Phenomenology at collider experiments [Part 2: SM measurements]

Frank Krauss

IPPP Durham

RAL HEP Summer School 7.9.-18.9.2009

Outline

Know your Standard Model

Historical example: Mono-jets at $Sp\bar{p}S$

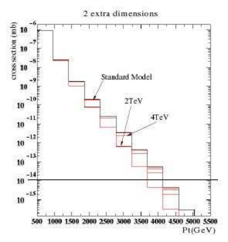
- In Phys. Lett. **B139** (1984) 115, the UA1 collaboration reported
  - 5 events with $E_{\perp,\mathrm{miss}} > 40$ GeV+a narrow jet and
  - 2 events with $E_{\perp,\mathrm{miss}} > 40$ GeV+a neutral EM cluster

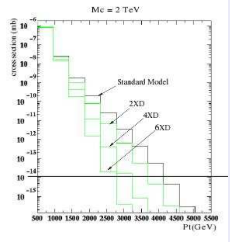
  They could "not find a Standard Model explanation" for them, compared their findings with a calculation of SUSY pair-production (J.Ellis & H.Kowalski, Nucl. Phys. **B246** (1984) 189), and they deduced a gluino mass larger than around 40 GeV.
- In Phys. Lett. **B139** (1984) 105, the UA2 collaboration describes similar events, also after 113 nb^{-1}, without indicating any interpretation as strongly as UA1.
- In Phys. Lett. **B158** (1985) 341, S.Ellis, R.Kleiss, and J.Stirling calculated the backgrounds to that process more carefully, and showed agreement with the Standard Model.

Example: PDF uncertainty or new physics

Consider the ADD model of extra dimensions (KK towers of gravitons) and its effect on the dijet cross section:

(Note: Destructive interference with SM)





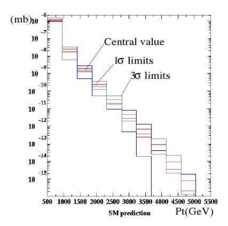
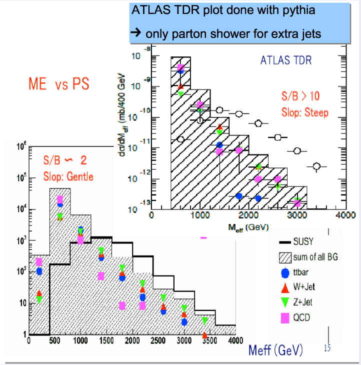
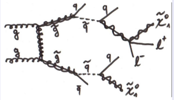


Figure from S.Ferrag, hep-ph/0407303

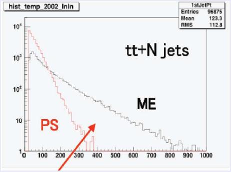
Example: Inclusive SUSY searches



Typical process



Shape of tt-events



To take home

- It is simple to "find" new physics by misunderstanding, mismeasuring, or misinterpreting "old" physics, i.e. the SM
- Therefore: Control of backgrounds paramount to discovery!!!
- Know your Standard Model and its inputs
- Don't trust just one Monte Carlo/one theorist/one calculation:
  Be sceptical!
- If possible, infer from well-understood data.
- Also: New measurements for important SM parameters (see below).

W mass measurements

Why is this important?

- The *EW* sector of the SM can be parameterized by 4 parameters. Example: α, $\sin^2\theta_W$, v, λ
- But other observables related to them: M_W, M_Z, M_H, G_F, ... This is due to the mechanism of EWSB underlying the SM.
- Example: At tree-level weak and electromagnetic coupling related by

$$G_F = \frac{\pi\alpha}{\sqrt{2}m_W^2 \sin^2\theta_W^{\rm tree}}$$

- Natural question: Is the picture consistent? This is a precision test of the SM and its underlying dynamics.
- First tests: SM passed triumphantly, seems okay even at loop-level.

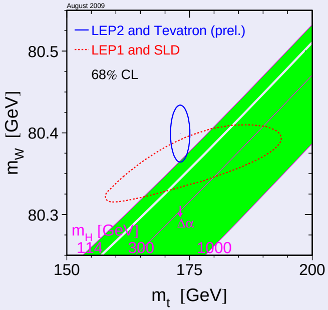
Why is this important? (cont'd)

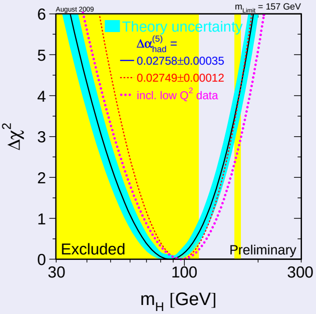
- Naively $\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$ connects masses with ew mixing angle. (Weinberg-angle, θ_W)
- Loop-corrections to it from self-energies etc..
  - Interesting correction:

$$\Delta\rho_{s.e.} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \dots\right]$$

  - Relates m_W, m_t, m_H.
- For a long time, m_t was most significant uncertainty in this relation; by now, m_W has more than caught up.

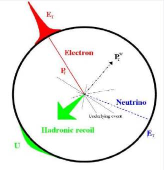
Why is this important? (cont'd)

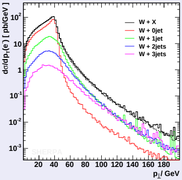




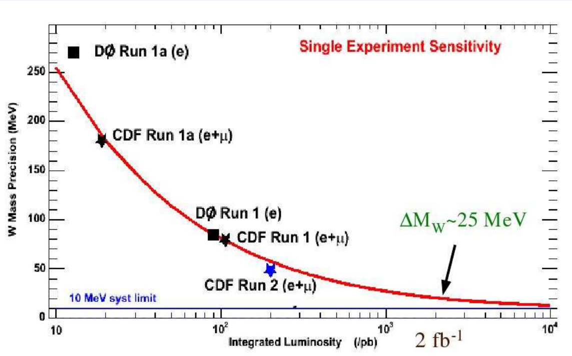
Some technical aspects of the measurement

- But: How to measure the mass?
- From LEP: Direct measurements. Hampered by comparably low stats and jet-energy uncertainties.
- Tevatron: Measurement in leptonic mode, but then the ν's escape.
- So, how to do it at a hadron collider?
- Jacobean peak in $p_\perp^\ell$
  Even better: transverse mass
  $M_\perp^{\ell\nu} = \sqrt{2p_\perp^\ell \not{E}_\perp (1 - \cos\theta_{\ell,\text{miss}})}$
  Their position relates to m_W
- QCD effects controlled by Z.

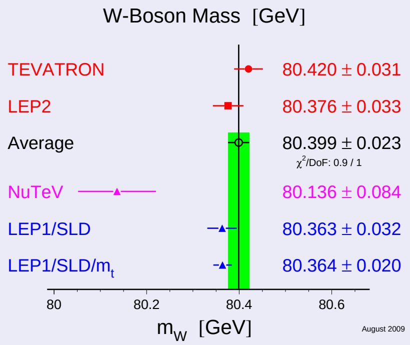




Anticipated sensitivity



Actual measurements

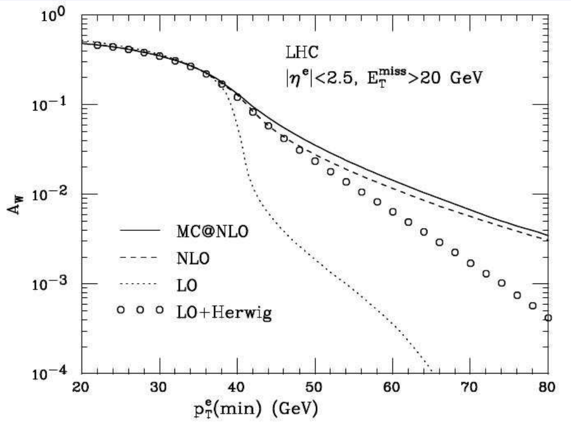


Projection to LHC

- Already now, each modern Run-2 measurement more precise than any individual LEP-2 measurement.

  (Single most precise measurement by D0, 2009, 1fb^{-1}: $\Delta M_W = 43$ MeV)
- Accuracy goal for LHC: 15 MeV.
- With current theoretical technology (MC@NLO etc.) this is a close call.
- Probably need high-precision tools, including QED, weak corrections mixed with QCD.

LHC: First serious look into acceptances



W width measurements

Why is this important?

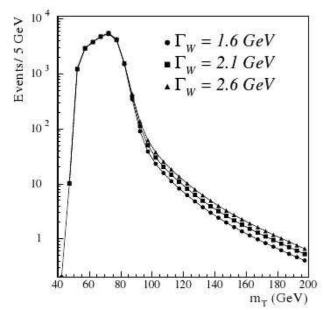
- Naively, in the SM (massless fermions):
$$\Gamma_{W\to\ell\ell'} = m_W \frac{\alpha N_c}{12\sin^2\theta_W}|V_{\rm CKM}|^2, \qquad N_c = 1,3 \text{ for leptons/quarks}$$
- Loop corrections: Another precision test of the SM.
- Are there other decay channels?

Method 1: Indirect

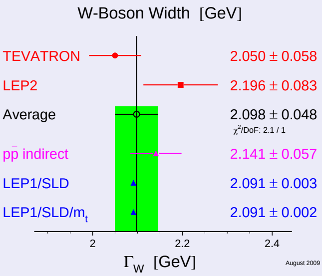
- Basic idea: Z properties well-known, relate W and Z.
- Assume W- and Z-production cross section well-known as well as $\Gamma_{W\to\ell\nu}$.
- Then measure leptonic W branching ratio through:
$$\frac{\sigma_{p\bar{p}\to W\to\ell\nu}}{\sigma_{p\bar{p}\to Z\to\ell\ell}} = \frac{\sigma_{p\bar{p}\to W}}{\sigma_{p\bar{p}\to Z}} \times \frac{{\rm BR}(W\to\ell\nu)}{{\rm BR}(Z\to\ell\ell)}$$
- Can translate BR to width, since partial width well-known.

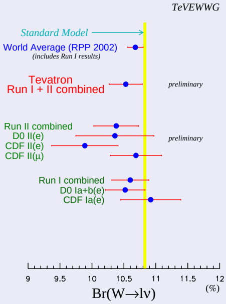
Method 2: Direct

- Idea: While peak of transverse mass distribution determined by m_W, shape defined by Γ_W.
- Therefore: Build MC templates for varying Γ_W (or even better in m_W-Γ_W plane) and fit.
- Quality control again through Z-bosons.
- Note: This is almost model-independent.



Results from Tevatron





$W^\pm$ charge assymetries at Tevatron

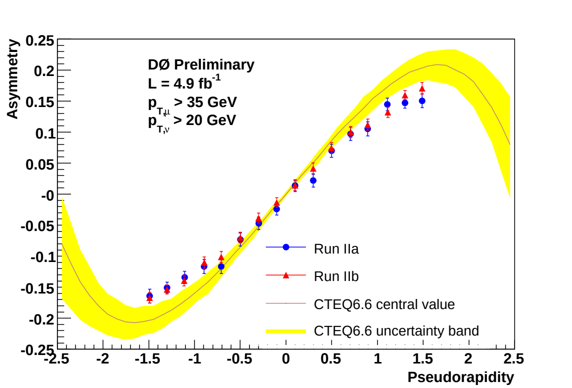
Why is this important?

- Define the forward direction at Tevatron as the direction of the proton, and the backward direction through the antiproton/
- The different valence content leads to W^+ bosons produced with a forward tilt asnd the W^- bosons with a backward tilt (see first lecture).
- Measuring the assymetry of leptons emerging from the W's allows then for a check of the PDFs.
- Use the μ-assymetry

$$A(\mu) = \frac{N_{\mu^+}(\eta) - N_{\mu^-}(\eta)}{N_{\mu^+}(\eta) + N_{\mu^-}(\eta)}\,.$$

Results

Example: Muons with $p_\perp > 35$ GeV.

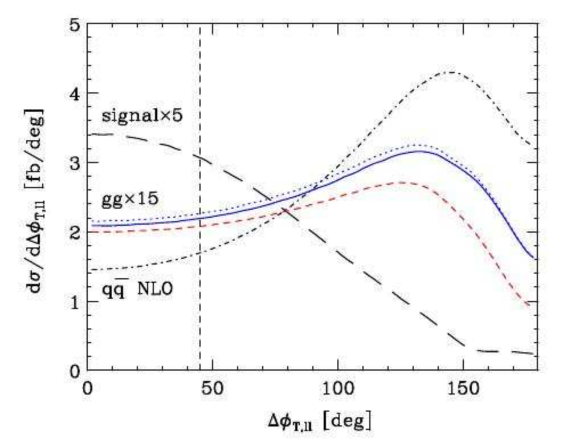


Boson pair production

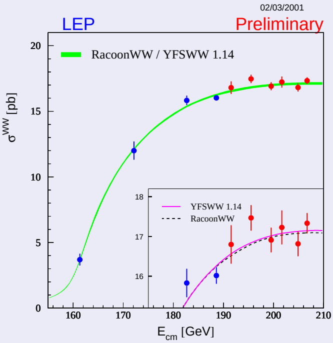
Why is this important?

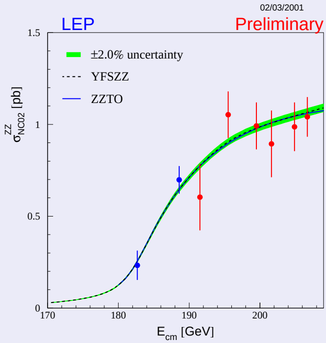
- Major background to current measurements ($t\bar{t}$, $H \to WW$) and future discoveries ($\chi^{\pm}$-pair production etc.).
- Interesting in its own right:
  - With no Higgs boson or similar: Cross section would explode or WW-scattering becomes strongly-interacting.
  - Maybe the first mode where alternatives to the Higgs scenario show.
  - Structure of interactions entirely dominated by gauge principle, but: are there non-Standard exotic couplings?

$H \to WW$ and backgrounds

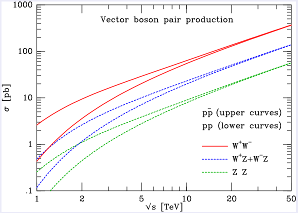


Cross sections in *ee*-annihilation





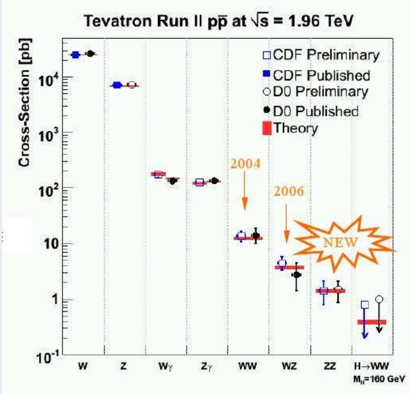
Cross sections in hadronic collisions



Typically factor of 2 suppression per $W \longrightarrow Z$.

In HE limit dominated by sea ($pp \longrightarrow p\bar{p}$).

Theory consistent with experiment.

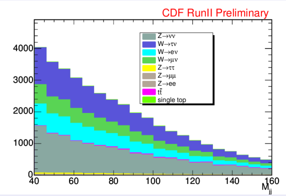


Example: WW & WZ in $jj + \not{E}_\perp$ final states

(Recent measurement by CDF, 3.5 fb^{-1})

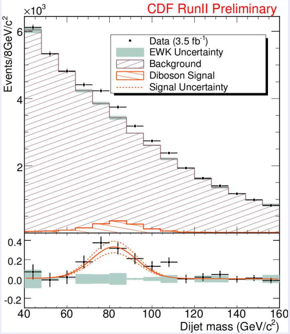
- Motivation (1): Check for consistency with SM.
- Motivation (2): Topologically similar to VH
  $\Longrightarrow$ An excellent bootcamp analysis!
- Backgrounds: EWK ($V+$ jets, $t\bar{t}$, single top) + QCD.

Sample Description	Expected # of Evts	Expected % of Sample
$Z\to\nu\nu$	12804	28.9
$Z\to ee$	5	0.0
$Z\to\mu\mu$	300	0.7
$Z\to\tau\tau$	430	1.0
$W\to e\nu$	6389	14.4
$W\to\mu\nu$	5672	12.8
$W\to\tau\nu$	10697	24.1
$t\bar{t}$	388	1.0
single top	221	0.6



Example: WW & WZ in $jj + \not{E}_\perp$ final states

(Recent measurement by CDF, 3.5 fb^{-1})



	Systematic	% uncert.
Extraction	EWK shape	7.7
	Resolution	5.6
	Total extraction	9.5
Acceptance	JES	8.0
	JER	0.7
	$\not{E}_T$ resolution model	1.0
	Trigger inefficiency	2.2
	ISR/FSR	2.5
	PDF	2.0
	Total acceptance	9.0
	Luminosity	5.9
	Total	14.4

- Final result: $\sigma = 18 \pm 2.8(\mathrm{stat}) \pm 2.4(\mathrm{syst}) \pm 1.1(\mathrm{lumi})$ pb, in agreement with SM.

Testing anomalous gauge couplings at Tevatron

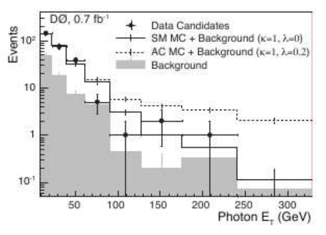
- In principle gauge structure and gauge self-interactions defined by form of gauge-covariant derivative $D^\mu = \partial^\mu + (i/g)A^\mu$ and $F^{\mu\nu} = [D^\mu,\, D^\nu]$.
  If fields do not commute, terms like $[A^\mu,\, A^\nu]$ emerge. They result in self-interactions with structure constants f^{abc}, coming from $A^\mu = A^\mu_a T^a$ (the T^a are generators of the group - matrices), and with $f^{abc}T^c \propto [T^a,\, T^b]$.
- But there are other gauge-invariant options for the gauge self-interactions.
  Example: $WW\gamma$ vertex.

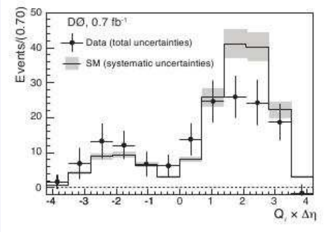
$$
\begin{aligned}
\mathcal{L}_{WW\gamma} \quad = \quad & -ie[(W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu W^{\mu\nu}A^\nu) + i\kappa W^\dagger_\mu W_\nu F^{\mu\nu} \\
& + \frac{\lambda}{m_W^2}W^\dagger_{\mu\nu}W^{\mu\rho}F^\nu_\rho + \tilde{\kappa}W^\dagger_\mu W_\nu \tilde{F}^{\mu\nu} + \frac{\tilde{\lambda}}{m_W^2}W^\dagger_{\mu\nu}W^{\mu\rho}\tilde{F}^\nu_\rho]
\end{aligned}
$$

(Terms $\tilde{\lambda}$ and $\tilde{\kappa}$ are CP-violating, $\lambda - 1$ and κ violate parity.)

Testing anomalous gauge couplings in $W\gamma$ at Tevatron

- Simple test for anomalous $WW\gamma$ couplings at Tevatron in $W\gamma$-FS.
- Good observables: $p_\perp^\gamma$ and $Q_\ell \delta\eta_{\ell\gamma}$ with ℓ from W decay.
- The latter is result of "radiation zero" due to interference of diagrams.
- Various backgrounds: e.g. QCD (with $j \to \gamma$ conversion)
- Need cuts on γ: minimal $p_\perp$ etc..





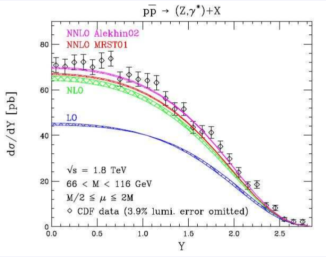
Solution for a technical problem: luminosity measurement

The need for a standard candle

- For many measurements (total cross sections): Need luminosity
$$\mathcal{L}[\mathrm{fb}^{-1}\mathrm{s}^{-1}] \times \sigma[\mathrm{fb}] = \mathrm{event\ rate}[\mathrm{s}^{-1}]\,.$$
- But design luminosity $\neq$ real luminosity.
- So, we need a way to measure instantaneous luminosity.
- Simple idea: Use equation above with a process yielding sufficiently large event rates (then statistical error small)
$\longrightarrow$ maybe $\sigma_{pp}^{\mathrm{tot}}$?
- Problem: We do not know it well enough. There's some fit parameterizations, but it is soft QCD physics, so no a priori theoretical knowledge.
(At Tevatron: typically error of $\mathcal{O}(10\%)$ due to lumi)
- Solution: Use best known process (from theory point of view).

Luminosity measurement with gauge bosons: Theoretical precision

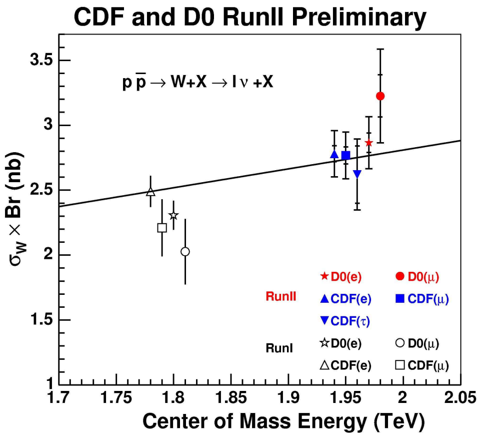
- Drell-Yan type processes best known processes at hadron colliders.
- Results available up to NNLO (the $2 \to 1$ case!).
- Due to dependence on $x_{1,2}$ only, also differential xsec w.r.t. rapidity known up to NNLO. That's great to get the acceptance correct.



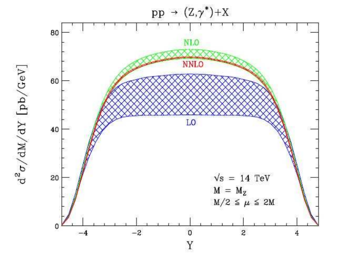
(from C. Anastasiou et al., Phys. Rev. D **69** (2004) 094008)

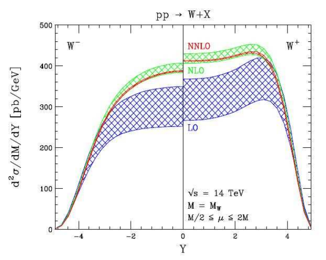
There will be ≈ 20 leptonic W/s at LHC, in principle enough for a sufficiently precise measurement of luminosity.

Theory vs. Tevatron data



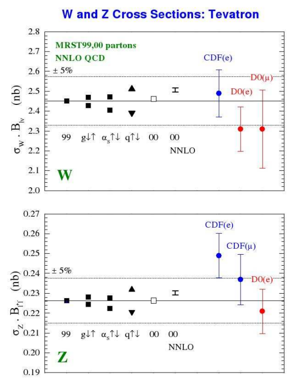
Theoretical precision

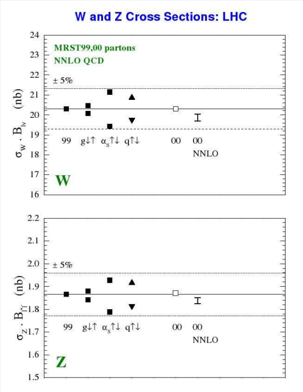




(from C. Anastasiou et al., Phys. Rev. D **69** (2004) 094008)

Systematic uncertainties





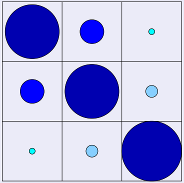
Seemingly, main uncertainty from PDFs.
Ratios may be a way to overcome this(at least partially).

Flavor physics

CKM matrix

- Inter-generation transitions dominated by mass spectrum and CKM matrix;

Relative size of CKM Matrix
(not to scale)



- dominant: $t \to b$, $b \to c$, ...

Basic properties

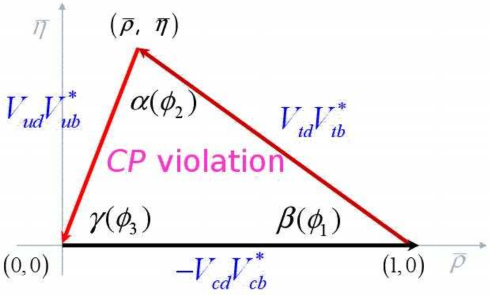
Up to $\mathcal{O}(\lambda^3)$:

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ \lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Source of CP-violation in V_{13}-elements but cosmologically not sufficient;
- unitarity of CKM matrix: triangles ($V_{ik}V^*_{kj} = \delta_{ij}$);
- size of CP-violation in SM given by area of the triangle.

"The" unitarity triangle

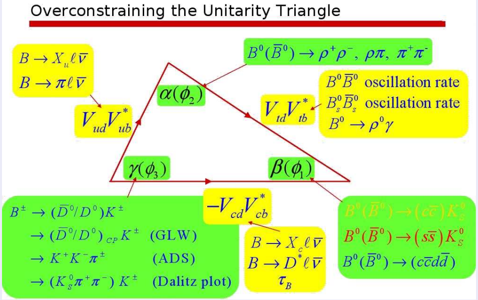
$$\text{Unitarity}: \; V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



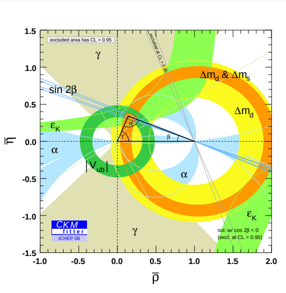
$$CP\ violation \propto J = \Im\mathrm{m}\left[V_{ud}V_{cs}V_{us}^*V_{cd}^*\right] \simeq A^2\lambda^6\eta \sim 10^{-5}\text{ , the Jarlskog invariant}$$

D.Hitlin, Talk at "Flavor in the Era of LHC", 2005)

Turning measurements into the CKM framework



(from D.Hitlin, Talk at "Flavor in the Era of LHC", 2005)



(from CKMFitter homepage)

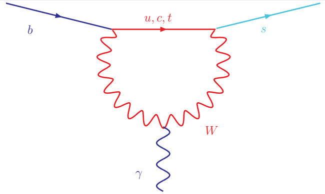
The *B*-physics relation to new phenomena

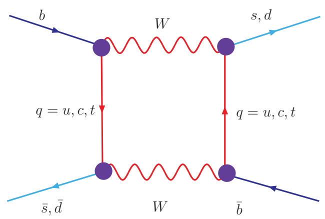
- There is an amazing consistency of the current flavor-physics measurements: The CKM-picture seems to be about right.
- However, many new physics models can have a similar pattern in their flavor sector (they need to, to survive!).
- So, important question: where to look for new physics?
    - FCNC processes (flavor-changing neutral current).
      Forbidden at tree-level in the SM (no $Z \to \bar{b}s$-vertex etc.).
      Come through loops $\longrightarrow$ next transparency.
    - Rare processes (like $B^+ \to \tau^+\nu_\tau$) and CP-asymmetries

Flavor physics

FCNC as window to new physics

- In SM: Only charged flavor changes, due to CKM matrix.
- Therefore: FCNC like $b \to s$ or $B\bar{B}$-mixing always loop-induced:



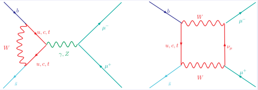


- Heavy particles running in loop (W, t): FCNC tests scales similar to potential new physics scales.

B-physics: $B_s \to \mu\mu$

General comments

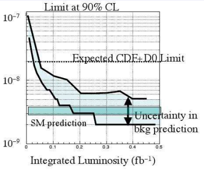
- Two contributions (SM): Penguin & Box
- Both suppressed by $V_{tb} V_{ts}^*$
- $\mathrm{BR}^{(\mathrm{SM})}_{B_{s,d}\to\mu\mu} \approx 10^{-9}$



Prospects at LHC

- Simple: leptonic final state
- Minor theoretical uncertainties
- But: Huge background
- Mass resolution paramount

Exp.	ATLAS	CMS	LHCb
σ_m (MeV)	77	36	18

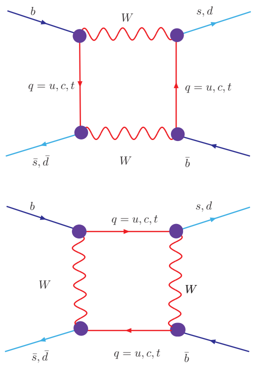


(from T.Nakada, Talk at "Flavor in the Era of LHC", 2007)

Mixing phenomena: $B_s\bar{B}_s$-mixing

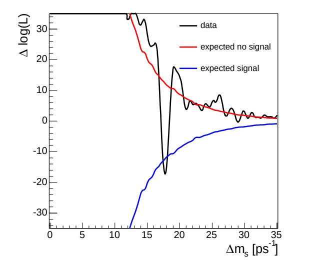
Theoretical background

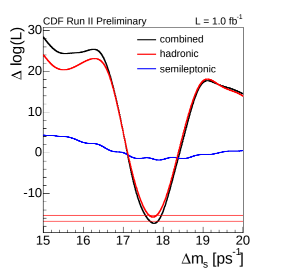
- Mixing phenomena transmitted by boxes in SM: $\propto |V_{ts}V^*_{tb}|^2$ due to GIM.
- $B_s\bar{B}_s$-mixing very important for unitarity triangle (ratio with $B_d\bar{B}_d$ cancels hadronic uncertainties)
- But: high oscillation frequency in $B_s\bar{B}_s$-mixing $\longrightarrow$ tricky to see!
- Especially complicated: Tag the flavor - is it a b or a $\bar{b}$ decaying.
- One of Tevatron's strategies: check for a neighboring K from fragmentation.



Results for B_s-mixing

(Recent measurement by CDF, 1 fb^{-1})



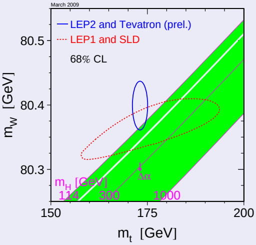


- Final result: $\Delta m_s = 17.77 \pm 0.10(\text{stat}stat) \pm 0.07(\text{sys})$
  $|V_{td}||V_{ts}| = 0.2060 \pm 0.0007(\text{exp}) \pm 0.008(\text{theo})$

Top-physics: Mass measurements

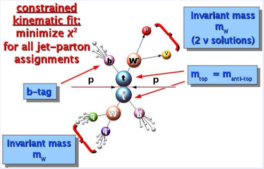
Why is this important?

- Strong correlation of top- and W-mass (self-consistency check of SM)
- A change in m_t by 2 GeV shifts SM expectation of m_H by 15%.
- Once the Higgs-boson is found: Do mass and Yukawa-coupling agree?
- Important input in many (loop) calculations. Example: FCNC processes.



Experimental techniques: Upshot

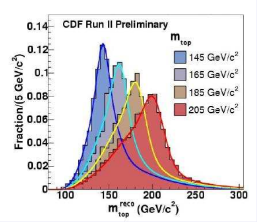
- Typically, three different channels considered separately: dileptons ($b\bar{b}\ell\bar{\nu}\bar{\ell}'\nu'$), semi-leptonic ($b\bar{b}\ell\bar{\nu}jj$), hadronic ($b\bar{b}jjjj$).
- Three different methods: Template, matrix element, cross section (see next transparencies).
- Depend partly on top-reconstruction.
- Main systematics: jet energy scale (JES). Solution: "in situ"-calibration through $W \to q\bar{q}'$ (m_W known).



(from C.Schwanenberger's talk at ICHEP08)

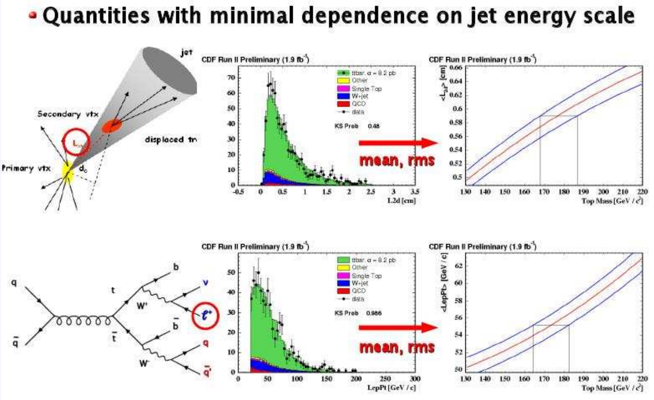
Template method

- Basic idea: Run many MC samples for different values of m_t & compare observables (distributions) with experiment.
- Use observables strongly correlated with m_t: Naive choice $m_{\rm reco.}$.
- Alternatively, look for observables that are least sensitive to badly controlled inputs (like JES).
- Examples: $p_\perp^\ell$, vertex displacement of b-decay (see next slide)



(from C.Schwanenberger's talk at ICHEP08)

Alternative template method



(from C.Schwanenberger's talk at ICHEP08)

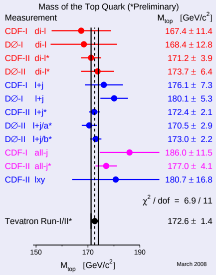
Matrix element method

- Per event define a probability for being signal- or background-like:

$$\mathcal{P}(X_{\rm seen}) \propto |\mathcal{M}_{ab\to X}|^2 |\langle X|X_{\rm seen}\rangle|^2$$

- Here $|\langle X|X_{\rm seen}\rangle|^2$ is “transfer function”:
  Probability to see $X_{\rm seen}$ when X was produced
  $\longrightarrow$ needs to be taken from MC
  & checked with control data.
- At Tevatron: LO-matrix element $\mathcal{M}_{ab\to X}$ for $X = t\bar{t}$+decays.

Results



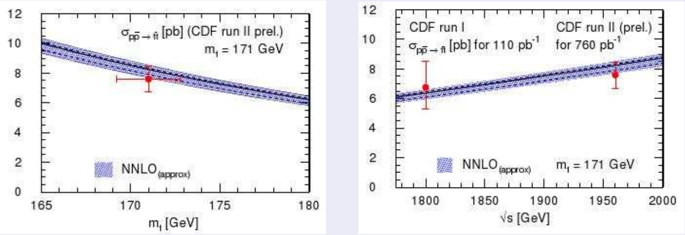
(from joint CDF/D0, CDF/9225, D0/5626)

Some remarks on m_t from $m_{\rm reco}$

- Need m_t in well-defined renormalization scheme:
  at NLO: $|m_t^{\bar{MS}}(m_t) - m_t^{\rm on-shell}(m_t)| \approx 8$ GeV!!!
  Then: Which top-mass has been measured?
- Answer: We do not know.
  Due to comparison with MC, it is a LO m_t with QCD parton showers (some HO QCD) and modelling of fragmentation, underlying event, color-reconnection, ...
  My suspicion: It is an "MC"-scheme, close to on-shell.
- But therefore, need either to understand underlying MC better or use better observables, independent of reco and MC.
- Examples for better observables: $\sigma_{t\bar{t}}$, $\mathrm{d}\sigma_{t\bar{t}}/\mathrm{d}M_{t\bar{t}}$.

Top-mass from $\sigma_{t\bar{t}}$

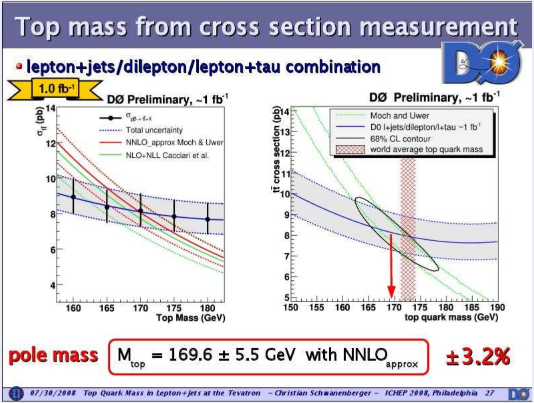
- Production cross section depends on m_t:



(from S.Moch & P.Uwer, arXiv:0804.1476)

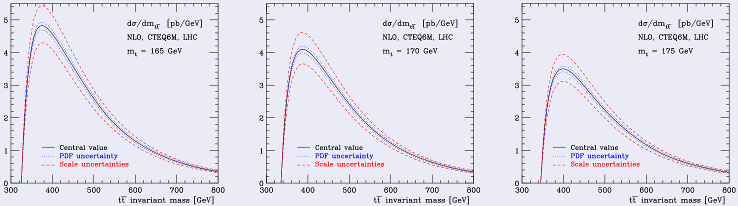
- Main theoretical uncertainties due to HO, around 8-10 %.

Top-mass from $\sigma_{t\bar{t}}$: Results



(from C.Schwanenberger's talk at ICHEP08)

Taking the top-mass from $\mathrm{d}\sigma_{t\bar{t}}/\mathrm{d}M_{t\bar{t}}$



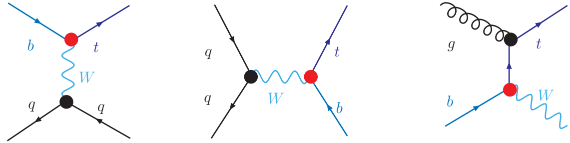
(from R.Frederix & F.Maltoni, arXiv:0712.2355)

- Theory uncertainty: $0.25\delta m_{tt}/m_{tt}$ at NLO.

Single-top production

Process characteristics

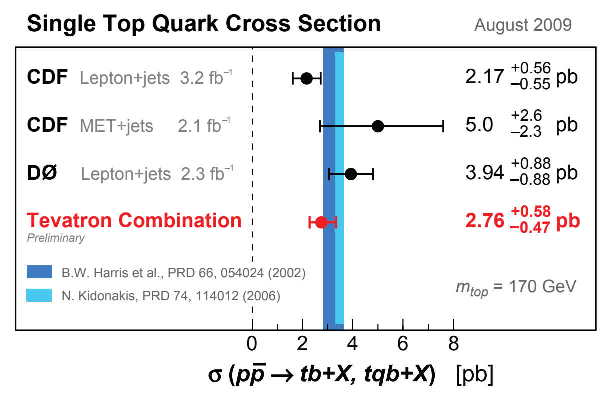
- Important: Only direct, model-independent measurement of V_{tb}



- At Tevatron: important background to WH
- Cross section quite large, ≈ 40 % of $\sigma_{t\bar{t}}$.
- Tricky signature, huge backgrounds: especially top-pairs (sometimes "irreducible": tW at NLO), W+jets, etc..
- Involved analysis techniques: matrix elements, neural networks, boosted decision trees.

Single-top production: Combination of results

Cross sections at Tevatron

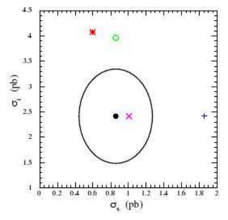


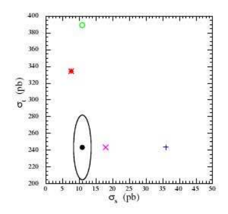
(from arXiv:/0908.2171 [hep-ex])

New physics aspects in single-top production

- Sensitive to new physics, different impact in different channels (t-channel, s-channel and T-W associated)

$\sigma^{(Tevatron)}_{\rm singlet}$ $\sigma^{(LHC)}_{\rm singlet}$





×: Z'
o: $Z \to tc$
+: $\Pi^{\pm}$
∗: 4th q
SM with 3σ theory uncertainty

(from T.Tait & C.P.Yuan, Phys. Rev. D **63** (2001) 014018)

The charge of the top-quark

Basic idea

- In the SM, $Q_t = 2/3$, so a charge measurement confirms that the top quark fits the pattern of the isodoublets in the quark sector.
- There are potentially two ways to determine the charge of the top:
  - Check the strength of the coupling to the photon directly, through the $tt\gamma$ coupling, e.g. by building the ratio $\sigma_{t\bar{t}\gamma}/\sigma t\bar{t}g$.
    This seems feasible at a linear collider, at Tevatron/LHC it is more difficult due to initial state radiation.
  - Infer the charge from the decay products, i.e. from the W and the b.
    This is the method used at Tevatron.
- The trick is to make pairings of W's, where the charge is known from the lepton, and the b-jet, such that $m_{bW} \approx m_t$. The problem is to check whether the jet originated from a b or a $\bar{b}$, leading to charges 2/3 (SM) or 4/3 (XM), respectively, for a top-quark.

Measuring the charge of the top

(from CDF-Note 8967)

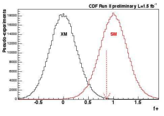
Jet charge

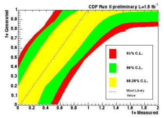
- Consider cone jets with $R = 0.4$ and $p_\perp > 20$ GeV.
- Define jet charge by

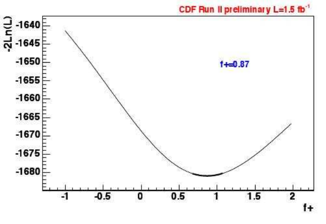
$$Q_J = \frac{\sum\limits_{i\in\text{tracks}} Q_i(\vec{p}_i\cdot\vec{p}_J)^\eta}{\sum\limits_{i\in\text{tracks}} (\vec{p}_i\cdot\vec{p}_J)^\eta}\,.$$

- $\eta = 1/2$ has been optimized with MC.
- Label each pair as being SM ($f_+ = 1$) or XM-like ($f_+ = 0$), measure $\langle f_+\rangle$.

Result: $Q_t = 2/3$

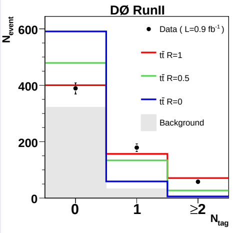


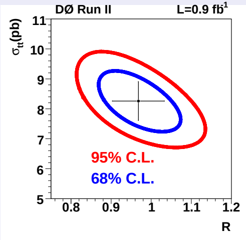




Top decays

V_{tb} from top decays



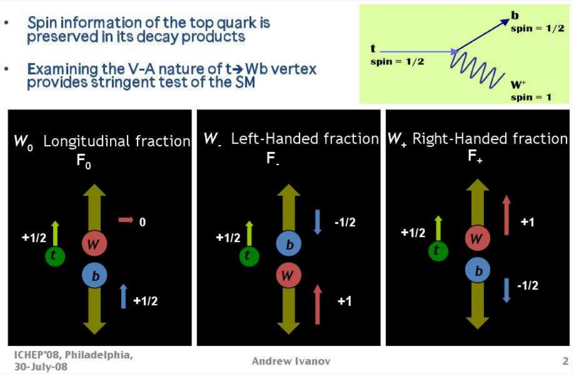


(from D0, Phys. Rev. Lett. 100 (2008) 192003)

- Simultaneous fit to $\sigma_{t\bar{t}}$ and $\mathrm{BR}(t \to Wb)/\mathrm{BR}(t \to Wq)$
- Underlying assumption: $\sum_q \mathrm{BR}(t \to Wq) = 1$

W-helicity in top-quark decays

Why is this important?



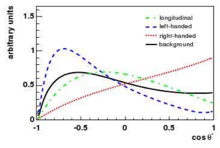
Measurement of the W-helicity in top-quark decays

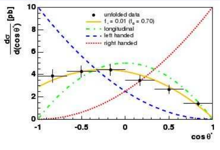
- Measure $\cos\theta^*$
  from $\angle_{\ell t} = \angle_{\ell b}$ in W-rest frame.
- $\mathcal{P}(\cos\theta^*) = f_0 w_0 + f_+ w_+ + f_- w_-$

  with $w_0 = \frac{3}{4}(1-\cos^2\theta^*)$

  $w_+ = \frac{3}{8}(1+\cos\theta^*)^2$

  $w_- = \frac{3}{8}(1-\cos\theta^*)^2.$
- SM: $f_0 = 0.697 \pm 0.002,\ f_+ = \mathcal{O}(10^{-4})$,
  $f_- = 1 - f_0 - f_+$.
- $f_0 = 0.66 \pm 0.16$ & $f_+ = -0.03 \pm 0.07$
  (recent CDF-measurement)



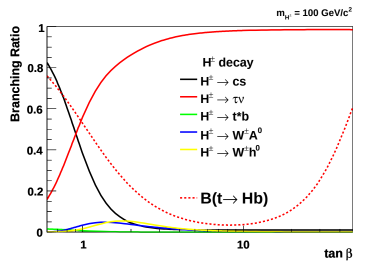


(from CDF-Note 9431)

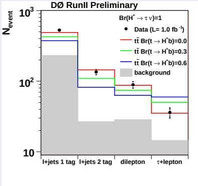
Charged Higgs bosons in top decays?

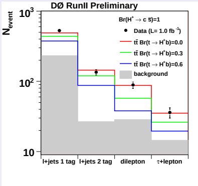
Theory considerations

- If $m_{H^\pm} < m_t - m_b$ decay mode is, in principle, open.
- If decays of $H^\pm$ along CKM picture, $H^\pm \to \tau\nu$ and $H^\pm \to cs$ dominant:



Experimental results





(from D0-conf/5715)

The next generation(s)?

Theoretical background

- There is no *a priori* reason to assume 3 generations only.
- Some models, like, e.g. little Higgs, predict the existence of further elementary fermions, like t'.
- Reason against 4th generation: Only 3 ν's with $m_\nu < m_Z/2$ at LEP.

Gauge sector of the SM

To take home

- The gauge sector is THE crucial point for the SM.
- There is an intricate interplay with other parameters, especially m_t. (Remark: Adopt the following point: all matter particles want to have masses $\approx v$, so the real question is not why the top is so heavy but why the electron is so light!)
- Need to check the consistency: shed light on mechanism of EWSB.
- Even after Higgs boson will be found: Must match the pattern!
- Potentially a window to new physics, in particular through VV-pair production: Unitarity (see lecture 5), anomalous gauge couplings etc..

Flavor sector of the SM

To take home

- There are many interesting questions in the flavor sector:
  - Rare/FCNC decays of b (and of t)
  - Check properties, especially of the top-quark: coupling, CKM elements, charge.
  - m_{top} is an important input, but more (theoretical) work needed to ensure that meaningful results at sufficient accuracy have been extracted from data.
- Top production (single and in pairs) is a relevant background to nearly all new physics searches at LHC $\longrightarrow$ we need to understand this as good as possible.
- LHC is a top-factory! Can go for high precision: not only mass, also V_{tb}, width, rare decays, ...