Top quarks: from Stony Brook to the LHC

Eric Laenen

YITP at 40, Stony Brook, May 2007

YITP in NL

van Baal, de Boer, EL, Schellekens, Schalm, Schoutens, Skenderis, Vandoren, Vermaseren, de Wit

Outline

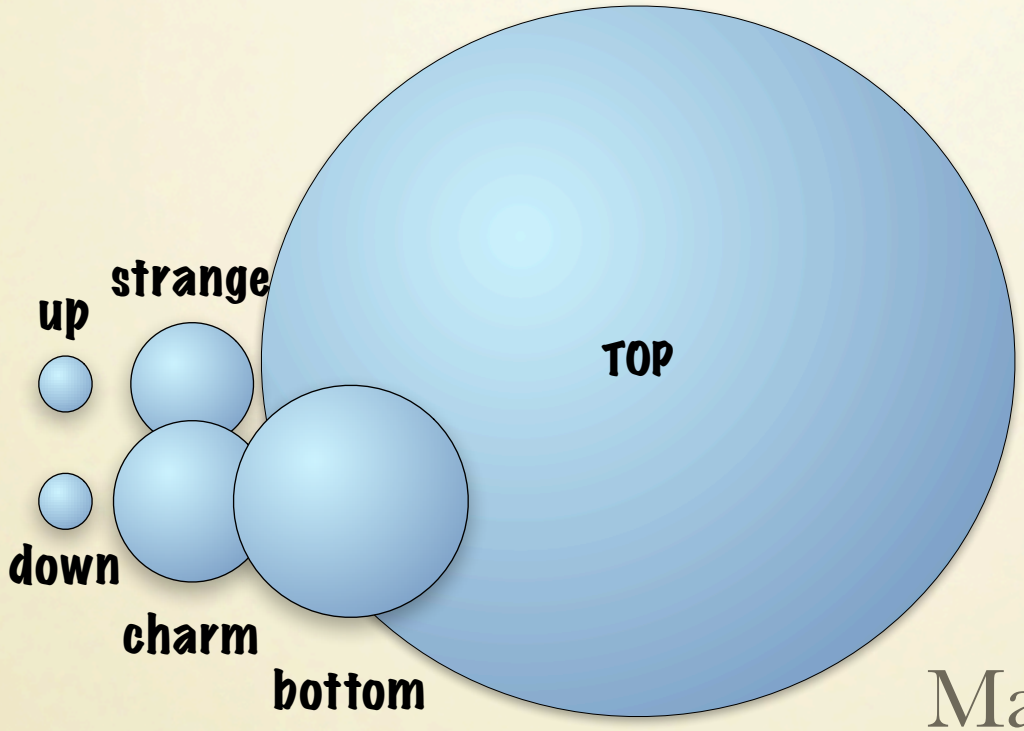
- Top
- @ Stony Brook
- @ LHC

Top

the biggest and most expensive of the quarks

12

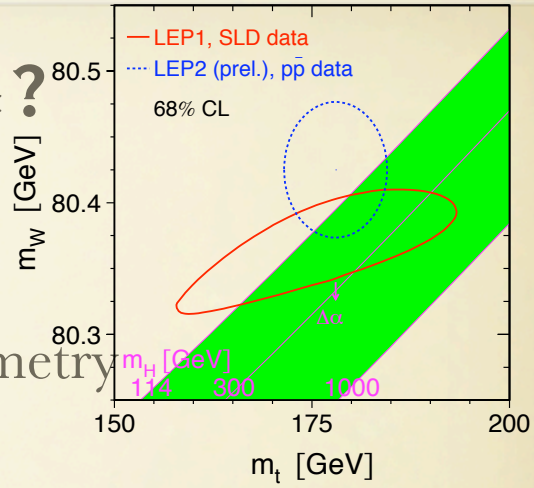
Quark flavors



Mass [GeV]

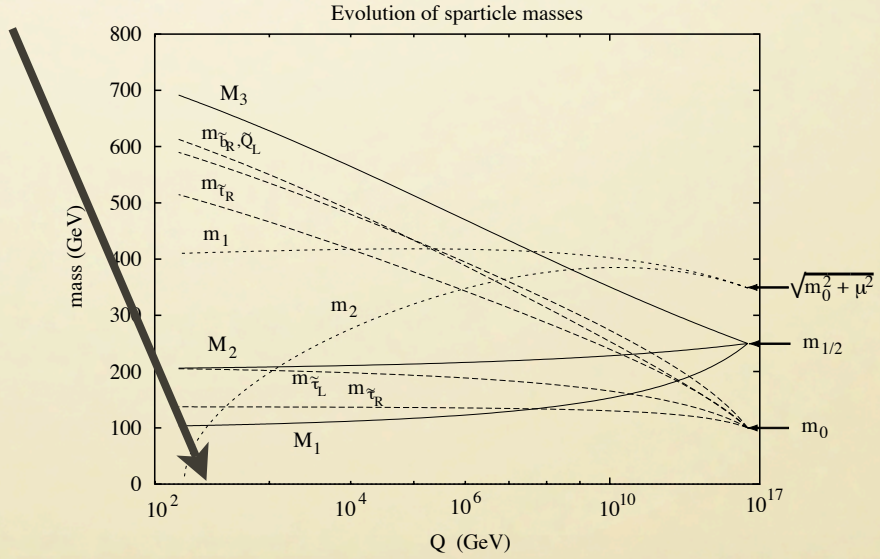
- up: 0.01
- bottom: 5
- top: 175

WHY IS TOP INTERESTING?



- Important input to constraining Higgs mass
- Large mass → couples strongly to whatever breaks EW symmetry
- Discovery tool for Higgs production at LHC via tt+Higgs
- Production characteristics sensitive to various forms of physics beyond the Standard Model
- Top perhaps key in EW symmetry breaking (topcolor, radiative EW symmetry breaking)

Radiative EW



Top at Stony Brook

- In early 90's the goal was: discovery via pair production
- After run I at Tevatron: mass > 91 GeV
- Required: calculation of inclusive pair production cross section
- First calculation at SB by Jack Smith, Willy van Neerven et al

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QCD corrections to heavy-quark production in $p\bar{p}$ collisions

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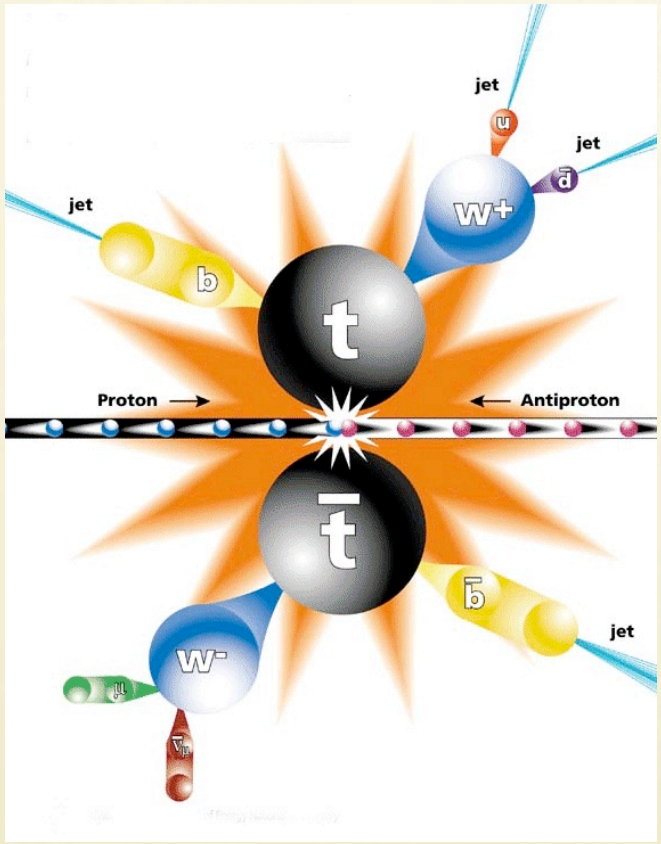
(Received 16 August 1988)

We investigate QCD corrections to the cross section and differential distributions for $p+\bar{p}\rightarrow Q+\bar{Q}+X$, where Q and $\bar{Q}$ are heavy quarks. We calculate the order-α_s corrections to the

Willy van Neerven 1947-2007

Top Pair Production



PERTURBATIVE QCD DESCRIPTION

$$d\sigma = \alpha_s^2(c_0 + c_1\alpha_s + c_2\alpha_s^2 + ...)$$

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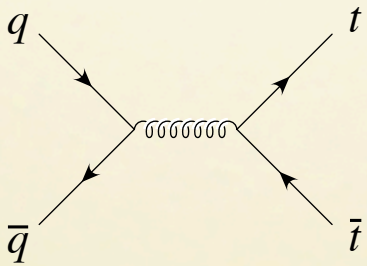
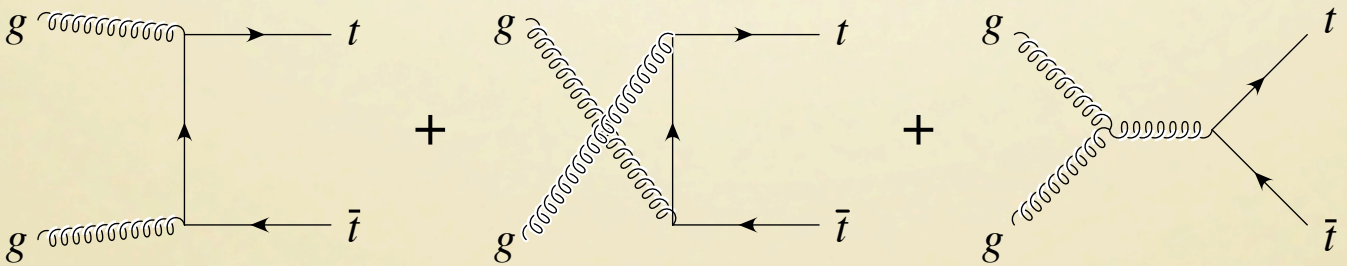


Leading Order



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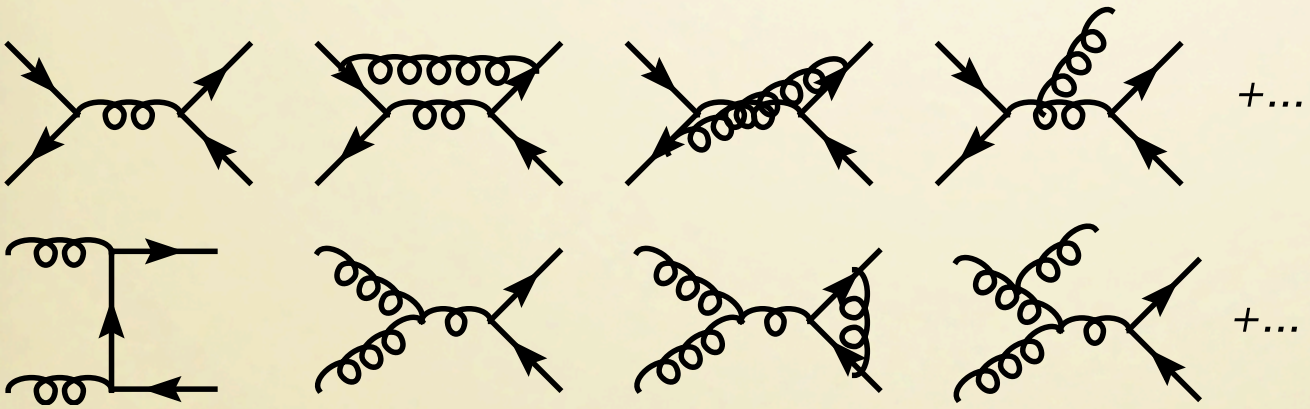
Next-to-Leading Order



Beyond NLO

All-order resummation of soft gluon contributions to heavy quark production in hadron–hadron collisions

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Received 21 May 1991
Accepted for publication 9 September 1991

Top quark production cross section

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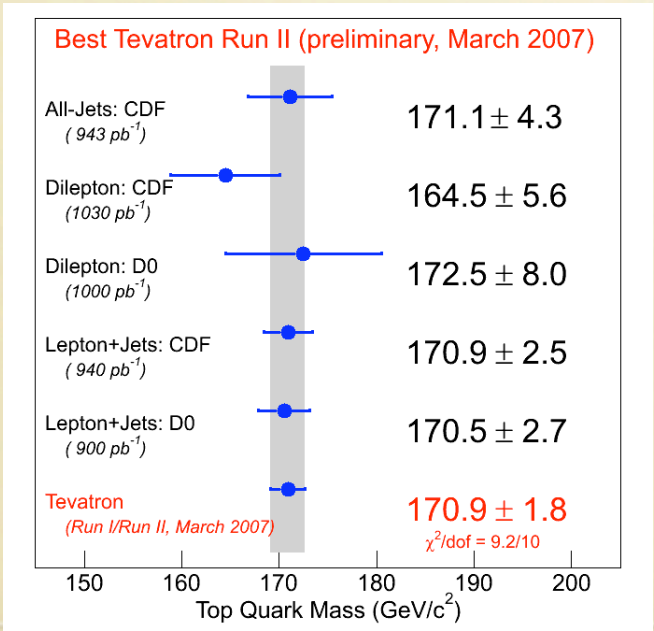
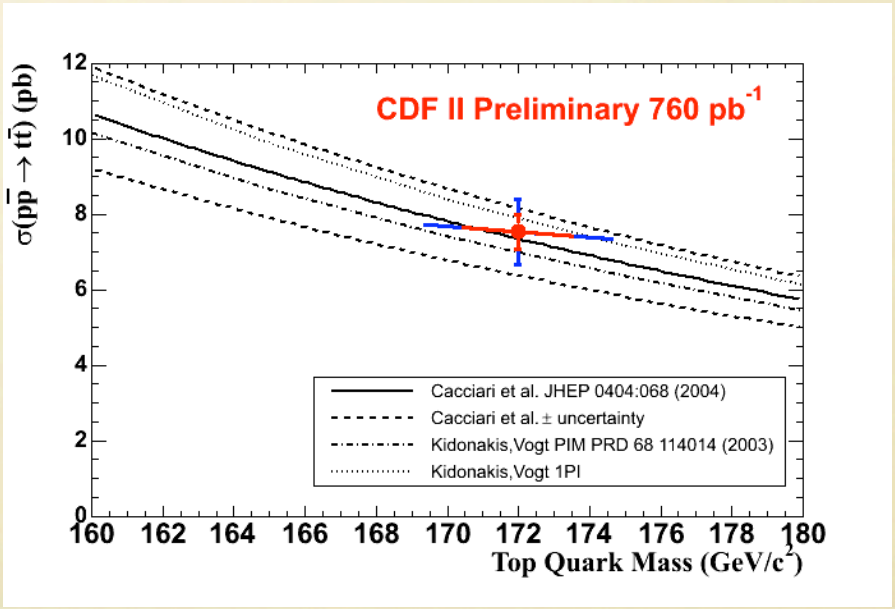
Received 18 October 1993; revised manuscript received 2 December 1993

- Top was likely so heavy that in most cases at the Tevatron, not much energy was left for extra radiation
- Soft gluons give large corrections → (re)sum them
- Gave additional 20% cross section → happy experimenters
- Renewed interest in resummation

Impact

- D0 and CDF experiments used results in acceptance determinations for top discovery analysis
- Deeper insight into resummation since then (Sterman and collaborators), better calculations.
- Latest results:





Top at LHC

- Start in 2008, top quark factory (8 MegaTops/year)
- Calibrate detector
- Can rediscover top using very simple selection criteria
- Top quark physics major part of physics program

Top quark physics

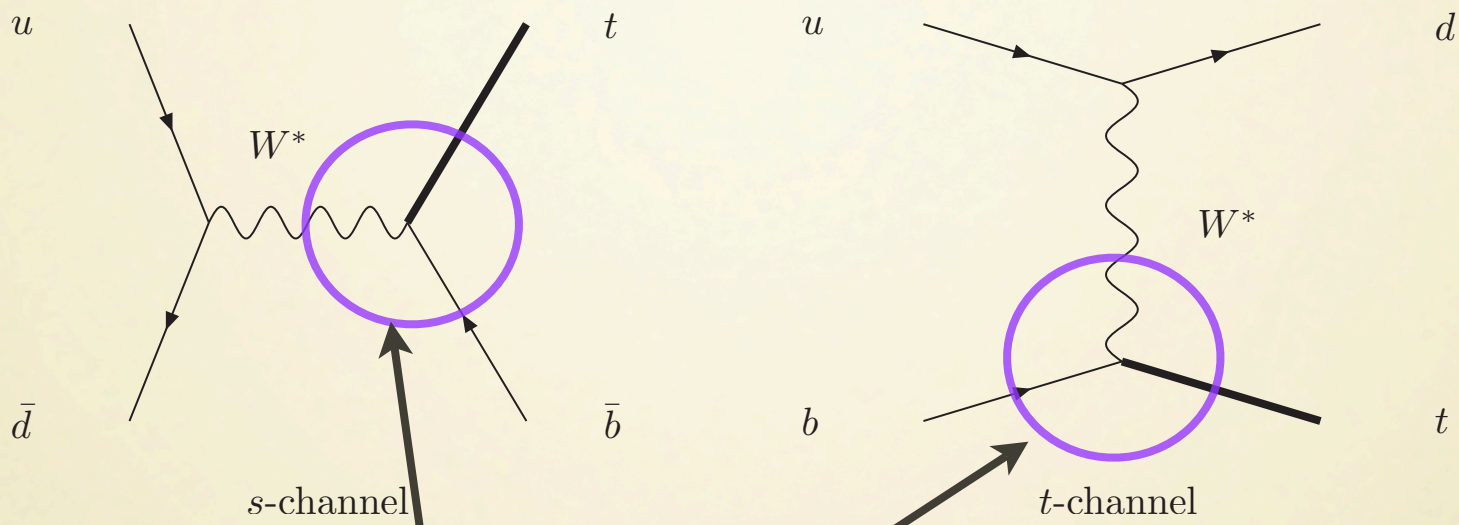
- Precise study of properties and behavior
- Large mass → small QCD coupling
- Free quark

Top couplings

- coupling to W bosons mixes flavors, is left-handed $\frac{g}{\sqrt{2}} V_{tq}\,(\bar{t}_L \gamma^\mu q_L) W^+_\mu$
- coupling to gluons vectorlike $g_s \left[T_a^{SU(3)}\right]^{ji} \bar{t}_j \gamma_\mu t_i A^a_\mu$
- coupling to Z parity violating $\frac{g}{4\cos\theta_w}\,\bar{t}\left((1-\frac{8}{3}\sin^2\theta_w)\gamma^\mu - \gamma^\mu\gamma^5\right) t\, Z_\mu$
- coupling to Higgs of Yukawa type, strength 1 $y_t\, h\bar{t}t$

All these structures should be tested!

Single top production

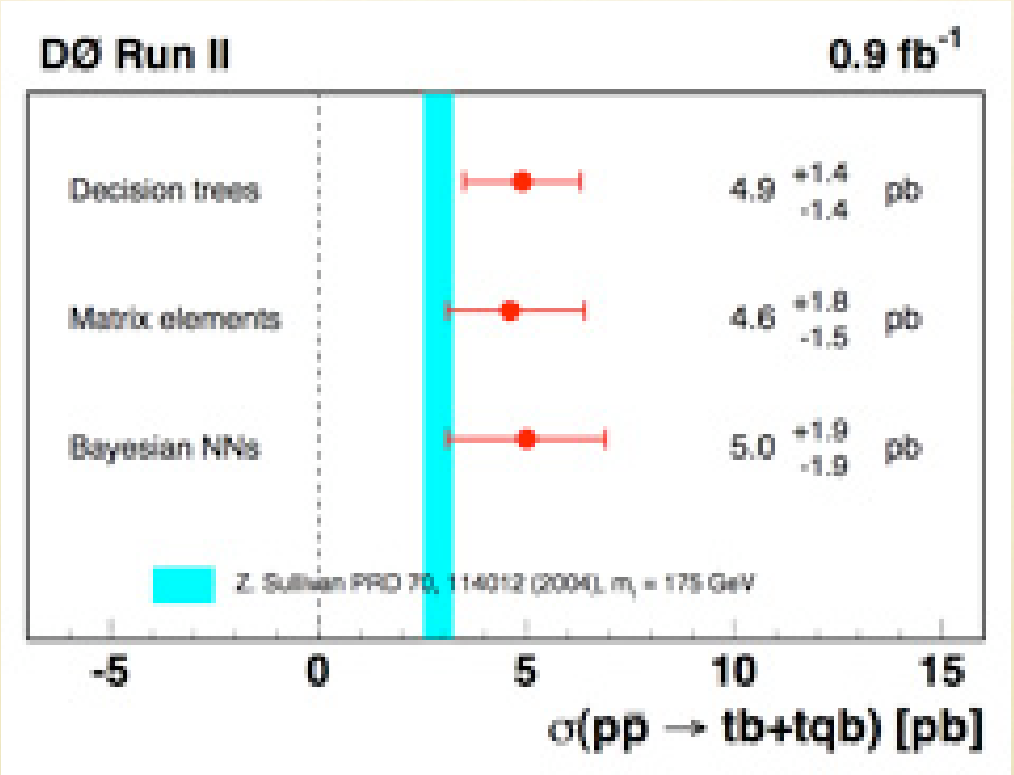


- Likely visible at Tevatron, barely. Detailed scrutiny at LHC
- Measure Vtb per channel, check handedness
- Requires again good theoretical description

Single top evidence

December'06: evidence for single top

Bayesian dudes

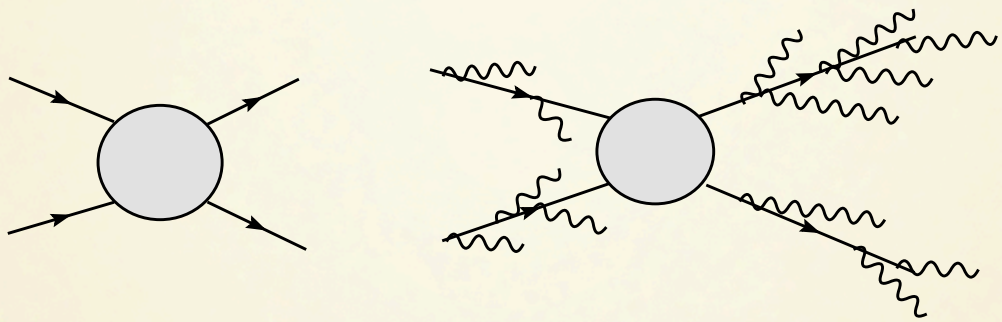


$0.68 < |V_{tb}| < 1 \quad (D0,\ 2007)$

Status of single top production calculations

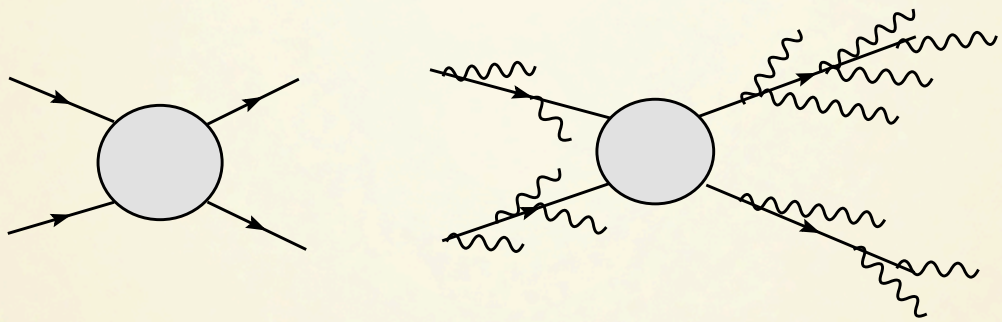
- Many NLO calculations, all agree
- Theoretically well-defined, precise, but with at most 1 extra parton
- General purpose Monte Carlo programs (PYTHIA, HERWIG) provide more realistic final states, but theoretically not precise
- Best of both: MC@NLO (Frixione, Webber)

Monte Carlo at NLO



- Set up calculation as Markov chain, fill histograms event by event
- Draw random events from a physics distribution, imitating Nature
- Include up to NLO exact. Beyond, use parton shower algorithms
- Very flexible, allows realistic simulation of final states
- Experiments are adopting it

Monte Carlo at NLO



Real emission + MC parton shower

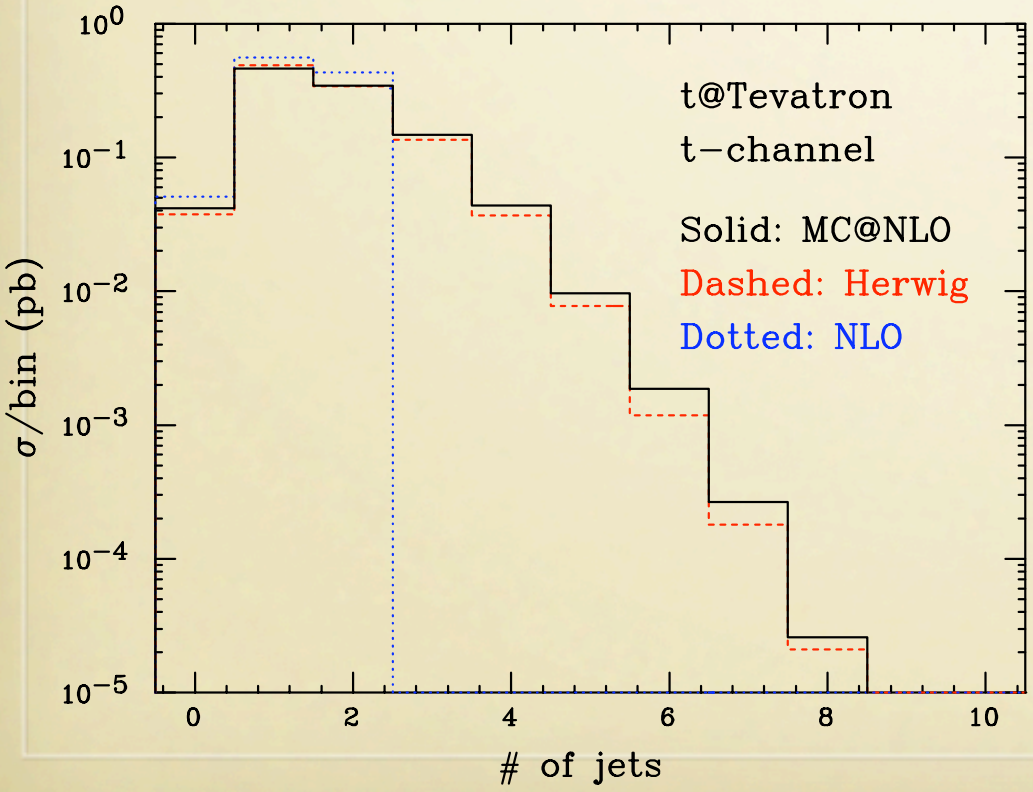
$$\frac{d\sigma}{dO} = \int_0^1 dx \Big[I_{MC}(O, x_M(x)) \frac{\alpha(R(x) - B\,Q(x))}{x} + I_{MC}(O, 1) \frac{B + \alpha V + \alpha B(Q(x) - 1)}{x} \Big]$$

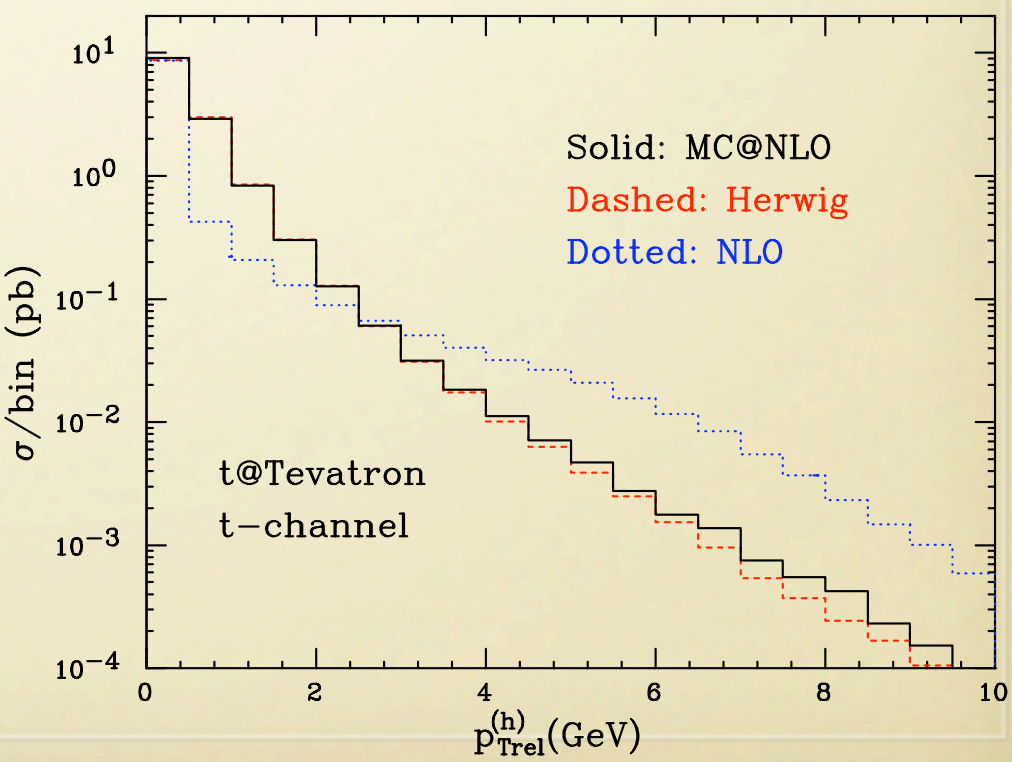
Born + virtual + MC parton shower

Single top and MC@NLO

Frixione, EL, Motylinski, Webber '05

- Included s- and t-channel production
- First time: final state jets included

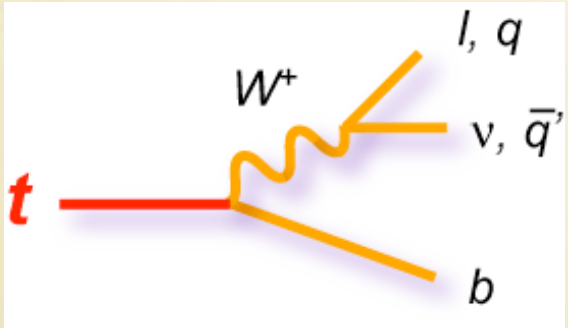


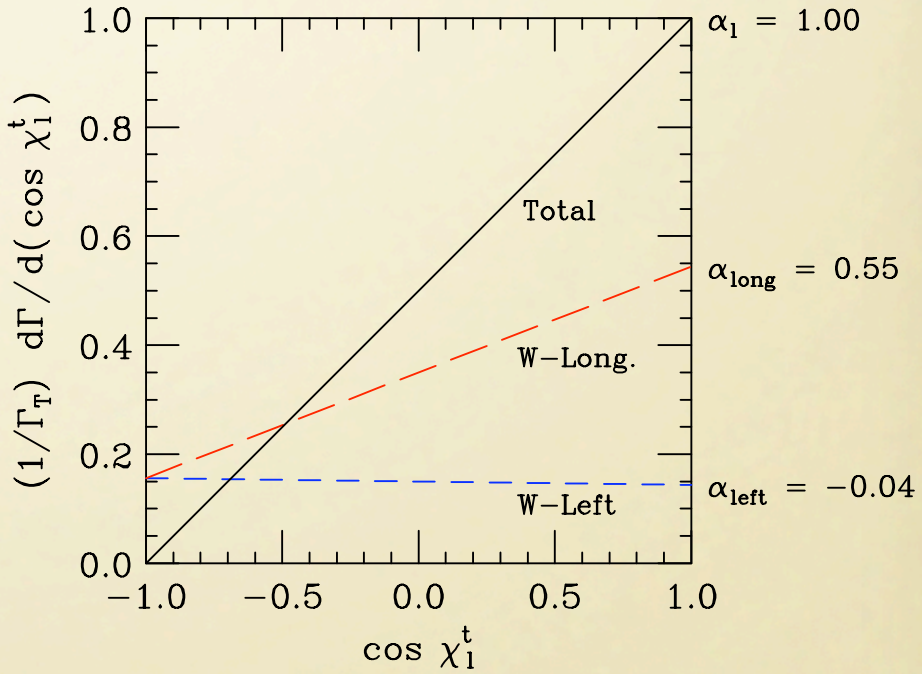


TOP SPIN CORRELATIONS IN MC@NLO

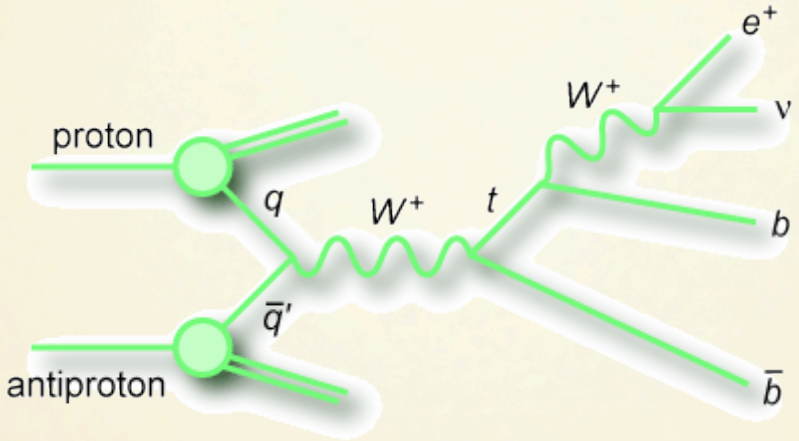
Frixione, EL, Motylinski, Webber '06

- Top 100% polarized at moment of production
- 100% correlation between top spin and lepton from its decay → could check handedness of coupling





Spin correlations in MC

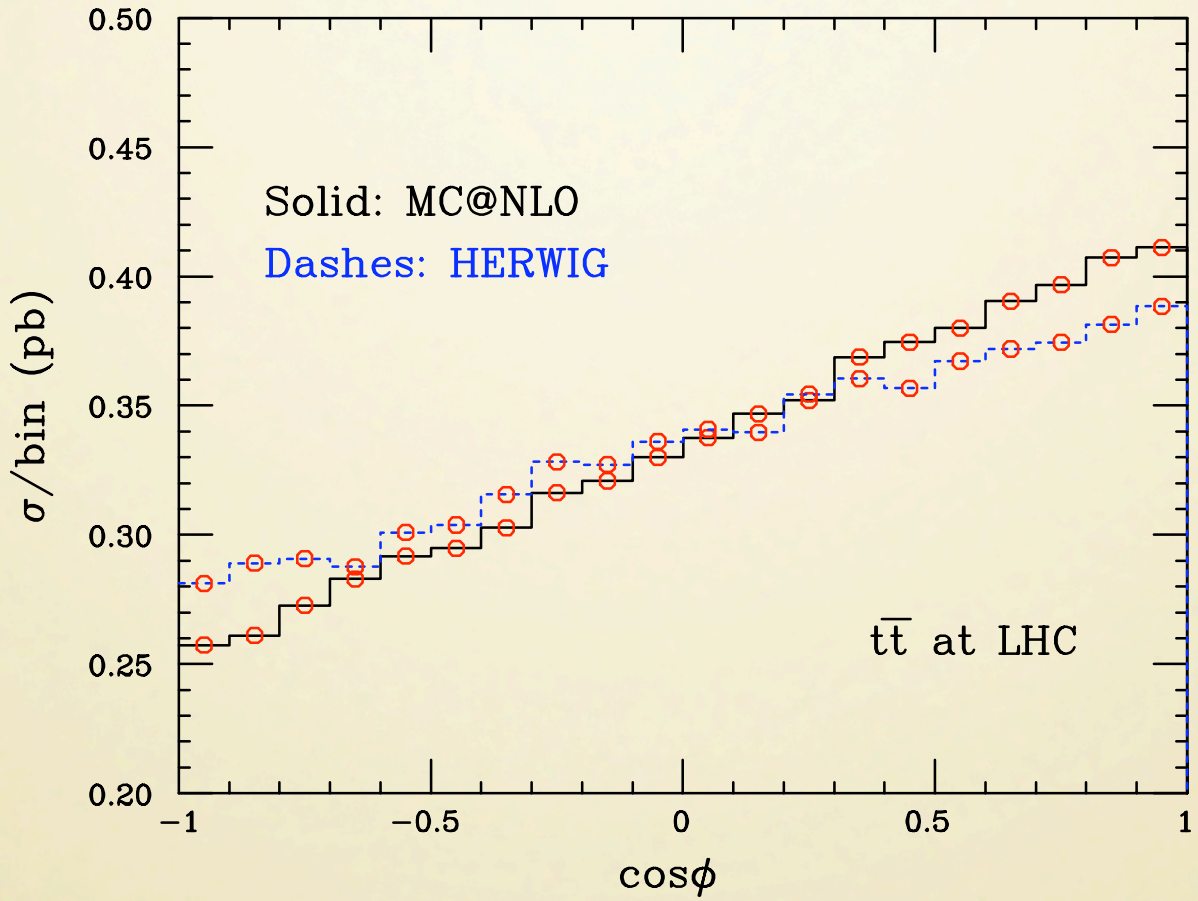


$$d\sigma^{\mathrm{NLO}}(e^+\nu_e b) < d\sigma^{\mathrm{NLO}}(t_{s'}) \otimes \rho_{s's}$$

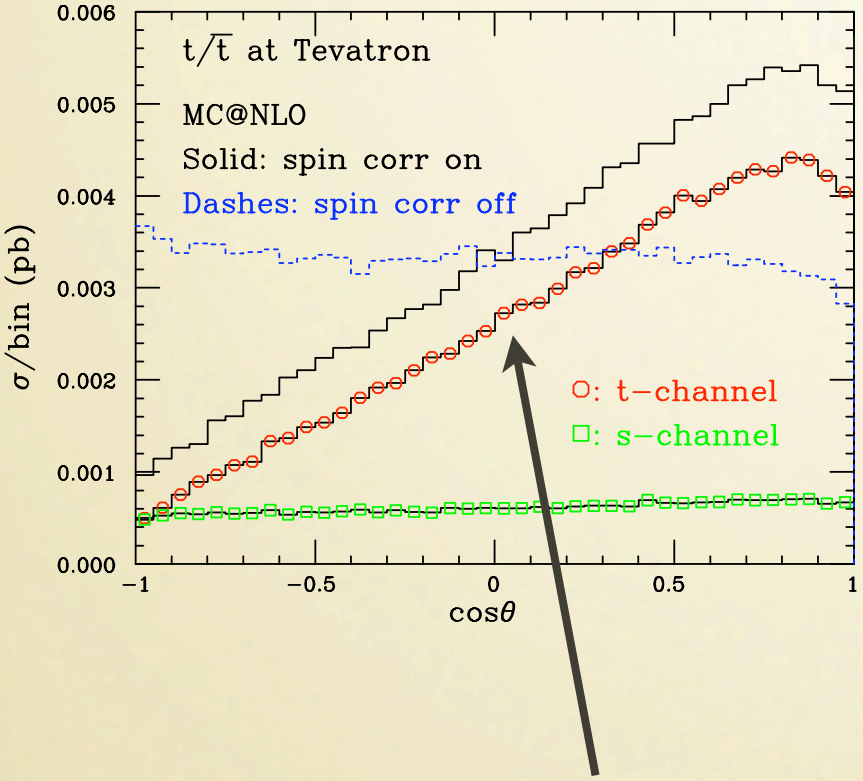
Spin-density matrix

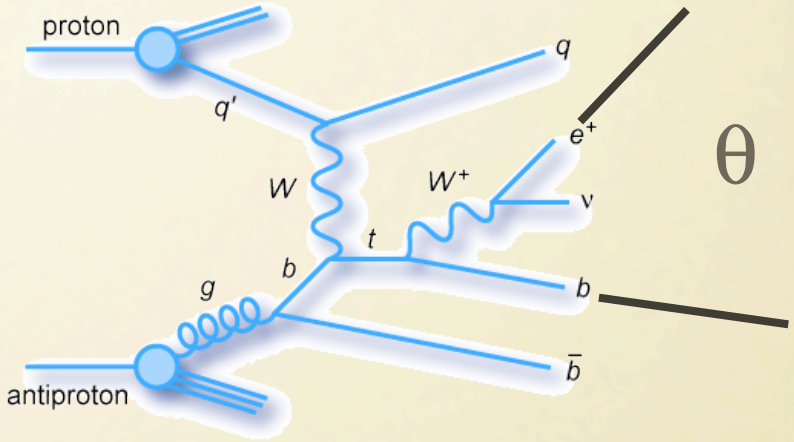
Use hit-and-miss unweighting to very efficiently include spin correlation effects

SPIN CORRELATIONS IN PAIR PRODUCTION



SPIN CORRELATIONS FOR SINGLE TOP





Clear correlations where expected

Visible when adding higher orders and final state realism

Summary

- Personally, I am very grateful for all that I learned in Stony Brook
- Top quark part of YITP history (Smith et al)
- LHC top factory, top physics expected next year