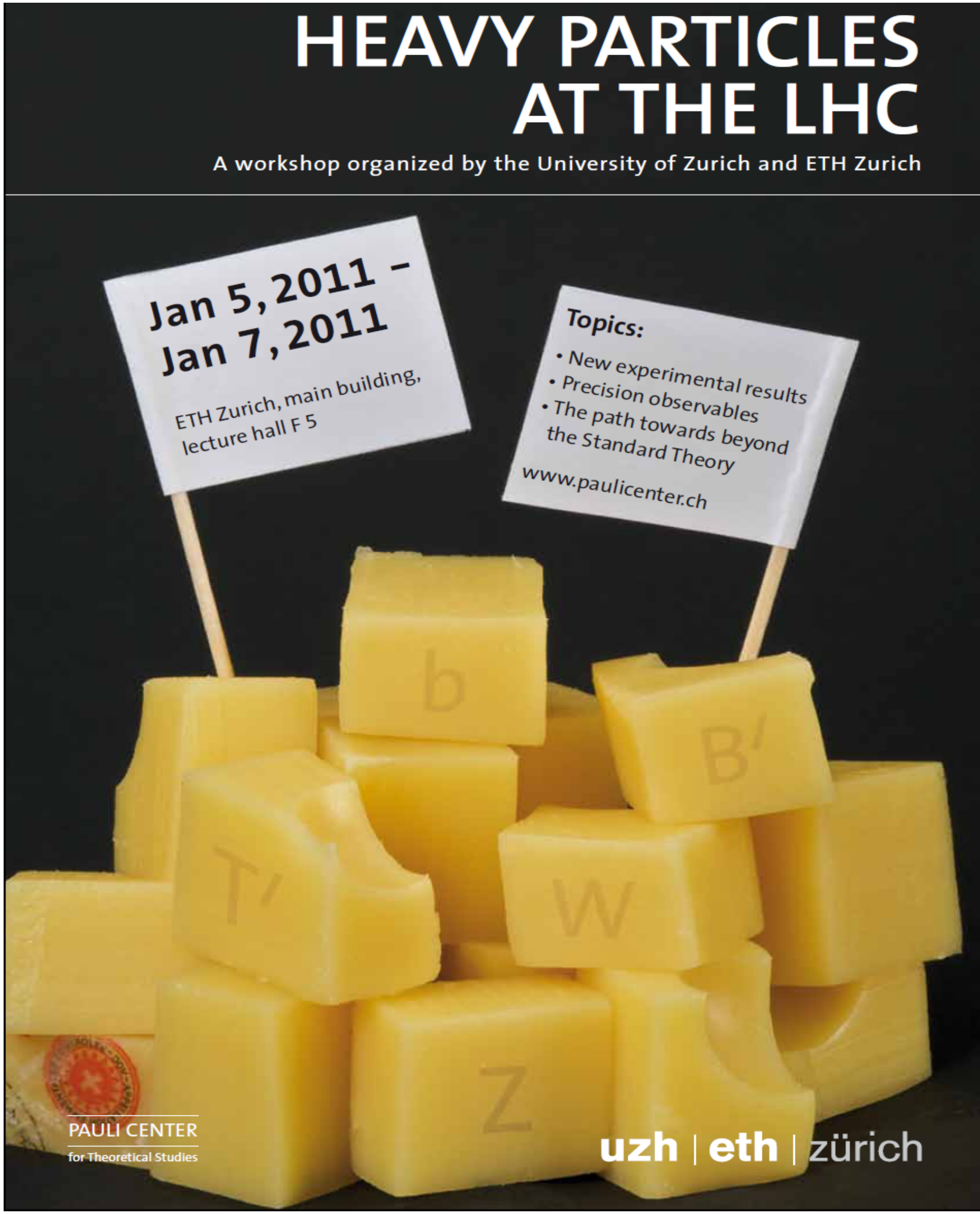


Summary Talk

S. Dawson, BNL

January 7, 2011

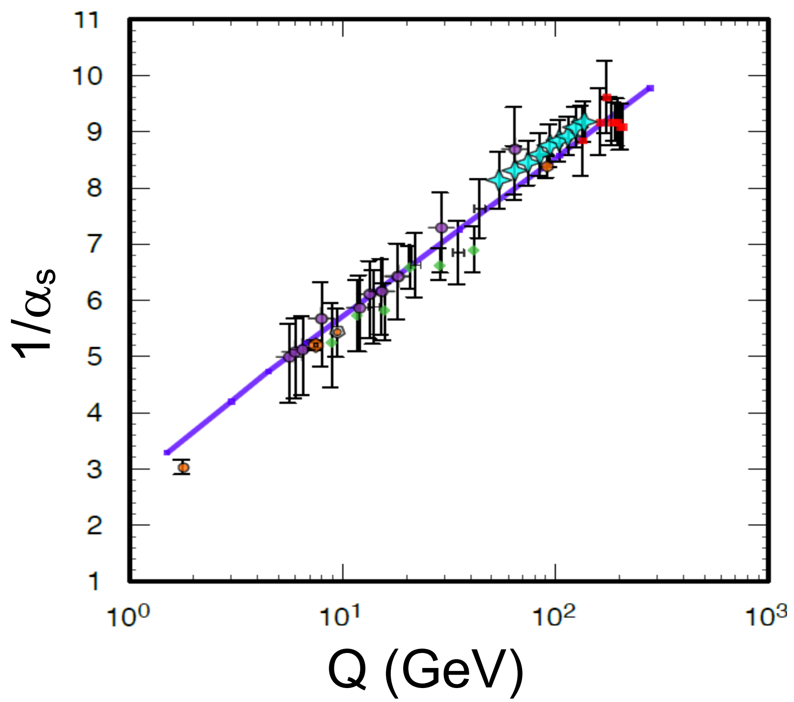
Apologies

- For all the results I don't mention here
- For inadequate referencing

- Why have a summary talk?
  - To give a "big picture synthesis"
  - For observers in internet land

Why Emphasize Heavy Particles? (#1)

- Perturbation theory converges well



- Precise predictions: $\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \ldots.$

Kronfeld & Quigg, arXiv:1002.5032

Why Emphasize Heavy Particles? (#2)

- Effective Field Theory (EFT) works
- Classify Beyond the SM (BSM) physics by new operators involving SM particles [Willenbrock]
  - Operators, O_i, restricted by symmetries of SM

$$\boxed{L = L_{SM} + \sum_i c_i \frac{O_i}{\Lambda^2} + \ldots}$$

  - Valid at scales $Q << \Lambda$
- Classify EFT by hierarchy of scales [Signer, Neubert]

SM → SCET → Soft Wilson Lines

Integrate out hard fields

Integrate out collinear fields

Why Emphasize Heavy Particles? (#3)

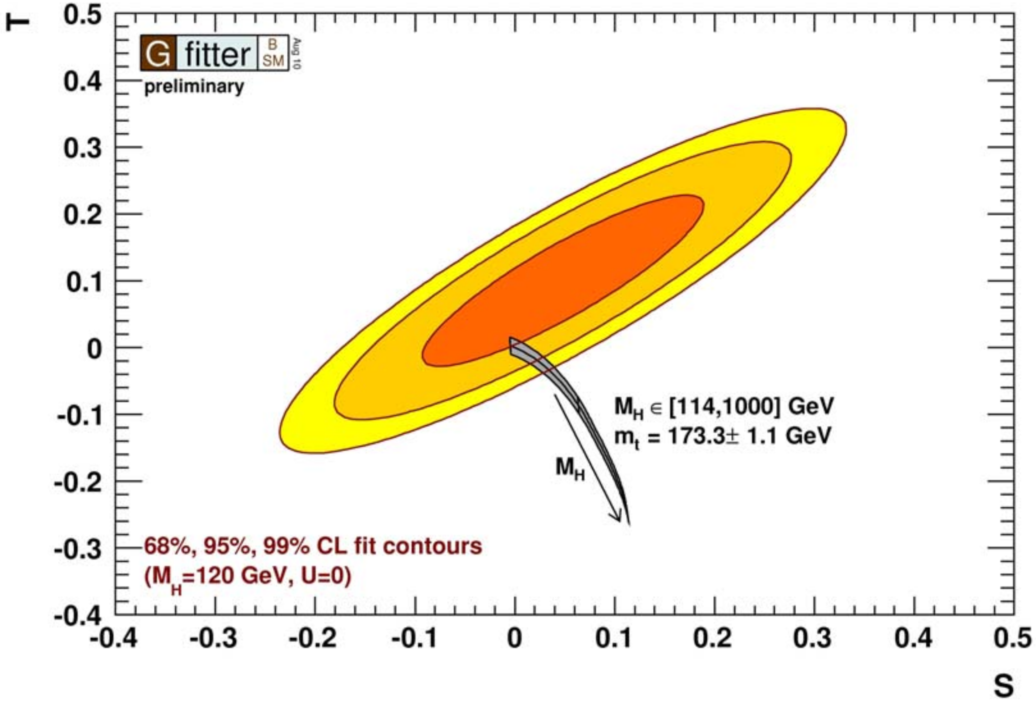
- Potentially large BSM effects in heavy particle production and decay
- Example: Top quark
  - The top is heavy! (Why is $M_t >> M_b$?)
  - Top coupling to Higgs large $\sim M_t/v \sim 1$
  - Top coupling to longitudinal W's large $\sim M_t/M_W$
  - Top decays before it can hadronize
  - Large top mass can drive electroweak symmetry breaking

Why Emphasize Heavy Particles? (#4)

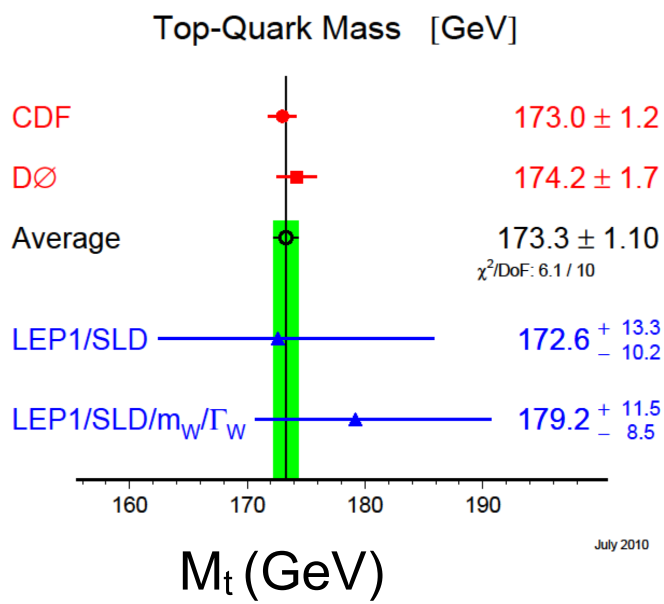
- New particle searches
  - SUSY particles [Barbieri, Blanke, Kulesza, Plehn, Schwinn]
  - Kaluza Klein states in extra-dimension models [Flacke]
  - Heavy leptons [Picek]
  - Generalized search strategies [Wacker]
  - Something we haven't thought of yet *(EFT particularly useful here)*

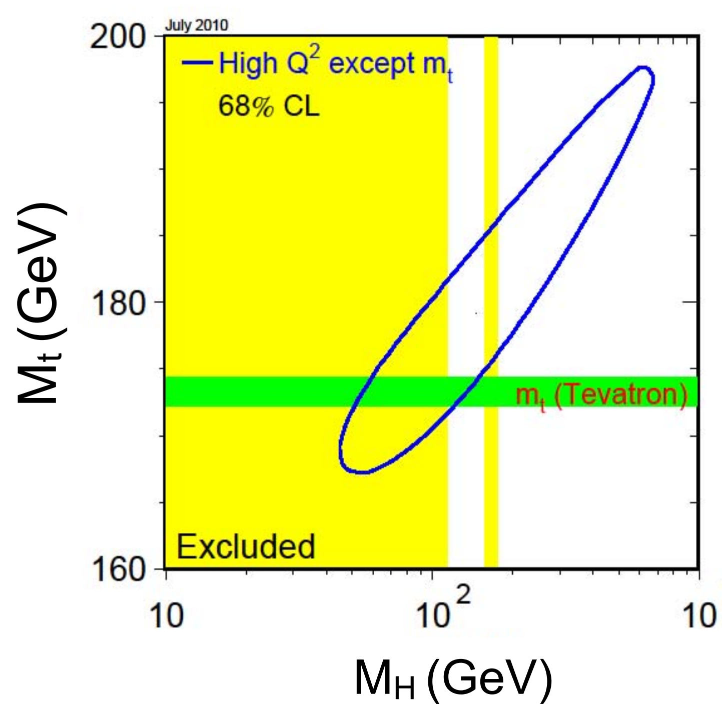
Standard Model Works

- BSM physics must be consistent with precision electroweak measurements



The Top Quark





Is the Standard Model self-consistent?

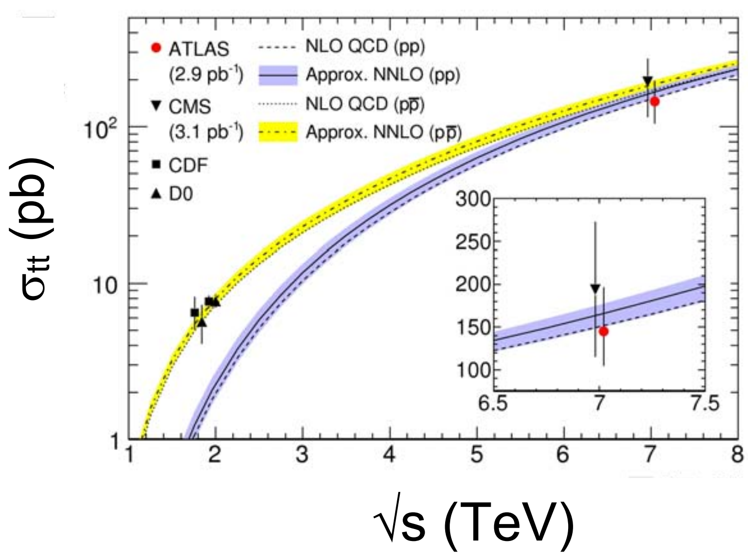
Top at the Tevatron

- Top is mature….several 1000 tops/experiment
- Tevatron combination: M_t=173.3±1.1 GeV
  - SM Higgs constraint driven by δM_W.
  - Need δM_W ~ 7 MeV
- Top pair cross section to 6% by using Z for luminosity normalization
  - CDF: σ_{tt} = 7.50 ± 0.31 ± 0.34 ± 0.15 pb (stat+syst+lum/ Z thy)
- No $t\bar{t}$ resonances to 900 GeV
- 4th generation, $M_{t'}$>335 GeV

[Wallny]

Top Quark at the LHC

- Top quarks observed with ~3 pb^{-1}!
- Cross section measured [Kroeninger, Krutelyov]
- Top sample at LHC will surpass Tevatron in 2011
- Expect 5σ for single top in 2011



ATLAS: 37 top candidates (semi-leptonic/di-lepton channels):

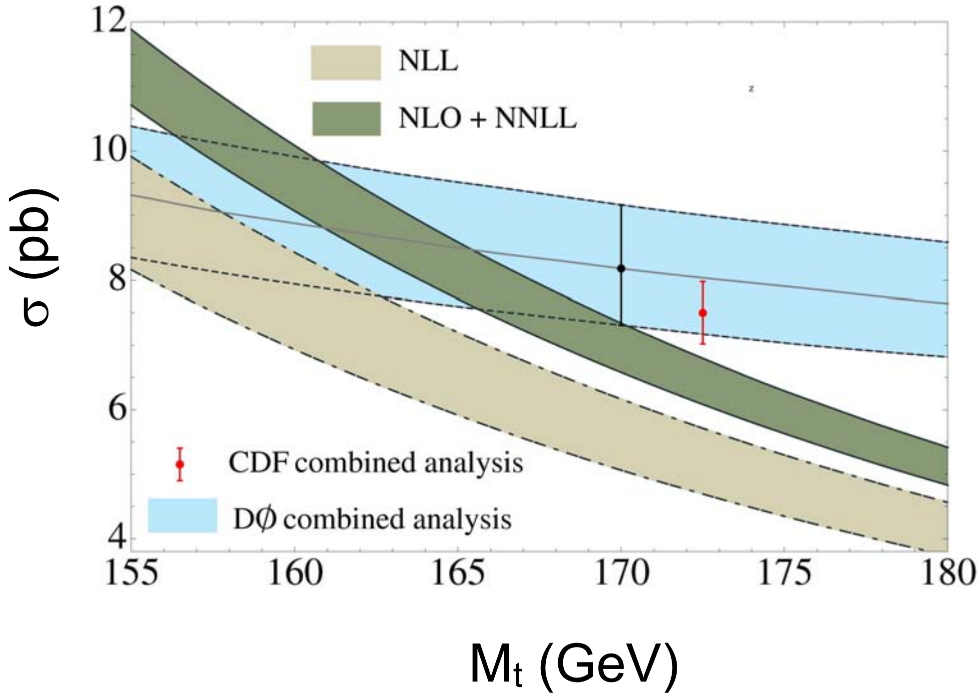
$$\sigma_{tt} = 145 \pm 31^{+42}_{-27}\ pb$$

CMS: 11 top candidates (di-lepton channel)

$$\sigma_{tt} = 194 \pm 72 \pm 24 \pm 21\ pb$$

CMS, arXiv: 1010.5994, ATLAS, arXiv:1012.1792

Top Quark: Cross Section and Mass



$\delta\sigma/\sigma(\text{exp})\sim 6\%$

$\delta M_t(\text{exp})\sim 1$ GeV

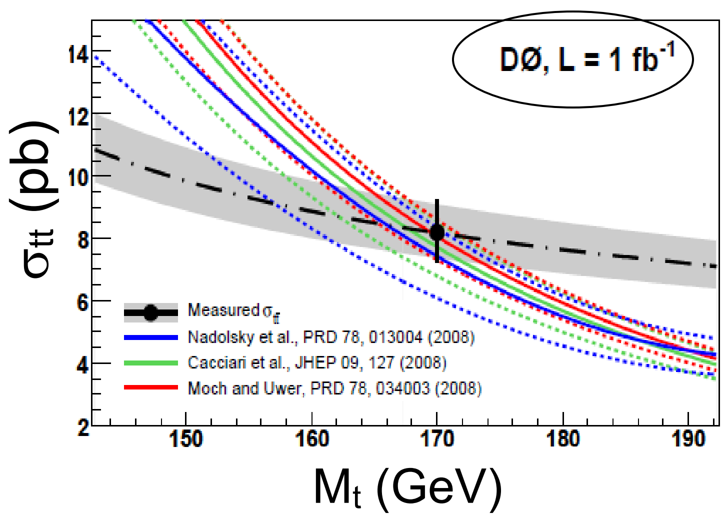
Is the Standard Model self-consistent?

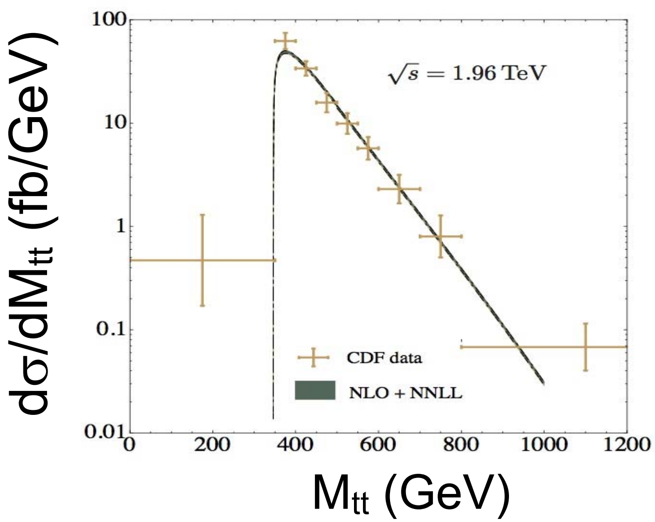
Is there room for BSM physics here?

Ahrens, Ferroglia, Neubert, Pecjak, Yang, arXiv:1003.5827

Top Mass From σ

- Note spread of higher order estimates [Moch]
  - Need full NNLO
  - Better scale dependence using running top mass
- Determine M_t from $d\sigma/dM_t$
  - D0 09: NLO $M_t=165^{+6.1}_{-5.9}$ GeV; NNLO $M_t=169.1^{+5.9}_{-5.2}$
  - Neubert: $M_t=163^{+7.2}_{-6.2}$ GeV





Top Pair Production Cross Sections

- LHC goal: $\delta\sigma_{tt}/\ \sigma_{tt} \sim 5\%$
  - LHC will have $10^5 - 10^6$ tops
- Resummation
  - Threshold and Coulomb effects [Schwinn]
  - EFT calculation [Neubert]
- Towards NNLO [Abelof, Czakon, Ferroglia]
- Spin correlations between production/decay [Melnikov]
- Beyond the narrow width approximation (NWA) [Pozzorini, Papadopoulos]
- Inclusion of showering at NLO [Alioli]
- Top as a tool for BSM physics [Plehn, Kaplan]
  - Top is background for SUSY, Higgs searches,…

Resummation in Top Pair Production

- Threshold + Coulomb corrections [$\beta=\sqrt{(1-4M_t^2/s)}$]

$$\sigma \approx \sigma_0 \exp\left[\ln(\beta) g_0(\underbrace{\alpha_s \ln(\beta)}_{\text{LL}}) + g_1(\underbrace{\alpha_s \ln(\beta)}_{\text{NLL}}) + \alpha_s g_2(\underbrace{\alpha_s \ln(\beta)}_{\text{NNLL}}) + ..\right] \sum \left(\frac{\alpha_s}{\beta}\right)^k (...)$$

- Near threshold, heavy particles non-relativistic
  - $E \sim m\beta^2 \sim$ soft gluon momenta
  - Simultaneous resummation of threshold logs and Coulomb effects [Schwinn]

$$\sigma_{NLO+NNLL}(pb) = 6.77$$
$$\sigma_{NLO+NLL}(pb) = 6.57$$

(Tevatron)

  - Expand to obtain approximate NNLO result

$$\sigma_{NNLO(approx)+NNLL+Bound-State} = 7.14$$

* M_t=173.1 GeV

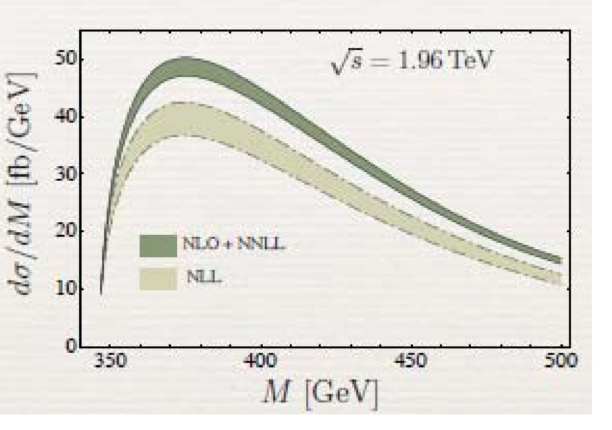
Beneke, Falgari,Schwinn, arXiv:1007.5414

Resummation in EFT for Top Pairs

- Cross section factorizes
  - σ ~(Hard)(Jet)(Soft)
- Use SCET to integrate out hard & soft modes at appropriate scales [Neubert]
- NLO +NNLL resummation
  - Includes resummation of soft gluon effects above threshold

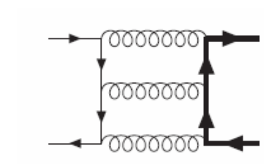
Tevatron

$$\sigma_{NLO+NNLL}(pb) \quad = 6.30$$
$$\sigma_{NNLO,approx}(pb) \quad = 6.14$$

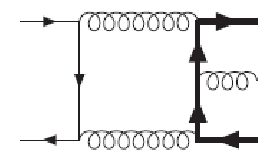


Towards an NNLO Calculation

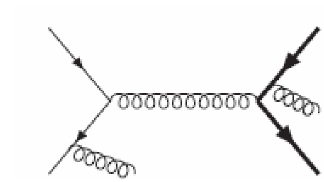
- Ingredients:
  - 2-loop virtual diagrams for $gg, q\bar{q} \to t\bar{t}$

    - Completely known numerically, some pieces known analytically [Czakon, Ferroglia]
  - 1-loop diagrams for $gg \to t\bar{t}g$, etc

    - Known from NLO $pp \to t\bar{t}j$ calculation
    - NNLO subtraction terms needed [Abelof]
  - Tree diagrams for $gg \to t\bar{t}gg$, etc

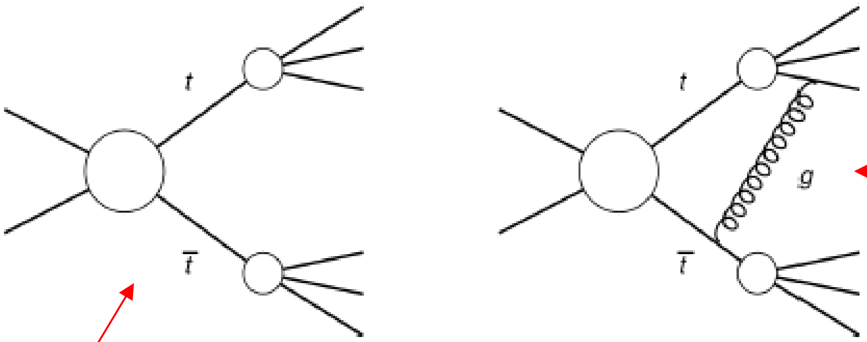
    

    - Known numerically [Czakon]

It appears clear that this calculation can be finished (WOW!)

Need Decays in Top Calculations

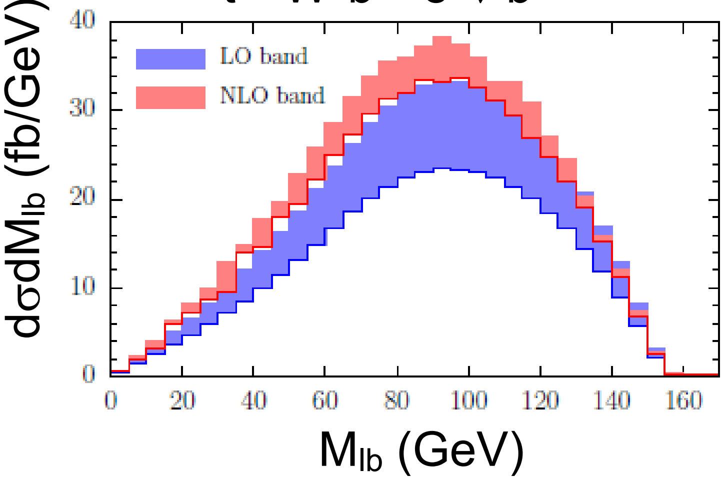
- Top quarks keep polarization as they decay
- Measurements of top mass involve correlations between kinematics and mass
- Finite width effects expected to be small
  - Log ($\alpha_s\Gamma_t/M_t$) terms cancel in inclusive observables

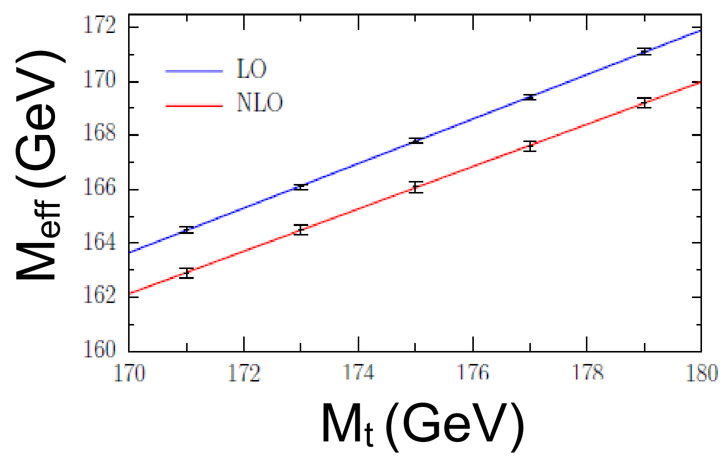


On-Shell Top Production and Decay

- Expect contributions from non-factorizable corrections to be $O(\alpha_s\Gamma_t/M_t)$
- Keep top on mass shell, include production/decays to NLO with spin correlations [Melnikov]

$t \to W^+ b \to e^+\nu\, b$



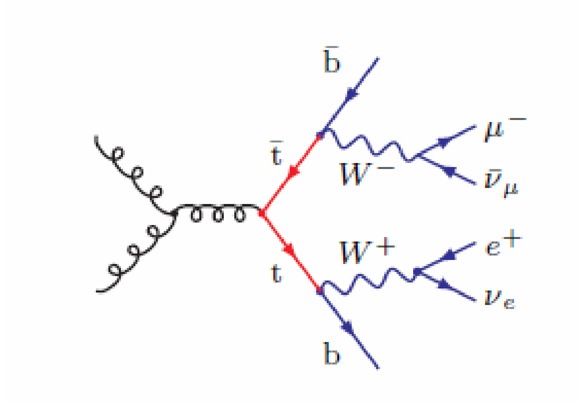


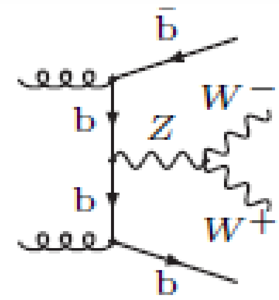
Obtain reliable top quark mass

Biswas, Melnikov, Schulze, arXiv: 1006.0910

Top Production and Decay

- $W^+W^-b\bar{b}$ at NLO: technical *tour de force*
  - Includes off-shell tops/non-resonant backgrounds
  - Finite width effects could be important for percent level precision in σ; shape of top resonance (for M_t measurement)
  - For total σ, finite width effects ~1% at Tevatron
  - Calculation can tell us which distributions can be calculated with NWA



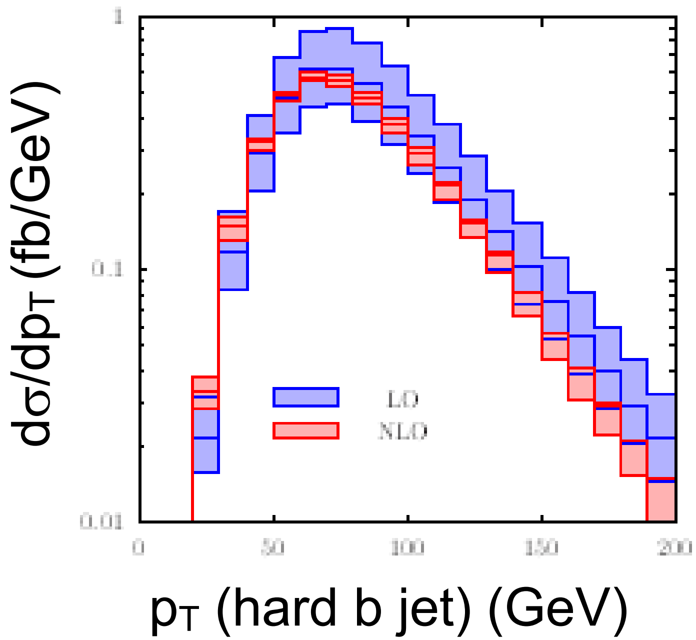


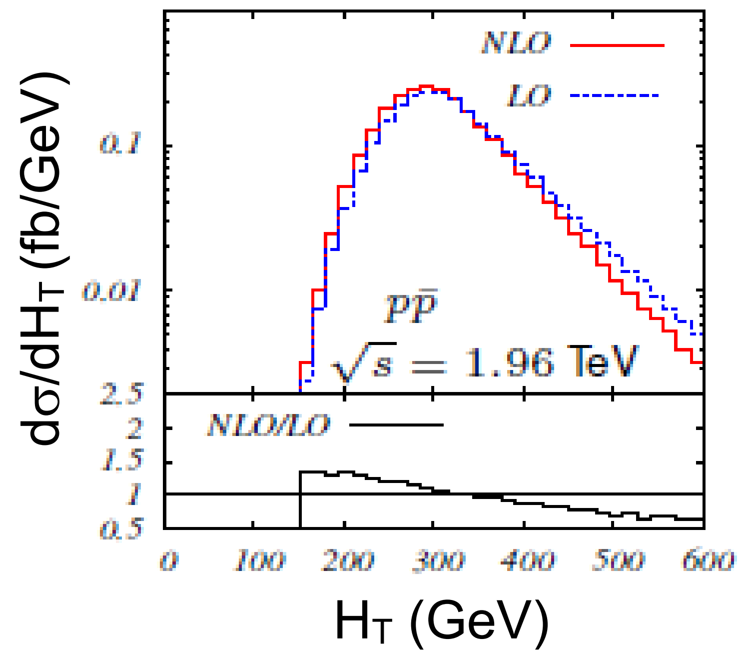
Pozzorini: Feynman diagrams + tensor integrals

Papadopoulos: OPP + HELAC

Denner, Dittmaier, Kallweit, Pozzorini, arXiv:1012.3975; Bevilacqua, Czakon, van Hameren, Papadapoulos,Worek, arXiv:1012.4230

$W^+W^-b\bar{b}$ at NLO: Tevatron Distributions





Pozzorini

Papadopoulos

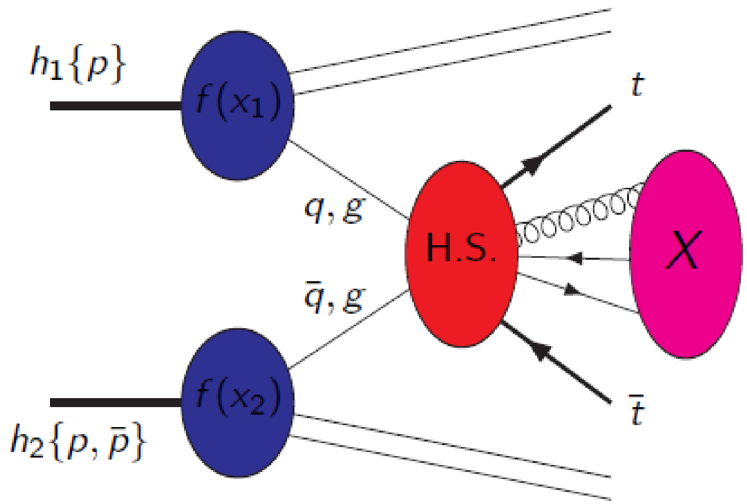
Shape distortions from LO

Top Production with Parton Showers

- Need to include NLO corrections with parton shower Monte Carlos
  - MC@NLO and POWHEG
- tt+jet at NLO implemented in POWHEG [Alioli]
  - Uses virtual contribution from Dittmaier et al.
  - Good agreement between fixed order POWHEG and NLO calculations
    - Different subtraction so non-trivial check
  - POWHEG distributions in progress
    - Observe effects of showering in exclusive quantities

Immense Effort Computing NNLO Top Pair Cross Section

- But there is another piece…

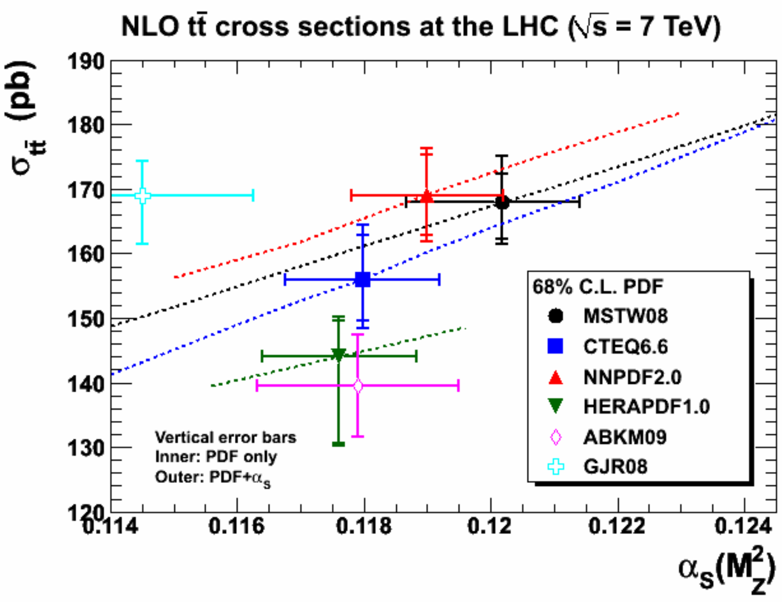


$$\sigma_{pp}(S, M_t^2) = \sum_{ij} \int ds \underbrace{L_{ij}(s, S, \mu)}_{\text{Partonic luminosity}} \underbrace{\hat{\sigma}_{ij}(s, M_t^2, \mu)}_{\text{Partonic cross section}}$$

Must be fit from data

What is Theory Precision on Top Cross Section?

- Scale uncertainty is ~ 10%
- PDF uncertainties of top cross section driven by differences in gluon distributions at large x and different α_s [Stirling]



Unsatisfactory situation: Measurement of top pair cross section could be used to distinguish between PDFs

PDF4LHC, arXiv:1101.0536

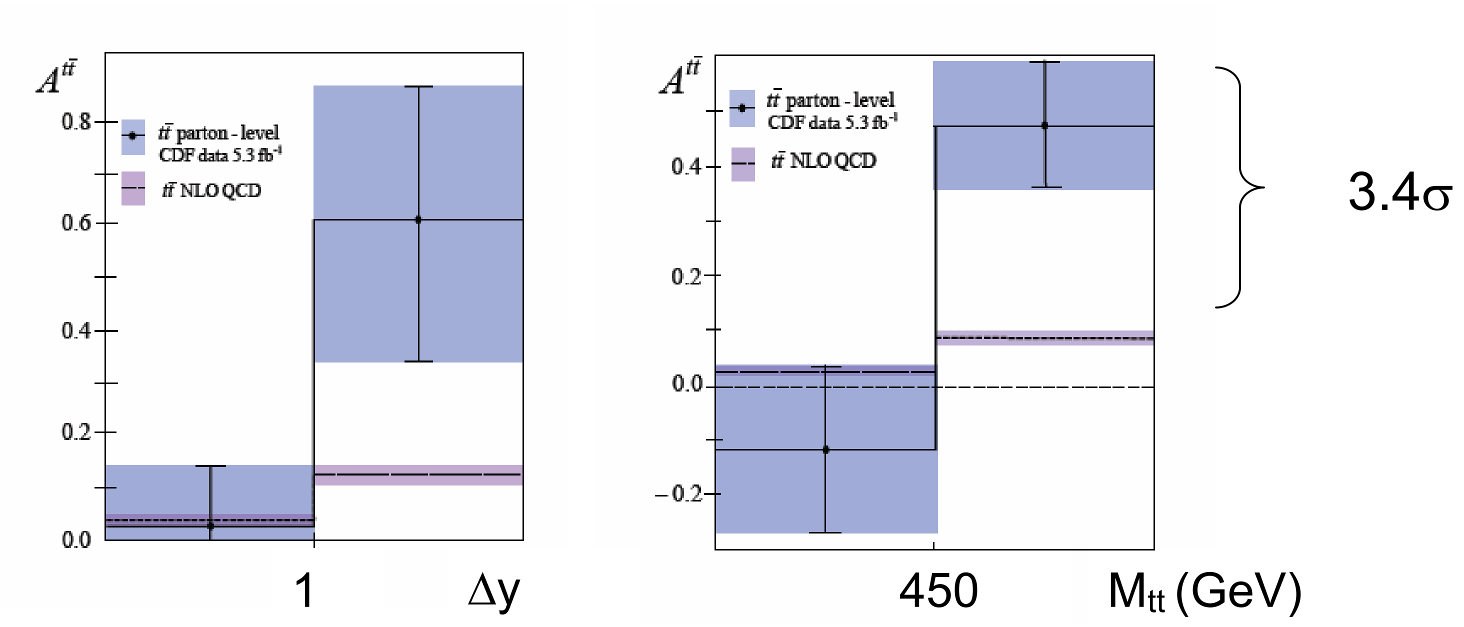
Asymmetry in Top Quark Production

$$A_{fb}(\text{lab}) = \frac{\int_{y>0} N_t(y) - \int_{y>0} N_{\bar{t}}(y)}{\int_{y>0} N_t(y) + \int_{y>0} N_{\bar{t}}(y)}$$

- Asymmetry is zero at LO
  - Both D0 & CDF measure non-zero effect: ~ 2.7σ from 0
- Theory with full decays: A_{fb}(lab) =0.051$\pm$.0013
  - Agrees with result from NWA [Papadopoulas, Pozzorini]
  - CDF A_{fb}(lab)=.158 $\pm$.074 [corrected] (5.3 fb^{-1})
  - Theory/experiment difference ~ 2σ
  - Hard to explain with BSM models [Rodrigo, Frederix]
  - Combining A_{fb} with $d\sigma/dM_{tt}$ strongly restricts BSM physics

Differential A_{fb}

- CDF with 5.3 fb^{-1}: differential A_{fb} in Δy, M_{tt}

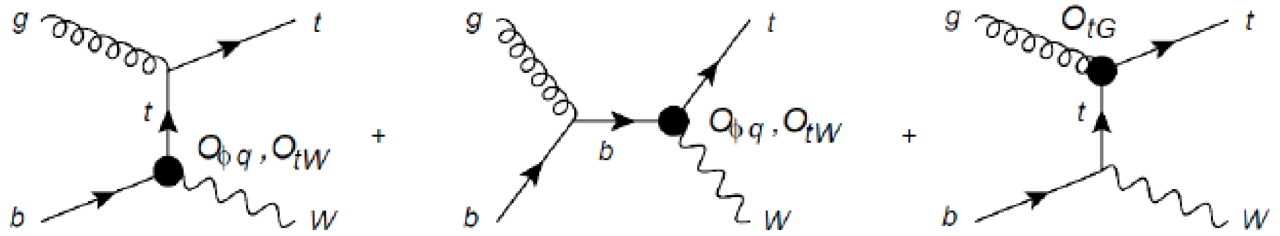


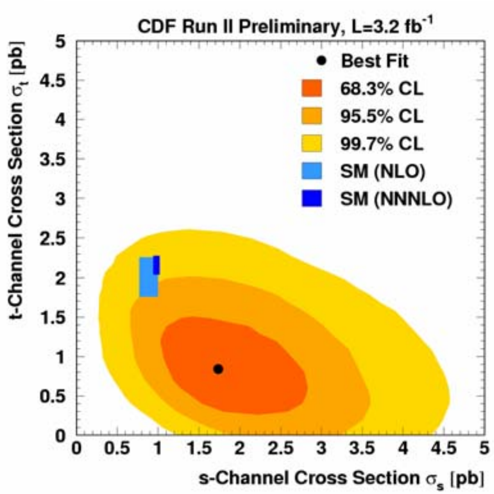
[Wallny]

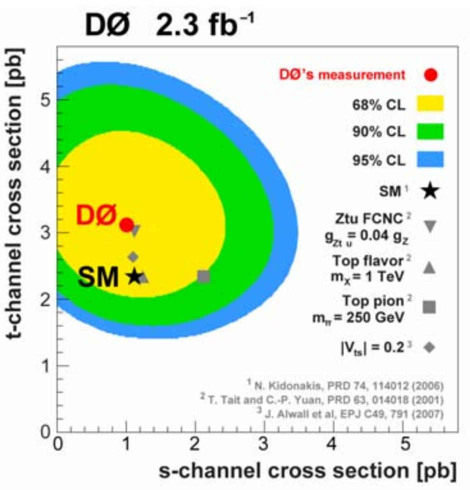
CDF, arXiv:1101.0034

Single top

- Subtlety in s-t channel separation beyond LO
- BSM physics contributes differently to s-t channels [Willenbrock]

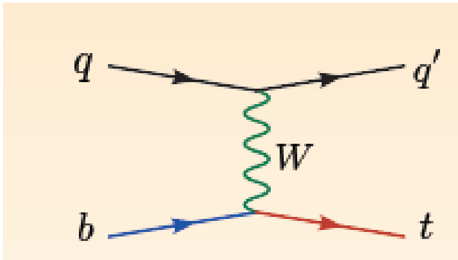




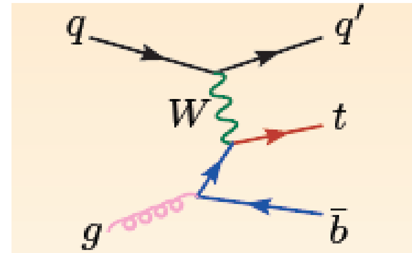


[Wallny]

Single Top Production



5FNS



4FNS

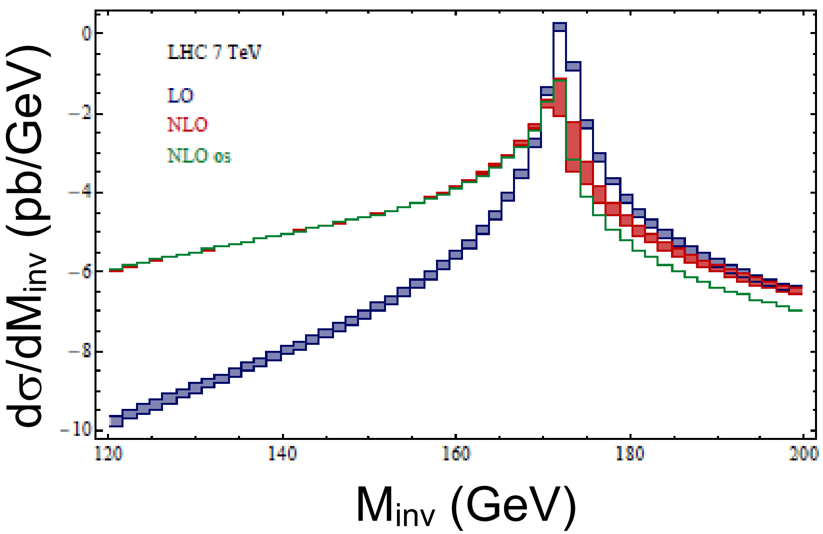
[Frederix]

- 4 and 5FNS are different orderings of perturbation theory
- NLO calculation in 2 schemes
  - Total cross sections in agreement
  - Differences in exclusive quantities involving spectator b quark
  - Doesn't explain s-channel cross section issue
- Next: match 4FNS with parton shower

Decays in Single Top Production

- Improve NWA by expanding in $(p_t^2-M_t^2)/M_t^2 << 1$ and using pole approximation
  - Method requires small parameter:
    $(150\ \text{GeV})^2 < (p(b)+p(l)+p(\nu))^2 < (200\ \text{GeV})^2$

$M^2_{inv}=(p(b)+p(W))^2$



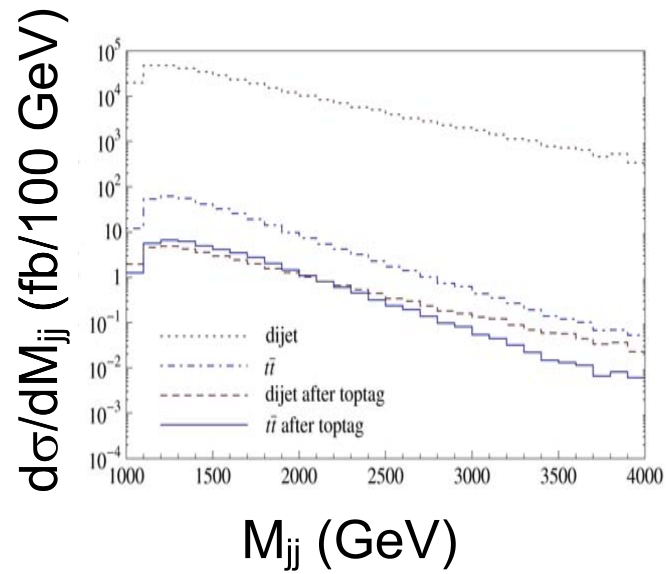
[Signer]

Top Tagging

Many examples of BSM physics have heavy particles decaying to top

- Tag top using jet substructure by looking for clusters of energy within jets [Kaplan, Plehn]
  - Fat jet→ΔR~1
  - Identify tops with p_T ~ 1-2 TeV
  - HEPTopTagger extends p_T ~ 250 GeV
- Techniques can efficiently suppress dijet backgrounds to heavy resonances decaying to top

14 TeV

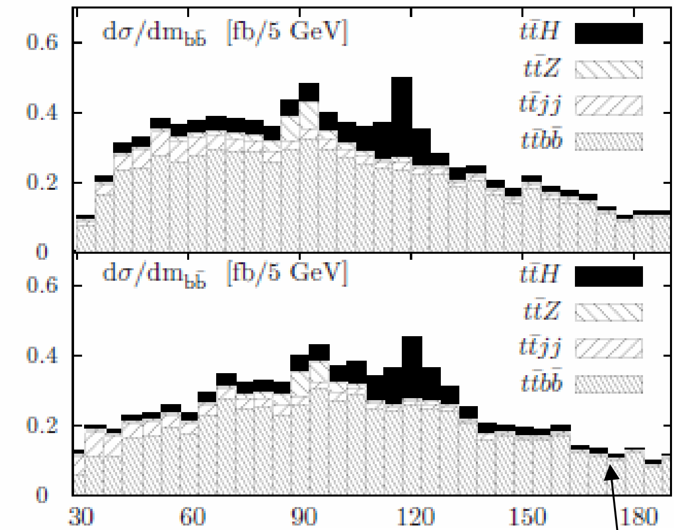


Kaplan

Kaplan, Rehermann, Schwartz, Tweedie, arXiv: 0806.0848

Top tagging

- $t\bar{t}H$, $H \rightarrow b\bar{b}$, large continuum background [Plehn] (S/B~1/9)
  - Look for 1 fat Higgs, 1 fat top jet
  - Tease out signal, S/√B~ 4-5 for 100 fb^{-1}
- Top tagger can help to find $\tilde{t} \rightarrow t + E_T^{miss}$
  - Tag 2 hadronic fat jets
  - Helps to eliminate backgrounds
  - S/√B~6 with 10 fb^{-1}



M$_{bb}$(GeV)

Underlying event included

HEPTopTagger

Plehn,Spannowsky, Takeuchi, Zerwas, arXiv:1006.2833; Plehn, Salam, Spannowsky, arXiv:0910.5472

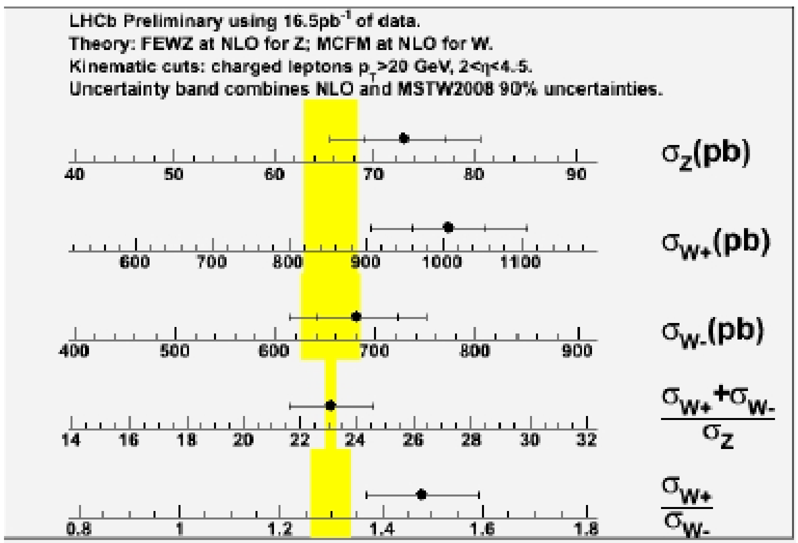
b's are Heavy Too

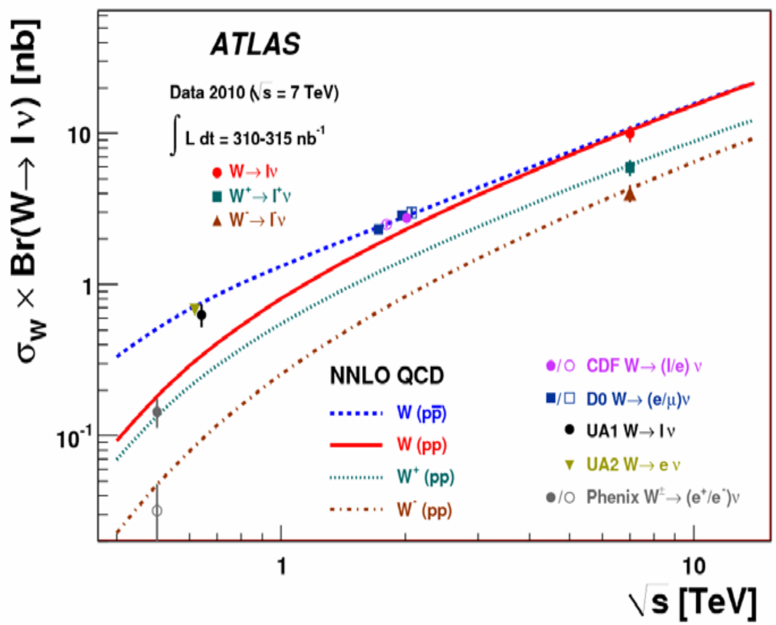
- b cross section is perturbative
  - Cross section measurements at CMS from semi-leptonic decays, b-tagged jets, exclusive B hadron decays [Chiochia]
  - MC@NLO+Herwig generally below data at low p_T
  - FONLL, POWHEG + Phythia in better agreement
  - Phythia above data for p_T below 50 GeV
- Need to understand properties of b-jets for BSM physics searches
  - Measure angular correlations between b jets
  - Aim is to understand collinear $g \rightarrow bb$ splitting

Important testing ground for perturbative QCD and Monte Carlo programs

W/Z

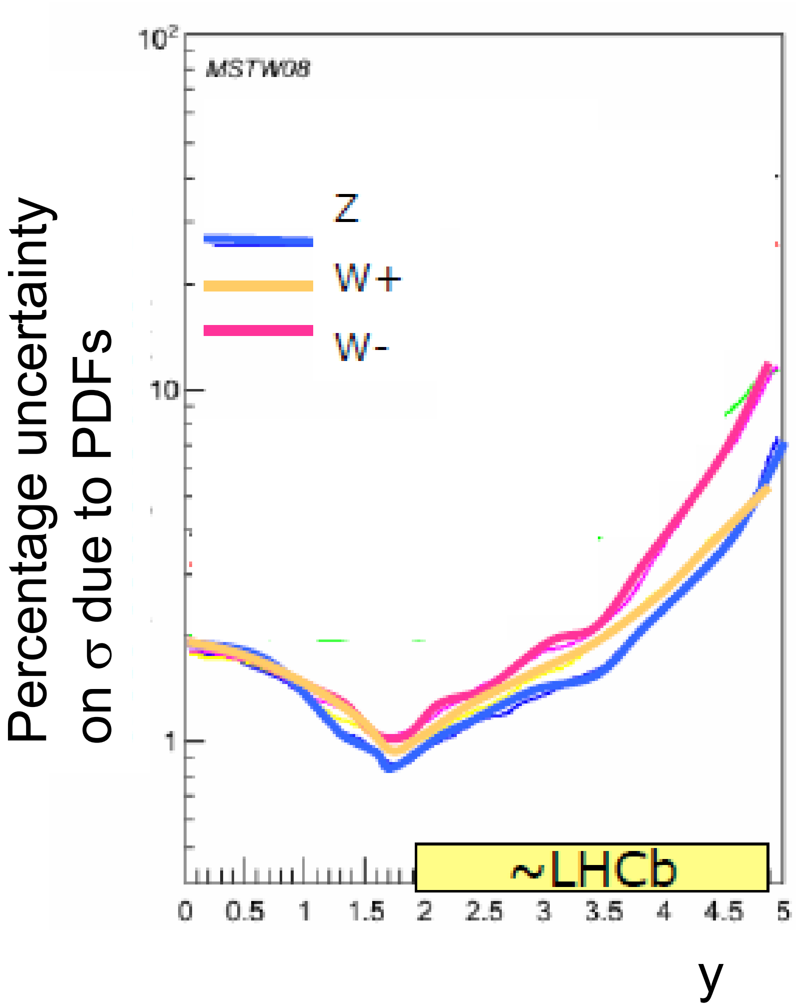
Measurements of W/Z cross sections in forward region by LHCb [McNulty]





Many uncertainties cancel in $\sigma_W/\ \sigma_Z$
→Excellent agreement with NNLO theory

LHCb Kinematic Regime Different

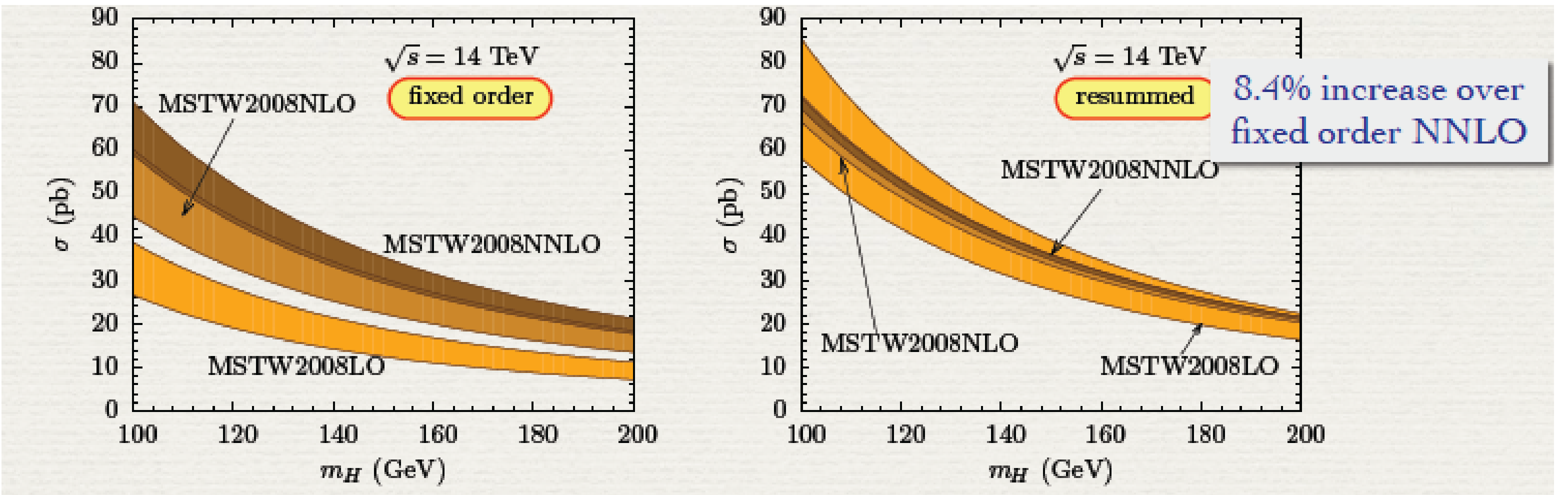


Goal: Use measurements of W/Z production in forward region to probe PDFs in new kinematic regime

[McNulty]

Higgs

- Precision predictions from SCET



[Neubert]

Significant change in rates with resummation

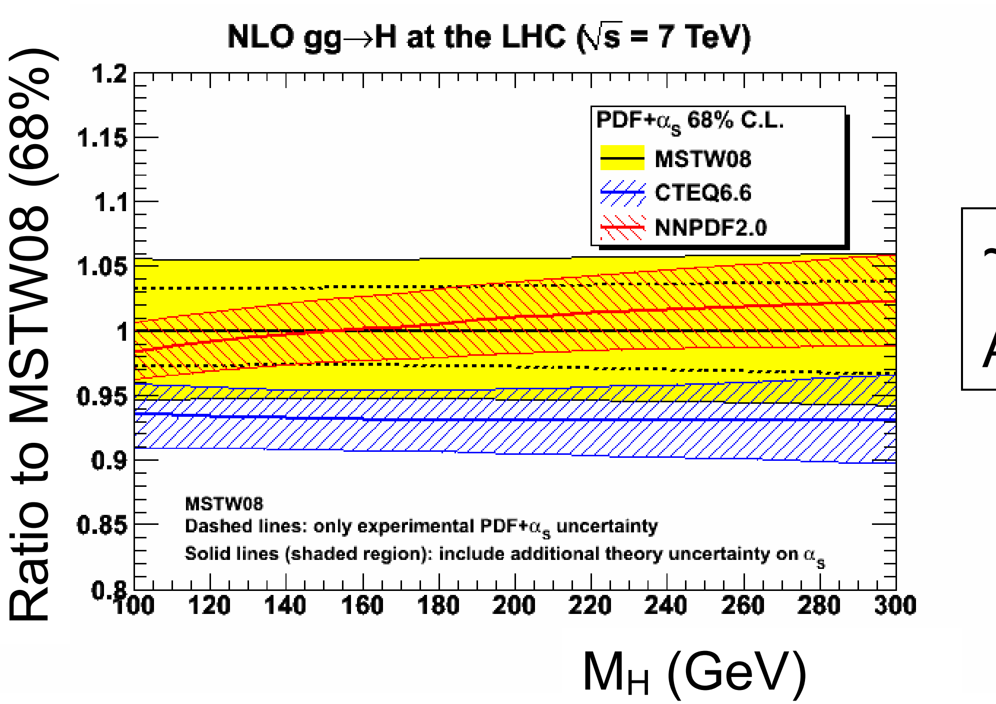
Scale variation improved by resummation

Compete NNLO calculation for gg→H exists!

Higgs cross section working group, arXiv:1101.0593

PDF Uncertainties in Higgs Production

- Smaller PDF uncertainties than for top production [Stirling]

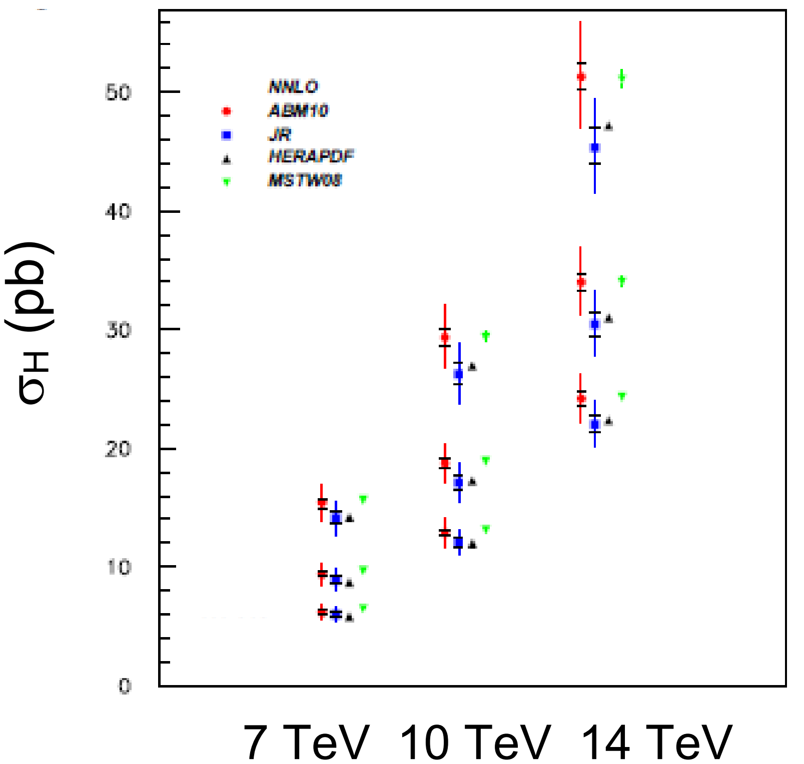


~5-10% PDF uncertainty

Agreement between PDFs

PDFs and the Higgs

- Redo ABKM NNLO fit to include D0 Run II data
- Higgs NNLO results consistent between PDF sets

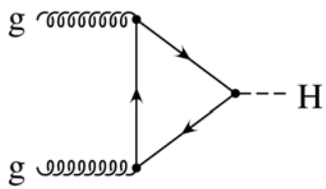


M_H=120,150,180 GeV

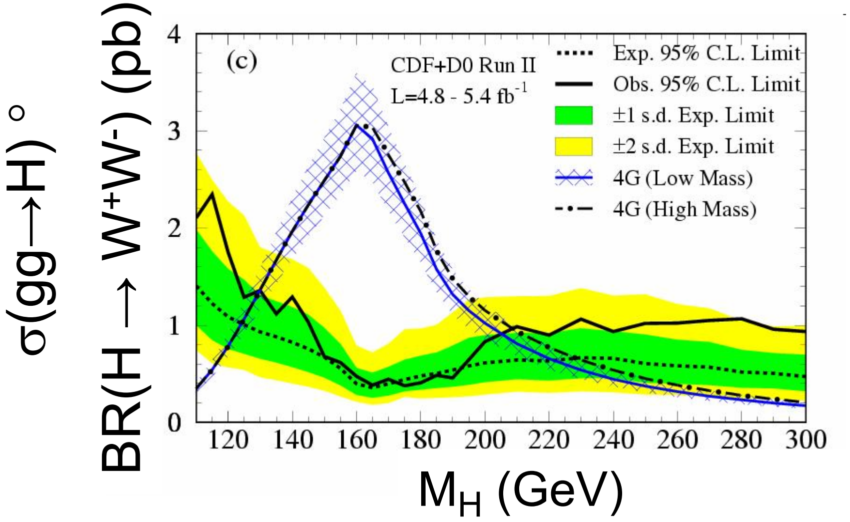
[Moch]

Higgs Production Sensitive to BSM Physics

- NNLO calculation with 4th Generation fermions [Furlan]



Tevatron excludes M_H [131 GeV, 204 GeV]



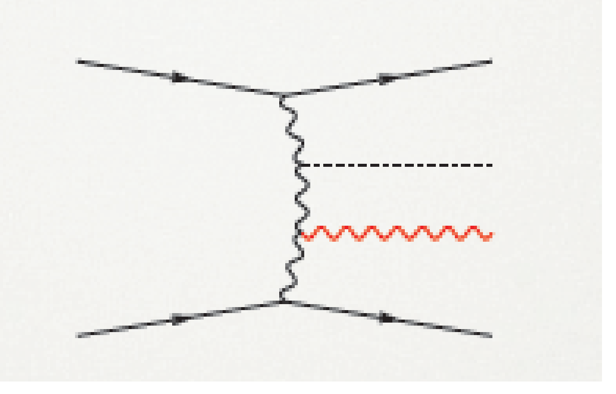
- Composite Higgs Model with vector-like fermions
  - At NNLO, rate reduced by 30-35% relative to SM with 1 multiplet

Reliable predictions for BSM Models

Anastasiou, Boughezal, Furlan, arXiv:1003.4677

Vector Boson Fusion

- QCD corrections to Higgs + photon in VBF [Figy]
  - Hard photon helps to suppress QCD background
  - Goal is to use $H \to b\bar{b}$ channel
  - $S/\sqrt{B} < 3$ for M_H=120 GeV, L=100 fb^{-1}
  - QCD corrections ~ 1%



SUSY Models

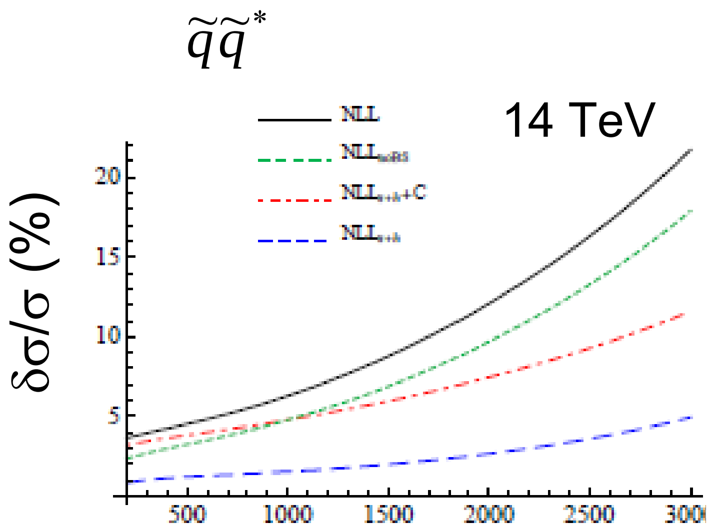
- Not just the MSSM [Barbieri]
  - Increase mass bound on lightest Higgs by adding U(1), SU(2), or gauge singlet… M_h ~200-300 GeV
  - Higgs contributions to precision measurements compensated by new contributions to ΔT
  - Typically some coupling becomes non-perturbative
  - Non-standard squark spectrum with couplings arranged not to violate flavor bounds

$$\widetilde{M}_{q1,q2} >> \widetilde{M}_{g} >> \widetilde{M}_{q3}$$

  - Need $\widetilde{M}_{q1,q2}$ > 10 TeV

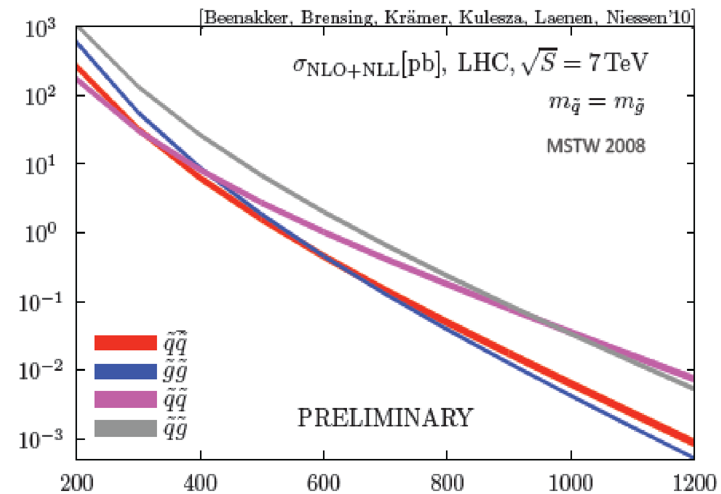
SUSY Cross Sections

- Resum threshold logarithms [Kulesza, Schwinn]



M_{squark} (GeV)

Schwinn



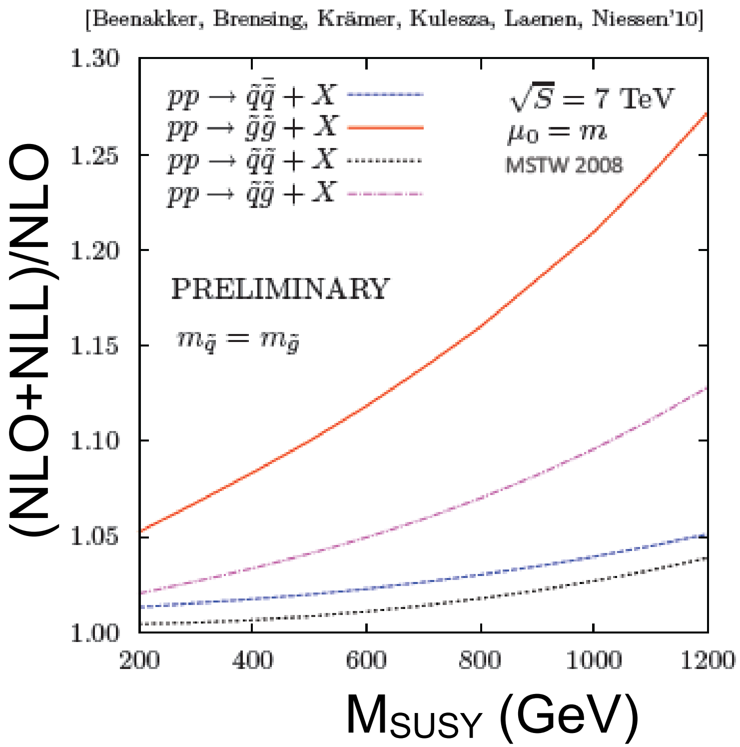
M_{SUSY} (GeV)

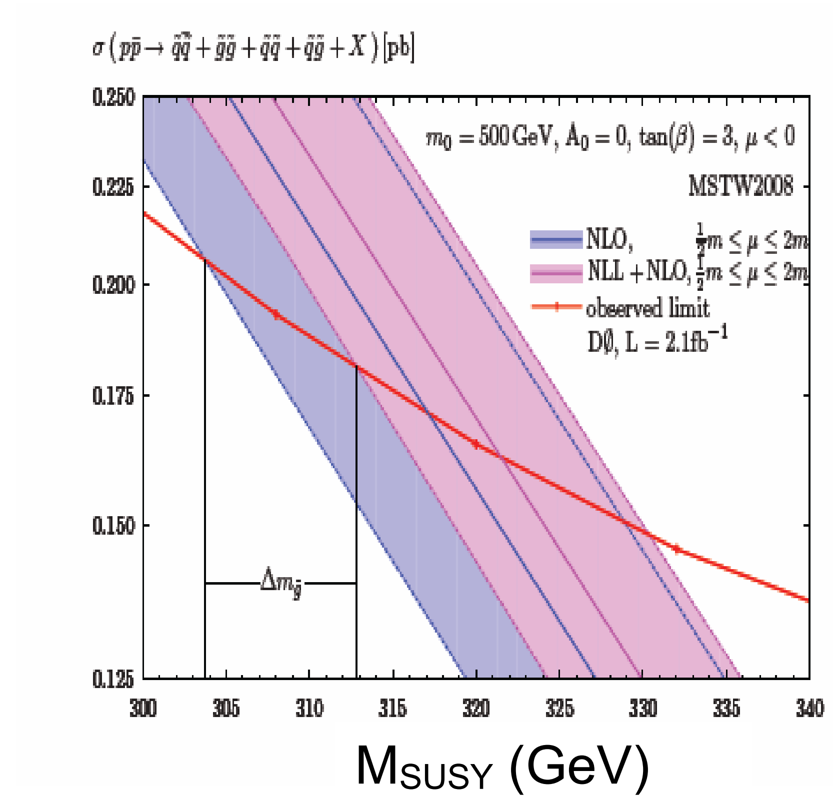
Kulesza

Resummation reduces scale dependence

Resummation Changes SUSY Limits

Kulesza





Expect mass limits to shift by ~ 10 GeV

How Do We Know It's SUSY?

- Couplings are related in MSSM: $ht\bar{t} \Leftrightarrow hh\tilde{t}\,\tilde{t}^{*}$
- MSSM sum rule:

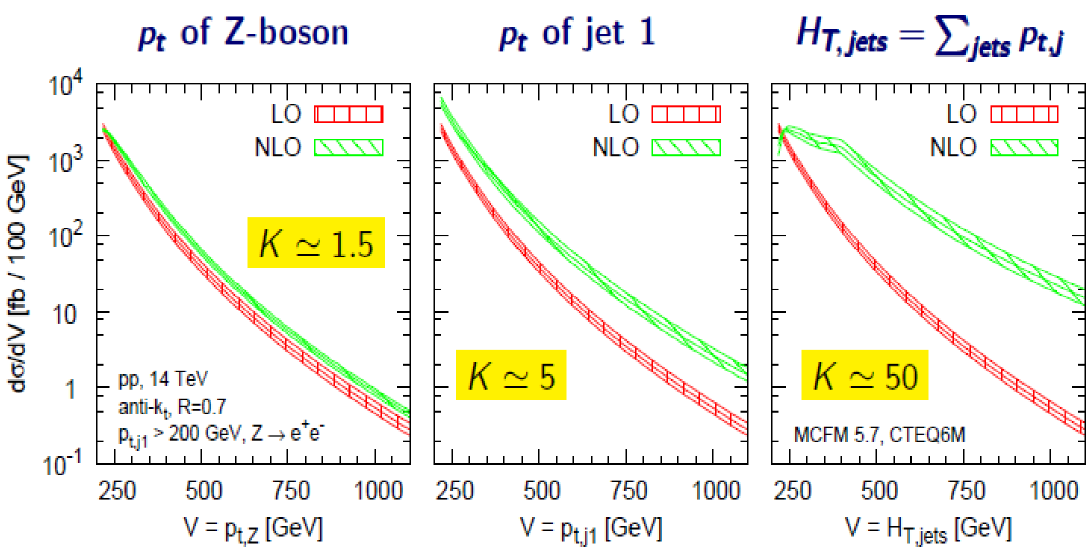
$$\boxed{M_t^2 - M_W^2 \cos 2\beta = \tilde{M}_{t1}^2 \cos^2\theta_t + \tilde{M}_{t2}^2 \sin^2\theta_t - \tilde{M}_{b1}^2 \cos^2\theta_b - \tilde{M}_{b2}^2 \sin^2\theta_b}$$

- Masses of $\tilde{M}_{t1}, \tilde{M}_{b1}, \tilde{M}_g, \tilde{M}_\chi$ from M_{T2} method
- Obtained reasonable measurements for masses
  - Able to predict mixing angles assuming MSSM
  - Need linear collider to test sum rule

[Blanke]

Large QCD Effects

- Knowledge of backgrounds crucial for BSM searches
- QCD can be unexpectedly large [Salam]
- Example: Z+ jets is background to gluino pair production



Large corrections from real radiation

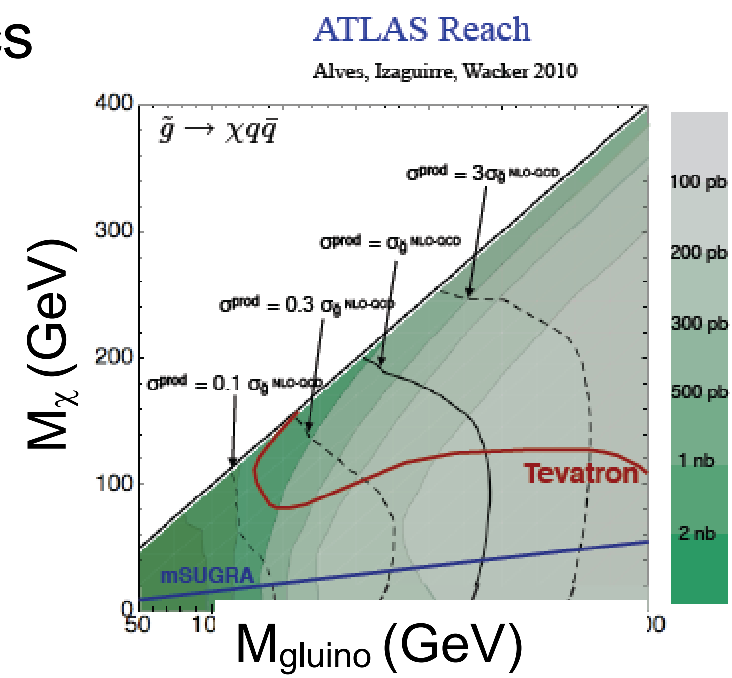
Technique for approximating NNLO rates

H_T is a dangerous variable for BSM searches

Rubin, Salam, Sapeta, arXiv:1006.2144

Model Independent Searches for New Physics

- Look for colored objects plus jets [Wacker]
- Try to be as general as possible
- Base cuts on simple kinematics
  - EFT approach
  - Avoid MSUGRA biases
  - MSUGRA has specific kinematics



Alves, Izaguirre, Wacker, arxiv:1008.0407

- Thanks to the Organizers
  - For superb organization
  - For great physics

Almost all data agree with SM predictions

Hopefully, there will be some surprises soon!