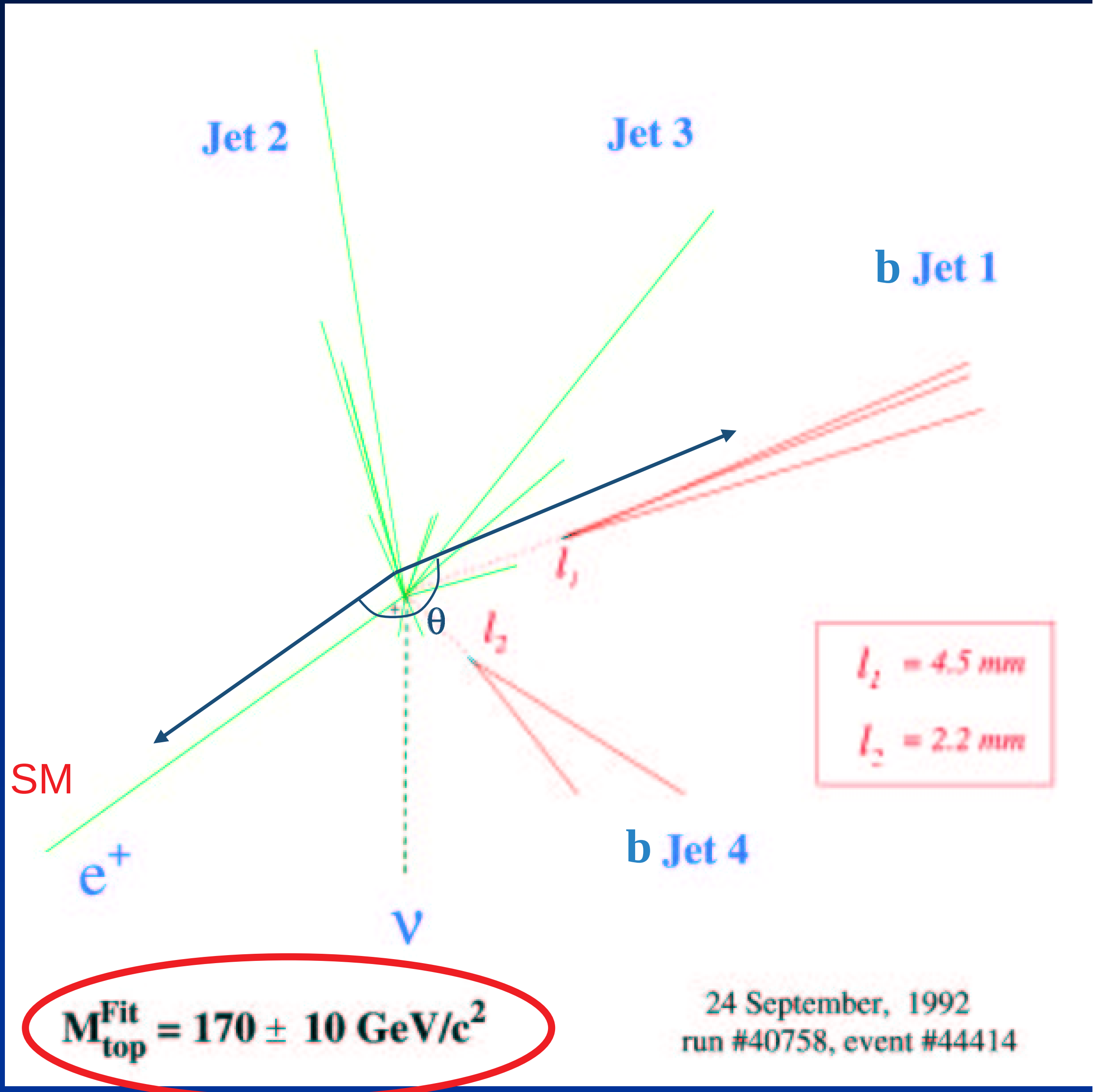
The truth about top-quark production

Aspen Winter Conference 2004

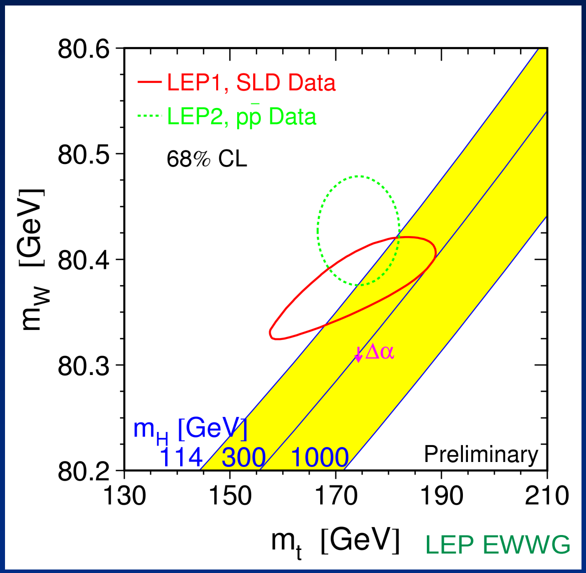
Zack Sullivan
Fermi National Accelerator Laboratory

Contents

- M_t
  - $\sigma_{t\bar{t}}$ & new physics
- $Y_t \approx \frac{\sqrt{2}\,M_t}{246\text{ GeV}} \approx 1$
  - $t\bar{t}H$ & tH
- $\vec{s}_t$
  - W_L, $t\bar{t}$, single top
- V_{tb} $t \rightarrow Wb$ @ 99.92% in SM
  - $\sigma_{tj}, \sigma_{tb}, \sigma_{tW}$
  - New resonances



How well do we know M_t ?
(How well do we need to know it?)

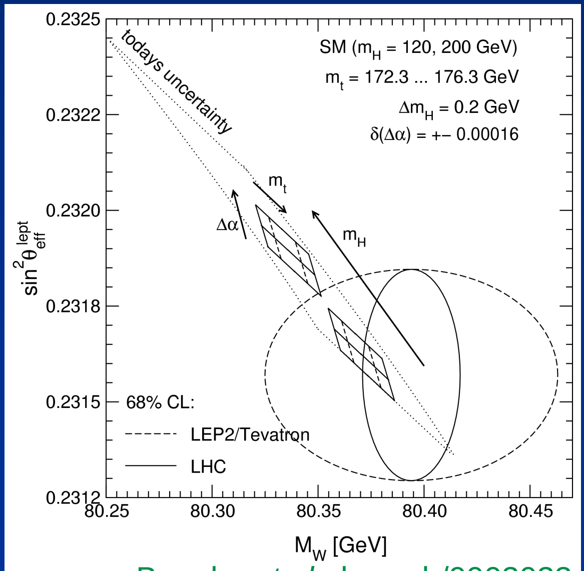


- M_t = 174.3 ± 5.1 GeV (Run I) ← ±3%
- Already better than EW precision
- M_H only logarithmically sensitive to M_t

A better way to look at it:

- Assume M_H known
- M_W will be known to ~20 MeV
  - Need M_t to ~3 GeV
- LC can measure M_W to ~6 MeV

  Giga-Z can measure $\sin^2\theta_W$ ~10^{-5}
  - Need M_t to ~1 GeV



Beneke *et al.*, hep-ph/0003033

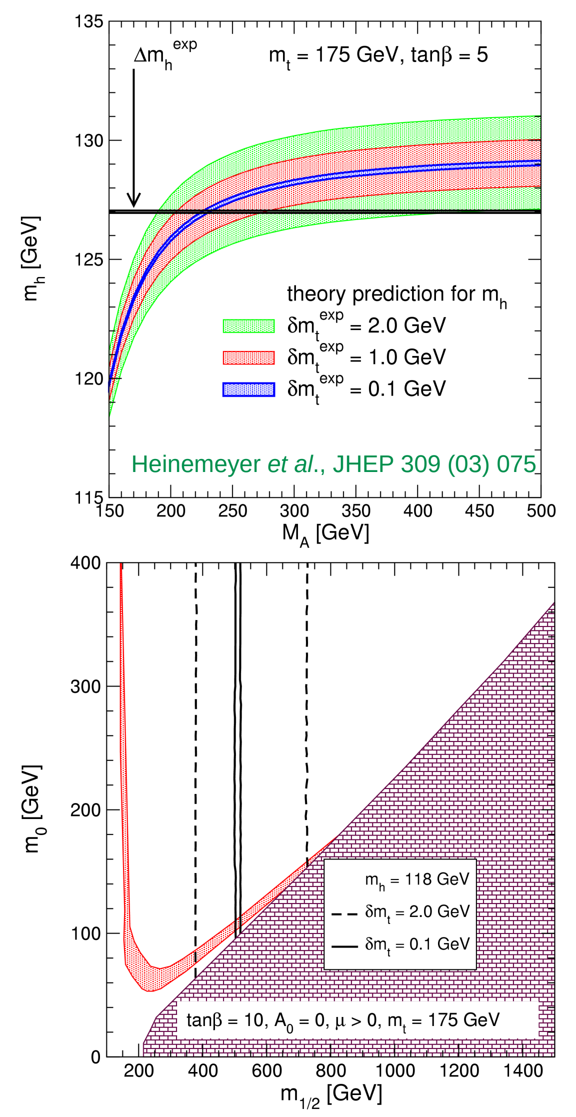
How well do we know M_t ?

(How well do we want to know it?)

- SUSY Higgs masses, e.g.

$$\Delta m_h^2 \cong \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta} \ln\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2}\right)$$

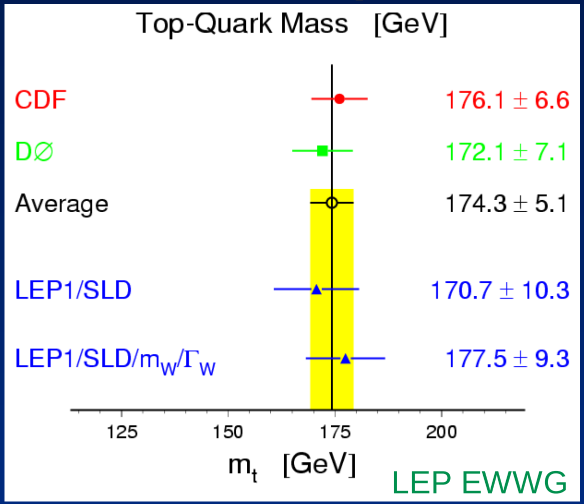
  - Exp. error will be ~200 MeV (LHC)
  - $\delta m_h \sim \delta m_t$, so want δm_t ~100 MeV
    - Note: 4-loop corrections to m_h are comparable in size. Needs major work
- Smaller error in M_t allows indirect access to M_A, A_t, $m_{1/2}$, etc.



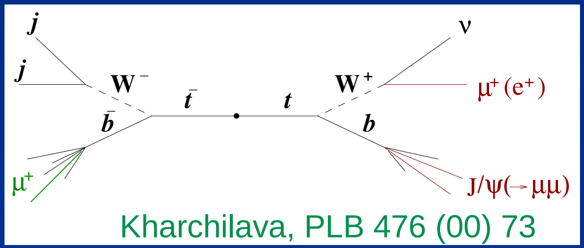
How well do we know M_t ?

(How do we do get there from here?)

- Tevatron: Run IIa reach ~±3 GeV
  - Currently use kinematic fits to M_{Wb}
  - Better choice: assign each event a probability that is a function of M_t
  - Run IIb systematic wall at ~±2 GeV



- LHC: Several channels can reach <1 GeV (stat.)
  - To reach systematics < 1 GeV use: $M_{J/\psi\ell\nu}$ w/ template for M_t (~400 fb^{-1})



- LC: Strive for δM_t ~100–200 MeV
  - Requires scan of $t\bar{t}$ threshold

All require accurate calculations of $t\bar{t}$ production & kinematics

$t\bar{t}$ Cross Section

"NNLO-NNNLL"

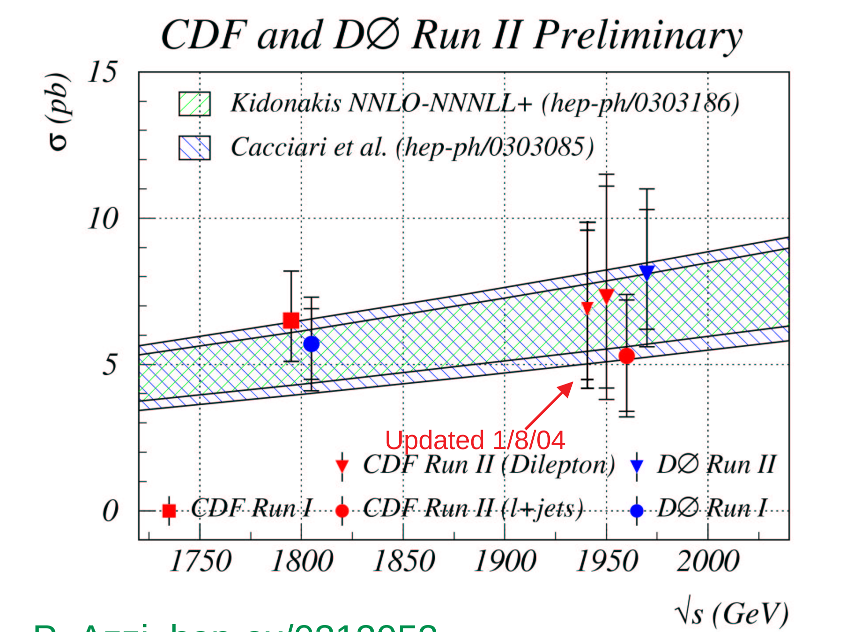
- Really NLO + Sudakov resummation, re-expanded
  - i.e. add soft gluons at threshold
- Results depend on expansion kinematics: 1PI vs. PIM

  1PI: $s = (p_q + p_{\bar{q}})^2$

  PIM: $s = M_{t\bar{t}}^2 = (p_t + p_{\bar{t}})^2$
- Tevatron updated:

(Kidonakis, Vogt, PRD 68 (03) 114014)

	σ	1PI/PIM	scale	PDF
Run I	5.24	± 0.31	± 0.2	± 0.6 pb
Run II	6.77	± 0.42	± 0.2	± 0.7 pb



P. Azzi, hep-ex/0312052

- LHC is not dominated by threshold kinematics:

  825 ± 50 ± 100 ± 90 pb ← ±20%

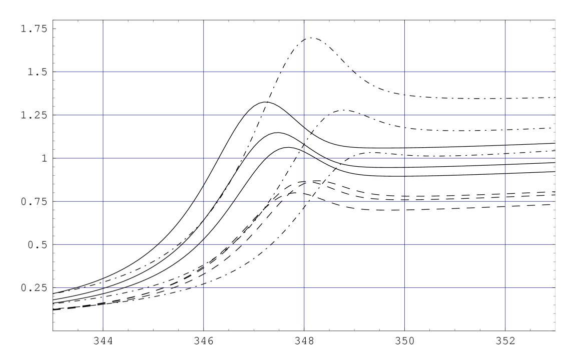
Full NNLO calculation needed!

$t\bar{t}$ threshold at a Linear Collider

- Use 1S or PS mass, not pole
- Large non-relativistic corrections

$$\sigma_{t\bar{t}} \propto v \sum \left(\frac{\alpha_s}{v}\right) \times \left\{ \begin{matrix} 1 \\ \sum (\alpha_s \ln v)^i \end{matrix} \right\} \left\{ \begin{matrix} \mathrm{LO}(1) + \mathrm{NLO}(\alpha_s, v) + \mathrm{NNLO}(\alpha_s^2, \alpha_s v, v^2) \\ \mathrm{LL} \quad + \mathrm{NLL} \quad\quad + \mathrm{NNLL} \end{matrix} \right\}$$

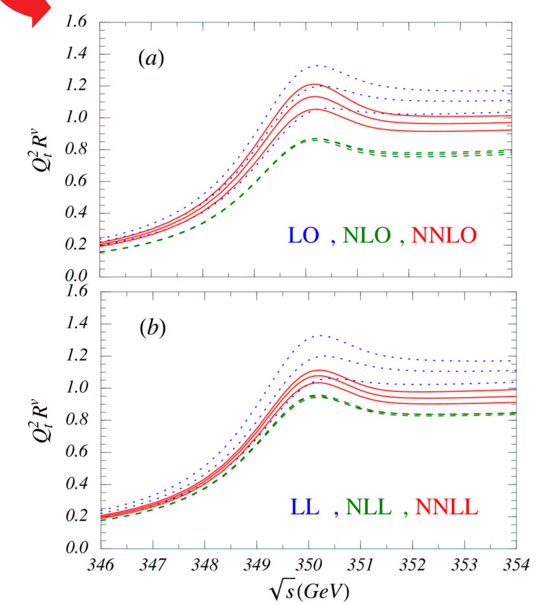
$$m_t v^2 \equiv \sqrt{s} - 2m_t$$



Yakovlev, Groote, PRD 63 (01) 074012

- Most of NNLL terms done
  - Caused change in normalization
  - New uncertainty in $\sigma_{t\bar{t}}$ is ±6% before ISR/beamstrahlung/etc.
- δm_t ~100 MeV still attainable

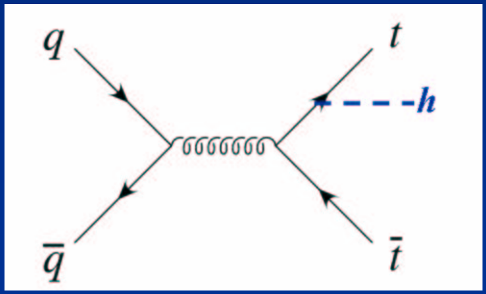
A. Hoang, hep-ph/0310301



A. Hoang, hep-ph/0310301

Y_t from M_t & theory

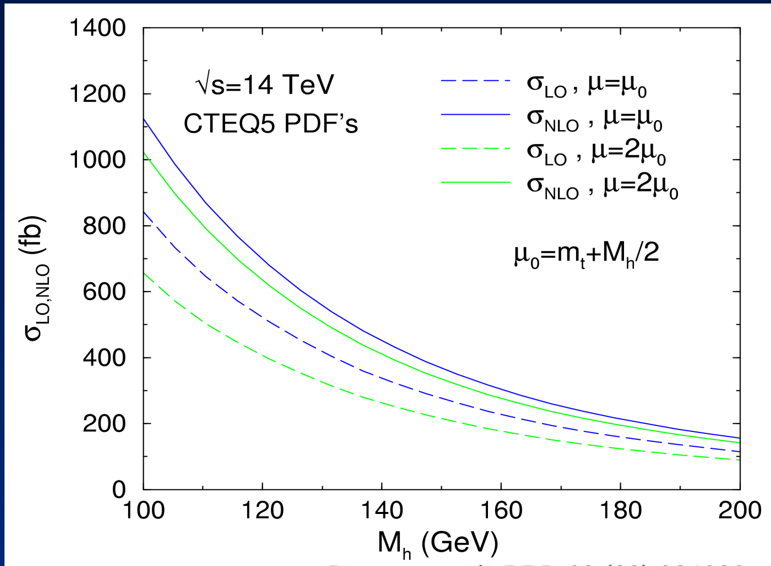
- $Y_t \approx \frac{\sqrt{2}\, M_t}{246\ \text{GeV}} \approx 1.00 \pm 0.03$ ← We want this precision
- We want to measure Y_t directly to confirm its relationship with the top-quark mass.
  - gluon fusion through top loop
    is subject to interference effects
  - Higgs exchange at threshold is too weak
  - ttH associated production is the best
    - Limited at LHC to 10-15%
    - LC will have very limited mass reach, but similar precision



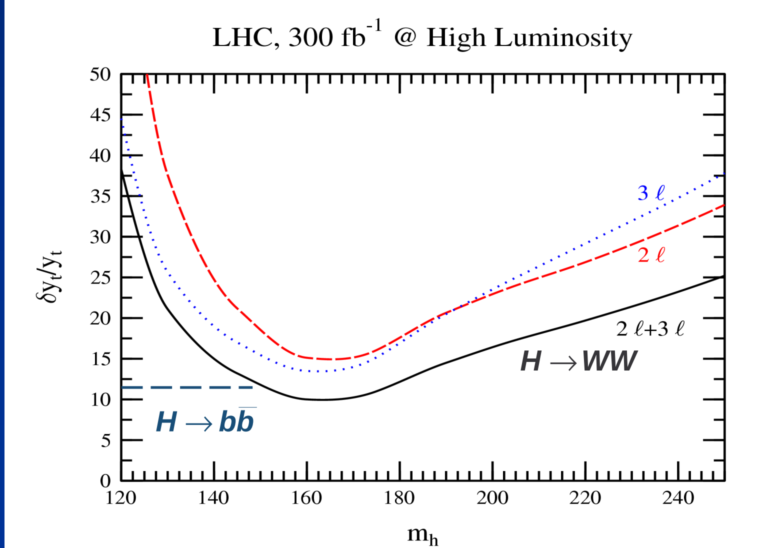
- No known way to get down to ~1%.

$t\bar{t}H$ at LHC

- Fully differential NLO cross section done 2 ways
  Beenakker *et al.*, NPB 653 (03) 151;
  Dawson *et al.*, PRD 68 (03) 034022
  - Uncertainties: (~± 20%)
    μ: ±15%, PDF ±6%, M_t ±7%
- Combining $H \to b\bar{b}$, $H \to WW$
  $\Rightarrow$ δY_t ~±10% at best.



Dawson *et al.*, PRD 68 (03) 034022



Maltoni, Rainwater, Willenbrock, PRD 66 (02) 034022

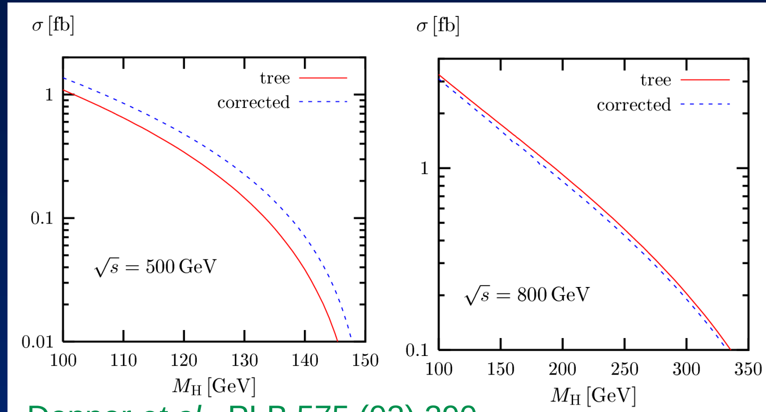
$t\bar{t}H$ at a LC

- Many 10% corrections to cross section at NLO

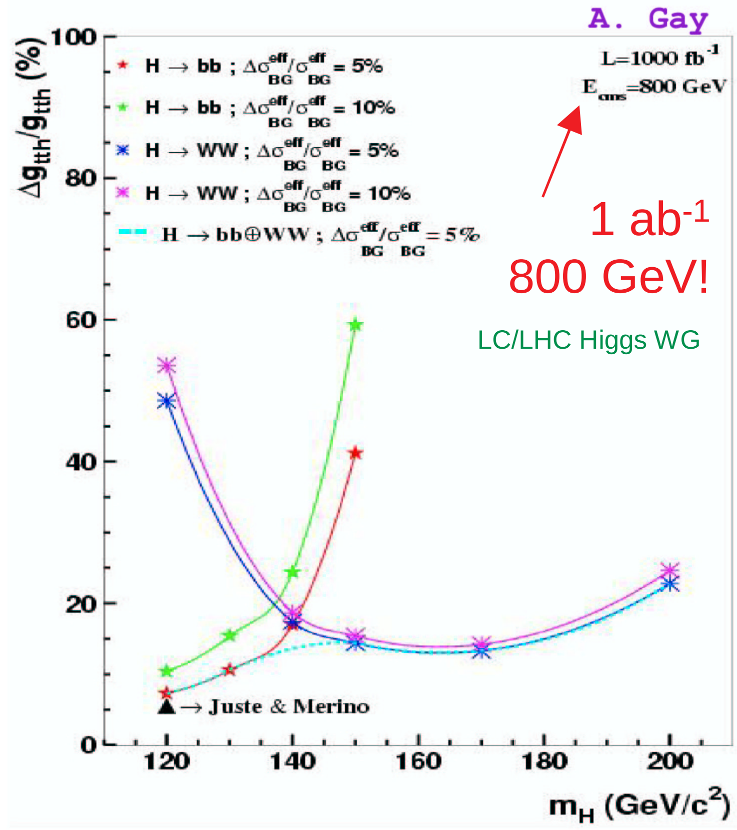
  You *et al*., PLB 571 (03) 85; Belanger *et al*., ibid 163; Denner *et al*., PLB 575 (03) 290

- $\sigma_{t\bar{t}h}$ varies up to ±50% in SUSY Zhu, hep-ph/0212273
- Only tenable with high energy collider ≥ 800 GeV
  - Need lots of luminosity
- At best get to ±10% error in Y_t if M_H < 180 GeV

Not very promising…

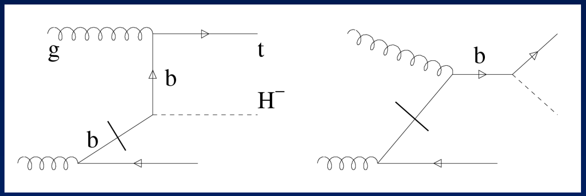


Denner *et al*., PLB 575 (03) 290



Zack Sullivan, Aspen 2004 February 2

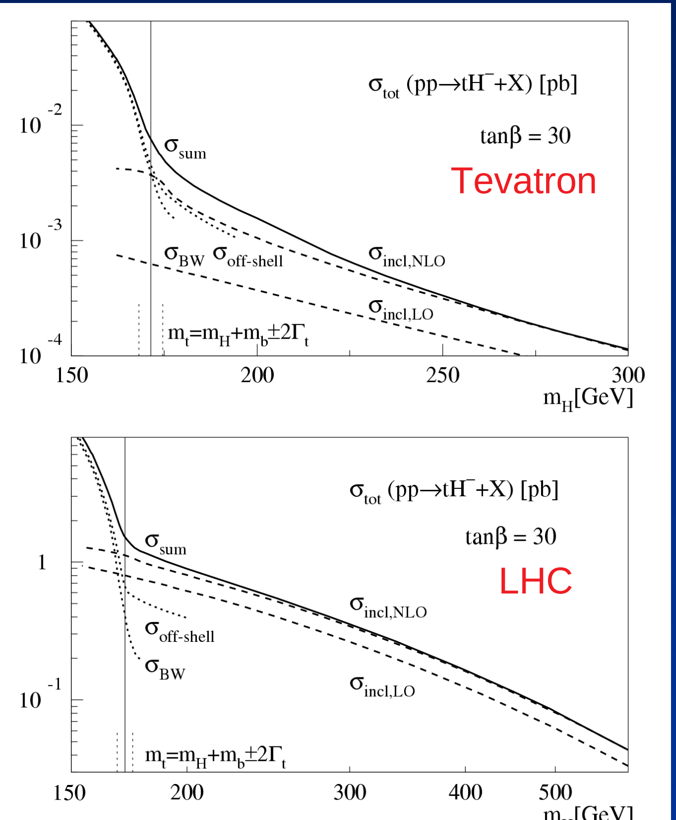
tH^- at Tevatron & LHC



- If "*H*" is SM-like may need to see $H^\pm$ to know we have 2HDM
- If $M_t > M_H$ produce $t\bar{t}$ w/ $t \to bH^+$
  - $t \to bH^+$, $H^+ \to t\bar{b}$ known at NLO

Carena *et al.*, NPB 577 (00) 88

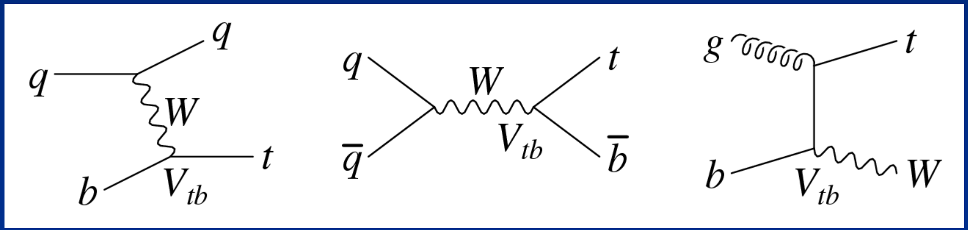
- NLO rates known, but now fully differential Berger *et al.*, hep-ph/0312286
  - Allows for correlations in decays
- Up to 50% corrections if μ parameter and tanβ are large



Berger *et al.*, hep-ph/0312286

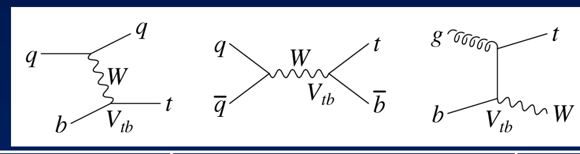
V_{tb}

- In the SM $V_{tb} = 0.99915 \pm 0.00015$
- Measuring B($t \rightarrow Wb$) only tells us $V_{tb} \gg V_{td}, V_{ts}$
  - CDF measured $\frac{\mathrm{BR}(t \rightarrow Wb)}{\mathrm{BR}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24}$ PRL 86 (01) 3233
- Single-top cross section proportional to $|V_{tb}|^2$
  - Measure B($t \rightarrow Wb$) in $t\bar{t}$, extract $\delta V_{tb} \sim \delta\sigma_t/2$



- Run I limits on cross sections:
  - *s*-channel: 18 pb [17 pb]
  - *t*-channel: 13 pb [22 pb] CDF, PRD65 (02) 091102 [DØ, PLB 517 (01) 282]

Single-top-quark production



	Tevatron Run I	Tevatron Run II	LHC	Dominant Uncertainties
σ_t (NLO)[1]	1.45±0.08 pb	1.98±0.13 pb	247±12 pb	PDFs
σ_s (NLO)[1]	0.75±0.07 pb	0.88±0.09 pb	10.7±0.9 pb	$\pm 2.5\% \times \delta M_t$
σ_{tW} (LL)[2]	0.06±0.01 pb	0.09±0.02 pb	56±8 pb	PDFs & scale
Total	**2.26±0.11 pb**	**2.95±0.16 pb**	**314±15 pb**	

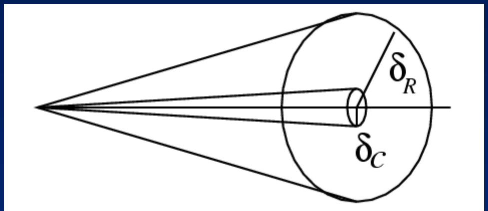
- *s*-/*t*-channel now known fully differentially[1]
  - Reduced uncertainty from modeling of kinematics 15% → 6%
  - First honest PDF uncertainties now (add to above):
    - $\delta\sigma_t$ = +11 –8 %; $\delta\sigma_s$ = +4.7 –3.9 %

[1] Harris, Laenen, Phaf, ZS, Weinzierl, PRD 66 (02) 054024
[2] Tait, PRD 61 (00) 034001; Belyaev, Boos, PRD 63 (01) 034012

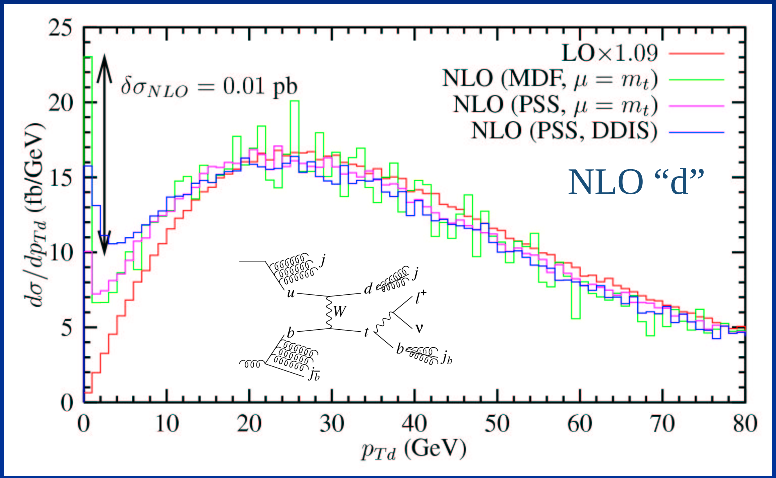
Paradigm of “jet calculations”

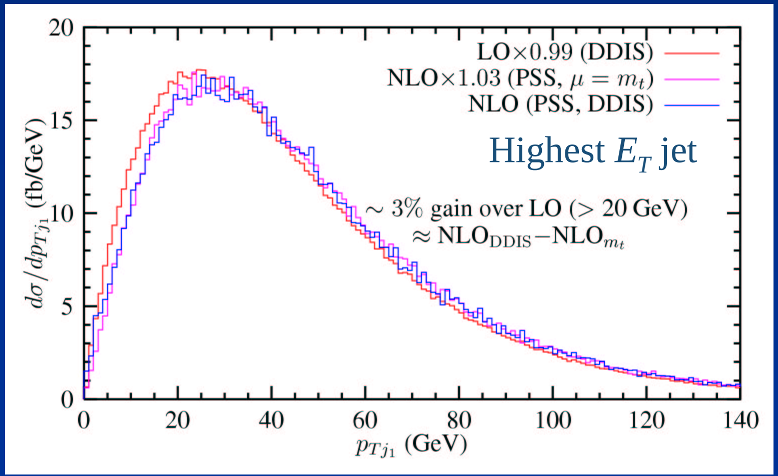
How do we interpret fully differential NLO?

- We are calculating jets <u>not</u> partons
  - Calculations are not well defined w/o a jet definition or hadronization function

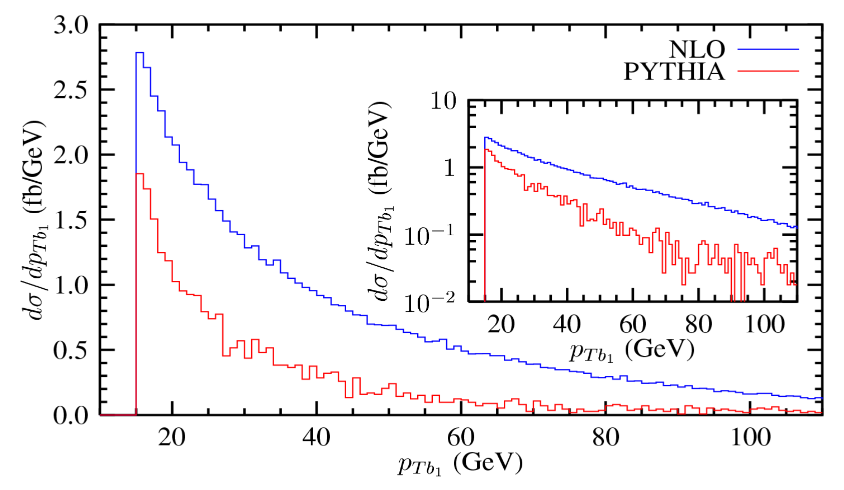


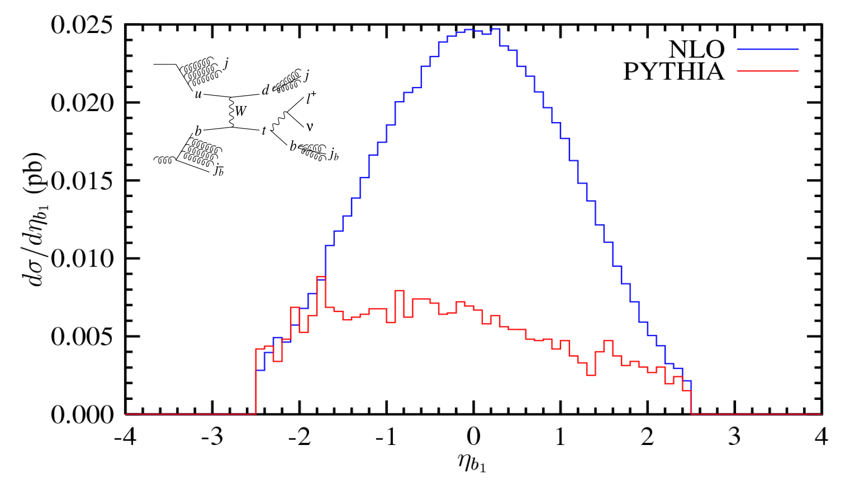
- Bad things happen if you treat jets as partons:





Problems with PYTHIA/HERWIG

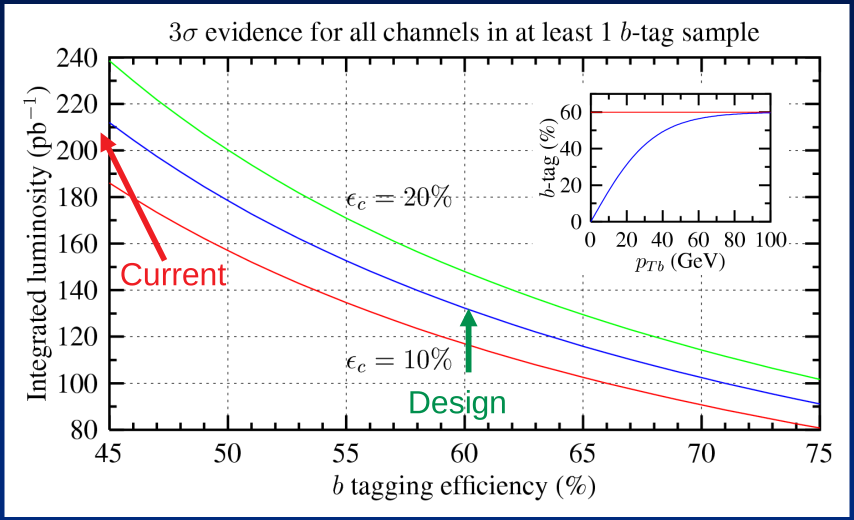


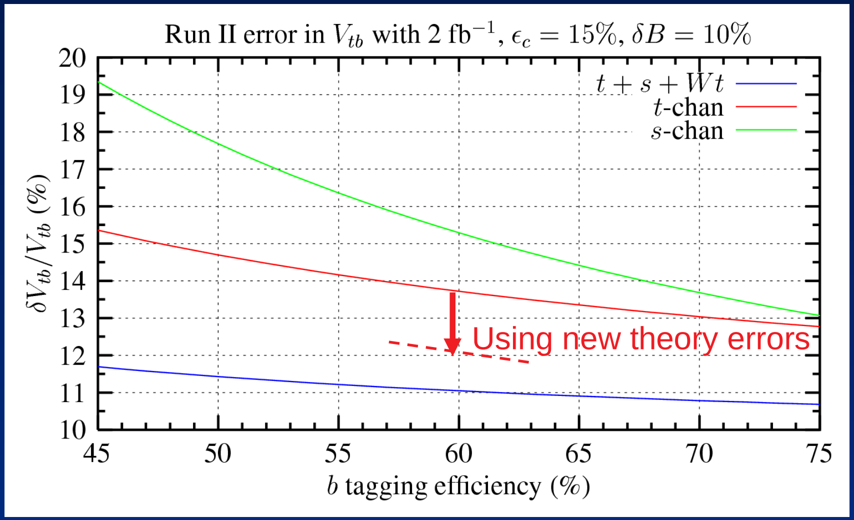


- Current showering event generators do not produce enough hard IS radiation to model *t*-channel
- Completely missing most of sample w/ extra hard *b*

- Killer: pseudorapidity shape is wrong
  - Factor of 3 underestimate σ_t
  - Danger for neural nets
- Background to *W*-Higgs, or any *W*+2 *b*-tag
- NLO must be used to correct MC samples

B tagging is everything…



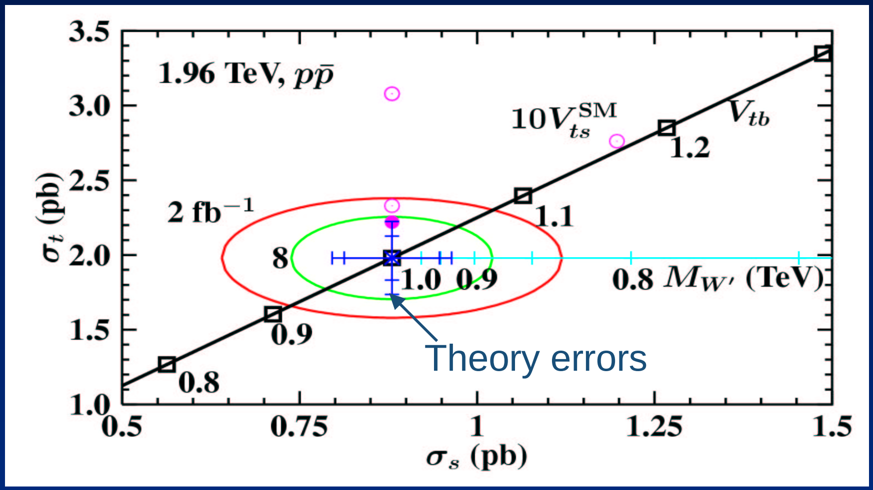


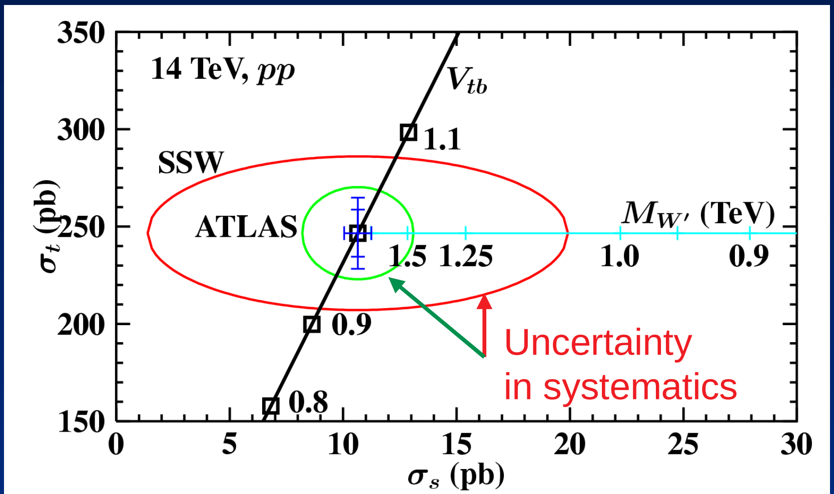
- When reach design need 130 pb^{-1} for "evidence"
- Should have enough data on tape any day now…

- Extraction of V_{tb} will be statistics limited
- Using new *t*-channel theory should improve extraction in exclusive and combined channels

  @2 $fb^{-1} \rightarrow \delta V_{tb}$ ~12% (t-chan)

Experimental reach vs. theory

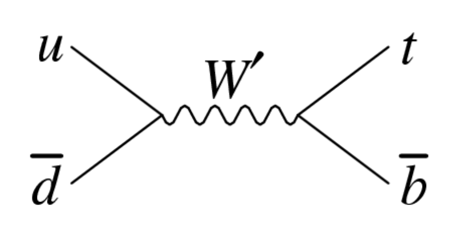




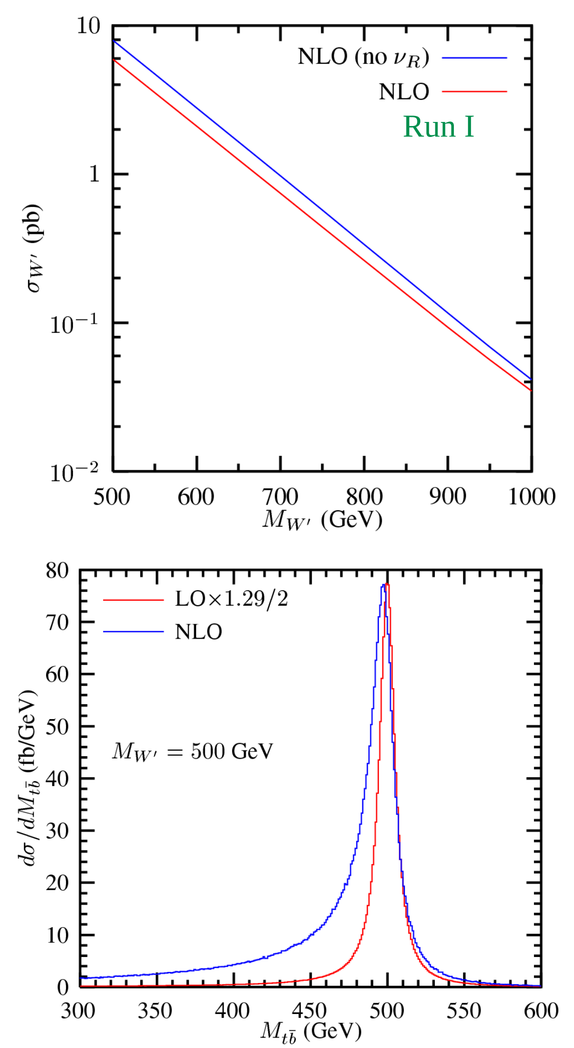
- Theory errors are smaller than experimental reach
  - Not necessarily true with extreme cuts
- Tevatron is statistics limited until ~30 fb^{-1}
- LHC is completely systematics limited
  - factor of 10 discrepancy in background estimates at LHC
  - A new study is needed to resolve whether *s*-channel is observable at the LHC – needs to use corrected NLO signal and backgrounds.

W' at Tevatron

- Best way to look for W' bosons.
  Simmons; Tait, Yuan (97)



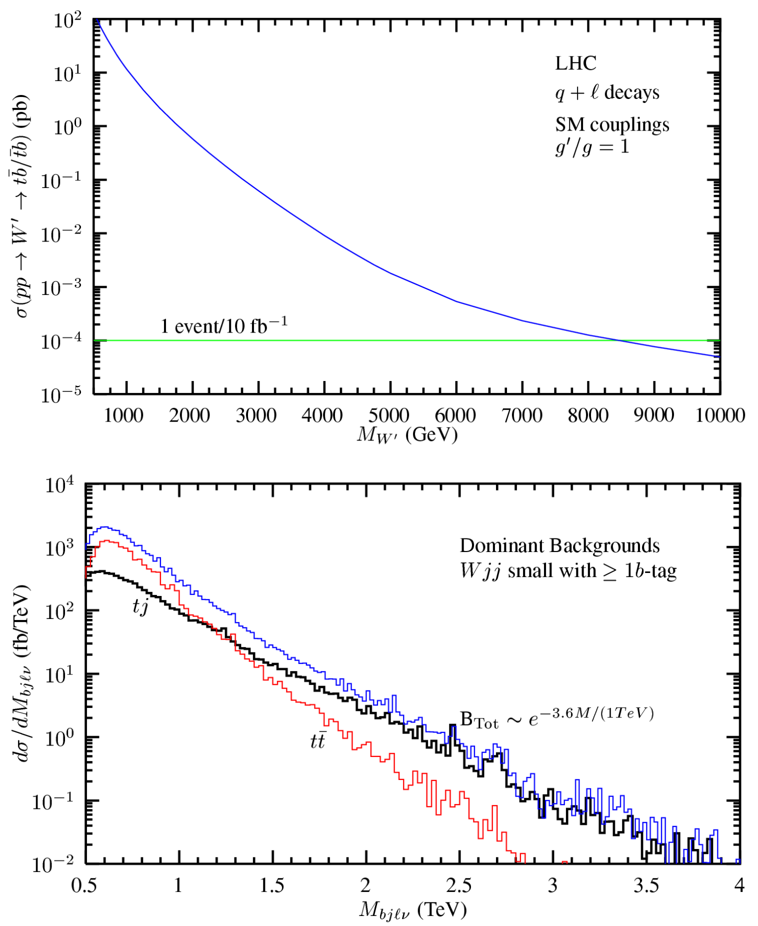
- Fully differential NLO for arbitrary V, A couplings ZS, PRD 66 (02) 075011
  - First use “modified tolerance method” for PDF uncertainties
  - CDF used: $M_{W'}$>550 GeV (was 420 GeV)
    PRL 90 (03) 081802
  - Look for resonant peak in *Wbb* invariant mass – same rate for L/R-handed
  - Use spin correlations to tell if W' has left or right-handed interactions
- Run II can reach 800-900 GeV (2 fb^{-1})



ZS, PRD 66 (02) 075011

W' at LHC

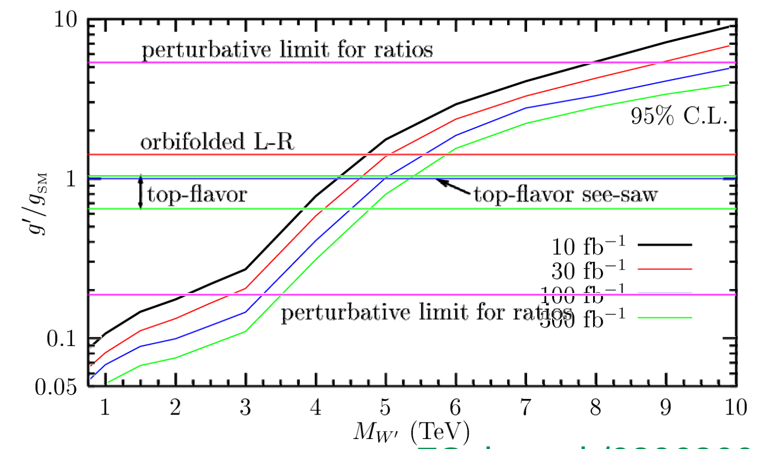
- Huge cross section at LHC
  - 10 TeV W' @ 50/yr (high lum.)
  - Total rate less than *s*-channel single-top sample if $M_{W'}$>2 TeV
  - Must use invariant mass
- Only background > 1 TeV: *t*-channel single-top
  - Completely missed by HERWIG/PYTHIA!



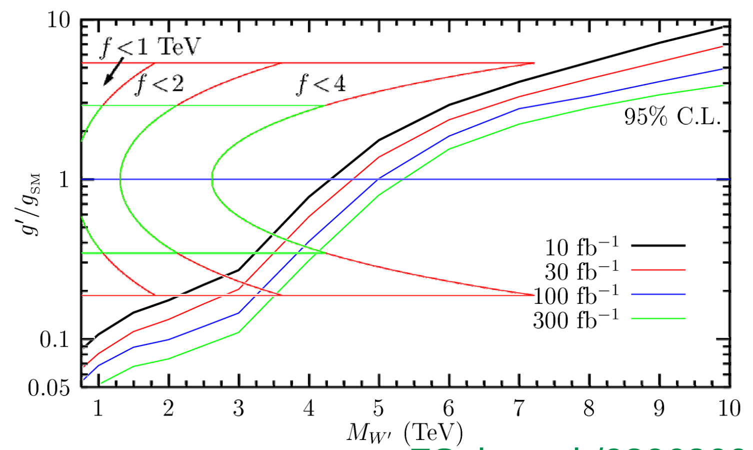
ZS, hep-ph/0306266

W' at LHC

- Using $M_{bj\ell\nu}$ can reach 5.5 TeV
  - PDFs induce kinematic limit here
  - Can reach couplings 10× smaller than g_{SM}!
  - Most perturbative theories predict couplings within factor of 2 of g_{SM}



ZS, hep-ph/0306266



ZS, hep-ph/0306266

- Coupling limit is model independent (if $\Gamma_{W'} < M_{W'}$)
- Can use ZS, PRD 66 (02) 075011 to find limits in favorite model
- Littlest Higgs models can be ruled out in 1 year at LHC!

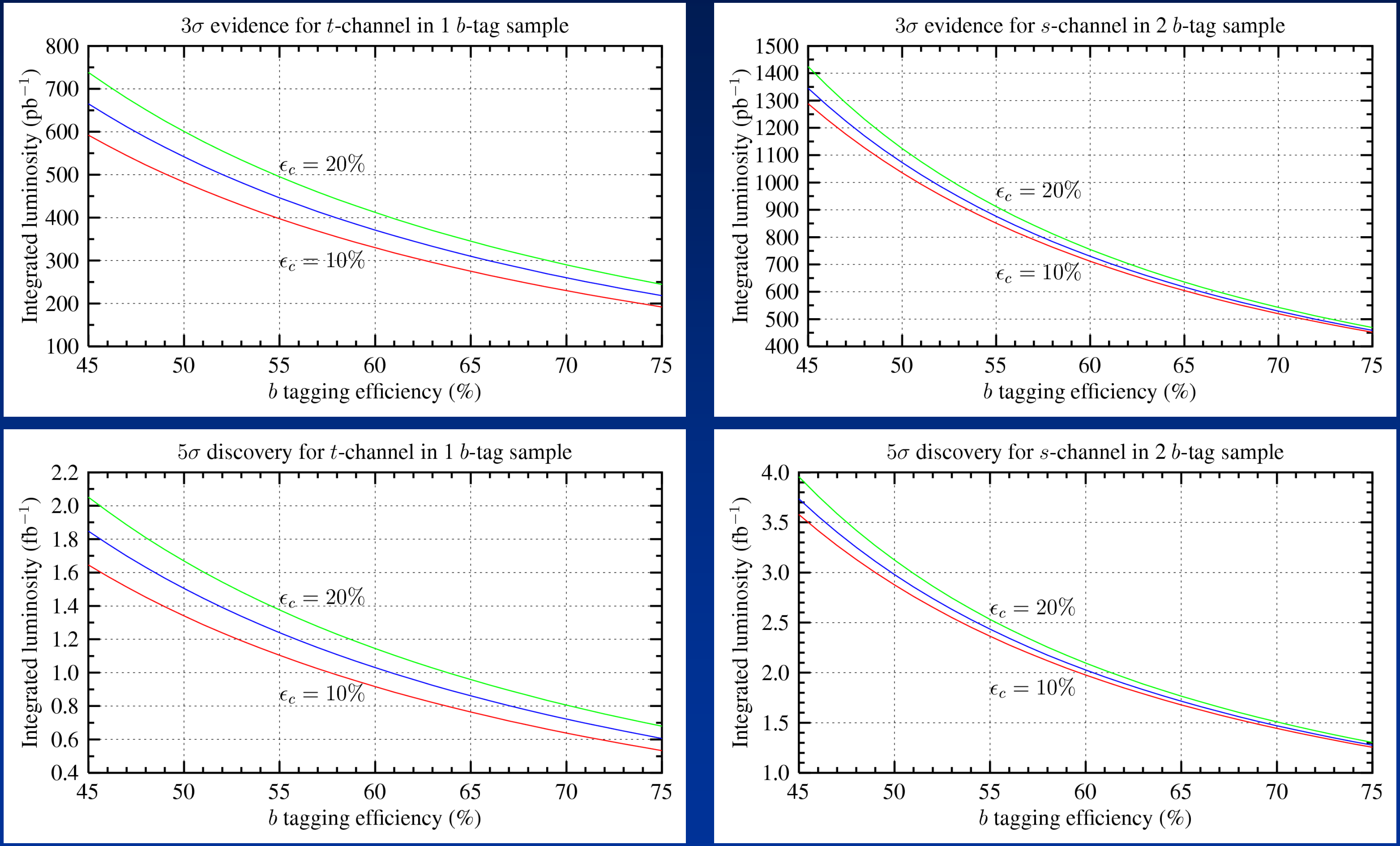
Conclusions

- Top quark theory is in good shape for current experiments, i.e. Tevatron, HERA, flavor physics
- When LHC turns on we will need
  - NNLO $t\bar{t} \to WW+X$ fully differential cross sections
    - Needed for improved measure of M_t
    - Accurate backgrounds for SM and beyond (large systematics)
  - Vast improvements in: event generators, PDFs, fragmentation functions ($t \to BX$), high energy (1 TeV) objects
  - Investigate polarization in single-top-quark kinematics
  - Data: this will help pin down many of these issues
- Finding the truth about top quarks will be challenging:
  - δM_t can get to: 3, 2, 1, 0.1 GeV; δY_t can only reach ±10%
  - $\vec{s}_t$ can see at Tevatron (maybe LHC); V_{tb} ~±7-9% (Tevatron)

Will LHC compete? Work needed!

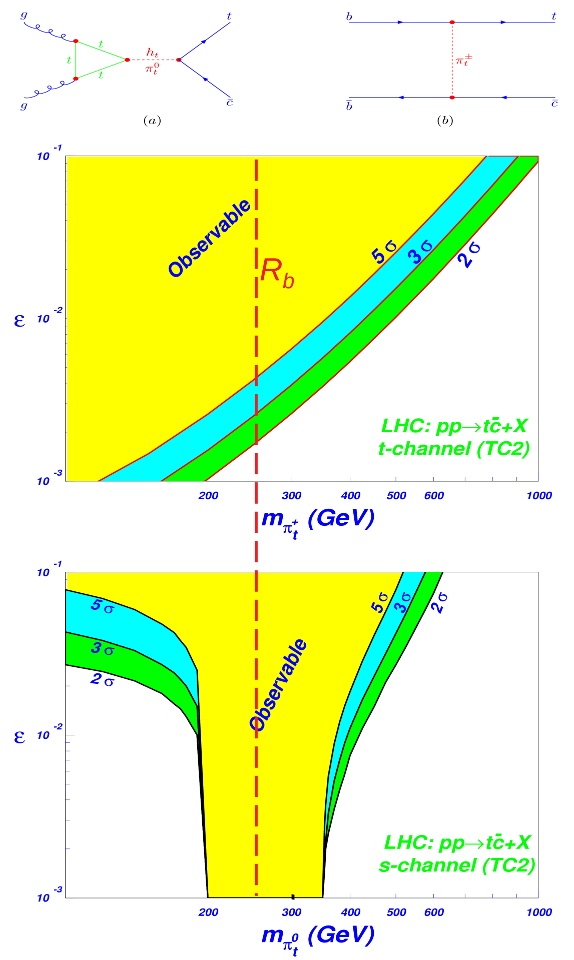
A few of the slides not shown

Required luminosity for *s*/*t*-channel



Topcolor-Assisted Technicolor

- Both π^+ and π^0 might appear in single-top-quark production
- Width is typically few $\times$100 GeV, so may not be clear resonance
- Cross section large enough to reach ~1 TeV for π^+ at LHC
  - ε is fraction of M_t due to TC
  - R_b puts lower limit of $M_\pi > 250$ GeV



Cao *et al.*, PRD 67 (03) 071701

$t u \gamma / Z$ FCNC

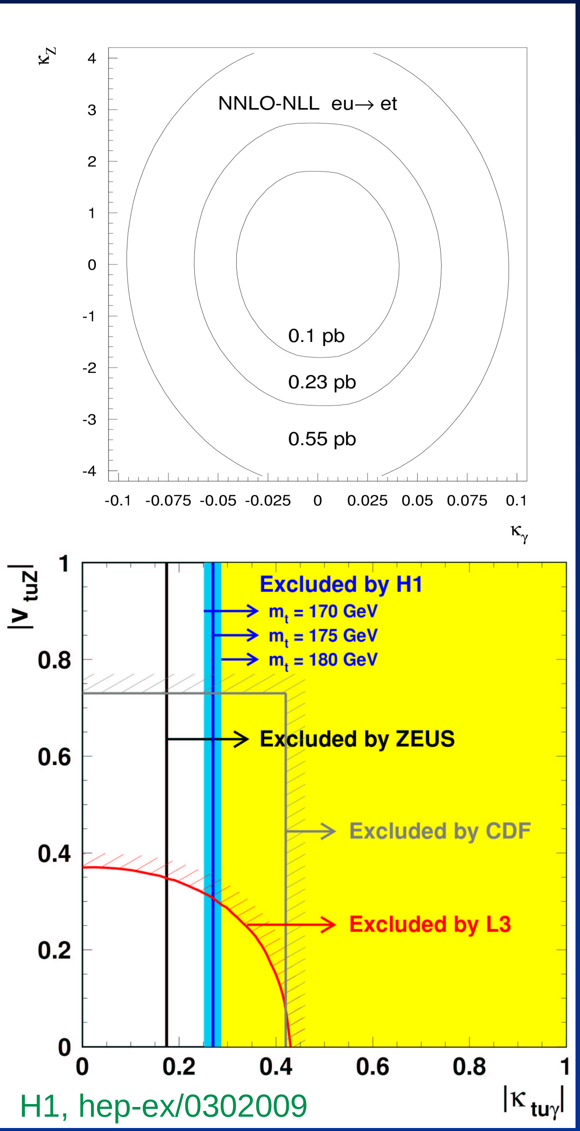
- SM single-top cross section at HERA is 10^{-2} fb (1 event/100 years)

  Stelzer, ZS, Willenbrock PRD 56 (97) 5919

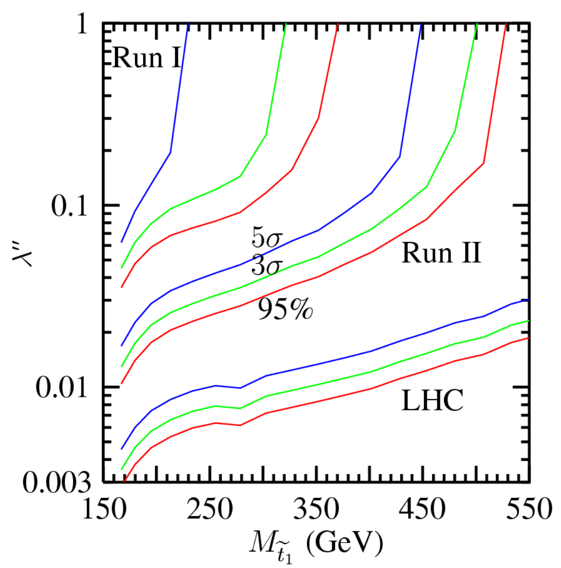
- Threshold resummed cross section now known

  Kidonakis, Belyaev, JHEP 0312 (04) 004

  – too small to see at Tevatron/LHC in remaining parameter space
  – HERA will improve factor of 2 over next few years



R-parity-violating $\tilde{t}$ production



Berger, Harris, ZS, PRD 63 (01) 115001

- Only known way to look for λ''_{3jk} couplings

Berger, Harris, ZS, PRL 83 (99) 4472; PRD 63 (01) 115001

- R_p-conserving decay looks just like single-top: $b\,\ell$ + missing E_T

- Look for resonant structure in transverse mass M_T
- Can cover much of MSSM parameter space