Heavy flavor production

some issues, some results

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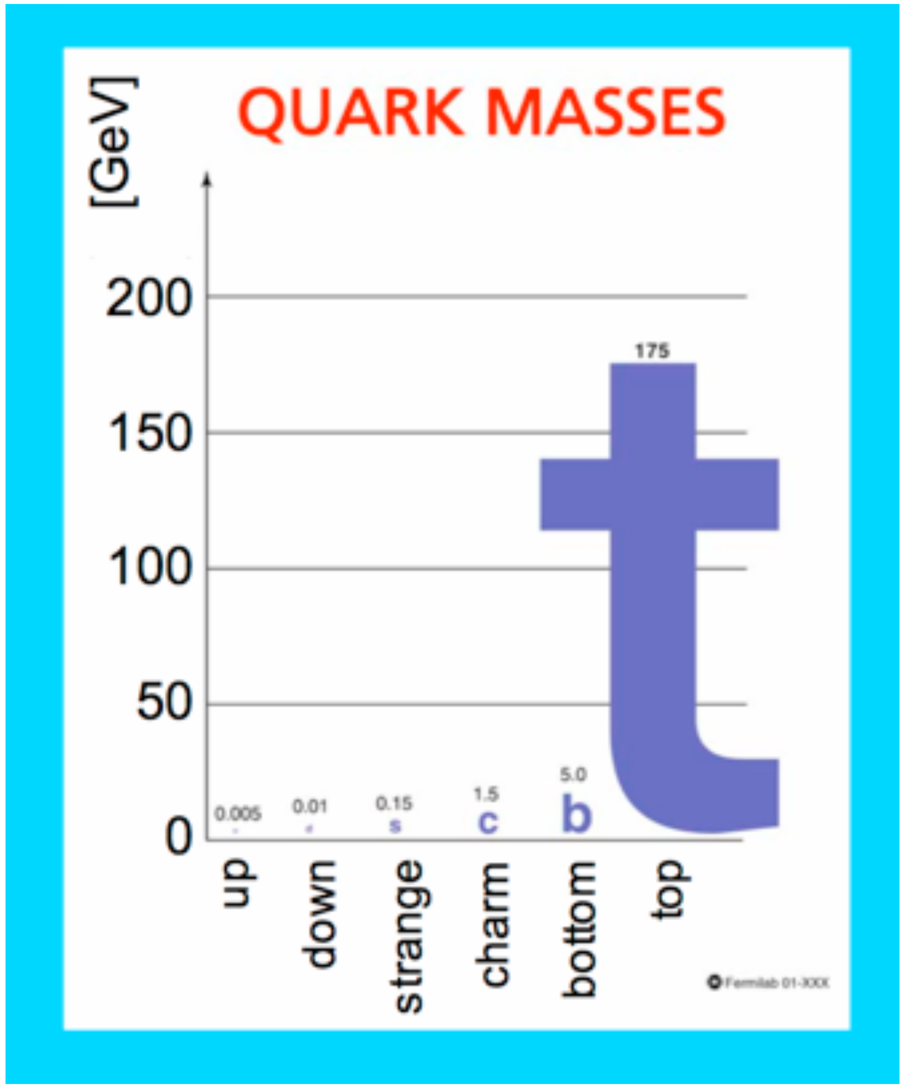
Overview

- Production, NLO
- Charm, Bottom, Top
- Mass definition
- New Physics
- Conclusions

Heavy quark teaching history

- Charm (1974)
  - ✓ made SM consistent, cemented belief in QCD
  - ✓ GIM, spectroscopy, ...
- Bottom (1977)
  - ✓ announced 3rd family, allowed for CKM mechanism
  - ✓ B-factories
- Top (1995)
  - ✓ Bizarrely heavy
  - ✓ Completes 3rd generation
    - What will top teach us?

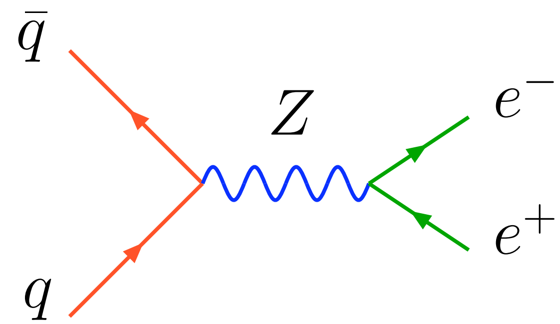


Heavy flavors are special

- Because they are colored and heavier than muon
  - taggable (semi-leptonic decay, displaced vertices)
- Mass (well) beyond Λ_{QCD}
  - perturbative QCD
  - sets scale, thresholds etc
- Important to understand the production well
  - (keeping in mind maturity of analysis)
- Not only a topic by itself, also very relevant for
  - PDF's
  - Jet-tagging
  - New physics
  - ...

LO, NLO, etc

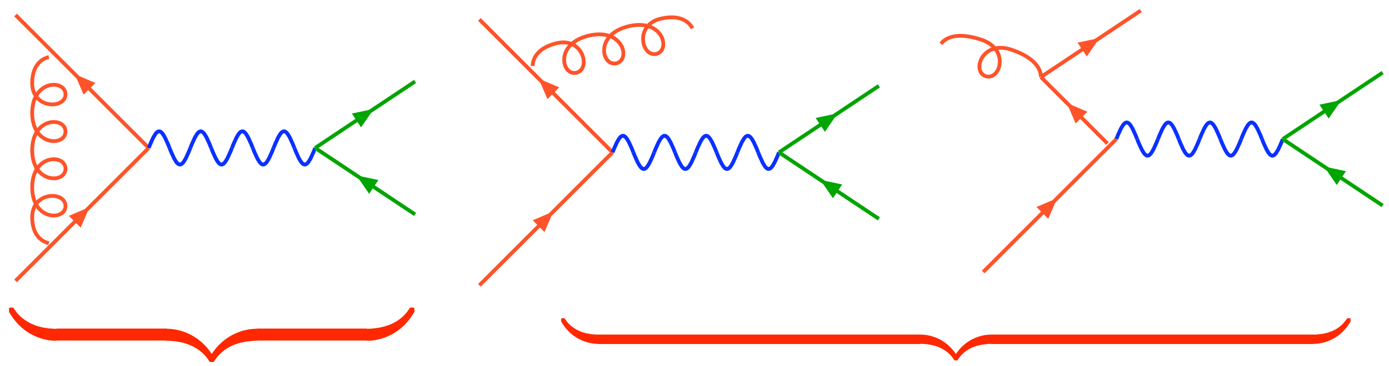
LO $\hat{\sigma}^{(0)}$



Combine with PDF's, put in MC integrator, apply cuts etc

Calculate in D=4-2ε dimensions

NLO $\hat{\sigma}^{(1)}$

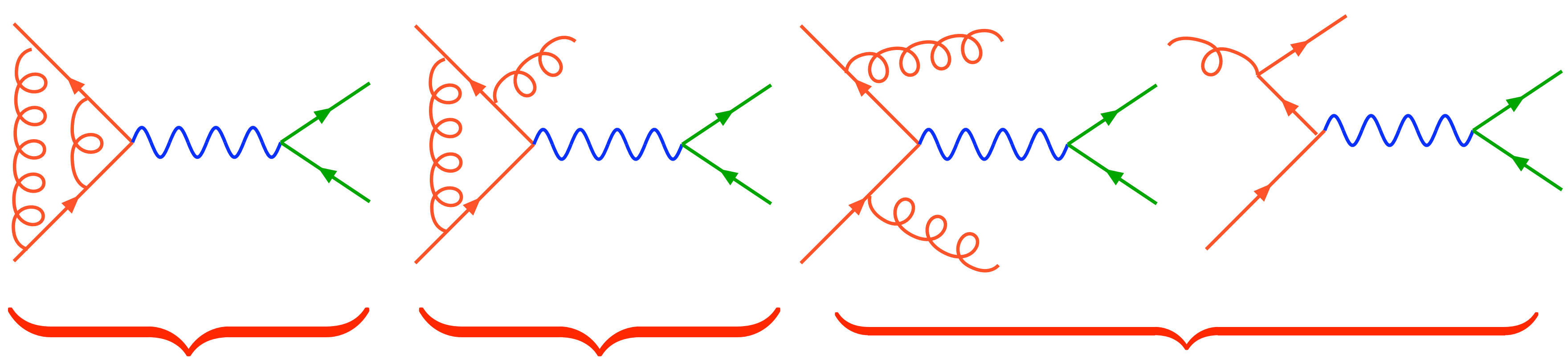


1 loop

1 extra parton

Cancel IR poles $1/\varepsilon^2$ before anything else

NNLO $\hat{\sigma}^{(2)}$



2 loop

1 loop +
1 extra parton

2 extra partons

Cancel IR poles $1/\varepsilon^4$ etc before anything else; hard!

NLO cross sections at hadron colliders

Multi-differential hadronic NLO cross section

NLO PDF's

$$\frac{d\sigma^{pp\to X}}{d^3p_1\dots d^3p_n} = \sum_{a,b}\int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F)$$

$$\times\, \hat{\sigma}_{ab}(p_a+p_b \to p_X, \alpha_s(\mu_R), \mu_R, \mu_F) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$

Multi-differential partonlevel NLO cross section

Power corrections.

Renormalization and Factorization scale

All should be known as accurately as possible (but quantify the error)

Benefits:

- Normalization of cross section, less uncertainty
- Better physics modelling

Why go beyond LO?

For precision; to measure, verify of falsify

- Accurate prediction of production rates
  - ✓ In particular: standard candles (V-boson production as luminosity monitor)
- Better modelling of distribution shapes due to extra partons
- Large corrections (10-100%) → convergence of PT? Case in point: gg → Higgs
  - ✓ Self-diagnostics of PT
- New channels open up beyond LO, not necessarily small

Developments at higher order

"In QCD, easy things have been done, progress now slow". Not so...

- Fast, substantial progress on very difficult calculations
- Many new ideas that bring make the impossible possible.
- Intensive numerics for loops, and computer algebra
  - ✓ FORM [Vermaseren], now open source
- Concrete results for many 2 to 3,4 results at NLO
  - ✓ "extremely time and theorist- consuming"
- Standardization efforts underway
- 2 to 4+ full NLO codes appearing

The Higher Order revolution: all it took was a list...

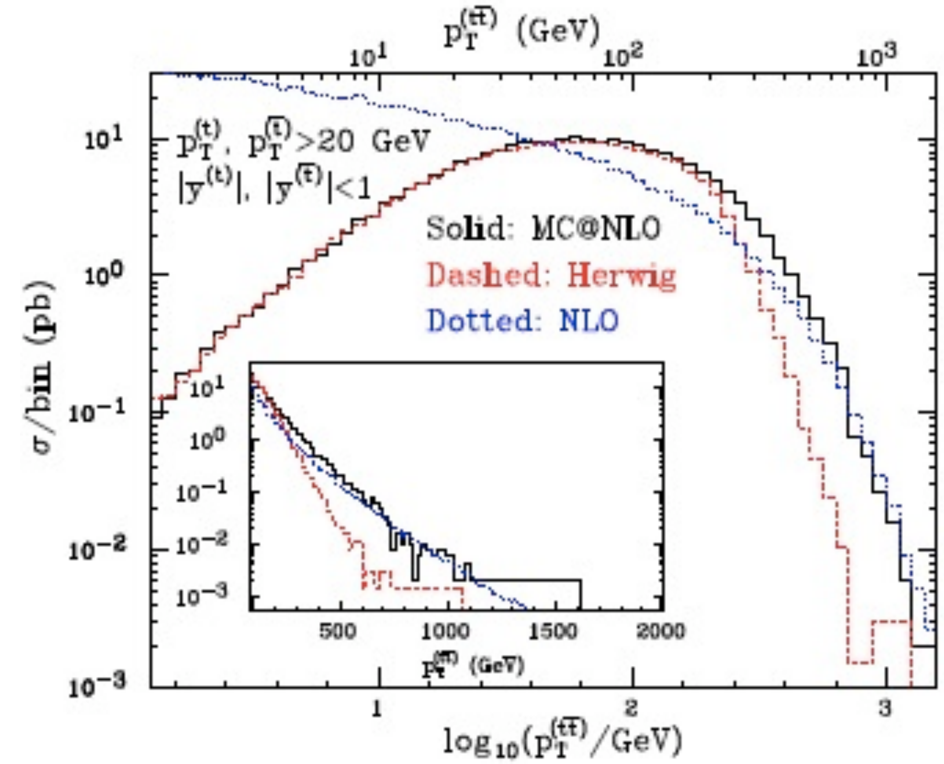
- Theorists have used the LHC construction years well. Enormous innovation in once-boring topic of NLO
  - analytical (spinor/twistor/unitarity methods), numerical (loop + radiative)
- Many new NLO programs, standardization, automation taking place rapidly
  - pace of progress truly remarkable
  - MCFM, HelacNLO, Blackhat, Rocket, Grace, MadFKS, GOLEM, Samurai ...
  - important to (learn to) use the tools, and when
  - key: communication
- Progress toward NNLO
  - valuable, but not needed for everything
  - exact is very tough, esp. for hadron collisions
  - much progress, resummation based, captures most

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4,5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9,10]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14,15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VVb\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

MC@NLO, POWHEG

Frixione, Webber;
Nason, Oleari

- Advanced MC's, include heavy flavor production, single top production, spin correlations
  - much used by collaborations
- Combine best of NLO and parton showers
- Advantages come at a cost
  - cannot vary HERWIG/PYTHIA parameters at will, and still retain NLO accuracy
    - ✓ certain variations upset the cancellations between orders (e.g. separate ISR, FSR variations)
    - ✓ ok variations: μ_F and μ_R. PDF's (beware PDF's in PS)
- When to use?
  - when normalization matters, for good measurements
  - not too many hard jets (then use LO Alpgen, MadEvent, etc...)
  - to check HERWIG, PYTHIA, SHERPA ranges
- POWHEG and MC@NLO treat showers differently beyond NLO
  - often useful to try both

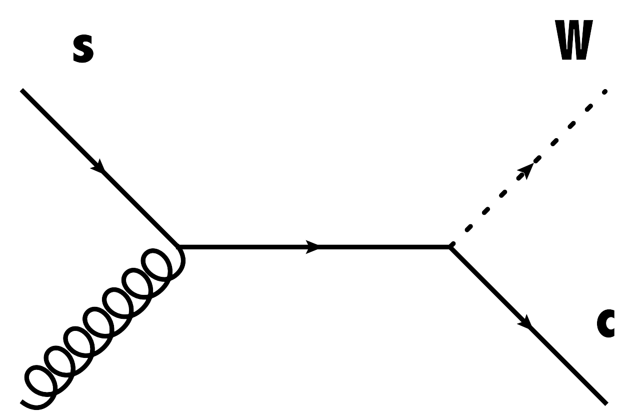


Near-future NLO + PS

- POWHEG Box
  Hamilton, Nason, Oleari
  - allows for merging-in many existing NLO calculations
    - ✓ many with heavy quarks
- MadLoop + MadFKS
  Hirschi, Frederix, Frixione, Garzelli Maltoni, Pittau
  - automating NLO now very close
  - automatic MC@NLO for all these codes also near
    - ✓ many with heavy quarks

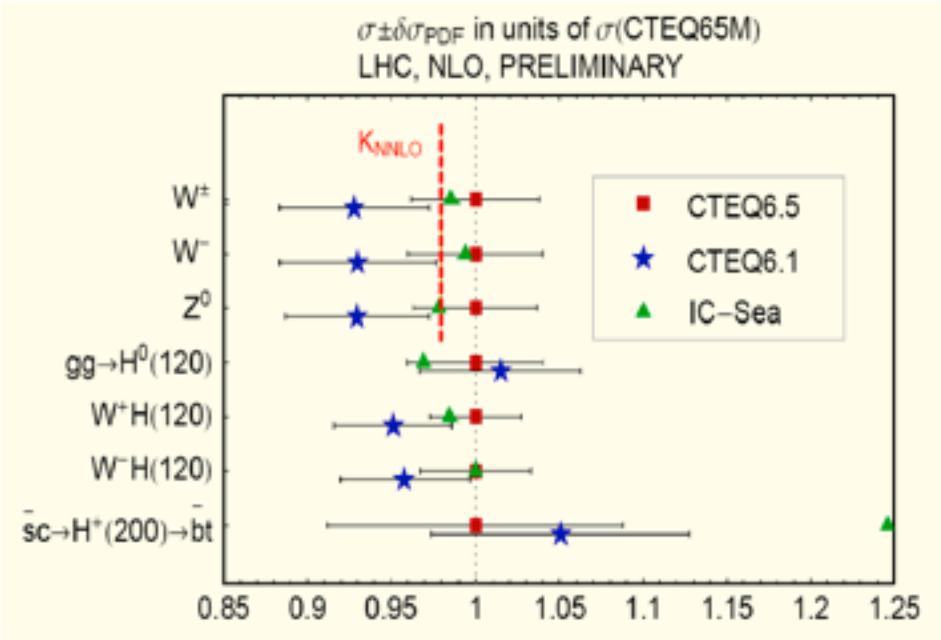
Charm in hadron colliders

- Mass acts as regulator, has no noticeable kinematical (threshold) effect.
- Virtue: it can be tagged, affords direct view on parton
  - Input for charm fragmentation functions at large p_T
- Mostly useful in association with other particles (W,Z,..)
- W + charm is handle on s-quark PDF



Heavy flavors in PDF's

- A long and often confusing tale. Many, many acronyms
  - when to treat c, or b (never t) as a parton
    - ✓ = let it contribute to QCD evolution
  - near threshold: mass is needed
    - ✓ Fixed Flavour Number Scheme
  - far above (large pT): treat as parton
    - ✓ Zero Mass Variable Flavour Number Scheme
  - or just stick to one? Or use hybrid (GM-VFNS)?
  - Theoretical rigor is required here when going beyond LO
- Important consequences for high-scale benchmarks
  - up to 10% at LHC

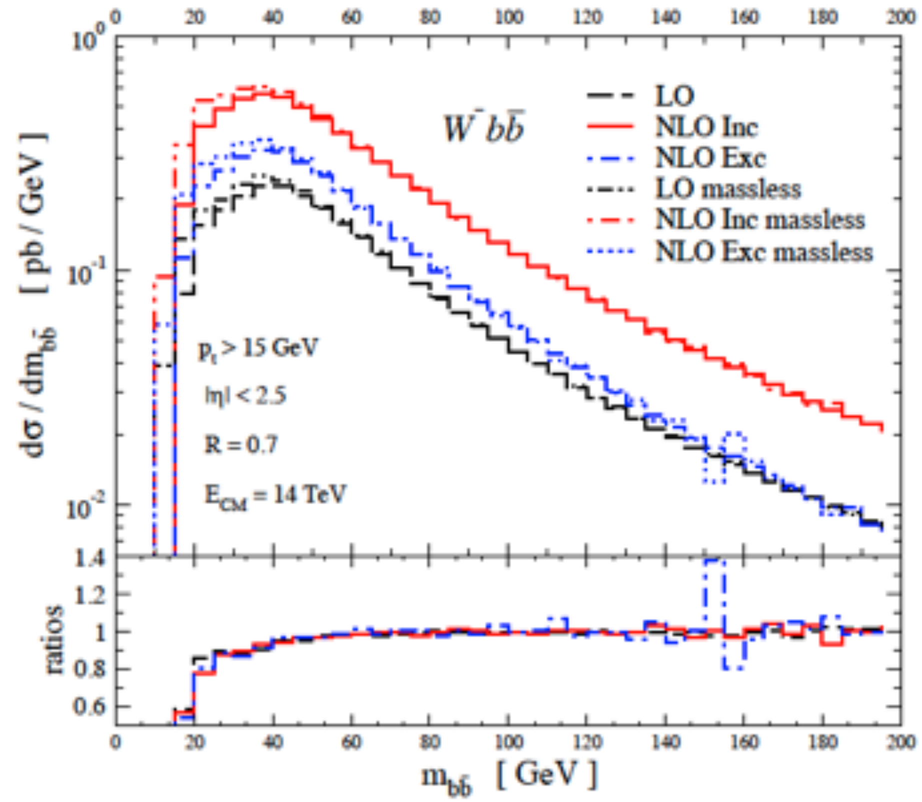


Heavy flavors in PDF's

- Pro's and con's FFNS
  - +: heavy flavor made in hard scattering, get kinematics right
    - ✓ thresholds, deadcone effects
  - -: when hard scale (pT, Q, ...) >> mass, large logs ln(pT/m) spoil PT
    - ✓ (...but this can be very instructive)
- Pro's and con's VFNS
  - +: easier in calculations, correct when scales are large
    - ✓ automatic summation of large logs through DGLAP equation
  - -: badly wrong at low scale
- GM-VFNS: best (or worst) of both
  - many versions, difficult for outsider to judge/choose

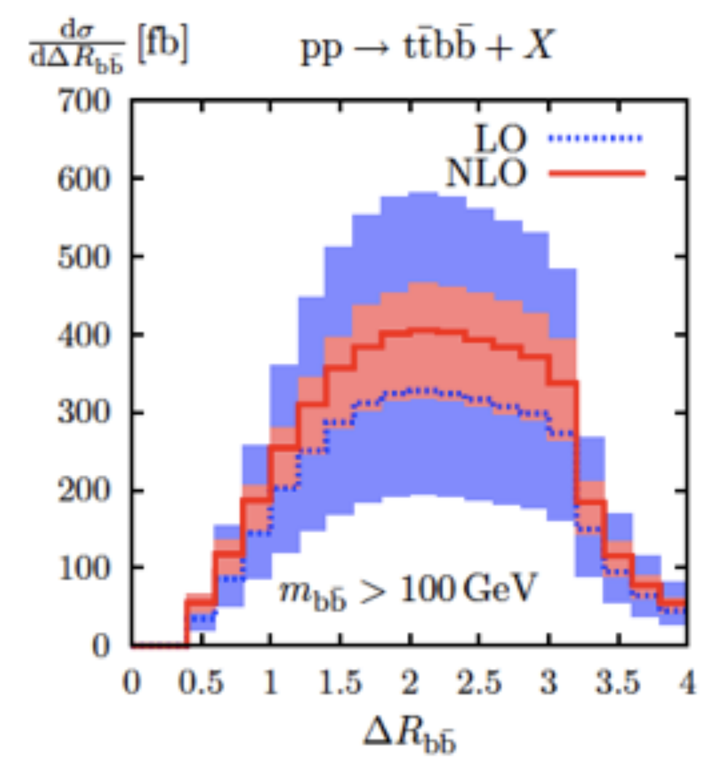
Associated heavy flavors

Cordero, Reina, Wackeroth



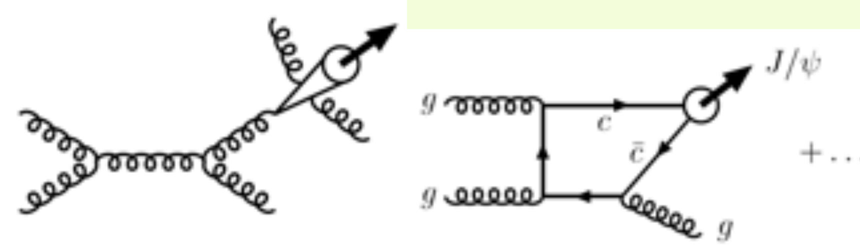
- Perhaps the most prominent way of producing heavy flavors
  - W/Z + n b/c + m jets
    - ✓ W + 4 jets[b] (tt)
    - ✓ W + 2 jets [b,bb] (t, H)
    - ✓ many BSM searches
  - ttbb (for ttH background)
- NLO predictions are appearing
  - Wbb
  - ttbb (2 groups, agreement)
  - bbbb

Greiner, Guffanti, Guillet, Reiter, Reuter



Bredenstein, Dittmaier, Denner, Pozzorini
Bevilacqua, Czakon, Papadopoulos, Pitta, Worek

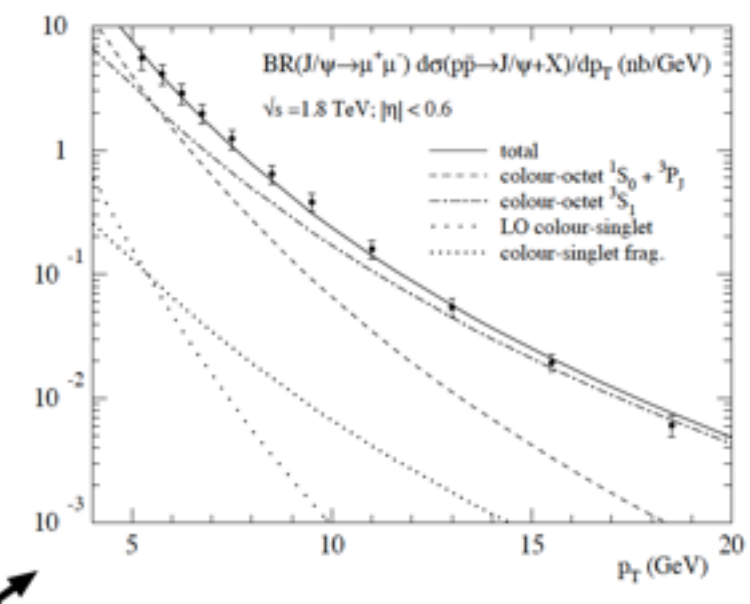
p_T distributions of onia

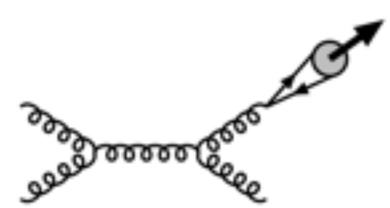


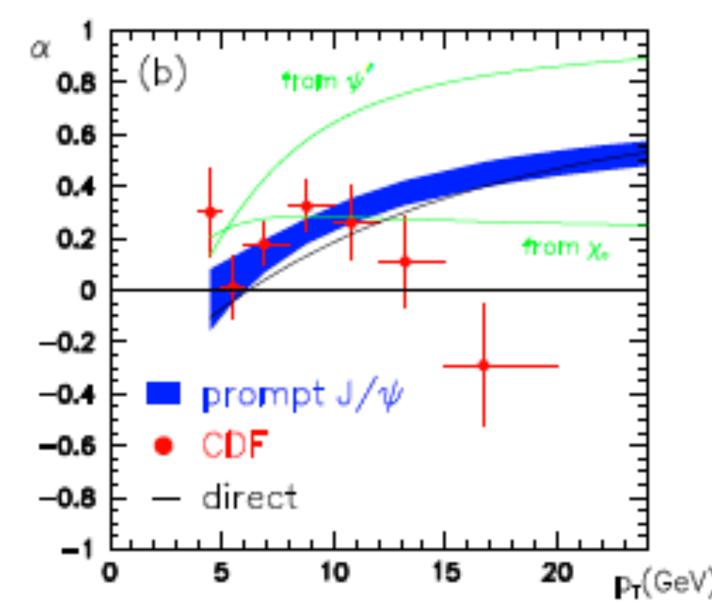
- Tevatron/HERA have left us a puzzle in high pT onium production
- Original model: compute $Q\bar{Q}$ cross section, apply onium projector
  - seriously insufficient, even including fragmentation
- NRQCD approach separates physics of production (m) and binding (mv)

$$\mathcal{L}_{\rm NRQCD} = \psi^\dagger \left(iD_0 + \frac{\vec{D}^2}{2m} \right) \psi + \chi^\dagger \left(iD_0 - \frac{\vec{D}^2}{2m} \right) \chi + \mathcal{L}_{\rm light} + \delta\mathcal{L}$$

  - form $Q\bar{Q}$ in singlet, octet, etc, then transition to onium
  - order in relative velocity v
- There are other, less-rigorous models (Color Evaporation, ..)
- HERA: color-singlet ok
- Clear prediction of NRQCD for hadron colliders:
  - at larger p_T fragmentation dominates, ${}^3S_1[8]$ production, → transverse polarization
    - ✓ not borne out by data
    - ✓ is v too large for charmonium?
- Production mechanism important to understand, also for heavy ion collisions



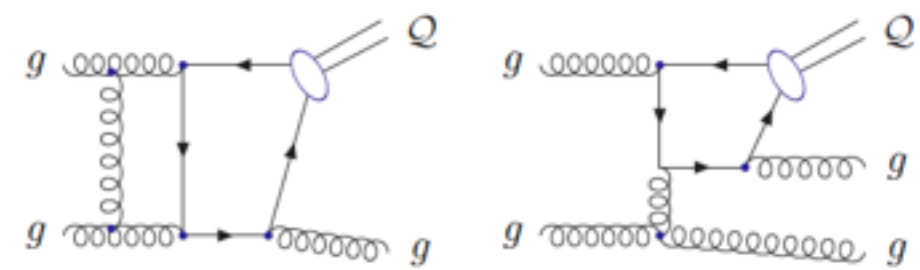




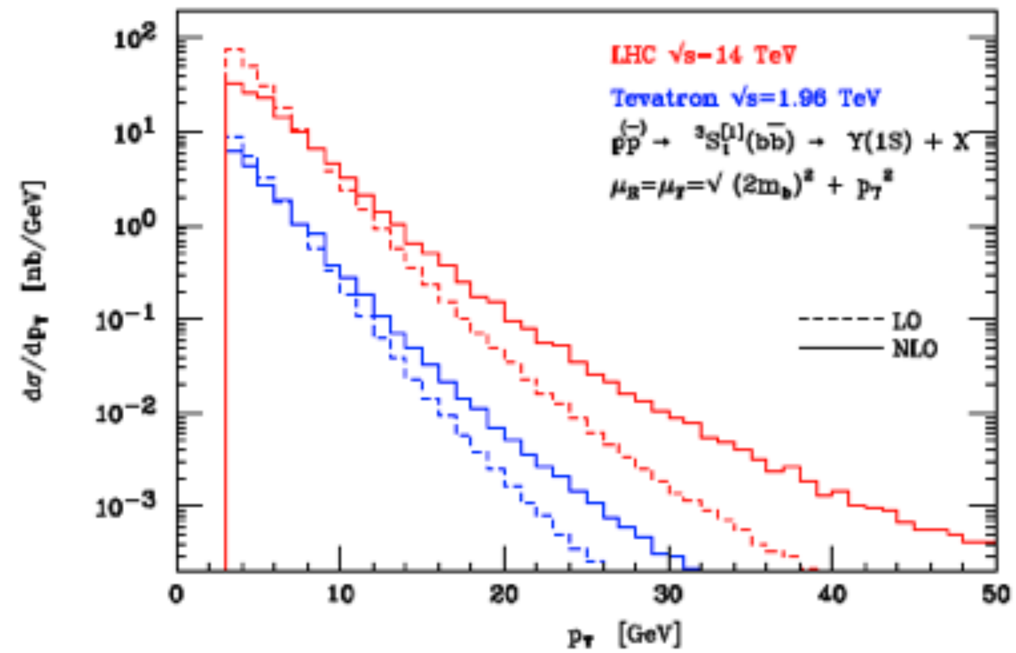
p_T distributions of onia

Campbell, Maltoni, Tramontano
Gong, Wang

$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\bar{Q}[n]+X)\langle \mathcal{O}^H[n]\rangle$$

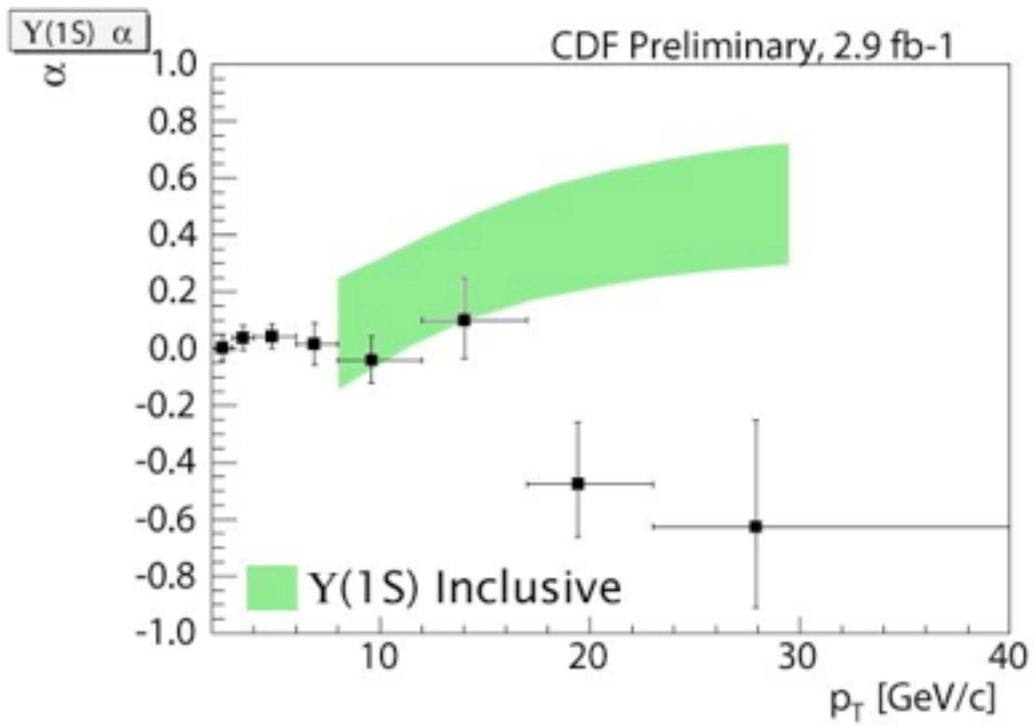


- Theory progress: inclusion of higher order corrections
  - NLO corrections to $^3S_1$ color singlet J/Ψ,Υ production
    - ✓ corrections large
    - ✓ not yet available for color octet production
    - ✓ still leaves issue with universality of non-pert. matrix elements
  - MadOnia
    - ✓ for fast tree-level calculation of quarkonium amplitudes
  - NRQCD factorization for gluon fragmentation proven to all orders in v
    - ✓ requires "gauge-completed" operator matrix elements

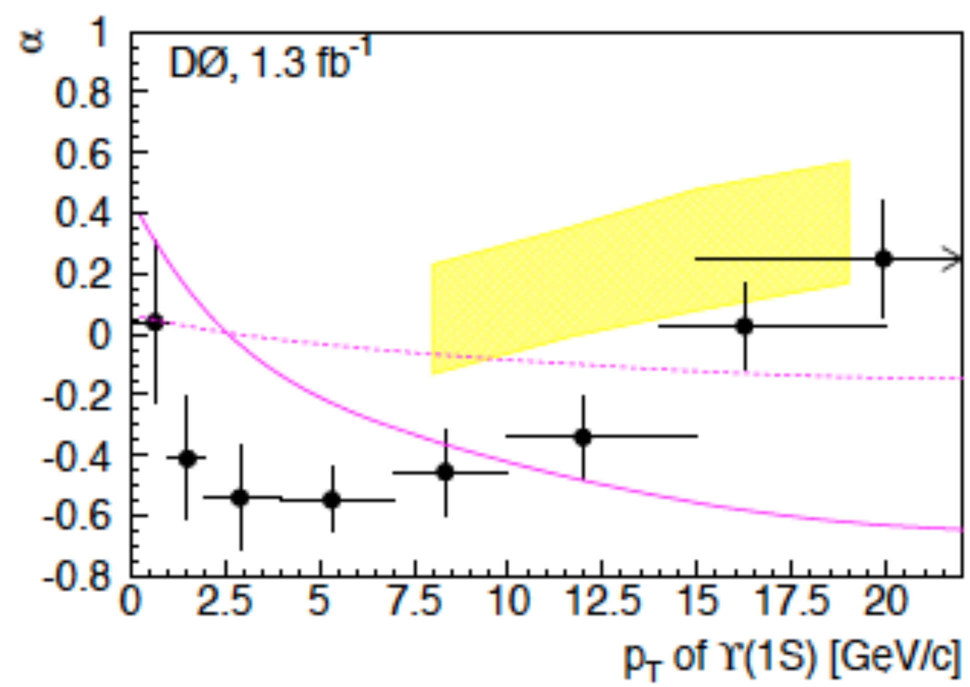


p_T distributions of onia

$$\frac{d\Gamma(\psi \to l^+ l^-)}{d\cos\theta} \propto 1 + \alpha \cos^2\theta$$



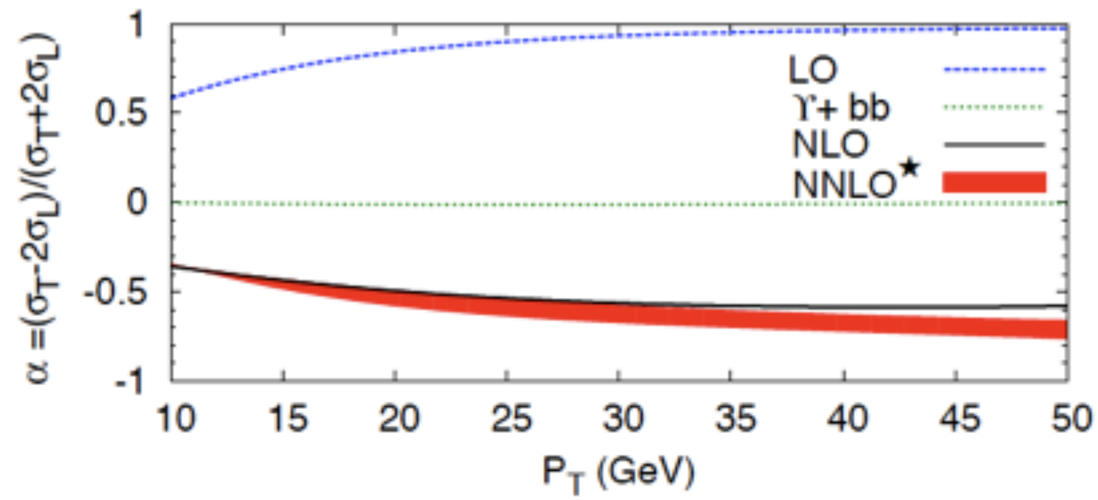
- Υ(1S) (or other Υ(nS)) could help answer "v" issue
  - but CDF and D0 have different recent results
    - ✓ hint of polarization at large p_T?
  - ATLAS/CMS should have about 10 Υ(1S)/GeV events at p_T=50 GeV after 1/fb (including branching fraction)
    - ✓ enough for angular distributions (i.e. polarizations?)



Tuesday, April 5, 2011

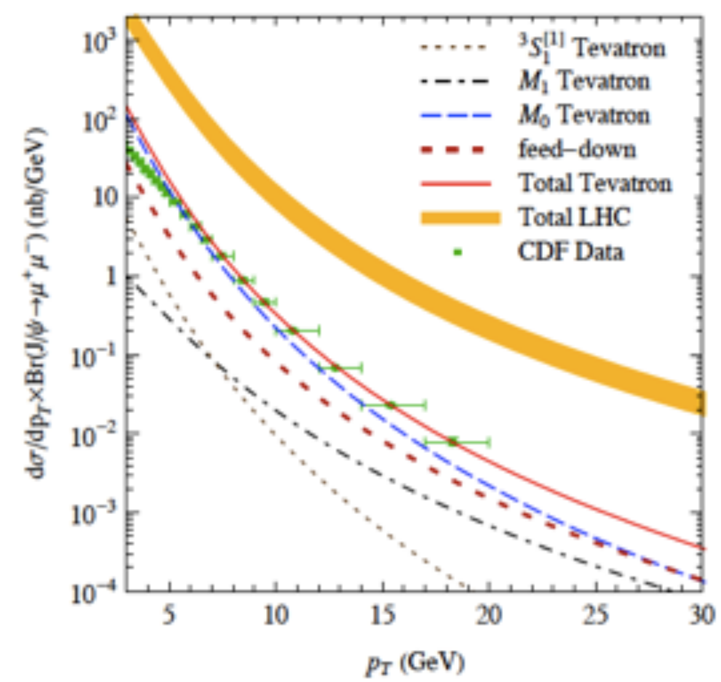
onia at NLO

Artoisenet, Campbell, Landsberg, Maltoni, Tramontano

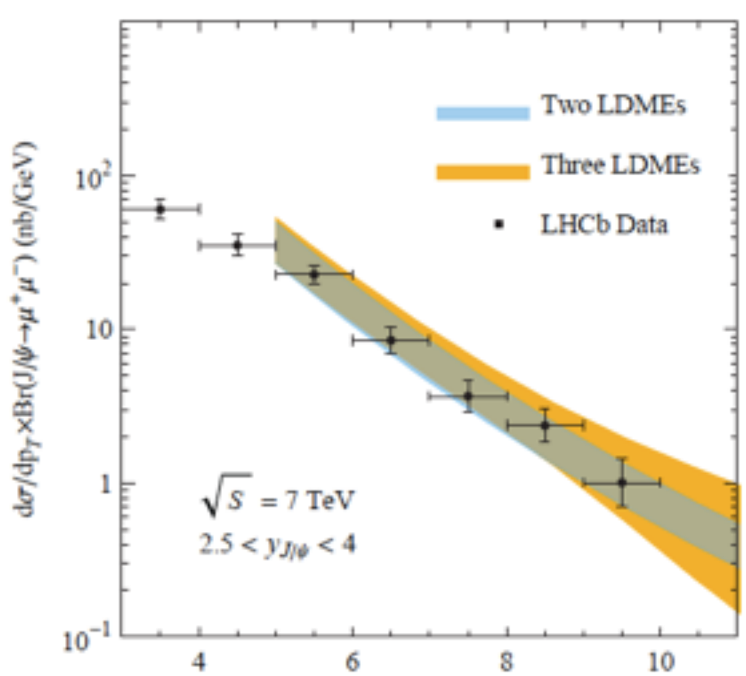


- NLO and NNLO* (only 2-real)
  - corrections (color-singlet) can change polarization (ϒ at Tevatron)
- Complete NLO for J/ψ at Tevatron: might be [8] dominated at large pT
  - unpolarized!
  - involves fitting 2 or 3 matrix elements
- Some tension with results of other NLO calculation
- Good agreement with first LHC data

Ma,Wang, Chao

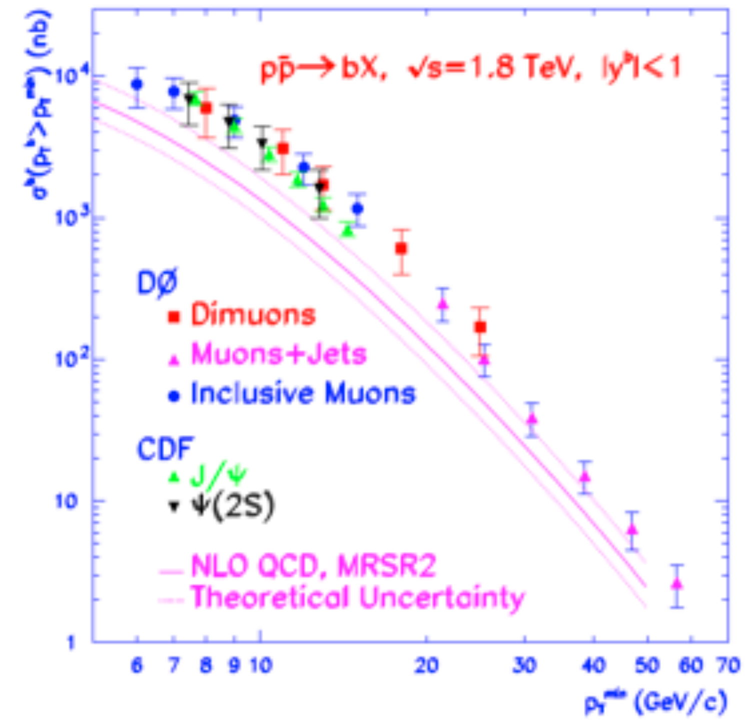


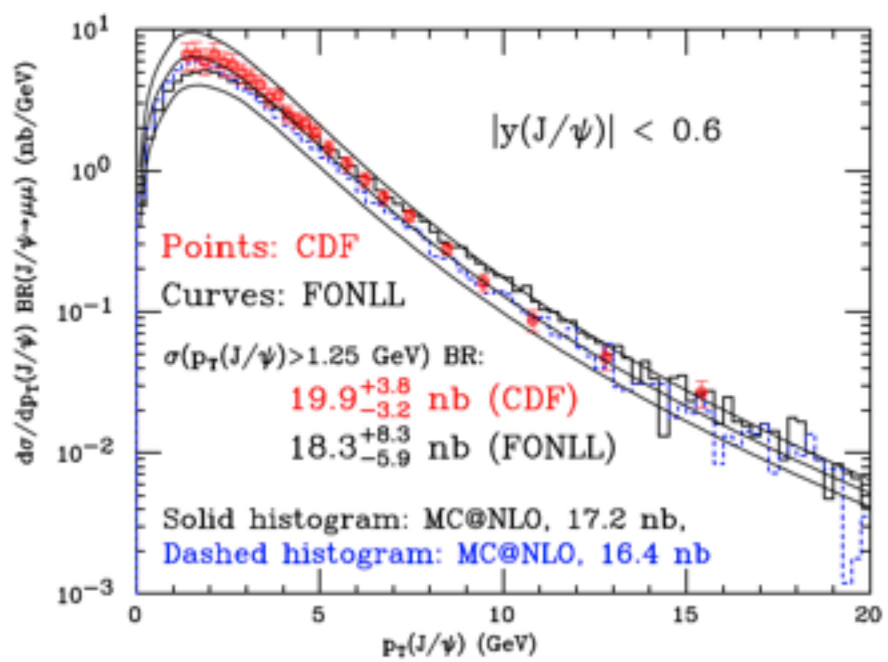
Butenschoen, Kniehl



b's at Tevatron

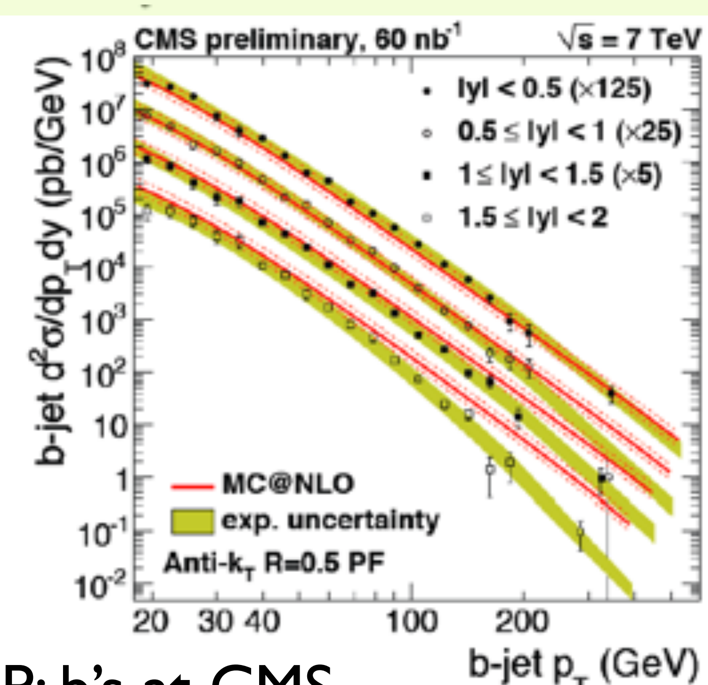
Cacciari, Nason

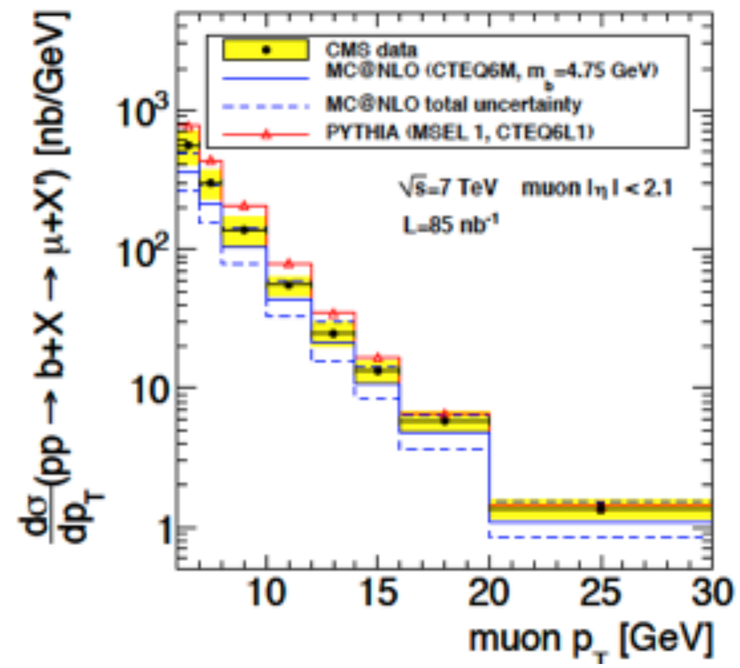




- Story fades into memory, but still a parable
- Seemingly straightforward NLO calculation for b-quarks disagreed with Tevatron data for years. Data/Theory: 3
  - (for b-jets there was no problem)
- There was *much* new physics speculation
- Solution due to
  - Proper use of Fragmentation Functions (fit well to e+e- data)
    - ✓ Fit only what is known. Peterson form too constraining
  - FONLL resummation of large log(p_T/m)
- Reproduced by MC@NLO
- Conclusion:
  - Let's be careful out there

b’s at CMS



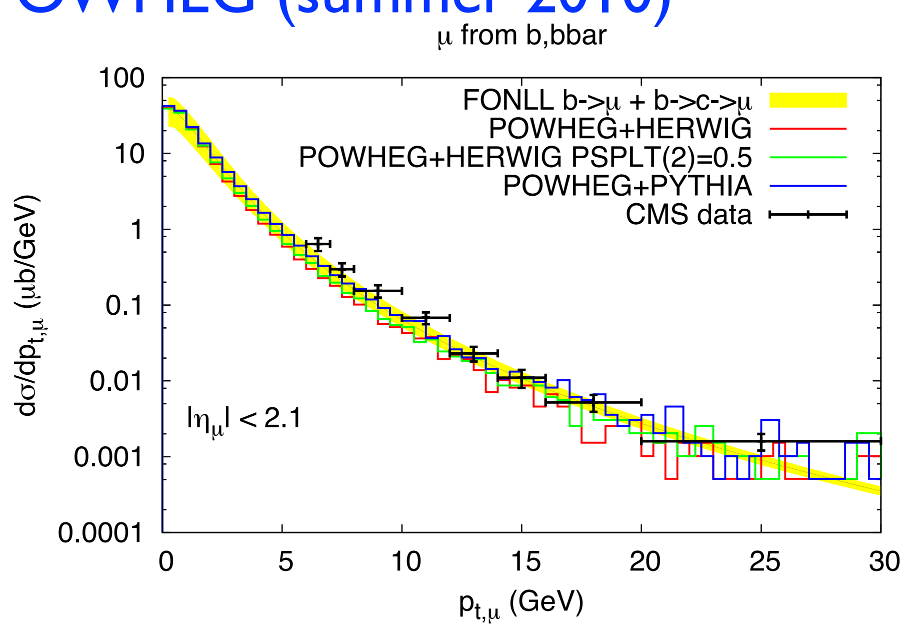


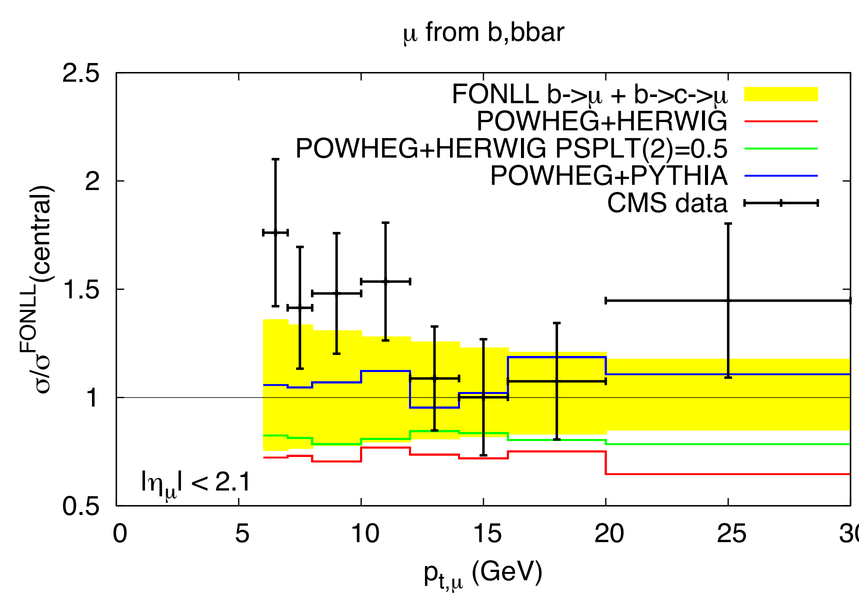
- ICHEP: b’s at CMS
  - b-jets, discrepant with MC@NLO at large p_T
  - b → μ, discrepant at small muon pT

Ulmer, Moriond

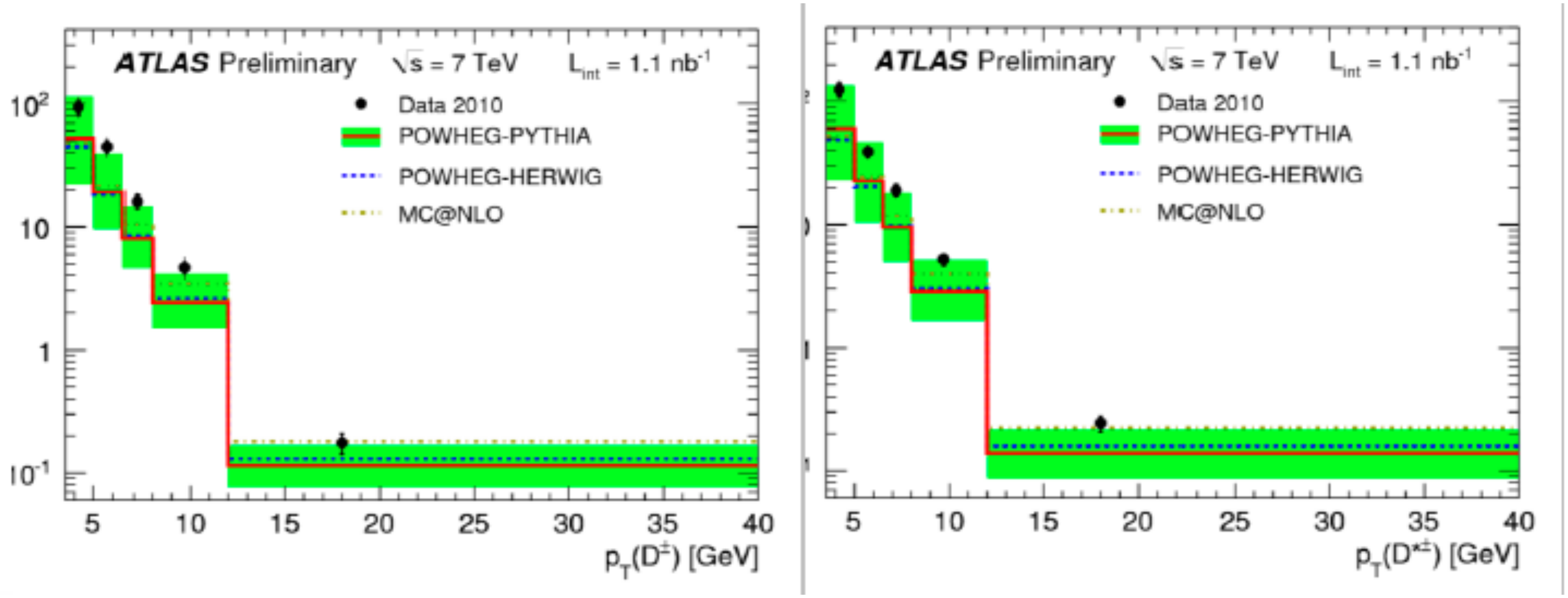
- Interesting early data puzzle...
  - POWHEG (summer 2010)

Cacciari, Nason





Inclusive c's at ATLAS



Dolezal, Moriond

- Moriond: D's at ATLAS
  - Data exceed theory (but not by much)

top

- Special; huge mass
  - strong coupling to EWSB
  - good for QCD, no hadronization ($m_t > m_W + m_b$)
  - spin information preserved due to rapid decay
- Until Higgs comes along, star of hadron colliders
- Top physics: check its properties and behavior very stringently
  - There is much to check
    - ✓ cross section, mass, width
    - ✓ couplings, branching ratios
    - ✓ ...
- Trouble maker for SM, life raft for MSSM, Little Higgs, etc

Top knowns

- Mass: 173.3 ± 1.1 GeV
- Width Γ: 1.50 GeV at NLO
- V_{tb} > 0.88 ± 0.07
- Q_{top} more likely 2/3 than 4/3
- V-A coupling to W-bosons fairly well-established
- σ(tt)
  - 7.2 (CDF) and 6.9 (D0) pb at Tevatron (8% error)
  - 180 ± 18 pb (ATLAS), 158 ± 19 pb (CMS)
    - ✓ All in remarkable agreement with SM

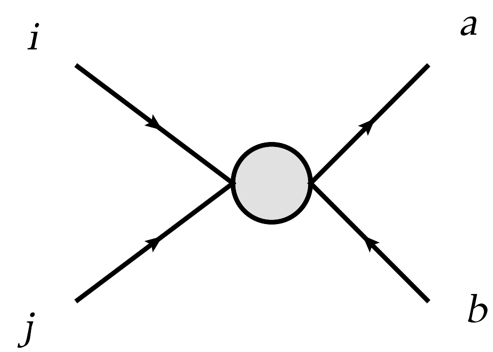
Top cross section

- First property measured
  - checks production mechanism
- Theory
  - inclusive cross section at NLO, but expect NNLO in not too far future
  - approximate results based on resummation
    - ✓ sensitive to "QCD - antenna" of lowest order
  - Don't forget to report "visible" cross sections
    - ✓ less unfolding, more precise
- tt + jet, tt + 2jets now also known to NLO
  - Very impressive calculations

Dittmaier, Uwer, Weinzierl; Melnikov, Schulze

Bevilacqua, Czakon, Papadopoulos, Worek

$$\sigma_{tt} = C(\alpha_s) \times \exp[G(\alpha_s, \ln Th]$$
$$= \sigma_0 + \sigma_1 + \sigma_2 + \ldots$$



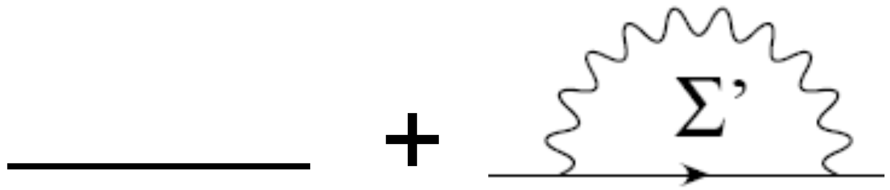
$\delta_{ij}\delta_{ab}$ $\quad T^c_{ij}T^c_{ab}$ $\quad$ L=1,2

Heavy quark mass

$$\frac{1}{p^2 - m^2 - \delta m^2}$$

- Electron mass "easy": defined by pole in full propagator
  - ✓ Scattering of external, physical electrons and photons, on-shell
  - ✓ No real ambiguity what electron "pole" mass is
- Quarks are confined, physical on-shell quarks do not exist
  - ✓ "Pole mass " leads to intrinsic non-perturbative ambiguity of few hundred MeV
- $\overline{\text{MS}}$ mass (aka short-distance mass)
  - ✓ Treat mass term in Lagrangian as two-point coupling, let it run
- Particularly clear for top mass (pole: 172, MSbar: 162)
  - LHC: accuracy of 1 GeV possible (like Tevatron).
  - ✓ Claim ILC: 100 MeV accuracy, but for what mass?

Heavy quark mass schemes



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

Pole mass scheme $\qquad m^0 = m_{Pole} + \Sigma(m, m)$

$\overline{\text{MS}}$ scheme $\qquad m^0 = \bar{m}(\mu) - \frac{\alpha_s}{\pi}\frac{1}{\epsilon}$

Other scheme uses energy of tt pair (for Schroedinger eq)

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

Quark-antiquark potential

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

Bad behavior cancels
between V and m(pole)
"Potential subtracted mass"

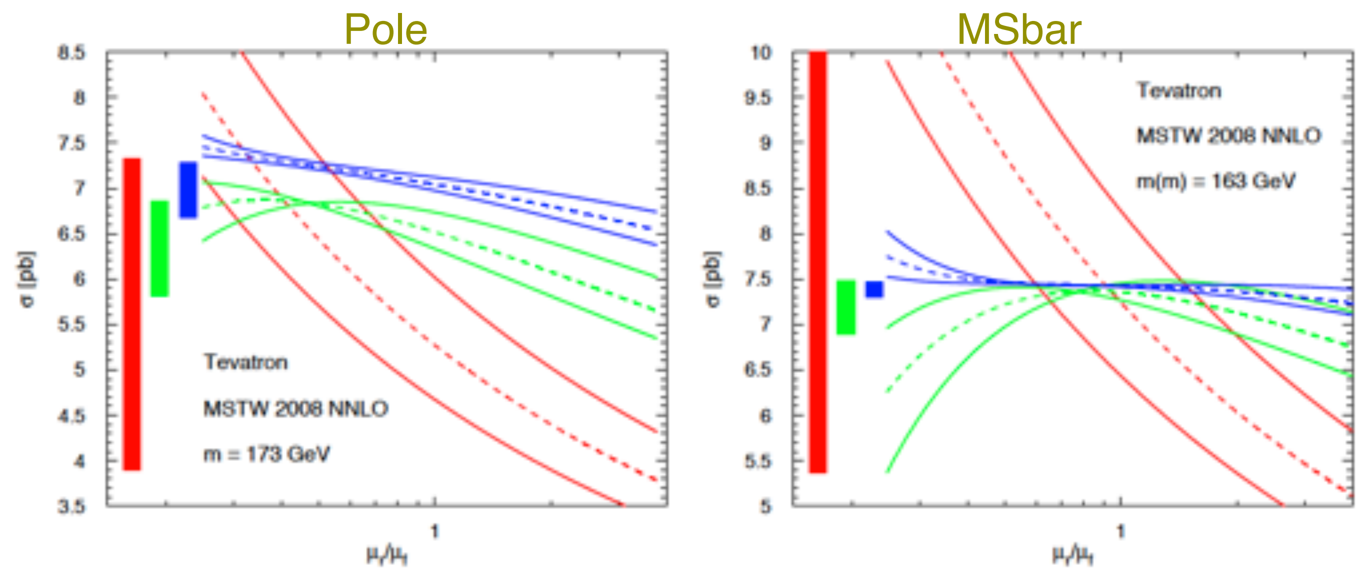
Bad behavior in self energy

$$\Sigma(m, m) \sim \sum_n \alpha_s^{n+1}(2\beta_0)^n n! \quad = -\frac{1}{2}\int \frac{d^3q}{(2\pi)^3} V(\vec{q}^2)$$

Beneke

Heavy quark mass determinations

Moch, Langenfeld, Uwer



- Various definitions exist, not trivial to relate measurements to Lagrangian parameters
- Used: Lattice methods, plus EFT
- In e+e- can one could infer the mass from
  - threshold scan of tt cross section
  - event shapes
  - "right" mass definition depends on observable

$$m = m(\mu)\Big(1 + \alpha_s(\mu)d^1 + \alpha_s^2(\mu)d^2 + \ldots\Big)$$

Fleming, Hoang, Mantry, Stewart; Beneke, Signer; Hoang

- What do hadron colliders infer when reconstructing top?
  - Pole mass? MC mass?

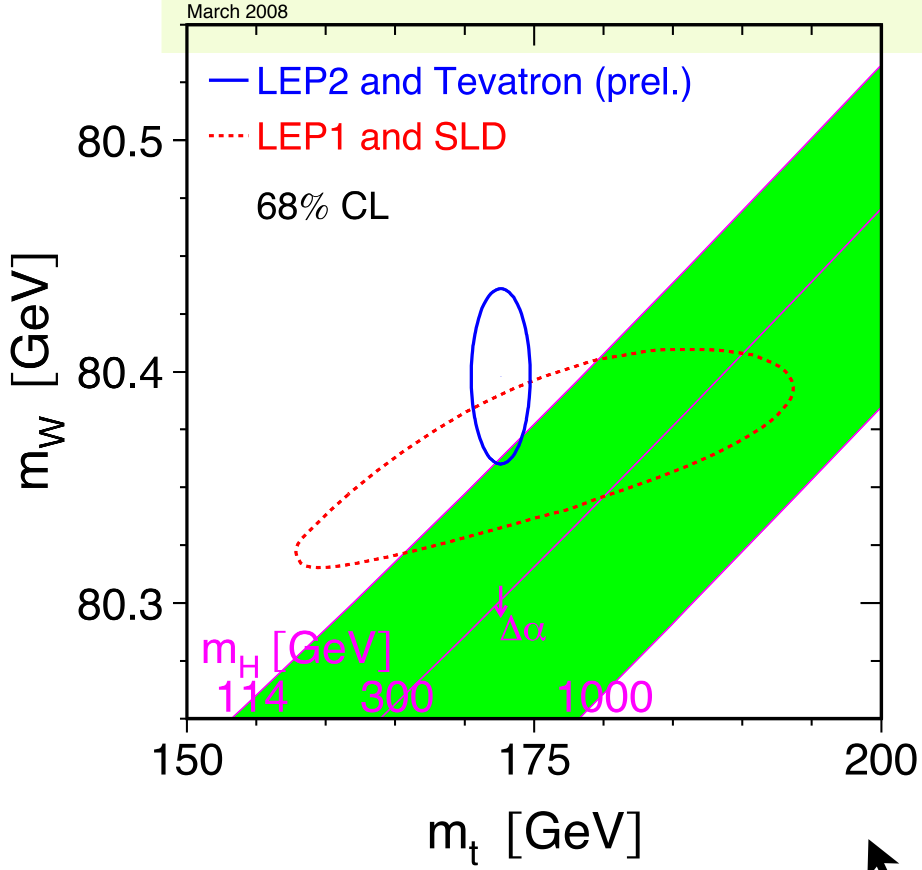
Hoang, Stewart

- Extract running mass from inclusive cross sections (tt from Tevatron, cc and bb from DIS at HERA)

Moch, Uwer

$$m_c(m_c) \;=\; 1.01 \;\pm 0.09(\mathrm{exp}) \;\pm 0.03(\mathrm{th})\ \mathrm{GeV} \qquad \text{at NNLO}_{\text{approx}}$$

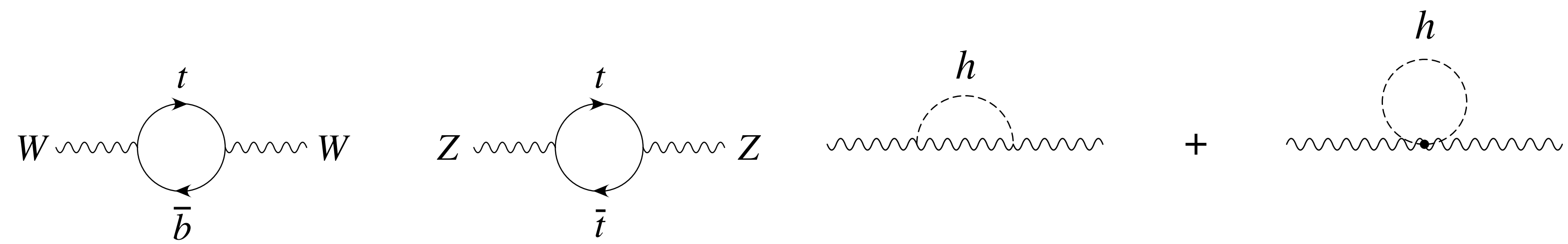
Top mass



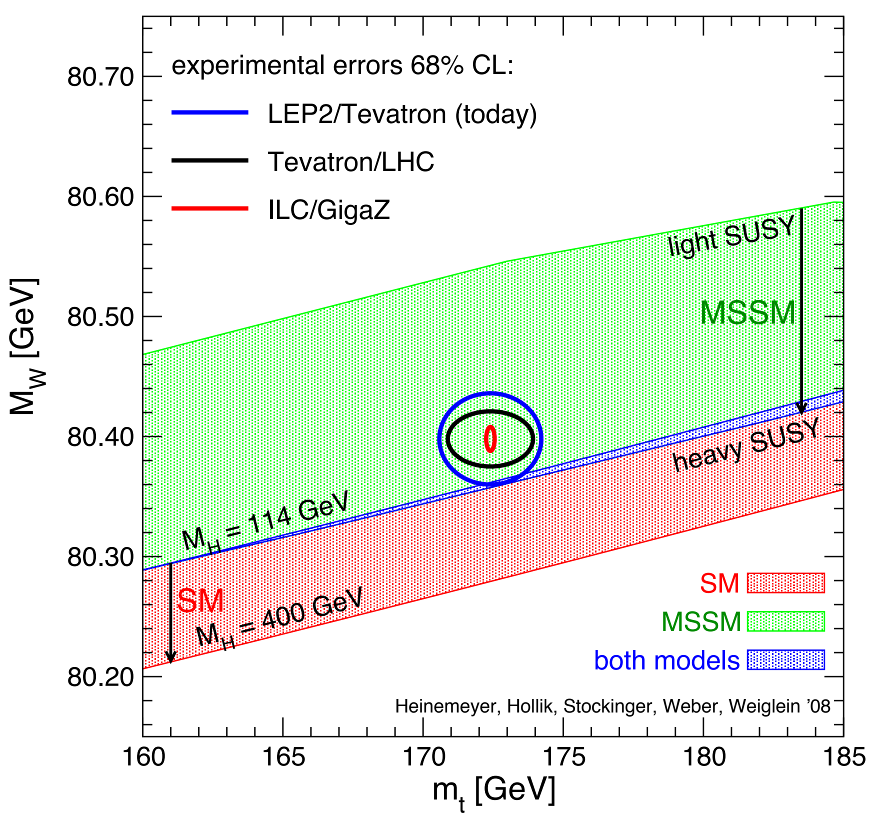
now: 173.3 ± 1.1 GeV (Tevatron)

<1% !!

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_w}\frac{1}{1-\Delta r(m_t, m_H)}$$



Heinemeyer, Weiglein



- Measure via reconstruction of final state, or via cross section
- Relate m_W, m_t, m_H to constrain SM, MSSM
- But even with known Higgs mass, 6 MeV uncertainty on m_W, only need 1 GeV accuracy on top mass
  - but do need 100 MeV once new physics is found

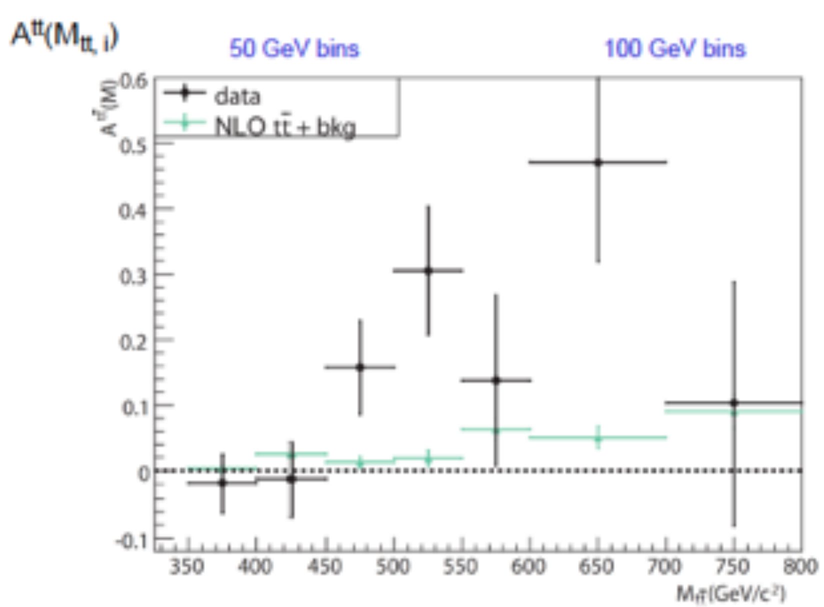
Charge asymmetry

aka forward-backward asymmetry

- Rate difference of top vs. anti-top at fixed angle (or rapidity)
- At LO from Electroweak, or BSM mechanisms
- Shows up in QCD first at $O(\alpha^3_s)$ through (a) interference Born-Virtual, or (b) radiative.

Rodrigo, Kuhn

  - Interference of C-odd and C-even amplitudes. Proportional to SU(3) d_{abc}
- Prospects at LHC not so clear; wrong beams (pp), would need high p_T cut to enhance quark-antiquark channel
  - But check anyway!

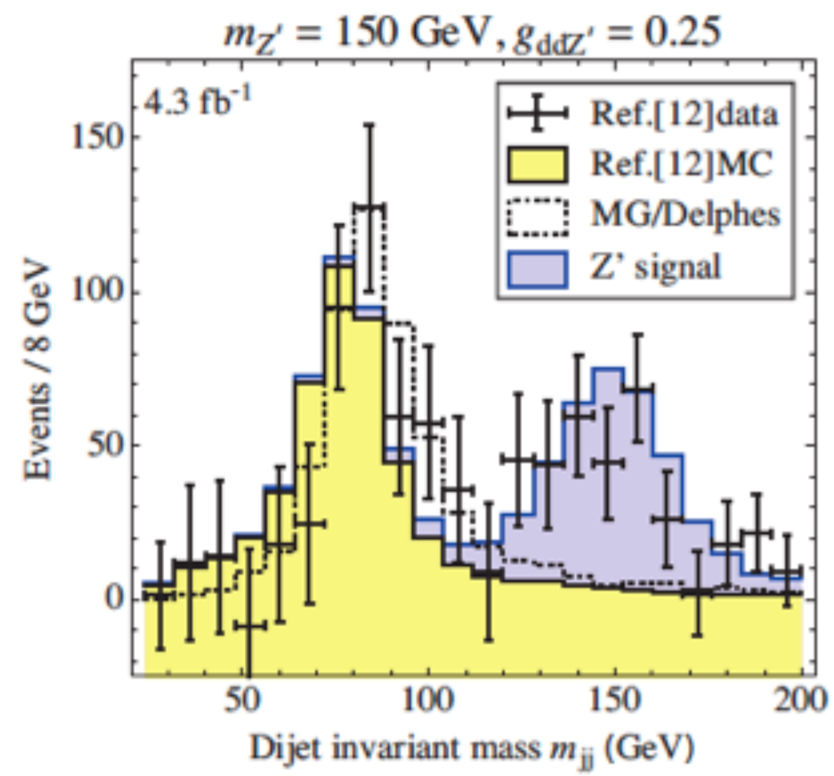


CDF: 0.475 ± 0.114 [5.3 fb^{-1}]

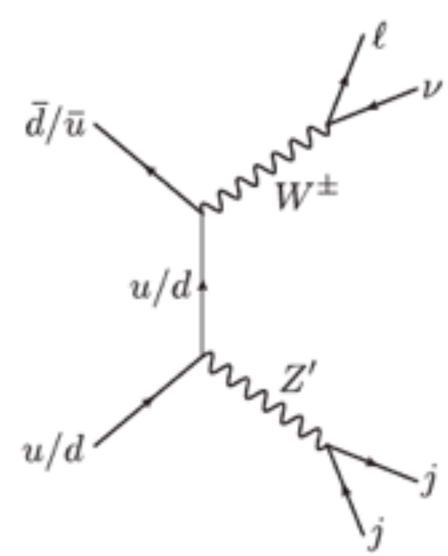
QCD: 0.088 ± 0.013

D0: also saw discrepancy in 2008

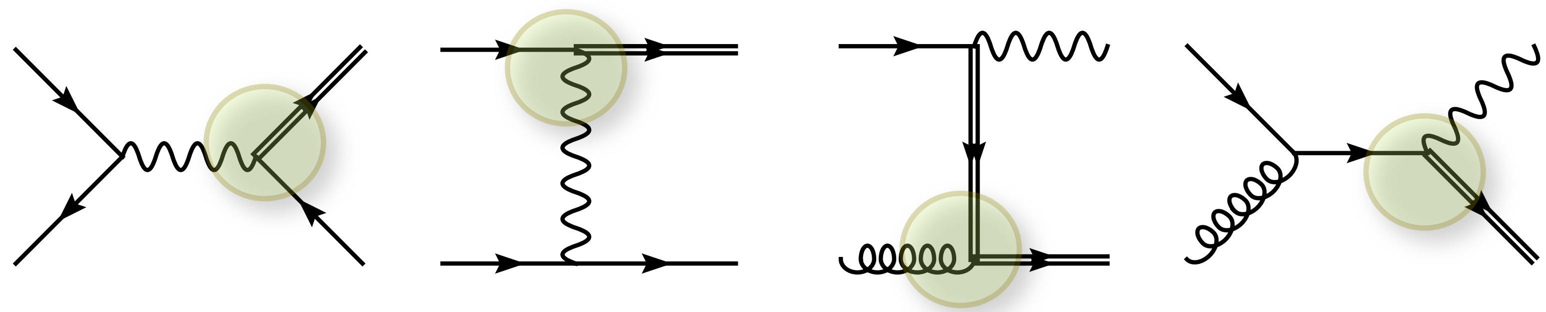
New physics hints



- Forward-backward symmetry
  - ✓ At LHC, check A(LR) — Godbole, Rindani, Singh, Choudl
- CDF W-jj anomaly (3.3 σ)
  - jets **not** b-tagged
- Ideas
  - ✓ Techni-pion resonance
  - ✓ Axigluons
  - ✓ Leptophobic Z' — Buckley, Hooper, Kopp, Neil
  - ✓ MSSM Higgs



Single top production



(1) (2) (3)

s-channel: timelike W

4 pb @ LHC7

t-channel: spacelike W

62 pb @ LHC7

Wt channel: real W

10 pb @ LHC7

- Weak production of top, through left-handed charged current process
- Allows measurement of V_{tb} per channel
- Check of structure of Wtb vertex
- Sensitive to New Physics
- Now first evidence at LHC (cut & count), easier than for Tevatron

Conclusions

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- Heavy flavors central to LHC7 analyses
  - charm
    - ✓ onia, jet-tagging, PDF’s, ..
  - bottom
    - ✓ QCD description, onia, rare decays, jet-tagging, top-reconstruction,..
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    - ✓ check the Tevatron, use gg initial state
    - ✓ with more data, higher energy: resonances, start precise theory comparisons to tell new from known
      - increasingly important!

Conclusions

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      - increasingly important!
- Vast array of new theory tools available for good predictions
  - use right tool for right job: let's keep talking