From top to bottom (and charm)

Heavy flavors at early LHC

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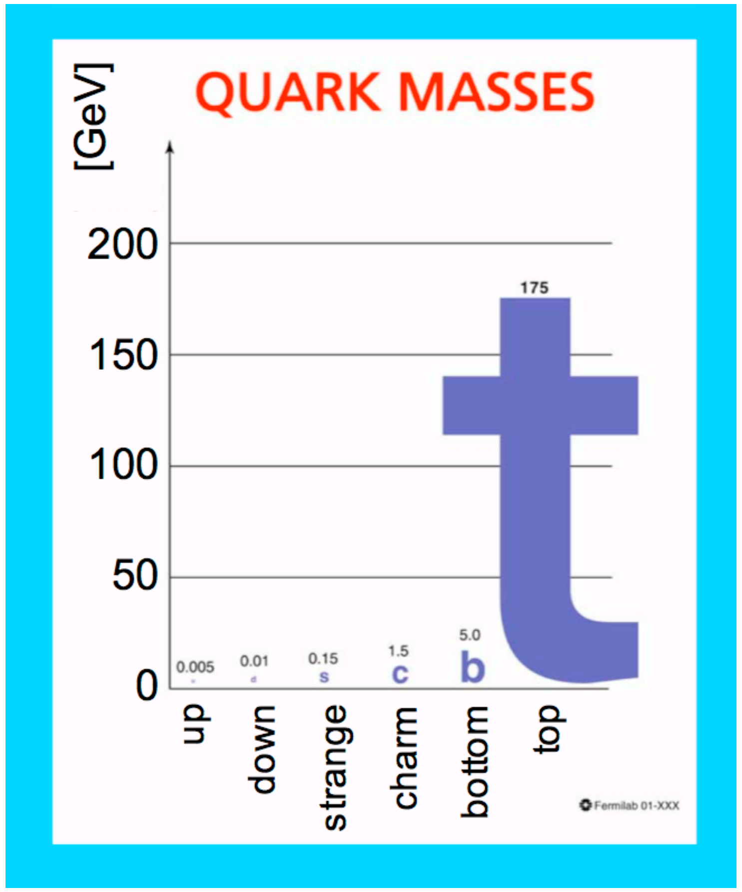
Overview

- What is special about heavy flavors?
- Production
- Charm
- Bottom
- Top
- Conclusions

Heavy quark history

- Charm (1974) made SM consistent, cemented belief in QCD
  - ✓ GIM, spectroscopy, ...
- Bottom (1977), announced 3rd family, allowed for CKM mechanism
  - ✓ B-factories
- Top, discovered by CDF and D0 in 1995
  - ✓ Bizarrely heavy
  - ✓ Completes 3rd generation
  - ✓ What will top's contribution be? (LHC14: T-factory)

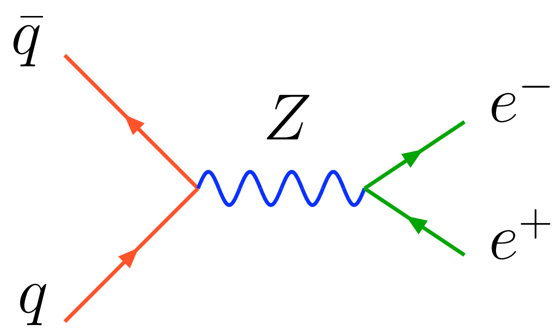


Heavy flavors are special

- 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 just a topic by itself, also relevant for
  - PDF's
  - Jet-tagging
  - New physics
  - ...

LO, NLO, etc

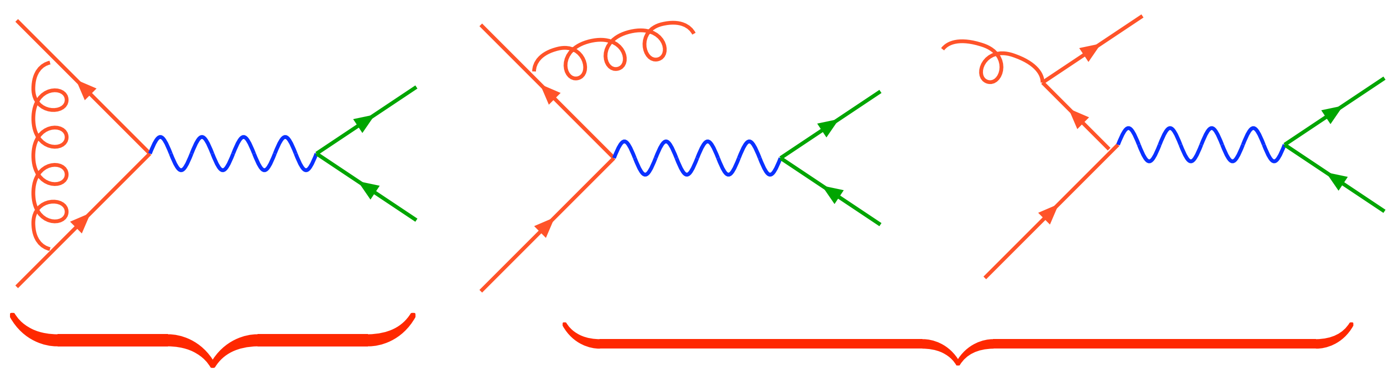
LO $\hat{\sigma}^{(0)}$



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

Calculate in D=4-2ε dimensions

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

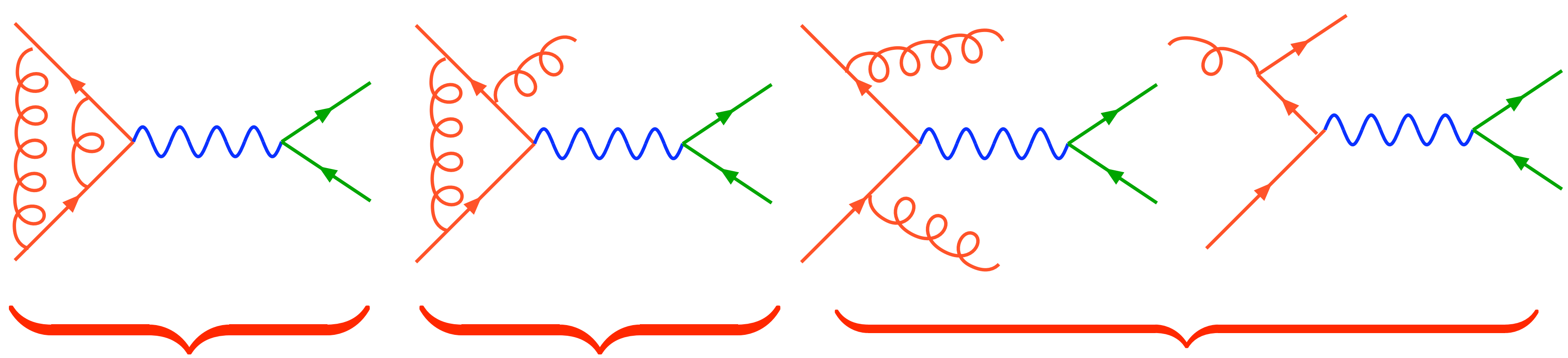


1 loop

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

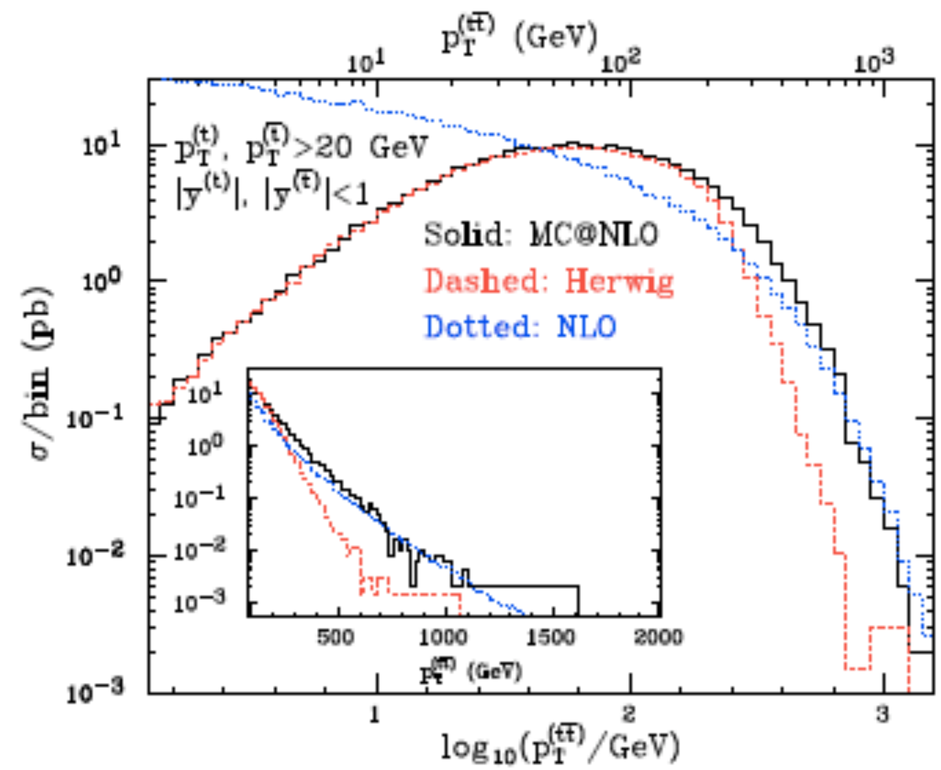
The Higher Order revolution

- 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, ...
  - 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. $pp \to V V V$	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. $pp \to VV\, b\bar{b}$,	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. $pp \to W b\bar{b}j$	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

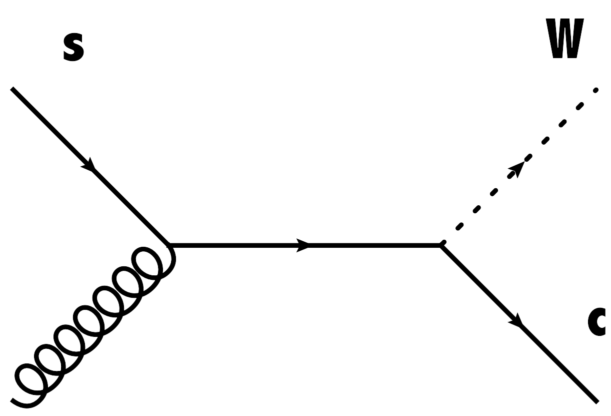
MC@NLO, POWHEG

- 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



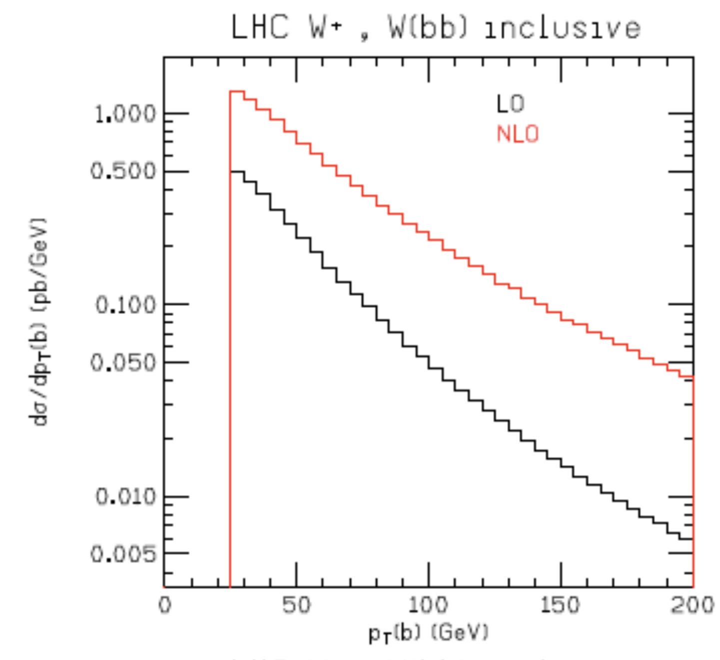
Charm at LHC

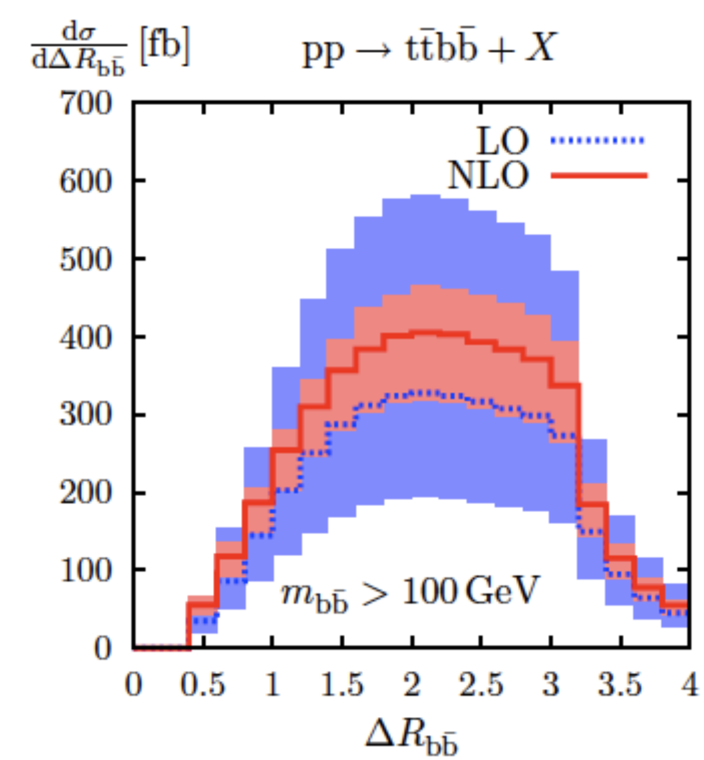
- Mass is just regulator, has no noticeable kinematical (threshold) effect.
- Virtue: it can be tagged, affords direct view on parton
  - Input for charm fragmentation functions at large p_T
- Mostly useful in association with other particles (W,Z,..)
- W + charm is handle on s-quark PDF



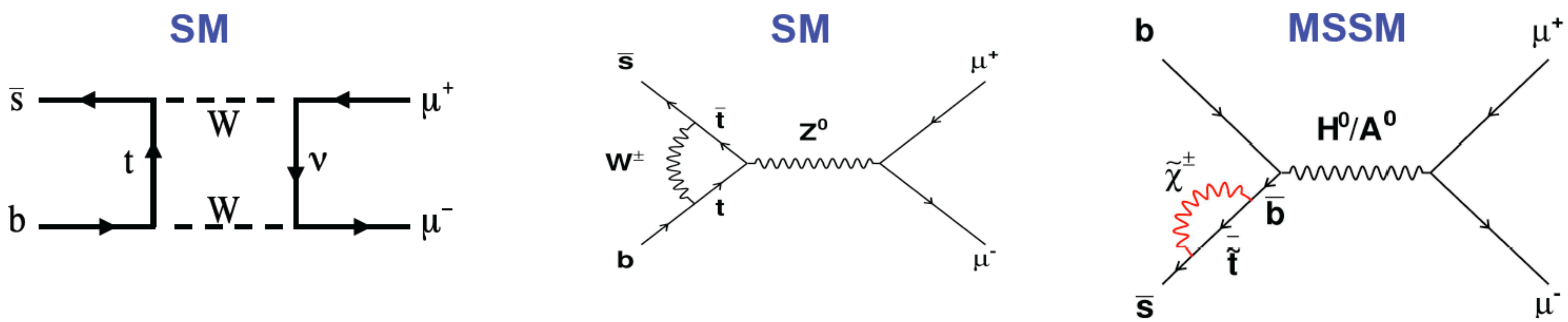
Associated heavy flavors

- 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





$Br(B_s \to \mu^+\mu^-)$



- Quite clean SM prediction $(3.6\pm0.4).10^{-9}$
- Rare decay, sensitive to many BSM effects
  - SUSY (x10), Little Higgs (x1.3), RS (x1.1)
  - esp. large tan(β), related to GUT theories
- CDF&D0 upper bounds (95%CL) SM x10
- Mostly for LHCb (but also ATLAS/CMS)
  - backgrounds (combinatorial) pesky
  - 2008 estimate: after 1 year LHCb can exclude or discover NP in this way
    - ✓ but it's not 2008 anymore..

$$H = \frac{G_F \alpha V_{tb}^* V_{tq}}{\sqrt{2}\pi \sin^2\theta_W}\left[C_S Q_S + C_P Q_P + C_A Q_A\right]$$

$$Q_A = \bar{b}_L \gamma^\mu q_L \bar{l} \gamma_\mu \gamma_5 l$$

Model/Observable	$Br(B_s \to \mu^+\mu^-)$
CMFV	20%
MFV	1000%
AC	1000%
RVV2	1000%
AKM	1000%
δLL	1000%
FBMSSM	1000%
GMSSM	1000%
LHT	30%
RSc	10%

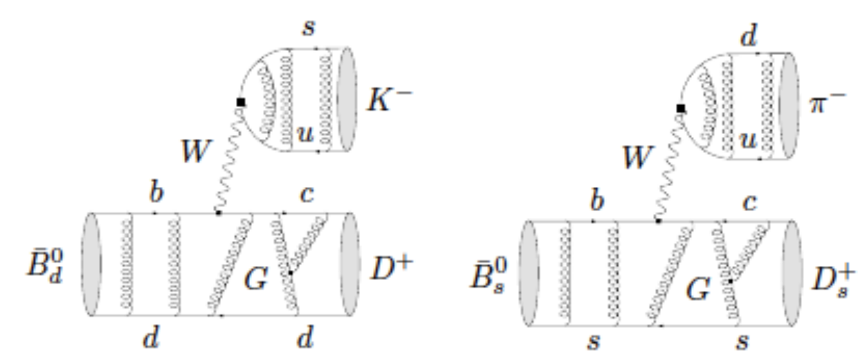
Some recovery for Br($B_s \to \mu^+\mu^-$)

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B_q \to X)\frac{f_q}{f_s}\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}$$

Key ratio, uncertainty limits potential

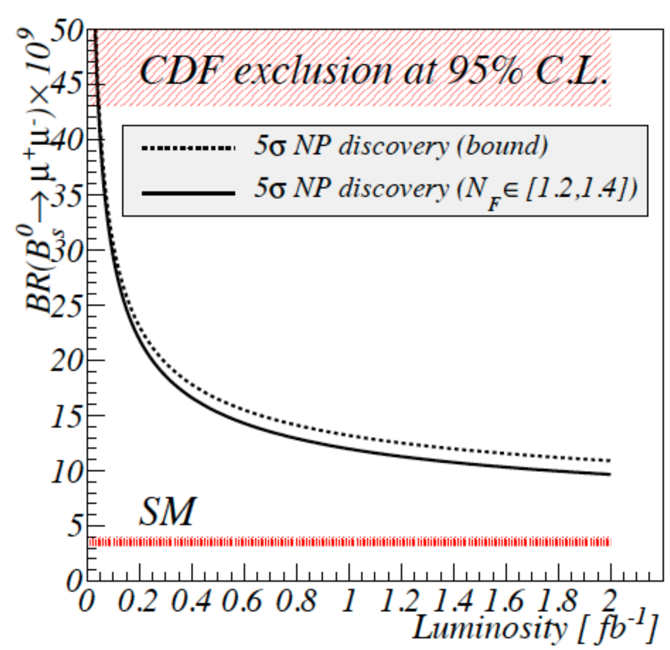
- f_q: probability that b-quark → B_q meson
- Many experiments extracted it
  - environment influence likely
    - ✓ at B-factories $f_u+f_d+f_s=1$, not at hadron colliders
  - each experiment should measure its own
- New idea, use

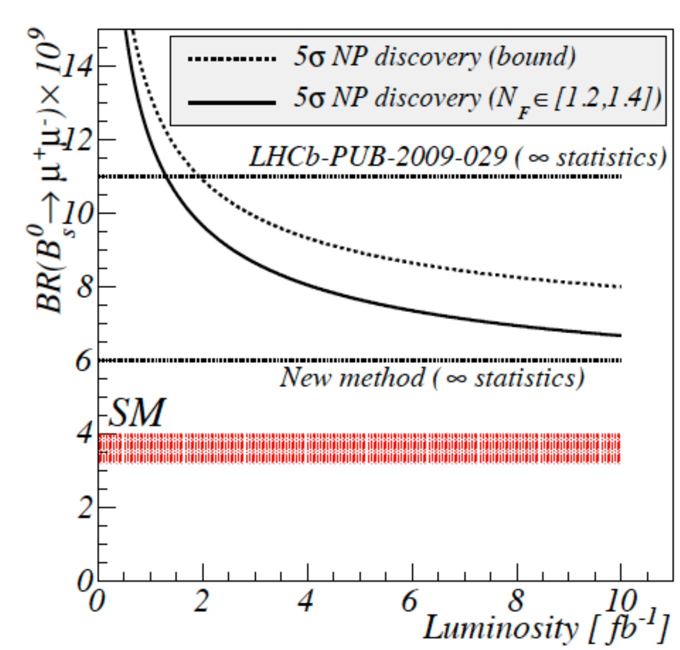
$$\bar{B}_s \to D_s^+\pi^- \quad \bar{B}_d \to D^+K^-$$



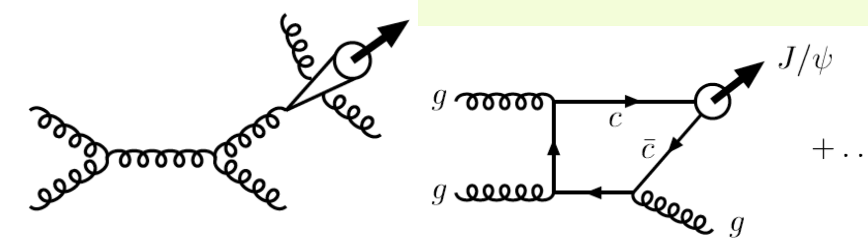
  - 5.6% uncertainty at LHCb for 1/fb
  - factorization
  - potential good
  - use LHCb value for ATLAS/CMS

Fleischer, Serra, Tuning





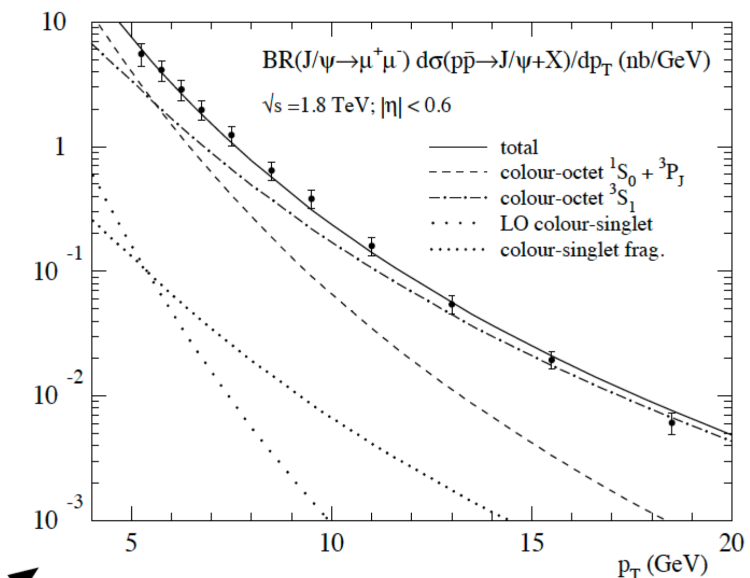
p_T distributions of onia



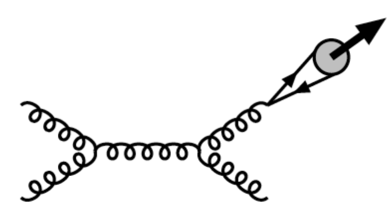
- Tevatron/HERA have left us a puzzle in high pT onium production
- Original model: compute $Q\bar{Q}$ cross section, apply onium projector
  - seriously insufficient, even including fragmentation
- NRQCD approach separates physics of production (m) and binding (mv)

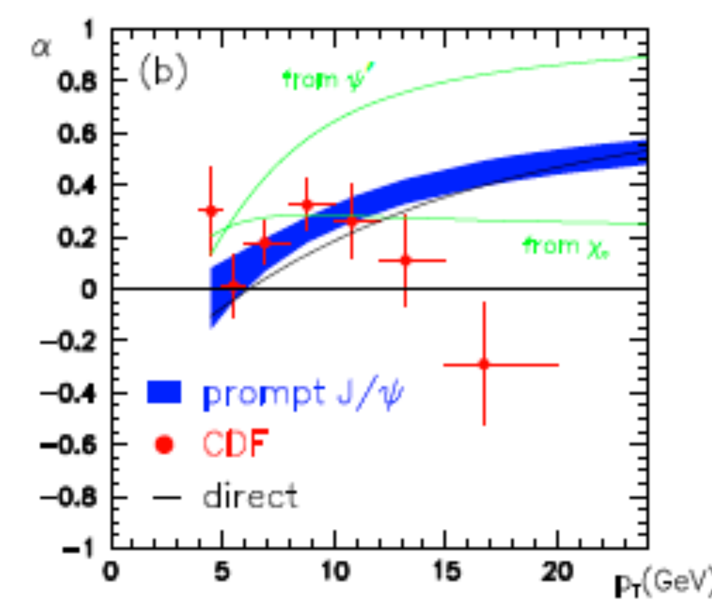
$$\mathcal{L}_{\rm NRQCD} = \psi^\dagger\left(iD_0 + \frac{\vec{D}^2}{2m}\right)\psi + \chi^\dagger\left(iD_0 - \frac{\vec{D}^2}{2m}\right)\chi + \mathcal{L}_{\rm light} + \delta\mathcal{L}$$

  - 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

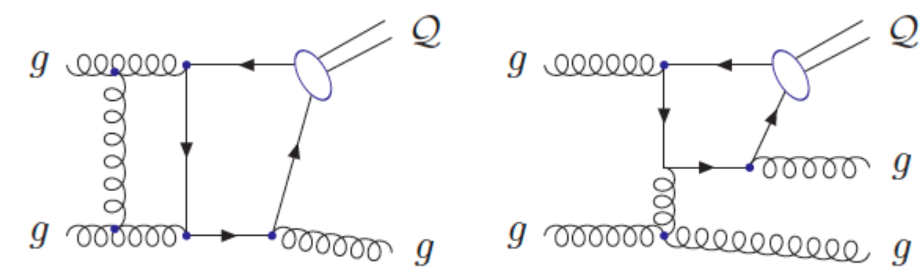




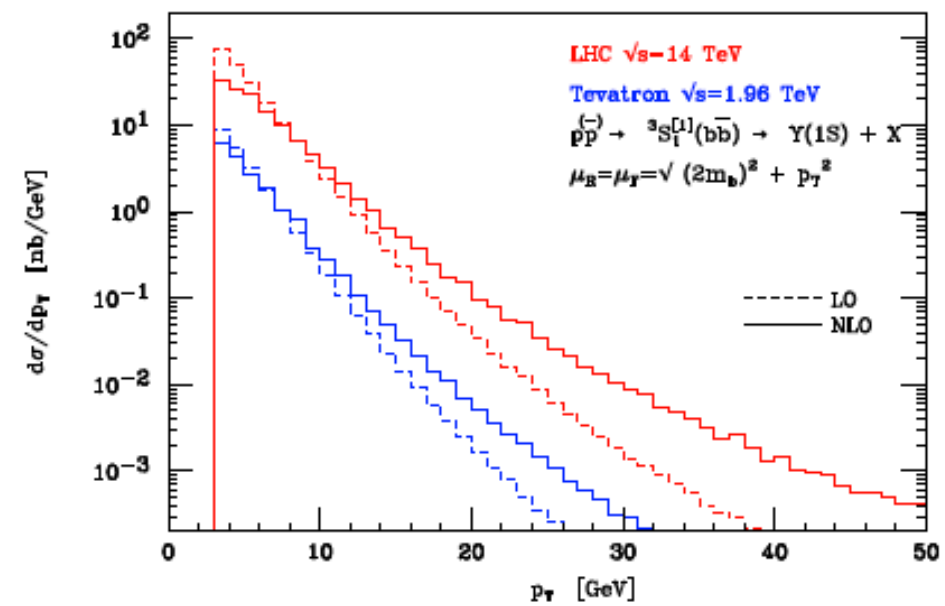
p_T distributions of onia

Campbell, Maltoni, Tramontano
Gong, Wang

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

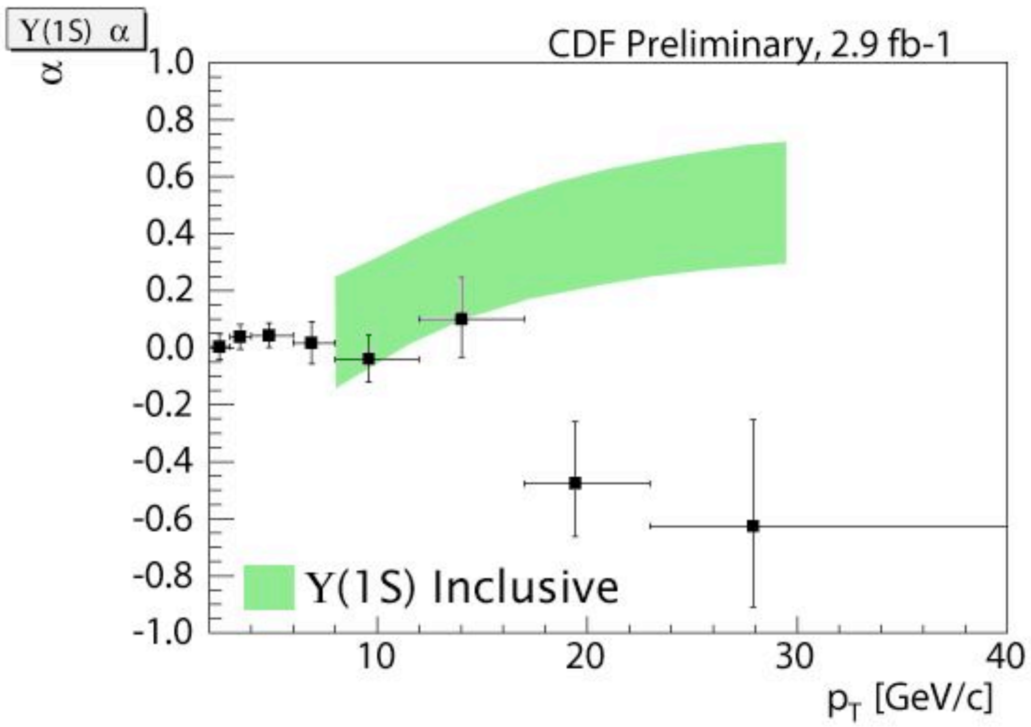


- Theory progress: inclusion of higher order corrections
  - NLO corrections to $^3S_1$ color singlet J/Psi, Y production
    - ✓ corrections large
    - ✓ not yet available for color octet production though
    - ✓ still leaves issue with universality of non-pert. matrix elements
  - MadOnia
    - ✓ 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

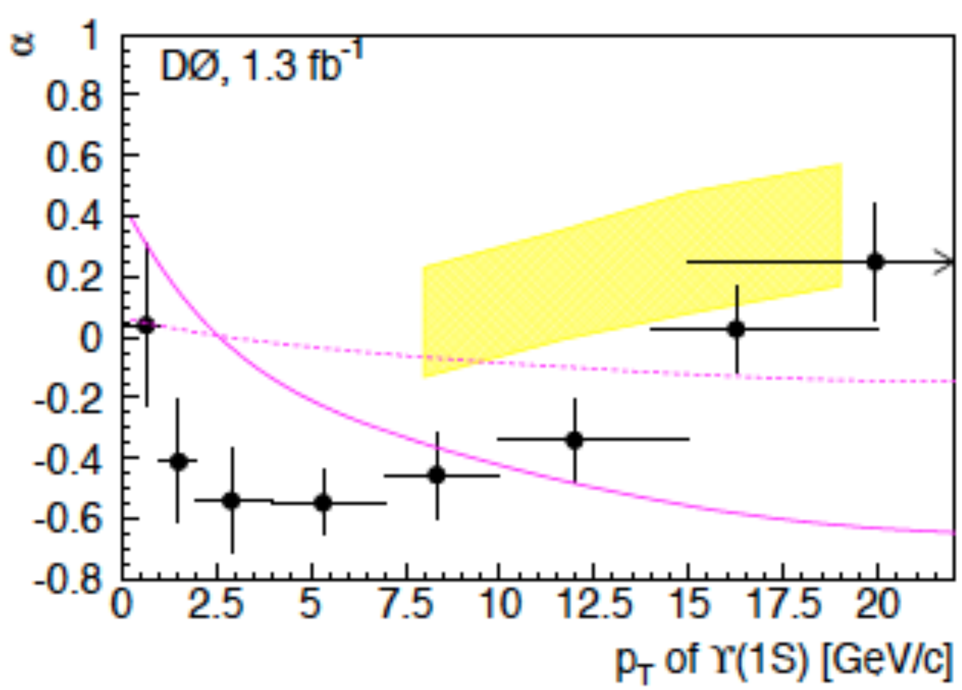


p_T distributions of onia

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

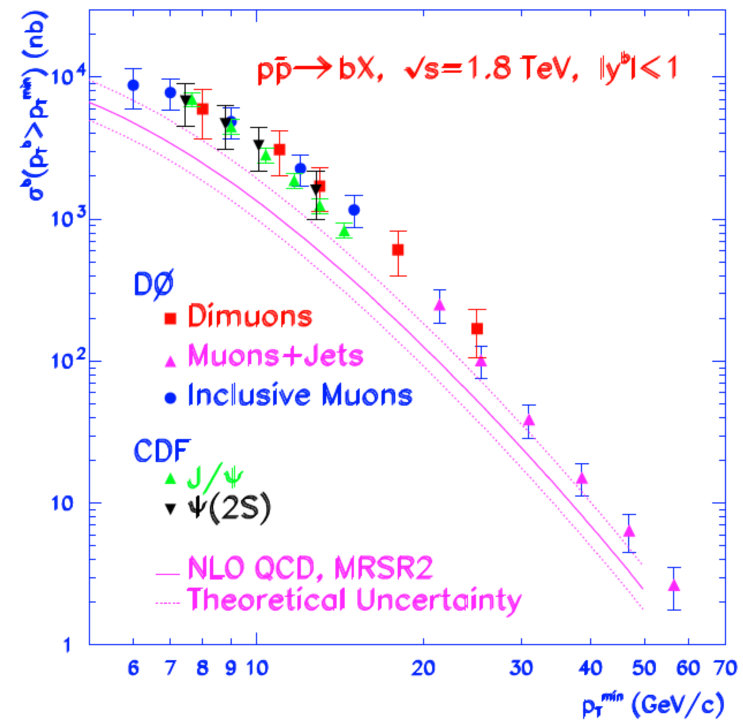


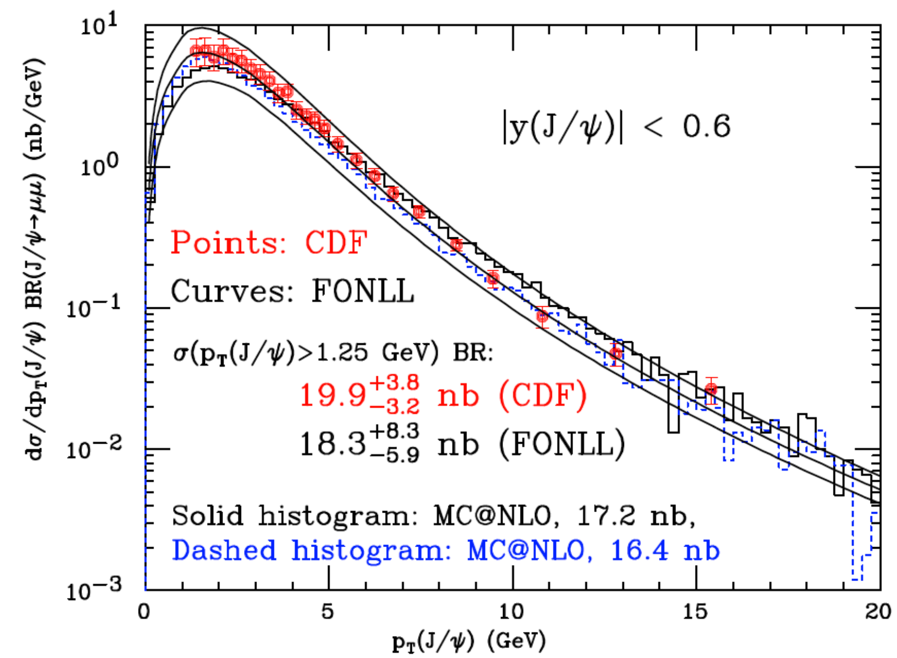
- Υ(1S) (or other Υ(nS)) could help answer "v" issue
  - but CDF and D0 have different recent results
    - ✓ hint of polarization at large p_T?
  - ATLAS/CMS should have about 10 Υ(1S)/GeV events at p_T=50 GeV after 1/fb (including branching fraction)
    - ✓ enough for angular distributions (i.e. polarizations?)



b's at Tevatron

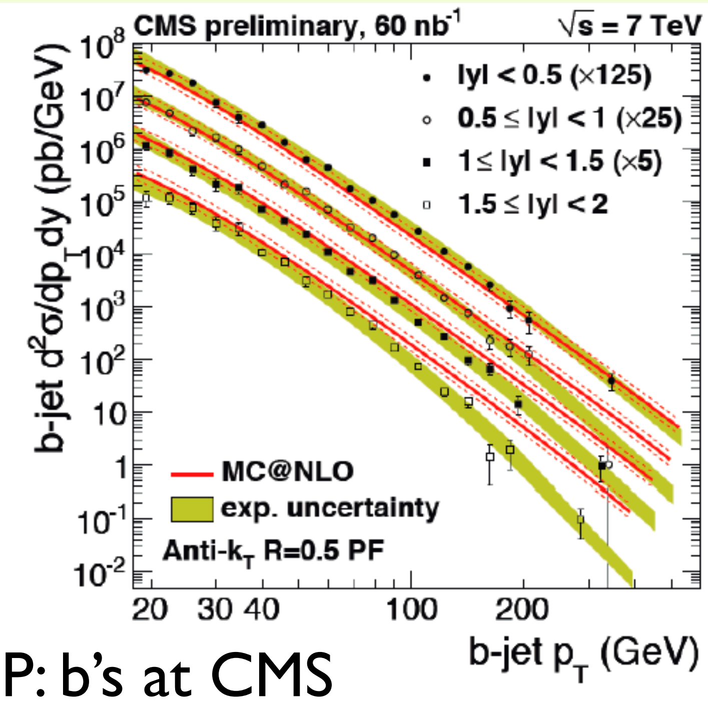
Cacciari, Nason

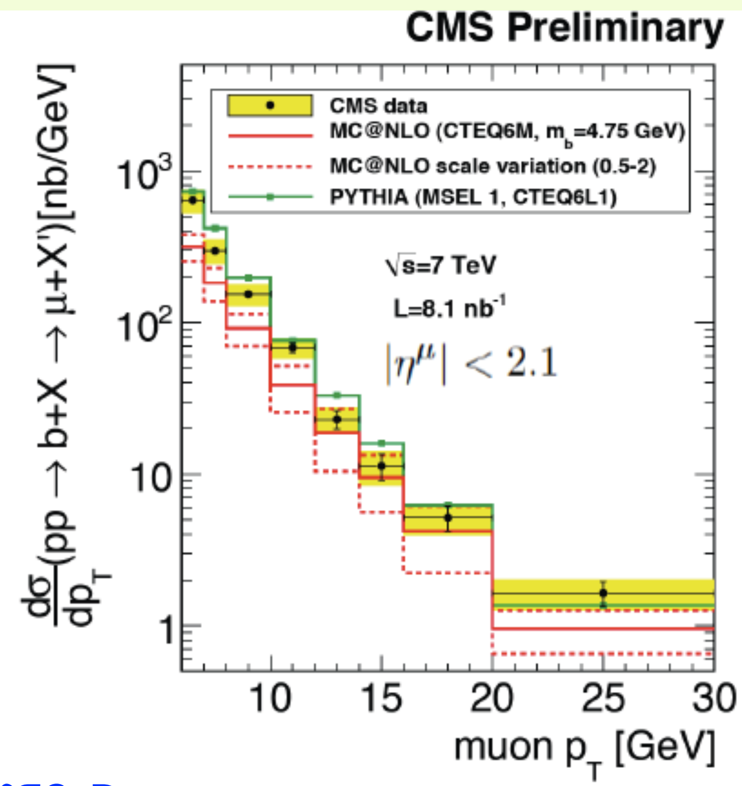




- Story fades into memory, but still a parable
- Seemingly straightforward NLO calculation for b-quarks disagreed with Tevatron data for years. Data/Theory: 3
  - (for b-jets there was no problem)
- There was *much* new physics speculation
- Solution due to
  - Proper use of Fragmentation Functions (fit 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

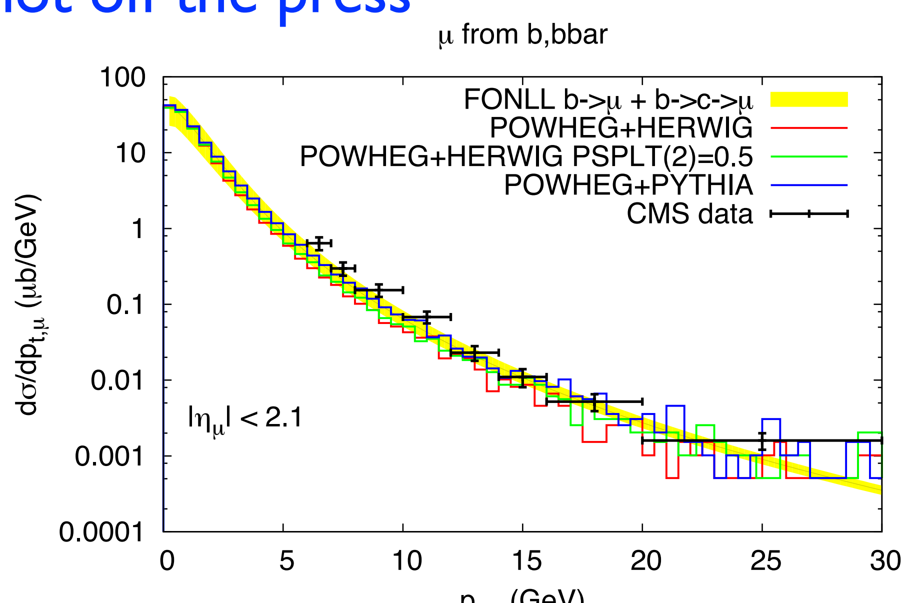


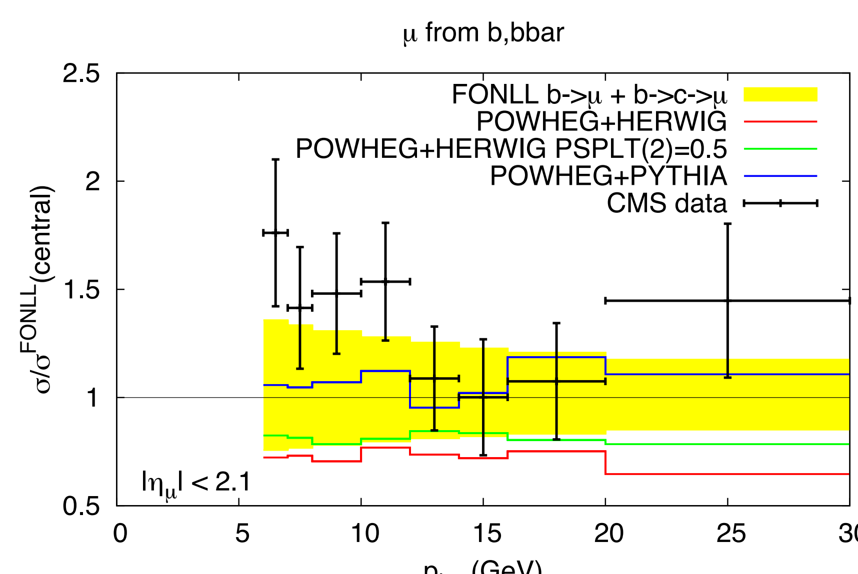


Caminada, ICHEP

- ICHEP: b’s at CMS
  - b-jets, discrepant with MC@NLO at large pT
  - b → μ, discrepant at small muon pT
- Interesting early puzzle...
  - hot off the press

Cacciari, Nason





Top

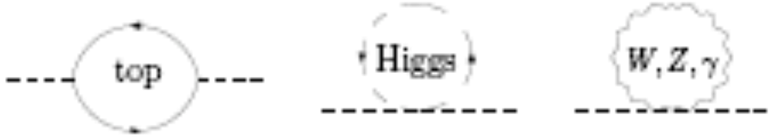
- Cross section at 7 TeV: 160 pb
  - at end of 7 TeV run, double Tevatron sample
    - ✓ Both for pair and single top
    - ✓ Tevatron now: 3000 b-tagged tops / expt
- Primary mission: check the Tevatron
  - very valuable
    - ✓ as such (new energy, pp)
    - ✓ training for 14 TeV run (exp't and theory!)

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

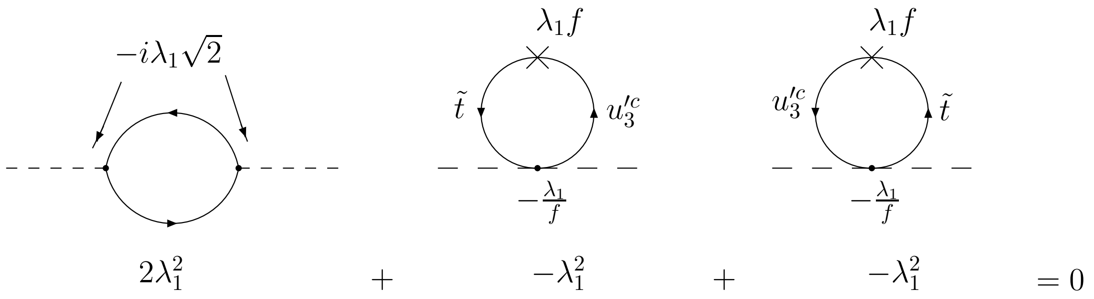
Top and Little Higgs

Arkani-Hamed, Cohen, Georgi



Little Higgs models: Higgs is a pseudo-Goldstone boson, therefore light

- Symmetries forbid one-loop Higgs mass term: solves little hierarchy problem
- ..which was caused, anyway, mostly by top loop corrections
- Little Higgs models cancel (top) quadratic divergences with similar particles of same spin (vectorlike top T e.g.)



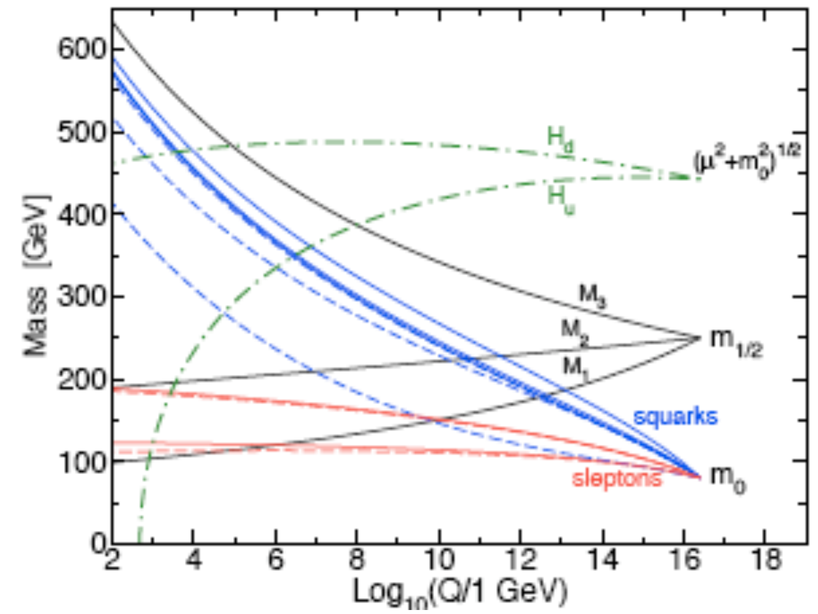
Han, Logan, Wang

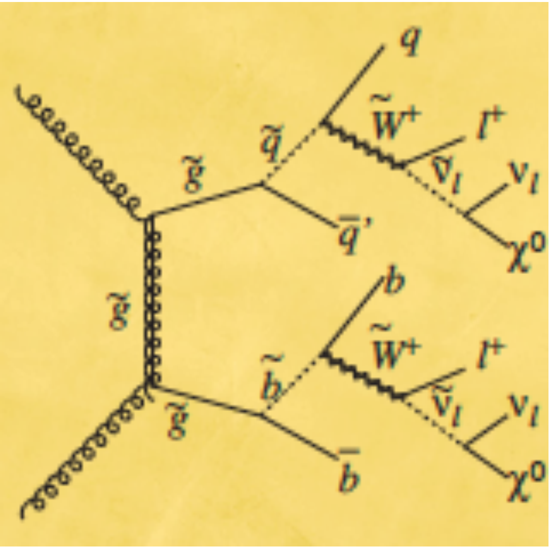
Good number of models (gauge groups, T-parity), can be unraveled with full LHC data sample

- measuring couplings in the top, T sector, and m_T (cross section 0.01-100 fb)
- test vector character of T

Top and SUSY

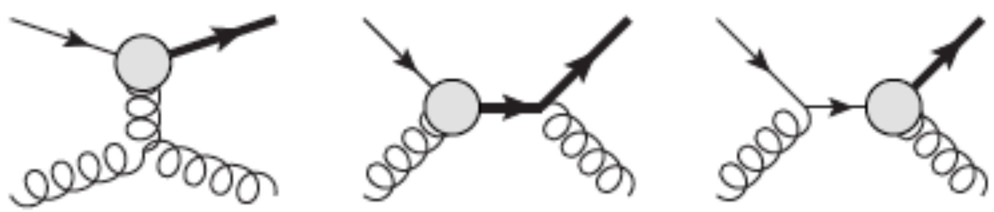
- Top keeps MSSM alive via (top, stop) corrections on lightest Higgs mass
- Radiative EW symmetry breaking
- Many LHC SUSY signals involve top, or top mimics them
- Heavy Higgses may decay to top, which can determine their CP properties
  - with (much) luck, could see signals at LHC7

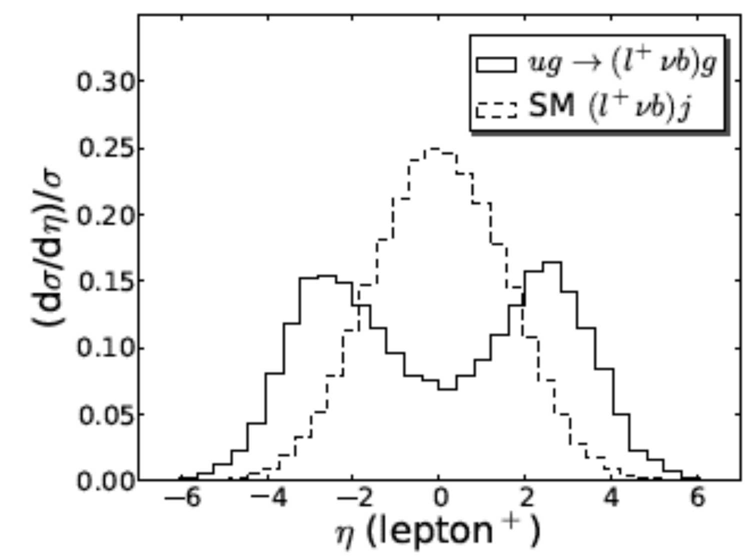




Single top in MRSSM

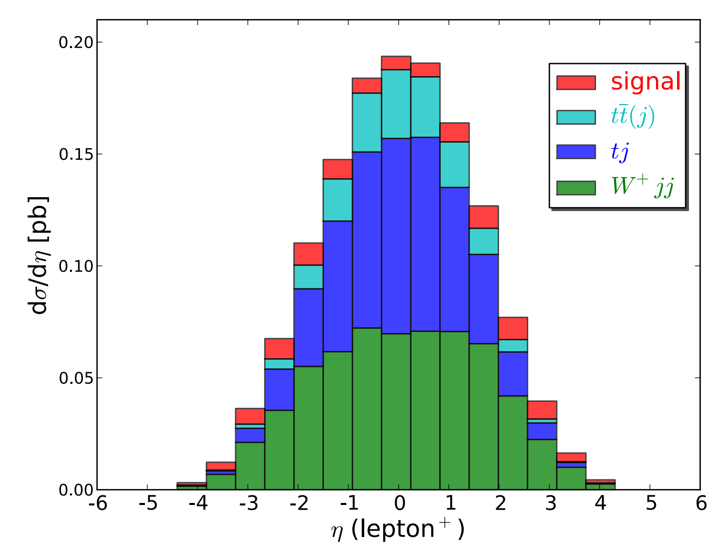
Herquet, Knegjens, EL



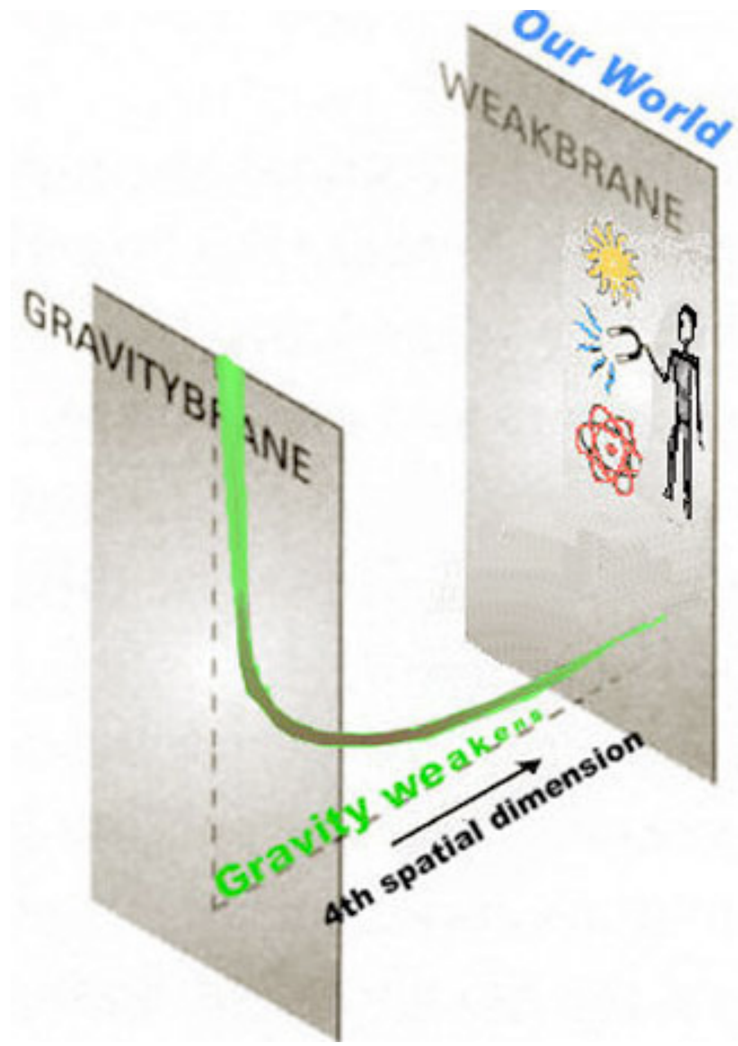


- Top could be produced very forward if FCNC u-g-t coupling is enhanced
  - by Dirac gluino (continuous R-symmetry)
    - ✓ evades K,D,B mixing expt constraints
  - can look for forward tops
  - estimate of signifance at 7 TeV/fb, about 2.2
  - also in 2 → 1 production

Plehn, Rauch, Spannowsky



Top and extra dimensions



New particles, Kaluza Klein modes

- Gluon KK modes show up as resonances in reaction gg →tt
  - with (much) luck, could be visible
- Angular distributions of top decay leptons can distinguish scenarios

4th generation

"Four statements about four generations", Holdom et al

- SM4: an often-neglected new physics model, suitable for early testing
- Limits (PDG)
  - $m_{t'} > 256$ GeV, $m_{b'} > 128$ GeV, $m_{\tau'} > 101$ GeV, $m_{\nu'_\tau} > 85$ GeV
- Viable, and useful
  - Not excluded by EW precision data (for certain patters of masses'). Also CKM matrix has room for 4th row and column
  - New source of CP violation → SM baryogenesis problem lessened
  - ...
- Amenable to direct and indirect searches
  - e.g. CMS studied b' → tW → bWW at LHC14, with 100/pb. Significant for $m_{b'}$ about 300 GeV

Parametrizing new physics

- Often done using arbitrary form factors instead of SM couplings
- Effective field theory brings order to this

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

  - symmetry
  - many form factors, but only few operators for top physics
  - radiative corrections, off-shell tops
  - example:

Willenbrock at TOP2010

- **General form of *Wtb* vertex:**

$$\boxed{\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} \cancel{V_{tb}} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}}$$

Effective field theory $V_{tb} + C_{\phi q} \frac{v^2}{\Lambda^2}$ $\sqrt{2} C_{tW} \frac{v^2}{\Lambda^2}$

contribute only at $\mathcal{O}\left(\frac{m_b v}{\Lambda^2}\right), \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$

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
  - σ ≅ 7.6 pb
  - V-A coupling to W-bosons fairly well-established
- ...
- Much to measure at LHC
  - many studies done for 10 TeV/100 pb
  - for 7 TeV, need typically more than twice the luminosity

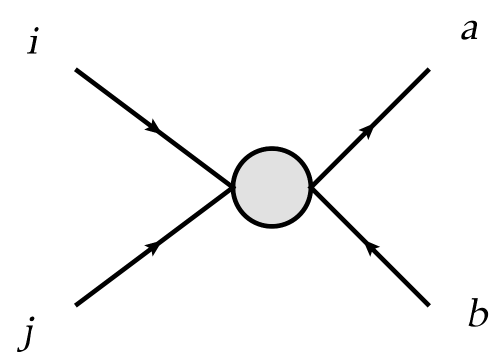
Top cross section

- First property to measure
  - 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

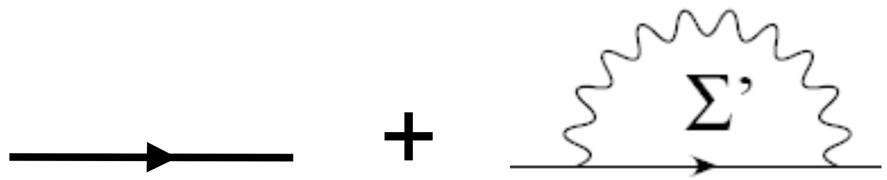
Top cross section

- More to learn from top cross section
  - extraction of top mass (pole and msbar)
  - gluon PDF
  - important here to think about the luminosity monitor
    - ✓ CDF already normalized to Drell-Yan (uncertainty down from 8.6% to 7%)
      - $\sigma_{tt} = 7.70 \pm 0.52$ pb

Top 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
- LHC: accuracy of 1 GeV possible (like Tevatron).
  - Claim ILC: 100 MeV accuracy, but for what mass?



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

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

Quark-antiquark potential

Energy of tt pair (for Schrodinger eq)

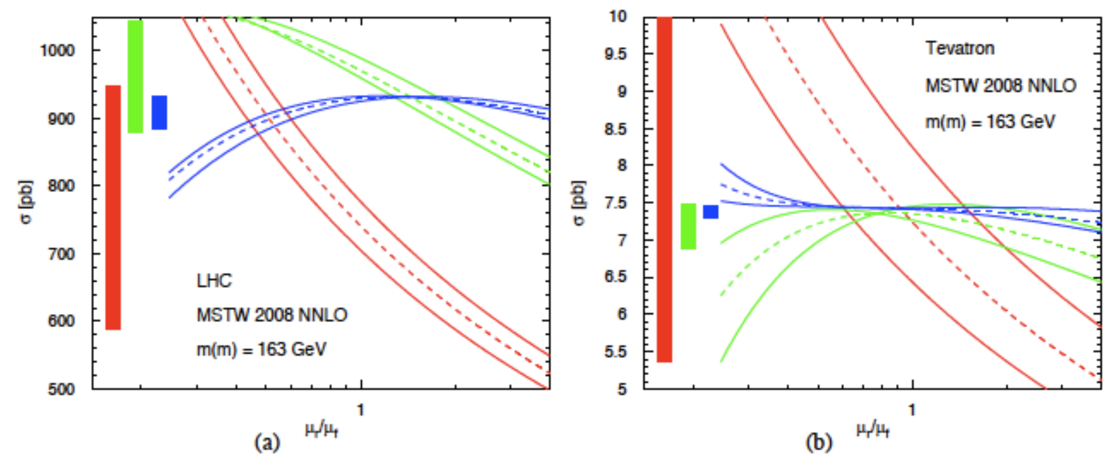
$$E_{\text{static}} = \quad 2m^0 - 2\Sigma(m,m) + V(r)$$
$$= 2m^{\text{PS}}(R) + \left[V(r) - \int_{q<R} \frac{d^3 q}{(2\pi)^3} V(\vec{q}^{\,2}) \right]$$

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

Beneke

Top mass

Moch, Langenfeld, Uwer



- Other definitions exist
- not trivial to relate measurements to Lagrangian
- In e+e- can one can infer the mass from
  - threshold scan of tt cross section
  - event shapes
  - "right" mass definition depends on observable

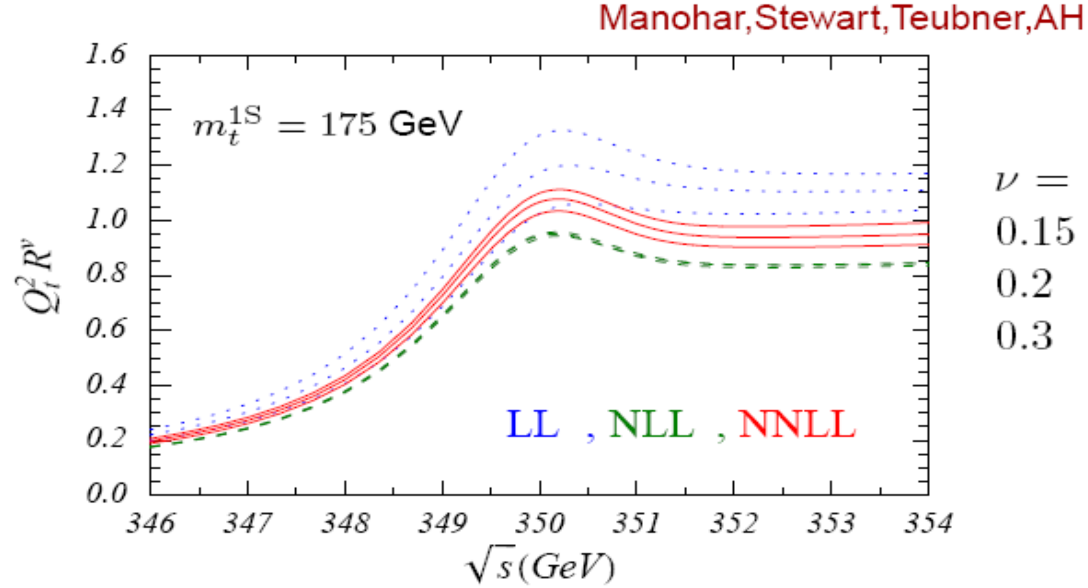
$$m = m(\mu)\Big(1 + \alpha_s(\mu)d^1 + \alpha_s^2(\mu)d^2 + \ldots\Big)$$

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

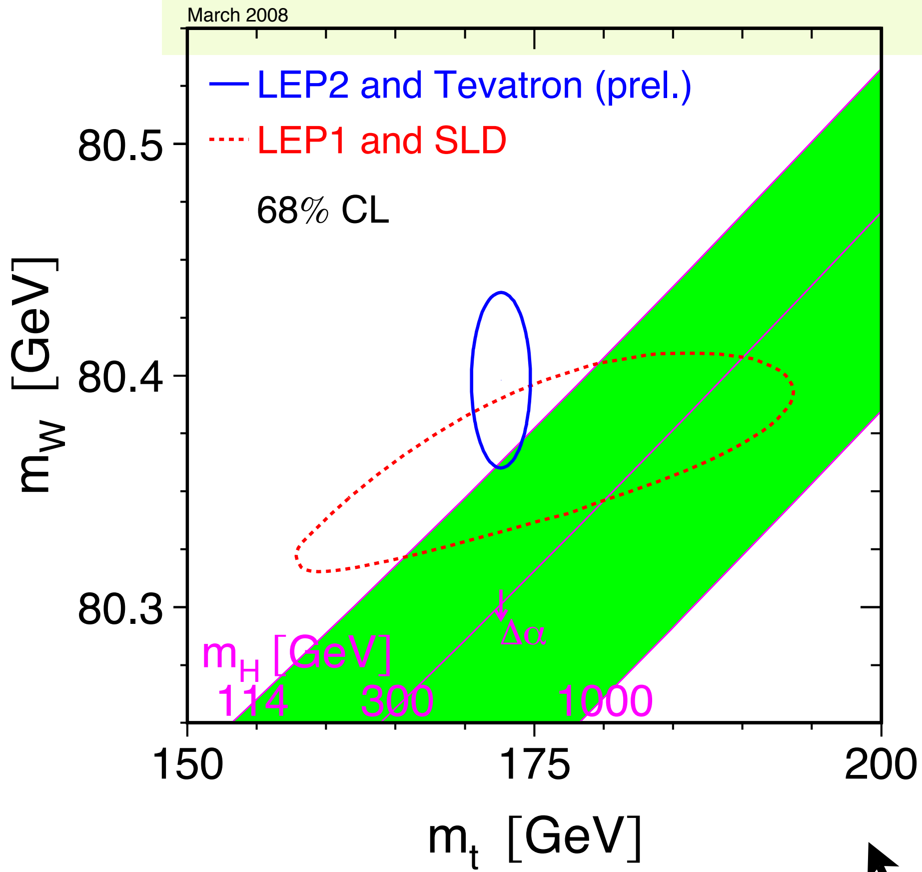
- What do hadron colliders infer when reconstructing top?
  - Pole mass?
  - MC mass?

Hoang, Stewart

Manohar,Stewart,Teubner,AH



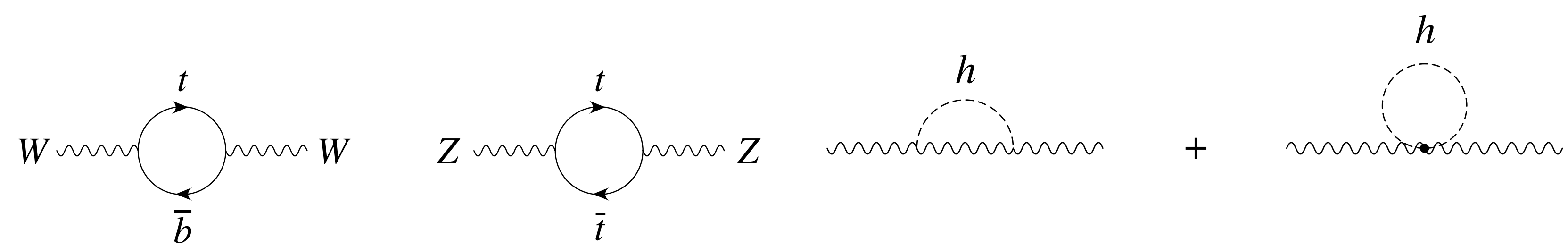
Top mass



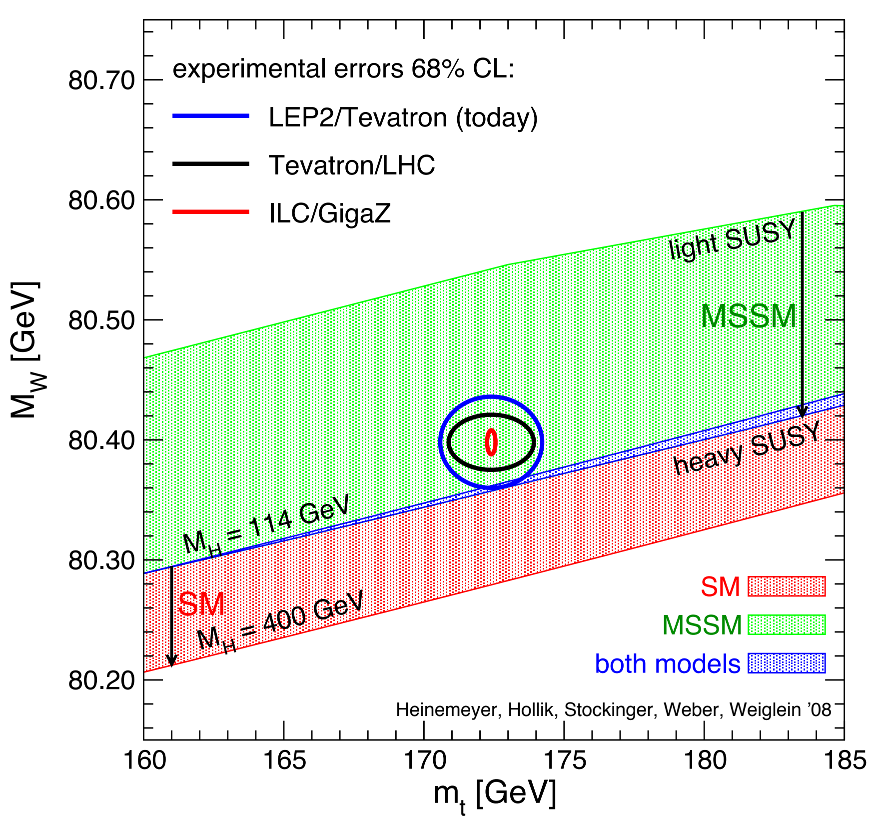
now: 173.3 ± 1.1 GeV (Tevatron)

<1% !!

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



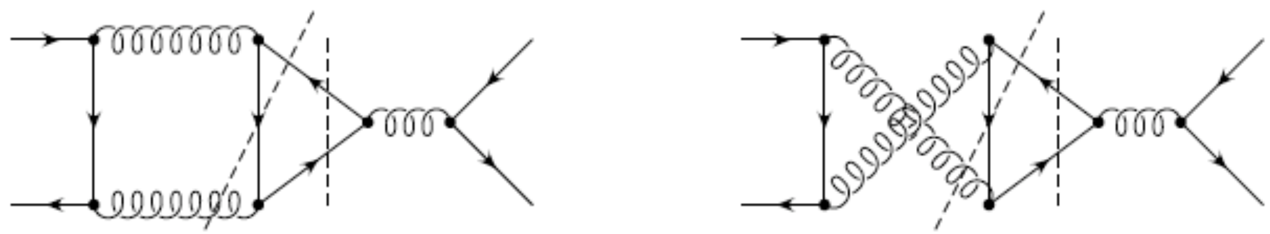
Heinemeyer, Weiglein



- 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!

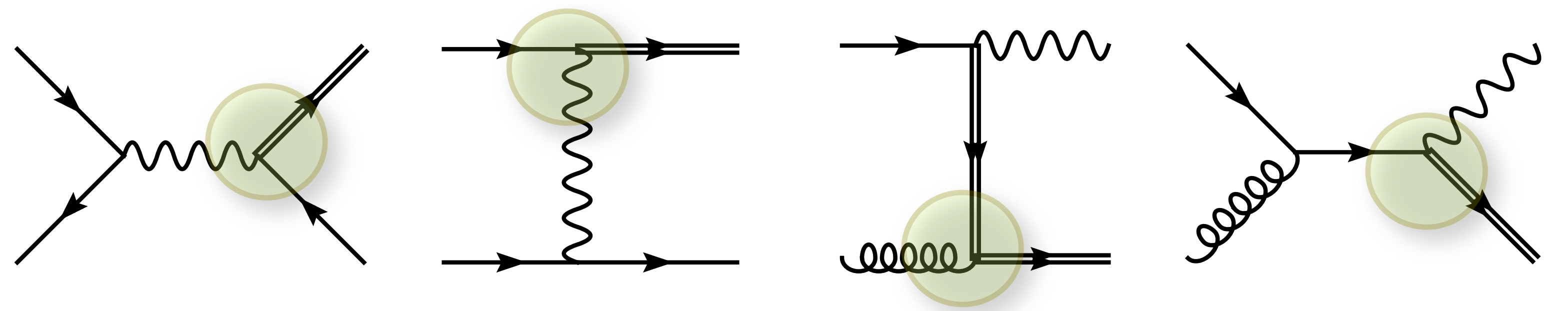
ICHEP 2010:

CDF: 15 ± 5 ± 2.4 % [5.3 fb^{-1}]

D0: 8 ± 4 ± 1 % [4.3 fb^{-1}]

QCD: 1%

Single top production



(1) (2) (3)

s-channel: timelike W

4 pb @ LHC7

t-channel: spacelike W

62 pb @ LHC7

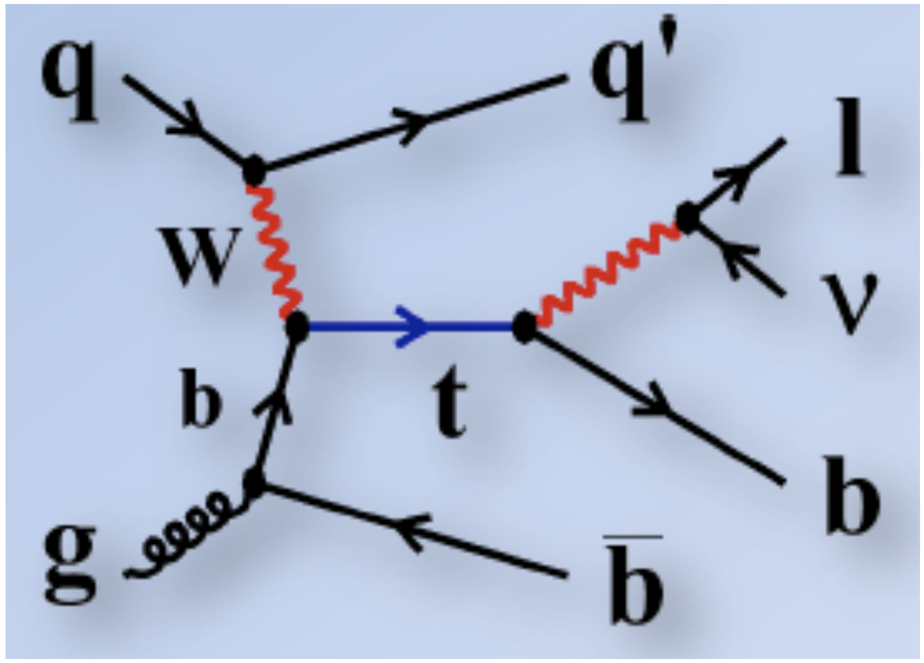
Wt channel: real W

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

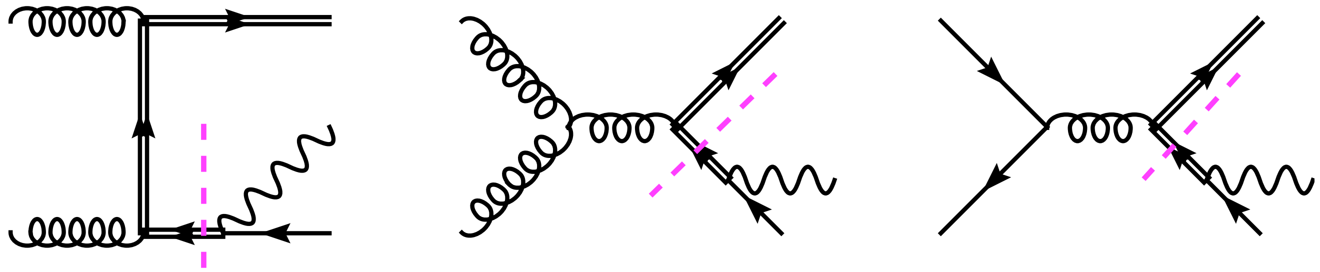
Single top at LHC

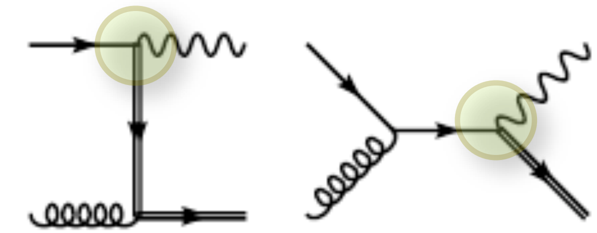
- For 1/pb
  - s-channel not likely to be isolated
  - Wt channel not likely in 1/fb
  - t-channel dominant, should be possible
    - ✓ sensitive to FCNC's
    - ✓ measure V_{tb}
    - ✓ b- PDF
- S/B better than at Tevatron
  - ATLAS, CMS are forming strategies
    - ✓ for LHC10 for 200/pb uncertainties on cross section 40%
  - Won't be easy to see for LHC7 for 1/fb



Single top in Wt mode meets tt...

Frixione, EL, Motylinski, Webber, White





+ non-resonant diagrams

Serious ***interference*** with pair production (15 times bigger)

- What can one do in event generation?
- Generic for NLO with heavy unstable particles
- Can one actually *define* this process?

Can we define Wt as a process?

We also include p_T veto. Two approaches

- Constructed a gauge invariant, local counterterm. Diagram subtraction (DS)
- Also make version with diagrams removed (DR) (not gauge invariant)
- DS - DR is measure of interference

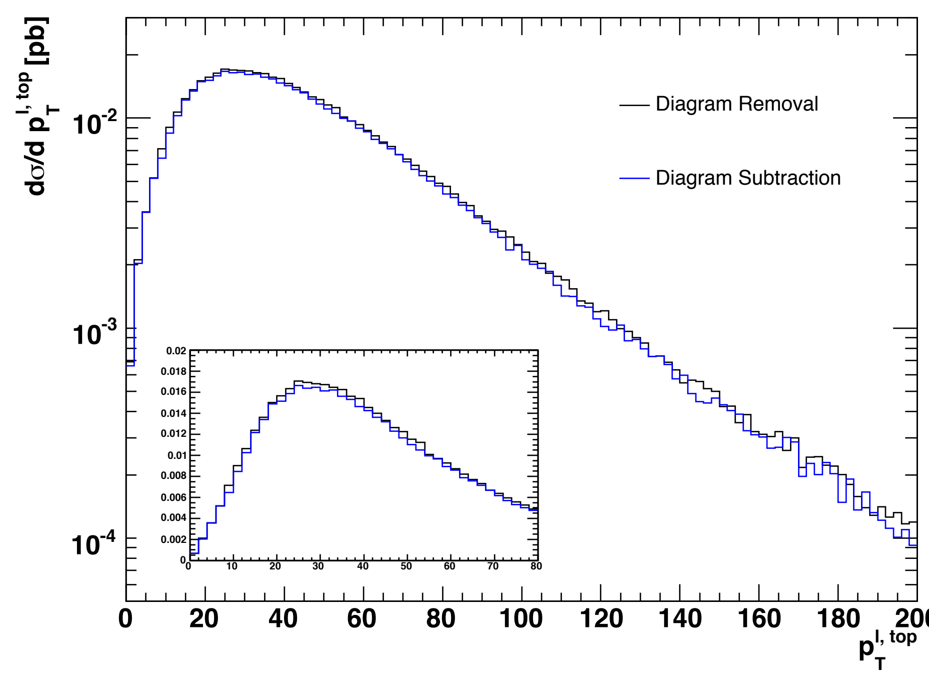
Momentum reshufling

$$\tilde{\mathcal{D}}_{gg} = \frac{BW(M_{\bar{b}W})}{BW(M_t)}\,|A^{t\bar{t}}_{gg}|^2_{\mathrm{reshuffled}}$$

$$d\sigma^{(2)} + \sum_{\alpha\beta}\int \frac{dx_1 dx_2}{2x_1 x_2 S}\mathcal{L}_{\alpha\beta}\left(\hat{\mathcal{S}}_{\alpha\beta} + \mathcal{I}_{\alpha\beta} + \mathcal{D}_{\alpha\beta} - \widetilde{\mathcal{D}}_{\alpha\beta}\right)d\phi_3$$

Compare

- Run both codes to check interference
- Mostly, interference effects quite small
- Next question: can one isolate Wt?



Can/should we isolate Wt?

White, Frixione, EL, Maltoni

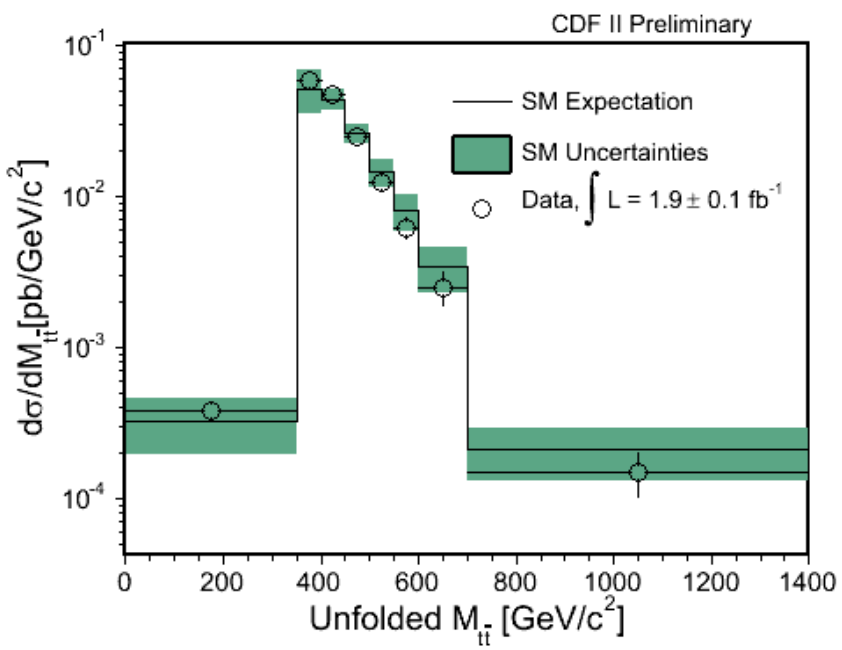
- Answer subject to cuts
  - ✓ Cuts to isolate Wt
  - ✓ Cuts to isolate to suppress Wt and tt as background to H->WW
- Separation allows important NLO corrections for tt and for Wt

e_b	r_{lj}	$\sigma_{Wt}^{DR}/\text{pb}$	$\sigma_{Wt}^{DS}/\text{pb}$	$\sigma_{t\bar{t}}/\text{pb}$
1.0	10^4	$1.206^{+0.039}_{-0.017}$	$1.189^{+0.021}_{-0.010}$	$5.61^{+0.74}_{-0.54}$
0.6	30	$0.717^{+0.020}_{-0.014}$	$0.696^{+0.020}_{-0.005}$	$4.29^{+0.45}_{-0.46}$
0.6	200	$0.748^{+0.014}_{-0.011}$	$0.726^{+0.014}_{-0.007}$	$4.36^{+0.56}_{-0.42}$
0.4	300	$0.505^{+0.026}_{-0.009}$	$0.494^{+0.008}_{-0.008}$	$3.31^{+0.40}_{-0.37}$
0.4	2000	$0.512^{+0.011}_{-0.010}$	$0.503^{+0.001}_{-0.007}$	$3.35^{+0.37}_{-0.38}$

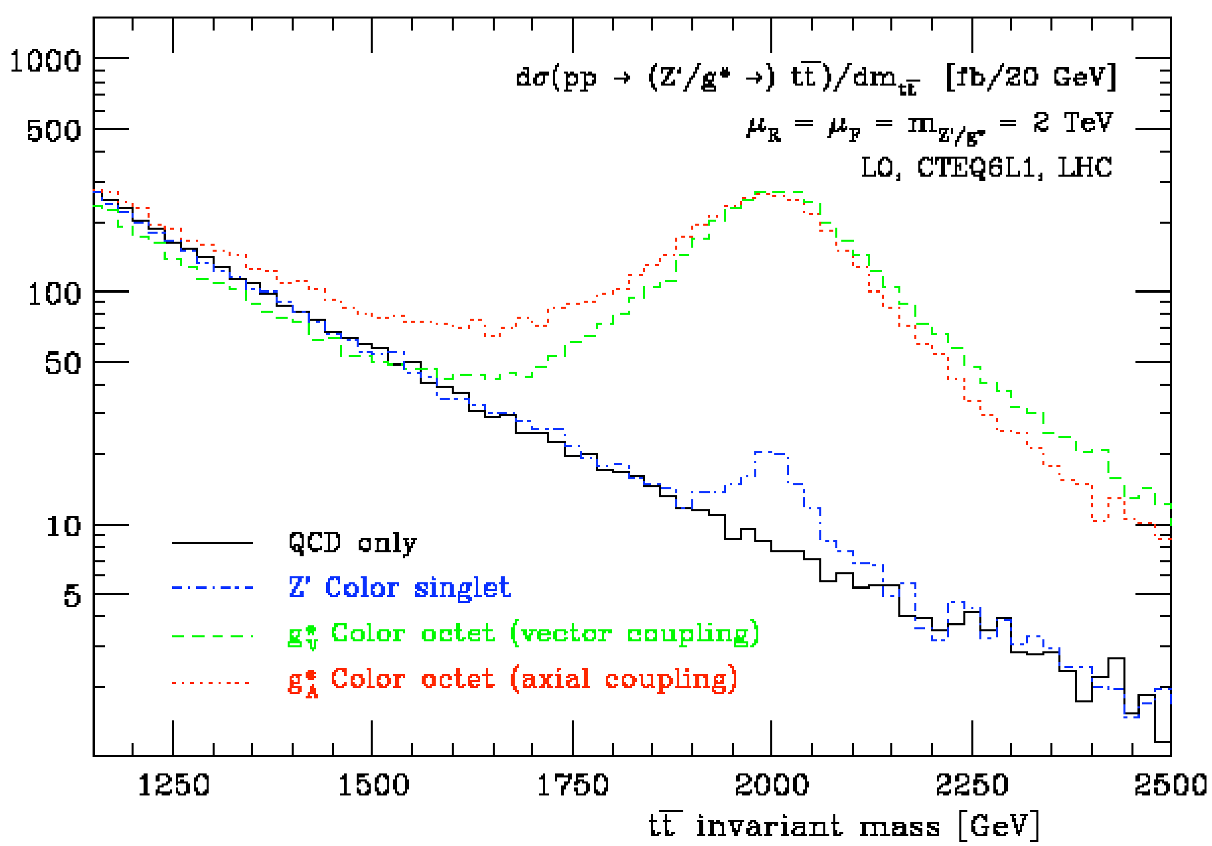
Process	σ_{NLO}/fb
$H \to WW$	81.8 ± 0.4
$t\bar{t}$	12.25 ± 0.3
Wt (DR)	6.91 ± 0.06
Wt (DS)	6.89 ± 0.07

Resonances and m_{tt}

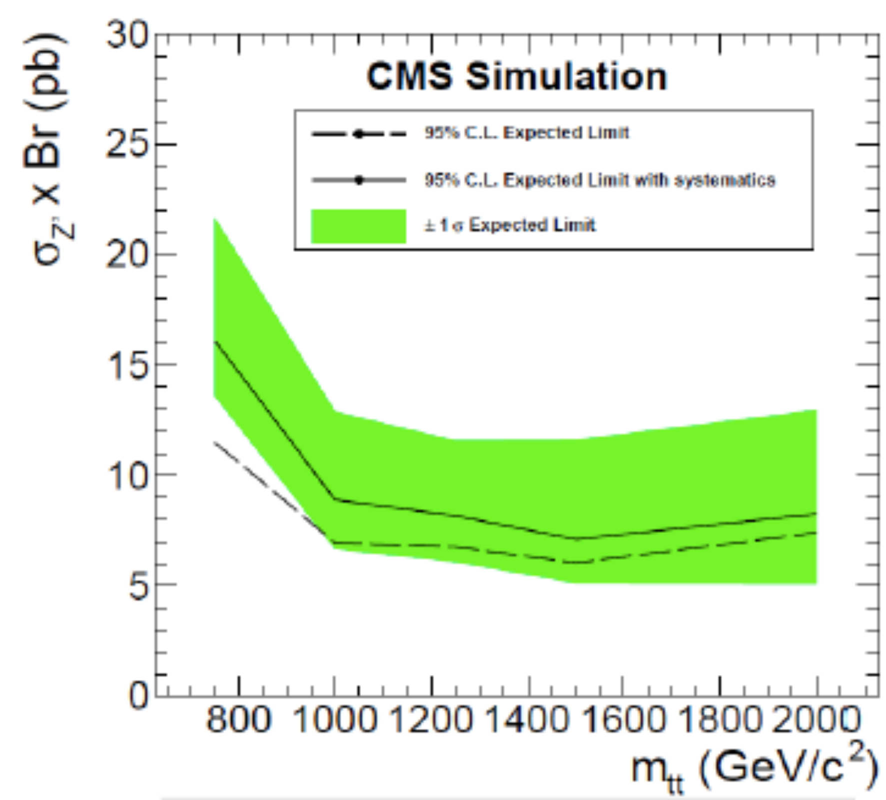
Frederix, Maltoni



- Sensitive to many SM extensions decaying to top pairs
  - Z', Heavy Higgs, KK, ...
- Bottom-up approach, don't assume full model
- used Madgraph
- Study of (pseudo) scalar, vector, spin-2 resonances. Gives masses, widths, parity, spin. Interference matters, peak-dip

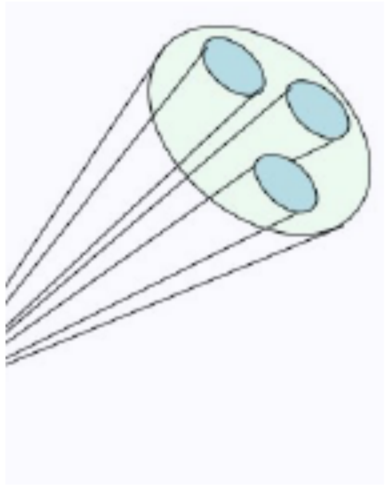


CMS for LHC10 / 100pb sensitive to masses > 800 GeV



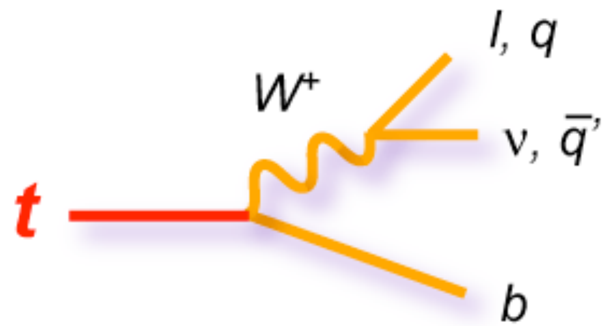
Boosted tops

Thaler, Wang
Kaplan, Rehermann, Schwartz, Tweedie
Almeida, Lee, Perez, Sung, Virzi



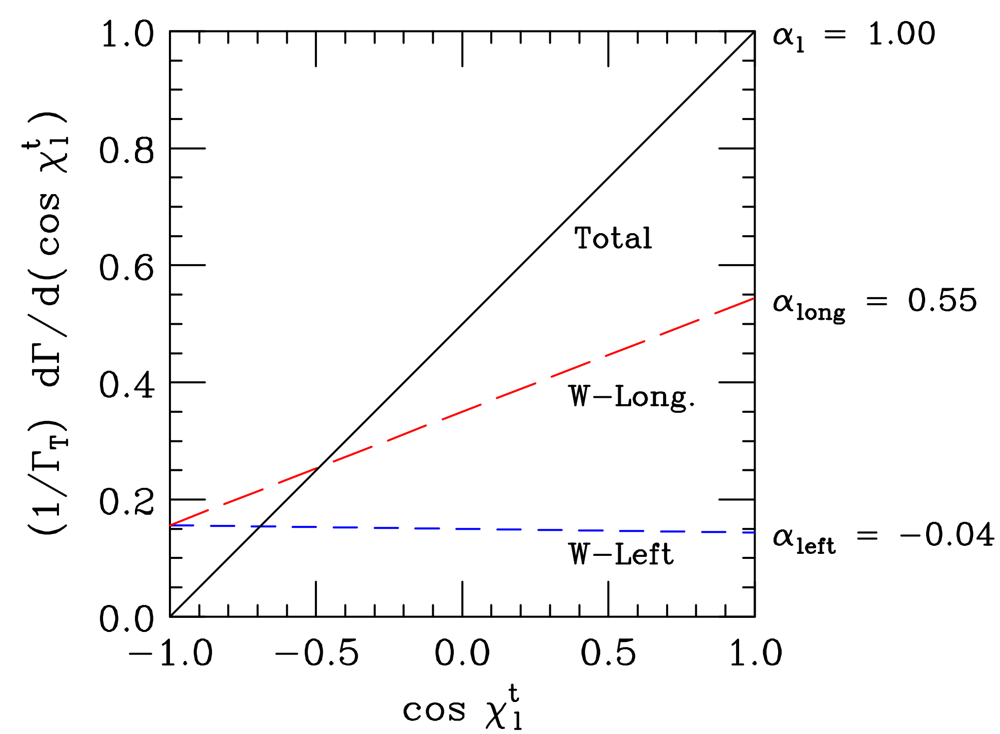
- Identify high p_T tops as fat "top-jets" using substructure
  - possibly sensitive to heavy resonance decays
  - very efficiently rejection of (dijet) backgrounds
- First measurements from CDF
  - $p_T > 400$ GeV,
  - cuts σ by 100
- ATLAS/CMS can do this
  - energy higher
  - granularity ok, can distinguish substructure
- Generic probe for many new physics types, well worth pursuing
  - resonances, heavy Higgs, colorons, Z'
  - stop, t' etc

Top decay: spin



$$\frac{d \ln \Gamma_f}{d \cos \chi_f} = \frac{1}{2}(1 + \alpha_f \cos \chi_f)$$

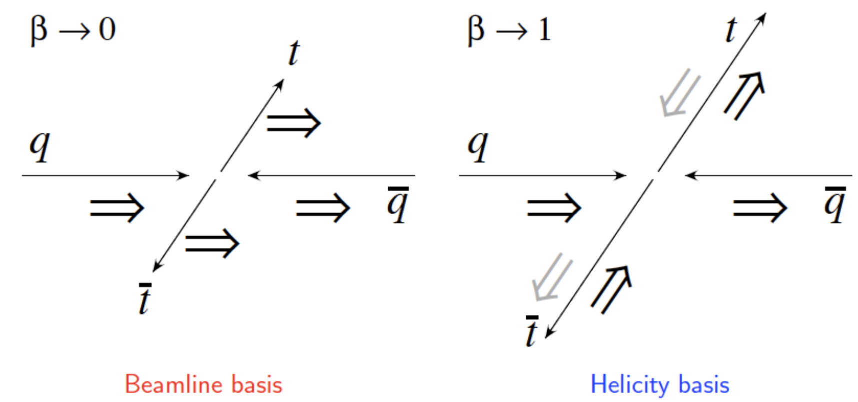
- Top self-analizes its spin: 100% correlation ($\alpha_f = 1$) of t-spin with l^+-direction
- Worthy of verification (e.g. charged Higgs decay would lower α_f)
- Powerful probe of spin quantum numbers of top, and its producer



Spin correlations in pair production

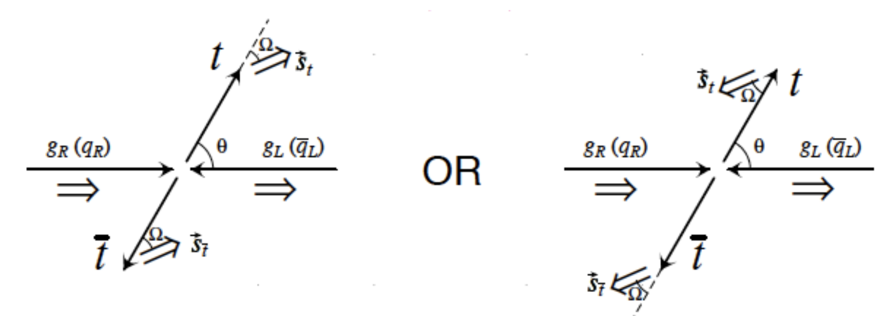
Mahlon, Parke
Bernreuther, Brandenburg,
Si, Uwer

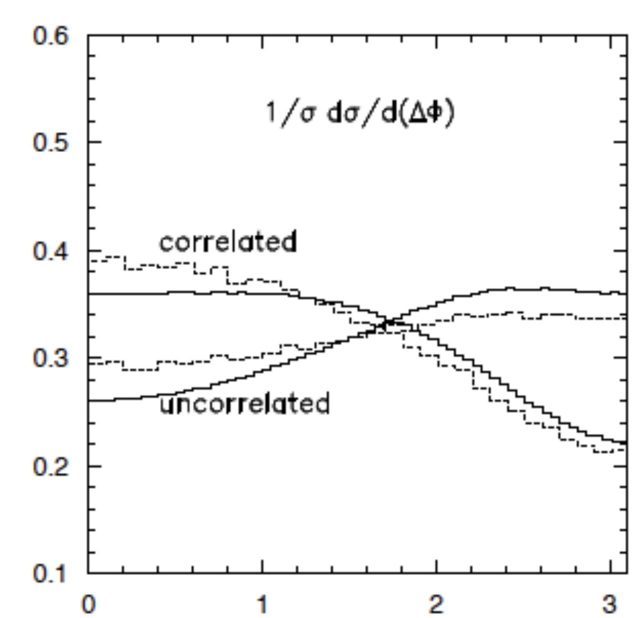
qq channel, through s-channel gluon

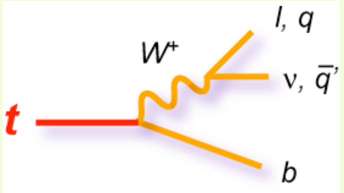


- Spins configuration of initial state and tt final state are correlated
  - brought out best by optimal choice of spin axes.
    - ✓ Tevatron, near threshold: beamline basis. At high pT helicity: helicity basis
    - ✓ LHC, constrain to phase space by tt invariant mass cut
  - LHC correlations for ΔΦ(ll) seem robust, including NLO in QCD and EW
- Tevatron and LHC complimentary here

gg channel, helicities depend on phase space



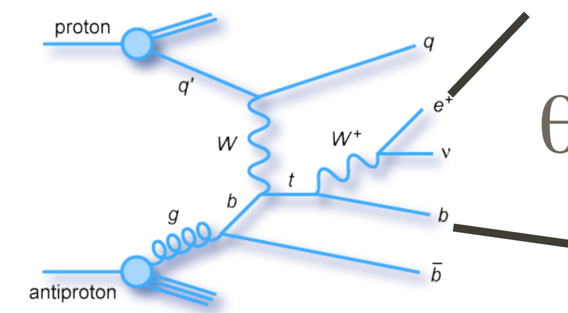


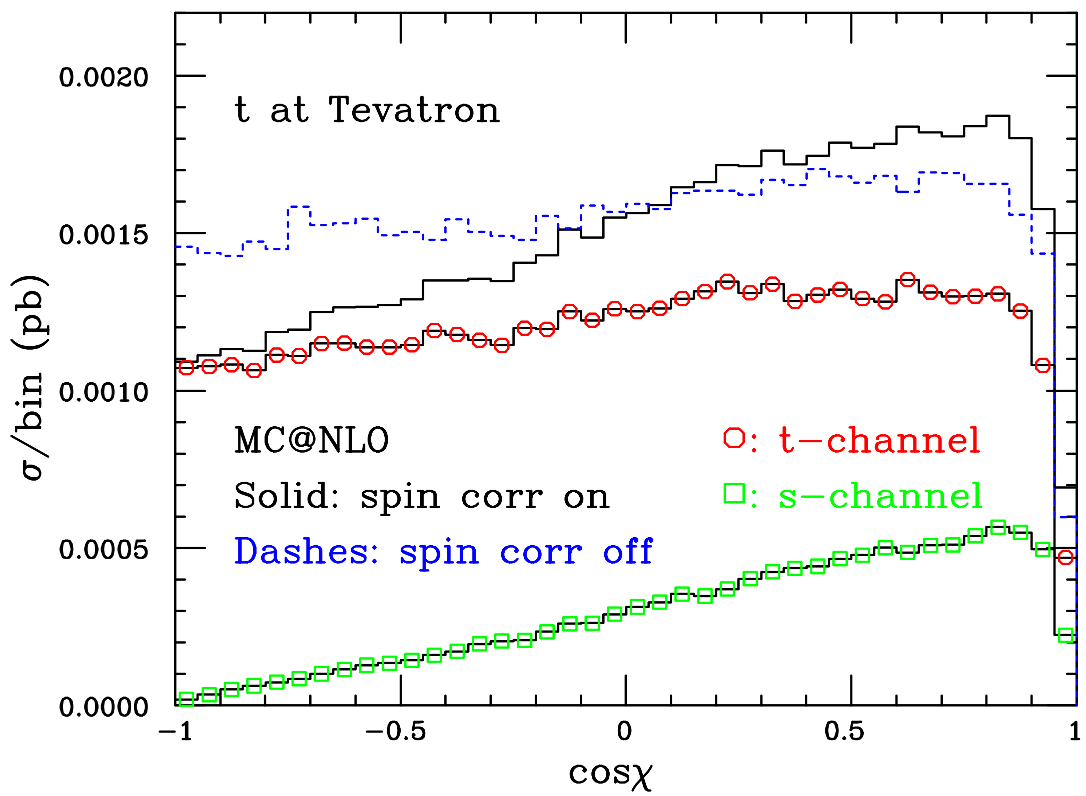


Spin correlations for single top (MC@NLO)

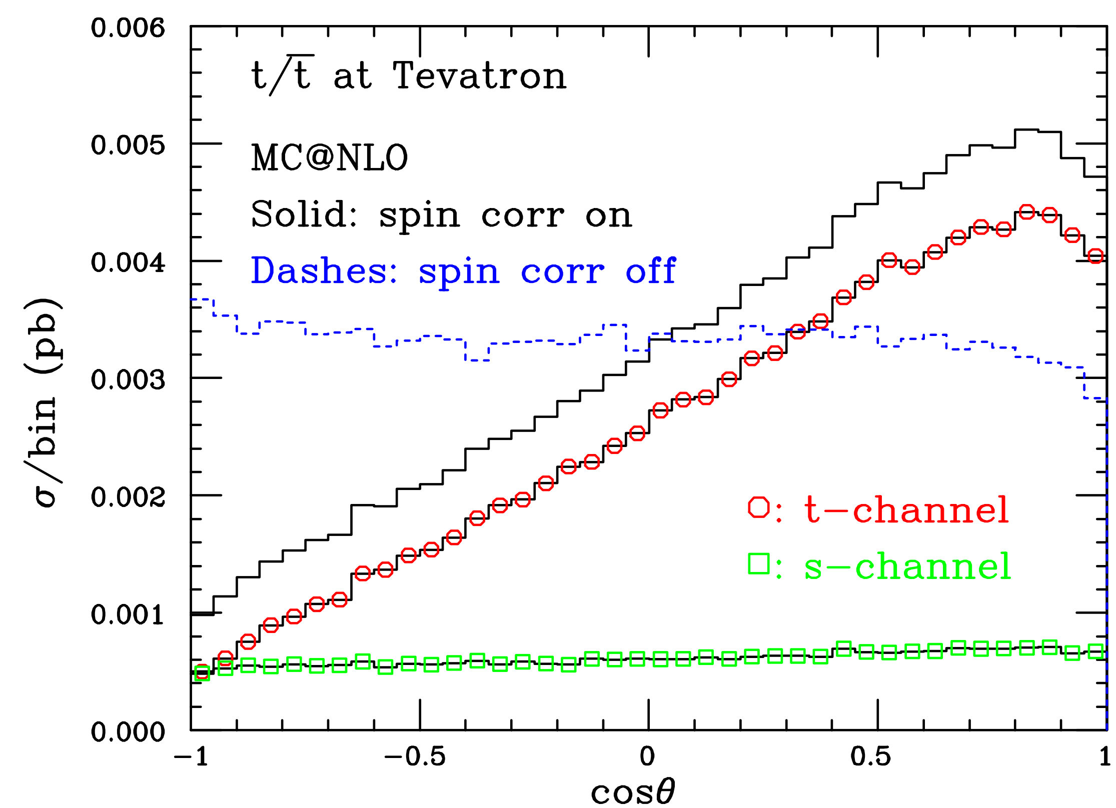
Frixione, EL, Motylinski, Webber

- Top is produced polarized by EW interaction
- Angle of lepton with appropriate axis different per channel
- Use (initially) to discriminate from background





Beam direction



Hardest, non-b jet

Robust correlation, even in event generation. Remains strong at LHC7, LHC14 Motylinski

Conclusions

Conclusions

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

Conclusions

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  - top
    - ✓ check the Tevatron, use gg initial state
    - ✓ with more data, higher energy: resonances, start precise theory comparisons to tell new from known
- Form good habits in using vast array of new theory tools
  - let's keep talking