Comments on the Top Mass Relevant for ILC and LHC

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Outline

- General remarks
  - Field theoretic aspects: Short-distance vs. pole mass
  - Renormalon problem
  - Top mass in MC programs
- Top threshold at ILC
- Total cross section at LHC
- Jet reconstruction: status
- Outlook and Conclusions

General Remarks

Quantum Field Theory:

Particles: Field-valued operators made from creation and annihilation operators

Lagrangian operators constructed using correspondence principle

Classic action: m is the rest mass

No other mass concept exists at the classic level.

$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_{\mathrm{classic}} + \mathcal{L}_{\mathrm{gauge-fix}} + \mathcal{L}_{\mathrm{ghost}}$$

$$(p^2 - m^2)\, q(x) = 0$$

$$\mathcal{L}_{\mathrm{classic}} = -\frac{1}{4} F^A_{\alpha\beta} F_A^{\alpha\beta} + \sum_{\mathrm{flavors}\ q} \bar{q}_\alpha (i\not{D} - m_q)_{\alpha\beta}\, q_b$$

$$D^\mu = \partial^\mu + i g T^C A^{\mu C}$$

$$i \frac{p + m}{p^2 - m^2 + i\epsilon}$$

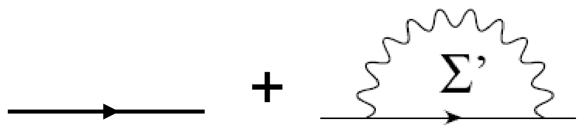
$$-i \frac{\left(g^{\mu\nu} + \frac{p^\mu p^\nu}{p^2}(\xi - 1)\right)}{p^2 + i\epsilon}$$

classic particle poles

Concept of a Quark Mass

Renormalization: UV-divergences in quantum corrections

Fields, couplings, masses in classic action are bare quantities that need to be renormalized to have (any) physical relevance



$$= \not{p} - m^0 + \Sigma(p, m^0)$$

$$m^0 \, \frac{\alpha_s}{\pi} \left[-\frac{1}{\epsilon} + \text{finite stuff} \right]$$

Mass Renormalization Schemes you know:

Pole mass: mass = classic rest mass

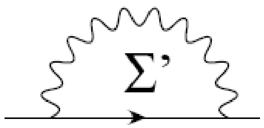
$$m^0 = m^{\text{pole}} + \delta m^{\text{pole}} \qquad \delta m^{\text{pole}} = \Sigma(m, m)$$

$\overline{\text{MS}}$ mass:

$$m^0 = \overline{m}(\mu) - \frac{\alpha_s}{\pi} \frac{1}{\epsilon}$$

Concept of a Quark Mass

So … do we have to care?



$$\Sigma(m,m) = -\frac{4}{3}\int \frac{d^4q}{(2\pi)^4}\,\alpha_s\,\gamma^\mu \frac{q+k+m}{(q+k)^2-m^2}\gamma_\mu \frac{1}{q^2}$$

$$\overset{q \ll m}{=} \frac{2}{3}\int \frac{d^3q}{(2\pi)^3}\frac{\alpha_s(q)}{\vec{q}^2} = -\frac{1}{2}\int \frac{d^3q}{(2\pi)^3}\,V(\vec{q}^2)$$

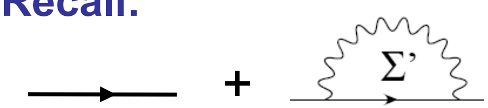
<u>On-shell limit:</u> Causes linear sensitivity to infrared momenta leads to factorially growing coefficients in perturbation theory.

$$\Sigma(m,m) \sim \sum_n \alpha_s^{n+1}(2\beta_0)^n n!$$

OK, we can absorb the bad correction into the mass

What's the problem?

Recall:



$$= p - m^0 + \Sigma(\not{p}, m^0)$$

$$\sim p - m^{\text{pole}}$$

Concept of a Quark Mass

→ The on-shell limit is intrinsic to the definition S-matrix elements involving external heavy quarks. (Cannot be avoided in perturbation theory)

→ Linear infrared sensitivity for the Quark self-energy AND the Interaction in the on-shell limit.

→ The heavy quark on-shell limit is, however, artificial/unphysical and all linear infrared sensitivity cancels in a IR-safe process.

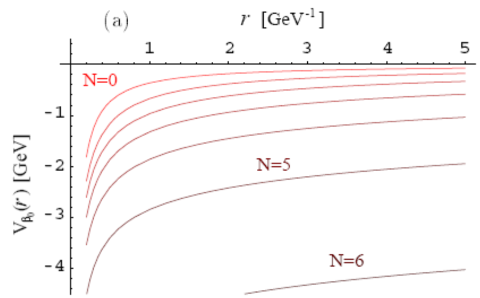
→ Use of pole mass prohibits the cancellation to become manifest.

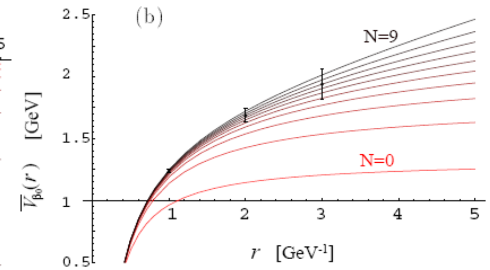
- Pole mass: order-dependent concept
- In practice: Relevant if one asks for precision $\delta m_t < 1$ GeV

Examples

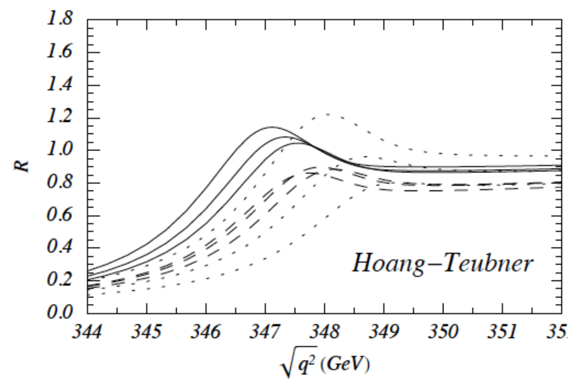
pole mass scheme | Short-distance mass scheme

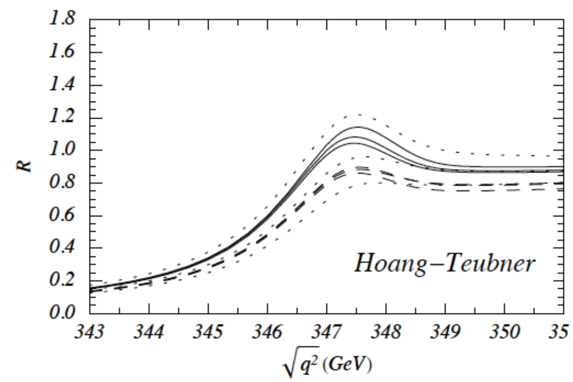
Static energy:



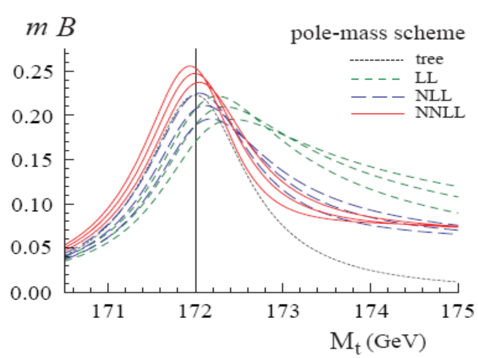


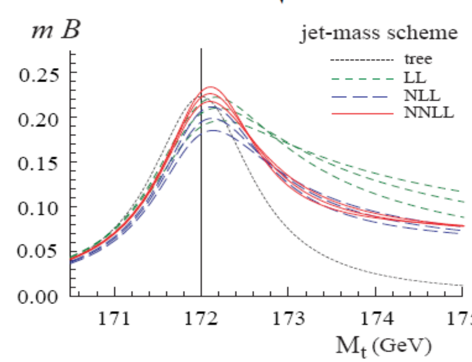
Top Threshold @ LC:





Reconstructed Top jets:





Fleming etal.

Concept of a Quark Mass

Short-distance mass schemes:

$$m^{\text{sd}}(R) = m^{\text{pole}} - R\left(a_1\frac{\alpha_s}{4\pi} + a_2\left(\frac{\alpha_s}{4\pi}\right)^2 + \ldots\right)$$

Generic form of a short-distance mass scheme.

$\overline{\text{MS}}$ mass: $R = \overline{m}(\mu)\,, \quad a_1 = \frac{16}{3} + 8\ln\frac{\mu}{m}$

Processes where heavy quarks are off-shell and energetic.

Threshold masses (1S, PS, RS, kinetic masses)

$$R \sim m\alpha_s$$

Quarkonium bound states: heavy quarks are close to their mass-shell.

Jet masses (jet mass)

$$R \sim \Gamma_Q$$

Single quark resonance: heavy quarks are very close to their mass-shell.

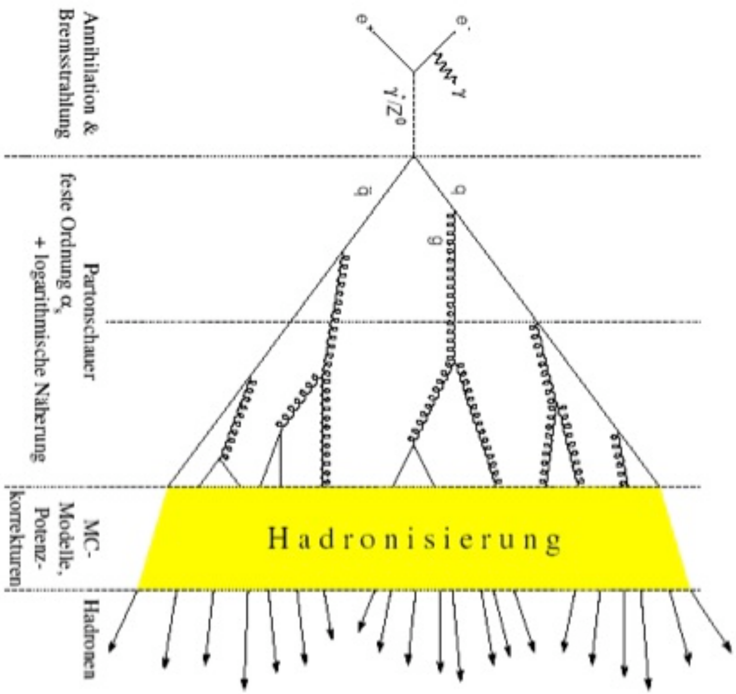
The a_i's are chosen such that the renormalon is removed.

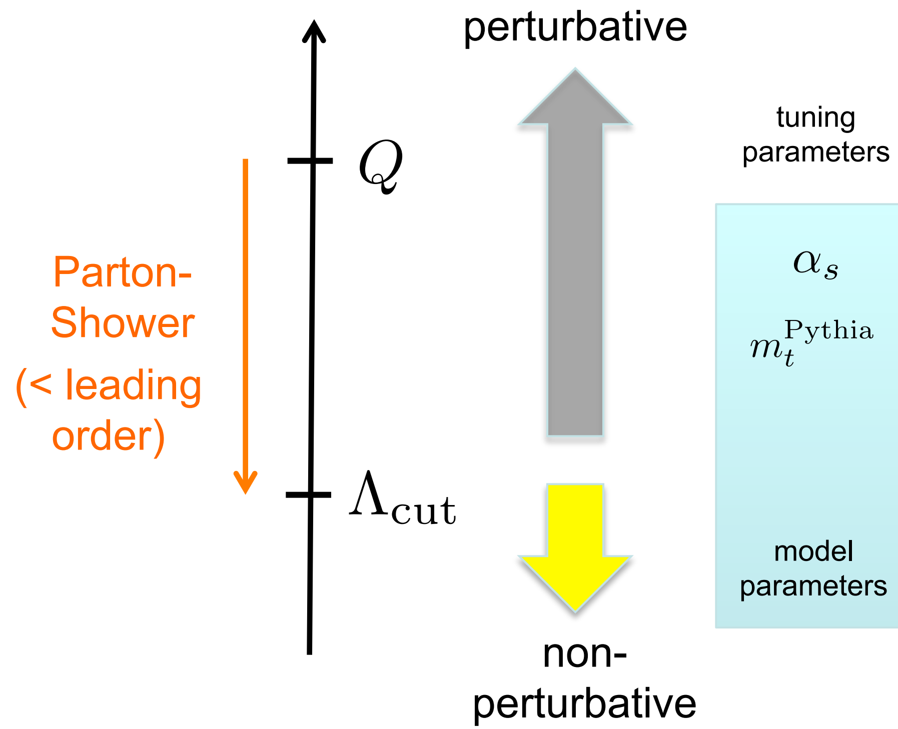
The scale R is of order the momentum scale relevant for the problem.

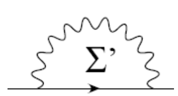
MC Mass

Universal instrument to describe hadronic final states.

- Hadronization model and α_s are “tuned” to experimental data.





Where is 

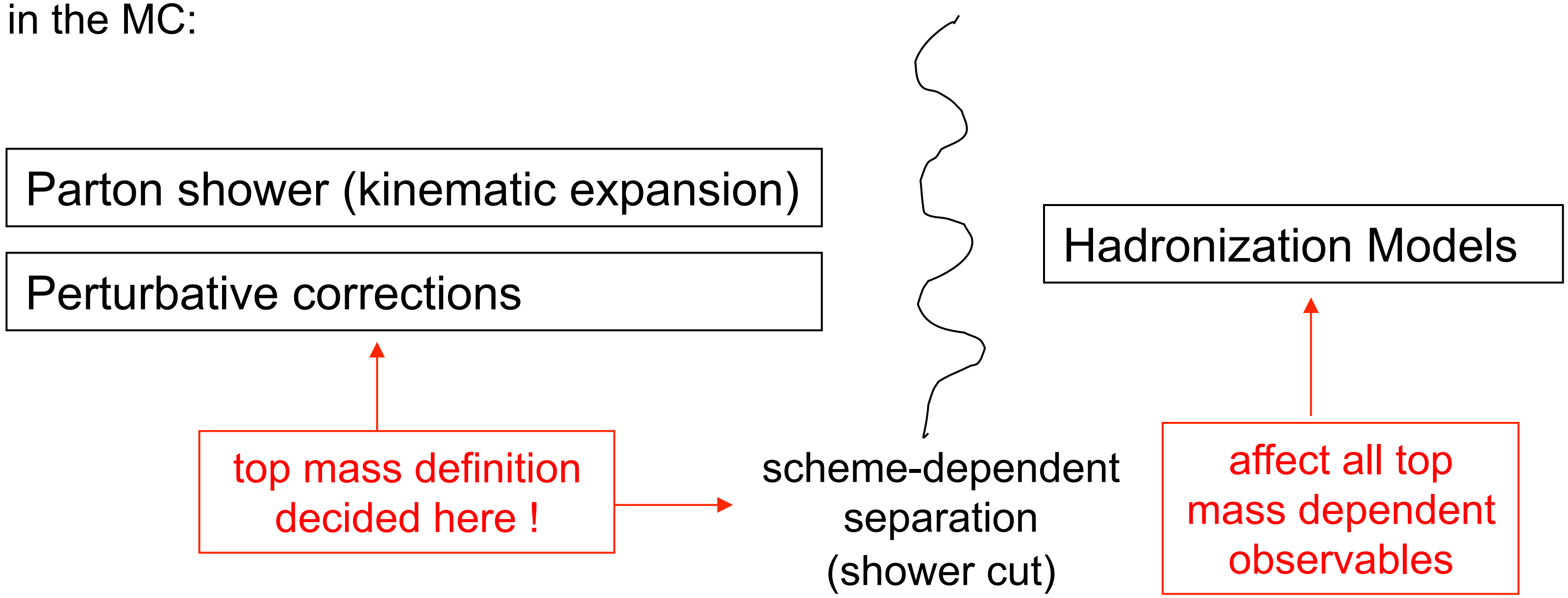
?

- ME corrections (controllable in principle)
- Parton-shower: $m_t^{\rm Pythia}$ is a short-distance mass! Due to shower cut $\Lambda_{\rm cut}$?

Answer might be process- and observable-dependent !

MC Mass

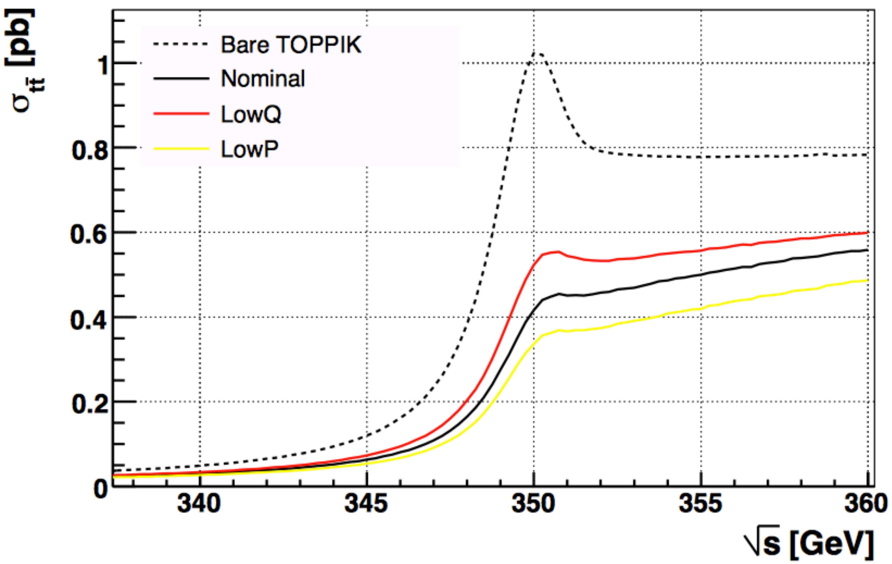
- Concept of mass in the MC depends on the **structure and reliability of the perturbative part** and the **interplay of perturbative and nonperturbative part** in the MC:



- Assume that the MC is a good QCD box (LO of s.th. more precise): How can one pin down the relation between m_t^{Pythia} and the Lagrangian mass ?
- Is the MC really a good QCD box ? **Is the MC more a model or more QCD ?**

Answer for m_t^{Pythia} might be process- and observable-dependent if the MC is not a good QCD box !

Total ttbar Cross Section (ILC)



Principle: m_t from $\sigma_{tt}(m_t)$

Advantages:

- count number of $t\bar{t}$ events
- color singlet state
- background is non-resonant
- physics well understood (renormalons, summations)
- Top decay protects from non-pert effects

Much of the discriminating power of the approach related to the strong mass-dependence (ttbar resonance).

Peak position very stable in theory predictions (threshold mass scheme).

Typical results:

$\rightarrow \delta m_t^{\text{exp}} \simeq 50$ MeV

$\rightarrow \delta m_t^{\text{th}} \simeq 100$ MeV

What mass?

$\sqrt{s}_{\text{rise}} \sim 2m_t^{\text{thr}} +$ pert.series

(short distance mass: 1S $\leftrightarrow \overline{\text{MS}}$)

Total ttbar Cross Section (ILC)

Theory issues (Pros) : Multi-scale problem (m, mv, mv^2 ~ 1.5 GeV)

- NNNLO fixed-order approach (pQCD for total cross section) … published shortly, I guess
- NNLL RG-improved approach (pQCD for total cross section) Hoang, Stahlhofen (2013)

Norm and shape of $\sigma_{\mathbf{tot}}$ much less precise than peak position: $d\sigma_{\mathbf{tot}}/\sigma_{\mathbf{tot}}$ ~ 5%

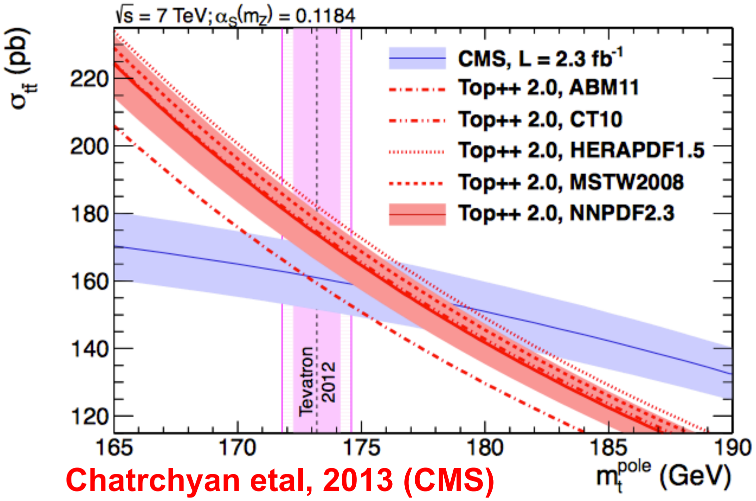
Theory issues (Cons) : Only little / no progress has been achieved in 10 years

- Electroweak/unstable particle theory for total cross section (w.i.p)
- Differential distributions (almost nope)
- Unstable particle effects in distributions (none)
- Monte-Carlo-Simulations for threshold (w.i.p.)
- PDF's for ILC (impact of luminosity spectrum, ISR, etc) (very little)

⇨ Last 10 years: Most energy went into QCD corrections of total cross section.
Still many more problems to be addressed: Status: "strong arms, thin legs"

At this time: $\delta_{\text{theory}} >> \delta_{\text{experiment}}$

Total ttbar Cross Section (LHC)



Chatrchyan etal, 2013 (CMS)
arXiv:1307.1907

Principle: m_t from $\sigma_{tt}(m_t)$

Theory Progress:

- NNLO (qq channel)+NNLL available
- Pole and MSbar predictions available

Czakon, Mitov + other groups

- Theory issue: large sensitivity to gluon pdf ↔ α_s
- Experimental issue: get σ_{tot} from σ(experiment)
- Norm errors feed in the top mass errors

$$\Rightarrow \quad m_t^{\rm pole} = 176^{+3.8}_{-3.4}\,{\rm GeV}$$

Chatrchyan etal, 2013 (CMS)
arXiv:1307.1907

No apparent discrepancy at this time with assumption $m_t^{pole} = m_t^{Pythia}$.

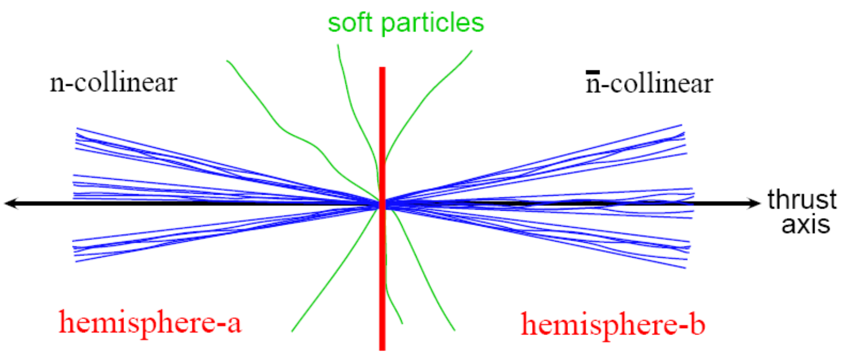
Smaller errors hard, because many hard problems need to be resolved.

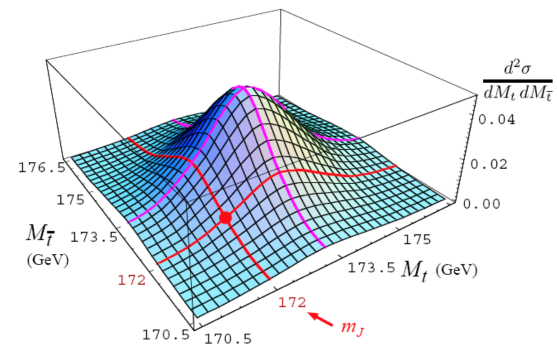
Reconstructed Top Jets (ILC)

Invariant mass distribution: (boosted tops)

Fleming, Mantry, Stewart, AH (2008)

- Hemisphere top jets
- Related to event-shapes





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

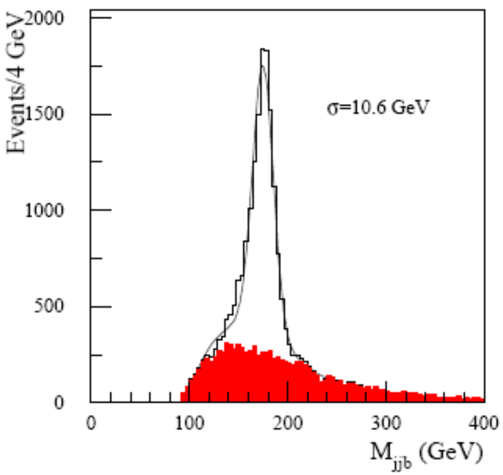
JET JET SOFT

→ Differential strongly top mass-dependent observable.

Top Mass dependent Distributions

Developments/w.i.p: (SCET: highly energic top quarks)

- Variable flavor number scheme for final state jets (w.i.p.)
- Jet mass distribution at the LHC (w.i.p.)
- Heavy quark effects in pdf's (ACOT scheme)
- Jet substructure for top initiated jets
- Effects of the underlying event
- p_T distributions



Aims:

→ Measure top mass directly without MC.

→ Tests: How well does MC do QCD? / "Measure" the MC top mass ?

Outlook & Conclusion

Conclusion:

→ MC most versatile tool to analyze data
QCD parameters in MC not a priori well understood: $m_t^{\rm Pythia}$.

→ Top Threshold: Lot of progress for total cross section. Still lots of open questions and subtleties (distributions missing!, electroweak, photons, finite lifetime effects) ⇨ more conceptual progress needed

→ Top Jets (boosted Tops): progress/w.i.p for LC and LHC.
Direct top mass determination independent of MC.
Direct competition to top threshold (very slow Tops) is emerging.

→ Measurement of MC top mass OR Test: MC = QCD box ?
Only feasible for distributions.