Phenomenology at collider experiments [Part 2: SM measurements]

Frank Krauss

IPPP Durham

HEP Summer School 31.8.-12.9.2008, RAL

Outline

Know your Standard Model

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

- 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),

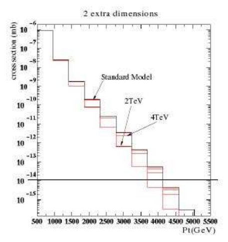
  and they deduced a gluino mass larger than around 40 GeV.
- In Phys. Lett. **B139** (1984) 105, the UA2 collaboration describes similar events, also after 113 nb^{-1}, without indicating any interpretation as strongly as UA1.
- In Phys. Lett. **B158** (1985) 341, S.Ellis, R.Kleiss, and J.Stirling calculated the backgrounds to that process more carefully, and showed agreement with the Standard Model.

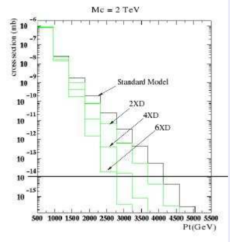
Know your Standard Model

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)





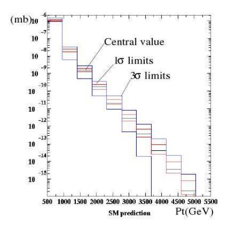
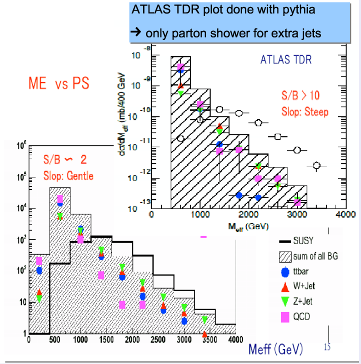


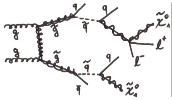
Figure from S.Ferrag, hep-ph/0407303

Know your Standard Model

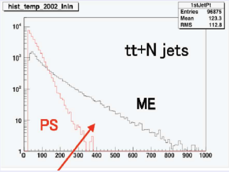
Example: Inclusive SUSY searches



Typical process



Shape of tt-events



Know your Standard Model

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).

Solution for a technical problem: luminosity measurement

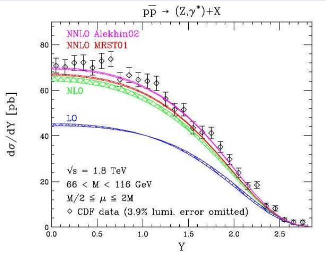
The need for a standard candle

- For many measurements (total cross sections): Need luminosity
$$\mathcal{L}[\text{fb}^{-1}\text{s}^{-1}] \times \sigma[\text{fb}] = \text{event rate}[\text{s}^{-1}]\,.$$
- 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 σ_{pp}^{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.

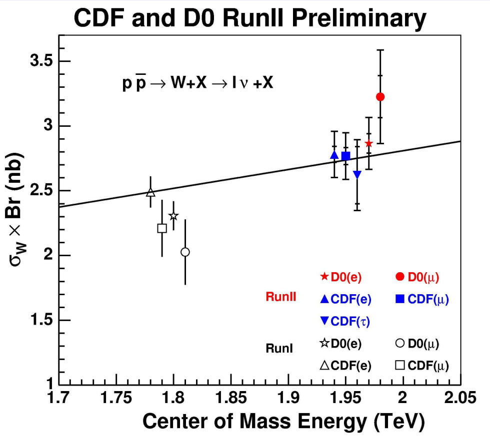


(from C. Anastasiou et al., Phys. Rev. D **69** (2004) 094008)

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

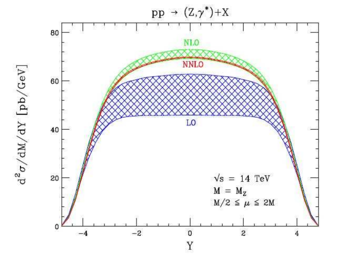
Luminosity measurement with gauge bosons

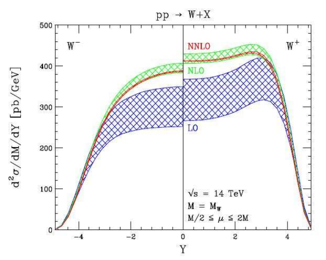
Theory vs. Tevatron data



Luminosity measurement with gauge bosons

Theoretical precision

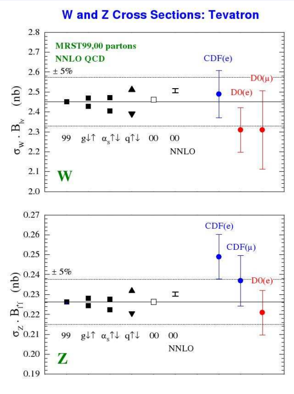


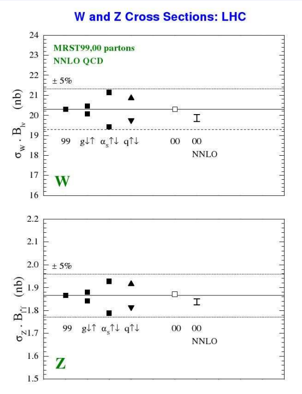


(from C. Anastasiou et al., Phys. Rev. D **69** (2004) 094008)

Luminosity measurement with gauge bosons

Systematic uncertainties





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

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.

W mass measurements

Why is this important? (cont'd)

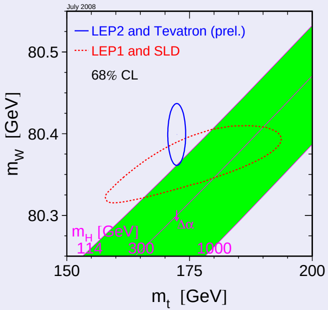
- Naively $\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$ connects masses with ew mixing angle. (Weinberg-angle, θ_W)
- Loop-corrections to it from self-energies etc..
  - Interesting correction:

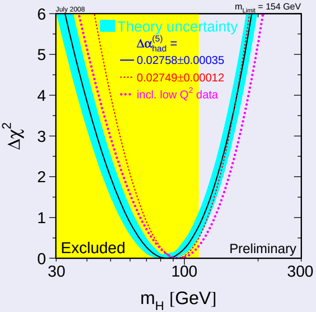
$$\Delta\rho_{s.e.} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots\right]$$

  - 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.

W mass measurements

Why is this important? (cont'd)

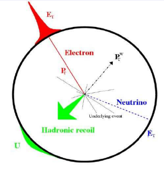


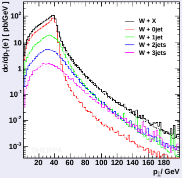


W mass measurements

Some technical aspects

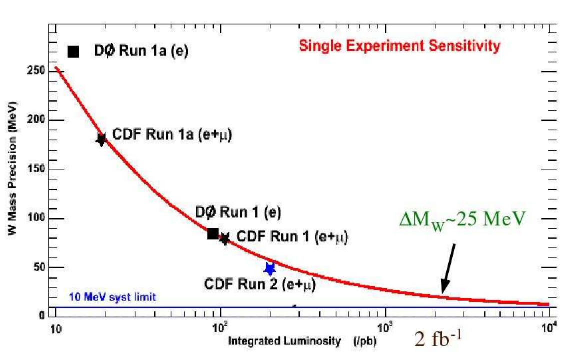
- But: How to measure the mass?
- From LEP: Direct measurements. Hampered by comparably low stats and jet-energy uncertainties.
- Tevatron: Measurement in leptonic mode, but then the ν's escape.
- So, how to do it at a hadron collider?
- Jacobean peak in $p_\perp^\ell$
  Even better: transverse mass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





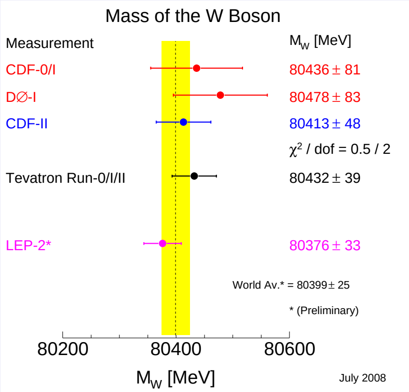
W mass measurements at the Tevatron

Anticipated sensitivity



W mass measurements

Results

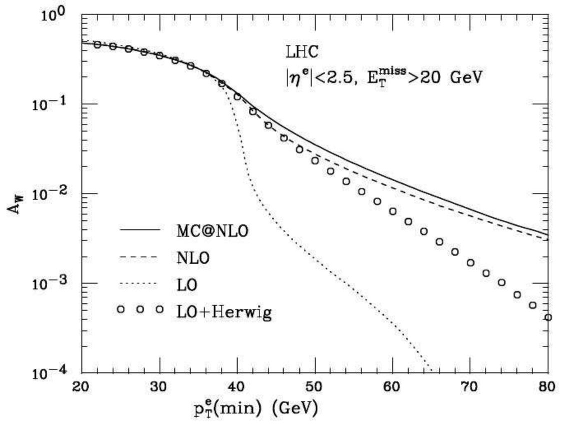


Projection to LHC

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

W mass measurements at the 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?

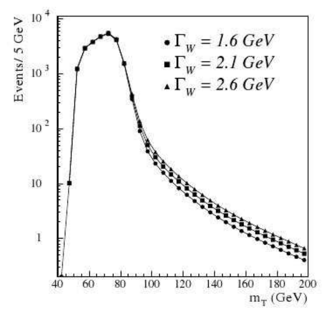
Method 1: Indirect

- 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.

W width measurements

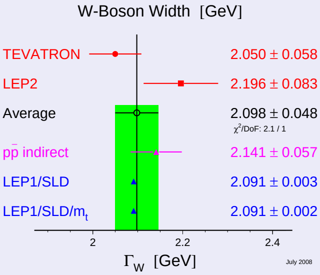
Method 2: Direct

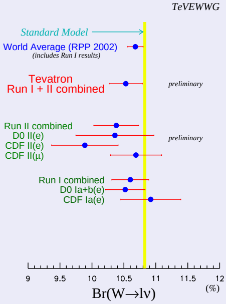
- Idea: While peak of transverse mass distribution determined by m_W, shape defined by Γ_W.
- Therefore: Build MC templates for varying Γ_W (or even better in m_W-Γ_W plane) and fit.
- Quality control again through Z-bosons.
- Note: This is almost model-independent.



W width measurements at Tevatron

Results





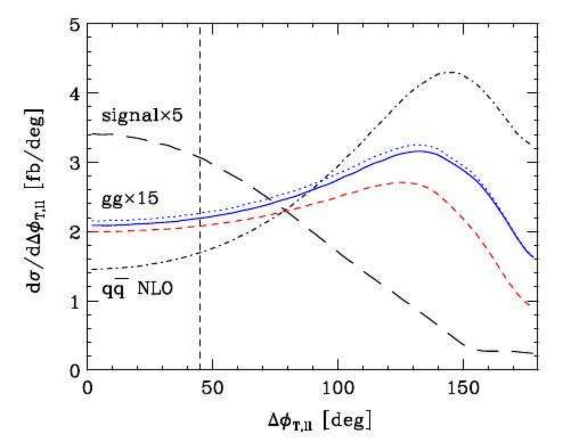
Boson pair production

Why is this important?

- Major background to current measurements ($t\bar{t}$ etc.) and future discoveries ($H \to WW$).
- 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?

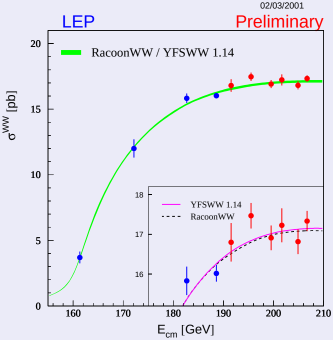
Boson pair production

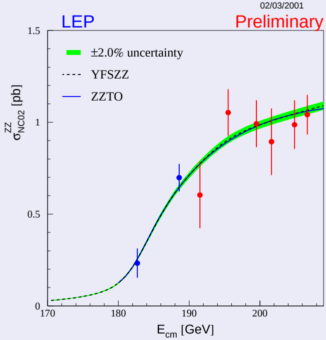
$H \longrightarrow WW$ and backgrounds



Boson pair production

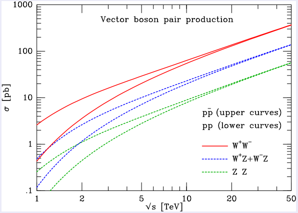
Cross sections in *ee*-annihilation





Boson pair production

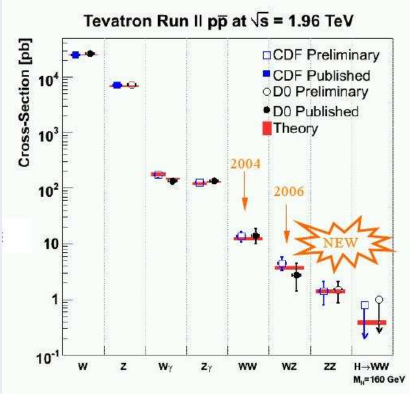
Cross sections in hadronic collisions



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

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

Theory consistent with experiment.



Boson pair production

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.

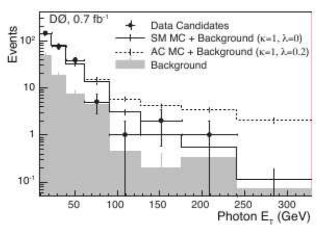
$$\begin{aligned}\mathcal{L}_{WW\gamma} \quad = \quad & -ie[(W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu W^{\mu\nu}A^\nu) + i\kappa W^\dagger_\mu W_\nu F^{\mu\nu} \\ & + \frac{\lambda}{m_W^2}W^\dagger_{\mu\nu}W^{\mu\rho}F^\nu_\rho + \tilde{\kappa}W^\dagger_\mu W_\nu \tilde{F}^{\mu\nu} + \frac{\tilde{\lambda}}{m_W^2}W^\dagger_{\mu\nu}W^{\mu\rho}\tilde{F}^\nu_\r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

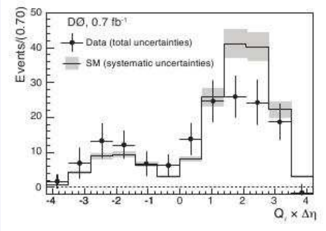
(Terms $\tilde{\lambda}$ and $\tilde{\kappa}$ are CP-violating, $\lambda - 1$ and κ violate parity.)

Boson pair production

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..





Gauge sector of the SM

To take home

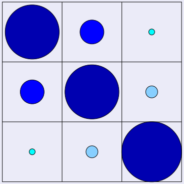
- The gauge sector is THE crucial point for the SM.
- There is an intricate interplay with other parameters, especially m_t. (Remark: Adopt the following point: all matter particles want to have masses $\approx v$, so the real question is not why the top is so heavy but why the electron is so light!)
- 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 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

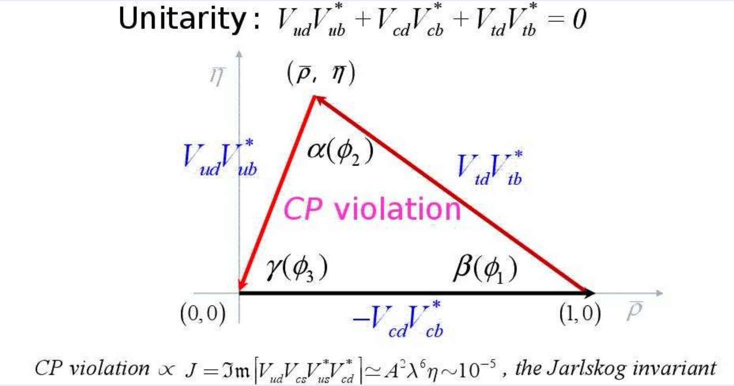
Up to $\mathcal{O}(\lambda^3)$:

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

- 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.

Flavor physics

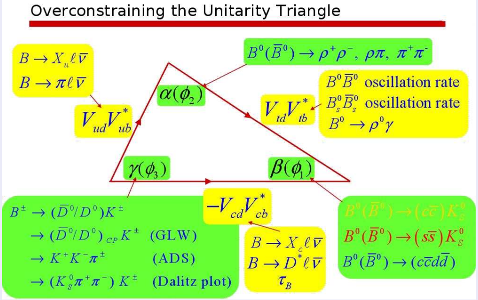
"The" unitarity triangle

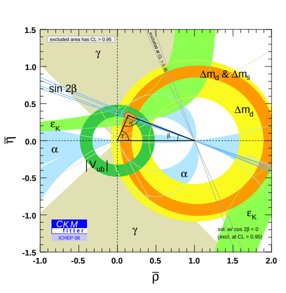


D.Hitlin, Talk at "Flavor in the Era of LHC", 2005)

Flavor physics

Turning measurements into the CKM framework





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

(from CKMFitter homepage)

Flavor physics

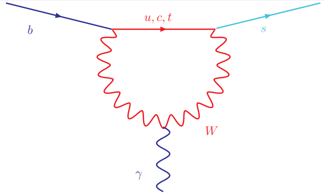
Relation to new physics

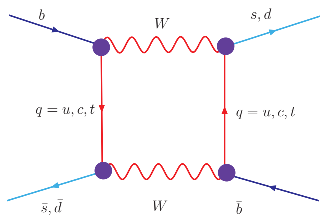
- There is an amazing consistency of the current flavor-physics measurements: The CKM-picture seems to be about right.
- However, many new physics models can have a similar pattern in their flavor sector (they need to, to survive!).
- So, important question: where to look for new physics?
  - FCNC processes (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:



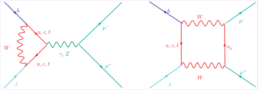


- Heavy particles running in loop (W, t): FCNC tests scales similar to potential new physics scales.

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

General comments

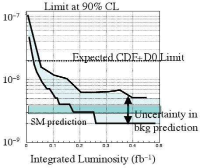
- Two contributions (SM): Penguin & Box
- Both suppressed by $V_{tb}V_{ts}^*$
- $\mathrm{BR}^{(\mathrm{SM})}_{B_{s,d}\to\mu\mu} \approx 10^{-9}$



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

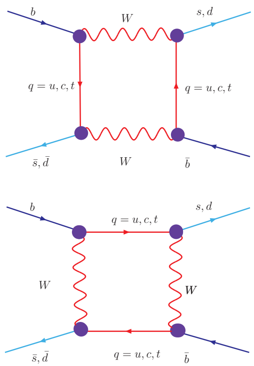


(from T.Nakada, Talk at "Flavor in the Era of LHC", 2007)

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

Theoretical background

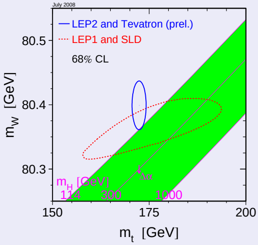
- Mixing phenomena transmitted by boxes in SM: $\propto |V_{ts}V_{tb}^*|^2$ due to GIM.
- $B_s\bar{B}_s$-mixing very important for unitarity triangle (ratio with $B_d\bar{B}_d$ cancels hadronic uncertainties)
- But: high oscillation frequency in $B_s\bar{B}_s$-mixing $\longrightarrow$ tricky to see!
- 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.



Top-physics: Mass measurements

Why is this important?

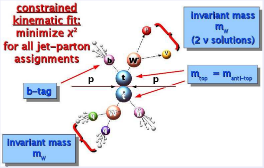
- Strong correlation of top- and W-mass (self-consistency check of SM)
- A change in m_t by 2 GeV shifts SM expectation of m_H by 15%.
- Once the Higgs-boson is found: Do mass and Yukawa-coupling agree?
- Important input in many (loop) calculations. Example: FCNC processes.



Top-mass measurements

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).

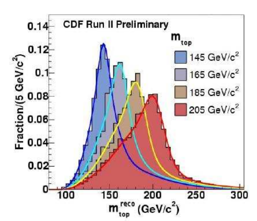


(from C.Schwanenberger's talk at ICHEP08)

Top-mass measurements

Template method

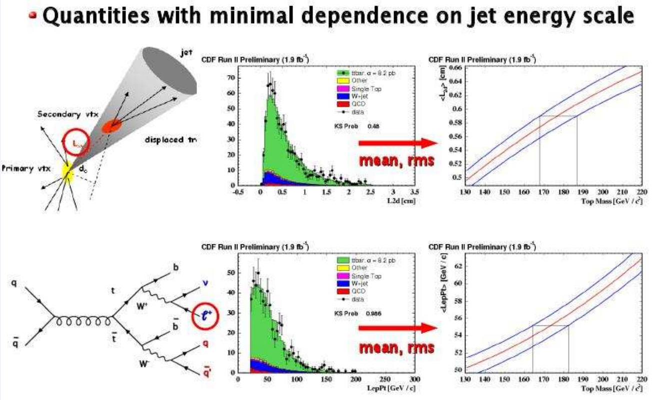
- Basic idea: Run many MC samples for different values of m_t & compare observables (distributions) with experiment.
- Use observables strongly correlated with m_t: Naive choice $m_{\rm reco.}$.
- Alternatively, look for observables that are least sensitive to badly controlled inputs (like JES).
- Examples: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



(from C.Schwanenberger's talk at ICHEP08)

Top-mass measurements

Alternative template method



(from C.Schwanenberger's talk at ICHEP08)

Top-mass measurements

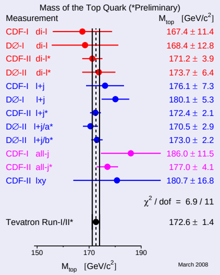
Matrix element method

- 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)

Top-mass measurements

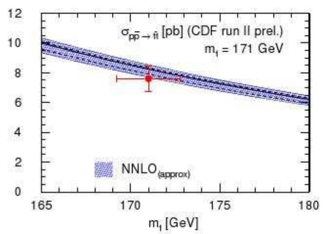
Some remarks on m_t from $m_{\rm reco}$

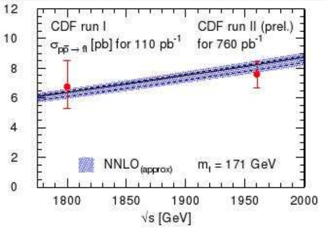
- Need m_t in well-defined renormalization scheme: at NLO: $|m_t^{\bar{MS}}(m_t) - m_t^{\rm on-shell}(m_t)| \approx 8$ GeV!!! Then: Which top-mass has been measured?
- Answer: We do not know. Due to comparison with MC, it is a LO m_t with QCD parton showers (some HO QCD) and modelling of fragmentation, 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 measurements

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

- Production cross section depends on m_t:



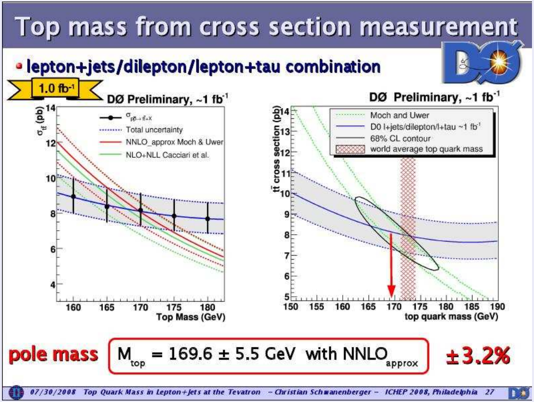


(from S.Moch & P.Uwer, arXiv:0804.1476)

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

Top-mass measurements

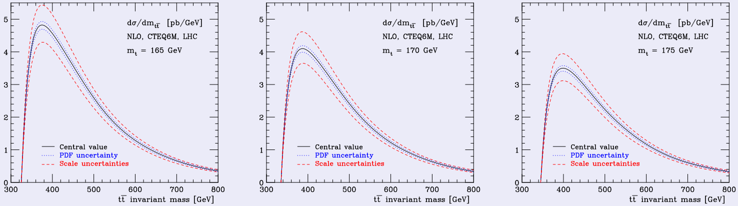
Top-mass from $\sigma_{t\bar{t}}$: Results



(from C.Schwanenberger's talk at ICHEP08)

Top-mass measurements

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



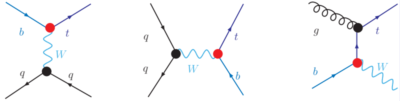
(from R.Frederix & F.Maltoni, arXiv:0712.2355)

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

Single-top production

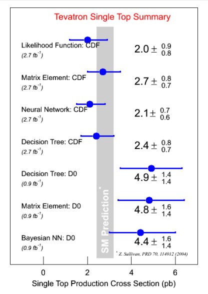
Process characteristics

- 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, W+jets, etc.
- Involved analysis techniques: matrix elements, neural networks, boosted decision trees.

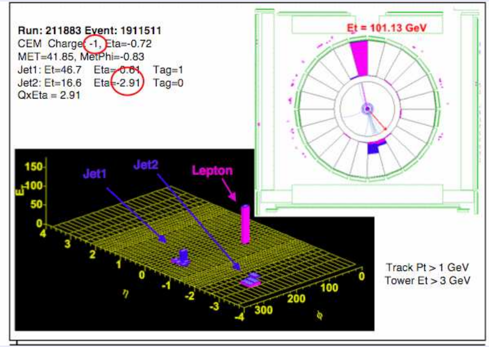
Cross sections at Tevatron



(from T.Junk's talk at ICHEP08)

Single-top production

A candidate event



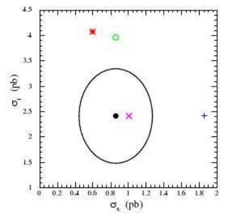
(from CDF homepage)

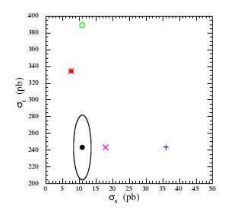
Single-top production

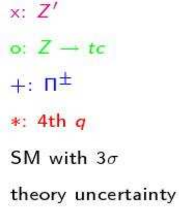
New physics aspects

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

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







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

The charge of the top

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.

The charge of the top

(from CDF-Note 8967)

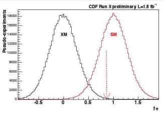
Jet charge

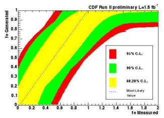
- Consider cone jets with $R = 0.4$ and $p_\perp > 20$ GeV.
- Define jet charge by

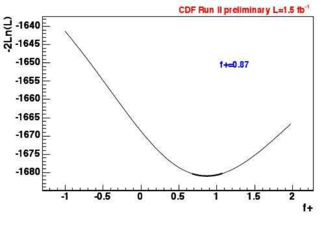
$$Q_J = \frac{\sum\limits_{i\in\text{tracks}} Q_i(\vec{p}_i\cdot\vec{p}_J)^\eta}{\sum\limits_{i\in\text{tracks}} (\vec{p}_i\cdot\vec{p}_J)^\eta}\,.$$

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

Result: $Q_t = 2/3$

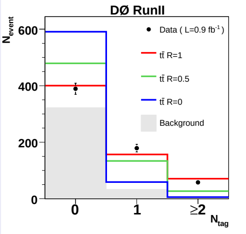


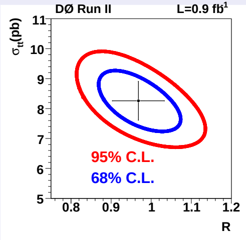




Top decays

V_{tb} from top decays



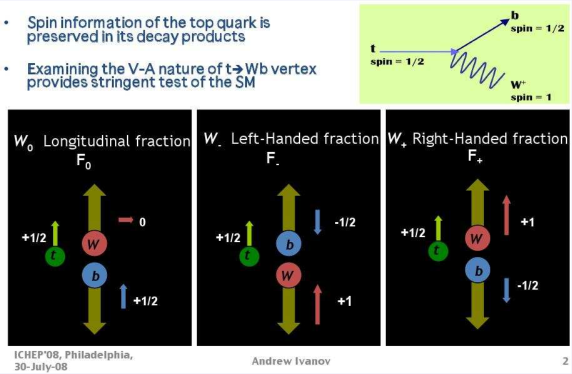


(from D0, Phys. Rev. Lett. 100 (2008) 192003)

- 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?



W-helicity in top-quark decays

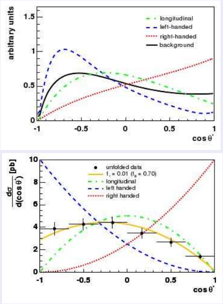
Measurement

- 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)

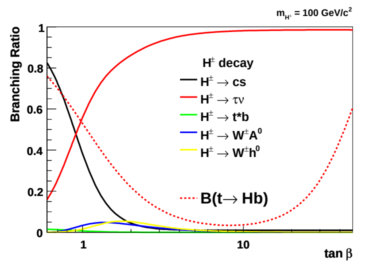


(from CDF-Note 9431)

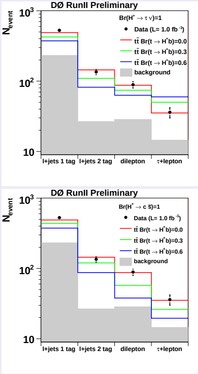
Charged Higgs bosons in top decays?

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.

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.
  - $m_{\rm top}$ 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, ...