Hadronization Effects

- Introduction and Motivation -

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Hadronization WS, June 13, 2019

Content

- Why do we care?
- Examples where it matters a lot.
- MC top mass problem
- Some recent MC studies
- Conclusions

Why do we care?

- Hadronization effects suppressed for cross sections or distributions governed by hard scales Q >>Λ_{QCD} : → OPE: $(\Lambda_{QCD}/Q)^n$

- Hadronization effects non-OPE-like for distributions governed by scales close to Λ_{QCD}.

- Become increasingly important at high precision.

- Future of LHC: high precision requirement to gain sensitivity in the search for new physics.

- Very few hadron level theoretical predictions (≃ analytic predictions with theoretically controlled power corrections or hadronization functions)

- Hadronization effects depend on the scheme we use for our partonic calculations (→ factorization scale dependene, renormalons)

Why do we care?

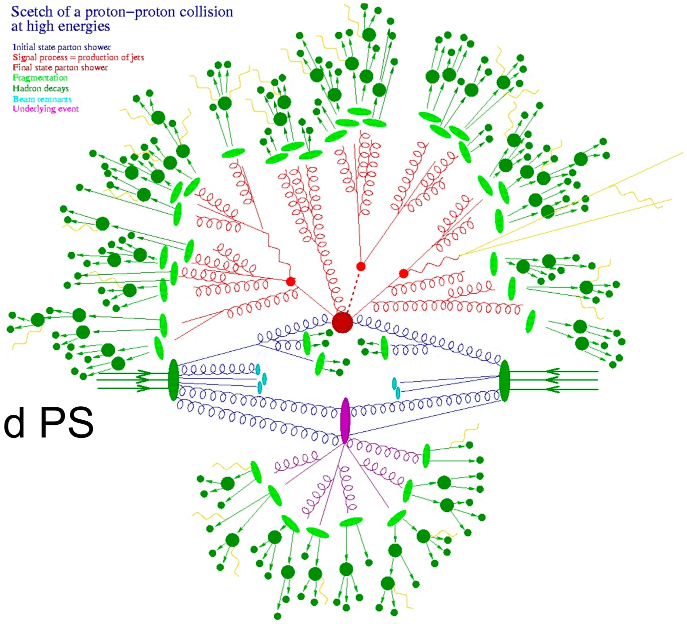
- Collider community generally not very devoted to worry out hadronization effects or willing to spend time on it.

- Bulk of hadronization effects for LHC cross sections described by hadronization models contained in MC event generators.

- Development and implementation of hadronization models left to MC authors.

  1) Hard matrix elements (HME)
  2) Parton shower (PS)
  3) Hadronization Model → ”tuning”

- Fixed by fits to sets of standard observables
- Must compensate for deficiencies of HME and PS
- Sometimes used to estimate hadronization corrections for parton level computations

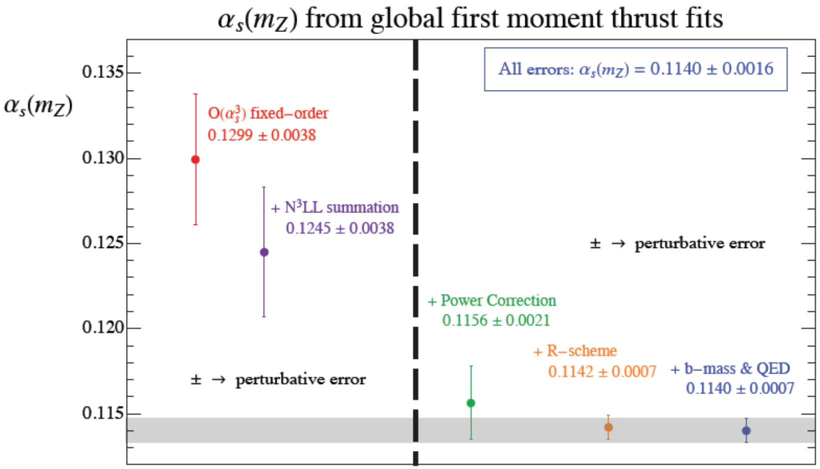


Why do we care?

- For some high precision observables we are running into brick walls using the current approach:

  in particular for the determination of QCD parameters

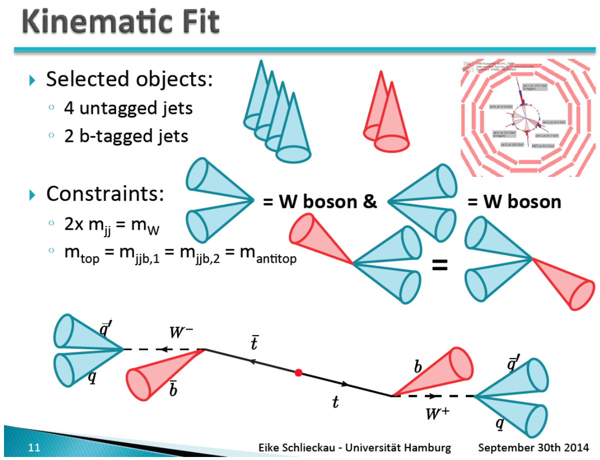
Strong coupling from event shapes problem:



- Fit for power corrections leads to strong coupling below world average. Missing subleading power resummation?
- Using hadronization corrections from MC generators leads to strong coupling compatible with world average
- Who is right?

The MC Top Mass Problem

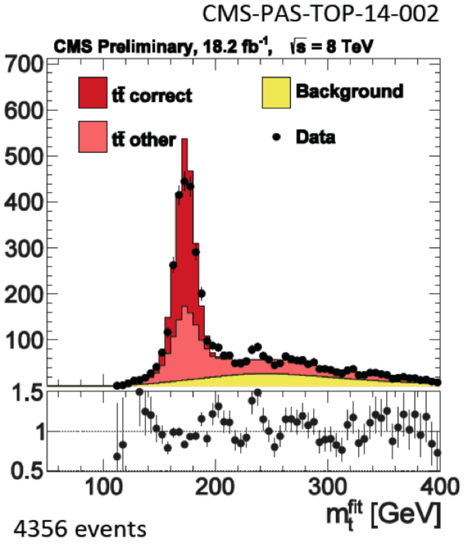
Direct kinematic methods:



Kinematic Fit

- Selected objects:
  - 4 untagged jets
  - 2 b-tagged jets
- Constraints:
  - 2x $m_{jj} = m_W$
  - $m_{top} = m_{jjb,1} = m_{jjb,2} = m_{antitop}$

e.g. template fits



- ⊕ High leading order top mass sensitivity
- ⊕ Insensitive to norm uncertainties (pdf, ..)

- ⊖ Parton shower and hadronization dominated
- ⊖ Purely based on MC
- ⊖ MC uncertainties ?
- ⊖ Meaning of m_t^{MC} ?

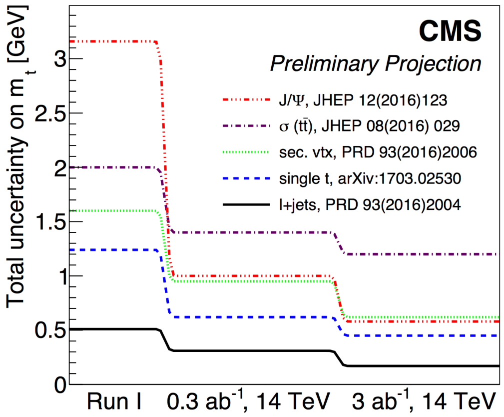
$$m_t^{\rm MC} = 174.34 \pm 0.64 \quad \text{(Tevatron final, 2014)}$$

$$m_t^{\rm MC} = 172.44 \pm 0.49 \quad \text{(CMS Run-1 final, 2015)}$$

$$m_t^{\rm MC} = 172.69 \pm 0.48 \ \text{(ATLAS Run-1 final, 2018)}$$

Most precise method.

I will focus on it!



Relevant already today because of very high leading order sensitivity.

← $\Delta^{ex} m_t \sim 200$ MeV
(HL-LHC projection)

For an ultimate precision of 200 MeV all methods are going to have the same level of complication.

The MC Top Mass Problem

Better statement: Scheme is (un)determined by the structure <u>and</u> the theoretical (in)precision of the parton shower.

Quark mass scheme encodes the amount of unresolved radiation surrounding the heavy quark in our calculations. Pole mass assumes all real radiation is resolved.

Parton shower describes (almost) all radiation explicitly: m_t^{MC} must be close to m_t^{pole} !

But:

a) Parton showers are working in the approximation of a stable top quark. (Narrow width approximation)

b) Parton showers are not uniformly precise for all observables. (They are not fully next-to-leading order precise for all observables even with NLO matching.)

c) The shower cutoff Q_0 treats all radiation below Q_0 as unresolved.

Without any further systematic study of what the quantum structure of parton showers and MC event generators is, the only conservative (= absolutely save and undisputable) statement one can make is that the MC top mass parameter agrees with the pole mass within an theoretical uncertainty of size of the top quark width:

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} \pm \max(\Gamma_t, Q_0)$$

Why do we care?

- Having MCs with smaller uncertainties and better systematic control of theoretical uncertainties (power counting) would better help to improve the situation.

My opinion on
overall status
↓

- We need:

1. More precise FO computation (lots of work) 😀
2. Parton shower matching (lots of work) 😀
3. Parton showers with better systematics and controllable uncertainties 😕 → Jack's, Zoltan's and Matthew's talks (Tuesday)
4. Hadronization models (new models or existing automatically better?) 😖 → Stefan's and Cody's talks

We also need analyses and theory tool that can quantify precisely the precision of current MC generators and their theoretical limitations.

- Hadron level analytic factorization predictions → Adi's and Andrea's talks
- Dedicated studies of parton showers and hadronization models <u>by themselves</u>

  → hadronization models should not be used to fix problems of parton showers

The MC Top Mass Problem

To start the systematic considerations we should set up a notation so that we can discuss the different issues in a systematic way.

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}$$

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup
- (Affected by finite width effects?)

Non-perturbative contribution:

- Effects of hadronization model
- May depend on parton shower setup

Monte Carlo shift:

- Contribution arising from systematic MC uncertainties
- E.g. color reconnection, b-jet modeling, (finite width), ...
- Should be covered by 'MC uncertainty' or better negligible

- Scrutinize theoretical content of MC event generators, so that we can write an equality in the first place.

Lebel of systematics of MC decides whether the equality of to be

understood phenomenologically or field theoretically

Cutoff in Angular Ordered Parton Showers

Plätzer, Samitz, AHH; JHEP 1810 (2018) 200

The first step of a systematic theoretical examination:

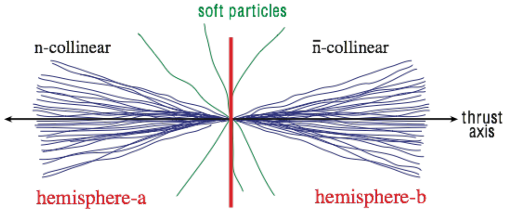
Δ_m^{pert} can be examined at $\mathcal{O}(\alpha_S)$ for τ_2 (2-jettiness) in the resonance region for e^+e^- collisions:

Restrictions:

- Parton level
- Boosted top quarks (dijet factorization and shower algorithm reliable)
- Narrow width approximation
- Examination of radiation in top production

2-Jettiness τ_2 distribution In the peak region (for e^+e^- and boosted tops) can be discribed using QCD dijet-factorization at NLL+NLO and coherent branching (CB) at NLL.

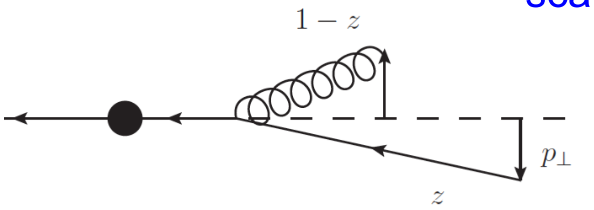
- Which role does the shower cut Q_0 play quantitatively?



Cutoff in Angular Ordered Parton Showers

→ Coherent branching: (basis of the Herwig parton shower)

Catani, Marchesini, Webber 1991
Gieseke, Stephens, Webber, 2003



scale in α_S: $\mu^2 = p_\perp^2 + (1-z)^2 m^2$ cutoff: $p_\perp^2 > Q_0^2$

Usually not present in analytic QCD !

→ QCD factorization (SCET+bHQET):

Fleming, Mantri, Stewart, AHH, 2007

$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2}\right)_{\rm hemi} = \sigma_0\, H_Q(Q,\mu_m) H_m\left(m, \frac{Q}{m}, \mu_m, \mu\right) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\left(\hat s_t - \frac{Q\ell^+}{m}, \Gamma, \mu\right) B_-\left(\hat s_{\bar t} - \frac{Q\ell^-}{m}, \Gamma, \mu\right) S_{\rm hemi}(\ell^+, \ell^-, \mu)$$

Ultra-collinear radiation

Large-angle soft radiation

- Correspondences can be cross checked by explicit computations.

Cutoff in Angular Ordered Parton Showers

Plätzer, Samitz, AHH; JHEP 1810 (2018) 200

Q_0=0 :

→ Computational scheme of resummed pQCD calculations

→ Coherent branching algorithm can be solved analytically in the same way

Outcome:

- Equivalence of CB and SCET at NLL order for Q_0=0 (massive quark case new!)
- NLL precision sufficient to specify the mass scheme at $\mathcal{O}(\alpha_S)$
- **Generator mass m_t is the pole mass m_t^{pole} for Q_0=0 !**

But for MC event generation parton showers require $Q_0 \gtrsim 1$ GeV, so it is mandatory to consider a finite shower cut !

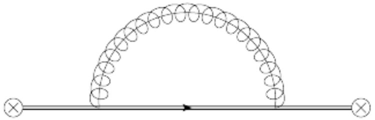
Cutoff in Angular Ordered Parton Showers

Plätzer, Samitz, AHH; JHEP 1810 (2018) 200

$Q_0 > 0$:

- Pole of the top quark propagator = $m_t^{CB}(Q_0) \neq m_t^{pole}$ (**coherent branching mass**)

$$\boxed{m_t^{\mathrm{CB}}(Q_0) = m_t^{\mathrm{pole}} - \frac{2}{3} Q_0 \alpha_s(Q_0) + \mathcal{O}(\alpha_s(Q_0)^2)}$$



- In the presence of the shower cut the **ultra-collinear radiation** generated by CB produces exactly the mass scheme change correction that is required so that the generator mass is exactly the coherent branching mass $m_t^{CB}(Q_0)$.

$$\sigma(m_1, Q, \ldots) = \sigma(m_2, Q, \ldots) + \delta m \times \frac{\mathrm{d}}{\mathrm{d}m} \sigma(m, Q, \ldots)\Big|_{m=m_1} + \ldots$$

$$\delta m = m_2 - m_1$$

Scheme change correction

- The shower cut also affects **large-angle soft radiation. T**he corresponding effects are directly tied to the amount of hadronization effects that are fixed by tuning (effects are the same for massless quarks)

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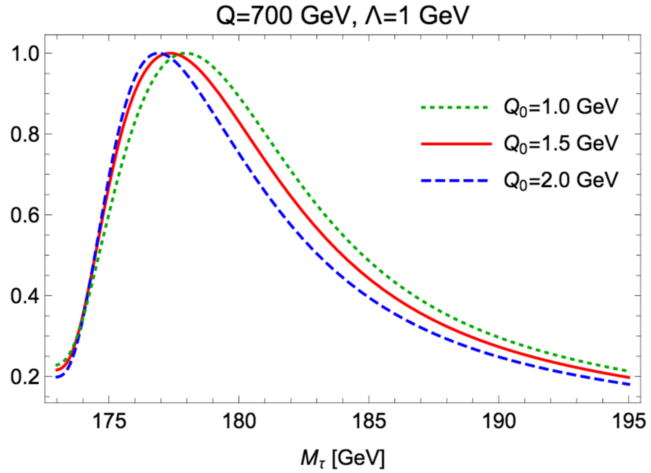
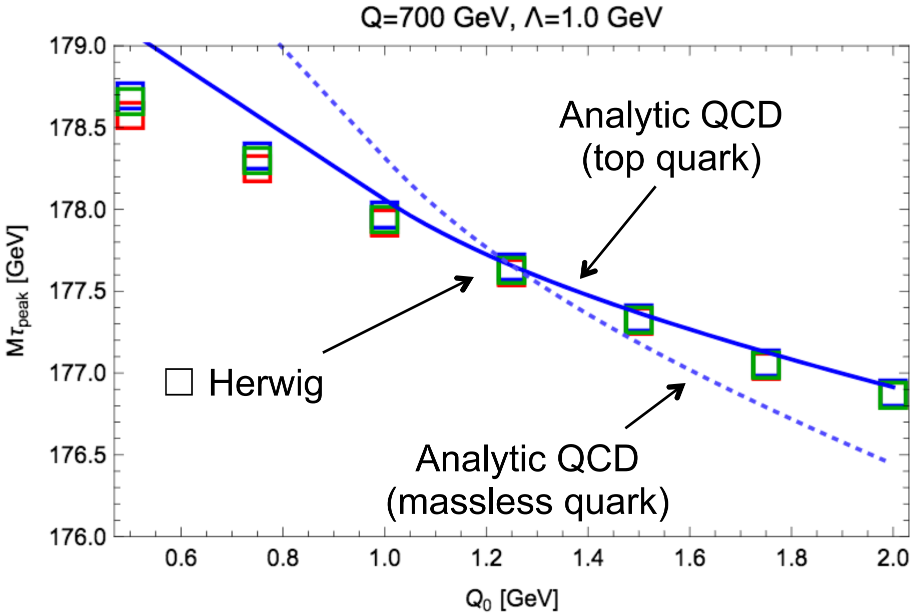
Q_0 Dependence: Herwig vs analytic QCD

Peak position of $M_\tau = \dfrac{Q^2\tau_2}{2m_t} \quad (Q = E_{\rm cm})$

- Depends on value of Q_0 (while keeping hadronization effects unchanged)
- Relative Q_0 dependence of hadronization and the top mass depends on Q





- Herwig simulations in full agreement with analytic calculation for CB algorithm

$$\tau_{\rm peak}(Q_0) = \tau_{\rm peak}(Q_0') - \frac{1}{Q}\Big[16 - 8\pi\frac{m}{Q}\Big]\int_{Q_0'}^{Q_0} {\rm d}R\,\frac{C_F\,\alpha_s(R)}{4\pi}$$

Plätzer, Samitz, AHH; JHEP 1810 (2018) 200

Q_0 Dependence: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

How well does Herwig's hadronization model match the analytic prediction?

We start with an analysis for massless quarks first.

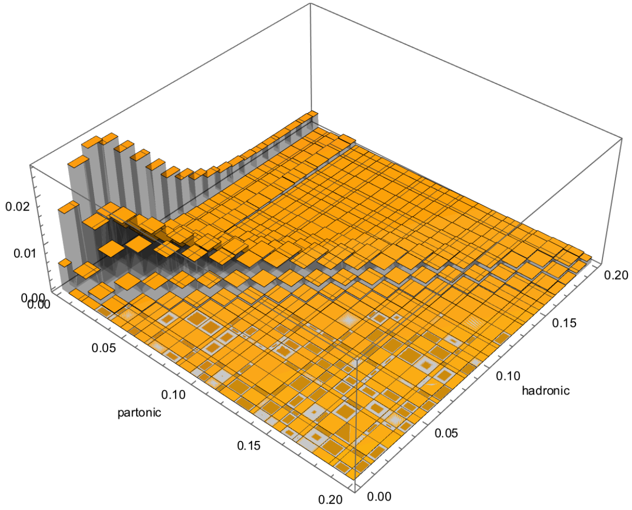
- For massless quark production a change of Q_0 only modifies the soft function

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau}(\tau, Q, Q_0) = \int_0^{Q\tau} \mathrm{d}\ell \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\tau}\Big(\tau - \frac{\ell}{Q}, Q, Q_0'\Big) \; S_{\mathrm{mod}}(\ell + \Delta_{\mathrm{soft}}(Q_0) - \Delta_{\mathrm{soft}}(Q_0'))$$

- Any change of the shower cut from Q_0 to Q_0' can be compensated by a modification of the soft function gap (or its first moment) by the amount

$$\Delta_{\mathrm{soft}}(Q_0) - \Delta_{\mathrm{soft}}(Q_0') = 16 \int_{Q_0'}^{Q_0} \mathrm{d}R \, \Big[\frac{\alpha_s(R) C_F}{4\pi} + \mathcal{O}(\alpha_s^2) \Big]$$

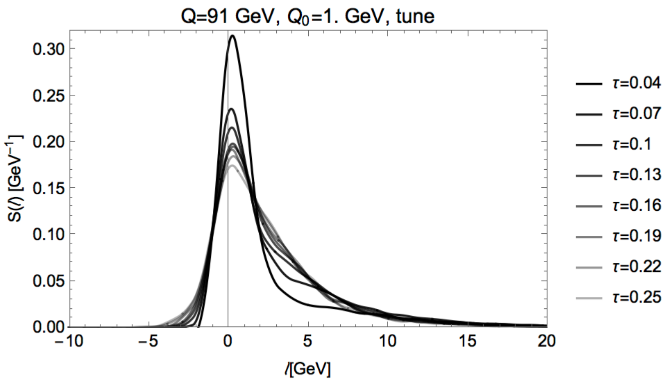
We modified Herwig to allow the extraction of the event-by-event (true!)parton-to-hadron level transfer matrix.

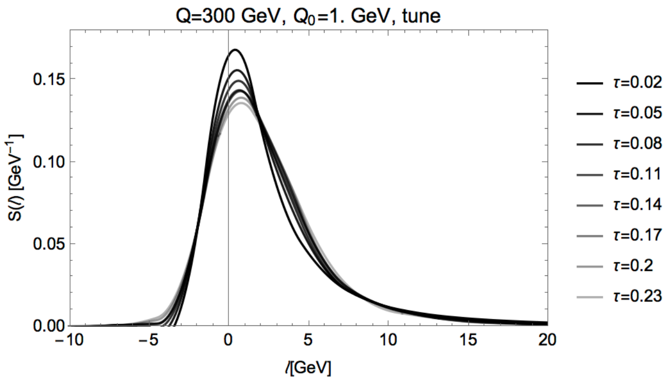


Q_0 Dependence: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

An ideal hadronization model could


Q=91 GeV, Q_0=1. GeV, tune


Q=300 GeV, Q_0=1. GeV, tune

The soft function model is not uniform, but seems to depend on where you are in the tail of the distribution and also on Q. But the really relevant information is their first moment which can be easily calculated from the extracted models.

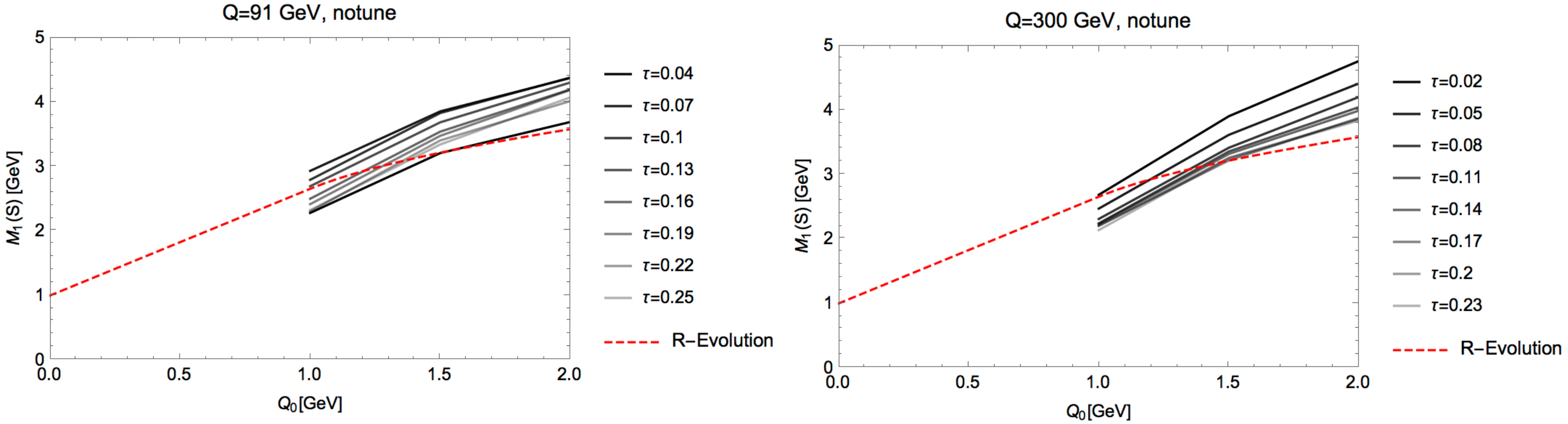
We can now test how Herwigs hadronization model responds to a change of the shower cut.

Q_0 Dependence: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

An ideal hadronization model would automatically compensate for a modified shower cut as it just evolves from a different scale and acts like a parton shower as long as Q_0 is perturbative.

Can Herwigs hadronization model do that?



To some extend yes, but not good enough. It overcompensates. Discrepancies at the level to 1 GeV can arise.

The spread in the hadronization models is quite significant. Maybe an artifact of the tuning to whole spectra rather then tail regions?

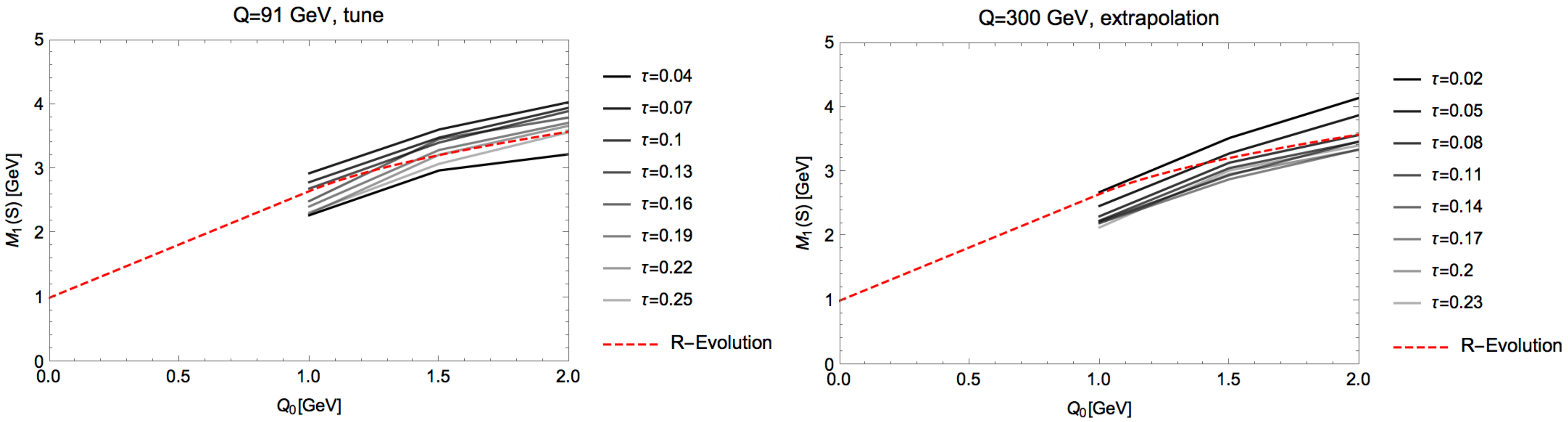
Q_0 Dependence: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

We now retune with the standard tuning observables:

event shapes, charged tracks, jet rates, y_{nm} at $Q=M_Z$

For the Q_0-dependent retuning we tune the MC to itself and not to data!



Improved behavior of Herwig's soft function model.

Retuning for each Q_0 is absolutely necessary.

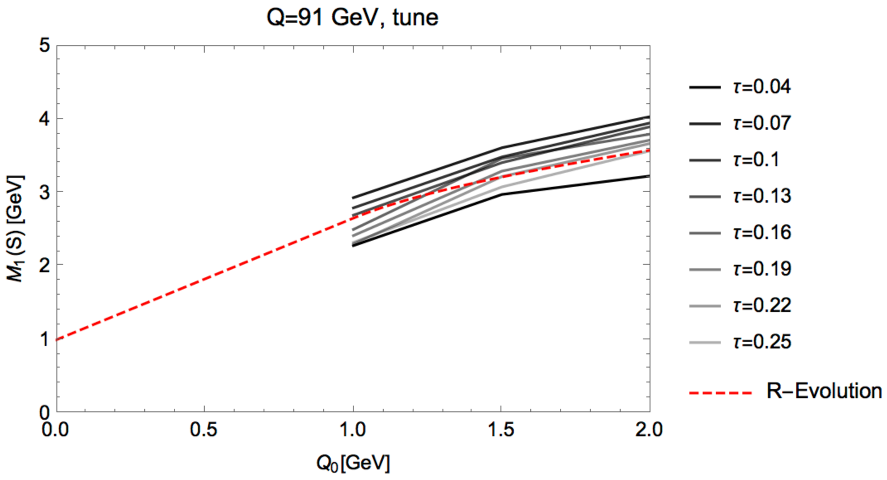
Also a reasonable extrapolation to Q=300 MeV which is far away from where the retuning was carried out.

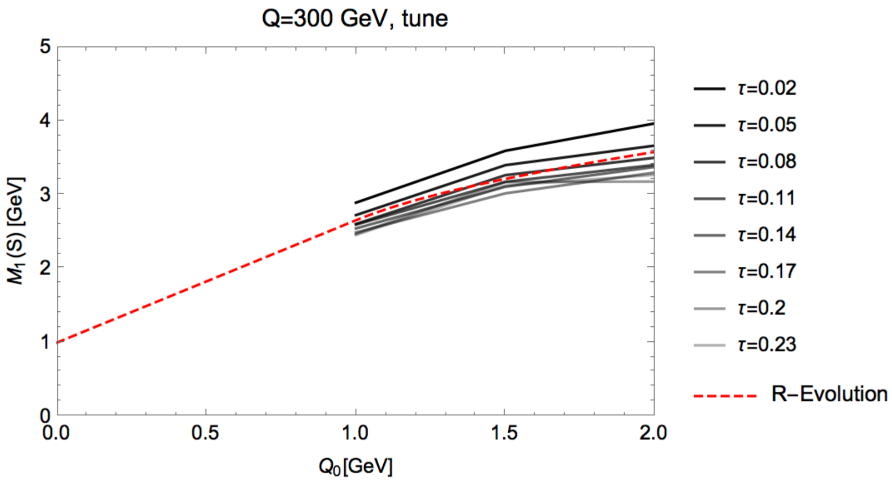
Q_0 Dependence: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

For the 300 GeV case we may also retune to

event shapes, charged tracks, jet rates, y_{nm} at Q=300 GeV





Improved behavior of Herwig's soft function model at 300 GeV.

After full local retuning Herwig's soft function models are fully compatible with QCD.

The quality of Herwig's hadronization model extrapolation to high energies is not optimal.

…. work in progress….

Q_0 Dependence: Herwig vs analytic QCD

Plätzer, Samitz, AHH; w.i.p

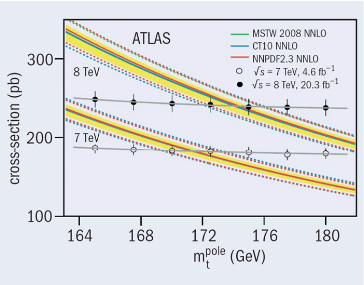
- Strong coupling determinations:
  - Switch pQCD predictions to MC IR regularization scheme
  - Extract strong coupling from MC
  - High precision analysis of extrapolations
  - Improved hadronization modelling
- Top mass:
  - Starting point of analysis of how hadronization affectx MC top mass parameter

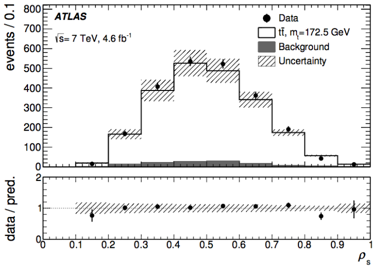
Backup Slights

The Top Mass Problem

Indirect global methods:

- Other measurements based on NLO and NNLO pQCD calculations of **σ**(tt, ttj):
  → "pole mass measurements", but uncertainties larger than for direct method



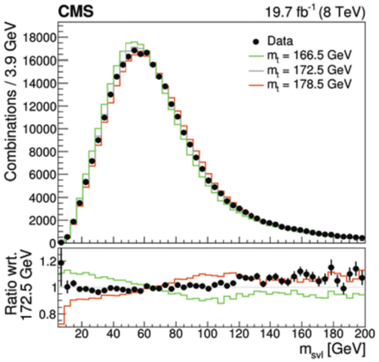


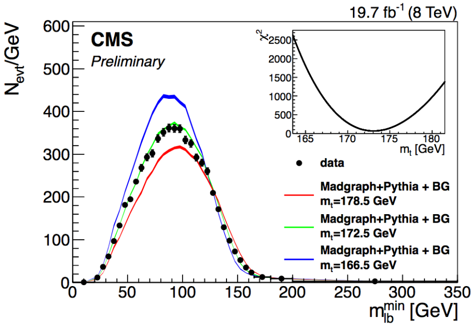
- ⊕ pQCD-FO calculations dominate
- ⊕ Control of mass scheme
- ⊖ Lower top mass sensitivity
- ⊖ High sensitivity to norm uncertainties (pdf, α_S, ..)

arXiv:1904.05237 : m_t^{pole} = 170. 5 ± 0.8 GeV from d**σ**(tt)/dX, X=N_{jet} , M_{tt} , y_{tt} + NLO/PS

arXiv:1905.02302 : m_t^{pole} = 171. 1 ± 1.1 GeV from **σ**(tt+jet) + NLO-QCD

- Hadron/lepton methods (M_{Bl}, M_{bl}, E_B, E_l, T_2, ..):





- ⊕ Experimentally clean
- ⊕ Partly based on pQCD
- ⊖ lower top mass sensitivity
- ⊖ strong dependence on MC simulations
- ⊖ Significant hadronization effects