

# DIS2018, Kobe, Japan

## WG4 summary: QCD+EW

Emanuele Re,  
Sadaharu Uehara,  
Mikko Voutilainen

# Theory results

- **Higher-order perturbative QCD at work:**

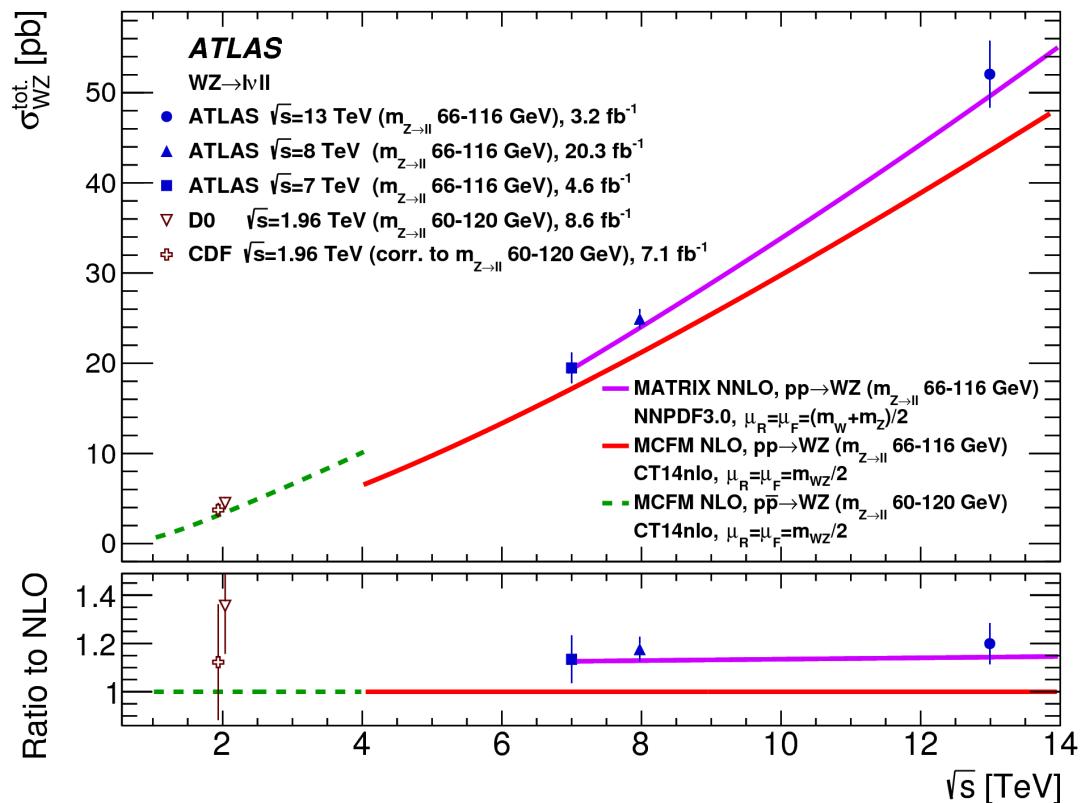
- ▷ Jets at the LHC
- ▷ Drell-Yan and Higgs distributions

- **The strong coupling:**

- ▷ status and new ideas

- **Monte Carlo event generators**

- Please follow links to talks for more details and references to papers
- Giving only a taster of all new results, much more in original talks



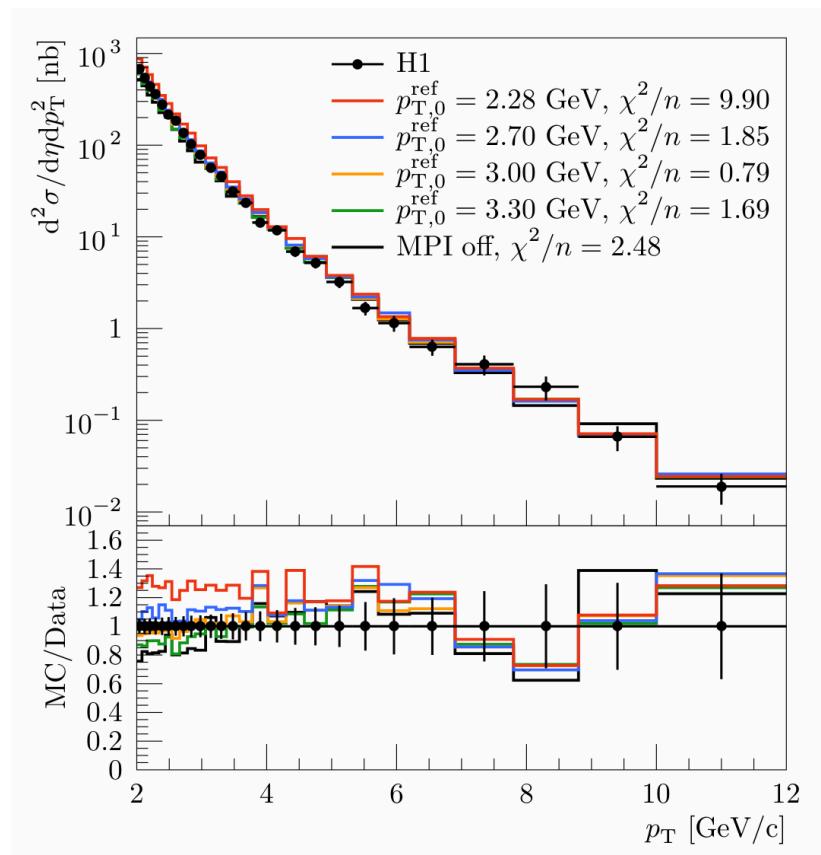
[Link to agenda](#)

# Monte Carlo generators

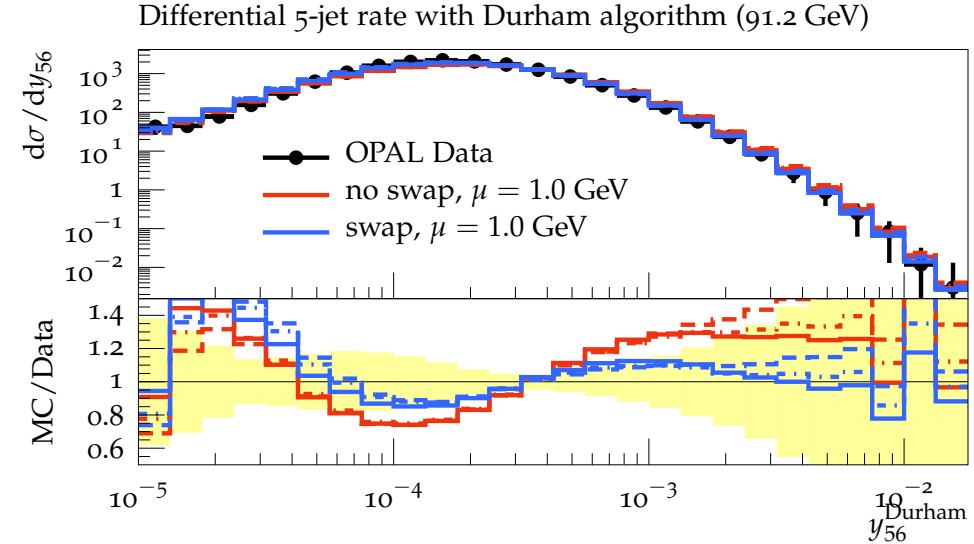
- essential for  $\sim$  all EXP analysis: need to keep up with EXP accuracy.

- photoproduction in **PYTHIA8**
- charged particle  $p_T$  at HERA: MPI probability for  $\gamma p$  between  $\gamma\gamma$  and  $pp$

- **Herwig7**: colour rearrangement for Dipole Showers
- better agreement with LEP data, now moving towards DIS



I. Helenius



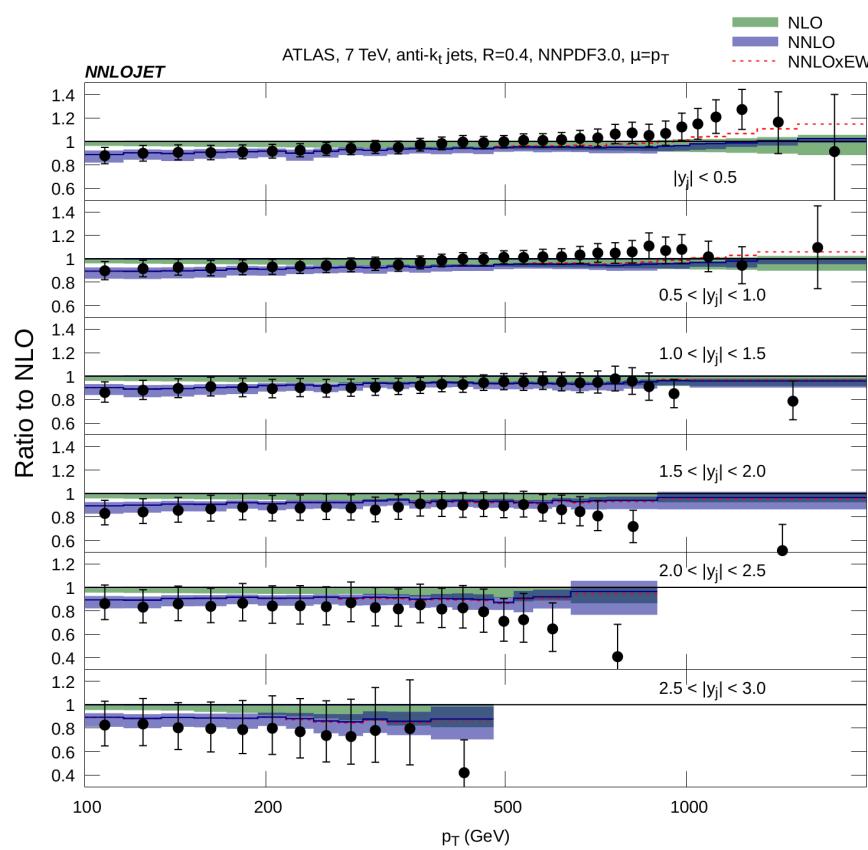
J. Bellm

- (N)NLOPS matching & merging / formal accuracy of PS  
[talk by E. Re + plenary by R. Frederix]

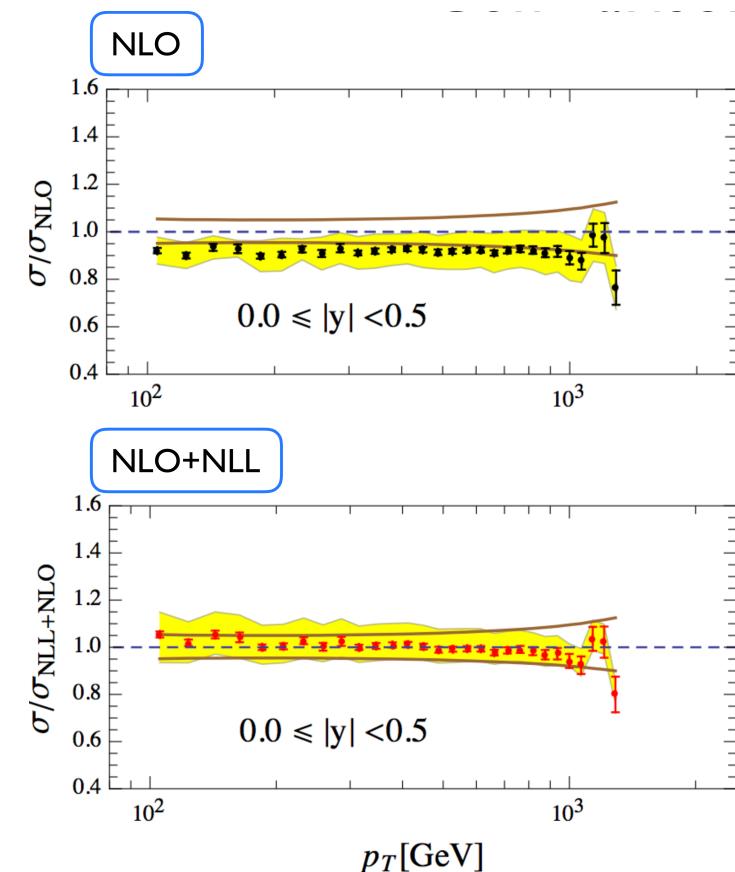
# Jets at the LHC

- ▶ test perturbative QCD, constrain PDFs, extract  $\alpha_S$ , BSM.

$$d\sigma = \alpha_S^2 d\sigma_{\text{LO}} + \alpha_S^3 d\sigma_{\text{NLO}} + \alpha_S^4 d\sigma_{\text{NNLO}}$$



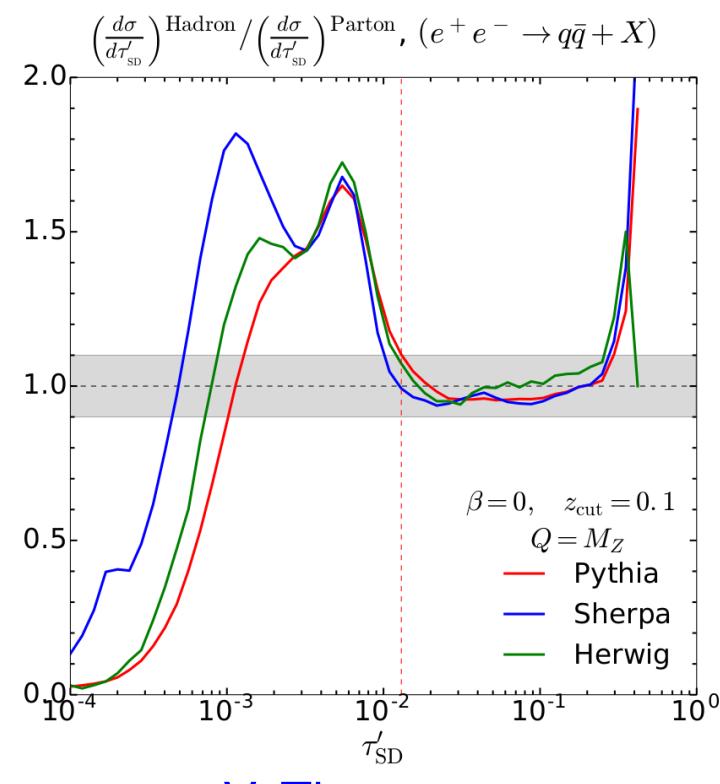
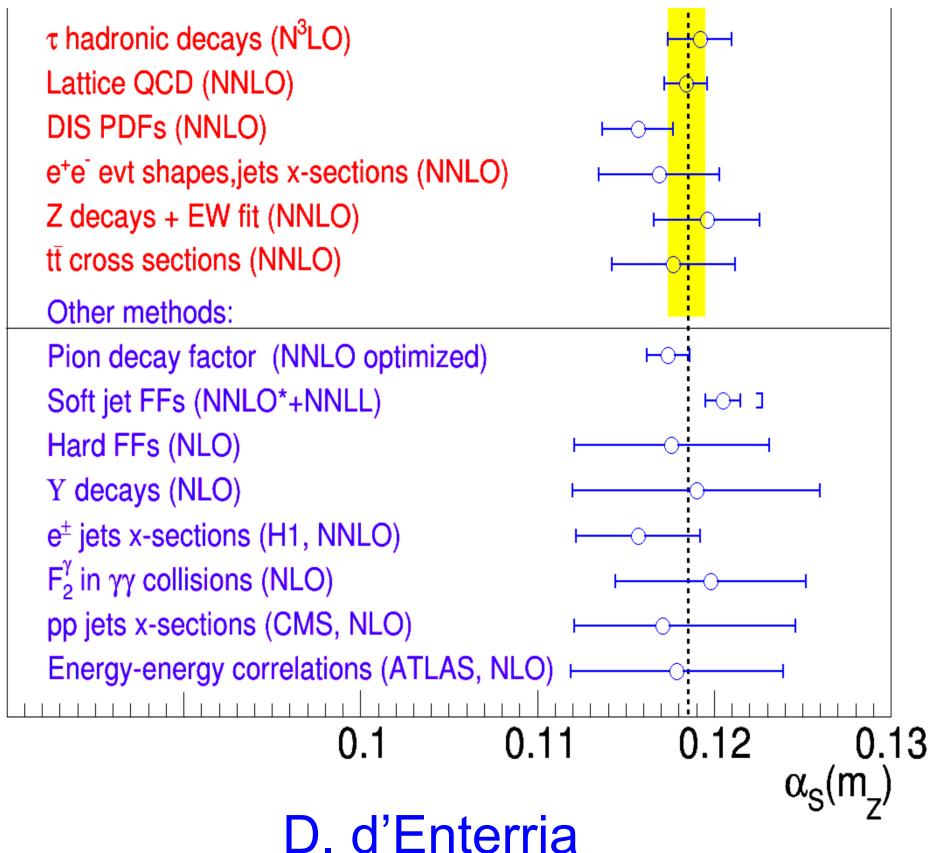
A. Huss

NLO +  $\log R$  &  $\log z$  resummation

F. Ringer

# $\alpha_s$ : status and new ideas

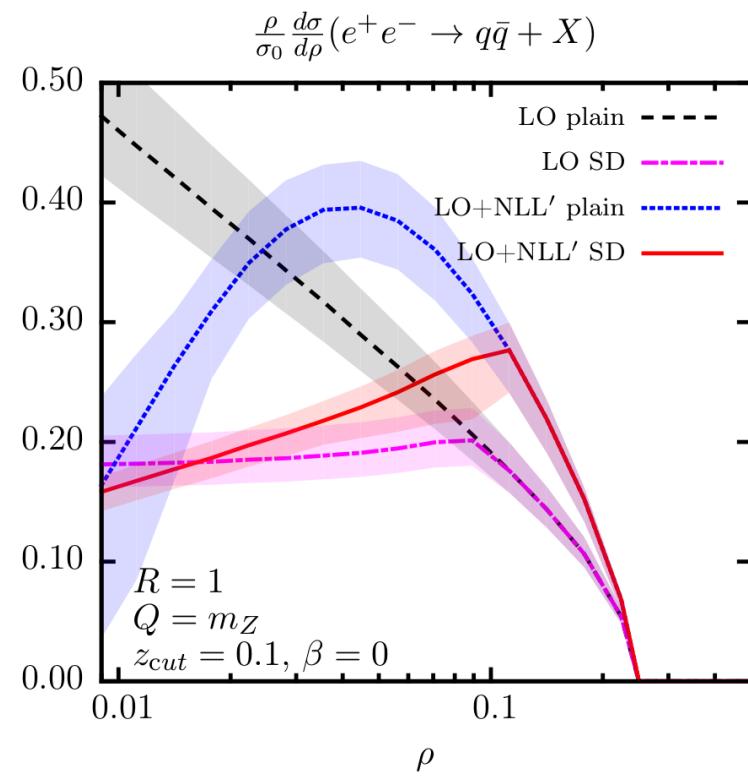
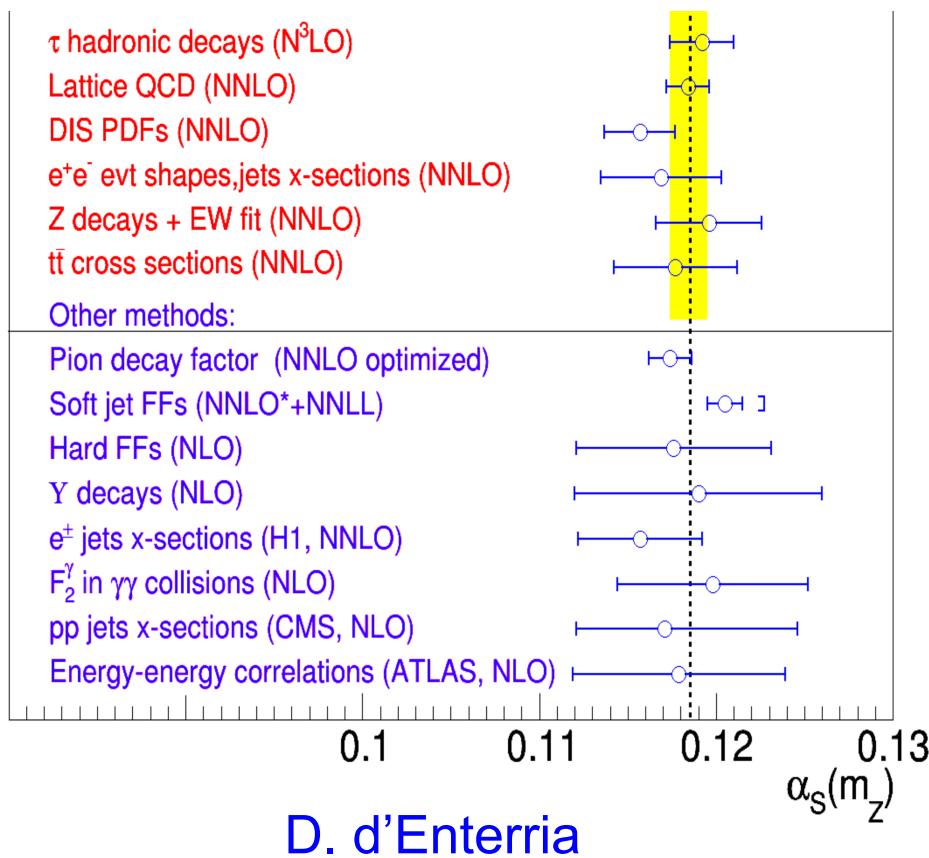
- least known coupling, impact on all x-sections: determined by comparing 6 observables to predictions
  - updates (at NNLO) awaiting official PDG combination
  - several other ideas available, work towards NNLO accuracy
  - event shapes at LEP: sensitive to non-perturbative QCD
  - reduced dependence using new techniques (soft drop)



V. Theeuwes

# $\alpha_s$ : status and new ideas

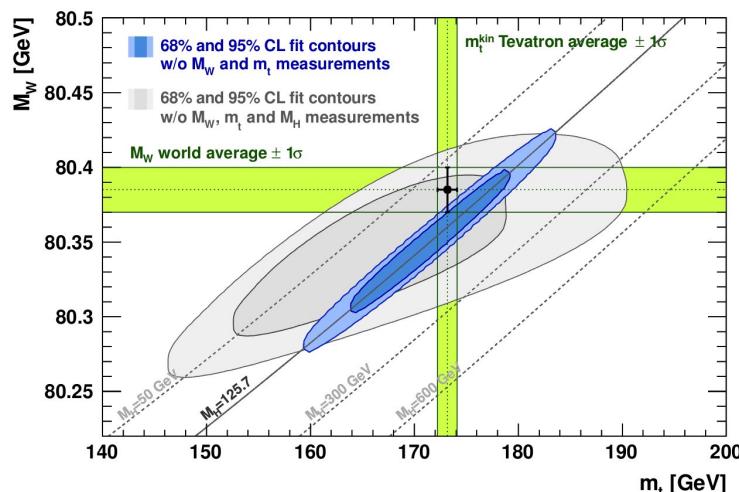
- least known coupling, impact on all x-sections: determined by comparing 6 observables to predictions
  - updates (at NNLO) awaiting official PDG combination
  - several other ideas available, work towards NNLO accuracy
  - event shapes at LEP: sensitive to non-perturbative QCD
  - reduced dependence using new techniques (soft drop)



# DY and Higgs distributions

- Drell-Yan distributions are measured with few per mill accuracy.

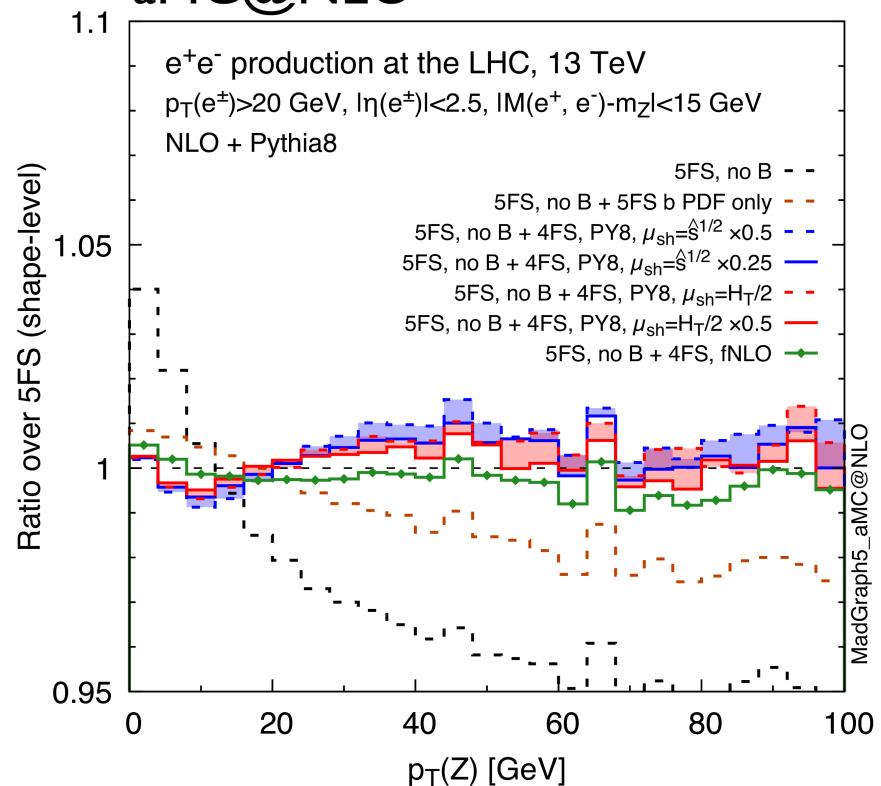
- test EW sector at the quantum level



- few per mille distortion  $\Rightarrow 10 \text{ MeV on } M_W$
- radiative corrections / interplay NC-CC: is all under control?
- PDF and QCD effects are dominant systematic uncertainties

- combination of 5FS and 4FS NLO+PS results + thorough study
- improved description of bottom-quark contributions, impact on  $M_W$  small but visible

aMC@NLO

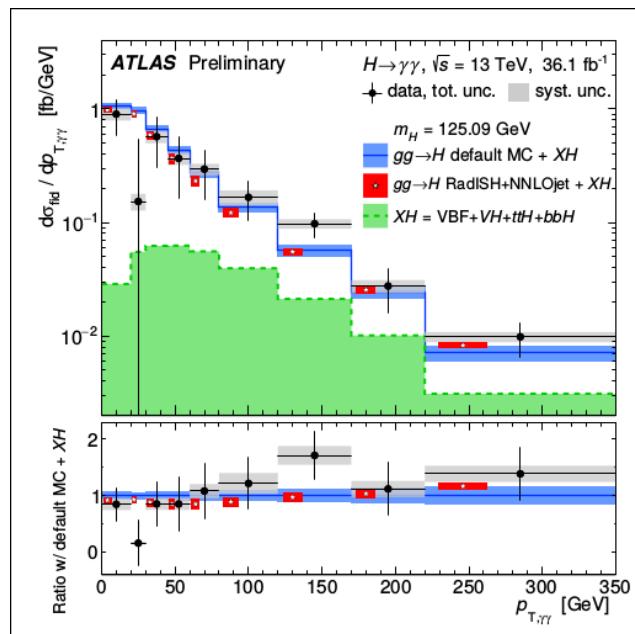


A. Vicini

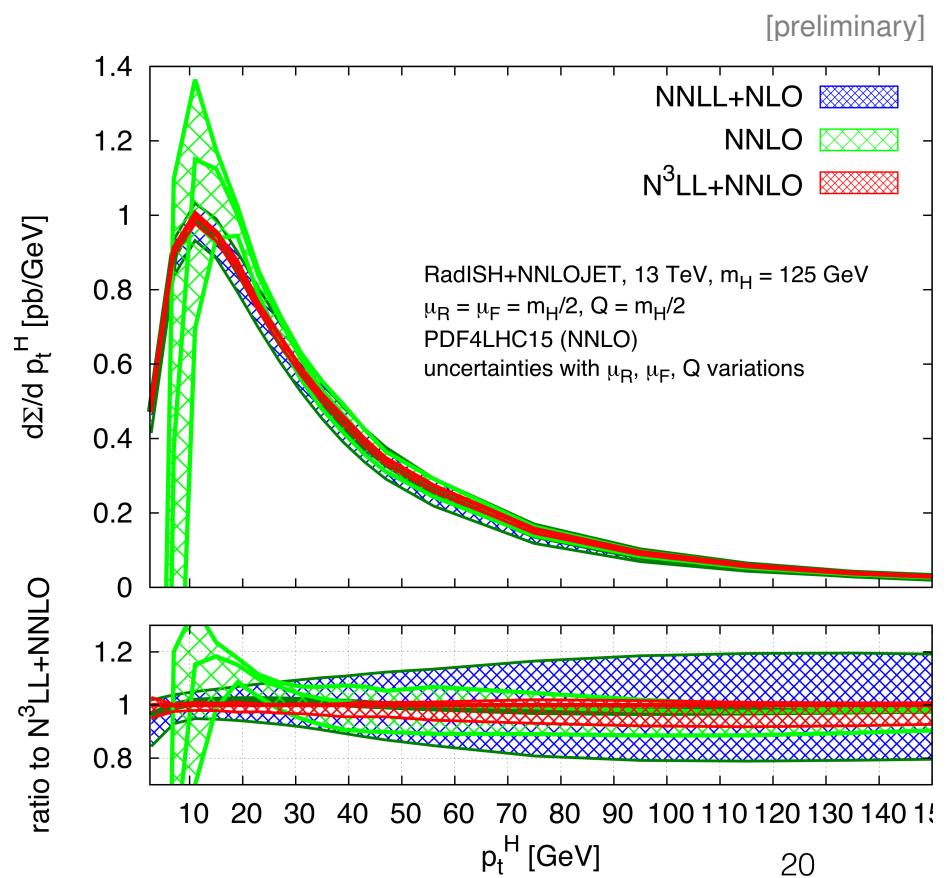
# DY and Higgs distributions

► transverse and inclusive observables (in colour-singlet production).

- EXP and TH clean → precision physics
- interesting for TH: test event generators, link between higher-order resummation and PS
- $p_{T,H}$  allows to set constraints on Higgs couplings (e.g. Yukawa couplings)



- new formalism to perform resummation directly in momentum space
- new state of the art:  $\text{N}^3\text{LL+NNLO}$  [ $p_{T,H}, p_{T,Z}, \phi^*$ ]

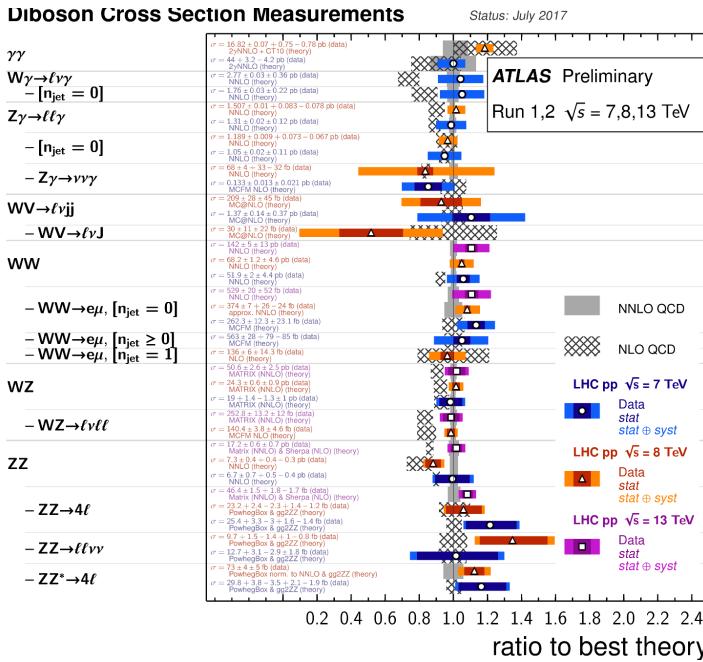


P. F. Monni

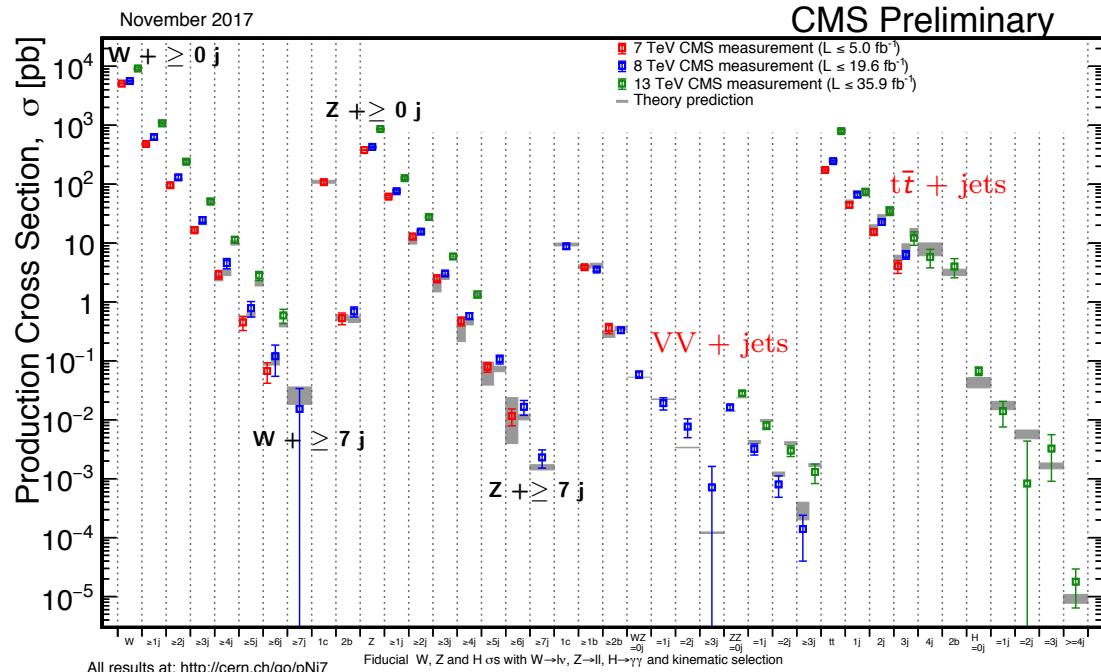
E. Re, S. Uehara, M. Voutilainen

# Experimental results

- **Foundations:** HERA, LHC objects ( $\mu$ )
- “**Pure” QCD:** inclusive jets, dijets
- “**Pure” EW:** dibosons  $VV, V\gamma$
- **QCD+EW:**  $V+jet$
- **Higgs connection:** VBS, VBF
- **Massive:** jet mass, boosted tagging,  $m_W, m_t$
- **QCD at  $e^+e^-$ :** hadrons at Belle & Babar



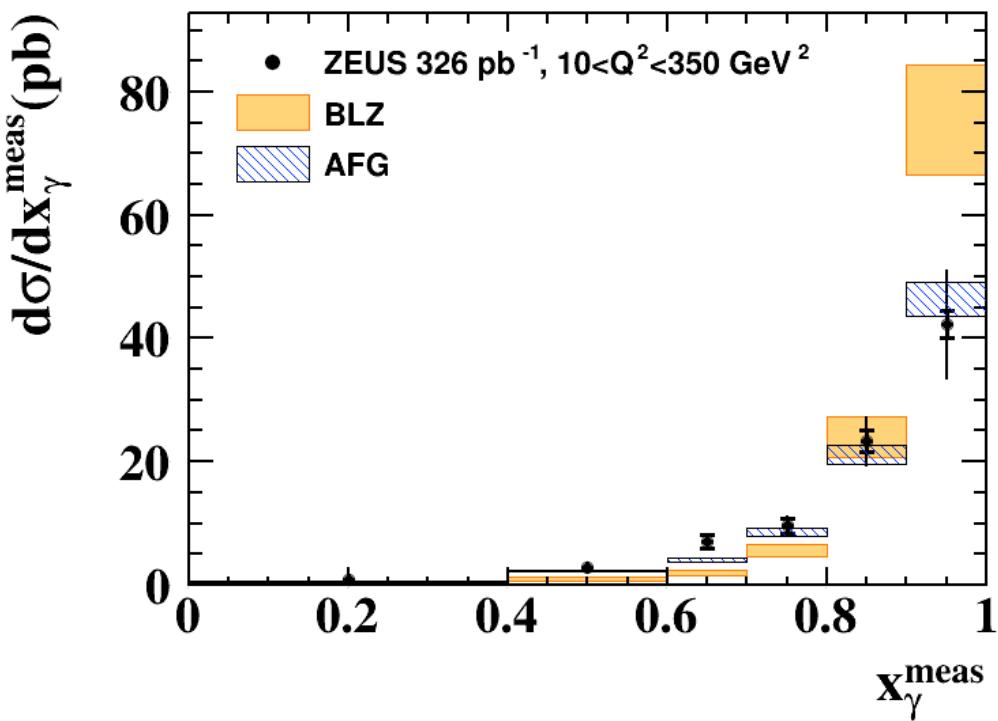
- Please follow links to talks for more details and references to papers
- Giving only a taster of all new results, much more in original talks



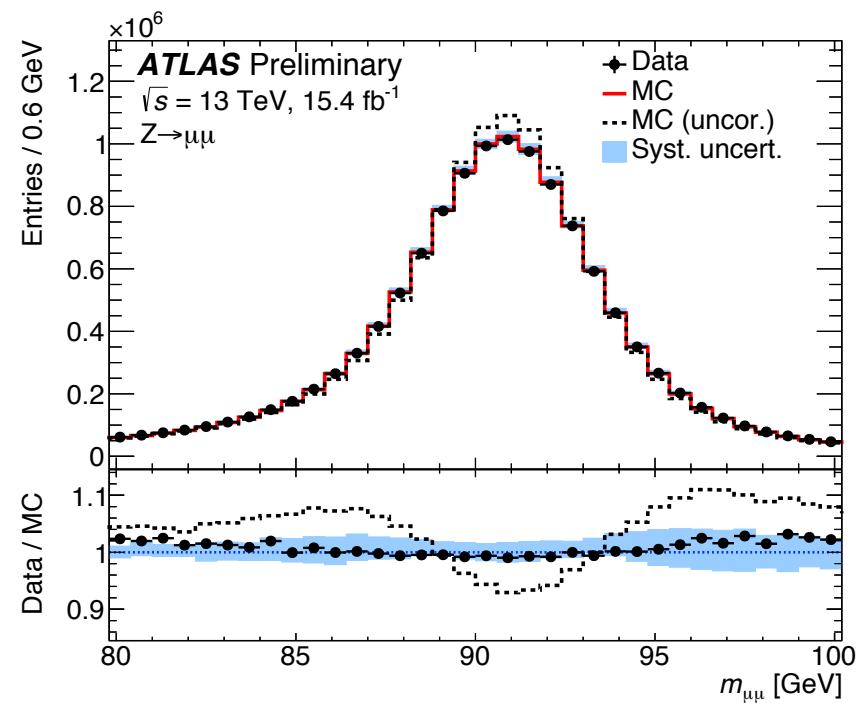
**Link to agenda**

# HERA, LHC muons

- HERA results on isolated photons — old experiment keeps on giving
- Muon object performance at ATLAS — experimental foundation for LHC precision physics



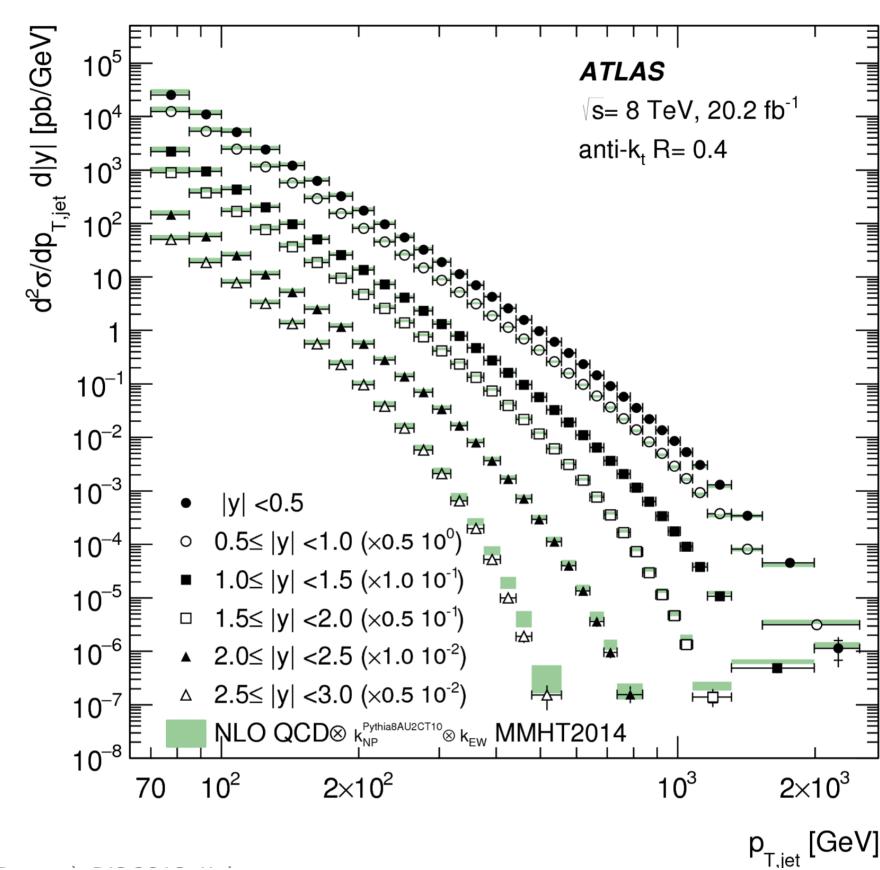
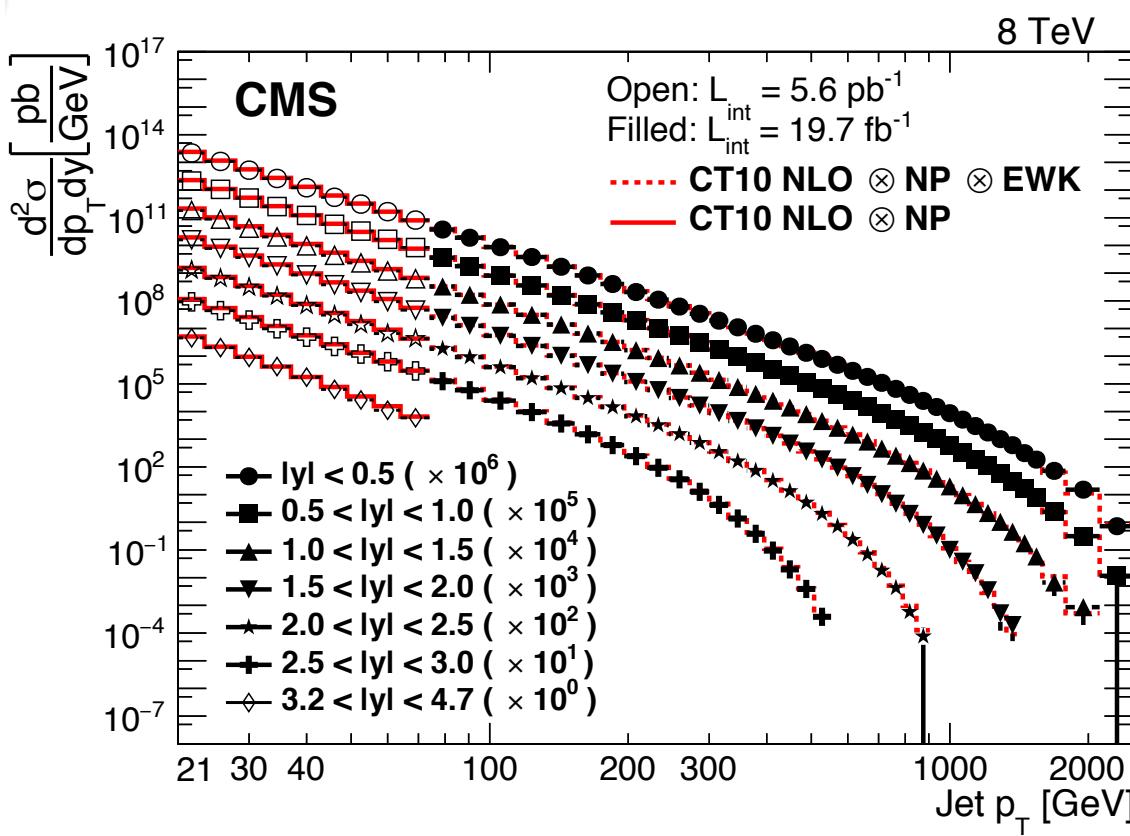
- AFG: NLO good
- BLZ: k<sub>T</sub> factorisation fair



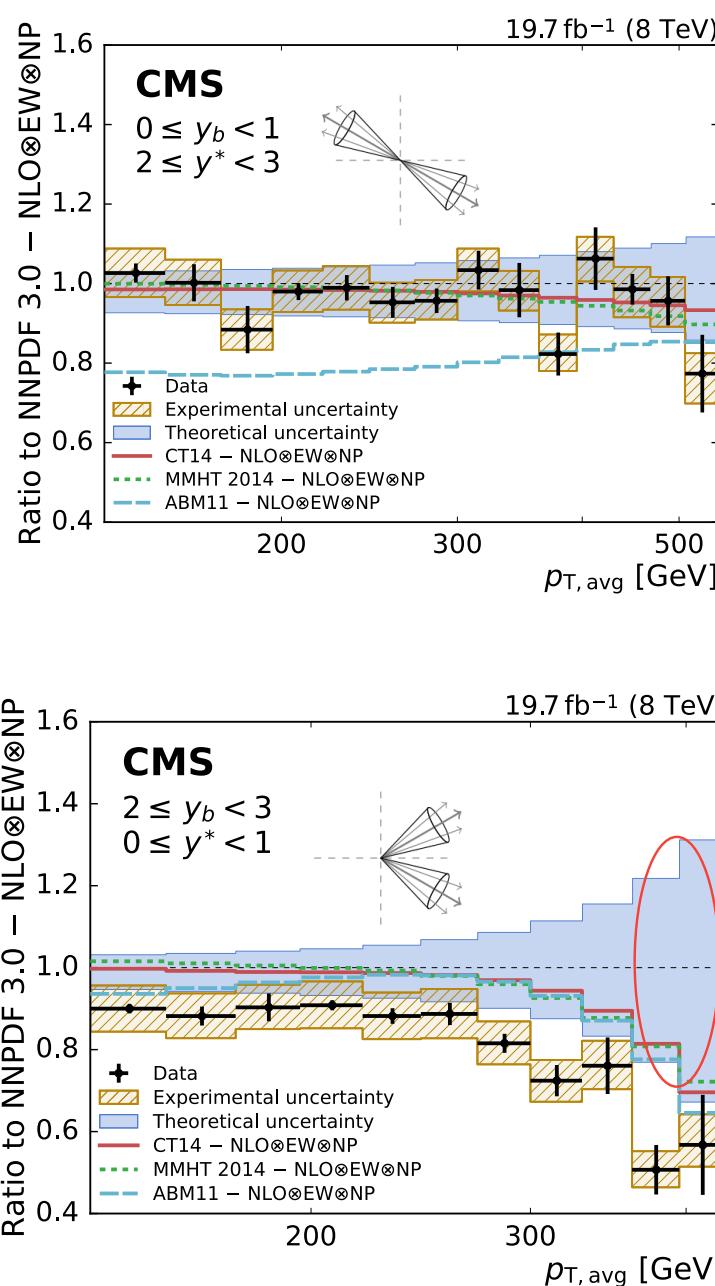
- $\mu$  p<sub>T</sub> scale ~0.1% (unc.)
- $\mu$  efficiency ~0.5% (unc.)
- $\mu$  p<sub>T</sub> resolution ~1% (unc.)

# Inclusive jets

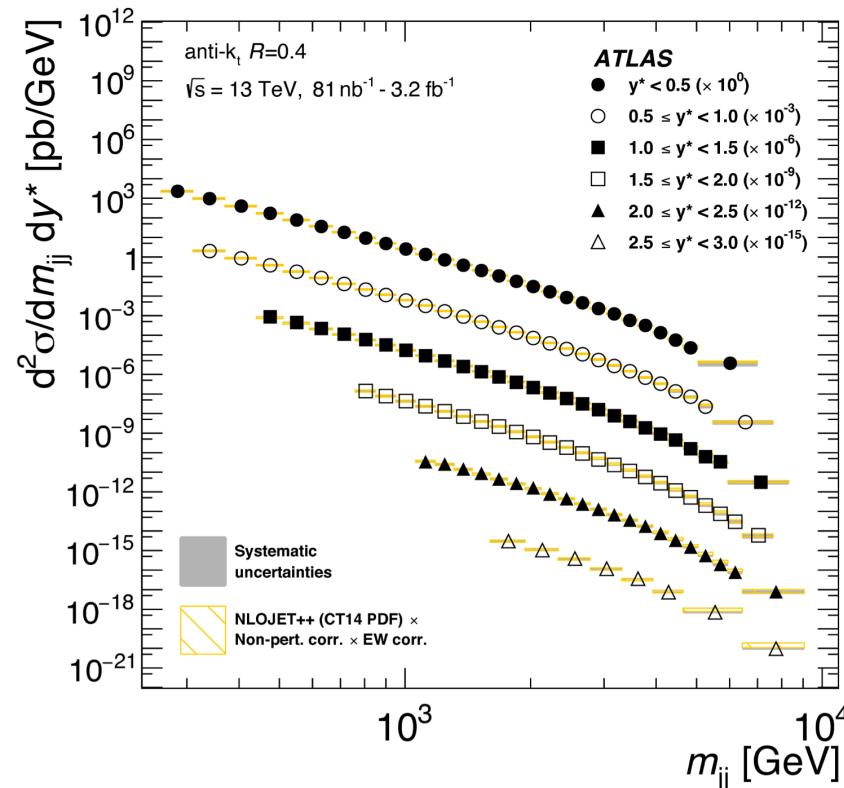
- State-of-the-art measurements from LHC are now 8 TeV
  - ▷ global PDF fits should add these as soon as ATLAS HEPData available
- New measurements out from 13 TeV, but will need time to reach Run I precision
  - ▷ Same  $|y|$  bins, same small  $R=0.4 \Rightarrow$  foundation ready for LHC combination, HERA style



# Dijets



- Dijet production by CMS at 8 TeV and ATLAS at 13 TeV
  - ▷ ATLAS differential in  $y^* = |y_1 - y_2|/2$  and traditional  $m_{jj}$
  - ▷ CMS triple-differential in  $p_{T, \text{avg}}$ ,  $y^*$  and  $y_b = |y_1 + y_2|/2$
- Separating forward-forward from forward-backward gives more sensitivity to PDFs



ATLAS-STDM-2016-03

- Wealth of EW data available from LHC
- Experimental precision <5%, already more sensitive than LEP for aTGC

## Summary

- ❖ About 50 ATLAS papers published on diboson physics studies
- ❖ Entering precision measurement era ( $\sigma^{\text{sys}} < 5\%$ ) to test SM at highest energy scale
- ❖ Sensitivities of aTGC surpass the LEP combined limits!

### For charged aTGCs

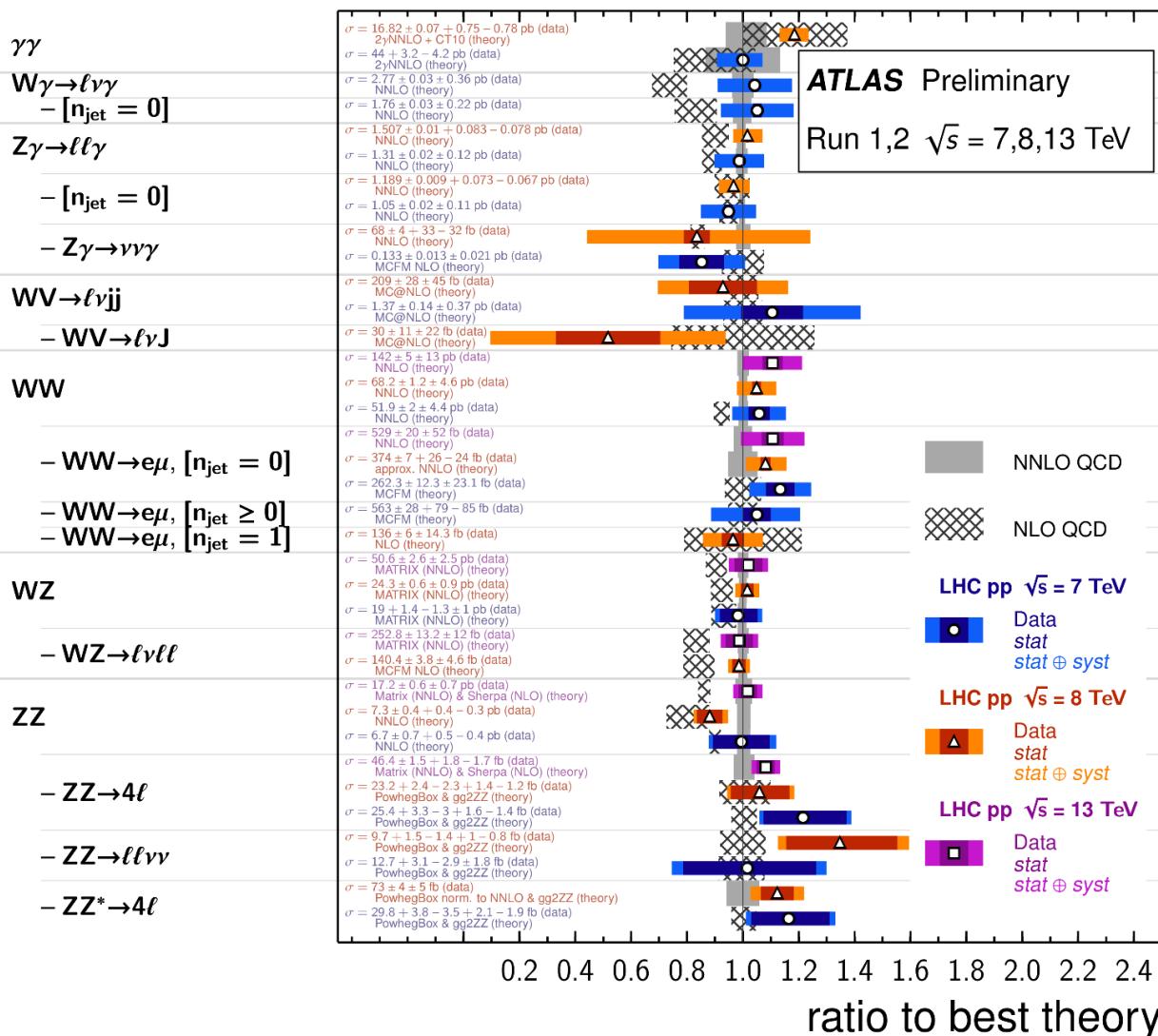
- $\Delta \kappa_\gamma$  limits  $\sim 6 \times 10^{-2}$
- $\lambda_\gamma$  limits  $\sim 1.3 \times 10^{-2}$
- $\Delta \kappa_Z$  limits  $\sim 2 \times 10^{-2}$
- $\lambda_Z$  limits  $\sim 1.3 \times 10^{-2}$
- $\Delta g_1^Z$  limits  $\sim 2 \times 10^{-2}$

### For neutral aTGCs

- $h_i^V$  limits  $\sim 10^{-4} - 10^{-6}$
- $f_i^V$  limits  $\sim 10^{-3}$

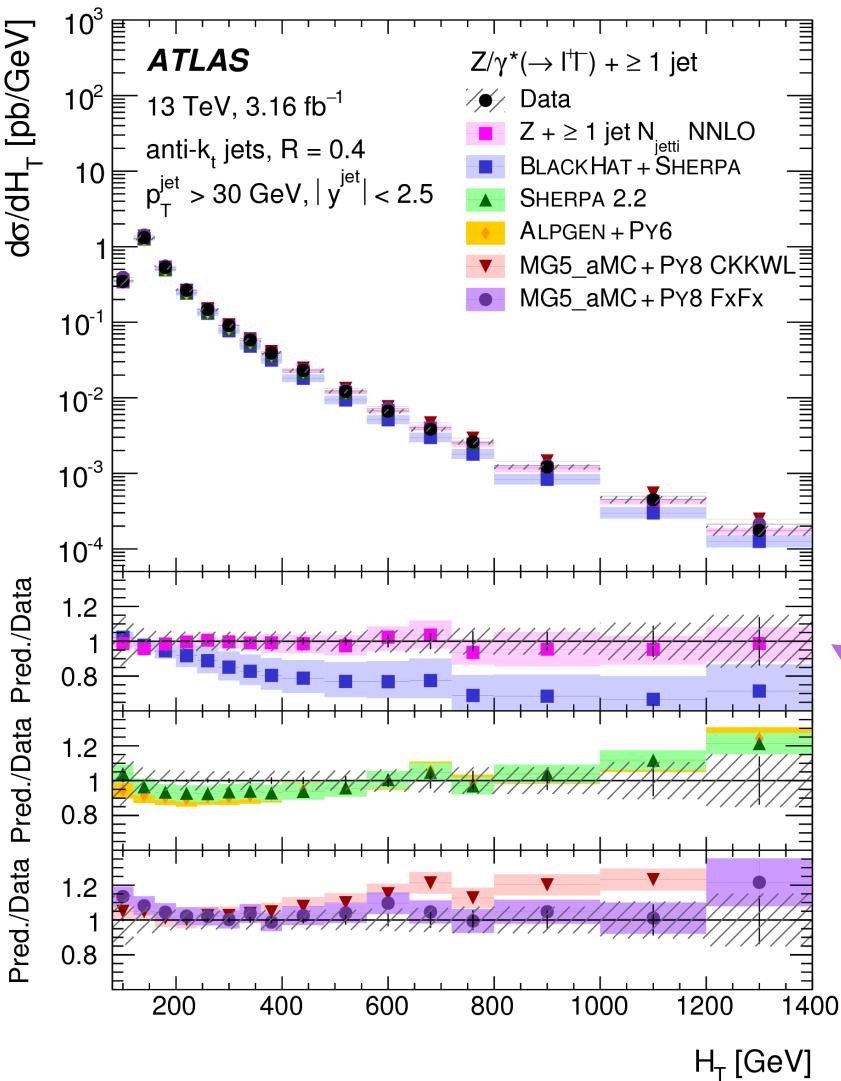
## Diboson Cross Section Measurements

Status: July 2017

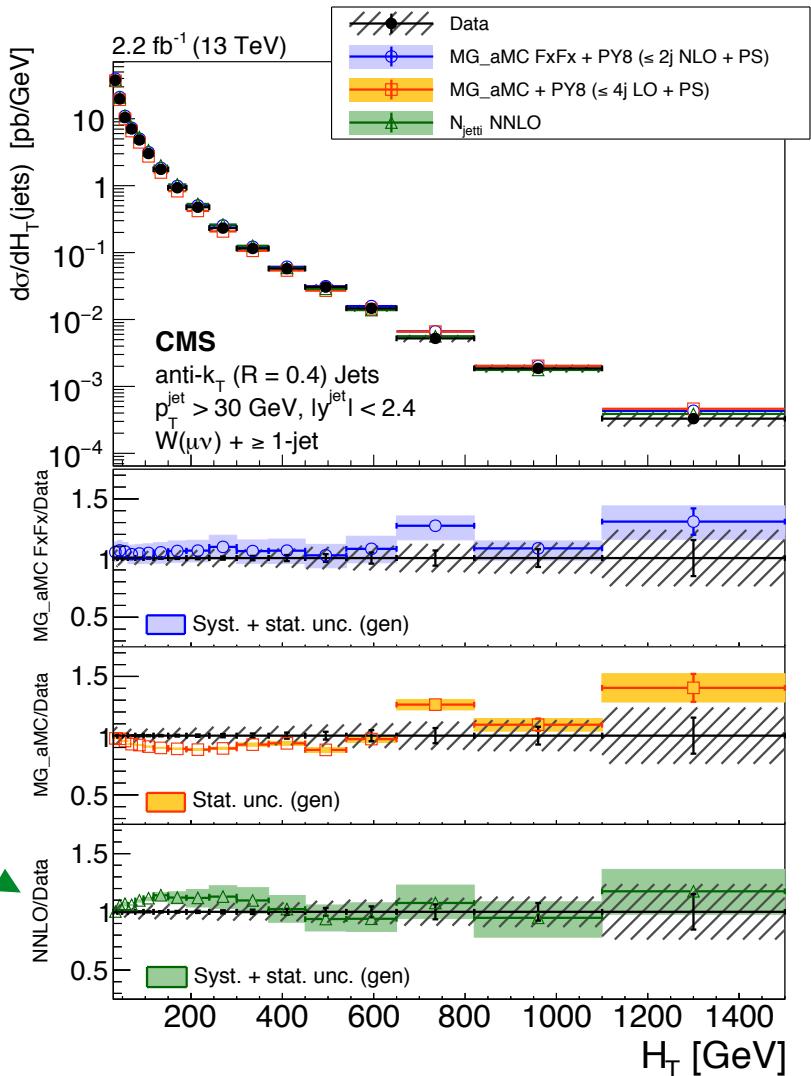


# V+jet

- Precision data on Z+jet (CMS,ATLAS 13 TeV) and W+jet (ATLAS 8 TeV, CMS 13 TeV)
- NNLO ( $N_{\text{jetti}}$ ) available and needed for accurate modelling, NLO multileg decent

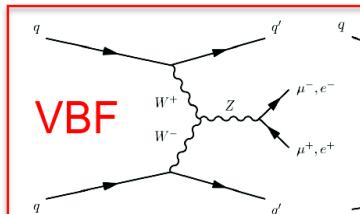


NNLO  
( $N_{\text{jetti}}$ )

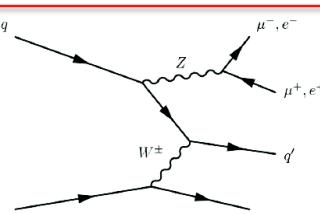


# VBF: Zjj / Wjj

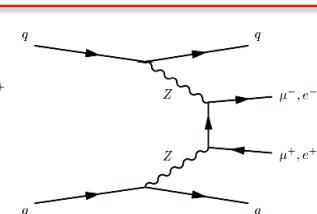
Vector boson fusion:



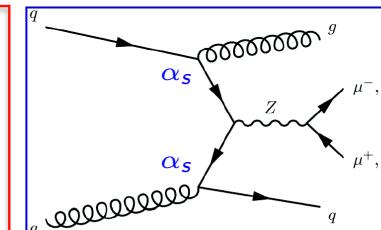
Bremsstrahlung-like:



Multiperipheral production:

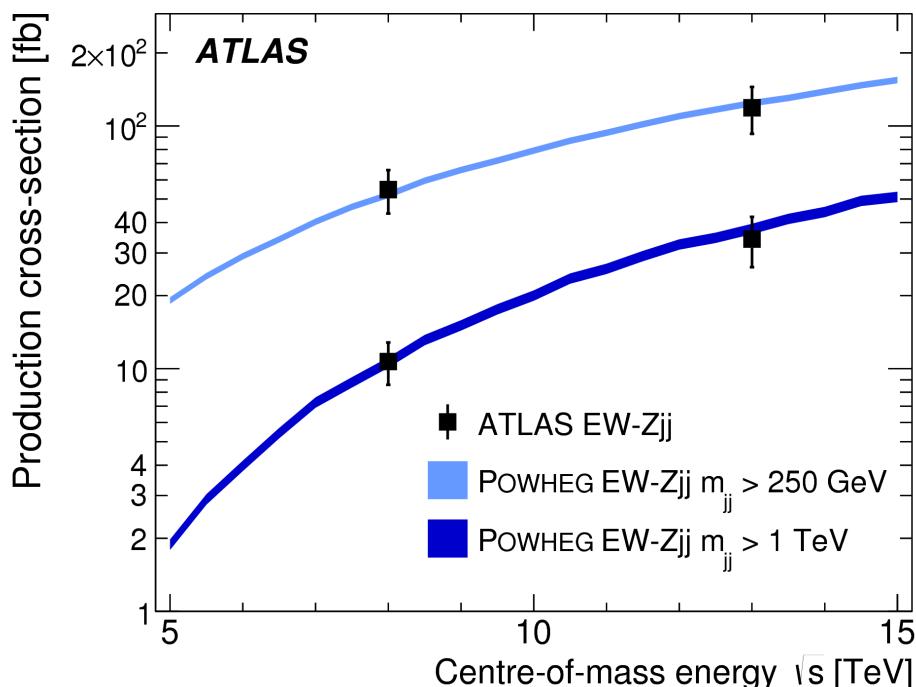


Electroweak production

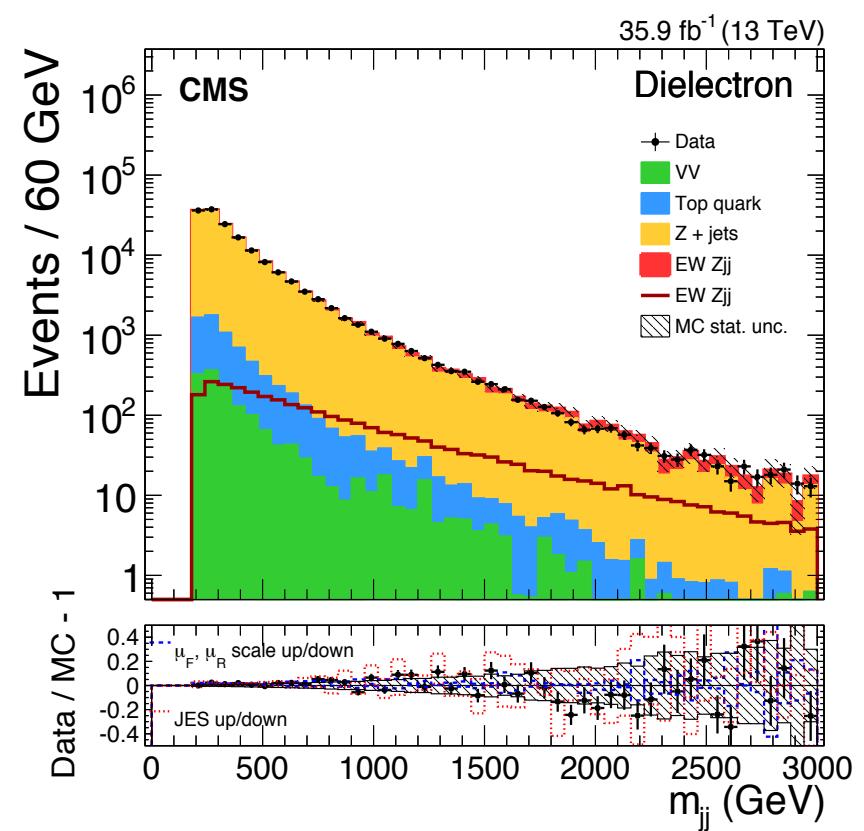


Strong production

- VBF of interest for e.g. Higgs couplings
- EW contribution extracted mainly with high  $m_{jj}$  requirement



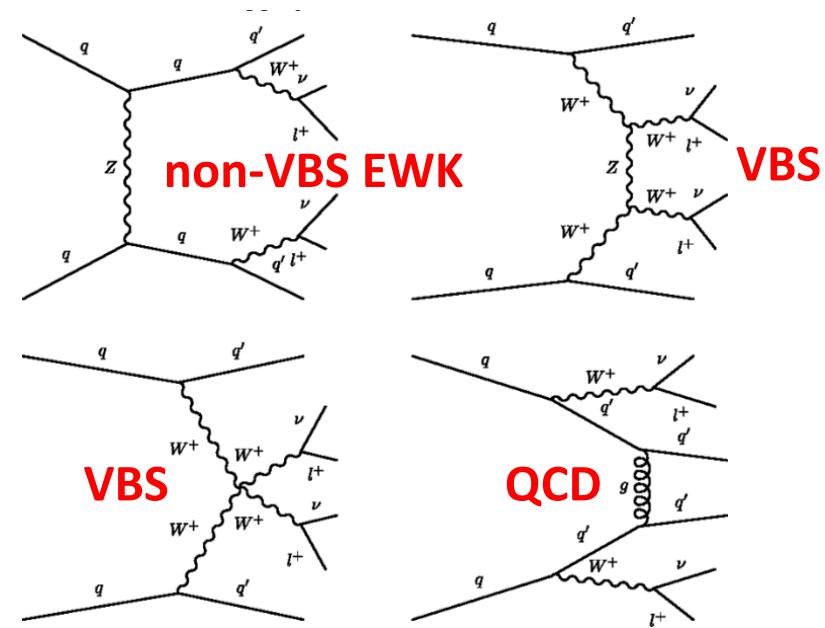
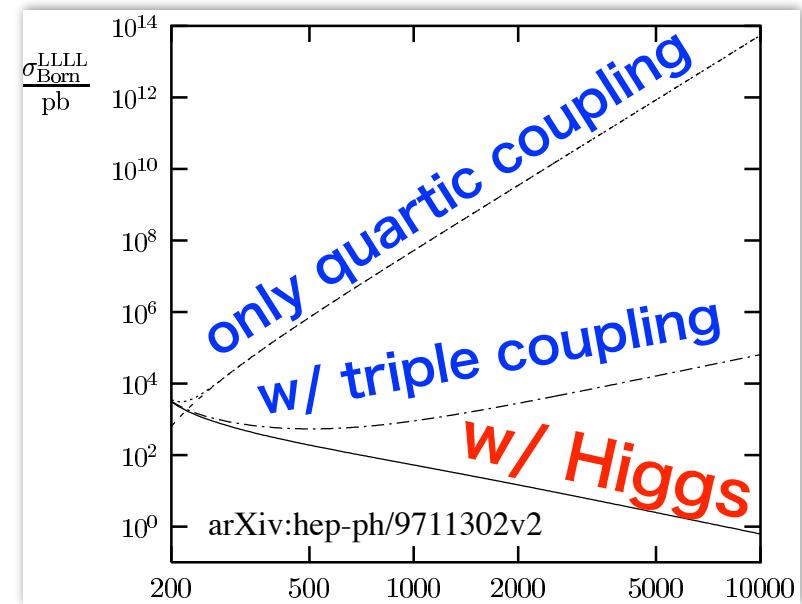
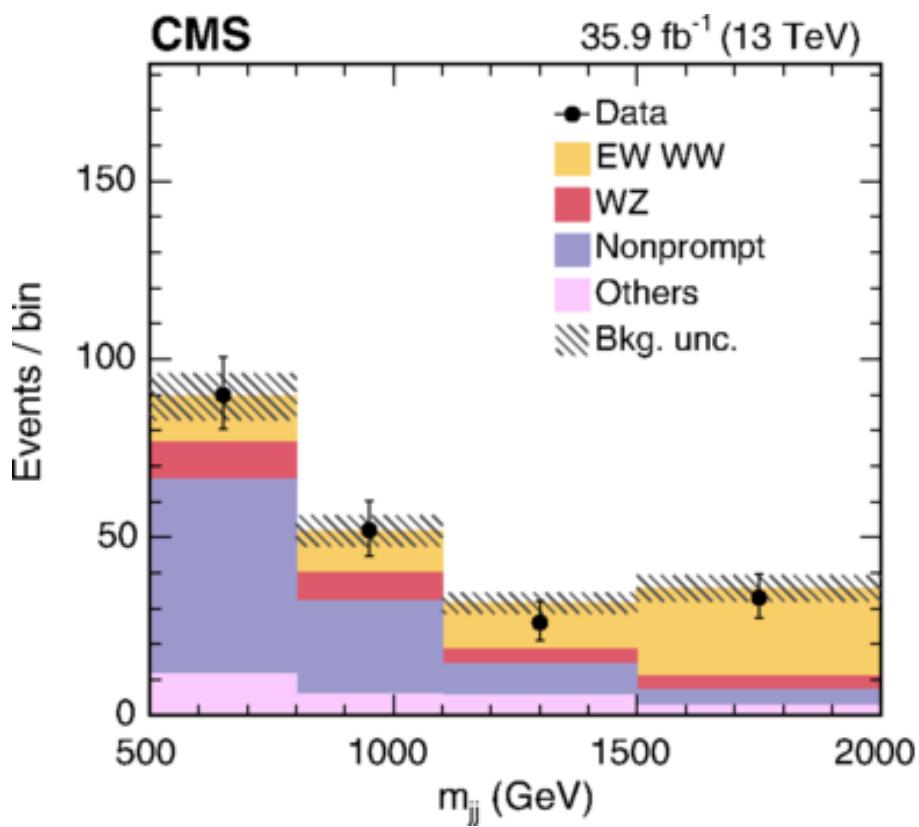
## VBF: Vector Boson Fusion



# VBS: 1<sup>st</sup> electroweak VVjj

- CMS: 1<sup>st</sup> measurement of EW VVjj at pp collider
  - WW scattering unitary with  $H \Rightarrow$  probe EW
  - Limits on dimension 8 EFT operators

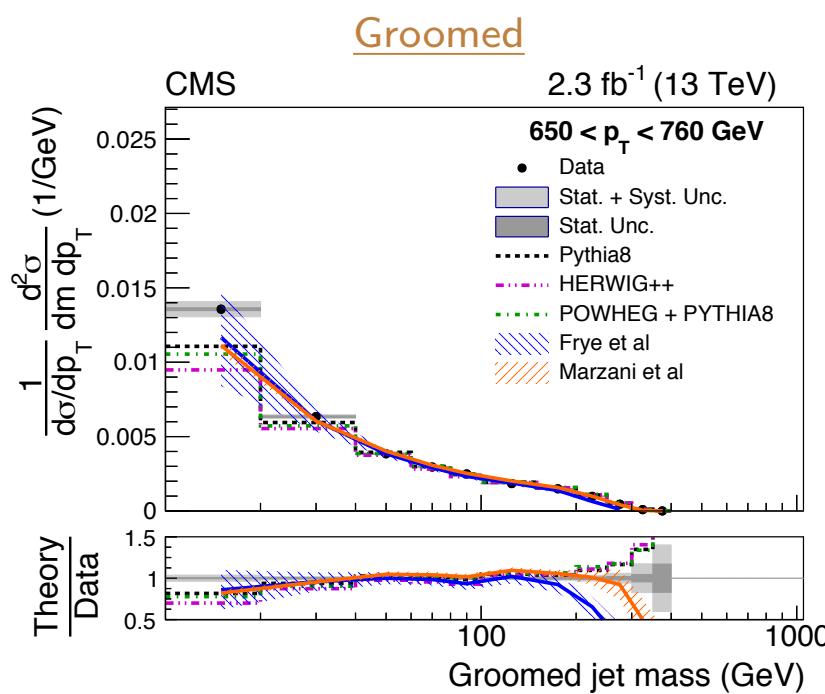
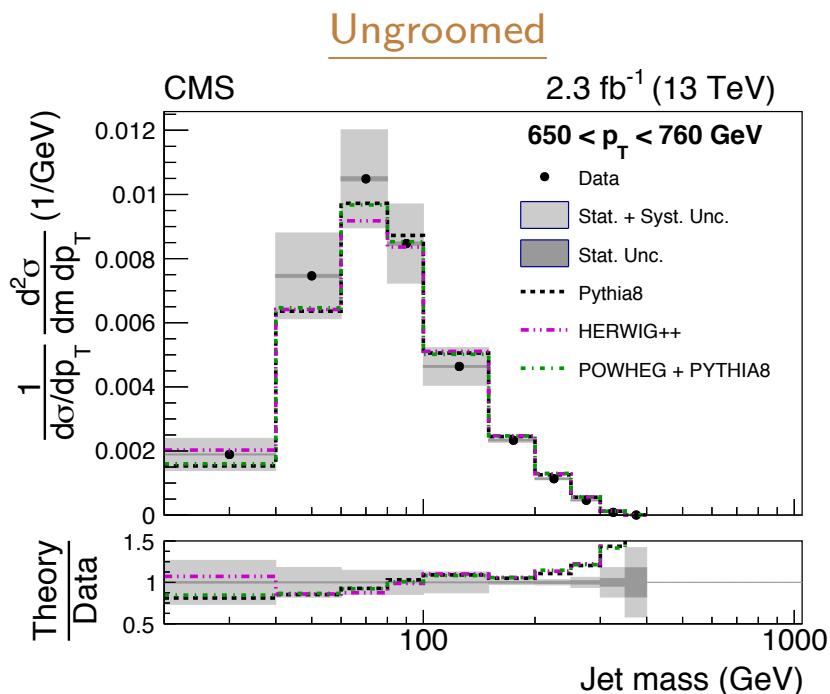
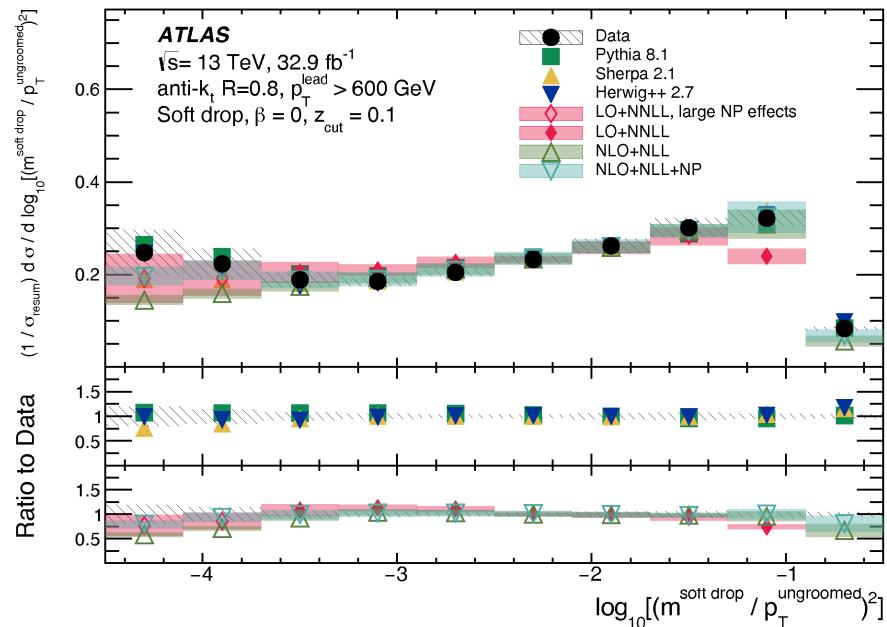
**VBS: Vector Boson Scattering**  
**EFT: Effective Field Theory**



# Jet mass

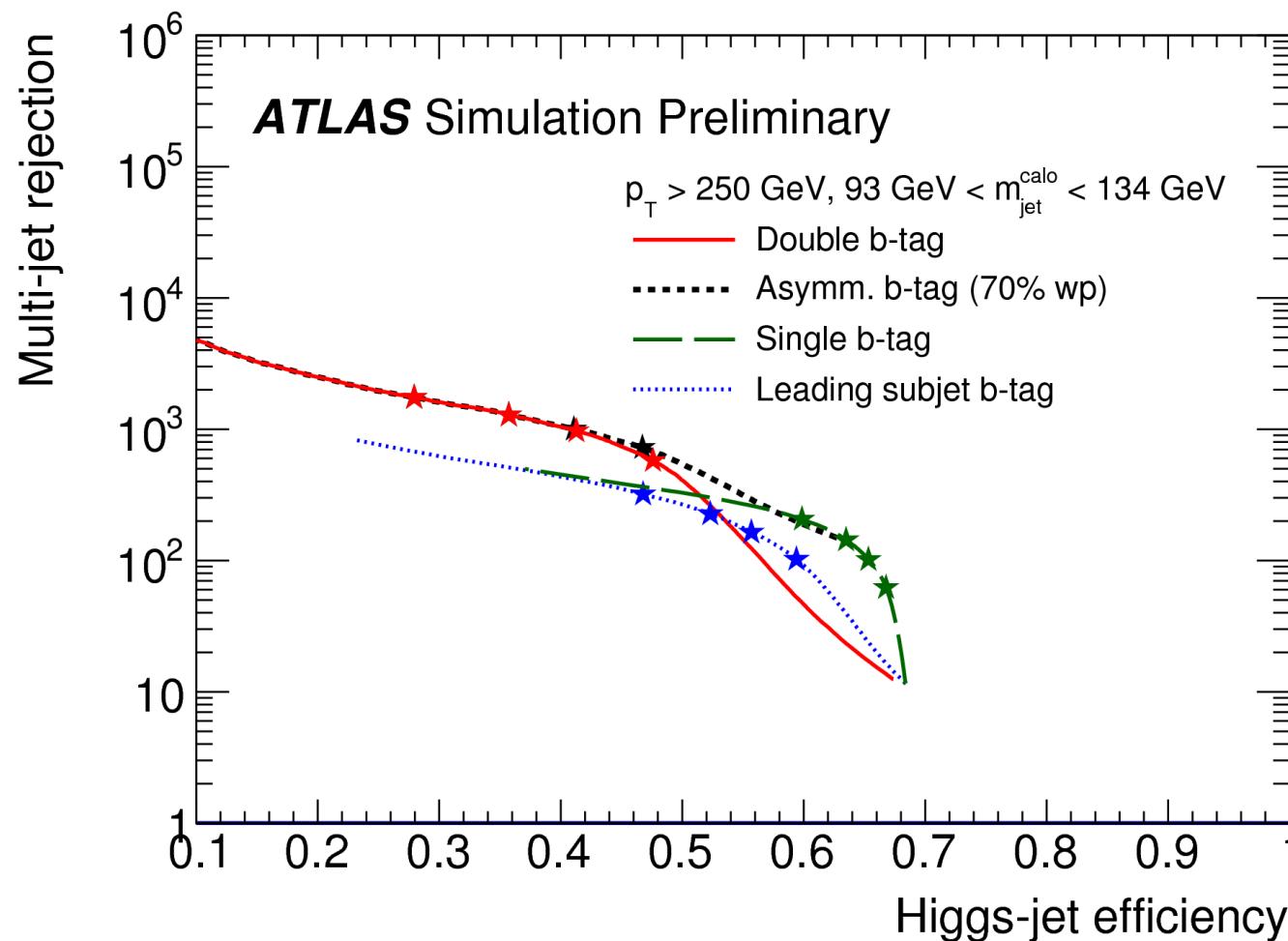
- Precise data on groomed soft drop mass and ungroomed jet mass from CMS+ATLAS
- With grooming, jet mass precisely calculable in pQCD (NLO+NLL precision)
- Solid foundation for boosted object tagging

## SD: Soft Drop (groomed)

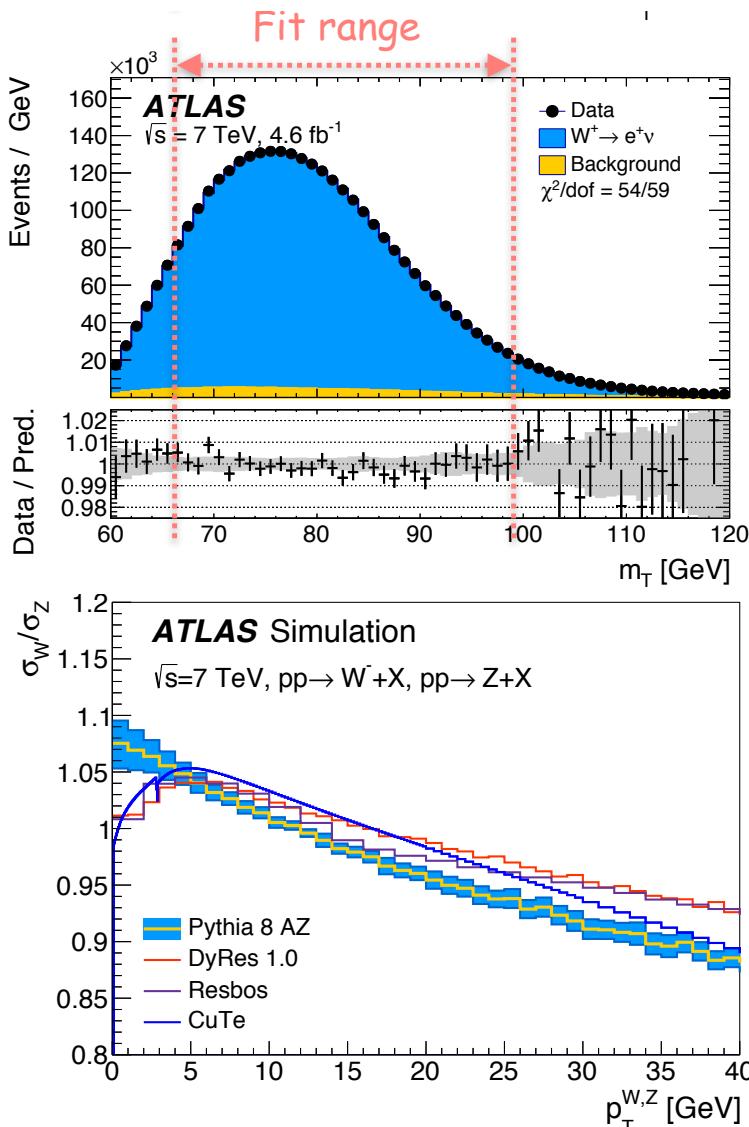


# Heavy object tagging

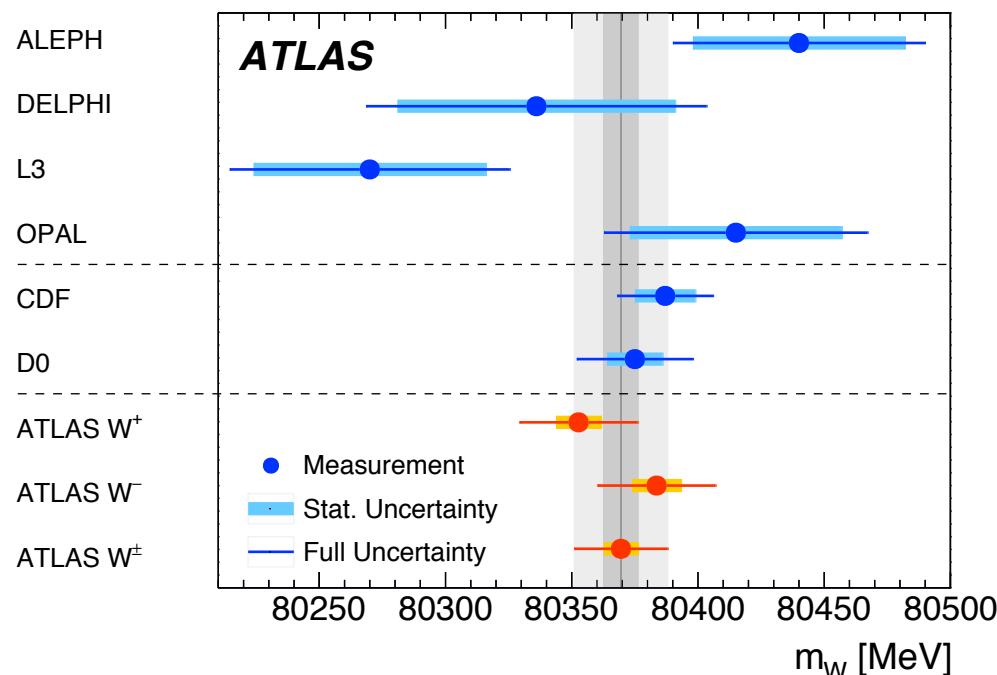
- boosted W, Z, top tagging already routine at the LHC — basic tools for HL-LHC
- boosted H( $\rightarrow bb$ ) tagging now becoming reality as well — only 6 years after H discovery
  - $D_2$  for two-prong decay
  - b-tagged R=0.2 subjets
  - Higgs mass



# EW precision, $m_W$



- Measurement of  $m_W$  from Jacobian peak ( $m_T, p_{T,j}$ ) needs extreme precision for PDFs and modelling of low  $p_T^W$
- New ATLAS measurement already impacts world average

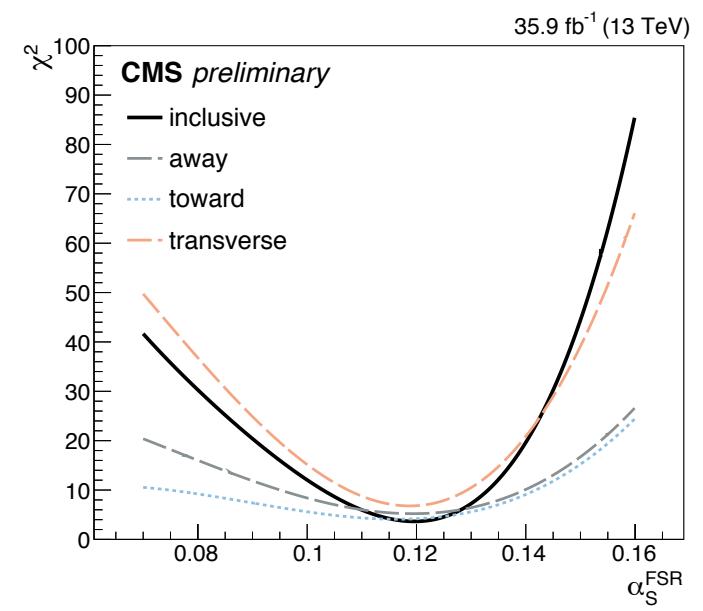
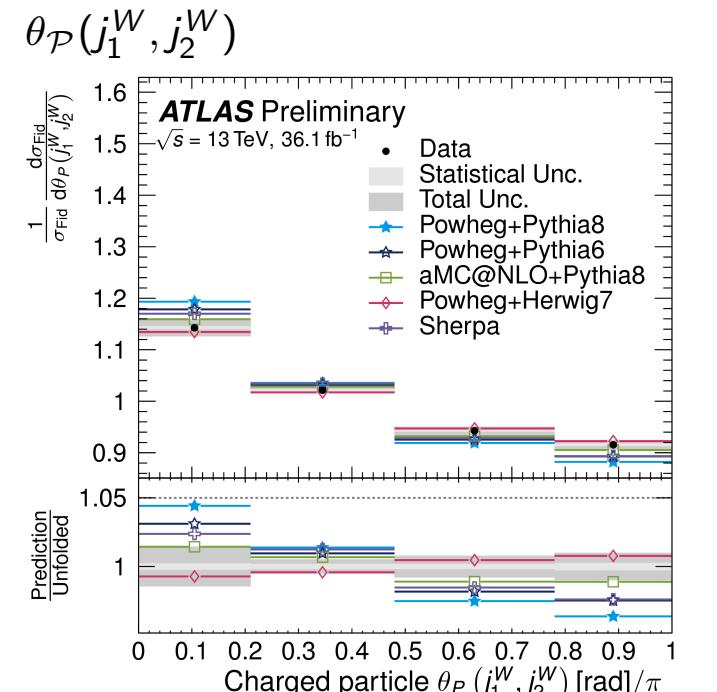
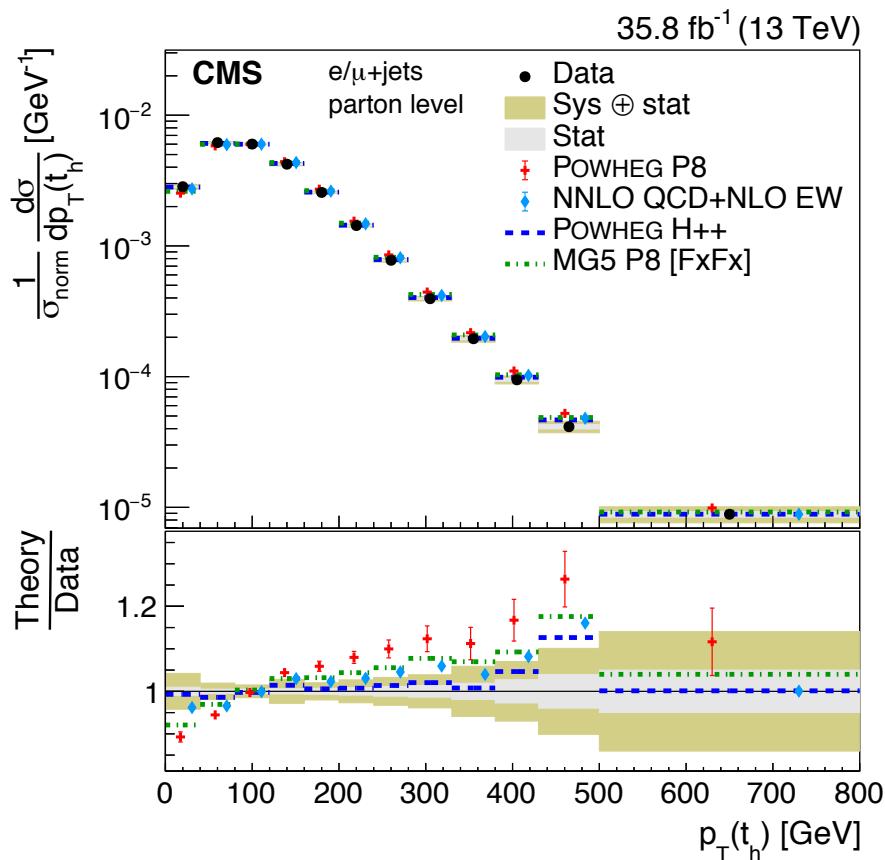


Impact of ATLAS measurement in global fit (arXiv:1803.01853):

- The uncertainty of world average improved from 15 MeV to 13 MeV
- The precision of the indirect determination reduced from 8 MeV to 7 MeV

# top quarks, $m_t$

- Similar experimental progress on  $m_t$  as on  $m_W$   
needs precise modelling:
  - color reconnection in  $W \rightarrow q\bar{q}'$  seems too strong in MC
  - top  $p_T$ : NNLO QCD + NLO EW good, but parton to particle level transition not yet understood
  - FSR modelling in parton shower constrained by underlying event and jet shapes

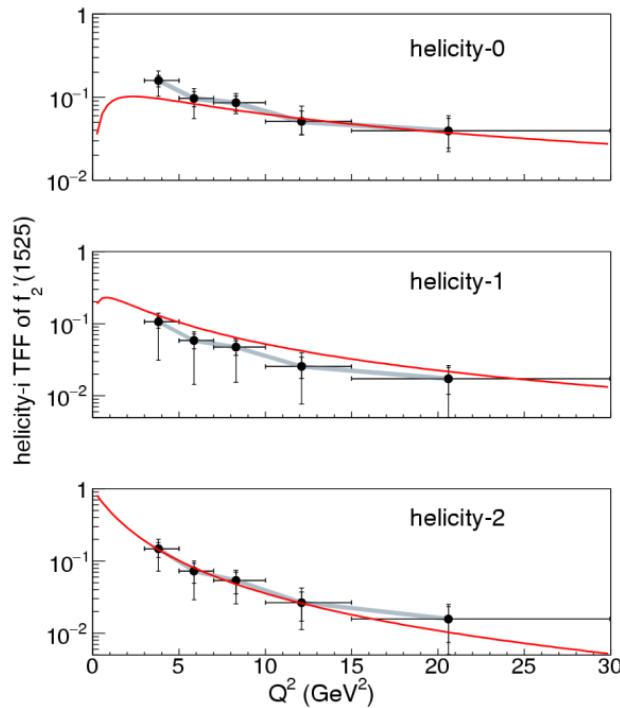
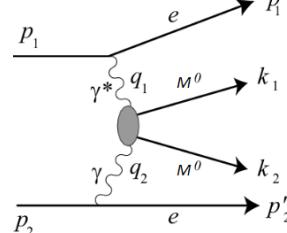


# $\gamma\gamma$ collisions at e<sup>+</sup>e<sup>-</sup> (Belle, KEKB)

$\gamma^*\gamma \rightarrow K^0_s K^0_s$  (S.Uehara, Tue #2 s.)

A large-Q<sup>2</sup> photon on a real photon:

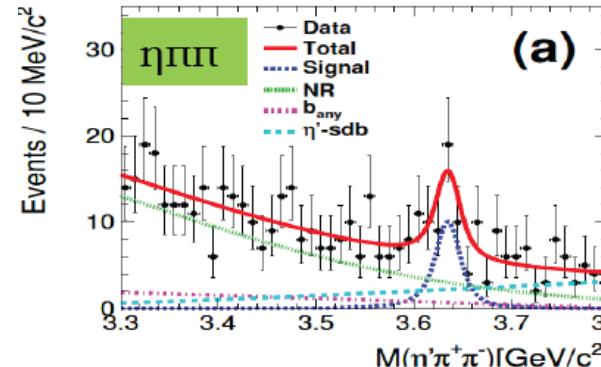
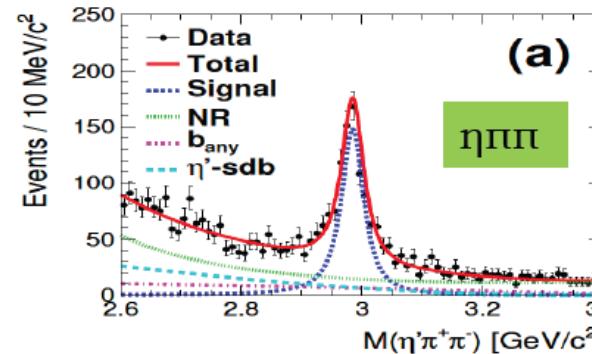
First measurement of the Transition form factor of  $f_2'(1525)$



Consistent with a QCD calculation of q-q-meson model by Schuler, Berends and van Glick

$\gamma\gamma \rightarrow \eta_c(1S,2S) \rightarrow \eta'\pi^+\pi^-$  (Q.N. Xu, Thu #1 j.s.)

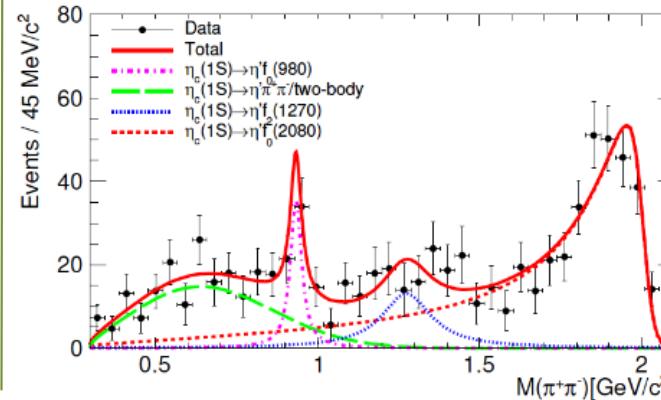
Meson spectroscopy and decay properties



$\gamma\gamma \rightarrow \eta_c(1S) \rightarrow \eta'\pi\pi$   
( $\eta' \rightarrow \eta\pi\pi$ )

First observation of  $\eta_c(2S) \rightarrow \eta'\pi\pi$  with a significance of  $5.5\sigma$

$$\Gamma_{\gamma\gamma} \mathcal{B} = 5.6^{+1.2}_{-1.1} \pm 1.1 \pm 6.9 \text{ eV}$$



Decay substructure

Observation of  $\eta_c(1S) \rightarrow \eta' f_0(2080)$

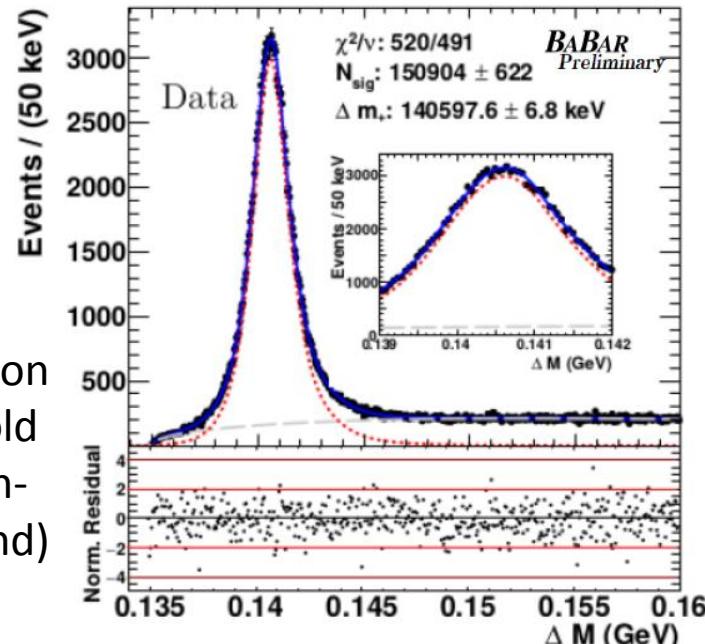
# QCD at e<sup>+</sup>e<sup>-</sup> (BaBar, PEP II)

(L. Zani, Thu #1 j.s.)

## Measurement of the D<sup>\*+</sup>(2010) – D<sup>+</sup> mass difference

Constrain the symmetry breaking due to *u-d* quark mass difference in chiral perturbation theory & lattice QCD

$$D^{*+} \rightarrow D^+ \pi^0, \\ D^+ \rightarrow K^- \pi^+ \pi^+$$



PDF:  
Resolution function  
(signal)+ Threshold  
function (combinatorial background)

After adding the bias

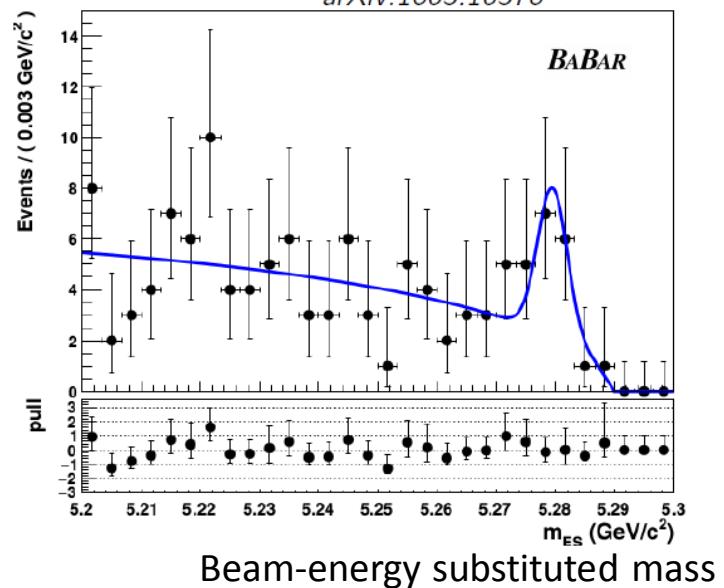
$$\Delta m_+ = (140\,601.0 \pm 6.8[\text{stat}] \pm 12.9[\text{syst}]) \text{ keV}$$

$$\Delta m_D = (4\,824.9 \pm 6.8[\text{stat}] \pm 12.9[\text{syst}]) \text{ keV}$$

## Search for B<sup>0</sup> → p p p p̄

- For better understanding of the mechanism of *hadronization into baryons*
- *Baryon puzzle*: Inclusive BF > Σ of Exclusives

$$BF = (1.14 \pm 0.47 \pm 0.17) \times 10^{-7} \\ arXiv:1803.10378$$



The first upper limit on this channel:

- 11 decay events with a significance of  $2.9\sigma$
- $\text{BF}^{\text{UL}} = 2 \times 10^{-7}$  at 90% CL

# Summary

- We're now well into LHC precision era with wealth of data and NNLO theory predictions
- PDF,  $\alpha_s$ ,  $m_W$  and  $m_t$  measurements laying solid foundation for Run II new physics searches
- New channels for exploration of Higgs potential and EW theory opening in Run II
- Deep understanding of jet mass and boosted topologies new tools for Run II and HL-LHC

