New results for precision Higgs Physics

Zoltán Trócsányi

University of Debrecen and MTA-DE Particle Physics Research Group
in collaboration with
A. Kardos, M.V. Garzelli

Loops and Legs in Quantum Field Theory, Weimar
April 29, 2014

NEW SZÉCHENYI PLAN

LHCphenOnet

Precision tools for Higgs Physics with PowHel

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Outline

- Motivation
- Method
- Predictions
- Conclusions and Plans

Motivation

Higgs boson discovered at the LHC

- m_H [GeV]=$125.5 \pm 0.2_{stat} \pm 0.6_{syst}$ (ATLAS 2013)
  $125.7 \pm 0.3_{stat} \pm 0.3_{syst}$ (CMS 2013)

- All measured properties are consistent with SM expectations within experimental uncertainties
  - branching ratios as predicted
  - spin zero
  - parity +
  - couples to masses of W and Z (with c_V=1 within experimental uncertainty)

t-quark: potential tool for discovery

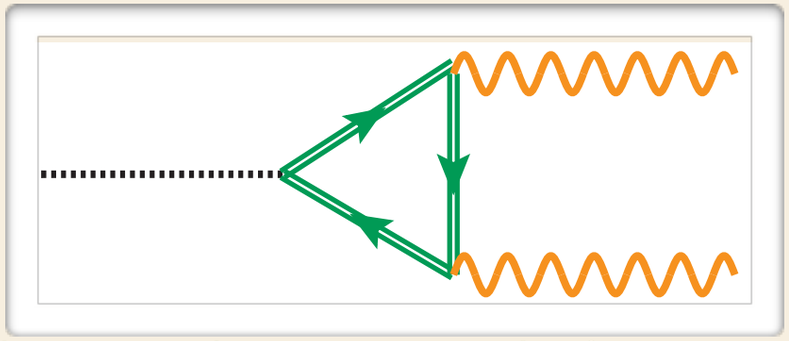
- The t-quark is heavy, Yukawa coupling ~1
  m_t [GeV]=173.34±0.64 (LHC+TeVatron, 2014)
  ($\Rightarrow y_t$=0.997±0.003)

  $\Rightarrow$ plays important role in Higgs physics
  (more tantalizing: $m_t\, m_Z = (125.7\pm0.3)^2$ GeV^2)
- y_t cannot be measured in $H \to tT$ decay ($m_t > m_H$)

How to measure y_t?

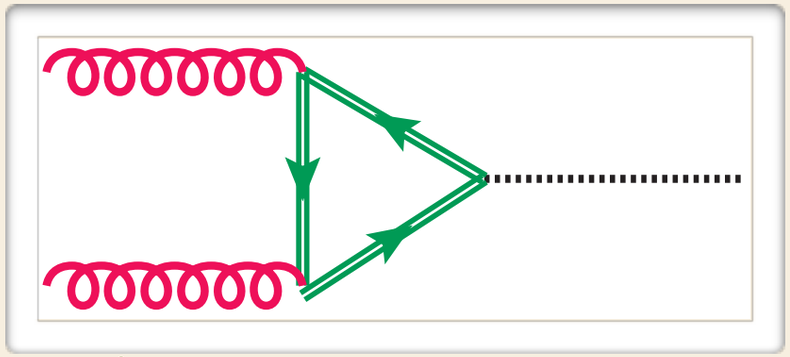
- $H \to \gamma\gamma$ is sensitive to y_t through t-quark loop,

  but rates are small and W loop also contributes



- $gg \to H$ is sensitive to y_t through t-quark loop

  if only SM model particles contribute (so far xsec is consistent with SM)

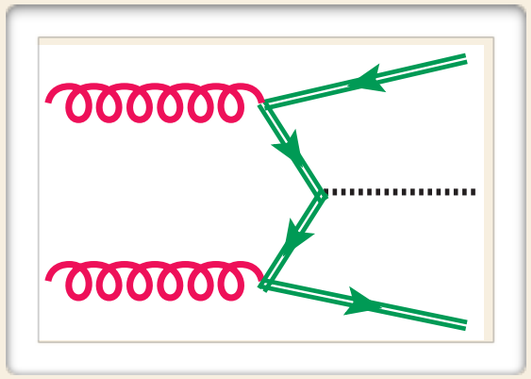


- $gg \to H$ is sensitive to BSM physics

  if y_t is measured separately

tTH hadroproduction

- y_t can be measured in pp $\rightarrow$ tTH through many decay channels (all very difficult):



  - hadrons with single lepton: $\mathrm{t} \rightarrow \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}jj,\ \mathrm{H} \rightarrow \mathrm{b}\bar{\mathrm{b}}$
  - hadrons with dilepton: $\mathrm{t} \rightarrow \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}\ell\nu,\ \mathrm{H} \rightarrow \mathrm{b}\bar{\mathrm{b}}$
  - hadrons with hadronic tau: $\mathrm{t} \rightarrow \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}jj,\ \mathrm{H} \rightarrow \tau_h^+\tau_h^-$
  - diphoton with lepton: $\mathrm{t} \rightarrow \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}jj,\ \mathrm{H} \rightarrow \gamma\gamma$
  - diphoton with hadrons: $\mathrm{t} \rightarrow \mathrm{b}\ jj,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}jj,\ \mathrm{H} \rightarrow \gamma\gamma$
  - same sign dilepton: $\mathrm{t} \rightarrow \mathrm{b}\ jj,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}jj,\ \mathrm{H} \rightarrow \ell\nu\ell[\nu]$
  - 3 leptons with di, trilepton: $\mathrm{t} \rightarrow \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}jj,\ \mathrm{H} \rightarrow \ell[\nu]\ell[\nu]$
  - 4 lepton with di, trilepton: $\mathrm{t} \rightarrow \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \rightarrow \bar{\mathrm{b}}\ell[\nu],\ \mathrm{H} \rightarrow \ell[\nu]\ell[\nu]$

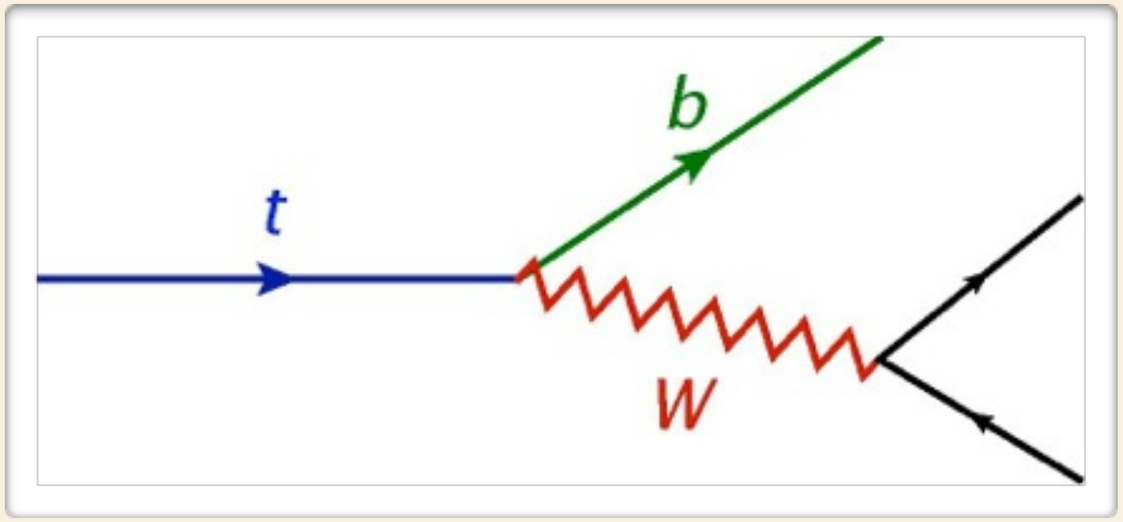
The importance of being top

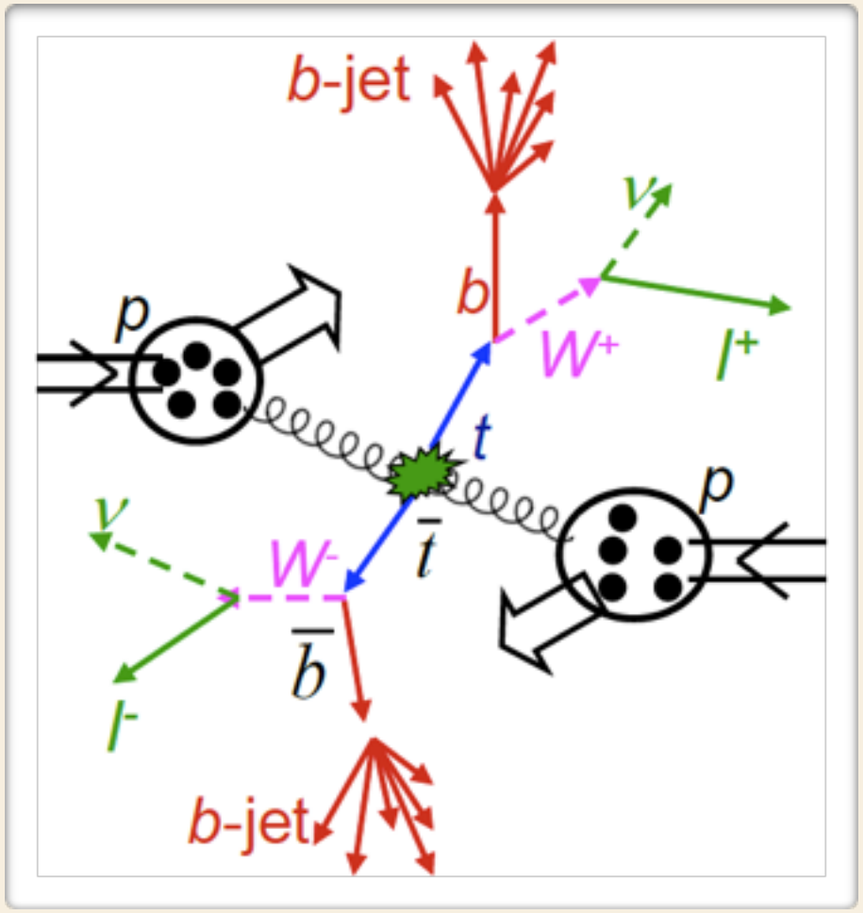
These require precise predictions of distributions at hadron level for

pp →tT+hard X, X = H,W,Z,γ,j,bB,2j...

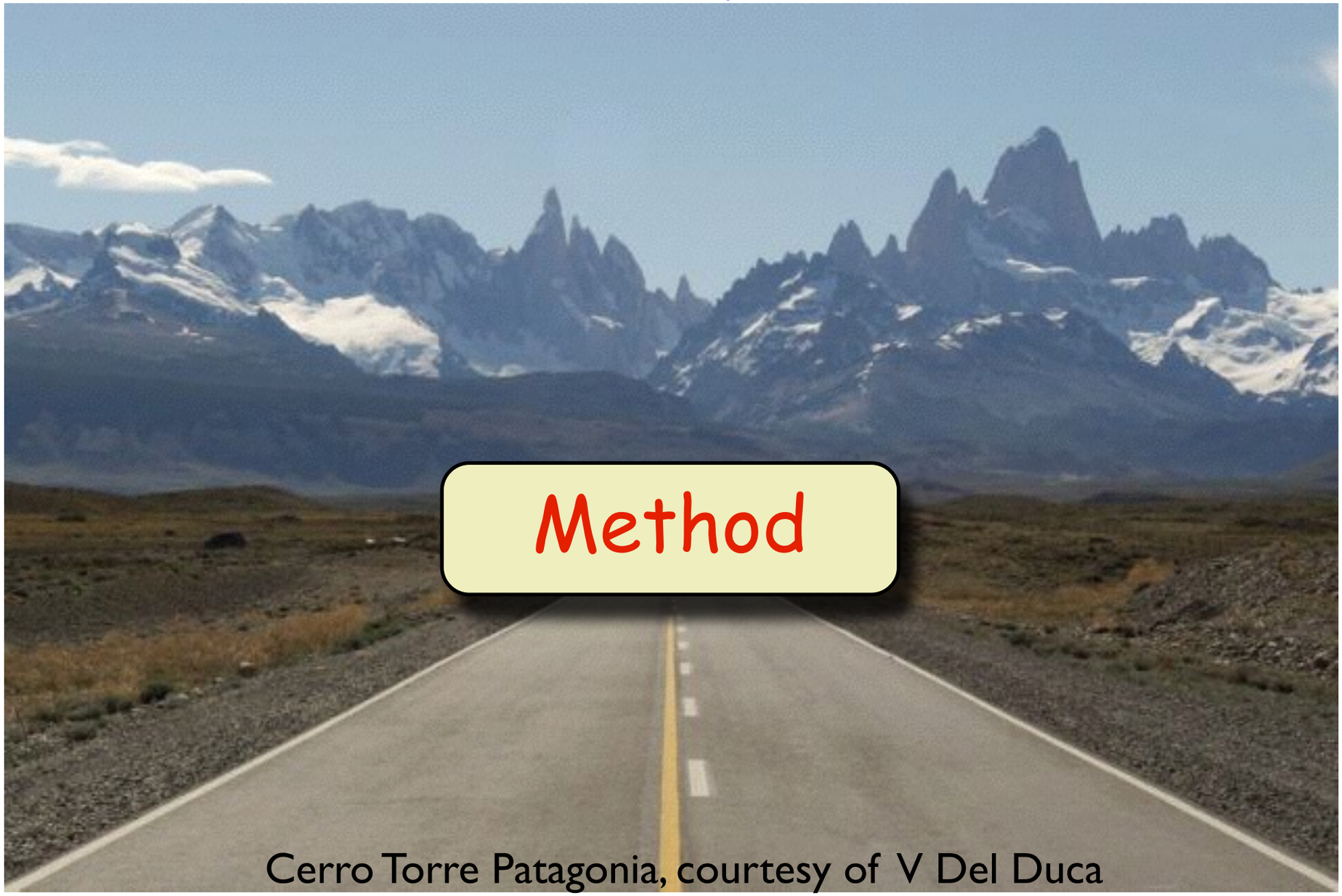
...with decays: the t-quark is not detected because it decays before hadronization

$$|V_{tb}|^2 \gg |V_{ts}|^2,\ |V_{td}|^2$$





...to distributions, full of pitfalls & difficulties



Cerro Torre Patagonia, courtesy of V Del Duca

There is a long way from loops and legs...

From standard SMC to POWHEG MC

SMC idea: use probabilistic picture of parton splitting in the collinear approximation, iterate splitting to high orders

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$$\mathrm{d}\sigma_{\mathrm{SMC}} = B(\Phi_n)\mathrm{d}\Phi_n \left[\Delta_{\mathrm{SMC}}(t_0) + \Delta_{\mathrm{SMC}}(t) \underbrace{\frac{\alpha_{\mathrm{s}}(t)}{2\pi}\,\frac{1}{t}\,P(z)}_{= \lim\limits_{k_\perp \to 0} R(\Phi_{n+1})/B(\Phi_n)} \Theta(t-t_0)\,\mathrm{d}\Phi_{\mathrm{rad}}^{\mathrm{SMC}} \right]$$

$$\int B(\Phi_n)\mathrm{d}\Phi_n = \sigma_{\mathrm{LO}}$$

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- POWHEG MC first emission:

$$\mathrm{d}\sigma = \bar{B}(\Phi_n)\mathrm{d}\Phi_n \left[\Delta(\Phi_n, p_\perp^{\min}) + \Delta(\Phi_n, k_\perp) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Theta(k_\perp - p_\perp^{\min})\,\mathrm{d}\Phi_{\mathrm{rad}} \right]$$

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \Big[R(\Phi_{n+1}) - A(\Phi_{n+1}) \Big] \mathrm{d}\Phi_{\mathrm{rad}}$$

[Frixione, Nason, Oleari arXiv: 0709.2092]

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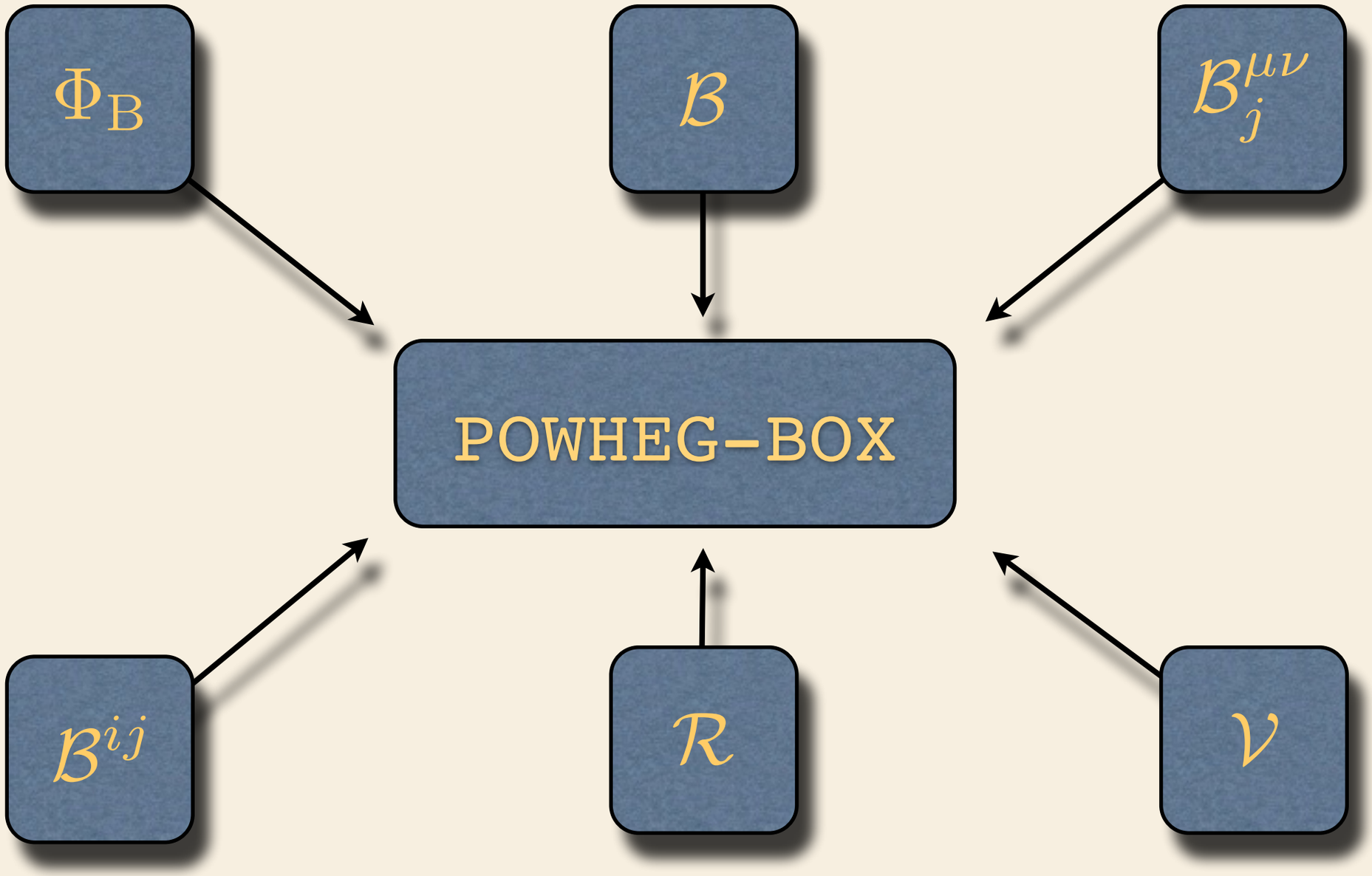
POWHEG-BOX framework



PowHel framework

HELAC-NLO

[Bevilaqua et al, arXiv: 1110.1499]

POWHEG-BOX

[Alioli, Nason, Oleari, Re, arXiv: 1002.2581]

PowHel

RESULT of PowHel:

Les Houches file of Born and Born+1st radiation events (LHE) ready for processing with SMC followed by almost arbitrary experimental analysis

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- Hadrons in final state
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  ...but we deliver the events on request

tTbB production

Choice of scales

- QCD corrections are
  - large with scales $\mu_0 = m_t$ or $m_t+m_{b\bar{b}}/2$ (about 80%)
  - moderate with dynamical scale $\mu_0=(m_t^2\, p_{T,b} p_{T,\bar{b}})^{1/4}$ (about 25%) (proposed by Bredenstein et al in arXiv:1001.4006), implying better convergence by emulating higher order effects through CKKW-type scale choice

Choice of scales

- QCD corrections are
  - large with scales $\mu_{fix} = m_t$ or $m_t + m_{b\bar{b}}/2$ (about 70%)
  - moderate with dynamical scale $\mu_{dyn} = (m_t^2\, p_{T,b} p_{T,\bar{b}})^{1/4}$ (about 25%) (proposed by Bredenstein et al in arXiv:1001.4006), implying better convergence by emulating higher order effects through CKKW-type scale choice,

but

  - we simulate higher order effects through the PS: μ_{dyn} is too small near threshold where cross section is largest, even for a b with p_T = 100 GeV and another b with p_T = 20 GeV μ_{dyn} = 90 GeV << m_t resulting in an artificially large xsection at LO

Choice of scales

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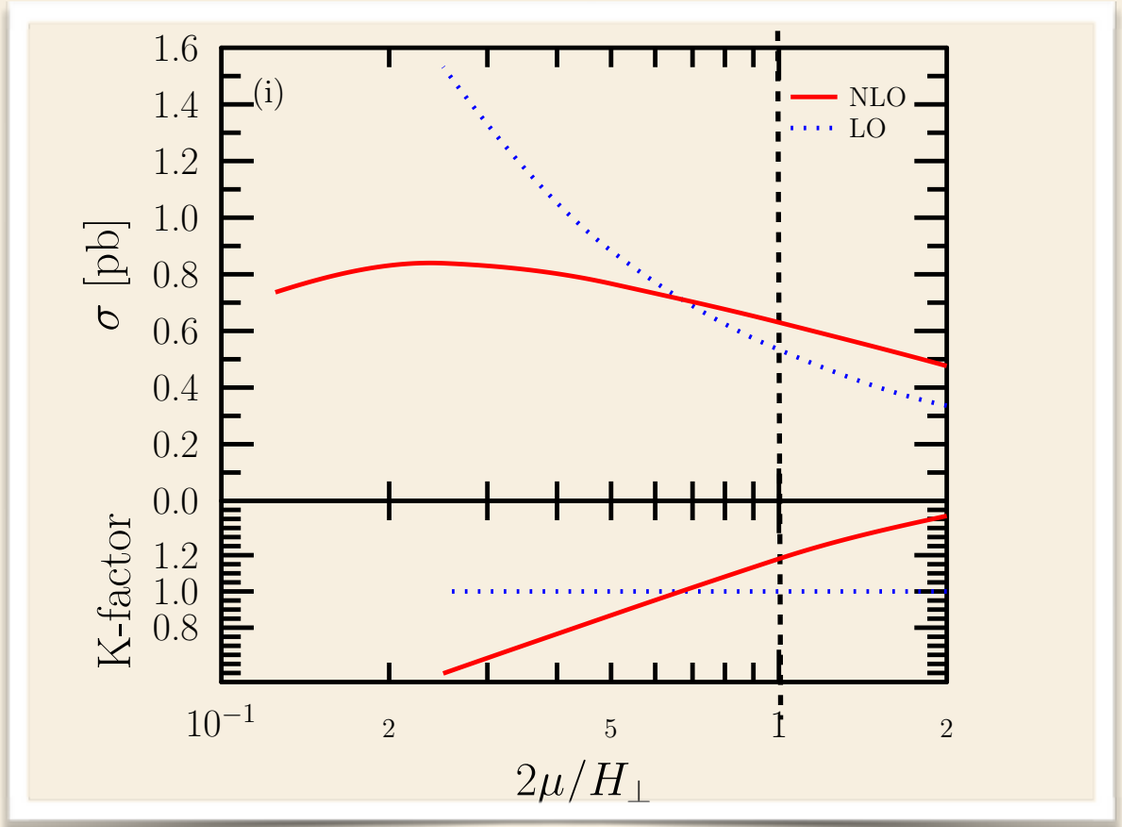
✓ the K factor is even smaller, implying good convergence



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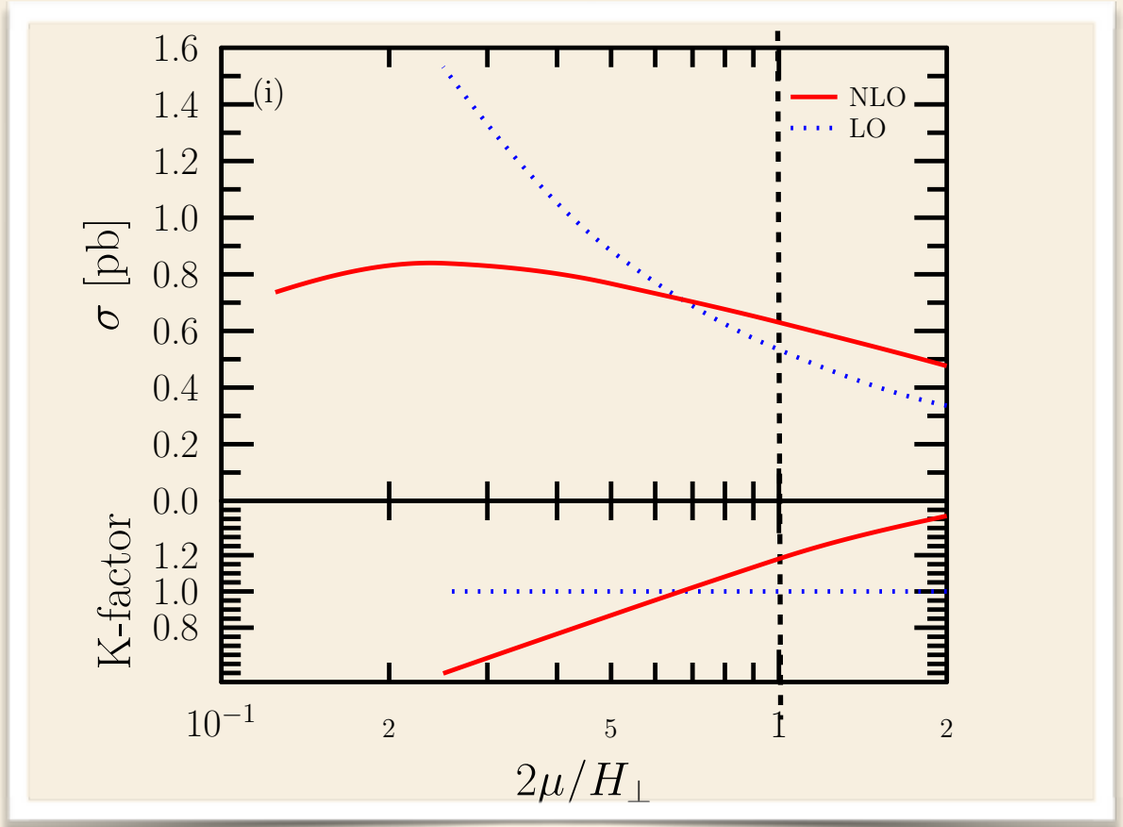

σ_{LO} = 534 fb, σ_{NLO} = 630 fb, K = 1.18

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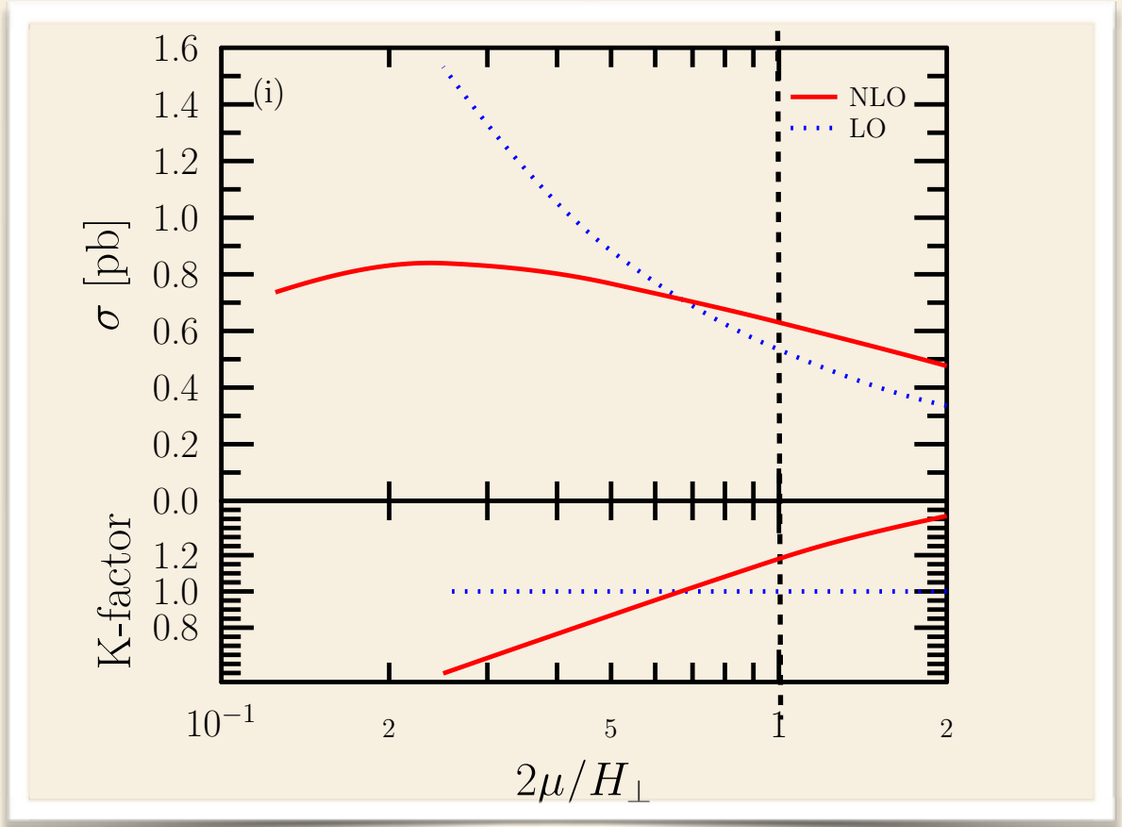

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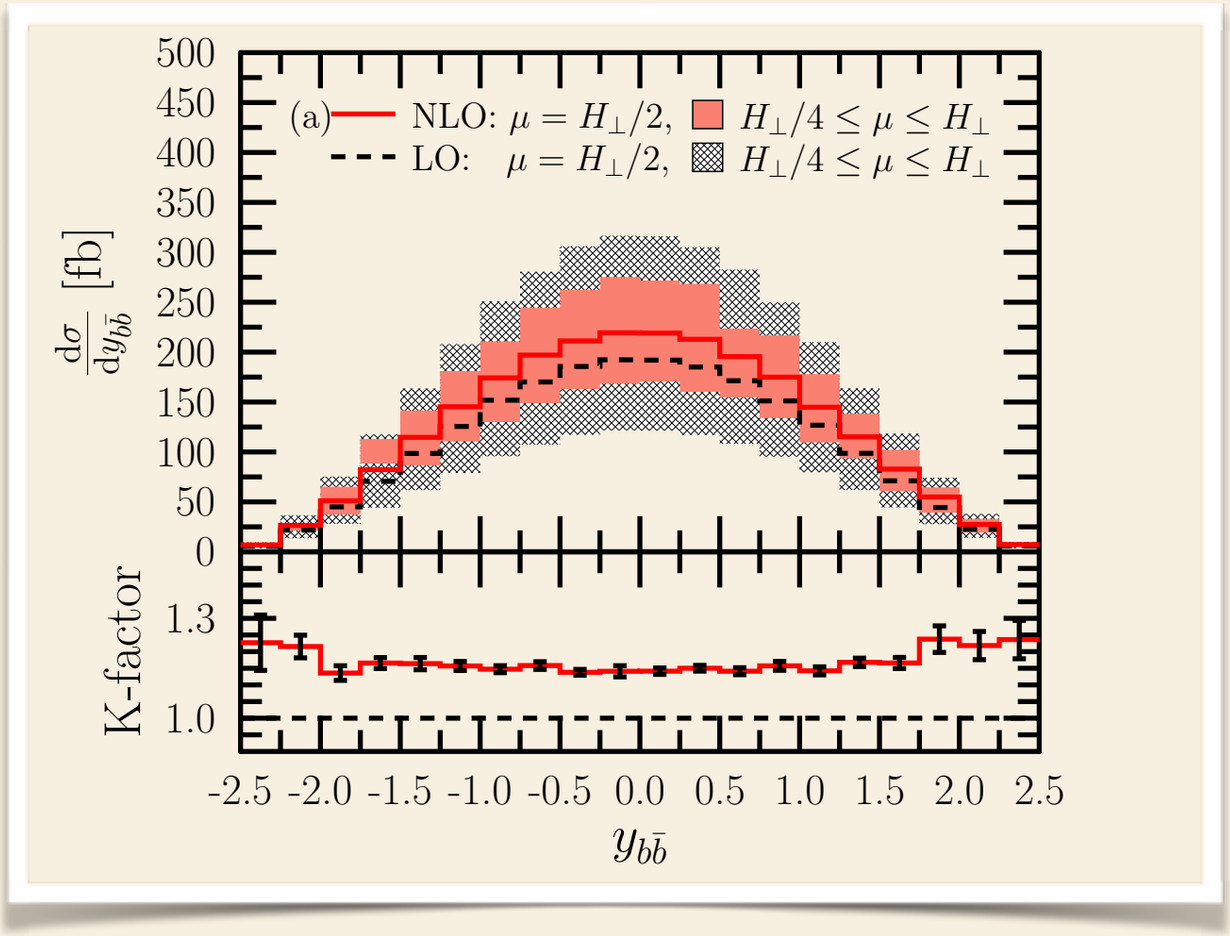
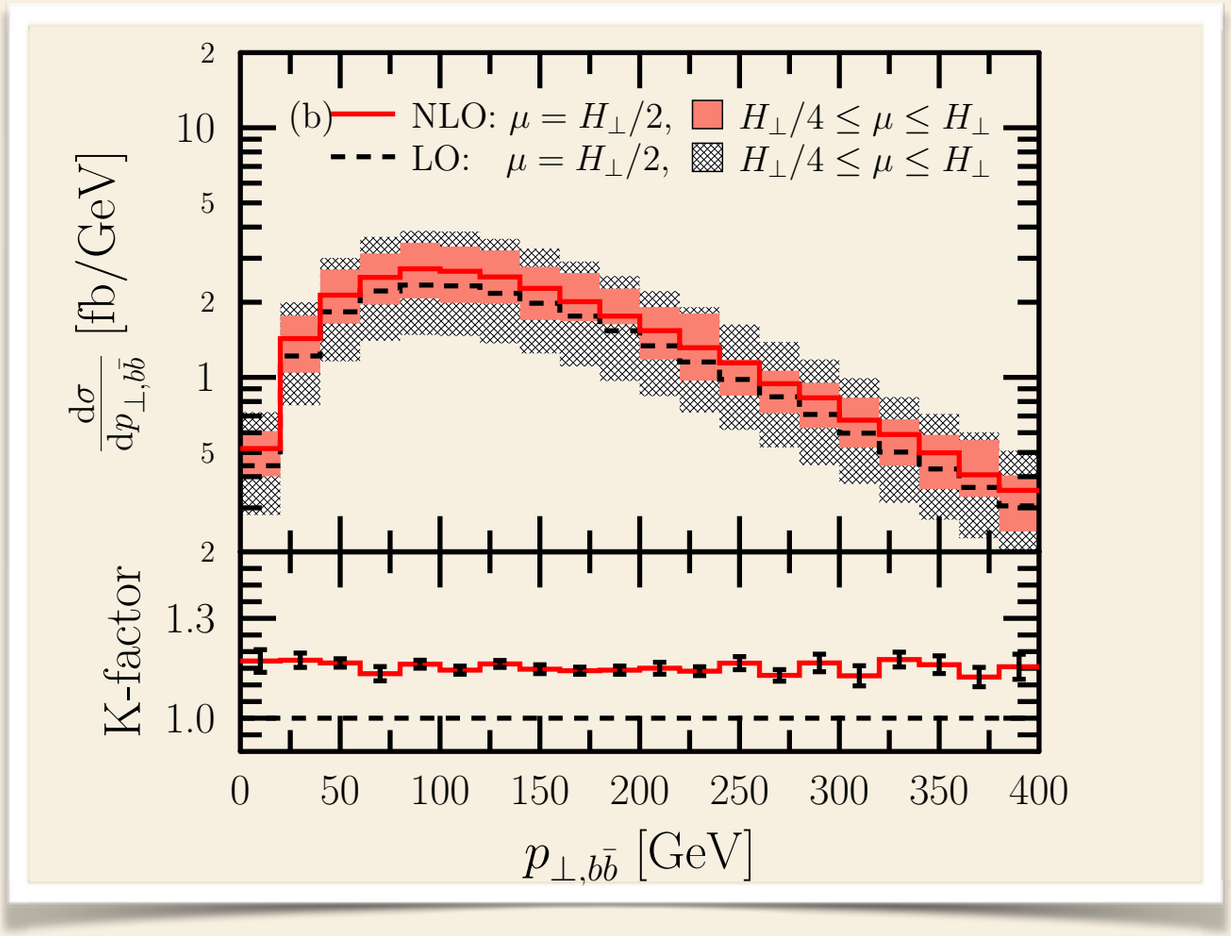
scale dependence: $^{+32\%}_{-22\%}$, largest if $\mu_R = \mu_F = \mu_{dyn}$

Small changes in shapes of distributions





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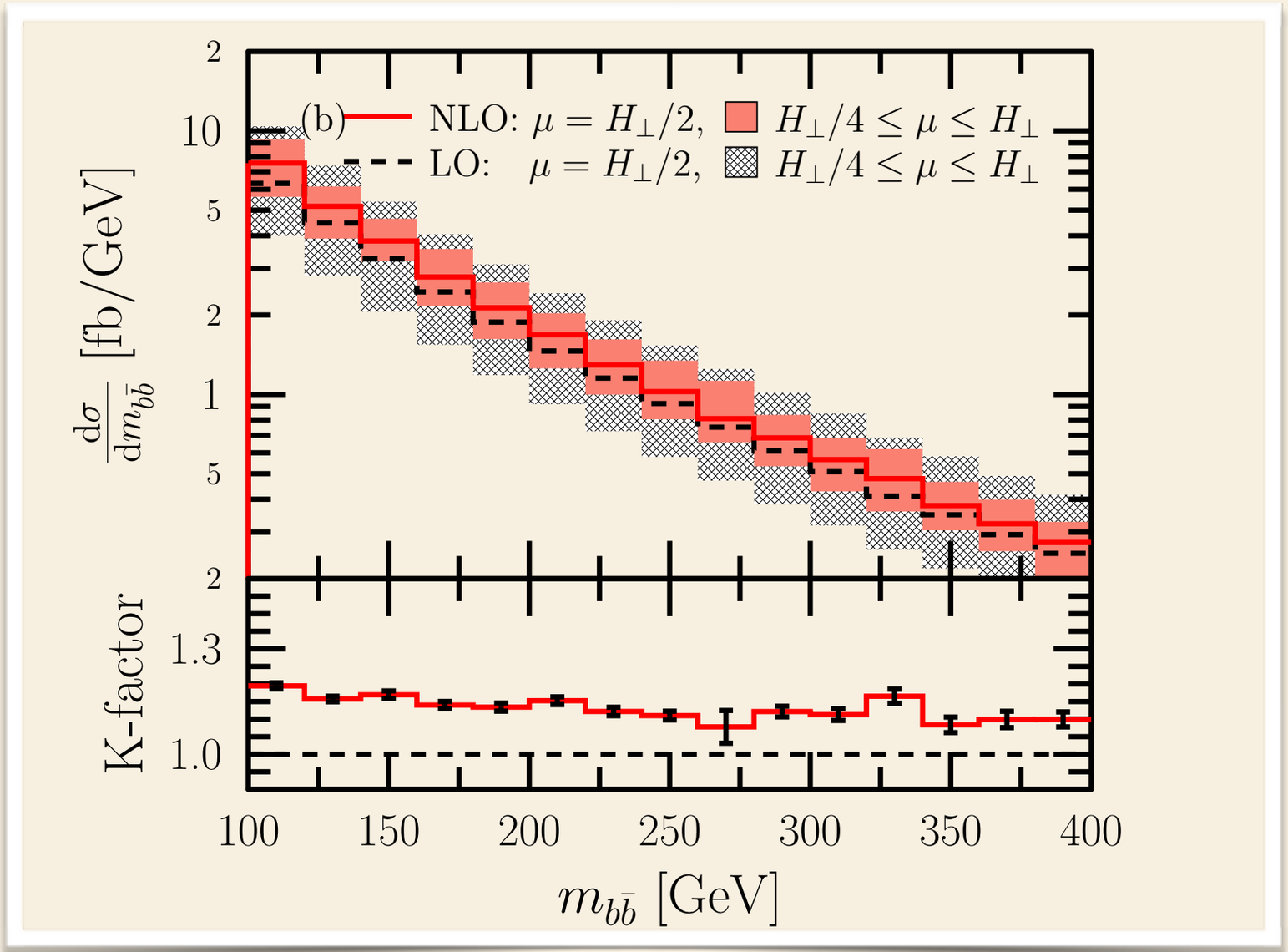

Formal accuracy of the POWHEG MC

$$\langle O \rangle = \int \mathrm{d}\Phi_{\mathrm{B}} \widetilde{B} \left[\Delta(p_{\perp,\mathrm{min}}) O(\Phi_{\mathrm{B}}) + \int \mathrm{d}\Phi_{\mathrm{rad}} \Delta(p_{\perp}) \frac{R}{B} O(\Phi_{\mathrm{R}}) \right] =$$

...

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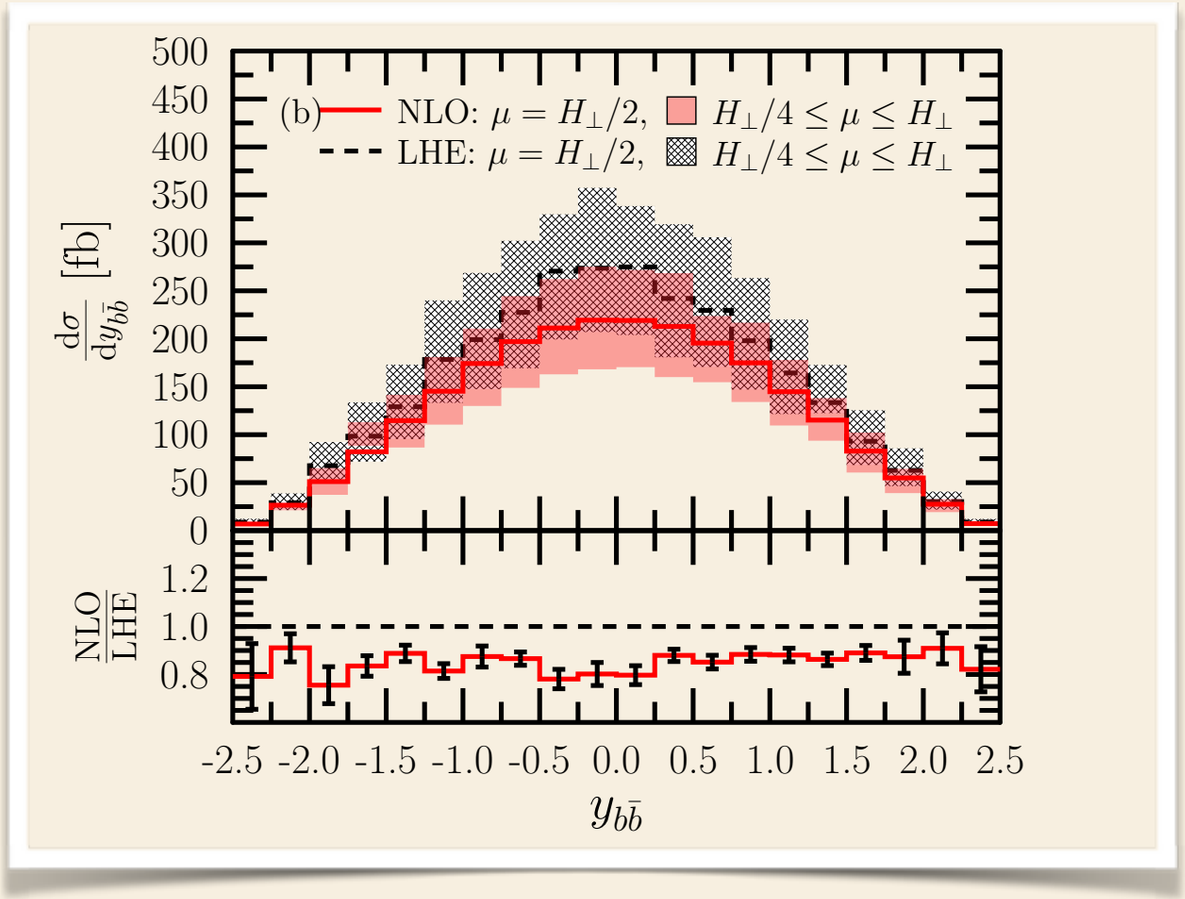
...

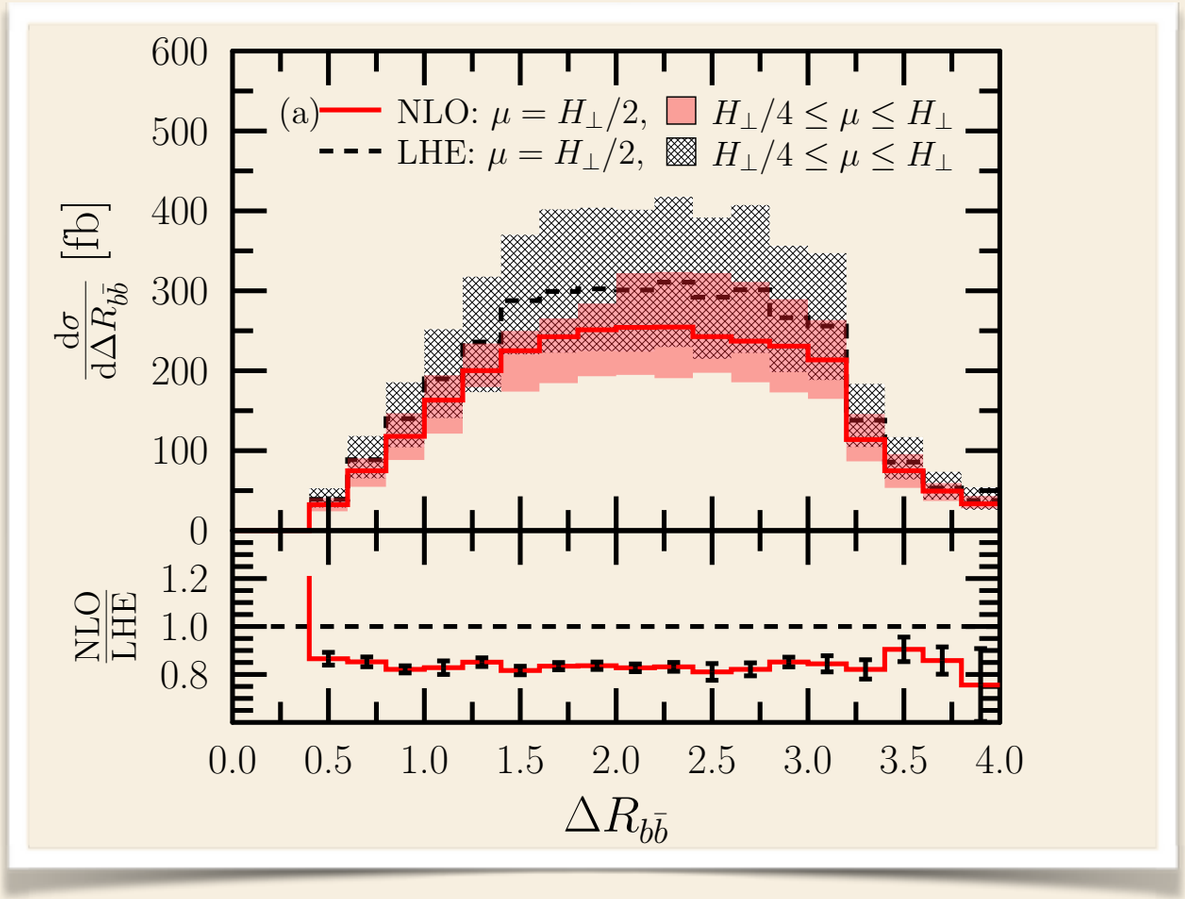
$$= \left\{ \int \mathrm{d}\Phi_{\mathrm{B}} \left[B + V \right] O(\Phi_{\mathrm{B}}) + \int \mathrm{d}\Phi_{\mathrm{R}} R O(\Phi_{\mathrm{R}}) \right\} (1 + \mathcal{O}(\alpha_{\mathrm{S}}))$$

$\langle O \rangle_{\mathrm{NLO}}$

Useful for checking

LHE vs. NLO


(b)
NLO: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
LHE: $\mu = H_\perp/2$, $H_\perp/4 \le \mu \le H_\perp$
$\frac{d\sigma}{dy_{b\bar{b}}}$ [fb]
$\frac{\text{NLO}}{\text{LHE}}$
$y_{b\bar{b}}$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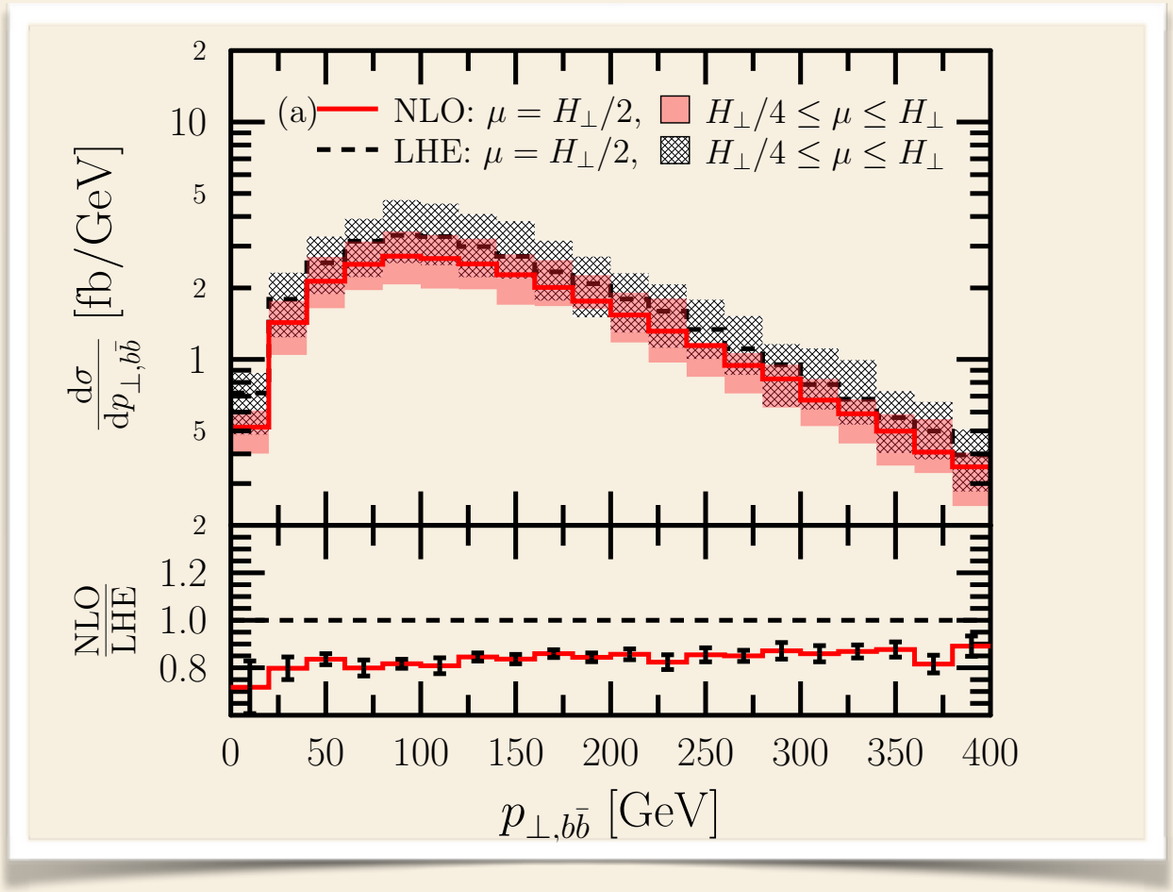
$\frac{d\sigma}{d\Delta R_{b\bar{b}}}$ [fb]
$\frac{\text{NLO}}{\text{LHE}}$
$\Delta R_{b\bar{b}}$

LHE vs. NLO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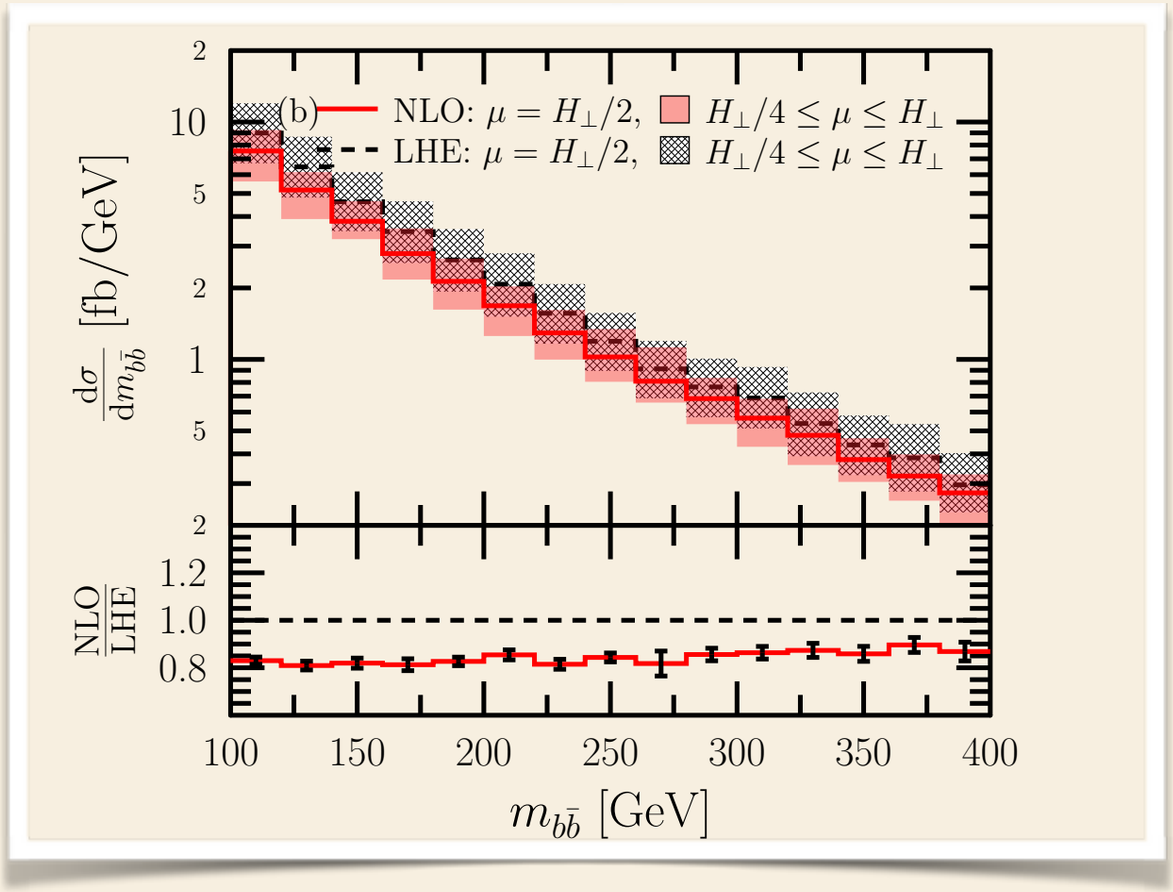
$\frac{d\sigma}{dp_{\perp,b\bar{b}}}$ [fb/GeV]
$\frac{\text{NLO}}{\text{LHE}}$
$p_{\perp,b\bar{b}}$ [GeV]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$\frac{d\sigma}{dm_{b\bar{b}}}$ [fb/GeV]
$\frac{\text{NLO}}{\text{LHE}}$
$m_{b\bar{b}}$ [GeV]

Message:

we can trust the LHE's, so can make

Predictions

Four possible forms of predictions

LHE: distributions from events at BORN+1st radiation

Decay: on-shell decays of heavy particles (t-quarks), shower and hadronization effects turned off

PS: parton showering (PYTHIA or HERWIG) included (t-quarks kept stable)

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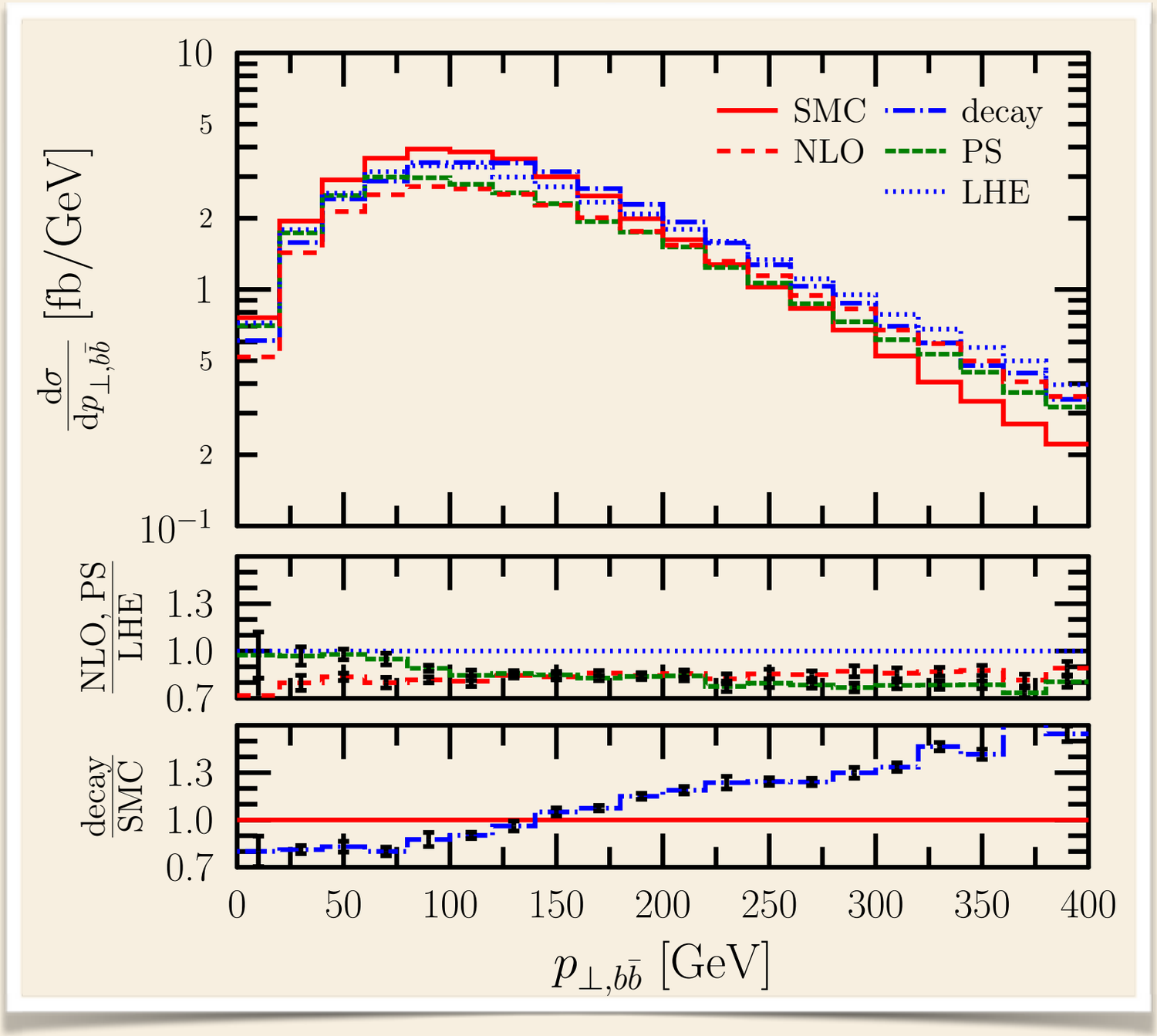
Number and type of particles are very different =>
to study the effect of SMC we employ selection cuts to keep the cross section fixed

NLO vs. PS and decay vs. full SMC at 14TeV, $\mu = H_T/2$



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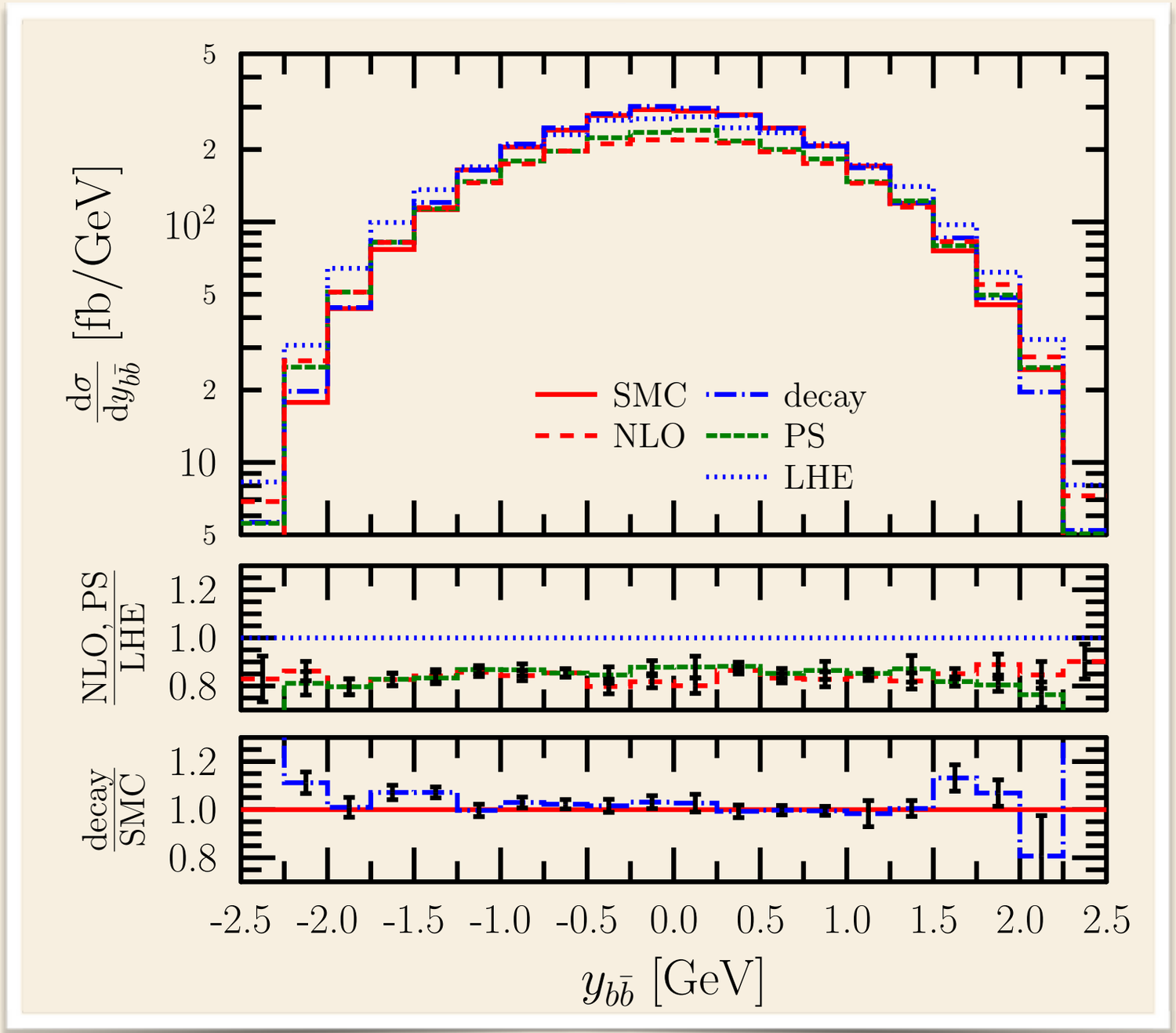

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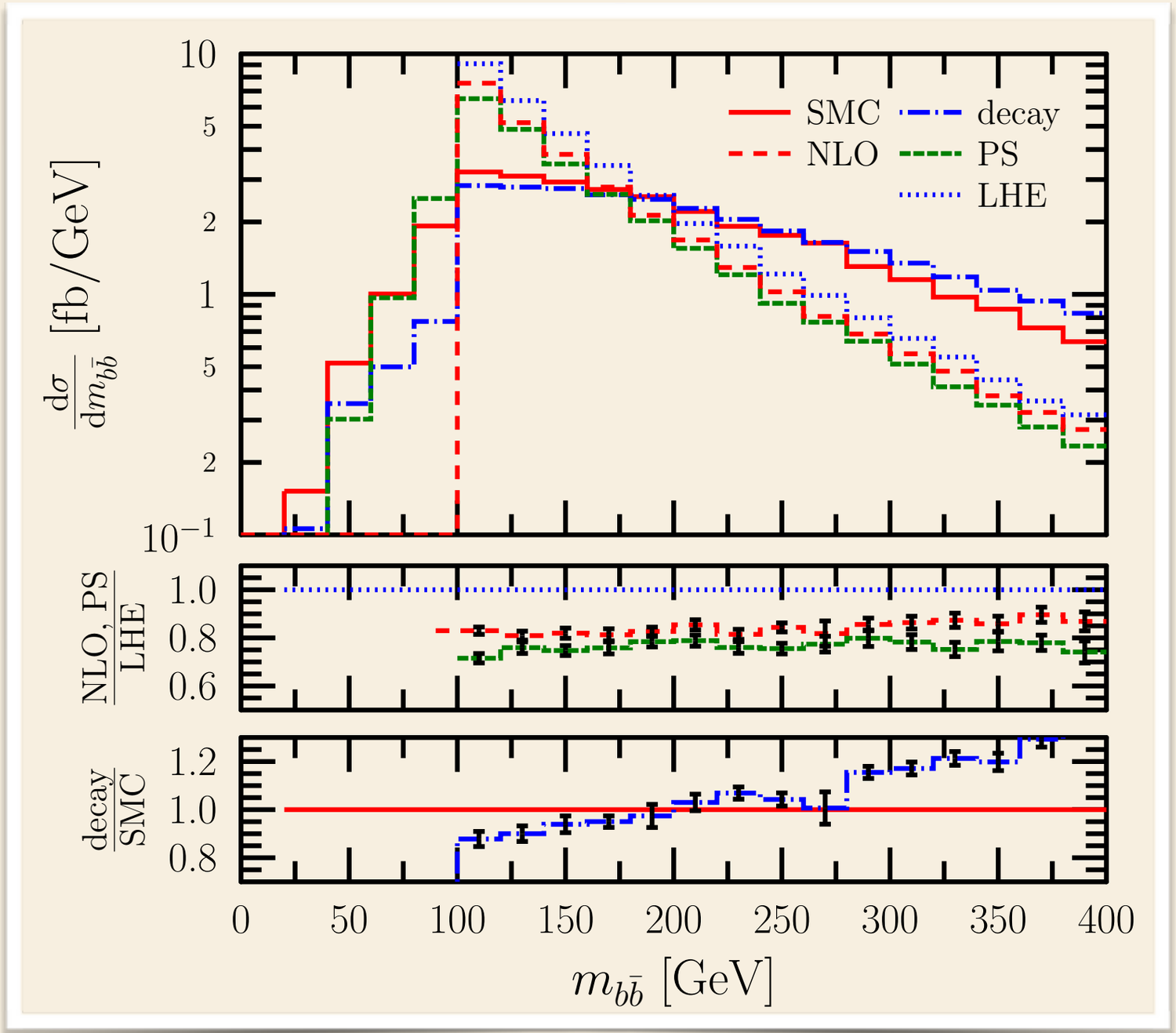

Comparison to CMS PAS TOP-13-010

Measurement of the Cross Section Ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ in pp Collisions at $\sqrt{s} = 8$ TeV

in dilepton decay mode

The CMS Collaboration

Final state	ee	$\mu\mu$	$e\mu$	All
$t\bar{t} + b\bar{b}$	18.1 ± 0.8	26.8 ± 1.0	60.9 ± 1.5	105
$t\bar{t} + b$	34.3 ± 1.1	51.4 ± 1.4	111	196
$t\bar{t} + c\bar{c}$	13.4 ± 0.9	20.5 ± 1.0	47.0 ± 1.6	80.9 ± 2.4
$t\bar{t} + LF$	244	359	822	1,425
$t\bar{t}$ others	20.5 ± 1.1	25.6 ± 1.1	63.7 ± 1.9	109
multijet	< 0.1	1.4 ± 1.2	1.4 ± 1.2	2.9 ± 2.2
$W + jets$	< 0.1	< 0.1	< 0.1	< 0.1
VV	< 0.1	0.3 ± 0.1	< 0.1	0.4 ± 0.7
Single top-tW	7.9 ± 2.0	11.6 ± 2.5	25.1 ± 3.7	44.7 ± 4.1
$Z/\gamma* \to ll$	5.6 ± 4.3	5.7 ± 3.9	2.9 ± 3.2	14.4 ± 5.7
Total expected	351	512	1,159	2,023
Data	367	506	1,145	2,018

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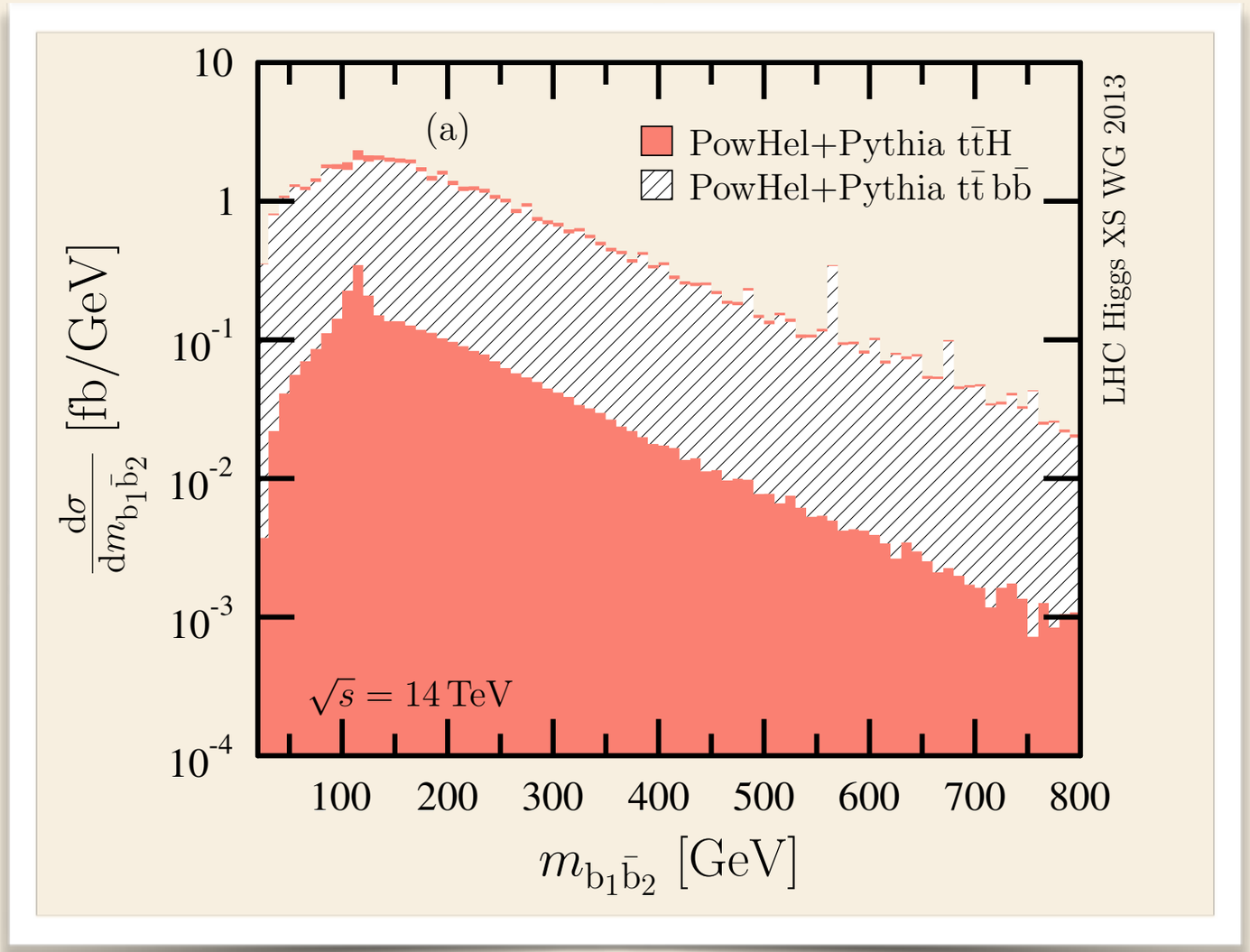
19.2±0.8 20.4±1.8 61.3±3.5 101±4

$t\bar{t}H$ signal on $t\bar{t}b\bar{b}$ background



Distribution of the invariant mass of the hardest $b\bar{b}$ jet pair in $pp \to t\bar{t}H$ and $t\bar{t}\,b\bar{b}$ at LHC (14 TeV)

Conclusions and outlook

Conclusions

- First computation of $pp \to t\bar{t}b\bar{b}$ at NLO + SMC accuracy [A. Kardos and Z.T. arXiv:1303.6291, Cascioli et al arXiv:1309.5912, Meierhofer this morning]
- NLO cross sections agree with published predictions and with CMS results
- Effects of decay of t-quarks could be important
- LHE event files for $pp \to t\bar{t}$, $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$jet, $t\bar{t}b\bar{b}$ processes available, to put into SMC and perform experimental analyses on events with hadrons

Processes available in PowHel

✓ tT	[Kardos et al, arXiv:
✓ tT + Z	1111.0610,1111.1444,
✓ tT + W	1208.2665,
✓ tT + H/A	1108.0387,
✓ tT + j	1101.2672,
✓ WWbB	PoS LL2012 057
✓ tT + bB	1103.6291]

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✓ tT + bB	1103.6291]

✓ tT +... (2 more processes coming soon)

The end

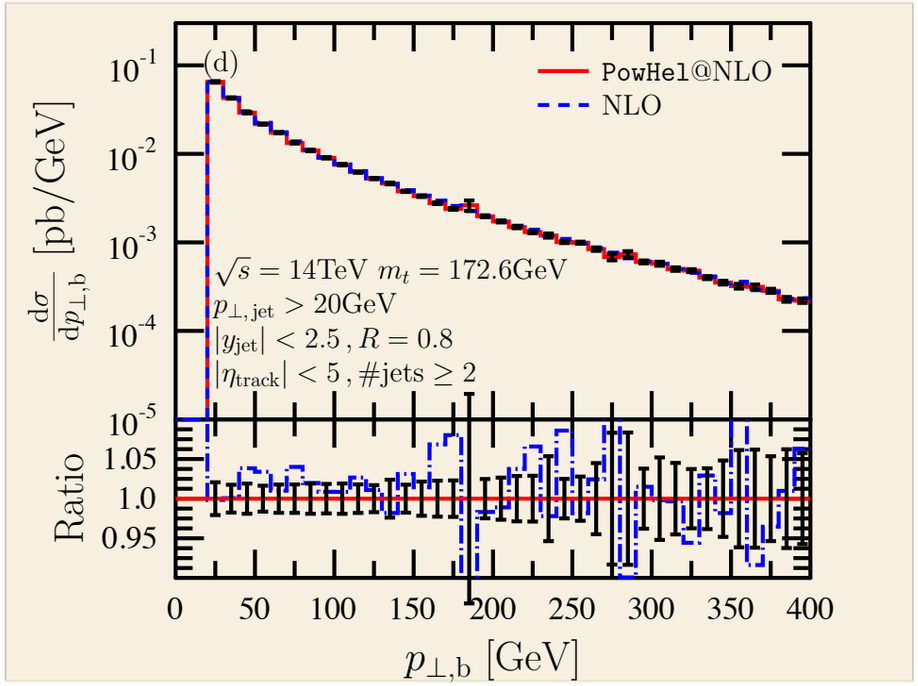
Appendix

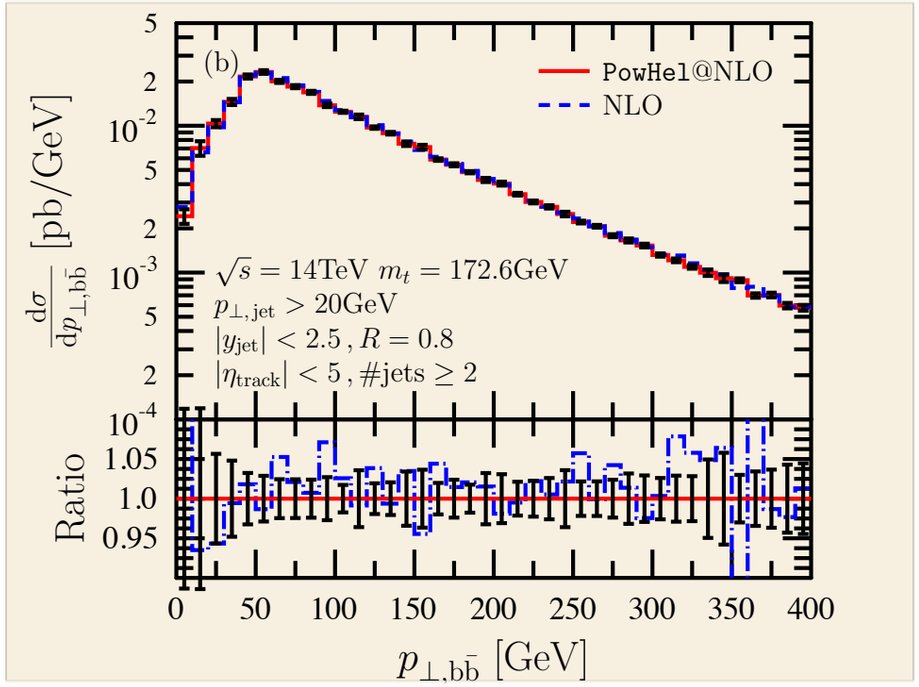
Selection cuts in NLO studies

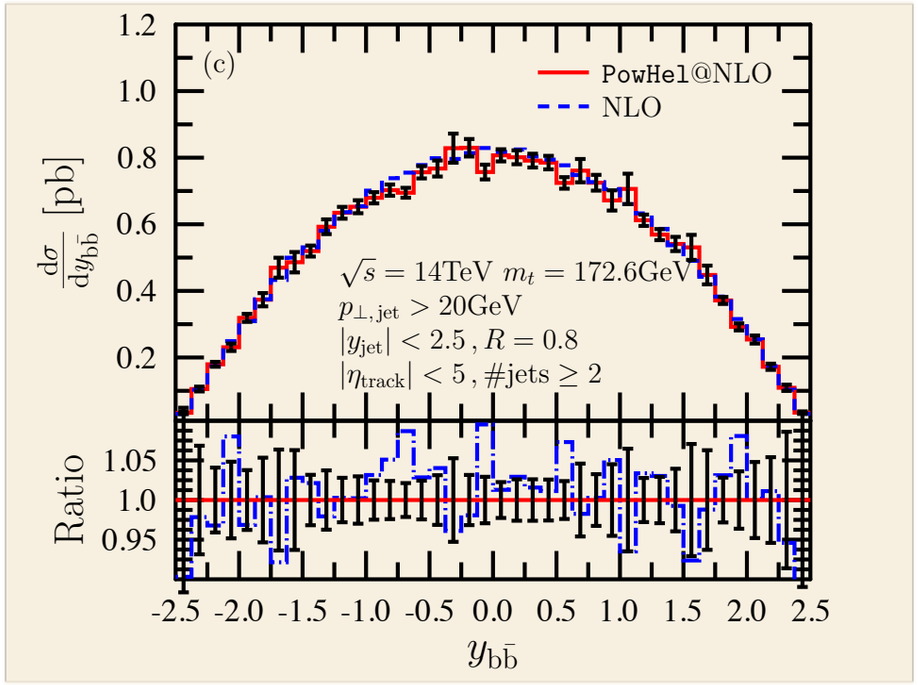
Cuts employed by Bevilacqua et al in arXiv:0907.4723

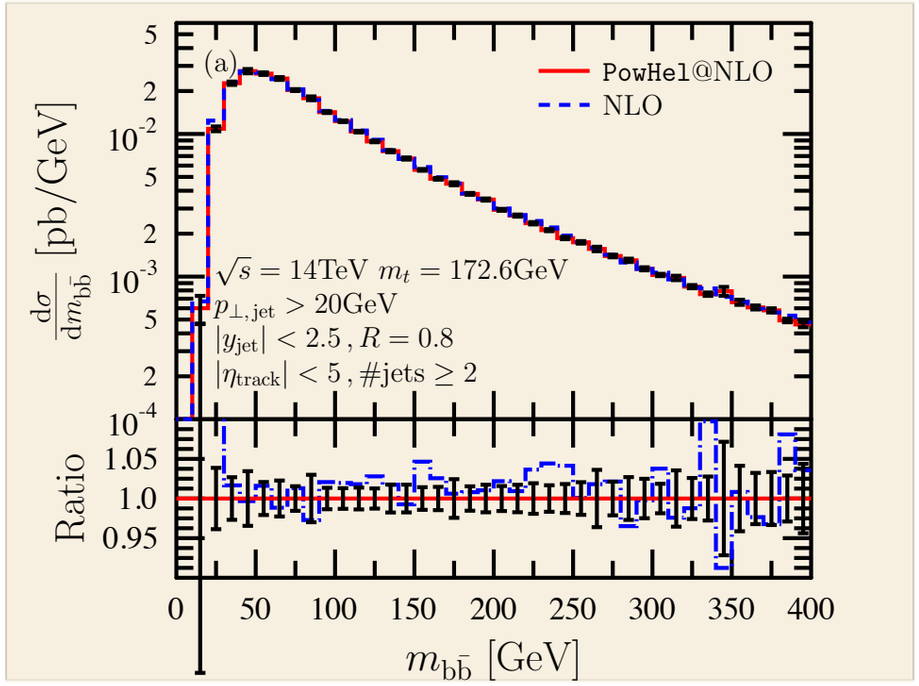
- A track was considered as a possible jet constituent if $|\eta^{track}|<5$, t-quarks were excluded from the set of possible tracks, jets were reconstructed with the k_T-algorithm using $R=0.4$
- Events with invariant mass of the $b\bar{b}$-jet pair below $m^{min}_{b\bar{b}} = 20$ GeV were discarded
- We require $p_{Tmin,j} = 20$ GeV and
- at least two, one b- and one $\bar{b}$-jet, with $|y_{b(\bar{b})}|<2.5$

Comparison to Bevilacqua et al: 0907.4723









Selection cuts for decay vs. SMC

- Applied on the LHE's:
  - A track was considered as a possible jet constituent if $|\eta^{track}|<5$, t-quarks were excluded from the set of possible tracks. Jets were reconstructed with the anti-k_T algorithm using R=0.4.
  - Events with invariant mass of the $b\bar{b}$-jet pair below $m^{min}_{b\bar{b}}$ = 100 GeV were discarded.
- Applied on LHE's and checked also on the existing particles at different stages of evolution:
  - we require $p_{Tmin,j}$ = 25 GeV and
  - at least two, one b- & one $\bar{b}$-jet with $|\eta_{b(\bar{b})}|<2.5$.

Comparison to CMS PAS TOP-13-010

- at least one pair of isolated (with R=0.3, I_{rel} = 0.15) opposite sign leptons with $p_{Tmin,\ell}$ = 20 GeV/c, $|\eta_\ell|<2.4$, 12 GeV < $m_{\ell\ell}c^2$ ($\notin$[77, 107] GeV if ee or μμ)
- p_T^{miss} = 30 GeV/c if ee or μμ
- jets reconstructed with the anti-k_T algorithm using R=0.4, with $p_{Tmin,j}$ = 20 (40) GeV and $|\eta_j|<2.5$
- at least four well separated jets with $\Delta R > 0.5$ both from leptons and jets

Comparison to CMS PAS TOP-13-010

Measurement of the Cross Section Ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ in pp Collisions at $\sqrt{s} = 8$ TeV

in dilepton decay mode

The CMS Collaboration

Final state	ee	$\mu\mu$	$e\mu$	All
$t\bar{t} + b\bar{b}$	4.0 ± 0.4	5.9 ± 0.5	13.3 ± 0.7	23.3 ± 1.5
$t\bar{t} + b$	13.6 ± 0.7	16.8 ± 0.8	37.9 ± 1.1	68.2 ± 2.1
$t\bar{t} + c\bar{c}$	3.1 ± 0.4	4.6 ± 0.5	9.5 ± 0.7	17.3 ± 1.6
$t\bar{t} + LF$	62.2 ± 2.0	94.1 ± 2.3	211 ± 3.6	368
$t\bar{t}$ others	9.5 ± 0.8	11.8 ± 0.8	28.3 ± 1.3	49.7 ± 2.2
multijet	< 0.1	0.3 ± 0.6	0.3 ± 0.6	0.7 ± 1.6
$W + jets$	< 0.1	< 0.1	< 0.1	< 0.1
VV	< 0.1	< 0.1	< 0.1	< 0.1
Single top-tW	2.8 ± 1.24	2.7 ± 1.2	4.4 ± 1.7	9.9 ± 2.7
$Z/\gamma* \to ll$	2.2 ± 3.02	< 0.1	2.9 ± 3.2	5.2 ± 3.9
Total expected	100	139	315	555
Data	90	148	311	549

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Total expected	100	139	315	555
Data	90	148	311	549

Cuts for background study for tTH

Applied after full SMC

- a track was considered as a possible jet constituent if $|\eta^{track}|<5$, jets were reconstructed with the anti-k_T algorithm using R=0.4

we require

- at least six jets with $p_{Tmin,j}$ = 20 GeV and $|\eta_j|<5$
- at least two b-jets & two $\bar{b}$-jets with $|\eta_{b(\bar{b})}|<2.7$, with MCTRUTH tagging
- at least one isolated (with R=0.4) lepton with $p_{Tmin,\ell}$ = 20 GeV and $|\eta_\ell|<2.5$
- p_T^{miss} = 15 GeV

to disentangle background in the semileptonic $t\bar{t}$ decay

$t\bar{t}H$ signal on $t\bar{t}b\bar{b}$ background