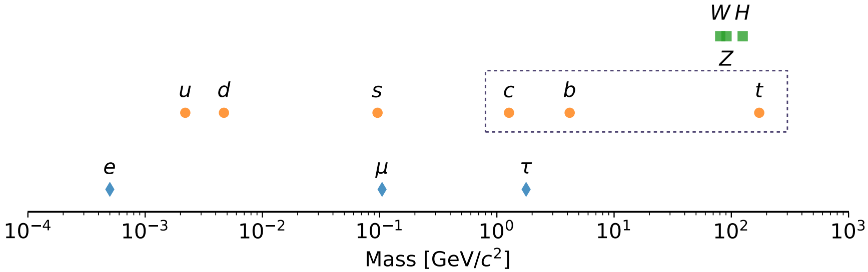
# WG5 Summary

## Physics with Heavy Flavours





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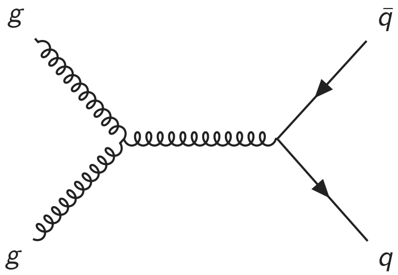
Friday 7th April 2017

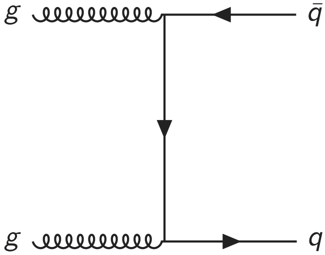
DIS 2017, Birmingham, UK

# What did we talk about?

1. Top quark pairs
2. Single top production and properties
3. Top quark mass
4. Beauty and charm quark production
5. Heavy flavour measurements for PDF fits (joint with WG1)
6. Properties of $B$ and $D$ hadrons
7. Exotic states
8. Quarkonia

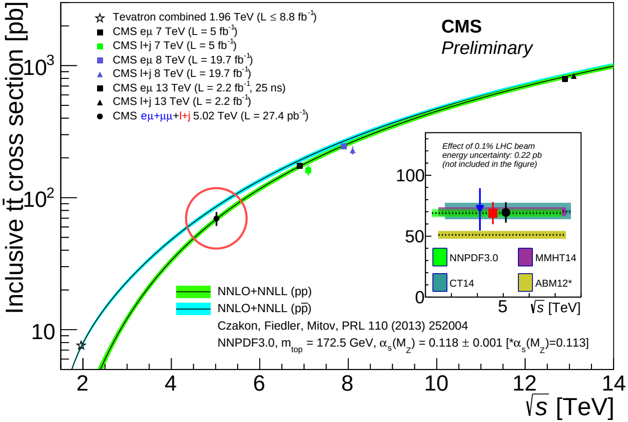
# Heavy flavour cross-sections in *pp* collisions




- Assume short- and long-distance processes factorise
- Test predictions of perturbative QCD
- Constrain non-perturbative QCD
- Useful for event modelling, MC generator tuning

Top quark is a particularly unique object, $\mathcal{O}(10^7)$ $t\bar{t}$ produced at the LHC so far

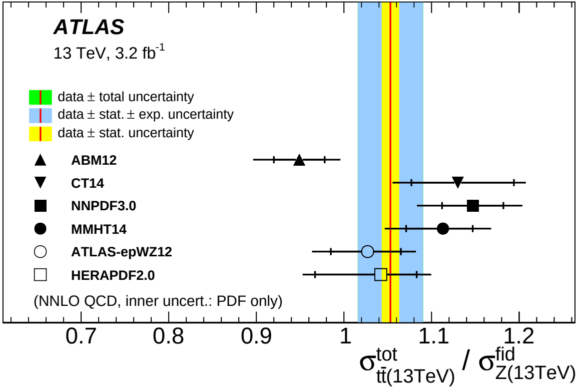



New! Combination of $\sigma(t\bar{t})$ at $\sqrt{s} = 5\,\text{TeV}$

# Top pair production



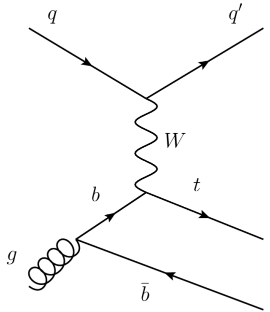
Top quark is a particularly unique object, $\mathcal{O}(10^7)$ $t\bar{t}$ produced at the LHC so far

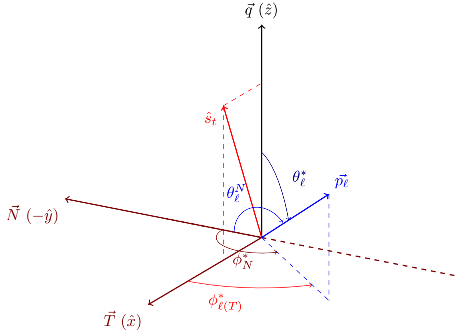



Measurement of $\sigma(t\bar{t})/\sigma(Z)$ at $\sqrt{s} = 13\,\mathrm{TeV}$, sensitive to quark-to-gluon PDF ratio

Single top productions probes electroweak physics

Example: Measure angular asymmetries in $Wtb$ vertex at the parton

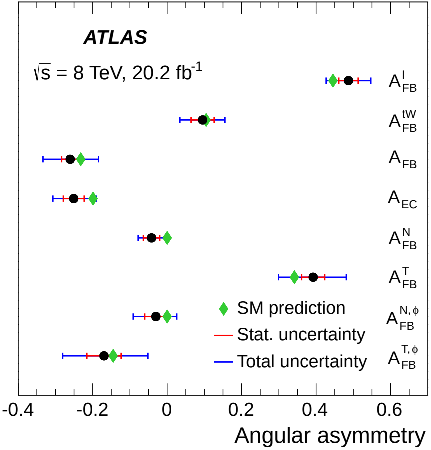



$$A_{\mathrm{FB}} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

Single top productions probes electroweak physics

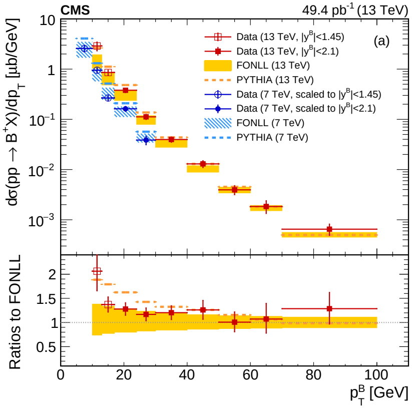
Example: Measure angular asymmetries in *Wtb* vertex at the parton



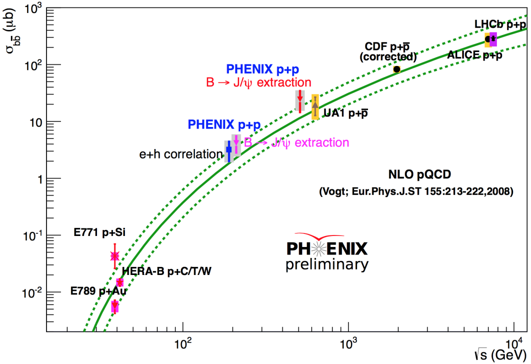
# Beauty production

P. Ronchese, M. Boer, X. Li

Charm and beauty production can test specific hadronisation schemes




$\sigma(pp \to B^+X)$ at $\sqrt{s} = 13\,\text{TeV}$




New $\sigma(pp \to b\bar{b})$ from PHENIX
at $\sqrt{s} = 200$ and $510\,\text{GeV}$

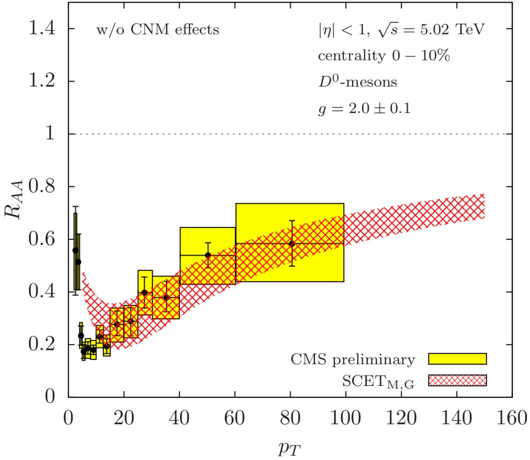
# Heavy flavour production in ion collisions

Z. Kang

Understanding quark-gluon plasma can help in understanding the early universe

At accelerators, interesting parameter is $R_H = \sigma(AA \to H)/\sigma(pp \to H)$

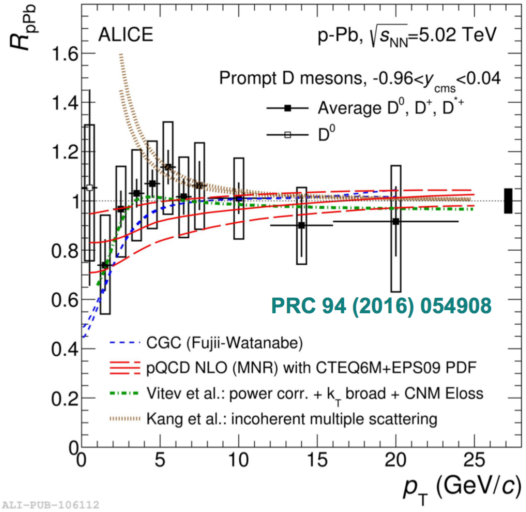
Study soft collinear effective theory for describing high $p_T$ objects traversing QGP



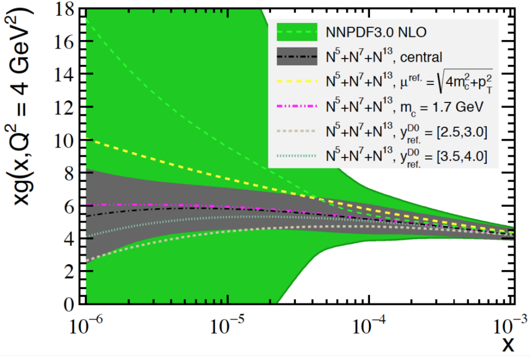

New $\sigma(pp \to b\bar{b})$ from PHENIX

Need to disentangle QGP from cold nuclear matter effects

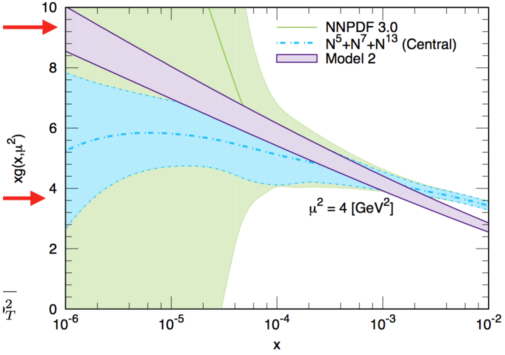
Use $p$Pb collisions as a probe of CNM



Significant improvement to high and low $x$ models when including (double) differential cross-sections

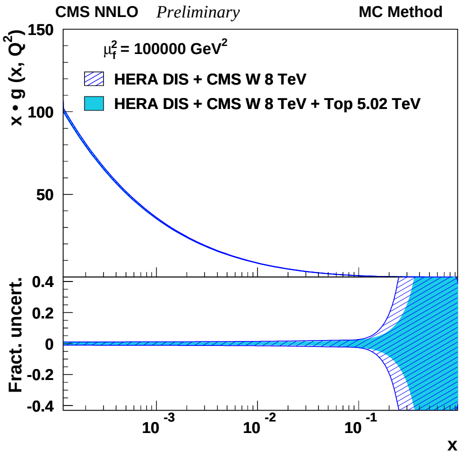



LHCb open charm

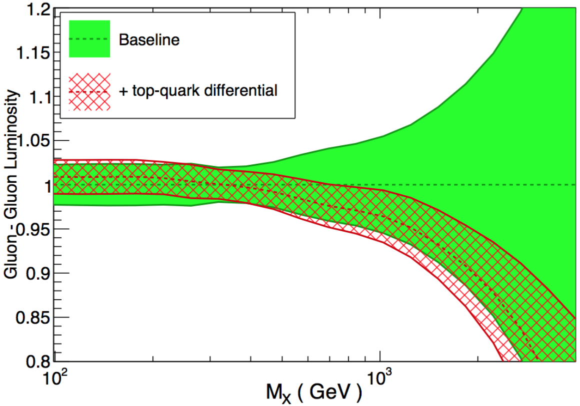



LHCb $J/\psi$

Significant improvement to high and low $x$ models when including (double) differential cross-sections




CMS $t\bar{t}$

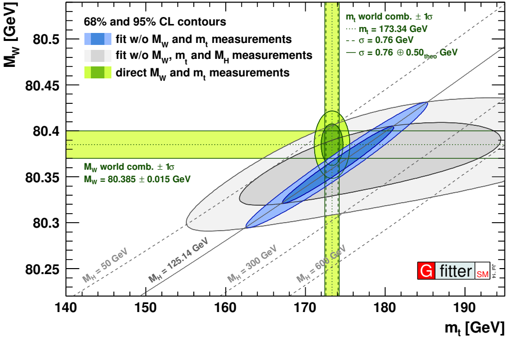



Combined ATLAS and CMS $t\bar{t}$

Production distributions of top quarks sensitive to $m_t$

Often reported experimentally by varying MC mass and choosing best-fit value to data

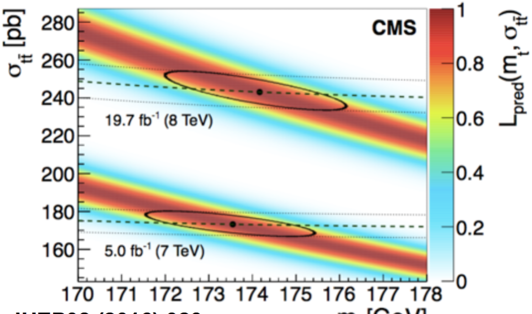
How to relate MC mass to the ‘true’ mass?




Top, $W^{\pm}$, and Higgs mass relationship very well-defined in the SM

Usually, include uncertainty on $m_t^{\mathrm{MC}} \leftrightarrow m_t^{\mathrm{true}}$ relation as uncertainty on $\sigma(t\bar{t})$

Alternative: simultaneously fit for $\sigma(t\bar{t})$ and $m_t^{\mathrm{MC}}$, determine MC $\leftrightarrow$ true relationship later

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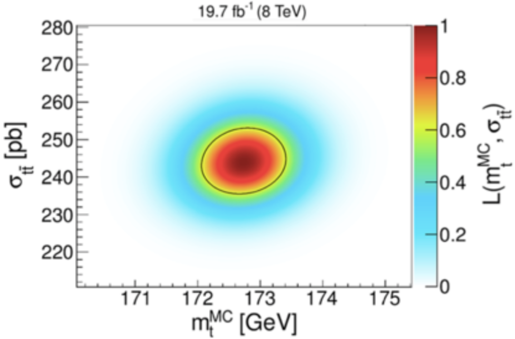
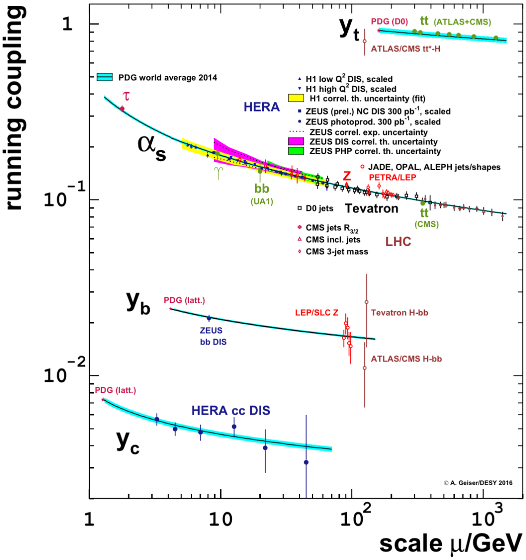


# Heavy flavour cross-sections as inputs

## Charm and bottom quark masses

Can measure the running of $c$ and $b$ using DIS data

Interpretation: higher scales $\leftrightarrow$ smaller distances, see less gluon field around the quark, hence less energy



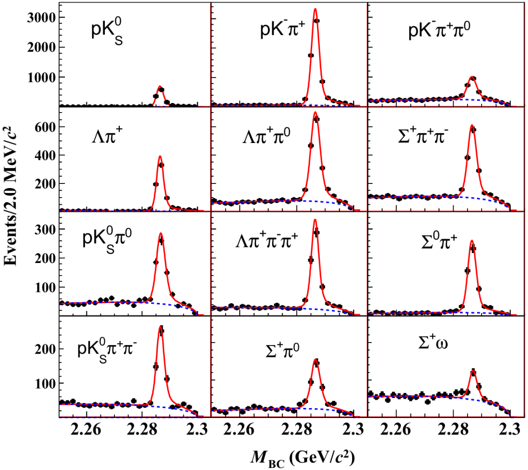
# Charm and beauty hadron properties

Heavy flavour hadron decays encompass a rich phenomenology:

- Neutral meson mixing, e.g. $D^0 \leftrightarrow \overline{D}^0$
- Violation of *CP* symmetry via the CKM matrix
- Sensitive to new particles entering loops in decay diagrams

Recent tensions in lepton universality and flavour-changing neutral currents (FCNC)

Several experiments competing, from no-longer-running to starting up this year

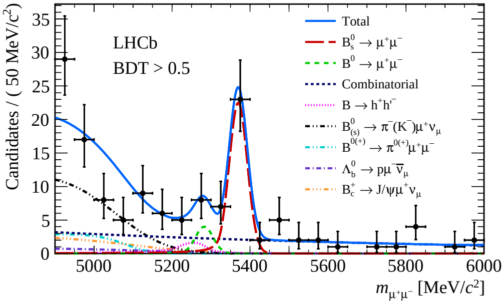


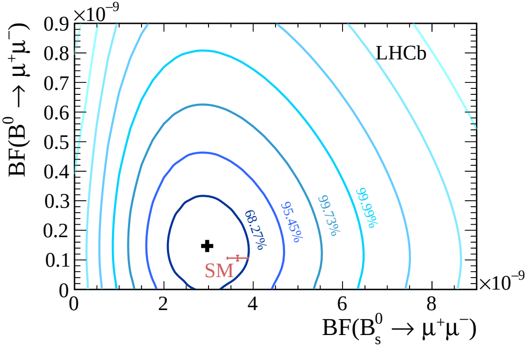

Large set of results from BESIII

Significant reduction in branching fraction uncertainties

Example: $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ from 25 % relative uncertainty (PDG) to 6 %

First observation by a single experiment of the FCNC process $B_s^0 \to \mu^+\mu^-$




$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.9) \times 10^{-9} \quad (7.8\,\sigma)$$

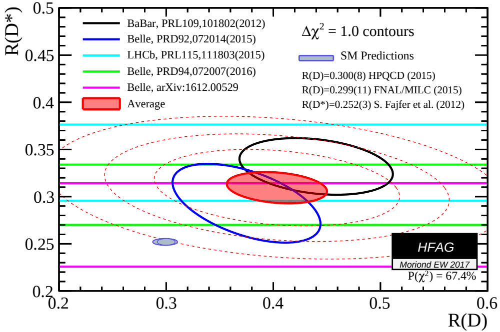
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.6^{+1.1}_{-0.9}) \times 10^{-10} \quad (1.9\,\sigma)$$

$$R(D^{*+}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^- \bar{\nu}_\mu)}$$

Test lepton universality

Sensitive to NP models like charged Higgs

Precise SM prediction due to cancellation of hadronic effects

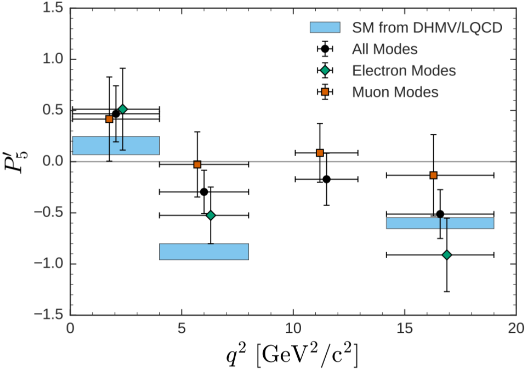



New Belle result consistent with SM, but still a $4\,\sigma$ tension

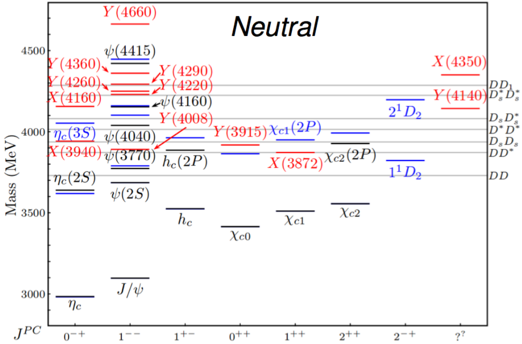
Experimental data exceeds predictions for effective operator $P_5'$ in $B \to K^* \mu^- \mu^+$

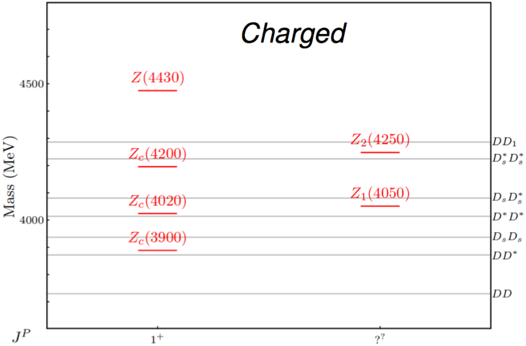
If significant, would require non-SM-like change in vector coupling strength $\mathcal{C}_9$

New results from Belle in both electron and muon modes and multiple $K^*$ states



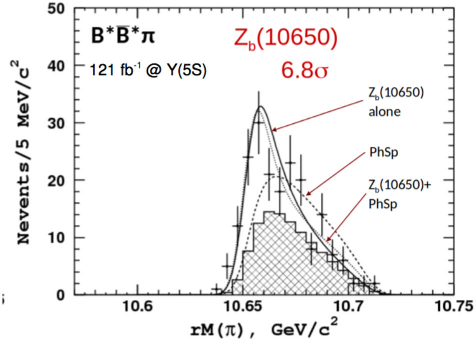

No lepton universality breaking, but 2.5 $\sigma$ deviation in one $P_5'$ bin

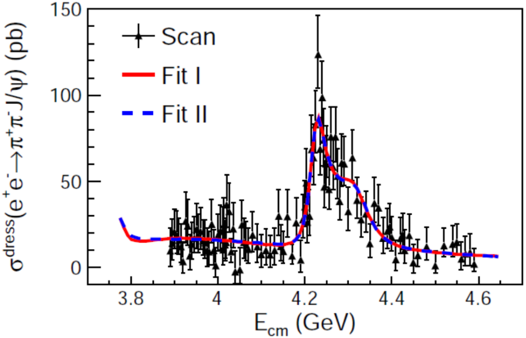



Expansive set of known exotic states so far

Systematic study of states presented by Belle and BESIII



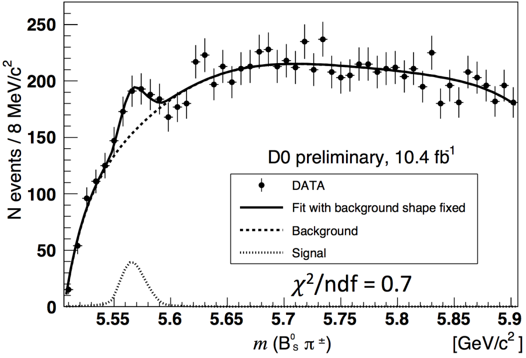



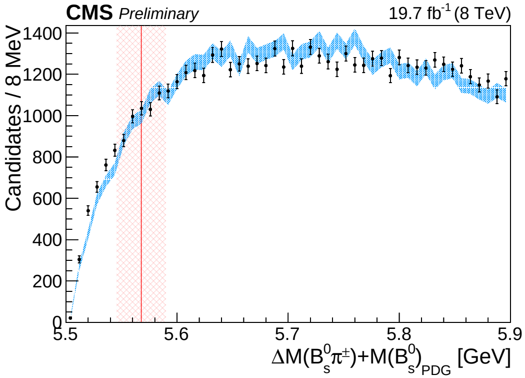

Further experimental and theoretical study of currently-known states is crucial

DØ collaboration announced discovery of $X(5568)$ state found in $B_s^0\pi^+$ spectrum

First used $B_s^0 \to J/\psi\phi$ decays, now report a consistent structure using $B_s^0 \to D_s^+\mu^-X$

LHCb nor CMS have been able to confirm the observation



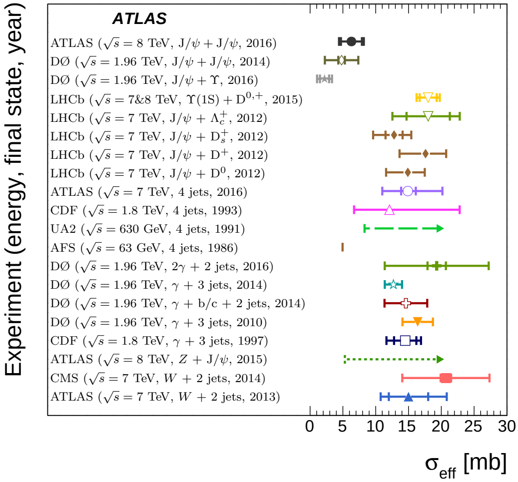



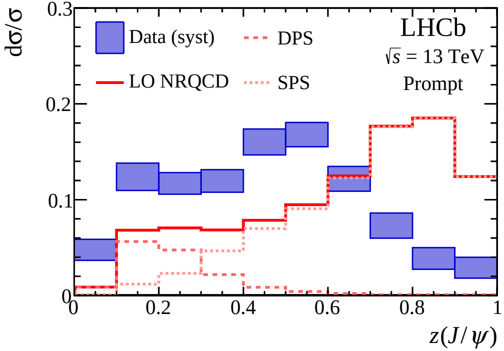

Explanation requires a significantly different production in $p\overline{p}$ to $pp$

# Quarkonia

M. Watson, J-P. Lansberg, P. Ilten

As a probe of double parton scattering



# Other highlights

- ATLAS and CMS measurements of *CP* violation using top production
- CMS measurements of FCNC processes with top quarks
- Belle II physics programme
- Discussion on intrinsic charm content of proton PDF
- Lots of impressive theoretical progress
- ...plenty more

# Summary

- WG5 saw a wide variety of very interesting topics
- Lots of cross-pollination
  - ALICE, ATLAS, CMS, and LHCb all overlap at least somewhat in most areas
  - Other experiments providing vital input in other areas of phase space
  - Theorists taking inputs from many more sources
  - Experimentalists trying to provide measurements with the highest utility
- Interplay of LHC heavy quark cross-section measurements with DIS is leading to greatly improved PDF precision, for better models for future colliders

# Thanks

Thanks to all the speakers and participants of WG5...

...and to the organisers for a great conference!

# Backup