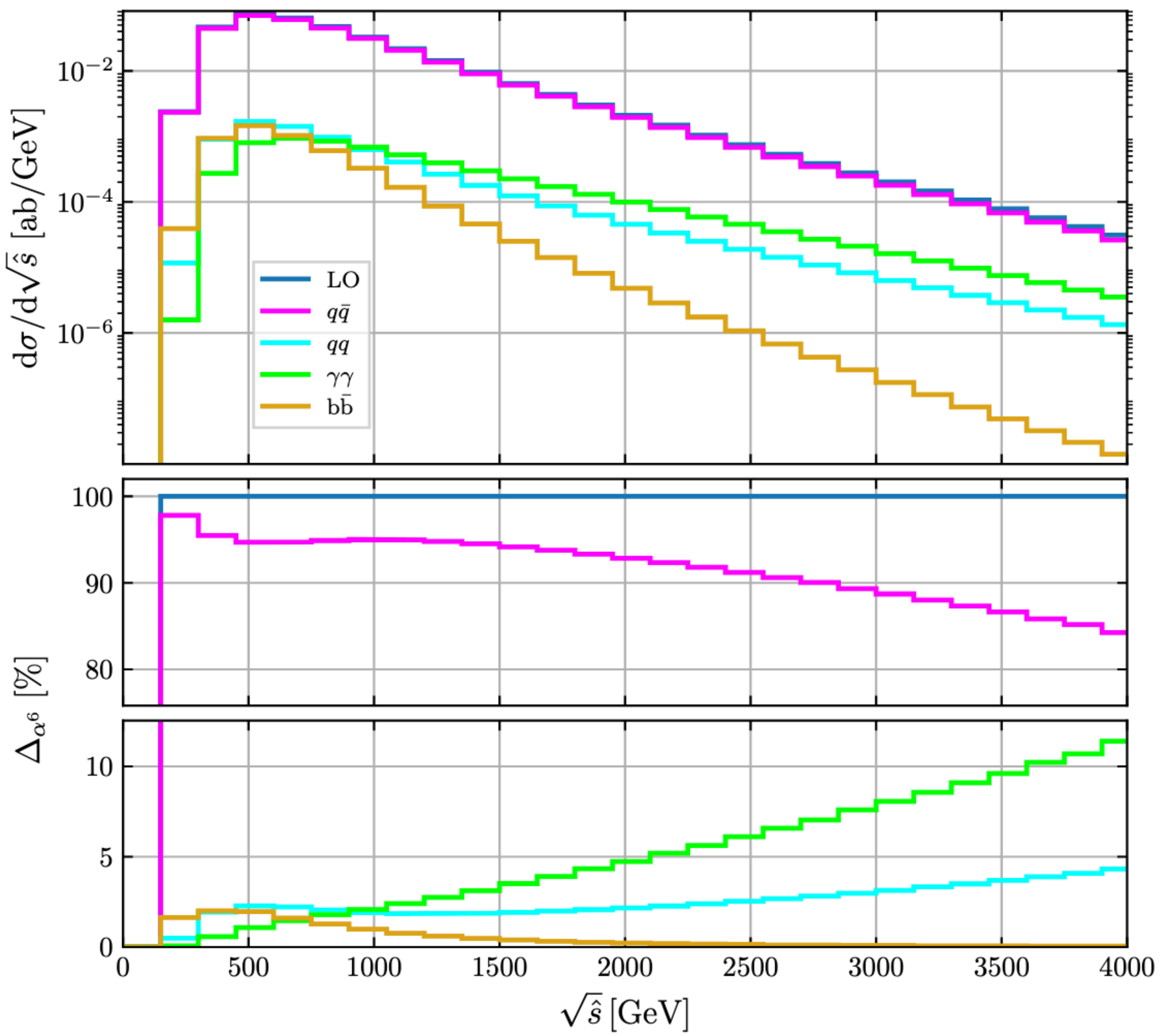
Real gluon radiation eluding cut constraints

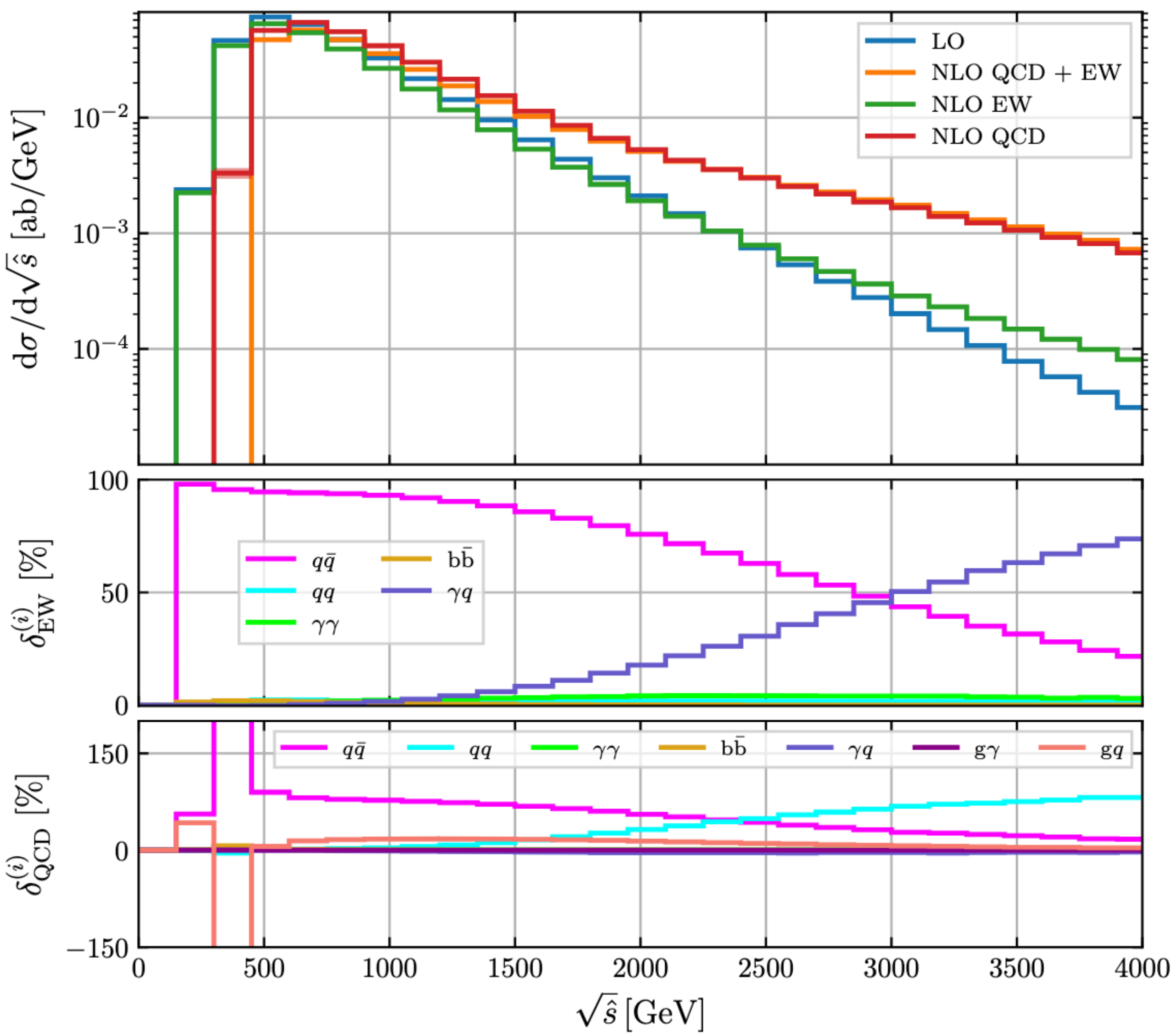
Top-enhanced loop corrections

Large NLO EW correction of -14.3%, due to missing cancellation between $q\bar{q}$ and γq channels

→ large EW Sudakov logarithms induced by $\langle\sqrt{s}\rangle \sim 750\,GeV$

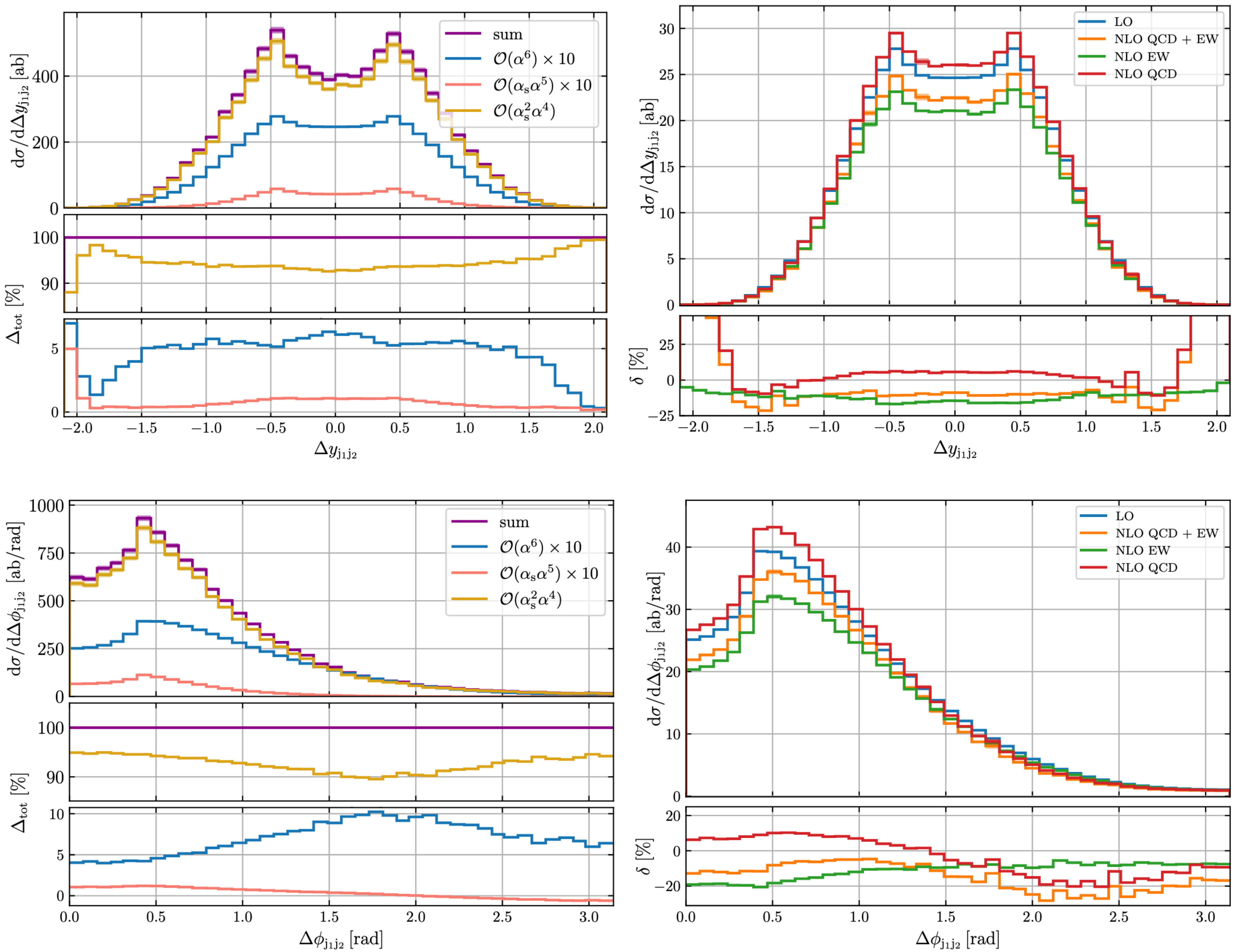
Differential cross sections: $\sqrt{\hat{s}}$



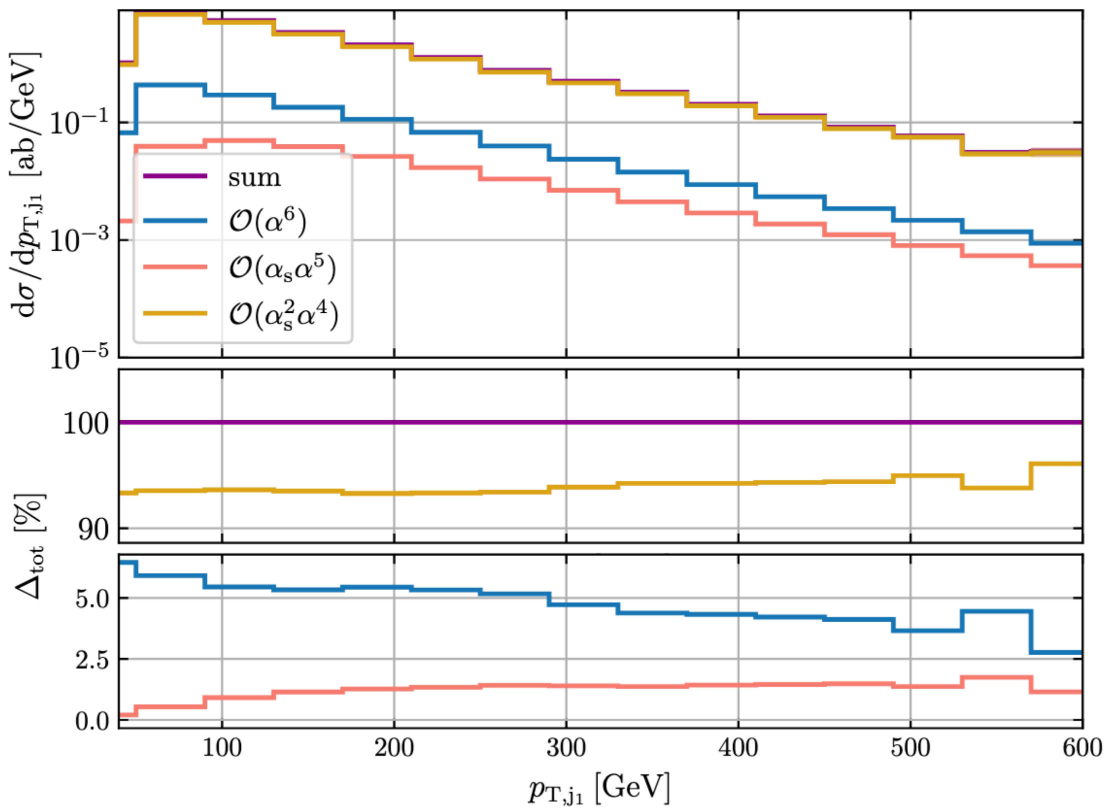


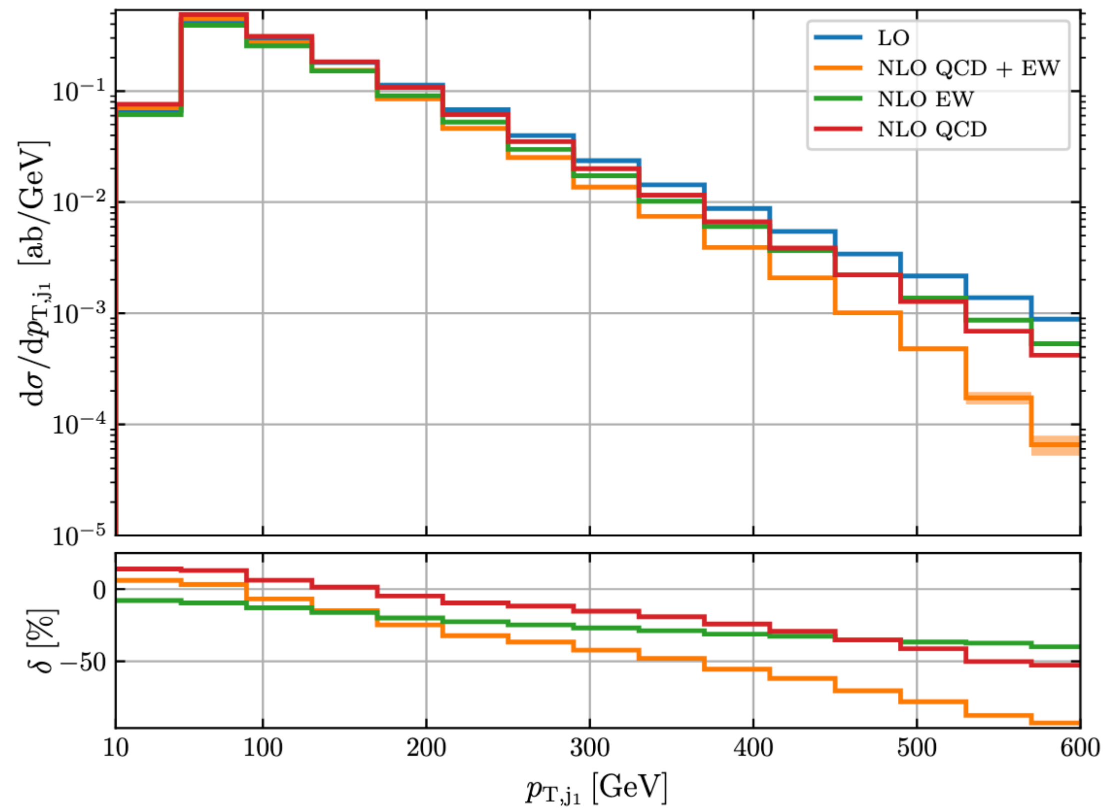
$$\delta^{(i)}_{\mathrm{EW/QCD}} = \frac{\sigma^{(i)}_{\mathrm{LO}} + \delta\sigma^{(i)}_{\mathrm{NLO\ EW/QCD}}}{\sigma^{\mathrm{tot}}_{\mathrm{LO}} + \delta\sigma^{\mathrm{tot}}_{\mathrm{NLO\ EW/QCD}}}$$

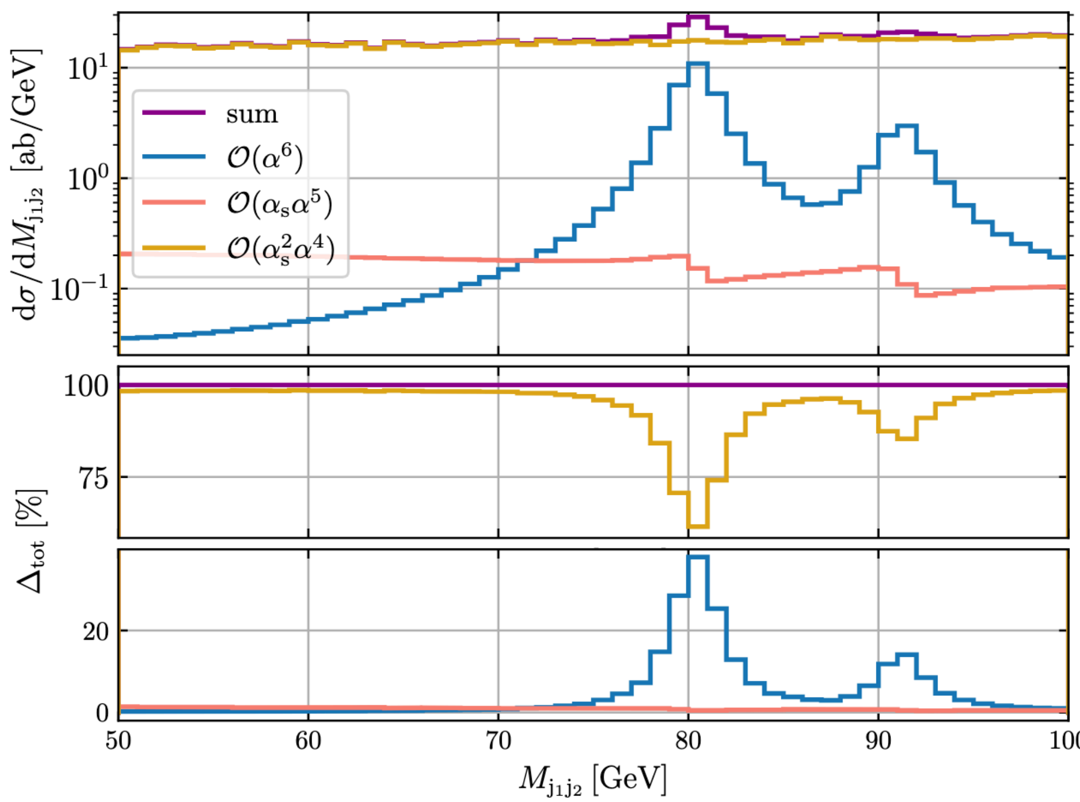
Differential cross sections: $\Delta y_{j_1 j_1}$ and $\Delta \phi_{j_1 j_1}$

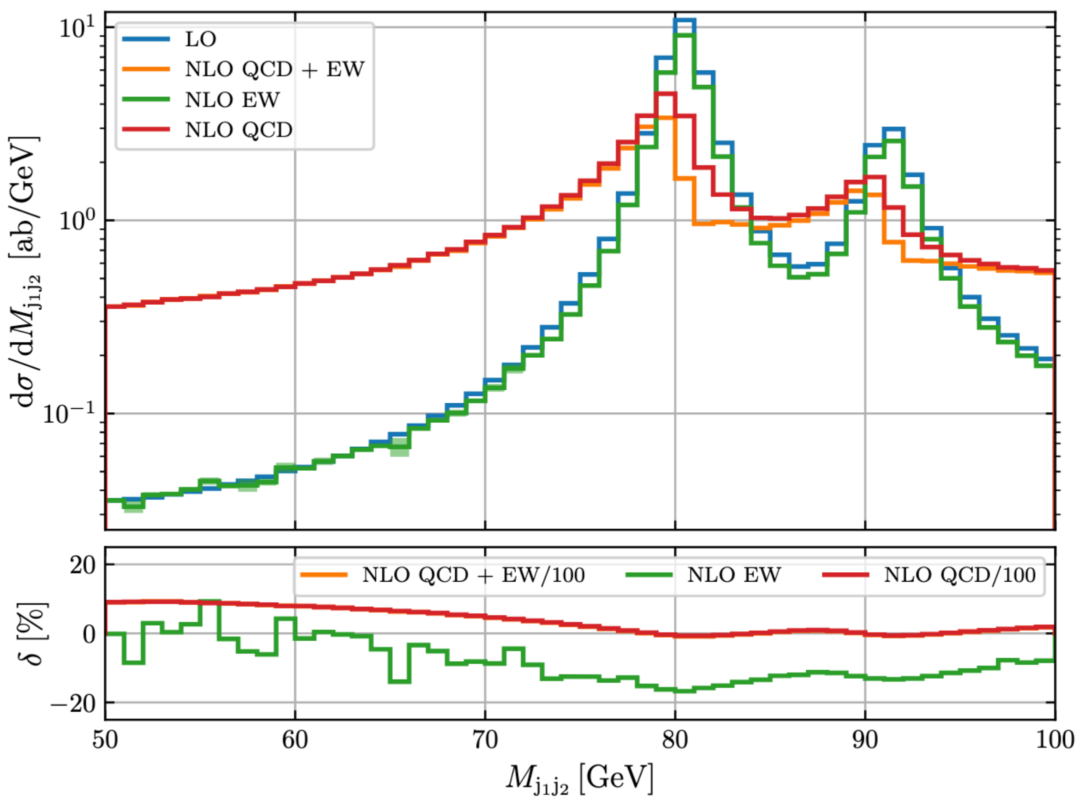


Differential cross sections: p_{T,j_1} and $M_{j_1 j_2}$

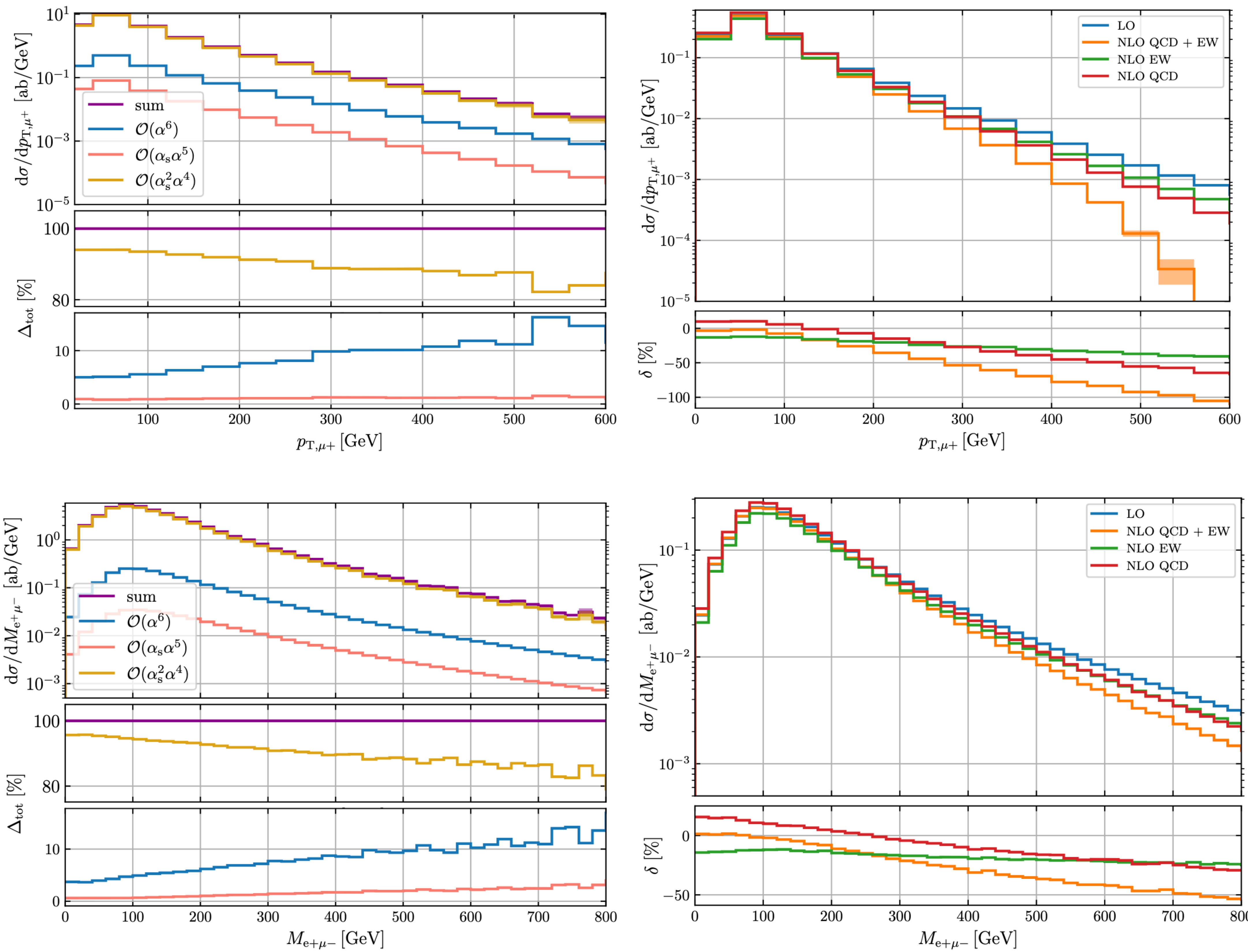








Differential cross sections: p_{T,μ^+} and $M_{e^+\mu^-}$



Differential cross sections: $\cos\theta_{\mu^+\mu^-}$ and $M_{e^+\mu^+\mu^-j_1j_2}$