Single-top theory summary

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Outline:

1. Higer orders & automation

2. 4F vs 5F: t-channel

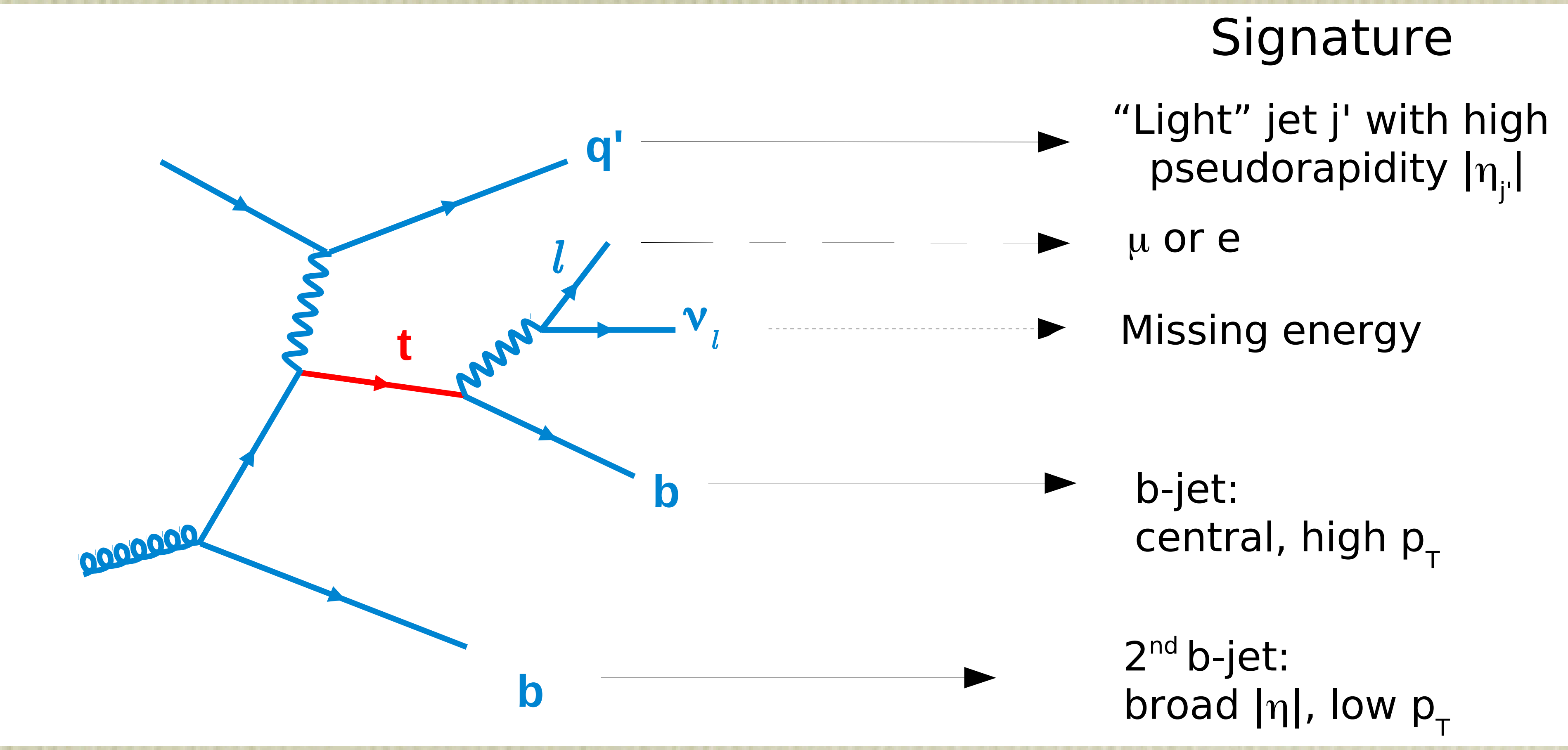
3. Top decay

4. 4F vs 5F: Wt

5. Conclusions

single top production and decay

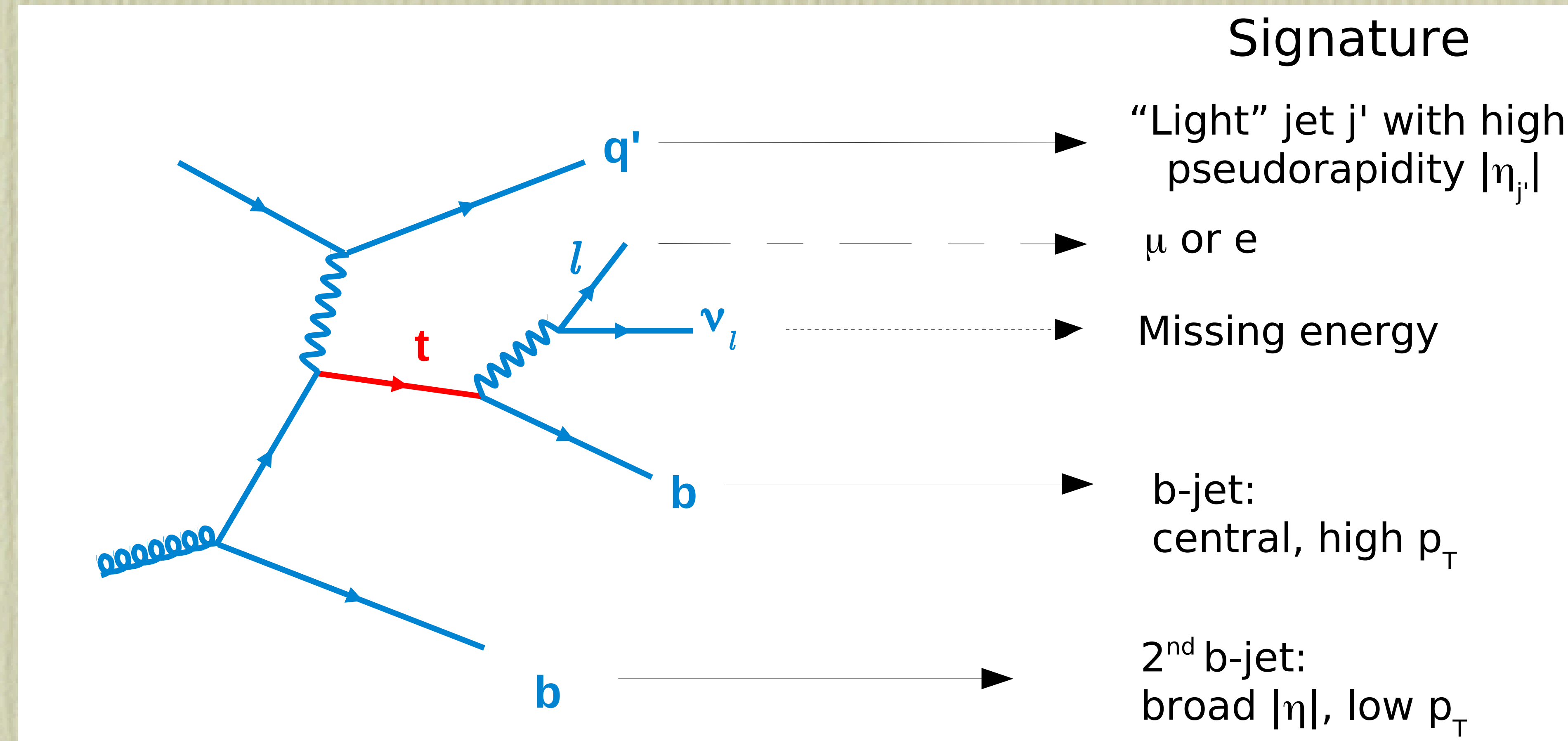
t-channel



[Picture by Orso M. Iorio]

single top production and decay

t-channel



[Picture by Orso M. Iorio]

Although single top production cross section is relatively large it's hard to disentangle the signal from all the backgrounds

$$u + \bar{d} \rightarrow W^+ + 2 \text{ jets}, \quad W^+ \hookrightarrow \nu + e^+$$

$$u + \bar{d} \rightarrow W^+ + c + \bar{c}, \quad W^+ \hookrightarrow \nu + e^+$$

$$u + c \rightarrow W^+ + d + c, \quad W^+ \hookrightarrow \nu + e^+$$

$$u + \bar{d} \rightarrow W^+ + b + \bar{b}, \quad W^+ \hookrightarrow \nu + e^+$$

$$u + b \rightarrow W^+ + d + b, \quad W^+ \hookrightarrow \nu + e^+ .$$

$$u + \bar{d} \rightarrow W^+ + Z, \quad Z \hookrightarrow b + \bar{b}, \quad W^+ \hookrightarrow \nu + e^+$$

$$u + \bar{u} \rightarrow t + \bar{t}, \quad \bar{t} \hookrightarrow \bar{b} + e^- + \bar{\nu}, \quad t \hookrightarrow \nu + e^+ + b$$

$$u + \bar{u} \rightarrow t + \bar{t}, \quad \bar{t} \hookrightarrow \bar{b} + q + \bar{q}, \quad t \hookrightarrow \nu + e^+ + b$$

$$u + \bar{s} \rightarrow W^+ + u + \bar{c}, \quad W^+ \hookrightarrow \nu + e^+$$

Most known at least at parton level with NLO QCD corrections

Higher order corrections mandatory to study single top production and decay at the LHC

Shower Monte Carlo, not enough for many purposes

with NLO

- reduction of theoretical errors: scales uncertainty, pdf uncertainty
- more accurate description of the shapes of distribution for hard final state leptons, jets and missing energy inclusive over extra jet radiation

+ PS

- all order resummation of leading logarithmic collinear singularity
- allows for full event simulation

NLO+PS (when doable) is optimal for a large set of observables, example:

Single top physics

NNLO orders corrections

- Threshold resummation performed for s, t and Wt production [Kidonakis 2011]
- Corrections are very stable and very small (good convergence)
- BTW there is no strong tension among data and NLO results for total cross sections
- Other input like b-pdf and mb determination bring higher theoretical errors [Campbell et al 2009]

CMS Collaboration
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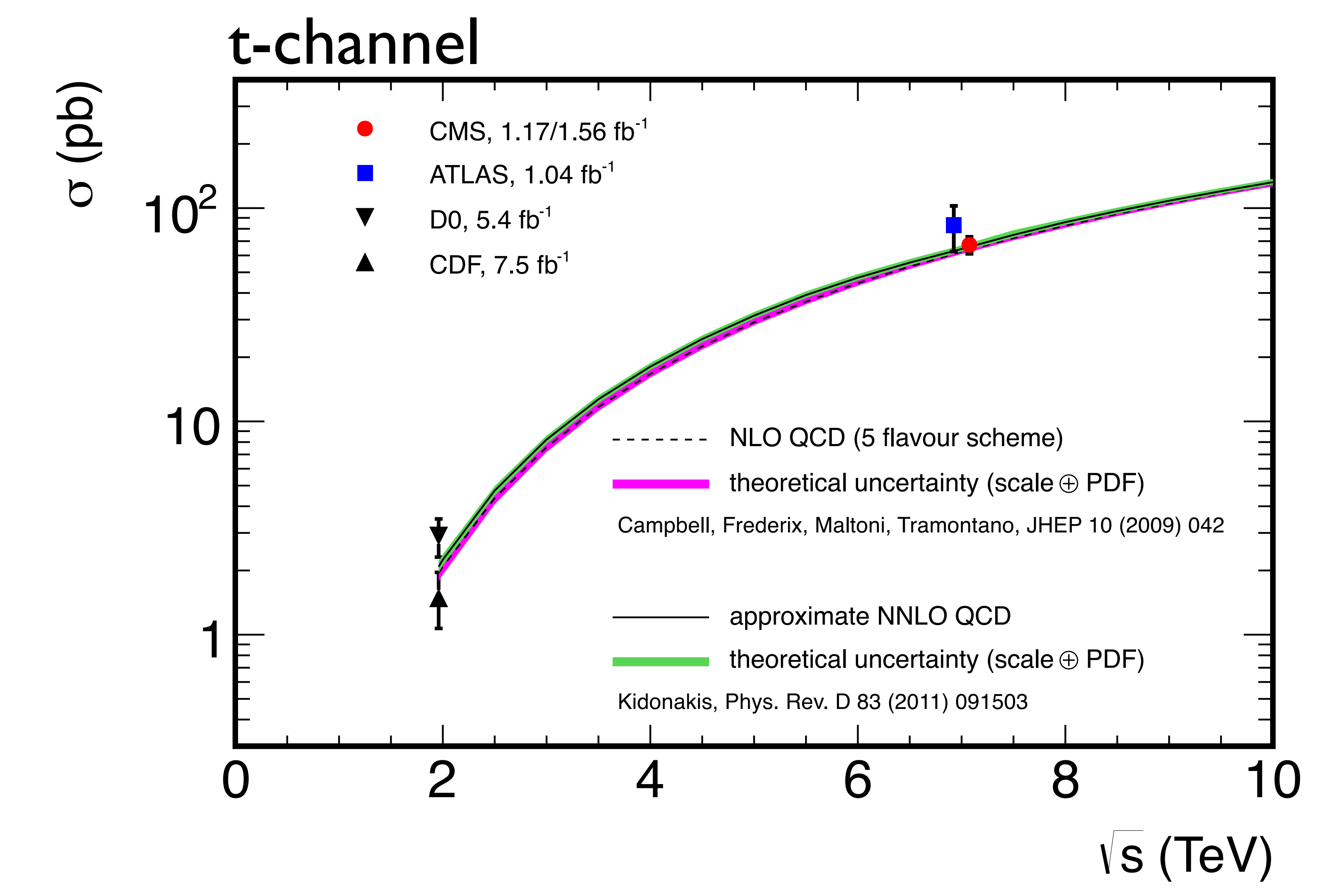
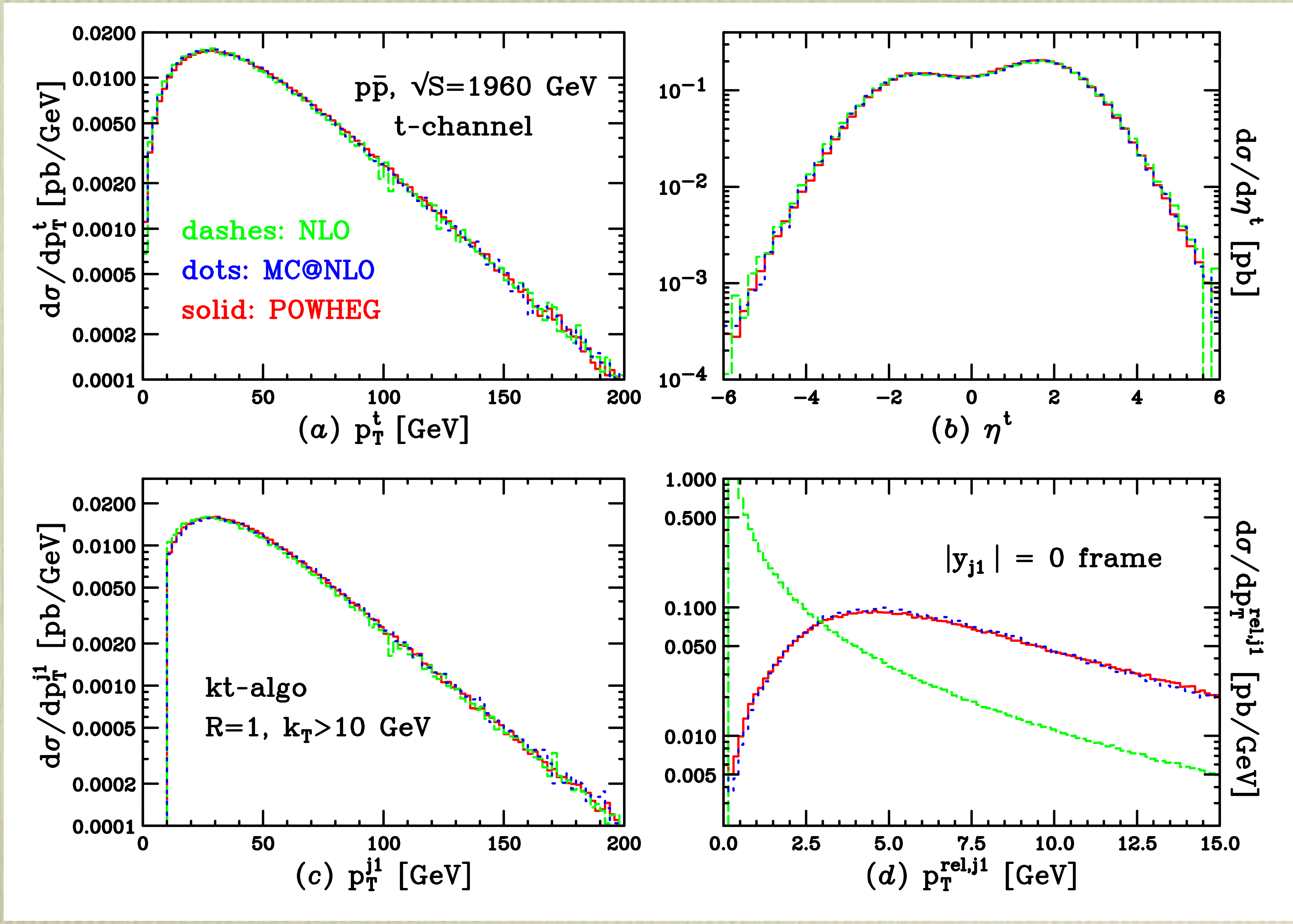


NLO+PS computation

MC@NLO [Frixione, Webber 2002] and POWHEG [Nason 2004] methods

- differ in the way they match NLO partonic events to the shower MC
- differences expected at NNLO
- using both one gets an estimation of the uncertainty related to the matching procedure

Single top NLO computations have been interfaced with Parton Shower in both MC@NLO and POWHEG



- top mass generated with Breit-Wigner
- 4 and 5 Flavor scheme computation implemented
- decay introduced with a non trivial procedure based on the LO matrix element

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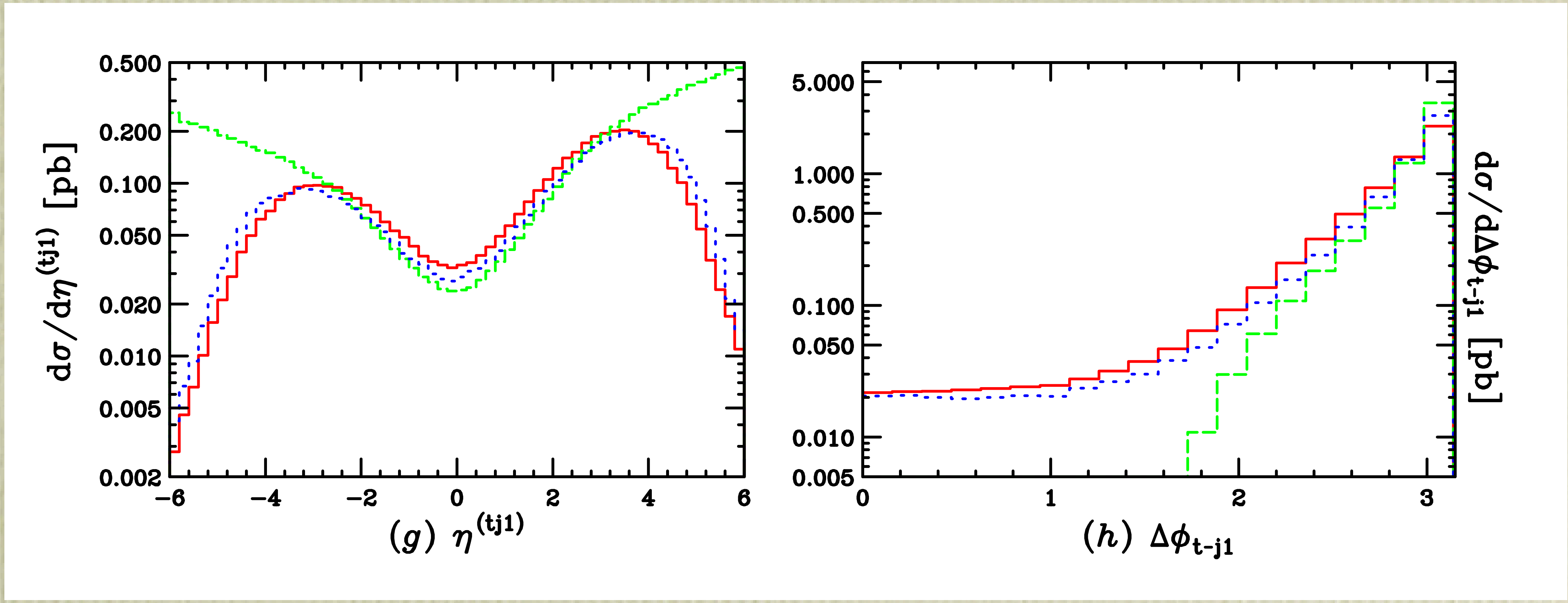

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NLO+PS computation is fully automated

MC@NLO method:

- Sherpa+OLP: Njets: fully automated for multijets, VB+jets, photons+jets
  GoSam: fully automated for SM
  OpenLoops: fully automated for SM (private)
- MadGraph+MC@NLO (just released): fully automated

POWHEG method:

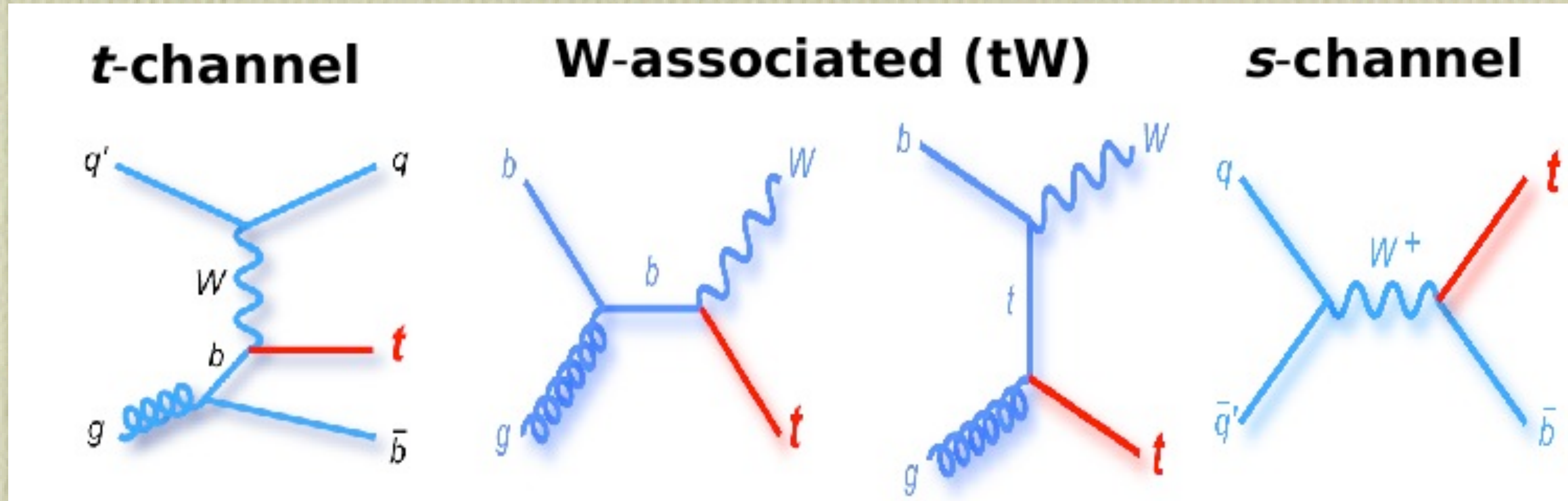
- POWHEG-Box: POWHEL=POWHEG+HELAC (ntuples produced for selected processes)
- POWHEG-Box+OLP: +MadGraph4+GoSam (*almost* fully automated)

OLP = One Loop Provider (*virtual matrix elements*)
many general SM and beyond one loop providers: FormCalc, MadLoop, Recola, XLoop, ...

Fully automated computation not always optimal/used:
- generally slower and less stable then analytic computation
+ much easier to obtain, almost no possibility to make mistakes

fast/stable analytic computations coded in MCFM, Blackhat, VBFNLO, ...

Production rates for single top at the LHC14 up to NLO QCD corrections



Mix with t-channel at higher order

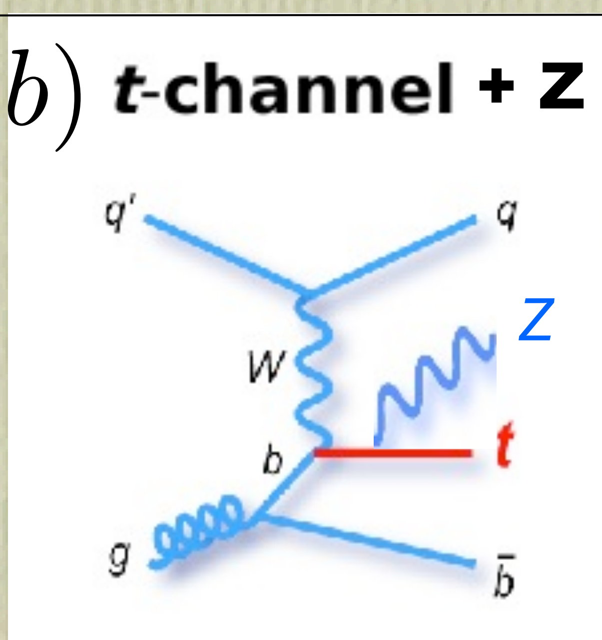
EW corrections by Beccaria et al

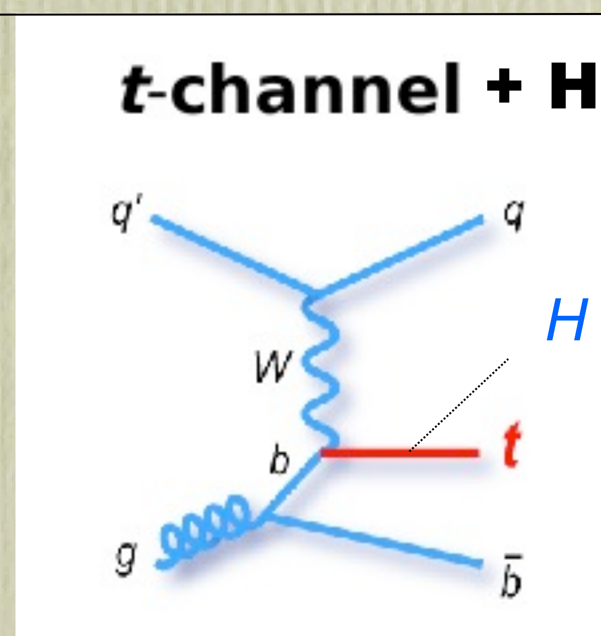
244pb (MCFM) **68.7pb (MCFM)** **10.4pb (MCFM)**

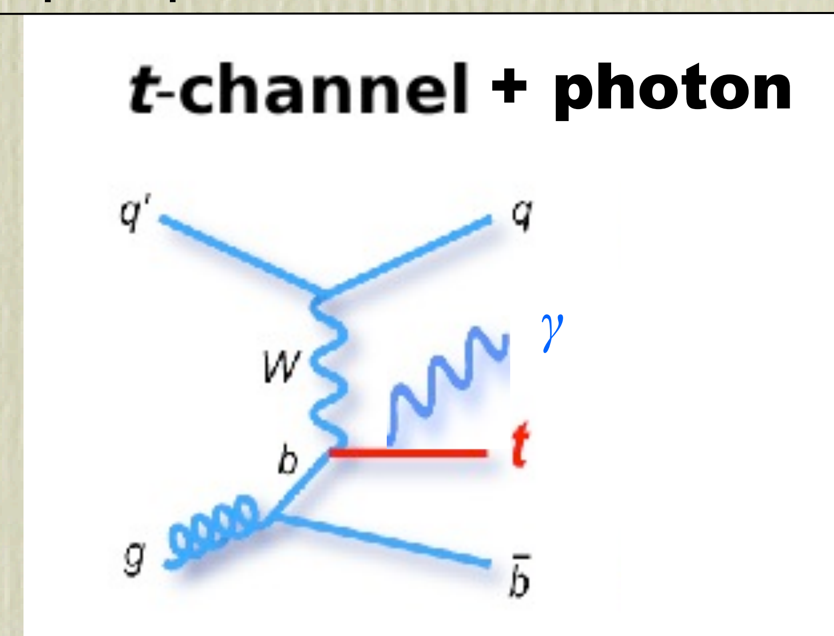
$O(pb)$

Probe Vtb, Wtb vertex, sensitive to b-pdf, q', W'

$O(fb)$







942fb (MCFM)

~ttZ
related to WZ

87.5fb (MCFM)

gauge cancellation

O(10fb) in actual searches

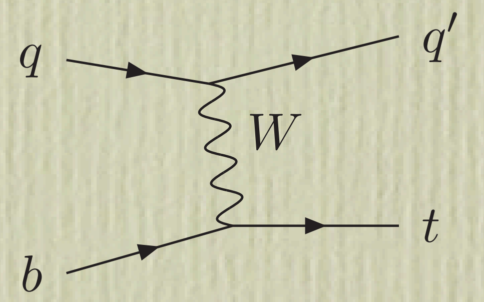
probes top EM
dipole moment

QCD corr. by [Fael, Gehrmann 2013]

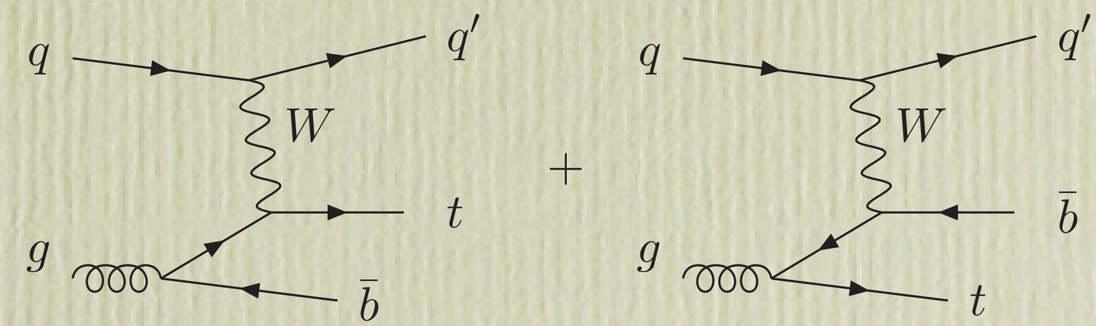
The production of a t-channel single top

- All the single top production mechanisms but the s-channel might be studied within a 5 or a 4 flavor scheme

Ex: t-channel



5F (2to2)



4F (2to3)

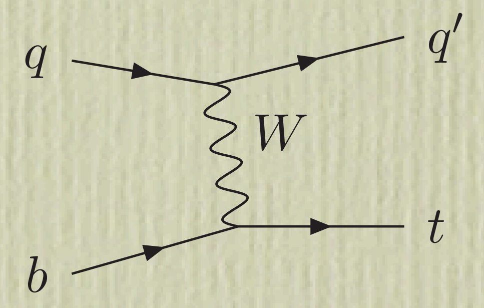
- 4F cross section dominated by a collinear logarithm

- resumming this logarithmic enhancement brings to the definition of a b-pdf

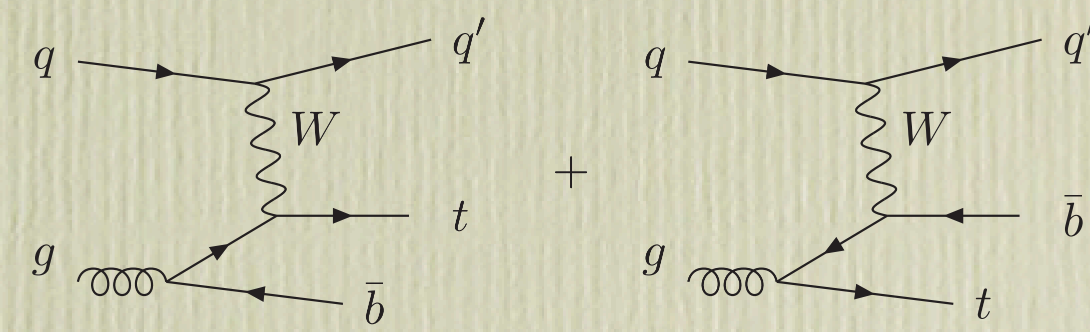
! when using 4F(5F) scheme the factorization scale should be chosen of the order of pt($\bar{b}$)max at which the differential cross section starts to deviate substantially from the collinear behaviour [Maltoni, Sullivan, Willenbrock 2003] ~mt/4 for t-channel single top ~(mt+mw)/4 for tW production

The production of a single top via the t-channel

- All the single top production mechanisms but the s-channel might be studied within a 5 or a 4 flavor scheme



5F (2to2)



4F (2to3)

- The two descriptions should agree at all orders
- More exclusive distributions, ie of the second b are more accurate in 4F
- Total cross section expected to be more precise in 5F but b-pdf might not to be accurate, furthermore, differences are small

$\sigma^{\rm NLO}_{\rm t-ch}(t+\bar{t})$	$2 \to 2$ (pb)					$2 \to 3$ (pb)				
Tevatron Run II	1.96	$^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	1.87	$^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (10 TeV)	130	$^{+2}_{-2}$	$^{+3}_{-3}$	$^{+2}_{-2}$	$^{+2}_{-2}$	124	$^{+4}_{-5}$	$^{+2}_{-3}$	$^{+2}_{-2}$	$^{+2}_{-2}$
LHC (14 TeV)	244	$^{+5}_{-4}$	$^{+5}_{-6}$	$^{+3}_{-3}$	$^{+4}_{-4}$	234	$^{+7}_{-9}$	$^{+5}_{-5}$	$^{+3}_{-3}$	$^{+4}_{-4}$

Included uncertainties: scale, pdf, mt, mb

In general for the b-initiated single top channels,
t-channel and tW, one could say:

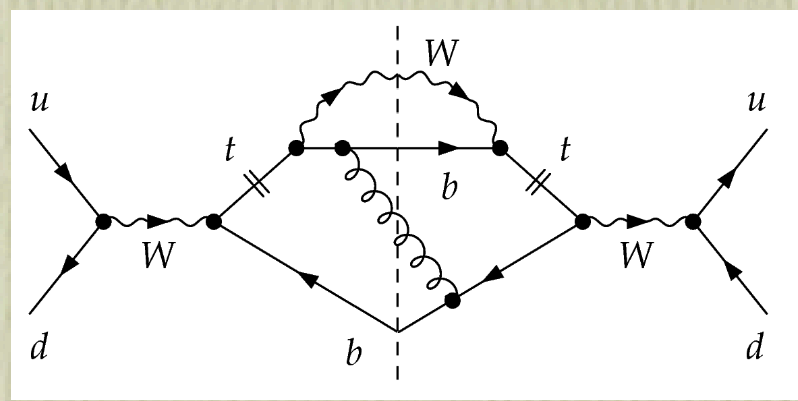
If the search strategy includes a resolved extra b-jet the 4 flavor scheme should be used for comparisons, otherwise the 5 flavor scheme should give more precise results

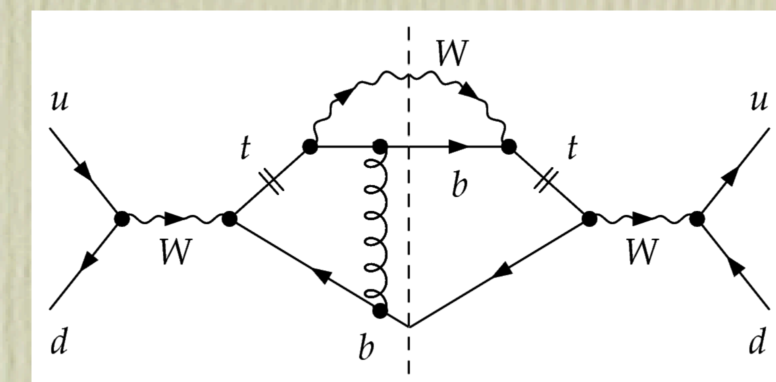
On the other end, often the differences are small and well within the combined scale+pdf+mb+mt uncertainties

The decay of the top quark

- Narrow Width Approximation: top is produced and decays exactly on its mass shell. Corrections to the production and decay stages can be combined

  ✴interference among QCD radiation in production and decay neglected





  ✴non resonant diagrams neglected

  ✴Implemented in MCFM [Campbell, Ellis, FT 2004]

$$|\mathcal{M}(\ldots p_t, p_W, p_b, p_g)|^2 \rightarrow |\mathcal{M}_0(\ldots p_t, \tilde{p}_W, \tilde{p}_b)|^2 \times D(p_t.p_g, p_b.p_g, m_t^2, M_W^2)$$

  a subtraction that makes finite the real correction to the decay, that is analitically integrable on the degrees of freedom of the extra radiation

- NWA is the first attempt to describe the top decay with NLO accuracy

  ✴ spin correlation conserved

  ✴ remarkably excellent for many distributions

  ✴ not good for W,b-jet invariant mass (and related) distributions!

In this case off-shell effects are indeed important

Neglecting interference among production and decay

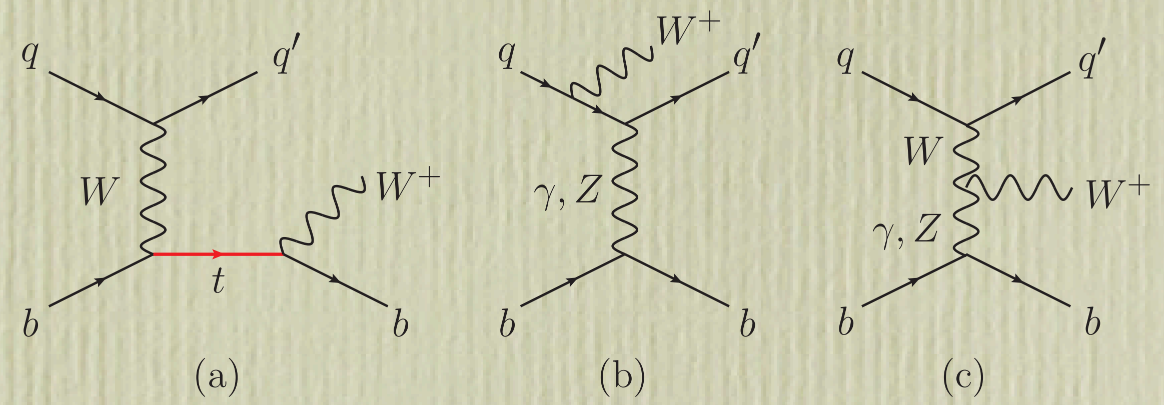
- Small correction to the total cross section [Fadin, Khoze, Martin 1994], [Melnikov, Yakovlev 1994]
- $O\left(\alpha_S \frac{\Gamma_t}{m_t}\right)$ confirmed for example in s-channel single top [Pittau 1996]

  and in e+e- to ttbar [Macesanu 2002]
- More recently in ttbar hadroproduction [Denner et al 2011, Bevilacqua et al 2011]
- Off-shell and non resonant effects for single top production first studied in the context of Effective Field Theory [Falgari, Meellor, Signer 2010]
- Confirmed with full NLO analytic computation performed using the <u>complex mass scheme</u> for the top quark description [Papanastasiou et al 2013]

Including interference among production and decay

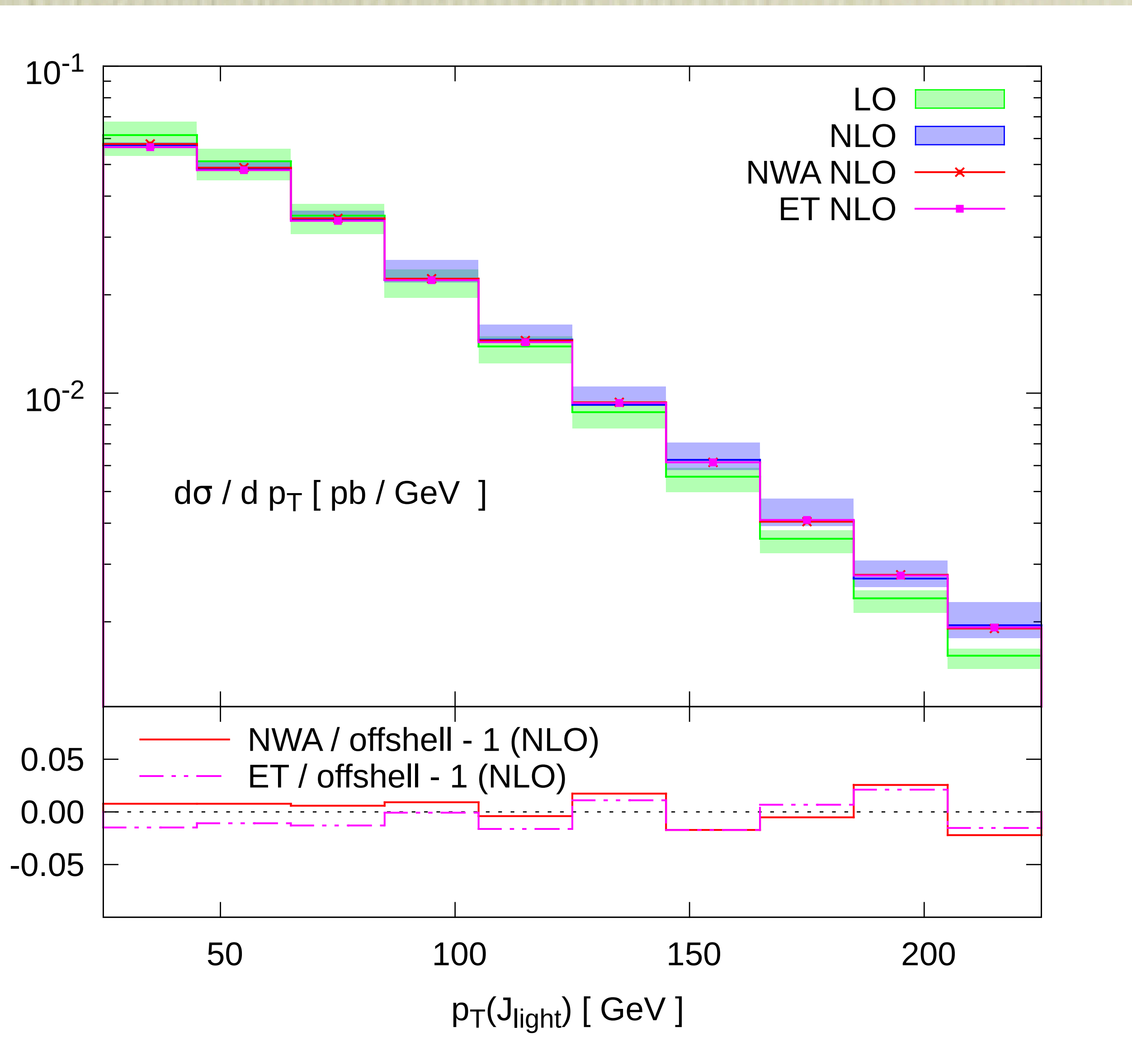
[Papanastasiou et al 2013]

LO



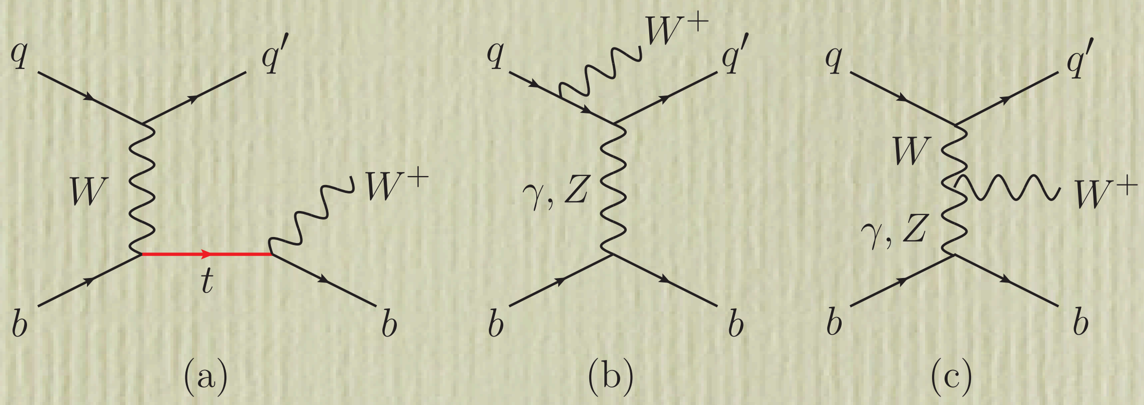
CMS = Complex Mass Scheme
NWA = Narrow Width Approximation
ET = Effective Field Theory

	LO	NLO
CMS [pb]	$4.184(1)^{+8.5\%}_{-12.3\%}$	$4.115(5)^{+0.5\%}_{+4.6\%}$
NWA [pb]	$4.223(1)^{+8.8\%}_{-12.2\%}$	$4.138(1)^{+0.9\%}_{+2.6\%}$
%diff	+0.9	+0.6
ET [pb]	$4.154(1)^{+8.8\%}_{-12.2\%}$	$4.074(1)^{+0.3\%}_{+4.0\%}$
%diff	-0.7	-1.0



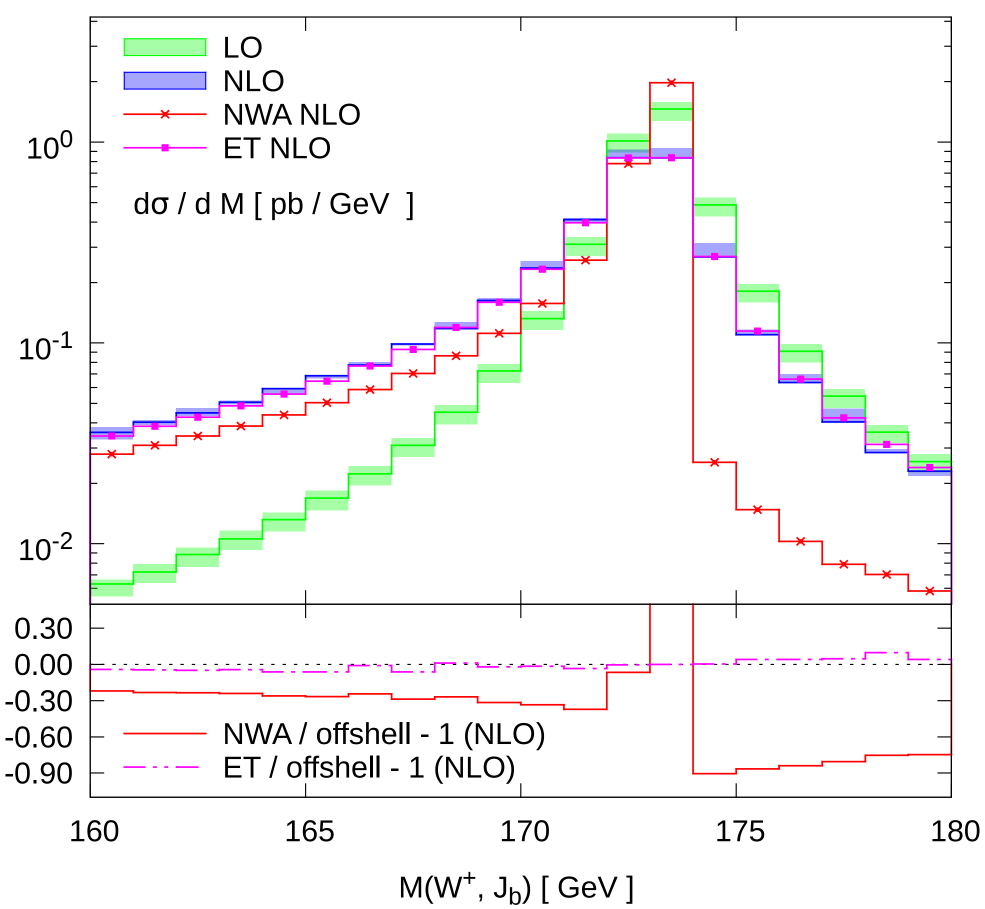
The decay of the top quark

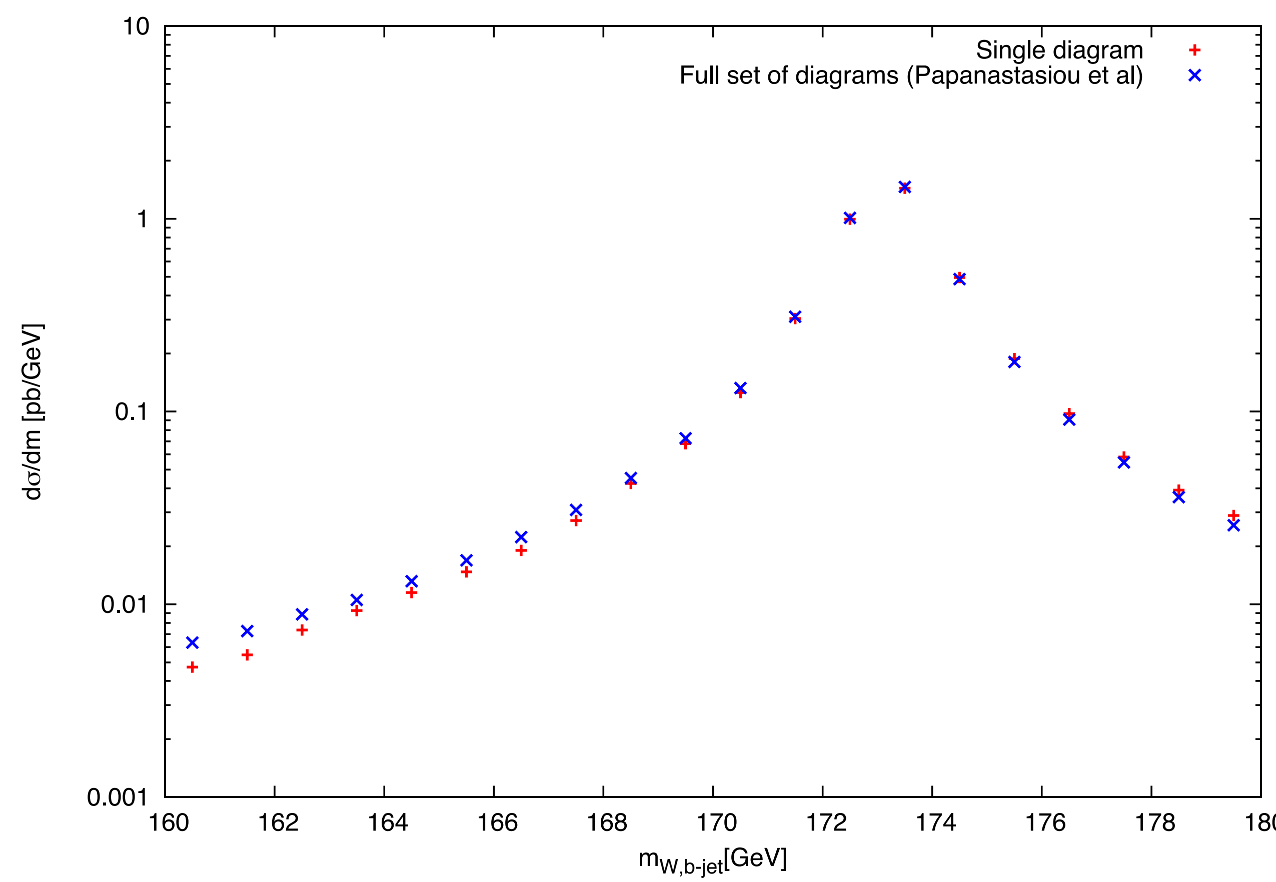
LO

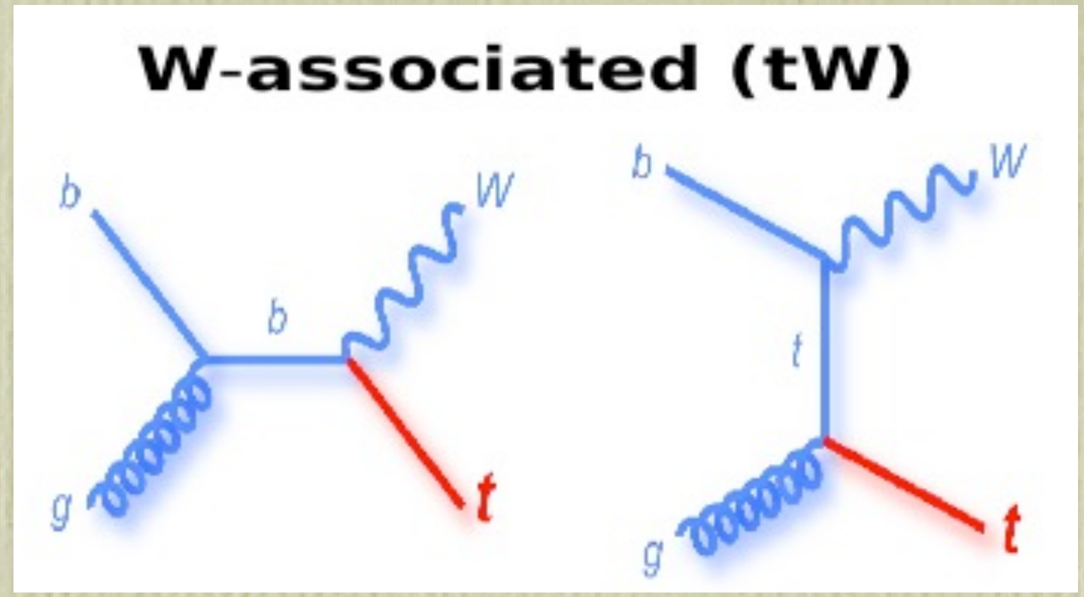


- ✳Single top diagram (a) plays the main role (not gauge invariant)
- ✳Impact of non-resonant diags seems marginal
- ✳could be useful to make other computations simpler and/or their integration more efficient

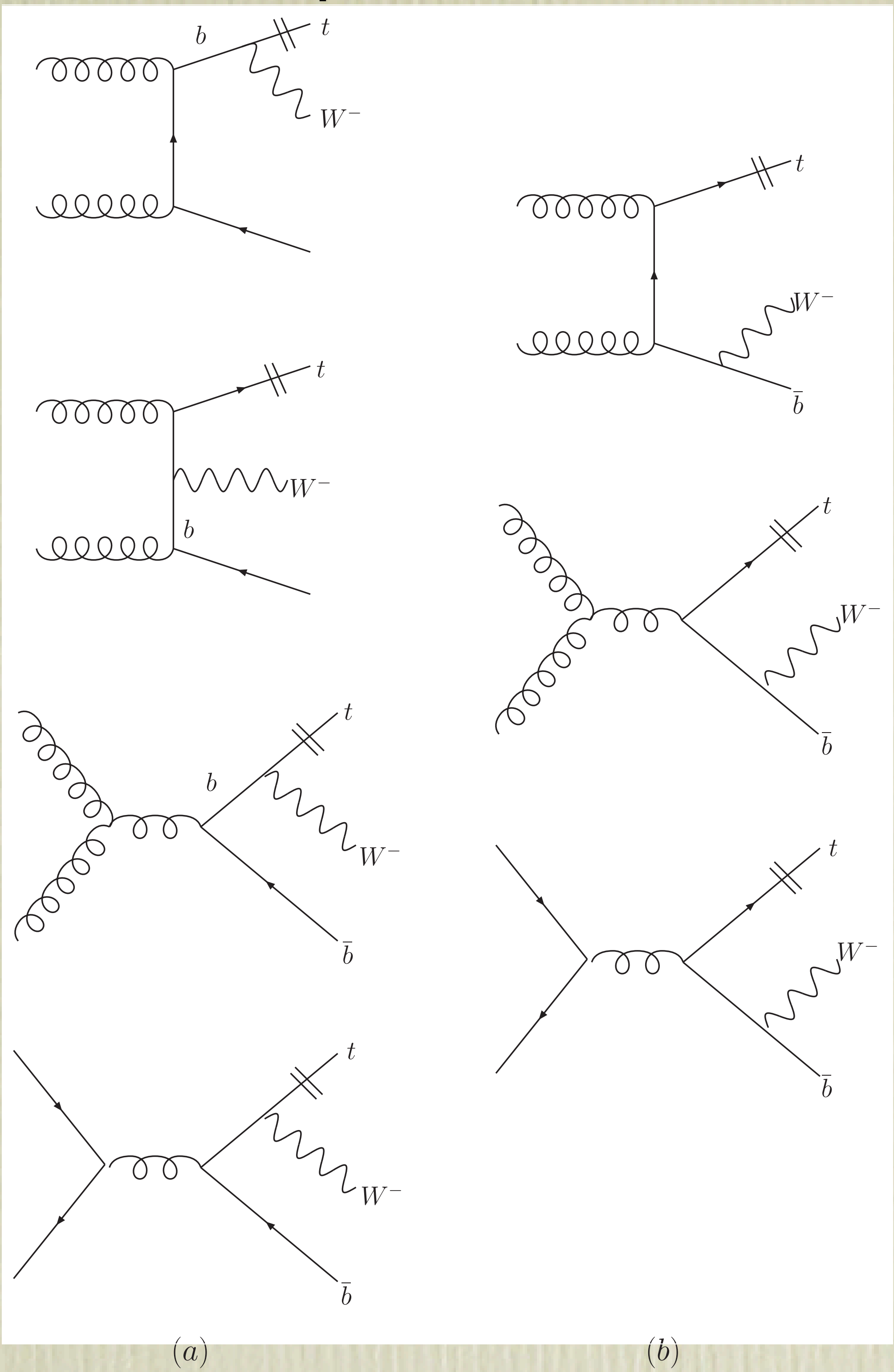
[Papanastasiou et al 2013]







- gg and qqbar real corrections contain tt production and decay



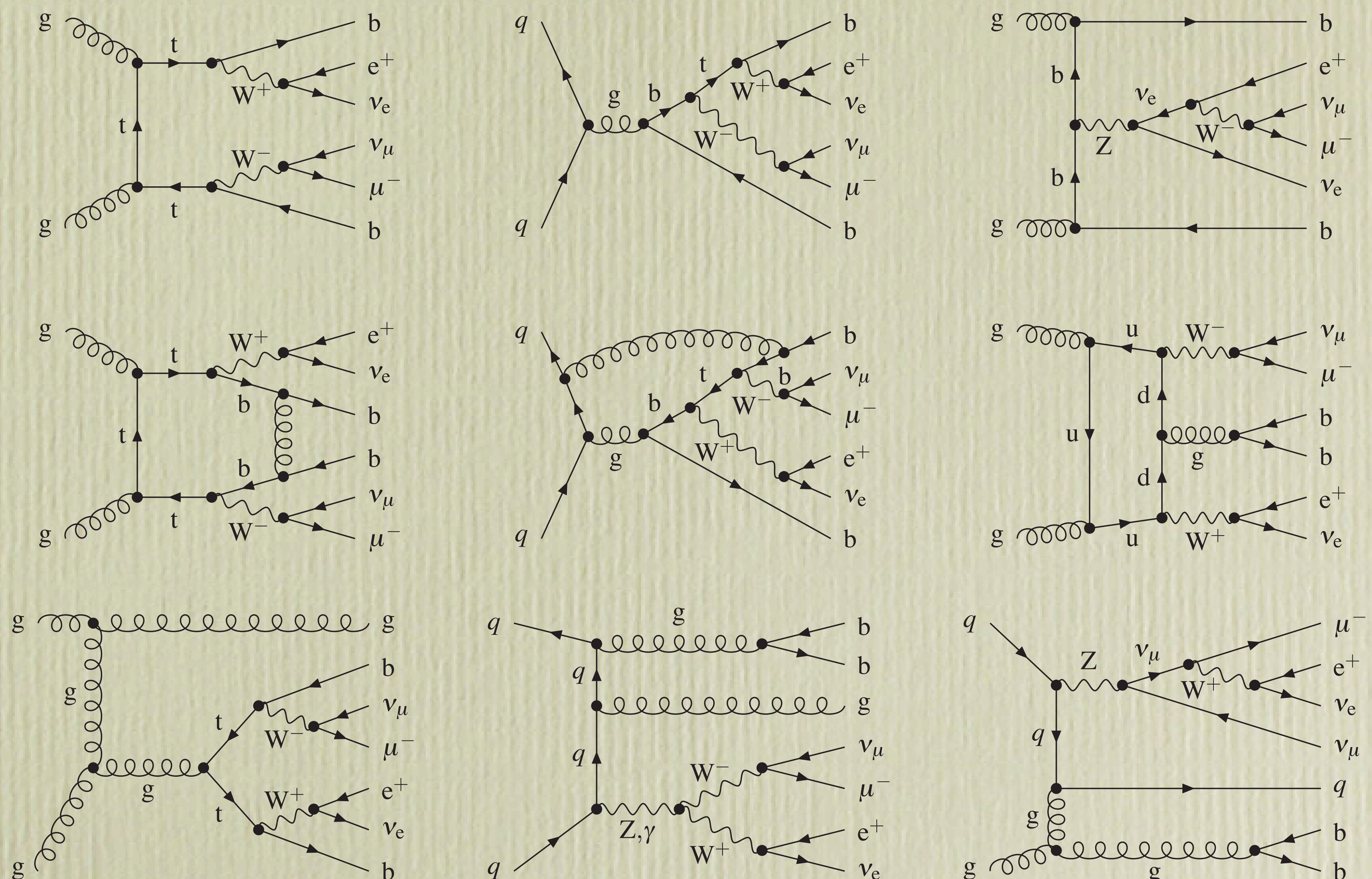
tW signature hard to define, can be described through different approaches.

One could start from WWbb....

WWbb @ NLO completed by two groups assuming a vanishing b quark mass

[Denner et al 2011, Bevilacqua et al 2011]

5F



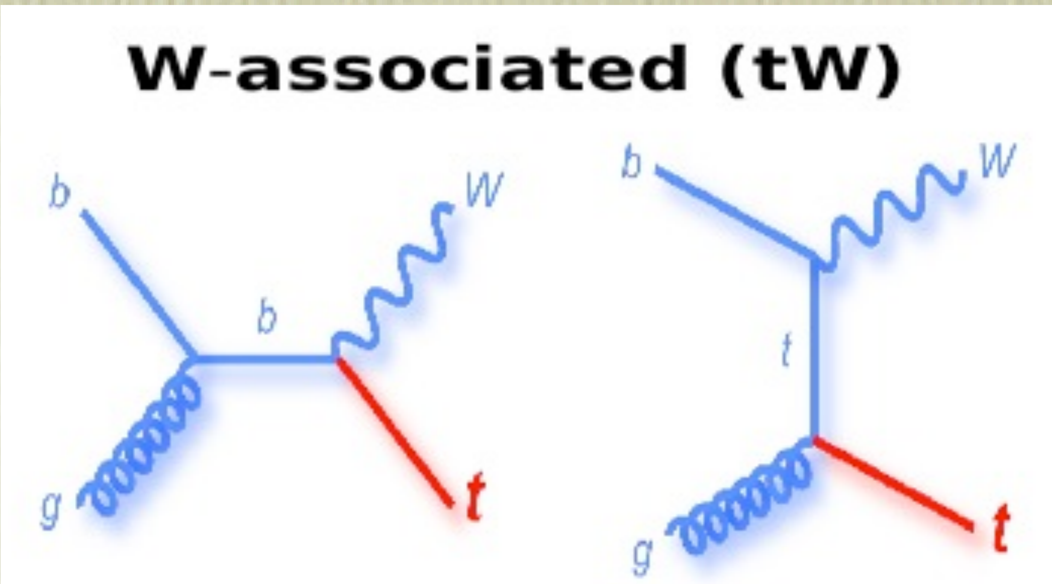
$m_b \neq 0$ needed to allow for an unresolved b-jet and study Wt production

Very recently two independent groups completed the computation of QCD corrections to WWbb with massive b's
[Frederix 2013] and [Cascioli, Kallweit, Maierhofer, Pozzoni 2013]

- Parton level NLO (easy to shower, results will then need of interpretation/validation)

- For Wt production the comparison among 4 Flavor vs 5 Flavor scheme is important from both theoretical and experimental reasons

- For Wt signal, the general rule should still apply: Wt+ps computation should still give the most precise predictions in case of unresolved extra b jet.



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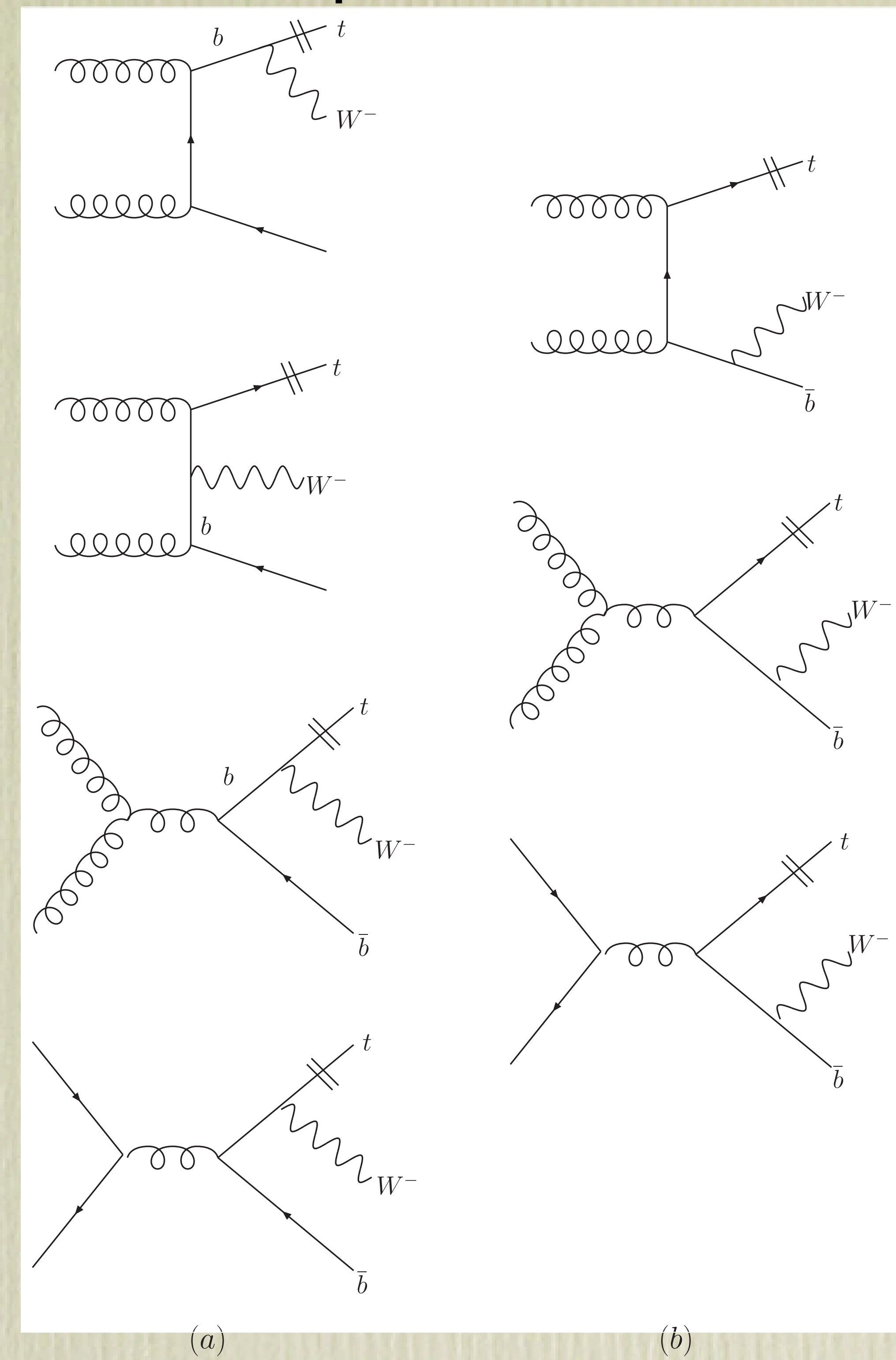

b-initiated computation however contains the resummation of the collinear ligarithm.
3 proposals:

- b-pdf inspired [Campbell, FT 2005] in MCFM
  - events with low pt-b already counted for at LO
  - b-jet veto to reduce interference with tt
  - parton level

- Removal of tt diagrams [Frixione et al 2008] in MC@NLO
  - gauge non-invariance, but the effect seems negligible

!! This in particular means that what is removed is also almost gauge invariant !!

- Subtract an extra cross section that locally removes the tt double resonant contribution [Frixione et al 2008] in MC@NLO
  - can be done in a gauge invariant way but introduces some uncompensated arbitrariness

Comparison with tW in MCFM

In Cascioli et al:

- full off-shell effects
- 4F, no resummation of the collinear log
- inclusion of bb-jets

In MCFM:

- Narrow width approximation
- 5F, resummation of the collinear log
- no bb-jets

$$\mathrm{d}\sigma_{\mathrm{W^+W^-b\bar{b}}} = \mathrm{d}\sigma_{\mathrm{t\bar{t}}} + \mathrm{d}\sigma^{\mathrm{FtW}}_{\mathrm{W^+W^-b\bar{b}}},$$

$$\mathrm{d}\sigma_{\mathrm{t\bar{t}}} = \lim_{\Gamma_\mathrm{t}\to 0}\left(\frac{\Gamma_\mathrm{t}}{\Gamma_\mathrm{t}^{\mathrm{phys}}}\right)^2 \mathrm{d}\sigma_{\mathrm{W^+W^-b\bar{b}}}(\Gamma_\mathrm{t}),$$

Table 2 Full $\mathrm{W^+W^-b\bar{b}}$ predictions and finite-top-width contributions for bins with 0,1 and ≥ 2 b-jets. Same conventions as in Table 1.

	μ_0	σ [fb]	σ_0 [fb]	σ_1 [fb]	σ_{2+} [fb]
LO	μ_{WWbb}	$1232^{+34\%}_{-24\%}$	$37^{+38\%}_{-25\%}$	$367^{+36\%}_{-24\%}$	$828^{+33\%}_{-23\%}$
NLO	μ_{WWbb}	$1777^{+10\%}_{-12\%}$	$65^{+20\%}_{-17\%}$	$571^{+14\%}_{-14\%}$	$1140^{+7\%}_{-10\%}$
K	μ_{WWbb}	1.44	1.73	1.56	1.38
LO	m_t	$1317^{+35\%}_{-24\%}$	$35^{+37\%}_{-25\%}$	$373^{+36\%}_{-24\%}$	$909^{+35\%}_{-24\%}$
NLO	m_t	$1817^{+8\%}_{-11\%}$	$63^{+20\%}_{-17\%}$	$584^{+14\%}_{-14\%}$	$1170^{+5\%}_{-9\%}$
K	m_t	1.38	1.80	1.56	1.29
	μ_0	σ^{FtW} [fb]	σ_0^{FtW} [fb]	σ_1^{FtW} [fb]	$\sigma_{2+}^{\mathrm{FtW}}$ [fb]
LO	μ_{WWbb}	$91^{+41\%}_{-27\%}$	$13^{+42\%}_{-27\%}$	$71^{+40\%}_{-27\%}$	$7^{+45\%}_{-29\%}$
NLO	μ_{WWbb}	$107^{+6\%}_{-11\%}$	$20^{+18\%}_{-17\%}$	$82^{+4\%}_{-10\%}$	$5^{+2\%}_{-10\%}$
K	μ_{WWbb}	1.18	1.49	1.16	0.77
LO	m_t	$63^{+36\%}_{-25\%}$	$8^{+36\%}_{-25\%}$	$49^{+36\%}_{-24\%}$	$6^{+46\%}_{-29\%}$
NLO	m_t	$100^{+17\%}_{-16\%}$	$16^{+22\%}_{-18\%}$	$77^{+16\%}_{-15\%}$	$6^{+12\%}_{-16\%}$
K	m_t	1.58	1.89	1.58	1.10

[Cascioli, Kallweit, Maierhofer, Pozzorini 2013]

Leptons:

$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \quad |\eta_\ell| < 2.5, \quad p_{\mathrm{T,miss}} > 20\mathrm{GeV},$

Jets: antikt, R=0.4

$p_\mathrm{T} > 30$ GeV and $|\eta| < 2.5$

PDF's: NNPDF in Cascioli et al
MSTW2008 in MCFM

	Cascioli et al: 0+1 b-jet off-shell + tW	MCFMtW
LO	84^{+35}_{-16} 57^{+21}_{-10}	89
NLO	102^{+7}_{-5} 93^{+16}_{-9}	97

Too much a good agreement!
Need of deep comparisons

Conclusions

- Single top production and decay studies test the Standard Model in a unique way

- Further, the large cross section at LHC with signature:

  "high pt lepton(s), missing energy, b-jets, light jets"

  are relevant backgrounds for Higgs searches and for a large number of BSM searches

- Predictions doable with fully automated frameworks that link the lagrangian to the event samples without human efforts
  - ✤ it is a remarkable fact that, the addition of one more extra jet radiation with respect to known analytic computation (i.e. more extensive computation) can be done in a fully automated way up to the NLO+PS without human effort.

- Automation is not the end of the game for the theorists: it's just the beginning of the fun!
  Great care is needed in the interpretation/validation of the results (quite often) case by case