State of the art POWHEG generators for Top Mass Measurements at the LHC

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In collaboration with:
J. Lindert, P. Nason, C. Oleari and S. Pozzorini [arXiv:1607.04538]
S. Ferrario Ravasio, P. Nason and C. Oleari [arXiv:1801.03944]

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- Top mass measurements
  - Mass determinations based on the top quark reconstructed from its decay products in the di-lepton channel
- POWHEG generators
  - NLO+PS top-pair generators available in `POWHEG BOX` that implement top decay at different levels of accuracy
- State of the art
  - In experimental analyses: `POWHEG-BOX-V2`/*hvq* (2007)
  - In theory: $b\bar{b}4l$ (2016)
- Goal
  - Explore the potential impact of an upgrade of the top-pairgenerator on top mass extractions

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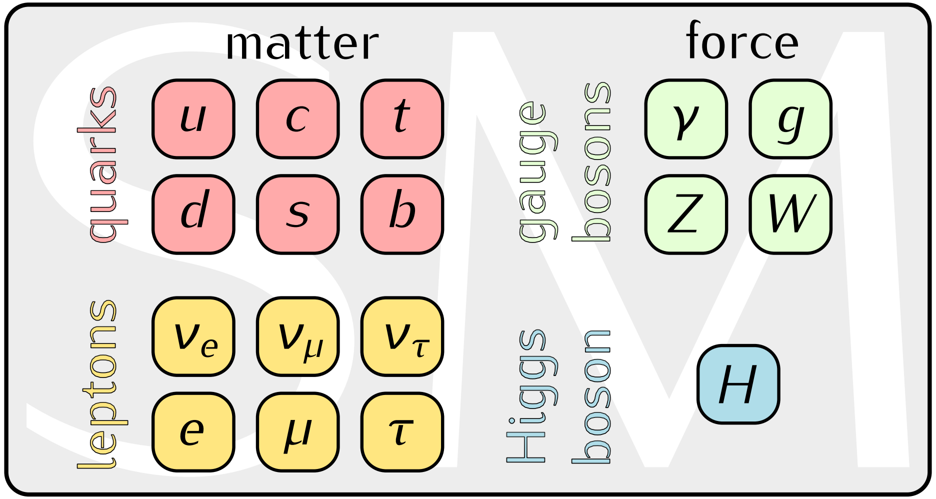
Top quark trivia

- 3rd family up-type quark



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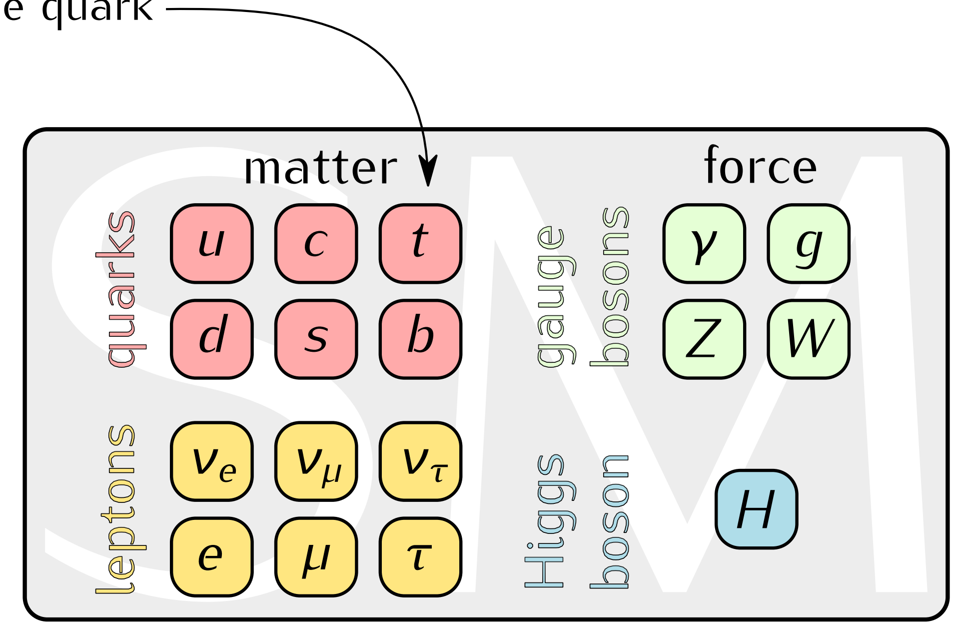
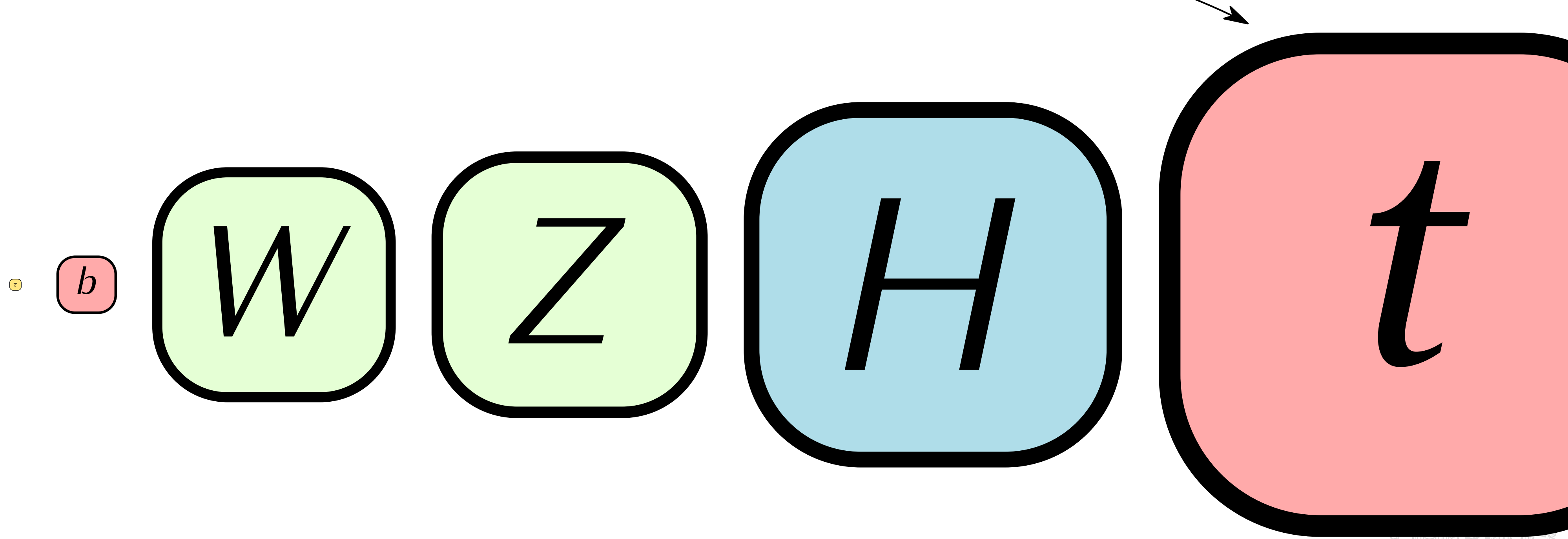


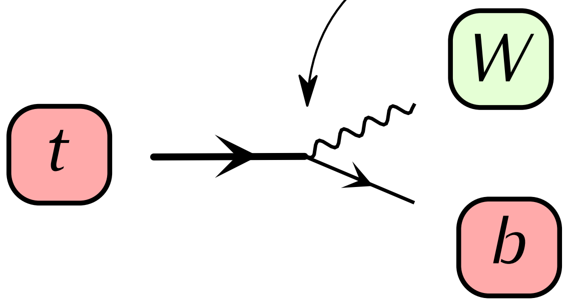
Top quark trivia

- 3^{rd} family up-type quark
- heaviest elementary particle so far, $m_t \sim 173$ GeV



Top quark trivia

- 3rd family up-type quark
- heaviest elementary particle so far, $m_t \sim 173$ GeV
- is very short lived, $\Gamma_t \sim 1.4$ GeV
  - relatively narrow resonance, $\Gamma_t/m_t \sim 0.8\%$
  - decays before it gets a chance to hadronize, unlike any other quark
  - decays electroweakly (EW) and almost exclusively as $t \to W + b$



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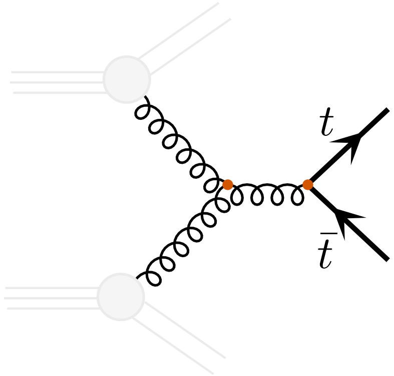

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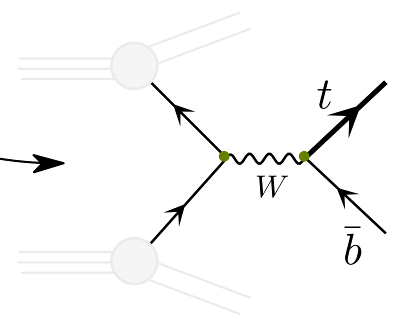

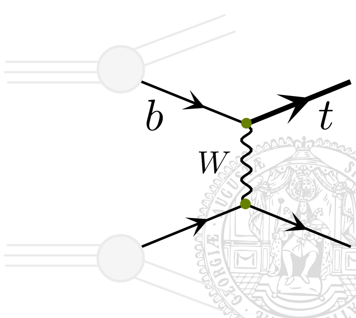

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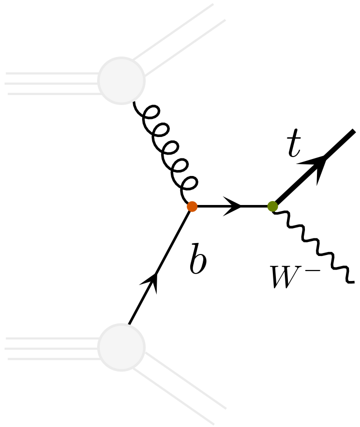
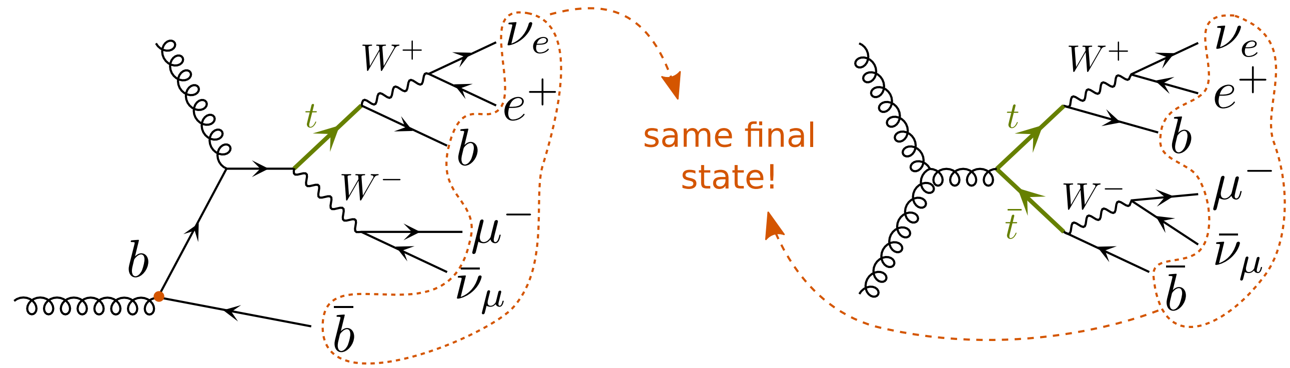
  - mixed in association with W



Top quark trivia

tW associated production @ NLO $\qquad$ $t\bar{t}$ production @ LO



- at a hadron collider produced:
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this classification does not apply at NLO!

Top quark trivia

arXiv id	observable	top backgrounds
1712.02758	Higgs and Z to $\varphi\gamma$, $\rho\gamma$	——————————————–
1712.02118	long lived charginos	$t\bar{t}$
1712.02304	$H \to ZZ^* \to 4l$	$t\bar{t}$, $t\bar{t}+Z$, $t\bar{t}+H$
1712.02332	squarks and gluinos	$t\bar{t}$, Wt, ST, $t\bar{t}+W/Z/WW$
1712.01602	$d\sigma_{tW}$	duh
1711.11520	top-squark pair	$t\bar{t}$, Wt, ST, $t\bar{t}+Z$
1711.08341	soft-drop jet mass	——————————————–
1711.03301	dark matter, other NP	$t\bar{t}$, ST (small contrs)
1711.03296	$\sigma_{W^+}/\sigma_{W^-}$ and $d\sigma_W$	$t\bar{t}$, ST
1711.02692	$\sigma_{\mathrm{(di)jet}}$	——————————————–
1711.01901	Supersymmetry	$t\bar{t}$, ST, Wt
1710.11412	dark matter + b/t quarks	$t\bar{t}$, ST, $t\bar{t}+W/Z/\gamma/H$, $t\bar{t}+WW/t\bar{t}$, ...
1710.09560	σ isolated-γ + h.f. jet	——————————————–
1710.09748	H^{++}	$t\bar{t}$, ST, $t\bar{t}W/Z/\gamma/H$
1710.07235	WW/WZ resonances	$t\bar{t}$, ST
1710.07171	pair-produced resonances	$t\bar{t}$
...	...	...

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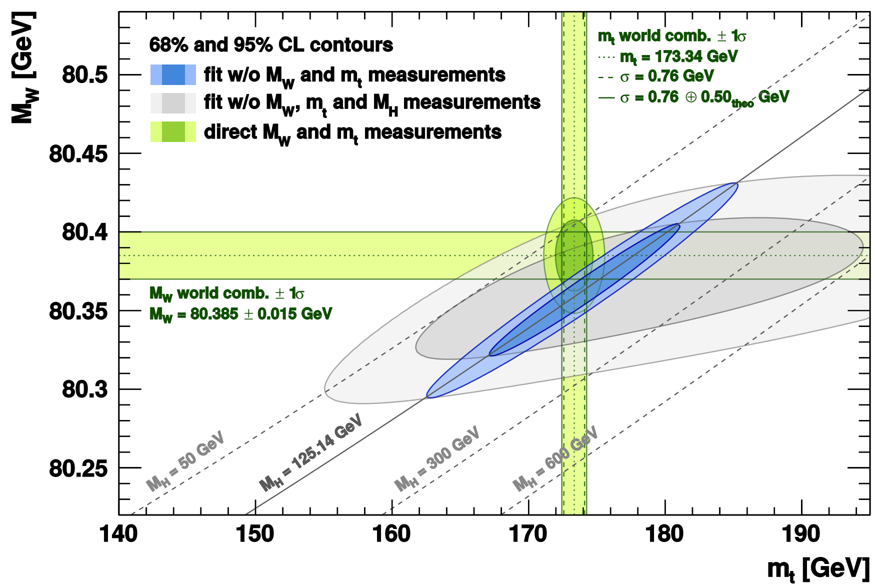
...	...	...

12/16 require reliable simulation of $t\bar{t}$!

Top quark mass

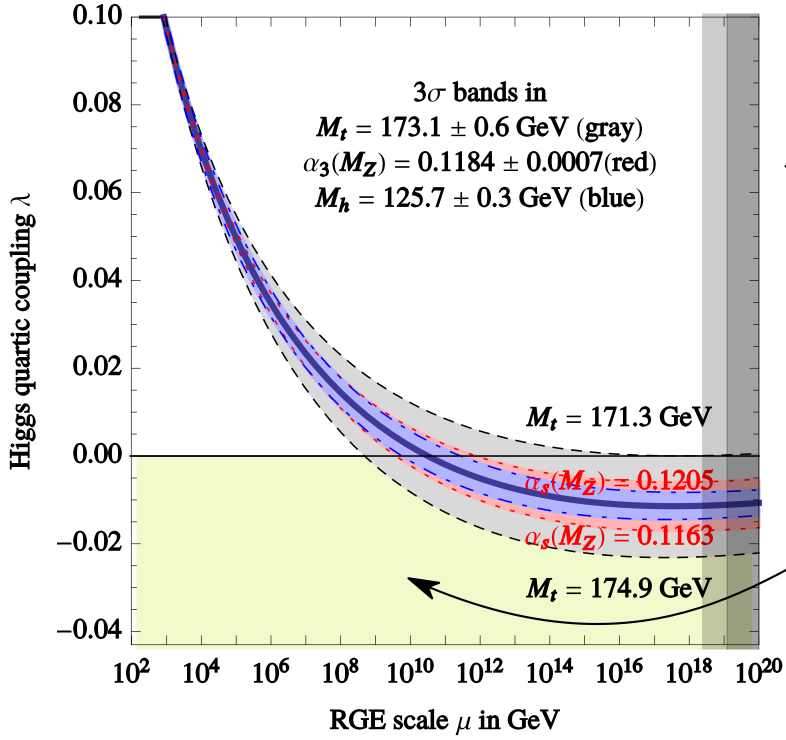
- m_H, m_W and m_T correlated in the SM
  - Accurate knowledge of m_T constitutes a precision test of the SM



Global fit to electroweak precision observables [arXiv:1407.3792]

Top quark mass

- Due to its large mass top couples to the Higgs boson rather strongly
  - RG flow of the Higgs quartic sensitive to the value of m_T



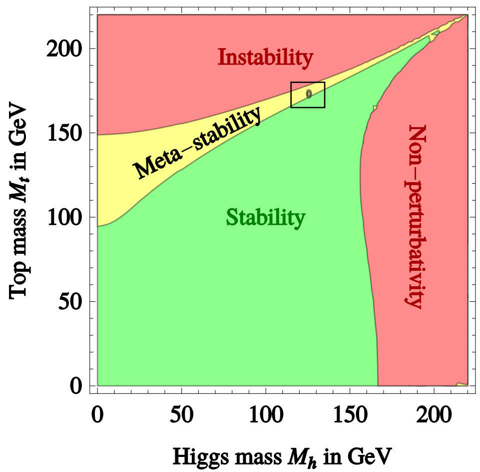
RG flow of the Higgs quartic coupling for m_H = 125.7 GeV [arXiv:1512.01222]

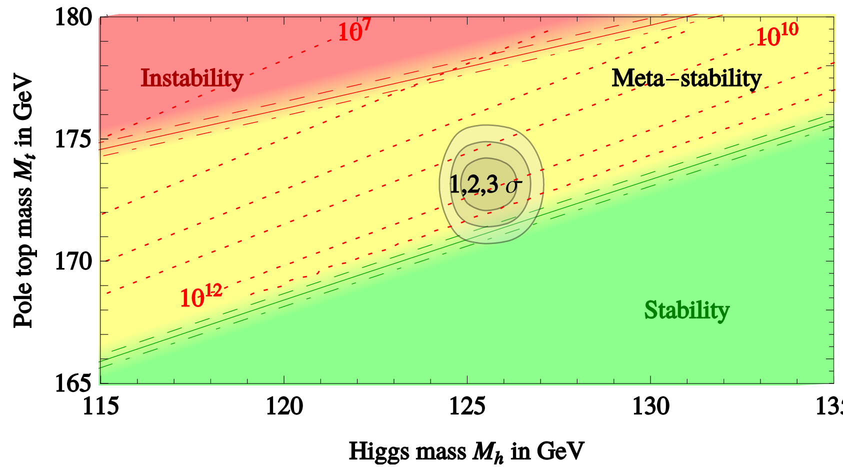
Higgs potential has no minimum for $\lambda < 0$!

Top quark mass

- Due to its large mass top couples to the Higgs boson rather strongly
  - Current values of m_H and m_t suggest the vacuum is metastable

[arXiv:1205.6497]





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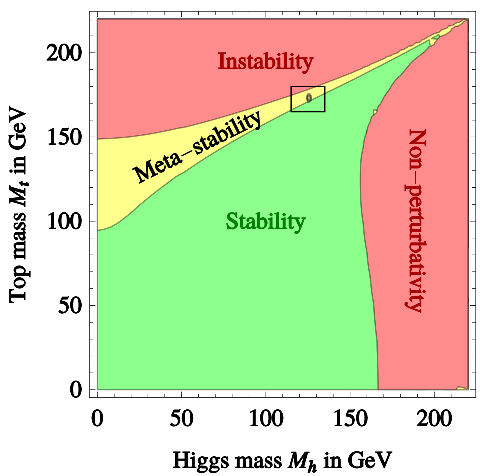

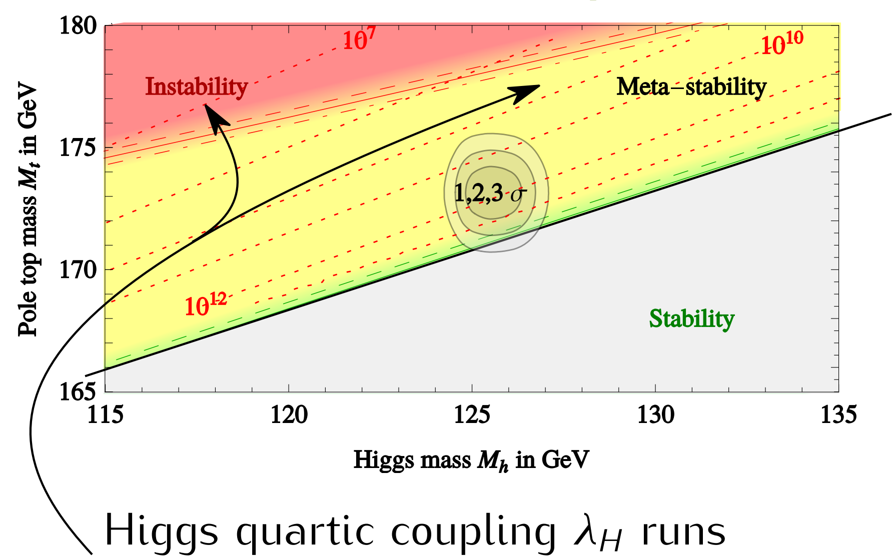

Higgs quartic coupling λ_H runs
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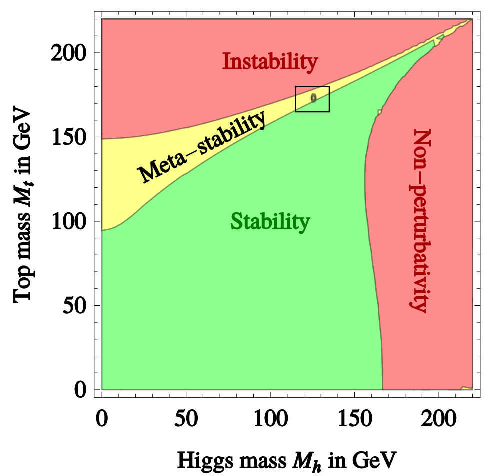
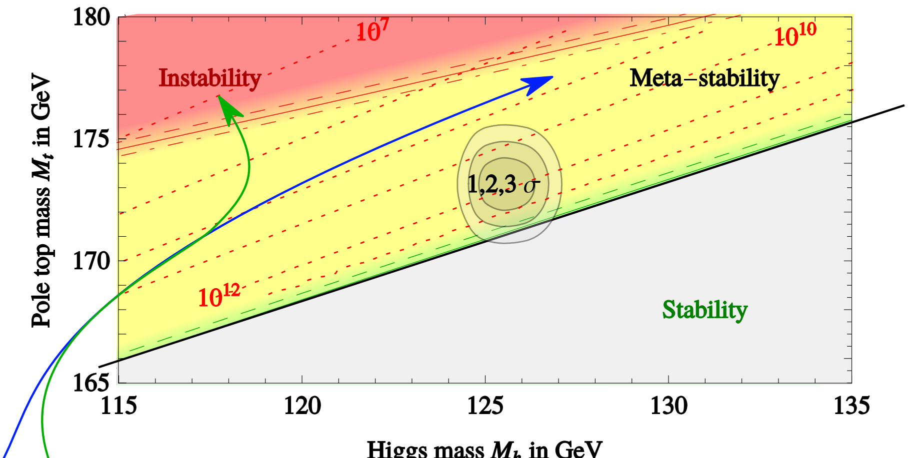


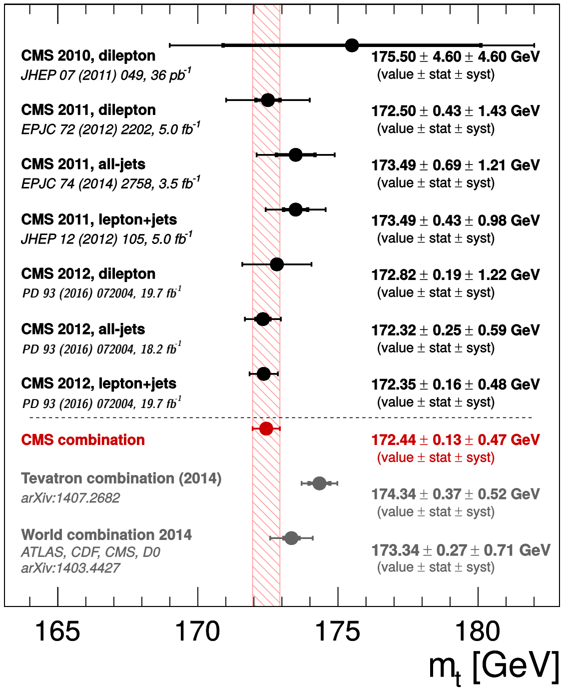


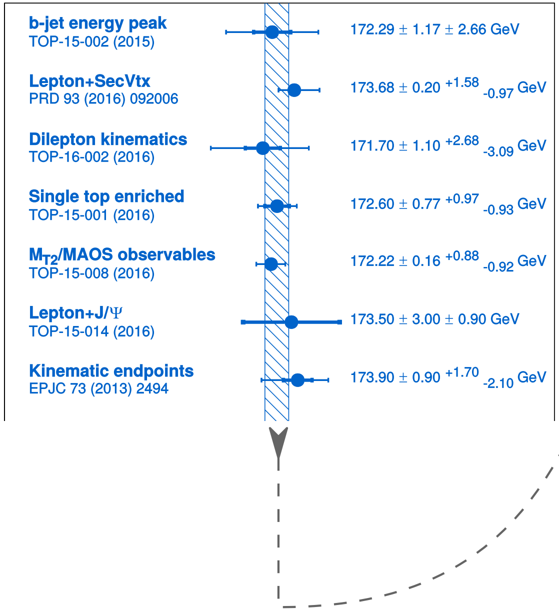
The vaccum life-time is long enough

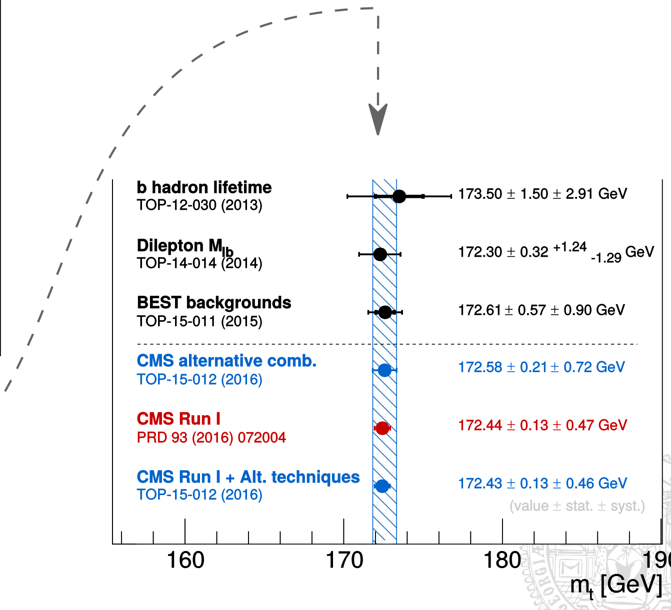
Higgs quartic coupling λ_H runs to negative values at Planck scale

Top quark mass

- m_T measurement at the LHC
  - Plethora of methods for m_t determination
  - Most precise ones rely on top reconstruction from its decay products
  - Top-quarks abuntantly produced at the LHC







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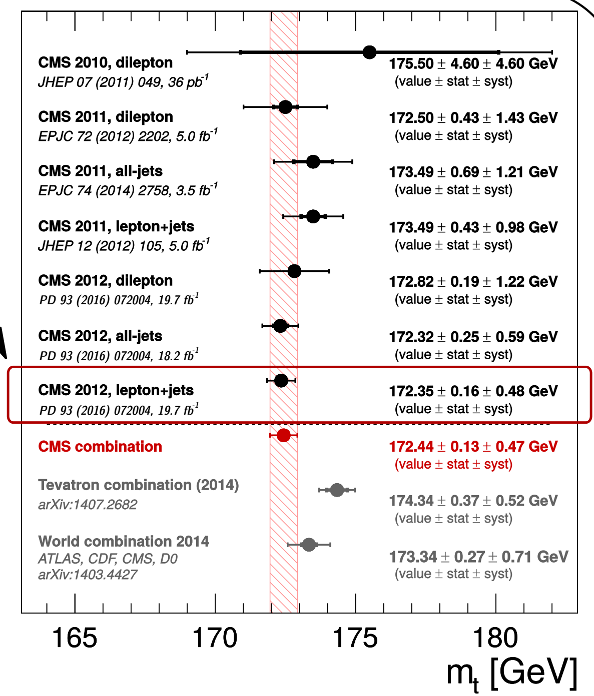

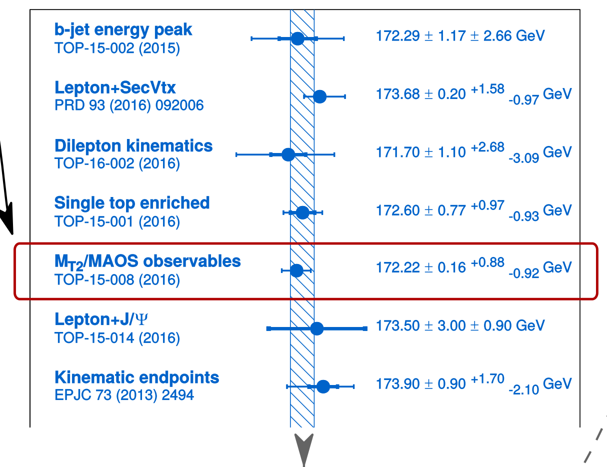

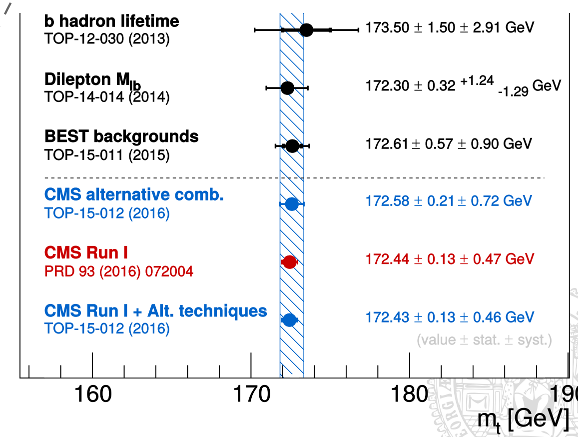

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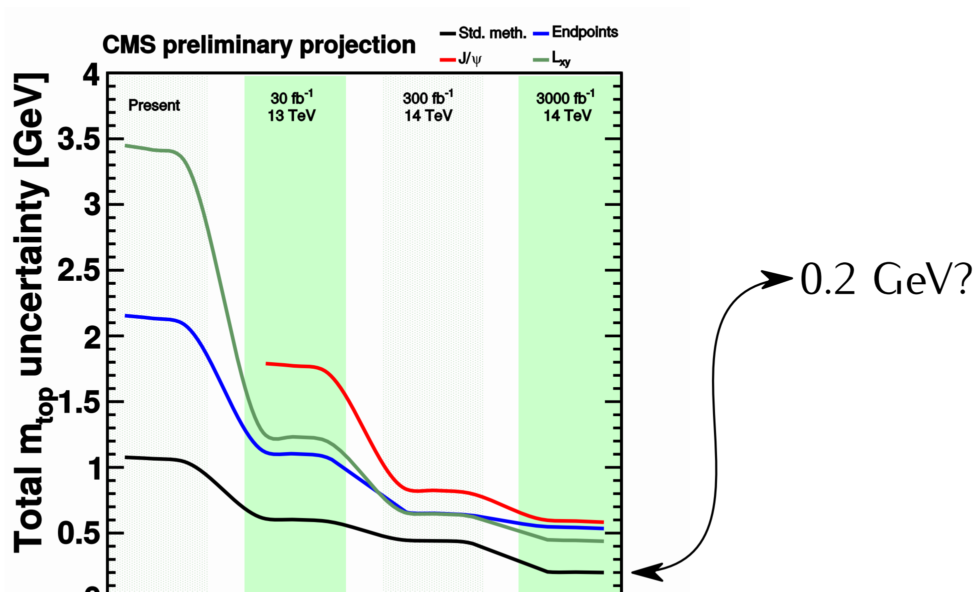

[arXiv:1404.1013]

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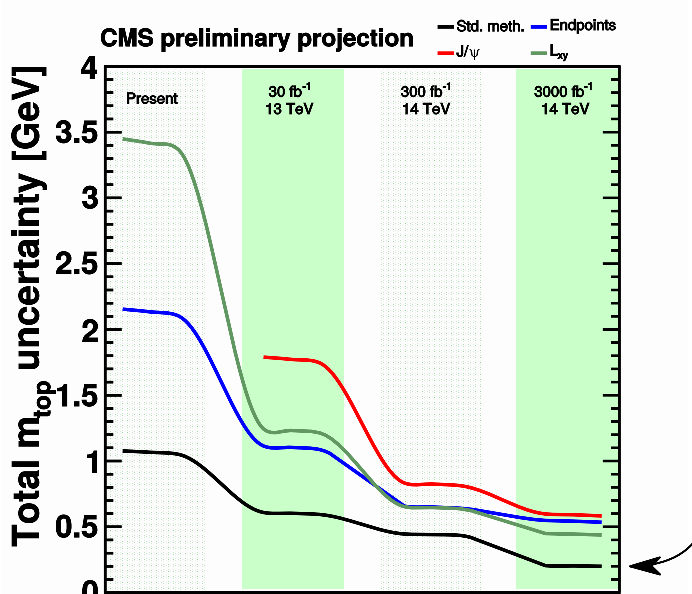


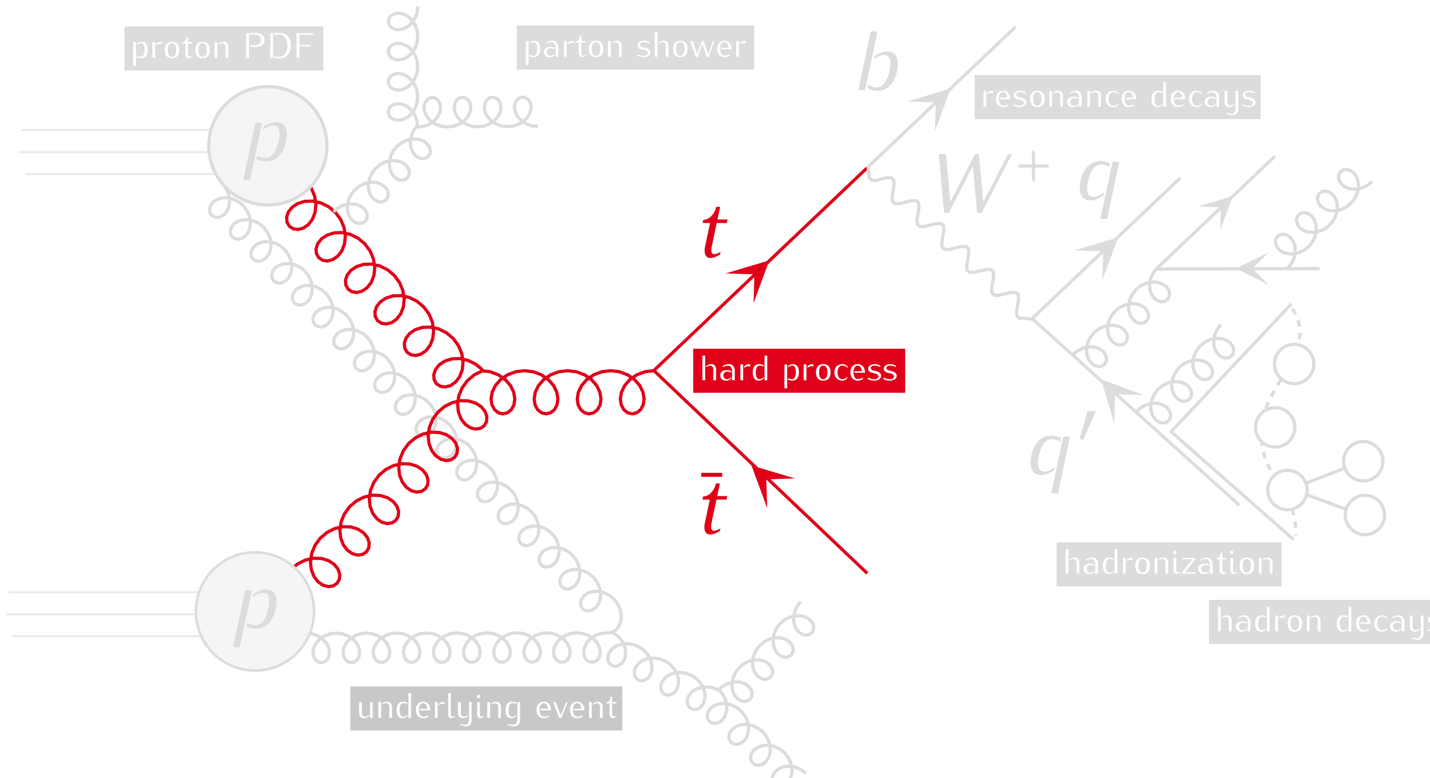
[arXiv:1404.1013]

0.2 GeV?

Are the theoretical predictions for top mass determinations precise enough?

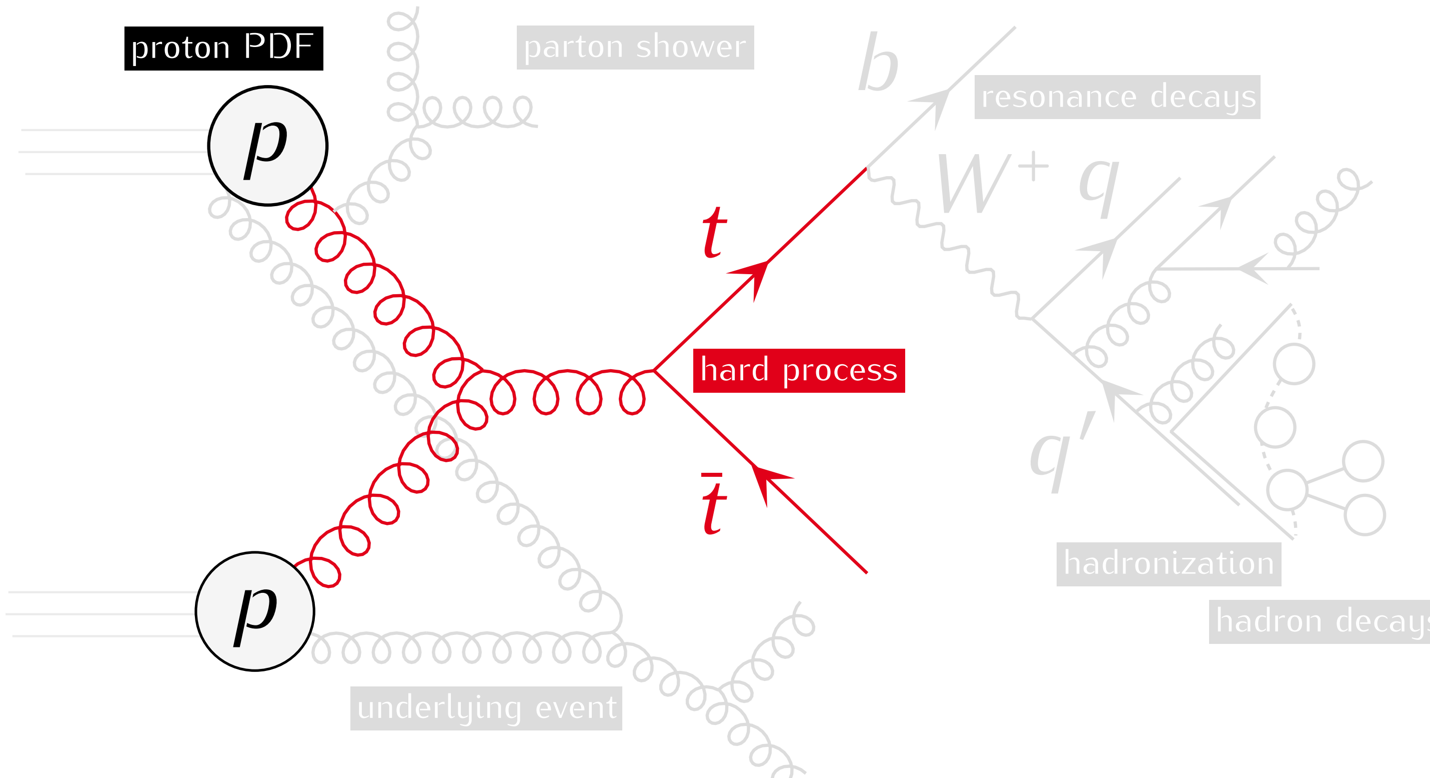
Simulating top-quark production

- Ingredients of a $t\bar{t}$ event
  - Hard process described in terms of a scattering amplitude or a matrix element



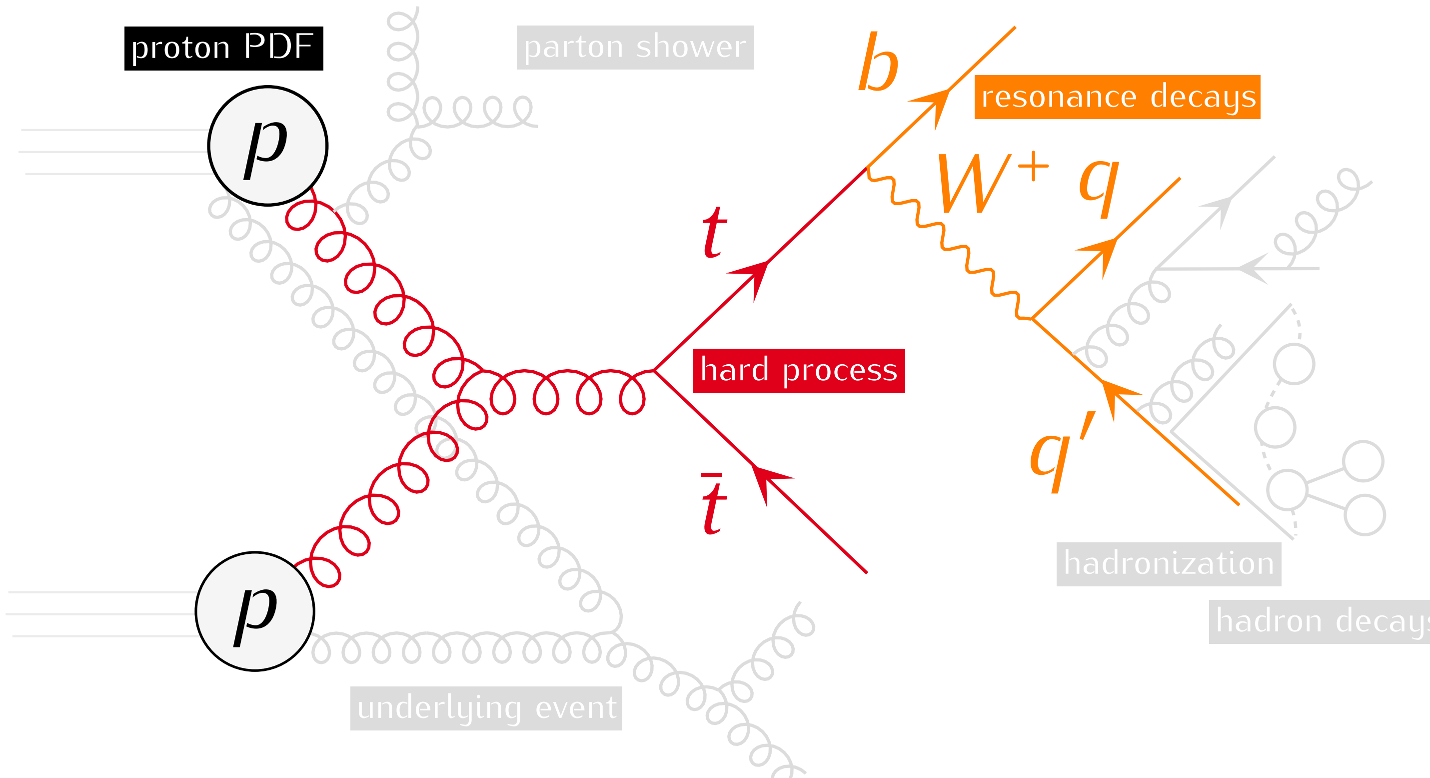
Simulating top-quark production

- Ingredients of a $t\bar{t}$ event
  - Proton PDFs extracted from data



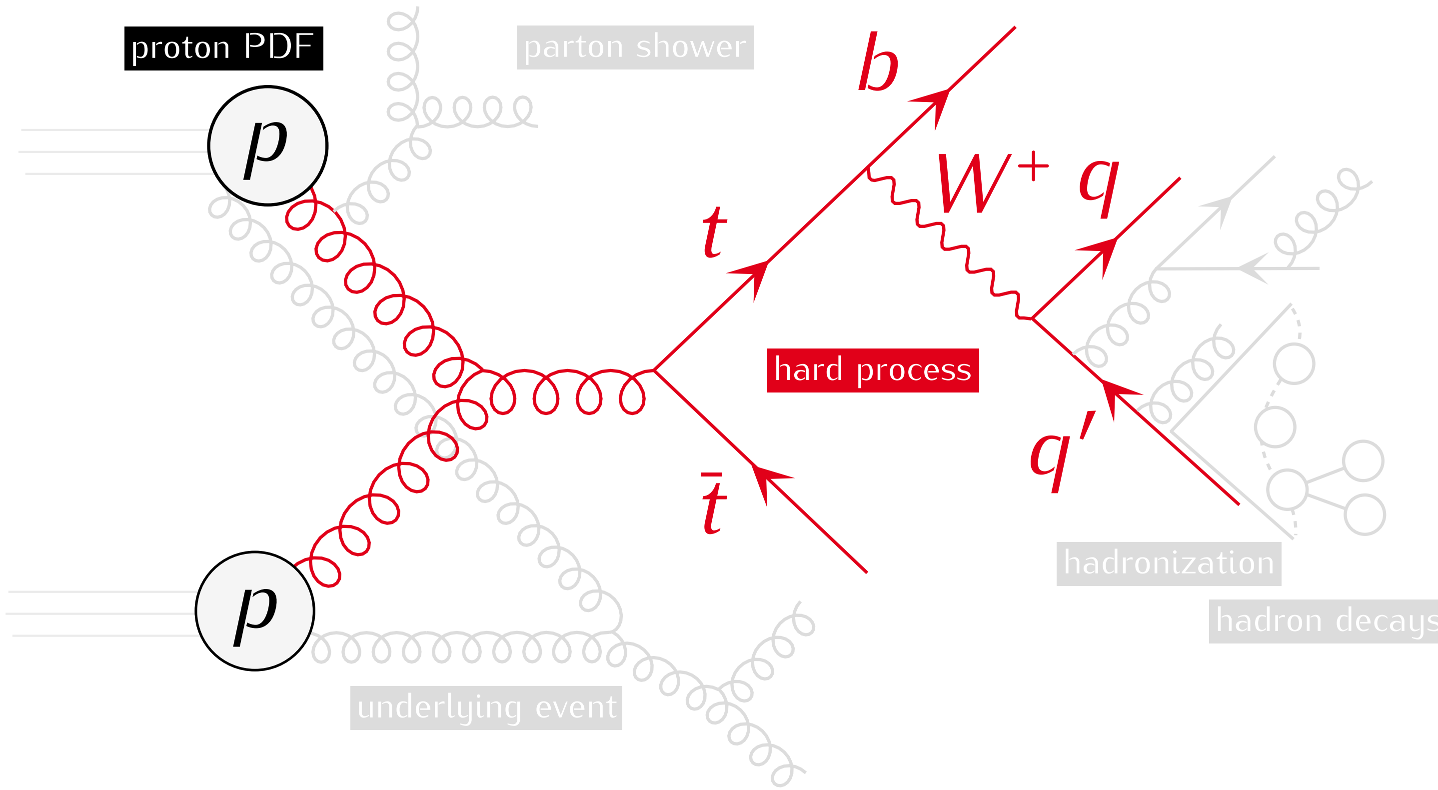
Simulating top-quark production

- Ingredients of a $t\bar{t}$ event
  - Resonance decays described by a matrix element in the Narrow Width Approximation



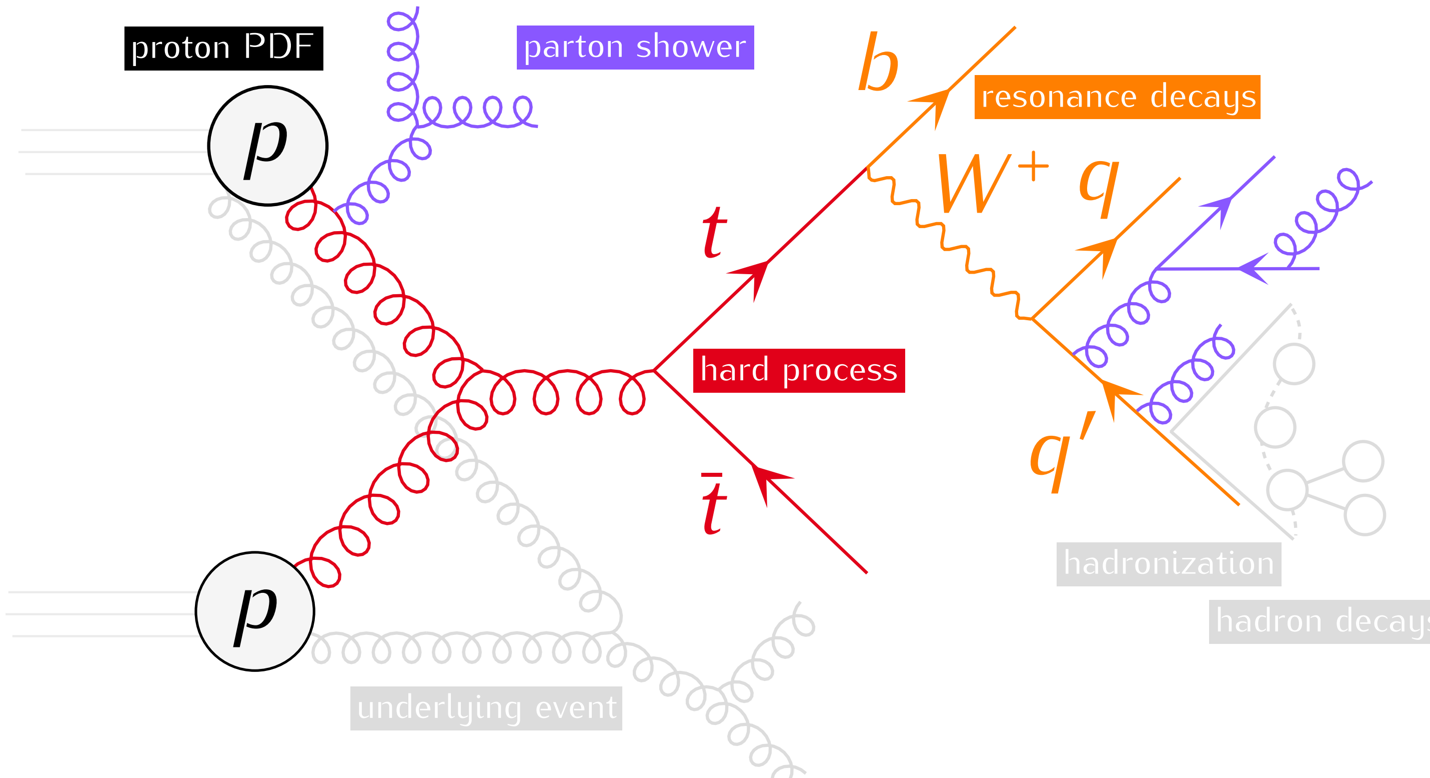
Simulating top-quark production

- Ingredients of a $t\bar{t}$ event
  - Resonance decays as a part of the hard process, accounting for off-shell effects ...



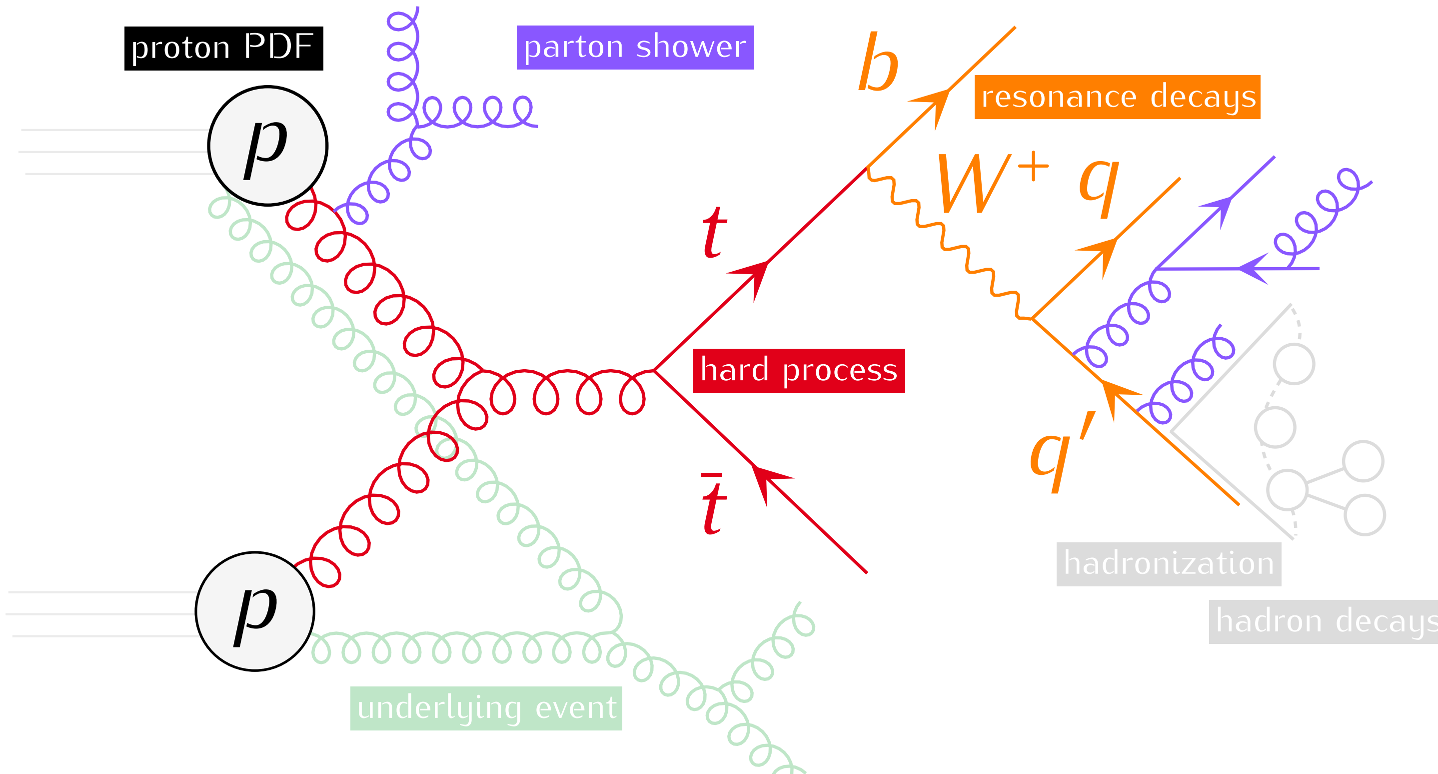
Simulating top-quark production

- Ingredients of a $t\bar{t}$ event
  - Higher order effects in the soft and collinear regions described by parton shower



Simulating top-quark production

- Ingredients of a $t\bar{t}$ event
  - Other ingredients including non-perturbative effects not calculable from first principles



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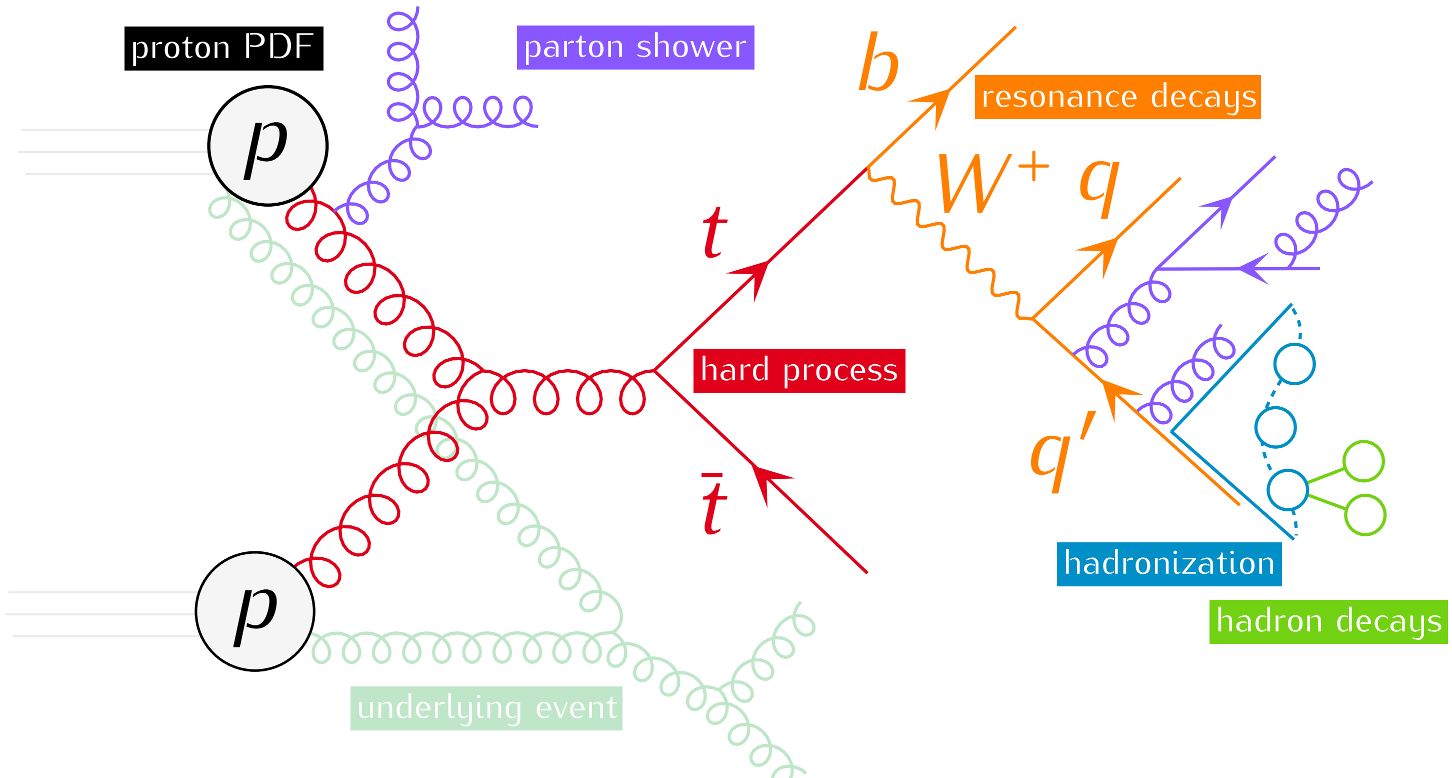
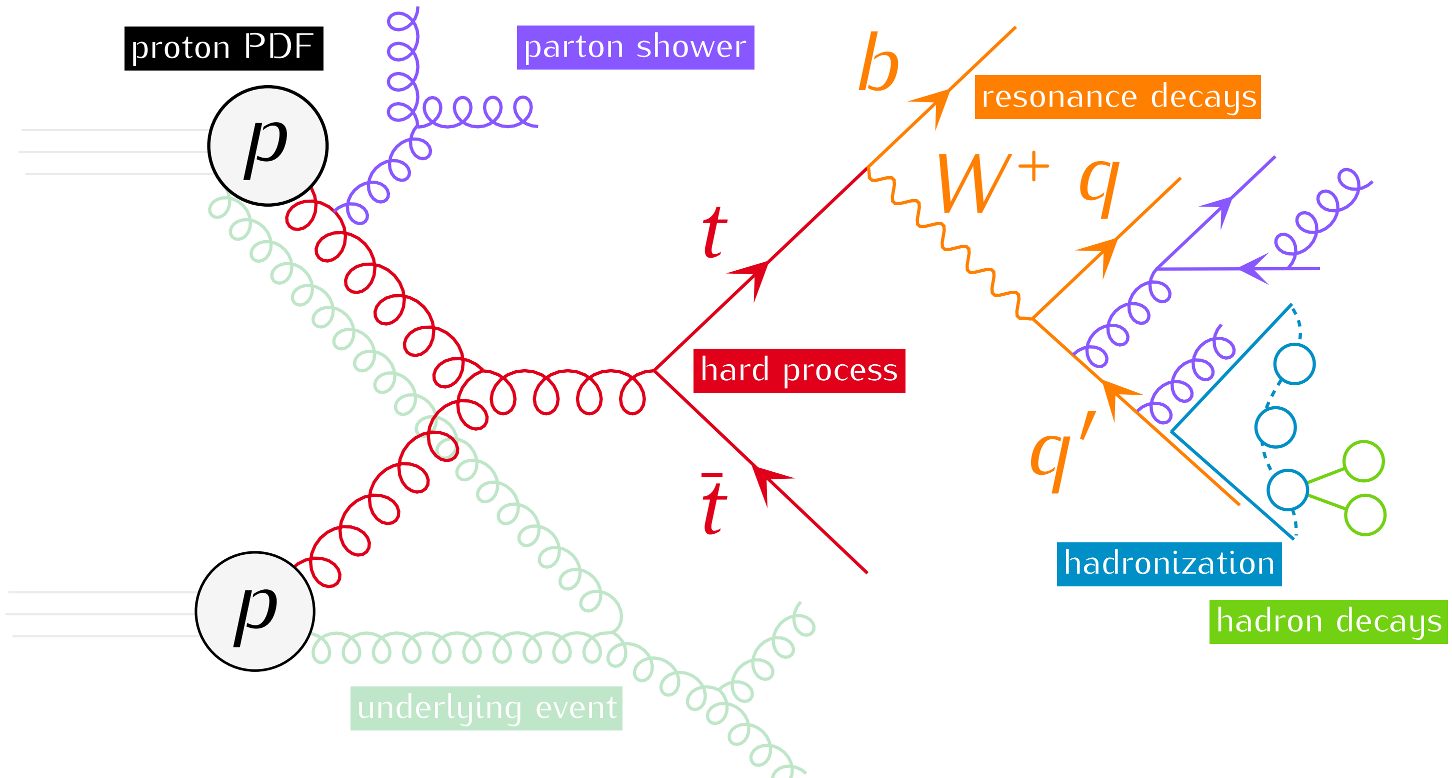


† inspired by M. Seidel

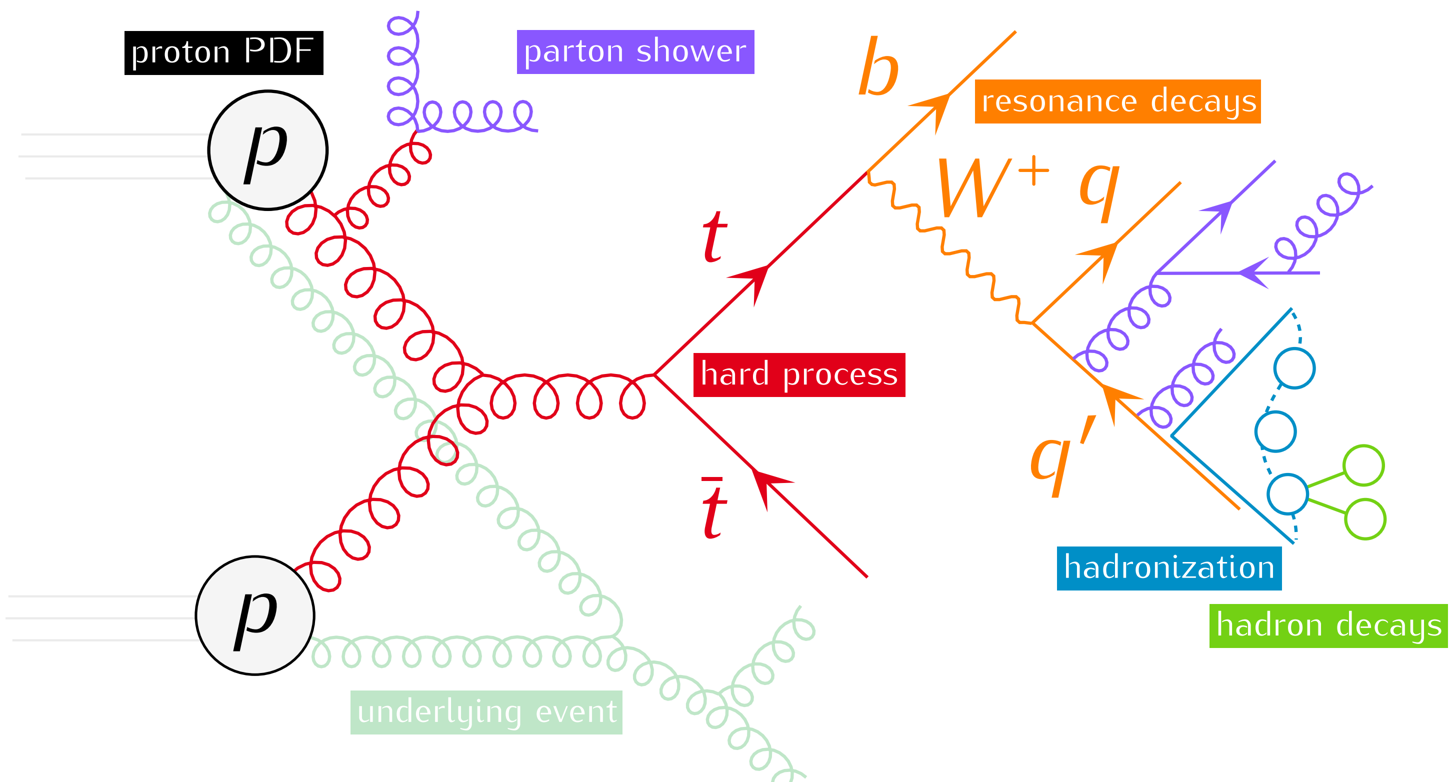
Simulating top-quark production

- Ingredients of a $t\bar{t}$ event: all available within general purpose Monte Carlo event generators
  - Pythia, Herwig, ...– higher order effects generally only in the collinear approximation



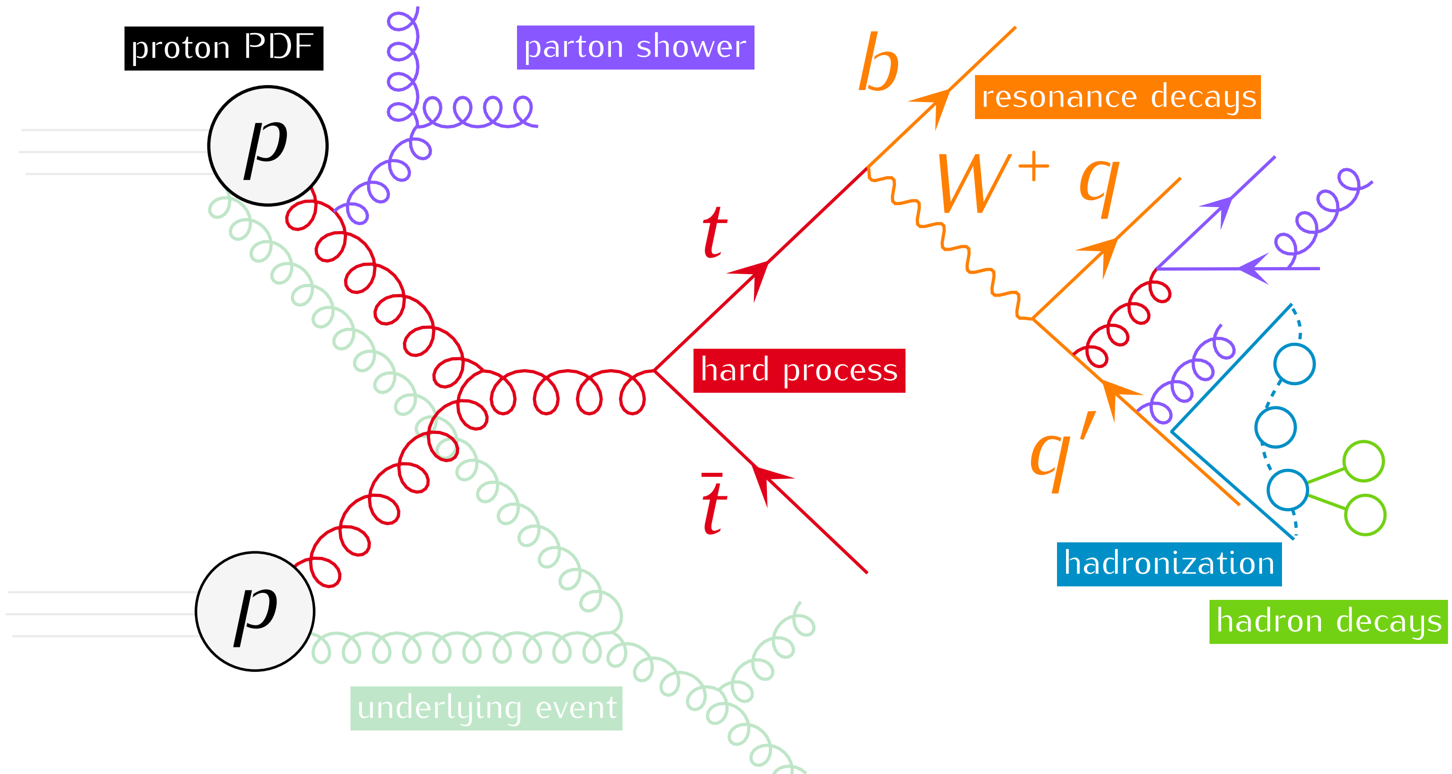
Simulating top-quark production

- Extending the description of higher order corrections in the full phase space requires a matching procedure: at NLO+PS there is MC@NLO and POWHEG

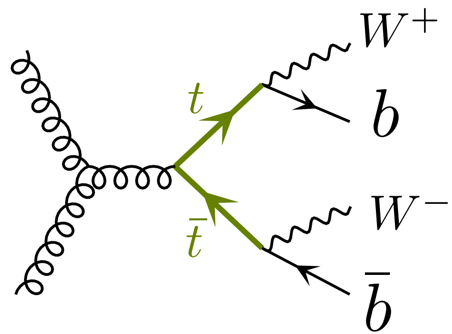


Simulating top-quark production

- Extending the description of higher order corrections in resonance decays in the full phase space requires a resonance aware matching procedure



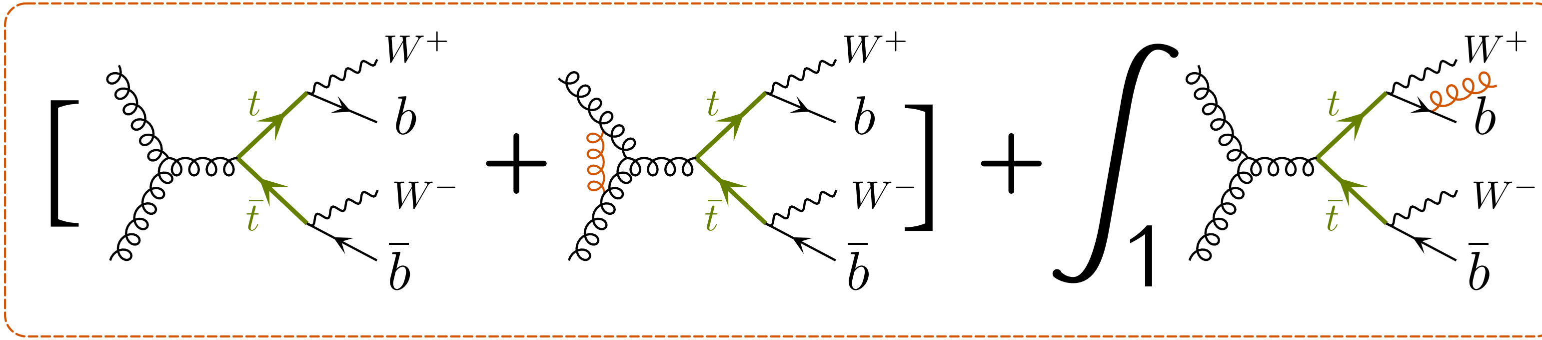
NLO+PS à la POWHEG



$$d\sigma = \overline{B}(\Phi_B)\, d\Phi_B \left[\Delta(q_{\text{cut}}) + \sum_\alpha \Delta(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)}\, d\Phi_{\text{rad}} \right]$$

$$\text{with } \Delta(k_T^\alpha) = \exp\left[- \int_{k_T^\alpha > q_{\text{cut}}} \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)}\, d\Phi_{\text{rad}} \right]$$

NLO+PS à la POWHEG



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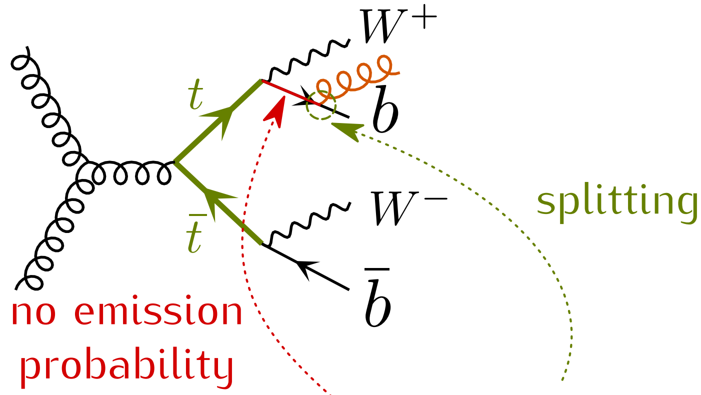
NLO+PS à la POWHEG



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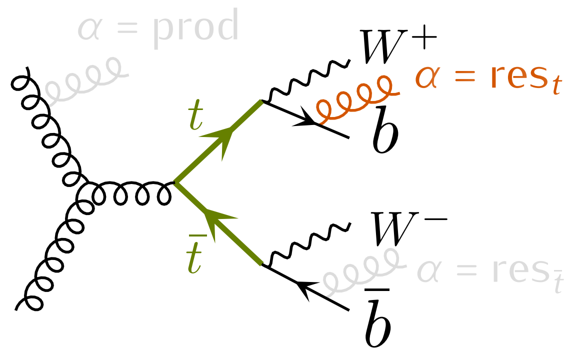
- Such a NLO calculation can be resummed using the standard formulation of the Parton Shower supplemented by a p_T veto

NLO+PS à la POWHEG



$$d\sigma = \overline{B}(\Phi_B)\, d\Phi_B \left[\Delta(q_{\mathrm{cut}}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_B, \Phi_{\mathrm{rad}}))}{B(\Phi_B)}\, d\Phi_{\mathrm{rad}} \right]$$

$$\text{with } \Delta(k_T^{\alpha}) = \exp\left[-\int_{k_T^{\alpha} > q_{\mathrm{cut}}} \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_B, \Phi_{\mathrm{rad}}))}{B(\Phi_B)}\, d\Phi_{\mathrm{rad}} \right]$$

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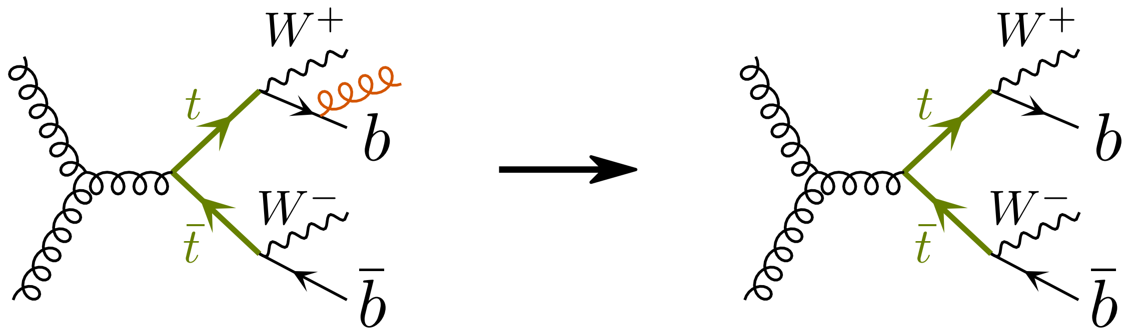

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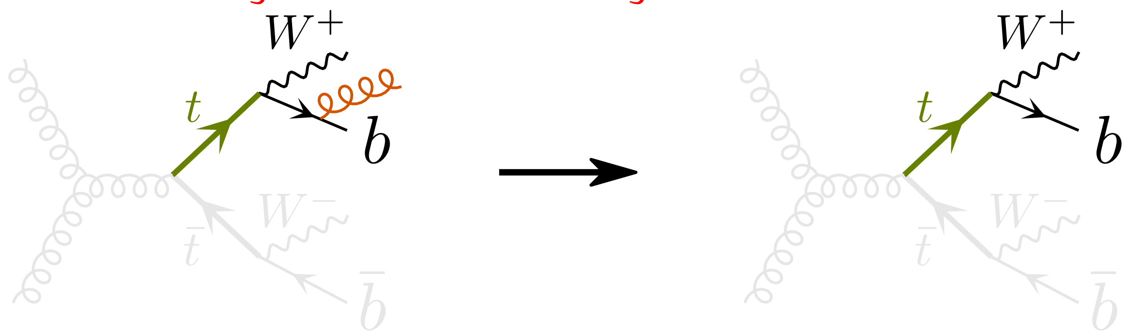
- In standard formulation of the POWHEG method:
  - $n+1 \leftrightarrow n$ mapping doesn't preserve top virtuality
  - Leading to unphysical suppression away from collinear singularities
  - Only one hardest emission is kept

NLO+PS à la POWHEG

Only radiation in decay is concerned!



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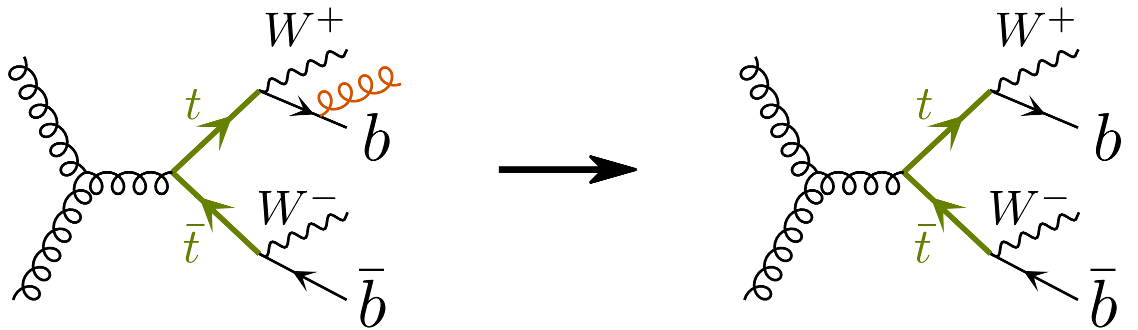
NLO+PS à la POWHEG RES

[TJ, P. Nason 2015]



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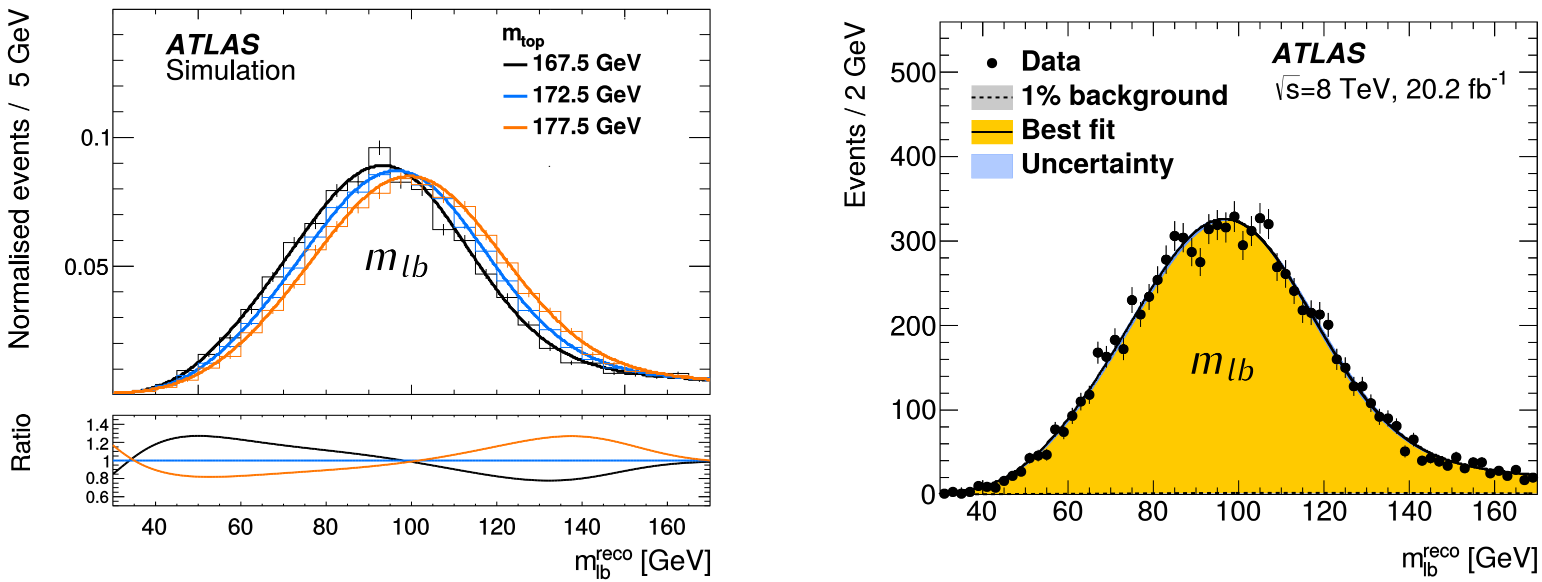
- In new “resonance-aware” formulation of the POWHEG method:
  - $n+1 \leftrightarrow n$ mapping preserves top virtuality
  - No unphysical distortions of the top line shape
  - Keeps multiple emissions: from production and each resonance

Accuracy of $t\bar{t}$ generators

- Are our theory predictions accurate enough?
  - Top-quark reconstruction heavily relies on Monte Carlo generators
  - m_T determinted by a fit to a template
  - Is uncertainity due to modelling properly taken into account?
- $pp \to \ell^+ \nu_\ell \, l^- \bar{\nu}_l \, b \, \bar{b}$ analysis [TOPQ-2016-03]:



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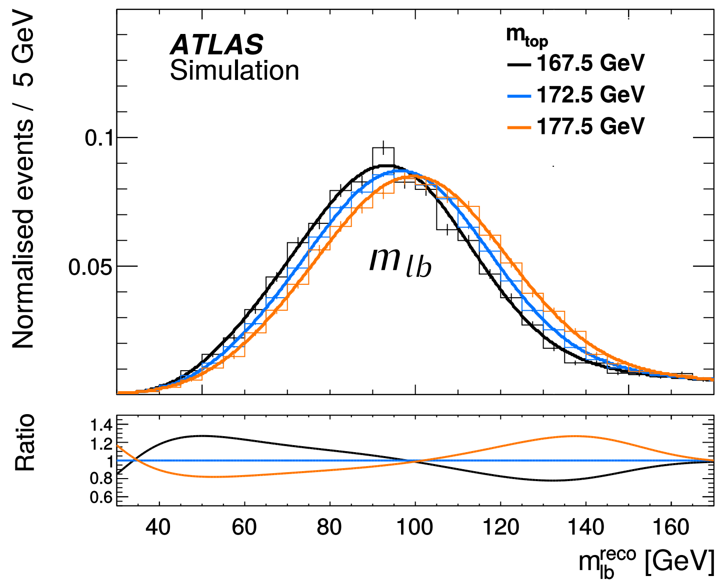
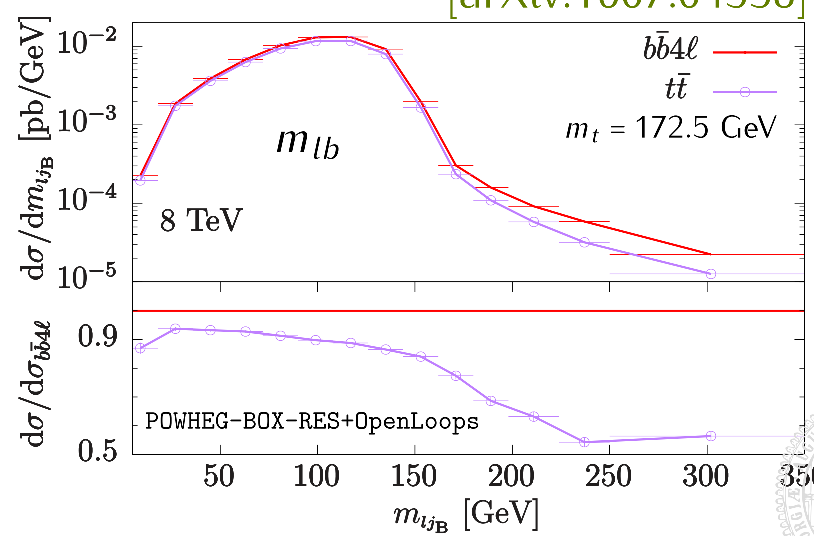
[arXiv:1607.04538]





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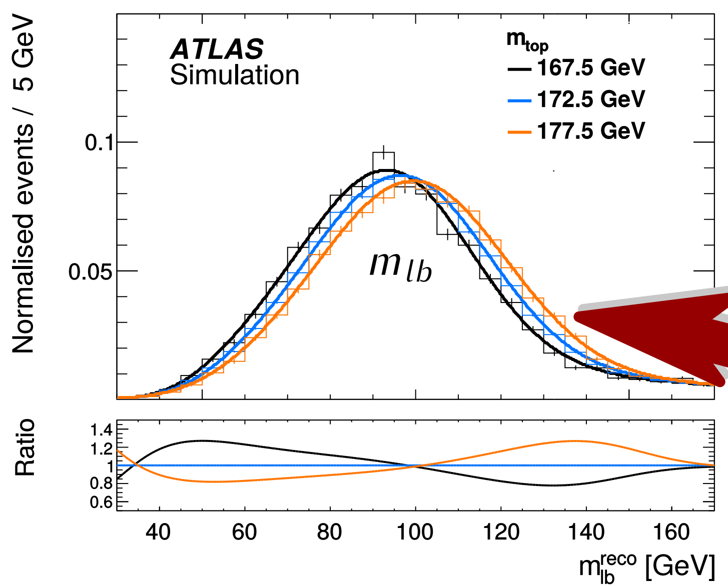

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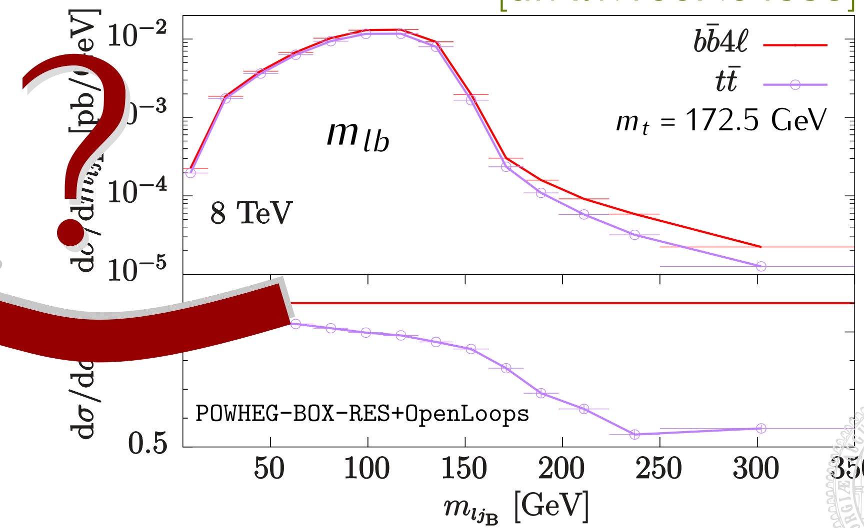

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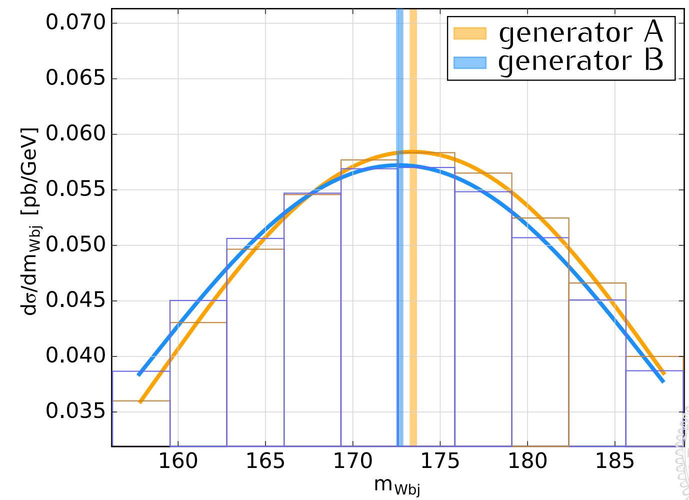
- Let's see:
  - Take Wb-jet system mass
  - Make a prediction with two generators (A and B) with $m_{\text{in}}^{\text{A}} = m_{\text{in}}^{\text{B}}$
  - Find the peaks at $m_{\text{out}}^{\text{A}}$, $m_{\text{out}}^{\text{B}}$ (e.g. using a polynomial fit)
  - Uncertainity: $|m_{\text{out}}^{\text{A}} - m_{\text{out}}^{\text{B}}|$



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- Let's see:
  - Take another observable
  - Generate pseudo data with generator A with m_{in}^{A}
  - Prepare templates with generator B for several m_{in}^{B}
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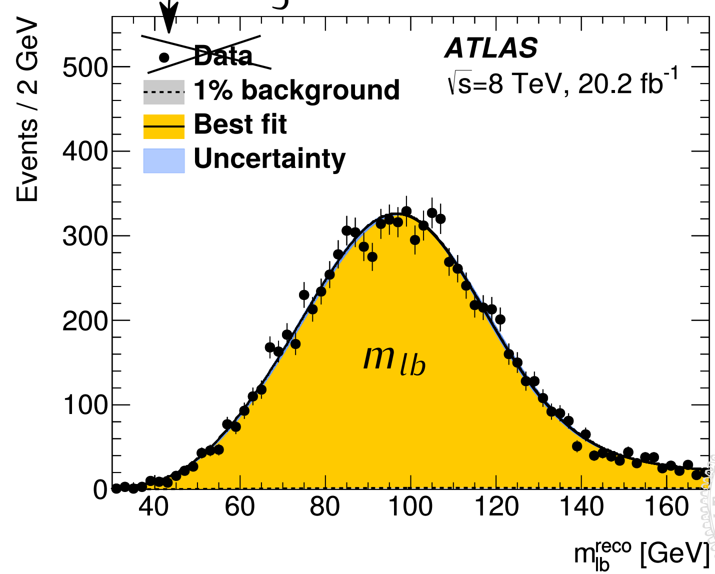
  - Uncertainity: $|m_{\text{in}}^{\text{A}} - m_{\text{fit}}^{\text{B}}|$

prediction from
generator A



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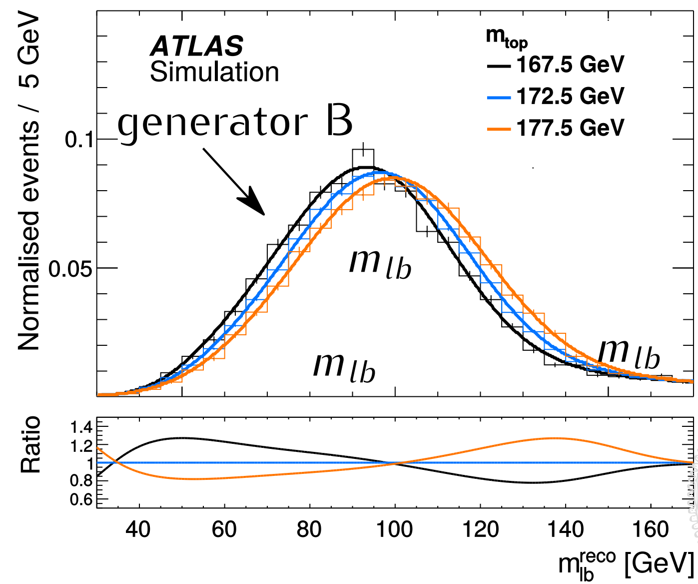

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- In the search for an answer we look at in [arXiv:1801.03944]:
  - Three generators implementing an increasingly precise treatment of $t\bar{t}$ production and decay in the di-lepton channel
  - Two SMCs: Pythia8.2 [Sjöstrand et al. 2014], Herwig7.1 [Bellm et al. 2015]
  - Observables:
    - Peak position of the Wb-jet system mass specturm
    - b-jet energy spectrum [Agashe et al. 2016]
    - Mellin moments of lepton spectra [Frixione et al. 2014]

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  - Observables:
    - Peak position of the Wb-jet system mass specturm
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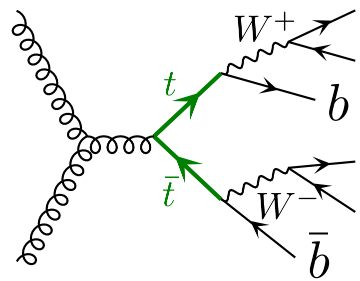
    - Mellin moments of lepton spectra [Frixione et al. 2014]

POWHEG $t\bar{t}$ NLO+PS generators

- `POWHEG-BOX/hvq` or *hvq* [Frixione, Nason, Ridolfi, 2007]



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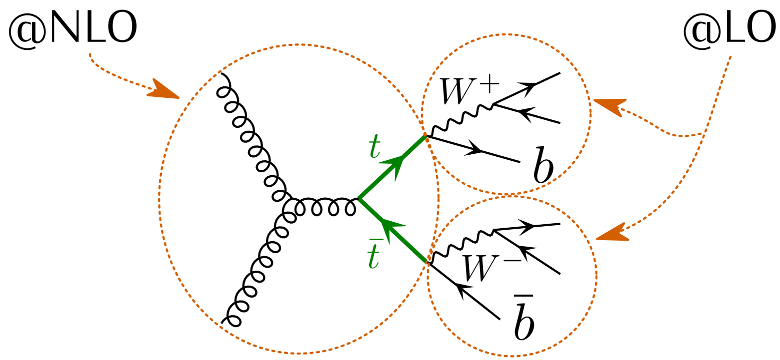

  - $t\bar{t}$ production at NLO
  - No NLO corrections in decays (radiation from b only by PS)
  - Spin correlations and off shell effects approximate
  - Includes hadronic W decays

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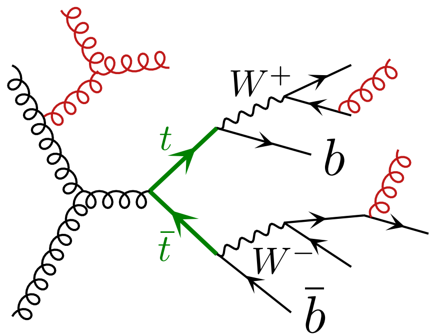

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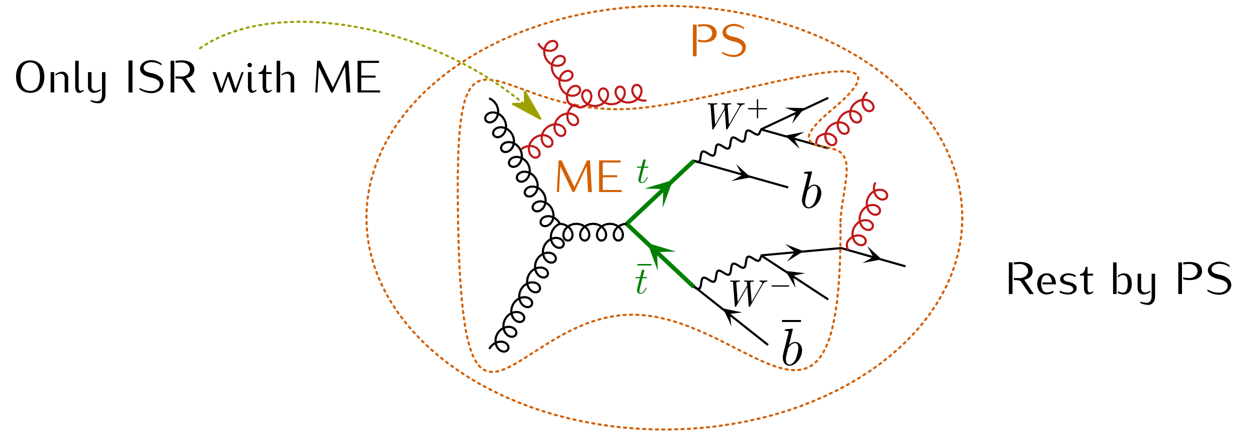

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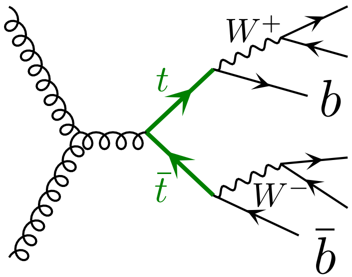
- POWHEG-BOX/ttb_NLO_dec or $t\bar{t}dec$ [Campbell, Ellis, Nason, Re, 2014]



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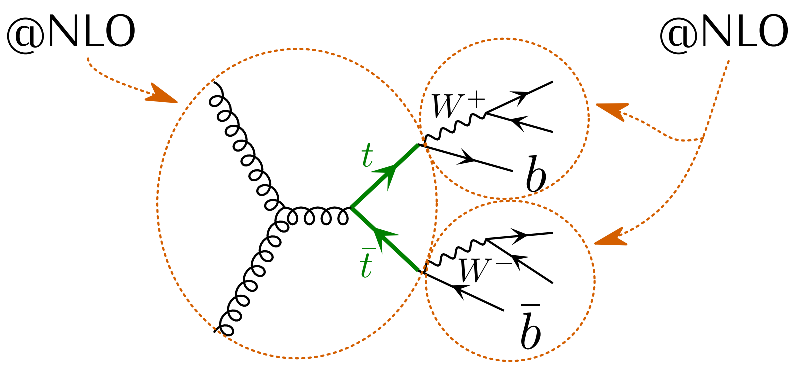

  - $t\bar{t}$ production at NLO
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  - Exact spin correlations and LO exact off shell effects
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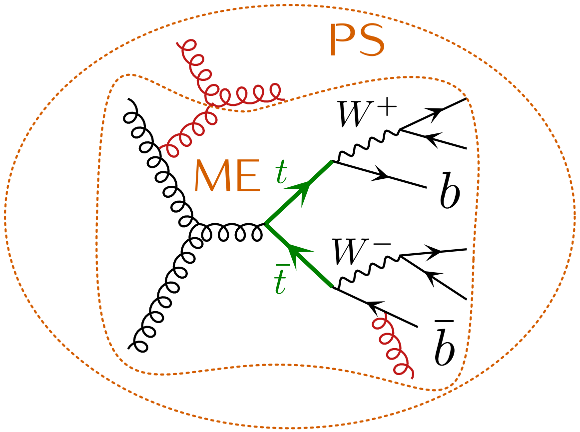

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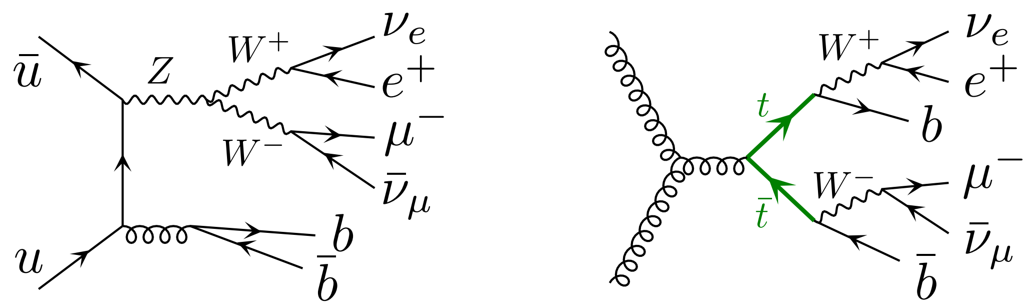
POWHEG $t\bar{t}$ NLO+PS generators

- `POWHEG-BOX-RES/bb4l` or $b\bar{b}4l$ [TJ, Lindert, Nason, Oleari, Pozzorini, 2016]



  - $pp \to \ell^+ \nu_\ell \, l^- \bar{\nu}_l \, b \, \bar{b}$ production at NLO
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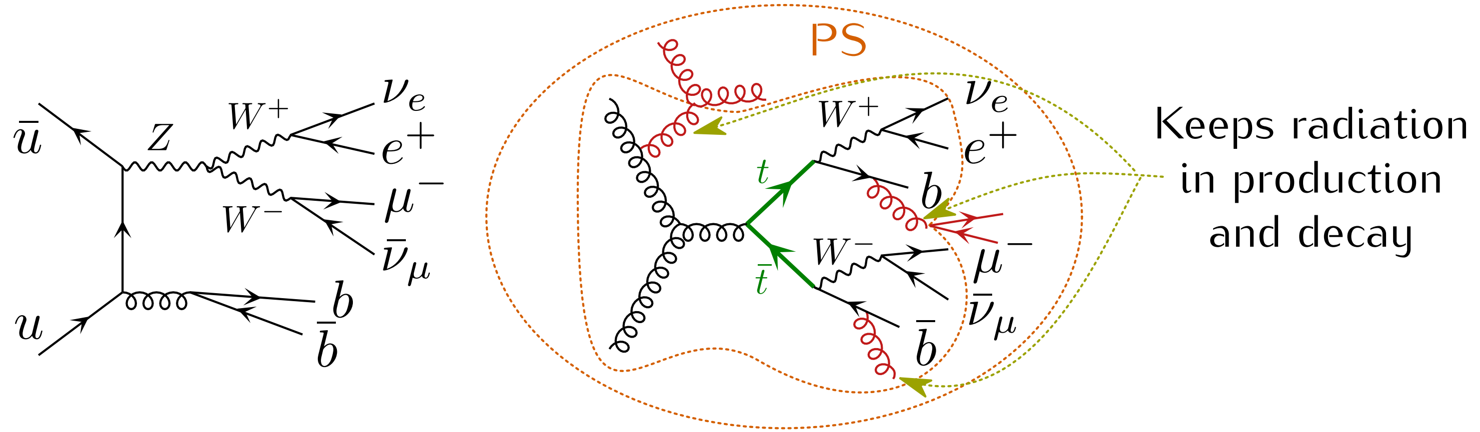

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POWHEG $t\bar{t}$ NLO+PS generators

	hvq	$t\bar{t}dec$	$b\bar{b}4l$
NLO in production	yes	yes	yes
NLO in decay	no	yes	yes
Radiation off b-quarks from tops	SMC	ME	ME
Spin correlations	approximate	yes	yes
Off shell effects	approximate	LO	yes
Production/decay interference	no	no	yes
Hadronic W decays	yes	yes	no

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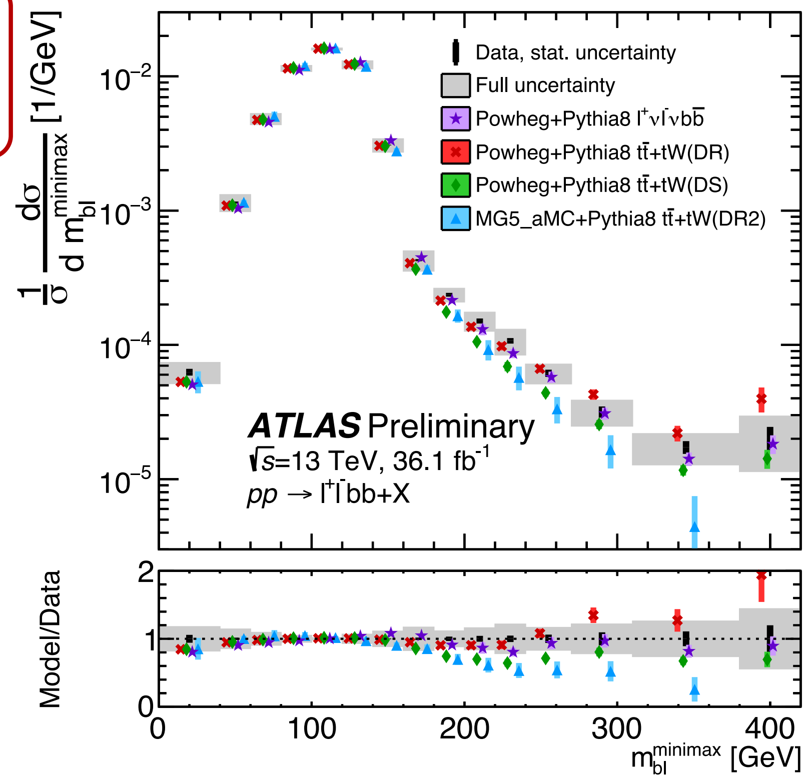
`POWHEG-BOX-V2` $t\bar{t}$

bb4l in action

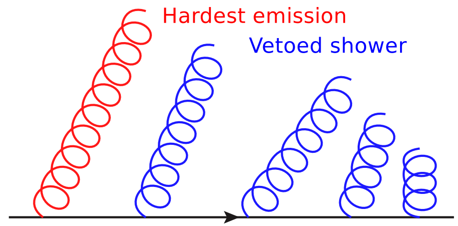
The unfolded results

- Powheg-Pythia8 lvlvbb describes the data well across the full spectrum
- Powheg+Pythia8 (hvq) models the ttbar core well, but…
  - In tail, the DR and DS predictions diverge
  - Consistent with data at ~2σ level
  - Difference brackets the data for most bins
- DR2 significantly under-predicts data in the tail

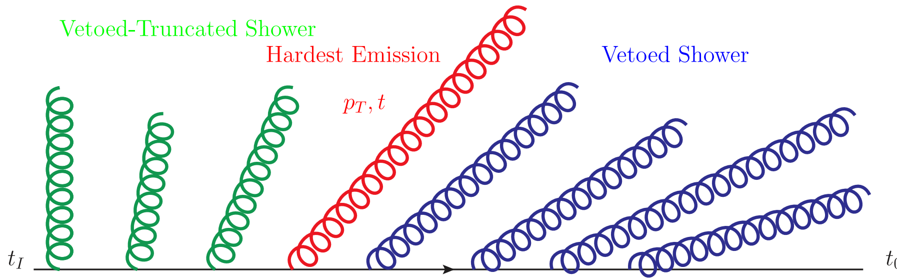


Shower Monte Carlo programs

- `Pythia8.2`: $k_\perp$-ordered shower, natural for matching with POWHEG



- `Herwig7.1`: angular-ordered shower, in principle requiring truncated showers

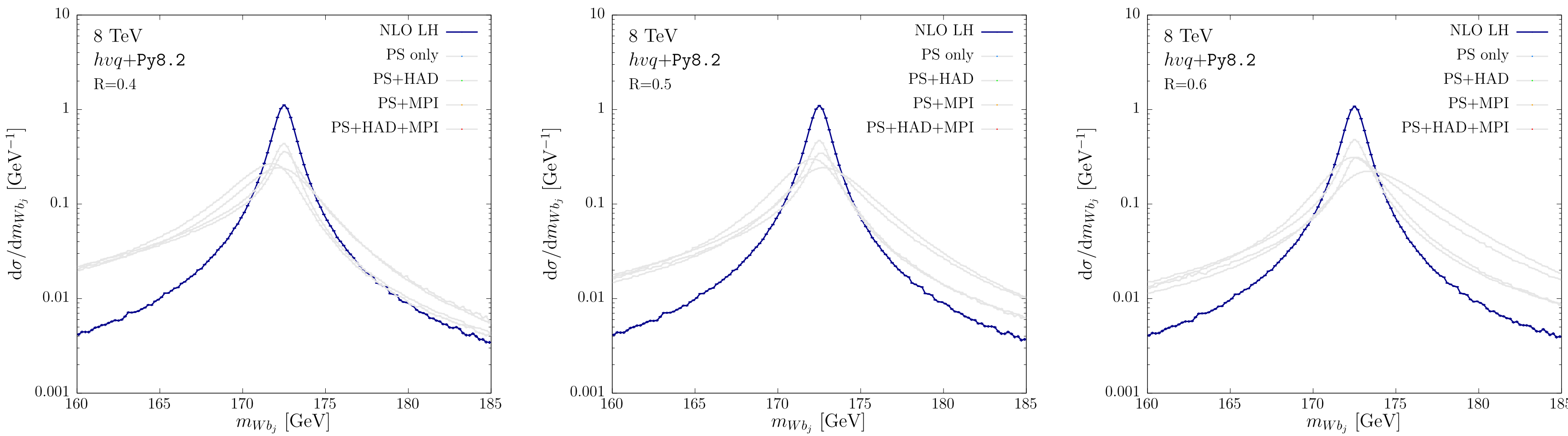


- Both require a custom interface to allow vetoing with multiple scales
  - `Pythia8.2`: `UserHooks::doVetoFSREmissions`
  - `Herwig7.1`: `FullShowerVeto::vetoShower`, `ShowerVeto::vetoTimeLike`

Results

- Our goal is to assess compatibility of the generators in terms of Wb-jet mass distribution peak position shifts with respect to the most precise one ($b\bar{b}4l$)
- Comparing generators we can learn whether:
  - Modelling of radiation from the b jet by SMCs is adequate
  - Interference effects in radiation from production and decay play a relevant role
- Peak positions are obtained through:
  - a.) ideal detector: a fit to a skewed Lorentzian
  - b.) including "detector effects": a fit of the distribution smeared by a Gaussian $\Delta = 15$ GeV to a skewed Lorentzian
- We also vary the perturbative scales, PDFs and the value of α_S: 7 point μ_r and μ_f variation, 30 PDF4LHC eigenvectors, PDFs with different values of α_S, respectively
- And compare the peak positions for different SMCs

Anatomy of the m_{Wj_B} peak



- Radiative corrections in decay (PS) enhance low-mass region
- Hadronization further enhance low-mass region and smear the peak
- MPI fills the high-mass tail
- Behaviour of each component is R dependent

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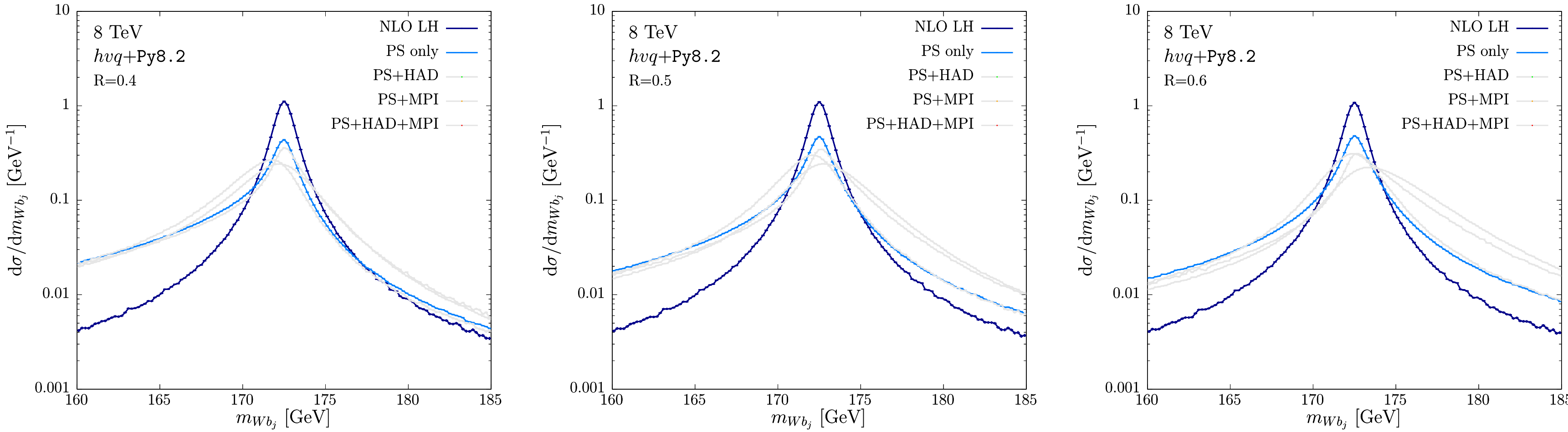

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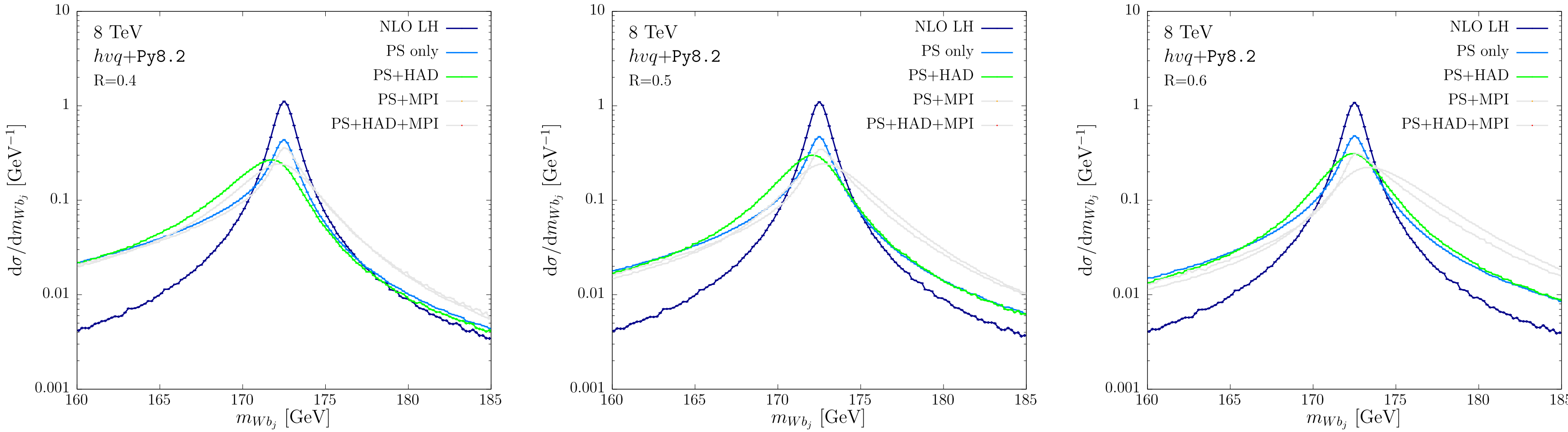

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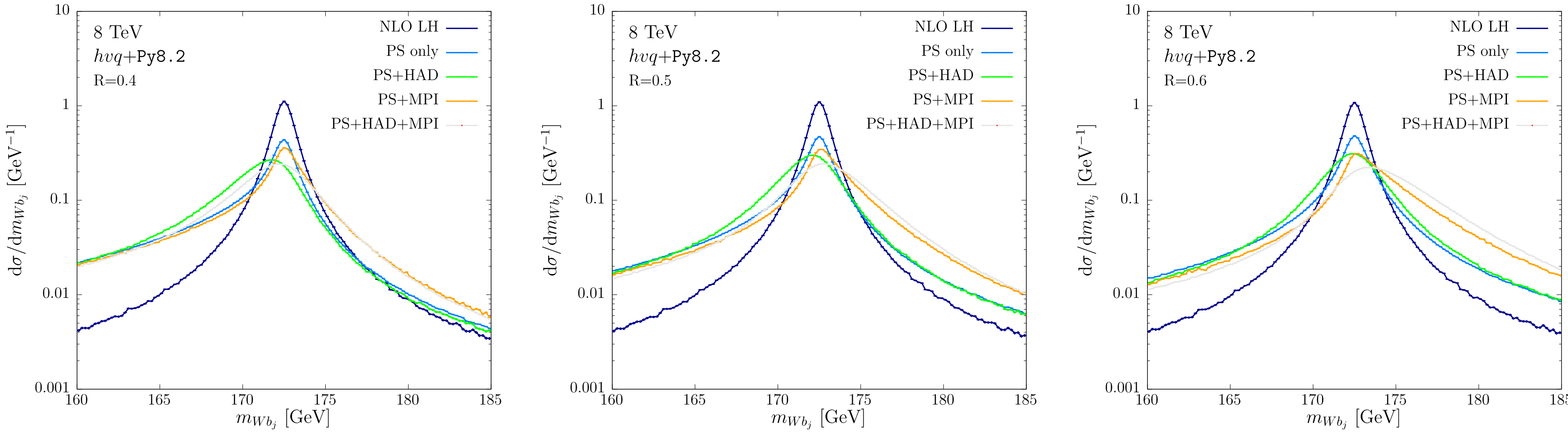

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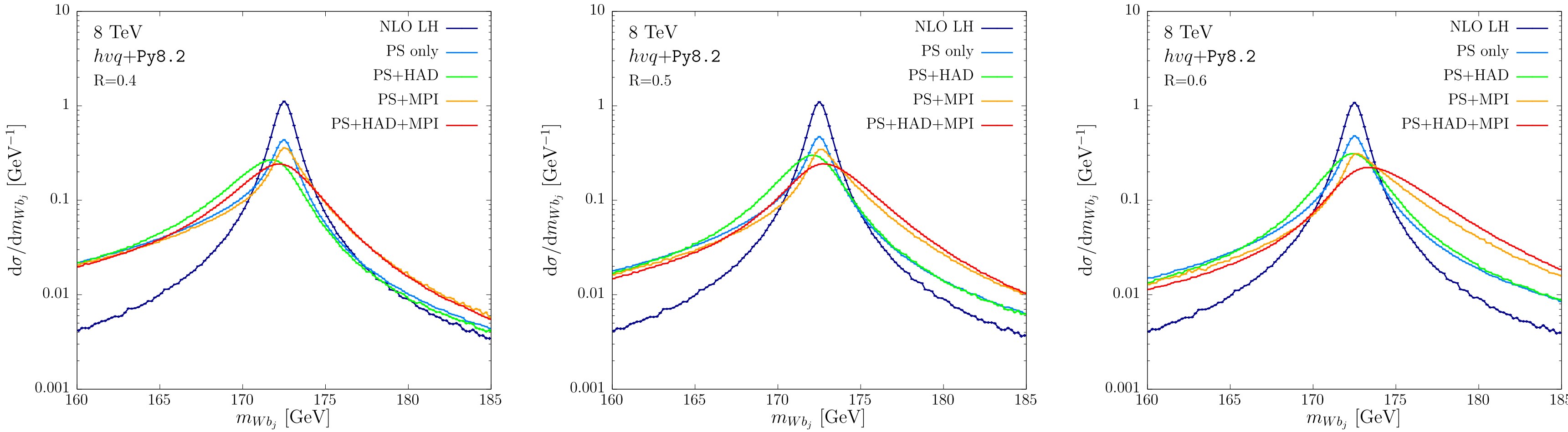

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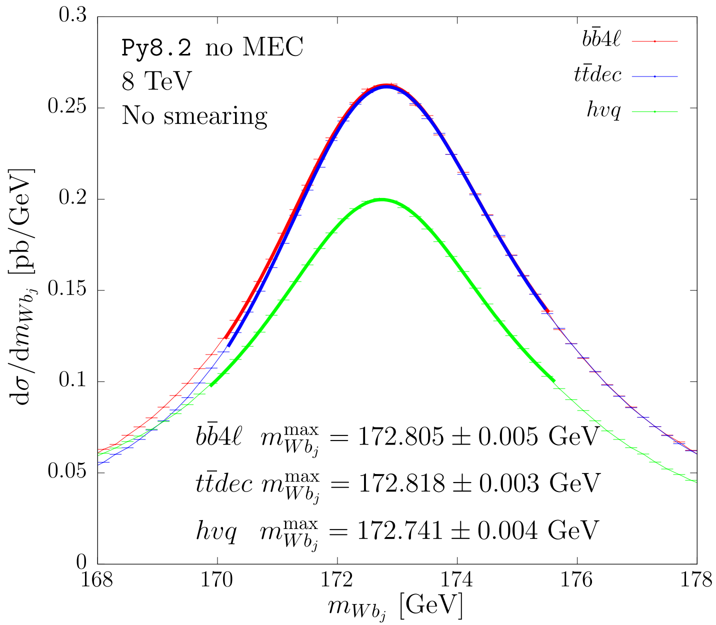
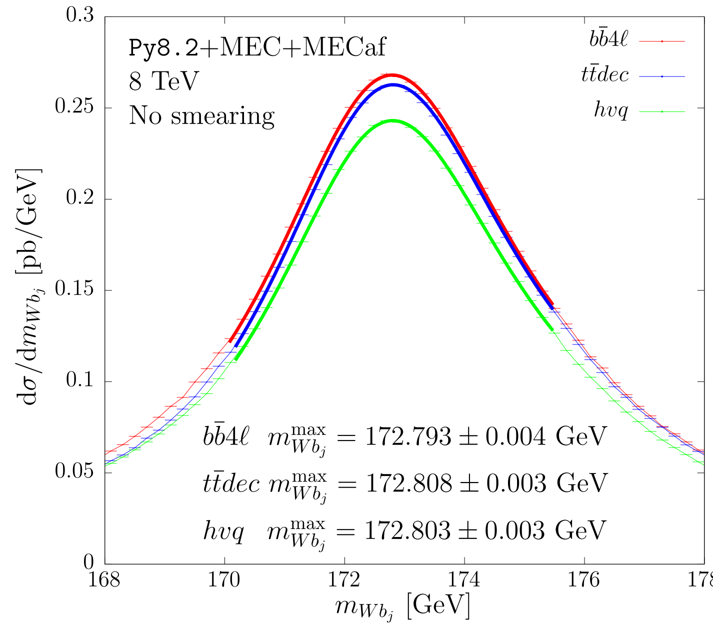
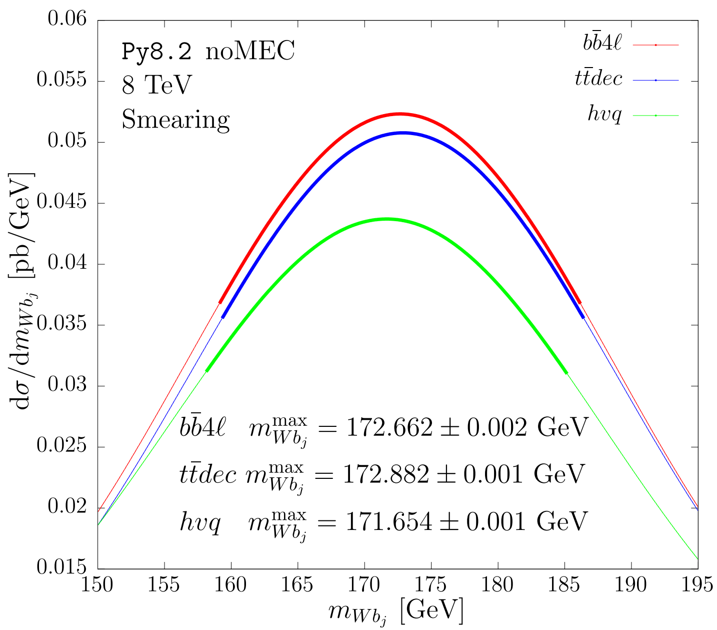
m_{Wj_B}: ideal detector

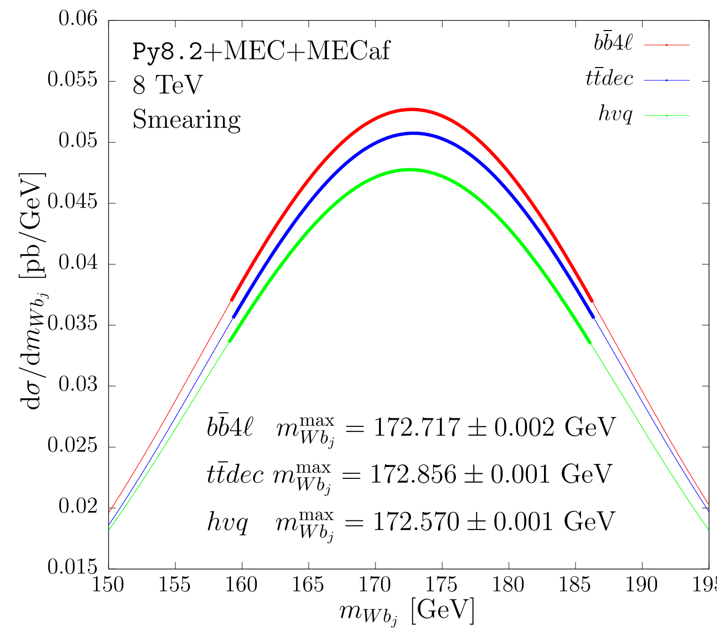




- A fit to skewed Lorentzian reveals:
  - Remarkable consistency between $b\bar{b}4l$ and $t\bar{t}dec$
  - Gentle shift of the hvq peak, of ~ $60MeV$, without MEC
  - MEC brings hvq impressively close to $b\bar{b}4l$
  - Consistency check: stability of $b\bar{b}4l$ and $t\bar{t}dec$ with respect to MEC

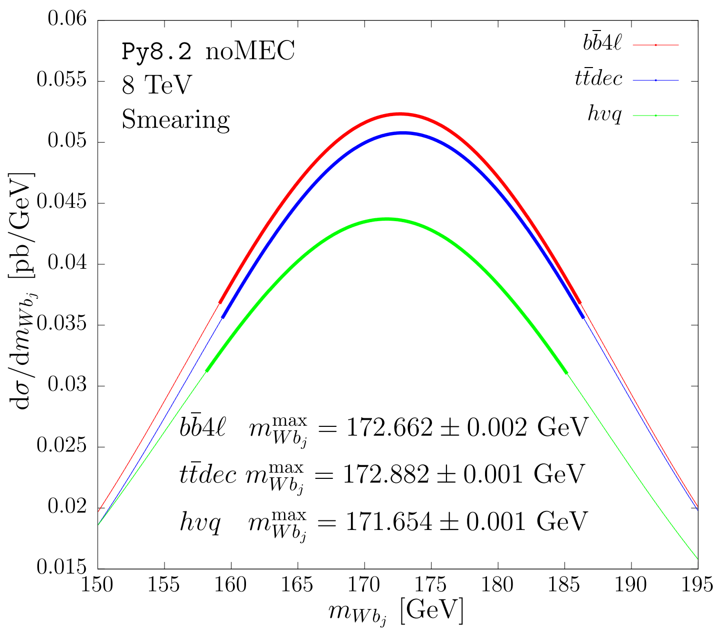
m_{Wj_B}: with "detector effects"

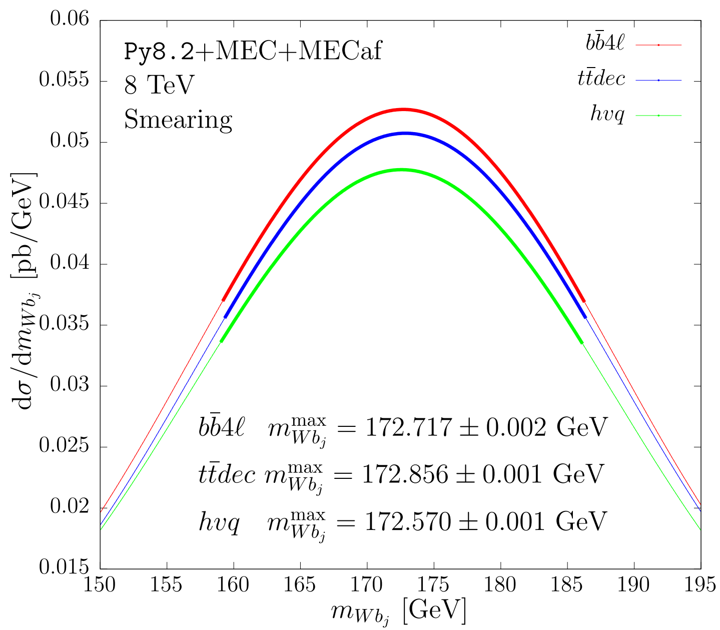




- A fit of the smeared m_{Wj_B} to a skewed Lorentzian reveals:
  - $t\bar{t}dec$ shift to $b\bar{b}4l$ of +140 MeV
  - hvq shift to $b\bar{b}4l$ of −147 MeV
  - All generators consistent with each other given current experimental precision

m_{Wj_B}: with "detector effects"



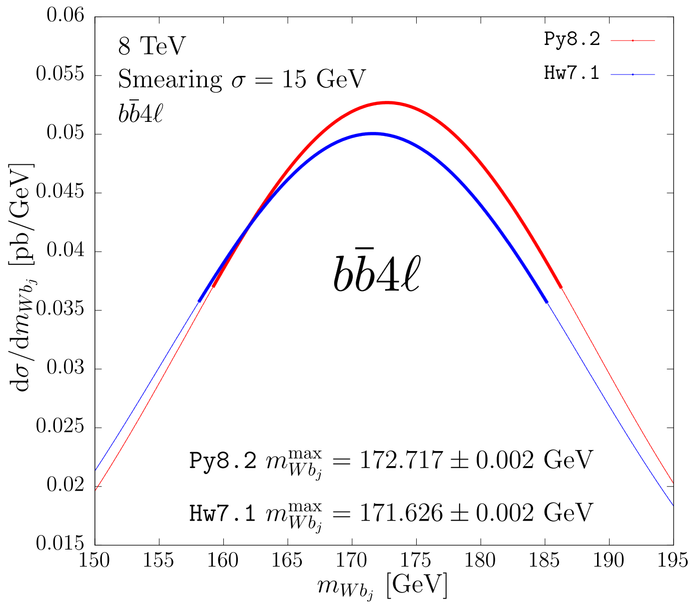


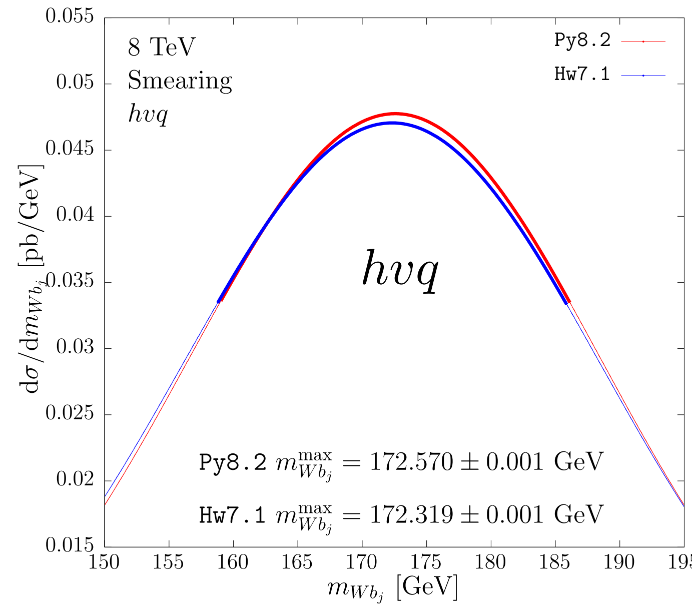
- Furthermore:

	% − $bb4\ell$	(μ_R, μ_F)	PDF	α_S
$b\bar{b}4\ell$	+0 MeV	$^{+86}_{-53}$ MeV	-	±64 MeV
$t\bar{t}dec$	**+140 MeV**	$^{+6}_{-6}$ MeV	-	±54 MeV
hvq	**−147 MeV**	$^{+7}_{-7}$ MeV	±5 MeV	±9 MeV

  - Only $b\bar{b}4l$ provides realistic scale variation uncertainity

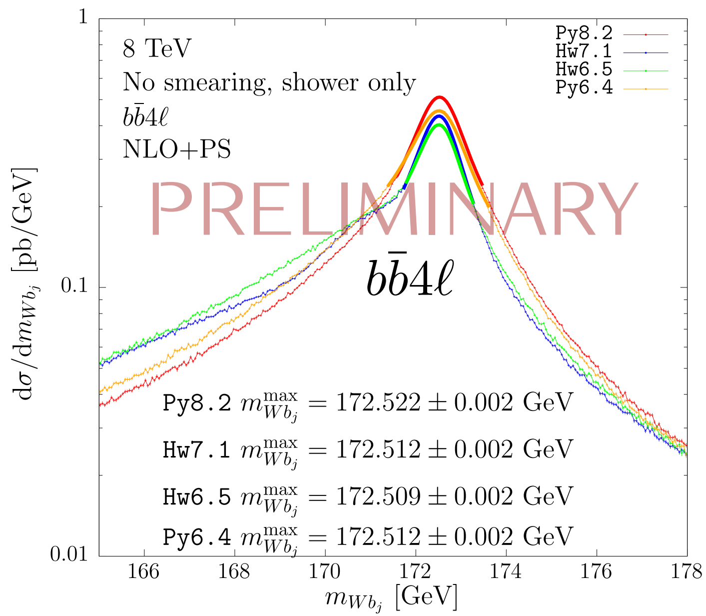
m_{Wj_B}: SMC comparison

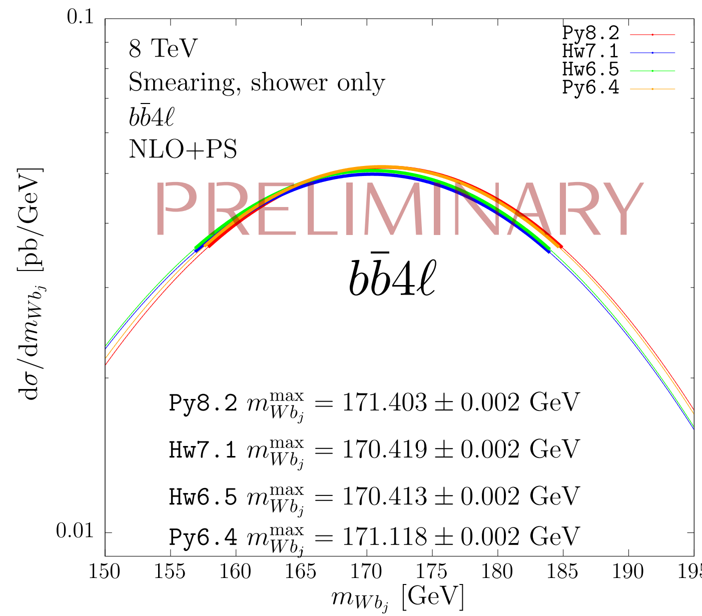




- *hvq*:
  - ~ 250 GeV shift, predictions consistent
  - description of radiation in decays by SMC (PS+MEC)
- $b\bar{b}4l$:
  - ~ 1 GeV shift
  - description of radiation in decays by ME

m_{Wj_B}: SMC comparison





- Note that the disagreement shows up at the PS level already
- Comparisons with "the older siblings":
  - Exhibit similar behaviour
  - `Pythia8.2`: dipole, `Pythia6`: $k_\perp$-ordered, `Herwig7.1/6`: angular-ordered

Summary

- Are our theory predictions accurate enough?
  - YES, if only using `Pythia8.2`
    - Wb-jet mass peak shifts under 200 MeV, even with smearing
    - `Pythia8.2` MEC do a great job eliminating a ~ 1 GeV shift
  - NO?, once `Herwig7.1` considered
    - hvq: predictions consistent, ~ 250 MeV shift
    - $b\bar{b}4l$ and $t\bar{t}dec$: dramatic shifts observed
- Do we understand the difference between `Pythia8.2` and `Herwig7.1`?
  - Both include MEC, we tried all available options in `Herwig7.1`
  - Angular ordered showers in princple require truncated shower but Seymour's prescription makes the agreement worse
  - Dipole shower kinematics (`Pythia8.2`) more reshuffling-stable than the angular shower ones (`Herwig7.1`)
  - Comparisons against `Pythia6`, `Herwig6` show the same trend
- Many more interesting results in [arXiv:1801.03944]

B-jet energy peaks

- Based on arxiv:1603.03445 (Agashe, Kim, Franceschini, Schulze).
- Investigated by CMS in [CMS-PAS-TOP-15-002], that finds

$$m_t = 172.29 \pm 1.17\,(\text{stat}) \pm 2.66\,(\text{syst})\ \text{GeV}\,.$$

- Purely hadronic observable, independent from the top production dynamics.
- At LO, neglecting off-shell effects, in the top frame we have:

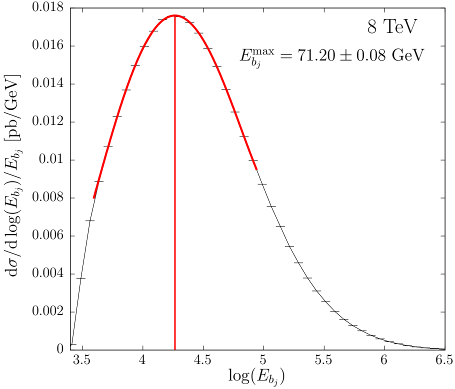
$$\boxed{E_{b_j} = \frac{m_t^2 - m_W^2}{2m_t}}\,.$$

- In the lab frame the distribution is squeezed, but the peak position does not vary.
- After the inclusion of perturbative and non-perturbative effects, for $m_t \approx m_{t,\,c}$, we have:

$$\boxed{E_{b_j}^{\max} = O_c + B(m_t - m_{t,\,c})}.$$

B-jet energy peaks

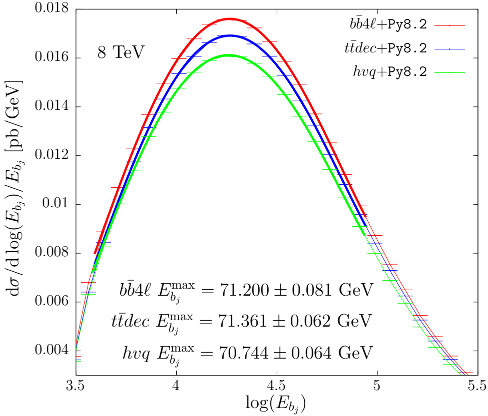
- We fit $\frac{d\,\sigma}{d\,\log E_{b_j}}\frac{1}{E_{b_j}}$ to a fourth order polynomial.



- We find $B \simeq \frac{1}{2} \Rightarrow \boxed{\Delta m_t \simeq -2\Delta E_{b_j}^{\max}}$.

B-jet energy peaks: which NLO generator?

- Large difference between $b\bar{b}4\ell$ and hvq ($\Delta E_{b_j}^{\max} \approx -0.5$ GeV, $\Delta m_t \approx 1$ GeV), but still well below the systematic error quoted by ATLAS (**2.66 GeV**).
- Small difference between $b\bar{b}4\ell$ and $t\bar{t}dec$.



Leptonic observables

- Based on arXiv:1407.2763 (Frixione, Mitov).
- Independent from non-perturbative physics effects.
- Similar analysis performed by ATLAS in arXiv:1709.09407, that finds

$$m_t = 173.2 \pm 0.9\,(\text{stat}) \pm 0.8\,(\text{syst}) \pm 1.2\,(\text{theo})\ \text{GeV}\,.$$

- Measure $\langle O_i \rangle$ for several O_i:

$$\left\{ p_\perp(\ell^+),\, p_\perp(\ell^+\ell^-),\, m(\ell^+\ell^-),\, (E(\ell^+)+E(\ell^-)),\, (p_\perp(\ell^+)+p_\perp(\ell^-)) \right\}\,.$$

- Assume $\langle O_i \rangle = O_{\text{c},i} + B_i(m_t - m_{t,c})$, where $O_{\text{c},i}$ and B_i can be determined with a MC generator.
- Assuming $\langle O_i \rangle^{\text{exp}} = O_{\text{c},i}^{b\bar{b}4\ell}$, we extract $m_{t,i}$ and $\Delta m_{t,i}$ (due to statistical, scale, PDF etc. variations).

Leptonic observables

- *hvq* not able to describe observables depending on spin-correlation effects.
- The theoretical error (scale and PDF) we found (0.8 GeV) similar to the one found by ATLAS (1.2 GeV).