



TOP 2011

Top Quark: Theory Status

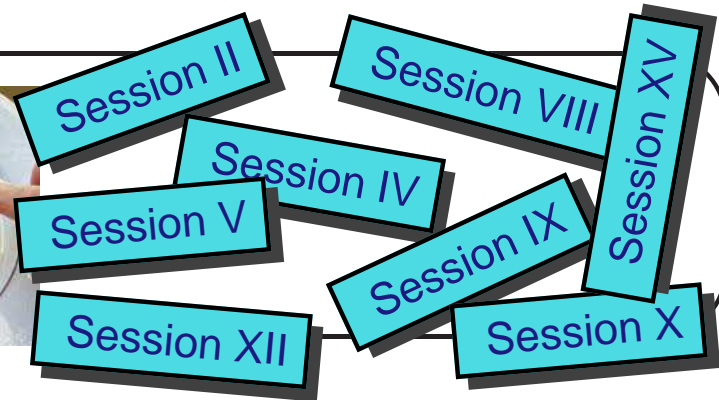
Adrian Signer

IPPP, Durham University

25–30 SEP 2011, SANT FELIU DE GUIXOLS, SPAIN

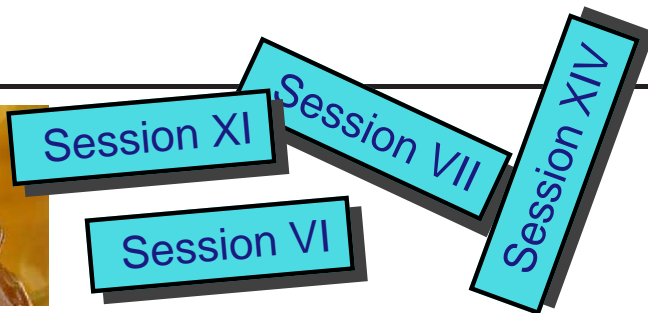
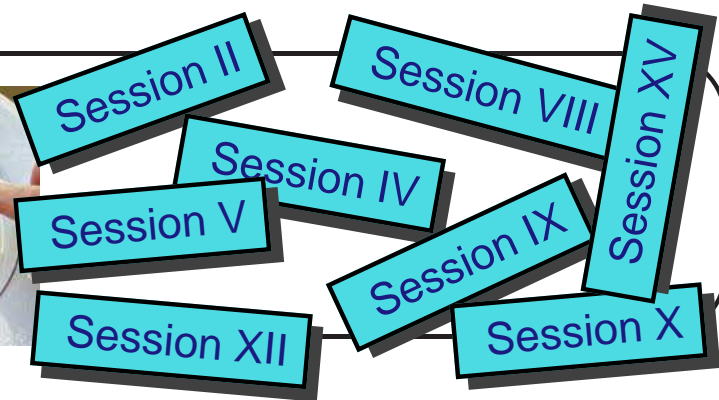


bread and butter
cross sections
mass determination
spin correlations





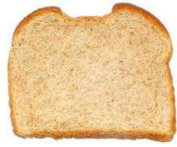
bread and butter
cross sections
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spin correlations



pure honey
exploring BSM



bread only
backgrounds



Session III

bread and butter
cross sections
mass determination
spin correlations



Session II

Session VIII

Session XV

Session IV

Session V

Session IX

Session XII

Session X



Session XI

Session VII

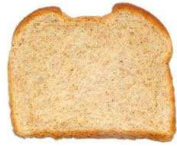
Session XIV

Session VI

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bread, butter and a bit of honey
forward-backward asymmetry

Session XIII



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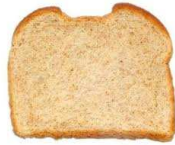
Session VI

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Session III

$\Gamma_t > \Lambda_{\text{QCD}} \implies$ top is “free quark”
 $y_t \simeq 1$, as it should \implies the top is
the white sheep in a herd of black sheep

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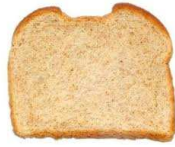
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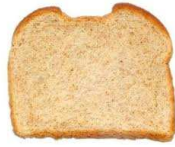
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pure honey
exploring BSM

top plays special
role in BSM



bread only
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prime example
of what this is all
about

bread, butter and a bit of honey
forward-backward asymmetry

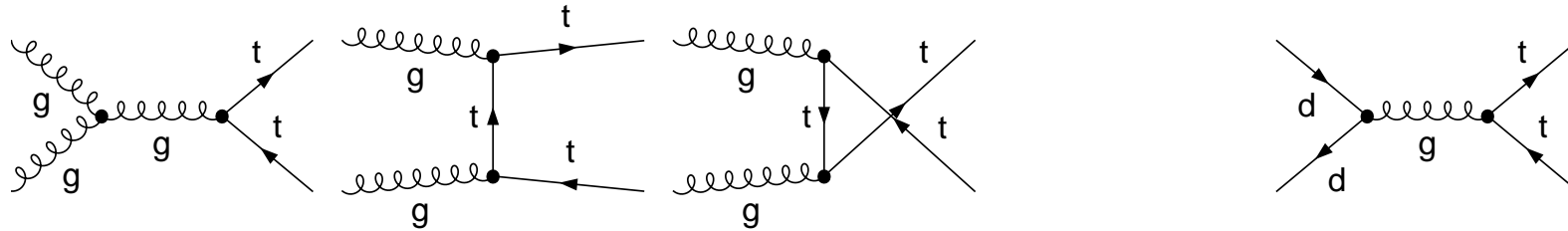
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pure honey
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top plays special
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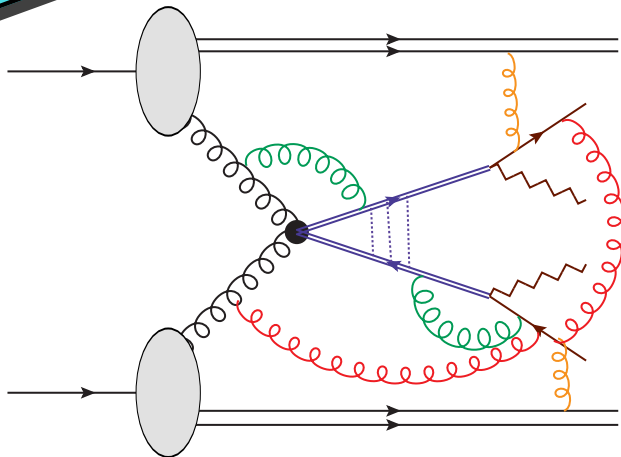
approximate (!)
expected / measured
SM cross sections in pb

Session IV

Session II

Session V

	Tevatron	7 TeV LHC	14 TeV LHC
$t\bar{t}$	7	160	900
$q\bar{q}$	~ 90%	~ 20%	~ 10%
gg	~ 10%	~ 80%	~ 90%



- decay, including spin correlations and NLO corrections
- bound-state effects
- non-factorizable corrections, off-shell effects
- (non-perturbative) colour connection to proton remnant



- fully exclusive known at \sim one-loop

electroweak corrections known [Bernreuther et.al., Kuhn et.al.]

spin correlations included [Bernreuther et.al., Melnikov et.al.]

non-factorizable corrections computed [Denner et.al., Bevilacqua et.al.]

included in MC@NLO and POWHEG [Frixione, Nason, Webber]

two-loop corrections on their way . . .

Session II

- inclusive cross section(s) known at \sim two-loop

two-loop nearly known [Czakon et.al, Moch et.al, . . .]

bound-state effects computed [Hagiwara et.al., Kiyo et.al.]

non-factorizable corrections computed [Beenakker et.al.]

resummation of logs under control [Ahrens et.al, Beneke et.al . . .]

Session XV

- further processes known at one-loop:

$t\bar{t}H$ [Beenakker et.al] and $t\bar{t}j$ [Dittmaier et.al.] ; \Rightarrow MC@NLO and POWHEG

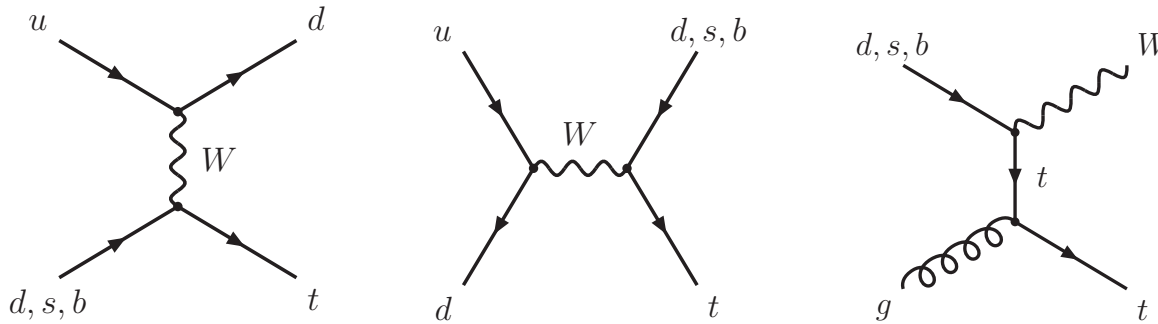
$t\bar{t}bb$ [Bredenstein et.al; Bevilacqua et.al.] and $t\bar{t}jj$ [Bevilacqua et.al.]

“background” processes $V + jets$

Session III

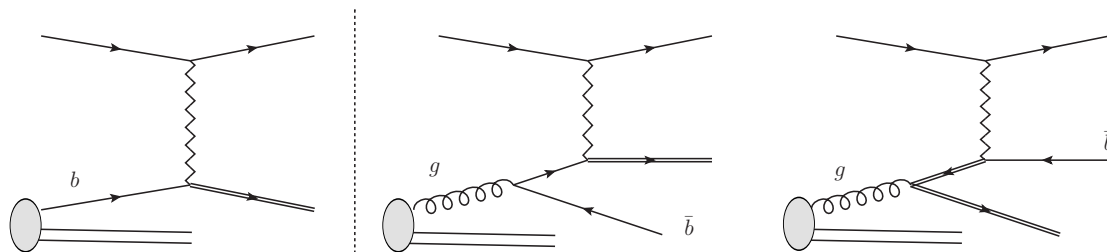


Session IX



approximate (!)
expected / measured
SM cross sections in pb

	Tevatron	7 TeV LHC	14 TeV LHC
$t(\bar{t})$ "t"-ch	1.2	40 (20)	150 (100)
$t(\bar{t})$ "s"-ch	0.55	2.5 (1.4)	7 (4)
tW^-	0.15	8	45



LO 5 Flavour

LO 4 Flavour

$b \in p \implies$ 5-flavour scheme

$b \notin p \implies$ 4-flavour scheme

[Campbell et.al]

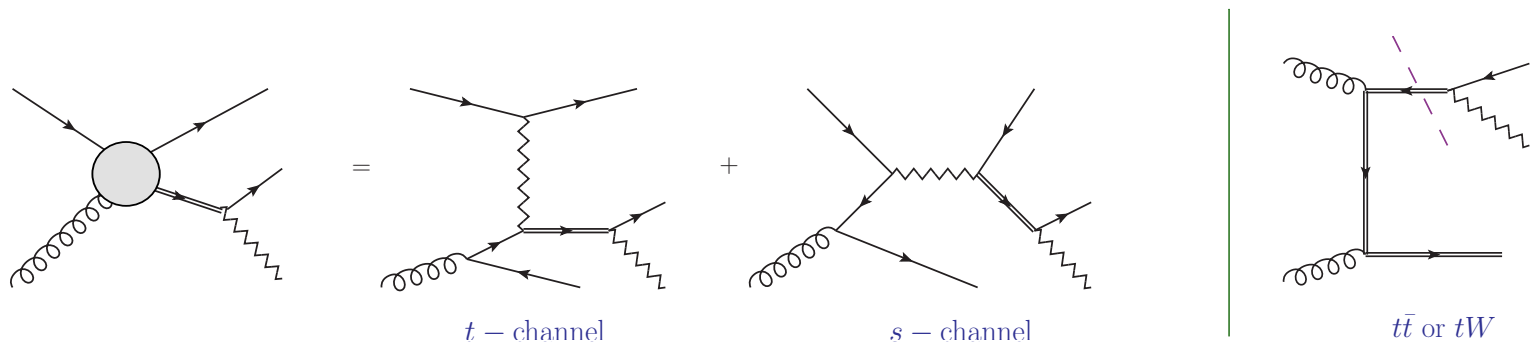


- NLO QCD corrections, production and hadronic decay for t -, s -channel and Wt known [Harris et.al; Campbell et.al; Cao et.al ...]
- all channels included in MC@NLO and POWHEG [Frixione, Laenen, Motylinski, Alioli, Nason, Re, Webber, White]
- EW corrections known [Beccaria et.al; Macorini et.al]
- non-factorizable corrections known [Falgari et.al.]
- resummation of inclusive cross section [Kidonakis, Wang et.al.]
- **Note:** issues with definition of cross section:

s and t channel mix (beyond LO)

→ more appropriate to talk about (tJ) , (tb) and (tW) cross sections

disentangling Wt vs $t\bar{t}$ non-trivial [Frixione et.al.]



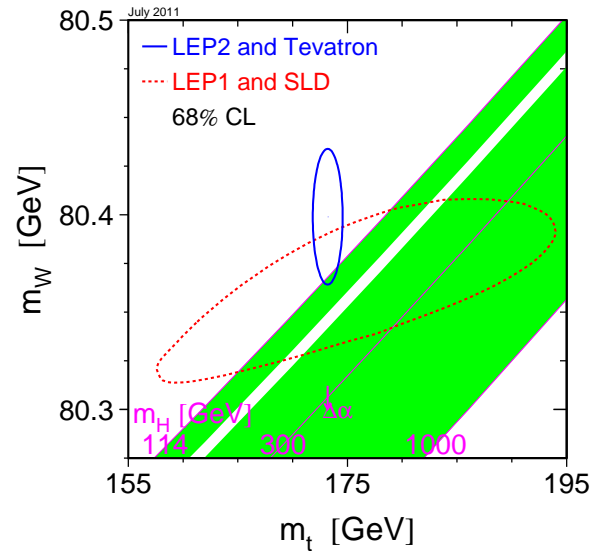


enhancements from special kinematic regions \implies order by order in α_s not sufficient

- in threshold region $\sqrt{1 - 4m_t^2/s} \equiv \beta \rightarrow 0$
 - “bound state” effects $(\alpha_s/\beta)^n$, can be resummed [Fadin, Khoze; Hagiwara et.al, Kiyo et.al, Beneke et.al]
 - resummation of soft logs $\alpha_s^n \log^{2n} \beta$, initially to NLL now NNLL and partly NNNLL [Bonciani, Catani, Mangano, Mitov, Nason, Czakon et.al., Beneke et.al., Ahrens et.al., Kidonakis,]
- note: cross section not necessarily dominated by small β , can use different resummation parameter (done at NNLL)
 - standard: $\beta \rightarrow 0 \implies \alpha_s^n \ln^m \beta$ with $m < 2n$
 - invariant mass: $1 - z \equiv 1 - M^2/\hat{s} \rightarrow 0 \implies \alpha_s^n \frac{\ln^m(1-z)}{(1-z)}$ with $m < 2n - 1$
 - SPI: $s_4 \equiv p_X^2 - m_t^2 \rightarrow 0 \implies \alpha_s^n \frac{\ln^m(s_4/m_t)}{s_4}$ with $m < 2n - 1$
- recover total cross section by integration
 - \implies treatment of formally subleading terms are numerically relevant
- approximate “NNLO” cross section [Aliev et.al. (Hathor), Ahrens et.al, Beneke et.al, Kidonakis . . .]



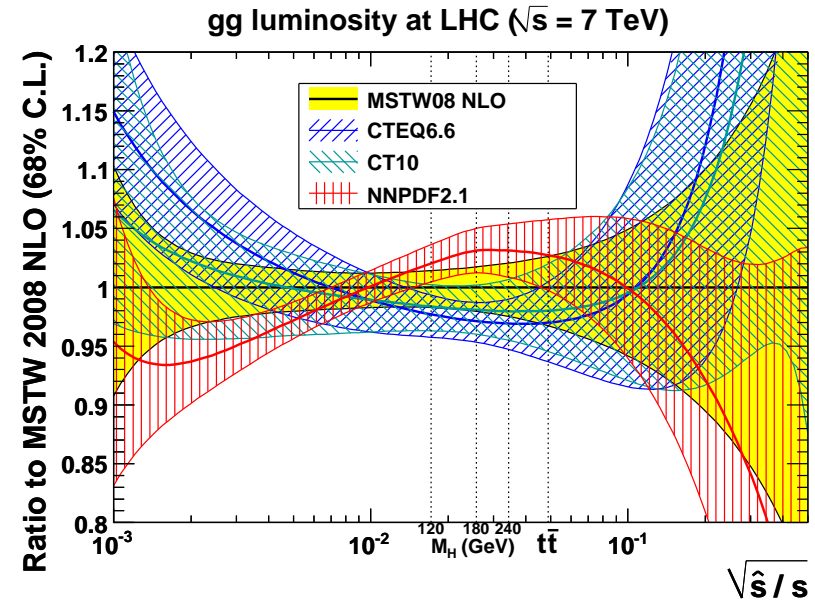
ew precision



LEP EWWG

m_t , but also V_{tb}

pdf



G. Watt (March 2011)

plot from G.Watt (HepForge)

$\sigma_{t\bar{t}}$, but also single top $\sigma_t/\sigma_{\bar{t}}$

other measurements: y_t , Γ_t , A_{FB} ... mainly as test of SM (or establishing BSM)

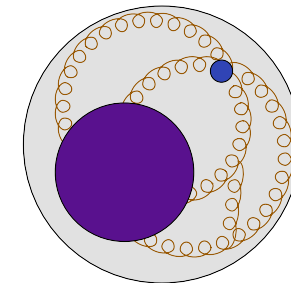


Problem 1: conceptual problem with pole mass; $\mathcal{O}(\Lambda_{\text{QCD}})$

The pole mass has an intrinsic uncertainty of order Λ_{QCD} in perturbation theory (infrared sensitivity, renormalon ambiguity)

consider (fictitious) meson:

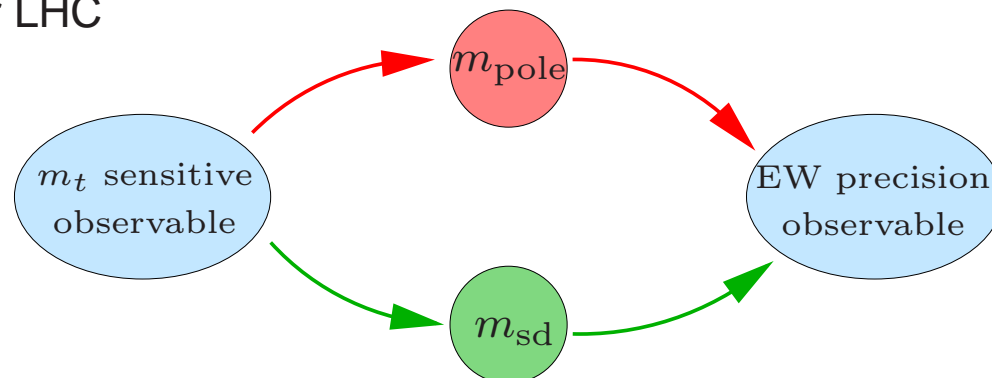
$$\underbrace{M}_{\text{well def. pole mass}} = \underbrace{m_Q}_{\text{pert. ambiguity}} + m_q + \underbrace{V(q^2)}_{\text{pert. ambiguity}}$$



Session X

There is a principal limitation of the usefulness of the pole mass: $\delta m_t > \Lambda_{\text{QCD}}$

- can be solved in principle by using other (short-distance) mass definitions
- highly relevant for m_t determinations at linear collider [Beneke et.al, Hoang et.al]
- probably (??) not relevant for LHC





Session X

Problem 2: how to relate m_{exp} to pole mass; $\mathcal{O}(\Gamma_t)$

- m_X determination by requiring $O^{\text{th}}(m_X) \stackrel{!}{=} O^{\text{exp}}$, in principle for any scheme X and any (mass sensitive and well measurable) observable O
- in practice limitation through lack of higher-order terms in O^{th}
- m_t measurements through kinematics of decay products are basically tree-level determinations
- pick a scheme where higher-order corrections are small, i.e. pole scheme \implies m_t extracted using decay products is “something like” the pole mass
- the issue is **not** (and never was) whether this mass m_{exp} is the pole mass or $\overline{\text{MS}}$ mass, but what the precise relation between m_{exp} and m_{pole} is
- care has to be taken when interpreting $m_{\text{exp}} \stackrel{??}{=} m_{\text{pole}}$
 however $m_{\text{exp}} \stackrel{!!}{=} m_{\text{pole}} + \mathcal{O}(\Gamma_t)$ is fine. (**Note:** non-factorizable corrections have been computed and seem to be small [Denner et.al., Bevilacqua et.al.]
- alternative ways to measure m_t , using different O , where higher-order corrections are known, e.g. total cross section [Langenfeld et.al] or other choices [Melnikov et.al.]
- the ultimate m_t determination with $\delta m_t \sim 100 \text{ MeV}$ from threshold scan at ILC.



Session VI

parametrizing ignorance [Aguilar-Saavedra et.al, Willenbrock et.al. ...]

- general approach, finite number of possibilities, respect generic constraints
- general vertices (e.g. Wtb) with anomalous couplings

$$-\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}$$

- effective dimension 6 (and higher) operators e.g:

$$O_{\phi q} = i(\phi^\dagger \tau D_\mu \phi)(\bar{q} \gamma^\mu \tau q) \quad \text{or} \quad O_{tW} = (\bar{q} \sigma^{\mu\nu} \tau t \tilde{\phi}) W_{\mu\nu}$$

complete analysis possible, devise sensitive observables

- similar to anomalous triple-gauge couplings, with similar problems (form factors)

Session XI

explicit models (i.e. a very long list of possible explicit models) [... (sorry)]

- more information
- can extend to high-energy region
- can compute anomalous couplings for a given explicit model

Session XIV

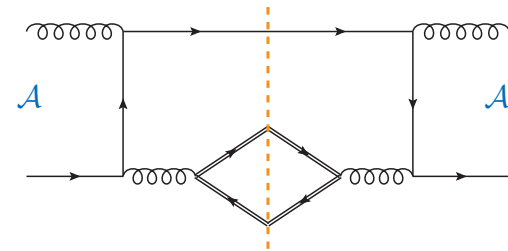
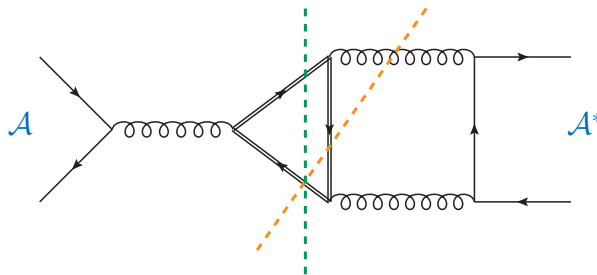
Session VII



definition: $A_{\text{FB}}^{p\bar{p}} = \frac{\sigma(y_t > 0) - \sigma(y_t < 0)}{\sigma(y_t > 0) + \sigma(y_t < 0)}$ or $A_{\text{FB}}^{t\bar{t}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$

- zero for QCD @ LO, non-zero but small for EW @ LO
- QCD @ NLO (from $q\bar{q}$ only) [Kuhn, Rodrigo]

Session XIII



$$A_{\text{FB}} = \frac{\alpha_s^3 + \mathcal{O}(\alpha_s^4)}{\alpha_s^2 + \mathcal{O}(\alpha_s^3)} = \sigma^{\text{virt}} + \sigma^{\text{real}} = +\infty - \infty \simeq \text{few\%} \quad (\text{soft singularities})$$

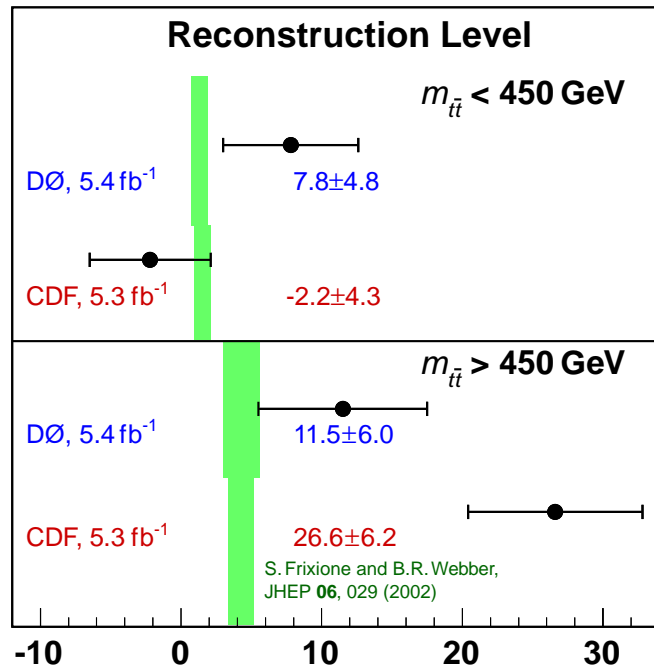
- EW @ NLO: increase $A_{\text{FB}}^{t\bar{t}}$, but not too much ($\sim 20\%$) [Hollik, Pagani]
- QCD @ NNLO: not known exactly, but from resummation small corrections expected, a SM value of $A_{\text{FB}}^{t\bar{t}} \gtrsim 0.2$ seems highly unlikely. [Almeida et.al, Ahrens et.al]
- Need BSM (tree-level) contributions to get $A_{\text{FB}}^{t\bar{t}} \gtrsim 0.2$



- 2011 Tevatron measurements

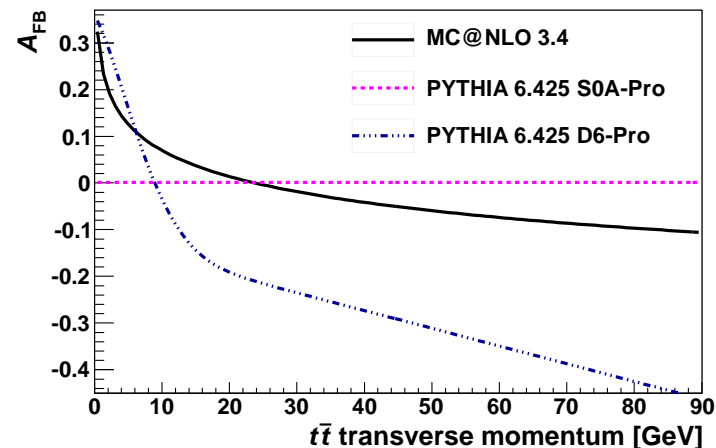
Session XIII

Forward-Backward Top Asymmetry, %



[plots from D0]

delicate dependence of A_{FB} on $p_T^{t\bar{t}}$



- there is a tension between experimental results and the theoretical SM value
- currently no convincing evidence that effect depends on $m_{t\bar{t}}$
- this could be BSM, but a more boring explanation is as likely (ok to get excited, but no reason to go insane)

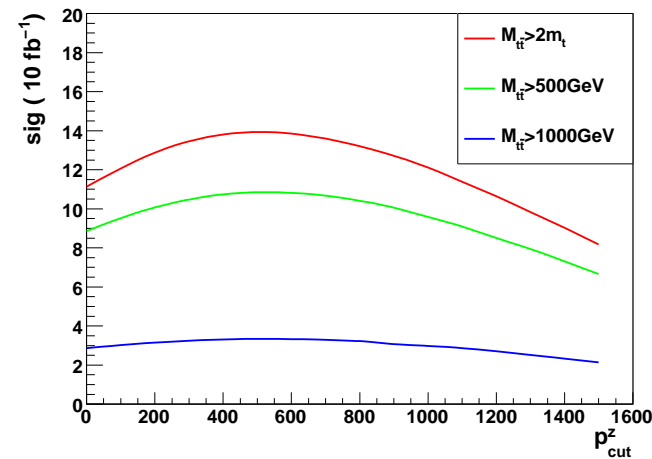
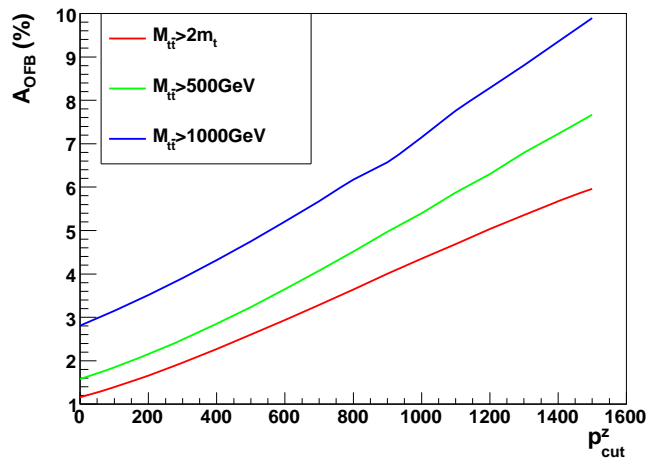


- “eliminate” large denominator, i.e. gg initial state, use $f_q(x) > f_g(x), f_{\bar{q}}(x)$ for x large.
- \bar{t} more central, t more forward
- several possibilities [Antunano et.al, Wang et.al, Hewett et.al, Aguilar-Saavedra et.al]

- central charge asym: $A = \frac{\sigma_t(|y_t| < y_{cut}) - \sigma_{\bar{t}}(|y_t| < y_{cut})}{\sigma_t(|y_t| < y_{cut}) + \sigma_{\bar{t}}(|y_t| < y_{cut})} \sim 1\%$

- one-side asym: $A = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)} \Big|_{P_{t\bar{t}} > P_{cut}, M_{t\bar{t}} > M_{cut}}$

Session XIII



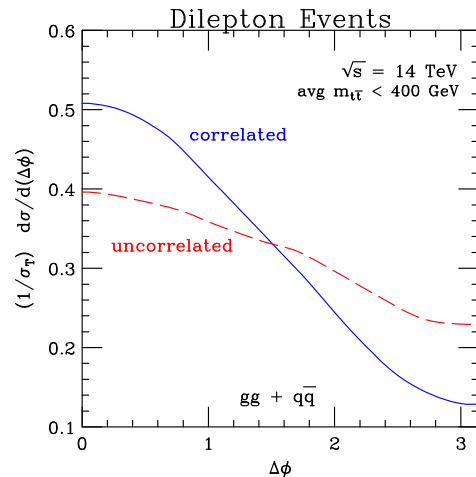
(example for 7 TeV LHC [Wang, Xiao, Zhu: arXiv:1008.2685])

- use A_{FB} in $t\bar{t}j$ and $t\bar{t}jj$ as cross-check for new-physics scenarios



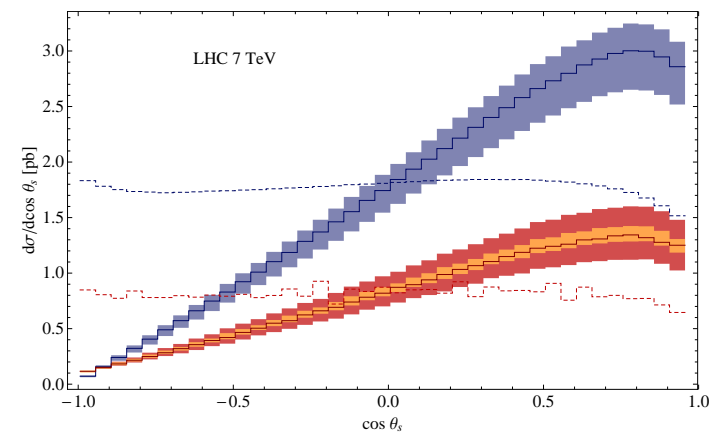
- $\Gamma_t > \Lambda_{\text{QCD}} \implies$ top quark decays before QCD blurs spin information [Mahlon, Parke; Bernreuther et.al; Motylinski; Cao et.al; Melnikov, Schulze, ...]
- detailed test of $t \rightarrow Wb \rightarrow \ell\nu b$ possible
- details depend on process (top pair production / single top), collider (Tevatron / LHC) and kinematic regime (invariant mass)
- find observable that strongly depends on spin correlation, e.g:

$t\bar{t} : \Delta\phi_{\ell\ell'}$ with $M_{t\bar{t}} < 400$ GeV



[Mahlon, Parke, arXiv:1001.3422]

single top: $\cos(\vec{p}_{\text{spec}}^*, \vec{p}_\ell^*)$



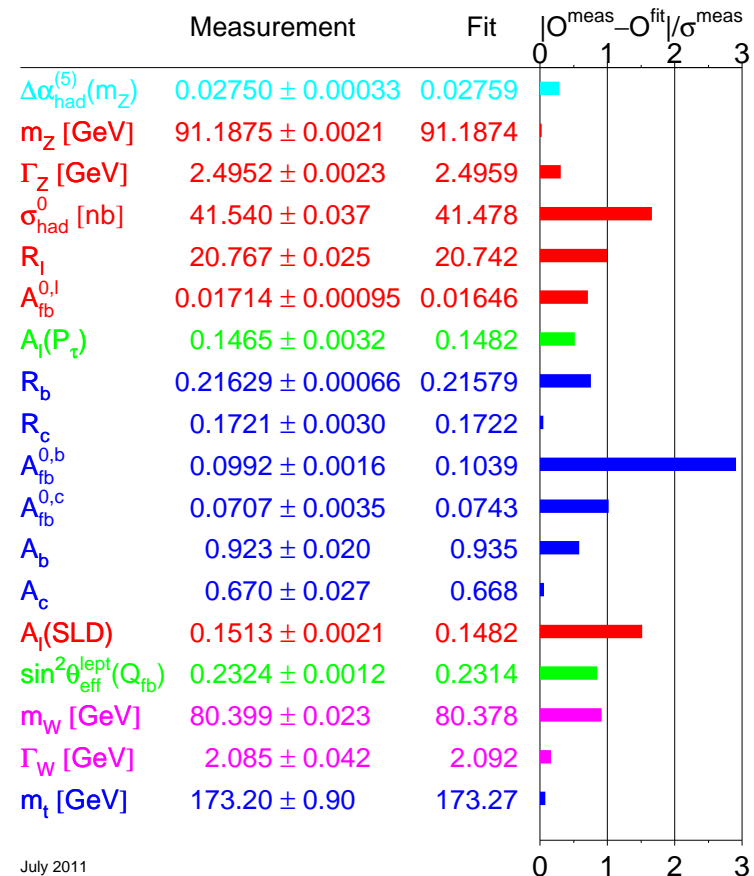
[Falgari et.al: arXiv:1102.5267]

- test against SM and BSM predictions

Session XII



- overall theory of top is in pretty good shape, with further progress on its way
- so far, most experimental results agree reasonably well with SM predictions, apart from . . .
- possible problem in A_{FB} (this somehow sounds familiar)
- **keep scrutinizing !**



July 2011

[LEP EWWG]