Single production of vector-like quarks

large width, NLO

Aldo Deandrea

IP2I - Université Lyon 1

ICHEP 2022 - July 7th 2022

based on JHEP 08 (2021), 107 with

T. Flacke, B. Fuks, Hua-Sheng Shao and L.Panizzi

Outline

Single VLQ production

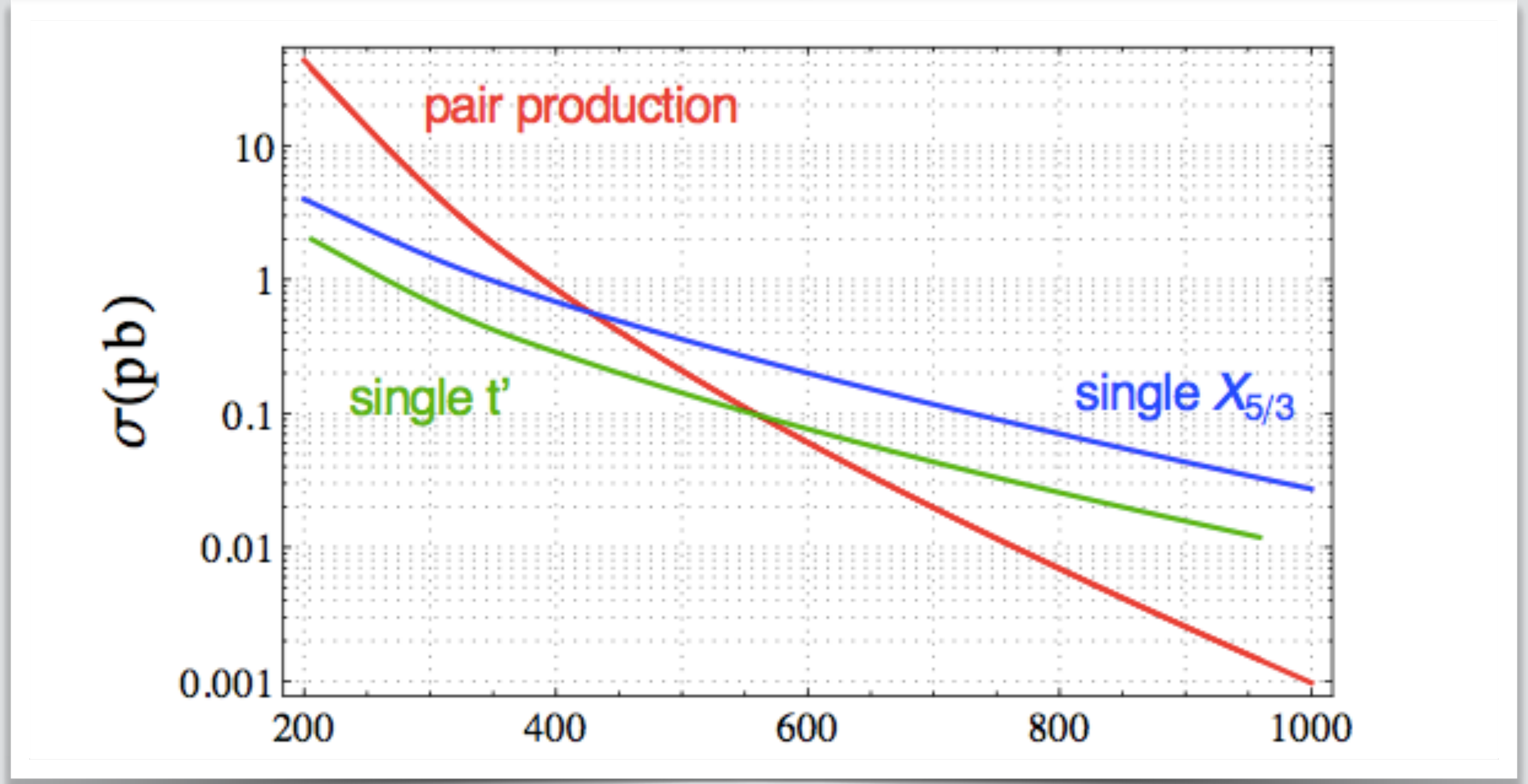
The large width, when and why

Including signal-background interference

Next-to-Leading Order (NLO) results

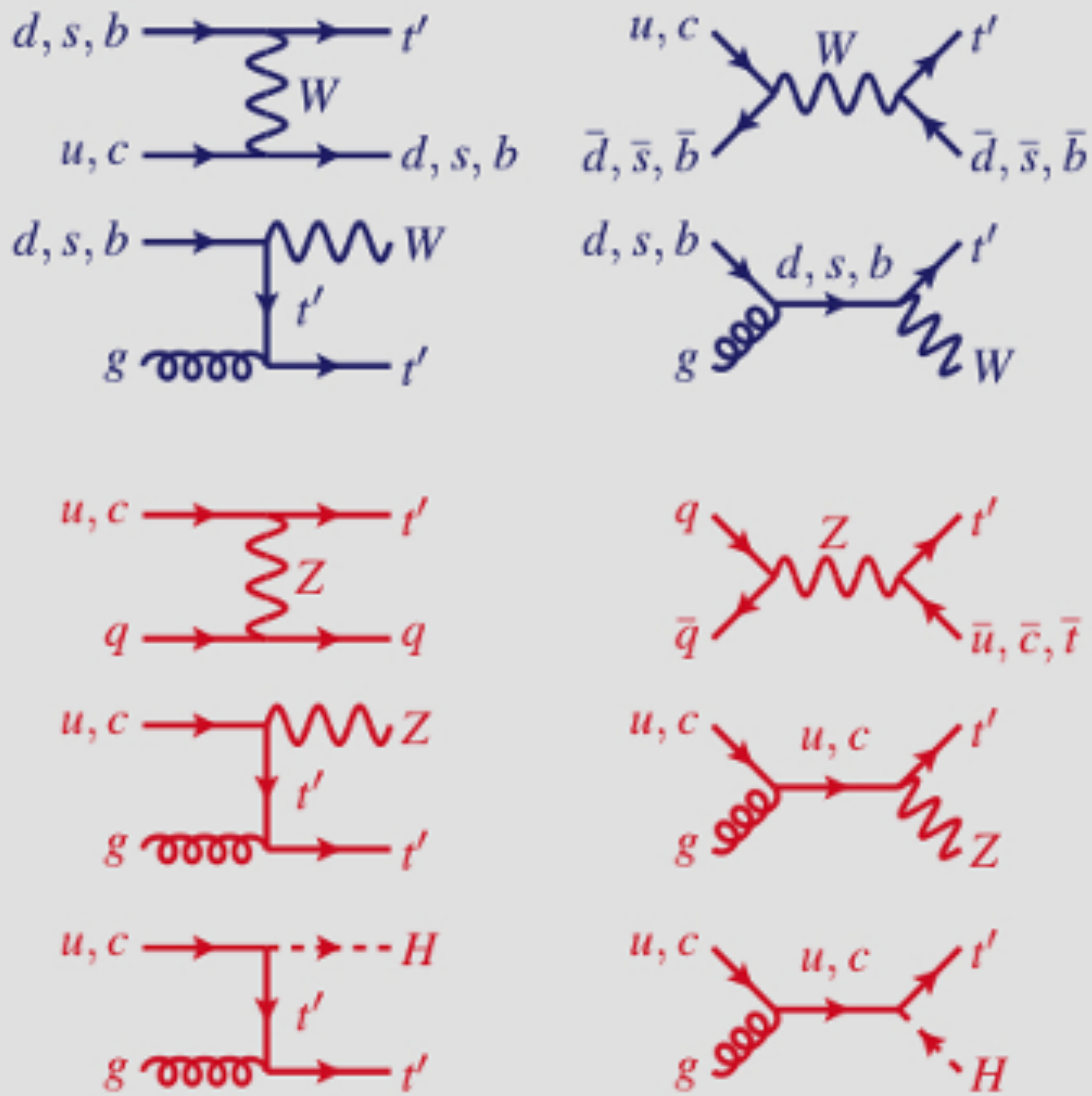
Single Vector-Like Quarks

- Single production: unique window to test BSM models
- Single production dominant with present mass bounds at LHC (~1 TeV)
- Decay: UV models suggest richer pattern than the usual modes with Z, W, h
- Models suggest multiplet structures, not just "isolated" VLQs



A.Deandrea ICHEP 2022

Example : T’ single production modes



Charged current channels are suppressed in $(X \;\; t')$ doublet, non-suppressed in singlet and triplets

FCNCs channels can be relevant in single production especially in the singlet t' and $(X \;\; t')$ doublet

courtesy L.Panizzi

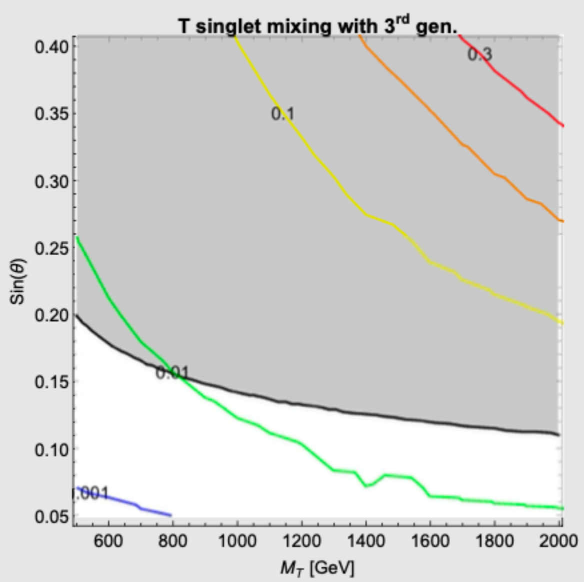
A.Deandrea ICHEP 2022

When and why large with?

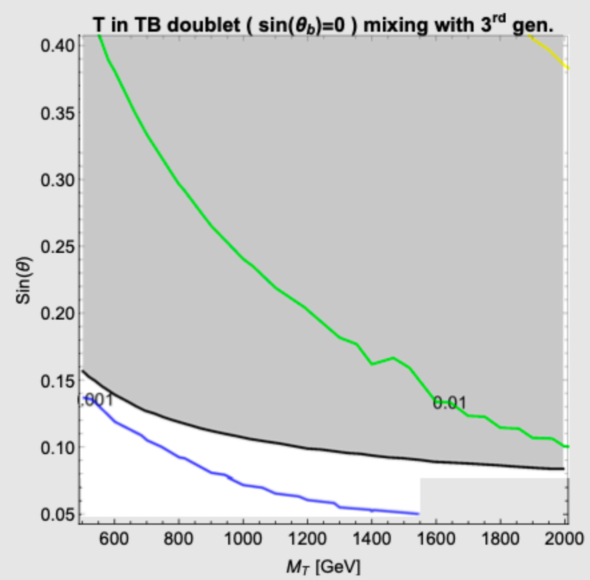
Two ways to obtain a large width

1 Increase couplings ⟶ bounds from other observables (flavour, EWPT); perturbativity

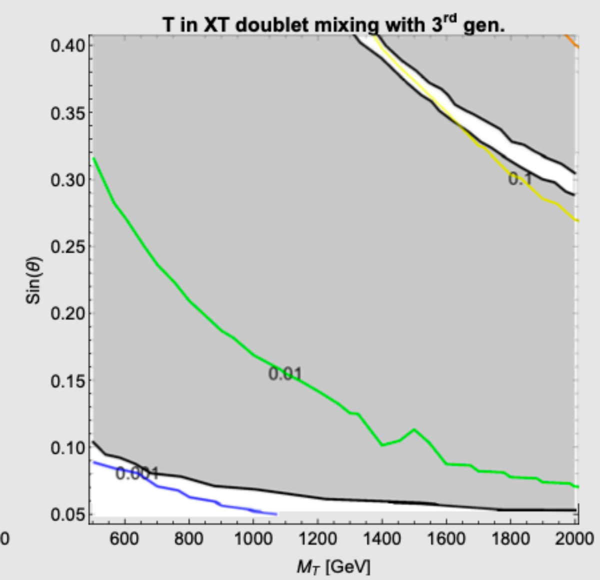
T singlet



(T B) doublet



(X T) doublet



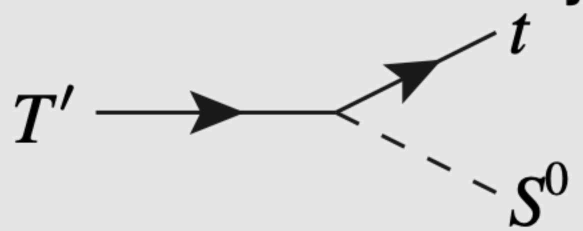
Minimal simplified models with large couplings already excluded by other observables

Moretti, O'Brien, **LP** and Prager, Phys. Rev. D **96** (2017) no.7, 075035
using data from Chen, Dawson and Furlan, Phys. Rev. D **96** (2017) no.1, 015006

⟶ non-minimal extensions with multiple VLQs: escape bounds with large couplings

Cacciapaglia, Deandrea, Gaur, Harada, Okada and **LP**, JHEP **09** (2015), 012
Cacciapaglia, Deandrea, Gaur, Harada, Okada and **LP**, JHEP **11** (2018), 055

2 Increase number of decay channels ⟶ new physics, non-minimal extension



Aguilar-Saavedra, López-Fogliani and Muñoz, JHEP **06** (2017), 095
Bizot, Cacciapaglia and Flacke, JHEP **06** (2018), 065
Benbrik *et al.* (**LP**), JHEP **05** (2020), 028
Banerjee, Franzosi and Ferretti, JHEP **03** (2022), 200

courtesy L.Panizzi

Width schemes

- Breit-Wigner

$$\frac{i(\not{p} + M)}{p^2 - M^2 + i\Gamma M}$$

- Running width

$$\frac{i(\not{p} + M)}{p^2 - M^2 + i\frac{p^2}{M^2}\Gamma M}$$

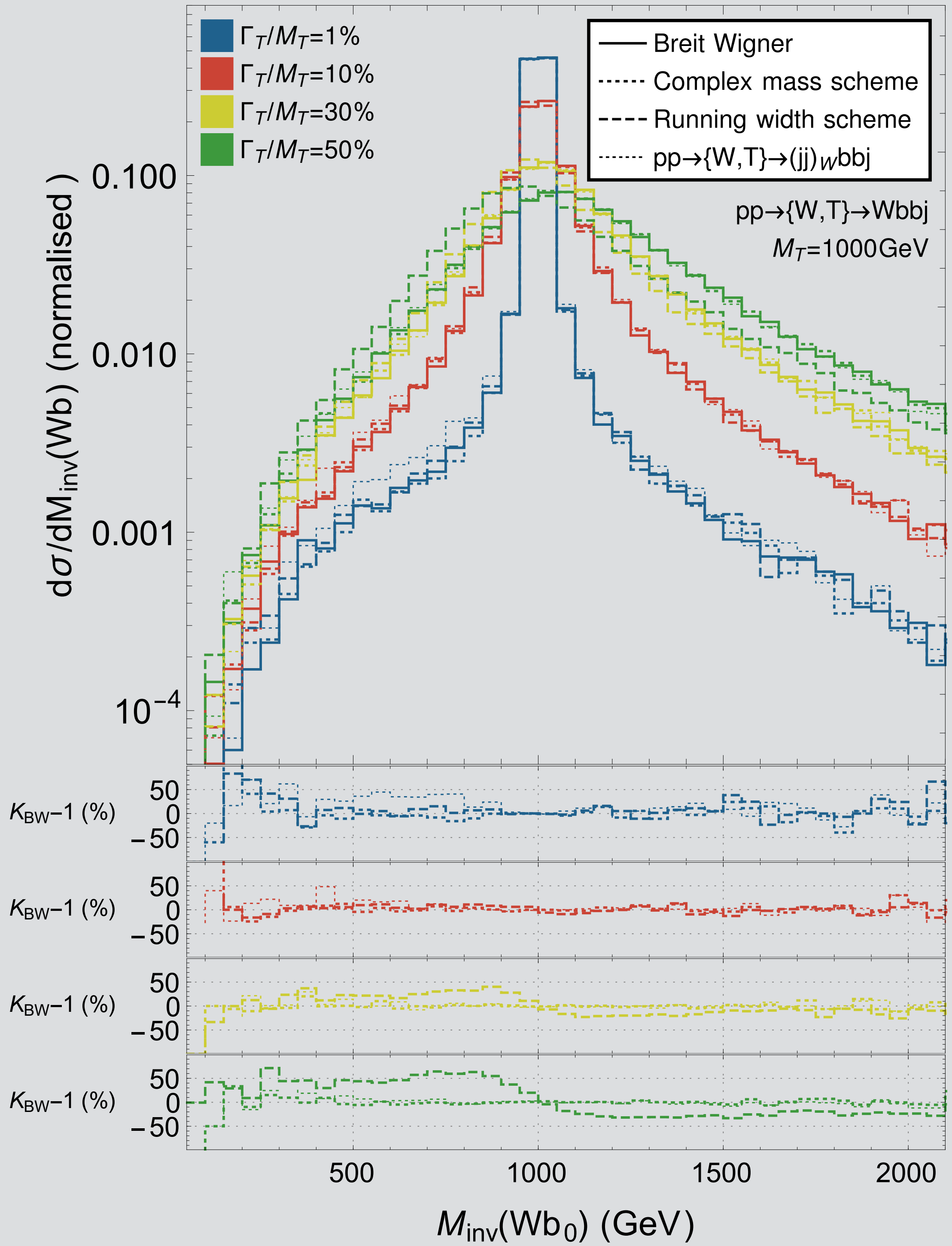
- Complex mass scheme

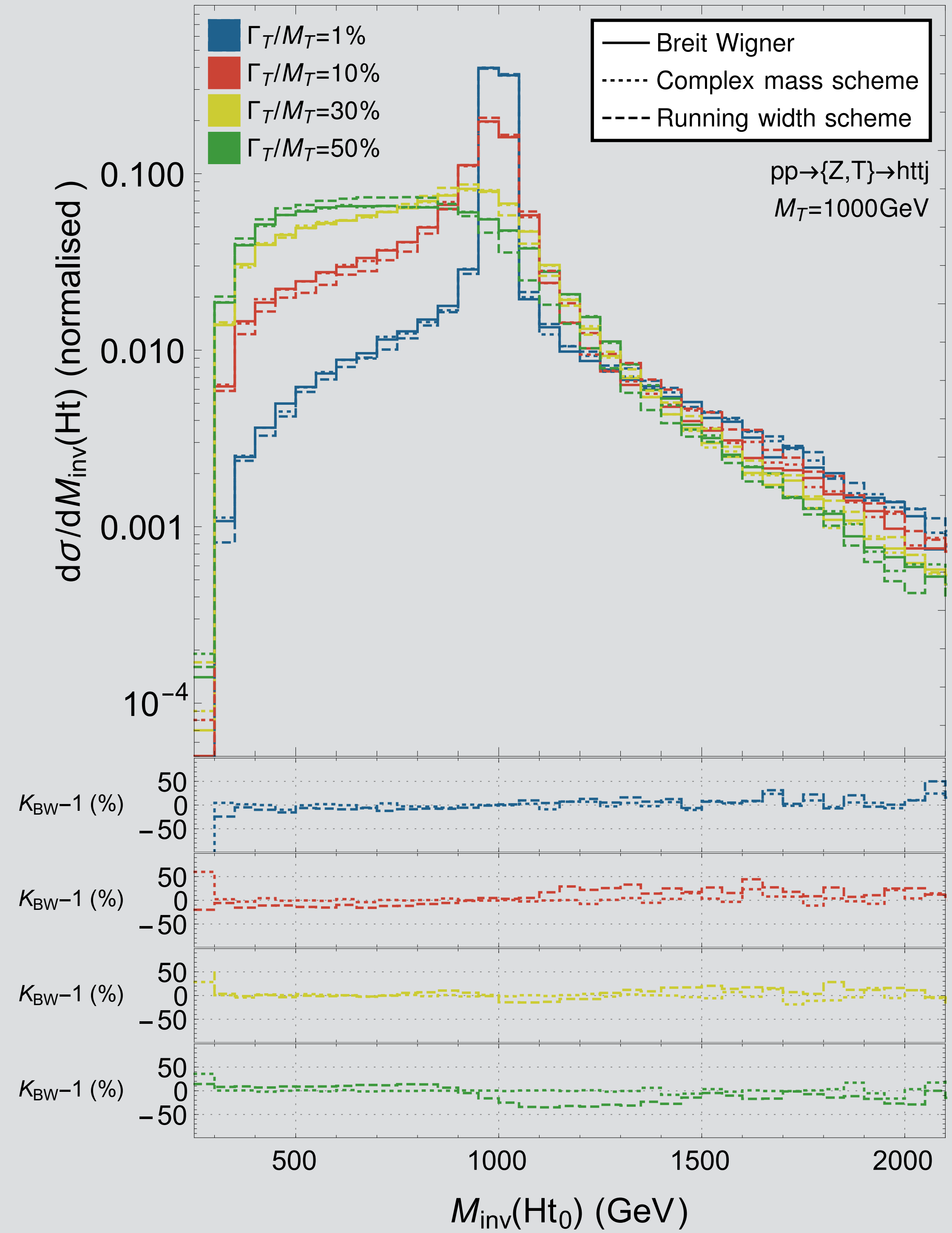
$$M^2 \to \tilde{M}^2 = M^2 - i\Gamma M$$

consistent, gauge-invariant and applicable at NLO

A. Denner et al., Nucl. Phys. B 560 (1999), 33-65 A. Denner et al., Nucl. Phys. B 854 (2012), 504-507

Width schemes

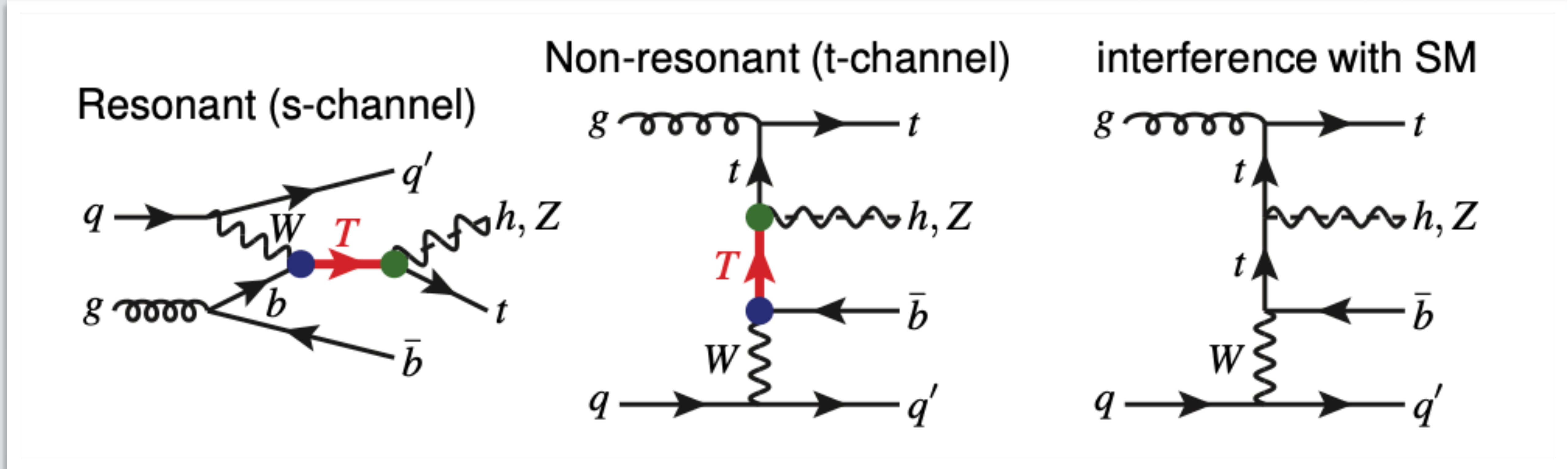




Small differences in the M_{inv} shape
In the RW the peak shifts to the left

A.Deandrea ICHEP 2022

When the width is large

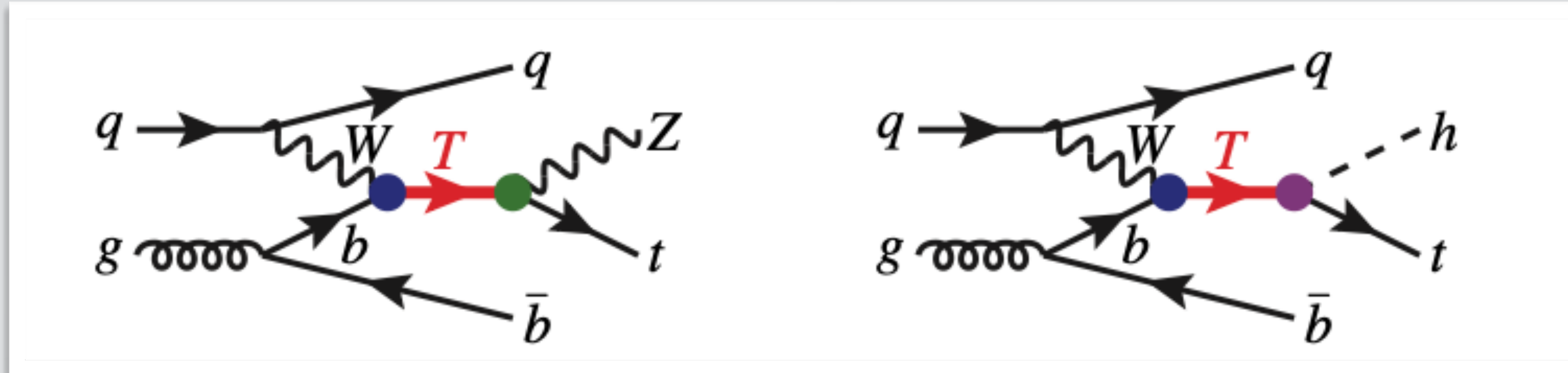


- Off-shell effects are not negligible anymore
- Subdominant topologies in the Narrow Width Approximation, may become important (t-channel)
- Outside the NWA all topologies leading to the same final state must be taken into account for gauge invariance
- Important to take into account interference effects, both between signal topologies, and between signal and SM background

A.Deandrea ICHEP 2022

Parametrisation for large width regime

example for W-mediated production



In the narrow-width approximation - no interference with the SM background

$$\sigma(\kappa, \tilde{\kappa} \text{ or } \hat{\kappa}, m_{\mathrm{T}}, \Gamma_T) = \sigma_P(\kappa, m_{\mathrm{T}}) BR_{T\to\text{decay channel}} = \kappa^2 \hat{\sigma}_{NWA}(m_{\mathrm{T}}) BR_{T\to\text{decay channel}}$$

In the large width case:

$$\begin{aligned}
\sigma_{\text{tot}}(pp \to Wbbj) &= \sigma^{\text{SM}}_{Wb} + \kappa^4\, \hat{\sigma}^{\text{VLQ}}_{Wb}(M_T, \Gamma_T) + \kappa^2\, \hat{\sigma}^{\text{int}}_{Wb}(M_T, \Gamma_T)\,, \\
\sigma_{\text{tot}}(pp \to Ztbj) &= \sigma^{\text{SM}}_{Zt} + \kappa^2\tilde{\kappa}^2\, \hat{\sigma}^{\text{VLQ}}_{Zt}(M_T, \Gamma_T) + \kappa\tilde{\kappa}\, \hat{\sigma}^{\text{int}}_{Zt}(M_T, \Gamma_T)\,, \\
\sigma_{\text{tot}}(pp \to htbj) &= \sigma^{\text{SM}}_{ht} + \kappa^2\hat{\kappa}^2\, \hat{\sigma}^{\text{VLQ}}_{ht}(M_T, \Gamma_T) + \kappa\hat{\kappa}\, \hat{\sigma}^{\text{int}}_{ht}(M_T, \Gamma_T)
\end{aligned}$$

κ, $\tilde{\kappa}$ and $\hat{\kappa}$ couplings: partial widths and rescaling of cross-section

NLO for large width

NLO QCD corrections can have a big impact on total cross-sections and distributions
Complex mass scheme required for gauge-invariance but not available at NLO

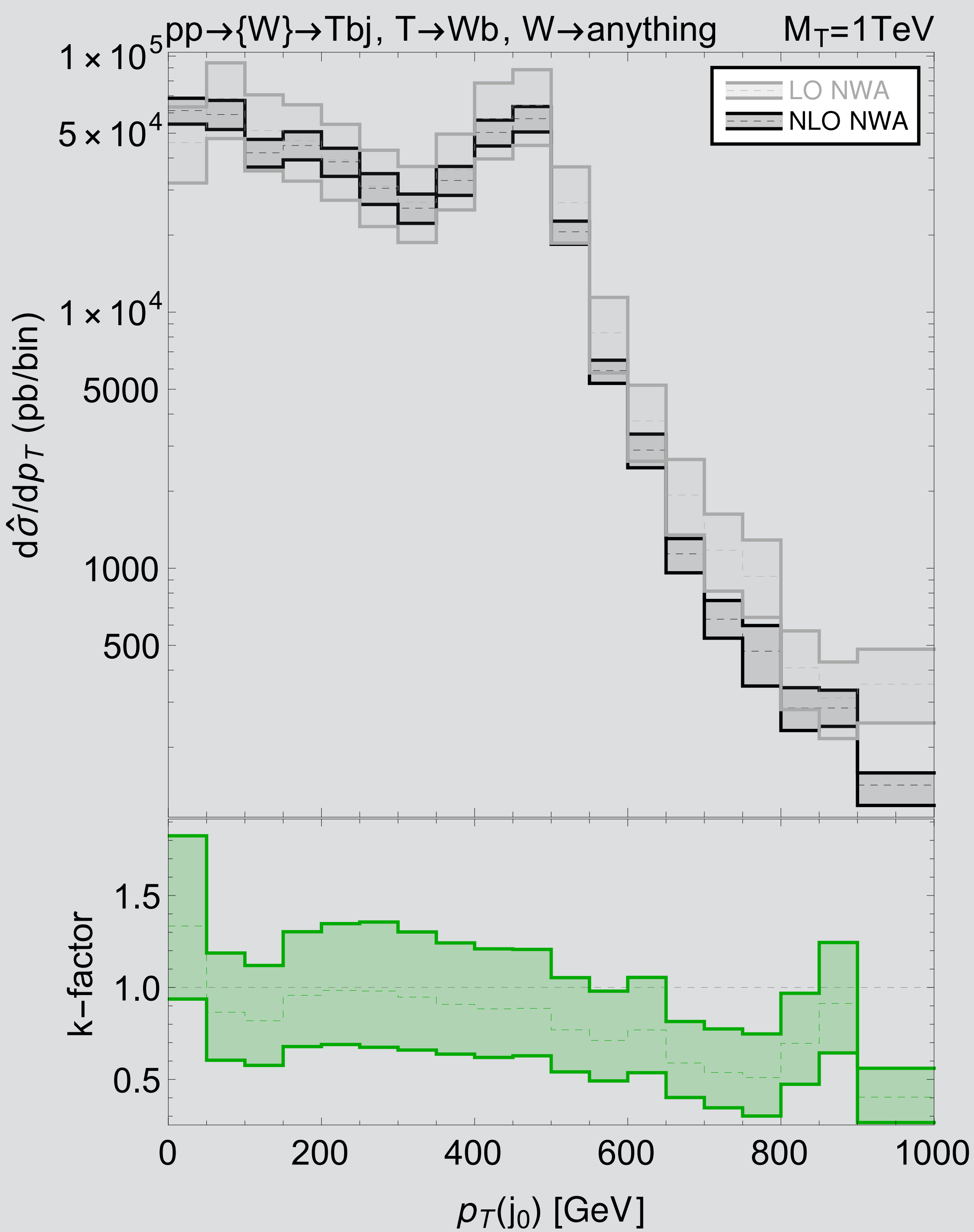
Approximate treatment

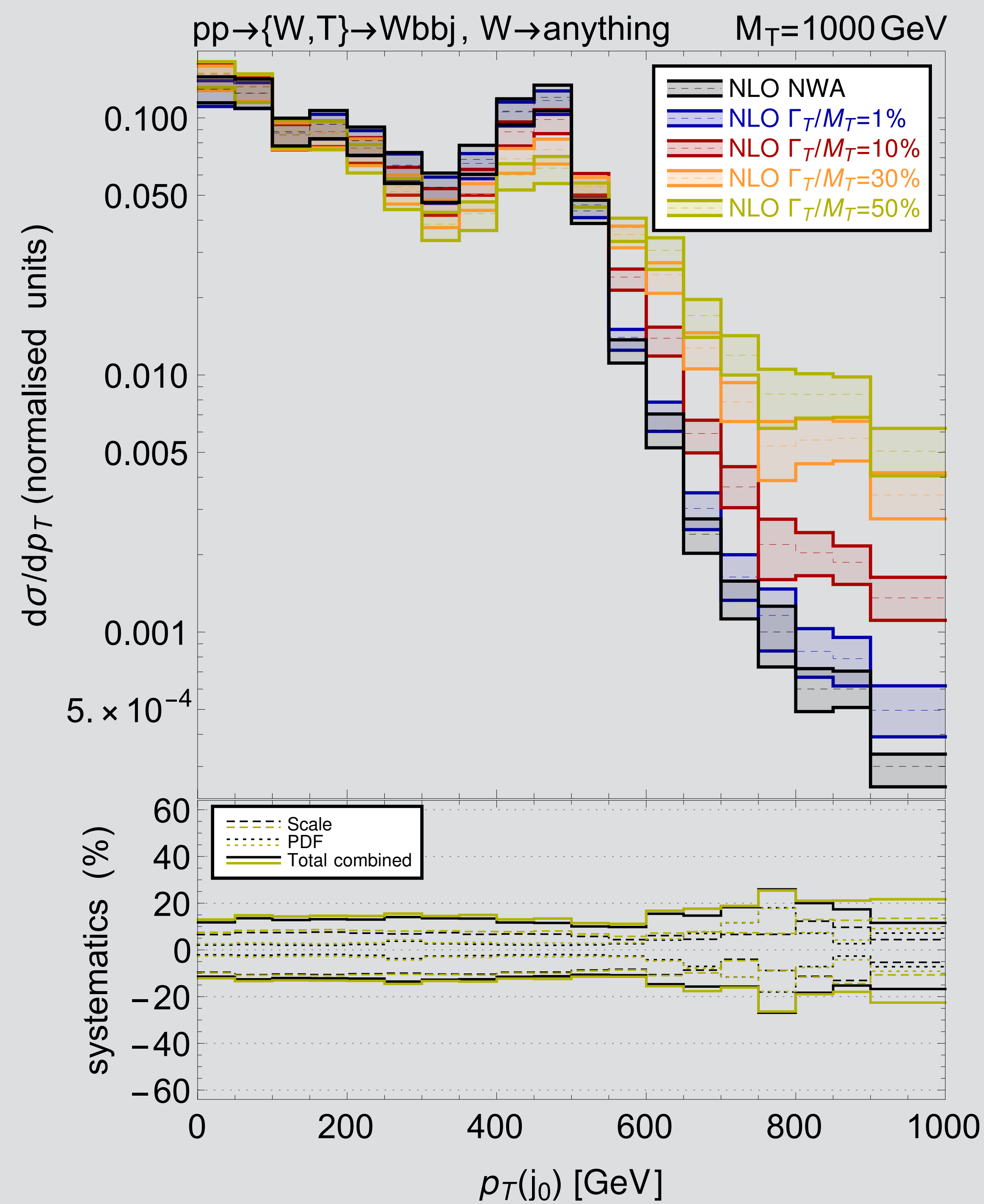
1) Generate events at LO with large width with complex mass scheme
2) Generate events at LO+PS and NLO+PS in the NWA
3) For a given observable O:

$$\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{NLO,LW}\}} \simeq \frac{\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{NLO,NWA}\}}}{\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{LO,NWA}\}}} \times \left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{LO,LW}\}} \equiv K_{\text{NWA}} \times \left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{LO,LW}\}}$$

Limitation: a differential K-factor independent of the width/mass ratio is applied
s-channel must be dominant over t-channel (K-factor is evaluated in the NWA)
interference must be negligible (simulations stop at the $2 \to 3$ processes)

Numerical results





NLO: reduction of theory uncertainties
Peak at M_T /2 independent of Γ_T

Large dependence of the width above M_T

A.Deandrea ICHEP 2022

Conclusion

- NLO correction allow improved predictions and reducing uncertainties
  - ✤ shape distortion, large K-factors
  - ✤ impacts total rates
  - ✤ impacts the tails of several distributions
- Large width effects are important in realistic cases and can induce off-shell effects, interferences
- We provide an approximate framework to deal with both