The Standard Model – Electroweak and QCD in ATLAS and CMS

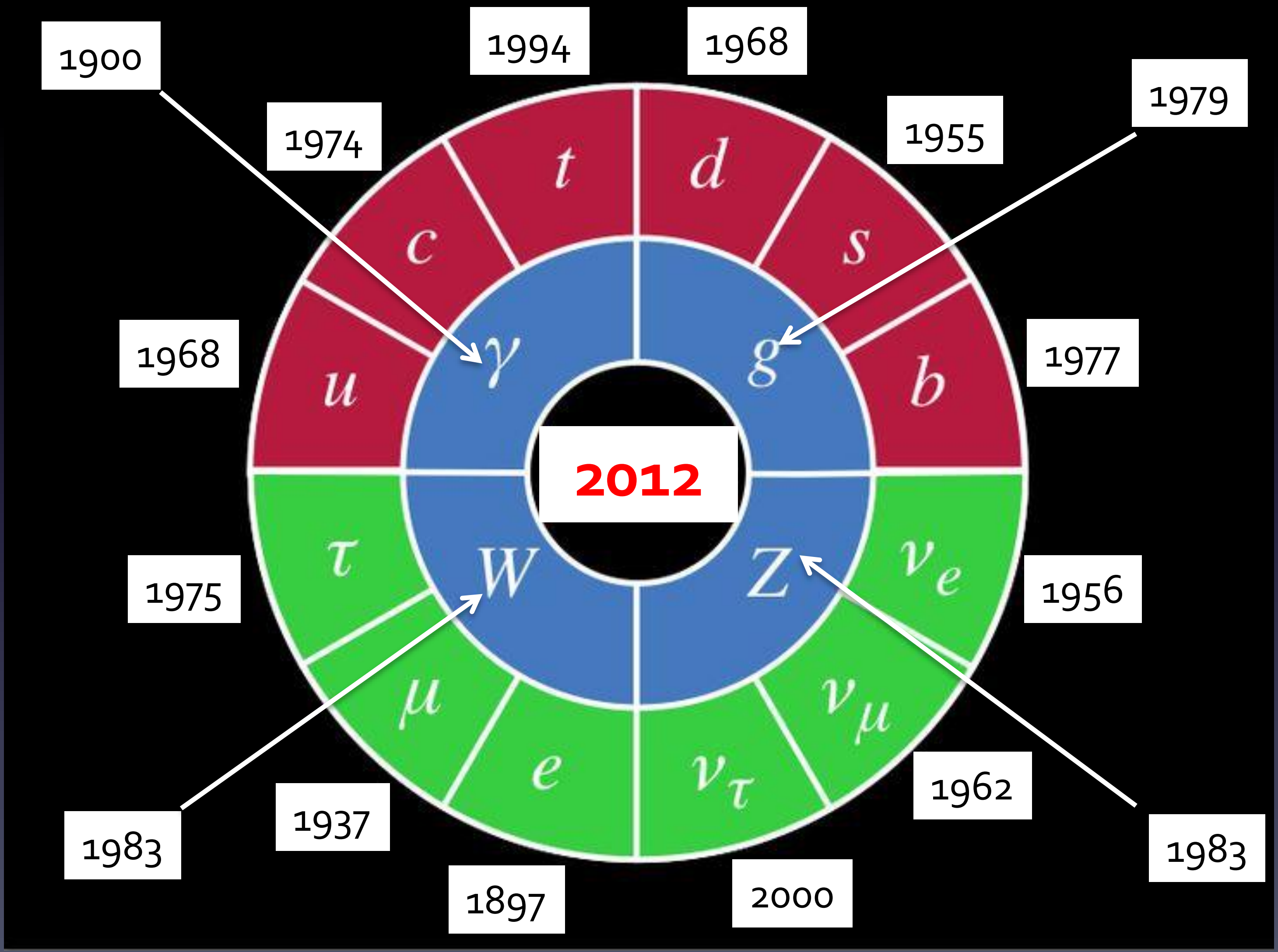
Hugo Beauchemin

Tufts University

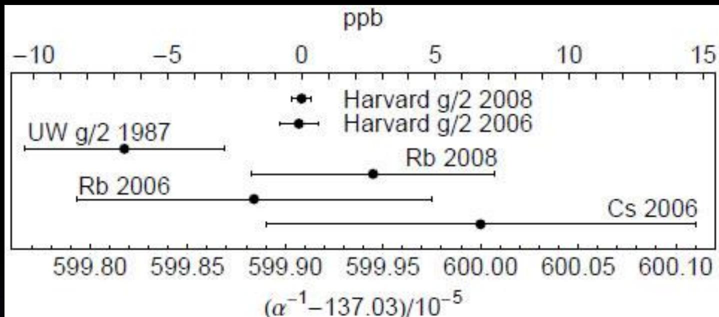
On behalf of the ATLAS and CMS Collaborations

Corfu2017, Corfu (Greece), September 3, 2017

The particle content of the Standard Model has fully been directly and unambiguously observed!

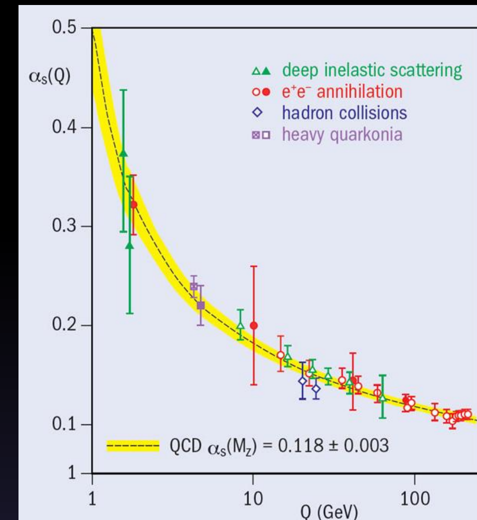


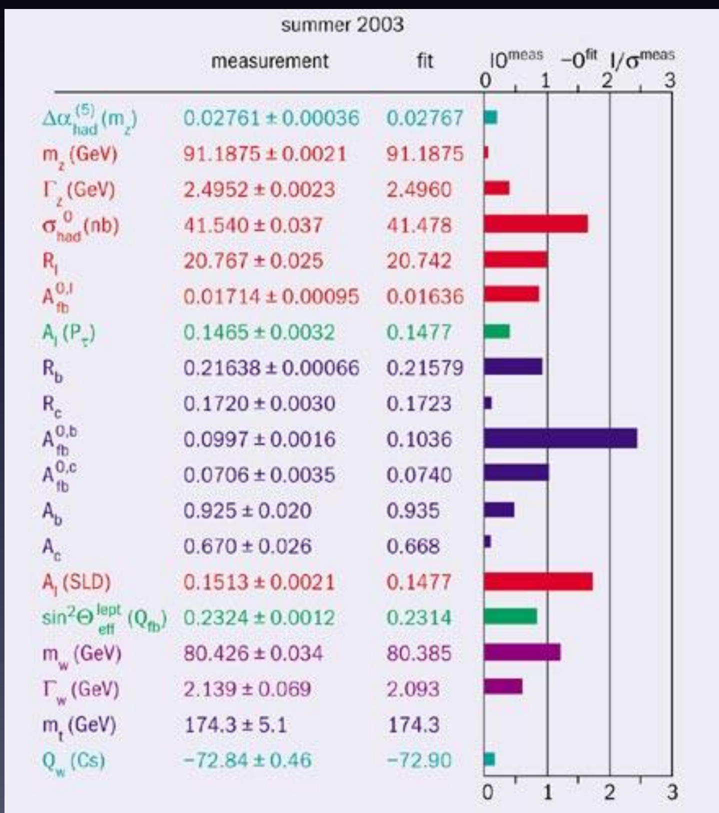
The description of the 3 fundamental interactions of the SM has long been confirmed to a high level of precision



Fine structure constant

Strong coupling constant

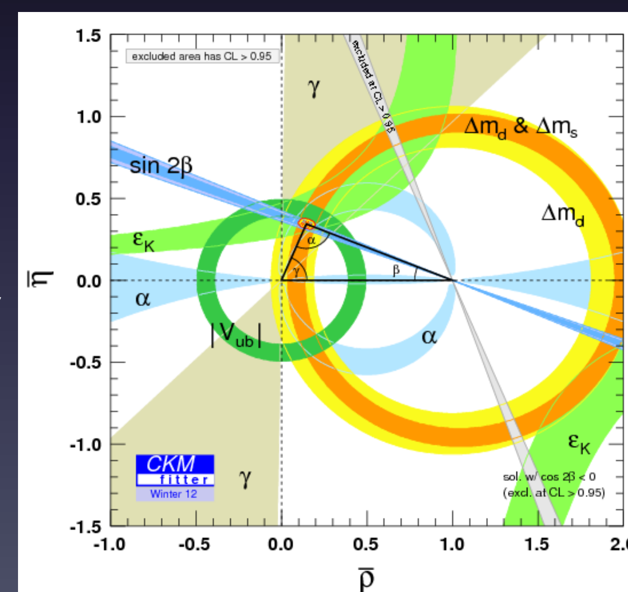




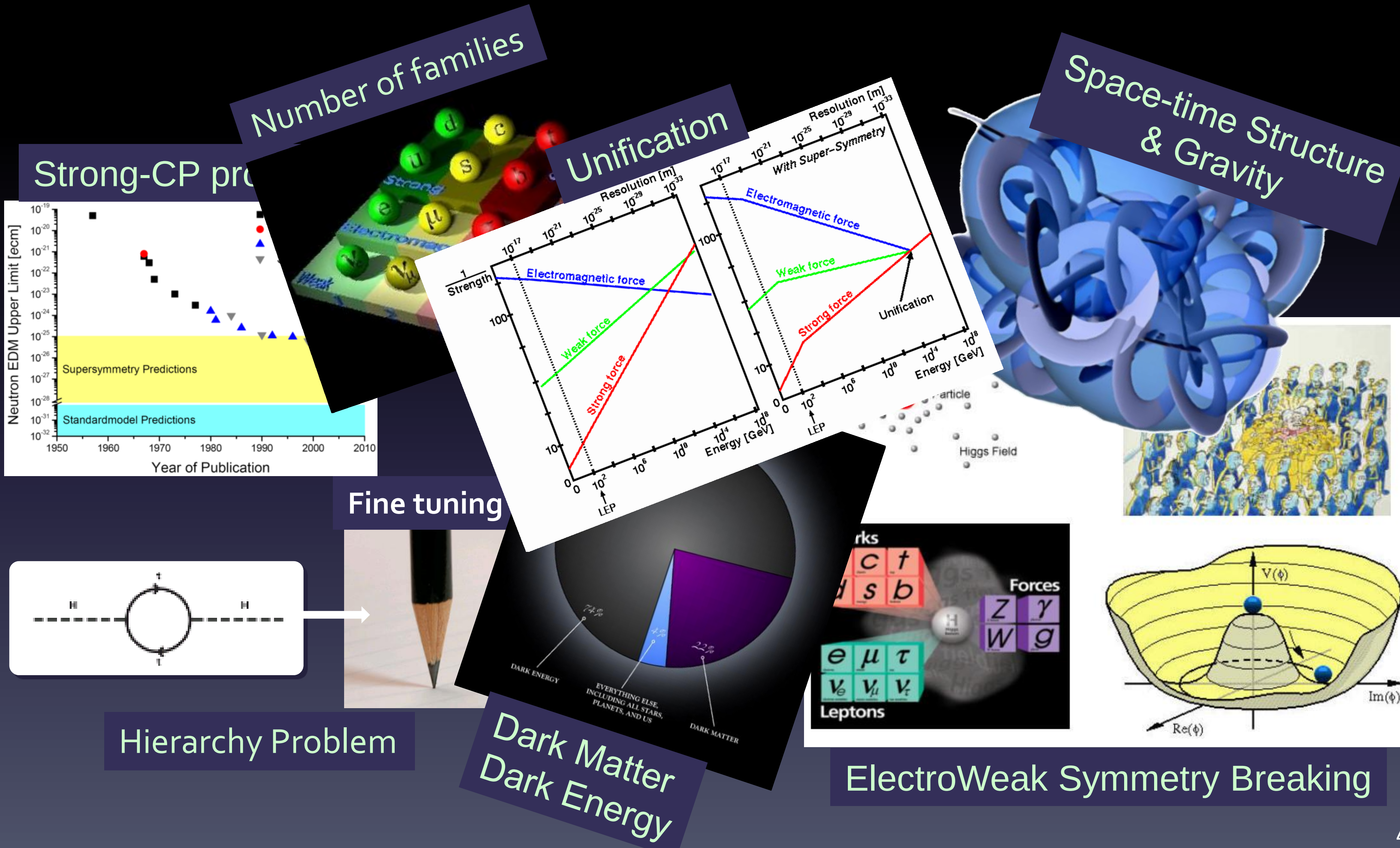
	measurement	fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z (GeV)	91.1875 ± 0.0021	91.1875
Γ_Z (GeV)	2.4952 ± 0.0023	2.4960
σ^0_{had} (nb)	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l (SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\Theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W (GeV)	80.426 ± 0.034	80.385
Γ_W (GeV)	2.139 ± 0.069	2.093
m_t (GeV)	174.3 ± 5.1	174.3
Q_W (Cs)	−72.84 ± 0.46	−72.90

Weak interaction parameters

Unitarity triangle



Of course we all believe that the SM is not the end of the story…

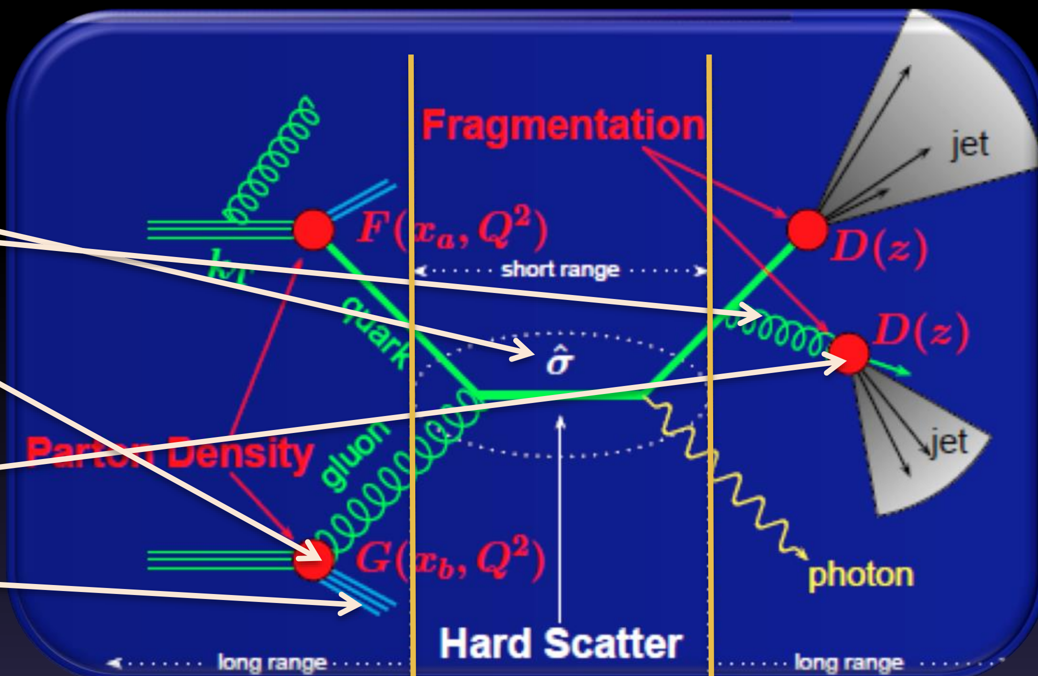


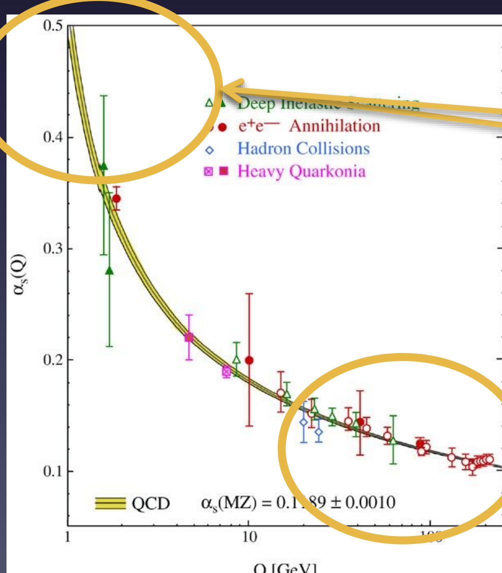
…so why dedicating so much effort in performing evermore precise and sophisticated measurements of Standard Model physics, known and well-established for decades???

Answer part A:
The Strong Interaction

The strong interaction intervenes in various ways and at various scales in **every** single event at the LHC

- Matrix element of interest $(\hat{\sigma})$
- Gluon emission (ISR/FSR)
- Proton structure (F,G)
- Fragmentation and hadronization $(D(z))$
- Underlying event





Long distance physics

Short distance physics

Long distance physics

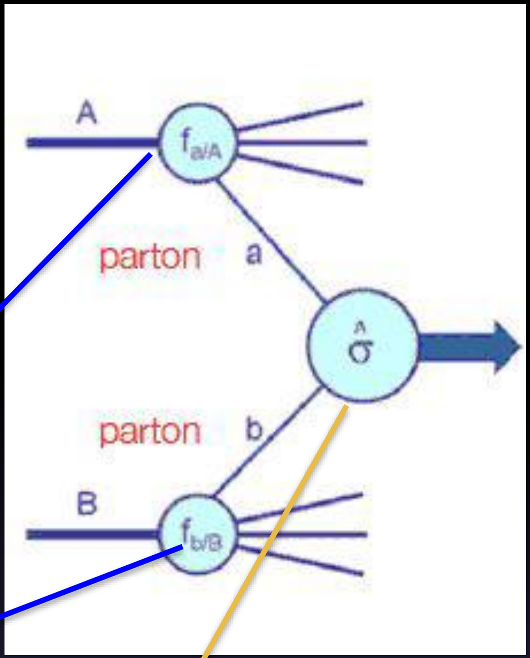
We can make robust predictions!

Not so sure…

Factorization theorem:

The probabilities for short-distance and long-distance processes factorize

The long-distance factors are universal and can be empirically obtained from ancillary measurements.



$$d\sigma(P_1,P_2) = \sum_{i,j,k} \int dx_1\, dx_2\, dz\, f_i(x_1,\mu_F) f_j(x_2,\mu_F) D_{k\to H}(z,\mu_F)$$
$$\times\, d\tilde{\sigma}_{ij\to k+X}(p_1 = x_1 P_1, p_2 = x_2 P_2, p_k = P/z, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F)$$

Evolution equations (e.g. DGLAP), analogous to β-functions for α_S, account for transition from one scale to the other

These QCD predictions involve assumptions, approximations, and phenomenological modeling impacting final state selections and differential cross section predictions

Parton shower accounting for the effect of evolution on final states:

- Soft and collinear approximation (where QCD radiation is enhanced)
- Leading order kernel functions
- Choice of ordering parameter

Parton distribution function (PDF):

- Uncertainties on measurements used to extract structure functions
- Modeling of structure functions at Q_0

$$F(x,Q_0) = A_1 x^{A_1}(1-x)^{A_2} P(x;A_3)$$

Fragmentation function:

- Gaussian modeling of D(x,s) at small x
- Supplemented by hadronization model

$$D(x,s) \propto \exp\left[-\tfrac{1}{2\sigma^2}\left(\xi-\xi_p\right)\right]$$

$$\xi \equiv \ln\left(\tfrac{1}{x}\right), \quad \xi_p \cong \tfrac{1}{4}\ln\left(\tfrac{s}{\Lambda^2}\right),$$

$$\sigma \propto \left[\ln\left(\tfrac{s}{\Lambda^2}\right)\right]^{3/4}$$

For some processes, higher-order corrections might be very large

- Tree-level processes start to contribute at higher orders
- Event selections can lead to large logs in the predictions
- Scale uncertainties can massively reduce at higher-order

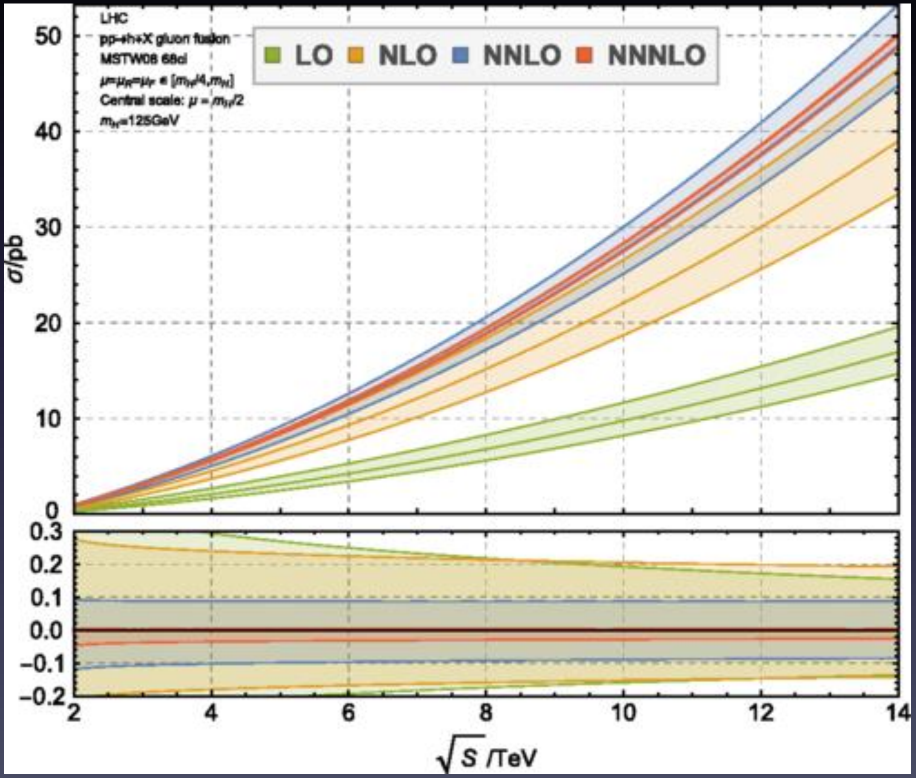
Example:

Higgs production (gluon fusion) vs √s

~70% NLO to LO QCD correction

~30% NNLO

N3LO also available!



So we need QCD-related precision measurements to improve theory predictions because:

- Errors in the SM predictions can mask new physics signals or lead to false discovery

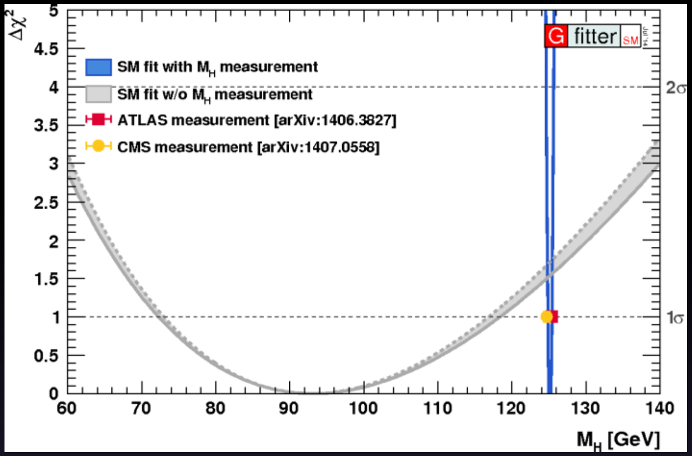
- Large uncertainties on SM predictions result in a suppression of the sensitivity of the experiments to new physics

- QCD uncertainties on new physics make it hard to understand a newly observed signal

Answer part B:
The Electroweak Interaction

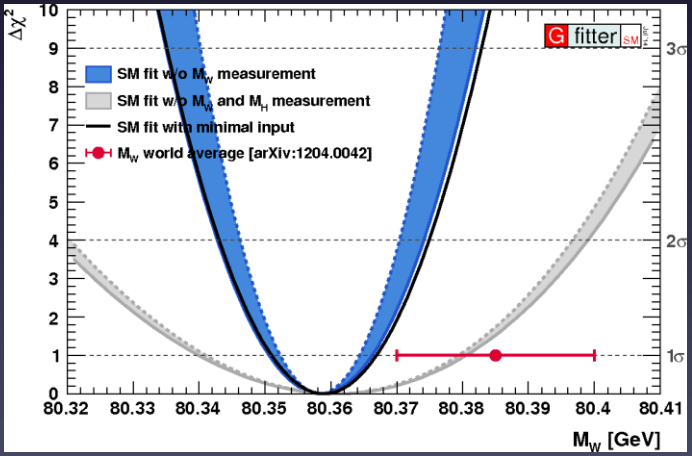
Consistency tests

- The SM contains 26 free parameters:
  - 12 fermions masses
  - 3 coupling constants
  - 9 matrix elements and phases
  - Higgs mass and vacuum expect. value



- Only 17 need to be measured: relations between EWK parameters in the SM

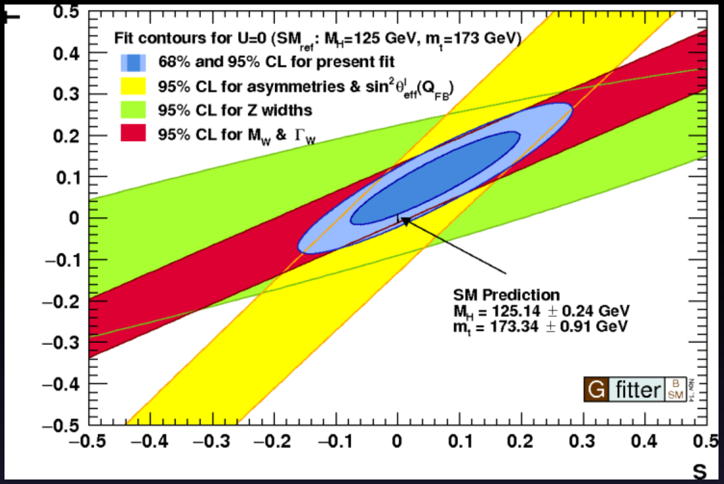
- Global fit tests can reveal inconsistencies between parameter measured values:
  - Issues with some of the measurements
  - Hints of new physics



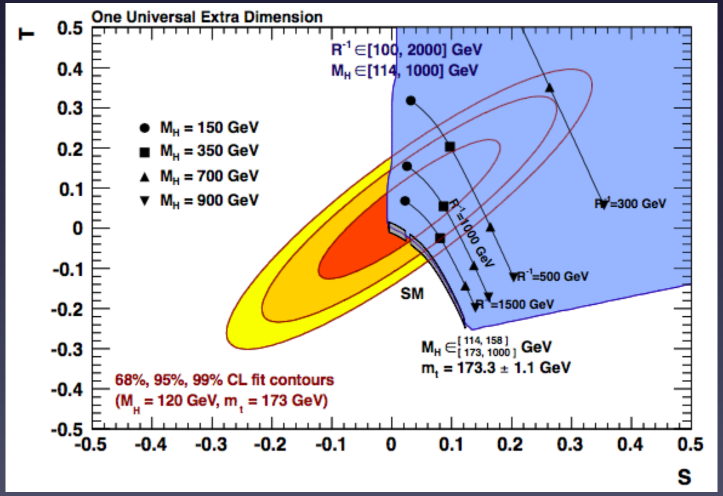
- New precise measurements of EWK parameters give more stringent consistency tests or could resolve tensions

Oblique parameters

- New physics can contribute to the EWK precision observables through virtual loops
- These effects can be parameterized by 3 gauge boson self-energy parameters: S, T and U
  - Involve assumptions such as the new physics scale must be much higher than the weak scale
- Consistency fits of EWK observables can reveal new physics and can provide information about its scale or effects



An example from UED models



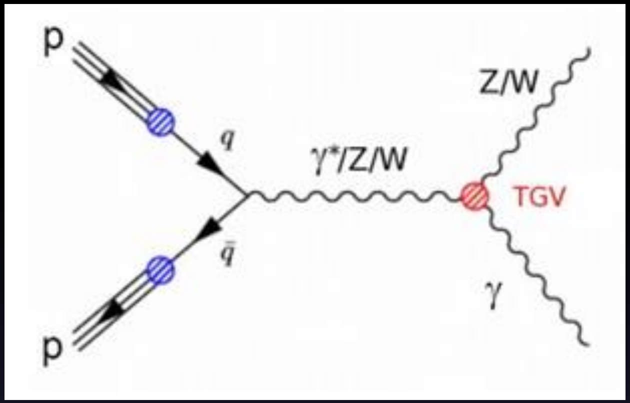
A Gateway to New Physics

- New physics can add a contribution to Triple or Quartic Gauge Couplings
  - aTGC: Diboson & Vector Boson Fusion
  - aQGC: Triboson & Vector Boson Scattering
- Can use Effective Field Theory to parametrize this new physics by adding higher dimension operators to L_{SM}:

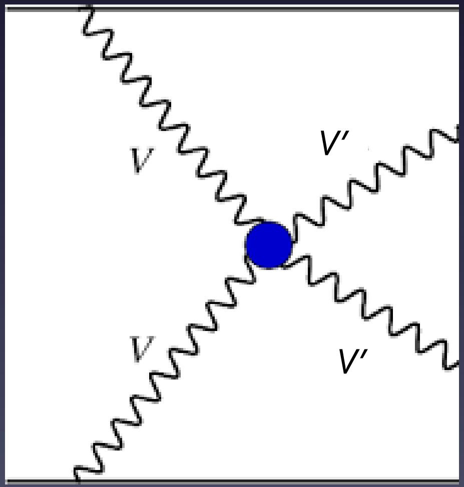
$$L = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots$$

- A plethora of new physics operators can be tested in this way, however keeping some model-dependence

An example of TGC

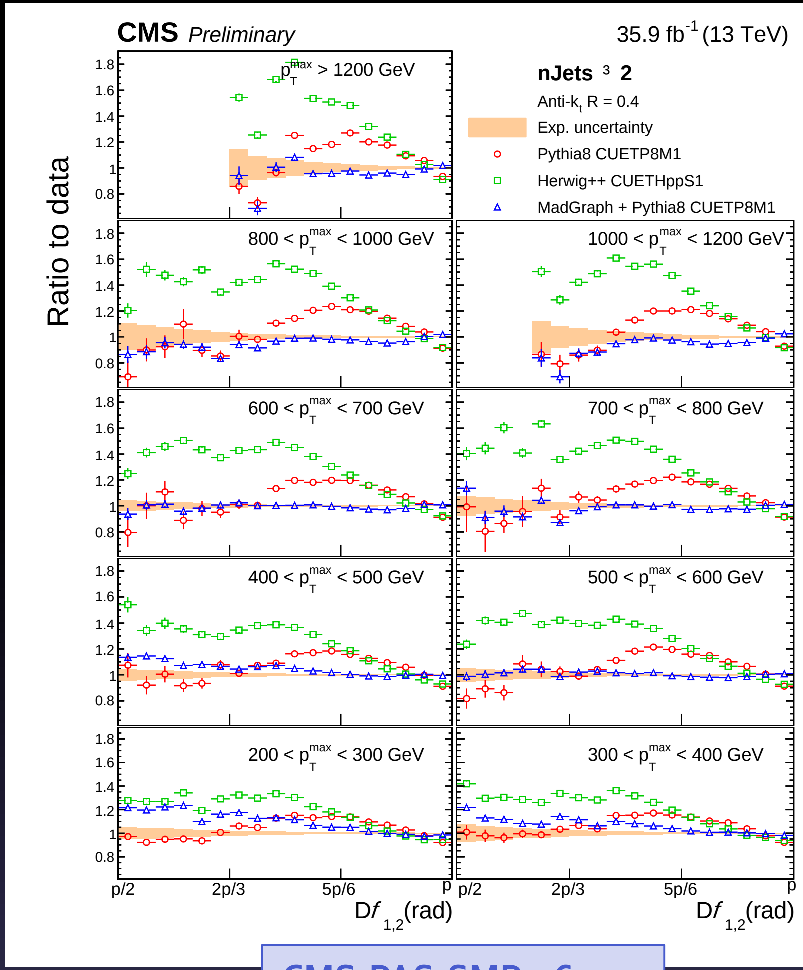


An example of QGC



Strategies

Choose to measure the differential cross section of observables for which theoretical predictions disagree for the SM effects under investigation



CMS-PAS-SMP-16-014

Example:

The azimuthal angular decorrelation ($\neq \pi$) between the two leading jets in inclusive 2-jets events is sensitive to parton emission of various "hardness"

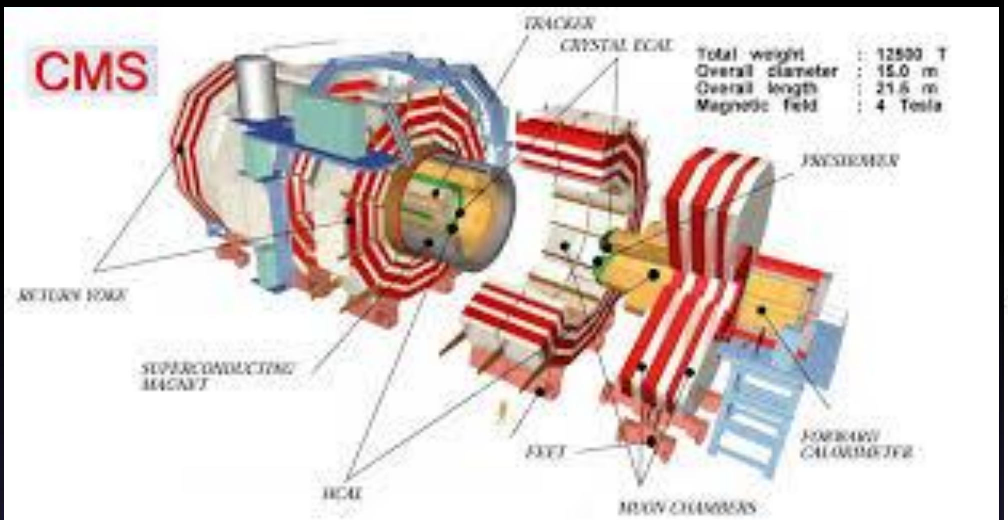
➡ Predictions on $\Delta\phi_{12}$ widely differ

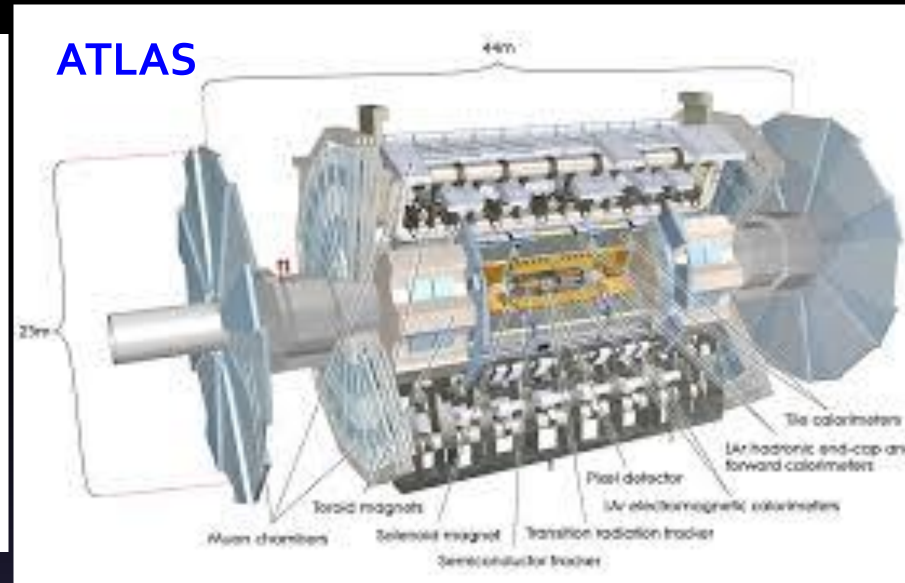
Perform the measurement to determine which calculations provide a better description of data and which theory improvement is needed

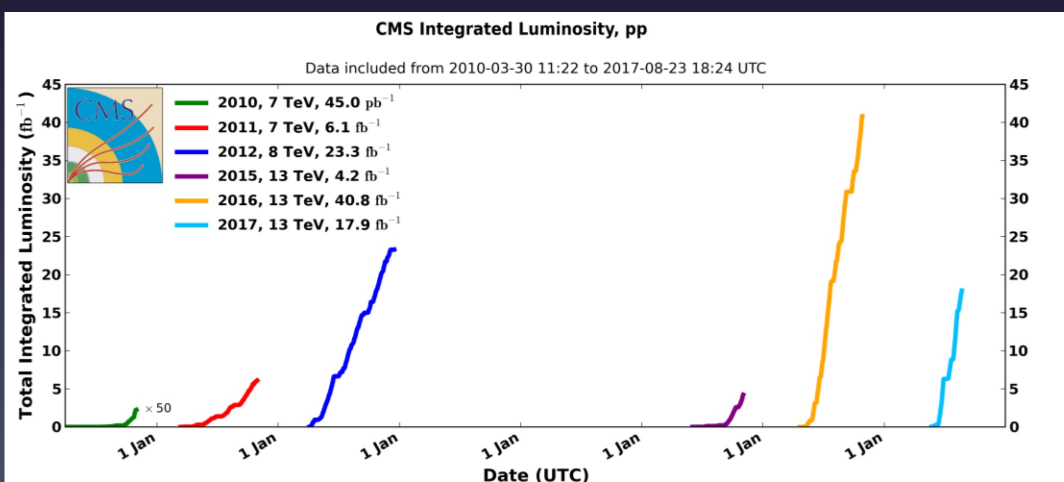
In our Example:

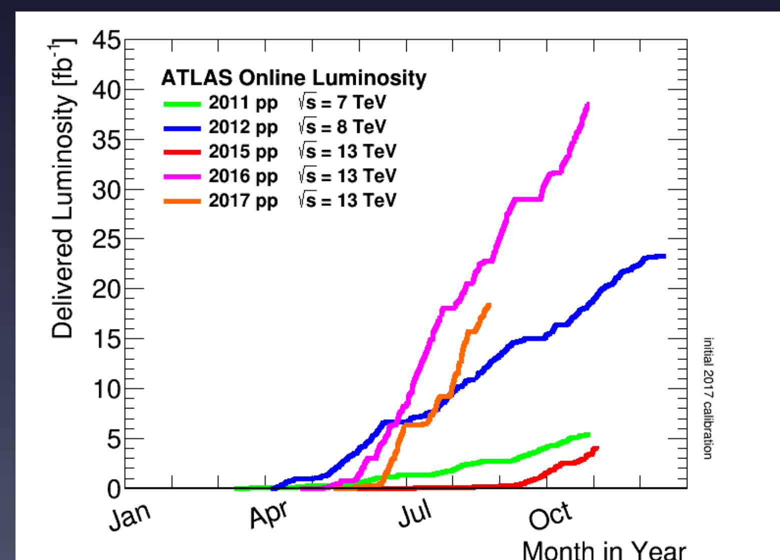
The Herwig parton shower provides a poor description of data especially at large angle, while matching a PS to a ME yields the best agreement

Our tools!


CMS
TRACKER
CRYSTAL ECAL
Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
PRESHOWER
RETURN YOKE
SUPERCONDUCTING MAGNET
FEET
HCAL
MUON CHAMBERS
FORWARD CALORIMETER


ATLAS
44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:22 to 2017-08-23 18:24 UTC
2010, 7 TeV, 45.0 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
2015, 13 TeV, 4.2 fb⁻¹
2016, 13 TeV, 40.8 fb⁻¹
2017, 13 TeV, 17.9 fb⁻¹
× 50
Total Integrated Luminosity (fb⁻¹)
1 Jan
Date (UTC)


ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
Delivered Luminosity [fb⁻¹]
initial 2017 calibration
Jan
Apr
Jul
Oct
Month in Year

- It is impossible to cover all the beautiful SM measurements that have been done by ATLAS and CMS in Run-1 and Run-2
  - >120 in each experiment
- It is also impossible to discuss in details the measurements to be presented below
- This presentation is based on a personal choice among the most recent results, and focuses on the conclusions relevant to the narrative
  - Will hopefully give a good taste of the progresses made thanks to our measurements

Parton Distribution Function

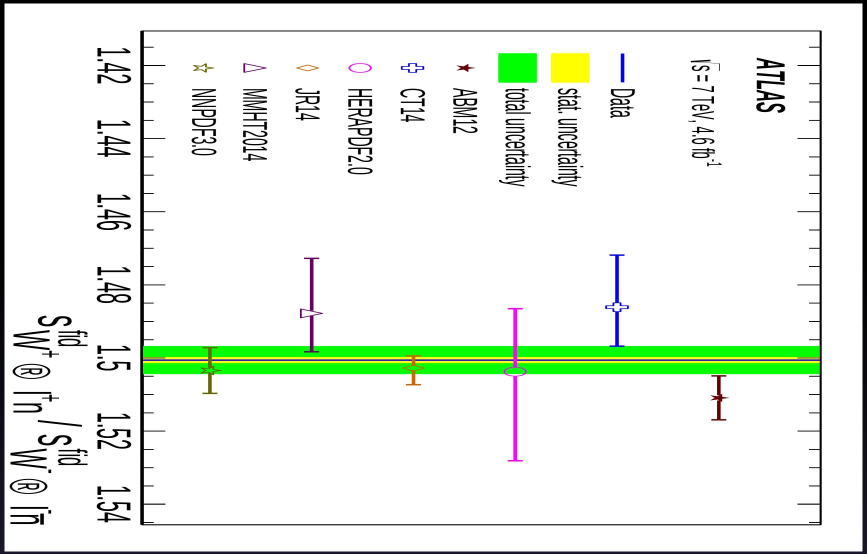
PDF: W/Z inclusive

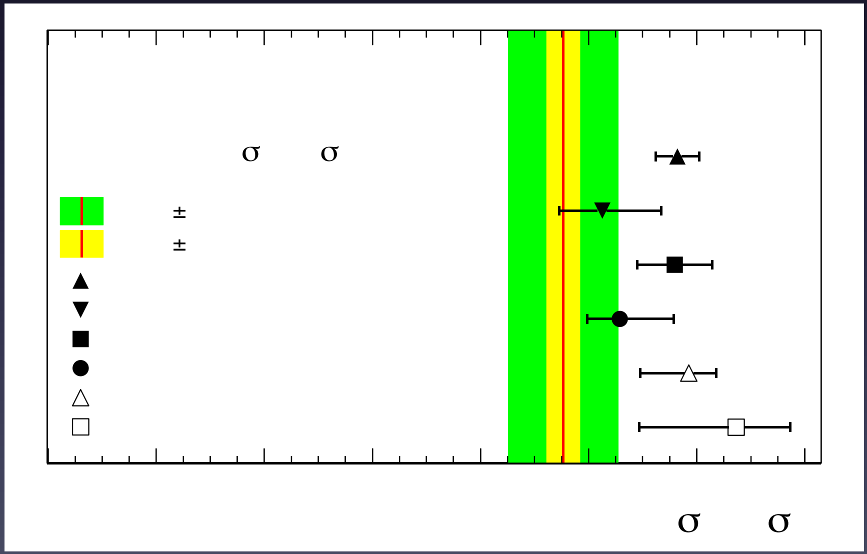
Eur. Phys. J. C77 (2017) 367

Phys. Lett. B 759 (2016) 601

- Physics motivation:
  - Light quark PDF fitting
  - Reference cross section
  - Calibrate lepton p_T and reconstruction efficiency
- Measurement results:
  - Reached an experimental precision of 0.4% for σ(Z)
    - Lumi. Uncert. ~1.8%
  - Measured ratio even more precise

Excellent agreement with JR14 and NNPDF3.0 in Run-1, but the best agreement is with CT14nnlo and MMHT14nnlo68CL in Run-2.

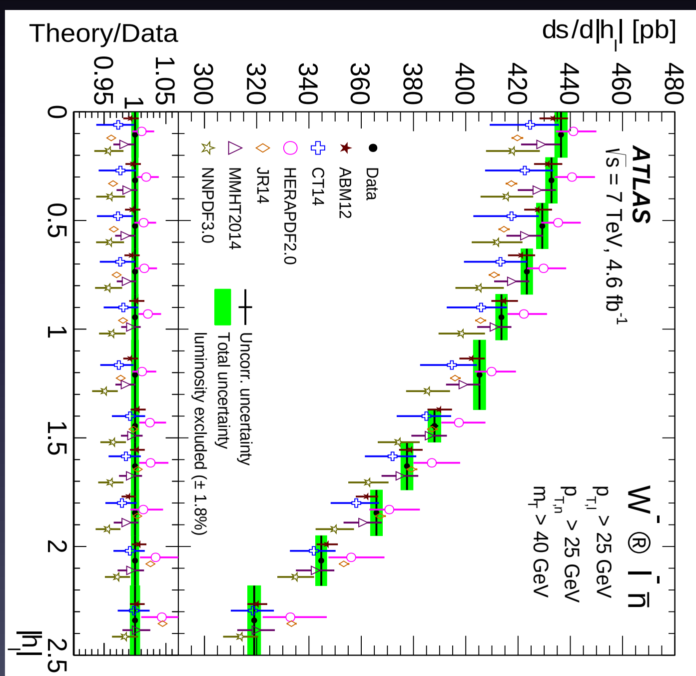




PDF: W/Z inclusive

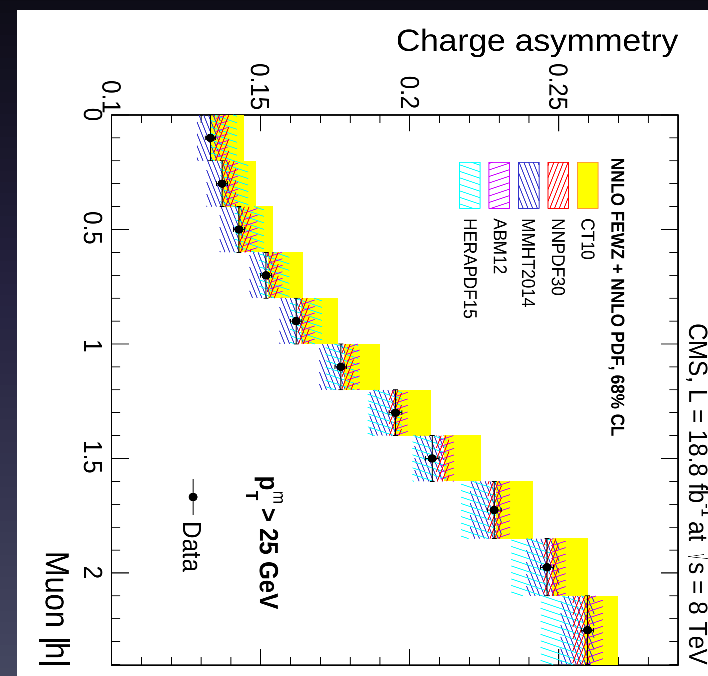
Eur. Phys. J. C76 (2016) 469

- Measuring differential cross sections increases the sensitivity to PDF since it provides more information
  - PDF fitting is using this information
  - Data uncertainties are smaller than PDF uncertainties and will therefore improve PDF uncertainties in new fits



ATLAS W-lepton pseudo-rapidity

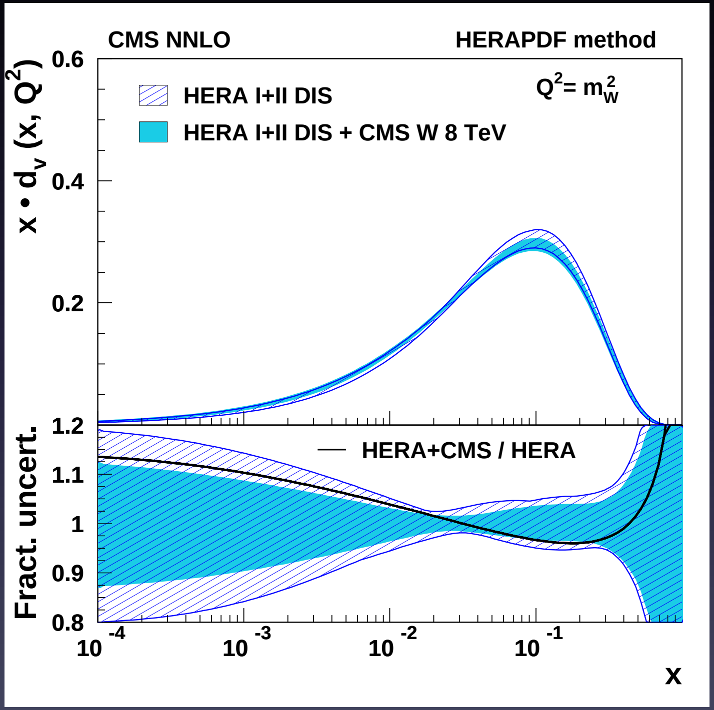
ABM12 gives the best description of both sets of data



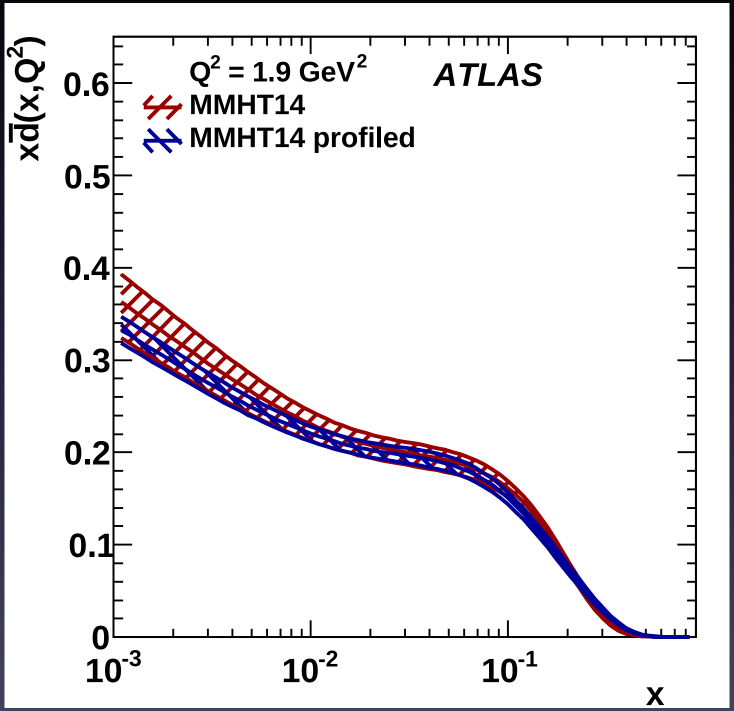
CMS W charge asymmetry

Impact on valence PDF

- When the latest W/Z inclusive differential cross section measurements are included in the PDF fits, the uncertainties get reduced and the central values shift



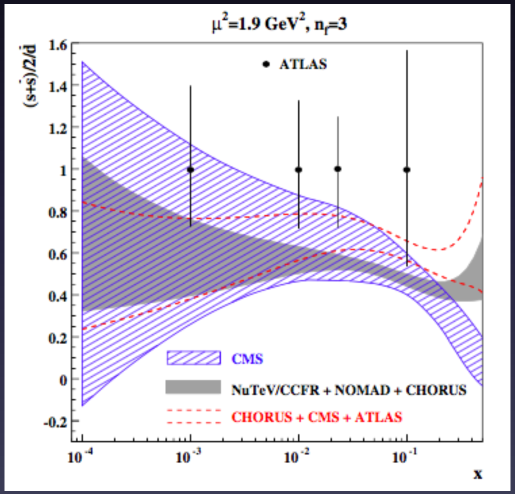
Impact of CMS W 8 TeV data on d-quark HERAPDF



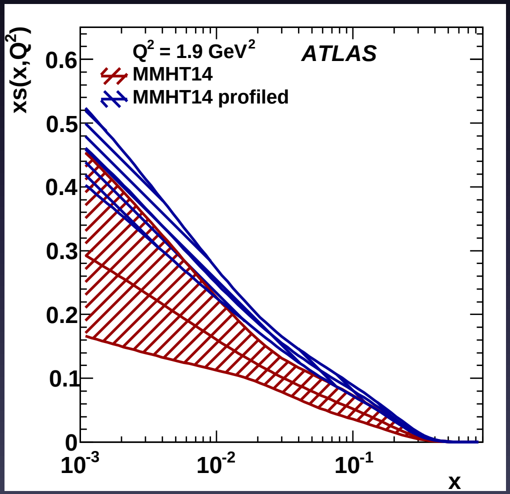
Impact of ATLAS W/Z 8 TeV data on dbar-quark MMHT14

Impact on s-quark PDF

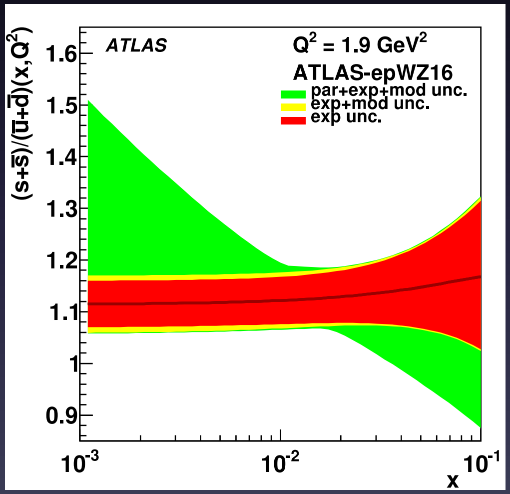
- 2010 ATLAS results indicated an enhancement of strangeness in PDF compared to neutrino-induced charged-current DIS
  - Poorly known at low-x due to restricted kinematic in fixed-target
  - Nuclear effects make PDF extraction more complicated
- Inclusive W/Z ATLAS data dramatically improve s-quark PDF and confirm strangeness enhancement



ABM Analysis
EPJC76(2016)471



Impact of ATLAS W/Z 8 TeV data on s-quark MMHT14



Strangeness ratio favored by ATLAS data

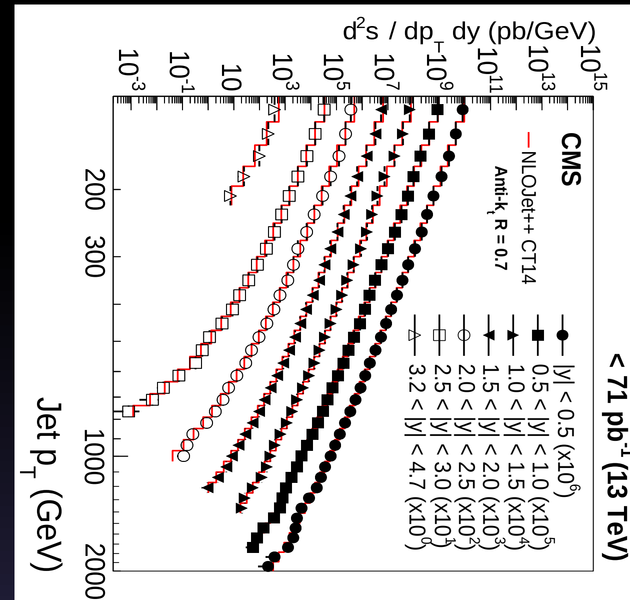
Suggest a restoration of SU(3) flavor symmetry in the sea distribution

Jet cross sections

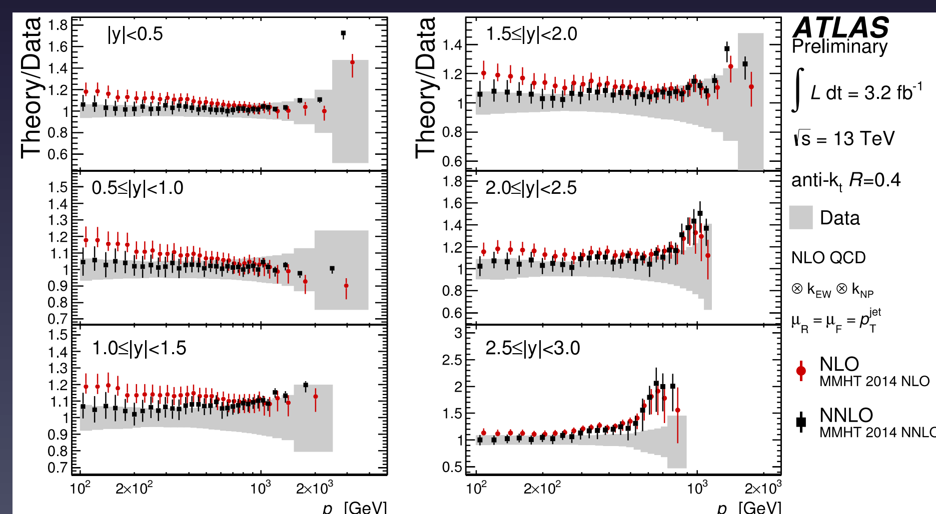
ATLAS-CONF-2017-048

Eur. Phys. J. C76 (2016) 451

- Double differential inclusive P_T vs y distribution obtained from pQCD predictions describes generic features of data up to the TeV scale covering many orders of magnitude in cross sections



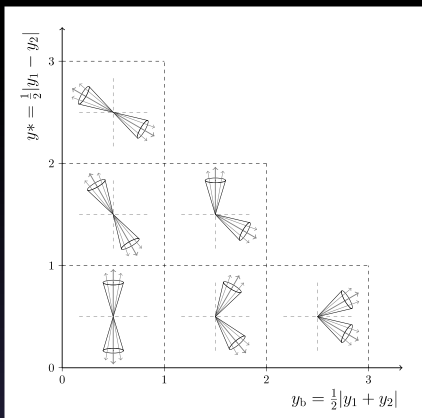
- Measurement results are probing the new NNLO level predictions
  - Tensions with NLO calculations
  - Can be used in PDF fits



In-depth Analysis of Jet Production

3D differential cross section

$$\frac{d^3\sigma}{dp_{T,avg}\,dy^*\,dy_b} = \frac{1}{\epsilon \mathcal{L}_{int}^{eff}} \frac{N}{\Delta p_{T,avg}\Delta y^* \Delta y_b}$$



arXiv:1705.02628

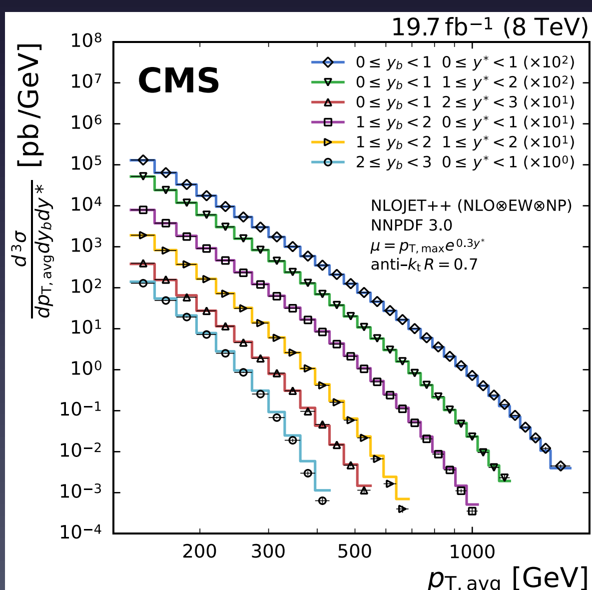
Probe of different topologies and radiation patterns

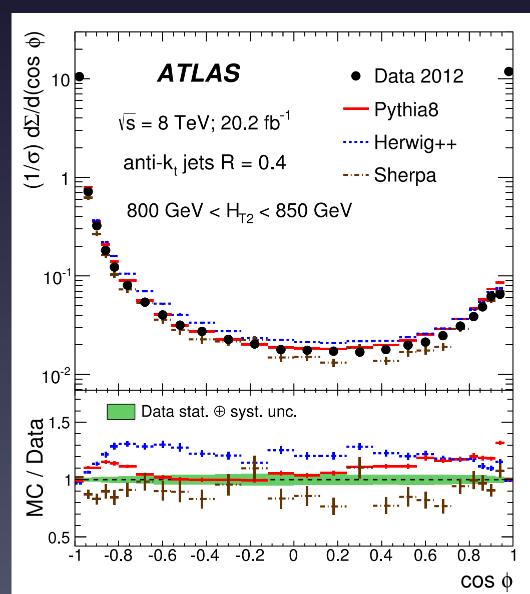
Jet Correlations

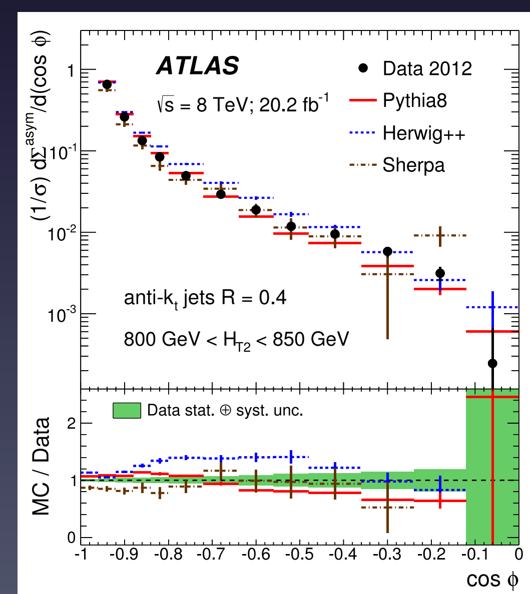
arXiv:1707.02562

Energy-energy-Correlation in transverse plane (TEEC) and its asymmetry (ATEEC)

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^A E_{Tj}^A}{\left(\sum_k E_{Tk}^A\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$



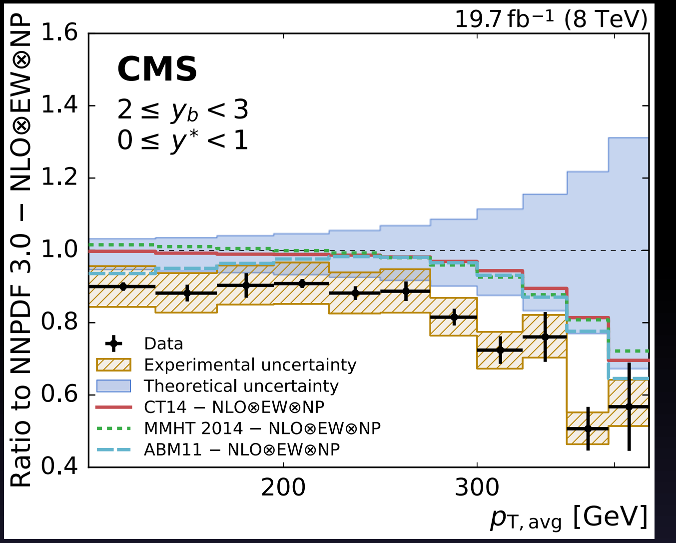




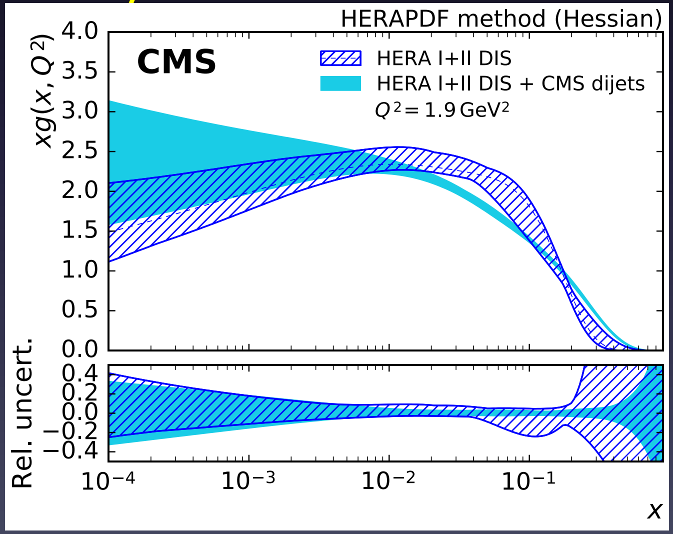
Constraints to PDFs

- The exp. uncert. on the CMS 3D differential cross sections is smaller than theoretical uncertainties on predictions
- Tensions with NLO predictions are also observed at high p_T and high boost

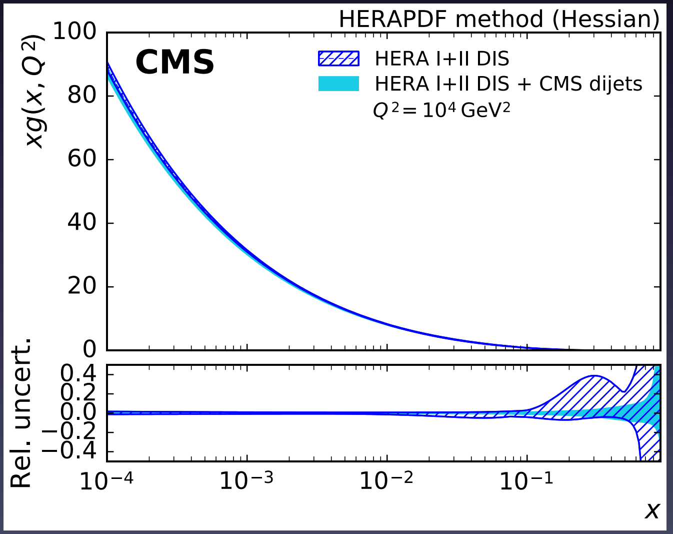
Measurements can be used to constrain the theory!



- Fit of free parameters of PDFs models
- HERAFITTER or xFITTER routines
- Need to account for correlations between all syst.



Significant impact on high-x gluon PDF at low-Q_2



Significant impact on high-x gluon PDF at high-Q_2

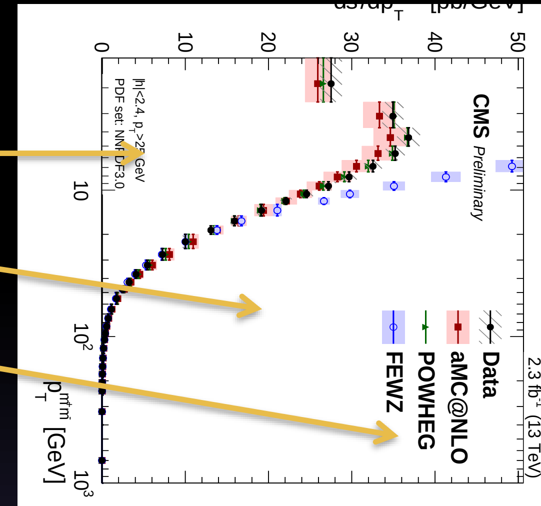
Soft Parton Radiation (QCD Bremsstrahlung)

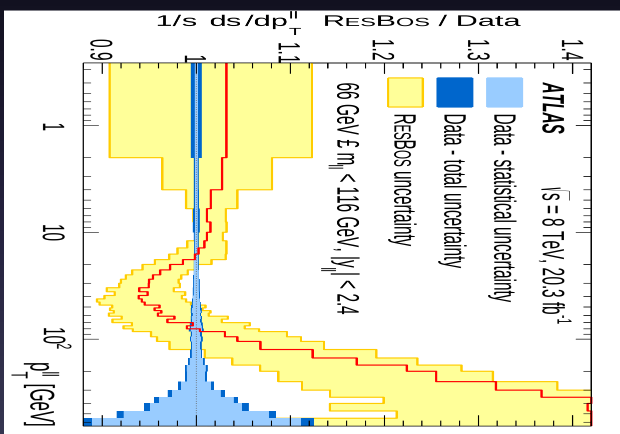
Vector Boson P_T

Eur. Phys. J. C 76, 5 (2016) 1-61

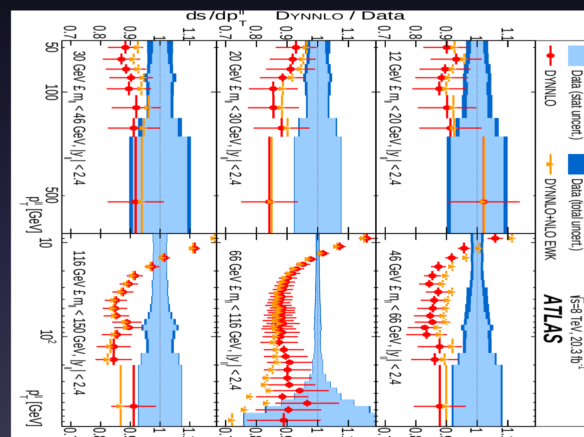
CMS-PAS-SMP-15-011

- Test multiple aspects of QCD predictions
  - Intrinsic-K_T
  - Low-p_T (W,Z): logarithmic resummations
  - High-p_T (W,Z): (N)NLO perturbative QCD
  - Important test of parton shower tuning

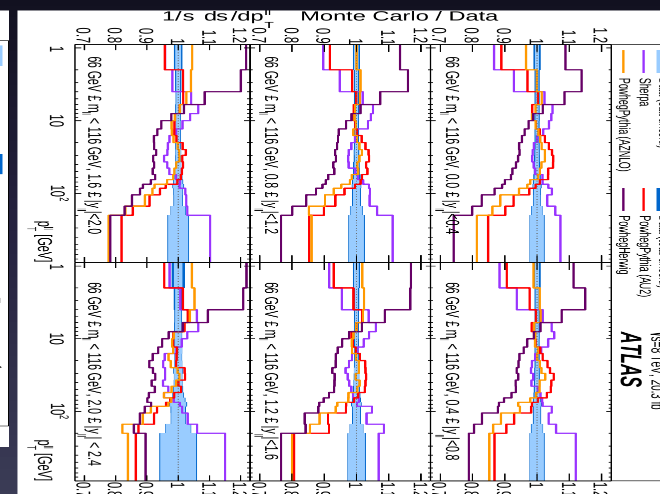




NNLL soft-gluon Resummation: (including GNW npQCD corr.) Good description at low and average P_T, but not when hard gluon emission dominates



NNLO Fixed order (DYNNLO): Cannot describe low P_T, but still does poorly at average P_T

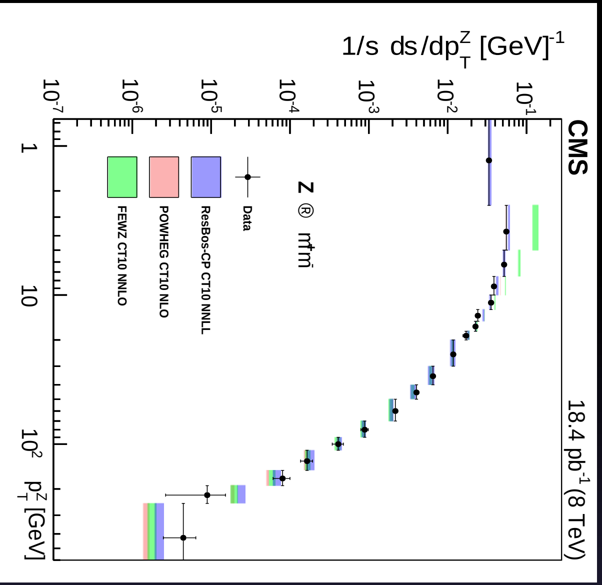


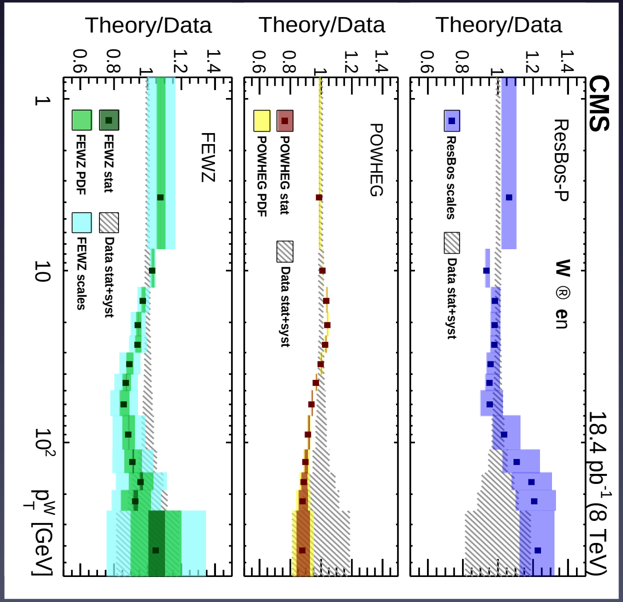
PS and tuning more important than NLO ME: variations on predictions are very large

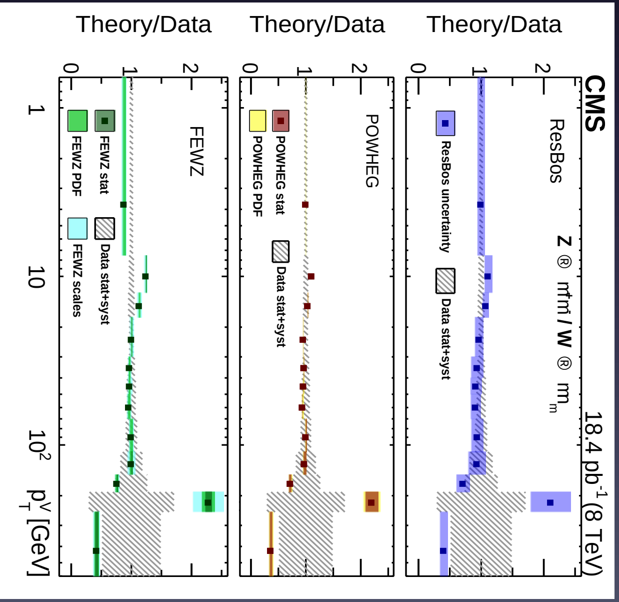
Vector Boson P_T

JHEP 02 (2017) 096

- CMS produced the measurement in a dedicated low luminosity run
  - Limit the impact of pile-up affecting non perturbative effects at low P_T
  - Also performed W P_T measurement
  - Measured the ratio of W P_T/ ZP_T accounting for all correlations







NNLO Fixed order (FEWZ):

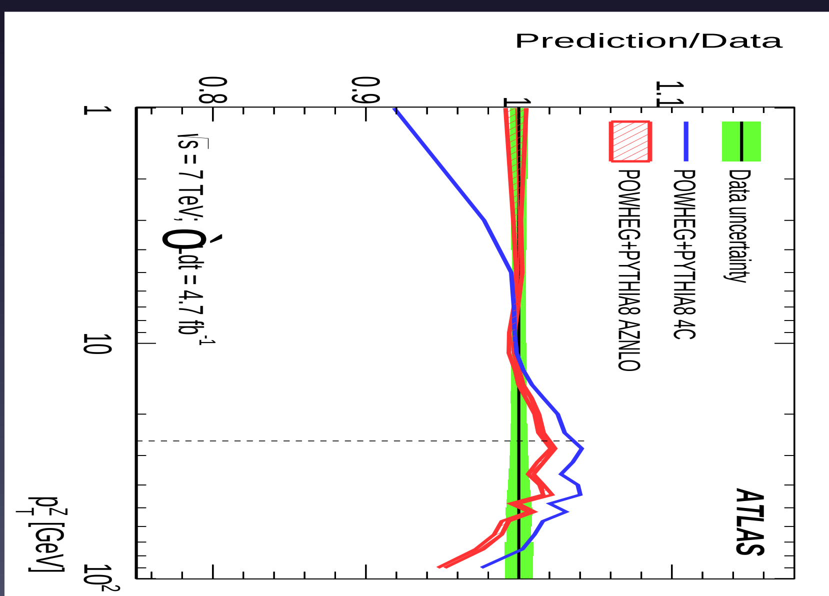
- Still does rather poorly at average P_T
- Normalizing on σ improves the first bin
- Lack of resolution in the very wide first bin
- Soft radiation not modeled the same in W and in Z

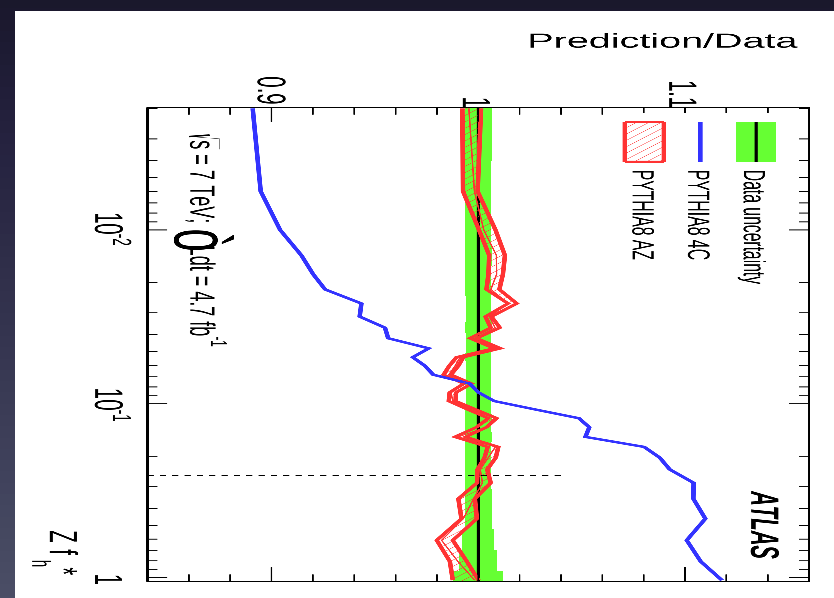
Need for tuning

JHEP 09 (2014) 145

- Huge advantage of PS tuning over more accurate ME predictions for low and average P_T region, less critical for high Z P_T values
  - True for both Z P_T and ϕ^*
  - Tuning effects larger for LO than NLO, but end point comparable

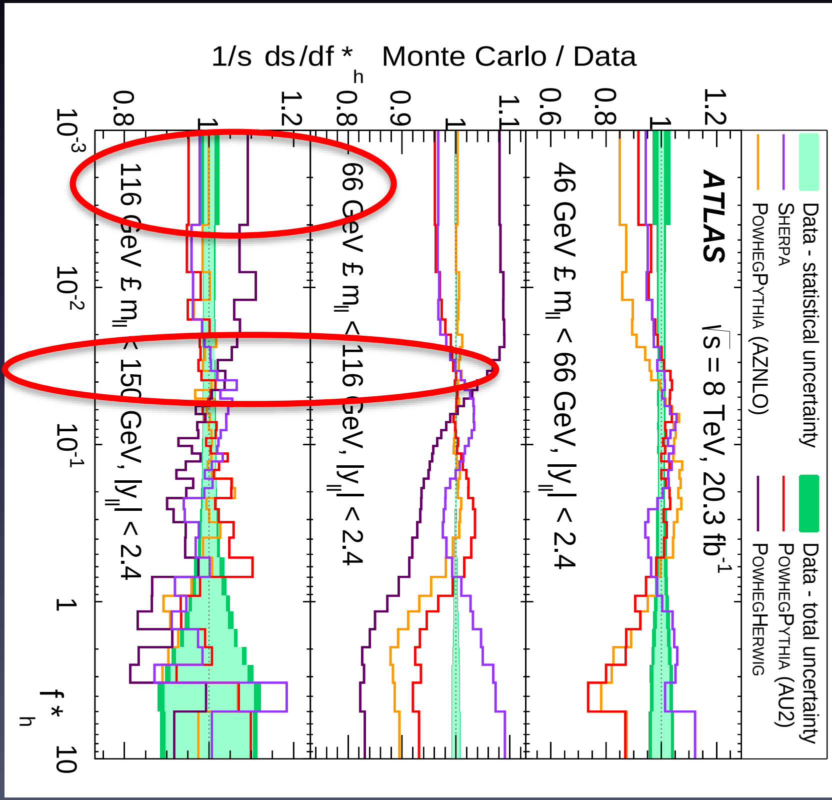
Parameter	Variation Range PYTHIA8 tune	Variation Range PYTHIA8+POWHEG tune
Primordial k_T [GeV]	1.0–2.5	0.5–2.5
ISR $\alpha_S^{ISR}(m_Z)$	0.120–0.140	0.118
ISR cut-off [GeV]	0.5–2.5	0.5–3.0
ISR α_S order	LO	NLO
PYTHIA8 base tune	tune 4C	tune 4C
POWHEG cut-off [GeV^2]	-	4.0





Limitations of tuning

- Tuning provides a better description of data with similar event topology
    - The AZNLO tune has been obtained from the 7 TeV ATLAS Z P_T and ϕ^* measurements for 66 GeV < m_{ll} < 116 GeV
    - It performs very well in the same phase space for 8 TeV data



- A tune will however often be sub-optimal in some other phase space regions.

- Tuning cannot be the solution to all QCD emission mis-modeling issues for future predictions
    - But it can be a useful tool for reweighting

k_T-Splitting

- Parton radiation is intimately related to jet clustering algorithms:

  sequential k_T-type jet algorithms produce infrared- and collinear-safe branching history of partons.

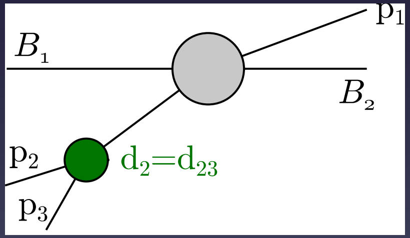
  - Each step of the k_T algorithm identifies the pair of partons which would most like proceed from QCD emission or splitting
  - Used to determine when a branching occur in CKKW for example

Criteria for combining partons i and j:

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2} \approx \min(E_i, E_j)\theta_{ij}$$

Splitting prob. for branching in partons i and j in the soft and collinear limit:

$$\frac{dP_{ij\to i,j}}{dE_i d\theta_{ij}} \sim \frac{1}{\min(E_i, E_j)\theta_{ij}}$$



Measuring the k_T-splitting scales at different steps of the iteration would allow to test branching modeling at different scales therefore testing resummation, parton shower, ME, etc.

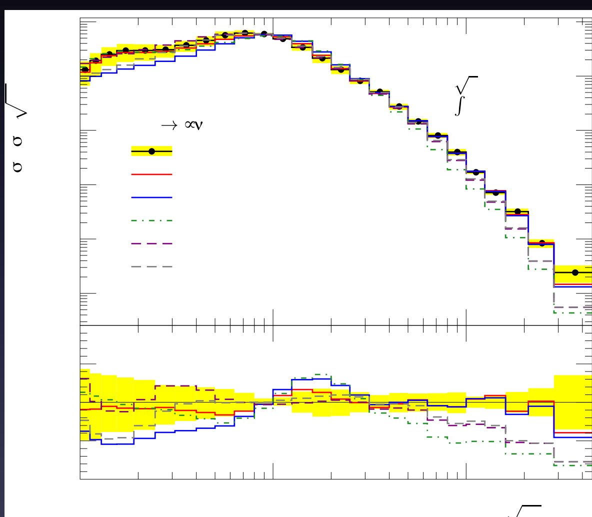
Eur. Phys. J. C 73, 5 (2013) 24-32

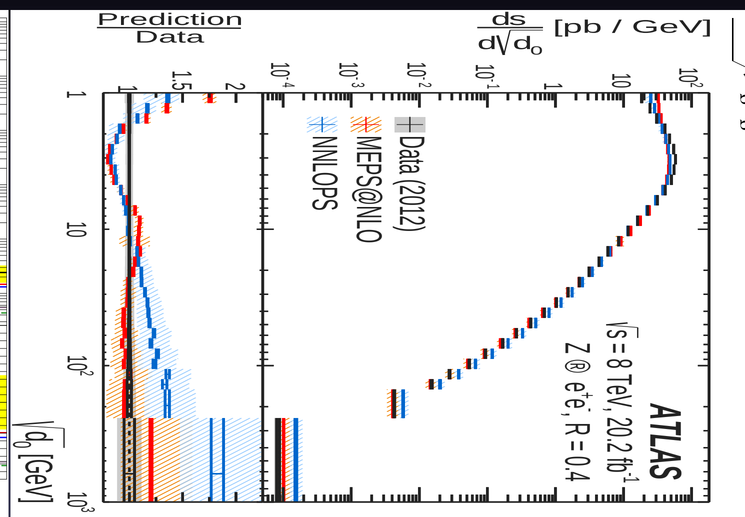
JHEP 08 (2017) 026

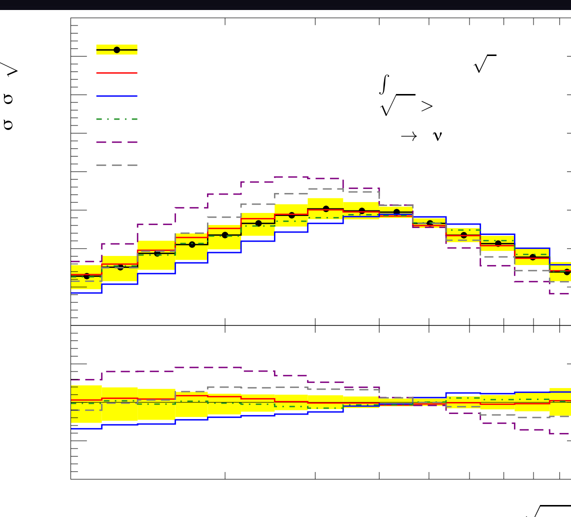
k_T-Splitting

- $\sqrt{d_k}$: k_T-splitting scales where number of input drops from k+1 to k
  - Large k and low $\sqrt{d_k}$ values are sensitive to soft emission and non-perturbative effects; low k and high $\sqrt{d_k}$ is sensitive to hard radiation
  - Can be used for tuning

$$\sqrt{d_k} = \sqrt{\min(d_{ij}, d_{iB})}$$







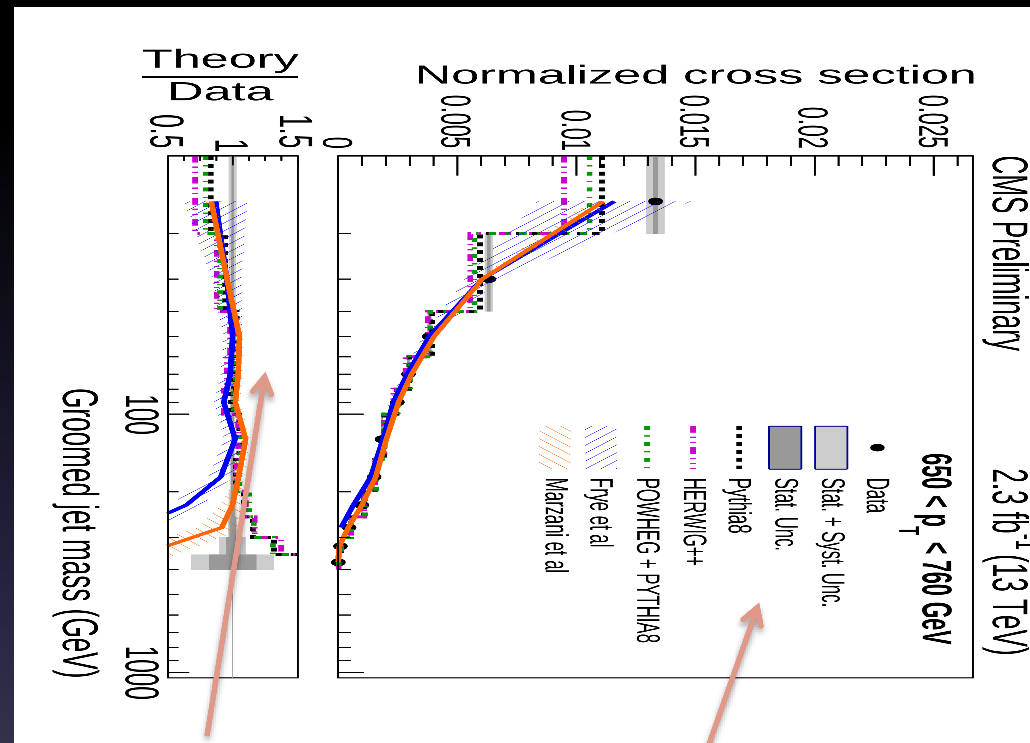
Low $\sqrt{d_0}$ is sensitive to PS and npQCD; high $\sqrt{d_0}$ is not sensitive to soft effects, but favors high-multiplicity LO over low-multiplicity at NLO

- Use tracks for more precision
- Improvements at high $\sqrt{d_0}$: Sherpa 2 uses NLO+tree-level+PS.
- NNLOPS is NNLO for Drell-Yan only, so ME up to 2 jets.

Ratio of scale is more precise. The $\sqrt{(d_1/d_0)}$ probes NLO to PS matching. The MC@NLO matching is better than the Powheg approach.

Soft drop groomed jet mass

- Soft drop is a jet grooming procedure that yields NNLL resummed jet observables.
  - Discard soft gluon emission until a sufficiently hard branching is found
  - PS and NNLL resummed predictions are in agreement with data showing a suppression of Sudakov corrections



Sensitive to npQCD effects

Sensitive to HO ME corrections

- Soft drop grooming stripped soft-radiation from the jet, suppressing the Sudakov peak ⟹ good test of ME calculations

Hard Parton emissions

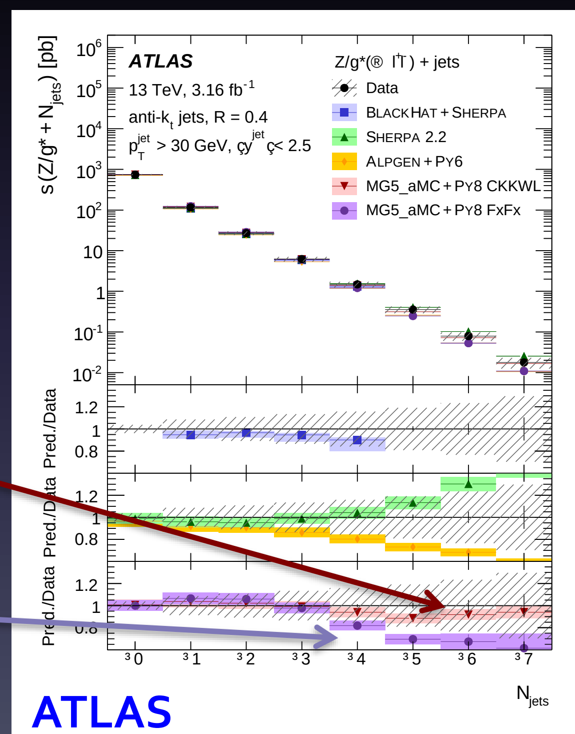
Hard radiation: V+jets

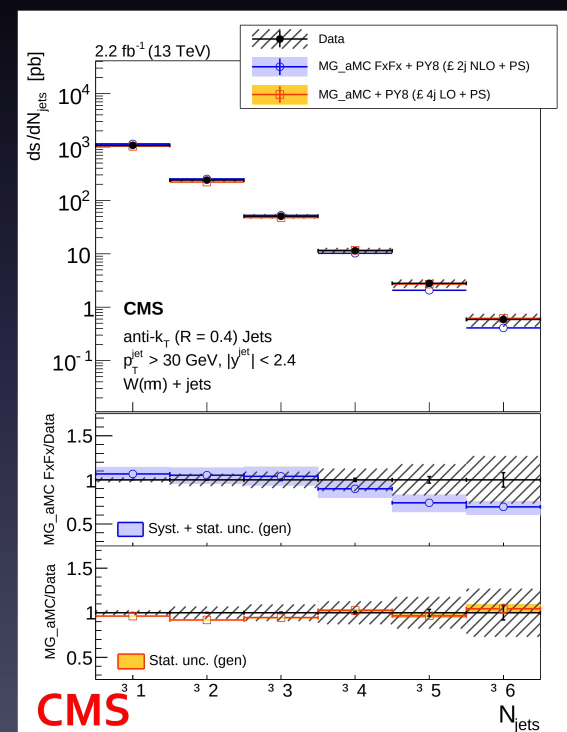
arXiv:1707.05979

Eur. Phys. J. C77 (2017) 361

- Test pQCD in more exclusive final states
  - Large phase space for QCD bremsstrahlung: room for hard radiation
  - Both ISR and FSR are entangled
  - Multiple scales in each event force more sophisticated predictions
  - Direct study of SM in regions where new physics is often predicted

- Multiplicities in good agreement with ME when jets are hard
  - PS lacks of large angle hard emission
  - More jets at LO ME is better than fewer jets at NLO
  - PS and merging matters at high N_{jets}



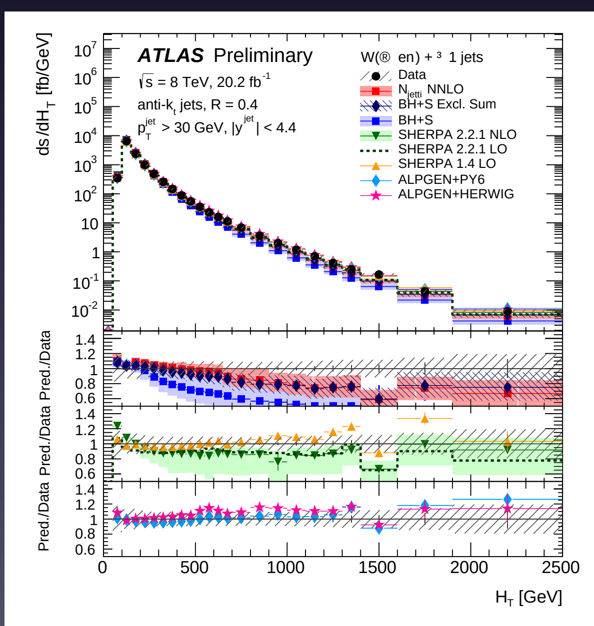


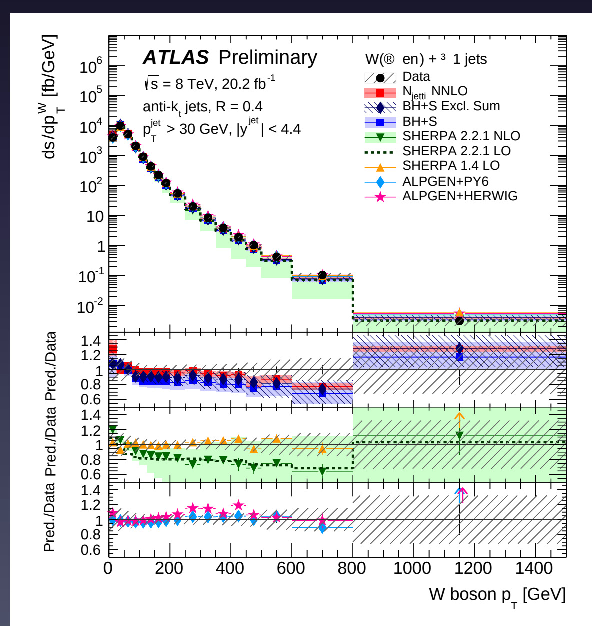
13 TeV data

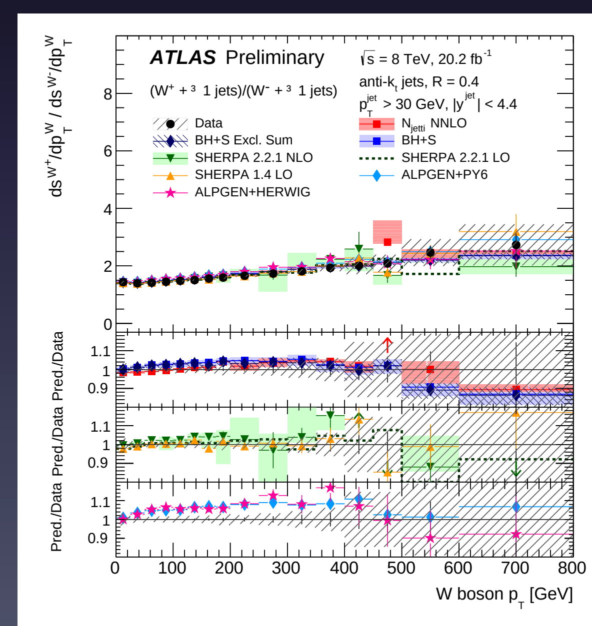
Hard radiation: V+jets

ATLAS-STDM-2016-014

- Lack of PS is detrimental to jet momentum modeling
  - Exclusive sum and NNLO not sufficient to restore agreement in H_T
  - Adding virtual corrections does not improve on exclusive sum with no matching procedure
- No significant sensitivity to the choice of PS (Alp+Pyt~ Alp+Her)
- Alpgen ME+MLM merging cannot describe W+/W-
- Is there a big issue with MEPS@NLO matching prescription?



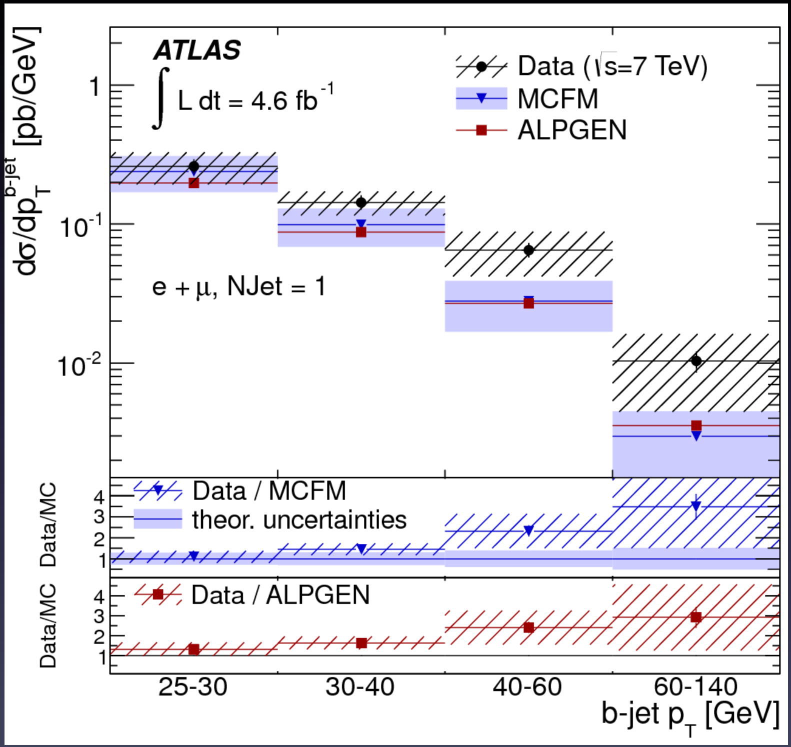


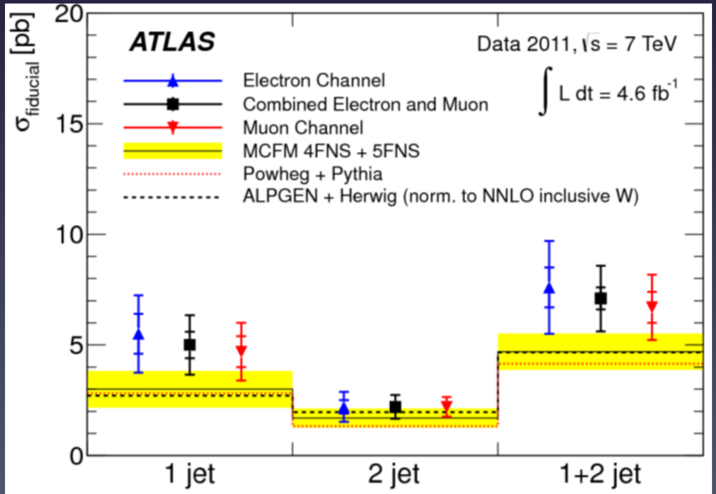


Heavy Flavor: W+b-jets

JHEP 06 (2013) 084

- Further theoretical uncertainties for heavy flavor jets:
  - Heavy flavor content of PDF
  - Gluon splitting pushed in the limit of invalidity when m_q is large
  - Mass effects in ME calculation
- 4FNS vs 5FNS:
  - b-quark from gluon splitting vs DGLAP (PDF)
- Tension between predictions and data
  - Systematically increasing with P_T
  - Experimentally very challenging





➔ Not yet significant

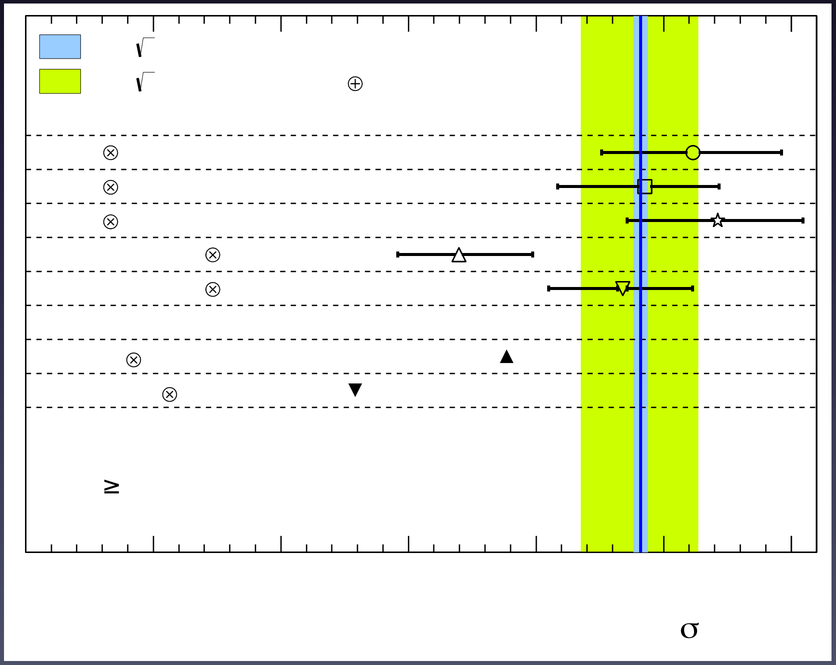
➔ Need more precision to conclude…

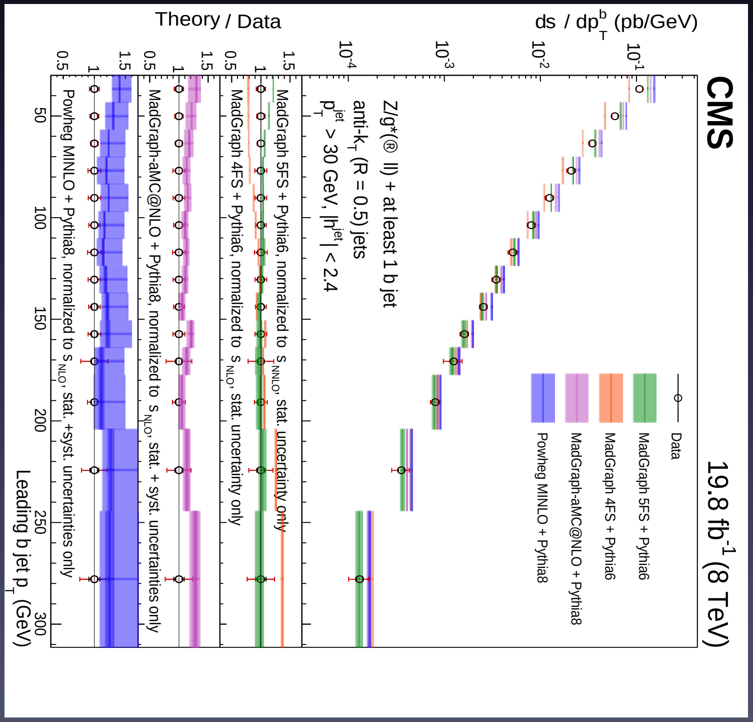
Heavy flavor: Z+b-jets

JHEP 10 (2014) 141

arXiv:1611.06507

- Data favor scheme where the b-quark is taken from PDF (5FNS)
  - Low p_T regime is not well-described by both approaches
  - LO+PS generators are underestimating the cross section
  - It is not clear if 5FNS is reliable for NLO predictions: disagreement is large at low p_T and predictions are systematically off at any p_T.

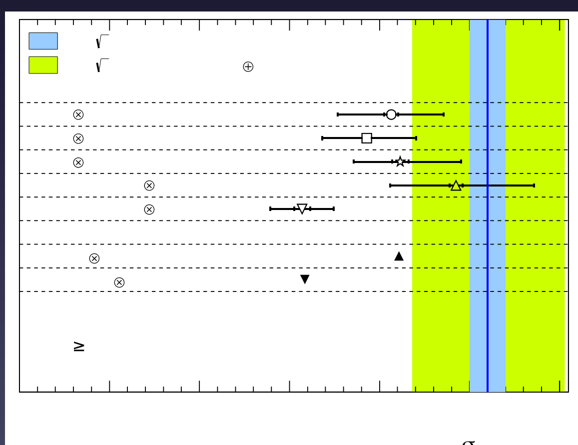


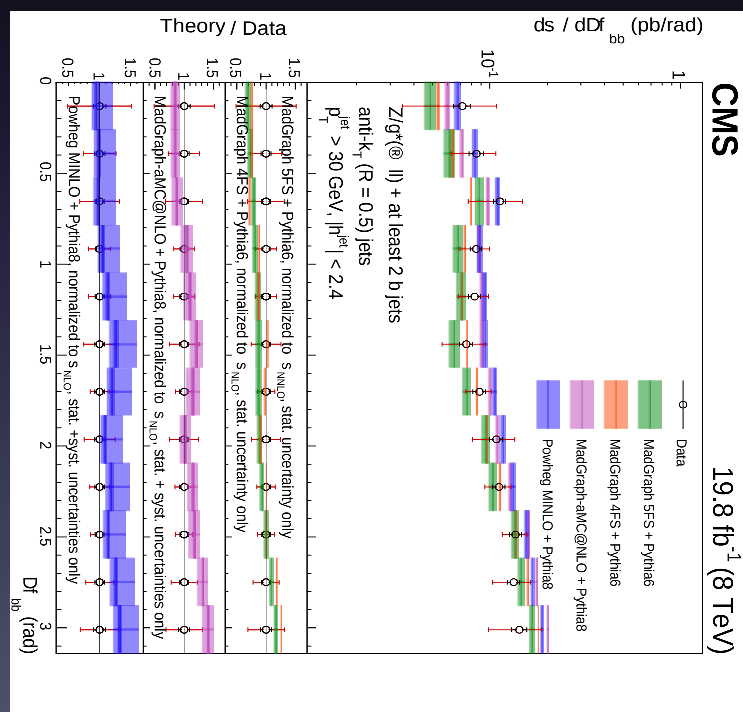


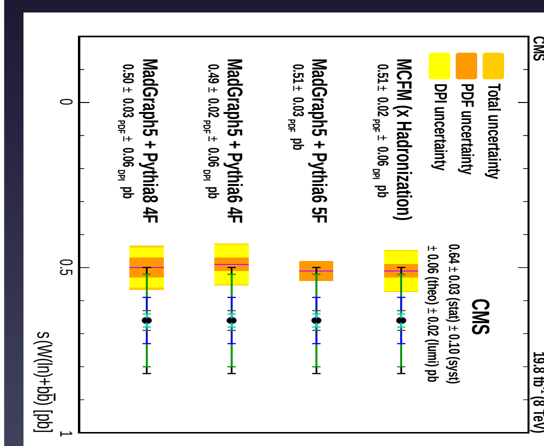
Heavy flavor: V+bb

EPJC 77 (2017) 92

- The flavor scheme seems not to matter much in cases where 2 b-quarks are in the final state
  - 4 and 5 FNS cross sections in Wbb and shapes in Zbb are very similar
  - Mostly come from gluon splitting in all cases
- Gluon splitting seems not to be very well understood in the collinear regime at LO, but NLO Powheg describes data well





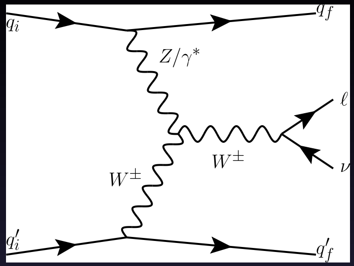


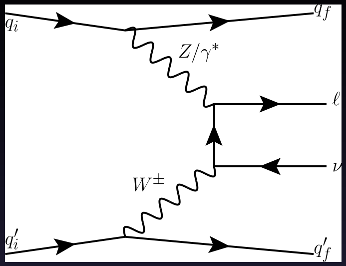
Measurement of various electroweak-dominated processes

Vector Boson Fusion

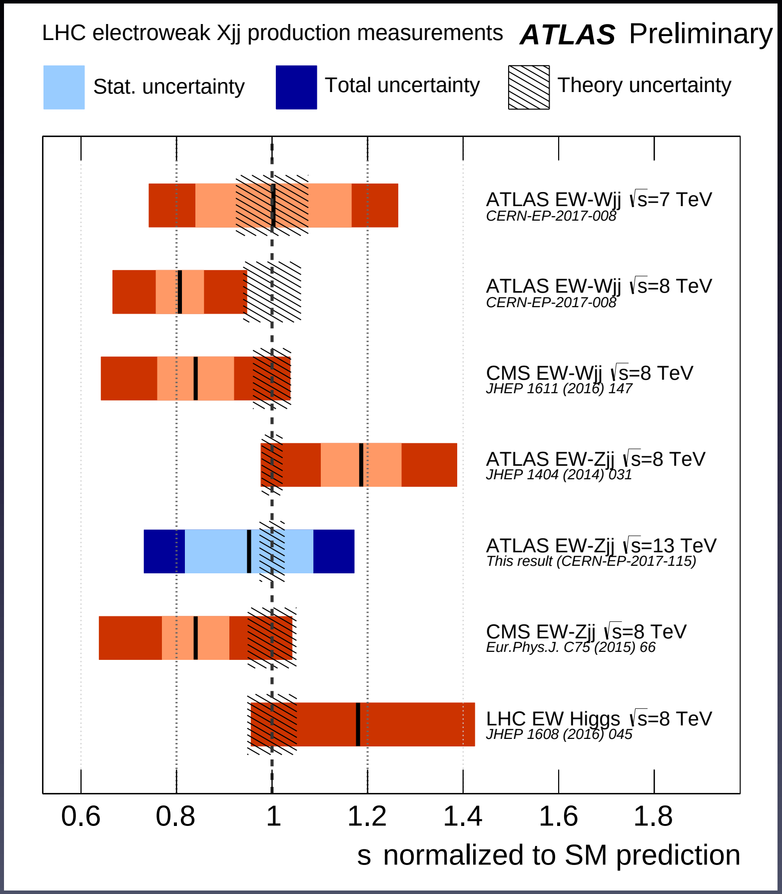
Eur. Phys. J. C77 (2017) 474

- Lepton+jets production in VBF processes are important backgrounds to many Higgs measurements or searches for new physics
  - 2 forward jets with large rapidity separation





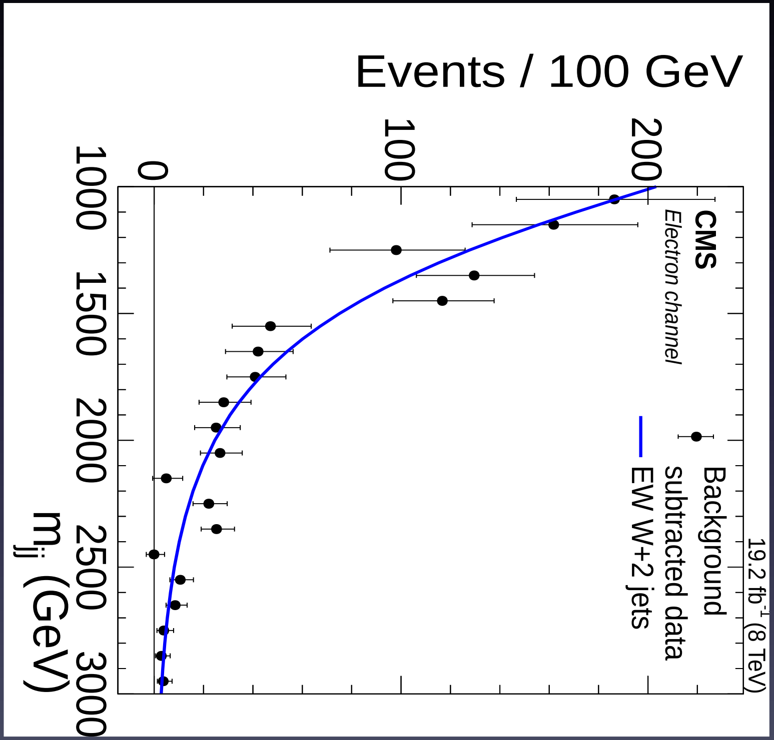
- Both ATLAS and CMS data are in globally good agreement with predictions
  - Processes observed at ≥5σ
  - Experimental uncertainties are significantly larger than theory uncertainty



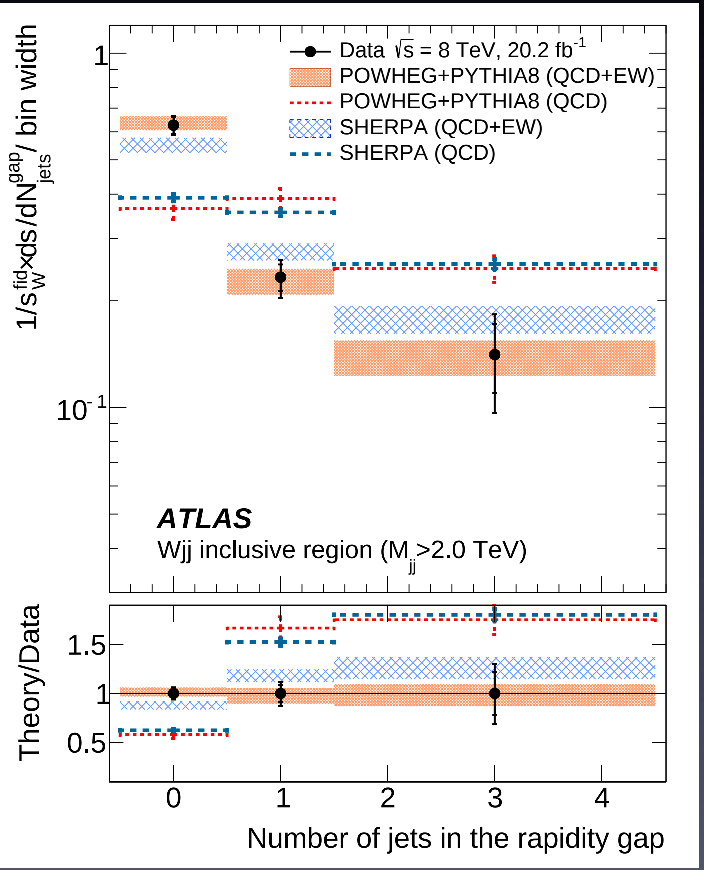
JHEP 11 (2016) 147

- The measurements non-ambiguously probed electroweak contribution to W+2-jets, despite a large QCD-related contribution

CMS EWK-extracted contribution to Wjj using the M_{jj} observable

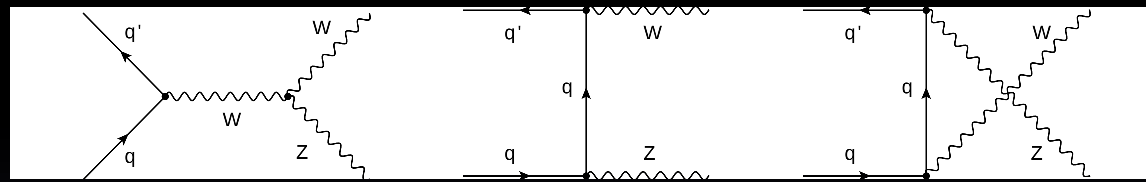


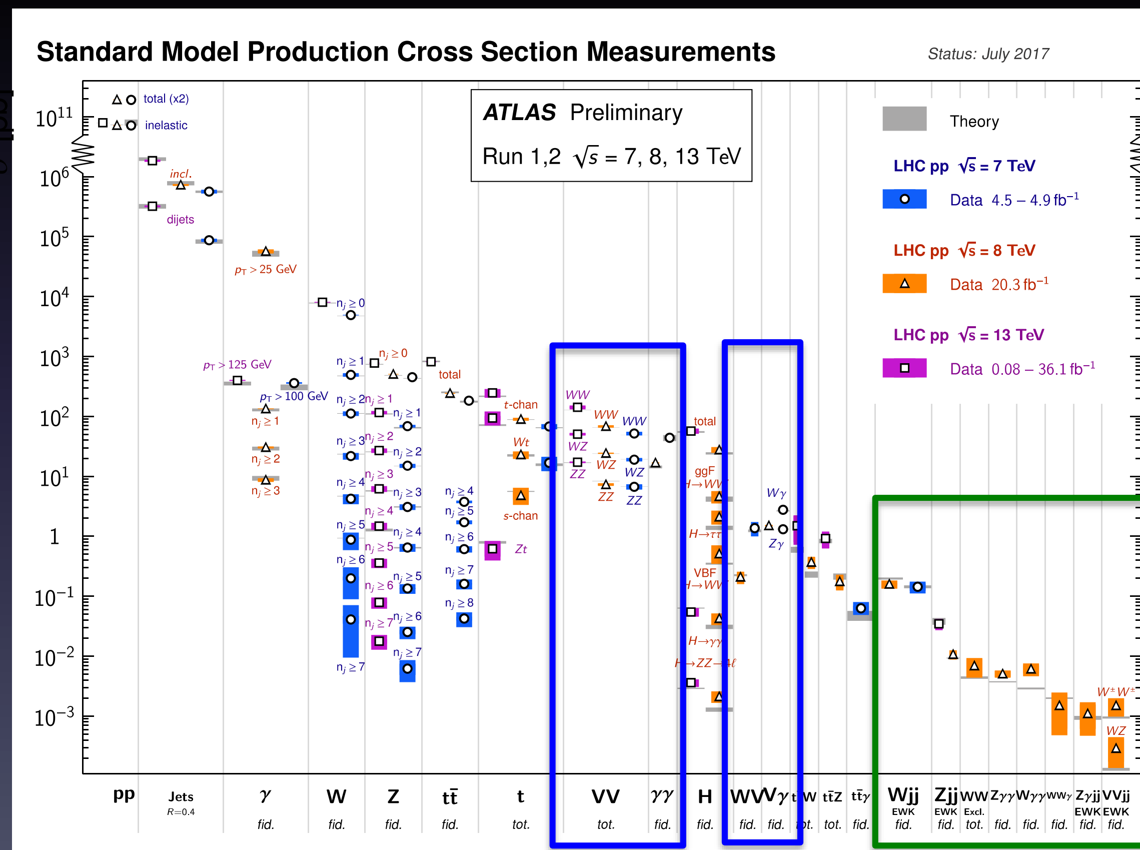
ATLAS clear test of EWK contribution using the number of jets in the rapidity gap



Multi-boson cross sections

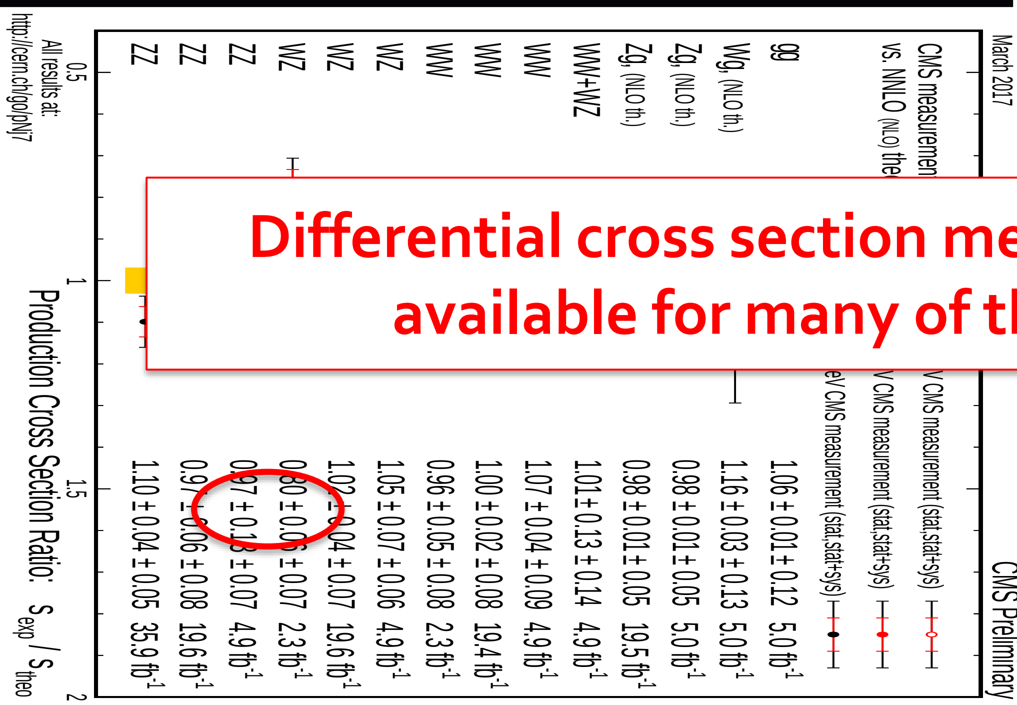
- A plethora of diboson(VV') cross section measurements probe EWK couplings at high precision
  - V = W, Z and γ
  - Many decay channels: eν, μν, ee, μμ, νν, jets
    - ≥1 lep. decay
  - Cross sections measured at √s = 7, 8 and 13 TeV
  - Cross sections covers many orders of magnitude
    - Some statistically limited measurements

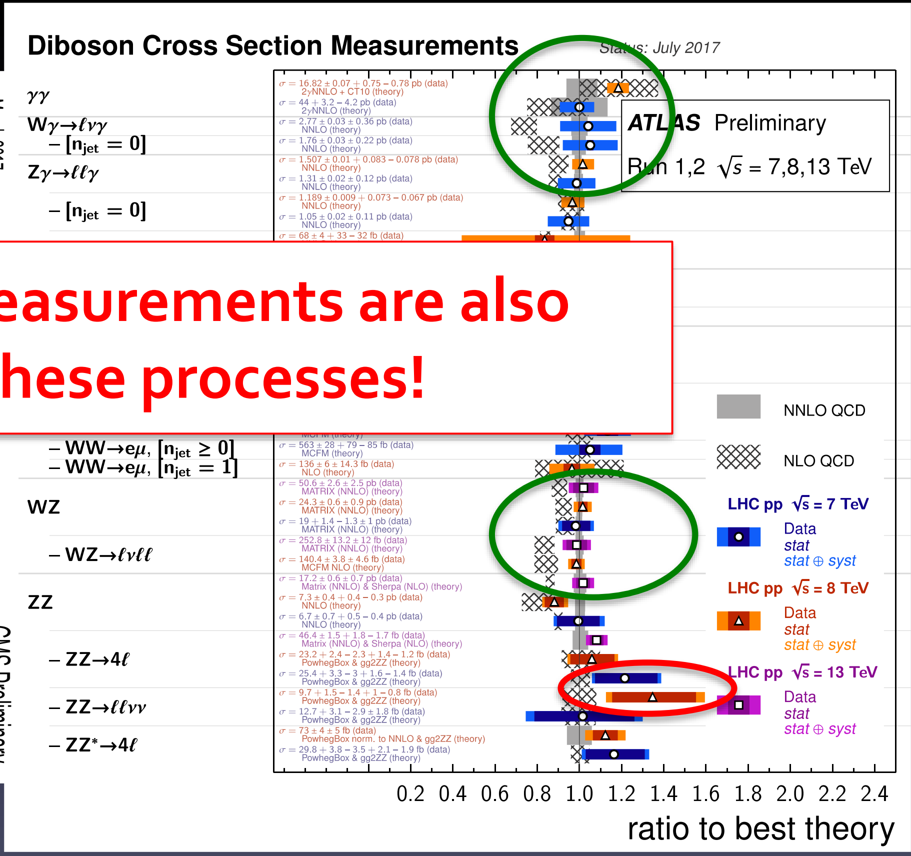




Diboson measurement results are challenging NLO predictions and mostly in excellent agreement with NNLO calculations

Data agree with the large shift in NNLO vs NLO
or
Comparable or more precise results than NLO predictions





Differential cross section measurements are also available for many of these processes!

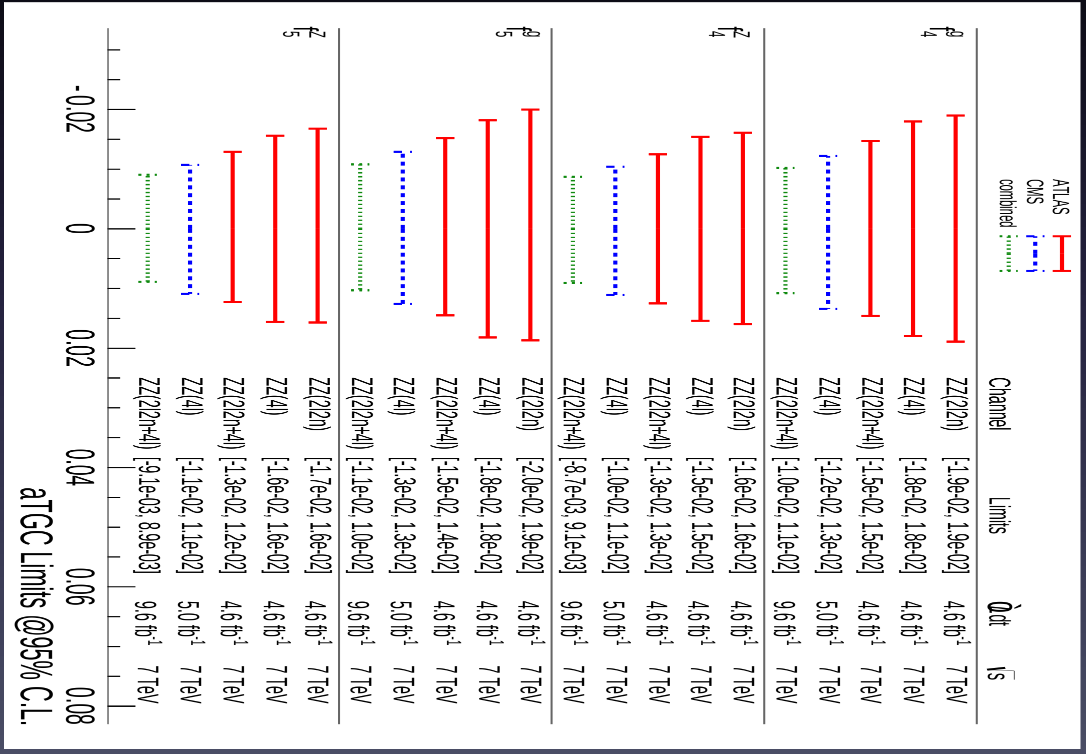
Tensions between predictions and data

Anomalous Triple Gauge Coupling

ATLAS-CONF-2016-036

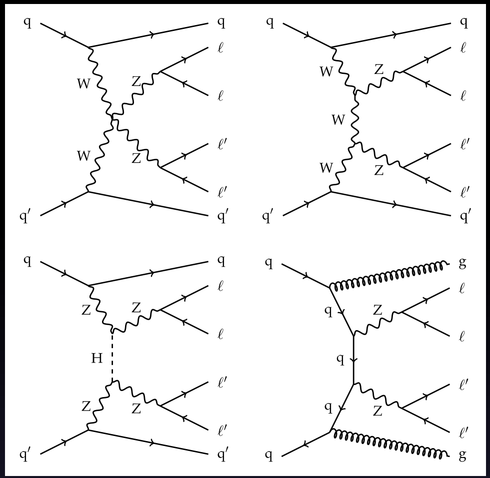
- Multiple coupling parameters to be constrained, depending on the higher-order effective operator considered
- Combined limits from ATLAS and CMS in the ZZ channel

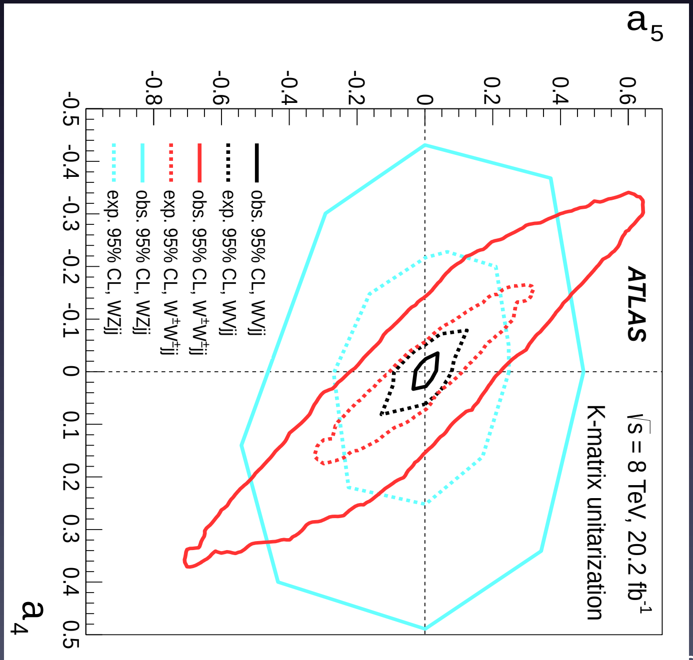
Coupling	Parameter	Channel
$WW\gamma$	$\lambda_\gamma, \Delta\kappa_\gamma$	WW, $W\gamma$
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta\gamma_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_4^Z, f_5^Z	ZZ
ZZZ	f_4^γ, f_5^γ	ZZ



Vector Boson Scattering

- It is a VBF process with a diboson final state
- It provides a unitarity test of the EWK sector
- No observation of a significant SM signal yet, but we are close to an observation
- BSM models enhance the signal with an anomalous aQGC
- Can be used to put limits on aQGC





Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.53	0.51	-0.46	0.44	2.5
f_{T1}/Λ^4	-0.72	0.71	-0.61	0.61	2.3
f_{T2}/Λ^4	-1.4	1.4	-1.2	1.2	2.4
f_{T8}/Λ^4	-0.99	0.99	-0.84	0.84	2.8
f_{T9}/Λ^4	-2.1	2.1	-1.8	1.8	2.9

arXiv:1708.02812

Phys. Rev. D96 (2017) 012007

Phys. Rev. D95 (2017) 032001

Phys. Rev. D93 (2016) 092004

Measurements of EWK parameters

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Weak mixing angle

Eur. Phys. J. C76 (2016) 325

CMS-PAS-SMP-16-007

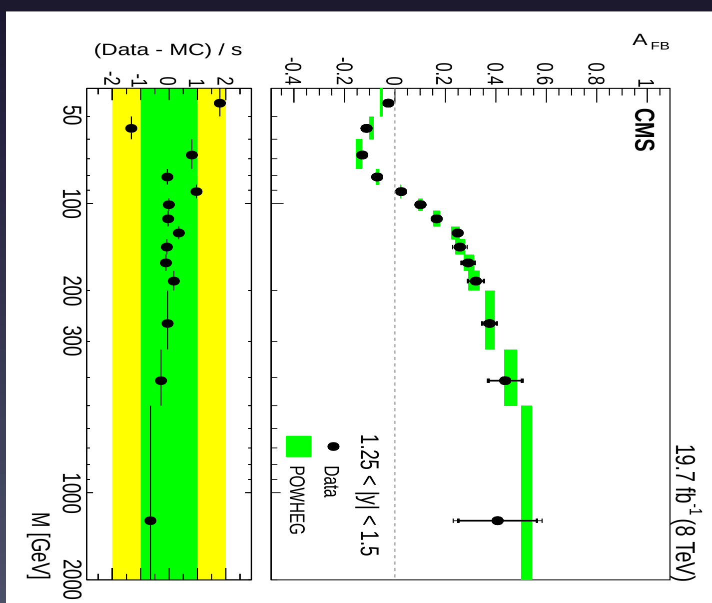
- $\sin^2\theta_W$ is measured using Forward-Backward asymmetry in Z events
  - Forward or backward events are defined in the Collins-Soper frame by:

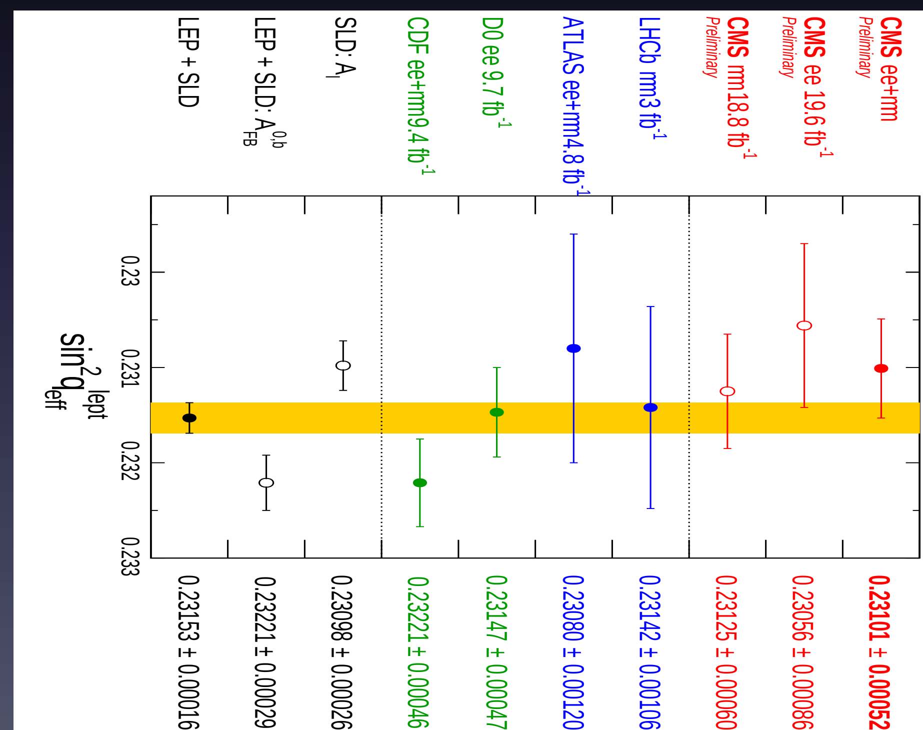
$$\cos\theta^* = \frac{2\left(p_1^+ p_2^- - p_1^- p_2^+\right)}{\sqrt{M^2\left(M^2 + P_T^2\right)}} \times \frac{P_Z}{|P_Z|}$$

  - The weak mixing angle is extracted using m_{ll} templates where the vector couplings of leptons to the Z boson are varied

$$v_f = T_3^f - 2Q_f \sin^2\theta_W$$

A_{FB} agrees well with predictions





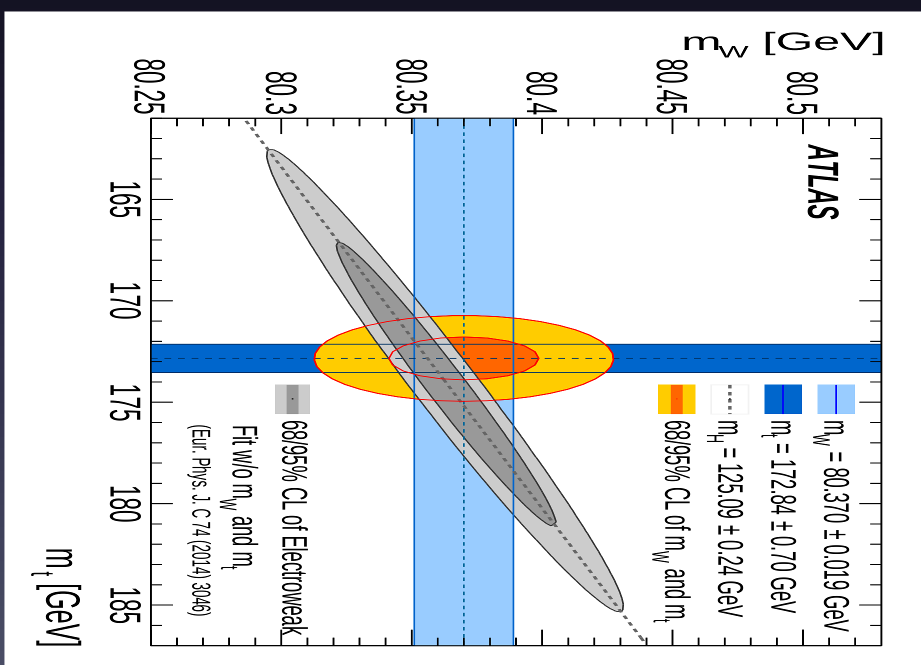
W mass measurement

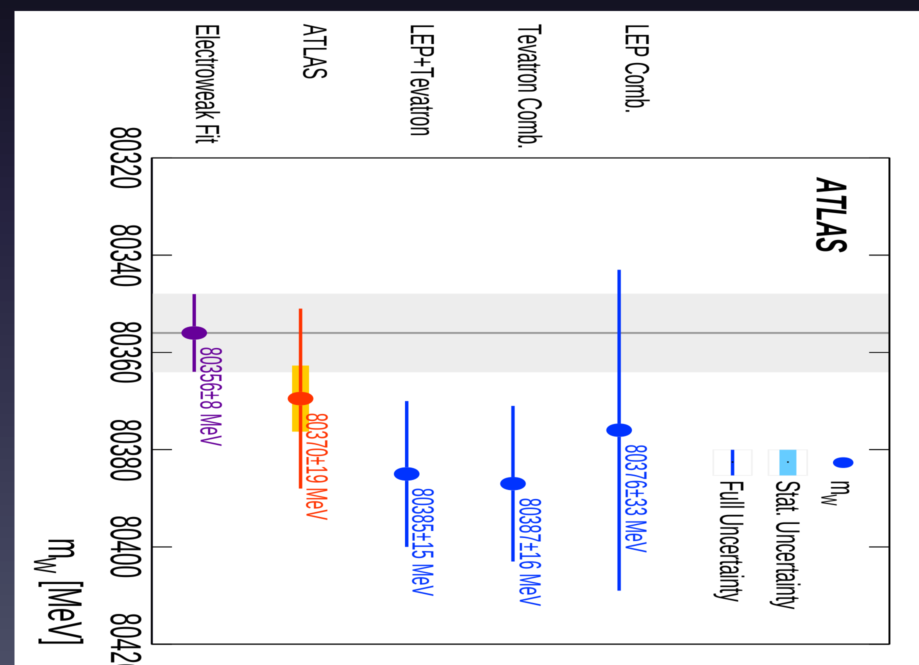
arXiv:1701.07240

- First LHC W mass measurement
  - Comparable in precision to CDF; better than any other measurements
  - Need several ancillary measurements to pin down the systematics
    - V pT, PDF, EWK, etc.
  - Will be more challenging at higher pile-up

$\delta m_W/m_W = 0.024\%$

m_W = 80370 ± 7 (stat) ± 11 (exp. syst.) ± 14 (modeling syst.) MeV





Conclusion

Conclusions

QCD and EWK are pervasive elements of particle physics:

- Subject of a variety of challenging experimental measurements… only a small subset has been shown
- Each measurement usually delivers an important message to the experimental and theoretical communities
- Comparison against state-of-the-art theory predictions
  - Tensions with predictions indicate where theoretical improvements are needed
  - Improved understanding of the proton, of soft and hard radiation, of gauge structure, and of anomalous couplings
- These measurements help reducing uncertainties, which improves search sensitivity to new physics

Mastering QCD and EWK is both essential for the future of the LHC program and for the advancement of our knowledge

Back-up slides

Focus of the presentation

- SM measurements focus on understanding the interactions rather than measuring the particle properties or explicitly looking for evidences for specific BSM scenarios
  - A model-independent approach to new physics
- It seeks maximal precision
  - Powerful approach to new physics when the background is large
- Multiple QCD phenomena:
  - PDF
  - Soft and hard parton emission
- Electroweak Measurements:
  - Gauge structure of EWK sector
    - Triple and quartic gauge couplings (and anomalous couplings)
  - Consistency test of SM

General measurement approach

- For such data to prediction comparison to be meaningful:
  - Background must be subtracted
  - Detector effects must be unfolded from data

$$\frac{d\sigma}{dO} = \frac{N_{data} - N_{bkg}}{L} U(O)$$

- The objective of such SM measurements is precision:
  - Measurement designed to minimize experimental errors
  - Dependence of measurement results on theory input is minimal
    - Fiducial cross section measurements
  - Well-defined quantities and final states
    - Define b-jets from B-hadrons and not b-quarks
- All systematic uncertainties with correlations must be assigned properly and taken into account in fits or in data-to-MC comparisons

More substantial introduction to theoretical QCD issues and needs for measurements

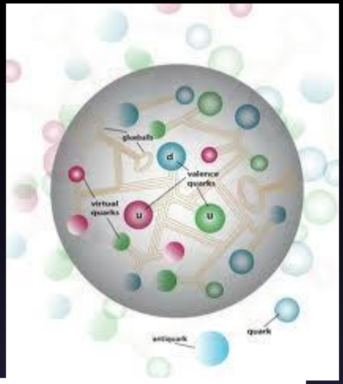
Issues with QCD (I)

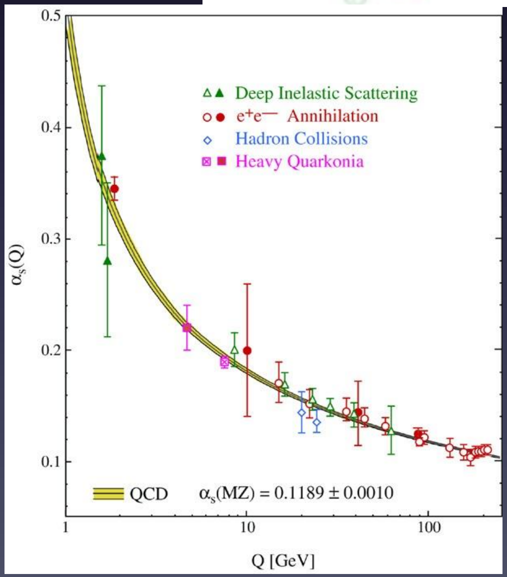
In quantum field theory, transition probabilities between initial and final states of interest can only be calculated perturbatively

Q: Is this a problem for the strong interaction given that hadrons / nucleons are strongly-coupled bound states ?

- Renormalization group equations tells how physics systems change when viewed at different scales

- For QCD, α_s evolves from being strong at low energy to be not so strong at high energy





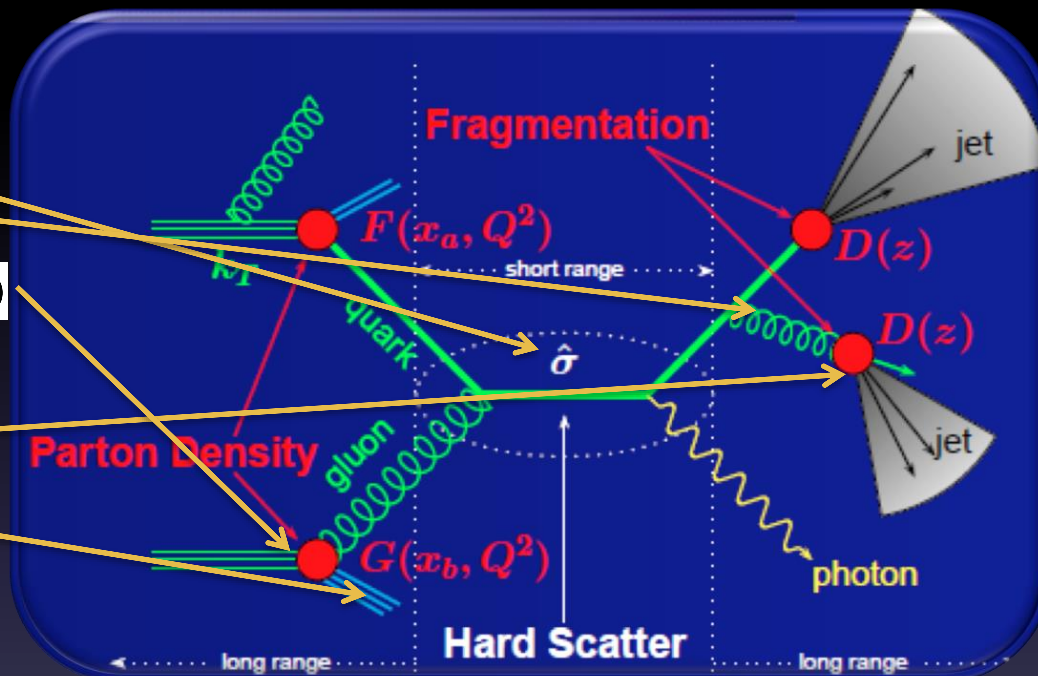
A: For distance scales probed at the LHC, quarks and gluons can be considered as free particles and physics processes involving them can be calculated using perturbation theory.

QCD predictions at very high energy are theoretically under control at the LHC

Issues with QCD (II)

The strong interaction intervenes in various ways and at various scales in an event

- Hard scatter
- QCD bremsstrahlung
- Parton density function (F, G)
- Fragmentation and hadronization $(D(z))$
- Multiple interactions



- Mo … d
  PD … rge
  dis …

Multiple scales are probed in any single events at the LHC!

Multiple scales are probed in any single events at the LHC!

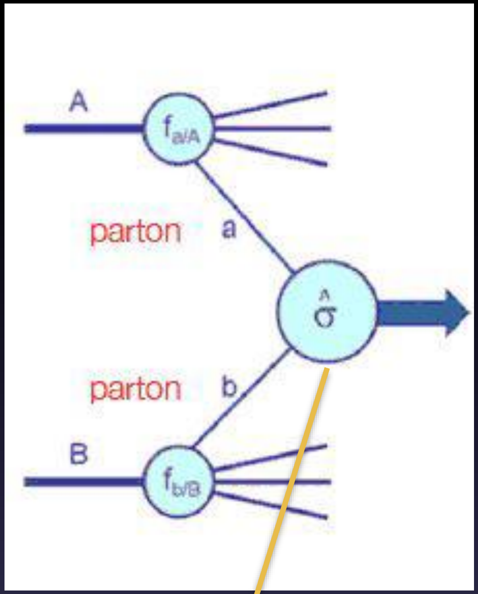
Issues with QCD (III)

There must be a solution, otherwise we wouldn't be doing HEP at hadron colliders since so long…

Factorization theorem:

Long distance and short-distance processes are incoherent: their probability amplitude factorize.

Low energy divergent behavior can be embedded into the factors describing large-distance physics



Predictions can be obtained from the convolution of short distance physics and a universal non-perturbative regime obtainable from data

$$\sigma(P_1,P_2) = \sum_{i,j} \int dx_1\, dx_2 f_i(x_1,\mu_F) f_j(x_2,\mu_F) \hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R\mu_F)$$

Allows for calculable predictions for many observables

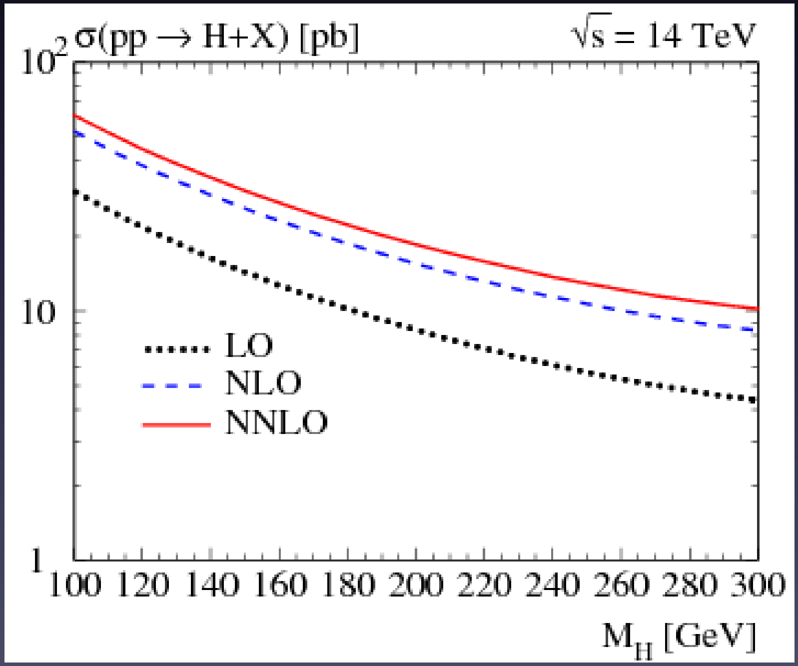
Need for higher order corrections (I)

- The key to make a discovery is to control systematic uncertainties and errors to maximize the sensitivity to the physics of interest and get convinced of the validity of a discovery.

Example:

Inclusive Higgs production cross section at 14 TeV

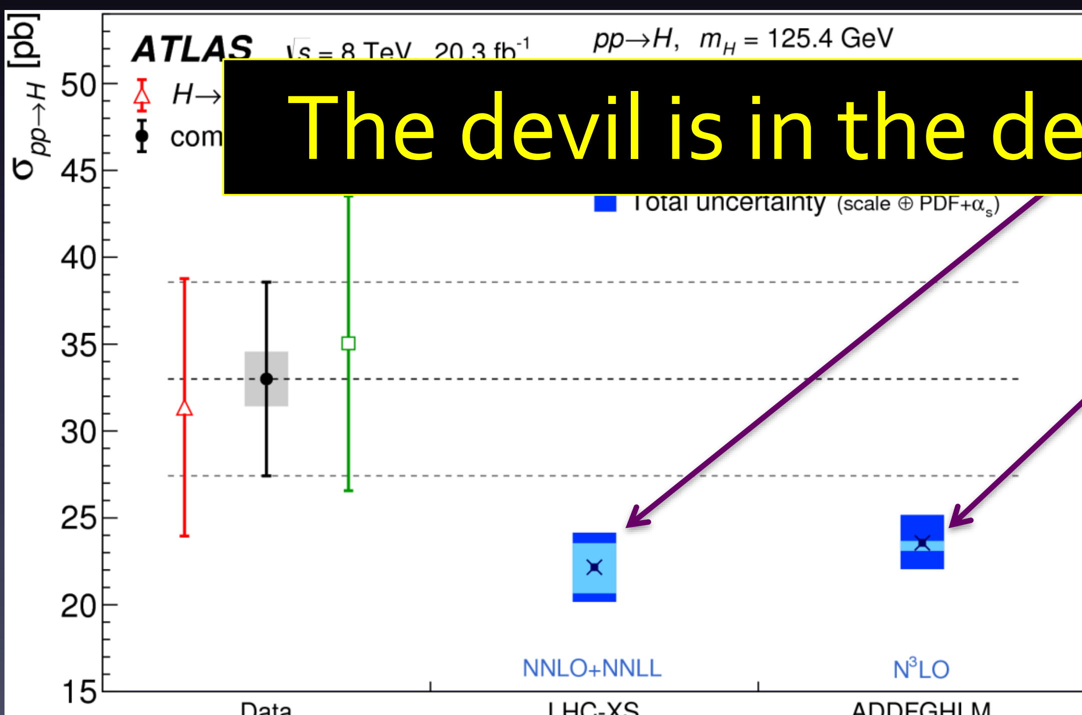
α_s is small at m_H, yet quantum corrections are large (NLO~75%, NNLO~30%)



- Higher order perturbative QCD corrections are very large for many Standard Model processes
  - Selections might promote a correction to be the main process of interest
  - Needed to be able to make claims for a new physics discovery

Need for higher order corrections (II)

- Higher order perturbative QCD corrections also contribute to significantly reduce the dependence of the predictions on the choice of factorization (μ_F) and renormalization (μ_R) scales
  - Largest uncertainties on cross section predictions



The devil is in the details

10% uncertainty
ted by μ_R/μ_F

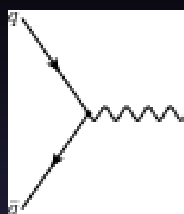
N3LO: 7% uncertainty dominated by PDF

In this example, the experimental uncertainties are larger than the theoretical ones, but they will be reduced, and most SM predictions are at most NLO

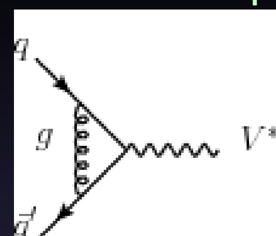
Potential problems (I)

- When selections are applied to optimize sensitivity to new physics or when distributions are being measured, higher order predictions in α_s are not necessarily the only key to precision

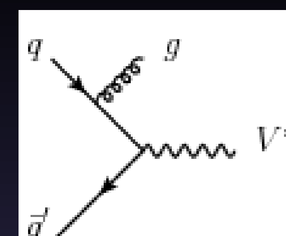
A <u>schematic</u> example: Consider Drell-Yan process when going from LO to NLO



V*

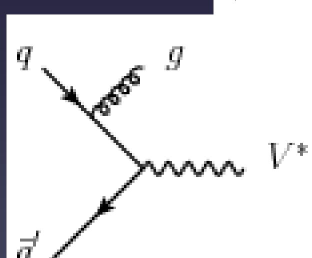


+



$$\left(\frac{d\sigma}{d\Omega}\right)_{NLO} \sim \left(\frac{d\sigma}{d\Omega}\right)\left[1 - \frac{\alpha_S}{\pi} f(Q^2)\log^2\left(\frac{Q^2}{\mu^2}\right) + \vartheta(\alpha_S^2)\right]$$

Finite prediction

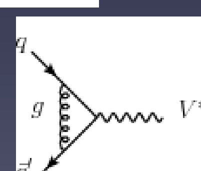


$$\left|m^{u\bar{d}\to Wg}\right|^2 \sim \left(\frac{\hat{t}^2 + \hat{u}^2 + 2Q^2\hat{s}}{\hat{t}\hat{u}}\right)$$

Diverges when E_g=0 or θ=0

(Q^2 is the virtuality of the W)

The exact same divergence occur in



but with opposite sign

Potential problems (II)

- From this calculation: fixed order calculations are of the form:

$$\frac{d\sigma}{dO} = \frac{d\sigma(W+0j)}{dO}\left[\alpha_S \log^2\left(\frac{Q^2}{\mu^2}\right)A_1 + \alpha_S^2 \log^4\left(\frac{Q^2}{\mu^2}\right)A_2 + \dots\right]$$

➡ The expansion is not anymore in a_S, but in $\alpha_S L^2$

- If μ^2 and Q^2, are very different, as expected if we separate large and short distance scales, the logs will be large and the perturbative expansion and unitarity will be compromised

- However, this is just an artifact of using fixed order calculation:

At higher order, processes such as W+1j, W+2j, etc., will follow the same rule, and the full sum at all orders should behave well:

$$d\sigma = d\sigma_0\left[1 + \alpha_S(a_{12}L^2 + a_{11}L + a_{10}) + \alpha_S^2(a_{24}L^4 + a_{23}L^3 + a_{22}L^2 + a_{21}L + a_{20}) + \dots\right]$$

Solution: resummation

- We can shuffle the terms and express the differential cross section as:

$$
\begin{aligned}
d\sigma &= d\sigma_0\left[1+\alpha_S L^2 a_{12}+\left(\alpha_S L\right)^2 a_{24}+\alpha_S L a_{11}\left(1+\alpha_S L^2\frac{a_{23}}{a_{11}}+\ldots\right)+\ldots\right] \\
&= d\sigma_0 \exp\left[\underbrace{L g_1(\alpha_S L)}_{\text{LL}}+\underbrace{g_2(\alpha_S L)}_{\text{NLL}}+\underbrace{\alpha g_3(\alpha_S L)}_{\text{NNLL}}+\ldots\right]
\end{aligned}
$$

- This procedure, called **resummation**, corresponds to an all-order evolution from large to small distance scales restoring the predictive power of pQCD and unitarity, similarly to the running of couplings
  - Equation used to evolve PDF : DGLAP equations
  - Ana … oss sections
  - Par … n to yield final sta…
  - Resummation at high-energy/small-x regime: BFKL approach

QCD contains all ingredients to address predictability issues at the LHC

A QCD program at the LHC (I)

- Huge theoretical progresses on QCD over the last decade
  - NLO revolution
    - Up to 5 partons in V+jets final states
    - Approximate NNLO for V+j; approximate N^{3}LO for Drell-Yan
  - NNLL resummation
  - NLO ME+PS matching/merging
  - NNLO PDF and lattice QCD
- However, the above QCD calculations cannot be exact, but involve assumptions, approximations, and phenomenological modeling impacting predictions
- The sources of uncertainty related to the modeling of various QCD e
  - PDF
  - Parton shower and matching
  - Infrared sensitive predictions
  - Electroweak corrections

The QCD prediction tools need some "tuning" or adaption in order to address concerns in broader range of situations

A QCD program at the LHC (II)

Below are a few examples of QCD modeling impacting differential cross section and specific event selection predictions

Parton showers model parton evolution through gluon emission and splitting, while resummation is limited to specific predictions:

- Soft and collinear approximations (where QCD radiation is enhanced)
- Leading order kernel functions
- Choice of ordering parameter

Parton distribution function (PDF):

- Uncertainties on measurements used to extract structure functions
- Modeling of structure functions at Q_0 $\quad F(x,Q_0) = A_1 x^{A_1}(1-x)^{A_2} P(x;A_3)$

Fragmentation function:

- Gaussian modeling of D(x,s) at small x
- Supplemented by hadronization model

$$D(x,s) \propto \exp\left[-\tfrac{1}{2\sigma^2}\left(\xi - \xi_p\right)\right]$$

$$\xi \equiv \ln\left(\tfrac{1}{x}\right), \quad \xi_p \cong \tfrac{1}{4}\ln\left(\tfrac{s}{\Lambda^2}\right),$$

$$\sigma \propto \left[\ln\left(\tfrac{s}{\Lambda^2}\right)\right]^{3/4}$$

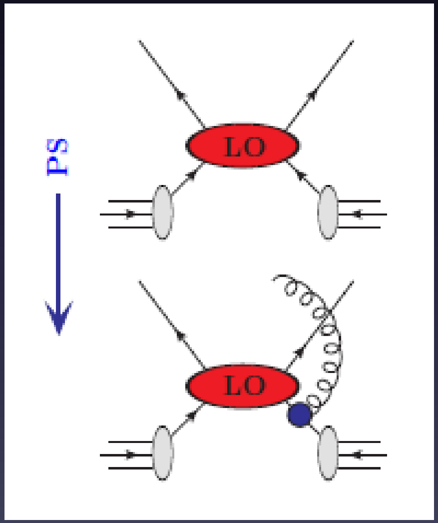
A QCD program at the LHC (III)

- While for some predictions the above QCD modeling can be accurate enough for a successful LHC physics program, there are event selections used in BSM searches in which they could be questioned:
  - Very high jet multiplicity
  - Multiple scales in the same event, such as very different jet p_T selections
    - Require sophisticated interplay between matrix element and resummation
  - Selections based on observables sensitive to soft radiation
    - E.g. Variables used to obtain Vector Boson Fusion –like final states
  - Gluons splitting in heavy-flavor quarks
- We can use LHC data to constrain QCD calculations. Measuring observables sensitive to the various effects pointed above allows to:
  - Determine best model/calculations for predictions
  - Tune fragmentation and parton shower parameters

Various level of predictions (I)

MC generators are the test benches of the various progresses made on the modeling of the different QCD effects over the past years

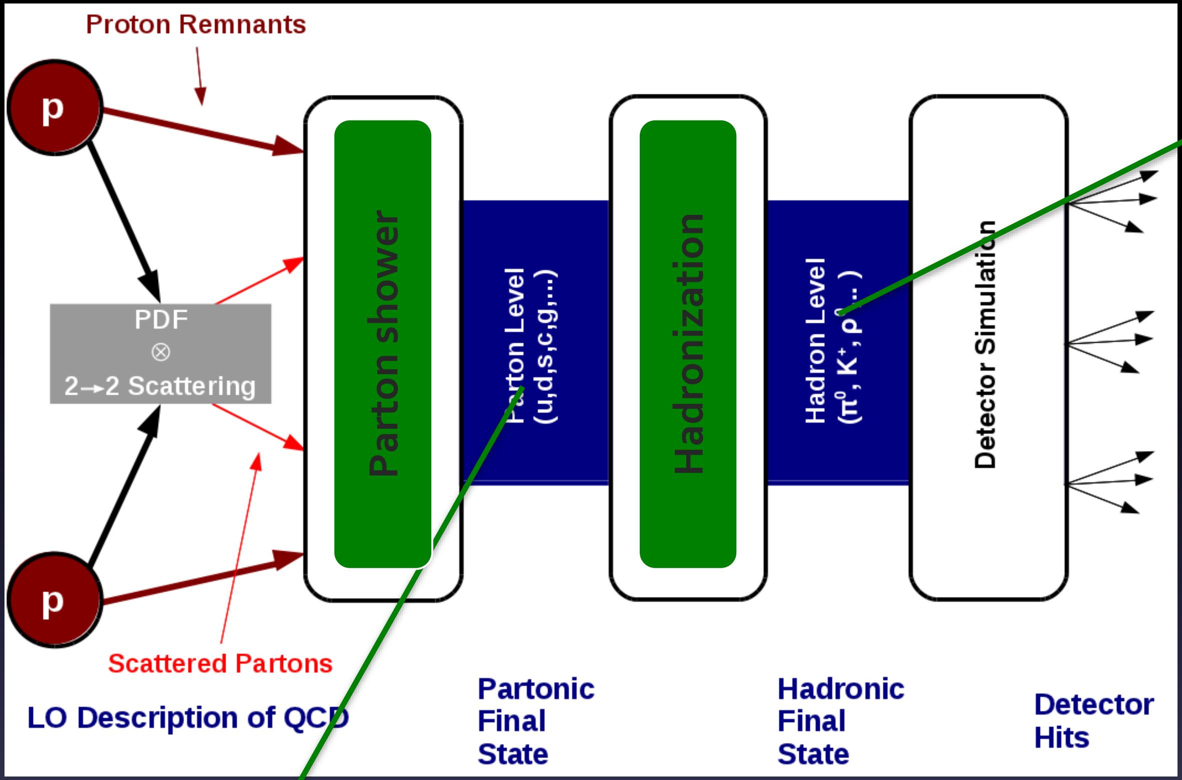
LO ME +PS → **Pythia (6, 8), Herwig**



These generators incorporate different modeling of QCD corrections

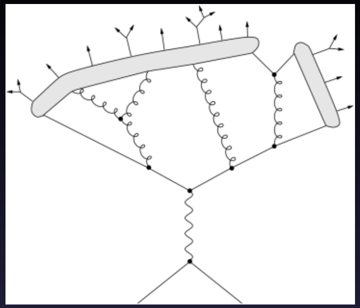
- Leading Order Matrix Element calculations
- Soft and collinear emission corrections integrated in a parton shower model
- Fragmentation and hadronization
- Underlying event

Pythia (8.175) vs Herwig++ (2.63)

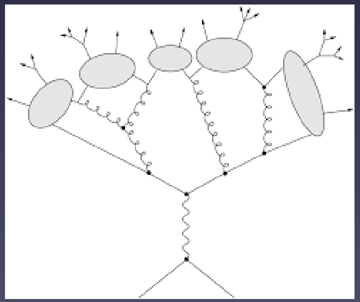


Hadronization:

Pythia: Lund string
(linear confinement)



Herwig: Cluster
(preconfinement)

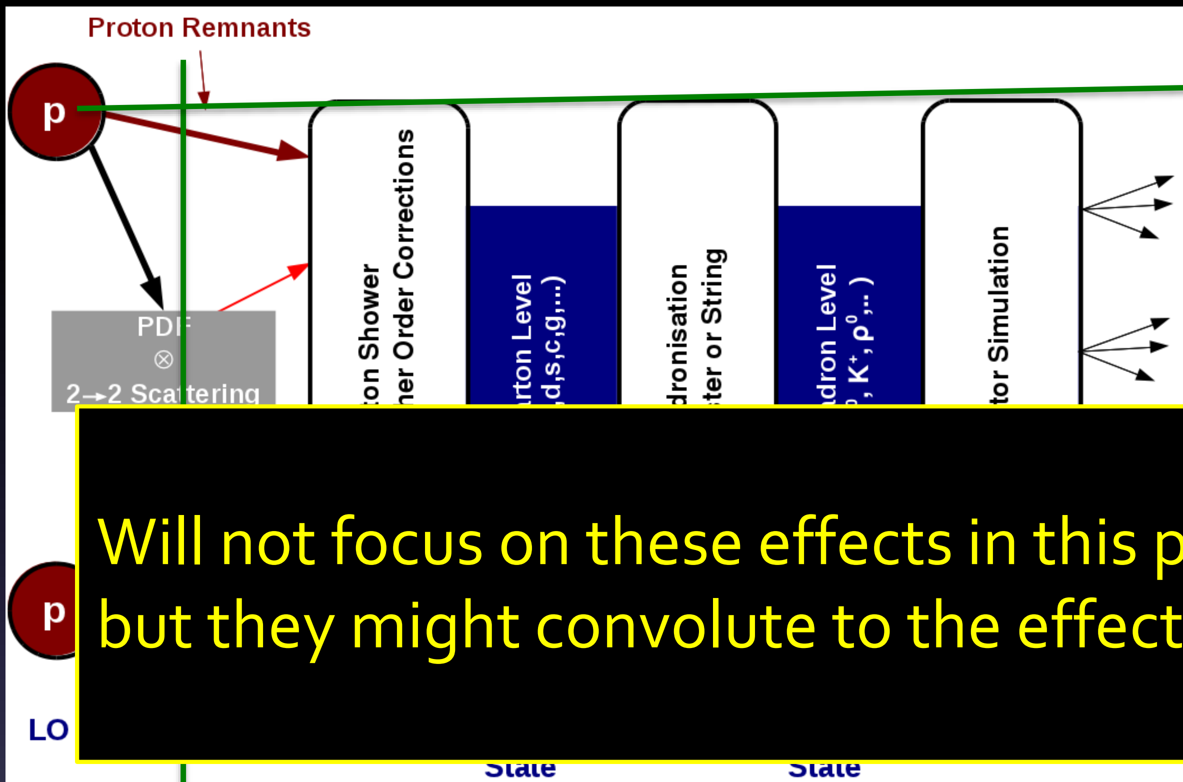


Showers ordering:
(nLL resummation)

Pythia: p_T ordering
(natural for a shower partly based on dipole approach)

Herwig: angular ordering
(deal with quantum interference)

Pythia (8.175) vs Herwig++ (2.63)



PDF:

Different PDFs can be used in generators, but there is the question of the compatibility

of

atrix

Will not focus on these effects in this presentation, but they might convolute to the effects of interest

Multiple interactions:

(Each generator is tuned for different PDF on Run-1 ATLAS data)

Pythia: AU2 & A14 tunes

(Many parameters)

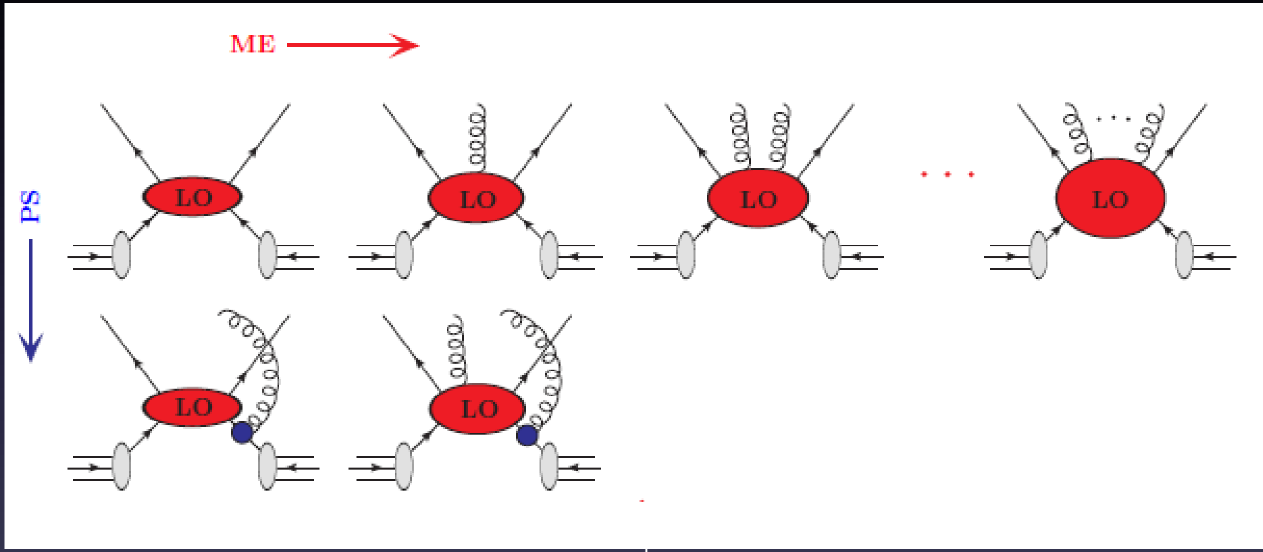
Herwig: EE3-EE5 tunes

(Fewer parameters)

Various level of predictions (II)

MC generators are the test bench of the various progresses made on the modeling of the different QCD effects over the past years

Tree-level multiple parton ME +PS → **Alpgen, Sherpa 1.4, MadGraph**



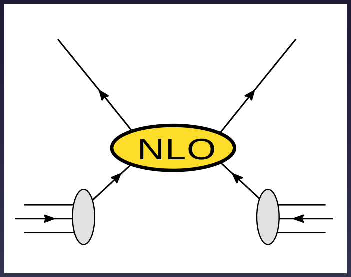
Again, different modelings of QCD corrections

- A **matching** procedure is needed to avoid the double counting of ME and PS partons
  - E.g.: MLM cone vs CKKW
- Alpgen and MadGraph interfaced to Pythia or Herwig
- Sherpa has its own PS+Had

Various level of predictions (III)

MC generators are the test bench of the various progresses made on the modeling of the different QCD effects over the past years

NLO multi-parton ME → **MCFM, BlackHat**



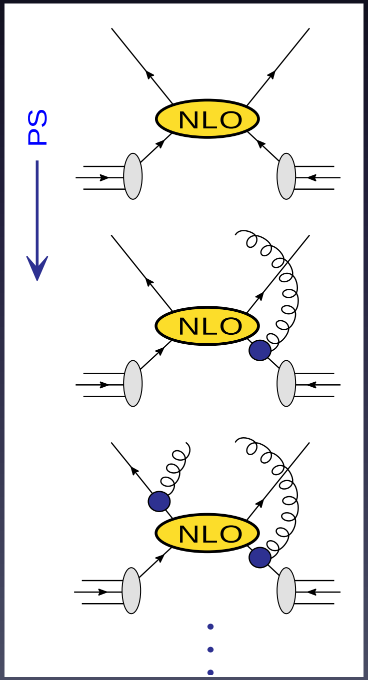
Differences in the matrix element calculations

- An NLO cross section for N=1,…5 partons
- Different calculation techniques
  - Feynman graphs: MCFM (up to 2 partons)
  - Unitarity: BlackHat (up to 5 partons)
- **No PS, had, or UE corrections**
- Need some kind of sum rules for inclusive final states
- NNLO:
  - Drell-Yan = FEWZ, DYNNLO
  - N_{jetti}NNLO: Z+jets, Loopsim: Approximate V+j

Various level of predictions (IV)

MC generators are the test bench of the various progresses made on the modeling of the different QCD effects over the past years

NLO ME for lowest multiplicity +PS → **POWHEG, MC@NLO MadGraph**



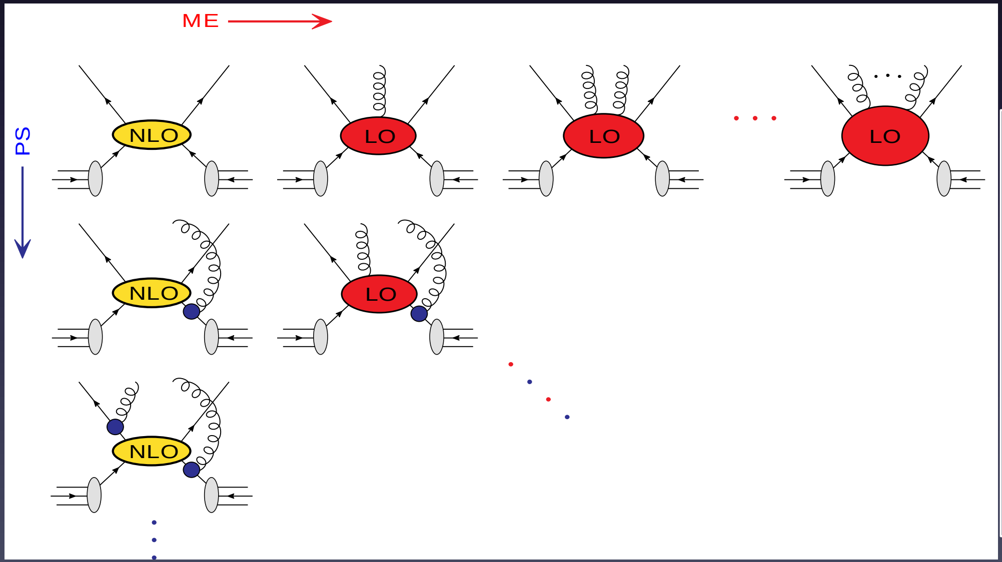
- Different merging procedures
- Interfaced to Pythia or Herwig for PS, had and UE
- MadGraph goes up to 2-jets at NLO

These generators incorporate different modeling of QCD corrections

Various level of predictions (V)

MC generators are the test bench of the various progresses made on the modeling of the different QCD effects over the past years

NLO ME for low multiplicity, LO for others + PS → **Sherpa 2.1 (MEPS@NLO),**

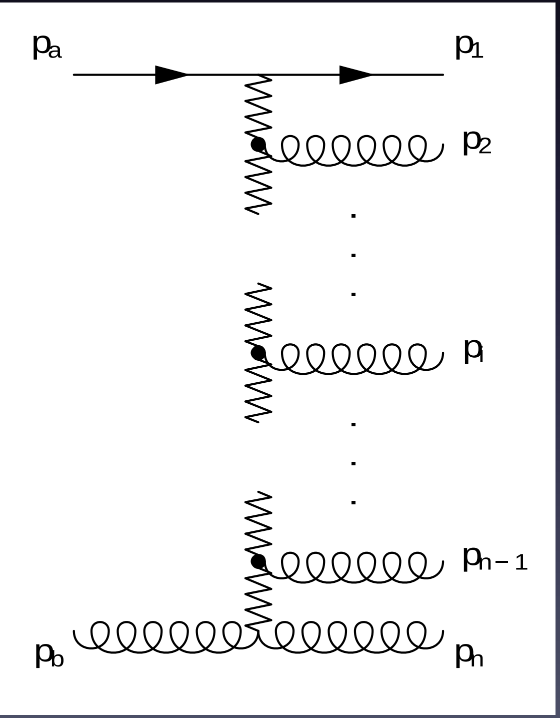


- MEnloPS:
  - NLO inclusive cross section
  - Normalization at NLO accuracy
- MEPS@NLO:
  - NLO for 1 and 2 partons
  - LO + PS for higher multiplicity
  - State of the art for V+jets

Various level of predictions (VI)

MC generators are the test bench of the various progresses made on the modeling of the different QCD effects over the past years

Resummation → **Resbos, HEJ**



- Resum large logs at all orders in α_s
  - Extend validity of perturbation theory
  - Improve normalization and shape
  - Analytical functions for Leading Logs, etc
- Low energy regime: Resbos (NNLL)
  - Logs from IR and collinear parton emission
- High Energy Regime: HEJ
  - Large invariant mass between jets
  - Approximation which captures hard wide-angle emission
  - BFKL-inspired

Generators used and tested

Non exhaustive list

Generator	Interfaces	Comments
ALPGEN	HERWIG+ JIMMY, PHOTOS, CTEQ6L1, AUET2 tune	mP- ME up to 5 parton, MLM matching
SHERPA	CTEQ6L1, Default UE tune	mP-ME up to 5 parton, CKKW matching; also NLO
PYTHIA	PHOTOS, MRST 2007 LO	LO ME+PS+Hadronization
MadGraph	Pythia 8.2 , NNPDF23NLO	4-jet tree-level +PS or 2-jet NLO+PS, CKKWL matching/FxFx merging, A14 PS tune
BLACKHAT*+SHERPA	CTEQ6.6M	NLO up to 5-jets (unitarity)
POWHEG	PYTHIA	NLO+PS (1-jet)
MC@NLO	HERWIG	NLO+PS
DYNNLO*		NNLO Drell-Yan
LOOPSIM*		nNLO W/Z+jets

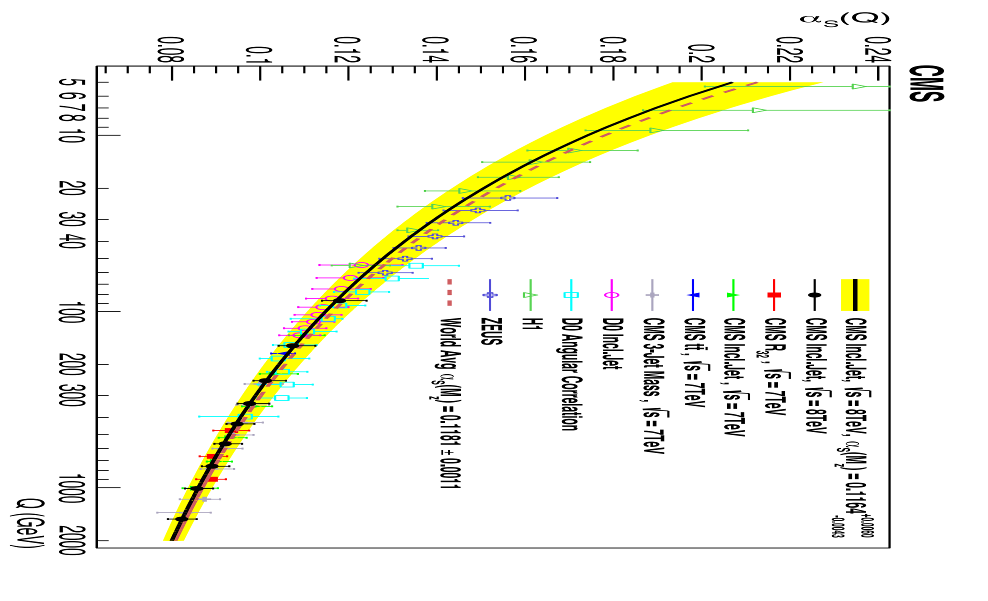
Complements on measurement results

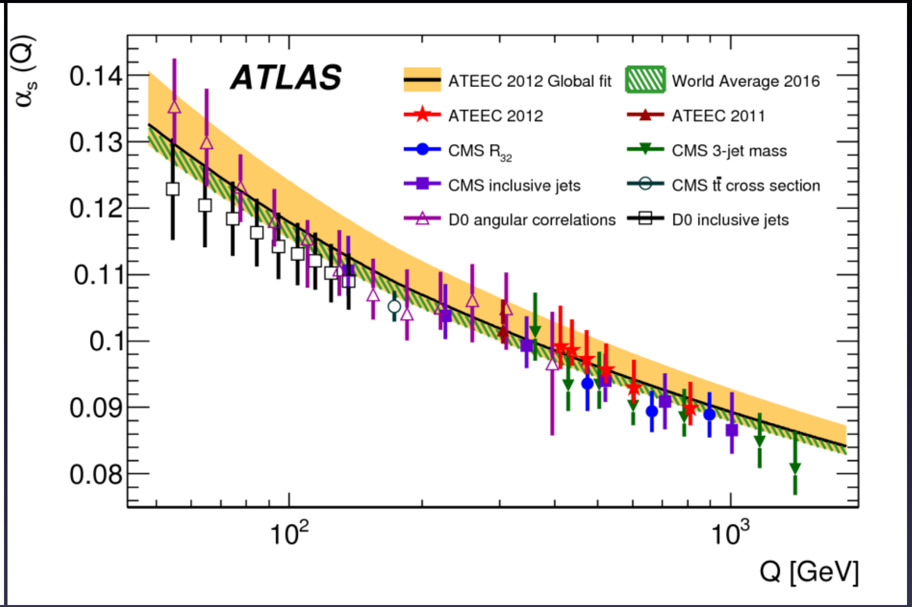
Measurements of α_s

JHEP 03 (2017) 156

arXiv: 1705.02628

- Precision on α_s impact all pQCD predictions from ME to PS and PDF
  - Test of Renormalization Group Equation at large scales
  - Can be precisely measured in multijet events at different scales





Analysis		$a_S(M_Z)$	Exp. error	Theo. error
Inclusive jets	CMS	0.1164	+/- 0.0015	+0.0059 / -0.0040
3D jet x-sec.	CMS	0.1199	+/- 0.0015	+0.0031 / -0.0020
TEEC	ATLAS	0.1162	+/- 0.0011	+0.0076 / -0.0061
ATEEC	ATLAS	0.1196	+/- 0.0013	+0.0061 / -0.0013

Vector Boson ϕ^*

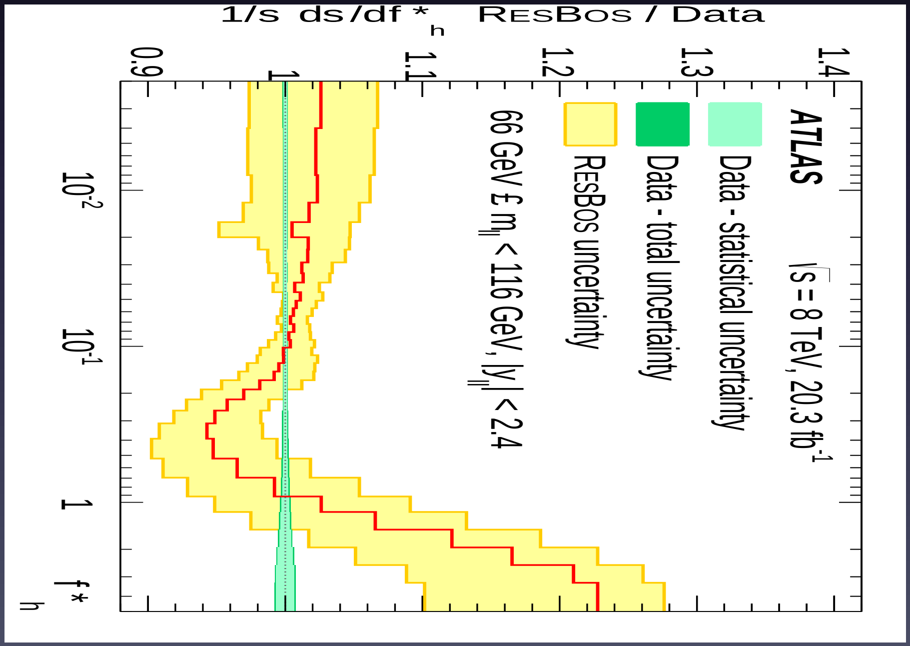
- Complementary physics can be obtained by measuring Z ϕ^*
  - Finer resolution (bin) at low P_T^Z
  - Smaller systematic
    - From 0.1% to 0.6%
    - 2% to 6% for theory

$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta_\eta^*)$$

$$\cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

- Depend solely on angle of two leptons
- Highly correlated to P_T^Z/M_{ll}
  - $0 < \phi^* < 1 \Leftrightarrow P_T^Z < 100$ GeV

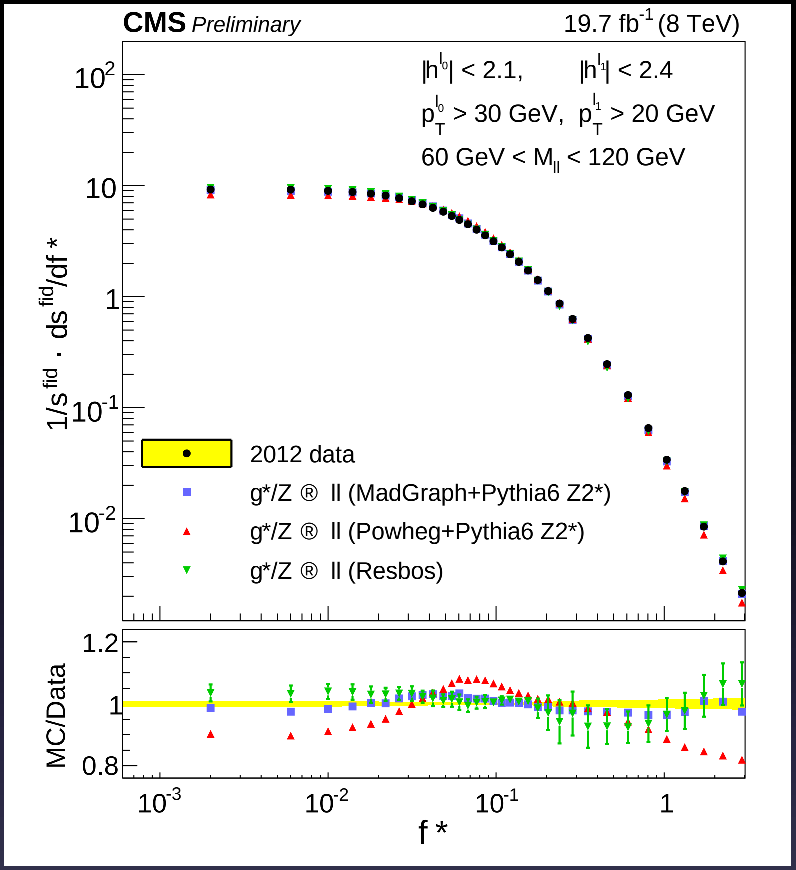
- Soft-gluon resummation (RESBOS) again provides a very good description of data in regimes where hard parton emission is not significant
  - Smaller uncertainties
  - Finer resolution
  - ϕ^* is ideal for tuning

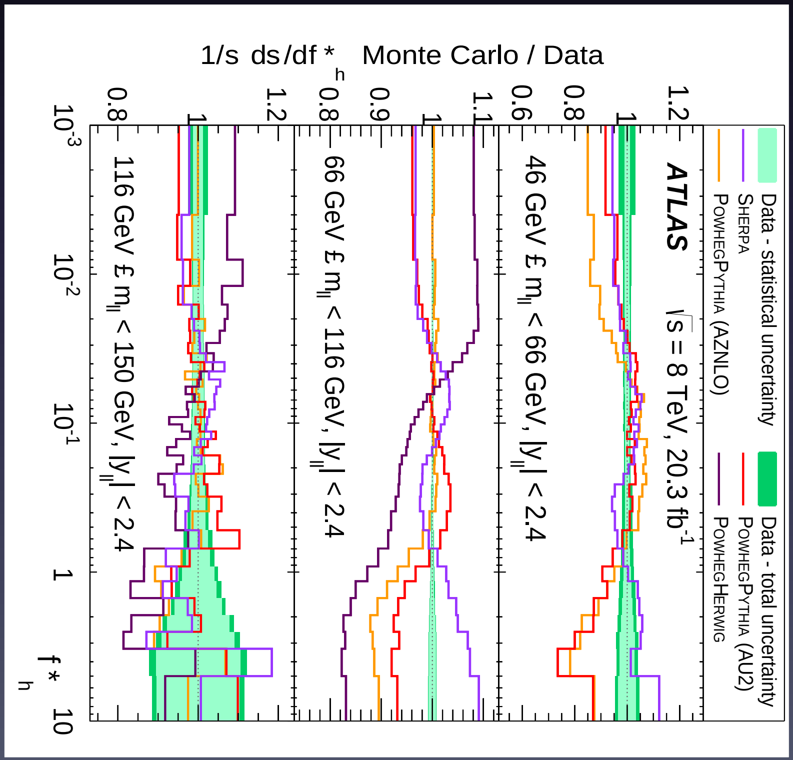


Vector Boson ϕ^*

CMS-PAS-SMP-15-002

- Parton shower approach to soft radiation can also provides a good description of low to average ϕ^* values
  - But high sensitivity to PS model or tuning

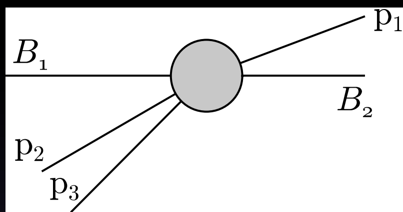




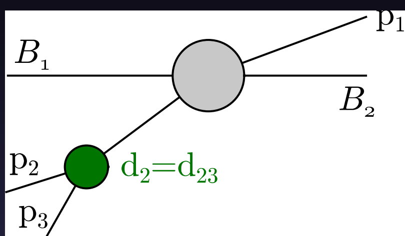
- ME hard parton emission better describes large ϕ^* or P_T values
- Sensitivity to merging or matching of ME to PS

k_T steps

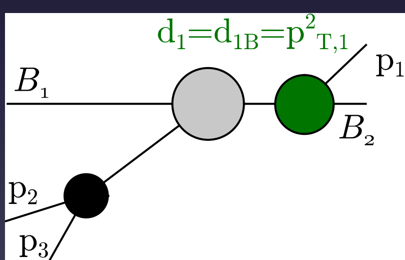
Illustration of the kt clustering sequence starting from the original input configuration (three objects p1, p2, p3, and beams B1, B2). At each step, k+1 objects are merged to k



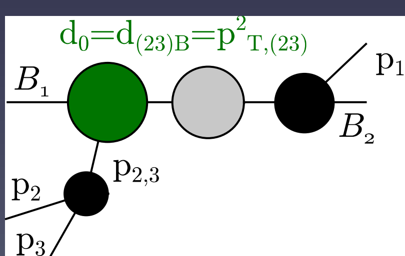
Initial situation



The min(d_{ij},d_{ib}) is between p_2 and p_3:
The two particles are merged and the new object is the sum of the two 4-vectors



The min(d_{ij},d_{ib}) is between p_1 and B_2:
p_1 is defined as a jet



The min(d_{ij},d_{ib}) is between p_{23} and B_1:
p_{23} is defined as a jet

EWK radiation corrections

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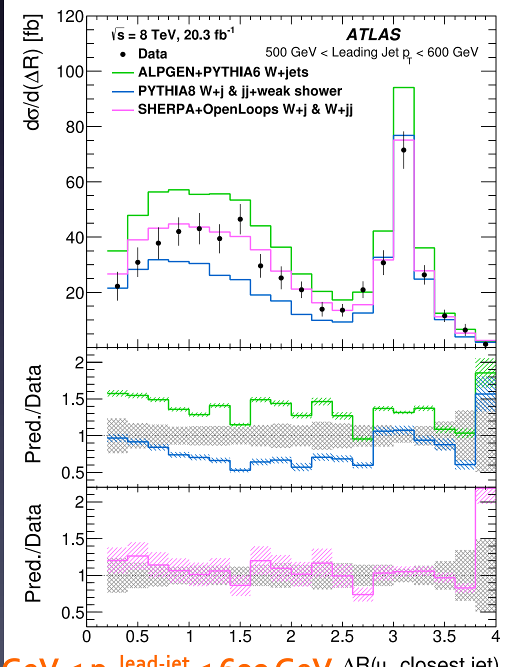
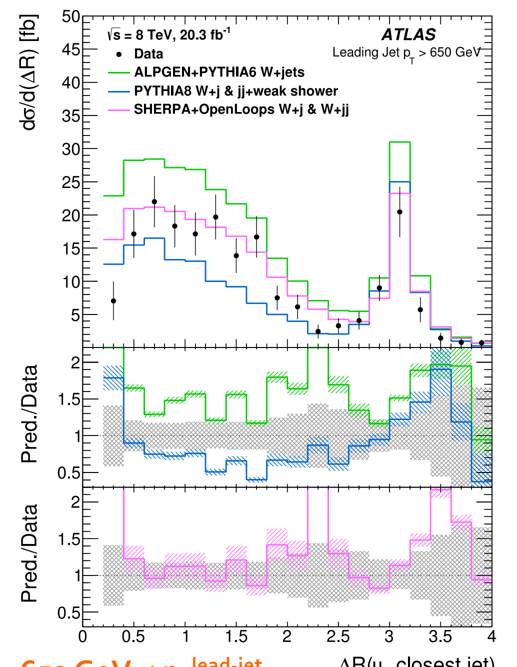
- At large momentum, dijet real emission of W is expected to have a large contribution to W+2-jets events when W and jets are collinear
  - Contribution scales as $O(\alpha \ln^2(p_{T,j}/m_W))$
- EWK predictions can be tested with a ΔR(muon-jet) measurement
  - Pythia 8.21: Both W+1-jet ME and dijet+EWK PS, all at tree level
  - Sherpa incorporates both NLO QCD and EWK corrections



500 GeV < $p_T^{\text{lead-jet}}$ < 600 GeV



650 GeV < $p_T^{\text{lead-jet}}$

Results:

- Collinear emission enhanced at large $p_{T,j}$
- Tree-level W+jets doesn't model normalization, and shape at low ΔR
- EWK PS is not enough
- Important to get QCD right
- Not clear if EWK is well-modeled

TEEC and ATEEC

- Energy dependence of event shape variables (thrust, sphericity) have high sensitivity to pQCD effects widely studied at LEP
- Energy-Energy Correlations (EEC) consist in the energy-weighted angular distribution of hadron pairs, and are infrared safe.
    - At hadron colliders, only the transverse energy-weighted angular distribution (TEEC) can be measured
    - The asymmetry between the forward and backward part of TEEC can also be measured (ATEEC).
    - The observables are suitable for precise tests of pQCD
        - With a quadratic dependence at NLO on α_s TEEC and ATEEC can be used to measure at different scale and RGE can be used to run it to M_Z.

TEEC:

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

ATEEC:

$$\left.\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\right|_{\phi} - \left.\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\right|_{\phi-\pi}$$

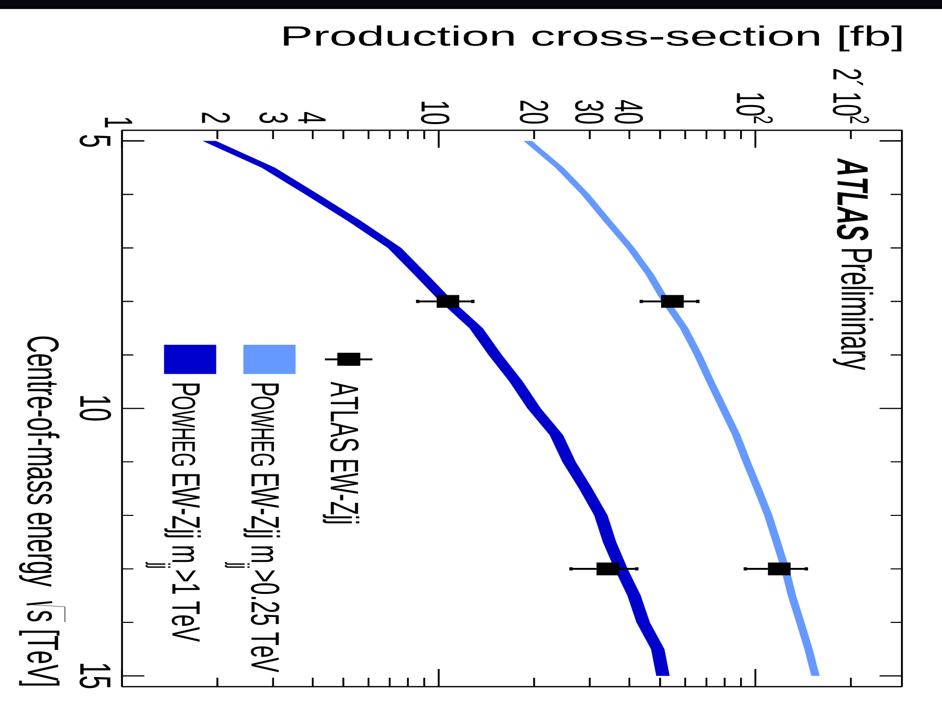
N: events in a cosϕ bin,
ij :jet pairs, ϕ_{ij} is ϕ_j-ϕ_i

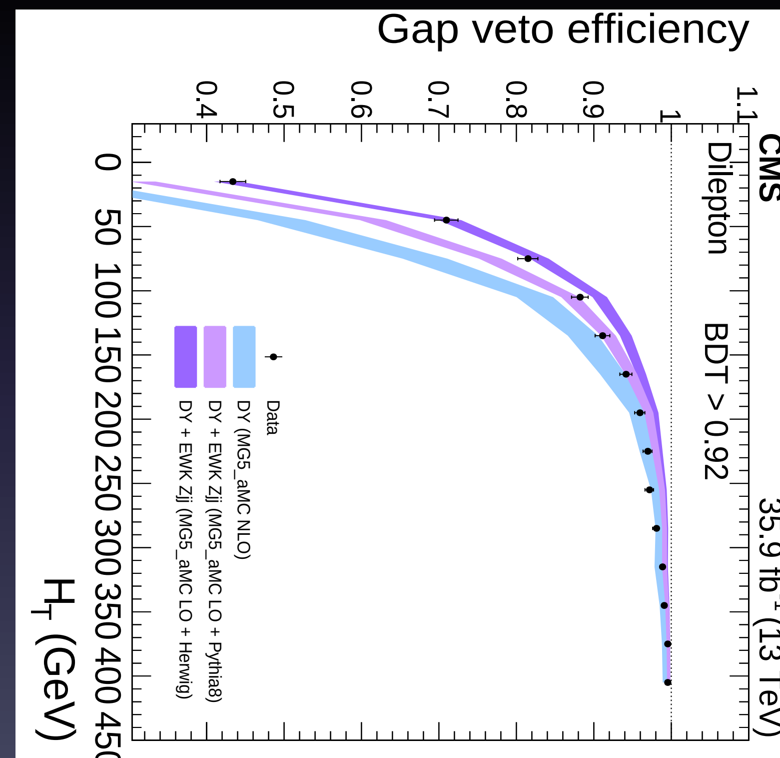
New Z VFB results

CMS-PAS-SMP-16-014

Public plots

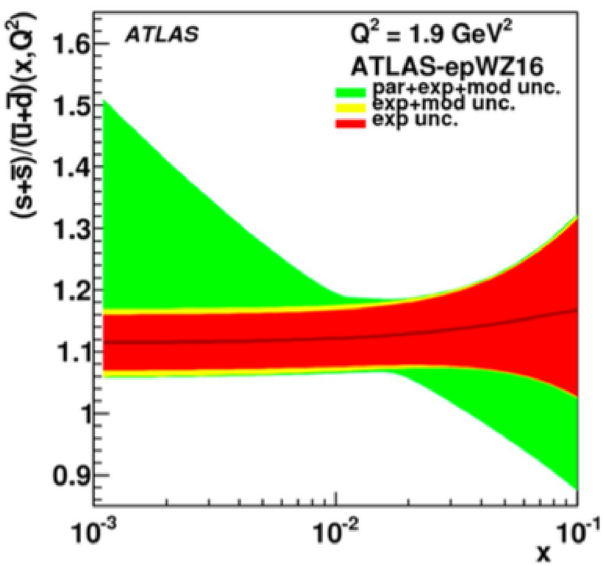
- EWK processes have also been probed in Zjj events in both ATLAS and CMS

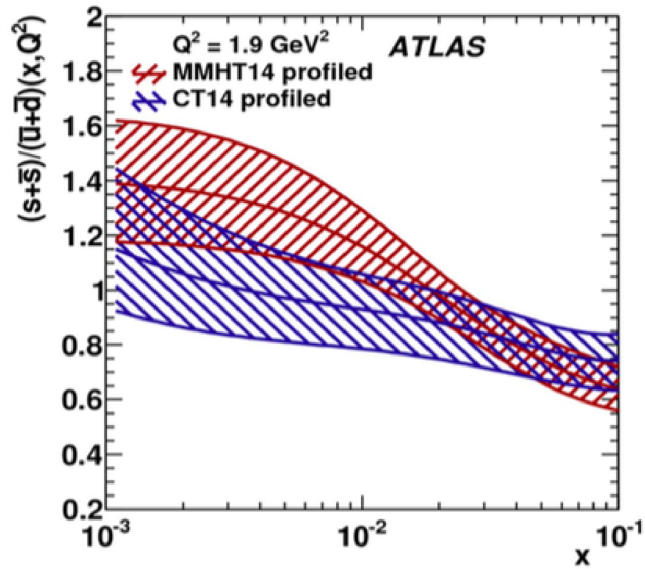




On s-quark PDF fit (I)

- Is that the ATLAS interpretation of the enhanced strangeness an artefact of a too restrictive parametrisation of the ATLAS PDF Set?





- Several Cross-Checks are already published in the 7 TeV W/Z high precision analysis (https://arxiv.org/abs/1612.03016):
  - We relaxed our parameterization and tested several variations, e.g. by freeing the low-x strange parameter Bsbar; this leads to the green band (leftplot), still showing enhanced strangeness at x=0.01
  - We profiled other PDF-sets (MMHT14, CT14) with different parameterization assumptions to the ATLAS W/Z 7 TeV Data. Both profiled PDF-Sets lead also to an enhanced strangeness (right plot).

On the s-quark PDF fit (II)

- Moreover, we tested
  - the sensitivity to the assumptions on the low-x behavior of light-sea quarks
  - the impact of adding measurement of the E866-experiment at x=0.1 to the ATLAS fit

  both tests lead to a consistent result of enhanced strangeness

- The W/Z precision measurement at 7 TeV is not the only measurement that suggests an enhanced strangeness
  - The ATLAS measurement of W+c production at 7 TeV (https://arxiv.org/abs/1402.6263) predicts a strange to down-sea quark ratio of 0.96 (see plot)
  - It should be noted that this is a fully independent measurement