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# Precision Physics at Colliders

HOW TO CHOOSE WISELY, MEASURE CAREFULLY, AND EXPLOIT RUTHLESSLY

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# Modus Operandi



## “Standard Model Physics” and Precision

- These lectures nominally meant to cover LHC experimental results and methods in QCD/top/electroweak/flavor physics, i.e., the most direct predictions of the Standard Model (excluding our newest member of the family, the Higgs field and its boson).
- A complete survey of these in three lectures is so broad as to not be meaningful!
- “Precision measurements” was alternatively suggested. That doesn’t quite narrow it down either. Lots of precise measurements are available with LHC data but not all of them are created equal.

## “Standard Model Physics” and Precision

- I have chosen to focus on precision measurements which bound the **fundamental symmetries and parameters of the Standard Model**, as well as the experimental validation of phenomenology required to make them.
- Some common methods and problems arise out these case studies of relevance for precision collider measurements of all types.
- Precision requires time and understanding. Many of these measurements are based on Run 1 data, with Run 2 versions still in progress.

## Syllabus: Review of six measurements

- Lecture 1, Friday Aug. 24
- The miracle of QCD: jets, tops, and  $\alpha_S$
- Lecture 2, Sunday Aug. 26
- The vise of precision electroweak:  $\sin^2\theta_W$  and  $M_W$
- Lecture 3, Monday Aug. 27
- The mystery of flavor: Capturing Wilson coefficients and testing lepton universality



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# Precision Physics at Colliders 1:

THE MIRACLE OF QCD

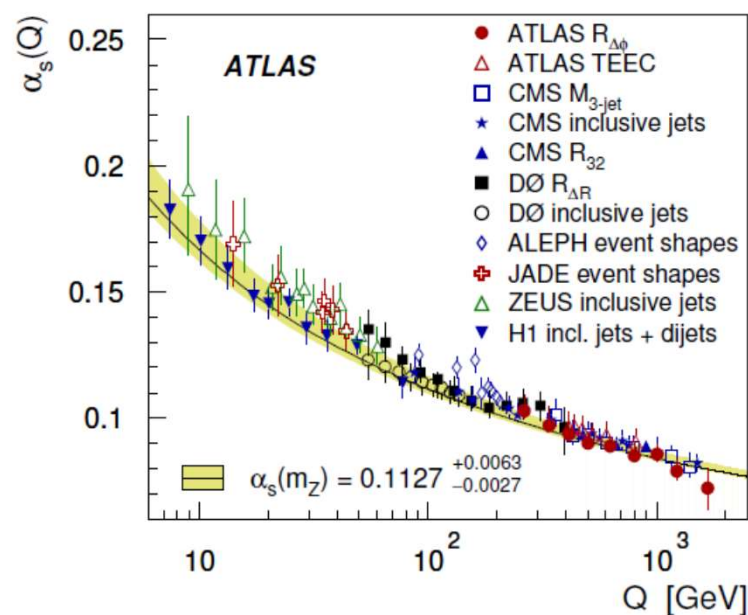
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# QCD, Jet phenomena, and the Strong Coupling

- QCD is (at LHC scales) perturbatively calculable, asymptotically free, has no broken symmetries, and depends only on quark masses and a **single coupling constant** to describe a huge range of high energy phenomena

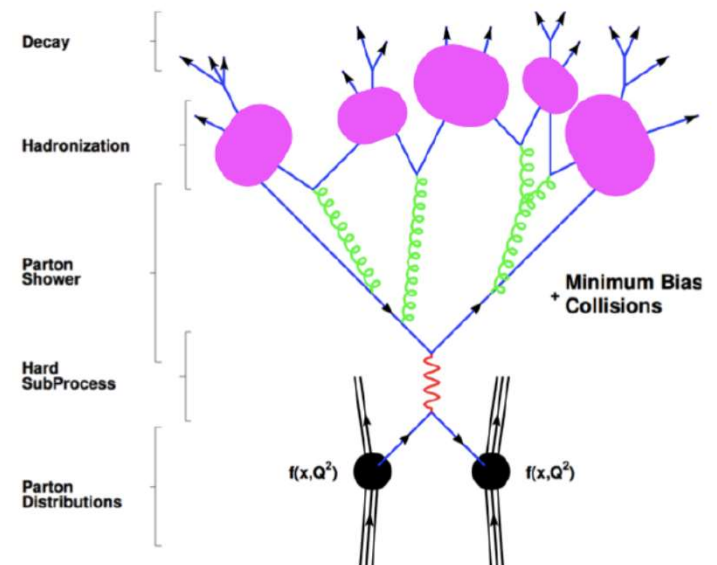
- Jet production
- Jet fragmentation
- Parton distribution function scaling with  $Q^2$
- Hadronic event shapes and energy flow correlations
- Deep inelastic scattering



- Lecture 1 goal:** We will address here how quark/gluon production can be measured to maximum precision and used to precisely obtain the strong coupling constant.

# Jets

- Qualitatively, jets are a **directed flow of particle energy**, indicative of the existence of a **hard free quark or gluon** in the proton scattering, which has subsequently **fragmented and hadronized**.
- Several steps to simulating and reconstructing jets:
  - The hard scattering of the quarks/gluons at a high energy scale  $Q$  (pQCD Feynman diagrams)
  - Fragmenting of the free parton into multiple softer partons (parton showering via pQCD-inspired methods and approximations)
  - Hadronization of soft partons at a GeV scale into (possibly unstable) hadrons
  - Decay of unstable hadrons into (quasi)-stable particles (K, pi, p, n, leptons)

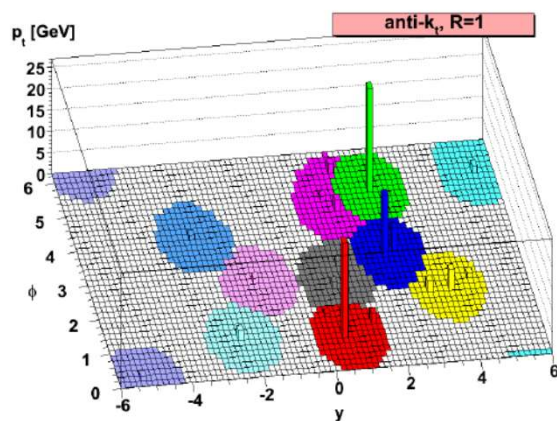




# Jets: jet clustering

[arxiv:0802.1189](https://arxiv.org/abs/0802.1189)

- Several steps to simulating and reconstructing jets:
  - Stable particles are detected in various ways
    - Charged hadrons (pions, kaons, protons): tracks and hadronic energy clusters
    - Neutral pions: decay to two photons
    - Other neutral hadrons (n, K<sub>0</sub>): hadronic energy with no track
    - e, mu: tracks with electromagnetic clusters or muon chamber tracks
  - A clustering algorithm determines how detected particles can be aggregated into jets based on their energy and direction



Consider all particle pairs,  $i, j$

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},$$

$$d_{iB} = k_{ti}^{2p}, \text{ Anti-Kt: } p = -1$$

If  $d_{ij}$  is the smallest, replace  $i$  and  $j$  with a combination

$$E_{T,k} = E_{T,i} + E_{T,j} \quad \eta_k = [E_{T,i}\eta_i + E_{T,j}\eta_j]/E_{T,k}, \quad \phi_k = [E_{T,i}\phi_i + E_{T,j}\phi_j]/E_{T,k}.$$

If  $d_{iB}$  is the smallest, terminate jet clustering

Hard anti-kt jets are circular in  $y$ - $\phi$  space of radius  $R$  (0.5, 0.7, 1.0); softer ones are crescents

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First Attempt at  $\alpha_s$ : Measure Jets  
and Their Cross Sections

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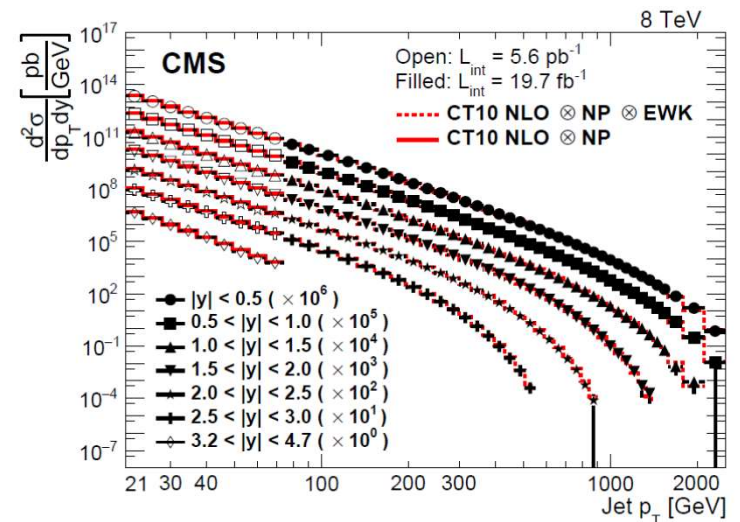
# Jet Cross Sections

[arxiv:1609.05331](https://arxiv.org/abs/1609.05331)

- To fully disentangle the effects of PDFs and the strong coupling, the jet production cross section must be sampled as a function of **jet PT** and **jet rapidity** over the widest achievable ranges

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T (2\Delta|y|)}$$

- Ingredients:
  - An accurate determination of jet energy and resolution
  - Luminosity measurement
  - Precise pQCD prediction
  - Unfolding
  - Strong coupling constraint

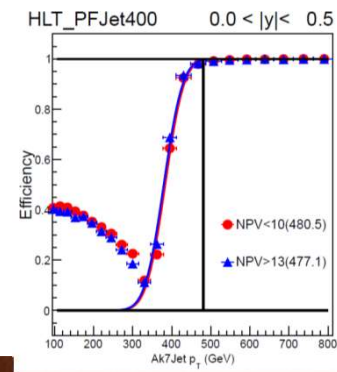
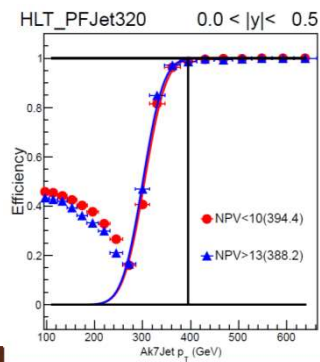
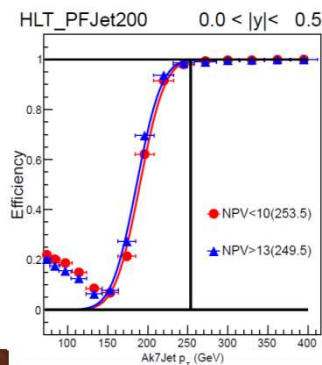


# Jet Samples and Efficiencies

- Jets can be captured from the trigger by selecting high energy calorimeter clusters.
  - Below 500 GeV jet  $p_T$ , prescaled triggers are necessary
  - For lowest  $p_T$  jets (<100 GeV), special low-pileup runs are necessary
  - Offline selection is  $\sim 150\%$  of trigger threshold, to guarantee  $\sim 100\%$  trigger efficiency and good sample overlap

Table 1: HLT trigger ranges and effective integrated luminosities used in the jet cross section measurement. The luminosity is known with a 2.6% uncertainty.

Trigger $p_T$ threshold (GeV)	40	80	140	200	260	320
Offline analysis $p_T$ range (GeV)	74–133	133–220	220–300	300–395	395–507	507–2500
Effective integrated luminosity ( $\text{pb}^{-1}$ )	$7.9 \times 10^{-2}$	2.12	55.7	$2.61 \times 10^2$	$1.06 \times 10^3$	$1.97 \times 10^4$



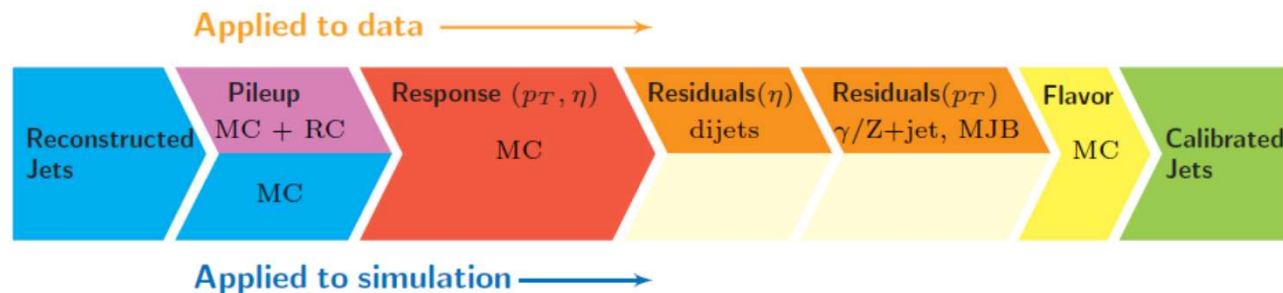


# Jets: jet energy corrections

[arxiv:1607.03663](https://arxiv.org/abs/1607.03663)

\* $c\tau < 1$  cm and excluding neutrinos

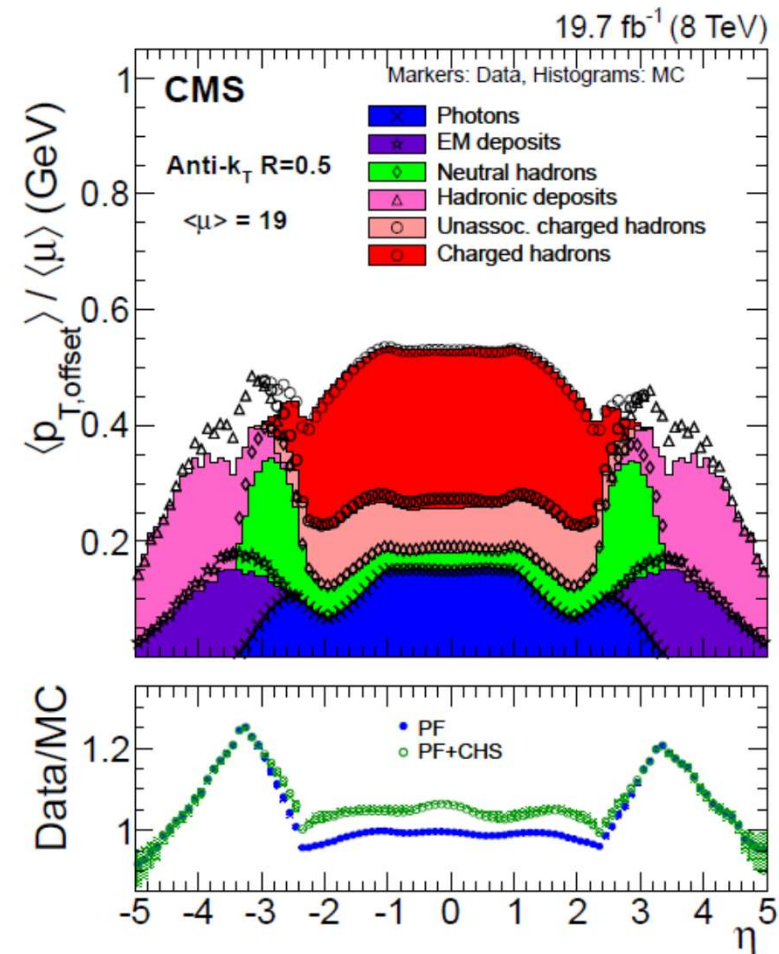
- The ideal detector will measure all particles produced
- The observable to be recovered and compared with prediction is **what the jet clustering algorithm returns for generator level stable\* particles**
- You measure what the algorithm returns for **detected particles**, which may have mismeasured energy, noise, inefficiencies, and pileup
- **Jet energy corrections** attempt to convert the measured result into the best estimator of the ideal one.
  
- Assume we start with properly calibrated particles/topoclusters which have been clustered
- In CMS, four classes of corrections applied:
  - **Pileup and noise subtraction**
  - **Detector response vs PT and eta** as judged by simulation
  - **Residual corrections** which account for unmodeled detector effects
  - **Flavor-specific corrections** which model simulated flavor-specific behavior





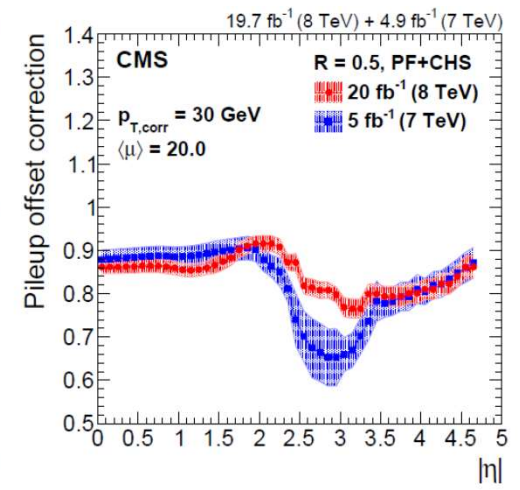
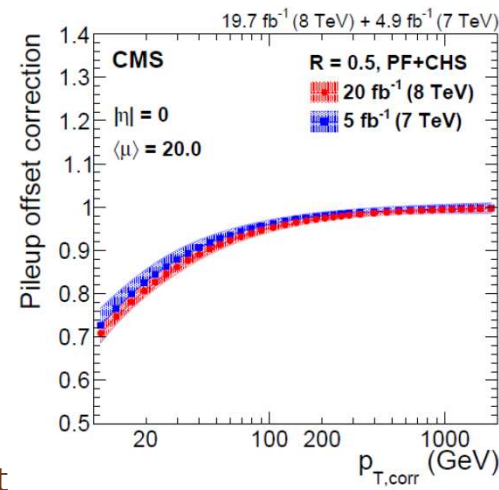
# Jets: pileup corrections

- BX-id and separation of calorimeter pulse shapes used to remove out-of-time energy
- Upon identifying the primary vertex, remove charged hadrons/leptons inconsistent with it (CHS, “charged-hadron subtraction”)
- Algorithms to identify energy flow patterns consistent with random clustering of pileup energy (“pileup jet ID”)
- Estimators of neutral hadron energy from pileup
  - Estimate median energy density and subtract that from the jet area (with PT and eta-dependent corrections)
  - Use energy-flow information to probabilistically infer neutral pileup (“PUPPI”!)



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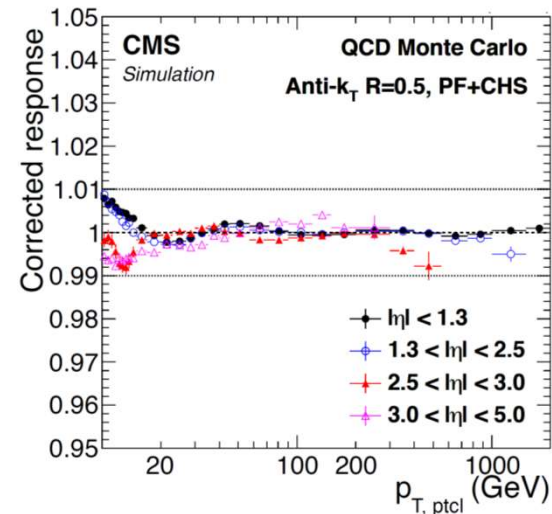
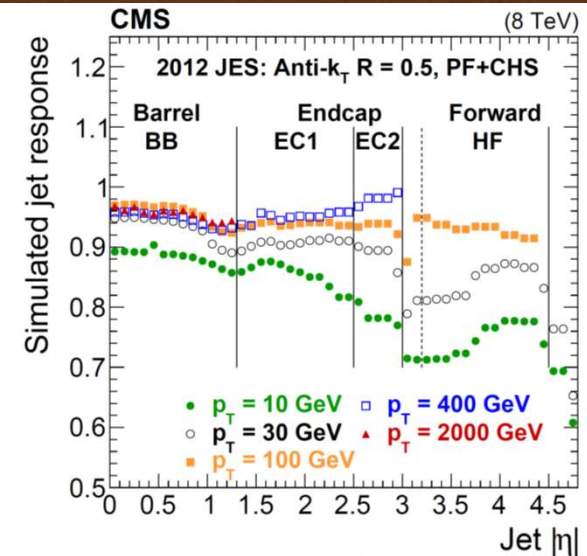
$$C_{\text{hybrid}}(p_{\text{T, uncorr}}, \eta, A_j, \rho) = 1 - \frac{[\rho_0(\eta) + \rho\beta(\eta) (1 + \gamma(\eta) \log(p_{\text{T, uncorr}}))] A_j}{p_{\text{T, uncorr}}}$$

# Jets: response corrections

- Inside the tracker acceptance (BB, EC1), 90-95% of jet energy can be reliably accounted for in AK5 jets.
- The more forward calorimetry can only capture 70-80%.

$$R_{\text{ptcl}}(\langle p_T \rangle, \eta) = \frac{\langle p_T \rangle}{\langle p_{T, \text{ptcl}} \rangle} [p_{T, \text{ptcl}}, \eta]$$

- After correcting for this effect using simulations, the residual variations with jet  $p_T$  and rapidity are of order 1% on average.

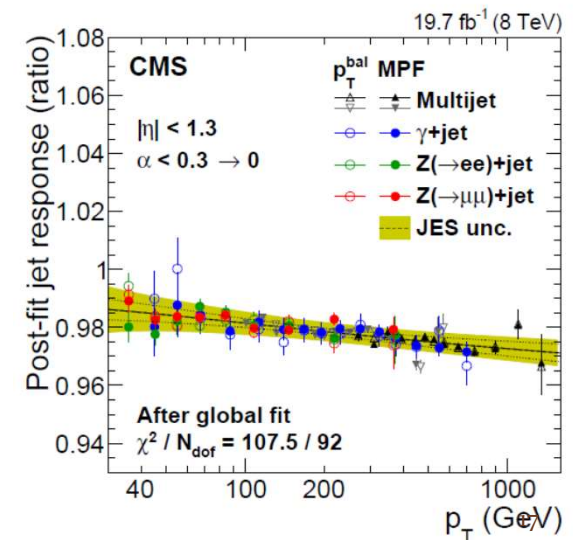
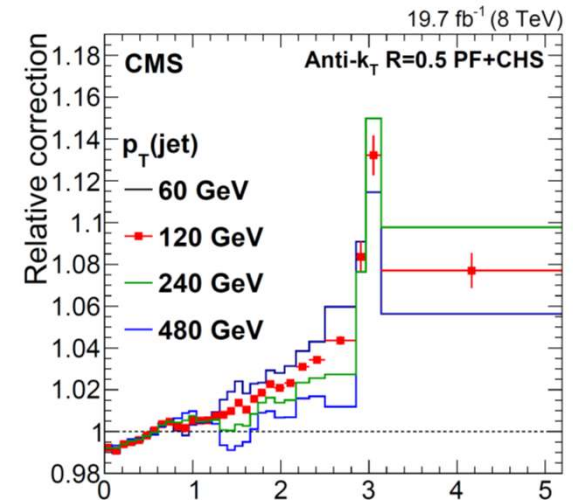


# Jets: residual corrections

- The **relative residual jet response versus rapidity** is estimated from data by analyzing the PT balance between dijets:

$$R_{\text{rel}}^{\text{MPF}} = \frac{1 + \langle \mathcal{B} \rangle}{1 - \langle \mathcal{B} \rangle} \quad \mathcal{B} = \frac{\vec{p}_{\text{T}}^{\text{miss}} \cdot (\vec{p}_{\text{T, tag}} / p_{\text{T, tag}})}{2p_{\text{T, ave}}}$$

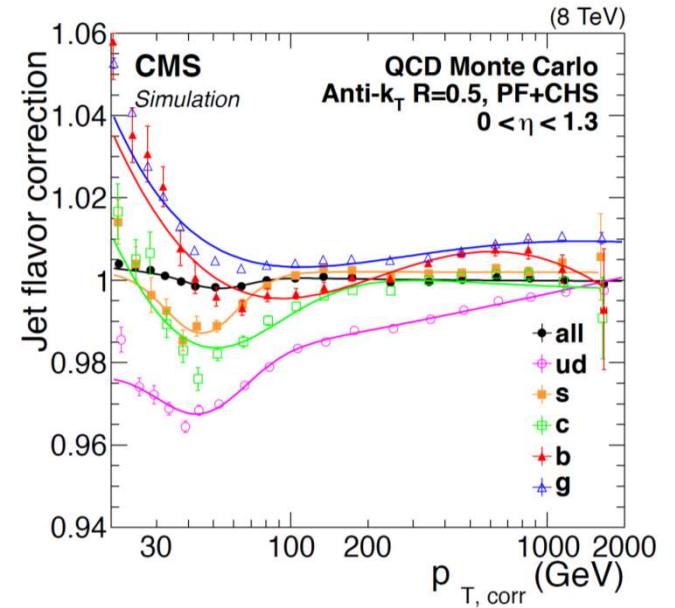
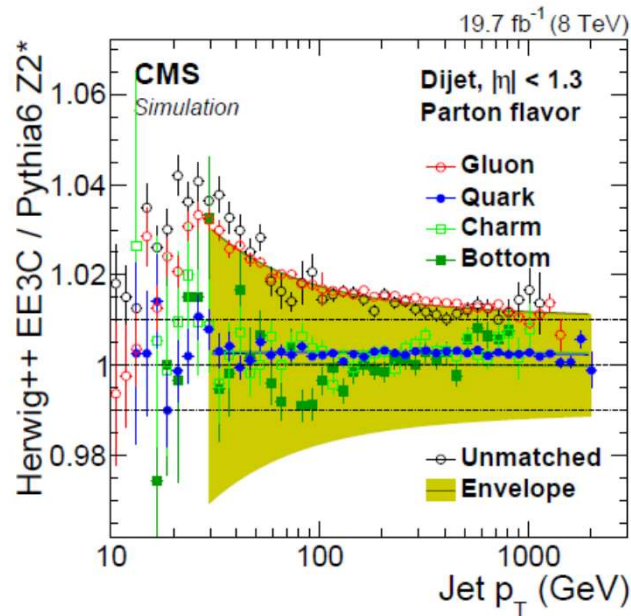
- This results in corrections of order 1-5% for barrel and endcap and 10-15% for forward jets.
- Differences in ISR/FSR and a possible logPT dependence is also introduced to this correction.
- An absolute response correction vs. rapidity and PT is obtained from a global fit to Z+jet, photon+jet, and multijet data, where Z and photon energies serve as an absolute reference.





# Jets: flavor corrections

- Corrections up to this point have averaged over hard scattering parton flavor. But response varies by several percent (gluons lowest response, u/d highest).

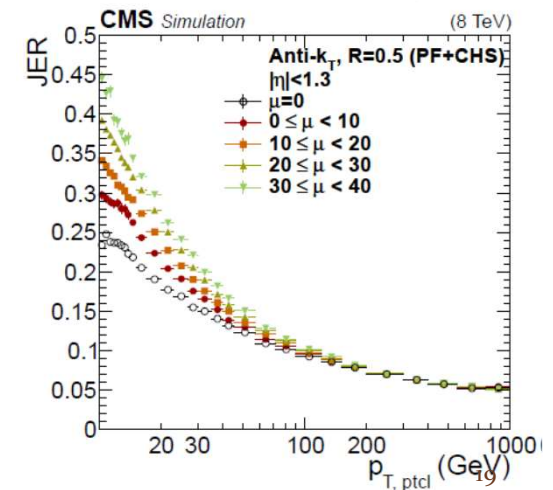
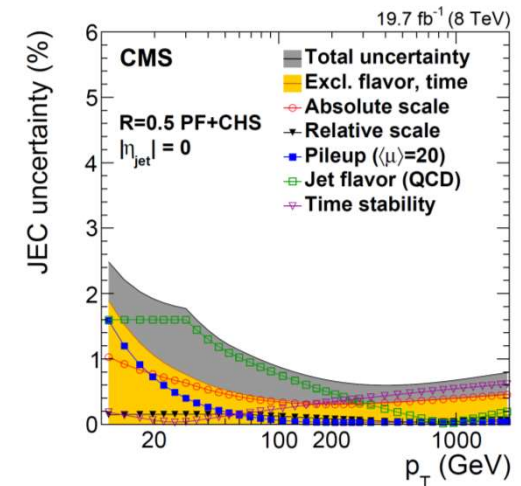


- Fragmentation/hadronization/UE modelling of these effects are uncertain at the 2% level (leading JES uncertainty)



# Jets: energy scale uncertainty and resolution

- Total uncertainty on JES is up to 2-3% for lowest jet PT, <1% for highest jet PT.
- Predominant components are flavor corrections and absolute scale from data.
- Jet energy resolution is typically
  - 15-20% at 30 GeV,
  - 10% at 100 GeV
  - 5% at 1000 GeV
- Corrections to simulated resolutions derived from dijet balancing, pileup dependence is relevant below jet PT of 100 GeV
  - 2-4% uncertain in the barrel
  - 6% in the endcaps
  - 20% in the forward (large MC variations)



# Luminosity measurement

CMS-PAS-LUM-12-001

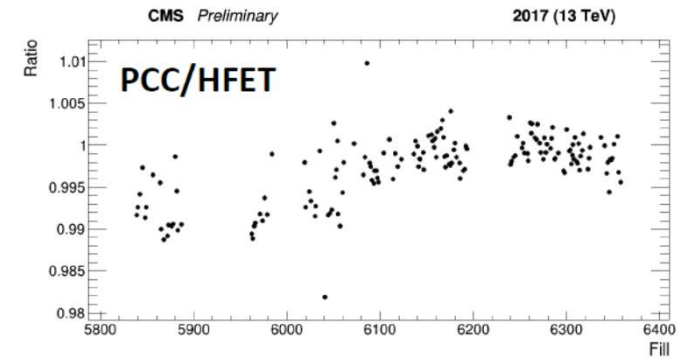
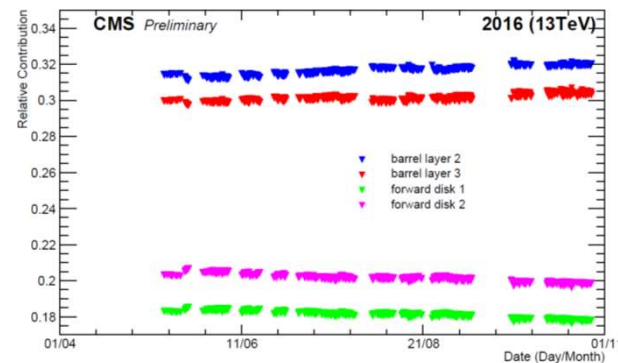
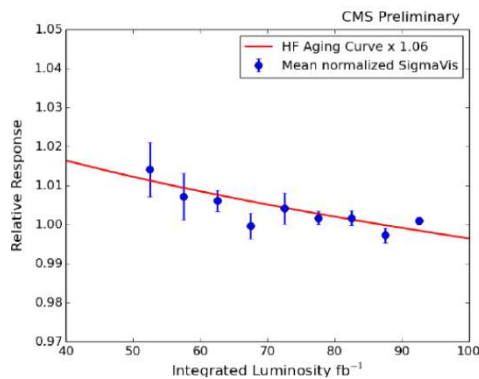
- Find observables  $\mu_{\text{vis}}$  which respond linearly to the instantaneous luminosity of each colliding proton bunch pair in a detector.
- Typically  $\mu$  are tracker hits or energy deposits of various kinds resulting from (perhaps multiple) inelastic pp scattering(s), with visible cross section for occurrence  $\sigma_{\text{vis}}$ . Then for  $N_{\text{BX}}$  bunch pairs, and LHC bunch revolution frequency  $f$ , the instantaneous luminosity is

$$L_{\text{total}} = \sum_{N_{\text{BX}}} \mu_{\text{vis}} \frac{f_{\text{LHC}}}{\sigma_{\text{vis}}}$$

- Monitor  $L$  and time-integrate it across a run to determine integrated luminosity across some basic time period (“lumi-segments”).
- Add up all the lumi’s from all of the lumi-segments you used (possibly correcting for trigger prescales!) to compute total integrated luminosity for your analysis.
- **PROBLEM:**  $\sigma_{\text{vis}}$  can NOT be determined from first principles and must be determined in a separate exercise.

# Luminosity measurement: luminometers

- A good luminometer has high response efficiency for single pp collisions and a linear response to multiple simultaneous pp collisions.
- Silicon pixel cluster, track, or vertex counting
- Forward hadronic calorimeter energy
- Special forward instrumentation (very forward pixel “telescopes”, Cerenkov light detectors, etc.)
- Linearity with in-time pileup, hit efficiency, stability over time, and “afterglow” (out-of-time) effects must be monitored and corrected



# Luminosity measurement: Van der Meer Scan method

- For colliding beam bunches with  $N_1$  and  $N_2$  protons, and transverse Gaussian widths  $\Sigma_x$  and  $\Sigma_y$ , purposely offsetting the beams by  $\Delta X$  and  $\Delta Y$  induces the variation

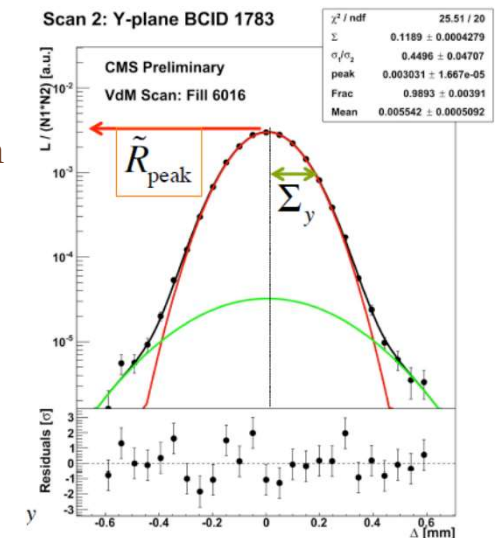
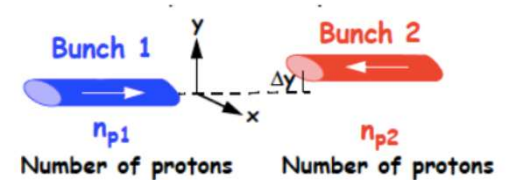
$$L(\Delta x, \Delta y) = \frac{\nu N_1 N_2}{2\pi \Sigma_x \Sigma_y} \exp\left(-\frac{\Delta x^2}{2\Sigma_x^2}\right) \exp\left(-\frac{\Delta y^2}{2\Sigma_y^2}\right)$$

The scan data can be fit to obtain the widths  $\Sigma_i$  and peak amplitude  $R$ , from which luminometer cross section can be directly obtained. For a luminometer reading  $\langle n \rangle_0$ :

$$\sigma_{\text{vis}} = 2\pi \Sigma_x \Sigma_y \langle n \rangle_0,$$

$$\langle n \rangle_0 = \frac{1}{2}(R_x + R_y),$$

- This fit can be extended to account for non-Gaussian tails or beam profile correlations in  $x$  and  $y$
- Scan redone periodically to test stability.



# Luminosity measurement: uncertainties

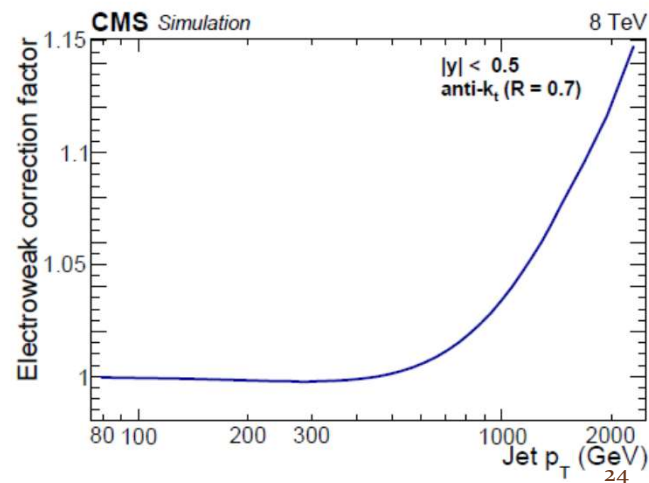
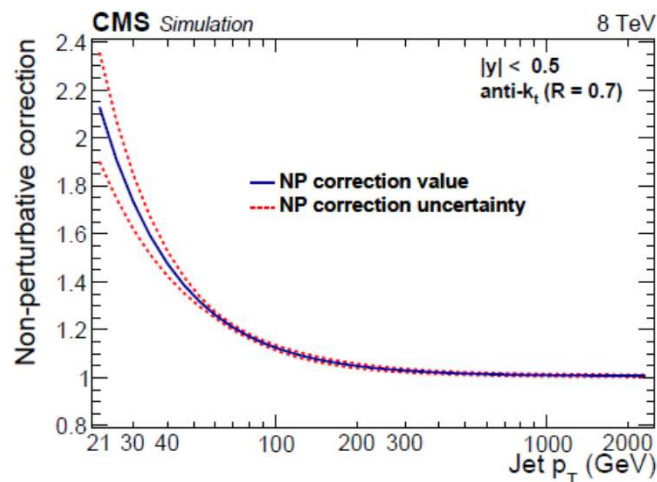
- Multiple luminometers can cross check each other and close at the 1.5% level.
- Effects from nonlinearities can be controlled at the 1% level
- X-Y correlations in the VdM scan beam profile and length scale uncertainties in the scan induce 1% uncertainties each.
- **Total integrated luminosity known to 2.5%**

Source	correction (%)	uncertainty (%)
Integration		
Internal stability	-	0.5
Linearity	-	0.6
Cross detector stability	-	1.5
Dynamic Inefficiency	0 – 1	0.3
Type 1 correction	7 – 12	0.7
Type 2 correction	0 – 4	0.5
CMS downtime	-	0.5
Normalization		
XY-Correlations	+0.8	0.9
Beam current calibration	-	0.3
Ghosts and satellites	-	0.4
Length scale	-1.6	0.8
Orbit Drift	-	0.4
Beam-beam deflection	+1.5	0.4
Dynamic- $\beta$	-	0.5
Statistical	-	0.3
<b>Total</b>		<b>2.5</b>



# QCD prediction model

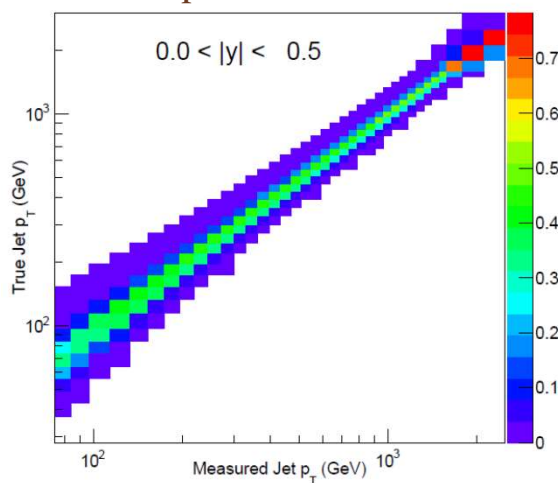
- Two variations to consider:
  - **Parton showering MC**
    - Particle-level predictions straightforward
    - Typically not state-of-the art pQFT ingredients
  - **Fixed-order pQCD calculation**, with non-perturbative/showering corrections obtained from ME+PS MC (Pythia/Herwig et al.) to get to the “particle level”.
    - Computationally easier and up-to-date
    - Corrections to particle level are nontrivial
- $$C_{\text{NP}} = \frac{d^2\sigma}{dp_T dy}(\text{LO} + \text{PS} + \text{MPI} + \text{HAD}) / \frac{d^2\sigma}{dp_T dy}(\text{LO} + \text{PS})$$
- Several **PDF families** considered as well as their variations
  - **NLO electroweak corrections** are relevant at the TeV scale, and are often needed separately from pre-packaged calculations.



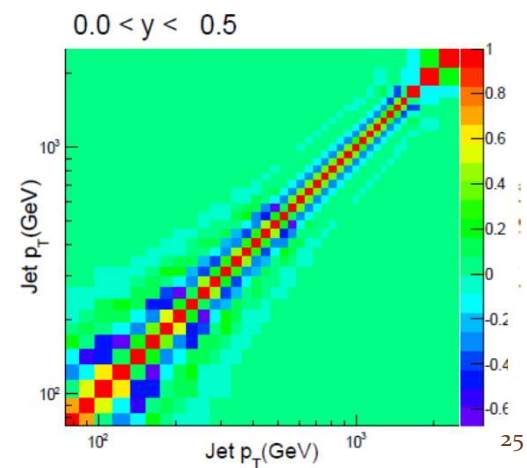
# Unfolding measured jet spectra

- If the resolution of the variable of interest is comparable to the bin size, then there is non-negligible migration of true values across multiple bins of measured value.
- The amount of cross-contamination depends in general on both the resolution model of the detector and the underlying true spectrum.
- Introduces correlated statistical uncertainties across bins
- Introduces a model-dependent systematic uncertainty
  - Iterative procedure and/or alternative models estimate it
- If these uncertainties are comparably large, consider larger bins!

Response matrix

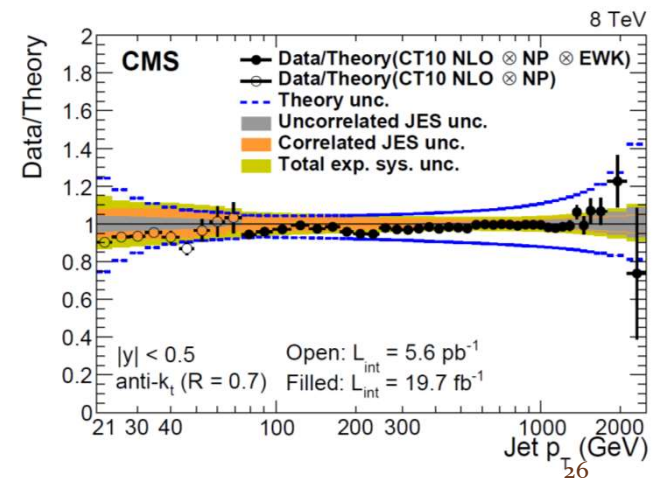
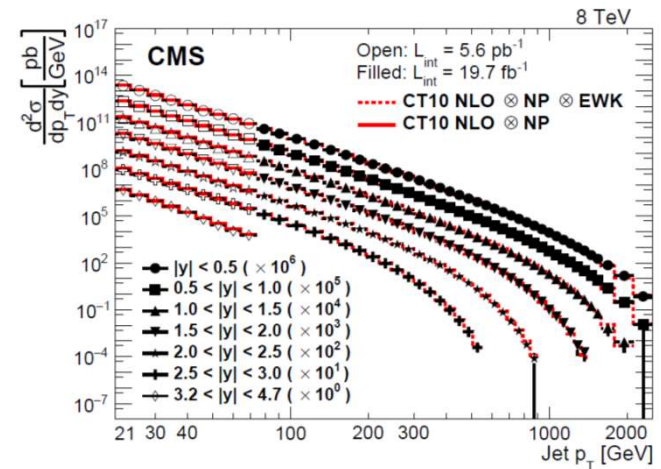
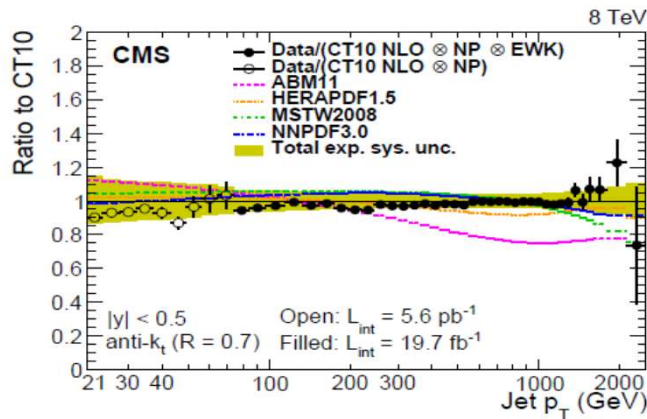


Correlation matrix



# Cross section results

- Good agreement across 17 orders of magnitude in cross section and 100X in jet PT!
- Tested with several PDF families (not all of them agreeing equally)
- Experimental uncertainty superior to NLO theory prediction (PDFs, factorization/renormalization scale) → can refine NLO PDFs or strong coupling, especially from higher jet PT/parton x
- JES, luminosity, unfolding are largest experimental uncertainties



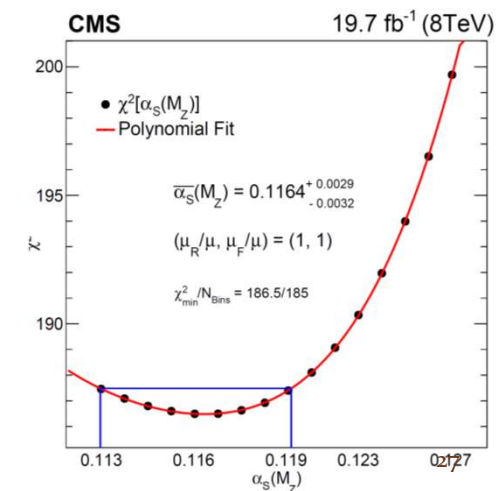
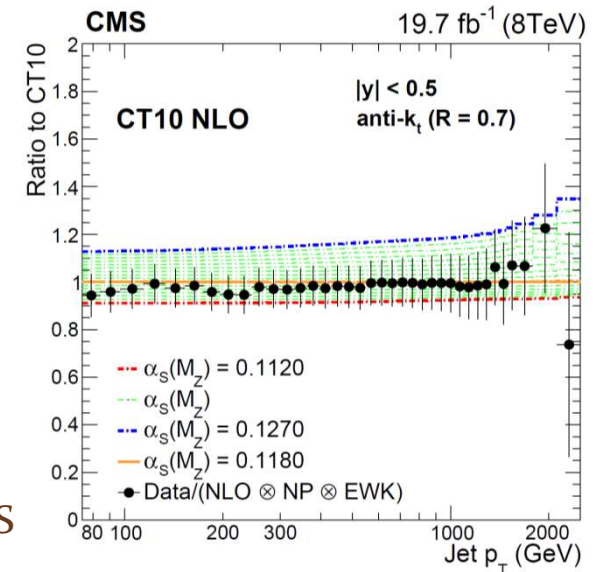
# Strong coupling constant

- The cross section is monotonic increasing with strong coupling, correlated across PT and rapidity
- A binned chi-2 analysis which accounts for correlations between the various bins gives a result in good agreement with the world average

$$\alpha_S(M_Z)(\text{NLO}) = 0.1164^{+0.0025}_{-0.0029}(\text{PDF})^{+0.0053}_{-0.0028}(\text{scale}) \pm 0.0001(\text{NP})^{+0.0014}_{-0.0015}(\text{exp}) \text{ CMS}$$

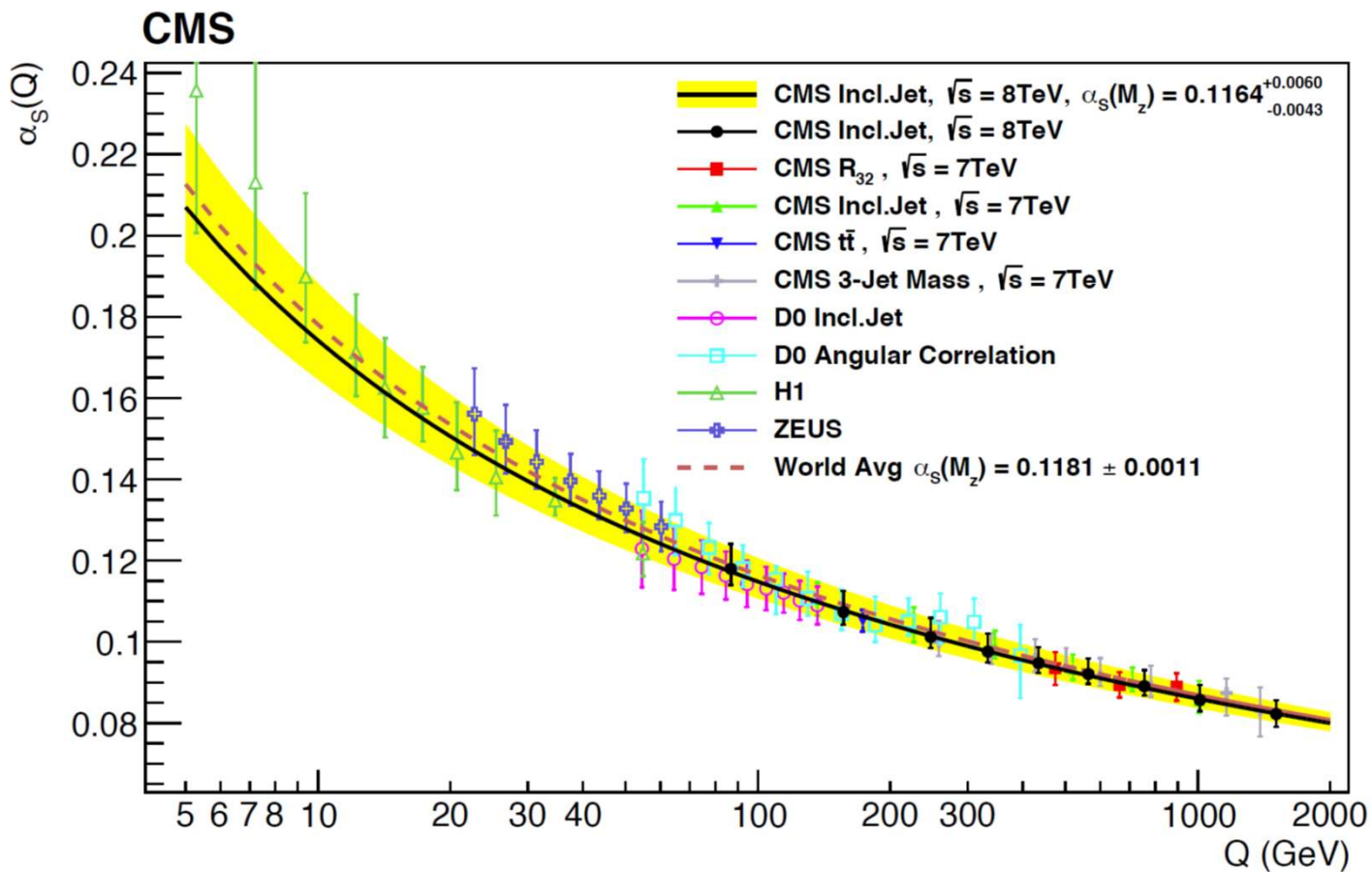
$$\alpha_S(M_Z) = 0.1181 \pm 0.0011 \quad \text{World average (Lattice QCD)}$$

- Uncertainties are predominantly theoretical (**higher-order corrections**) and/or PDF related
- NNLO (and NNLL corrections) comparisons are slowly entering the market here.
- Is there a simple QCD process we can calculate more precisely?





# Strong coupling results at proton colliders





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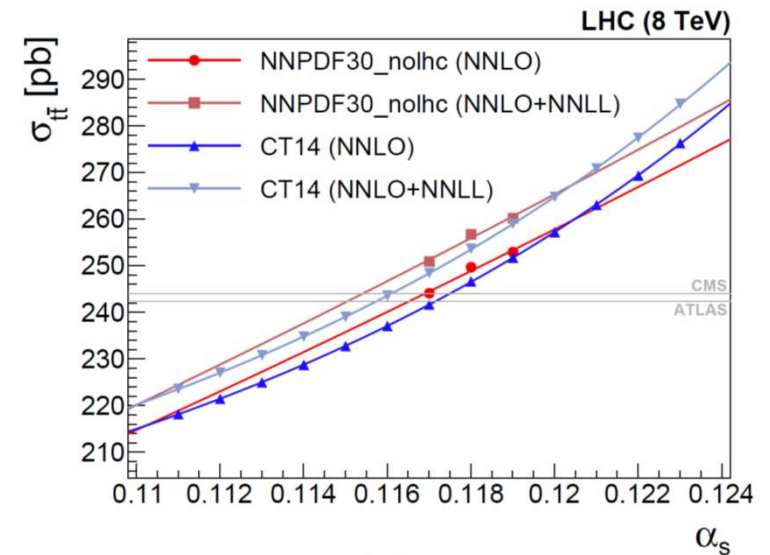
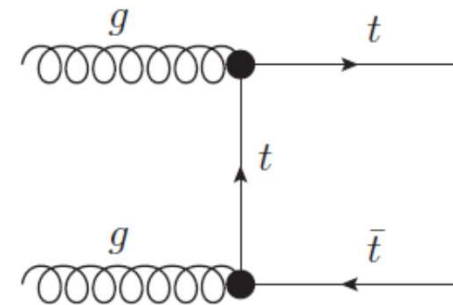
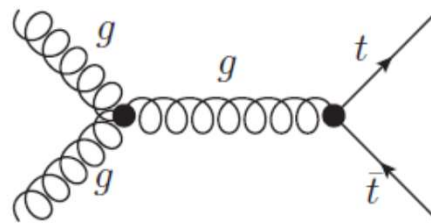
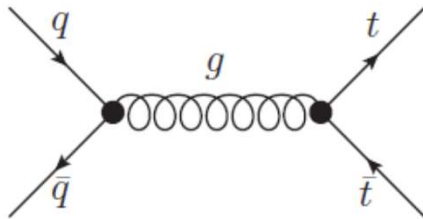
# Second Attempt at $\alpha_s$ : Top quarks

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# Top-quark production

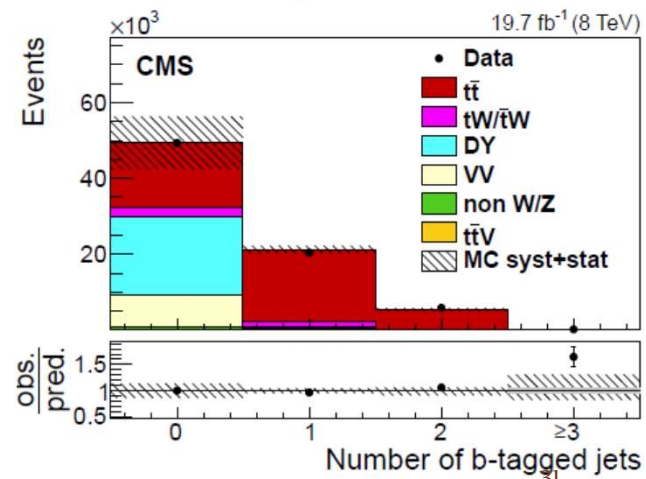
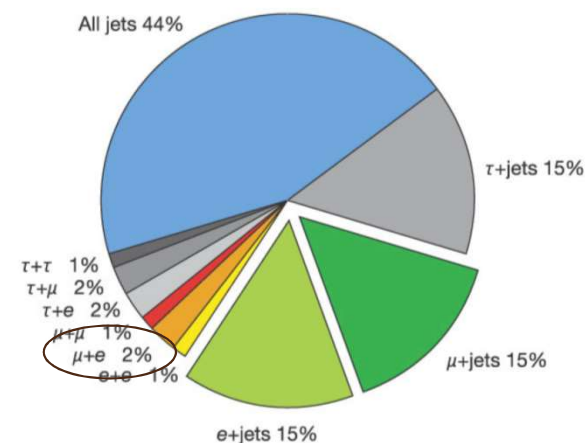
- With a large production cross section, high signal/background, intrinsically high  $Q^2$ , well-known mass, top pair production can be precisely measured AND precisely predicted.
- Top pair production at 13 TeV is close to 1 nb
- Inclusive cross section is computed to NNLO+NNLL
- If cross section precision is  $< 5\%$ , strong coupling is  $< 0.005$
- Top cross sections achieve this precision, with very different uncertainties than jet cross sections!



# Top pair inclusive cross section, dilepton channel

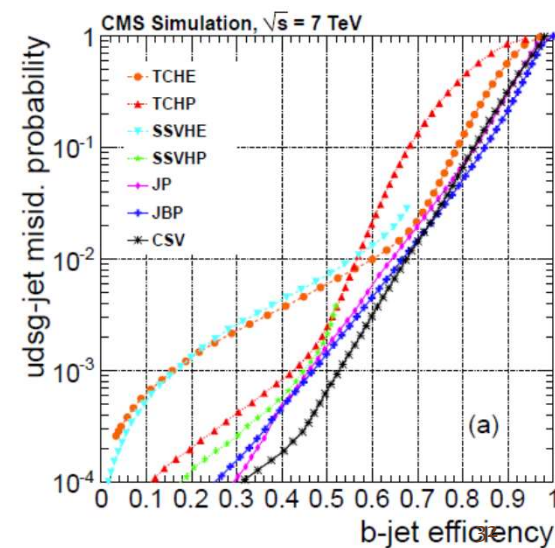
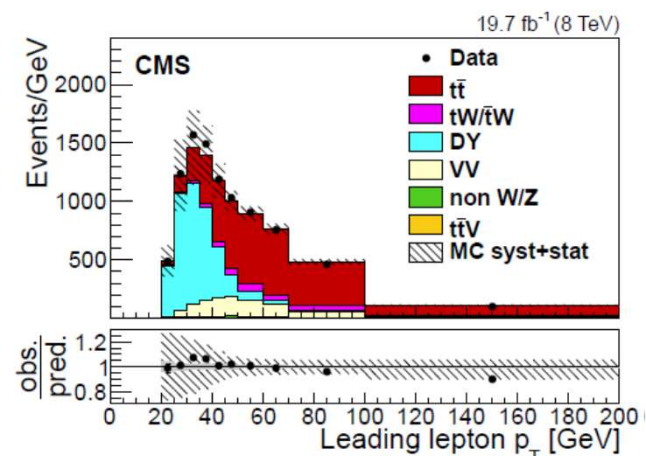
arxiv:1603.02303

- For an inclusive cross section, manageable systematics and low backgrounds are more important than highest statistics
- mu-e dilepton channel ( $t \rightarrow bW(\rightarrow \mu\nu)$ , anti- $t \rightarrow bW(\rightarrow e\nu)$ ) is a competitive choice despite the low W pair branching fraction
- The intended final state is an opposite sign e-mu pair, two b-tagged jets.
- Events with 0/1/2 b-tagged jets and 0/1/2/3 additional jets are retained as categories of interest to constrain background rates and nuisance parameters.
- About 20k candidates with two b-tagged jets in 8 TeV data



# Event selection and categorization

- Trigger selects e-mu or mu-e pairs with  $P_T$  of 17 GeV and 8 GeV resp. (93% efficiency)
- Offline lepton candidates have  $P_T > 20$  and  $|\eta| < 2.4$ , both from the primary vertex
- Isolation criteria for leptons reduce jet backgrounds (no more than 10-12% additional PF candidate energy in a cone of 0.3-0.4)
- Z boson candidates in data validate simulated lepton efficiencies
- Count AK5 PF jets with:  $P_T > 30$  GeV and  $|\eta| < 2.4$  and  $DR(\text{lepton}, \text{jet}) > 0.5$
- Jets are “b-tagged” if a minimum number of tracks form a significant secondary vertex or have a lifetime (working point of 50% eff, 0.1% fake light quark jets).





# Likelihood Fit Design

- The “visible” cross section is defined as that portion of the inclusive cross section which results in the W pair decaying to an e and mu both with  $PT > 20$  GeV and  $|\eta| < 2.4$ . MC acceptance correction w/uncertainty gives inclusive cross section.
- Define 12 categories of jet counting: **(0/1/2/3+ non-b-tagged jets) X ([0 or >2]/1/2) b-tagged jets**
- For the 8 categories with >0 non-b-tagged jets, differentially sample **the lowest jet PT**
- Construct a likelihood function of the event counts  $\mu_i$  over the 12 categories

$$L = \prod_i (\exp[-\mu_i] \mu_i^{n_i} / n_i!) \prod_{k=1}^K \pi(\omega_k) \prod_{m=1}^M \pi(\lambda_m)$$

$$\mu_i = s_i(\sigma_{\text{tt}}^{\text{vis}}, \vec{\lambda}) + \sum_{k=1}^K b_{k,i}^{\text{MC}}(\vec{\lambda}) (1 + \gamma_k \omega_k)$$

$$s_0 = s_{e\mu} \left[ 1 - 2\epsilon_b(1 - C_b\epsilon_b) - C_b\epsilon_b^2 \right]$$

$$s_1 = s_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b),$$

$$s_2 = s_{e\mu} \epsilon_b^2 C_b.$$

$\omega_k$  are scale factors for the 6 background processes (tW/DY/VV/Wjets&QCD/ttV/other tt)

$\lambda_m$  are scale factors for ALL of the nuisance parameters

$\pi(\omega)$ ,  $\pi(\lambda)$  are **prior distributions** for them from other data

Signal yield vs. b-tag category constrains  $\sigma_{\text{vis}}$ , b-tagging efficiency, and any b-tagging correlations.



# Likelihood Fit Design

- Fit for parameters of interest (visible cross section, background scale factors, readjusted nuisance parameters).
- If the data in the fit have constraining power on a nuisance parameter (jet energy scale, e.g.) beyond its prior uncertainty, the refit parameter will be “pulled” and its uncertainty is possibly reduced.
- Priors comes from MC (backgrounds, signal QCD normalization scale), or ancillary measurements (lepton efficiency, JES, lumi)
- Significant pulls or uncertainty changes in nuisances or backgrounds should be investigated

$$L = \prod_i (\exp[-\mu_i] \mu_i^{n_i} / n_i!) \prod_{k=1}^K \pi(\omega_k) \prod_{m=1}^M \pi(\lambda_m)$$

$$\mu_i = s_i(\sigma_{\text{tt}}^{\text{vis}}, \vec{\lambda}) + \sum_{k=1}^K b_{k,i}^{\text{MC}}(\vec{\lambda}) (1 + \gamma_k \omega_k)$$

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Signal yield vs. b-tag category constrains  $\sigma_{\text{vis}}$ , b-tagging efficiency, and any b-tagging correlations.

# Likelihood Fit Results

Name	Pull	Constr / $\sigma$	Contribution [%]
BTAGH_BFragmentation	0.1	0.8	$\mp 0.01$
BTAGH_DeltaR	0.02	0.8	$\mp 0.09$
BTAGH_GluonSplitting	-0.11	0.6	$\pm 0.02$
BTAGH_IFSR	0	1	$\mp 0.00$
BTAGH_IP-bias	-0.41	0.9	$\pm 0.01$
BTAGH_JetAway	0.4	0.7	$\mp 0.18$
BTAGH_KT	0	1	$\mp 0.00$
BTAGH_LT-Bias	0	1	$\mp 0.00$
BTAGH_LT-Cb	0.61	0.9	$\mp 0.03$
BTAGH_LT-others	0.19	0.6	$\mp 0.04$
BTAGH_MuPt	0	0.7	$\mp 0.01$
BTAGH_PS	0	1	$\mp 0.00$
BTAGH_PT-l2c	-0.18	0.8	$\mp 0.01$
BTAGH_SS-ptrel	0.9	0.9	$\mp 0.03$
BTAGH_TCT	0	1	$\mp 0.00$
JES: High $p_T$ Extra	-0.31	1	$\mp 0.10$
JES: Single pion ECAL	0.1	0.8	$\mp 0.05$
JES: Single pion HCAL	-0.19	0.9	$\mp 0.29$

0 OR >2  
btags

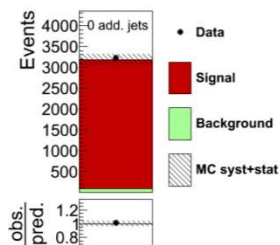
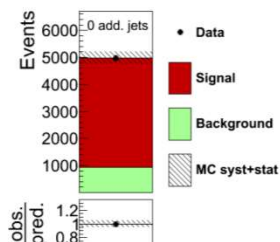
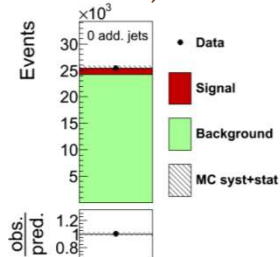
1 btag

2 btags

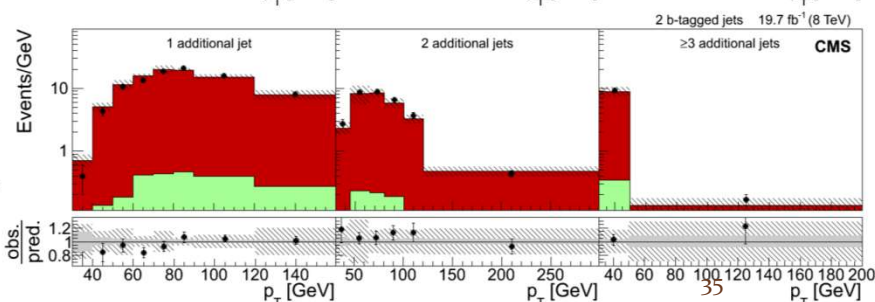
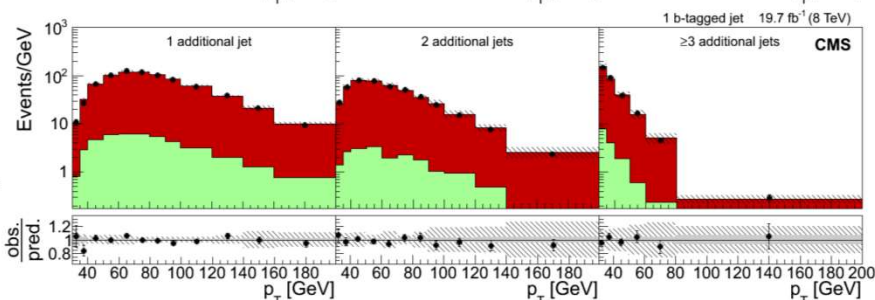
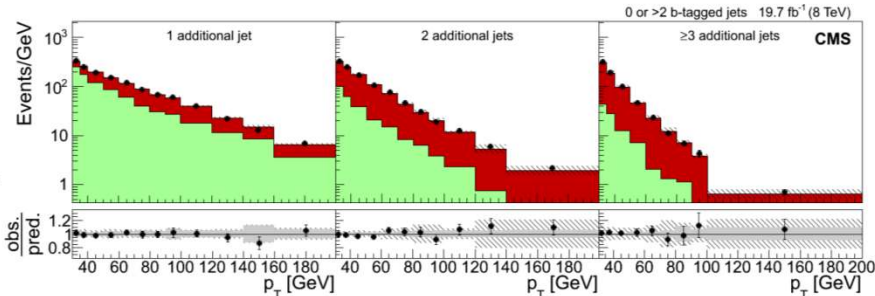
Abridged list of constrained nuisances...

Muon energy scale (8TeV)	-0.04	0.9	$\mp 0.05$
Muon ID (8TeV)	-0.03	1	$\mp 0.42$
Electron energy scale (8TeV)	0.01	1	$\mp 0.01$
Electron ID (8TeV)	-0.01	1	$\mp 0.48$
BTAGH_Statistic (8TeV)	1.1	0.6	$\mp 0.21$
BTAGH_JES (8TeV)	-0.01	0.9	$\pm 0.00$
Mistag (8TeV)	-1.9	0.9	$\mp 0.07$
Trigger (8TeV)	-0.07	1	$\mp 0.70$
Pile-up (8TeV)	0.3	0.9	$\pm 0.24$
Single top background (8TeV)	-0.75	0.9	$\mp 0.07$
Diboson background (8TeV)	-0.24	0.9	$\pm 0.35$
$t\bar{t}$ background (8TeV)	0	1	$\mp 0.04$
BG_QCD/Wjets (8TeV)	-0.2	1	$\pm 0.05$
$t\bar{t} + V$ background (8TeV)	0.06	1	$\mp 0.04$
DY background (0 b-jets) (8TeV)	0.11	0.7	$\pm 0.48$

0 extra jets



1 jet



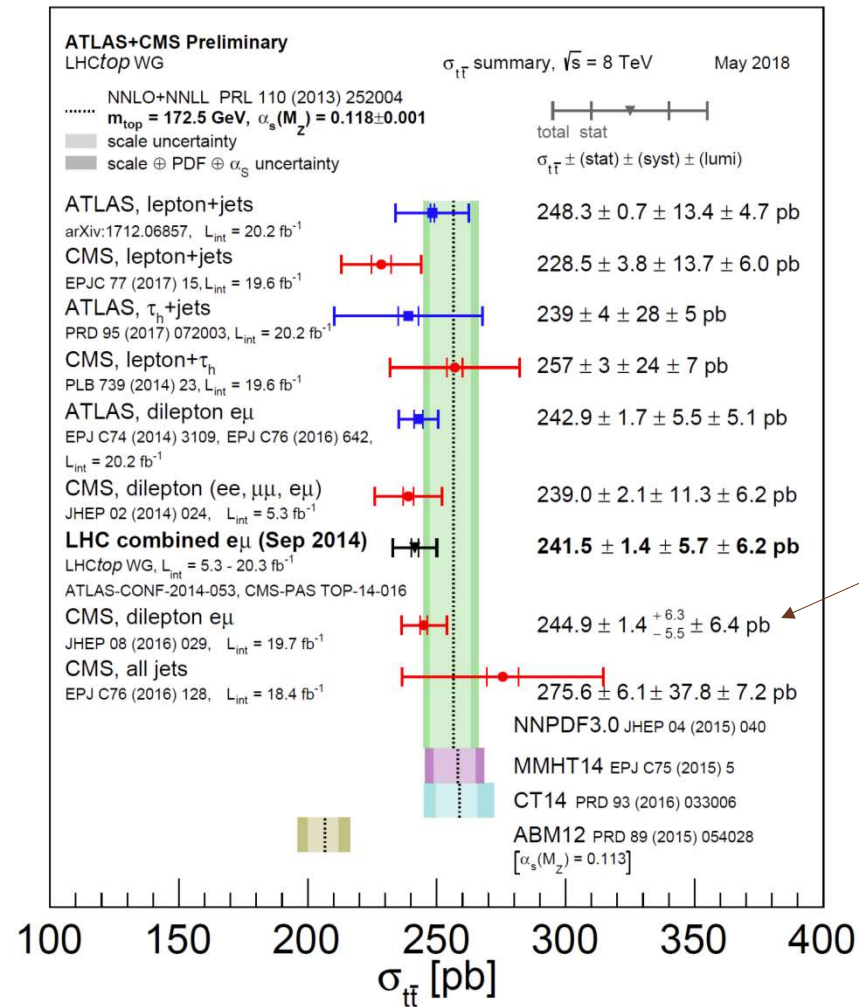
# Uncertainties

- In order of importance:
- **Luminosity is largest single uncertainty**
- **Lepton trigger and ID efficiency**
- **Drell-Yan background**
- JES and associated modelling uncertainties
- Single top and diboson background
- Signal and background shape modelling (QCD scales, generator variations)
- B-tagging
- Statistical

Source	Uncertainty [%]	
	7 TeV	8 TeV
Trigger	1.3	1.2
Lepton ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
Jet energy scale	0.8	0.9
Jet energy resolution	0.1	0.1
$t\bar{t}/t\bar{t}W$	1.0	0.6
DY	1.4	1.3
$t\bar{t}$ bkg.	0.1	0.1
$t\bar{t}V$	0.1	0.1
Diboson	0.2	0.6
W+jets/QCD	0.1	0.2
b-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
$\mu_R, \mu_F$ scales	0.3	0.6
ME/PS matching	0.1	0.1
MADGRAPH vs POWHEG	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top quark $p_T$ modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6

# Top pair inclusive cross sections at 8 TeV

- Dilepton and lepton+jets measurements are the most precise
- Hadronic least precise
- Experimental uncertainty is better than prediction uncertainty
- Scale unc. at NNLO is 4-6%



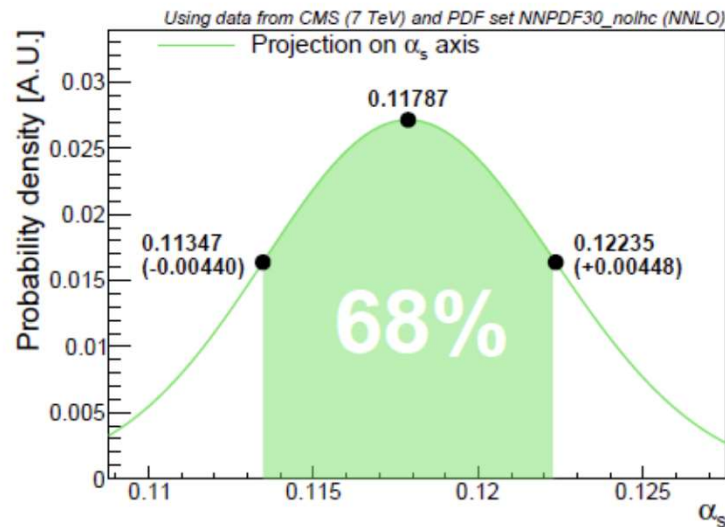
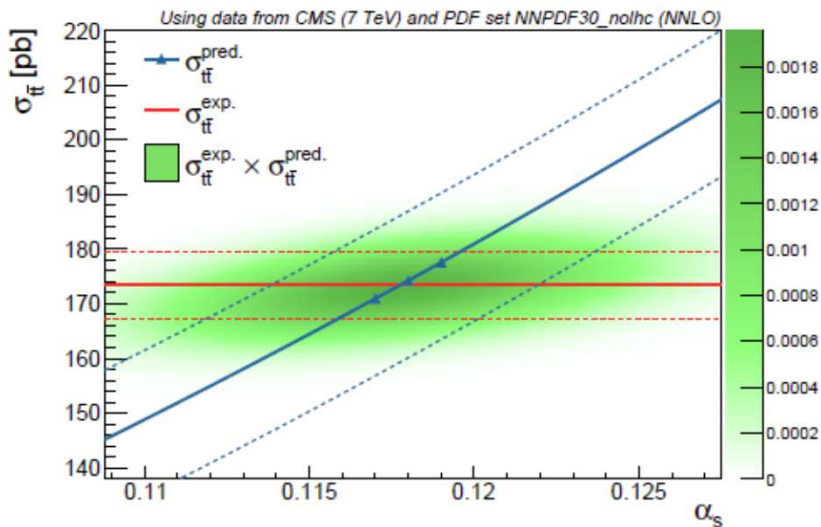
This measurement



# Strong coupling extraction from top pair inclusive cross section

arxiv:1708.07495

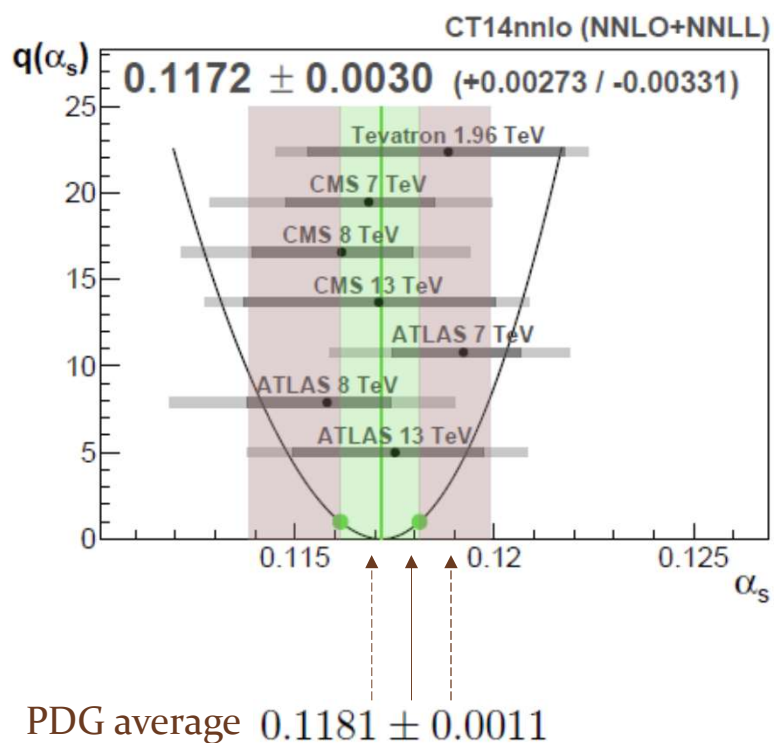
	$\sigma_{t\bar{t}}^{\text{pred}}(\alpha_s^{\text{ref}})$ [pb]	PDF unc. [%]	Scale unc. [%]	$m_t$ unc. [%]	$\frac{d \ln \sigma_{t\bar{t}}(\alpha_s^{\text{ref}})}{d \ln \alpha_s}$
<b>CT14 (NNLO)</b>					
LHC (7 TeV)	172.7	+4.5% -3.8%	+4.1% -6.5%	-2.6% +2.7%	2.486
LHC (8 TeV)	246.7	+4.0% -3.5%	+3.9% -6.3%	-2.5% +2.6%	2.404
LHC (13 TeV)	807.3	+2.6% -2.7%	+3.5% -5.6%	-2.3% +2.4%	2.133



Example strong coupling from 7 TeV xsec



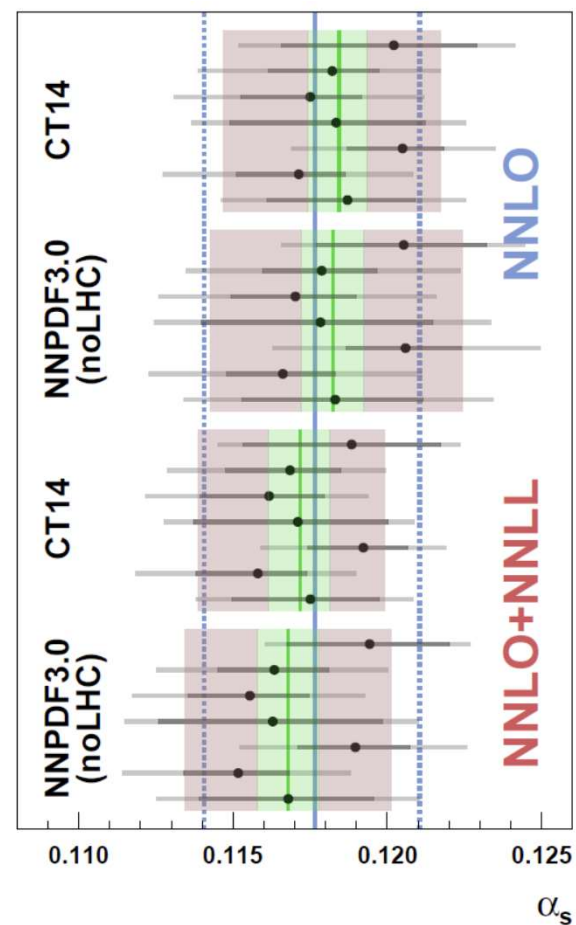
# Strong coupling extraction from top pair inclusive cross section



Good agreement across beam energies and experiments

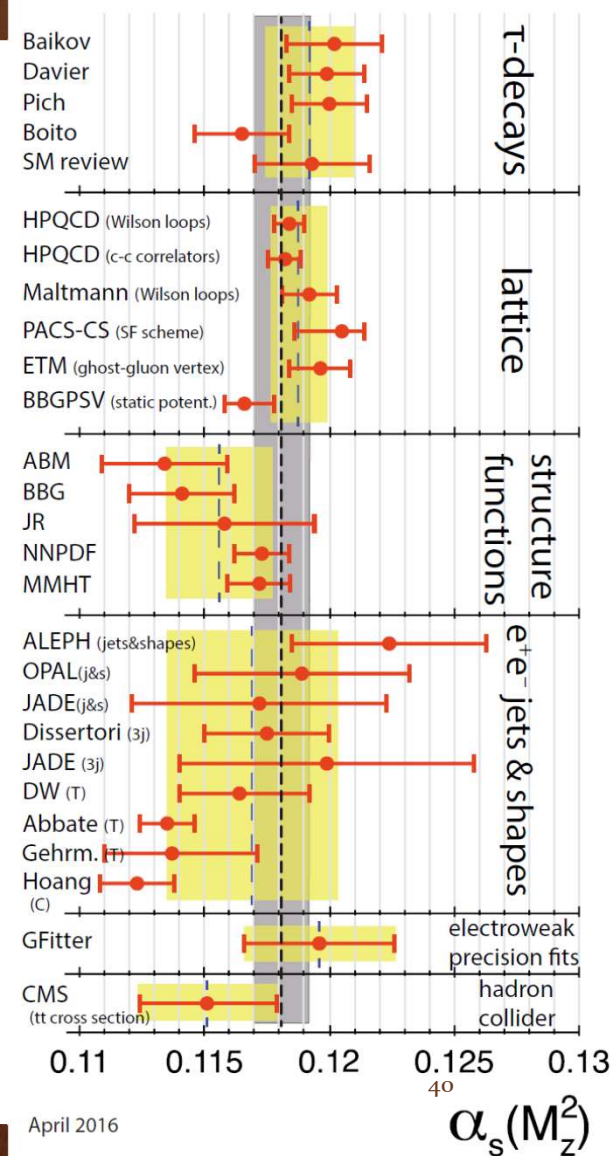
Consistent with world average (lattice), 3x uncertainty

About twice the precision from the inclusive jet measurement



# Conclusions for Lecture 1

- QCD miraculously and precisely describes a huge range of phenomena and energy scales with a single coupling. ~~An ugly nuisance to my analysis~~  
A beautiful and spectacular theoretical success with many more nuances to be learned at each (non)perturbative order.
- The most straightforward approach does not always prove to be the best. New opportunities arise at different epochs of beam energy, statistics, or theoretical advances.
- Precision-limiting factors tend to fall into the same simple categories (luminosity, JES, NLO scale/PDF dependence, jet variations with flavor, lepton efficiency). Improvements are possible but hard-won.
- Precision can sometimes be gained by simultaneously constraining nuisance parameters with the parameters of interest.
- Be ruthless and critical about your leading systematics!



# Syllabus

- Lecture 1, Friday Aug. 24
- The miracle of QCD: jets, tops, and  $\alpha_S$
- Lecture 2, Sunday Aug. 26
- The vise of precision electroweak:  $\sin^2\theta_W$  and  $M_W$
- Lecture 3, Monday Aug. 27
- The mystery of flavor: Capturing Wilson coefficients and testing lepton universality

## References

- CMS inclusive jet cross section at 8 TeV [arxiv:0802.1189](#)
- CMS jet energy scale at 8 TeV [arxiv:1607.03663](#)
- CMS luminosity measurement at 8 TeV [CMS-PAS-LUM-12-001](#)
- CMS top pair cross section in the emu channel at 7 and 8 TeV [arxiv:1603.02303](#)
- Strong coupling determination from the top pair cross section [arxiv:1708.07495](#)
- PDG discussion of the strong coupling [PDG QCD Review, see Sec. 9.4](#)