

Summary of workshop: Top mass: challenges in definition and determination

(Frascati, May 6-8 2015)

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- 1. Introduction**
- 2. Top mass definition and interpretation**
- 3. Strategies to measure the top mass**
- 4. Theoretical uncertainties on the top mass**
- 5. Experimental reviews from Tevatron and LHC**
- 6. Top mass and stability of the electroweak vacuum**
- 7. Conclusions**

Outline of the talks

Adrian Signer: What is m_t ?

Andrè Hoang The Top Mass: Interpretation and Theoretical Uncertainties

Sven-Olaf Moch: Measuring the top-quark running mass

Spyridon Argyropoulos: Effects of colour reconnection on the top mass

Roberto Franceschini: Top quark mass at the LHC: kinematics and beyond

Sandra Leone: Measurements of the top quark mass at the Tevatron

Marina Cobal: Top mass reconstruction techniques in ATLAS

Roberto Chierici: Top mass at CMS and World Averages

Vincenzo Branchina: Stability condition of the EW vacuum and top mass measurements:

Michael Scherer: The Higgs Mass, the Top Mass and the Scale of New Physics

A.Signer: Review of mass definitions

- consider top quark propagator $\frac{1}{\not{p} - m_0} \xrightarrow{\text{h.o.}} \frac{1}{\not{p} - m_0 - \Sigma}$
- full self energy involves all scales, also $k \lesssim \Lambda_{\text{QCD}}$

$$\Sigma = \Sigma_{\text{div}} + \Sigma_{\text{fin}} = \int_0^\infty d^D k \dots$$

- **pole mass** defined as (real part) of **position of pole** of propagator
 $(m_0 + \Sigma_{\text{div}} + \Sigma_{\text{fin}}) \Rightarrow m_{\text{pole}}$
 - many nice properties (e.g. no infrared singularity) and 'physical' mass for leptons
 - the pole mass has an intrinsic uncertainty of order Λ_{QCD} (since Σ_{fin} (**all scales**))
- **$\overline{\text{MS}}$ mass** does not have the problem of infrared sensitivity (only pure UV is absorbed into mass definition)

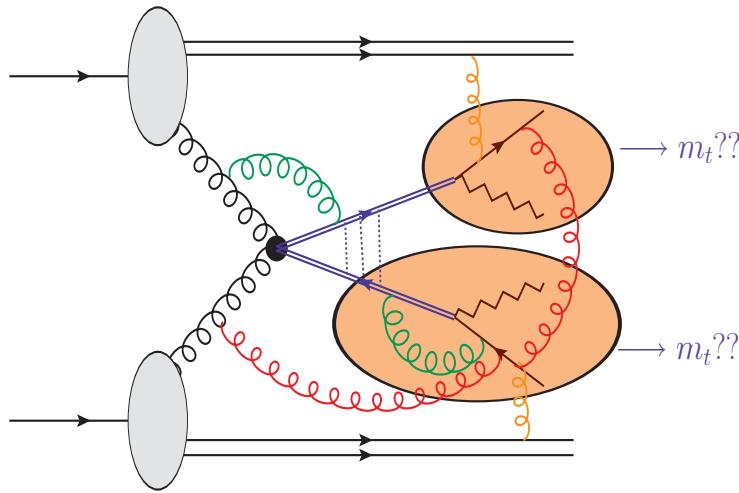
$$(m_0 + \Sigma_{\text{div}}) \Rightarrow m_{\overline{\text{MS}}} \rightarrow \text{short distance mass}$$

- but the pole of the propagator is far away from $m_{\overline{\text{MS}}}$ \rightarrow NOT a **threshold mass**
- potential subtracted mass (PS mass) [Beneke]

$$m_{\text{PS}}(\mu_{\text{PS}}) \equiv m_{\text{pole}} + \frac{1}{2} \int_{|\vec{q}| < \mu_{\text{PS}}} \frac{d^3 \vec{q}}{(2\pi)^3} V_{\text{Coul}}(q) \quad \text{with} \quad \mu_{\text{PS}} \sim m \alpha_s$$

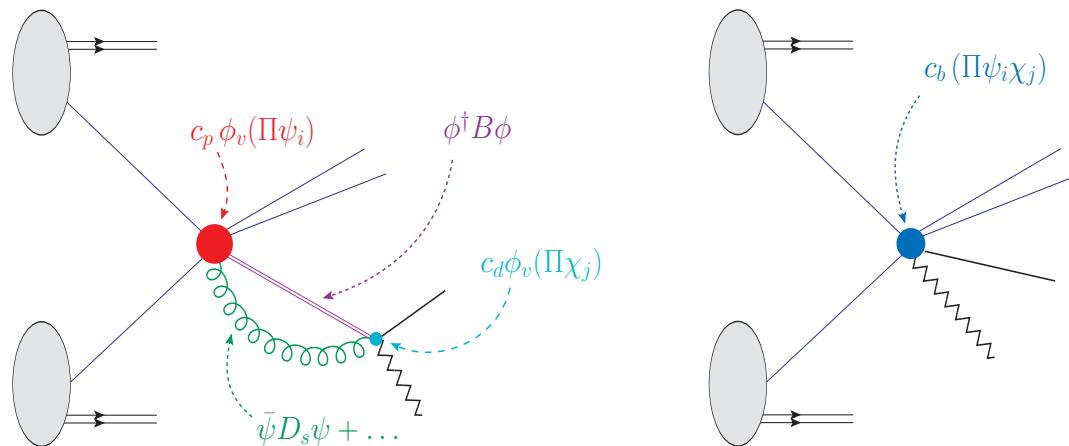
$$m_{\text{pole}} = m_{\text{PS}}(\mu_{\text{PS}}) + \mu_{\text{PS}} \left[\frac{\alpha_s}{2\pi} \delta_1 + \frac{\alpha_s^2}{(2\pi)^2} \delta_2 + \dots \right]$$

Investigation of off-shell effects in NLO top production and decay

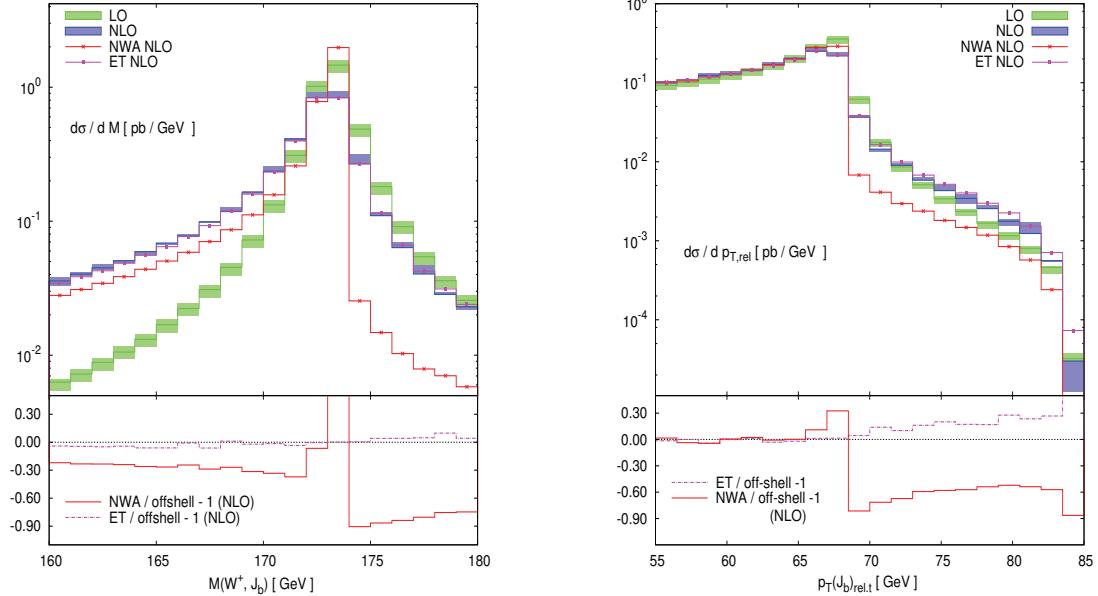


Effective field theory approach to capture dominant finite-width effects

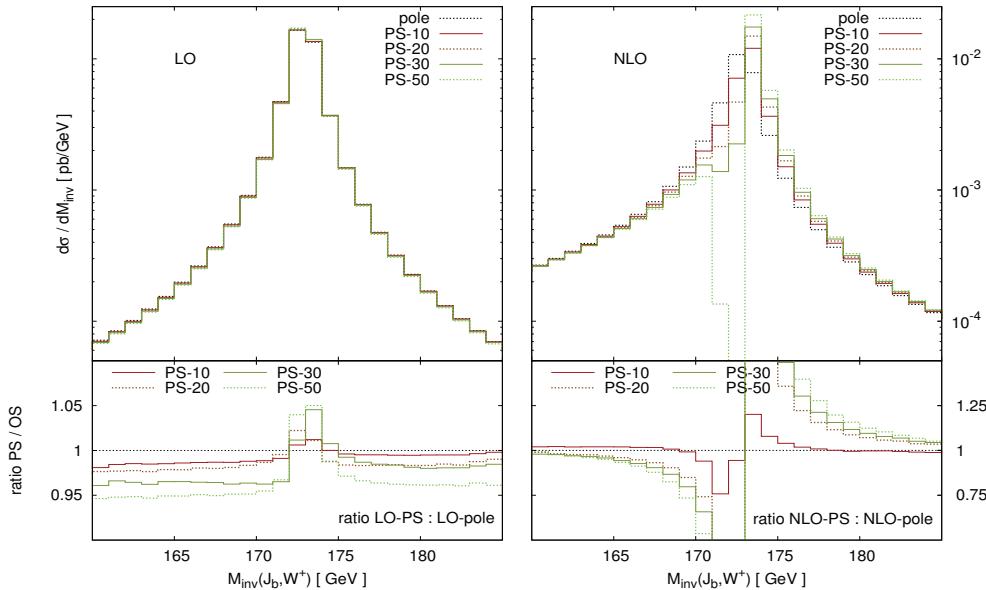
$$\mathcal{L} = \phi^\dagger B\phi + c_p \phi(\Pi\psi_i) + c_d \phi(\Pi\chi_j) + c_b (\Pi\psi_i\chi_j) + \bar{\psi}D_s\psi + \dots$$



EFT and complex mass scheme ($m_{t,0} = \mu_t + \delta\mu_t$ in aMC@NLO) for single top

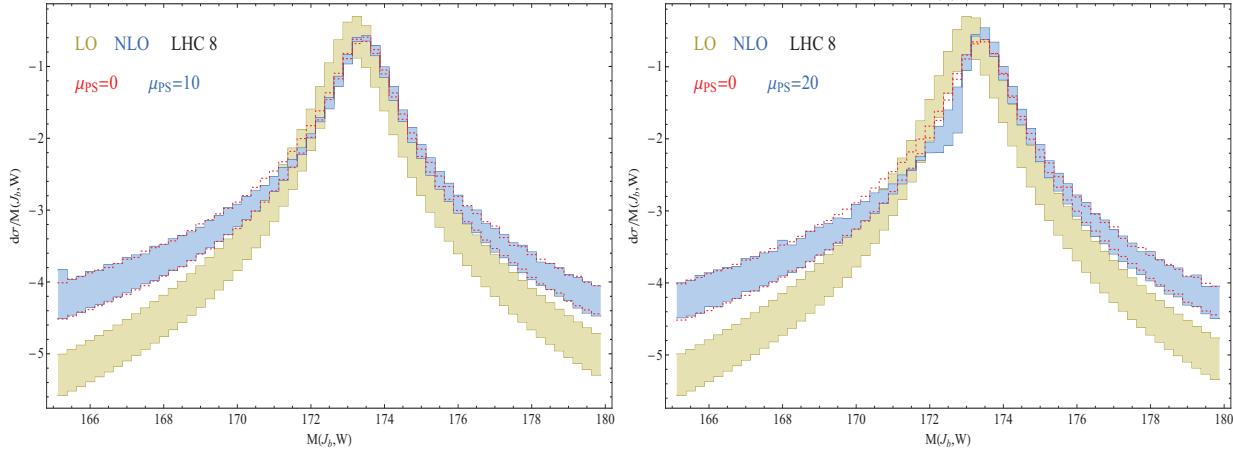
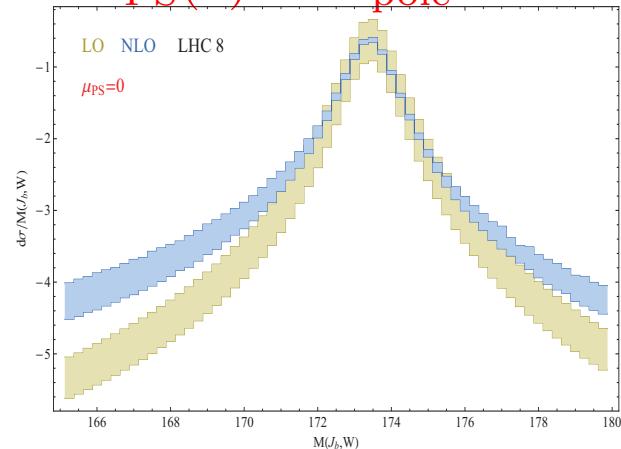


Using pole and PS masses at LO and NLO with $m_{\text{PS}}(0) = m_{\text{pole}}$



NLO analysis assuming true distribution at $m_{\text{PS}}(0) = m_{\text{pole}} = 173.3 \text{ GeV}$

- extract mass at NLO:
 $m_{\text{PS}}(10) = 172.6 \text{ GeV}$ and
 $m_{\text{PS}}(20) = 172.1 \text{ GeV}$
- perturbative behaviour very good for $\mu_{\text{PS}} = 10 \text{ GeV}$ and reasonable for $\mu_{\text{PS}} = 20 \text{ GeV}$
- $\mu_{\text{PS}} \gtrsim 30 \text{ GeV} \rightarrow \text{'bad' scheme}$



μ_{PS}	LO			NLO		
	m_{exp}	$m_{\overline{\text{MS}}}$	m_{pole}	m_{exp}	$m_{\overline{\text{MS}}}$	m_{pole}
0	173.3	162.6	173.3	173.3	162.6	173.3
10	172.8	163.1	173.9	172.6	162.9	173.7
20	172.4	163.3	174.2	172.1	163.0	173.9

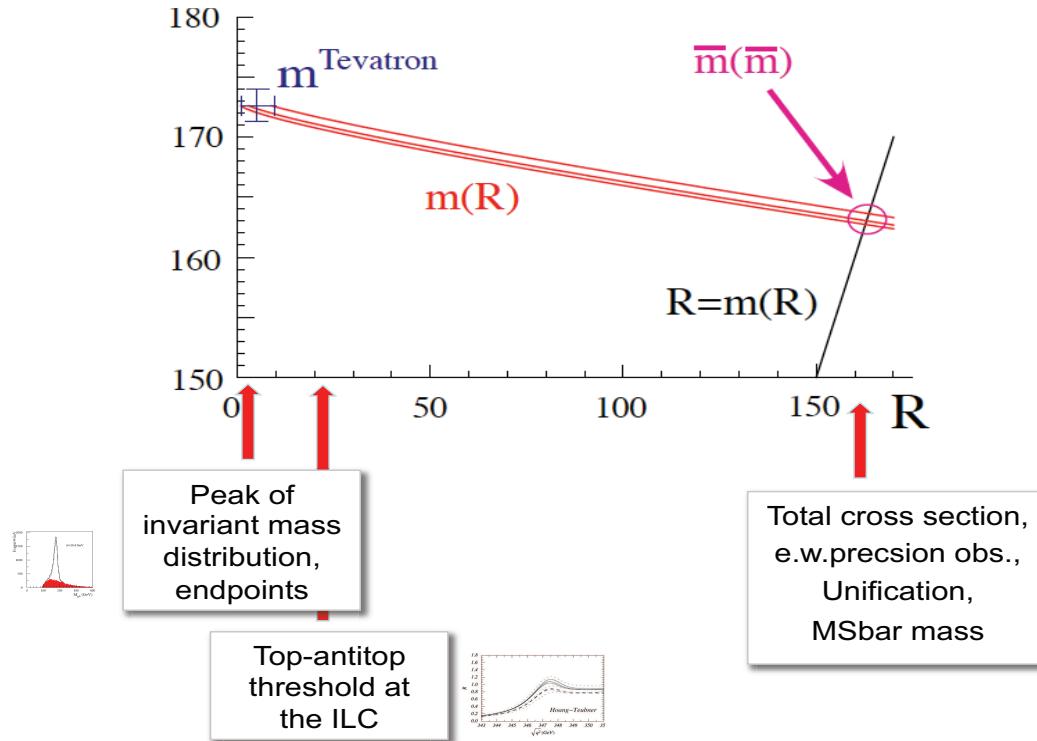
Using PS mass is doable; scheme ambiguity 300-600 MeV at NLO

A.Hoang: MSR masses and relation with pole and MC masses

$$m_t^{\text{MSR}}(R) \rightarrow m_{\text{pole}} \text{ for } R \rightarrow 0 ; m^{\text{MSR}}(R) \rightarrow \bar{m}_t(\bar{m}_t) \text{ for } R \rightarrow \bar{m}_t(\bar{m}_t)$$

$$m_{\text{pole}} = m^{\text{MSR}}(R, \mu) + \delta m(R, \mu) ; \frac{dm^{\text{MSR}}(R, \mu)}{d \ln \mu} = -R \gamma[\alpha_S(\mu)]$$

Identifying the Tevatron (MC) mass with the MSR mass at $\simeq 1$ GeV



$$m_t^{\text{MC}} = m_t^{\text{MSR}}(R = 1 \text{ GeV}) + \Delta_{t,\text{MC}}(R = 1 \text{ GeV}) , \Delta_{t,\text{MC}} \simeq \mathcal{O}(1 \text{ GeV})$$

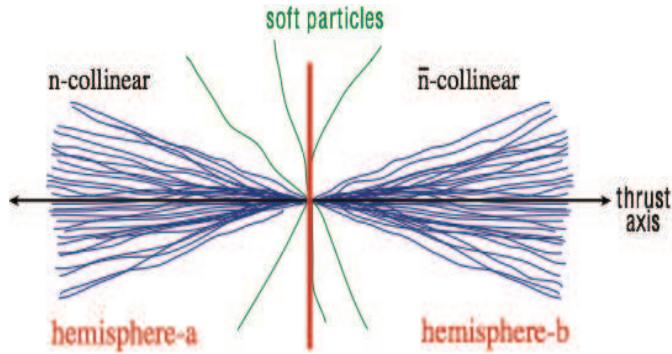
Analogy with b -flavoured mesons, employing PDG numbers for mesons and m_b^{1S}

$$m_B = m_b^{\text{MSR}}(R = 1 \text{ GeV}) + \Delta_{b,B}(R = 1 \text{ GeV}) \quad , \quad \Delta_{b,B} \simeq \mathcal{O}(1 \text{ GeV})$$

Table 1. Some B mesons masses, MSR masses $m_b^{\text{MSR}}(1 \text{ GeV})$ and $m_b^{\text{MSR}}(2 \text{ GeV})$ from $m_b^{1S} = 4780 \pm 66 \text{ MeV}$ [18], and corresponding values for $\Delta_{b,B}$. All in units of MeV, $\alpha_s(m_Z) = 0.1184$.

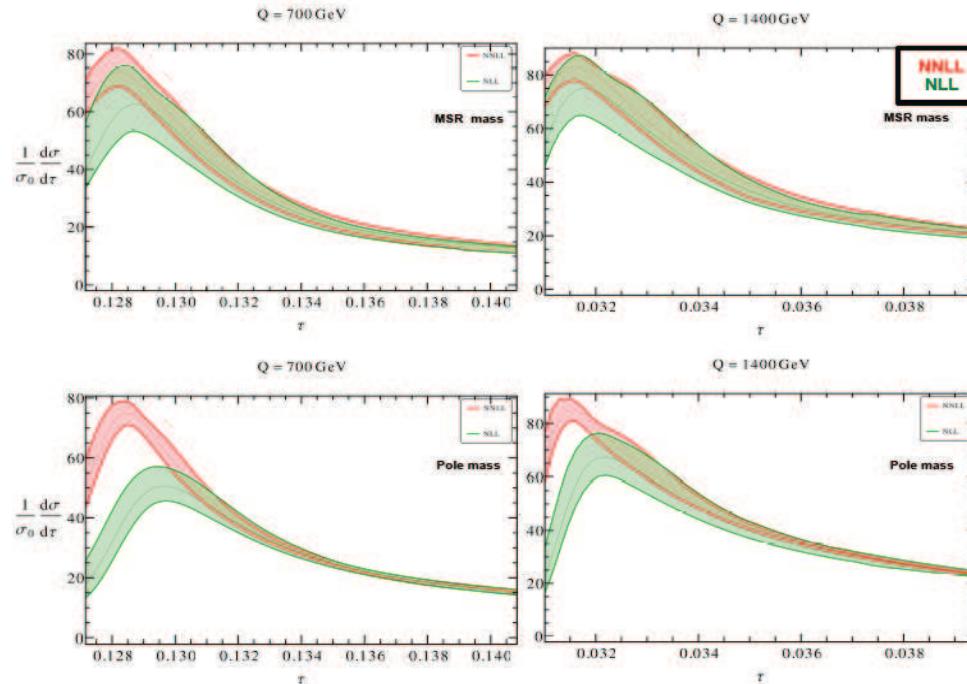
$m_b^{\text{MSR}}(1 \text{ GeV})$	$m_b^{\text{MSR}}(2 \text{ GeV})$	$m(B^0)$	$m(B^*)$	$m(B_1^0)$	$m(B_2^*)$
4795 ± 69	4571 ± 69	5279.58 ± 0.17	5325.2 ± 0.4	5724 ± 2	5743 ± 5
$\Delta_{b,B}(1 \text{ GeV})$		485 ± 69	530 ± 69	929 ± 69	948 ± 69
$\Delta_{b,B}(2 \text{ GeV})$		709 ± 69	754 ± 69	1153 ± 69	1172 ± 69

To extract the MC top mass: SCET with massive quarks and VFNS for final state jets
Hadronization after comparing with MC predictions at hadron level

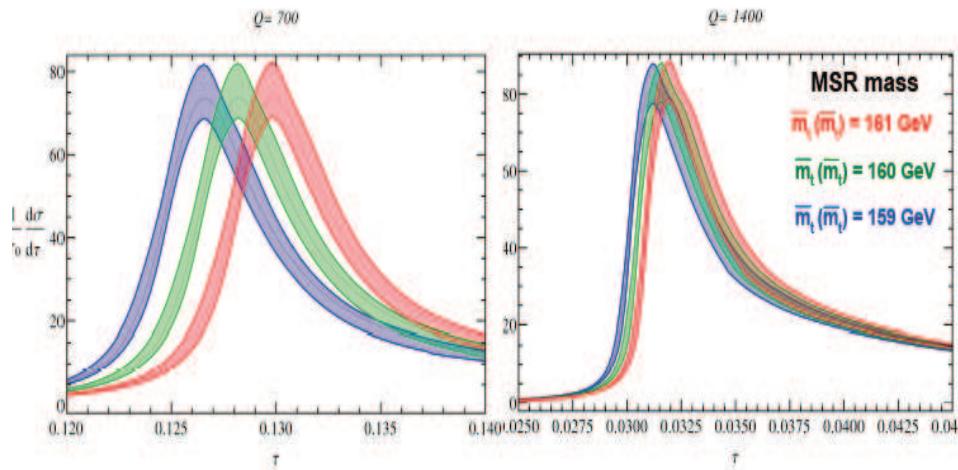


Resummation of $\ln\left(\frac{Q}{\mu_H}\right)$, $\ln\left(\frac{m_J}{\mu_m}\right)$, $\ln\left(\frac{\mu_J^2}{Q\mu_S}\right)$, $\ln\left(\frac{m_J\mu_B}{Q\mu_S}\right)$, $\ln\left[\frac{Q(\tau-\tau_{\min})+2\Lambda)}{\mu_S}\right]$

Thrust in e^+e^- : NLO+NNLL/NLL with power corrections and renormalon subtraction



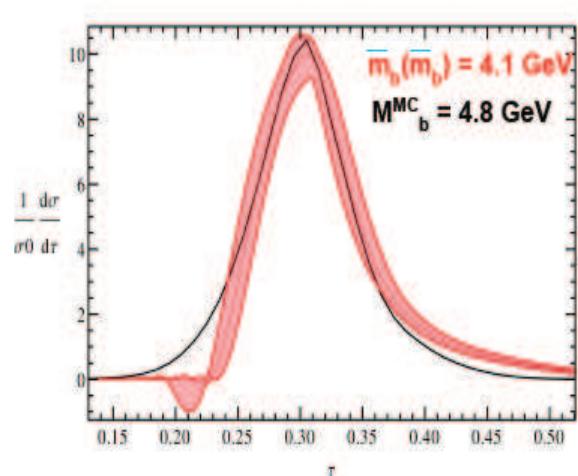
Peak sensitivity mostly at small \sqrt{s}



Comparison with Monte Carlo event generators

Theory vs Pythia

$Q=15 \text{ GeV}$



$Q=45 \text{ GeV}$

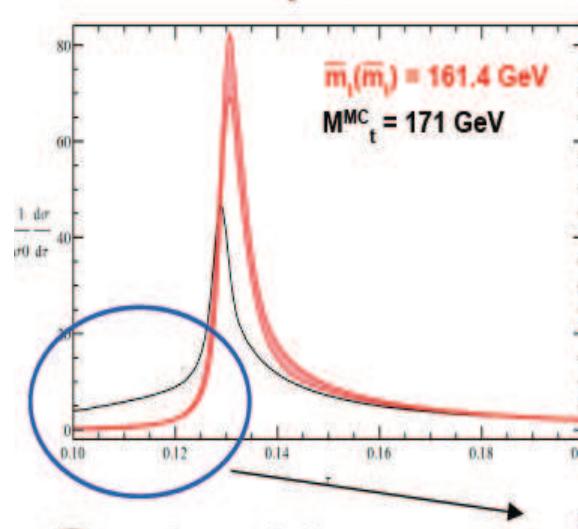


A. H. Hoang, V. Mateu, BD,
M. Butenschoen & Iain W. Stewart

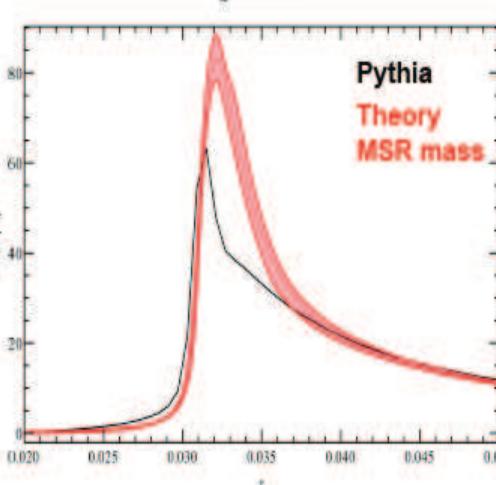
► Agreement of theory - Pythia :

- ✓ Good for bottom
- ✓ Some effect are likely missing
(shoulder region) → off shell top + electroweak effects

$Q=700 \text{ GeV}$



$Q=1400 \text{ GeV}$



$$\alpha_s(m_Z) = 0.1184$$

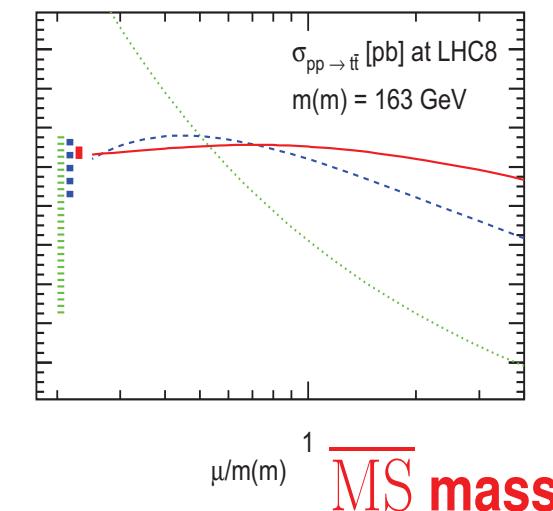
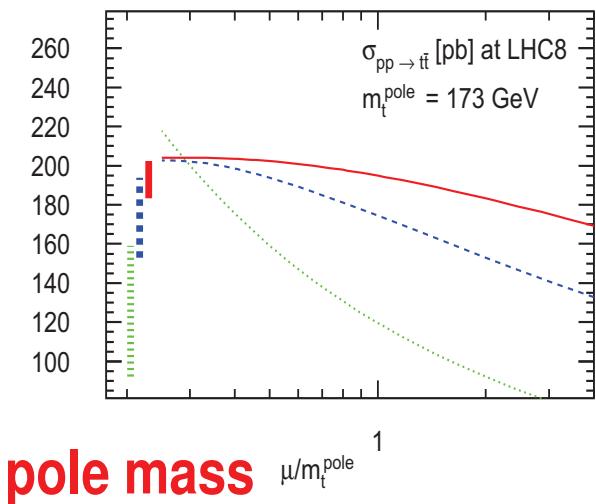
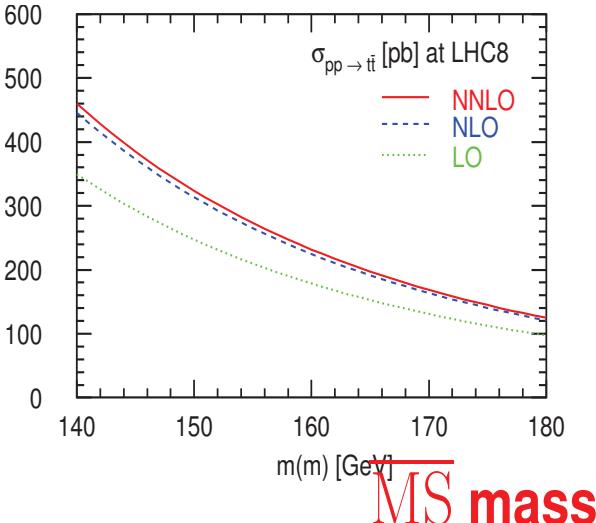
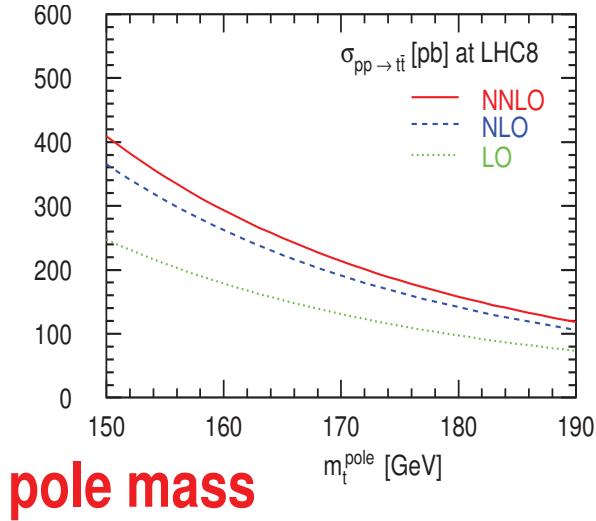
$$\Omega_1 = 0.5 \text{ GeV}$$

Preliminary Results

Shoulder region

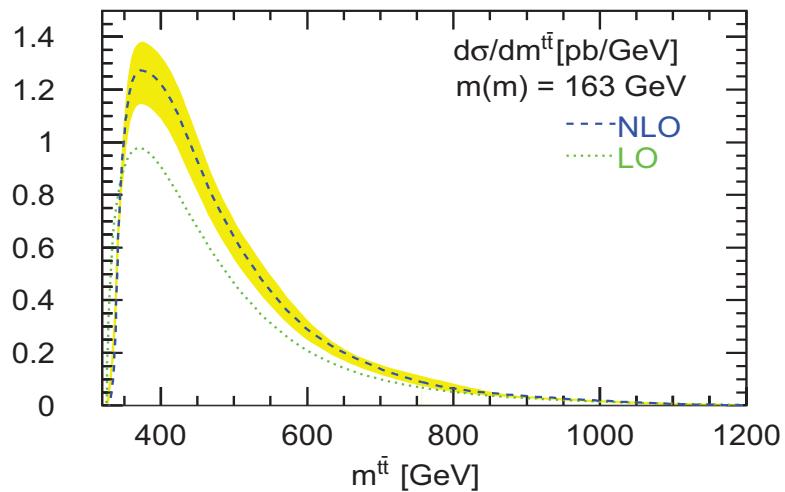
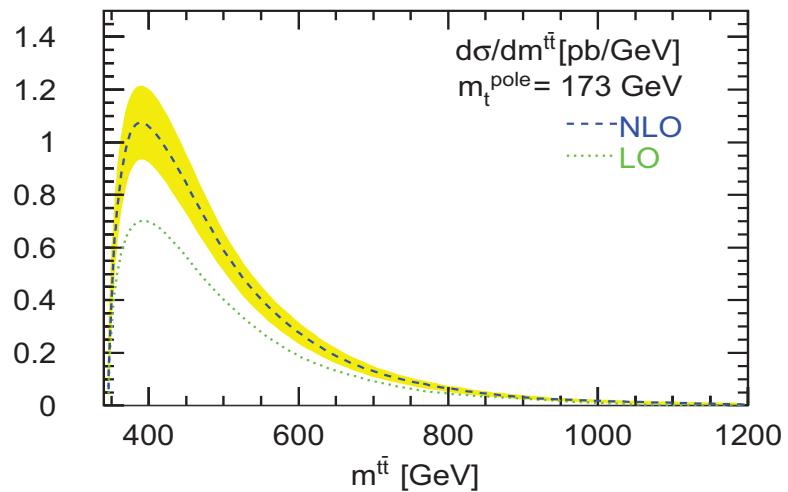
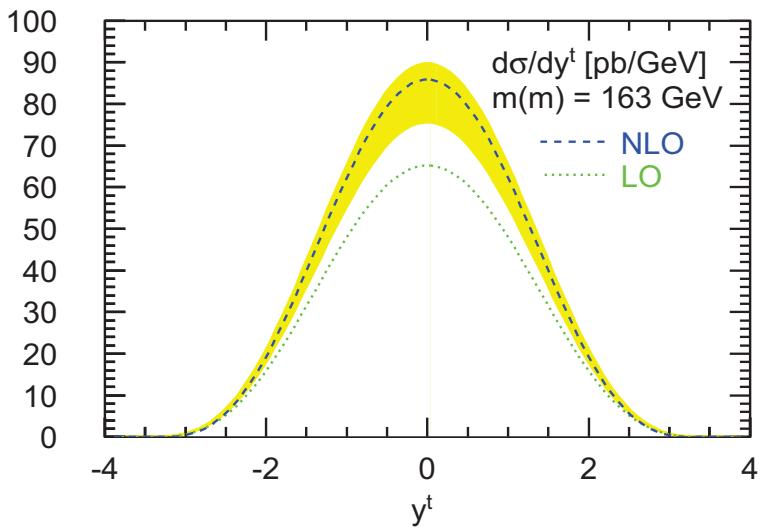
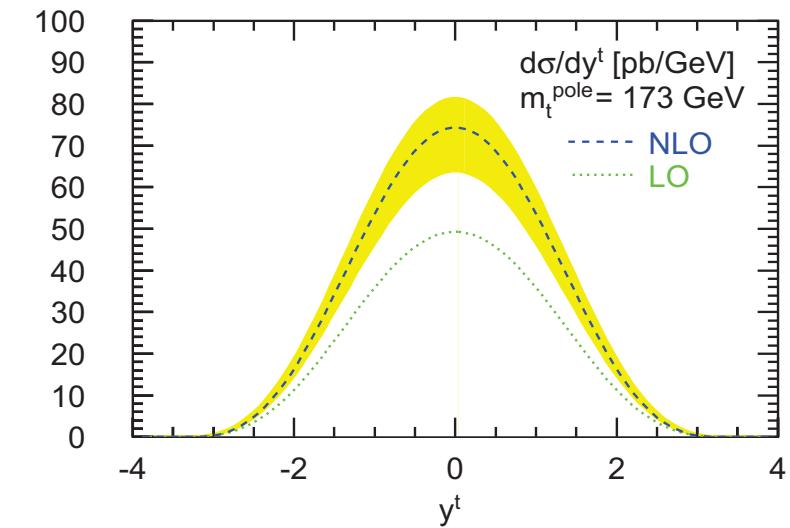
Final goal: table with $m_t^{\text{MSR}}(R)$, $m_{t,\text{pole}}$ and m_t^{MC} in terms of R

S. Moch: Extracting top running mass from NNLO $t\bar{t}$ cross section (Czakon, Fiedler and Mitov)



Using the $\overline{\text{MS}}$ mass seems to yield a milder scale dependence

Differential $t\bar{t}$ cross section using pole and $\overline{\text{MS}}$ masses



Left: pole mass. Right: $\overline{\text{MS}}$ mass

Also discussion on $\sigma(t\bar{t} + \text{jet})$ (overlap with ATLAS talk)

R. Franceschini: Measuring m_t by using kinematics and beyond

Kinematic methods: peak of $d\sigma/E_b$, endpoints of $m_{b\ell}$, $m_{3\ell}$ in $J/\psi + \ell$ events and m_{T2} ; fits of $W + b$ -jet invariant mass

Based on 4-momentum conservation, sensitive to new physics, easy to estimate uncertainties, no limited by statistics, but typically rely on LO kinematics

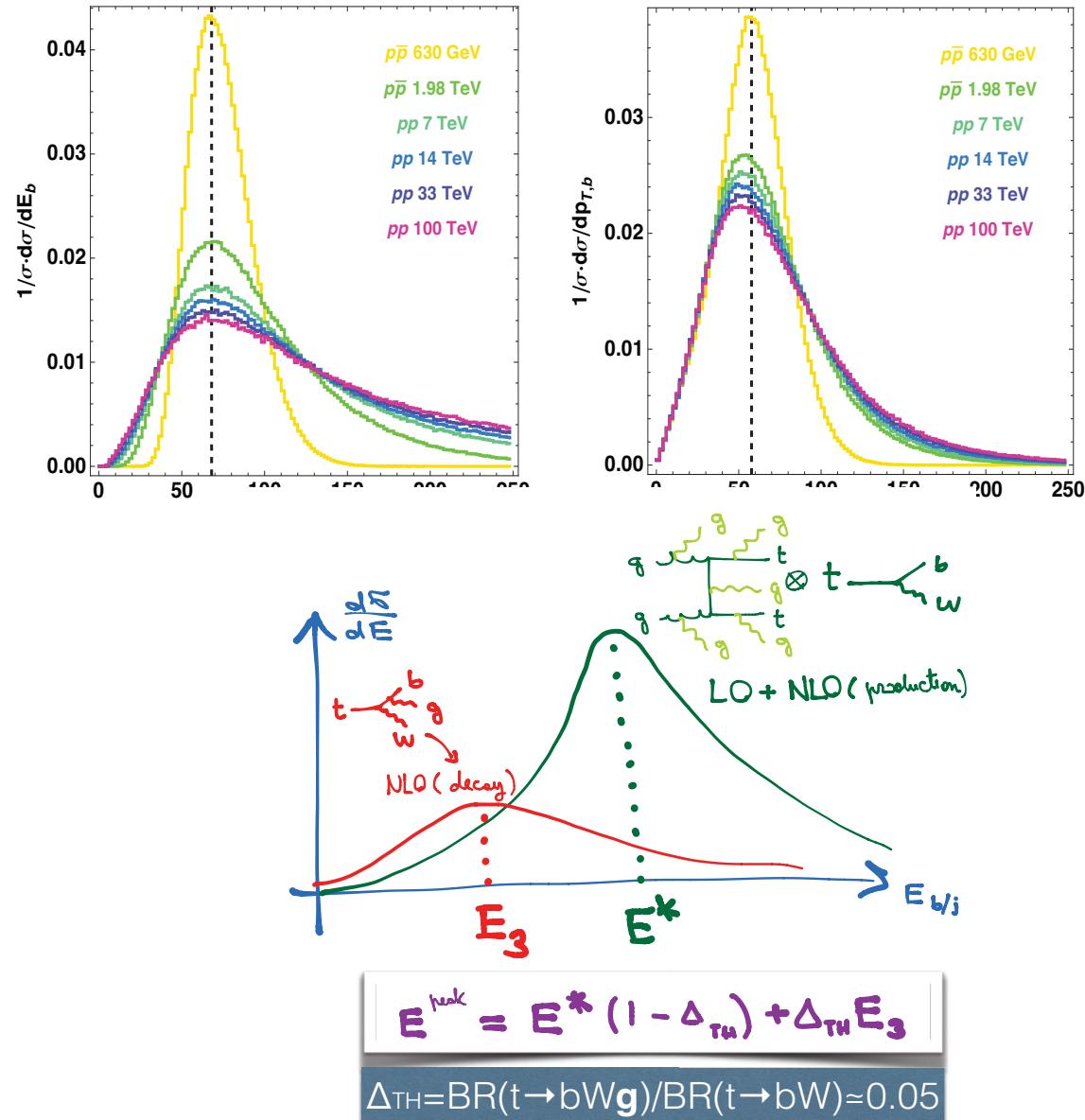
Dynamic measurements - beyond pure kinematic constraints: B lifetime, Mellin moments of purely leptonic observables, shapes of $m_{b\ell}$ and $m_{3\ell}$, $d\sigma/ds(t\bar{t}j)$

Sensitive to loop calculations, they allow to estimate the impact of theory ingredients like scale uncertainties, parton showers, etc.

Matrix-element methods: assumption that the full Lagrangian is known, along with the full transfer function from the Lagrangian to the experiments

NNLO+NNLL cross section, higher-order (loop) calculations, assuming no new physics in electroweak and strong interactions

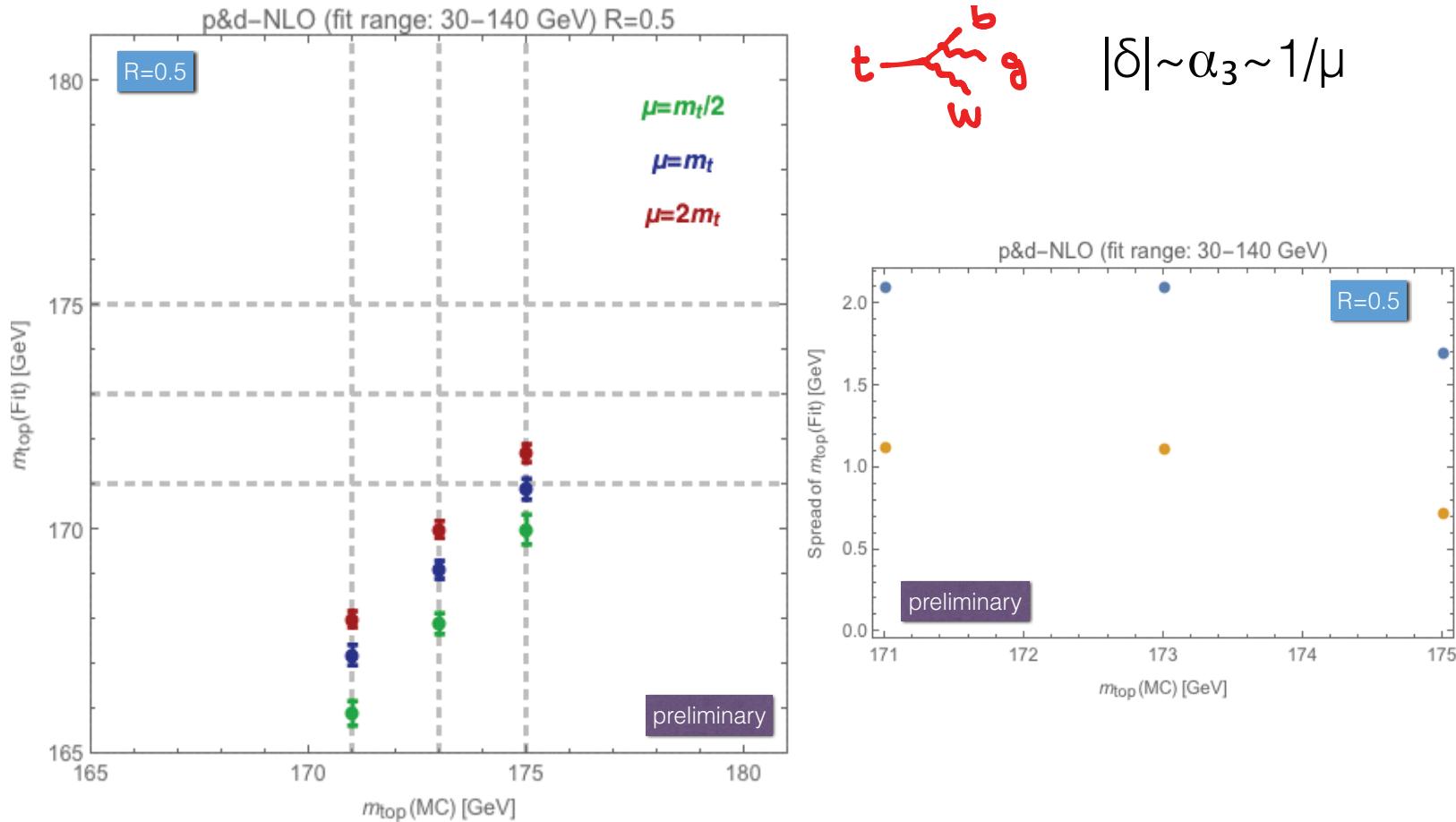
R. Franceschini: energy and transverse momentum peaks to extract m_t



At LO E_b peaks are invariant but not $p_{T,b}$; at NLO production and decay contributions

NLO: production & decay

(MCFM) R=0.5

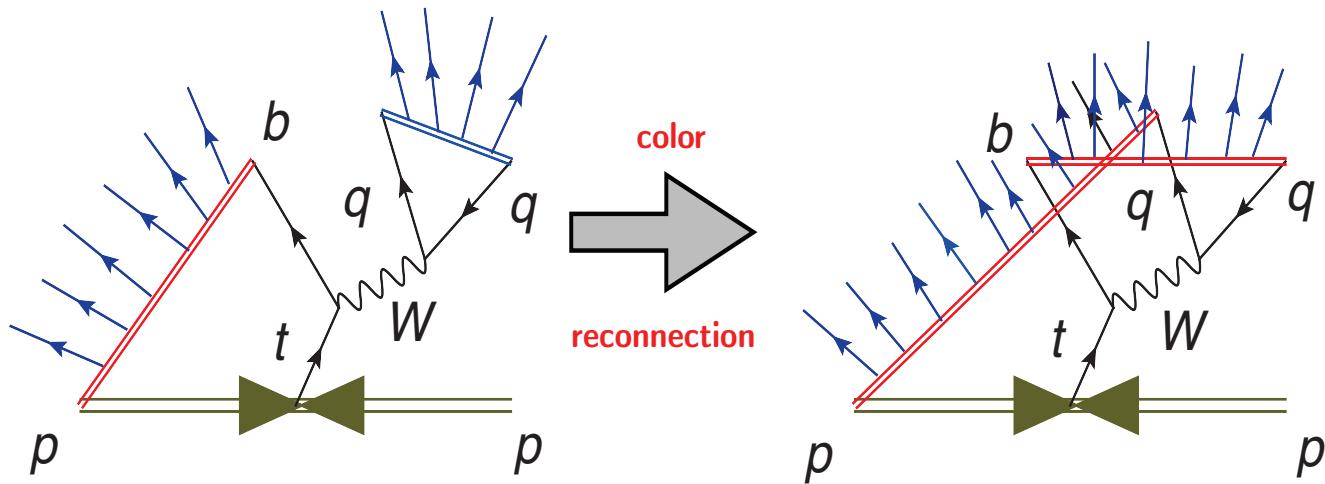


decay NLO sensitive to the scale choice: ± 1 GeV on m_{top}

$m_{\text{top}}(\text{Fit})$ is m_t from top decays at LO: $E^* = [m_{\text{top}}(\text{Fit})^2 - m_W^2 + m_b^2]/[2m_{\text{top}}(\text{Fit})]$

S. Argyropoulos: Effects of colour reconnection on top mass

Experiment	m_{top} [GeV]	Error due to CR	Reference
World comb.	173.34 ± 0.76	310 MeV (40%)	arXiv:1403.4427
CMS	172.22 ± 0.73	150 MeV (20%)	CMS-PAS-TOP-14-001
D0	174.98 ± 0.76	100 MeV (13%)	arXiv:1405.1756



Ambiguity in the definition of the top mass: $m_{\text{top}}^2 \neq (p_b + p_{j1} + p_{j2})^2$

CR models

Old

- default
- default ERD

New (toy models)

- forced random
- forced nearest
- forced farthest
- forced smallest $\Delta\lambda$
- smallest $\Delta\lambda$

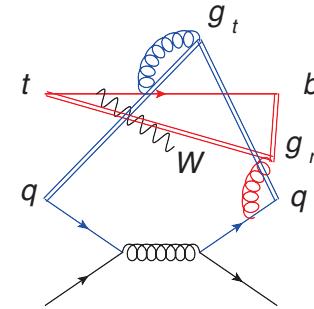
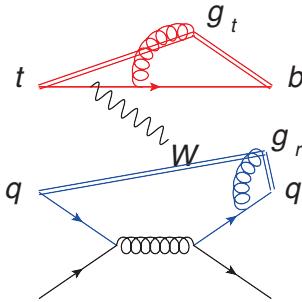
New (more sophisticated)

- swap
- move
- swap + flip
- move + flip

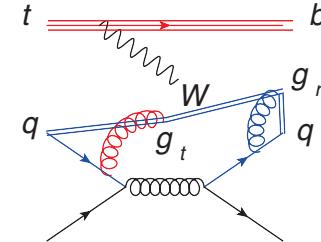
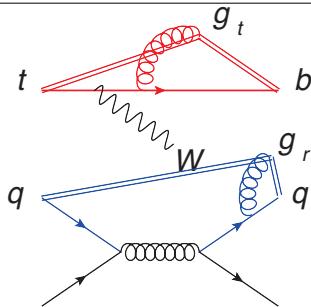
all events

only top events

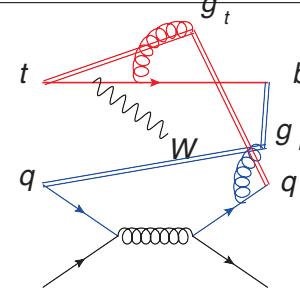
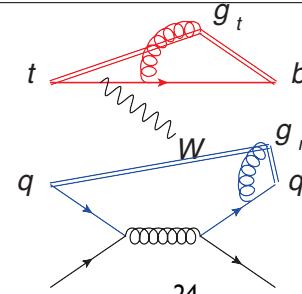
Color swap



Gluon move

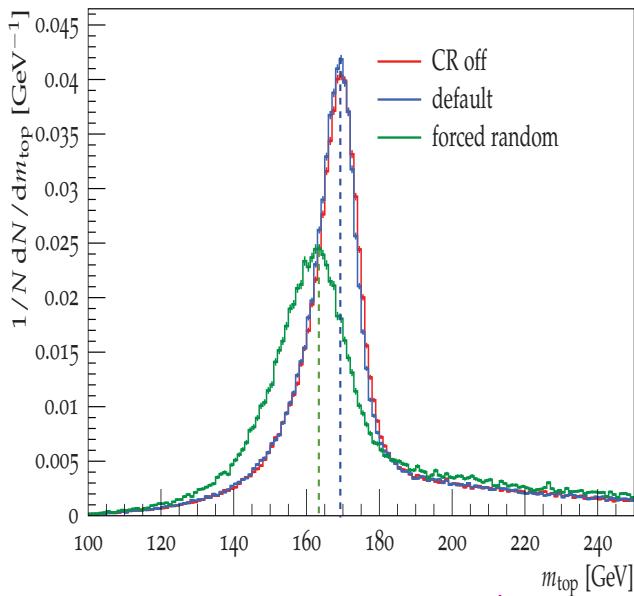


Color flip



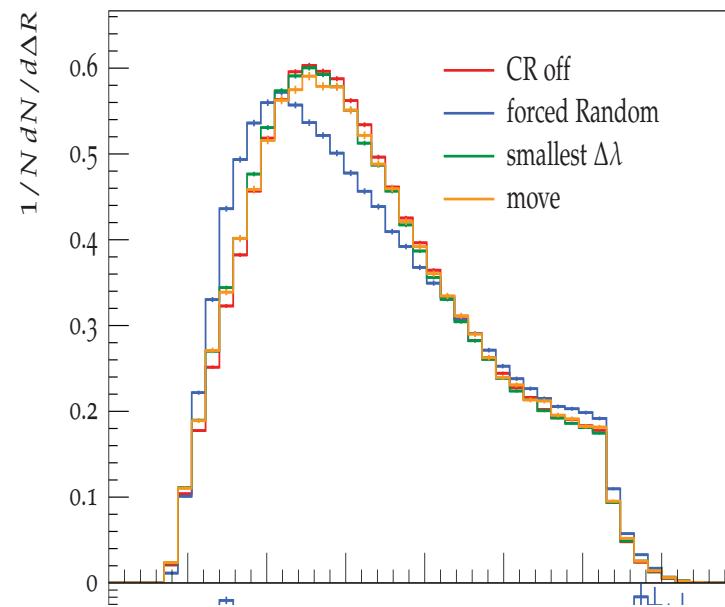
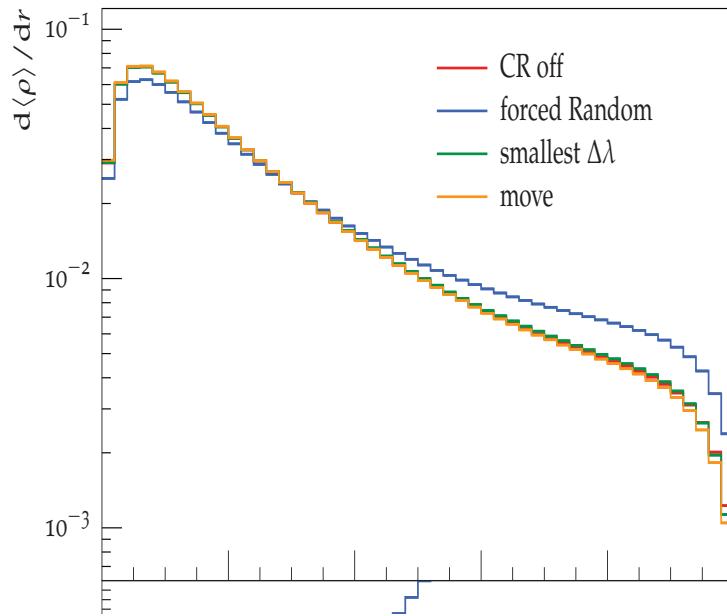
Impact on m_t before tuning

Reconstructed top mass, $m_W \in [75, 85]$ GeV, $p_T(\text{jets}) > 40$ GeV

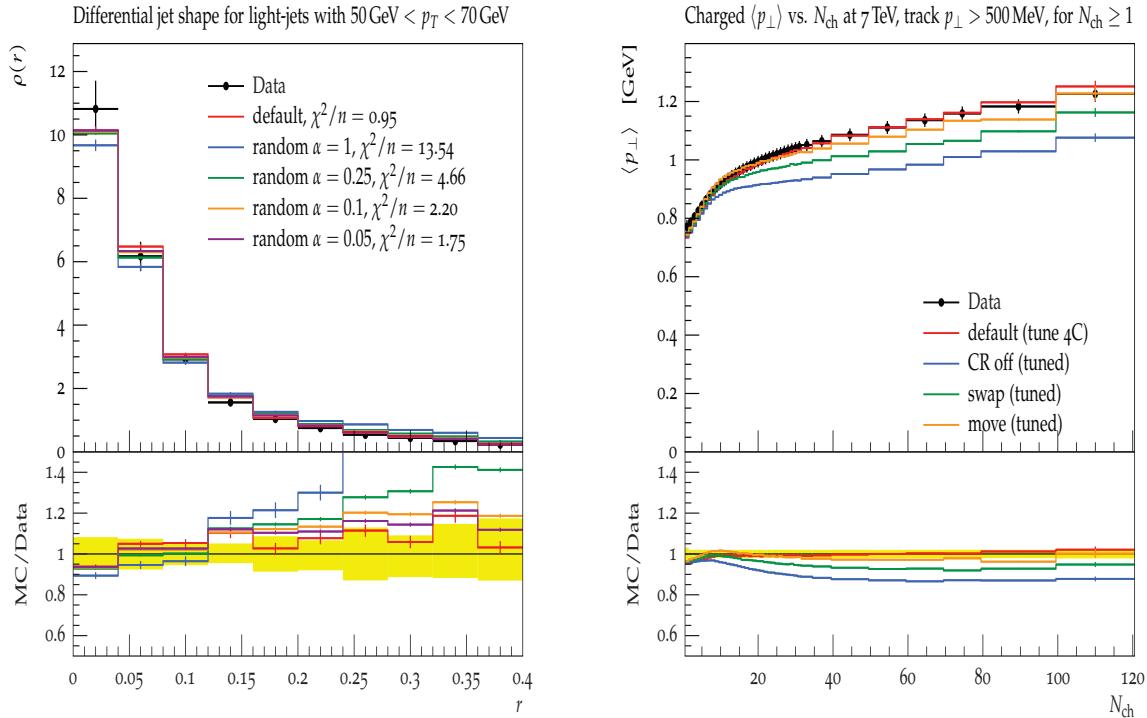


- $\Delta m_t = +0.21$ GeV (default);
- $\Delta m_t = +0.28$ GeV (default ERD);
- $\Delta m_t = -6.51$ GeV (forced random)

Differential jet shape and ΔR in $W \rightarrow j_1 j_2$ $\rho = \sum_i E_i(r - \Delta R/2, r + \Delta R/2)/E_j$



Tuning CR models



After tuning: $\Delta m_t^{\max} = 800 \text{ MeV}$; more realistically $\Delta m_t \simeq 500 \text{ MeV}$

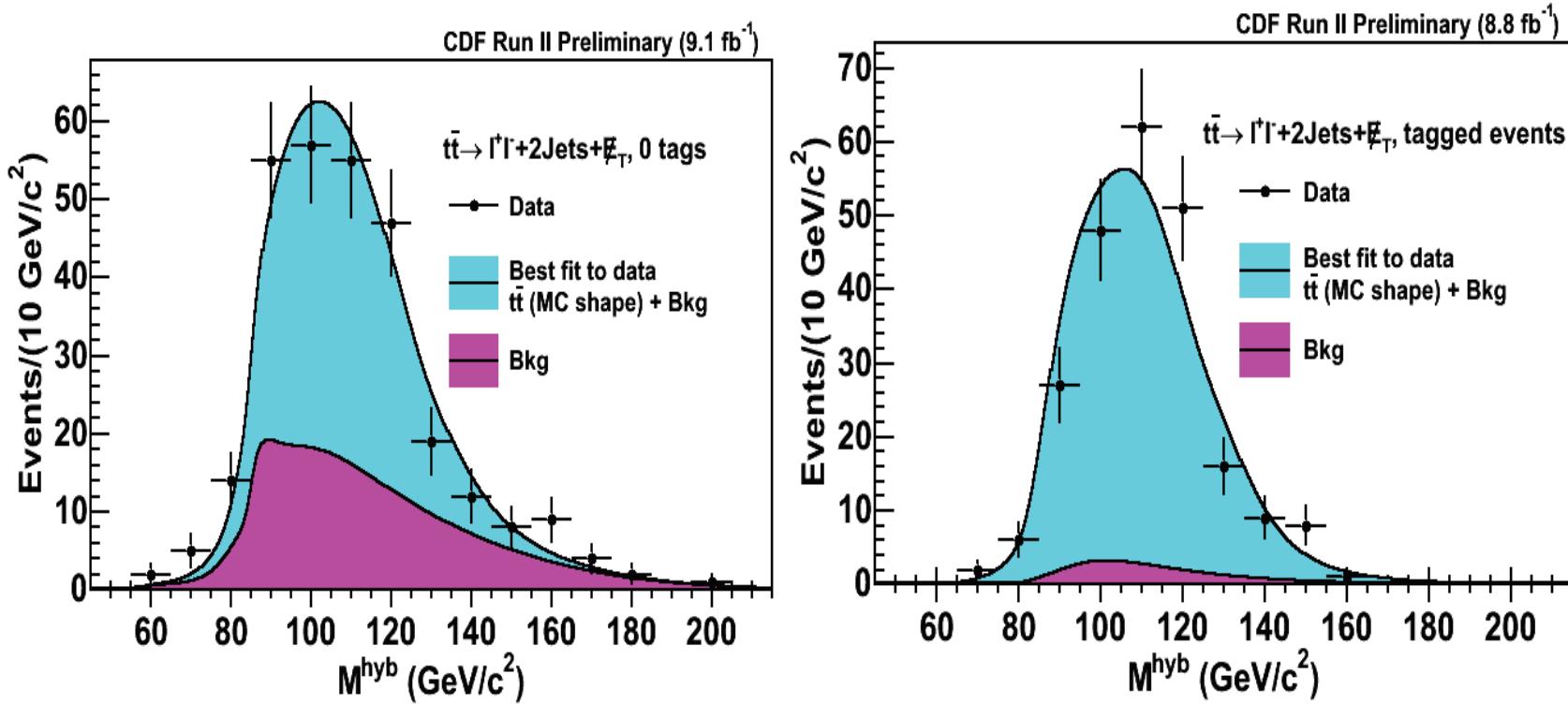
Model	$\Delta m_{\text{top}}^{\text{rescaled}} [\text{GeV}]$
default	+0.239
forced random (min)	-0.524
move	+0.239
swap (max)	+0.273

Future perspectives: more observables and tunings (charged particle multiplicity or p_T)

S. Leone: Top mass at Tevatron (mostly template method)

Recent CDF analysis in dilepton channel: $M^{\text{hyb}} = wM_t^{\text{reco}} + (1 - w)M_{b\ell}$

w is chosen to minimize statistical+JES errors: typically $w = 0.6$



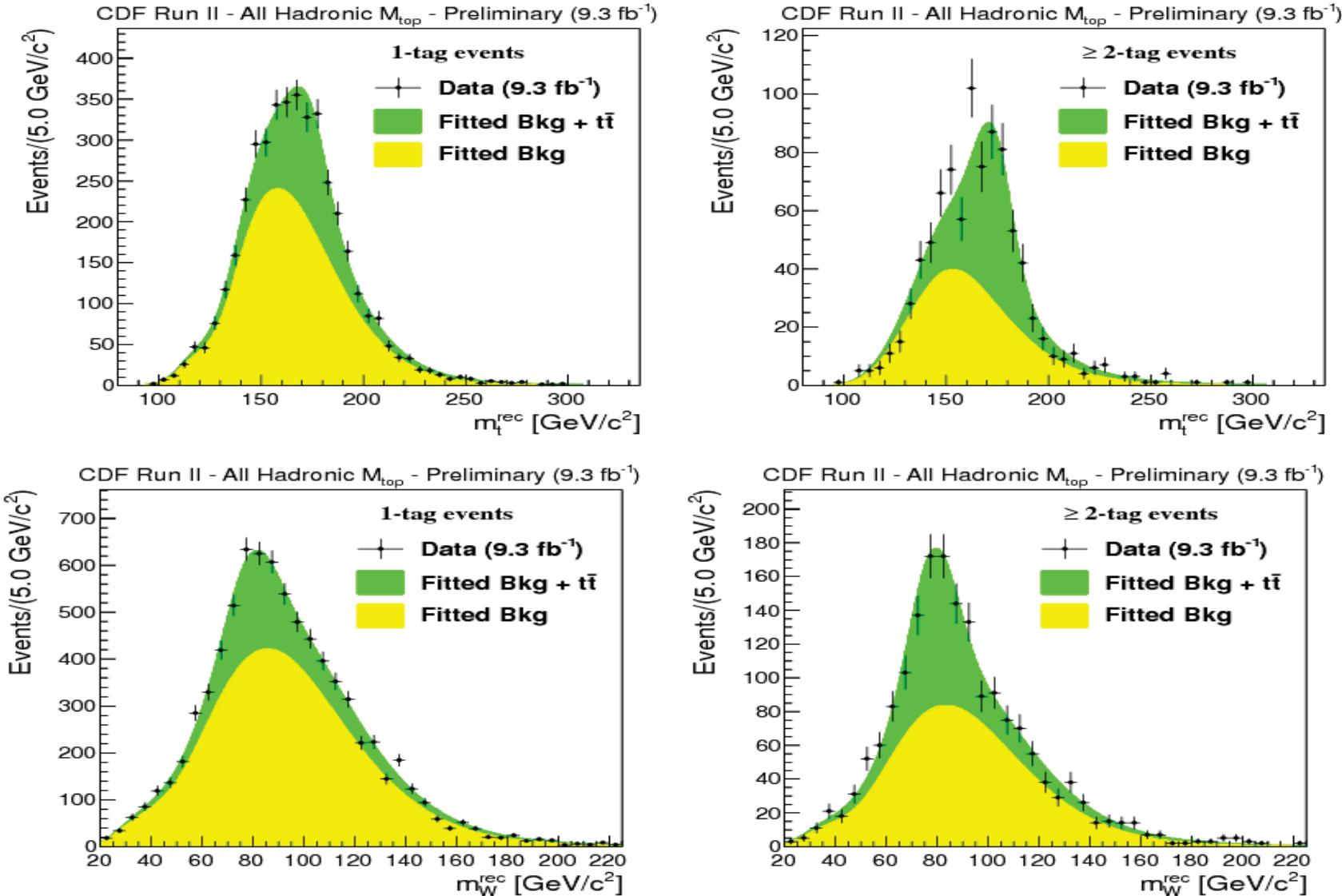
$$M_{\text{top}} = 171.5 \pm 1.9 \text{ (stat)} \pm 2.5 \text{ (syst)} \text{ GeV}/c^2$$

arXiv:1505.00500v1

Precision: 1.9%

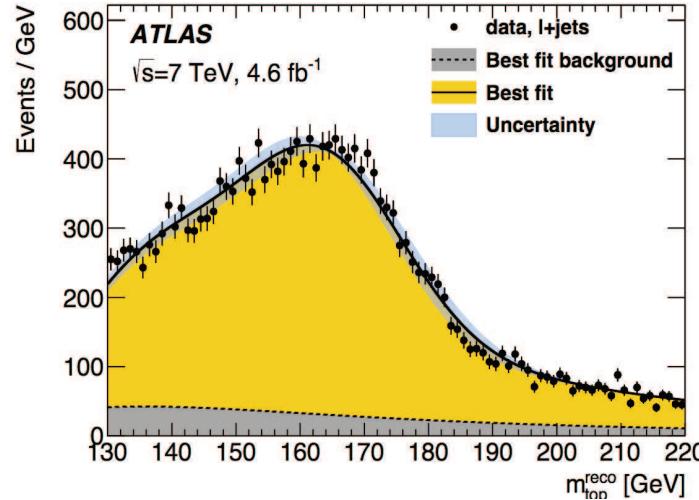
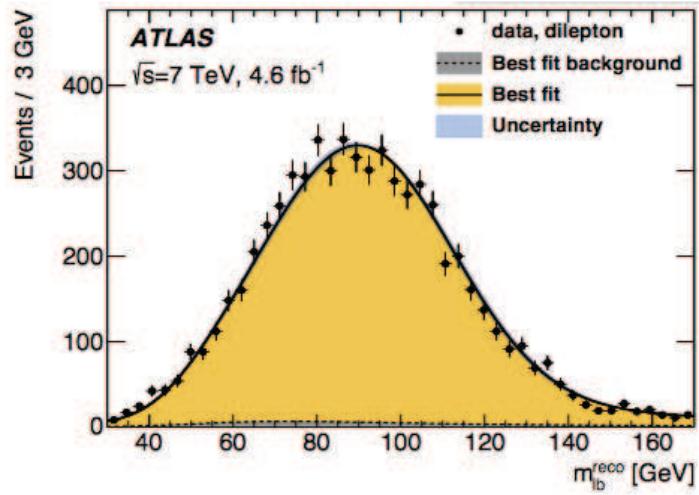
14% reduced uncertainty
compared to the previous
CDF result in this channel

All hadronic channel: template fit (CDF, PRD '14)



$$m_t = 175.07 \pm 1.19 \text{ (stat)}^{+1.55}_{-1.58} \text{ (syst)} \text{ GeV with a precision of } 1.1\%$$

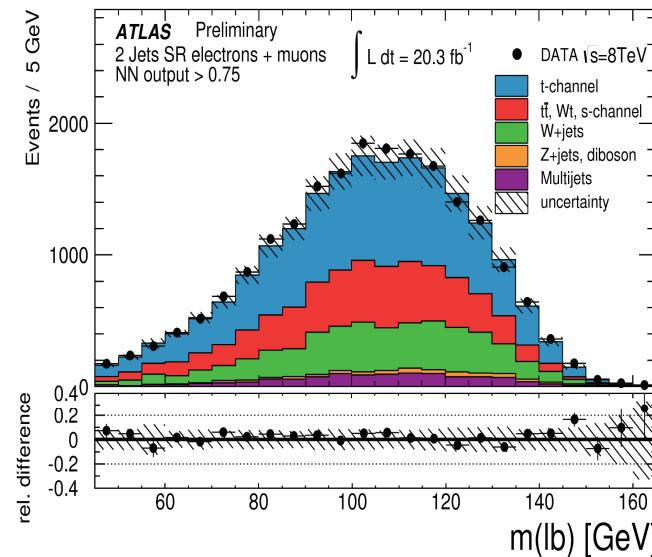
M. Cobal: Recent ATLAS analyses using template-like methods (1503.05427)



$\ell\ell$: $m_t = 173.8 \pm 0.5(\text{st}) \pm 1.3(\text{sys}) \text{ GeV}$; $\ell+\text{jets}$: $m_t = 172.3 \pm 0.8(\text{st}) \pm 1.0(\text{sys}) \text{ GeV}$

Combination: $m_t = [173.0 \pm 0.5(\text{stat}) \pm 0.8(\text{syst})] \text{ GeV}$

m_t in single top: multivariate method using NN ($m_{b\ell}$, H_T , MET, $m_T(W)$, ...)



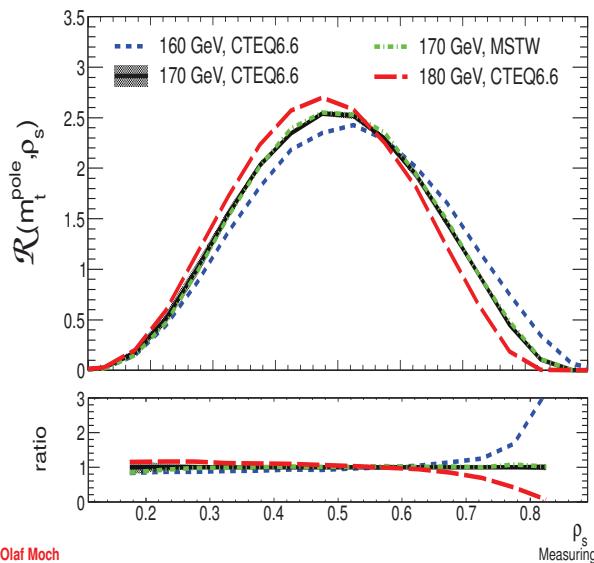
$m_t = [172.2 \pm 0.7(\text{stat}) \pm 2.0(\text{syst})] \text{ GeV}$

$\Delta m_t(\text{JES}) \simeq 1.5 \text{ GeV}$, $\Delta m_t(\text{had}) \simeq 0.7 \text{ GeV}$

Top mass in $t\bar{t} + 1$ jet using NLO calculation with pole mass (S.Moch et al)

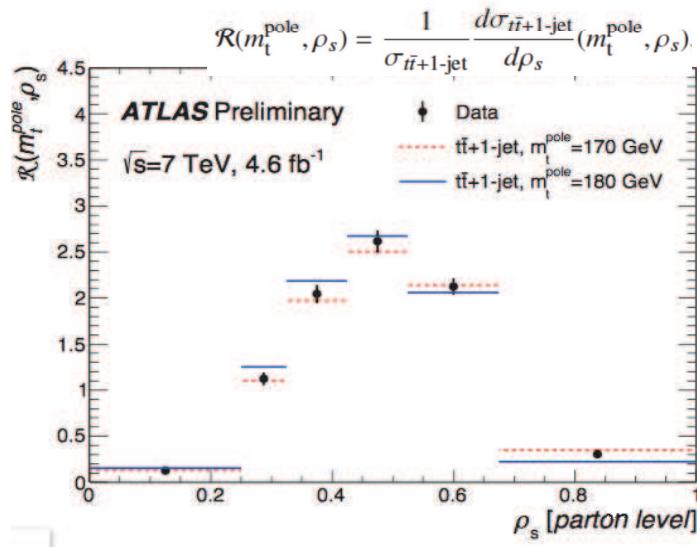
$$\mathcal{R} = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}(m_t^{\text{pole}})}{d\rho_s}$$

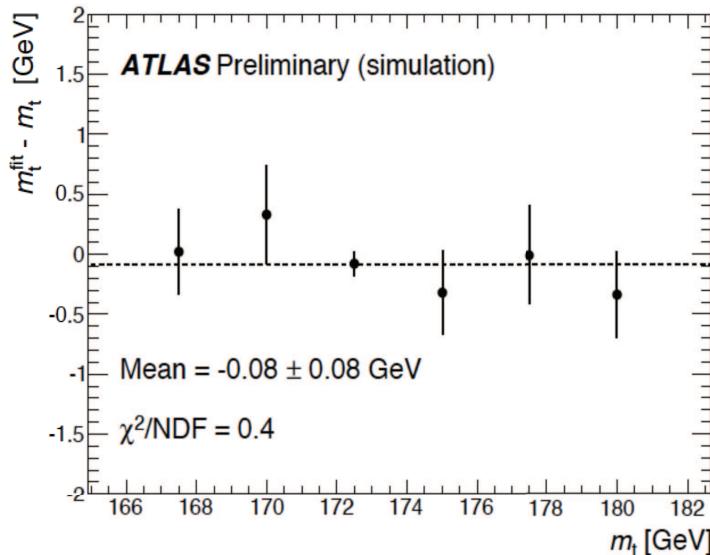
$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$



Sven-Olaf Moch

Based on unfolding the parton shower to recover the first POWHEG emission



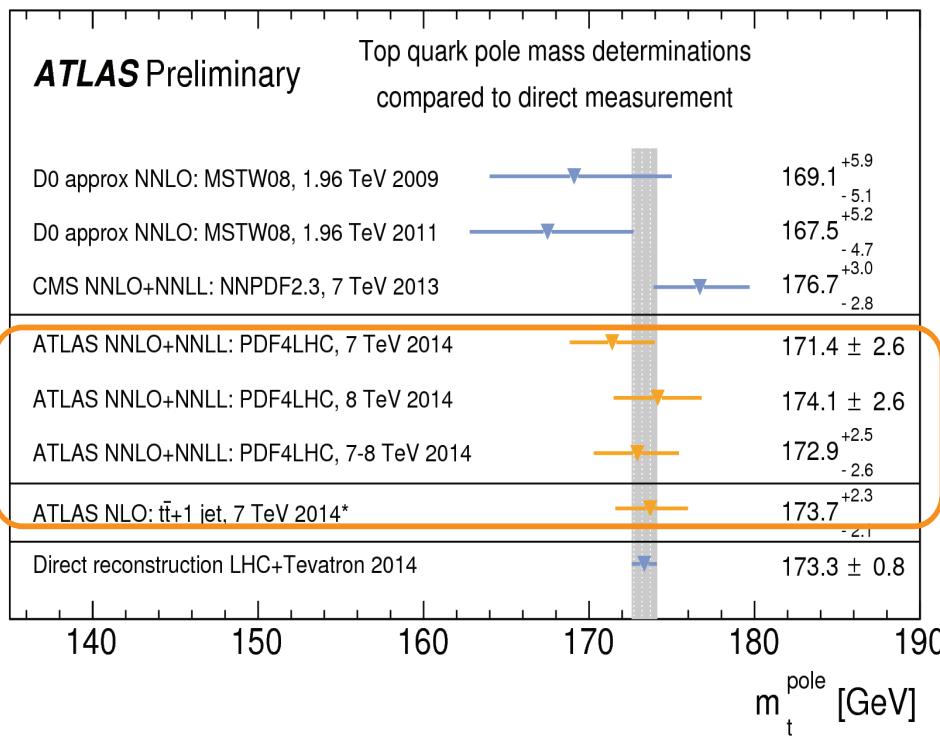


MC mass dependence

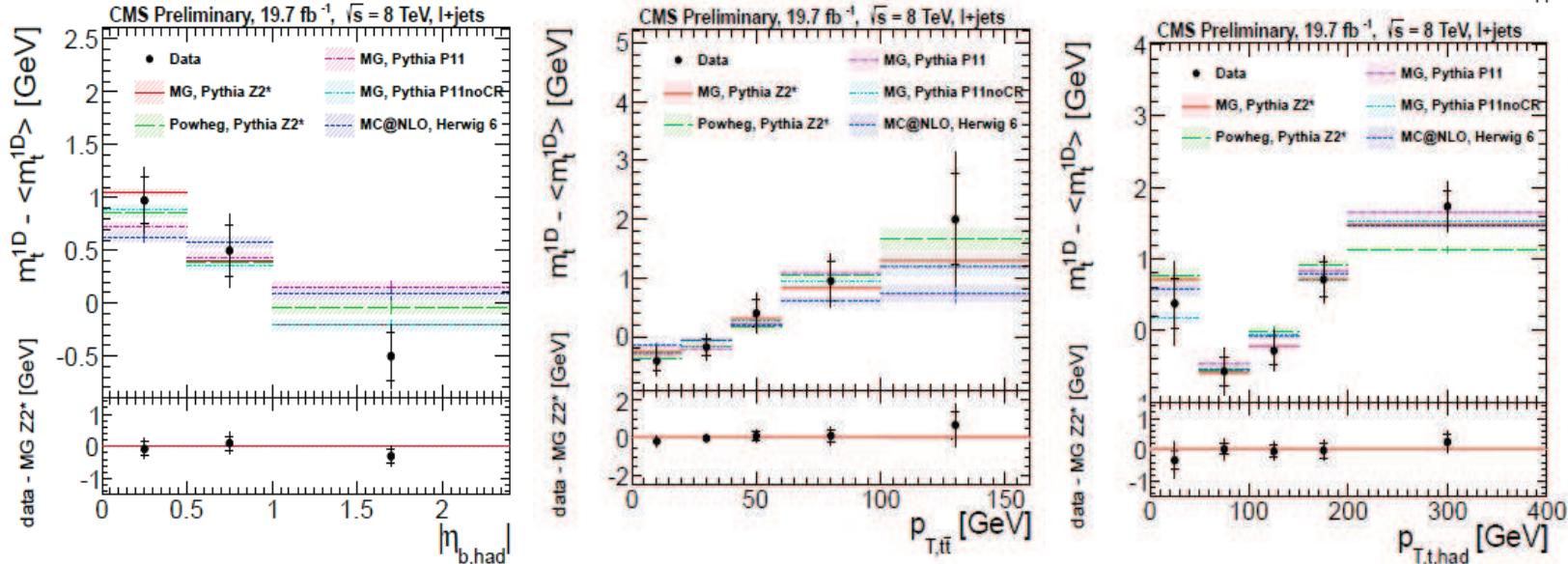
Closure & mass independence:

1) Unfold MC ($t\bar{t}$, PowHeg+Pythia) for several mass inputs:
167.5, 170, 172.5, 175, 177.5, 180 GeV

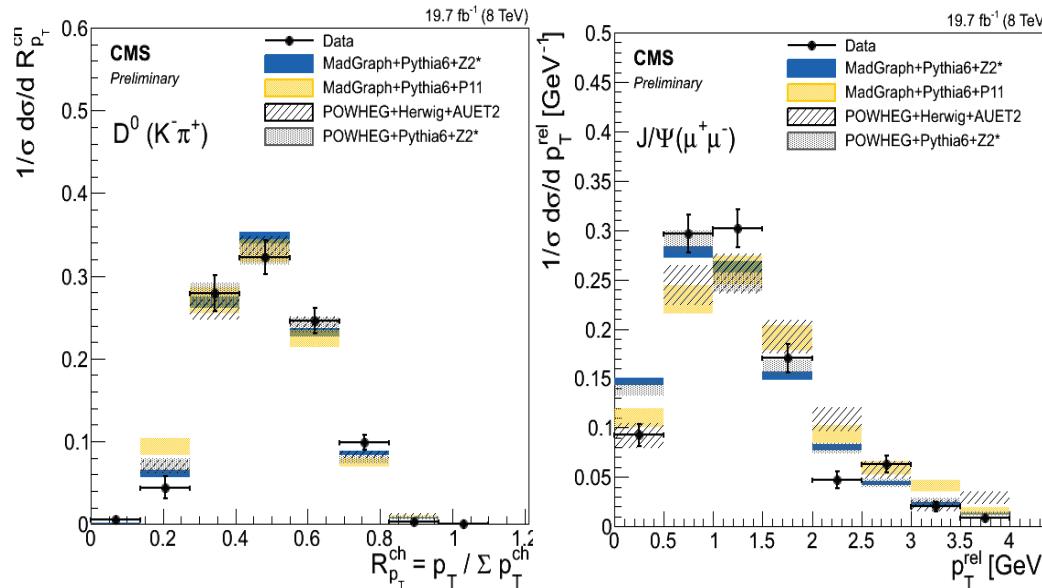
2) Fit using $t\bar{t}$ @ NLO+PS parametrization:



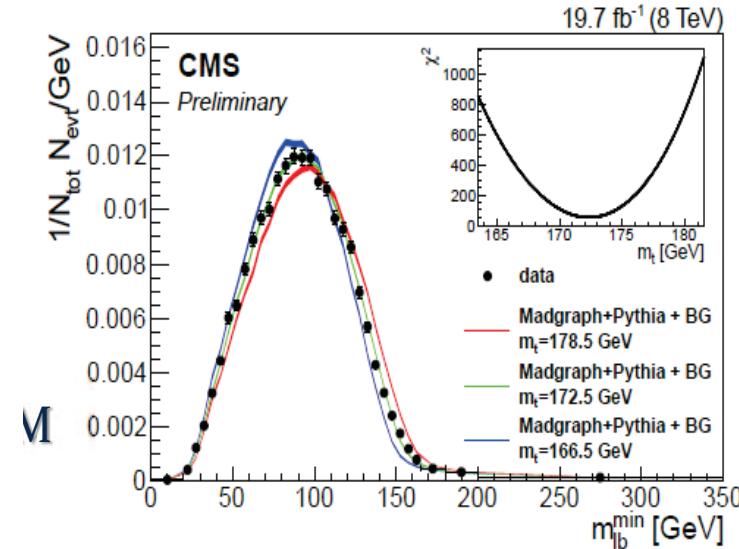
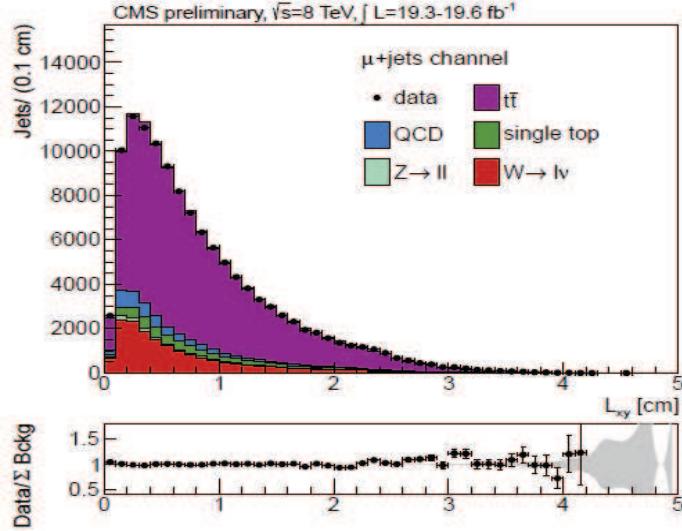
R. Chierici: Top pairs to constrain systematic uncertainty (MC generators)



Top events to study bottom-quark fragmentation

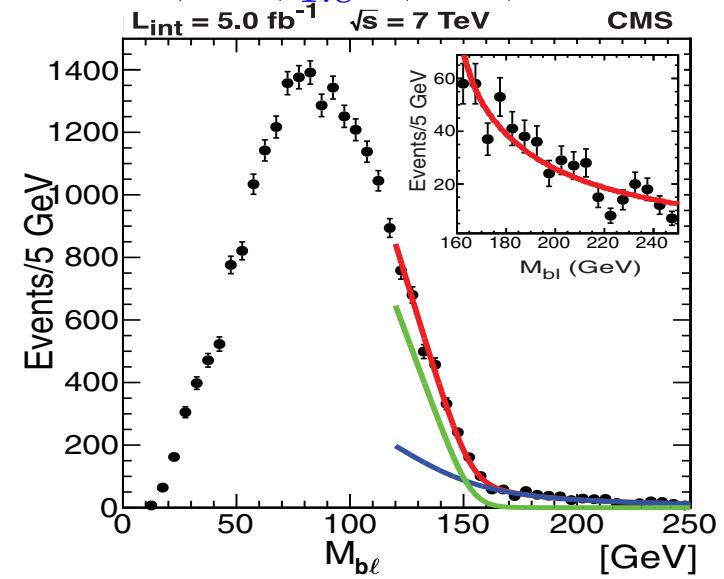
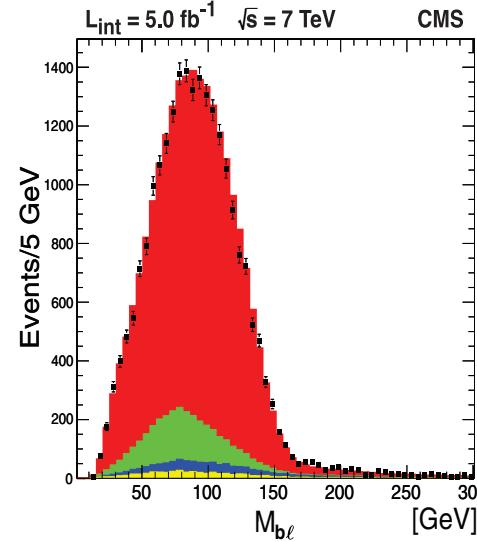
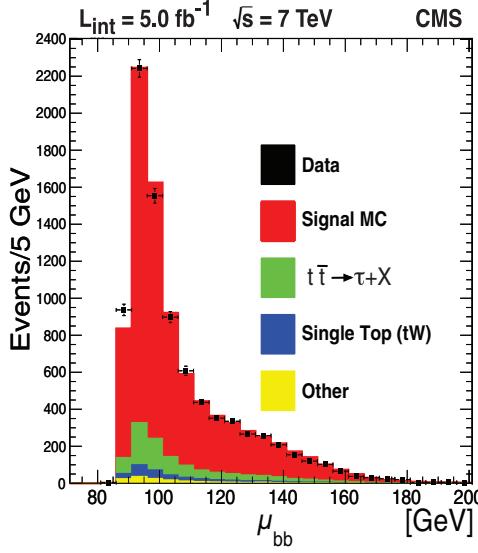


Alternative methods: B -hadron decay length (left) and $\ell + b$ -jet invariant mass (right)

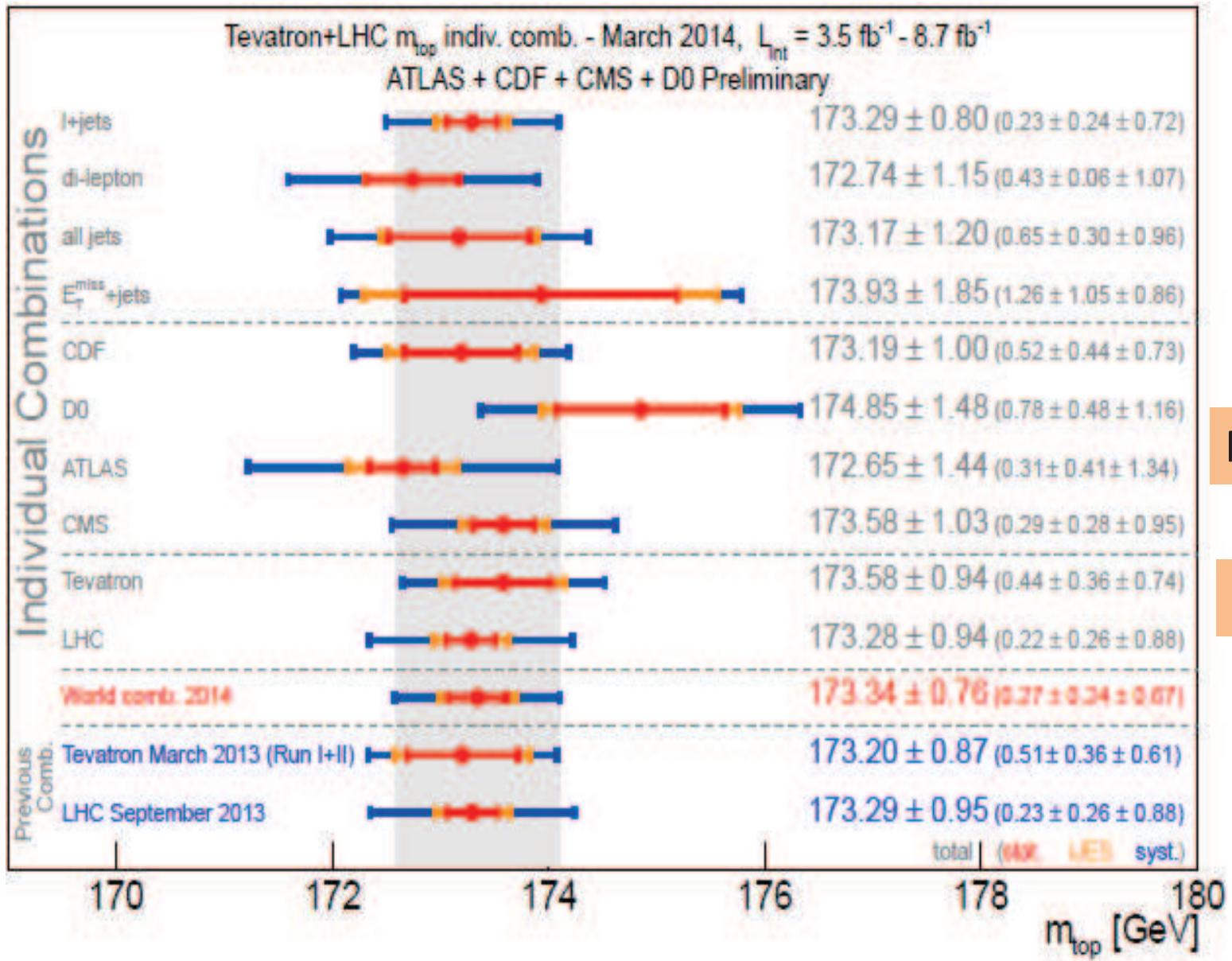


$$m_t = 173.5 \pm 1.5_{\text{stat}} \pm 1.3_{\text{stat}} \pm 2.6_{p_T}^{21} \text{ GeV } (B \text{ lifetime}) \quad m_t = 172.3 \pm 1.3 \text{ GeV } (m_{b\ell})$$

Kinematic endpoints (μ_{bb} , $\mu_{\ell\ell}$, $m_{b\ell}$: $m_t = 173.9 \pm 0.9(\text{stat})^{+1.2}_{-1.8}(\text{syst}) \text{ GeV}$)



Plans to use MCFM with pole mass for $M_{b\ell}$

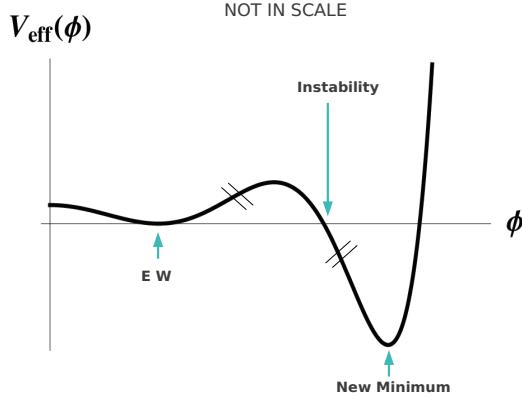


Per channel

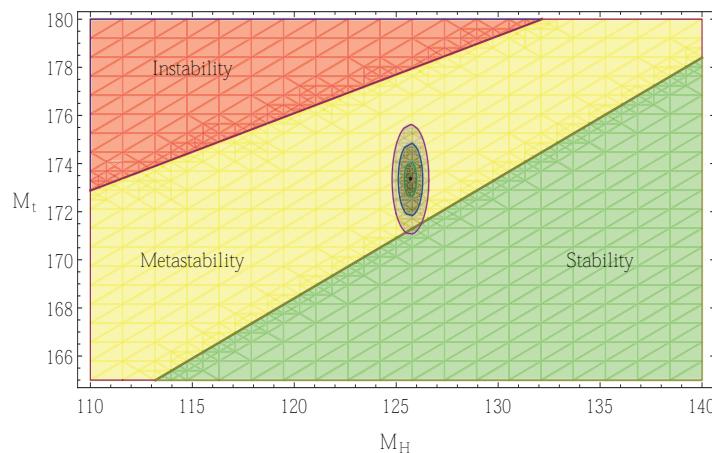
Per experiment

Per accelerator

V. Branchina: Top mass and stability of electroweak vacuum



Depending on M_H and M_t , the second minimum can be : (1) lower than the EW minimum (as in the figure) ; (2) at the same level of the EW minimum ; (3) higher than the EW minimum.



Stability region : $V_{\text{eff}}(v) < V_{\text{eff}}(\phi_{\min}^{(2)})$. **Meta-stability** region : $\tau > T_U$.

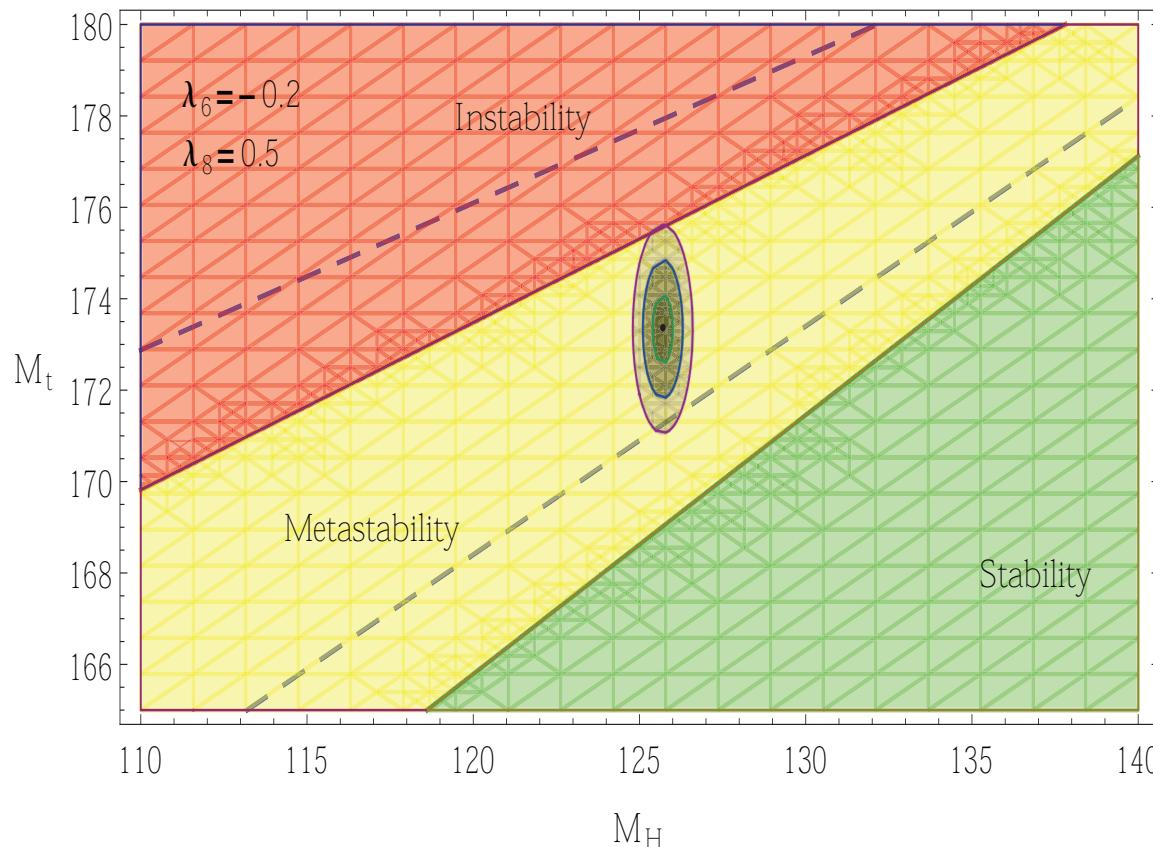
Instability region : $\tau < T_U$. Stability line : $V_{\text{eff}}(v) = V_{\text{eff}}(\phi_{\min}^{(2)})$. Instability line : M_H and M_t such that $\tau = T_U$.

Stability diagram depends on New Physics, even if it shows up at Planck scale

Toy model for New Physics at Planck scale:

$$V(\phi) = \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6} \frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8} \frac{\phi^8}{M_P^4}$$

Phase diagram with $\lambda_6 = -0.4$ and $\lambda_8 = 0.7$

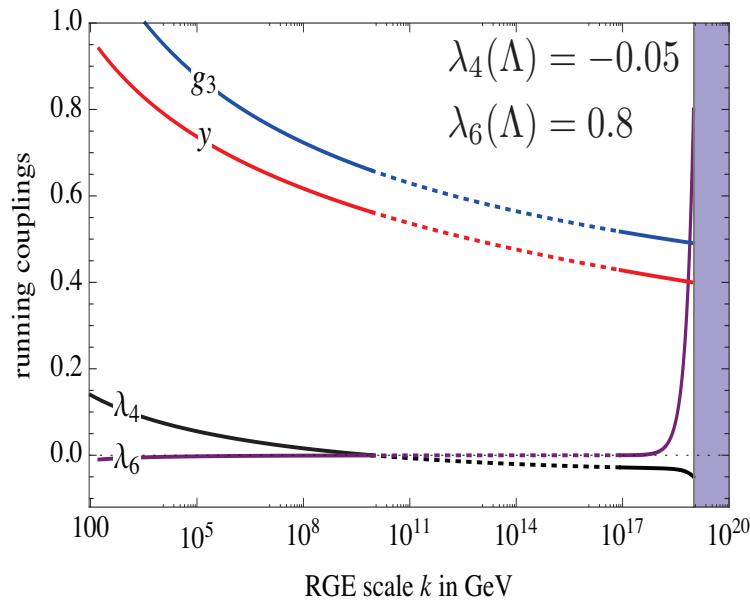
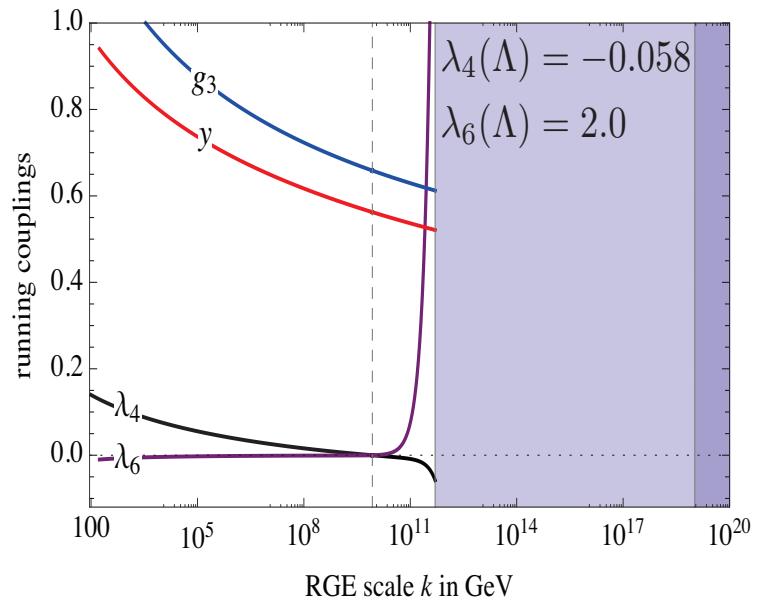


Lesson from toy model: the stability diagram is valid if one assumes that there is no New Physics up to M_P and that possible New Physics at M_P does not modify the tunnelling probability (regardless of precision on m_t)

M. Scherer: Stabilizing V_{UV} by adding a term $\sim H^6$

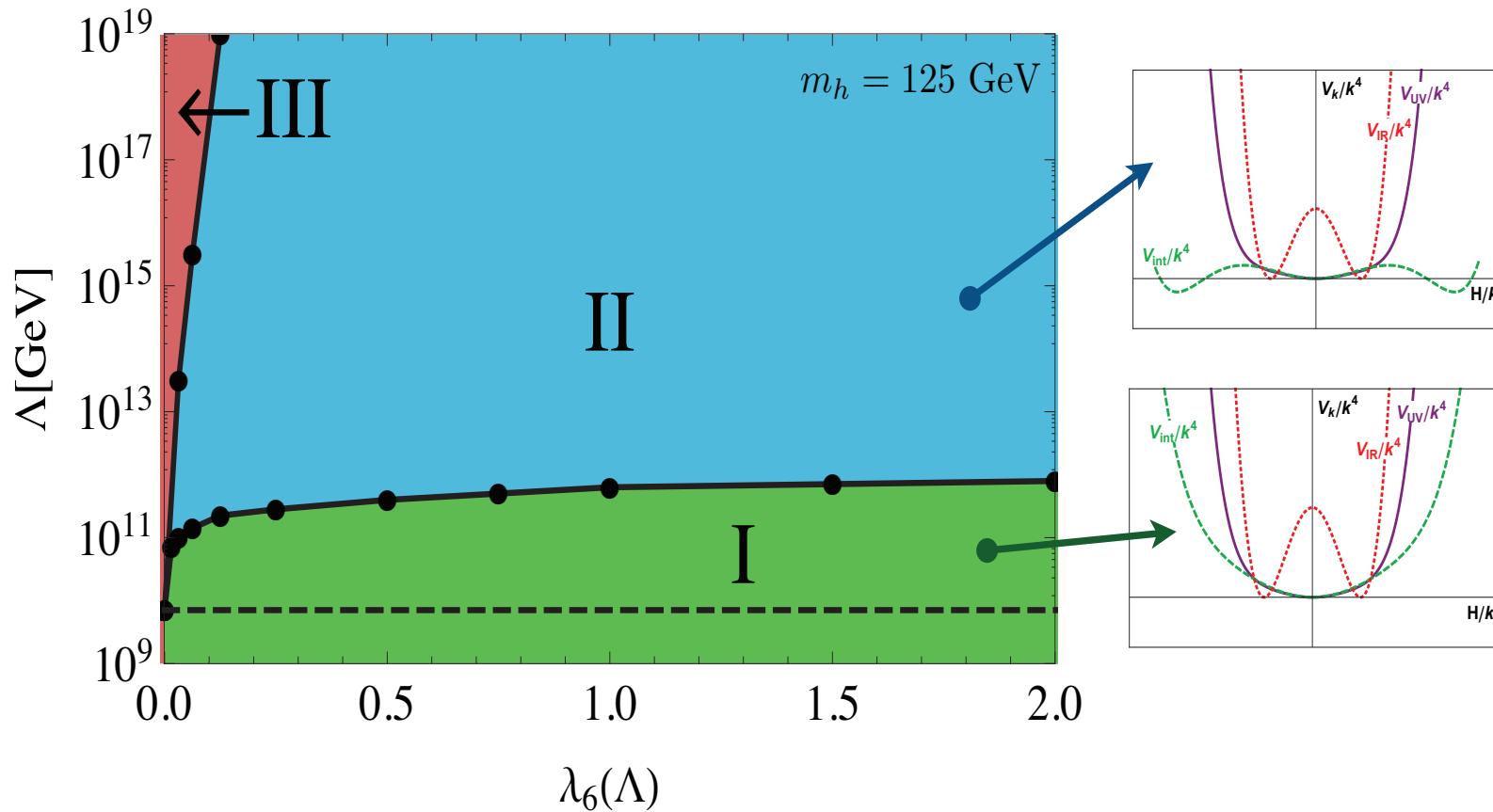
$$V_{\text{UV}} = V_{\text{eff}}(\Lambda) = \frac{\mu^2(\Lambda)}{2} H^2 + \frac{\lambda_4(\Lambda)}{4} H^4 + \frac{\lambda_6(\Lambda)}{8\Lambda^2} H^6$$

Choosing $\lambda_6(\Lambda) > \lambda_4^2(\Lambda)\Lambda^2/[3\mu^2(\Lambda)]$ removes second minimum at $H \neq 0$ at Λ



- ▶ Potential completely stable during entire RG flow
- ▶ Extend UV cutoff by orders of magnitude (~ 2)
- ▶ Potential develops 2nd Minimum during RG flow
 - ▶ Min @ $H=0$ only metastable
 - ▶ Small λ_6 sufficient to stabilize UV potential
 - ▶ Further studies required...

Stability diagram in terms of λ_4 and Λ



- ▶ Moderately small $\lambda_6(\Lambda)$ extend UV cutoff by 2 orders of magnitude at full stability (green)
- ▶ Pseudo-stable region (blue) - allows for more orders of magnitude
 - extend FRG study
 - possibility of meta-stable effective potential at $k \approx 0$

Conclusions

Very lively workshop in Frascati on top mass determination and definition

On the theory side, calculations and Monte Carlo implementation to address several open issues

Relation between Monte Carlo and theoretical mass definitions (SCET): ongoing work for e^+e^- collisions and prospects to extend it to hadron colliders

EFT approach to include off-shell effects at NLO and get consistent mass definitions

Novel observables proposed to extract m_t : cross section for $t\bar{t}$ and $t\bar{t}+\text{jets}$, energy peaks

New models for colour reconnection (major uncertainty on m_t) need further tuning to data

Crucial role played by the top mass on any statement on the stability of the electroweak vacuum (though depending on assumptions on New Physics at Planck scale)

From the experimental side, a number of increasingly precise measurements, with special effort to address consistent theoretical mass definitions (total cross sections, endpoint methods, . . .)