QCD corrections to the EW top-pair production BSM

Tomáš Ježo
University of Liverpool

in collaboration with
R. Bonciani, M. Klasen,
F. Lyonnet, I. Schienbein

PSR workshop
Münster
12 June

QCD corrections to the EW top-pair production BSM

- the Standard Model of particle physics (SM)
  - successful in describing wealth of experimental data
  - widely believed to be *incomplete*
- many theories beyond the SM predict the existence of new resonances
  - properties similar to SM Z and W
  - heavy, spin-1, neutral and charged resonances, denoted Z' and W'
  - mediate the neutral and charged current interactions of SM fermions
- observable at the Large Hadron Collider (LHC)
  - searched for in di-lepton, lepton-neutrino, top-pair, single-top, …
  - show up as peaks in invariant and transverse mass distributions
  - Z' and W' with SM-like couplings
    - ★ reachable up to masses of 5 TeV
    - ★ excluded with masses below 2.96 and 3.35 TeV

QCD corrections to the EW top-pair production BSM

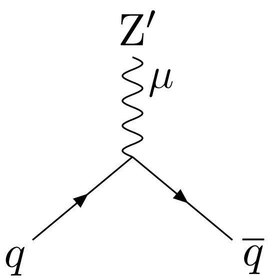
- top-pairs abundantly produced at LHC
  - 10 fb^{-1}, $\sqrt{s_{\text{had}}} = 14$ TeV: over 10^6 top-pairs
- top-pair SM precision calculations:
  - NLO QCD & EW
  - recently even NNLO QCD
- top-quark related observables likely sensitive to new physics
  - mass at the scale of EWSB ($m_{\text{t}} = 173.2 \pm 0.9$ GeV)
  - short lifetime, does not hadronize
- precise predictions required for accurate determination of model parameters

QCD corrections to the EW top-pair production BSM

- NLO QCD corrections to EW top-pair production beyond SM
- implement them in `POWHEG BOX` Monte Carlo event generator

QCD corrections to the EW top-pair production BSM

- NLO QCD corrections to EW top-pair production beyond SM
- implement them in `POWHEG BOX` Monte Carlo event generator
- top-pair production in the presence of:

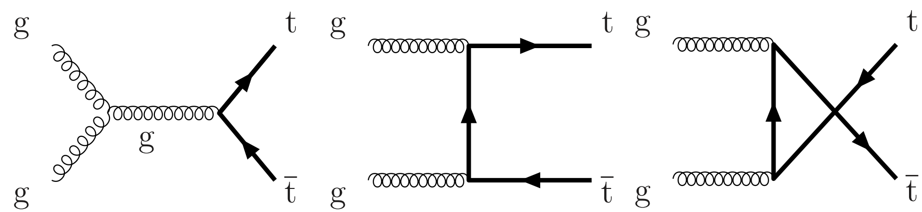


$$i(2\pi)^4 \frac{g_W}{4c_{\theta_W}} \gamma^\mu \left(a^q_{Z'} + b^q_{Z'}\gamma_5\right)$$, flavour-diagonal

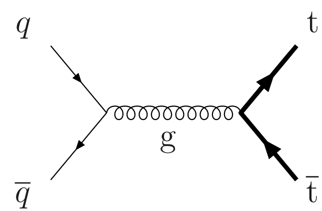
- precise predictions for top-pair production beyond the SM
  - strongly coupled: calculated by Yuan et al.
  - weakly coupled: recently calculated by Melnikov et al.

Born

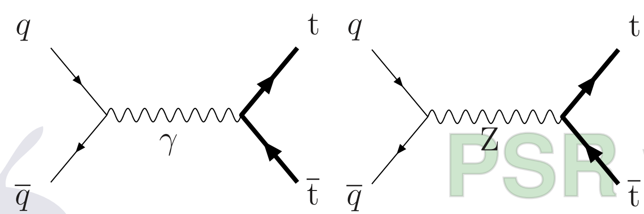
- $\hat{\sigma}^{\mathrm{LO}} = \hat{\sigma}_S^{\mathrm{LO}}(\alpha_S^2) + \hat{\sigma}_W^{\mathrm{LO}}(\alpha_W^2)$
- SM
  - gg, $\mathcal{O}(\alpha_S^2)$:



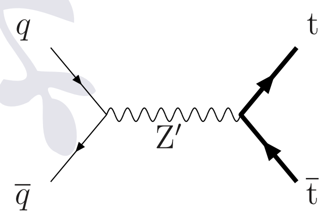
  - $q\bar{q}$, $\mathcal{O}(\alpha_S^2)$:



  - $q\bar{q}$, $\mathcal{O}(\alpha_W^2)$:



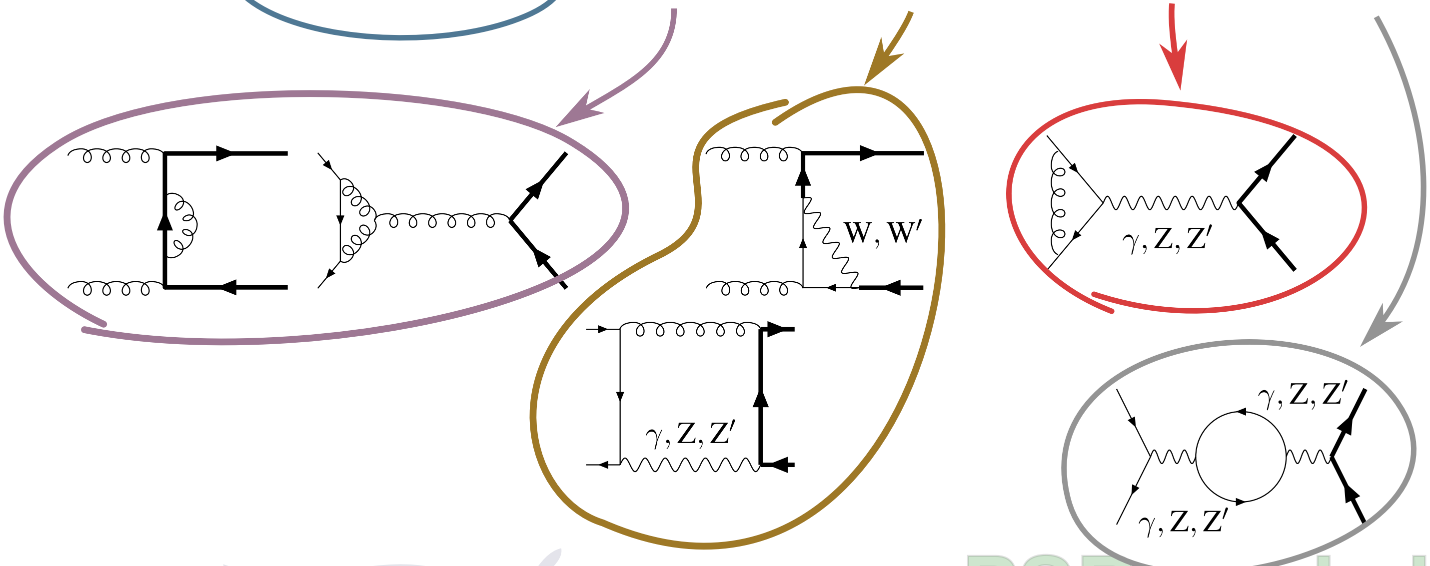
- beyond SM
  - $q\bar{q}$, $\mathcal{O}(\alpha_W^2)$:



Virtual Corrections

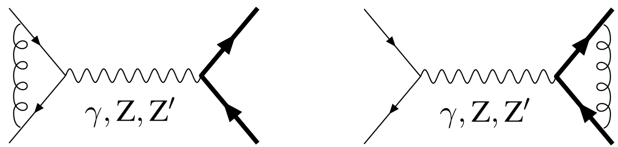
LO

- $\hat{\sigma}^{\text{NLO}} = \hat{\sigma}(\alpha_S^2) + \hat{\sigma}(\alpha_W^2) + \hat{\sigma}(\alpha_S^3) + \hat{\sigma}(\alpha_S^2\alpha_W) + \hat{\sigma}(\alpha_S\alpha_W^2) + \hat{\sigma}(\alpha_W^3)$



- $\mathcal{O}(\alpha_S^3)$ not affected by the presence of Z′
- we calculate $\mathcal{O}(\alpha_S\alpha_W^2)$

Virtual Corrections



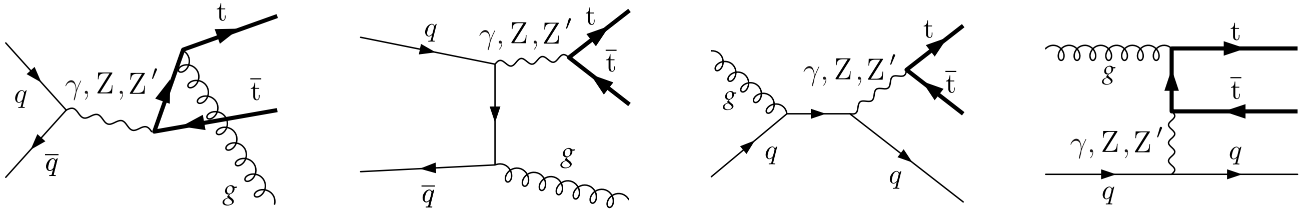
- calculated in dimensional regularization in $D = 4 - 2\epsilon$ dimensions fully analytically in terms of HPL's
- γ_5 treated by Larin's prescription including finite renormalization

$$\gamma_\mu \gamma_5 = \frac{i}{3!} \epsilon_{\mu\nu_1\nu_2\nu_3} \gamma_{\nu_1} \gamma_{\nu_2} \gamma_{\nu_3}, \quad \delta Z_5 = -2C_F$$

- UV divergences taken care of by multiplicative renormalization
  - $\overline{\text{MS}}$ scheme for light quarks
  - OS scheme for top quark

$$\mathcal{V} = \mathcal{V}_{\text{bare}} + \frac{\alpha_S}{\pi} \delta Z_{\text{WF,t}} \mathcal{B}, \quad \delta Z_{\text{WF,t}} = (4\pi)^\epsilon \Gamma(1+\epsilon) \left(\frac{\mu_r^2}{m_{\text{t}}^2}\right)^\epsilon C_F \left(-\frac{3}{4\epsilon} - \frac{1}{1-2\epsilon}\right)$$

Real Corrections



(a) (b) (c) (d)

- new channel opens up: *qg*
- IR divergences, after integration over 1 particle phase space
  - soft (S) divergences: radiation of a soft gluon (a), (b)
  - initial state collinear (ISC) divergences: (b), (d)
  - no final state collinear (FSC) divergences
- in *qg* channel, there are both QCD and QED ISC divergences

Divergences & POWHEG BOX

- UV divergences removed by UV renormalization
- IR S divergences cancel in the sum of real and virtual corrections, ISC divergences removed by collinear renormalization
- renormalized virtual and real corrections are separately IR divergent

$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}} + \int_n d\hat{\sigma}^{\mathcal{V}} + \int_{n+1} d\hat{\sigma}^{\mathcal{R}}, \text{ where } \int_n \ldots, \int_{n+1} \ldots \text{ separately divergent}$$

- can be treated within some subtraction formalism

$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}} + \int_{n+1} \left(d\sigma^{\mathcal{R}} - d\sigma^{\mathcal{A}} \right) + \int_n \left(d\sigma^{\mathcal{V}} + \int_1 d\sigma^{\mathcal{A}} \right)$$

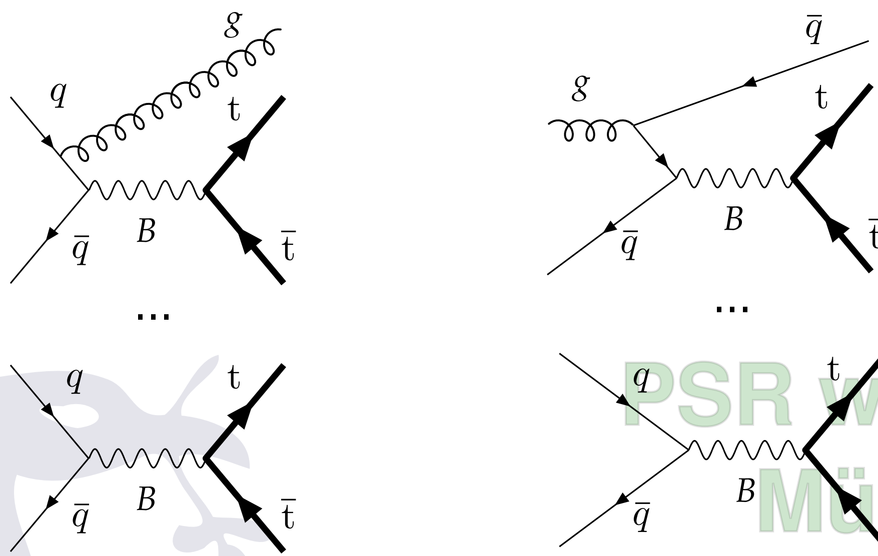
- in POWHEG BOX (FKS)
  - virtual: divergences are poles in ϵ, user provides only the finite part
  - real: treated using plus distributions in each singular region

Singular regions

- real cross section decomposes into the sum of contributions singular in one singular region only

$$R = \sum_{\alpha} R_{\alpha}$$

- singular regions:



Divergences & POWHEG-BOX

- in a singular region, the kinematics of the additional radiation

$$\xi = 2k_0/\sqrt{\hat{s}}, \quad y = \cos\theta, \quad \phi$$

- in a final state region

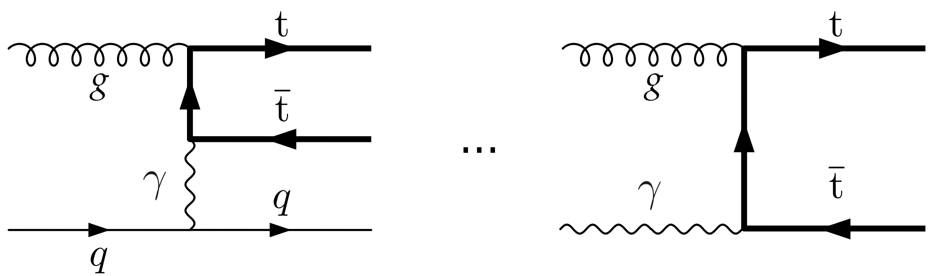
$$B_{\text{real}} = \int d\Phi_n d\phi dy \int_0^{X(y)} d\xi f(\xi, y) \left(\frac{1}{\xi}\right)_+ \left(\frac{1}{1-y}\right)_+ , \text{ where } f \sim \left[(1-y)\xi^2 R_\alpha\right]$$

$$B_{\text{real}} = \int d\Phi_n d\phi \frac{dy}{1-y} \int_0^1 d\tilde{\xi} \left[\frac{f(\tilde{\xi}X(y), y) - f(0, y)}{\tilde{\xi}} - \frac{f(\tilde{\xi}X(1), 1) - f(0, 1)}{\tilde{\xi}}\right] + \left[\log X(y) f(0, y) - \log X(1) f(0, 1)\right]$$

- where:
  - $\xi = 0 \ldots$ soft limit
  - $y = 1$ at fixed $\xi \ldots$ collinear limit
  - $\xi = 0, y = 0 \ldots$ soft-collinear limit

QED divergence

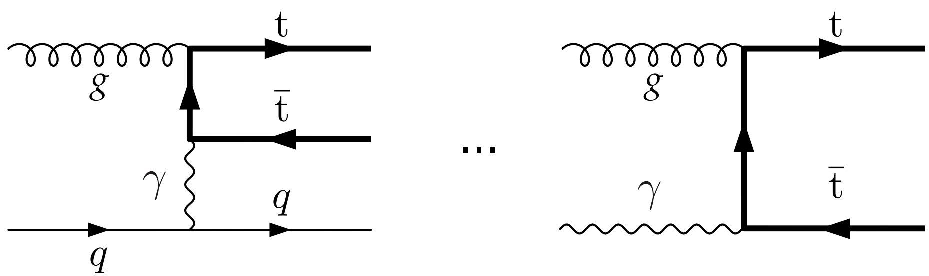
- QED divergences get properly treated provided
  - singular region is identified
  - correct soft and collinear limits have been implemented



- POWHEG BOX v2 partly implements the treatment of QED divergences
  - singular region ✗
  - soft and collinear limits
  - collinear remnants

QED divergence

- QED divergences get properly treated provided
  - singular region is identified
  - correct soft and collinear limits have been implemented

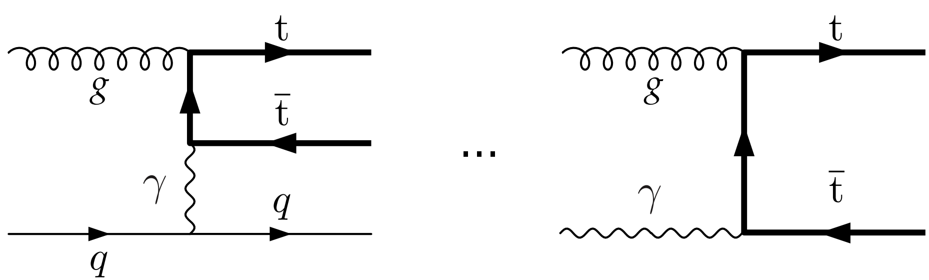


- POWHEG BOX v2 partly implements the treatment of QED divergences
  - singular region ✗
  - soft and collinear limits
  - collinear remnants

we had to modify the "find regions" algorithm

QED divergence

- QED divergences get properly treated provided
  - singular region is identified
  - correct soft and collinear limits have been implemented

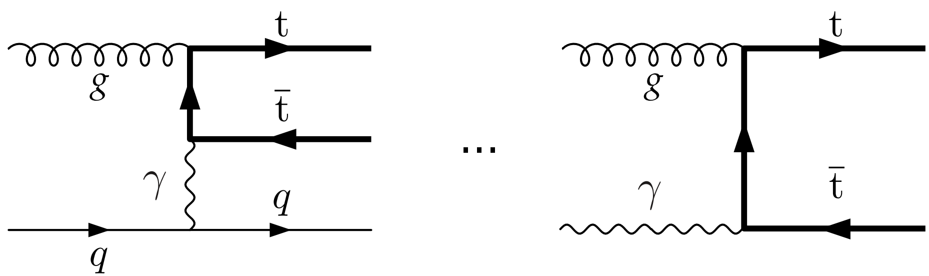


- POWHEG BOX v2 partly implements the treatment of QED divergences
  - singular region ✓
  - soft and collinear limits
  - collinear remnants

we had to modify the "find regions" algorithm

QED divergence

- QED divergences get properly treated provided
  - singular region is identified
  - correct soft and collinear limits have been implemented

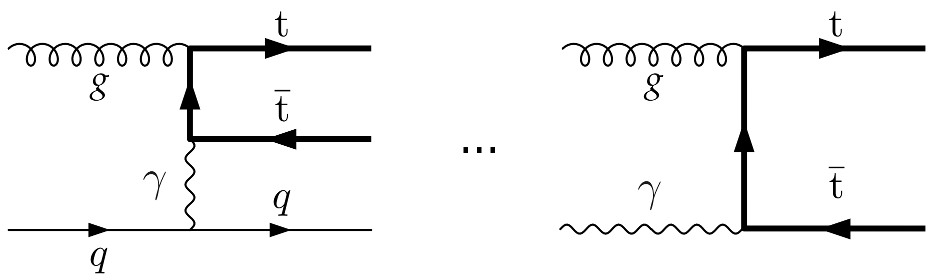


- POWHEG BOX v2 partly implements the treatment of QED divergences
  - singular region ✓
  - soft and collinear limits ✓
  - collinear remnants

we had to modify the "find regions" algorithm

QED divergence

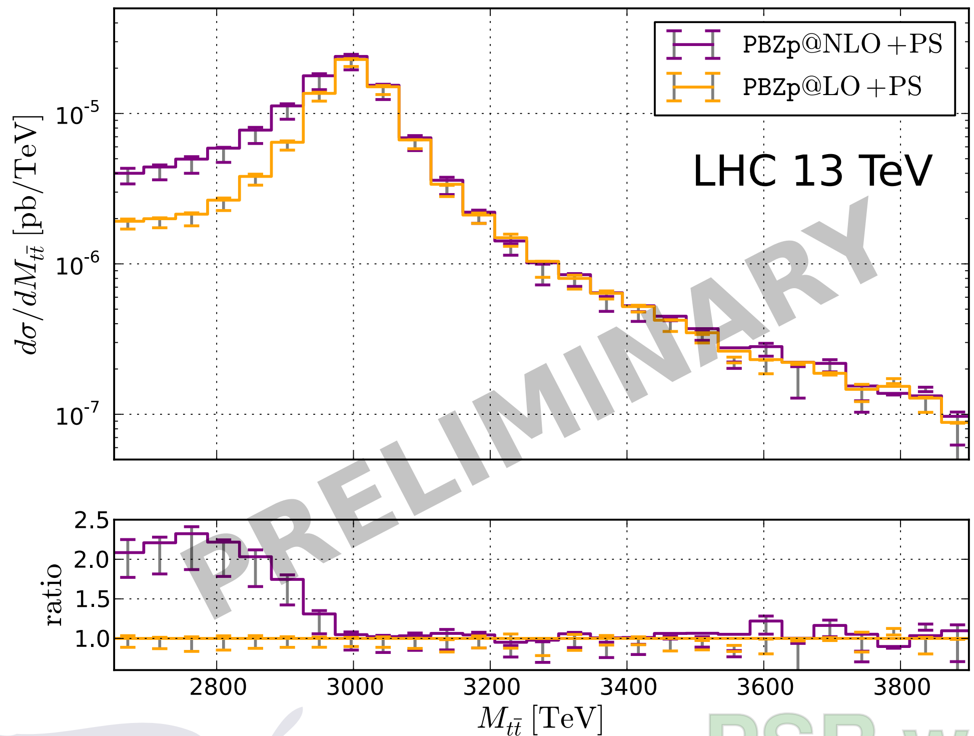
- QED divergences get properly treated provided
  - singular region is identified
  - correct soft and collinear limits have been implemented



- POWHEG BOX v2 partly implements the treatment of QED divergences
  - singular region ✓
  - soft and collinear limits ✓
  - collinear remnants ✓

we had to modify the
"find regions" algorithm

Results



- top-pair invariant mass distribution of $pp \to A/Z/Z' \to t\bar{t}$
- SSM Z', $m_{Z'} = 3TeV$, $G_{Z'} = 106.77GeV$

Summary and outlook

- we calculated QCD corrections to $pp \to A/Z/Z' \to t\bar{t}$
- implemented in POWHEG BOX v2
  - including modifications to singular region search algorithm

- we are calculating single top including W'
- top-quark decay in NW approximation
- EW corrections to QCD top-pair production