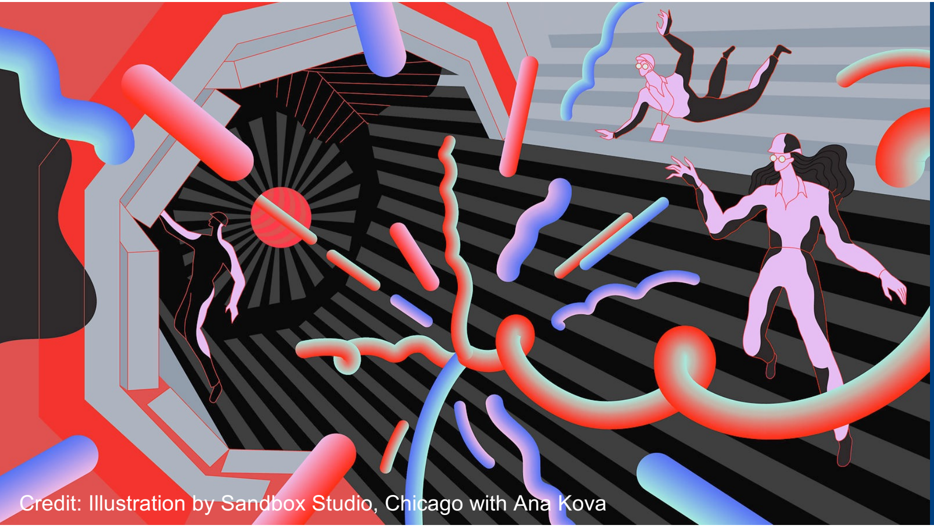
TAE 2023 – International Workshop on High Energy Physics
Benasque (Spain), 3-16 September 2023


Credit: Illustration by Sandbox Studio, Chicago with Ana Kova

Top Physics

(Lecture 1)

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d'Altes Energies

Outline

Lecture 1: Bread & butter Top Physics

- Introduction
- Top pair production cross-section
- Top mass

Lecture 2: Top and New Physics

- Top couplings
- Exotic top production & decay

Why is Top Physics interesting?

- Discovered in 1995 by CDF and D0 at Tevatron.
  Not a surprise: required by self-consistency of the SM.

- What was more surprising was the large mass.
- For m_t=172.55±0.33 GeV:

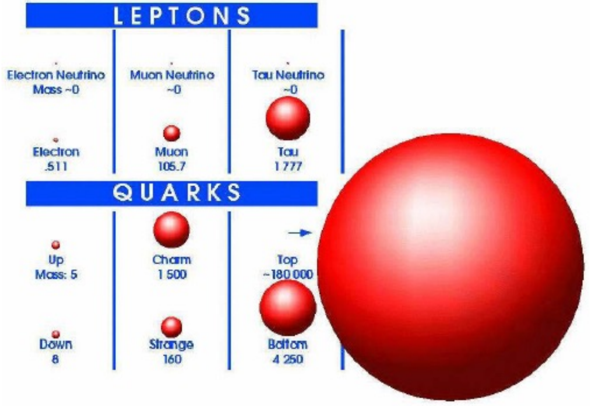
$$y_t = \frac{\sqrt{2}m_t}{v} = 0.991 \pm 0.002 \,!!$$

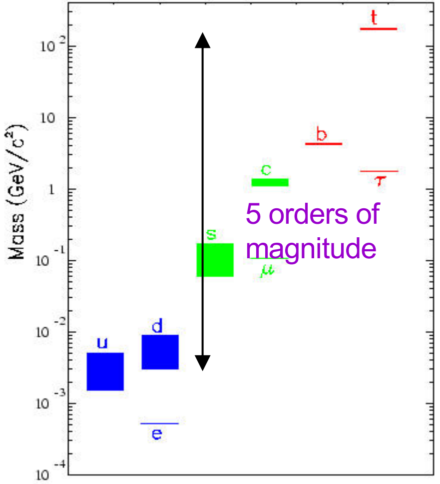
➔ Only quark with a “natural mass”.

➔ Main responsible for instability of Higgs mass against radiative corrections.

➔ May either play a key role in EWSB, or serve as a window to New Physics related to EWSB which might be preferentially coupled to it.

- Even if the top quark is just a normal quark:
  - most of the experimental measurements have no analogue for the lighter quarks,
  - will allow to make stringent tests of the SM.

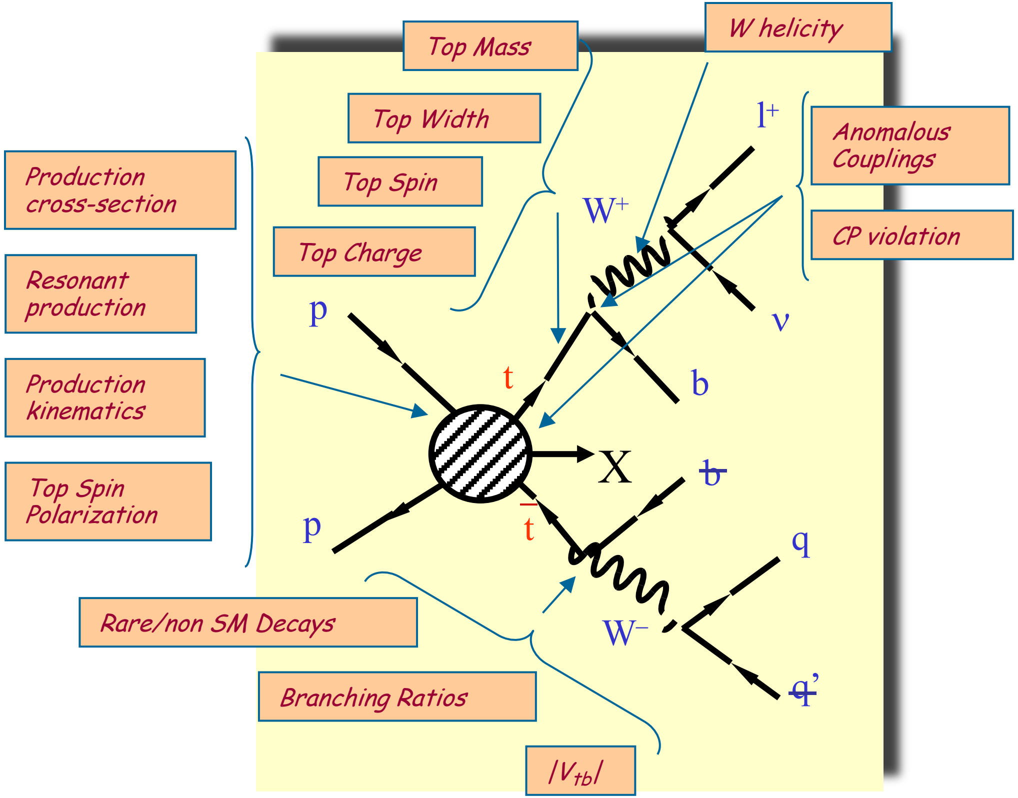




5 orders of magnitude

Outlining the top-quark profile

- Precision measurements of top quark properties crucial in order to unveil its true nature.



Top Mass

W helicity

Top Width

Top Spin

Top Charge

Production cross-section

Resonant production

Production kinematics

Top Spin Polarization

Anomalous Couplings

CP violation

Rare/non SM Decays

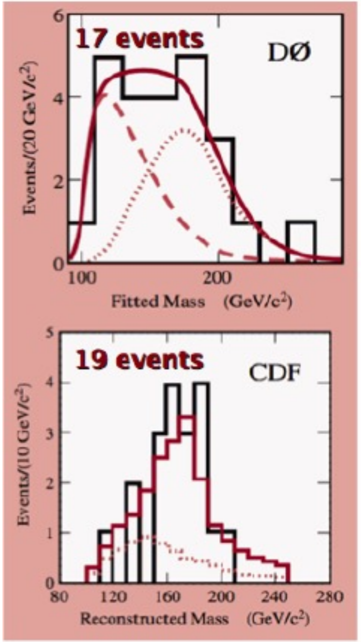
Branching Ratios

$|V_{tb}|$

Outlining the top-quark profile

- Large top samples in Tevatron Run 2 allowed to make the transition from the discovery phase to first precision measurements of top quark properties.

10s of tt events



PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

March 2nd,1995: First announcement of top discovery in a public seminar at Fermilab

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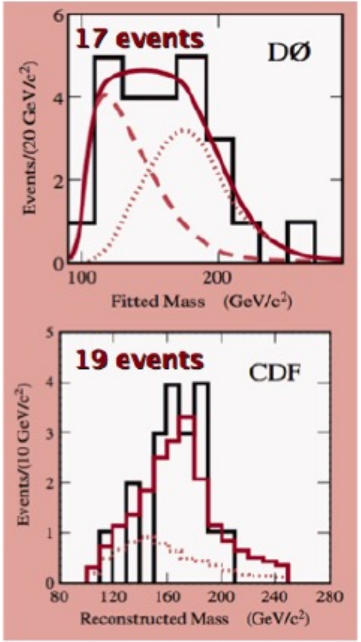

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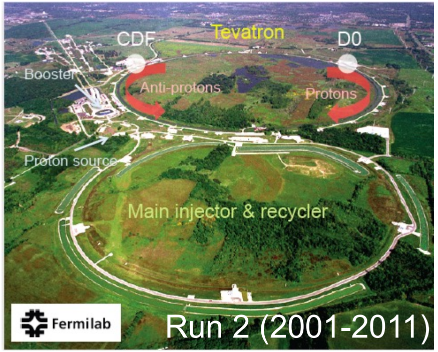
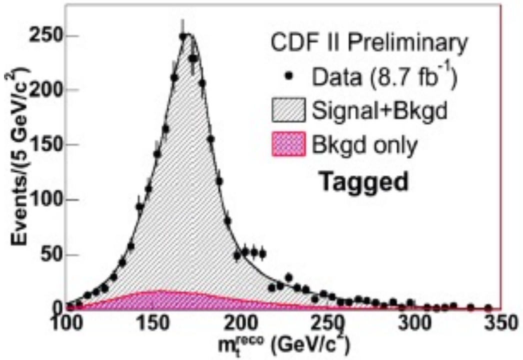
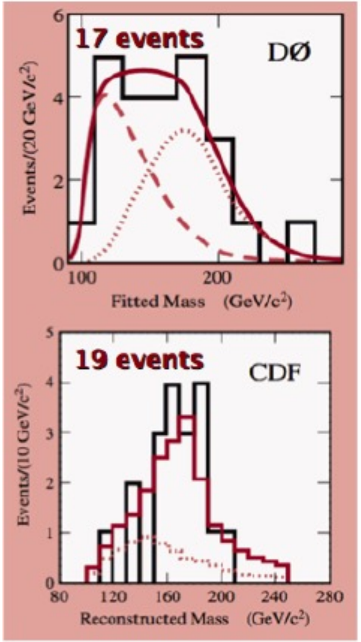




Outlining the top-quark profile

- Large top samples in Tevatron Run 2 allowed to make the transition from the discovery phase to first precision measurements of top quark properties.
- The LHC is the first real top factory and will allow a scrutiny of the top quark far beyond anything previously achieved.

10s of tt events



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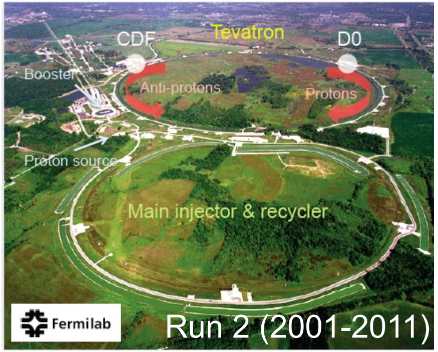
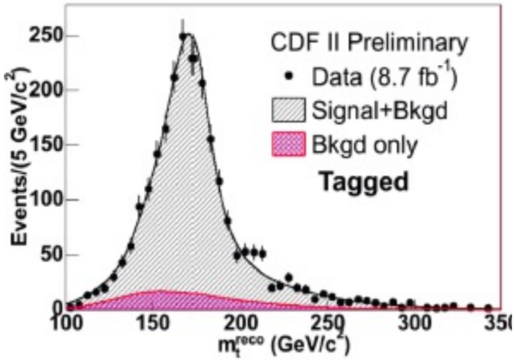
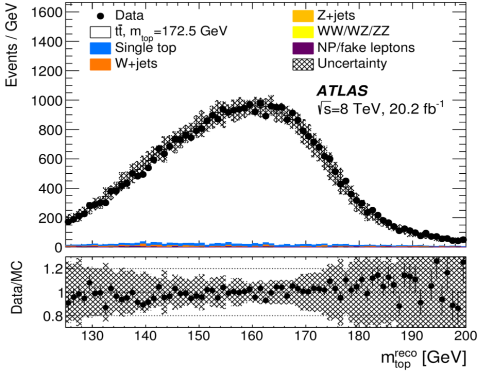




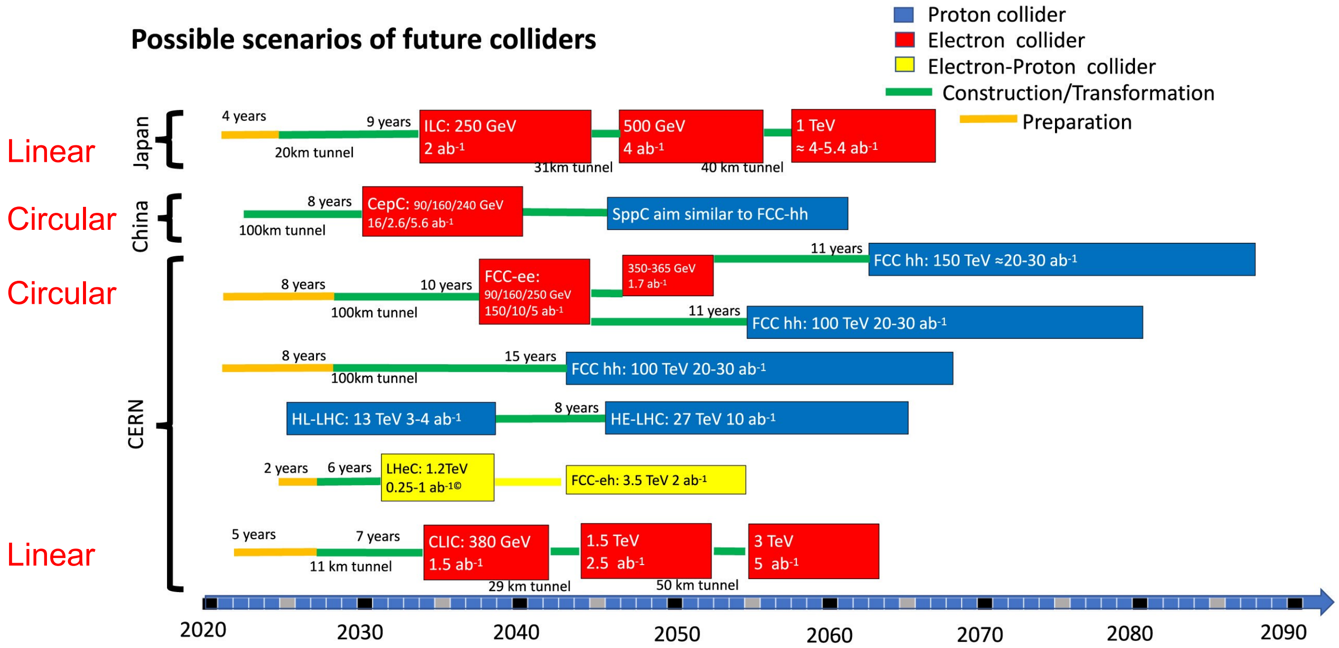
100000s of tt events



Outlining the top-quark profile

- A future e^+e^- collider would represent another quantum leap in precision of many top quark properties.

Possible scenarios of future colliders



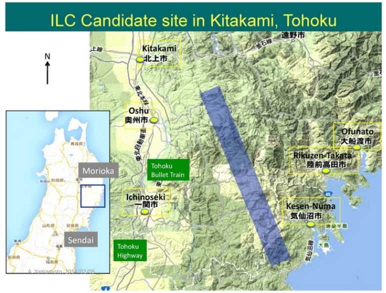
🟦 Proton collider
🟥 Electron collider
🟨 Electron-Proton collider
Construction/Transformation
Preparation

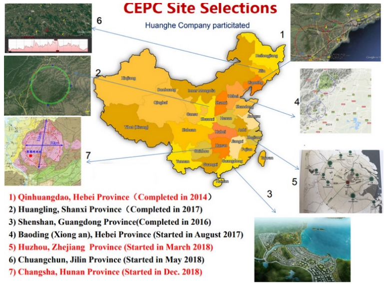
Linear — Japan
4 years | 9 years | 20km tunnel | ILC: 250 GeV 2 ab^{-1} | 31km tunnel | 500 GeV 4 ab^{-1} | 40 km tunnel | 1 TeV ≈ 4-5.4 ab^{-1}

Circular — China
8 years | 100km tunnel | CepC: 90/160/240 GeV 16/2.6/5.6 ab^{-1} | SppC aim similar to FCC-hh

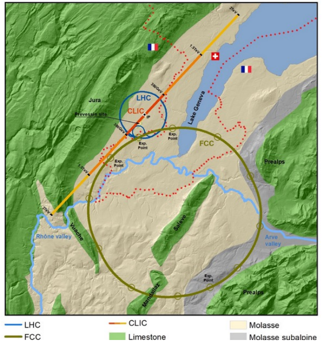
Circular — CERN
8 years | 10 years | 100km tunnel | FCC-ee: 90/160/250 GeV 150/10/5 ab^{-1} | 350-365 GeV 1.7 ab^{-1} | 11 years | FCC hh: 150 TeV ≈20-30 ab^{-1}
11 years | FCC hh: 100 TeV 20-30 ab^{-1}
8 years | 15 years | 100km tunnel | FCC hh: 100 TeV 20-30 ab^{-1}
HL-LHC: 13 TeV 3-4 ab^{-1} | 8 years | HE-LHC: 27 TeV 10 ab^{-1}
2 years | 6 years | LHeC: 1.2TeV 0.25-1 ab^{-1}© | FCC-eh: 3.5 TeV 2 ab^{-1}

Linear
5 years | 7 years | 11 km tunnel | CLIC: 380 GeV 1.5 ab^{-1} | 29 km tunnel | 1.5 TeV 2.5 ab^{-1} | 50 km tunnel | 3 TeV 5 ab^{-1}



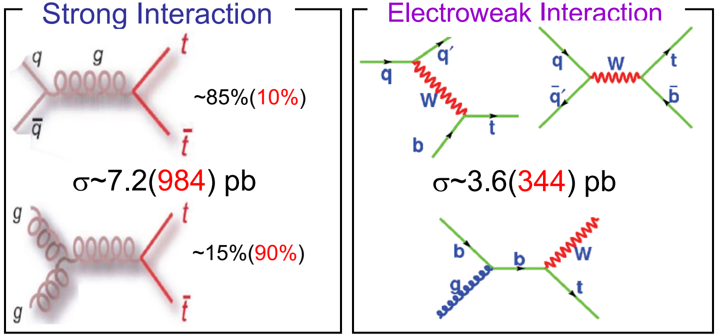


1) Qinhuangdao, Hebei Province（Completed in 2014）
2) Huangling, Shanxi Province（Completed in 2017)
3) Shenshan, Guangdong Province(Completed in 2016)
4) Baoding (Xiong an), Hebei Province (Started in August 2017)
5) Huzhou, Zhejiang Province (Started in March 2018)
6) Chuangchun, Jilin Province (Started in May 2018)
7) Changsha, Hunan Province (Started in Dec. 2018)



Top-quark production at a hadron collider

Tevatron $p\bar{p}$ @ 1.96 TeV (LHC pp @ 14 TeV)



Strong Interaction

~85%(10%)

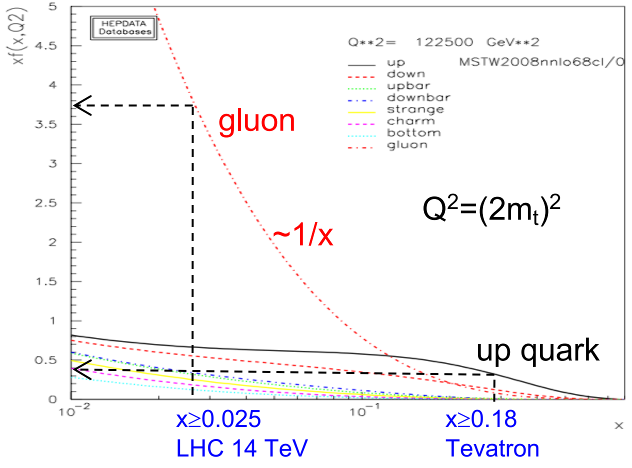
σ~7.2(984) pb

~15%(90%)

Electroweak Interaction

σ~3.6(344) pb

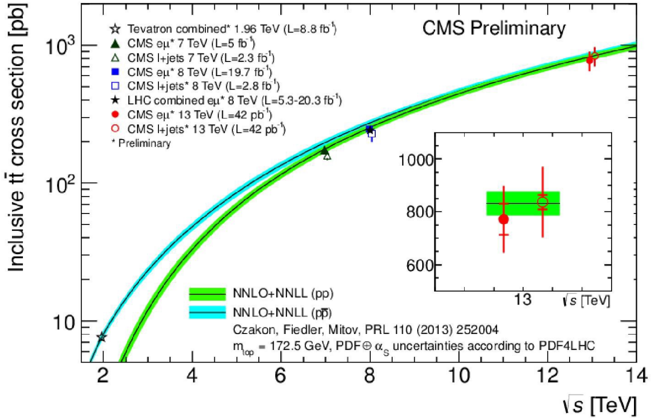
m_t=172.5 GeV



- Dominant production mechanism is in pairs, mediated by the strong interaction.
  Electroweak production of single top quarks ~1/2 of the tt rate.

	Number of tt events (*)
Tevatron	~70k
LHC 7 TeV	~0.9M
LHC 8 TeV	~5M
LHC 14 TeV (@ 10^{34} $cm^{-2}s^{-1}$)	**~95M/year**

(*) Produced/experiment



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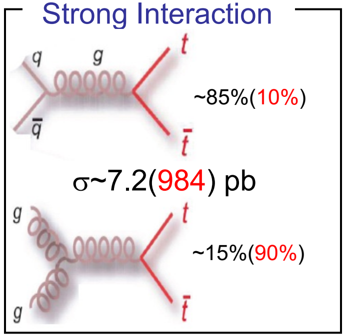
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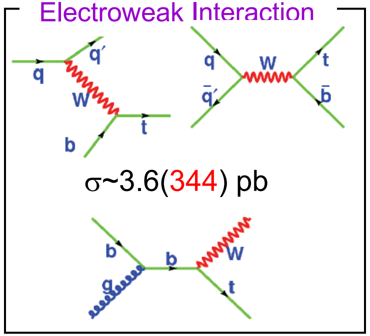
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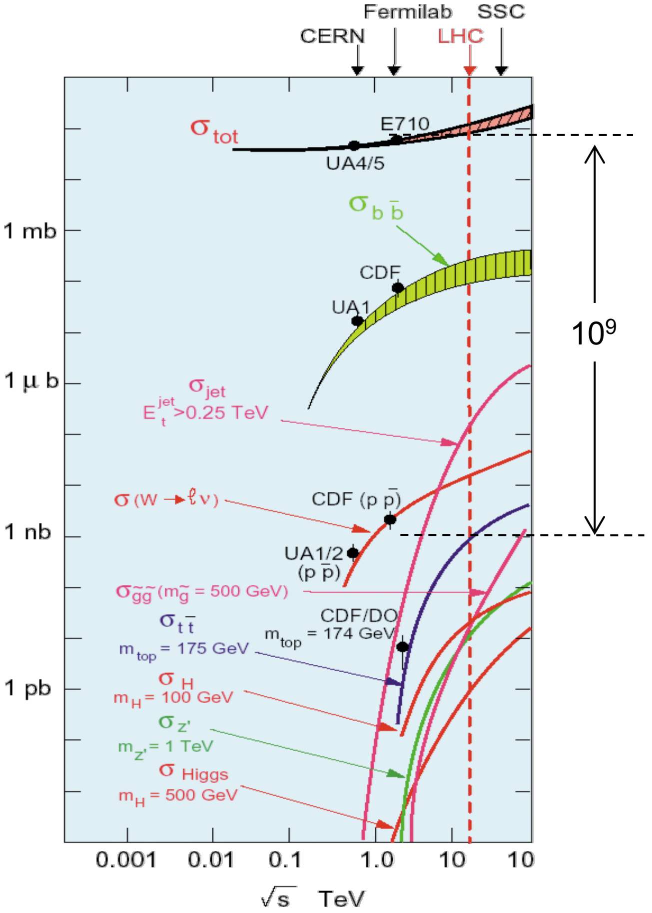

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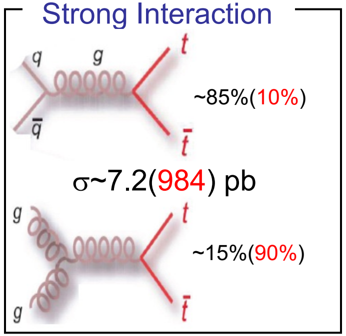

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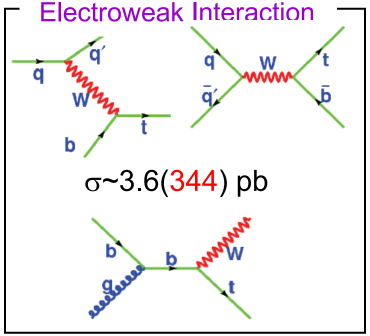

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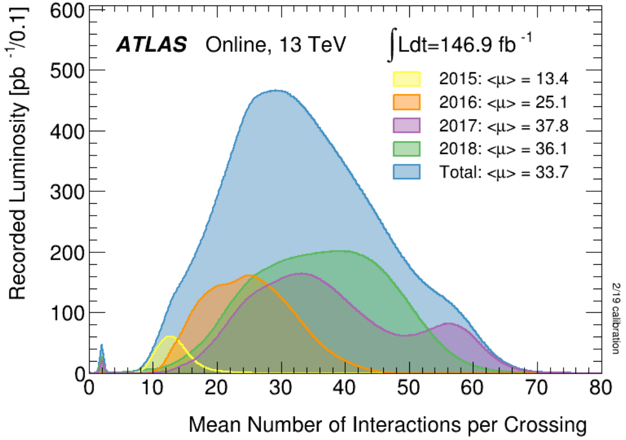
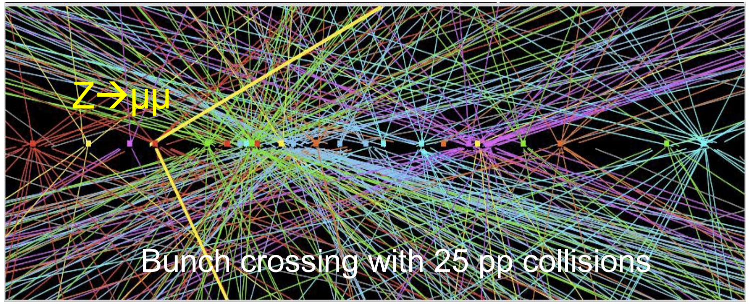
High instantaneous luminosity
➔ additional pp collisions (pile-up)





Bunch crossing with 25 pp collisions

Top-quark decay

Within the SM:

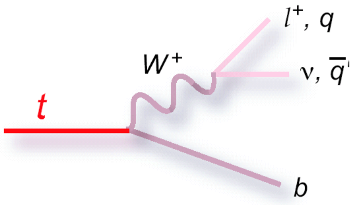
- $m_t > m_W + m_b \Rightarrow$ dominant 2-body decay t→Wb (t→Ws, Wd CKM suppressed)

  Assuming unitarity of 3-generation CKM matrix:

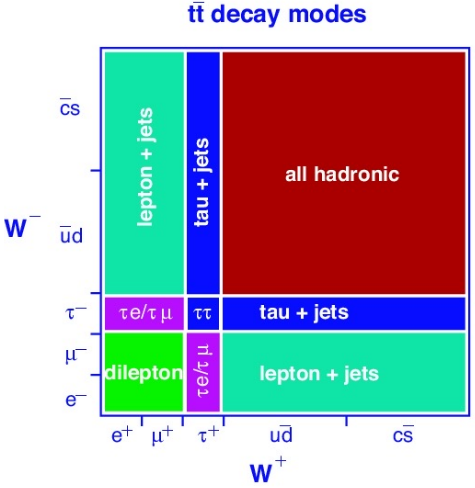
  $|V_{tb}|$ = 0.9990-0.9992 @ 90% CL

  ➔ B(t→Wb) ~ 100%
- $\Gamma_t^{SM} \approx 1.4$ GeV at m_t = 175 GeV $\Gamma_t >> \Lambda_{QCD}$

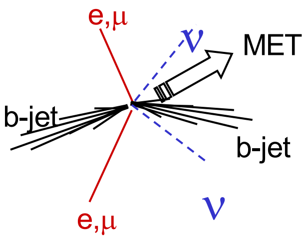
  Top decays before top-flavored hadrons or tt-quarkonium bound states can form.



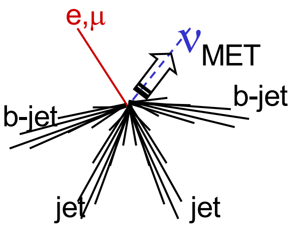
B(W→qq)~ 67%
B(W→lν)~ 11%, l=e,μ,τ



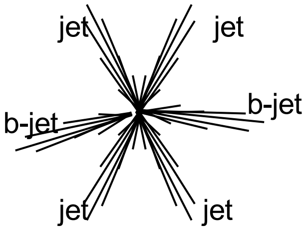
Typical final state signatures in top quark pair production:



Dilepton
(BR~5%, low bckg)



Lepton+jets
(BR~30%, moderate bckg)

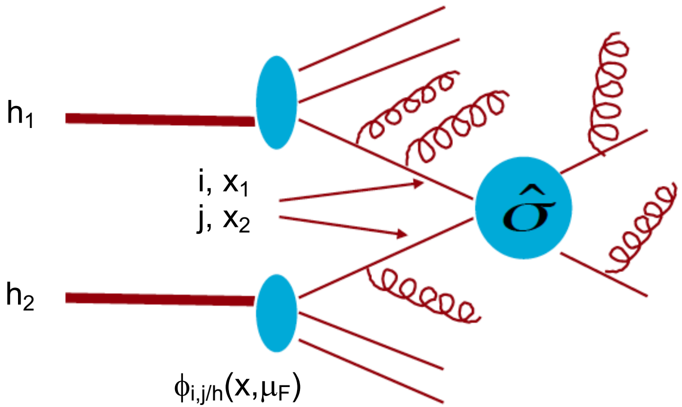


All-hadronic
(BR~46%, huge bckg)

➔ Top Physics requires multipurpose detectors!

tt Production Cross Section

Production cross-section



- Factorization theorem:

$$\sigma_{h_1h_2}(s,m_t)=\sum_{ij}\int dx_1dx_2\phi_{i/h_1}(x_1,\mu_F)\phi_{j/h_2}(x_2,\mu_F)\hat{\sigma}_{ij}(x_1x_2s,m_t,\alpha_s(\mu_R),\mu_R,\ \mu_F)$$

  - σ_{ij}: partonic cross section
  - $\phi_{i/h}(x,\mu_F)$: parton distribution function (PDF); represents probability density to observe a parton i with longitudinal momentum fraction x in incoming hadron h, when probed at a scale μ_F
  - μ_F: factorization scale; a free parameter; it determines the proton structure if probed (by virtual photon or gluon) with $q^2=-\mu_F^2$
  - μ_R: renormalization scale; defines size of strong coupling constant
    Usual choice:

$$\mu_R=\mu_F=\mu,\quad \mu\in\left(m_t/2,\ 2m_t\right)$$

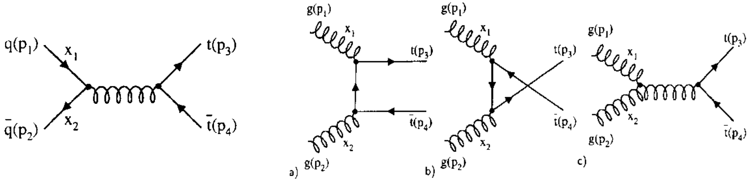
σ_{tt}: Theoretical predictions

- σ_{ij} is expanded in powers of strong coupling constant

$$\sigma_{ij}(\beta,\frac{\mu^2}{m_t^2}) = \frac{\alpha_s^2}{m_t^2}\{\sigma_{ij}^{(0)} + O(\alpha_s)\}$$

Leading Order (LO): ~α_s^2

  - Use LO PDFs
  - Normalization unreliable



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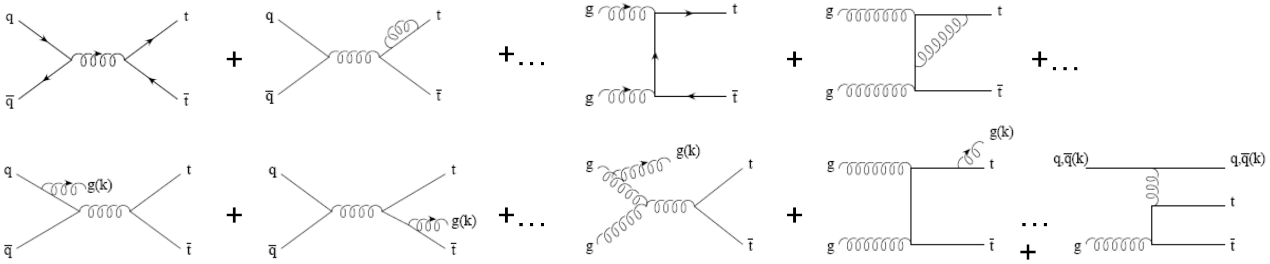
NLO: $\sim\alpha_s^3$; $L=ln(\mu^2/m^2)$

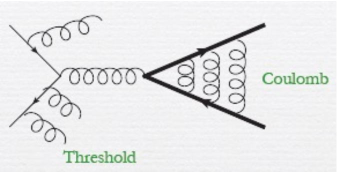
  - Virtual and real corrections are added to LO



  - Use NLO PDFs.
  - First meaningful cross section prediction.

"Approximate NNLO" = NLO+NLL resummation

  - Based on NLO+resummation of large logs up to NNLL accuracy.
  - Reduced scale dependence compared to NLO.



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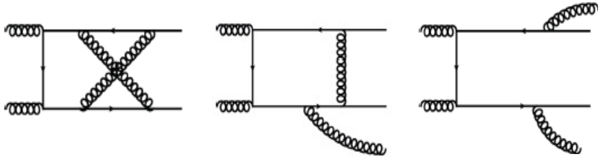
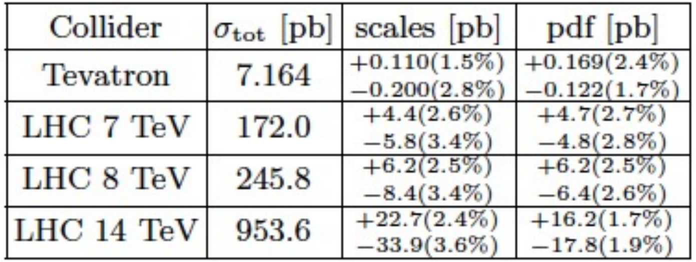
NNLO: ~α_s^4 ➔ current state-of-art: a monumental MILESTONE in perturbative QCD

- Includes:
  - 2-loop virtual
  - 1-loop virtual + 1 extra parton
  - 2 extra partons
- Use NNLO PDFs
- Further improve the prediction including NNLL resummation
- ~50% smaller scale dependence than NLO+NNLL



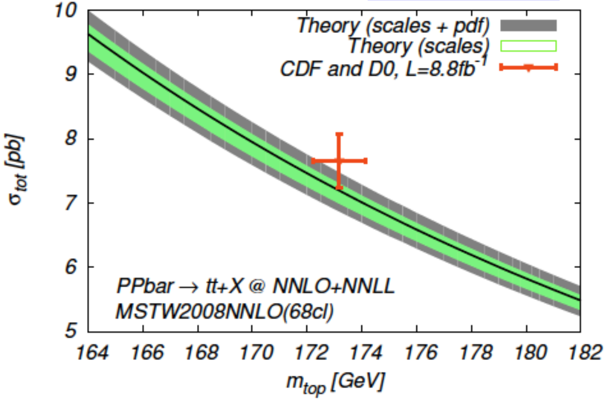


Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

±3%

±4%

arXiv:1303.6254

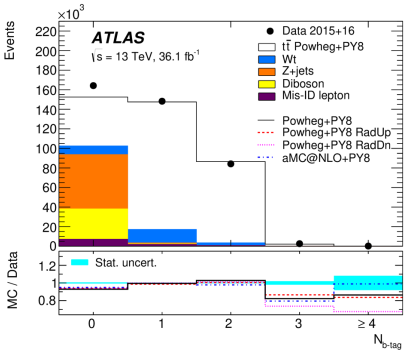


σ_{tt}: Measurement

- Master formula:

$$\sigma_{tt} = \frac{N_{data} - N_{bkg}}{BR \cdot A\varepsilon \cdot L}$$

N_{data}: observed number of events
N_{bkg}: predicted number of background events
BR: branching ratio
$A\varepsilon$: acceptance times selection efficiency
L: integrated luminosity



- Standard likelihood fit:
  - To estimate σ_{tt} from a binned distribution, a likelihood function, defined as the product of Poisson probabilities is maximized:

$$L(\sigma_{tt}) = \prod_{bins} P(N_k^{data},\ N_k^{pred}(\sigma_{tt}))$$

- Profile likelihood fit:
  - Fit in addition nuisance parameters parameterizing the effect of systematic uncertainties, each assumed to follow a Gaussian distribution. By including in the fit subsidiary data samples with sufficiently high statistics, leading systematic uncertainties can be constrained by data, thus improving the precision of the measurement.

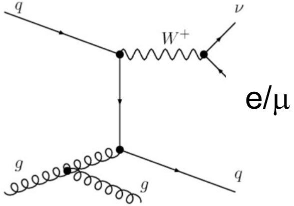
$$L(\sigma_{tt},\ \vec{\alpha}) = \prod_{bins} P(N_k^{data},\ N_k^{pred}(\sigma_{tt}, \vec{\alpha})) \prod_{syst} G(0,\ \sigma_{\alpha_i})$$

Backgrounds

- Top quark measurements at hadron colliders are affected by large backgrounds, primarily:

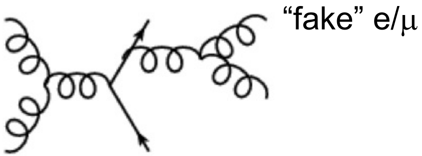
W/Z+jets ➔ with real leptons

- Estimated using MC simulation and sometimes normalized to data

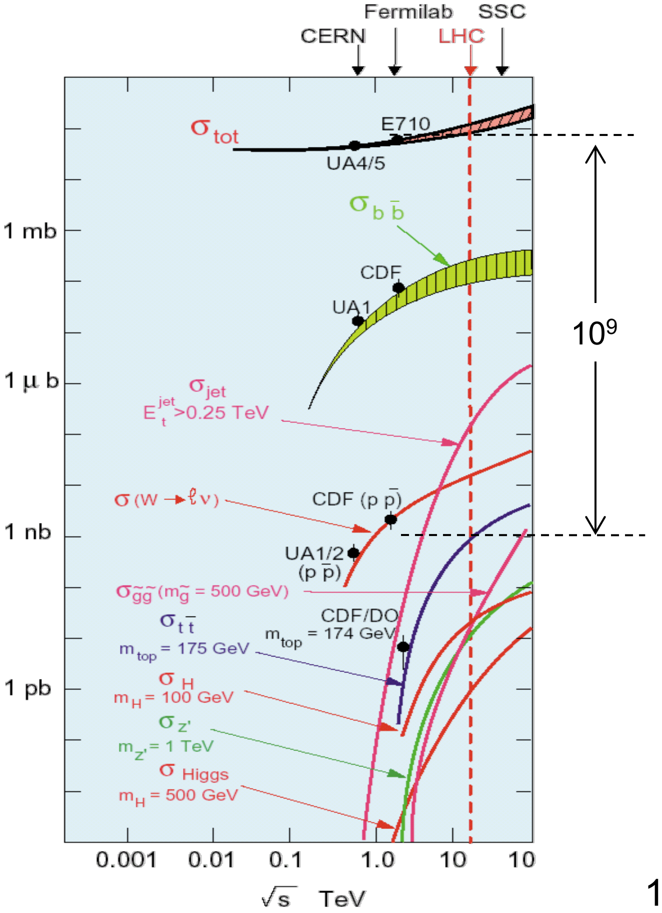


QCD multijets ➔ with jets misidentified as leptons and/or jet energy mis-measurements giving fake E_T^{miss}

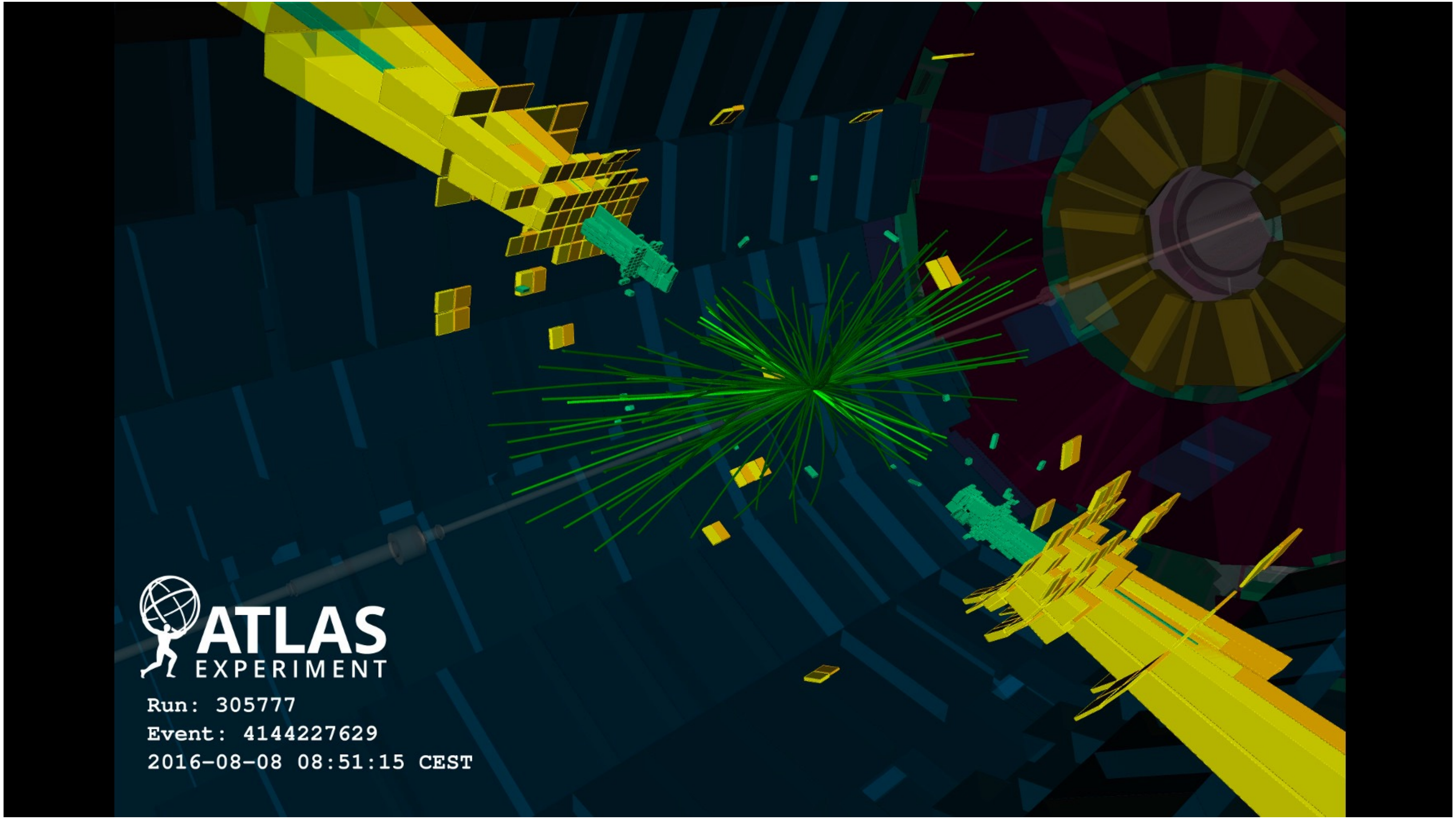
- Estimated directly from data



- A key experimental tool to suppress background is b-jet identification (b-tagging).

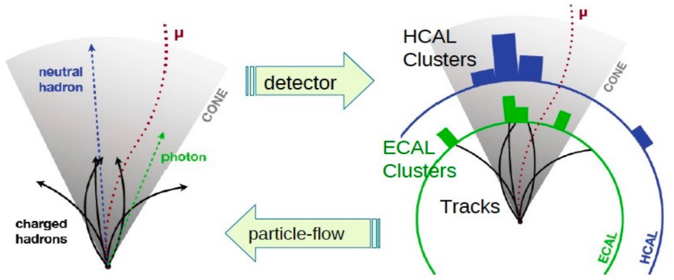


Jet reconstruction and calibration



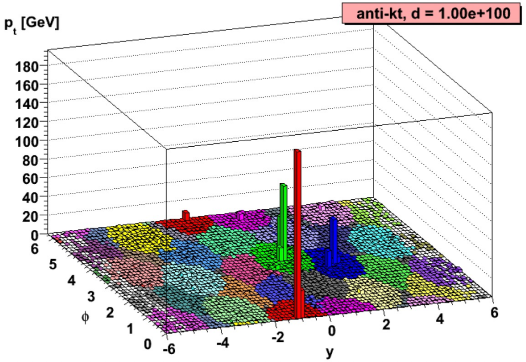
Jet reconstruction and calibration

- Energetic quarks and gluons hadronize into collimated sprays of hadrons that interact with the detector, denoted “jets”.
- Jets are reconstructed from clusters of energy in the calorimeters and tracks (”particle flow objects”) using a jet algorithm.
- Most commonly used at LHC: **anti-kt algorithm**

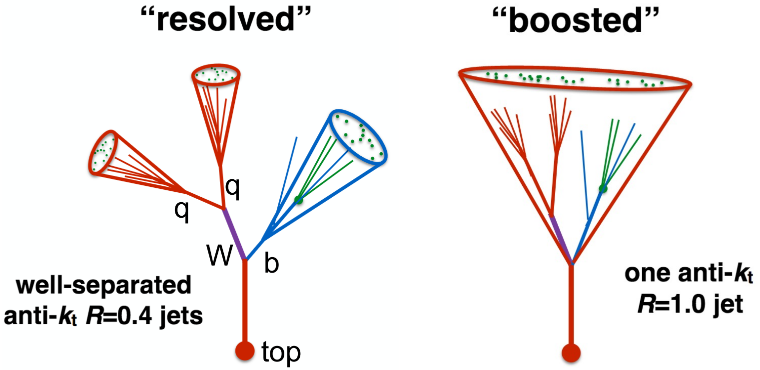


Clustering grows around hard cores

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = \frac{1}{p_{ti}^2}$$



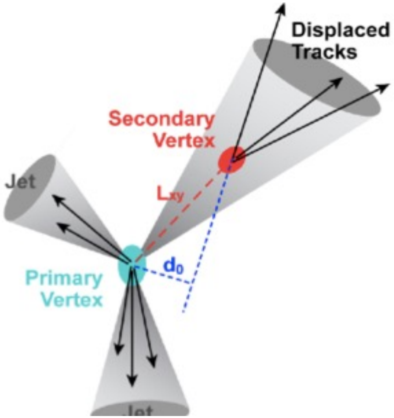
Gives ~circular jets
R=radius parameter



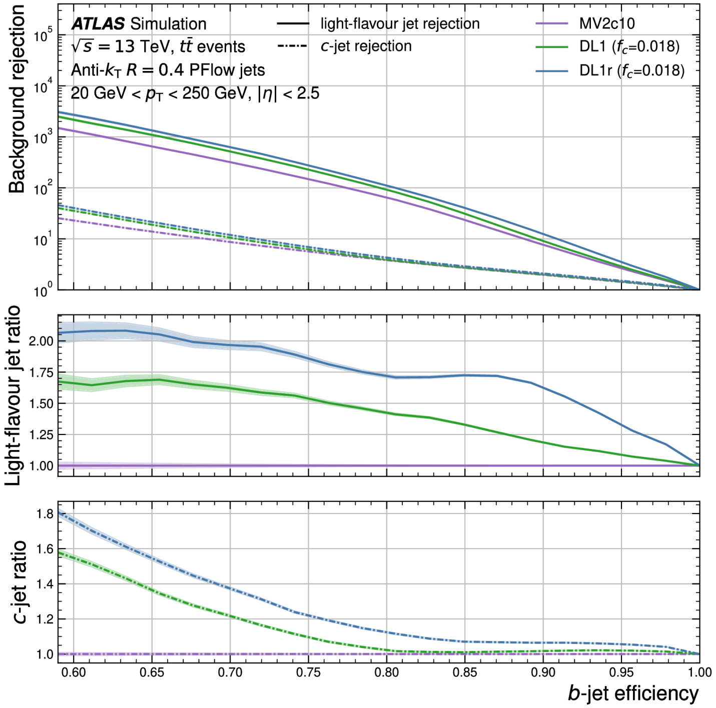
Many “boosted object” taggers exploiting jet substructure information!

- Reconstructed jet 4-momentum is calibrated to correspond to that of a jet formed by stable particles ➔ quite involved procedure (more on this later)!

Jet flavour tagging



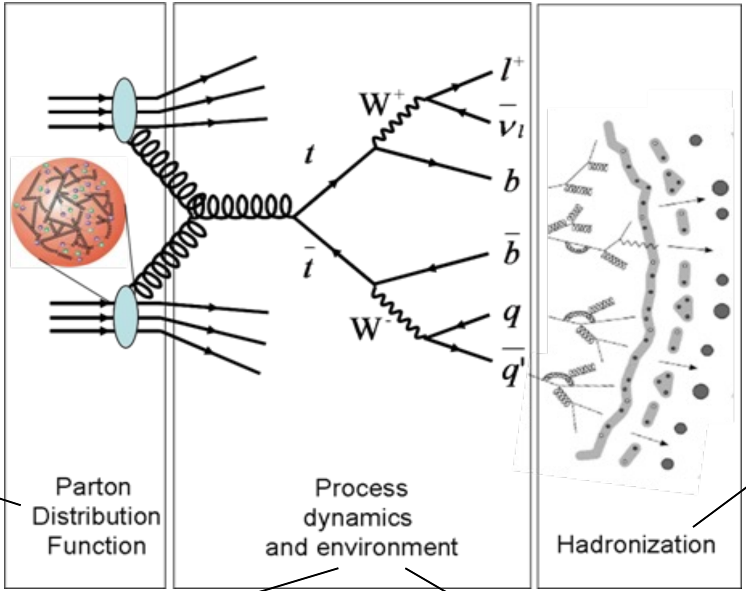
EPJC 83 (2023) 681



- Identify b-quarks through dedicated algorithms which combine information from:
  - Tracks with large impact parameter
  - Displaced secondary and tertiary vertices
  - Mass of secondary vertex
  - …
- Information often combined using multivariate techniques (e.g. Neural Networks).
- Performance of the algorithm calibrated in data control samples (e.g. tt events).

tt modeling

- Precise modeling of event kinematics extremely important (acceptance, differential distributions, systematic uncertainties,..).



- LO ME+PS → LO PDF
- NLO ME+PS → NLO PDF
- Follow PDF4LHC recommendations

- MCs interfaced to Pythia and/or Herwig.

- LO ME+PS MCs (ALPGEN, MadGraph)
- NLO ME+PS MCs (aMC@NLO, Powheg-Box, Sherpa)
- Different handling of QCD radiation

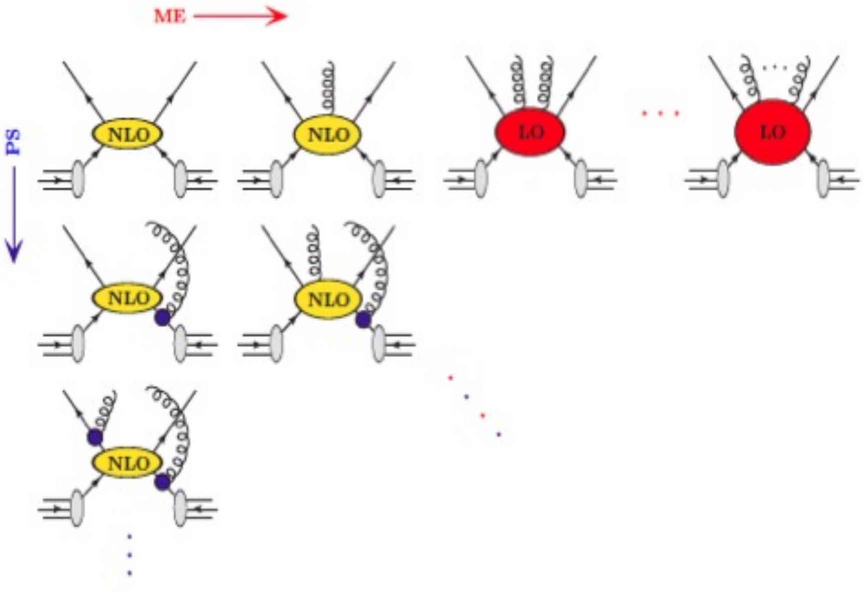
Additional aspects:

- Underlying event
- Color reconnection
- Pileup

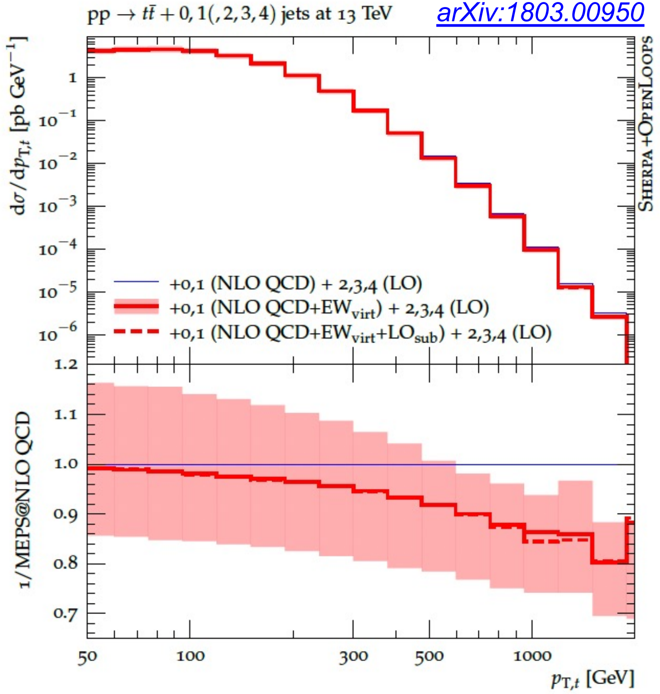
tt MC generators

- LO ME+PS MCs (ALPGEN, MadGraph) show in general good agreement with data. Typically go up to tt+≤3 jets.
- NLO ME+PS MCs (MC@NLO, Powheg-Box) consistently merge a NLO calculation with PS (provides resummation).
- SHERPA & aMC@NLO now merging NLO MCs of different jet multiplicities. Can also include EW corrections.

➔ current state-of-art, but this is a fast-developing field!



arXiv:1803.00950



Example: σ_{tt} in dilepton final states

- Very loose preselection: 1e, 1μ, ≥1 b-jet.
- Simultaneous measurement of σ and b-tagging ε counting events with 1 and 2 b-jets.

$$N_1 = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{\text{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\text{bkg}}$$

$\varepsilon_{e\mu}$: eμ preselection efficiency
ε_b: b-jet acceptance and tagging efficiency
c_b: 1/2 b-tag correlation (=1.007)

- Results:

$$\sigma_{tt} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \text{ pb } (\sqrt{s} = 7 \text{ TeV}) \quad \text{3.5\% unc.}$$
$$\sigma_{tt} = 242.9 \pm 1.7 \pm 5.5 \pm 5.1 \text{ pb } (\sqrt{s} = 8 \text{ TeV}) \quad \text{3.2\% unc.}$$
$$\sigma_{tt} = 824.7 \pm 6.9 \pm 12.1 \pm 18.4 \text{ pb } (\sqrt{s} = 13 \text{ TeV}) \quad \text{2.4\% unc.}$$

- Dominant uncertainties: signal modelling, luminosity, PDF

$\sqrt{s}$ values [TeV]	Measured cross-section ratio	NNLO+NNLL prediction
13/7	4.54 ± 0.08 ± 0.10 ± 0.12 (0.18)	4.69 ± 0.16
13/8	3.42 ± 0.03 ± 0.07 ± 0.10 (0.12)	3.28 ± 0.08
8/7	1.33 ± 0.02 ± 0.02 ± 0.04 (0.05)	1.43 ± 0.01

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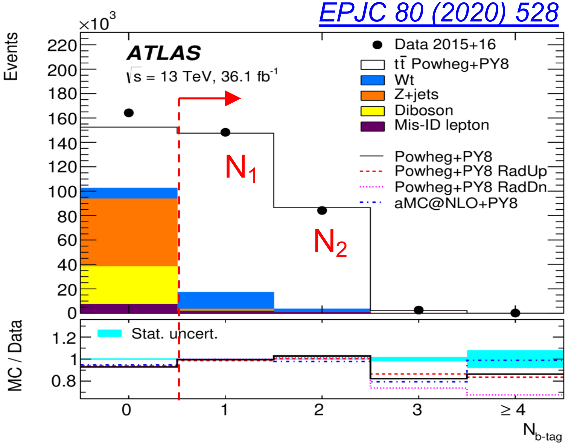
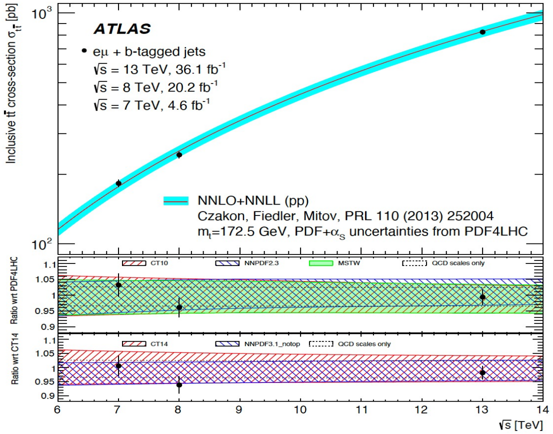
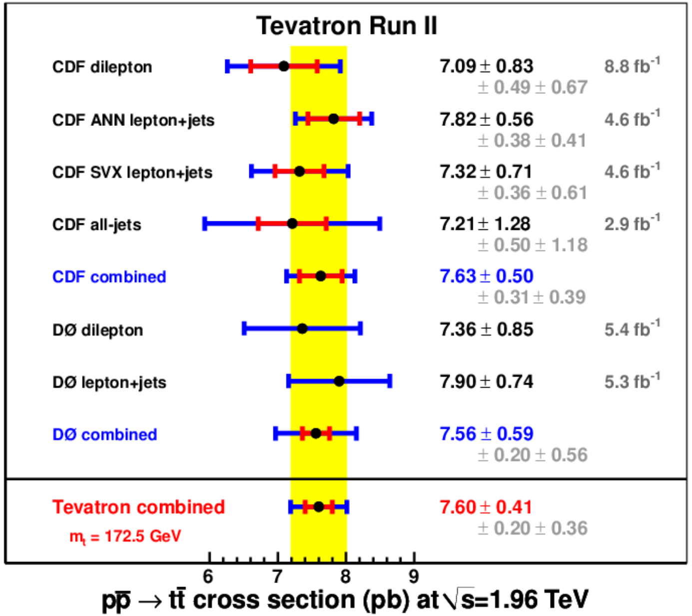
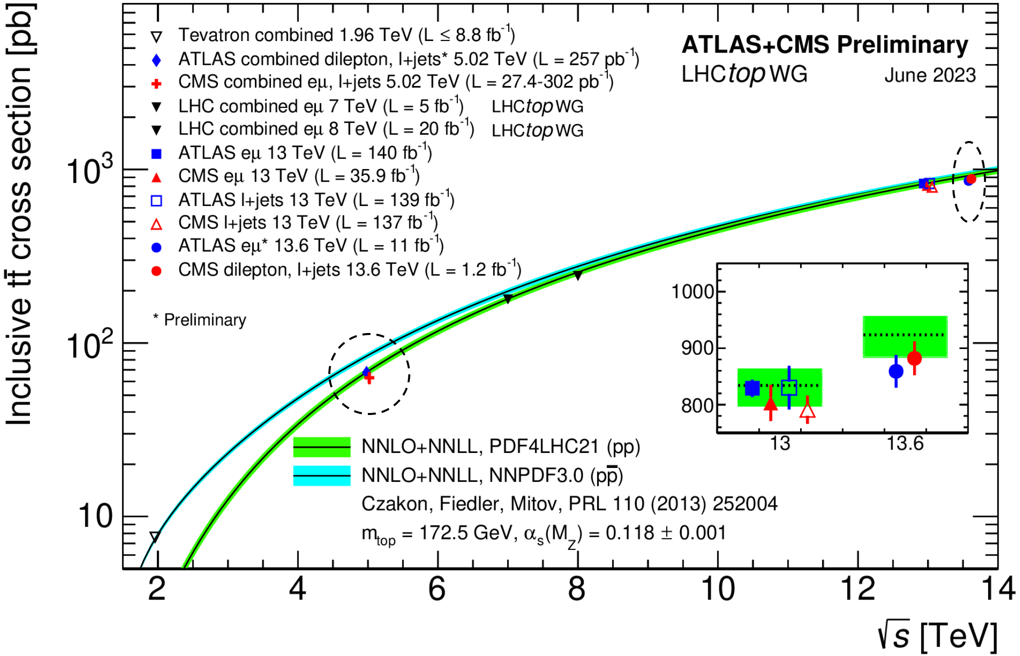




σ_{tt} summary: Tevatron and LHC



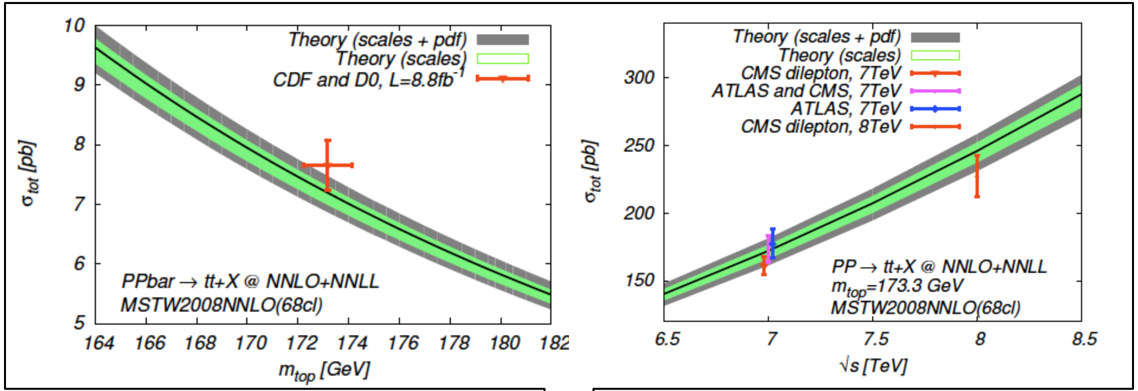
PRD 89 (2014) 072001



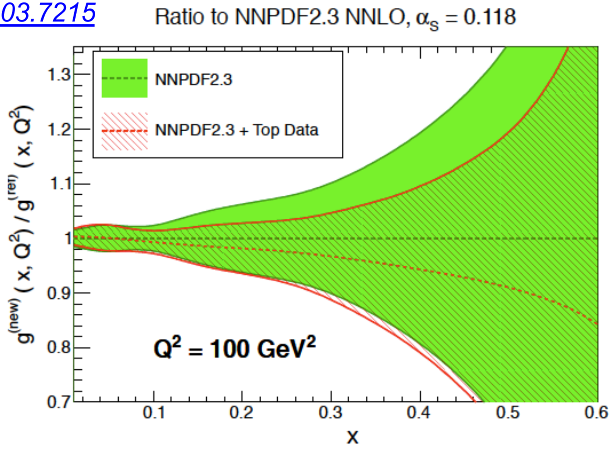
ATL-PHYS-PUB-2023-014

Good agreement with the SM

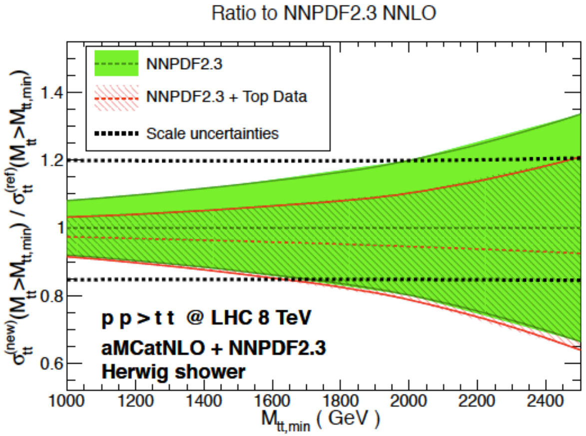
Implications of precise σ_{tt} measurement



arXiv:1303.7215



Improve gluon PDF at high x



Reduce theoretical error in the tail of m_{tt}

Differential cross-section measurements

- Motivation:
  - Comparison to existing (and future!) theoretical predictions: fixed-order calculations, ME+PS MCs
    ➔ crucial to improve tt modeling and reduce related uncertainties
  - Sensitive to BSM effects.
- Measurements unfolded to particle-jet or parton level.

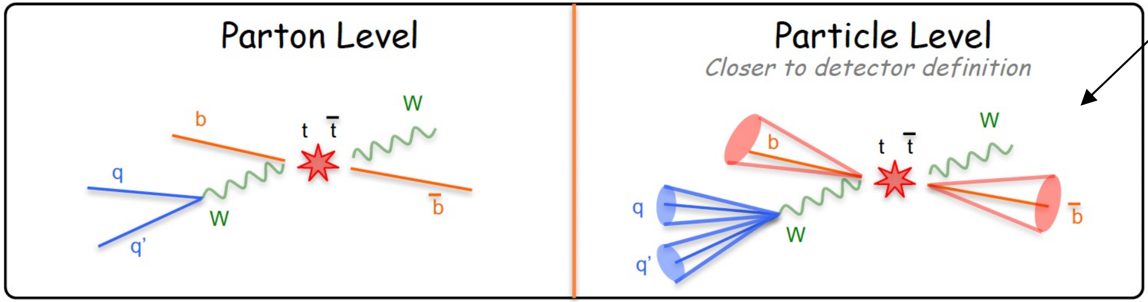
Parton level (full phase space):

- Top defined after QCD radiation and before it decays.
- Mimics definitions of bare quark widely used in fixed order theory calculations.

Particle level (fiducial phase space):

- Based on stable particles after hadronisation (see exact definition used https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions).
- Fiducial phase space defined according to detector level cuts.
- Reduced effect from extrapolation.

Less model dependent and thus more precise



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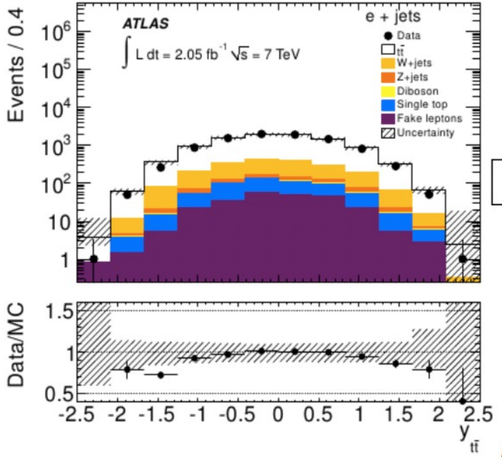
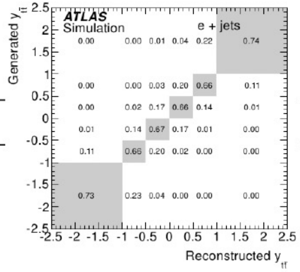
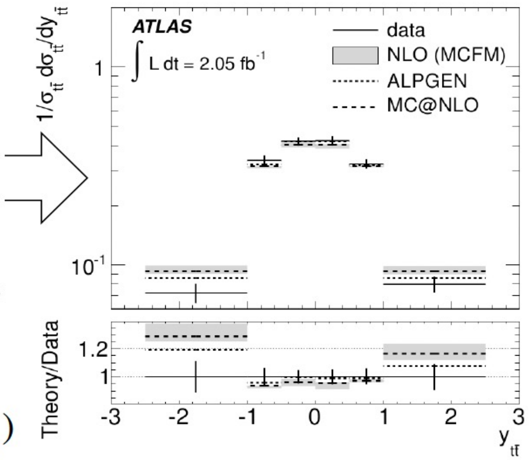


Account for experimental effects



bin migration matrix

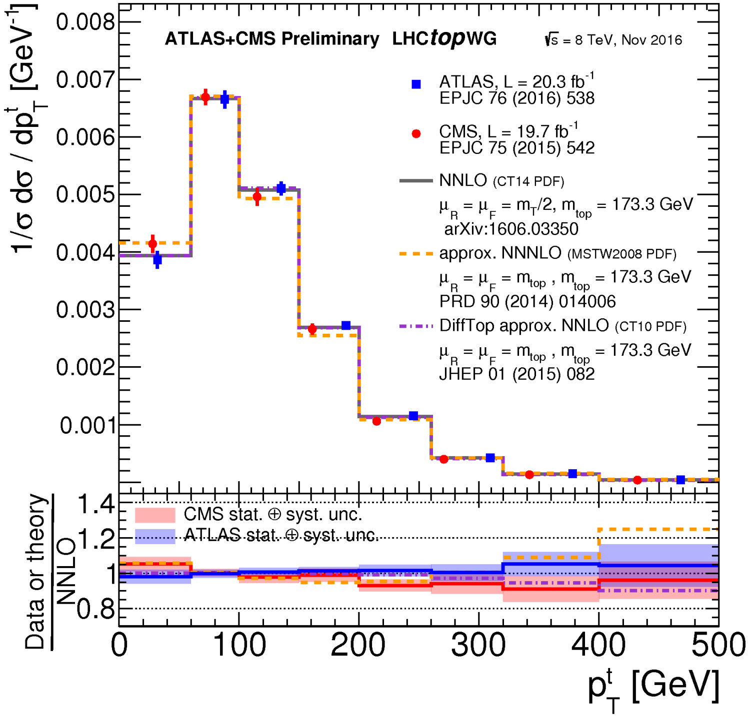


$$\left(\frac{d\sigma}{dX}\right)_i = \frac{\sum_j m_{ij}^{-1}(N_j - B_j)}{A_i L \Delta X_i}$$

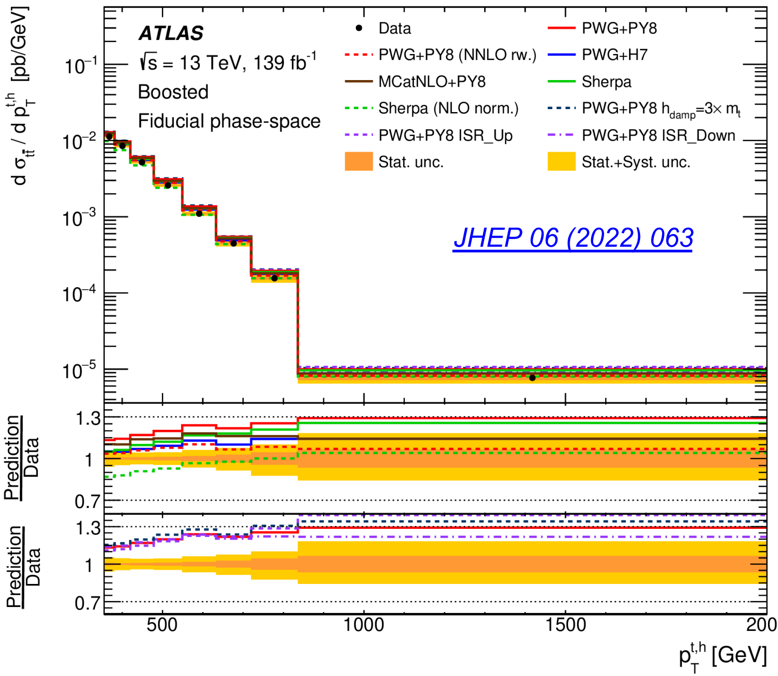
bin acceptance

Example: Top p_T spectrum

At parton level, resolved regime (√s=8 TeV)



At particle level, boosted regime (√s=13 TeV)



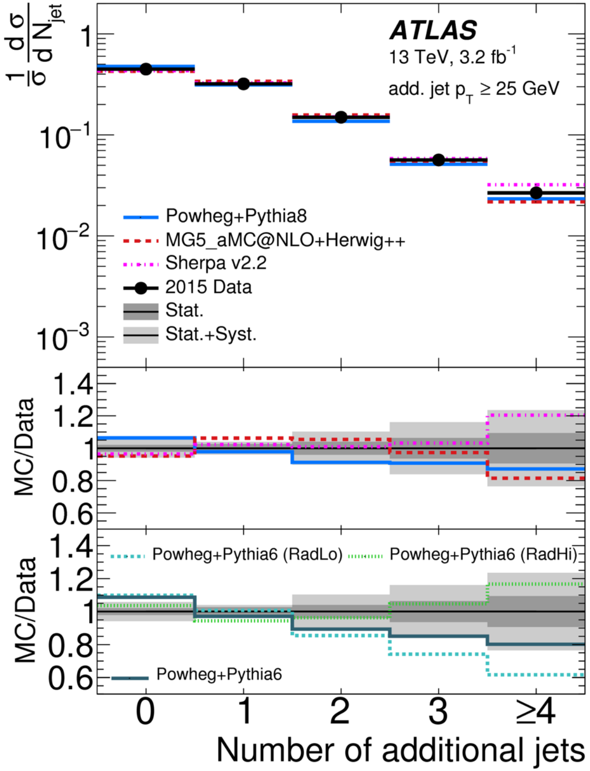
JHEP 06 (2022) 063

- MC generators (NLO+PS) predict a harder top p_T distribution at high values than observed.
- Improved description from NNLO calculation (but only fixed-order, not implemented in MC generator!)

Example: Observables sensitive to QCD radiation

- Probe correctness of simulation for high jet multiplicity QCD at the top scale and measure/tune initial/final state radiation (ISR/FSR) contributions ➔ important for top, Higgs and many BSM studies

EPJC 77 (2017) 220



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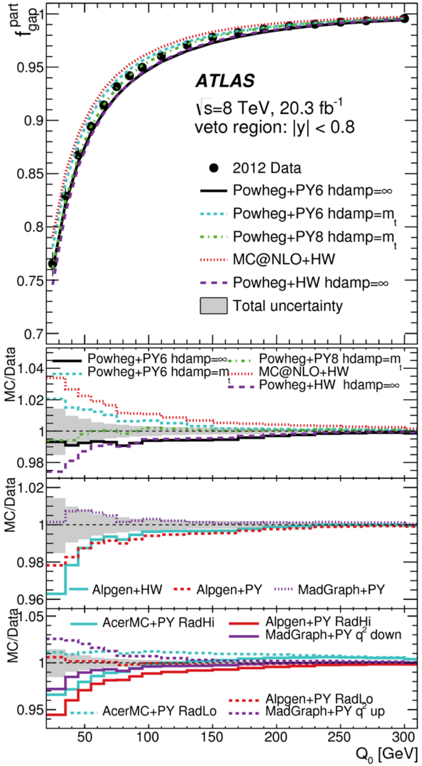
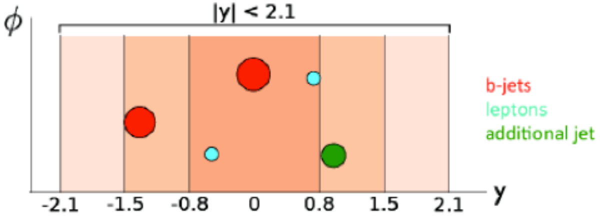




$$f_{Gap}(x) = \frac{N(x \leq threshold)}{N}$$

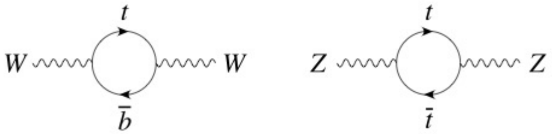
Fraction of events that do not contain additional jets above a given threshold

Top Quark Mass

Top quark mass

- Fundamental parameter of the SM.
- Important ingredient for EW precision analyses at the quantum level.

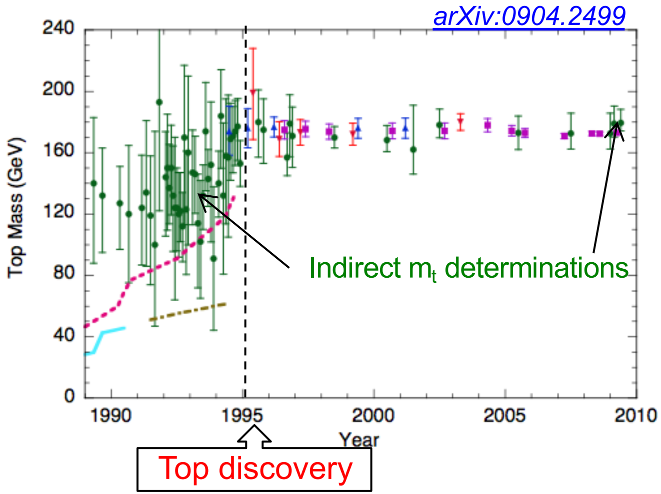
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

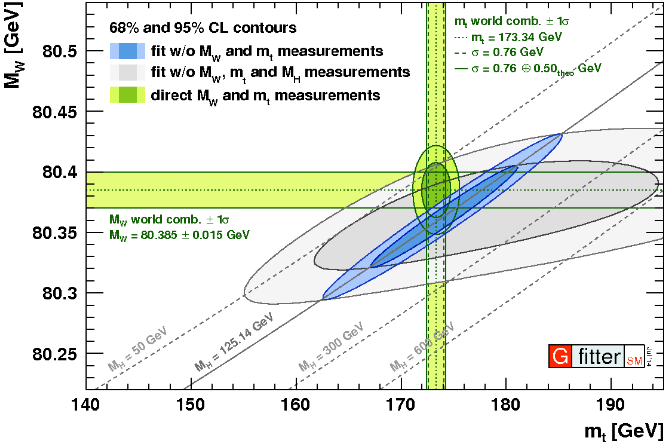


$$\Delta r_{\text{top}}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\text{Higgs}}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

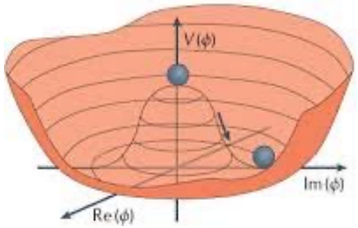
- Incisive consistency checks of the SM
- Constrain/rule out models of New Physics

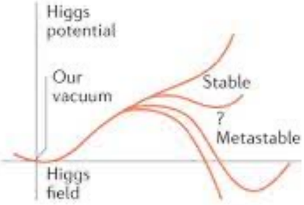


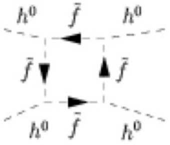


Top quark mass

- Large top-Higgs Yukawa coupling also results in large radiative corrections to Higgs quartic coupling.
- Extrapolating to the Planck scale assuming no New Physics contributions:

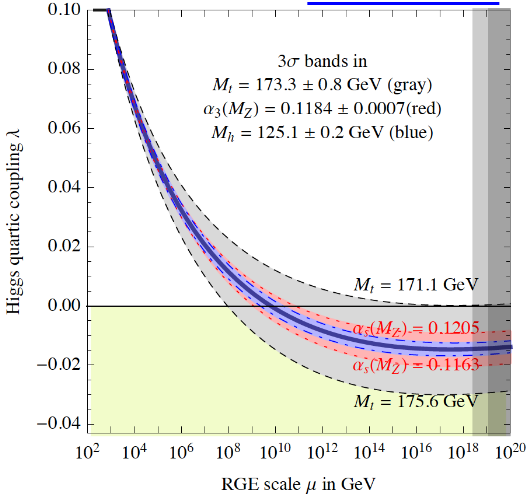


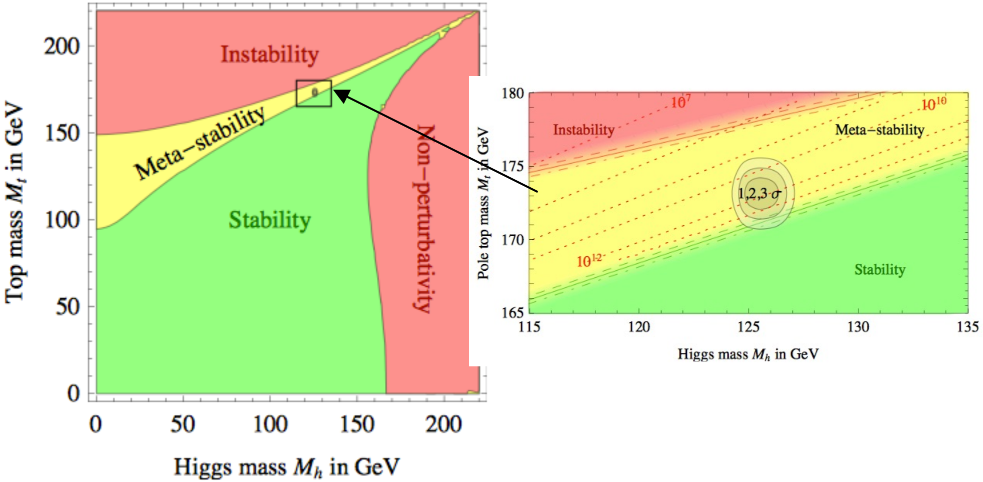




$$\lambda(M_{\rm Pl}) = -0.0143 - 0.0066\left(\frac{M_t}{\rm GeV} - 173.34\right) + +0.0018\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} + 0.0029\left(\frac{M_h}{\rm GeV} - 125.15\right)$$

arXiv:1307.3536

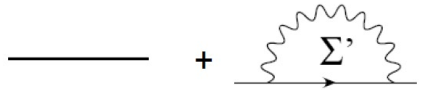




➔ Implications for stability of electroweak vacuum

Top mass in QCD perturbative calculations

- Parameters of the Lagrangian have no unique physical interpretation. Radiative corrections require definition of renormalization scheme.



$$= p - m^0 - \Sigma(p, m^0, \mu)$$

$$\Sigma(m^0, m^0, \mu) = m^0 \left[\frac{\alpha_s}{\pi\epsilon} + \ldots \right] + \Sigma^{\text{fin}}(m^0, m^0, \mu)$$

$\overline{\text{MS}}$ scheme:

$$m^0 = \overline{m}(\mu) \left[1 - \frac{\alpha_s}{\pi\epsilon} + \ldots \right]$$

A. Hoang @ Workshop on "Top mass: challenges in definition and determination", Frascati, May 2015

→ $\overline{m}(\mu)$ is pure UV-object without IR-sensitivity

→ Useful scheme for $\mu > m$

→ Far away from a kinematic mass of the quark

Pole scheme:

$$m^0 = m^{\text{pole}} \left[1 - \frac{\alpha_s}{\pi\epsilon} + \ldots \right] - \Sigma^{\text{fin}}(m^{\text{pole}}, m^{\text{pole}}, \mu)$$

→ Absorbes all self energy corrections into the mass parameter

→ Close to the notion of the quark rest mass (kinematic mass)

→ Renormalon problem: infrared-sensitive contributions from < 1 GeV that cancel between self-energy and all other diagrams cannot cancel.

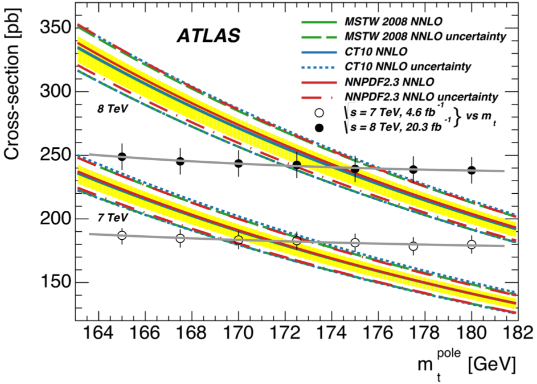
→ Σ^{fin} has perturbative instabilities due to sensitivity to momenta < 1 GeV (Λ_{QCD})

Should not be used if uncertainties are below 1 GeV !

Strategies to measure the top quark mass

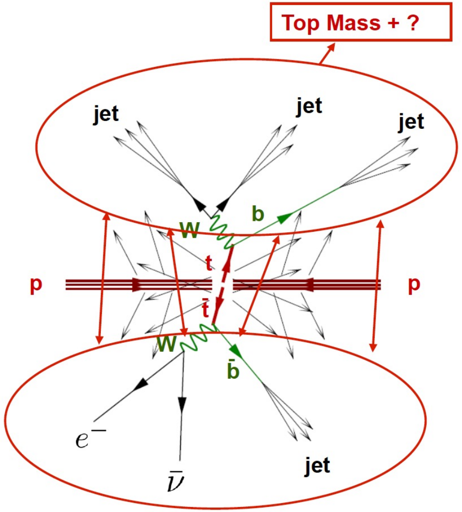
- **Indirect measurements**:
  - Based on the comparison of inclusive or differential tt cross sections to the corresponding theory calculations

➔ In principle well-defined top mass definition: pole mass or MSbar mass



- **Direct measurements**:
  - Exploiting information from the kinematic reconstruction of measured top-quark decay products, e.g.
    - Reconstructed m_t (tt or single top events)
    - B-jet energy spectrum
    - B hadron transverse decay length
    - Lepton p_T
    - Lepton+b-jet mass, lepton+J/ψ mass
    - …
  - Parametrise observable in m_{top} using MC simulation

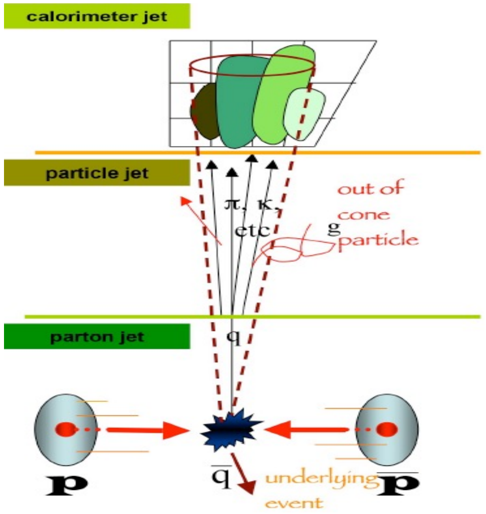
➔ Actual top mass definition not so clear: “MC top mass”



Handles for a precise m_t^{MC} measurement

Jet Energy Scale (JES)

- Direct top mass measurement requires precise mapping between reconstructed jets and original partons ➔ correct for detector, jet algorithm and physics effects
- Restores the jet energy scale to that of jets made of stable particles.
- Handles:
  - MC simulation
  - dijets, photon+jets, Z+jets
  - Z+b-jet (verification of b-jet energy scale)



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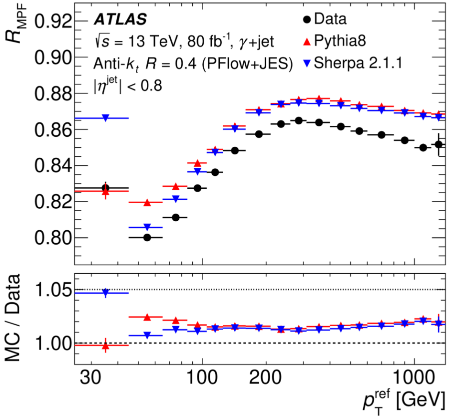
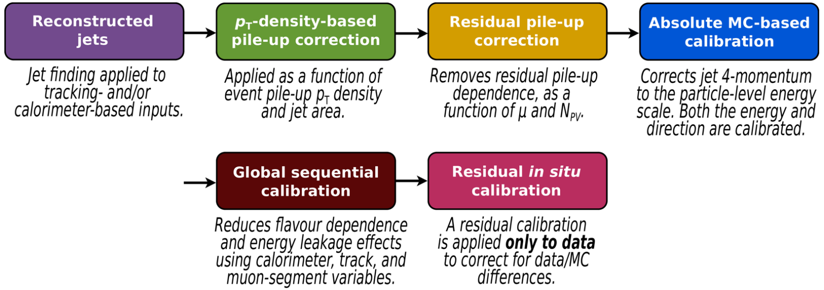


Residual in-situ calibration using Z+jets events

A sophisticated correction procedure (e.g. ATLAS):



Reconstructed jets
Jet finding applied to tracking- and/or calorimeter-based inputs.

p_T-density-based pile-up correction
Applied as a function of event pile-up p_T density and jet area.

Residual pile-up correction
Removes residual pile-up dependence, as a function of μ and N_{PV}.

Absolute MC-based calibration
Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.

Global sequential calibration
Reduces flavour dependence and energy leakage effects using calorimeter, track, and muon-segment variables.

Residual *in situ* calibration
A residual calibration is applied **only to data** to correct for data/MC differences.

Handles for a precise m_t^{MC} measurement

Jet Energy Scale (JES)

- Restores the jet energy scale to that of jets made of stable particles.
- Handles:
  - MC simulation
  - dijets, photon+jets, Z+jets
  - Z+b-jet (verification of b-jet energy scale)
  - W mass from W→jj in top quark decays (in-situ calibration in tt events!)

B-tagging

- Reduction of physics as well as combinatorial background

Sophisticated mass extraction techniques

- Maximize statistical sensitivity; minimize some systematic uncertainties (e.g. JES)

Simulation

- Accurate detector modeling and state-of-the-art theoretical knowledge (gluon radiation, b-fragmentation, etc) required.

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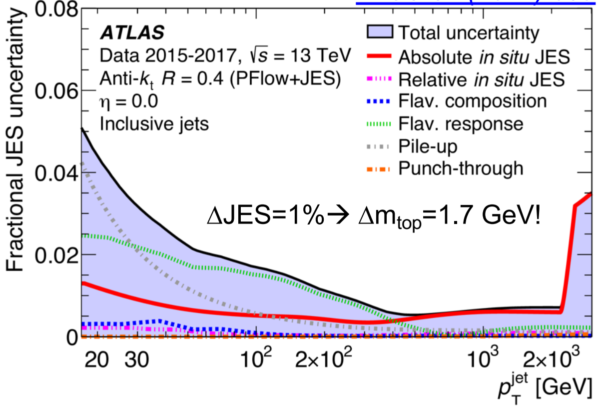

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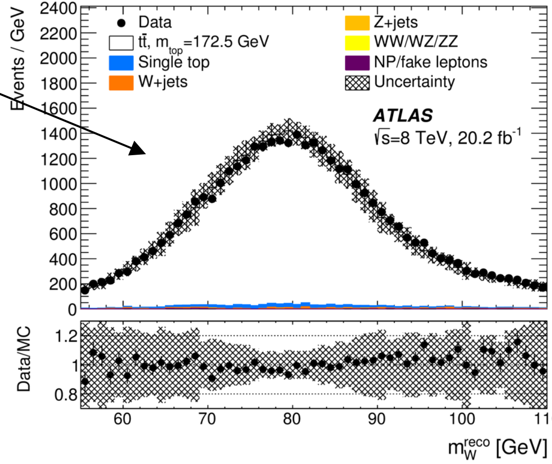
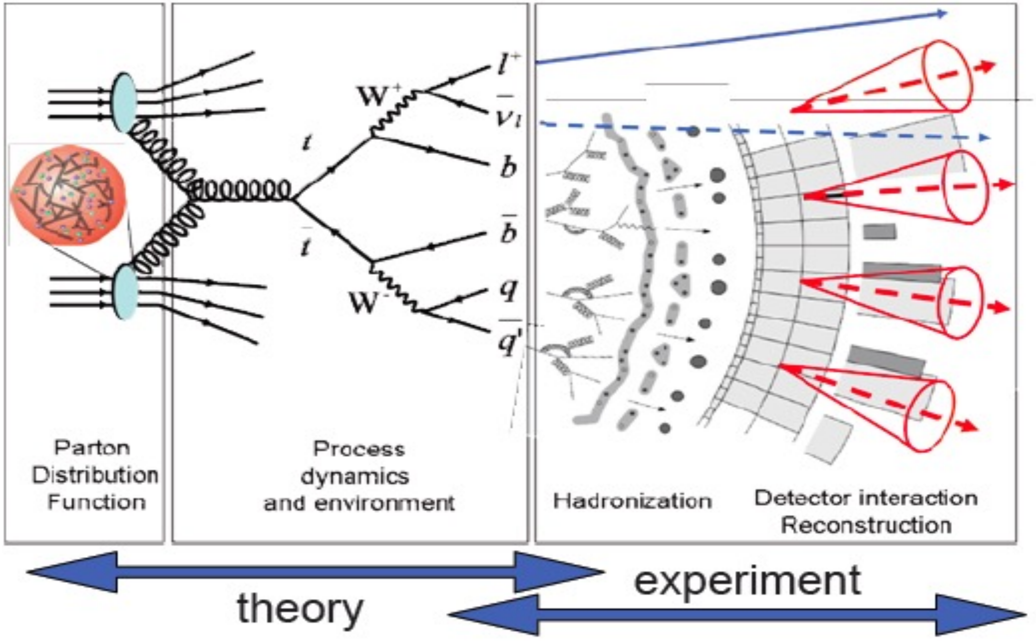


Systematic uncertainties

- Signal simulation (PDFs, MC generator, hadronization model)
- Event modeling and environment (underlying event, color reconnection, QCD radiation, pileup)



- Physics objects and detector modeling (JES, JER, b-tagging, E_T^{miss},…)
- Background contamination

➔ Can exploit data to verify proper modeling and/or further constrain size of systematic uncertainties.

m_t^{MC} extraction techniques: Template Method

- Identify kinematical variables strongly correlated with m_t. Compare data and MC with different m_t hypotheses.
- Example: reconstructed m_t from kinematic fit in l+jets channel. Usually pick solution with lowest χ^2.
- Reduce impact from JES in-situ by simultaneously fitting three observables:
    - m_t^{reco} (sensitive to m_t, JSF and bJSF)
    - m_W^{reco} (sensitive to JSF)
    - R_{bq}^{reco} (~p_{Tb}/p_{TW}, sensitive to bJSF)

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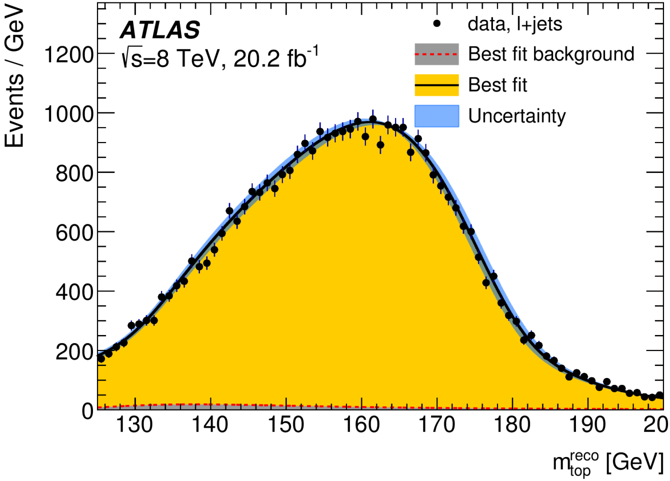
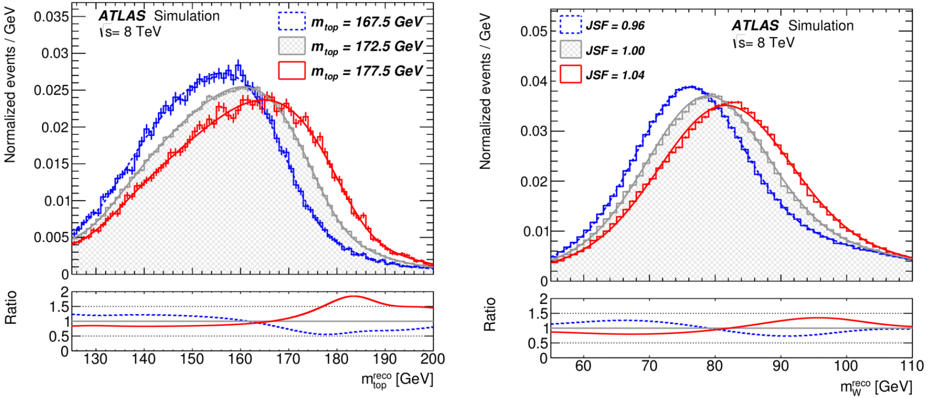


EPJC 79 (2019) 290



m_t = 172.08 ± 0.39 (stat+JSF+bJSF) ± 0.82 (syst) GeV

Total uncertainty: 0.91 GeV

(Dominant systematics: JES, JER, signal modeling)

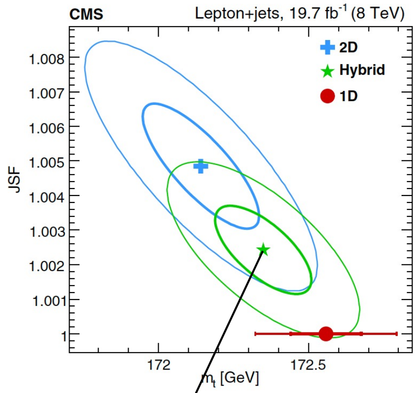
m_t^{MC} extraction techniques: Ideogram Method

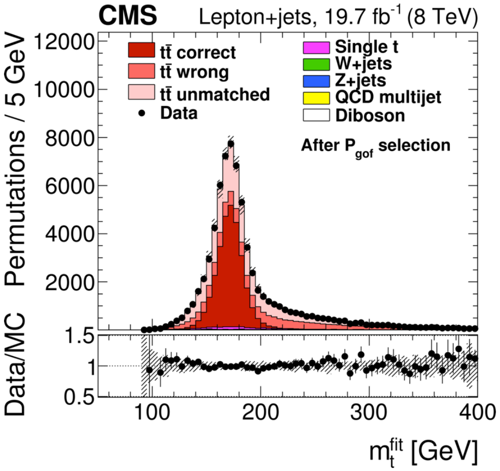
- Modification of the template method using multiple permutations with different weight.
- Starts from kinematic reconstruction, then computes event likelihood as a function of m_t and a JES overall factor.
- Different probability density functions used for different jet quark assignments.
- 2-dimensional event likelihood (ideogram) given by:

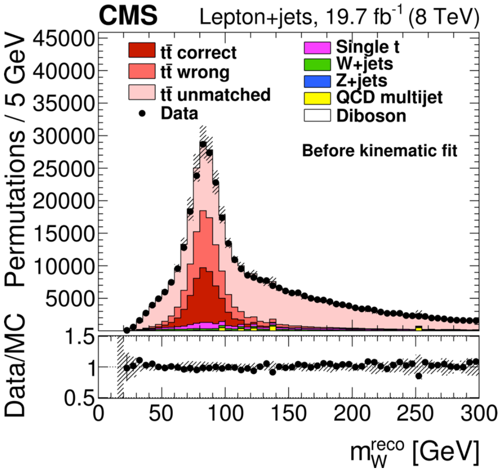
$$\mathcal{L}\left(\text{event}|m_{\mathrm{t}},\text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}\left(i\right)\left\{ f_{\text{sig}} P_{\text{sig}}\left(m^{\text{fit}}_{\mathrm{t},i}, m^{\text{reco}}_{\mathrm{W},i}|m_{\mathrm{t}},\text{JSF}\right) + \left(1-f_{\text{sig}}\right) P_{\text{bkg}}\left(m^{\text{fit}}_{\mathrm{t},i}, m^{\text{reco}}_{\mathrm{W},i}\right)\right\}$$

$$\mathcal{L}\left(\text{sample}|m_{\mathrm{t}},\text{JSF}\right) = \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_{\mathrm{t}},\text{JSF}\right)^{w_{\text{event}}} \qquad w_{\text{event}} = c\sum_{i=1}^{n} P_{\text{gof}}\left(i\right)$$

PRD 93 (2016) 072004







m_t = 172.35 ± 0.16 (stat+JSF) ± 0.48 (syst) GeV

Total uncertainty: 0.51 GeV

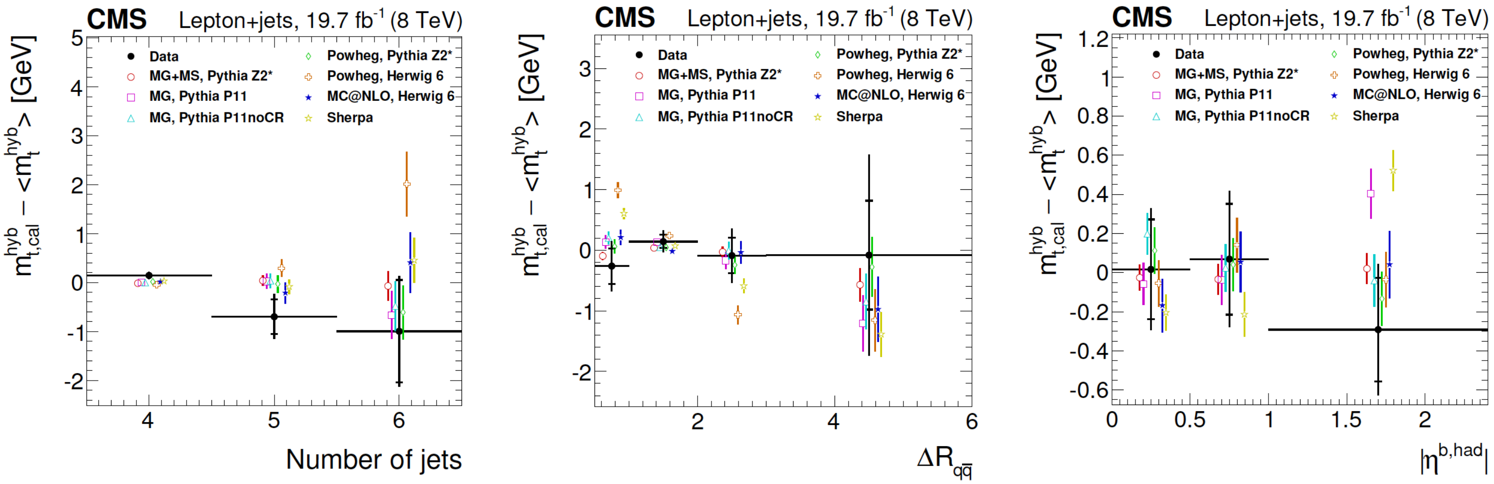
(Dominant systematics: flavor-dependent JES)

Was the single most precise measurement till recently…

Measured m_t^{MC} as a function of kinematics

- High sample statistics at the LHC allows to perform the m_t^{MC} measurement as a function of kinematic variables that are sensitive to radiation and color reconnection effects: n_{jets}, $p_T(t)$, ΔR_{qq}, $|\eta_b|$,…

PRD 93 (2016) 072004



Ndof = 27

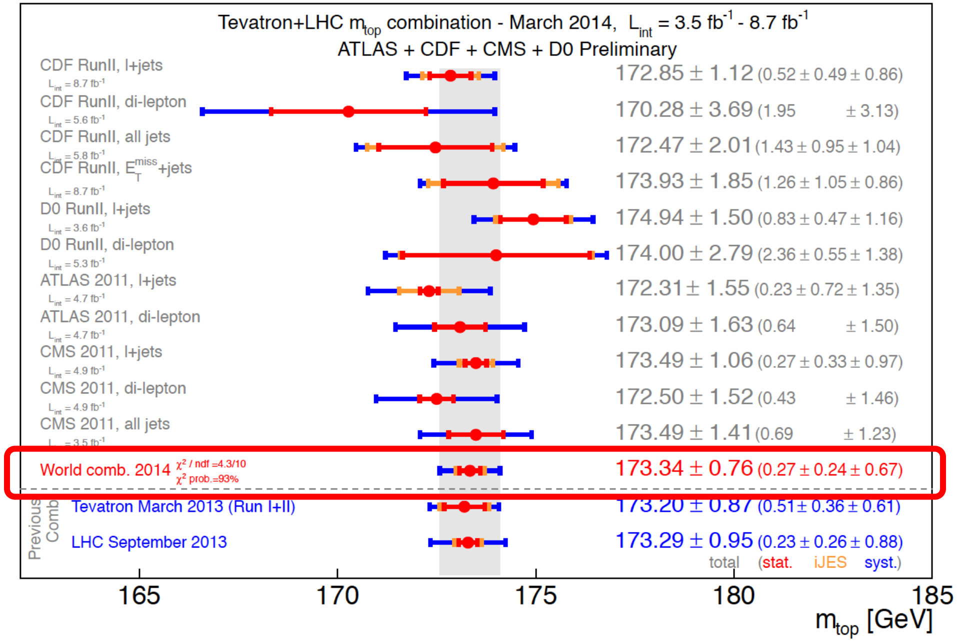
Simulation	χ^2	Standard deviations
MG + PYTHIA 6 Z2*	17.55	0.10
MG + PYTHIA 6 P11	37.68	1.73
MG + PYTHIA 6 P11noCR	31.57	1.15
POWHEG + PYTHIA 6 Z2*	19.70	0.20
POWHEG + HERWIG 6	76.48	4.84
MC@NLO + HERWIG 6	20.47	0.24
SHERPA	46.79	2.56

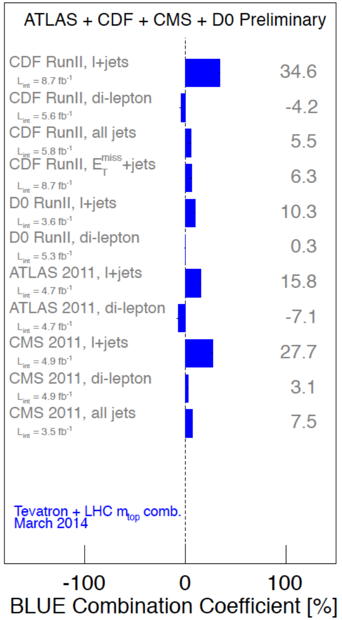
Data well described by models
(possible exception POWHEG+HERWIG)

Much potential with Run 2 (and beyond) statistics!

March 2014: First m_t^{MC} world average!

arXiv:1403.4427





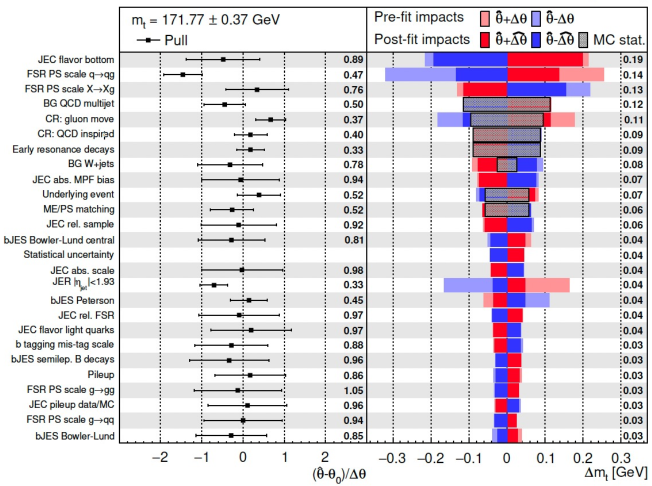
- Most precise individual measurements at the time were from CDF and CMS in lepton+jets.
- Stability checks performed on the impact of assumed correlations (results stable within 200 MeV for the central value and within 300 MeV for the uncertainty).

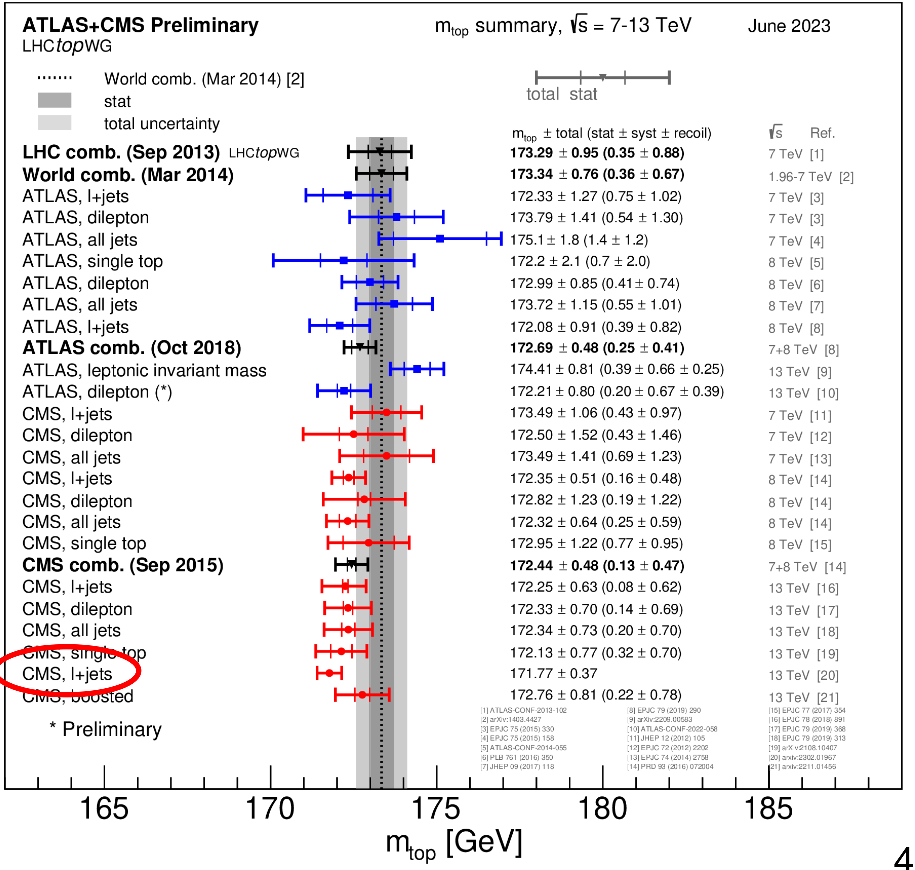
Summary of LHC m_t^{MC} measurements

- Now there are multiple measurements with a precision comparable or better than 2014 world average.

- The latest CMS result in the lepton+jets channel fits 5 observables and exploits the profiling of systematic uncertainties to reach <400 MeV precision:

arXiv:2302.01967





- The next combination will very challenging!

m_t^{pole} from σ_{tt} measurement

- Taking as input the ttbar cross section measured in the eμ channel.
- Important to obtain measurements as independent as possible on the assumed top quark mass.

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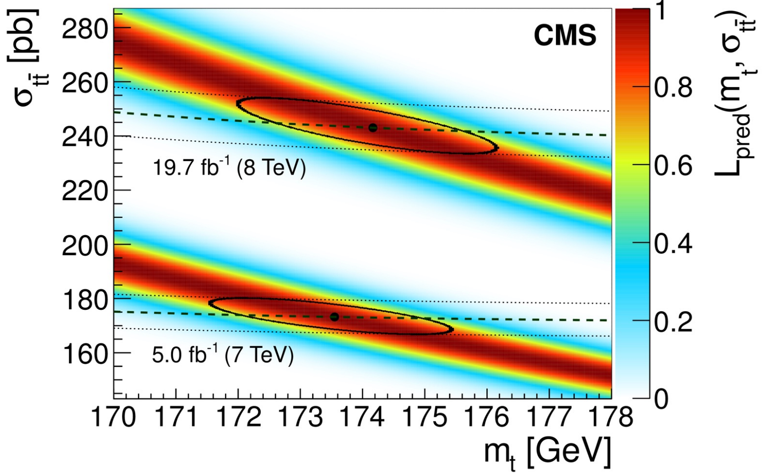
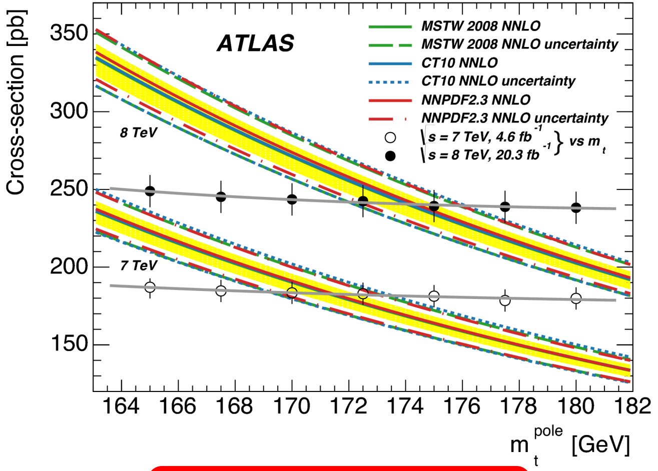


$$m_t^{pole} = 173.8\,^{+1.7}_{-1.8}\ \text{GeV}$$

EPJC 74 (2014) 3109



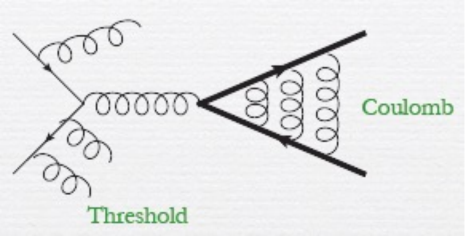
$$m_t^{pole} = 172.9\,^{+2.5}_{-2.6}\ \text{GeV}$$

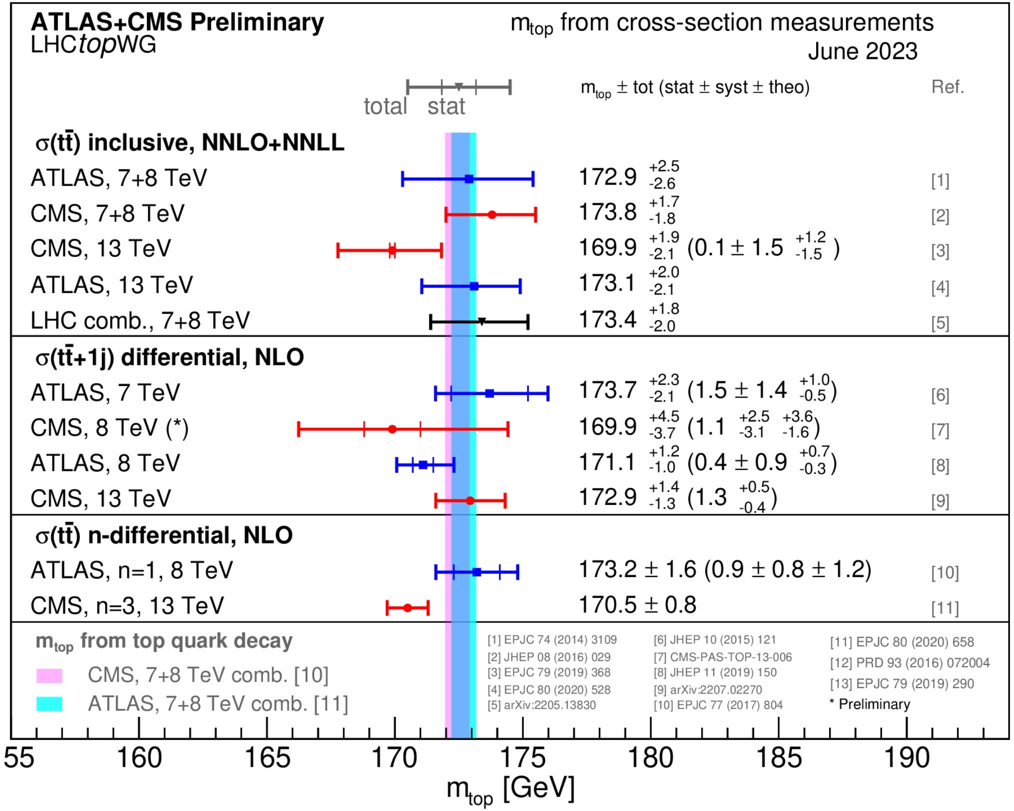
- Measurement dominated by theory uncertainties (scale and PDF).
- New PDFs have smaller uncertainties than previous generation, thanks to the inclusion in the fit of LHC data.
- At 13/14 TeV the uncertainties due to PDFs are smaller than a 7/8 TeV, as we probe gluon content at lower x.

Summary of LHC m_t^{pole} measurements

- Theoretical progress is the key to improve the precision and be competitive with the MC top mass determinations.

- <u>Caveat</u>: The top quark mass extractions from differential measurements may receive sizable corrections from Coulomb and soft-gluon resummation near the $t\bar{t}$ production threshold that are not explicitly accounted for in the theoretical predictions.





Recap

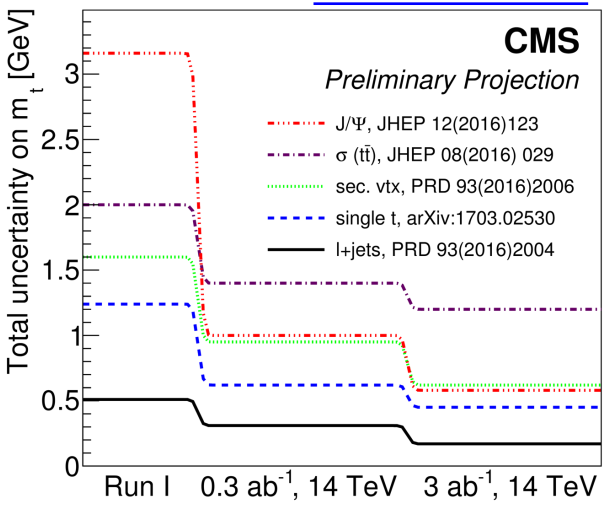
- The top quark mass is a fundamental parameter of the SM that needs to be measured as precisely as possible.
- Since the top quark is not a free particle the mass definition is not unique.
  - Mass definitions used in QCD perturbative calculations (e.g. m_t^{pole}) (used in EW fits, or EW vacuum stability studies).
    - The relations among these mass definitions is well known.
  - Mass as implemented in the Monte Carlo generators: m_t^{MC} .
    - Finding out precisely the relation between the MC mass and the masses defined in perturbation theory is a big theoretical challenge!

$$m_t^{pole} = m_t^{MC} + \Delta_t^{MC}$$

- Experiments have performed a wide range of top quark mass measurements using different techniques and datasets.
  - Very precise measurements of m_t^{MC} (<0.5 GeV!).
  - Direct measurements of m_t^{pole} also available (~1-2 GeV) where theoretical progress is key to improve the precision.

  And the precision will continue to improve.
- Addressing the issue on the top mass definition and the associated theoretical uncertainty is becoming more pressing than ever!

CMS-PAS-FTR-16-006



Next lecture

Lecture 1: Bread & butter Top Physics

- Introduction
- Top pair production cross-section
- Top mass

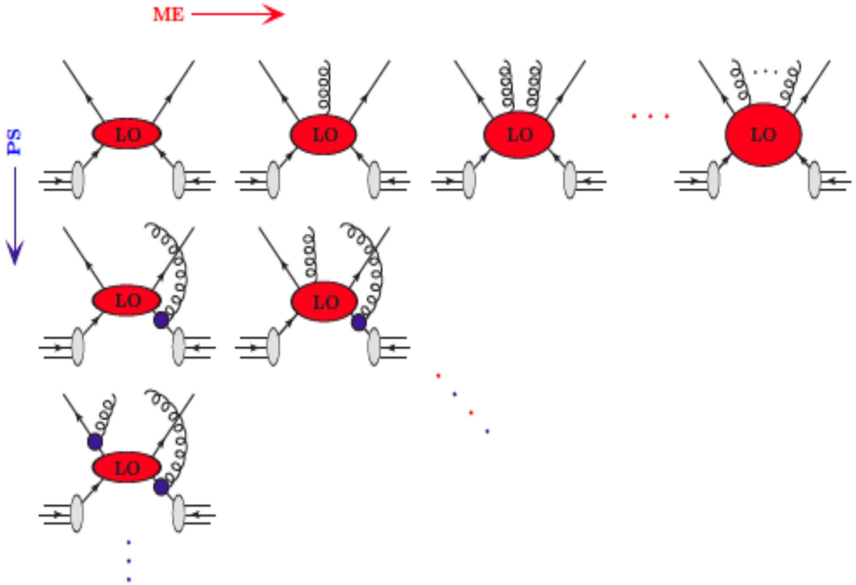
Lecture 2: Top and New Physics

- Top couplings
- Exotic top production & decay

Backup

tt MC generators

- LO ME+PS MCs (ALPGEN, MadGraph) show in general good agreement with data. Typically go up to tt+≤3 jets.



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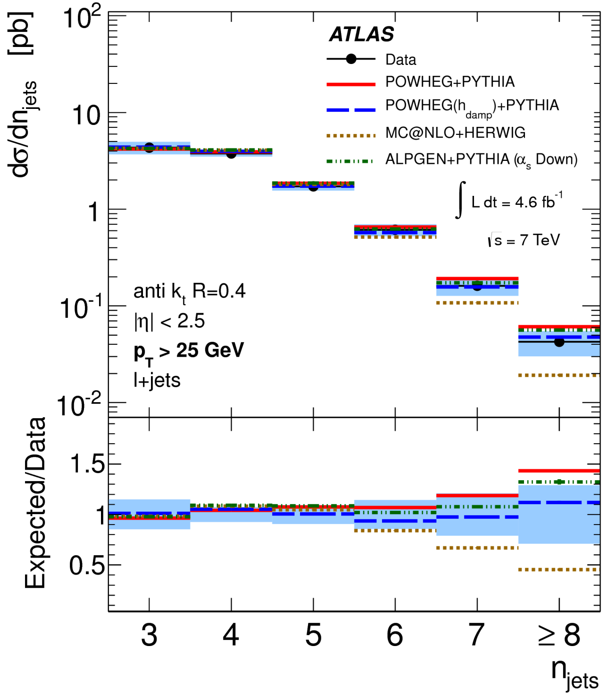
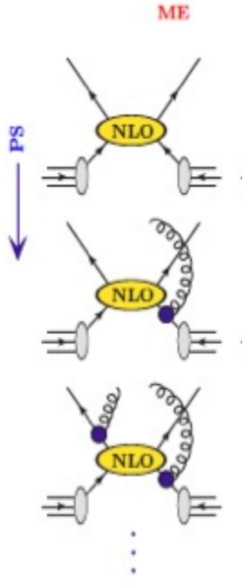


tt MC generators

- LO ME+PS MCs (ALPGEN, MadGraph) show in general good agreement with data. Typically go up to tt+≤3 jets.
- NLO ME+PS MCs (MC@NLO, Powheg-Box) consistently merge a NLO calculation with PS (provides resummation).



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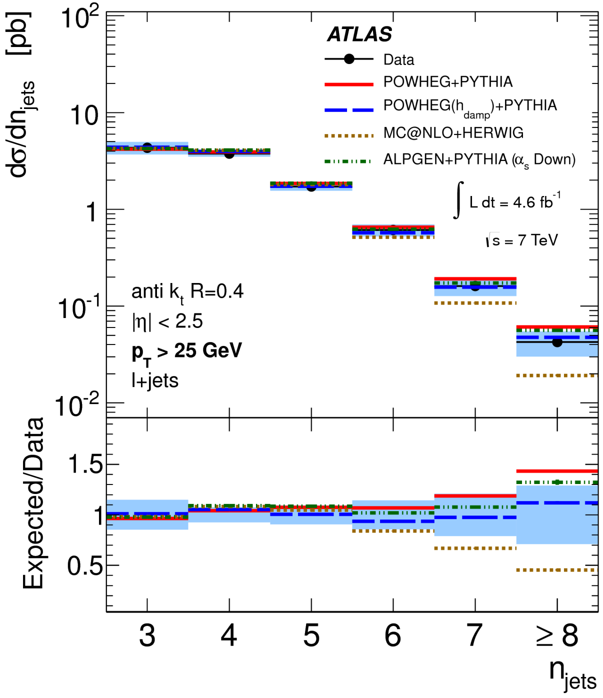
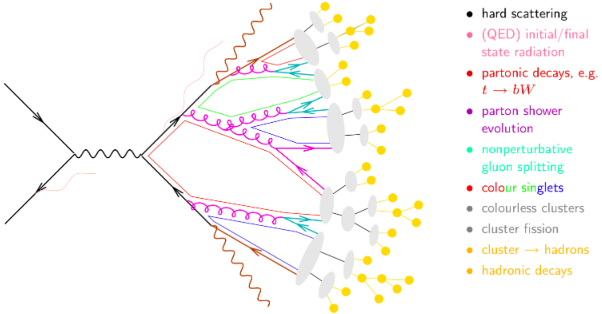


MC top quark mass

Slide from A. Hoang



1) Matrix elements (LO/NLO)
2) Parton shower (LL)
3) Hadronization model

- Full simulation of all processes (all experimental aspects accessible)
- QCD-inspired: partly first principles QCD ⇔ partly model
- Description power of data better than intrinsic theory accuracy.
- Top quark in parton shower: treated like a real particle ($m_t^{MC} \approx m_t^{pole} +?$).
- Top quark in matrix elements: $m_t^{MC} = m_t^{pole}$

But pole mass ambiguous by $O(\Lambda_{QCD})$ due to confinement.
Short mass definition more suitable.

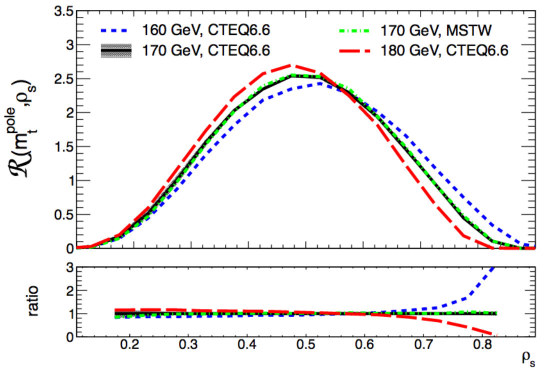
- Different approaches are being followed by theorists to calibrate de Monte Carlo top quark mass of a given generator (i.e. to relate it precisely with a theoretically well defined mass). See e.g. EPS 2017 talk from G. Corcella: https://indico.cern.ch/event/466934/contributions/2575362/attachments/1489674/2315013/corcella_eps_top.pdf

m_t^{pole} from $\sigma_{tt+1jet}$ measurement

- Sensitivity enhanced by mass-dependent radiation.
- Infer mass from (normalized) shape of ρ_S variable:

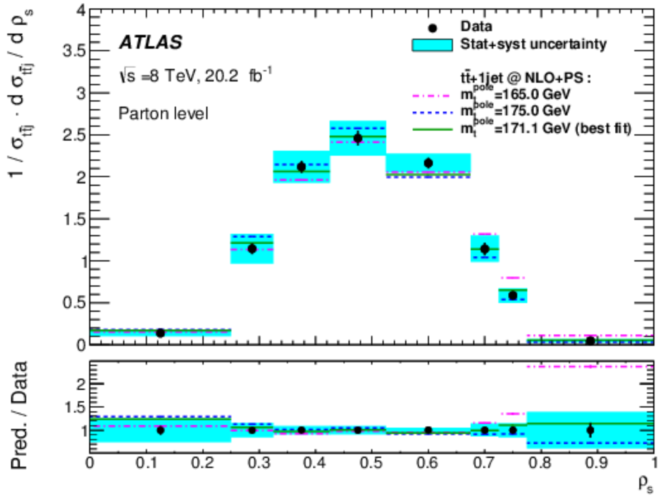
$$\mathcal{R} = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}(m_t^{\text{pole}})}{d\rho_S}$$

$$\rho_S = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \quad , \quad m_0 = 170\ \text{GeV}$$



- Large sensitivity for $\rho_S \geq 0.7$.
  - $\rho_S \rightarrow 1$ at threshold
  - $\rho_S \rightarrow 0$ for boosted production
- The observable is x5 more sensitive than σ_{tt}!
- Requiring one additional jet to the standard ttbar lepton+jets selection.
- Data is unfolded to parton level and compared to ttbar+1jet NLO+PS (difference NLO vs NLO+PS ~300 MeV)

JHEP 11 (2019) 150



$$\boxed{m_t^{\text{pole}} = 171.1 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst})\ {}^{+0.7}_{-0.3}\,(\text{theo})\ \text{GeV}}$$

Total uncertainty: +1.2/-1.1 GeV

(Dominant systematics: JES, signal modeling, scale variations)