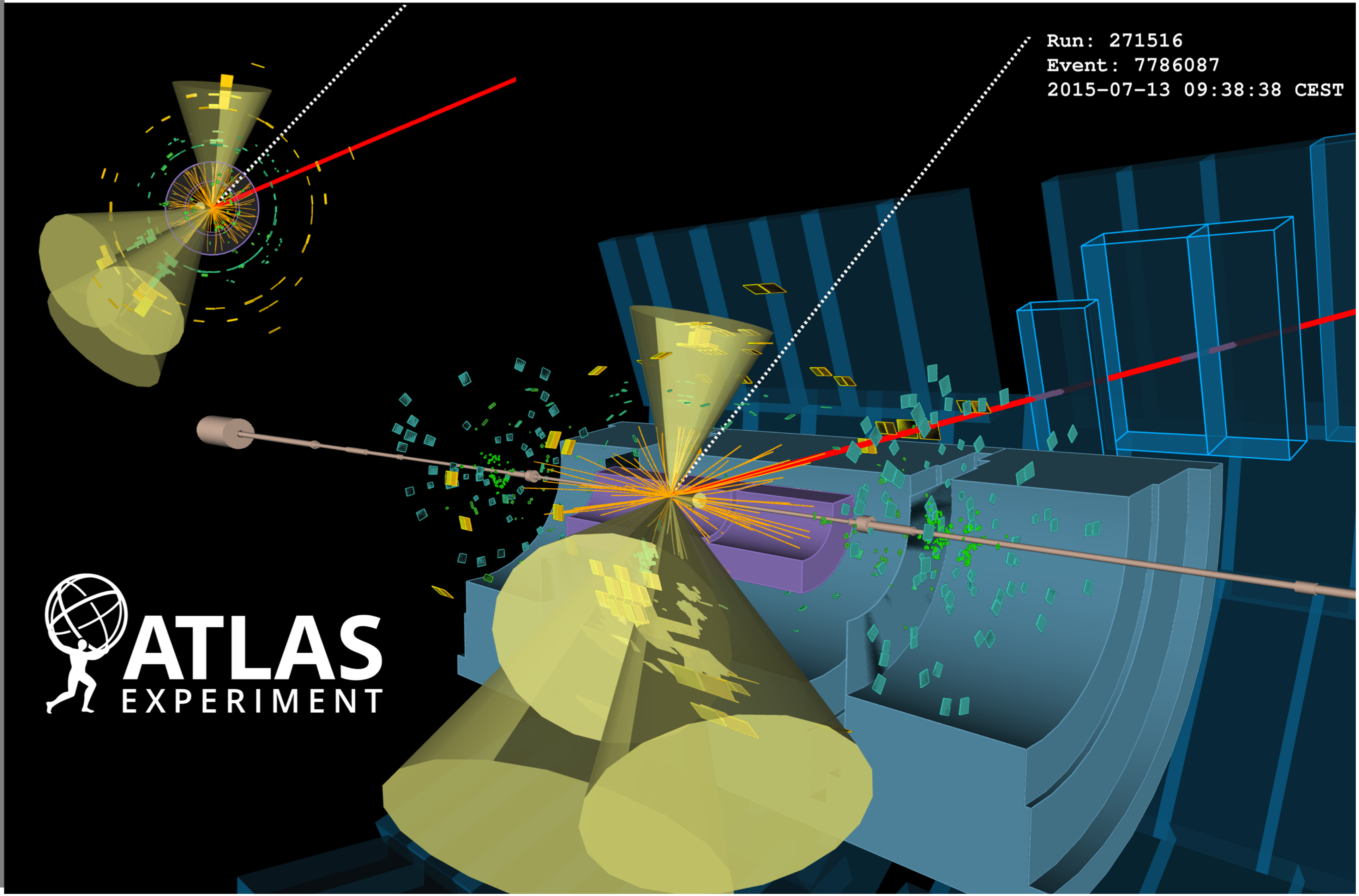
Top-Physics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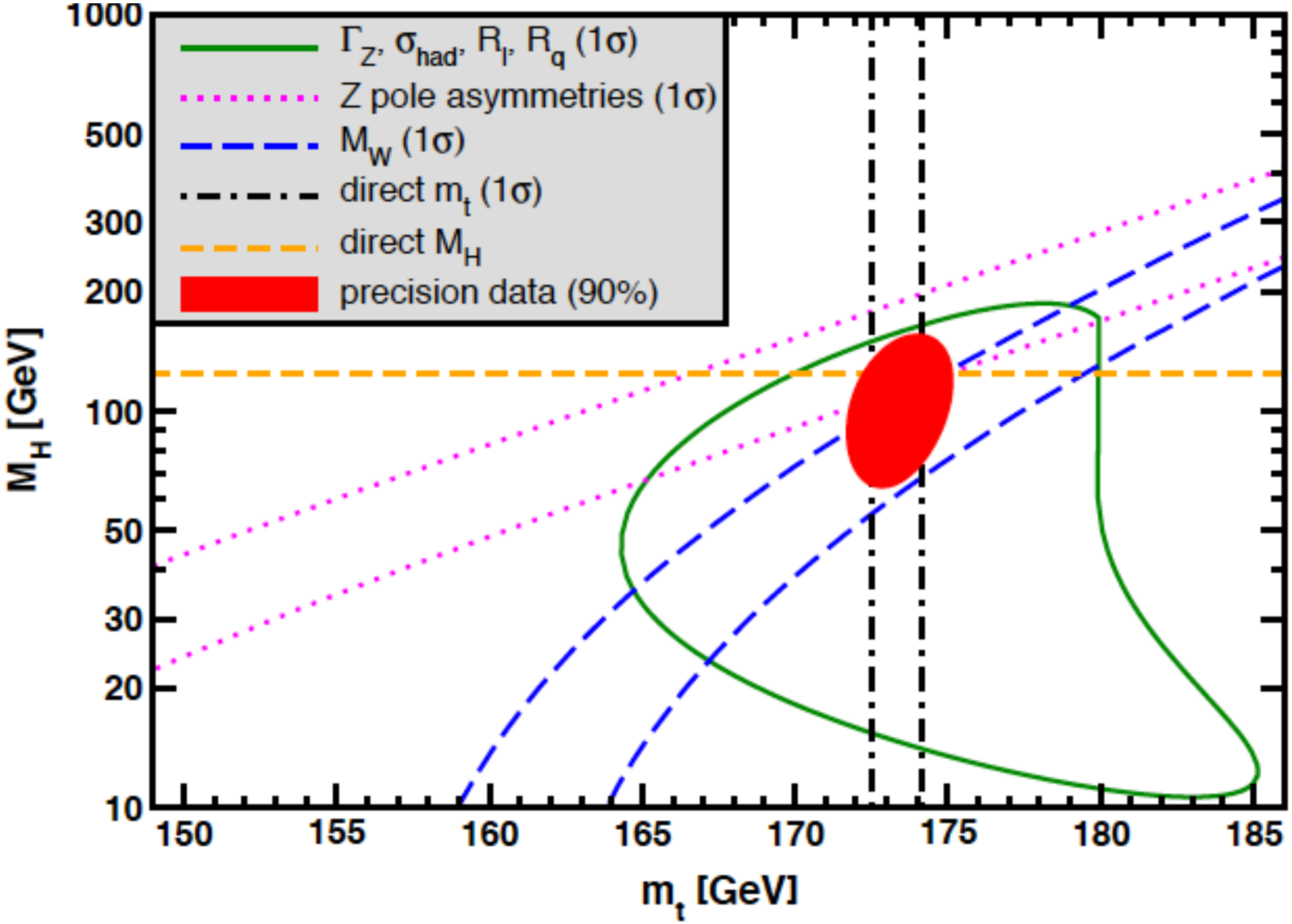
ATLAS
EXPERIMENT

Contents

m_t & m_H: Constraints on New Physics



Indirect Evidence @ LEP

W-Boson mass:

$$m_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{\sin^2\theta_W(1-\Delta r)}$$

Radiative correction [of order 3%]

where Δr contains all the one-loop corrections originate from top and Higgs loops ...

Top contribution:

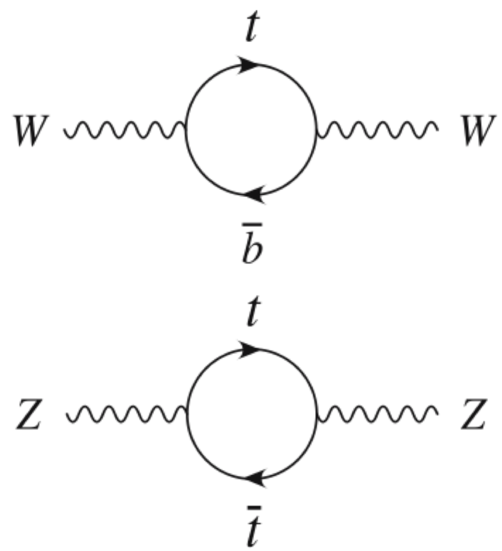
$$(\Delta r)_{top} \simeq -\frac{3G_F}{8\sqrt{2}\pi^2\tan^2\theta_W}m_t^2$$

[quadratic dependence]

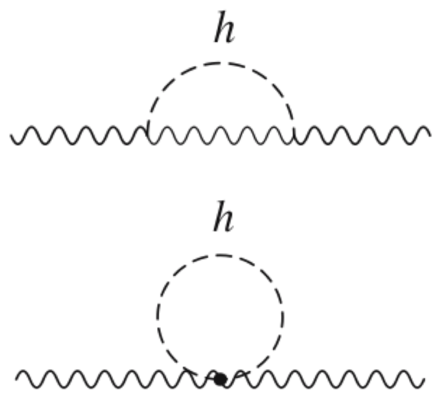
Higgs contribution:

$$(\Delta r)_{Higgs} \simeq \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left(\ln\frac{m_H^2}{m_Z^2}-\frac{5}{6}\right)$$

[logarithmic dependence]



Virtual top quark loops
contributing to the W and Z boson masses



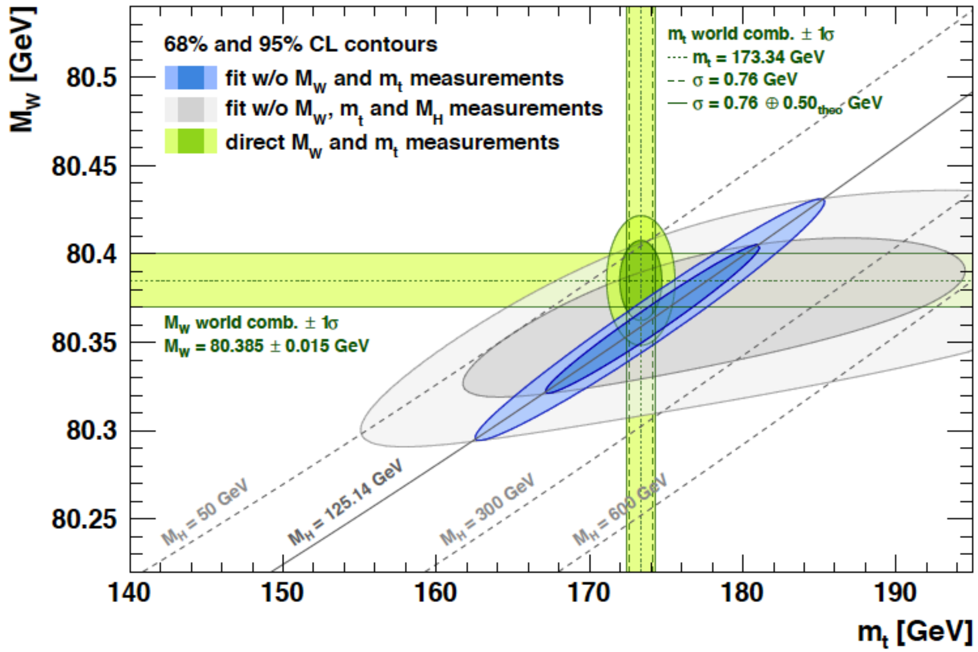
Virtual Higgs boson loops
contributing to the W and Z boson masses

Indirect Evidence @ LEP

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}	93^{+24}_{-20}
M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008	80.358 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011	91.2000 ± 0.010
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016	2.4945 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026	20.721 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001	0.01625 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007	0.23150 ± 0.00005
A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022	0.6680 ± 0.00016
A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004	0.93463 ± 0.00003
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003	0.0738 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004	0.1033 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011	0.21577 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\nabla)}$	$177.0^{+2.3}_{-2.4}{}^{(\nabla)}$	177.0 ± 2.3
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)^{(\dagger\triangle)}$	2757 ± 10	yes	2756 ± 10	2723 ± 44	2722 ± 42
$\alpha_s(M^2_Z)$	–	yes	0.1196 ± 0.0030	0.1196 ± 0.0030	0.1196 ± 0.0028

$^{(\circ)}$Average of the ATLAS [48] and CMS [49] measurements assuming no correlation of the systematic uncertainties.
$^{(\star)}$Average of the LEP and SLD A_ℓ measurements [12], used as two measurements in the fit.
$^{(\nabla)}$The theoretical top mass uncertainty of 0.5 GeV is excluded.
$^{(\dagger)}$In units of 10^{-5}.
$^{(\triangle)}$Rescaled due to α_s dependence.

Table 2: Input values and fit results for the observables used in the global electroweak fit. The first and second columns list respectively the observables/parameters used in the fit, and their experimental values or phenomenological estimates (see text for references). The third column indicates whether a parameter is floating in the fit. The fourth column quotes the results of the fit including all experimental data. In the fifth column the fit results are given without using the corresponding experimental or phenomenological estimate in the given row (indirect determination). The last column shows for illustration the result using the same fit setup as in the fifth column, but ignoring all theoretical uncertainties. The nuisance parameters that are used to parameterise theoretical uncertainties are given in Table 1.



Top mass prediction from EW fits …

$$m_{\rm top} = 179.4^{+12.1}_{-9.2}\ {\rm GeV}$$

Direct measurement from Tevatron …

$$m_{\rm top} = 173.3 \pm 1.1\ {\rm GeV}$$

Top Quark Discovery

History of top searches:

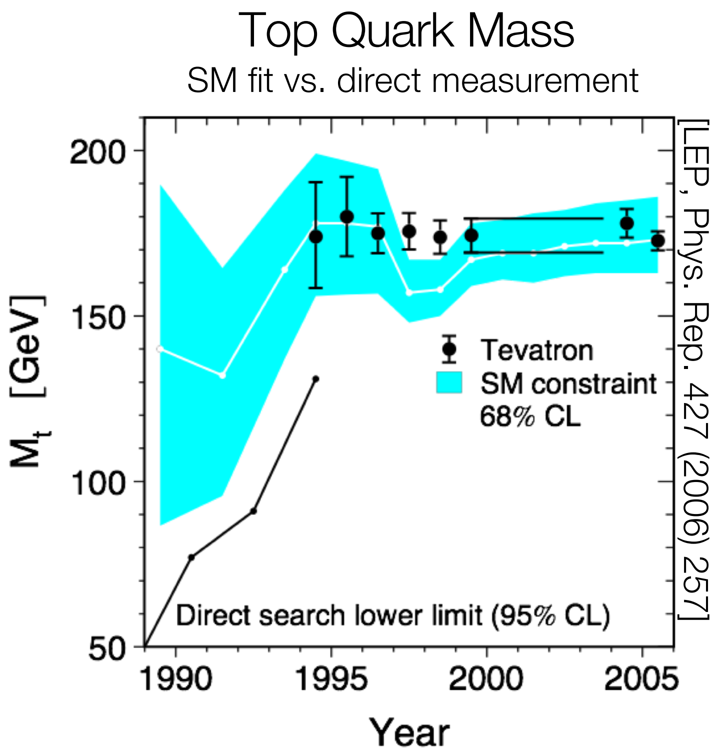
1973 Kobayashi/Maskawa:
Need for three quark generations
to incorporate CP violation into SM

1977 Discovery of bottom quark
[$m_b \approx 4.5$ GeV]

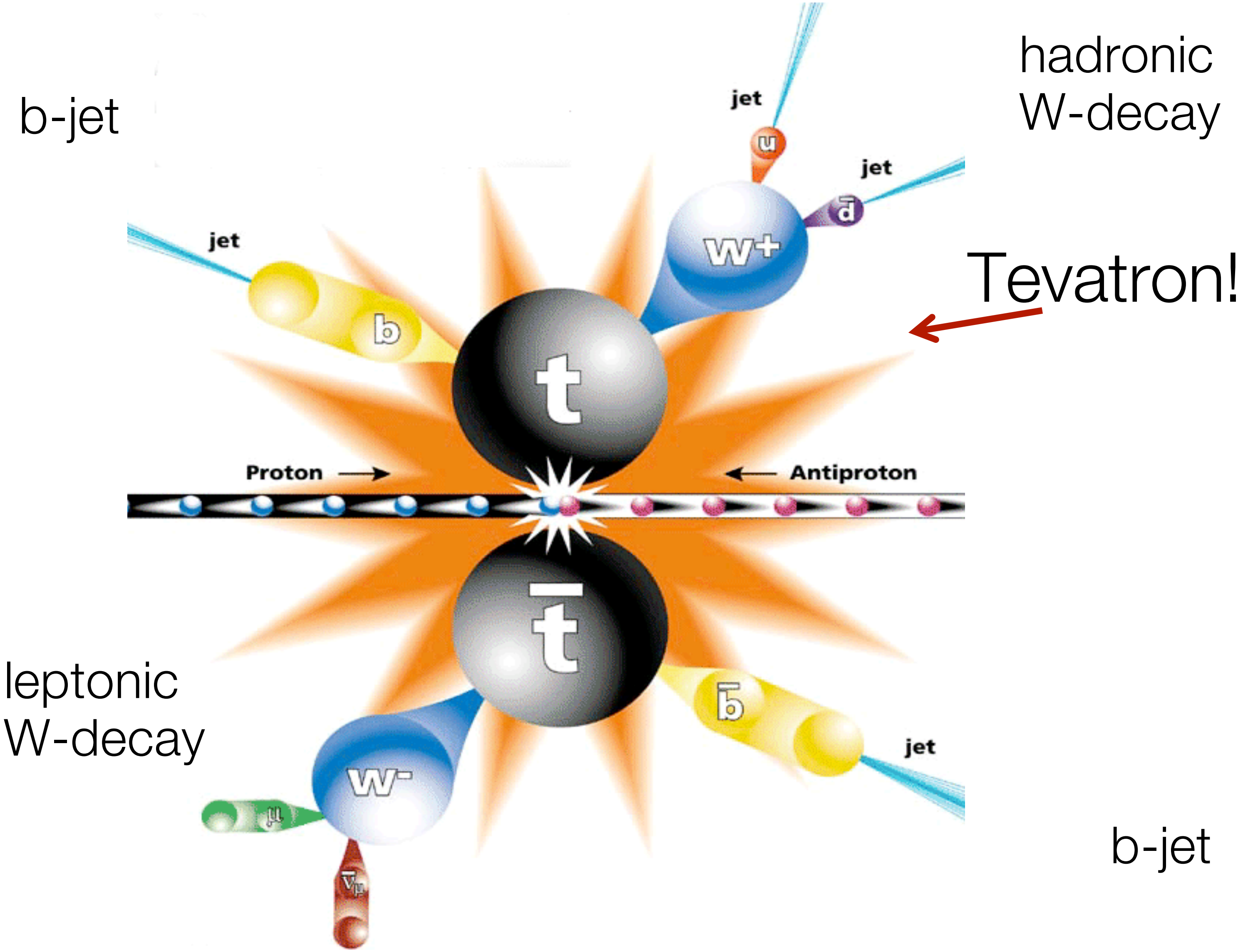
1980ies Search for light top ($m_t < m_W - m_b$)
in decays W → tb

1992 Tevatron Run I:
First indications for heavy top
quark decay t → Wb

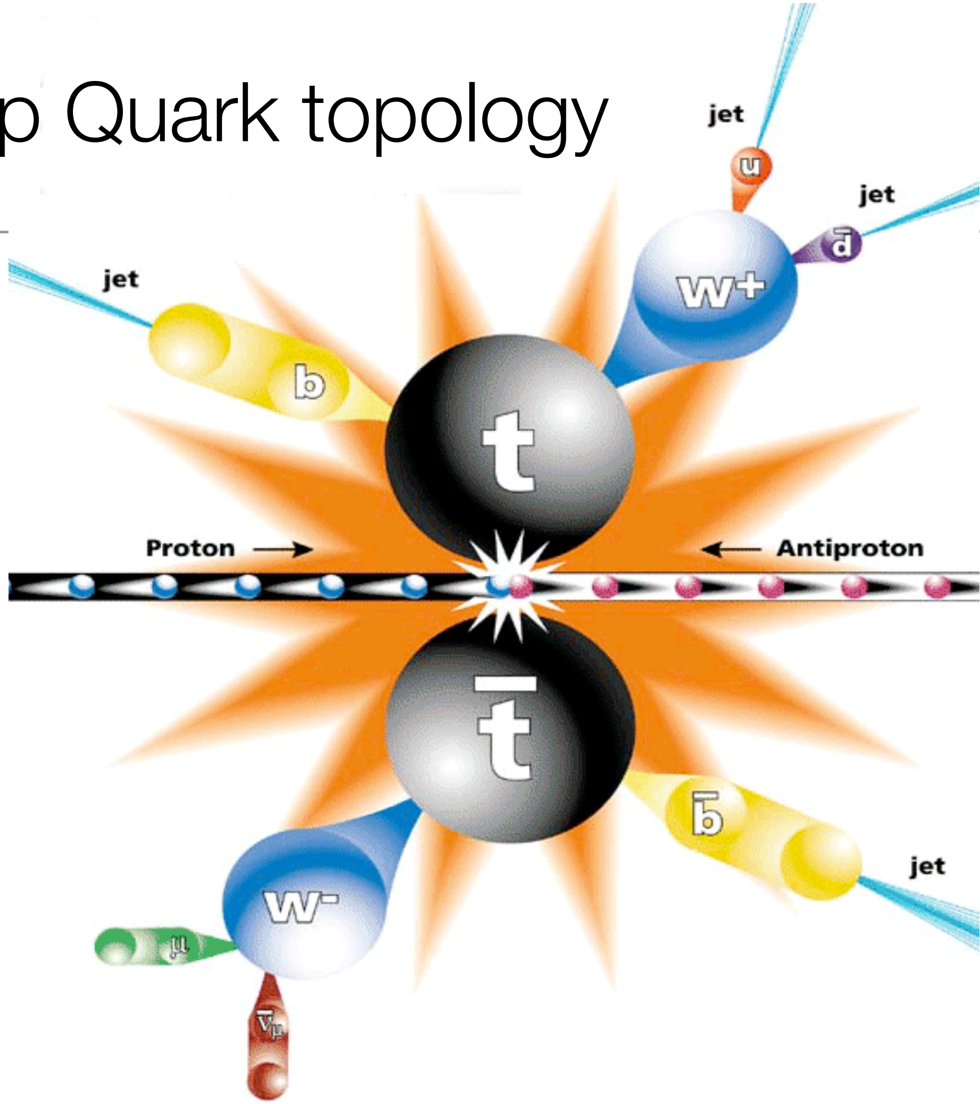
1995 Official discovery, $m_t \approx 175$ GeV
[CDF and DØ @ Tevatron]



Top Quark topology



Top Quark topology



A. $t\bar{t} \to W^+ b W^- \bar{b} \to q \bar{q}' b q'' \bar{q}''' \bar{b}$, (45.7%)
B. $t\bar{t} \to W^+ b W^- \bar{b} \to q \bar{q}' b \ell^- \bar{\nu}_\ell \bar{b} + \ell^+ \nu_\ell b q'' \bar{q}''' \bar{b}$,(43.8%)
C. $t\bar{t} \to W^+ b W^- \bar{b} \to \ell^+ \nu_\ell b \ell'^- \bar{\nu}_{\ell'} \bar{b}$. (10.5%)

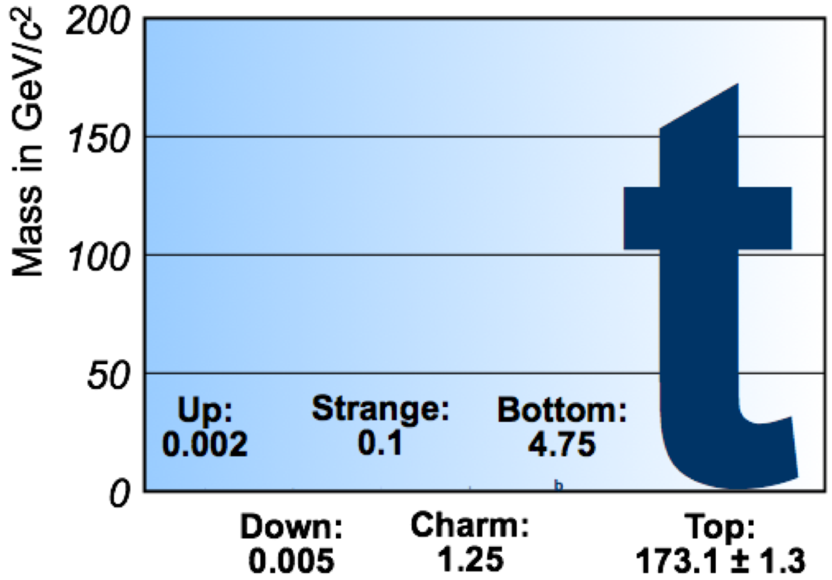
The quarks in the final state evolve into jets of hadrons. A, B, and C are referred to as the all-jets, lepton+jets (ℓ+jets), and dilepton ($\ell\ell$) channels, respectively.

Top Quark Properties

Top quark:

Mass: m_t = 173.3 ± 1.1 GeV
[2010 Tevatron combination]

Pointlike particle
with mass of gold atom
[35x heavier than b quark]



Mass in the Standard Model:

Yukawa coupling:
[see also later]

$$\mathcal{L}_{\text{Yukawa}} = -f\left[\bar{L}\phi R + \bar{R}(\phi^T)^* L\right] = -f\frac{v}{\sqrt{2}}\bar{q}q = -m_q\bar{q}q$$

Higgs vacuum expectation value: $v/\sqrt{2} \approx 175$ GeV,
i.e. $f \approx 1$ ➛ special role of top in EW symmetry breaking?

Top Quark Properties

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right],$$

Top quark lifetime: $\tau \approx 4 \times 10^{-25}$ s

From NLO QCD [experiment: only lower limits on τ]

Conversion to decay width: $\Gamma = \hbar c / c\tau \approx 1.4$ GeV

Compare with typical hadronization scale: $\Lambda_{QCD} \approx 250$ MeV

Important consequence: tops decay before hadronization

Top is the only “free” quark ➛ no bound states
[i.e. no toponium, top mesons/baryons]

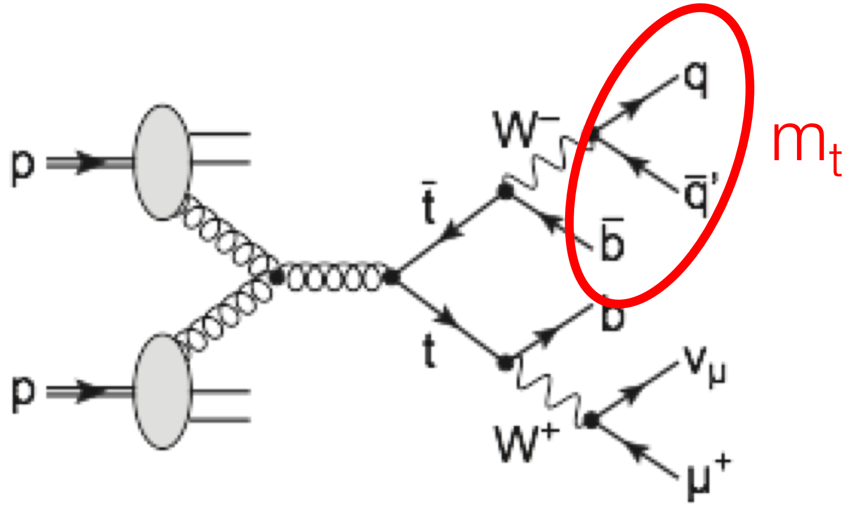
Spin/polarization passed on to decay productions
➛ direct access to quark properties

Physics program after top discovery: top properties
[Is the observed top really the 6th quark of the SM?]

Top as a "Standard Candle"

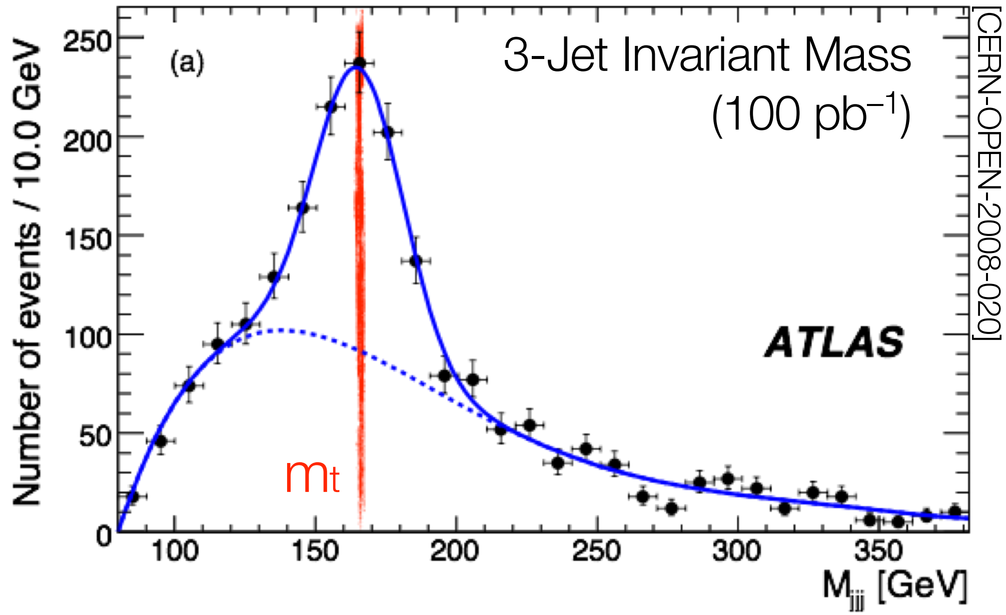
LHC: top also serves
as calibration source ...

- Produced copiously @ LHC
- Key background for new physics
- Final states contain everything ...
  [Leptons, MET, many jets ...]



Use top to calibrate e.g.

- jet/b-jet energy scale ...
  [jets/b-jets copiously produced]
- B-tagging algorithms ...



Top Physics at the LHC

1. "Rediscovering" top, i.e. measure cross section
2. Use top as a calibration source
3. High-precision top quark mass measurements
4. Single Top
5. Measure top properties [beyond mass & cross section]

   Electroweak couplings, spin correlations, asymmetries

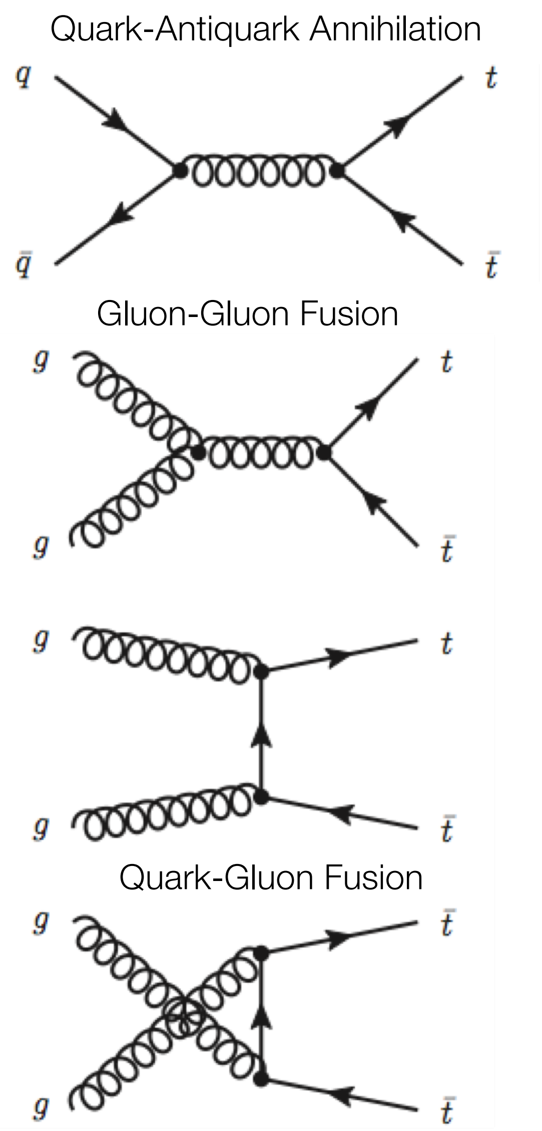
   Many measurements @ Tevatron limited by statistics ...
   LHC @ 10 TeV: 40k top pairs produced in 100 pb^{-1} ...
   [i.e. present Tevatron statistic almost after first year]

5. Search for new physics with top ...

   Enhancement of rare production/decay channels ...

   Heavy new particles decaying into top pairs ...

Top Pair Production



Top pair production

[discovery channel at the Tevatron; 1995]

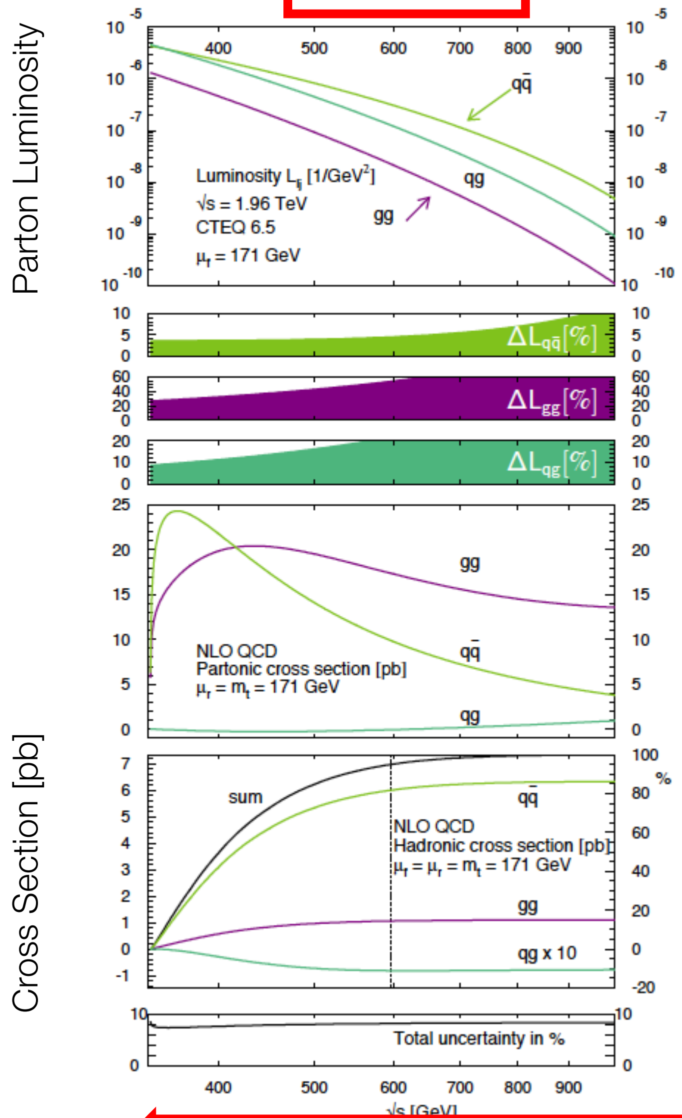
- 2x cross section of single top production
- Much better signal-to-background ratio than single top

Partonic sub-processes

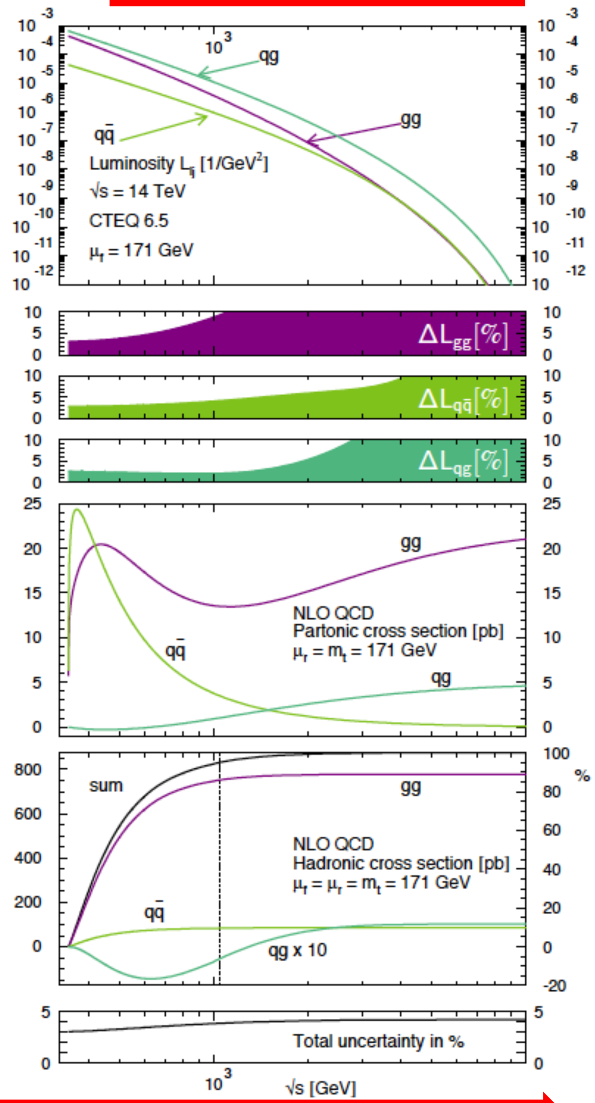
- Quark-antiquark annihilation ...
  - dominant at the Tevatron (85%)
  - less important at the LHC (10%)
- Gluon-gluon fusion ...
  - dominant at the LHC (90%)
  - less important at the Tevatron (15%)
- Quark-gluon fusion ...
  - not possible at LO, few percent contributions ...

Cross sections Top Pair Production

Tevatron



LHC [√s = 14 TeV]



Partonic cms

Master formula:

cross section = parton lumi × partonic cross section

$$\frac{d\sigma}{d\tau} = \sum_{jk} \frac{dL_{jk}}{d\tau} \cdot \hat{\sigma}_{jk}$$

LHC cross section:

ca. 100 x Tevatron

Moch, Uwer, [Phys. Rev. D78 (2008) 034003]

Cross Section Calculation

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{obs} - N^{bkg}}{\int \mathcal{L} \, dt \cdot \varepsilon}$$

Luminosity

determined by accelerator, triggers, …

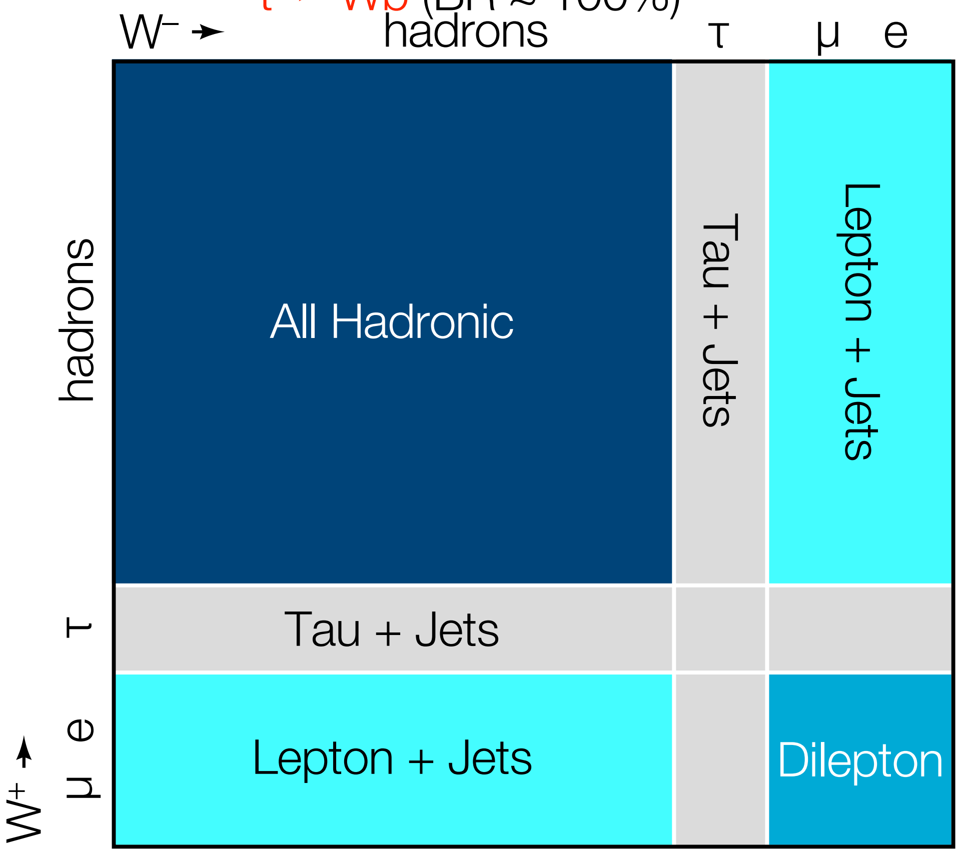
Efficiency

many factors, optimized by experimentalist

Top Quark Decays

SM top decay:

t → Wb (BR ≈ 100%)



Characterise top quark signatures by W decays:

All-Hadronic: 6 jets
[large QCD background]

Lepton+Jets: “gold-plated”

- Lepton, ν, 4 jets (2 b-jets)
- Lepton suppresses QCD, 24 possible jet combinations

Dilepton: interesting @ LHC

- 2 leptons, 2 ν, 2 b-jets
- very clean, ν ambiguities

The final states for the leading pair-production process can be divided into three classes:

A. $t\bar{t} \to W^+ b\, W^- \bar{b} \to q\, \bar{q}'\, b\, q''\, \bar{q}'''\, \bar{b},$ (45.7%)

B. $t\bar{t} \to W^+ b\, W^- \bar{b} \to q\, \bar{q}'\, b\, \ell^-\, \bar{\nu}_\ell\, \bar{b} + \ell^+\, \nu_\ell\, b\, q''\, \bar{q}'''\, \bar{b},$ (43.8%)

C. $t\bar{t} \to W^+ b\, W^- \bar{b} \to \ell^+\, \nu_\ell\, b\, \ell'^-\, \bar{\nu}_{\ell'}\, \bar{b}.$ (10.5%)

Cut-Based Signal Selection

Selection criteria ["cuts"]

designed to isolate signal from background ...

Optimize e.g. on:

Signal-to-background ratio

$$N_{sig}/\,N_{bkg}$$

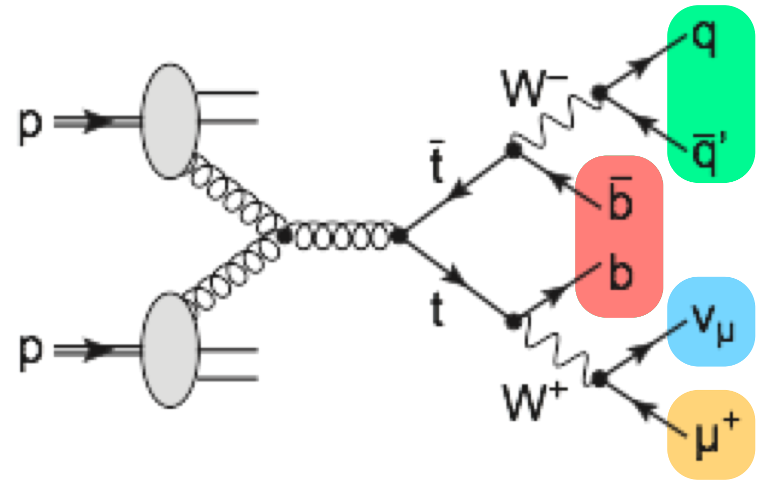
Signal significance

$$N_{sig}/\sqrt{N_{bkg}+N_{sig}}$$

Optimization uses MC or control samples

Don't optimize looking at the signal in data! BLINDED ANALYSIS

Example: Top Lepton+Jets Decay



high-p_T lepton: $p_T > 20$ GeV

neutrino: MET > 30 GeV

4 high-p_T jets: $p_T > 40$ GeV

2 b-jets: 1 or 2 b-tags

B-Tagging

Interesting particles decay into final states with b quarks

e.g. t ➛ Wb, H ➛ bb ...

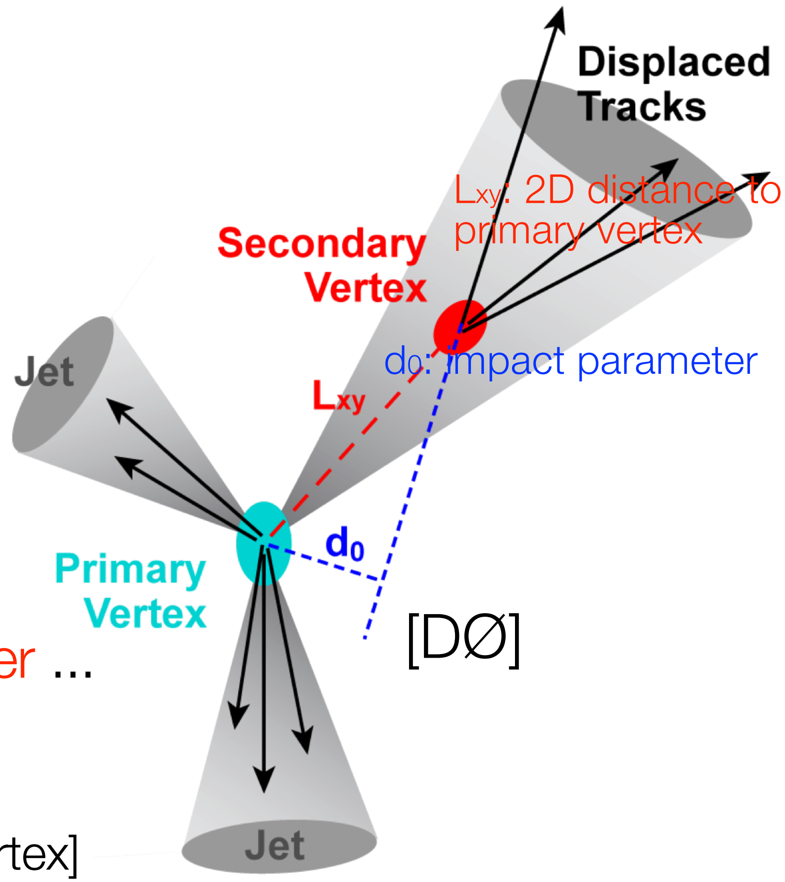
Thus: need powerful "b-tagging" ...

Approach I: Life time

B hadrons are massive and "long-lived" [cτ of $B^{\pm}$: 491 μm]

i.e.: tracks with large impact parameter ...

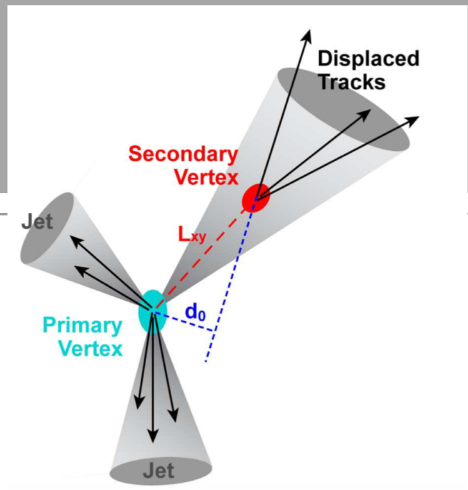
Displaced secondary vertex with large "vertex mass" ... [inv. mass of all charged particles in vertex]

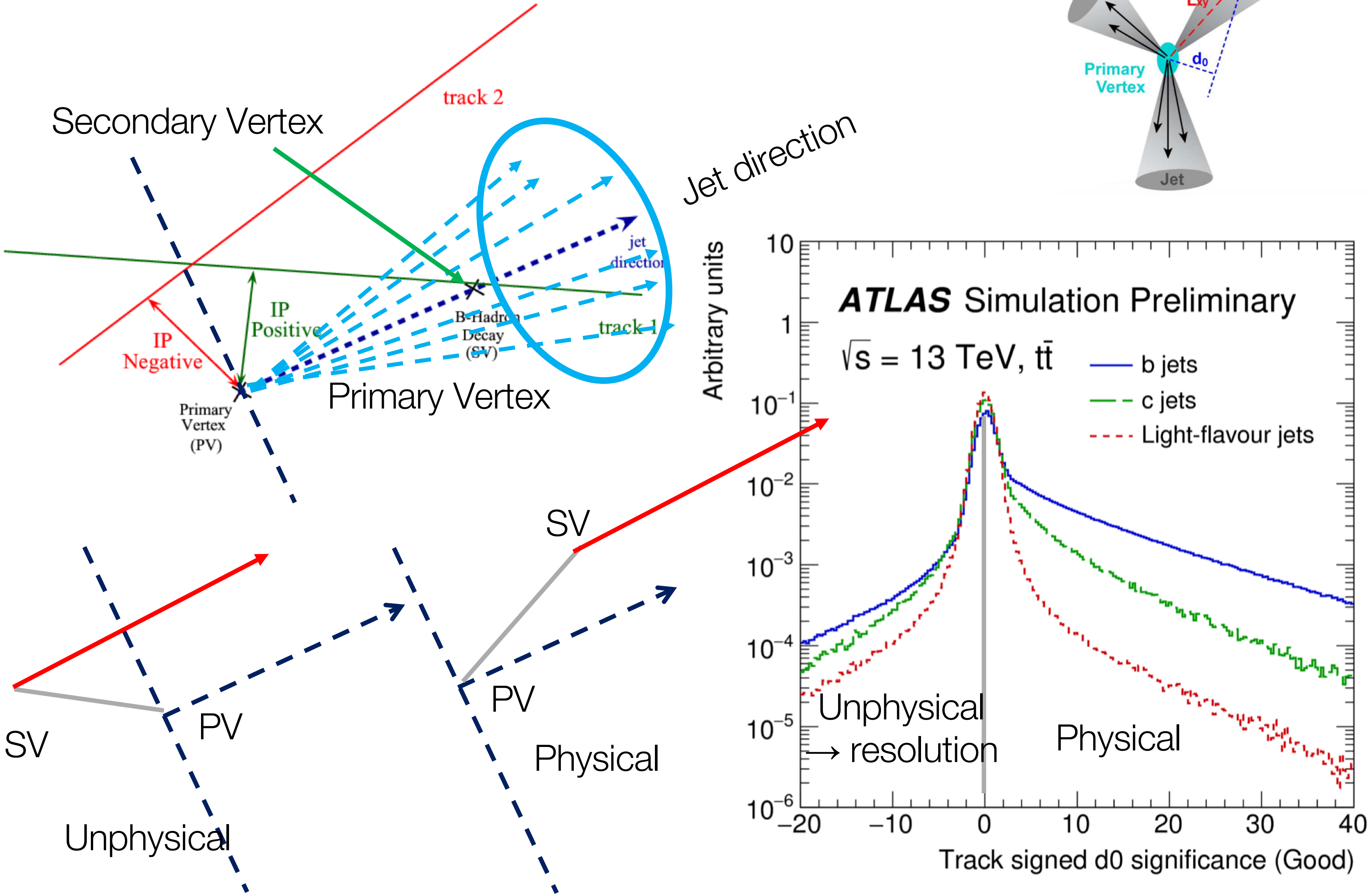


Approach II: Semileptonic decays [B → lνX]

Select jets with soft leptons ...

Signed Impact Parameter (δ)





B-Tagging in ATLAS & CMS

Design goals for b-taggers

- High selection efficiency for real b-jets ["tagging efficiency"]
- High rejection power for "fake" b-jets [low "mistag rate"]
- Robustness, e.g. against mis-alignment ...

Need trade-off

ATLAS default	CMS default
Likelihood ratio tagger $$w_{jet} = \sum_{\text{observables } j} \sum_{\text{tracks } i} \ln \frac{b_i(S_j)}{u_i(S_j)}$$ b_i, u_i: probability for b, light flavor jet S_j: any observable sensitive to heavy flavor, in ATLAS both 3D impact parameter and 2D secondary vertex	Comb. secondary vertex tagger [Likelihood ratio with many inputs] vertex mass, track multiplicity, secondary vertex significance, fractional energy of secondary particles, track rapidities, impact parameter significance

B tagging in ATLAS - 1

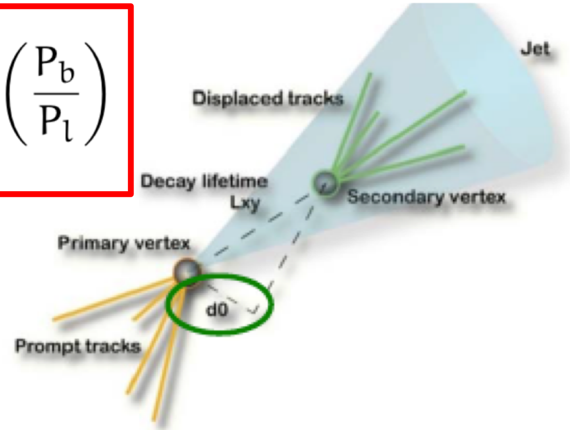
- Impact parameter (IP) base

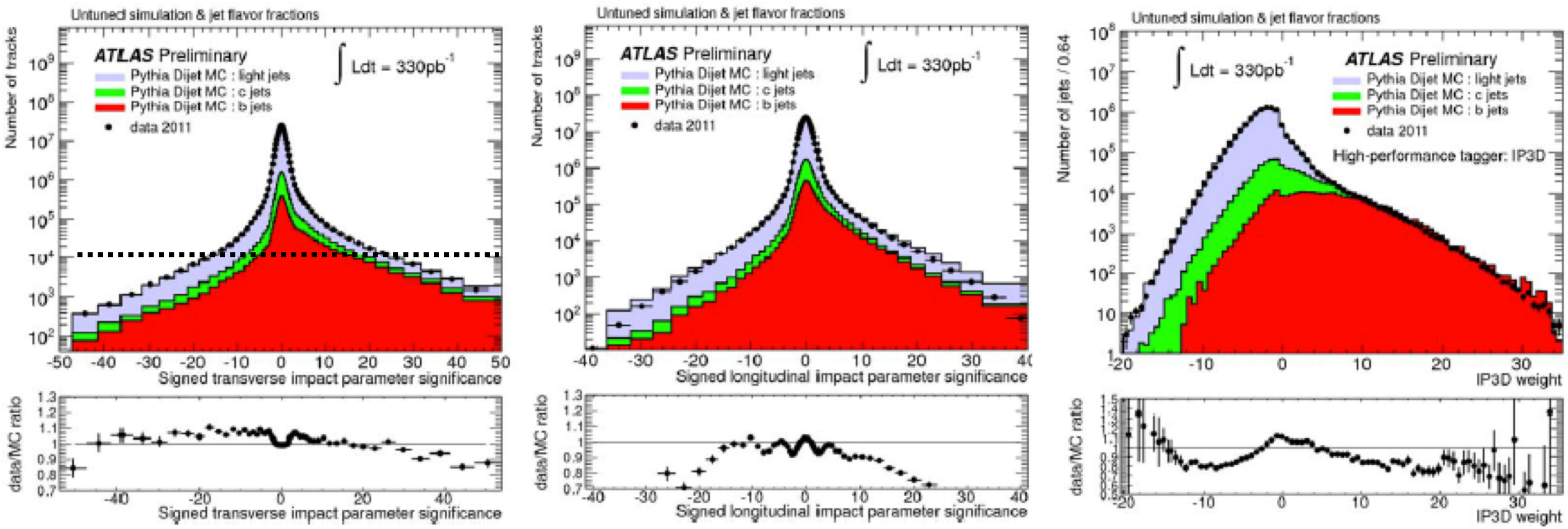
  IP3D: Log-likelihood base algorithm

  - Use transverse and longitudinal IP significance as the PDFs
  - $w_{track} = p_b / p_l$
  - $w_{jet} = \Sigma_{track} \log(w_{track})$

$$\text{IP3D} = \sum_{\text{tracks}} \log\left(\frac{P_b}{P_l}\right)$$

p_b distribution b-tagged,
p_l distribution light quark





B-Tagging algorithms in ATLAS

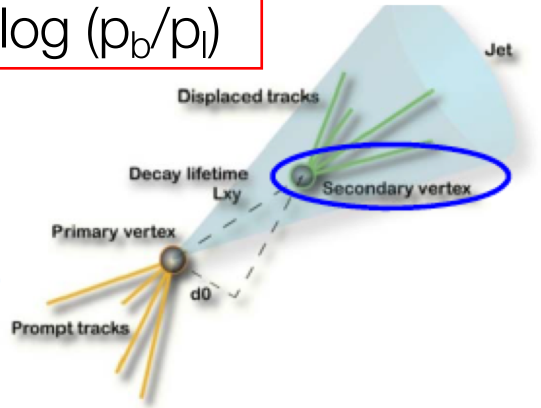
- Secondary vertex (SV) base

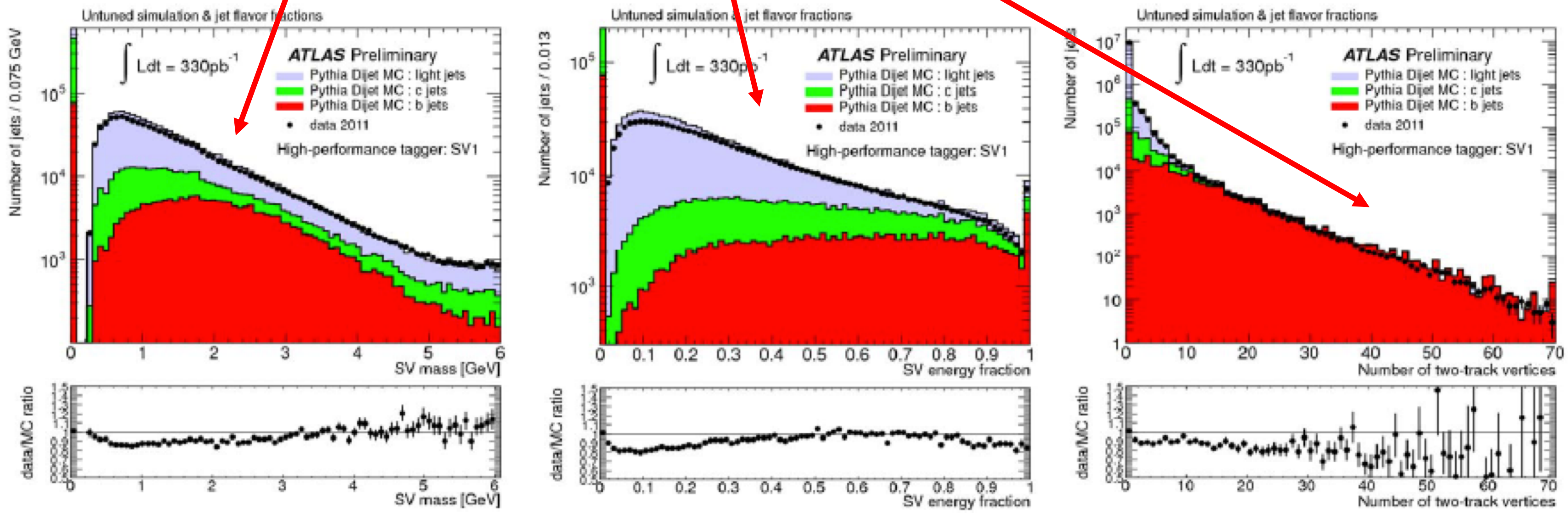
  SV1: Log-likelihood base algorithm

  - reconstruct SV and take likelihood ratio of:

    - 2D { SV mass, $\Sigma(P_T$ SV track$)/\Sigma(P_T$ all track in jet$)$ }
    - 1D number of two-track vertices
    - dR (jet-direction, PV→SV direction)

Likelihood ratio = $\log(p_b/p_l)$





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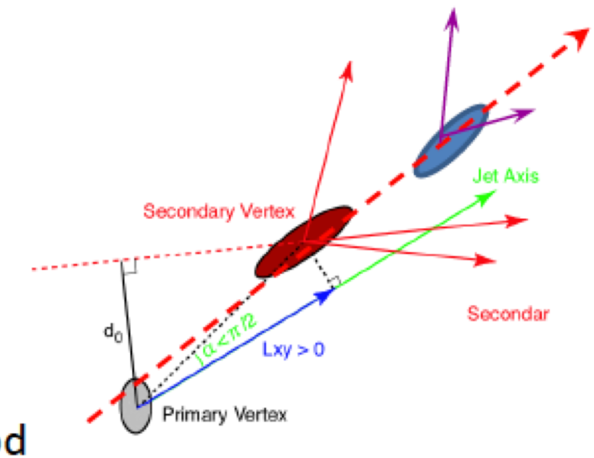
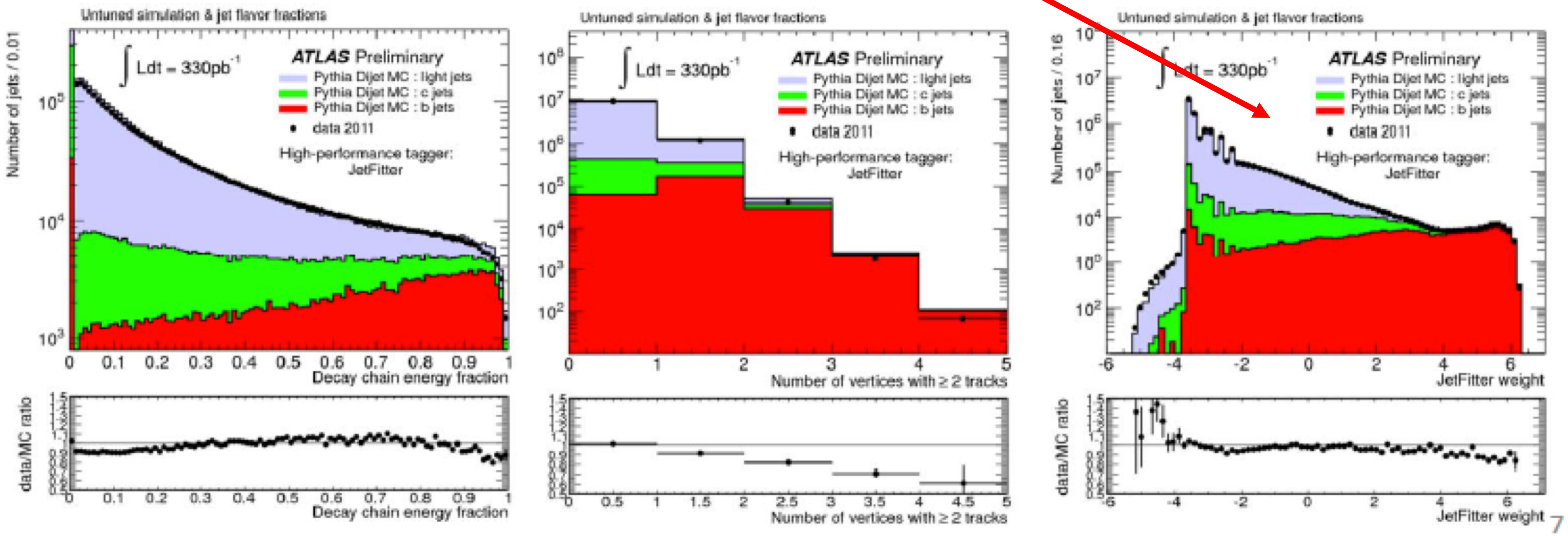
B-Tagging algorithms in ATLAS

- Secondary vertex (SV) base

  JetFitter: Special algorithm

  - Exploit the topology of weak B/C-hadron decay chain (b→c→X) inside jets
  - Use Kalman filter to find **a common line** on PV→b vertex → c vertex decay chain
  - Discrimination of b/c/light-jets based on likelihood similarly as SV1.





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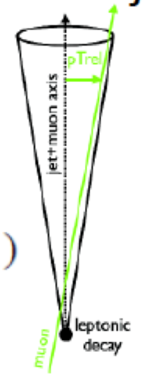
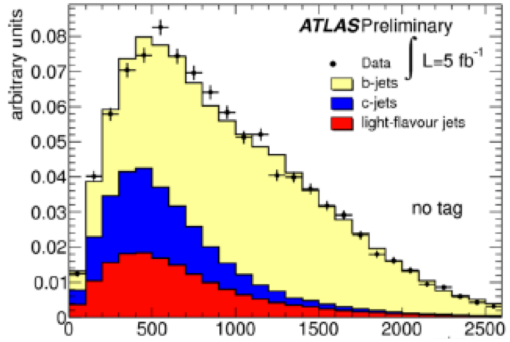
B tag algorithms calibration

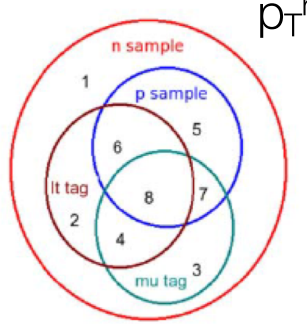
- B-tagging efficiency measurement in data with jets containing muon
  - **$p_T$rel**: Template fit of muon p_T respect to jet axis (p_T^{rel}) to get flavor fraction before and after b-tagging $\varepsilon_b = \frac{N_b^{tagged}}{N_b}$

$$p_T^{rel} = p \times \sin(\theta_{\mu-\{jet+\mu\}})$$





  - **System8**: Define 3 independent jet selection criteria to construct 8 samples.
    Use event counts to solve for b-tagging efficiency.
    (muon tag, life time tag, opposite side tag)



- Results combined to improve scale factor precision
  - Very good agreement b/w two methods
  - Total uncertainty is 5-19 %

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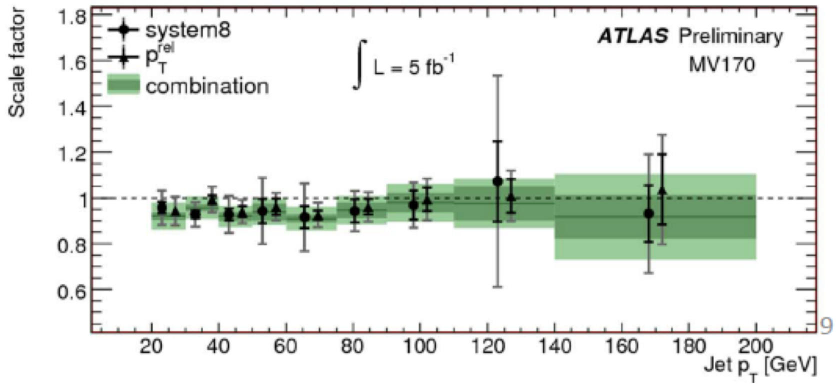


- **For high-p_T range, these calibration methods are taken over by ttbar method** (next page)

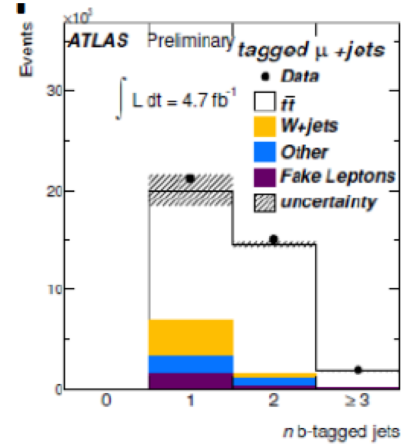
B tag calibration using ttbar events

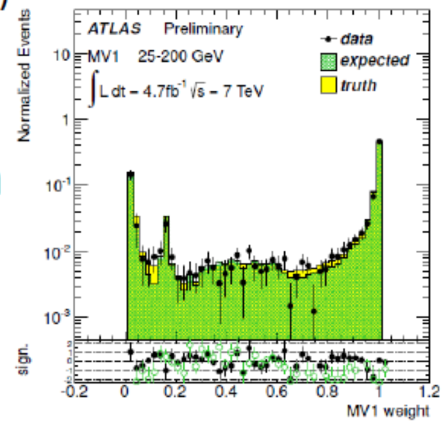
- Top events are nice calibration source due to its signature (t→Wb)

You expect two b quarks!!

- Calibration with di-lepton & single lepton channel
  - **Tag counting**: Use multiplicity of b-tagged jets
  - **Kinematic selection**: Measure tag rate for jets
  - **Kinematic fit**: Fit top-pair event topology

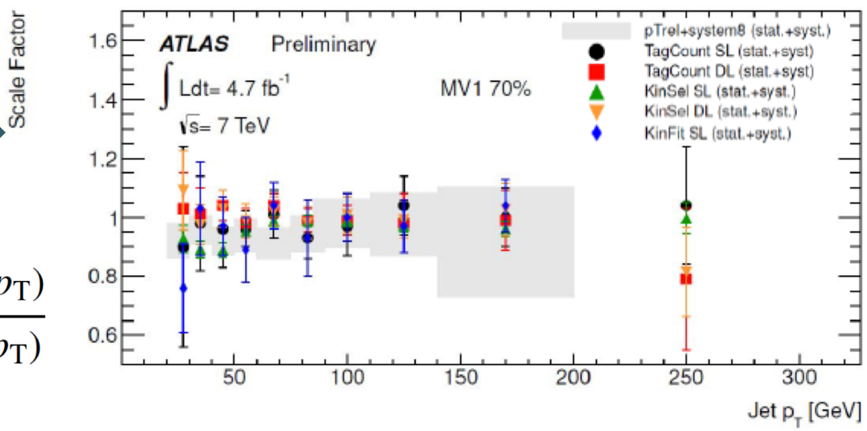
    to derive b-jet weight distribution (only l+jets)
- **Very good agreement among various method**
- **Also consistent result with muon-jet method**
- **Accuracy of ttbar calibration is ~2% for 2012 data**

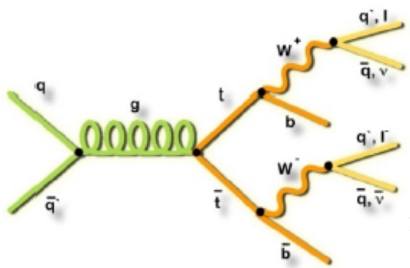




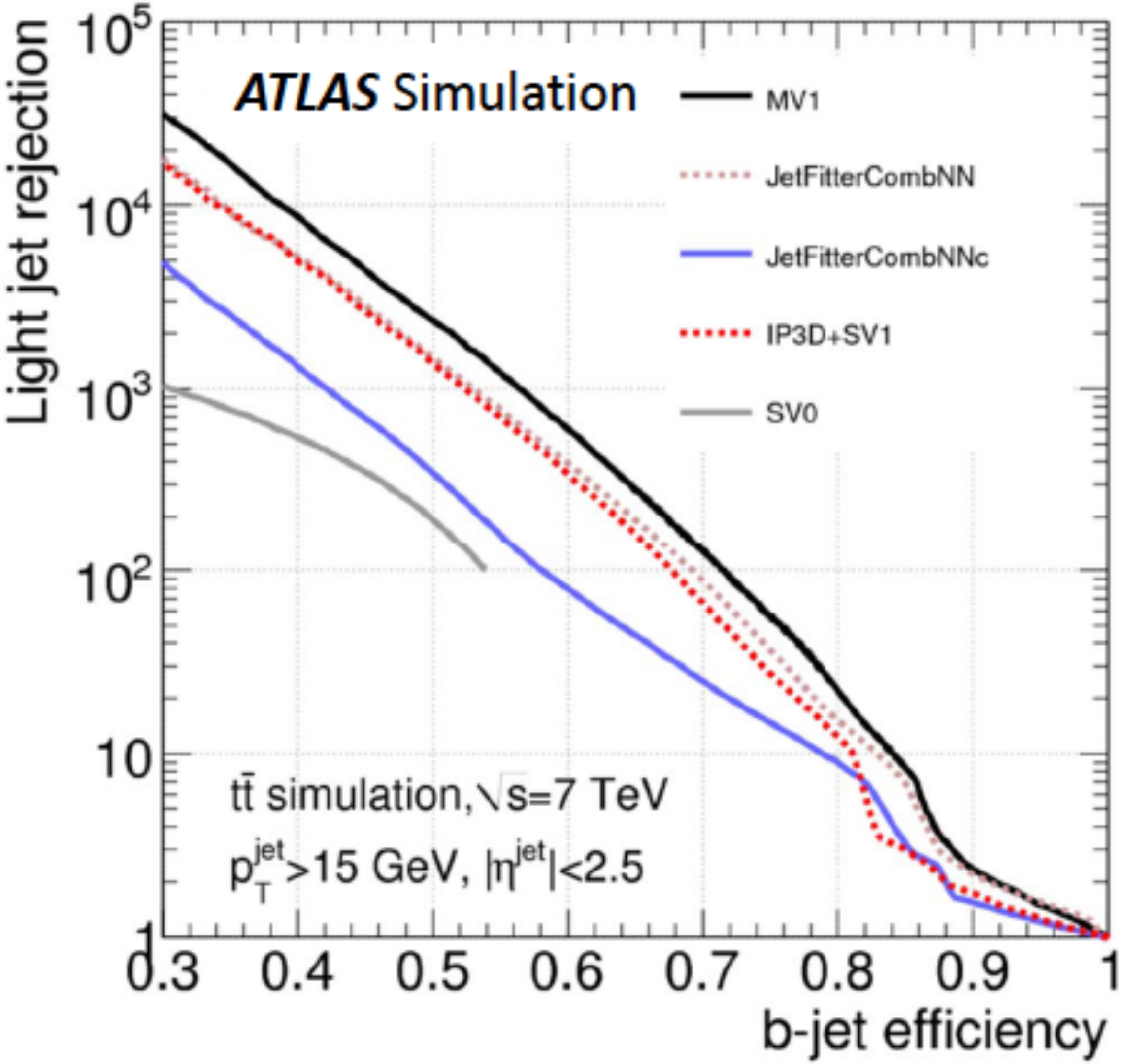
ATLAS-CONF-2012-097

$$\kappa_{\varepsilon_b}^{\mathrm{data/sim}}(p_\mathrm{T}) = \frac{\varepsilon_b^{\mathrm{data}}(p_\mathrm{T})}{\varepsilon_b^{\mathrm{sim}}(p_\mathrm{T})}$$





B tagging ATLAS: l-jet rejection vs b-jet efficiency



ATLAS-CONF-2012-043

Background in top-pair analysis

Physics background:

From data [control samples] & Monte Carlo simulation

Indistinguishable from signal and pass signal selection

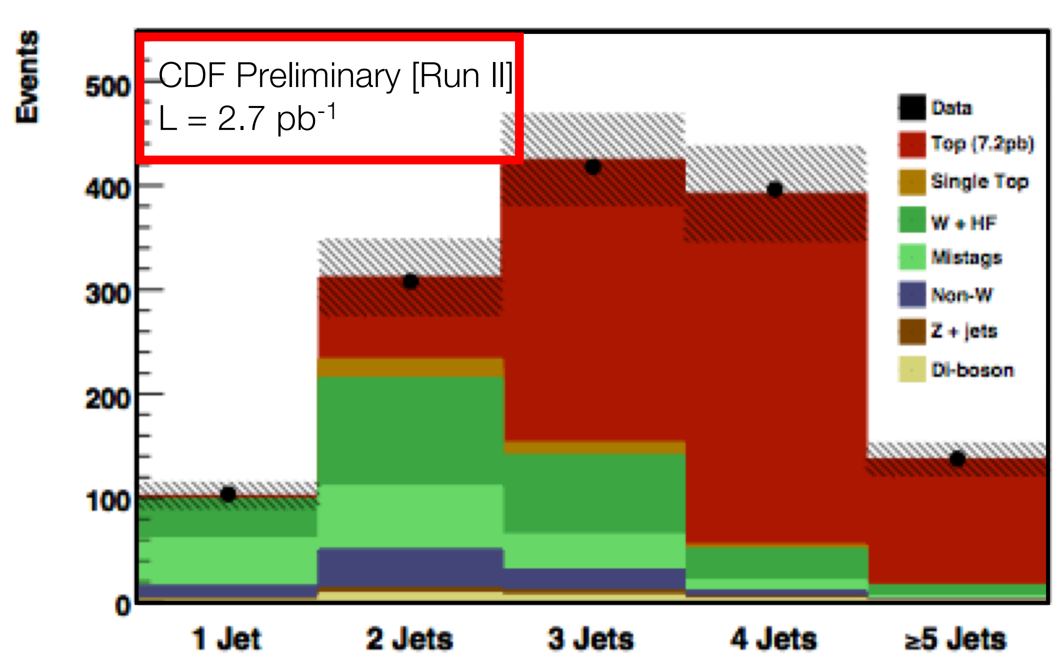
Instrumental background:

Estimation from data ...

Misidentification ...
[e.g. jet looks like (“fake”) electron]

Noise seen in detectors ...

Beam backgrounds …



CDF Note 9462
[http://www-cdf.fnal.gov/.../ttbar_secvtx_3invfb/]

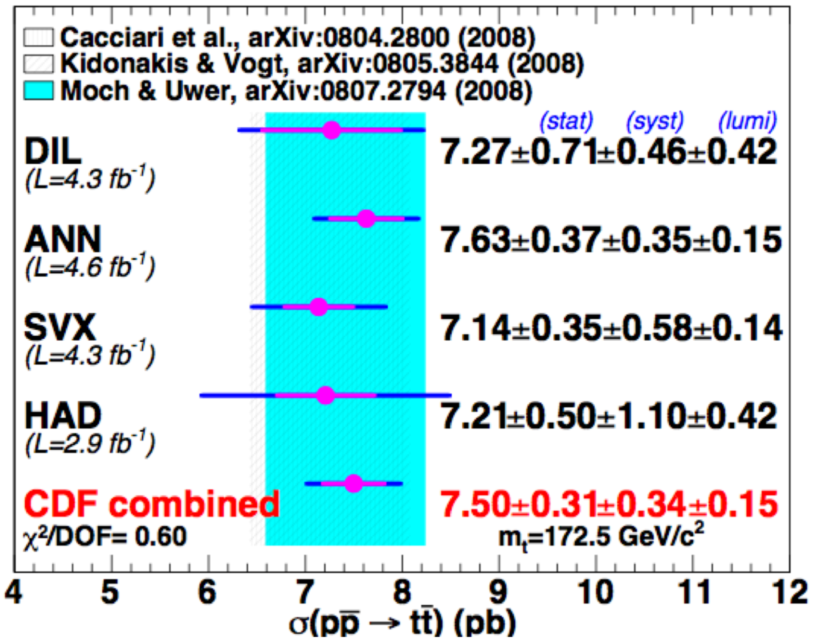
Top Pair Candidates

Predicted vs. observed events
as a function of jet multiplicity ...

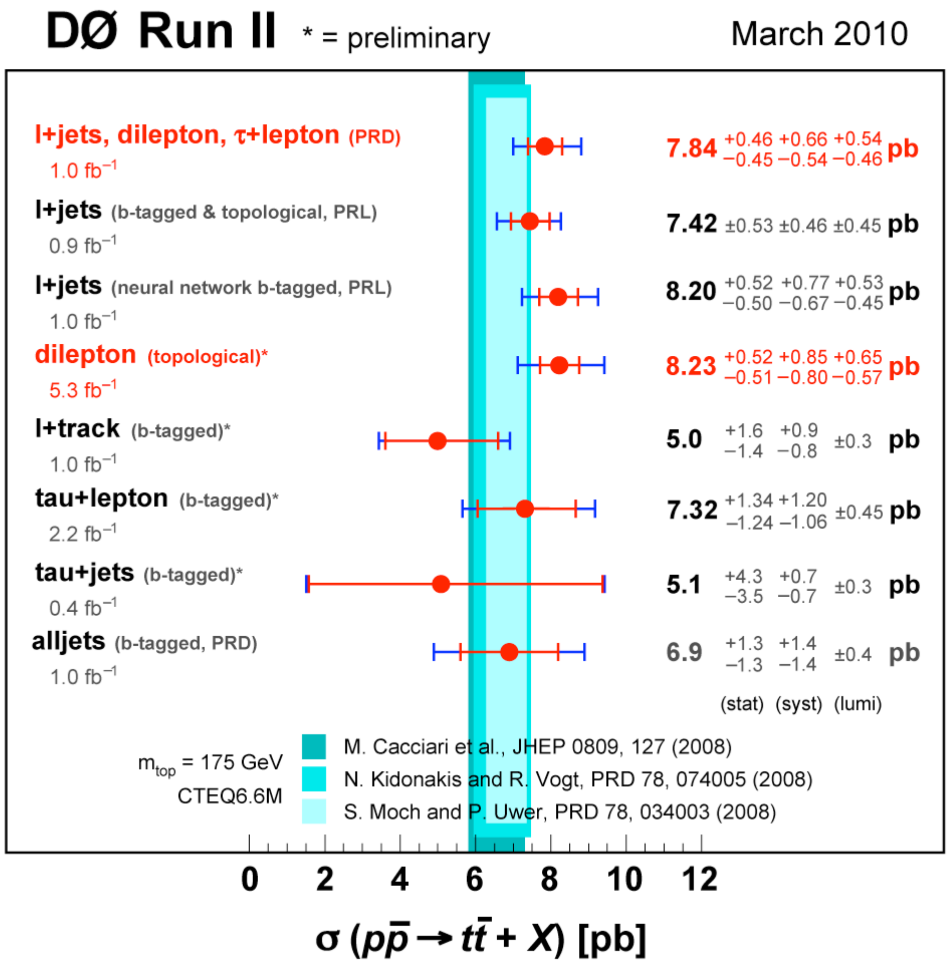
Tevatron Results

Remark: Cross section decreasing with increasing m_t

CDF [m_t = 172.5 GeV]



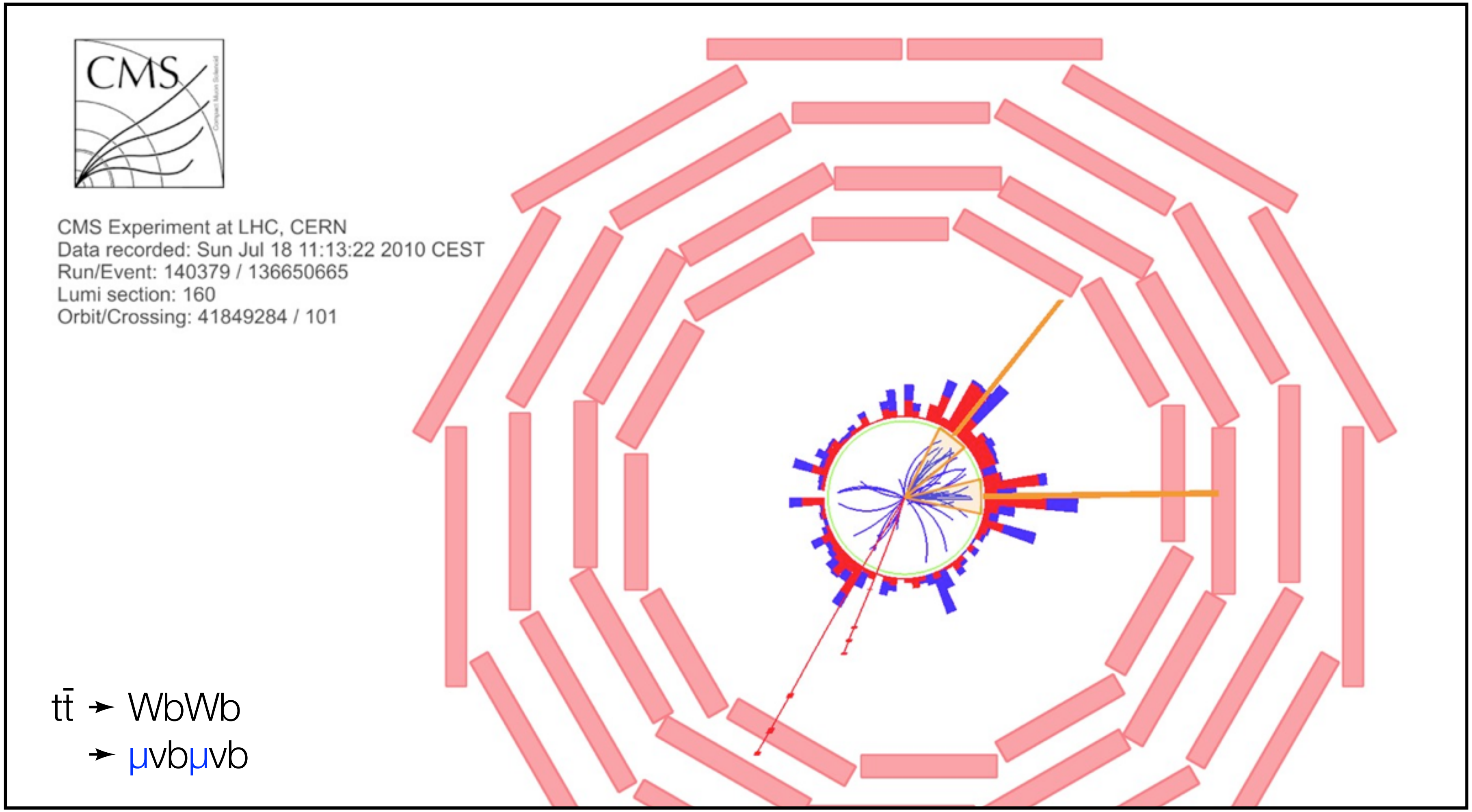
DØ [m_t = 175 GeV]



Measured cross sections agree well with theory

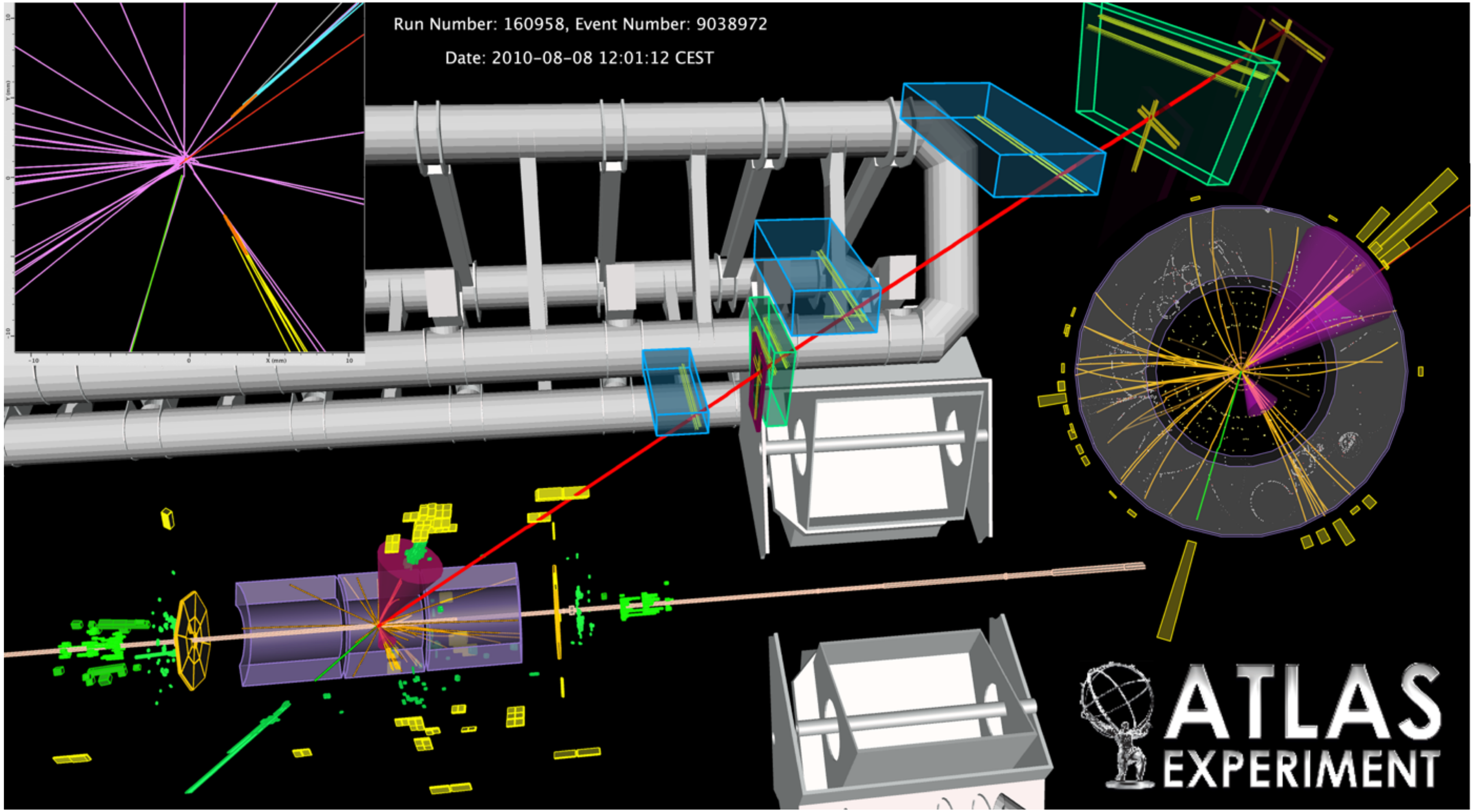
[NLO, approximate NNLO]

LHC Top Results



[CMS Top Candidate; Dimuon channel]

First LHC Top Results



[ATLAS Top Candidate; Dilepton (eμ) channel]

Theo uncertainties in tt-bar x-section

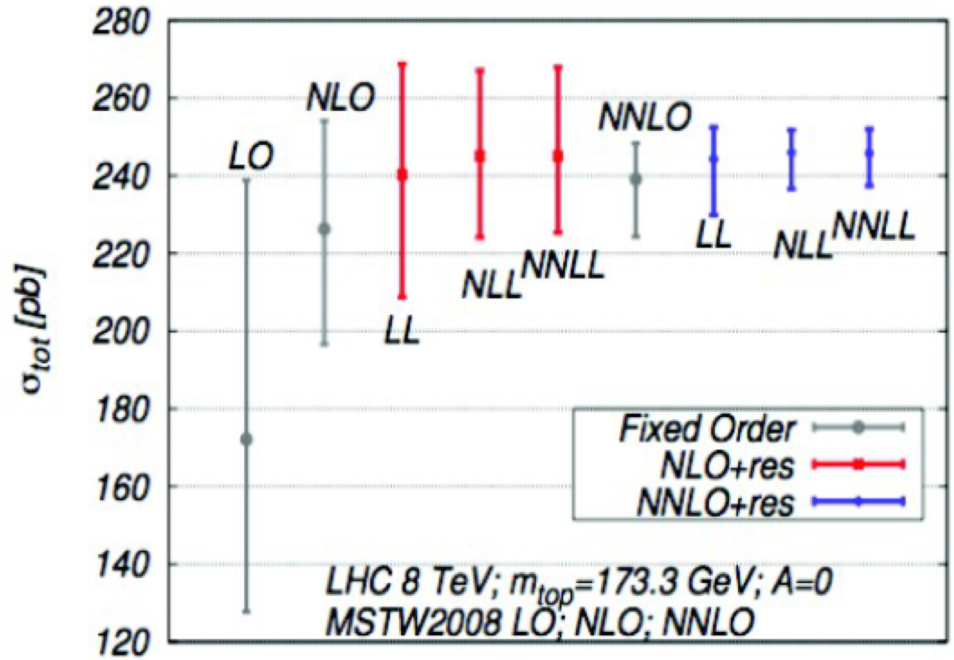
Long standing theoretical effort on fixed order QCD calculations
1989 NLO
1998 NLO+NLL
2008 NLO+NNLL
2013 NNLO+NNLL

Cross-Section rises by about 10% from NLO to NNLO+NNLL QCD

Precision improves from ~12% to ~3% (scale)
~ 8% to 5% (PDF)

Uncertainty on parton density function dominate

Electroweak corrections also sizeable $\alpha_s^2 \sim \alpha_{ew}$



Figures and numbers from:

Czakon, Mitov arXiv:1303.6254

Czakon, Mangano, Mitov, Rojo: arXiv:1303.7215

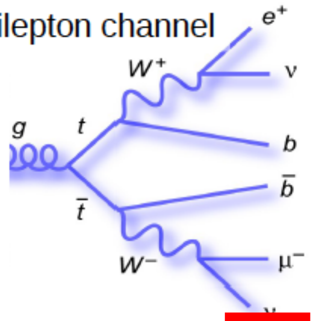
NNLO QCD calculation mandatory for precision analysis

centre-of-mass energy as $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$. Next-to-leading logarithmic (NLL) results for soft-log resummation have been available for a while [8, 9], and recently next-to-next-to-leading logarithmic (NNLL) cross sections resumming soft effects have been computed by several groups [10–12], thanks to a better understanding of the infrared structure of massive QCD amplitudes [13, 14] and to the calculation of the relevant anomalous dimensions [15, 16]. A combined resummation of soft

Top-antiTop x section

Top anti-top production cross section at 7 and 8 TeV

Dilepton channel



Select only electron and muon
Lepton-ID and isolation efficiency using Z->ll

Cross section measured counting b-jets

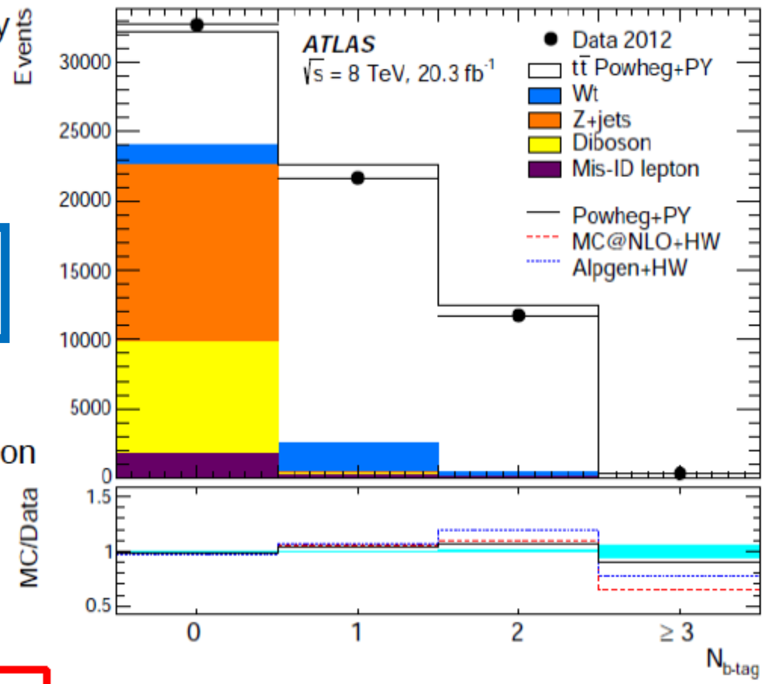
CR

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}\,2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}\,C_b\epsilon_b^2 + N_2^{\mathrm{bkg}}$$

b-jet acceptance and efficiency ϵ_b fitted with cross-section
$\epsilon_{e\mu}$ efficiency to pass lepton selection
kinematic correlation C_b of two b-jets taken from MC

ATLAS arXiv:1406.5375



Total inclusive top anti-top cross section

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb}\ (\sqrt{s} = 7\,\mathrm{TeV})$$

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}\ (\sqrt{s} = 8\,\mathrm{TeV})$$

	7 TeV	8 TeV
Precision achieved:	3.5%	4.0%

Uncertainties:	7 TeV	8 TeV
Statistics	1.7%	0.7%
Analysis systematics	2.3%	2.3%
Luminosity	2.0%	3.1%

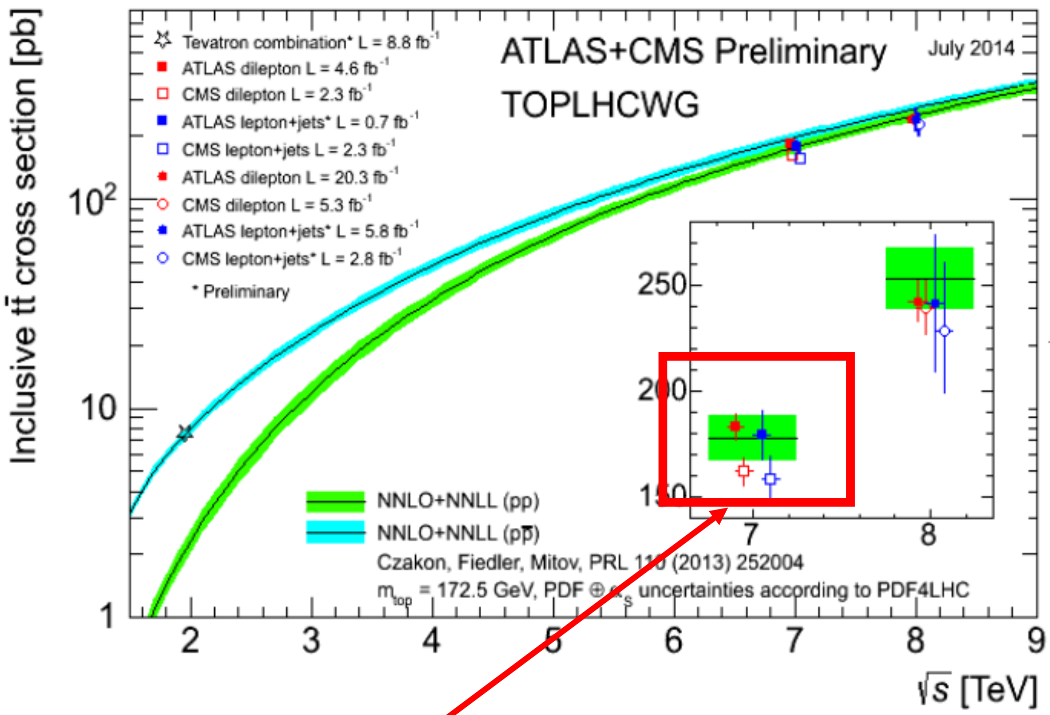
For data/theory also consider LHC beam energy uncertainty 0.6% → effect on ttbar cross section ~1.8%

Top-anti Top x-section results

Tancredi Carli (CERN)

XXXVII INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS ICHEP 2014

Summary of top anti-top production cross section measurements



Most precise results:

CMS JHEP 02 (2014) 024 JHEP 11 (2012) 067

ATLAS arXiv:1406.5375

Tevatron combination PRD 89 (2014) 072001

	Tevatron		LHC 8 TeV	
Precision	D0	CDF	ATLAS	CMS
total	7.8%	6.5%	4.3%	5.5%
stat	2.6%	4.0%	0.7%	0.8%
syst	4.3%	4.7%	2.3%	4.7%
lumi	6.1%	2.0%	3.1 %	2.6%

8 TeV: both measurements are in good agreement with NNLO+NNLL prediction
7 TeV: about 2 sigma tension between ATLAS and CMS measurements

Impressive experimental precision at Tevatron and LHC matching NNLO+NNLO precision of ~5%
LHC has already achieved better precision than latest Tevatron measurements

Excellent agreement of NNLO+NNLL predictions and precise experimental measurements

Single Top Quark Production Cross Section at the LHC in ATLAS

Andreas Wildauer

Max-Planck Institute for Physics, Munich, Germany

On behalf of the ATLAS Collaboration

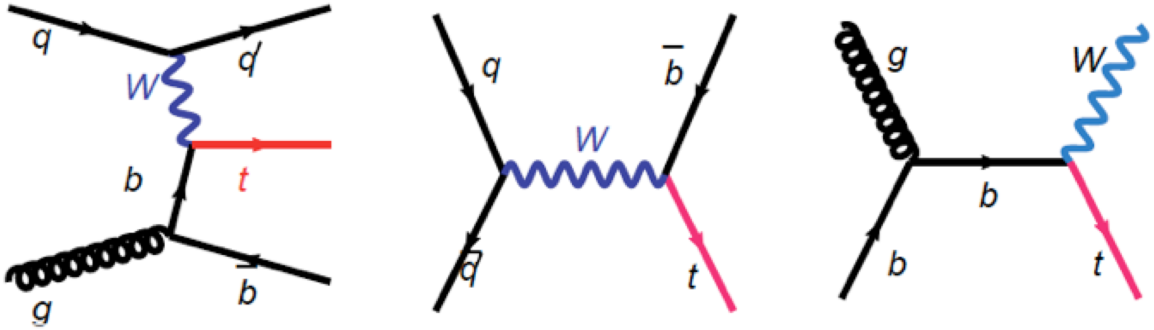
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Phenomenology 2013

May 6 – 8, 2013

University of Pittsburgh

Single Top production



σ_{theory} [pb]	t-channel	s-channel	Wt-channel
Tevatron	2.3	1.1	0.2
LHC 7 TeV	65.9	4.56	15.6
LHC 8 TeV	87.2	5.55	22.2

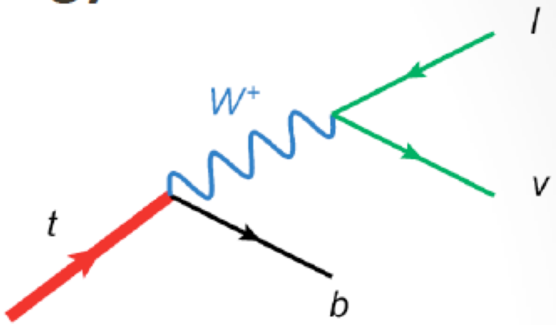
For m_t=173 GeV arXiv:1210.7813

Importance of single top

- Cross section is proportional to V_{tb}, test of unitarity of CKM
- 4th generation
- Test of b-quark structure function
- $t - \bar{t}$ cross section measurement can constraint PDF of u and d quarks
- Heavy W', charged H^+
- Anomalous couplings or FCNC in single top production

Event topology

- t-channel and s-channel: **single lepton topology**
- Wt-channel: **di-lepton topology**

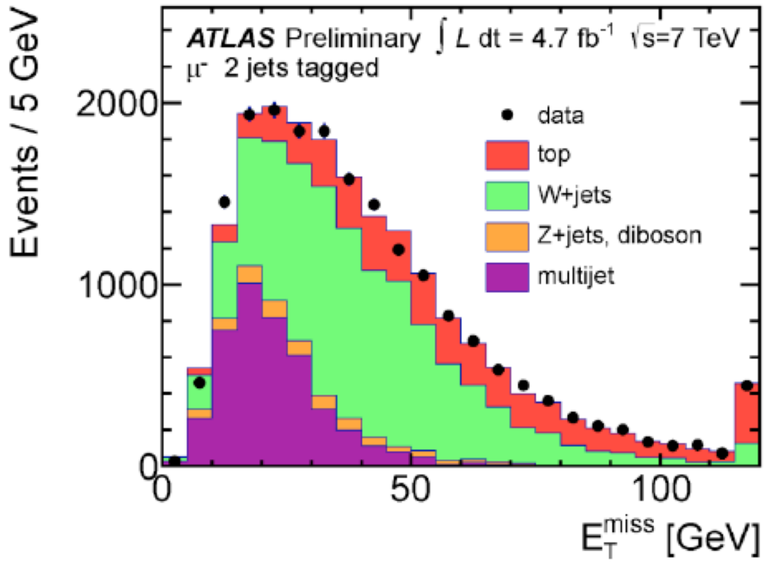


- Trigger on isolated high-p_T lepton
- Offline Event Selection
  - Lepton(s): isolated, central, $p_T > 25$ GeV
  - Jets: anti-kT (R=0.4), $|\eta| < 2.5$ (<4.5 for t-channel) $p_T > 25$-30 GeV
  - b-Jets: multivariate combination
    - ε_b = 50-60%, light jet rejection ~ 1:500
  - $E_T^{miss} > 25$-30 GeV
  - Transverse mass M_T of lepton and E_T^{miss} system > 30 GeV

Backgrounds, Multijets, Fakes

- Significant background for single lepton topology
- Passes selection if jet is mis-reconstructed as lepton
- s- and t-channel: jet-electron model (for fake electron and muon)
- Wt-channel: matrix element method

Shape:
Accept events with jets with electron-like properties
Normalisation:
max. likelihood fit to E_T^{miss} after event pre-selection



Combine probability of loosely selected real/background leptons to be reconstructed as tight lepton in the event

Background, W+jets, Z+jets

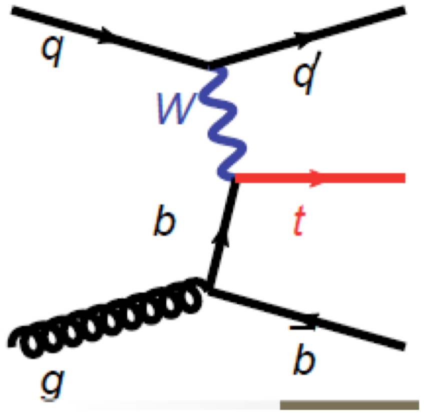
- similar topology as signal due to 1(2) leptons from W(Z) decay
  - especially if additional jets are b-jets
- Overall normalisation
  - s-channel: from data after subtraction of non-W background
  - t-channel: fit of the data to Monte Carlo
- Flavor composition: use tag counting method
- Scale Monte Carlo with E_T^{miss}/M_{ll} distribution to data in sideband with corrections from non-Z background

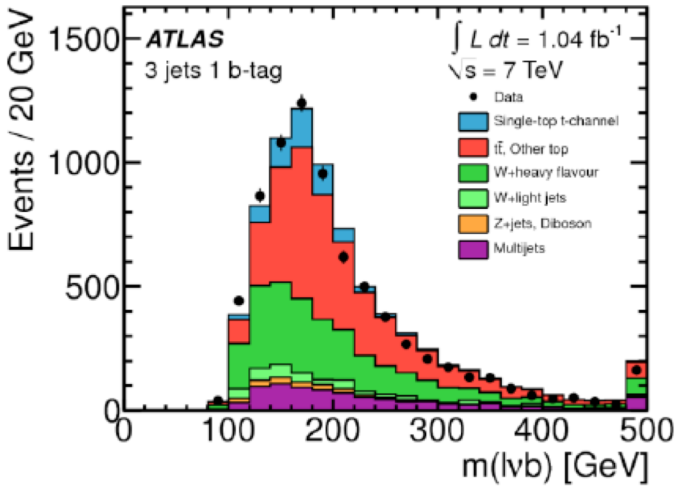
---

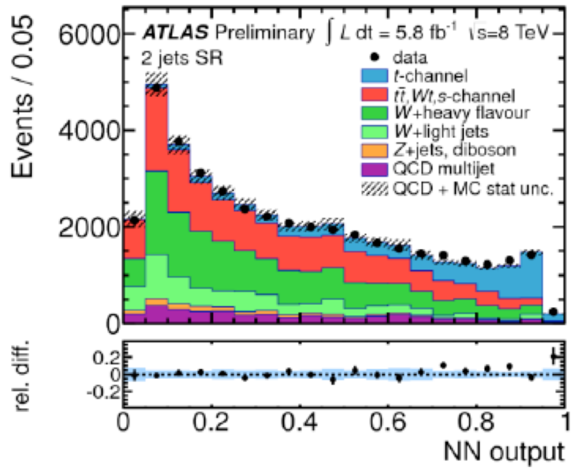
- All other backgrounds are taken from Monte Carlo using theoretical predictions for the cross sections
  - $t\bar{t}$, di-boson (WW,ZZ,WZ), s-, t-, Wt-channel

t-channel

- Measured at 7 TeV with 1.04/fb and 8 TeV with 5.8/fb
- Dominant backgrounds: $t\bar{t}$, multijets, W+jets
- Events with 1 lepton, 2 or 3 jets, exactly 1 b-tagged
- Multivariate analyses with maximum likelihood fit on full neural network output



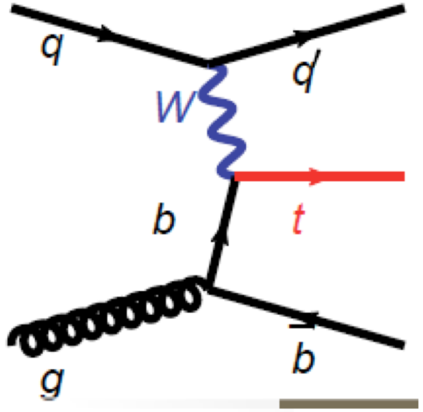


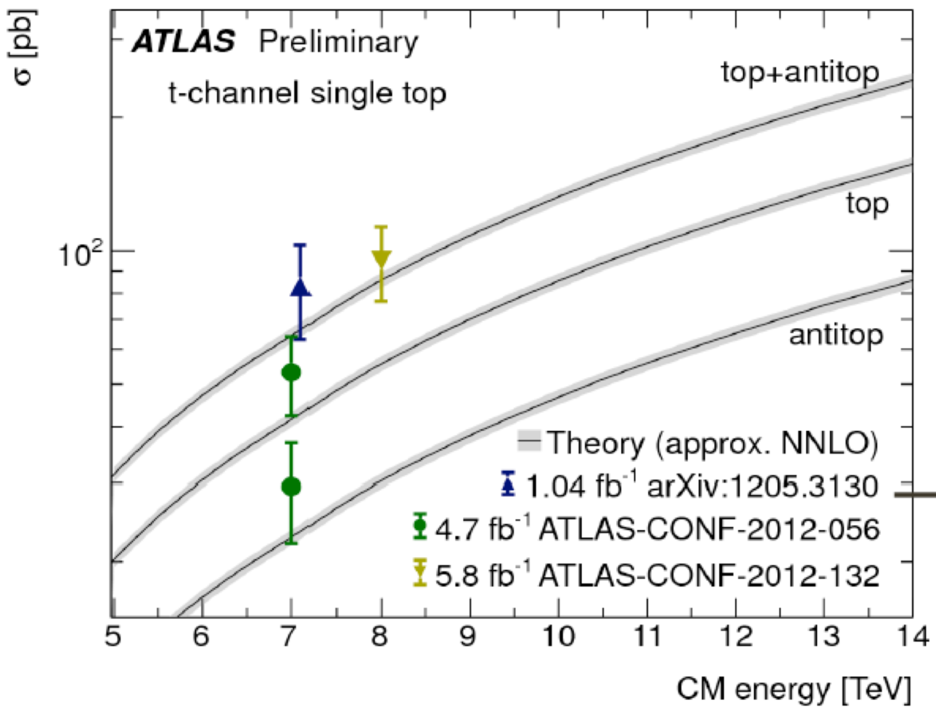


- 8 TeV: +35% signal cross section expected
  - But also: +40% $t\bar{t}$ and 25-35% W+jets cross section
- More pile-up due to higher inst. luminosity in 8 TeV data

t-channel Single Top

	Cross Section [pb]	V_{tb}	V_{tb} > X (@ 95% CL if V_{tb} [0,1])
7 TeV	83 ± 4 (stat) ± 20 (syst)	1.13 ± 0.14	0.75
8 TeV	95 ± 2 (stat) ± 18 (syst)	1.04 ± 0.11	0.80

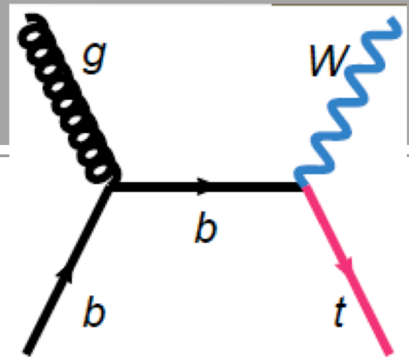




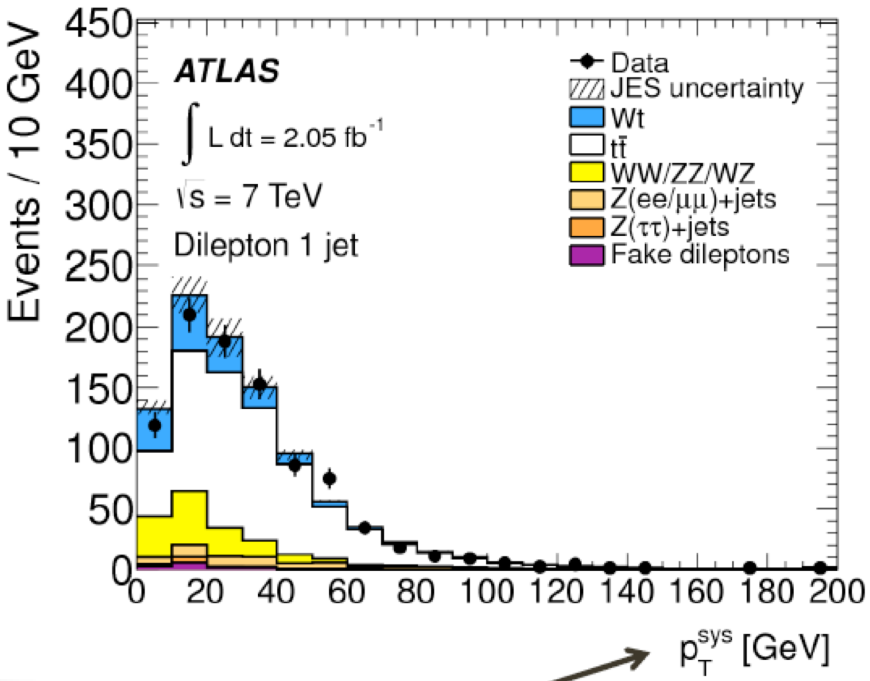
- Largest systematics for XS 7/8 TeV
  - ISR/FSR: 14% / 9%
  - b-tagging: 13% / 8.5%
  - Jet energy scale: 6% / 7.7 %

→ Now published in:
Phys. Lett. B 717 (2012) 330-350

Wt channel



- Measured at 7 TeV with 2.05/fb
- Backgrounds: $t\bar{t}$, di-lepton, di-boson, Drell-Yan (Z->ll)
- Events with 2 leptons, 1 central jet but no b-tag requirement
- Profile likelihood method on boosted decision tree output



σ = 17 ± 3 (stat) ± 5 (syst) pb

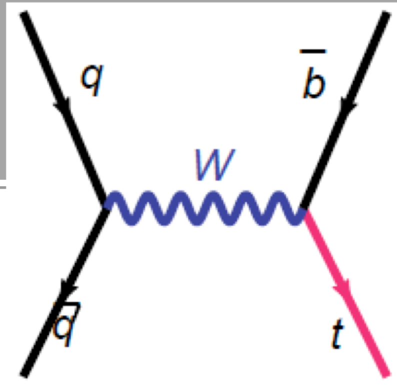
at 3.3σ level (3.4σ expected)

$V_{tb} = 1.03^{+0.16}_{-0.19}$

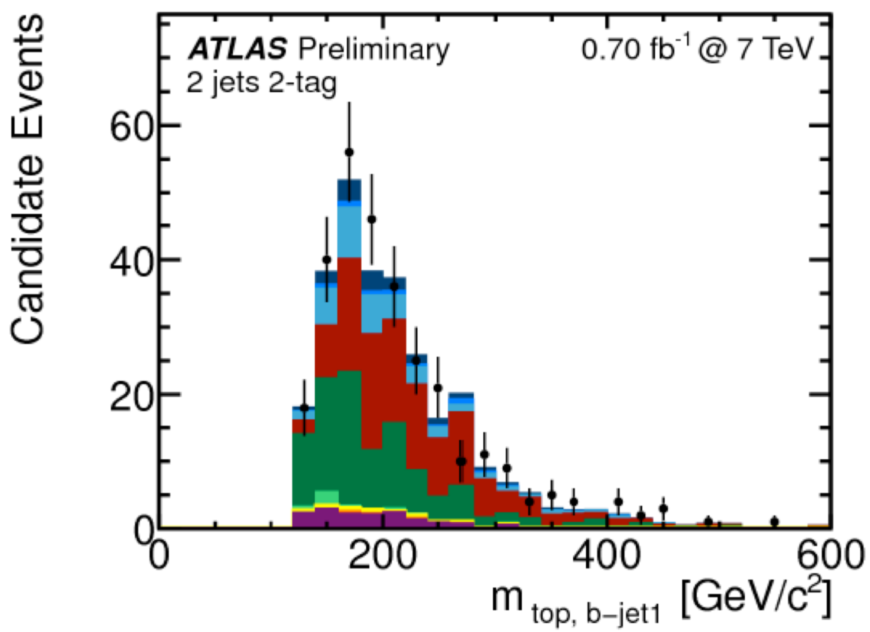
- Largest Systematics
  - Jet Energy Scale 16%
  - Parton Shower Model 15%
  - Pile Up, Generator 10%

Most sensitive variable: sum of p_T of all objects + E_T^{miss}

S-Channel



- Measured at 7 TeV with 0.70/fb
- Backgrounds: W+jets, $t\bar{t}$, multijets
- Events with 1 lepton, exactly 2 jets, exactly 2 b-tagged
- Cut based analysis, select discriminating variables by optimizing signal over (square root of) background ratio



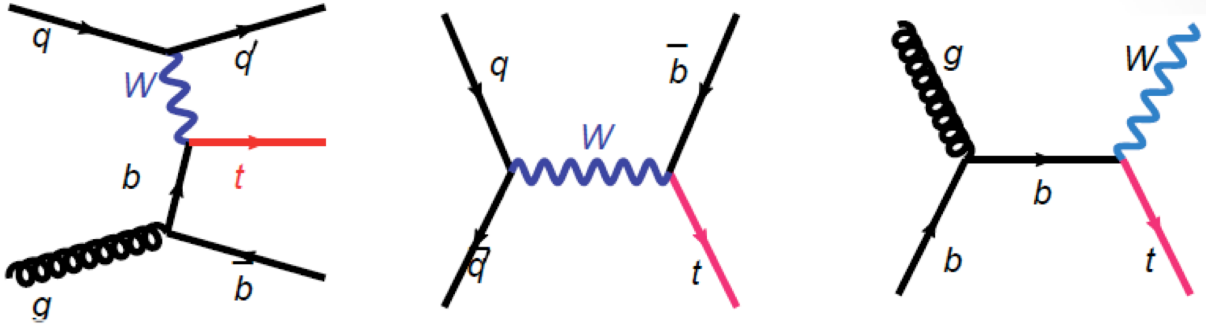
- Expected events MC
  - Signal 16 ± 1
  - Background 285 ± 17
- Observed events data: 296

$\sigma < 26.5$ pb $= 5 \times \sigma_{SM}$@95% CL

- Systematic uncertainties
  - b-tagging -30/+20%
  - MC Generator -60/+20%

Cross Section Summary Single Top

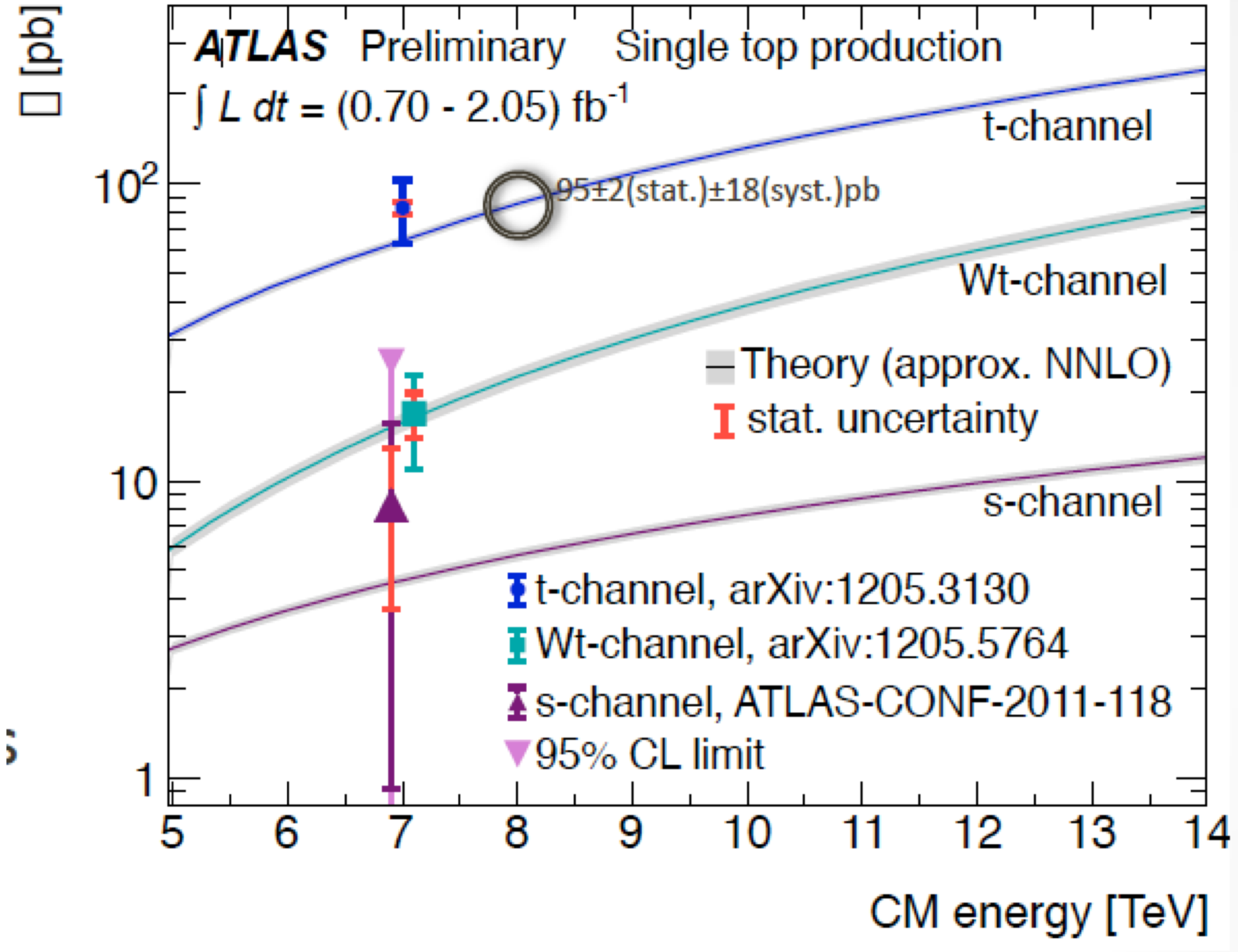
Cross sections:
Standard Model
Measured



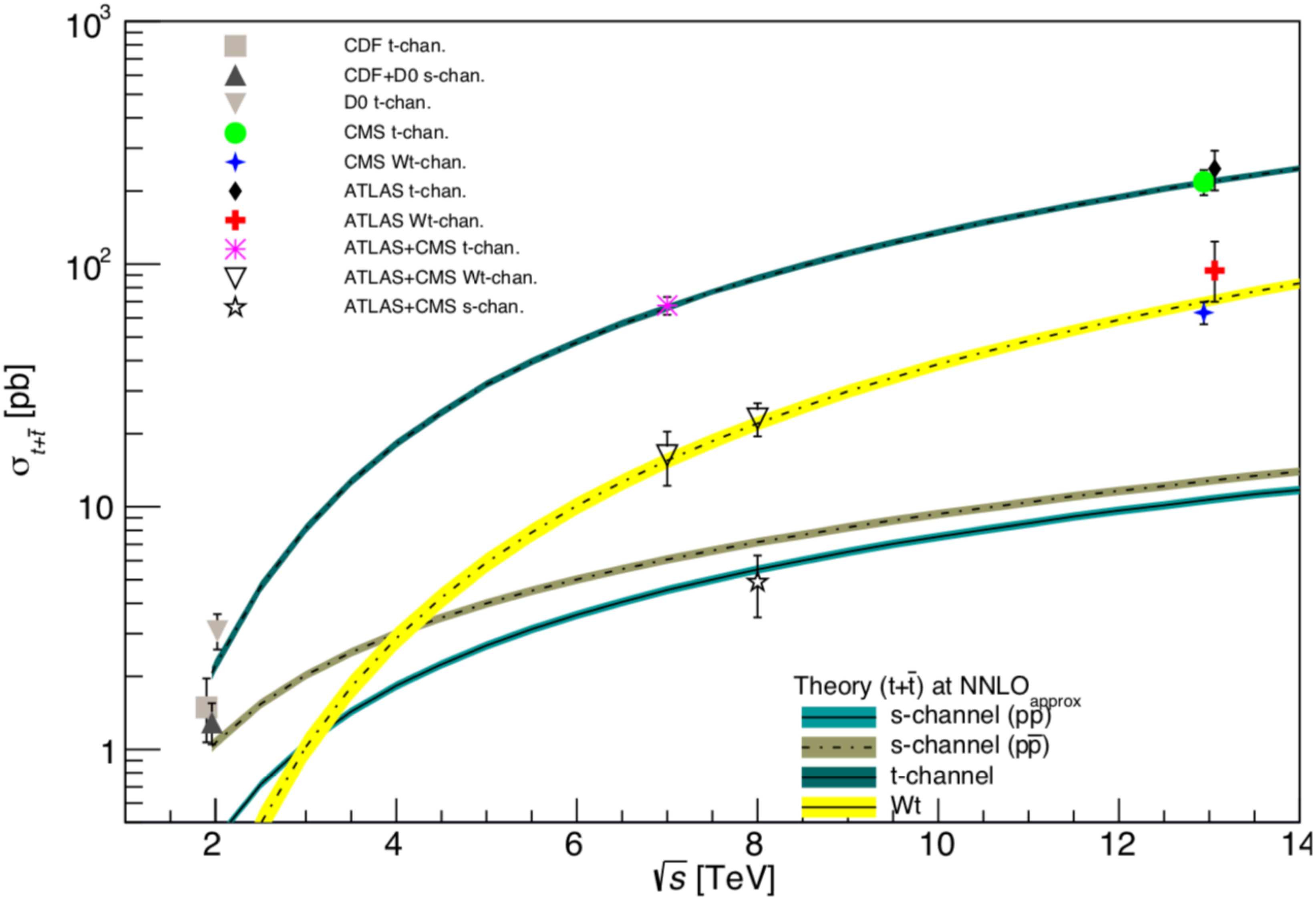
σ [pb]	t-channel	s-channel	Wt-channel
LHC 7 TeV	65.9	4.56	15.6
	83 ± 20	< 26.5	17 ± 6 @3.3σ
LHC 8 TeV	87.2	5.55	22.2
	95 ± 18	-	-

- t-channel cross section measured at 7 + 8 TeV
- evidence for Wt-channel production found
- s-channel still a challenge
- V_{tb} compatible with unity

Single Top Summary



Single top production (PDG 2019)



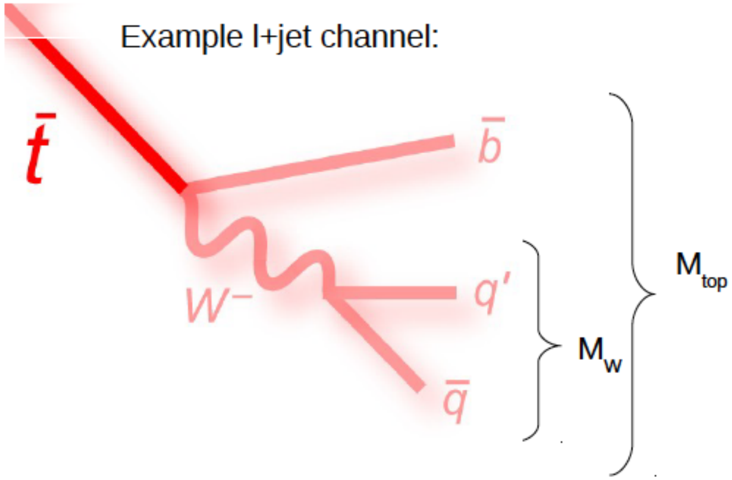
Top mass measurement

Tancredi Carli (CERN)

Top mass measurement methods

Standard technique: Direct mass reconstruction

Example l+jet channel:



Reconstruct top decay products with kinematic fit based on likelihood (ATLAS) or chi2 (CMS)

Template method (e.g. ATLAS, CDF)
fit template of reconstructed top mass from MC to data

Ideogram method (e.g. CMS)
Likelihood function to test compatibility of event kinematics with top decay hypothesis (all good permutations are used)

Ideogram: histogram where entries are weighted with the probability (hypothesis) → not "1"

Matrix element method (e.g. D0)
to calculate signal and background probability density for all parton-jet assignments as function of M_{top} and JSF

Non-standard techniques

1) NLO QCD comparison to inclusive and tt+jet cross sections (no MC used)
→ mass defined in NLO QCD calculation
2) kinematic endpoints (no MC used)
3) B-hadron lifetime
4) J/ψ final states (independent of JSF)

Exploit known M_W to constrain physics and detector effect

Fit M_{top} with n additional parameters

1D fit M_{top}

2D fit M_{top} and jet scale factor (JSF)
exploiting M_W constraint

3D fit M_{top}, JSF and bJSF (ATLAS 2013)
b-JSF relative b-to-light JSF using ratio jet from W-boson and b-jet

10

Top Quark Mass

Reminder:

Radiative corrections
connect m_W, m_t, and m_H ...

Top mass measurement:

Tevatron Run II:
Top mass better than 1%
[Best measured quark mass]

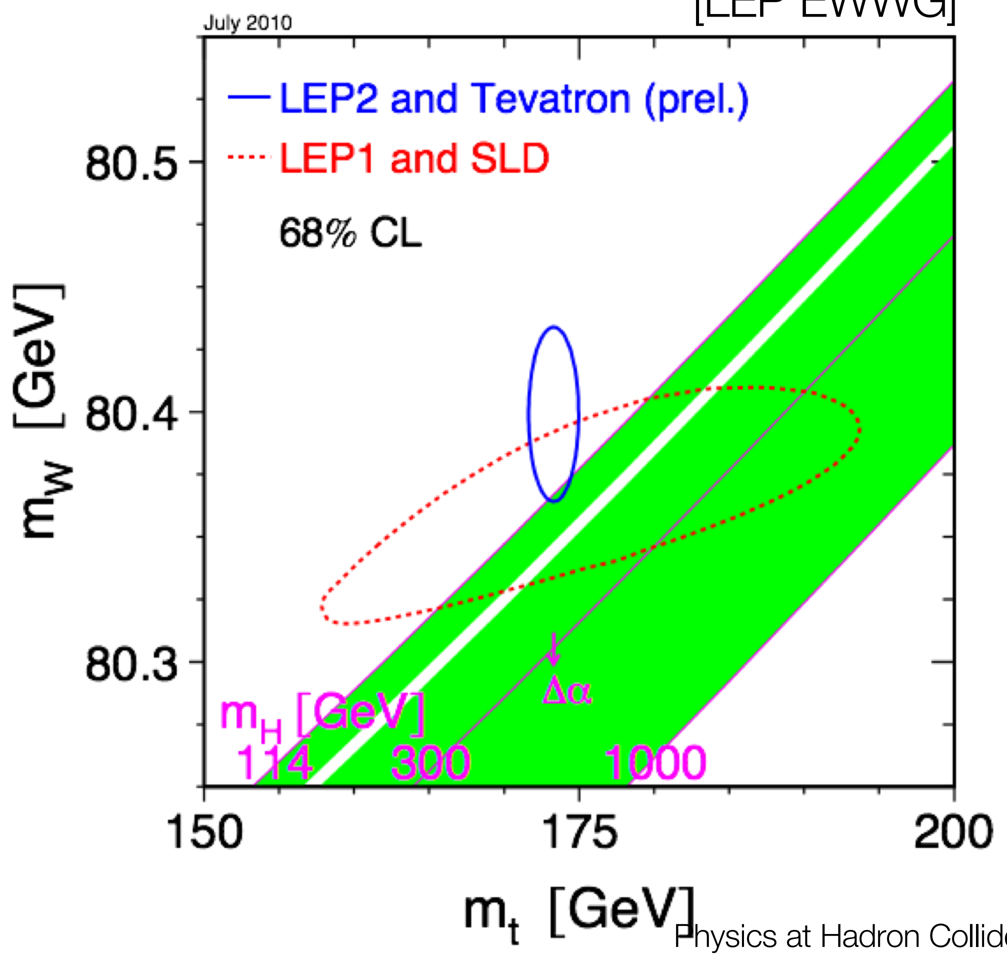
Reached after 5+ years

LHC: top mass to
better than 1 GeV

➛ very challenging

$m_t = 173.3 \pm 1.1$ GeV

[LEP EWWG]



m_t vs m_W in pdg 2017

10. Electroweak model and constraints on new physics

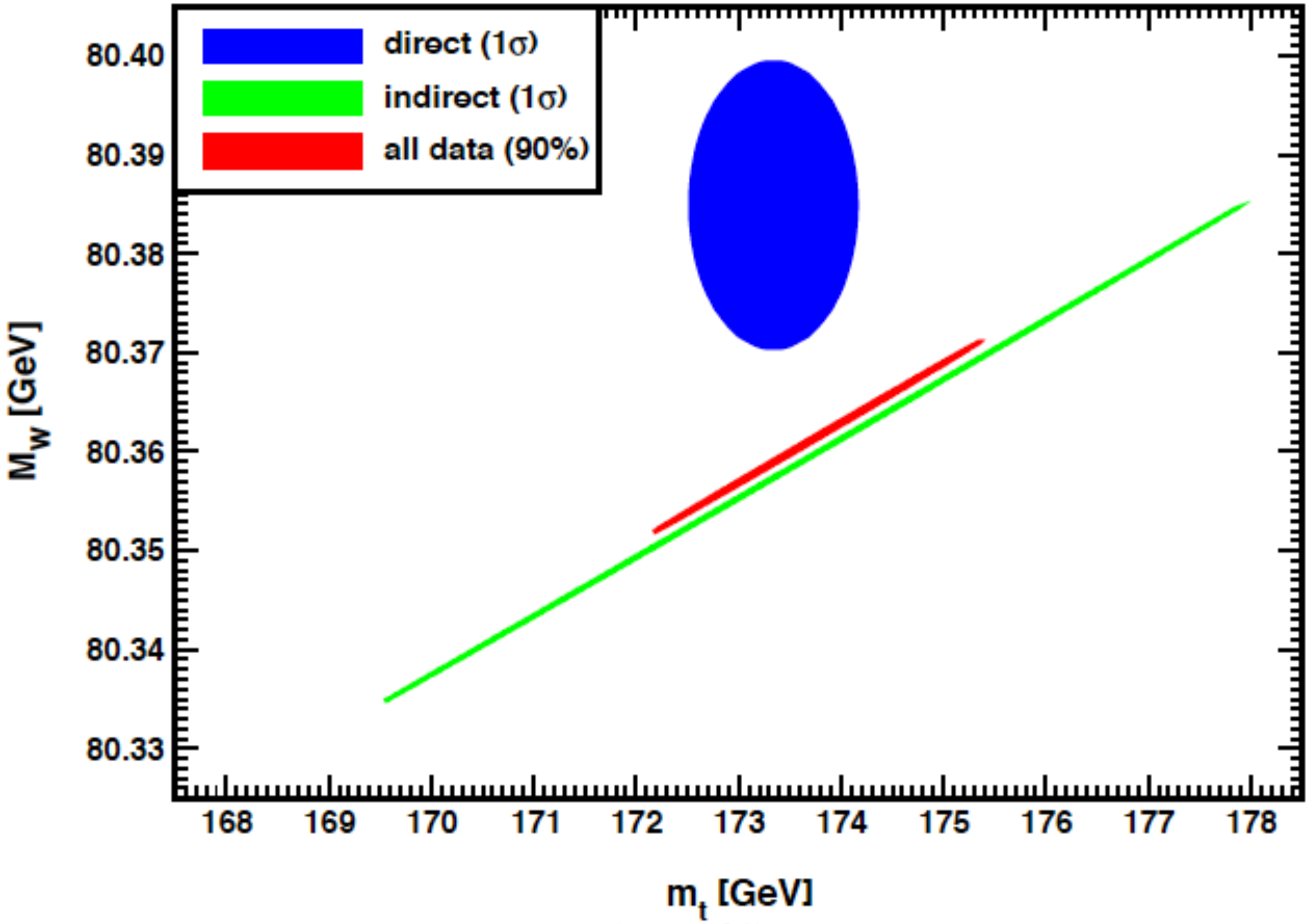


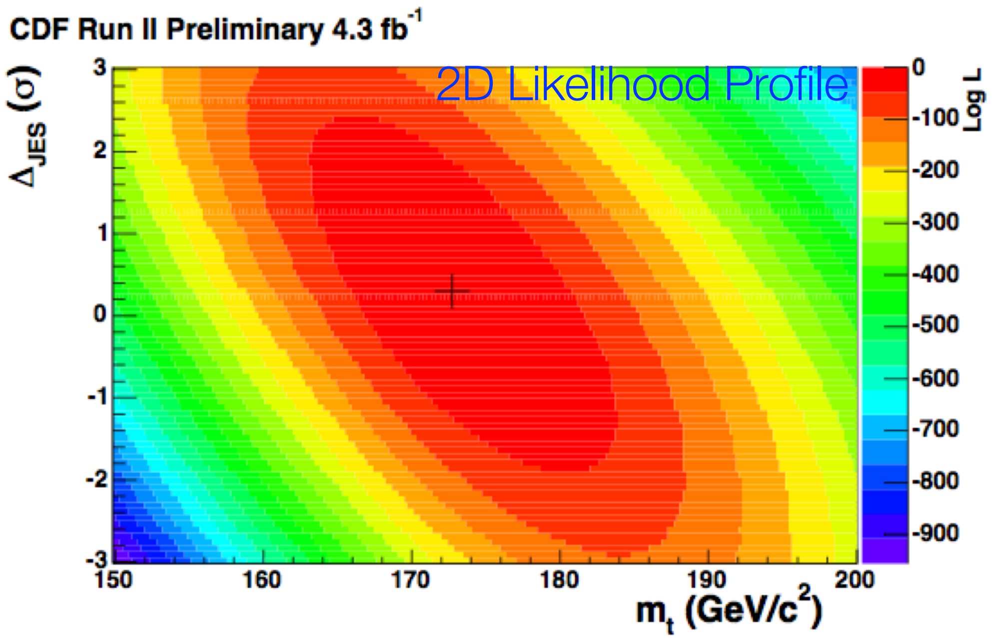
Figure 10.5: One-standard-deviation (39.35%) region in M_W as a function of m_t for the direct and indirect data, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data.

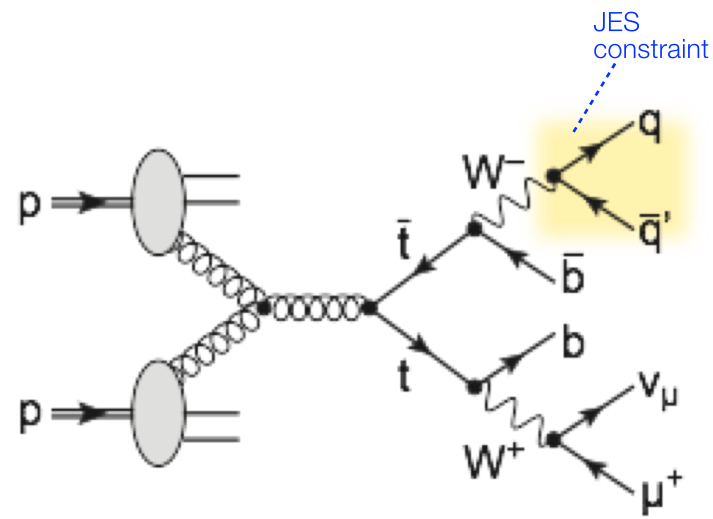
In-situ JES Calibration

Dominant uncertainty of top mass: Jet energy scale (JES)

Idea (for lepton+jets): hadronic top decay chain contains decay W ➛ qq' with well-known W mass [23 MeV vs. > 10 GeV]

"In-situ JES calibration": measure top mass and JES simultaneously [JES from known W mass]





CDF Top Mass Measurement 2009
[http://www-cdf.fnal.gov/.../mtm3_p23_public/]

Likelihood Methods

Goal: estimate parameter μ (e.g. top mass) from set of measurements x = (x_1, x_2, …)

Known probability density distribution to observe value x_i for a given value of μ: P(x_i|μ), e.g. Poisson distribution

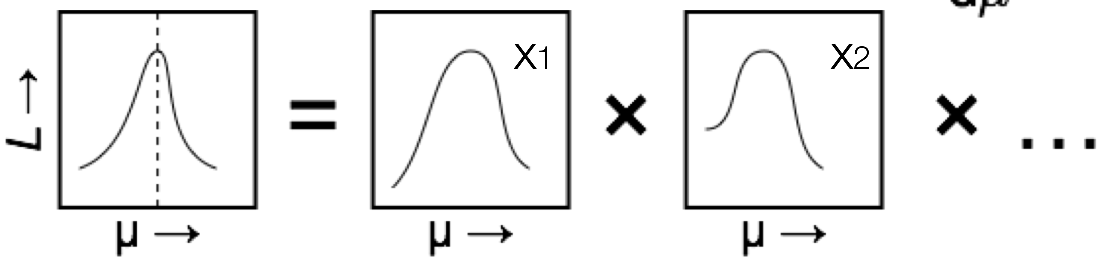
Construct joint probability (“likelihood function”) for full set of measurements x by multiplying individual probabilities

$$L(\mathbf{x}|\mu) = \prod_i P(x_i|\mu)$$

Maximum likelihood method: get estimator for μ from: $$\frac{dL(\mathbf{x}|\mu)}{d\mu} = 0$$

Find maximum of L

In pictures:



In practice: minimize $-\ln L(\mathbf{x}|\mu) = -\sum_i \ln P(x_i|\mu)$