On Subleties in Precision Top Mass Determination at the LHC and ILC

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LCWS 2013, Novermber 11-15, 2013, The University of Tokyo

Outline

- General remarks
  - Short-distance vs. pole mass, renormalon
  - Types of short-distance masses
  - R-evolution and the MSR mass
  - Top mass in MC programs
- Template and matrix element method
- Total cross sections
- Top jet cross sections
- Leptonic final states
- Outlook and Conclusions

See also (and motivated by): Juste etal. arXiv:1310.0799 (Snowmass writeup)

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.

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

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

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

$$D^\mu = \partial^\mu + igT^C A^{\mu C}$$

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

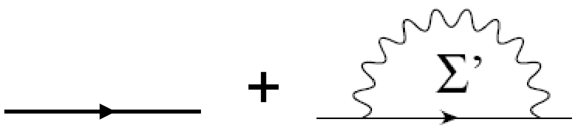
$$-i\frac{(g^{\mu\nu} + \frac{p^\mu p^\nu}{p^2}(\xi - 1))}{p^2 + i\epsilon}$$

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

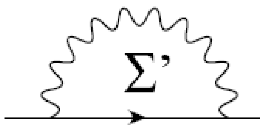
$$m^0 = m^{\rm pole} + \delta m^{\rm pole} \qquad \delta m^{\rm pole} = \Sigma(m, m)$$

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

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

Concept of a Quark Mass

So … do we have to care?



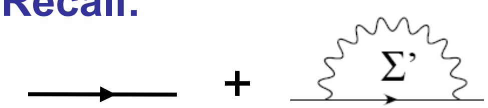
$$\Sigma(m,m) = -\frac{4}{3}\int \frac{d^4q}{(2\pi)^4}\,\alpha_s\,\gamma^\mu\,\frac{q+k+m}{(q+k)^2-m^2}\gamma_\mu\frac{1}{q^2}$$

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

Linear sensitivity to infrared momenta leads to factorially growing coefficients in perturbation theory.

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

Recall:



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

OK, we can absorb the bad correction into the mass

Isn't this just an argument in favor of the pole mass ?

Concept of a Quark Mass

Static energy of a static heavy quark-antiquark pair

$$E_{\rm static} = 2m^0 - 2\Sigma(m,m) + V(r)$$

$$\sim 2m^0 - \int \frac{d^3q}{(2\pi)^3}\,V(\vec{q}^{\,2}) + \int \frac{d^3q}{(2\pi)^3}\,V(\vec{q}^{\,2})e^{i\vec{q}\vec{r}}$$

Renormalon behavior cancels in the sum of self and interaction energy but UV-divergent.

$$= 2m^{\rm pole} + V(r)$$

UV-renormalized, but renormalon behavior appears.

$$= 2\left[m^{\rm PS}(R) - \frac{1}{2}\int_{q<R} \frac{d^3q}{(2\pi)^3}\,V(\vec{q}^{\,2})\right] + V(r)$$

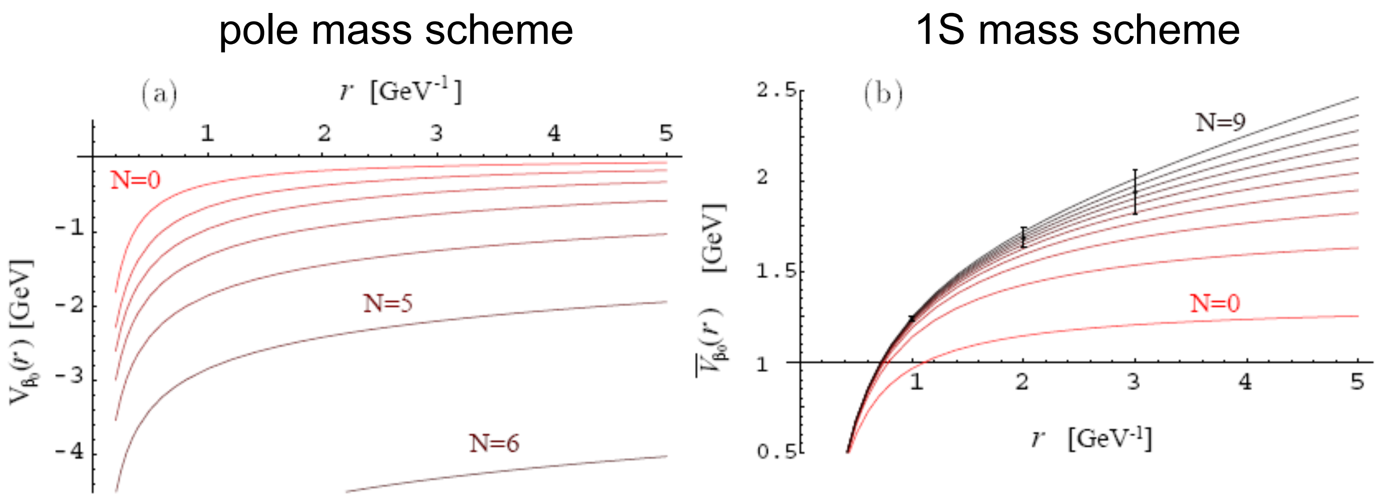
Renormalon behavior cancels in the sum of self and interaction energy and UV-finite.

$$= 2m^{\rm PS}(R) + \left[V(r) - \int_{q<R} \frac{d^3q}{(2\pi)^3}\,V(\vec{q}^{\,2})\right]$$

example of a short-distance mass scheme.

$$R\,(\#\alpha_s + \#\alpha_s^2 + \ldots)$$

Concept of a Quark Mass



Lessson: Same appears to happen for <u>ALL</u> quark mass dependent observables. Pole mass is an conceptually irrelevant concept and leads to artificially large corrections in higher orders. In fields where heavy quark masses need to be known with uncertainties below $\mathcal{O}(1)$ GeV **short-distance** masses must be used.

Top mass dependent quantities that can be computed with high precision and measured with small errors should expressed in short-distance mass schemes.

Concept of a Quark Mass

Short-distance mass schemes:

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

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.

Threshold 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.

R-Evolution

Common form for SD-masses:

$$m_{\text{pole}} = m(R,\mu) + \delta m(R,\mu)\,,$$

$$\delta m(R,\mu) = R \sum_{n=1}^{\infty} \sum_{k=0}^{n} a_{nk} \left[\frac{\alpha_s(\mu)}{4\pi}\right]^n \ln^k\left(\frac{\mu}{R}\right)$$

$$\begin{aligned}
\overline{\text{MS}}:&\quad \overline{m}(\mu), && R = \overline{m}(\mu);\\
\text{RGI [2]}:&\quad m_{\text{RGI}}, && R = m_{\text{RGI}};\\
\text{kinetic [3]}:&\quad m_{\text{kin}}, && R = \mu_f^{\text{kin}};\\
\text{1S [4]}:&\quad m_{\text{1S}}, && R = m_{\text{1S}} C_F \alpha_s(\mu);\\
\text{PS [5]}:&\quad m_{\text{PS}}, && R = \mu_f^{\text{PS}}\,.
\end{aligned}$$

Interesting:

Pole mass is the largest mass scheme $\rightarrow$ δm > 0 always !

Choice for R: typical physical scale of the mass-dependent observable. “Maximal” possible removal of IR-sensitive corrections.

Differences of SD-masses are renormalon-free <u>if the perturbative series is treated properly:</u> common renormalization scale μ

There are large logarithmic corrections in the relation of two SD-masses $m(R_1)$ and $m(R_2)$ for $R_1 >> R_2$.

R-Evolution

consider

PS – MS mass difference: $\overline{m} = \overline{m}(\overline{m})$

$$m_{\rm PS}(\mu_f) = \overline{m} + C_F\left(\frac{\alpha_s(\mu)}{\pi}\right)\left[\overline{m} - \mu_f\right] + C_F\left(\frac{\alpha_s(\mu)}{\pi}\right)^2\left[\overline{m}\left(10.08 - 0.78 n_\ell - \frac{\beta_0}{2}\ln\frac{\overline{m}}{\mu}\right) + \mu_f\left(-5.64 + \frac{\beta_0}{2}\ln\frac{\mu_f}{\mu}\right)\right]$$

→ • free of the $\mathcal{O}(\Lambda_{\rm QCD})$ renormalon for universal scale choice in α_s

• large logs for $\mu_f \ll \overline{m}$

There is no RGE related to UV-renormalization that can deal this these large logarithms!

R-Evolution

AHH, Jain, Scimemi, Stewart (2008)

Evolution in R:

$$m(R) = m_{\text{pole}} - \delta m(R) \qquad \delta m(R) = R \sum_{n=1}^{\infty} \left(\frac{\alpha_s(R)}{4\pi}\right)^n a_n$$

$$R\frac{d}{dR}m(R) = -\frac{d}{d\ln R}\delta m(R) = R \sum_{n=0}^{\infty} \gamma_n^R \left[\frac{\alpha_s(R)}{4\pi}\right]^{n+1}$$

renormalon-free !

$$m(R_1) - m(R_0) = \int_{R_0}^{R_1} \frac{dR}{R} R\,\gamma^R[\alpha_s(R)]$$

→
- free of the $\mathcal{O}(\Lambda_{\text{QCD}})$ renormalon for universal scale choice in α_s
- summation of $\ln^n(\frac{R_1}{R_0})$ terms

Way to go: R-evolve $m_{PS}(R)$ from μ_f to scale $\overline{m}$ where is can be related to the $\overline{\text{MS}}$ mass without large logs.

R-Evolution

Evolution in R:

$$m(R) = m_{\rm pole} - \delta m(R) \qquad \delta m(R) = R \sum_{n=1}^{\infty} \left(\frac{\alpha_s(R)}{4\pi}\right)^n a_n$$

$$R\frac{d}{dR}m(R) = -\frac{d}{d\ln R}\delta m(R) = R \sum_{n=0}^{\infty} \gamma_n^R \left[\frac{\alpha_s(R)}{4\pi}\right]^{n+1}$$

renormalon-free !

$$m(R_1) - m(R_0) = \int_{R_0}^{R_1} \frac{dR}{R} R\,\gamma^R[\alpha_s(R)]$$

$$\overset{\rm N^kLL}{=} \Lambda_{\rm QCD}^{(k)} \sum_{j=0}^{k} S_j\,(-1)^j\,e^{i\pi\hat b_1}\left[\Gamma(-\hat b_1 - j, t_1) - \Gamma(-\hat b_1 - j, t_0)\right]$$

$$\Lambda_{\rm QCD}^{(0)} = Re^t \qquad S_0 = \frac{\gamma_0}{2\beta_0}$$

$$\hat b_1 = \frac{\beta_1}{2\beta_0^2} \qquad t_{0,1} = -\frac{2\pi}{\beta_0\alpha_s(R_{0,1})}$$

MSR-Mass

Can the $\overline{\text{MS}}$ mass RG-run below the mass ??

Answer: Not quite, but we can construct a mass from it than can.

MSbar Scheme: $(\mu > \overline{m}(\overline{m}))$

$$\overline{m}(\overline{m}) - m^{\text{pole}} = -\overline{m}(\overline{m})\left[0.42441\,\alpha_s(\overline{m}) + 0.8345\,\alpha_s^2(\overline{m}) + 2.368\,\alpha_s^3(\overline{m}) + \ldots\right]$$

MSR Scheme: $(\mu < \overline{m}(\overline{m}))$

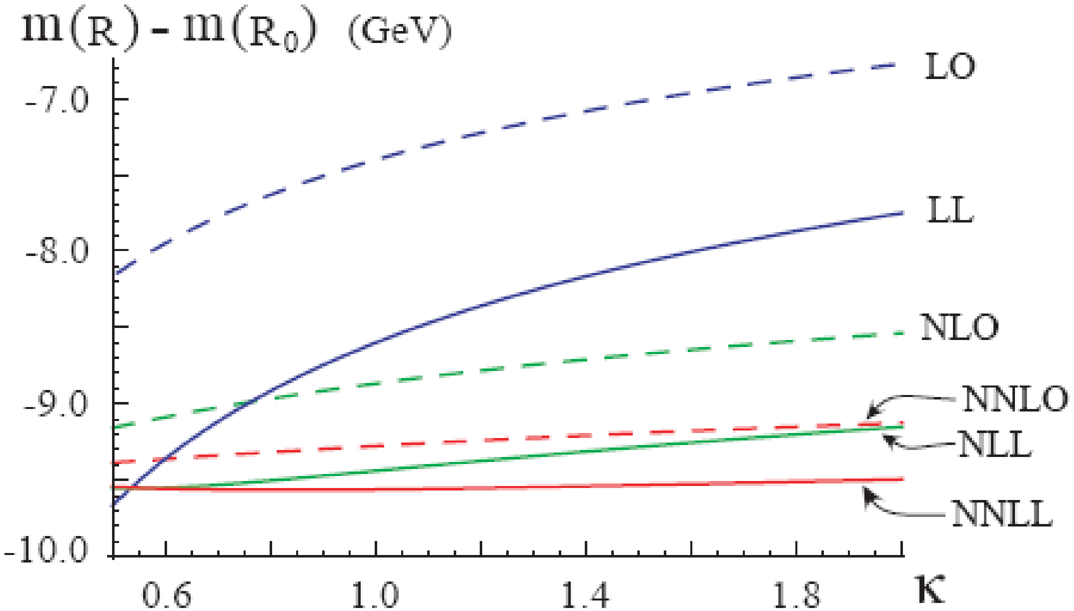
$$m_{\text{MSR}}(R) - m^{\text{pole}} = -R\left[0.42441\,\alpha_s(R) + 0.8345\,\alpha_s^2(R) + 2.368\,\alpha_s^3(R) + \ldots\right]$$

$$m_{\text{MSR}}(m_{\text{MSR}}) = \overline{m}(\overline{m})$$

$m_{\text{MSR}}(R)$ runs with the R-evolution equation
can be related to jet/resonance or threshold mass at small R

MSR-Mass

Jain, Scimemi, Stewart, AHH



$$R_0 = 3 \text{ GeV}$$

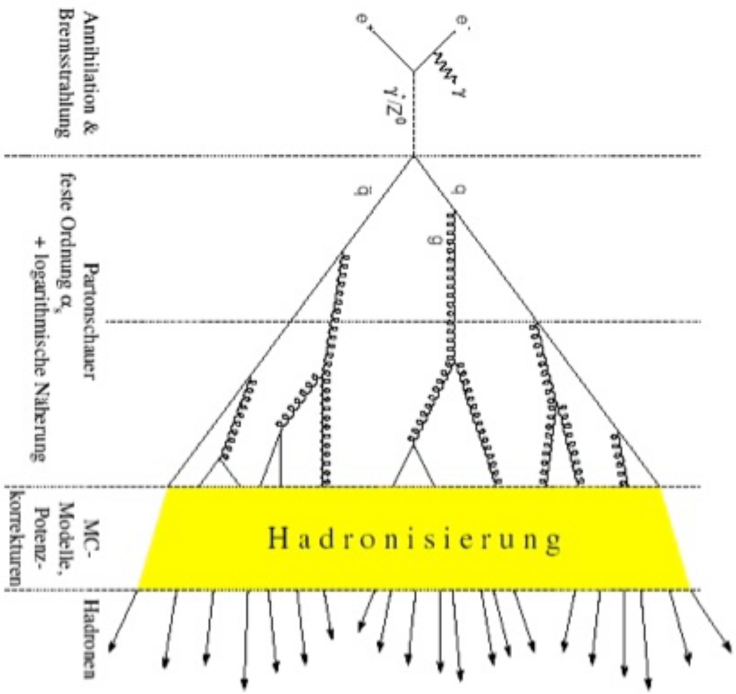
$$R = 163 \text{ GeV}$$

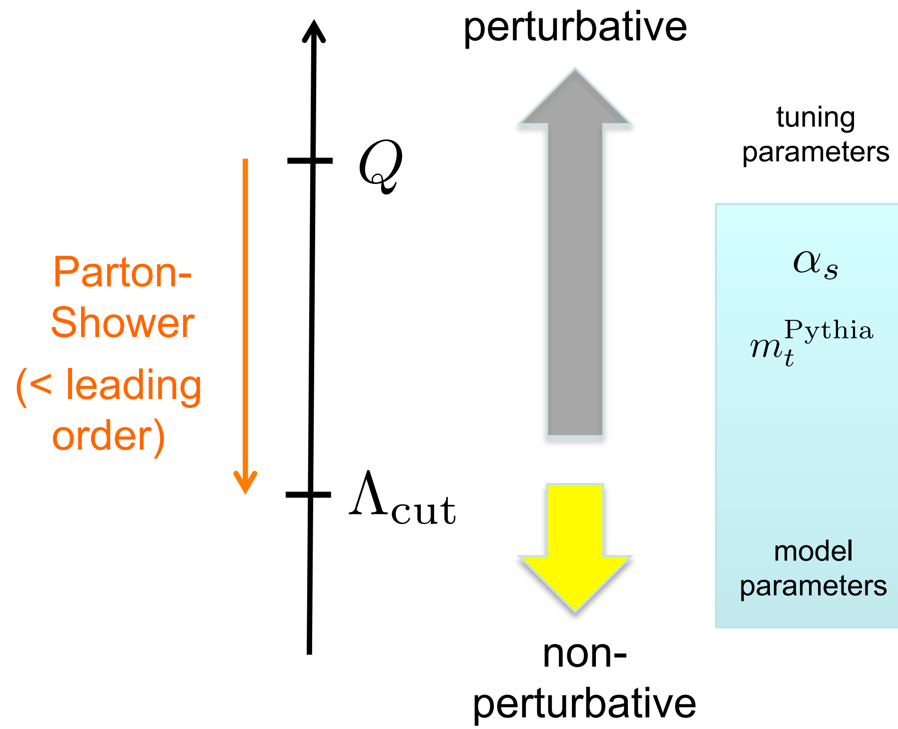
$$R \rightarrow \kappa R'$$

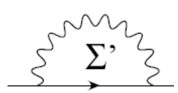
MC Mass

Universal instrument to describe hadronic final states.

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





Where is  **?**

⇒ ME corrections (controllable)

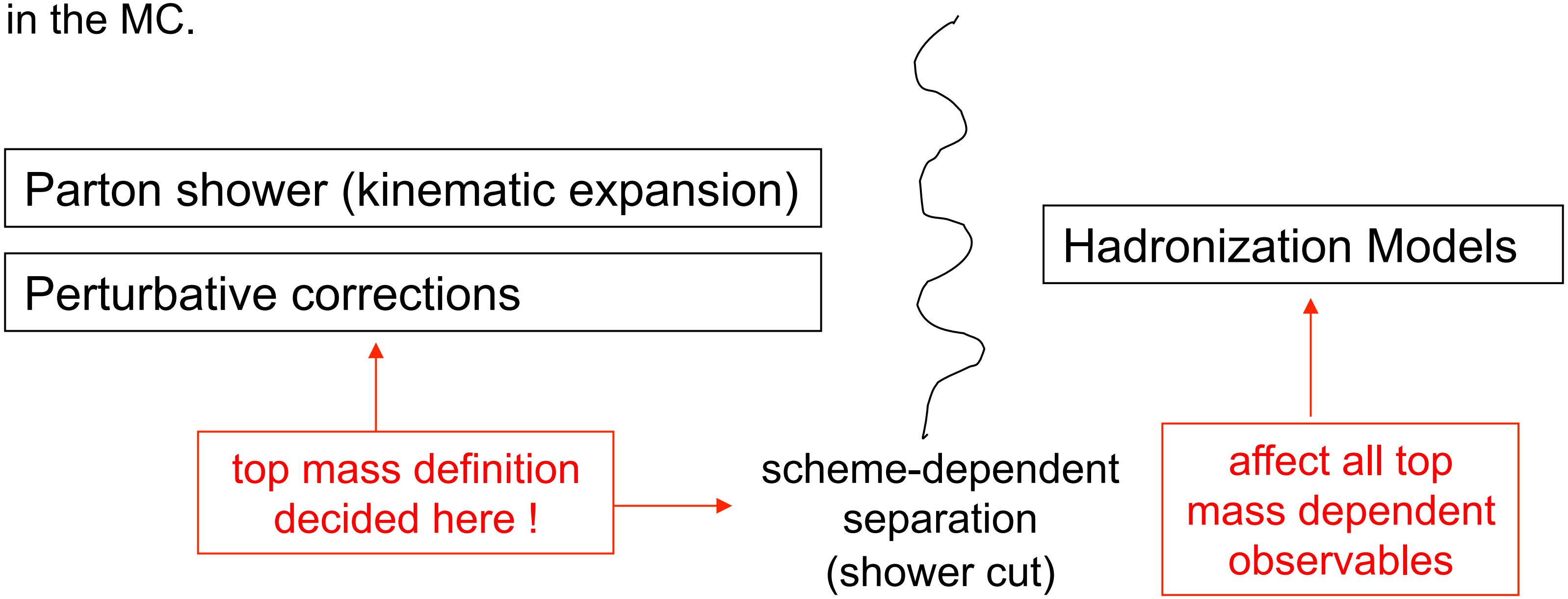
⇒ Parton-shower: $m_t^{\rm Pythia}$ is a short-distance mass!

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 !

Matrix-Element, Template Methods

- Methods inherited from Tevatron (still used at LHC): aims at best exploitation of small data statistics

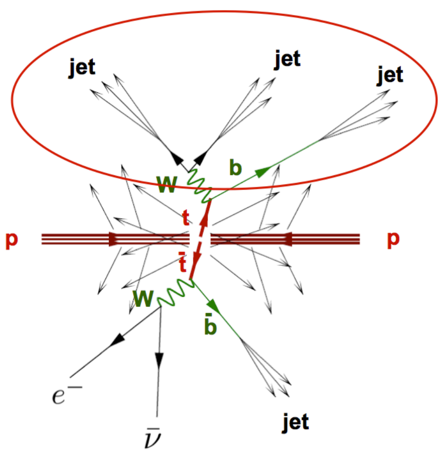
Principle: Compare may m_t-dependent observables with MC predictions

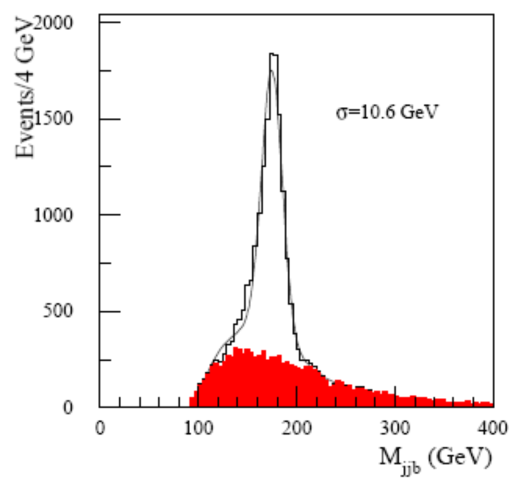
Fit best m_t value and likelihood of the event to be consistent with ttbar +background $\rightarrow$ greater weight for higher likelihood

Constraint on W-mass (lepton+jets)

Observable with (probably) highest impact:

Reconstructed top invariant mass distribution





Matrix-Element, Template Methods

- Methods inherited from Tevatron (still used at LHC): aims at best exploitation of small data statistics (my comment: very far from “blind analysis”)

Principle: Compare may m_t-dependent observables with MC predictions

Fit best m_t value and likelihood of the event to be consistent with ttbar +background $\rightarrow$ greater weight for higher likelihood

Constraint on W-mass (lepton+jets)

Observable with (probably) highest impact:

Reconstructed top invariant mass distribution

Problems addressed:

- Missmatch $E_{measured}$ vs. E_{true} (jet energy scale, b jet energy) $\rightarrow$ detector issues
- MC description of in-, out-radiation (jet cone), UE, ... $\rightarrow$ MC uncertainties

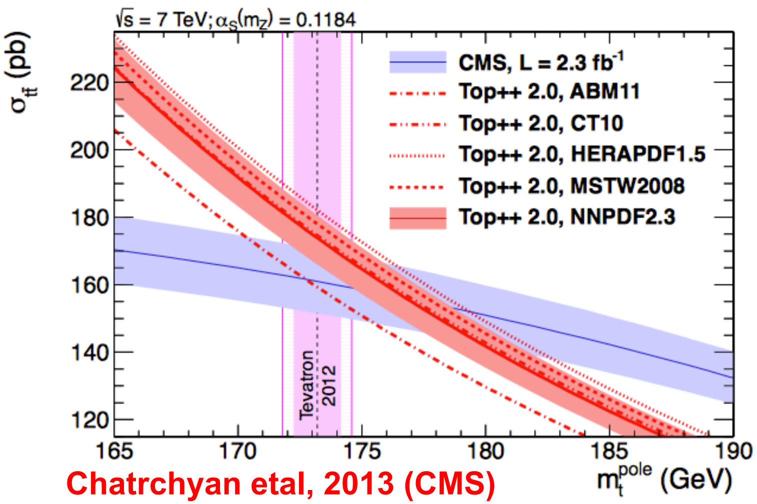
⇨ δm_t^{Pythia} < or $\approx$ 1 GeV

Problem not addressed: What is m_t^{Pythia} ?

$\rightarrow$ Additional conceptual uncertainty in m_t^{Pythia}: O(1GeV)

But with respect to what? $m_t^{Pythia} = m_t^{short\text{-}distance} + O(1GeV)$

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

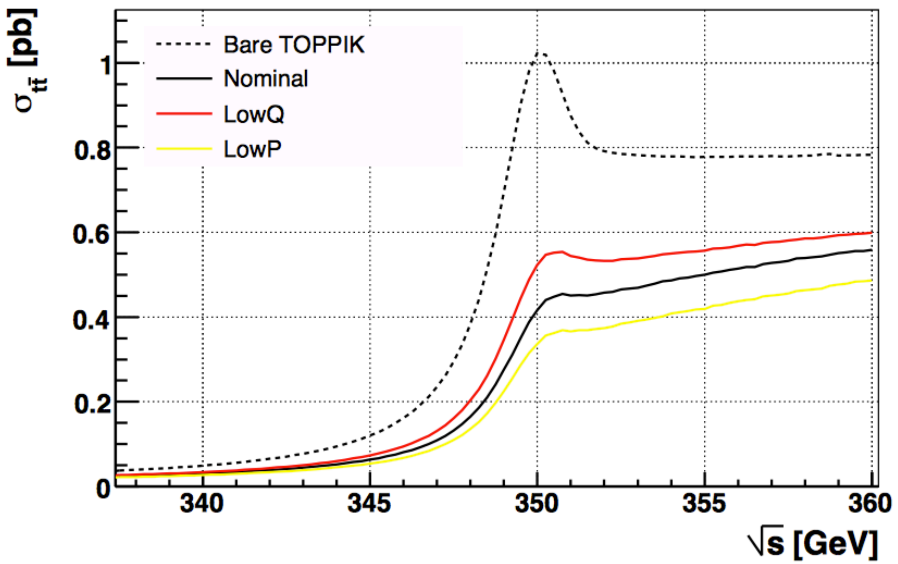
$$\Rightarrow \quad m_t^{\rm pole} = 176^{+3.8}_{-3.4}\,{\rm GeV}$$

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.

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:

- NNNLO fixed-order approach (pQCD)
- NNLL RG-improved approach (pQCD)
- Multi-scale problem (m, mv, mv^2 ~ 1.5 GeV → ultrasoft effects not an easy task)
- Electroweak corrections and unstable particle effects not statisfactorily known.
- Almost NOTHING known about mass dependent differential distributions (as a cross check)

Norm and shape of $\sigma_{\mathbf{tot}}$ much less precise than peak position: $d\sigma_{\mathbf{tot}}/\sigma_{\mathbf{tot}}$ ~ 5-10%

⇒ Impact of Luminosity spectrum crucial to prohibit feeding errors into mass measurements.

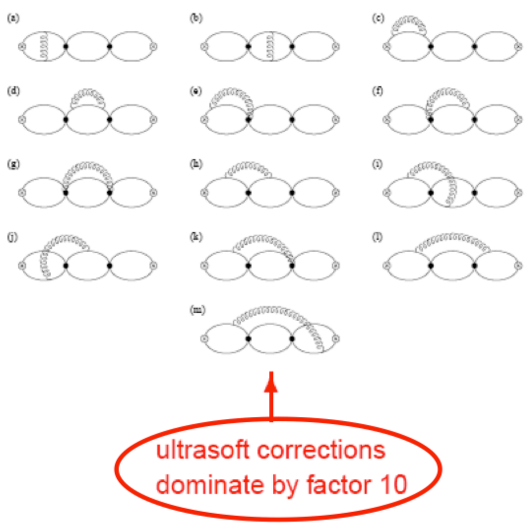
- Theory control essential for coupling measurements:
  - Strong coupling
  - Top Yukawa coupling
  - Top width
  - etc.

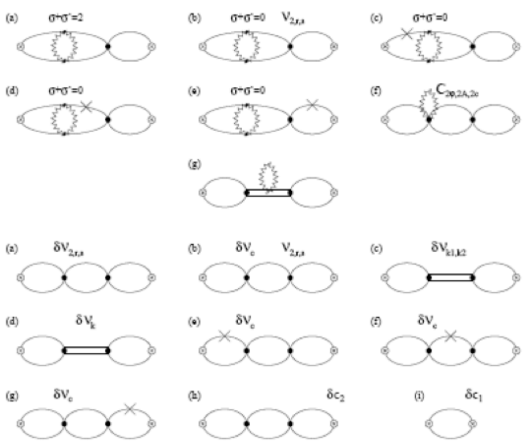
At this time: $\delta_{theory} >> \delta_{experiment}$

Total ttbar Cross Section (ILC)

Status of NNLL (QCD) predictions:

- All NNLL QCD effects known since 2000 except for NNLL RG-evolution of leading S-wave production current Wilson coefficient c_1.
- Non-mixing NNLL corrections to anom.dim. known since 2006 (apparently only computable in vNRQCD — Hoang (2006)
- Mixing usoft NNLL corrections to anom.dim. since 2011 — Hoang, Stahlhofen (2007,2011); Pineda (2011)





Non-mixing: from UV-div's of 3-loop vertex corrections

Total ttbar Cross Section (ILC)

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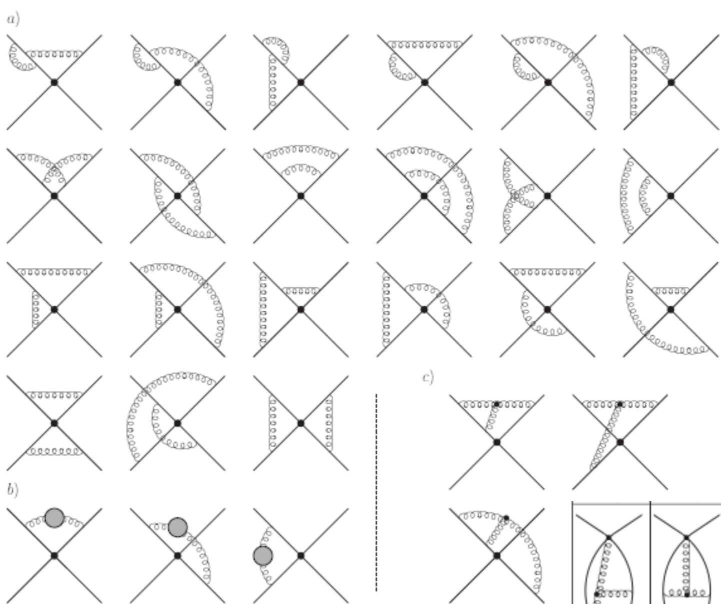
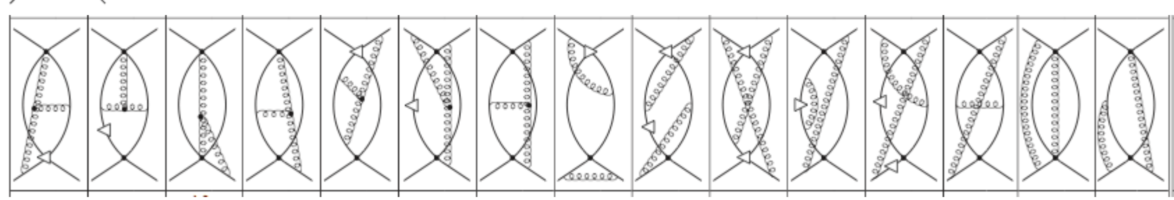


Mixing: 2-loop anom. dim.'s of coefficients in NLL anom.dim. of c_1.

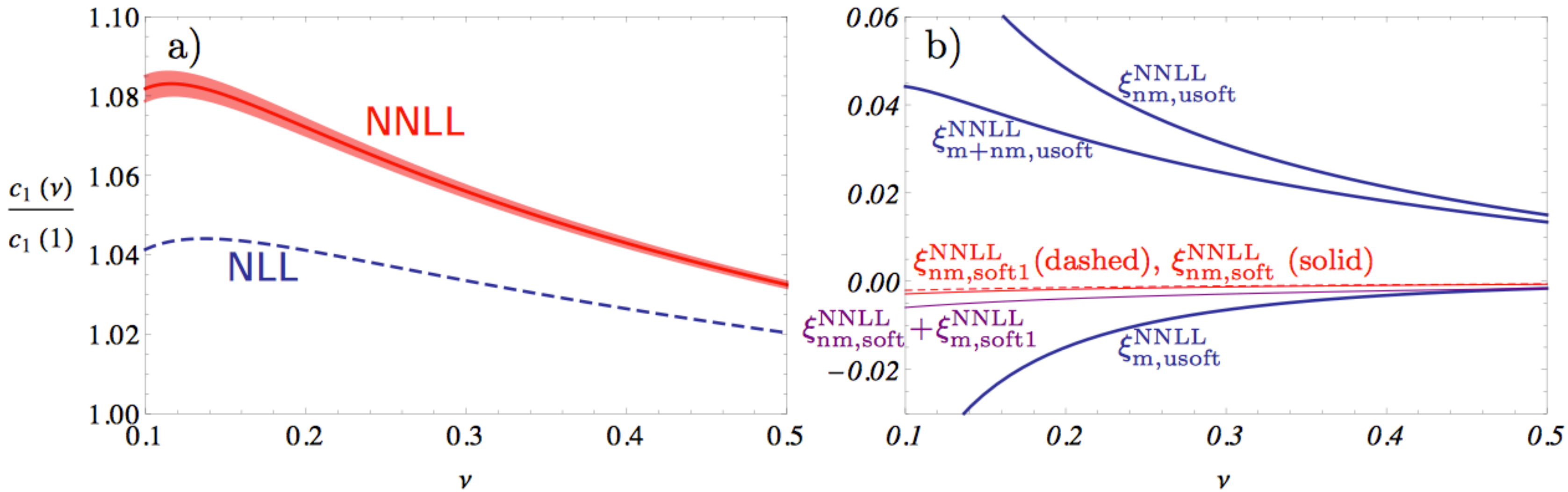
Known soft corrections (spin-dependent) tiny.



Total ttbar Cross Section (ILC)

Status of NNLL (QCD) predictions:

Hoang, Stahlhofen (2013)

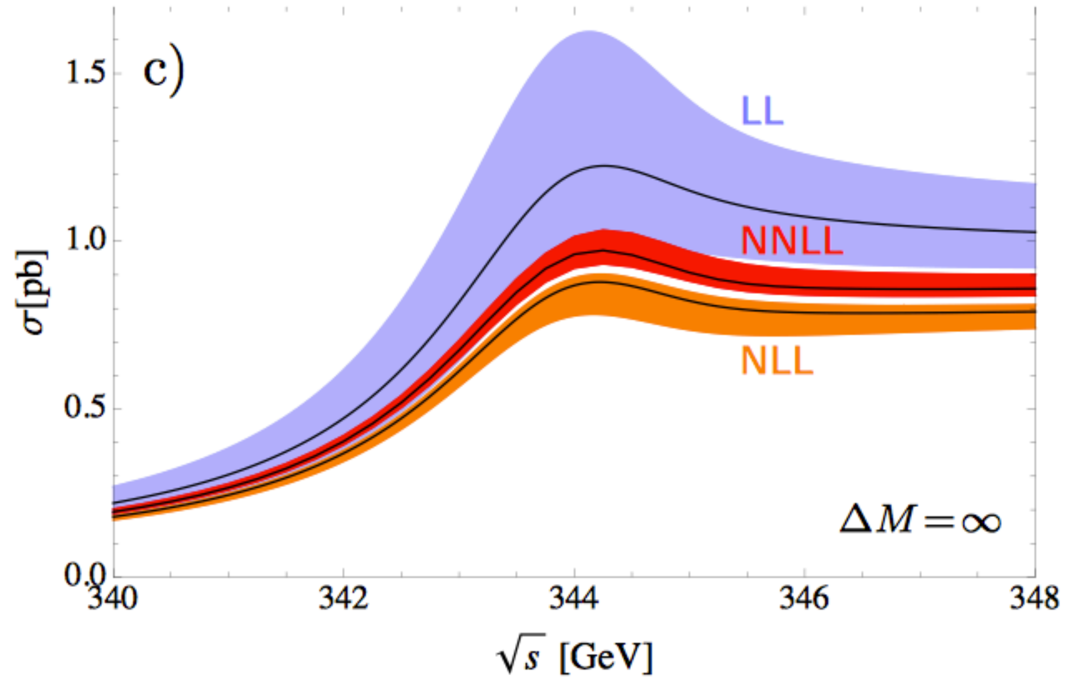


- Uncertainty in NNLL evolution due to missing soft mixing corrections small
- Evolution of c_1 stable
- Huge cancellations between mixing and non-mixing corrections
- Non-mixing corrections contain logs from NNNNLO fixed order !!

Total ttbar Cross Section (ILC)

Status of NNLL (QCD) predictions:

Hoang, Stahlhofen (2013)



- Double scale variation: v and hard scale: $\mu_h = h m_t \nu, \quad \mu_s = h m_t \nu, \quad \mu_u = h m_t \nu^2$
- QCD error at NNLL: $\dfrac{d\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} = \pm 5\%$
- First non-log ultrasoft corrections arise at NNNLL

Total ttbar Cross Section (ILC)

Status of NNLL (ew+unstable) predictions:

Hoang, Reisser, Ruiz-Femenia (2013)
→ Pedro's talk

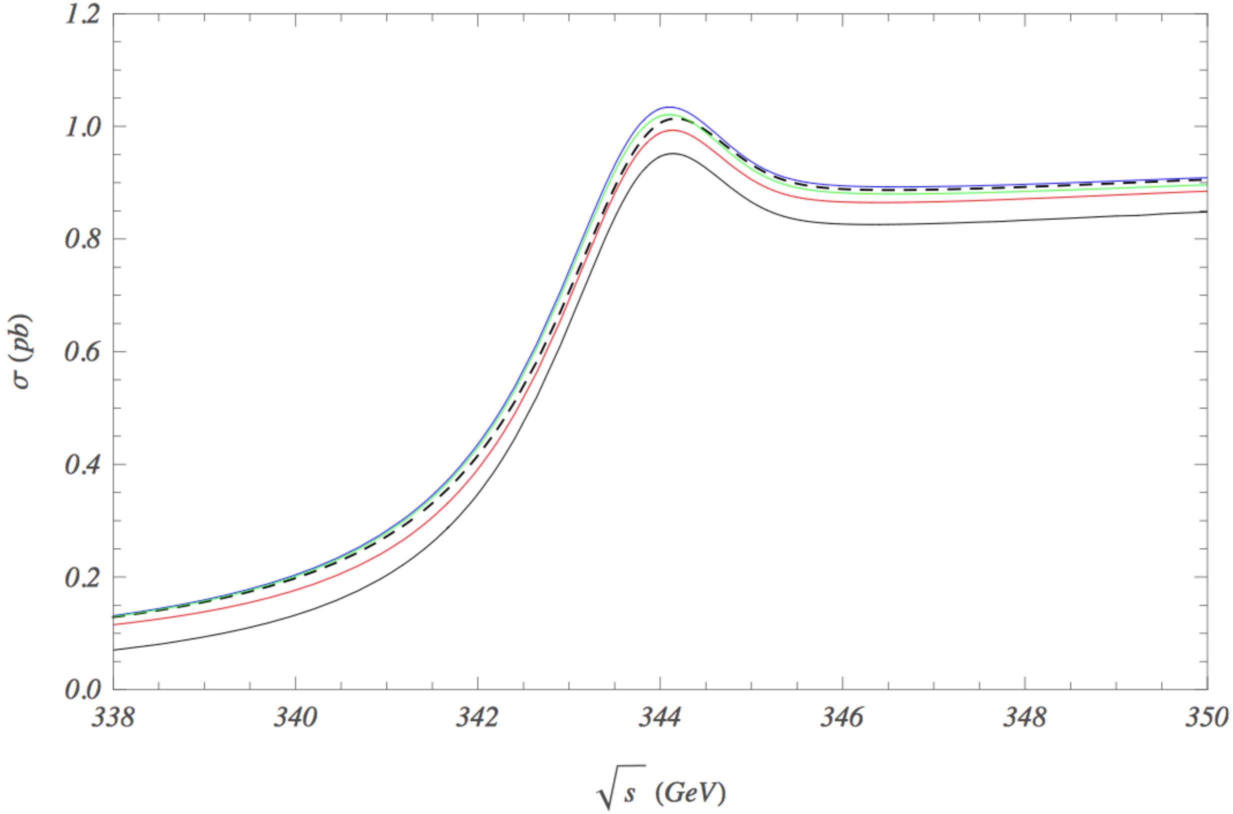
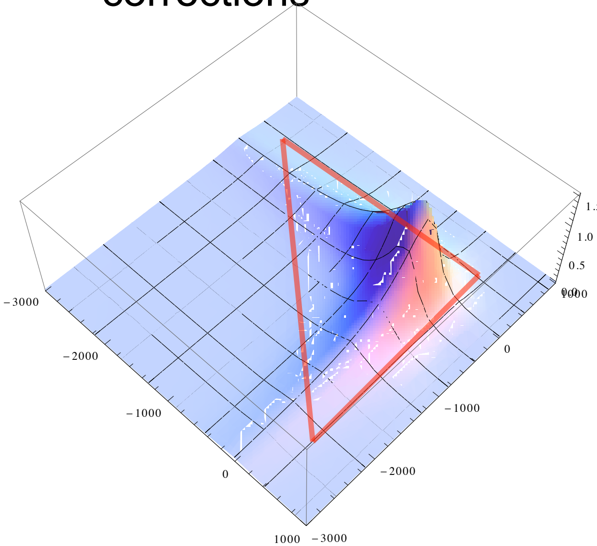


FIG. 21: Total inclusive top pair production cross section from NRQCD: starting from the pure QCD NNLL prediction (black dashed line), we add step-by-step the QED corrections (blue line), the hard electroweak corrections (green line), the type-1 finite lifetime corrections (red line) and the N^{3}LL phase space corrections (black solid line) for $\Delta M_t = 35$ GeV.

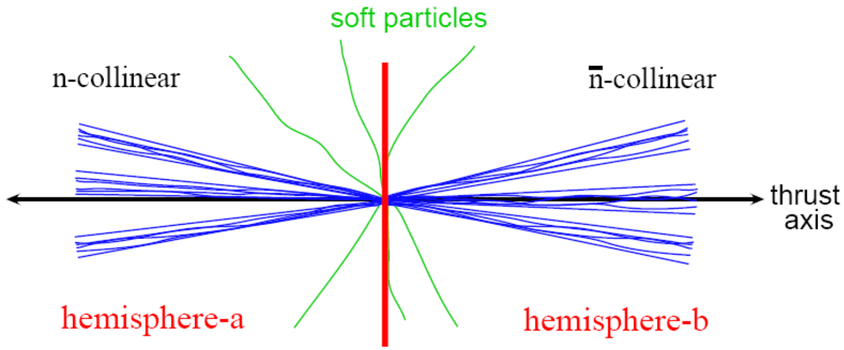
- Electroweak and finite lifetime corrections essential comparable to NNLL$_{QCD}$
- E→E+i Γ_t prescription leads to new UV divergences and sizeable phase space corrections



Reconstructed Top Jets (ILC)

Double differential jet invariant mass distribution:

Fleming, Mantry, Stewart, AH (2008)



- Hemisphere top jets
- Peak region only
- SCET → bHQET
- Related to event-shapes

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

JET JET SOFT

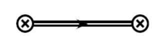
- Relevant top mass dependence in bHQET-jet function

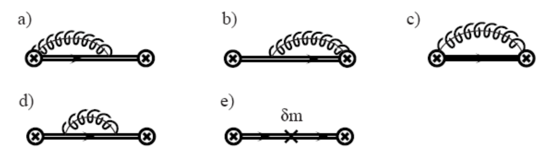
Reconstructed Top Jets (ILC)

bHQET jet function:

$$B_+(2v_+\cdot k) \;=\; \frac{-1}{8\pi N_c m}\,\mathrm{Disc}\int d^4x\, e^{ik\cdot x}\,\langle 0|\mathrm{T}\{\bar{h}_{v_+}(0)W_n(0)W_n^\dagger(x)h_{v_+}(x)\}|0\rangle$$

- perturbative, <u>any mass scheme</u>
- depends on m_t, Γ_t
- Breit-Wigner at tree level





$$B_\pm(\hat{s},\Gamma_t) = \frac{1}{\pi m_t}\frac{\Gamma_t}{\hat{s}^2+\Gamma_t^2} \qquad \hat{s} = \frac{M^2-m_t^2}{m_t}$$

- Describes soft cross talk of the top (and its decay b quark) with the anti-top (and its decay anti-b quark) in the <u>top rest frame</u>
- Soft function describes soft radiation in the <u>lab frame</u>

Issues sorted out for the first time.

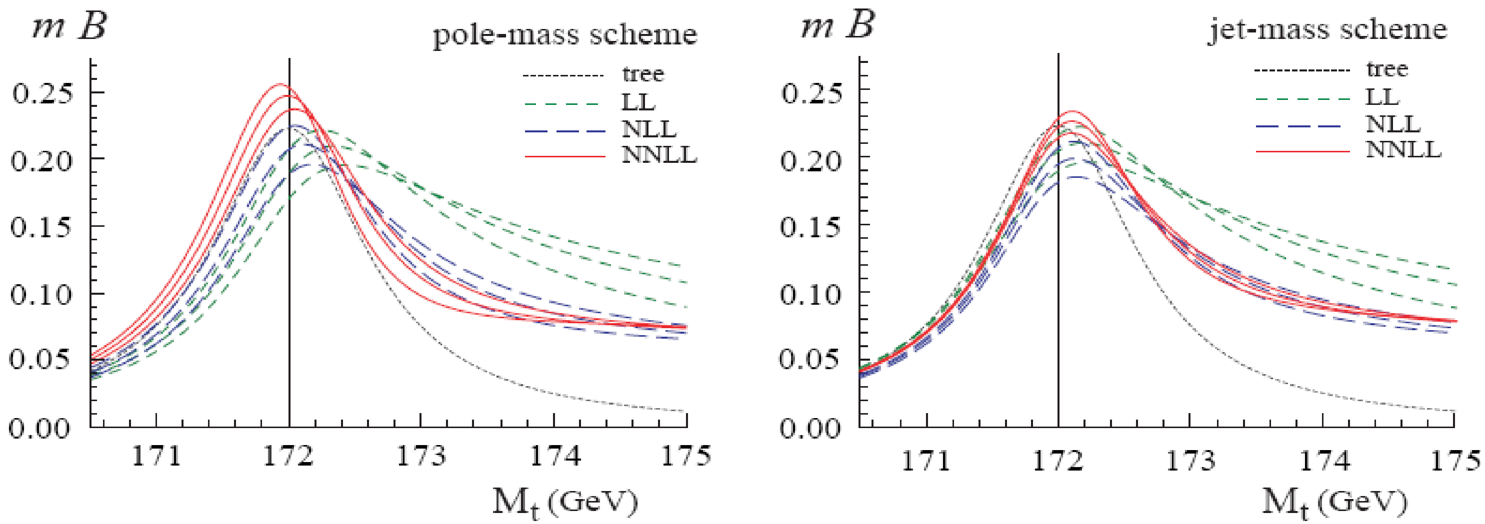
Results still true for LHC (but additional issues to resolved there)

Reconstructed Top Jets (ILC)

→ Jet function has an $\mathcal{O}(\Lambda_{\rm QCD})$ renormalon in the pole mass scheme

$$\mathcal{B}_\pm(\hat{s},0,\mu,\delta m) = -\frac{1}{\pi m}\frac{1}{\hat{s}+i0}\left\{1+\frac{\alpha_s C_F}{4\pi}\left[4\ln^2\left(\frac{\mu}{-\hat{s}-i0}\right)+4\ln\left(\frac{\mu}{-\hat{s}-i0}\right)+4+\frac{5\pi^2}{6}\right]\right\} - \frac{1}{\pi m}\frac{2\delta m}{(\hat{s}+i0)^2}$$

$$\delta m = m_t^{\rm scheme} - m_t^{\rm pole}$$



Jain, Scimemi, Stewart PRD77, 094008(2008)

$$m_{\rm pole} = m_J(\mu) + e^{\gamma_E} R\frac{\alpha_s(\mu)\,C_F}{\pi}\left[\ln\frac{\mu}{R}+\frac{1}{2}\right] + \mathcal{O}(\alpha_s^2)$$

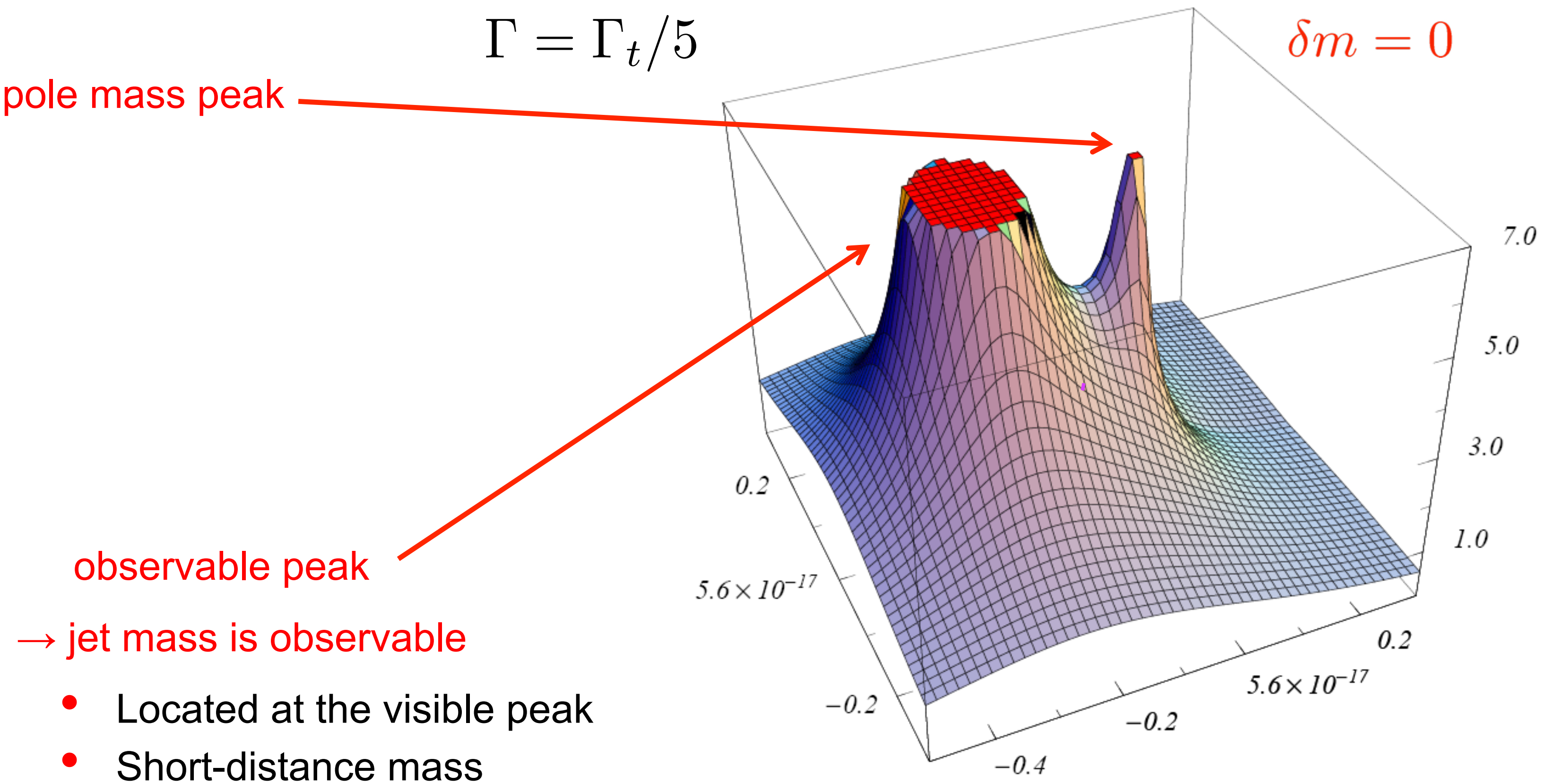
$$R \sim \Gamma_t$$

Reconstructed Top Jets (ILC)

Why is the pole mass not visible?

$$\hat{s} = \frac{M_t^2 - m_t^2}{m_t}$$

$$\Gamma = \Gamma_t/5$$



→ jet mass is observable

- Located at the visible peak
- Short-distance mass

Reconstructed Top Jets (ILC)

Lesson for the MC mass: (for top mass reconstruction only !)

⟶ Use analogies between MC set up and factorization theorem

Final State Shower

- Start: at transverse momenta of primary partons, evolution to smaller scales.
- Shower cutoff $R_{sc} \sim 1\ \mathrm{GeV}$
- Hadronization models fixed from reference processes

Factorization Theorem

- Renormalization group evolution from transverse momenta of primary partons to scales in matrix elements.
- Subtraction in jet function that defines the mass scheme
- Soft function model extracted from another process with the same soft function

Additional Complications:

Initial state shower, underlying events, combinatorial background, etc

} Let's assume that these aspects are treated correctly in the MC

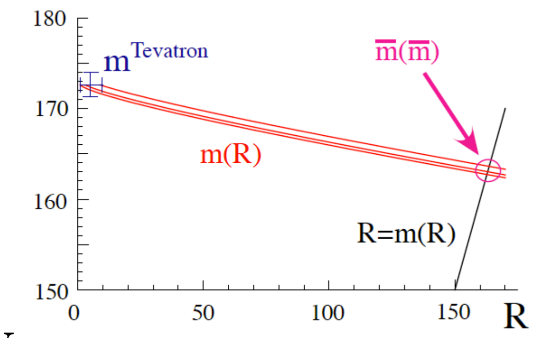
Reconstructed Top Jets (ILC)

Lesson for the MC mass: (for top mass reconstruction only !)

One may conclude:

constant of order unity

$$m_t^{\rm MC}(R_{sc}) = m_t^{\rm pole} - R_{sc}\, c \left[\frac{\alpha_s}{\pi}\right]$$



$$m_{\rm Tev} = m_{\rm MSR}(R = 3^{+6}_{-2}\ {\rm GeV}) = 172.6 \pm 1.4\ {\rm GeV}$$

R-RGE

AH, Stewart (2008)

$$\overline{m}(\overline{m})_{\rm Tev} = m_{\rm MSR}(3^{+6}_{-2}\ {\rm GeV}) = 163.0 \pm 1.3\ {}^{+0.6}_{-0.3} \pm 0.05\ {\rm GeV}$$

(ex) (R) (NNLL R-RGE)

Compatible with current top quark mass analysis (ME-method vs. σ_{tot}).

To be done: Apply concepts to LHC. (w.i.p.)

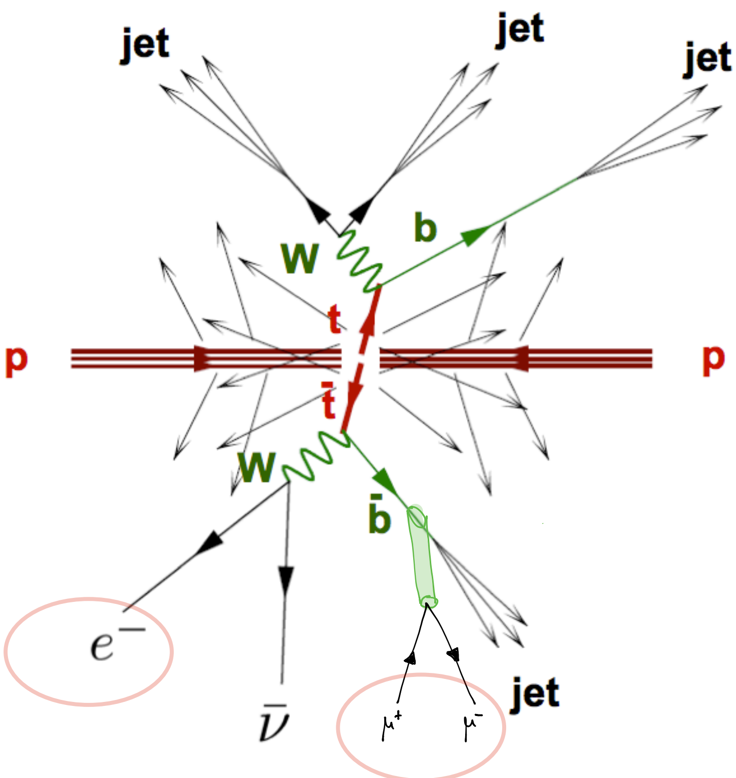
- beam functions (SCET)
- jet cone treatment (SCET)

Charmonium Method

Kharchilava 1999

Idea:

- Measure invariant mass of 3-leptons.
- Frame-independent
- Crystal clean experimentally
- Statistics loss (b→2 muons, suppressed by 10^{-5}) ok for LHC
- Direct access to the top in its rest frame
- Applicable at any c.m. energy
- Many problems drop out (pdf)



Issues: (all issues theoretical)

- Dependence on bottom fragmentation function (b→ J/psi)
- MC studies (δm_t ~ 1 GeV possible)
- Full theory treatment (QCD factorization) missing (only pQCD NLO corrections)
- Dependence on environment at the level of 1 GeV (initial state)
- Top mass issues still unresolved.

Denner etal. 2012

Biswas, Melnikov, Schulze 2010

Outlook & Conclusion

Conclusion:

→ MC most versatile tool to analyze data
QCD parameters in MC not a priori well defined m_t^{Pythia} .

→ Theoretical predictions based on factorization proofs and exact treatment of kinematic-dependent color-flow (= complete theory calculations) needed to resolve top mass-dependence. → hard because theory predictions are not so flexible (idealizations, no cuts, etc.)

→The analogy between MC generators and factorization indicates that the m_t^{Pythia} is a short-distance mass similar to the the jet mass.

Maybe combination of MC with complete theory predictions is a feasible approach. Such calculations exist for e+e- but at this time not for pp collisions.