

# QCD and Forward Physics

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HL/HE-LHC Meeting - Final Jamboree

CERN, 1 March 2019

# QCD and Forward Physics at the HE/HL-LHC

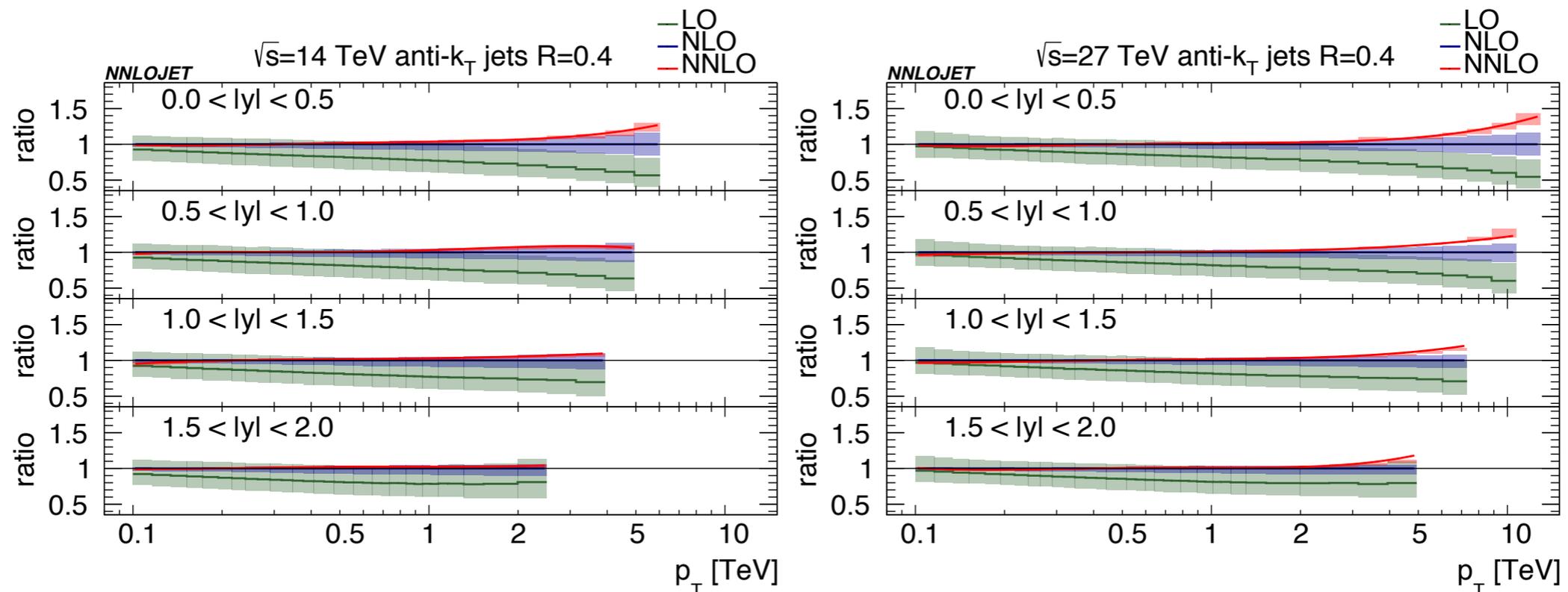
- Two chapters of yellow report dedicated to prospects for QCD and Forward physics:
  - ❖ **Strong Interactions:**
    - Projected HE/HL-LHC experimental reaches for **jet** and **photon** production.
    - Expected constraints on **PDFs** from final HL-LHC: ‘Ultimate’ PDFs.
    - Study of **underlying event** at HE-LHC, and prospects for studies of **double parton scattering** at HE/HL-LHC.
  - ❖ **Forward Physics:**
    - Prospects for **Central Exclusive Production** with increased reach of HL-LHC. Detailed case study: anomalous coupling constraints.
    - Experimental prospects for forward **proton tagging** studied in detail.

# Strong Interactions

# **Jets and Photons**

# Jet Production: Prospects

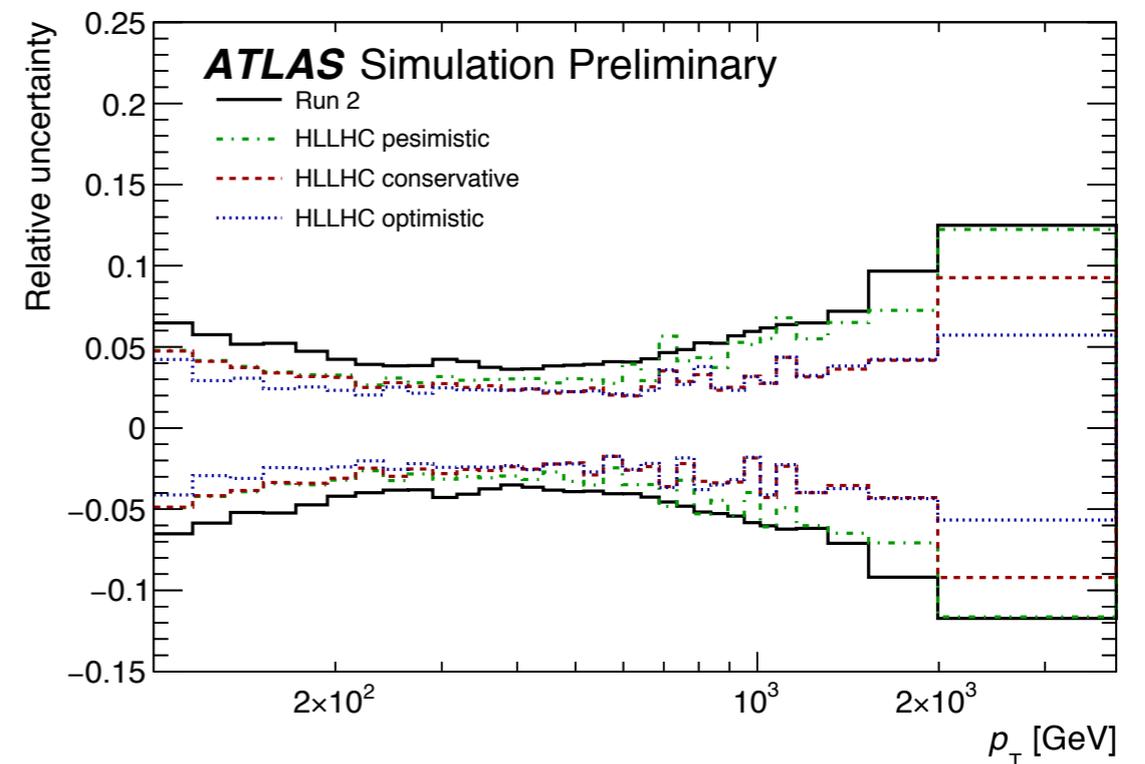
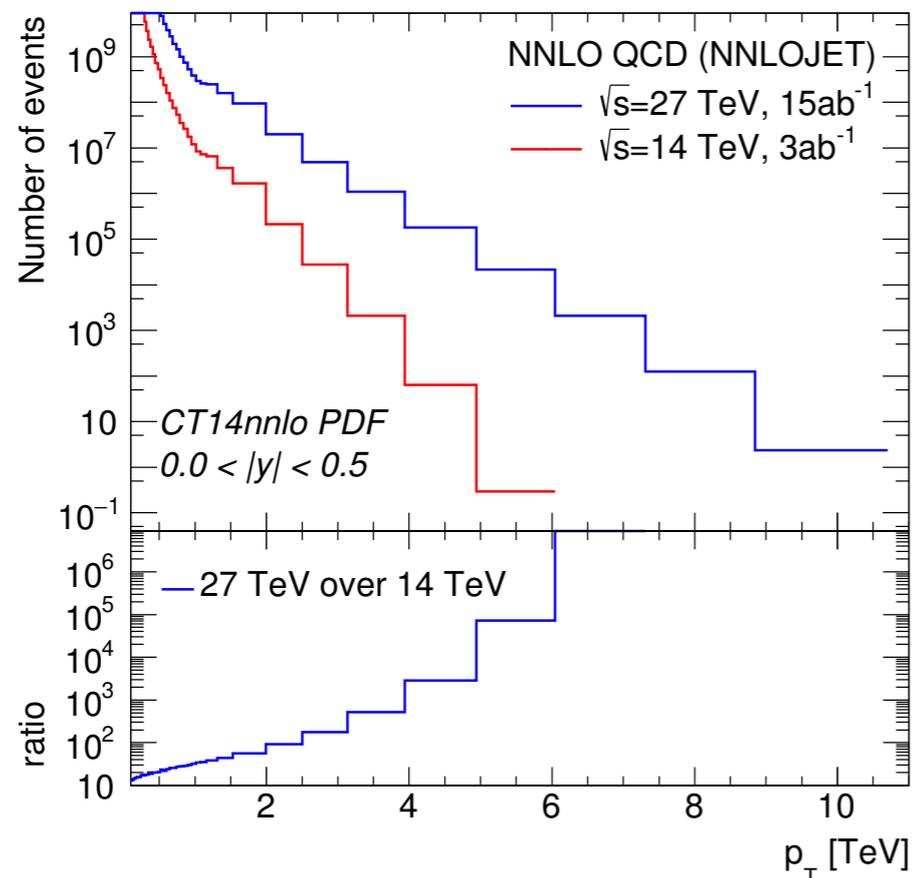
- Increased cross sections/reach at **HL** and **HE-LHC** will allow for precise multi-differential jet measurements:
  - ★ High  $p_{\perp}$  : sensitivity to higher-order QCD/EW and BSM.
  - ★ Fixed  $p_{\perp}$ , increased  $\sqrt{s}$  : push to low  $x \Rightarrow$  resummation effects.
- Theory: **NNLO** the standard now. Excellent convergence and small scale uncertainties out to large  $p_{\perp} \Rightarrow$  potential for PDF constraints.



Similar results for dijet production: see backup for more.

# Jet Production: Experimental Prospects

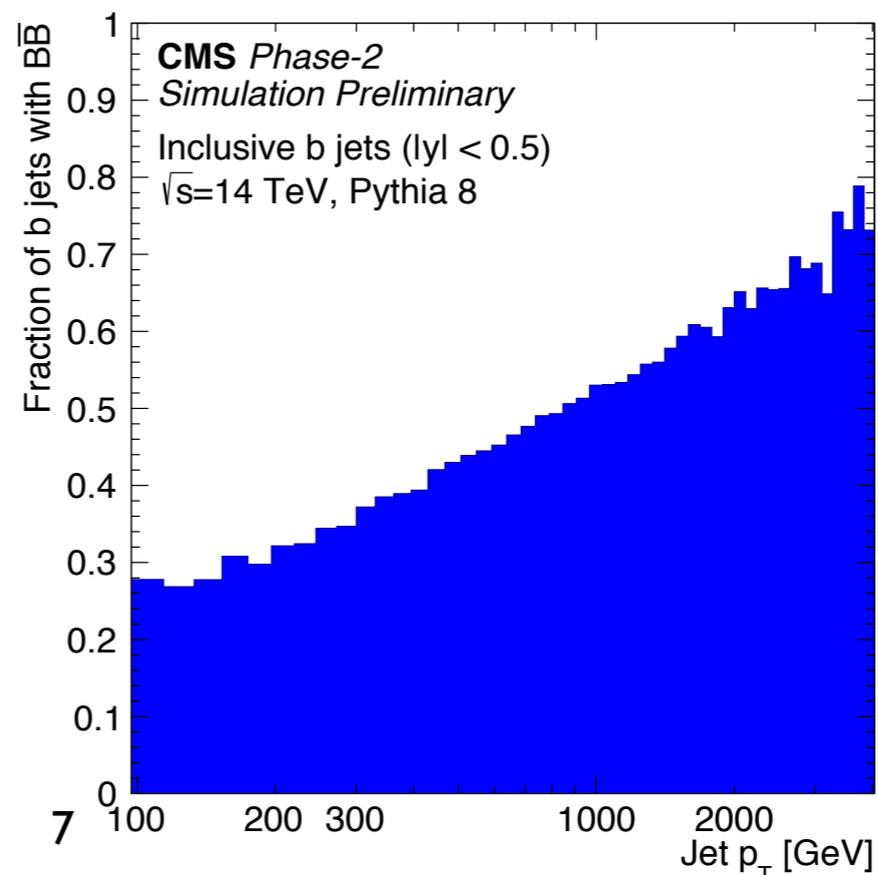
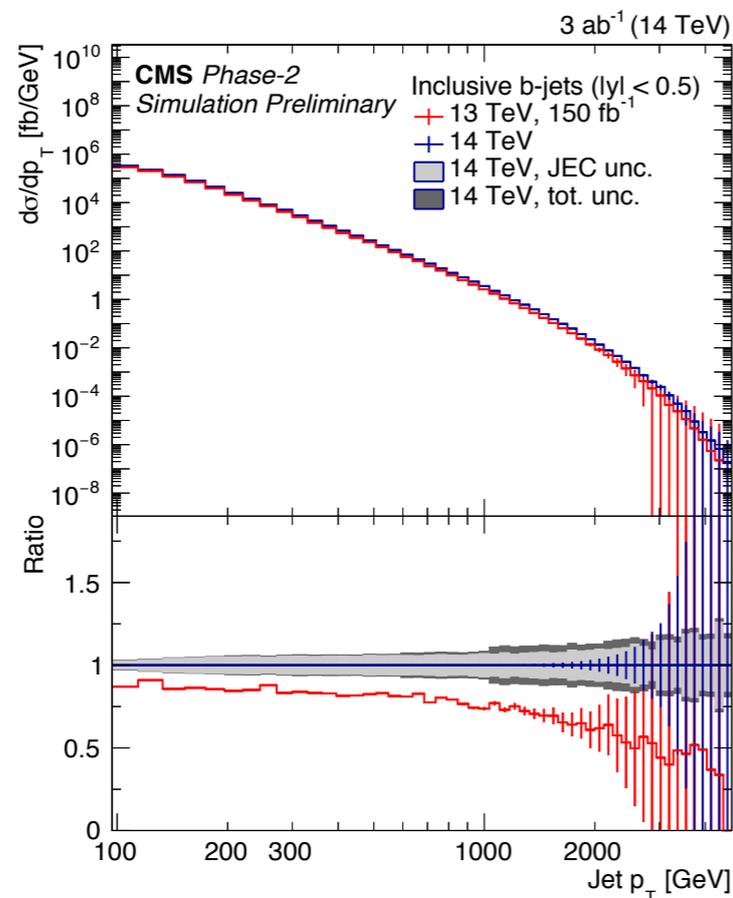
- **ATLAS** projections for inclusive jet production at **HL** and **HE-LHC**, including detailed study of systematic uncertainties:
  - ★ Potentially significant improvement in uncertainties at both low and high jet  $p_{\perp}$  demonstrated, depending on scenario considered.
  - ★ Extensive jet  $p_{\perp}$  reach:  $\sim 5$  (9) TeV at HL (HE) LHC.



Similar results for dijet production: see backup for more.

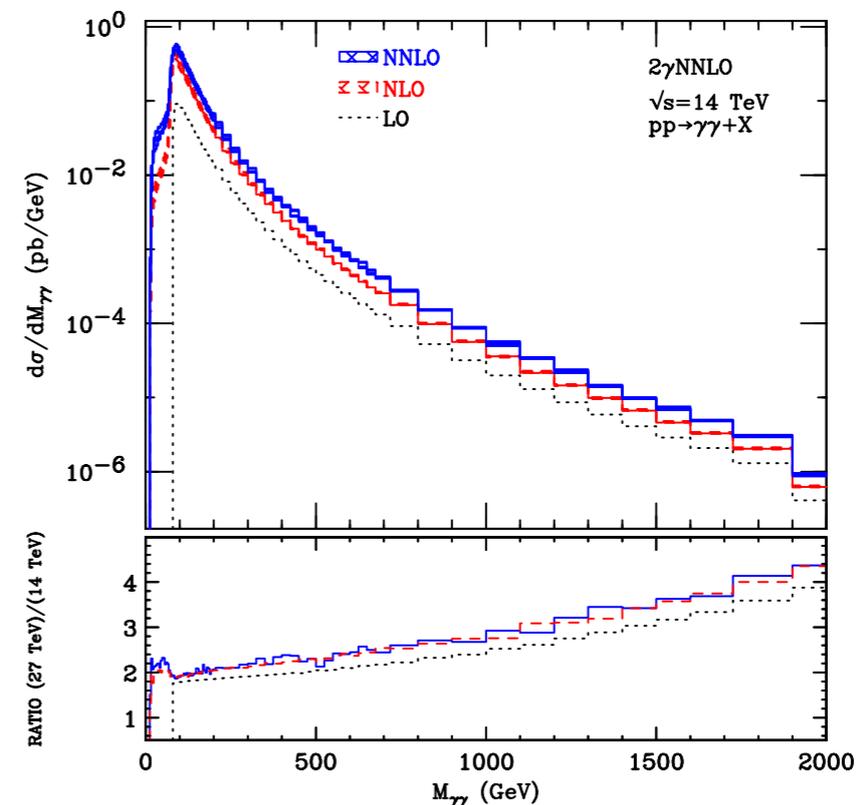
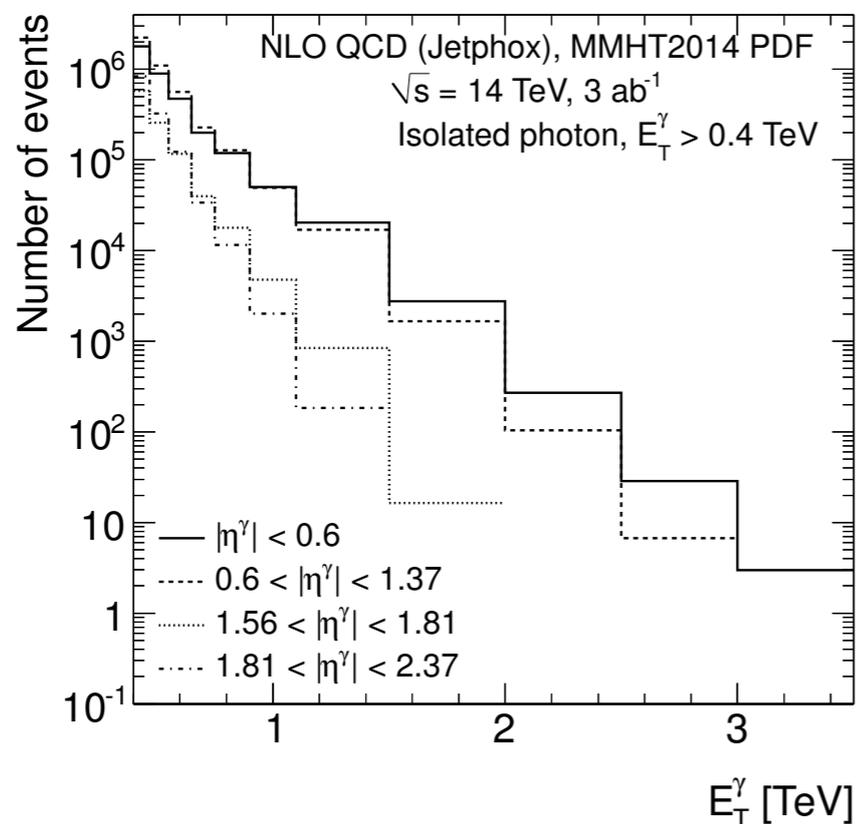
# Heavy Flavour Jet Production

- Heavy  $b$  quark jet production: sensitivity to higher-order corrections, parton shower, PDFs...
- **CMS** projections for b-jet production at **HL-LHC**:
  - ★ Increased  $b$ -jet reach:  $p_{\perp} \sim 3$  TeV.
  - ★ New regime:  $b$ -quark  $\sim$  massless w.r.t. high  $p_{\perp}$  jet large fraction of jets with  $B + \bar{B}$  due to PS ( $g \rightarrow b\bar{b}$ ): important to disentangle from  $b$ -quarks produced in hard subprocess.



# Photon Production

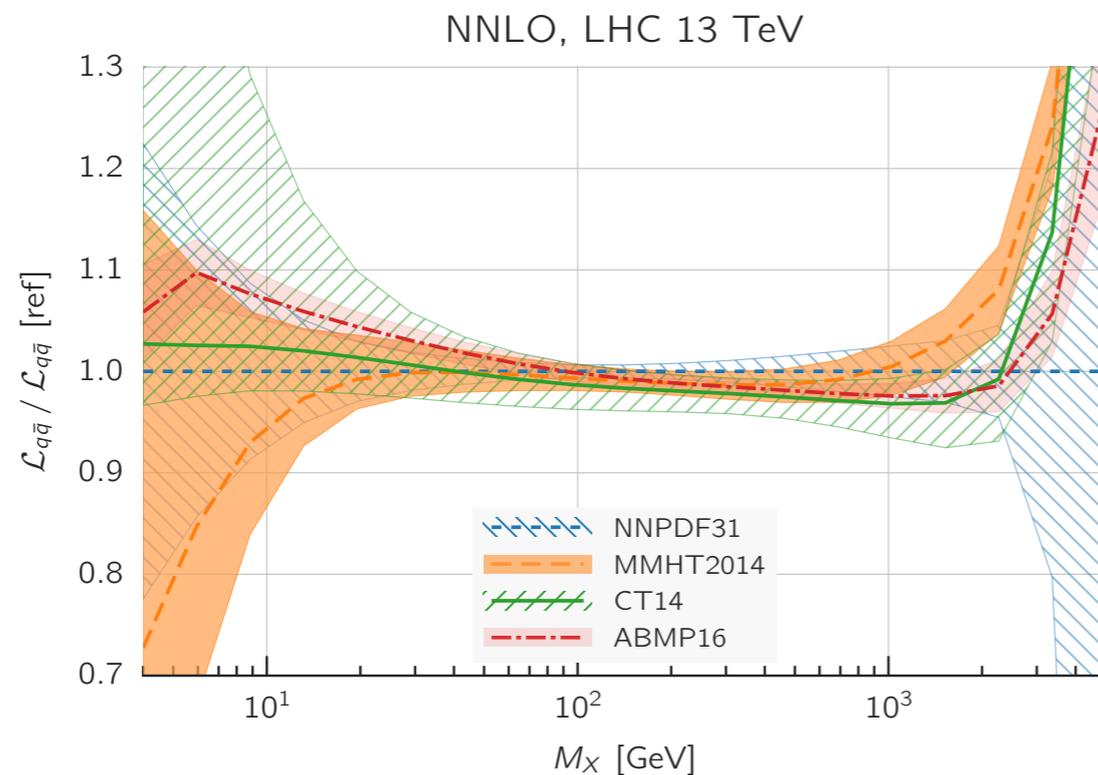
- Encouraging results for photon production: relatively clean probe of SM (PDFs...) and BSM.
  - ★ **Isolated photon**: **CMS** projections show extensive reach, with  $E_{\perp}^{\gamma} \sim 3(5)$  TeV for the HL(HE)-LHC. Increase by  $\sim 2-3$  w.r.t. existing data.
  - ★ **Diphoton** production: predictions with cutting-edge **NNLO** theory. Significant increase in reach with HE-LHC again shown.



# PDFs after the HL-LHC

# Ultimate PDFs

- The **HL-LHC** will provide a vast range of data with a direct impact on the PDFs (in particular in poorly known high  $x$  region relevant to BSM).
- **Question:** what exactly can we expect that impact to be?
- Collaborative effort to produce ‘ultimate’ PDF set, quantifying this expected impact.



• R. Abdul Khalek, S. Bailey, J. Gao,  
L.A. Harland-Lang, J. Rojo

# Basic Idea

Produce theory predictions for relevant processes, in kinematic region probed by HL-LHC



Produce pseudodata - binned predictions, provided with corresponding statistical + systematic errors



Perform initial profiling with PDF4LHC baseline to assess impact of HL-LHC pseudodata set

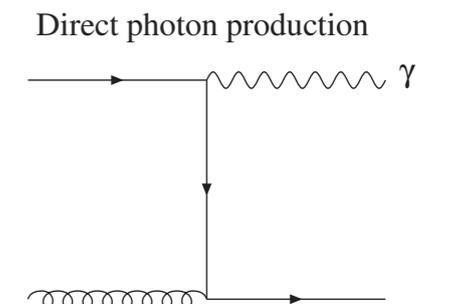
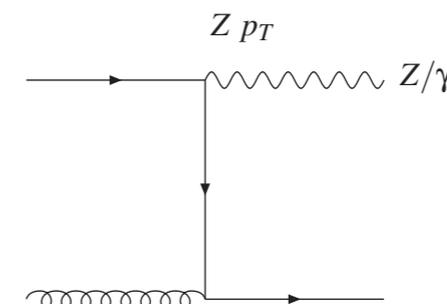
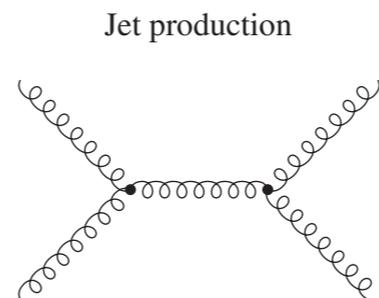
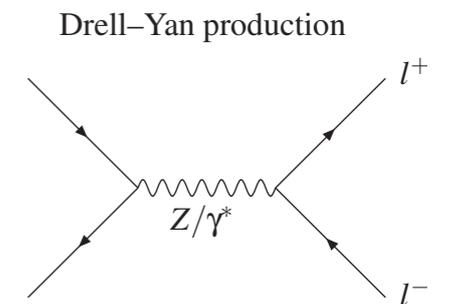
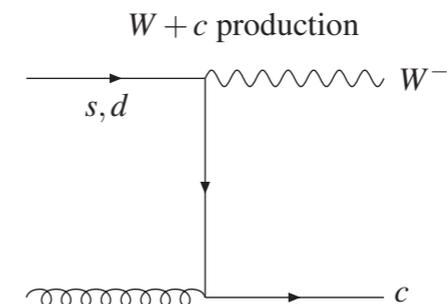
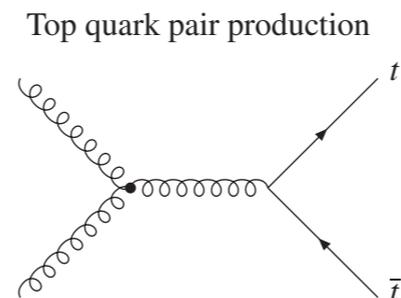


Public release of 'Ultimate PDF' set

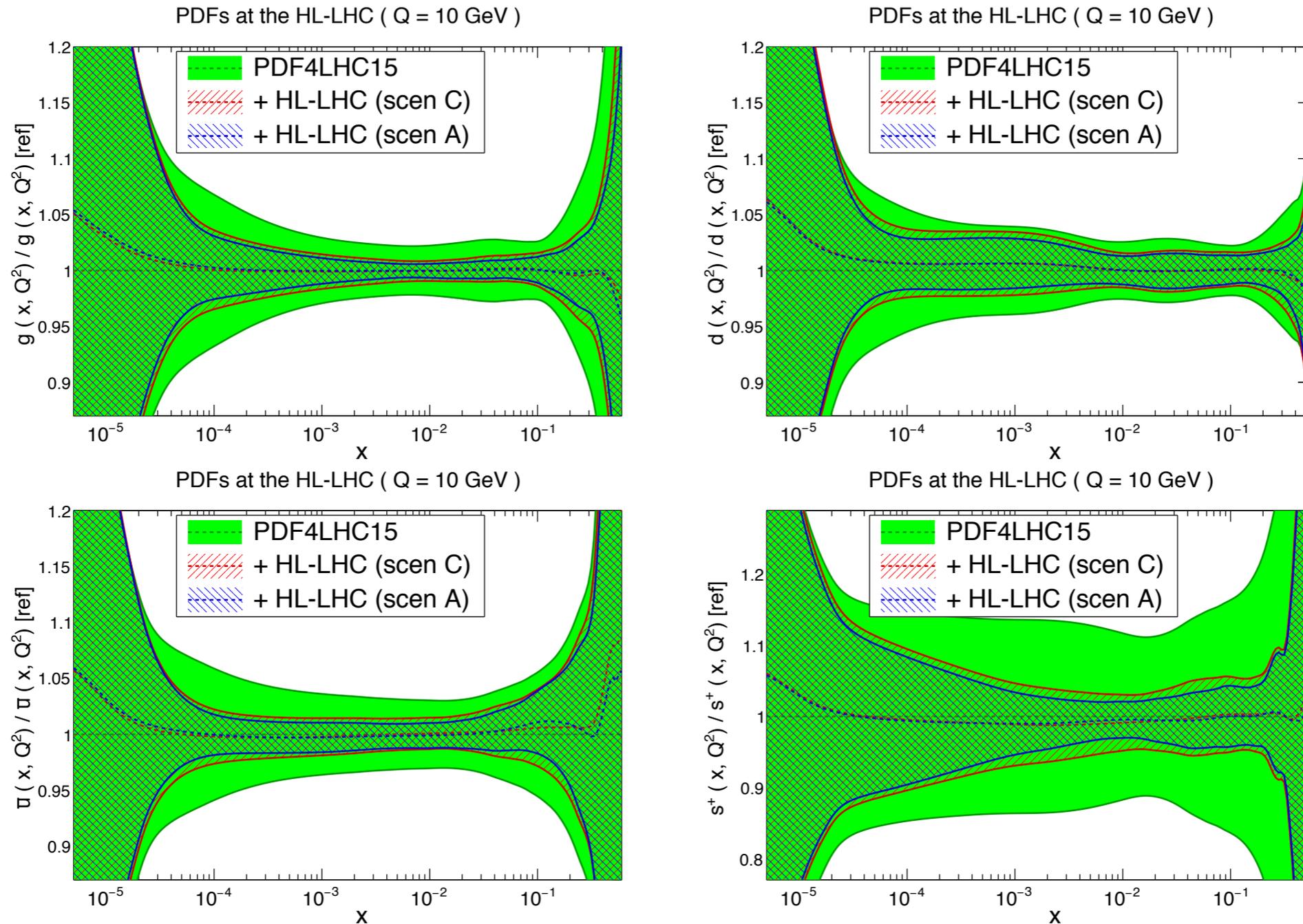
# LHC datasets

- Consider non-exhaustive list of **HL-LHC** processes. Emphasis on high  $x$  region + measurements not already limited by systematic uncertainties.

| Process              | Kinematics  | $N_{\text{dat}}$ |
|----------------------|---|------------------|
| $Z p_T$              | $20 \text{ GeV} \leq p_T^l \leq 3.5 \text{ TeV}$<br>$12 \text{ GeV} \leq m_{ll} \leq 150 \text{ GeV}$<br>$ y_l  \leq 2.4$                             | 338              |
| high-mass Drell-Yan  | $p_T^{l1(2)} \geq 40(30) \text{ GeV}$<br>$ \eta^l  \leq 2.5, m_{ll} \geq 116 \text{ GeV}$   | 32               |
| top quark pair       | $m_{t\bar{t}} \simeq 5 \text{ TeV},  y_t  \leq 2.5$   | 110              |
| $W$ +charm (central) | $p_T^\mu \geq 26 \text{ GeV}, p_T^c \geq 5 \text{ GeV}$<br>$ \eta^\mu  \leq 2.4$  | 12               |
| $W$ +charm (forward) | $p_T^\mu \geq 20 \text{ GeV}, p_T^c \geq 20 \text{ GeV}$<br>$p_T^{\mu+c} \geq 20 \text{ GeV}$<br>$2 \leq \eta^\mu \leq 4.5, 2.2 \leq \eta^c \leq 4.2$ | 10               |
| Direct photon        | $E_T^\gamma \lesssim 3 \text{ TeV},  \eta_\gamma  \leq 2.5$   | 118              |
| Forward $W, Z$       | $p_T^l \geq 20 \text{ GeV}, 2.0 \leq \eta^l \leq 4.5$<br>$60 \text{ GeV} \leq m_{ll} \leq 120 \text{ GeV}$  | 90               |
| Inclusive jets       | $ y  \leq 3, R = 0.4$   | 58               |
| Total                |   | 768              |



# Results



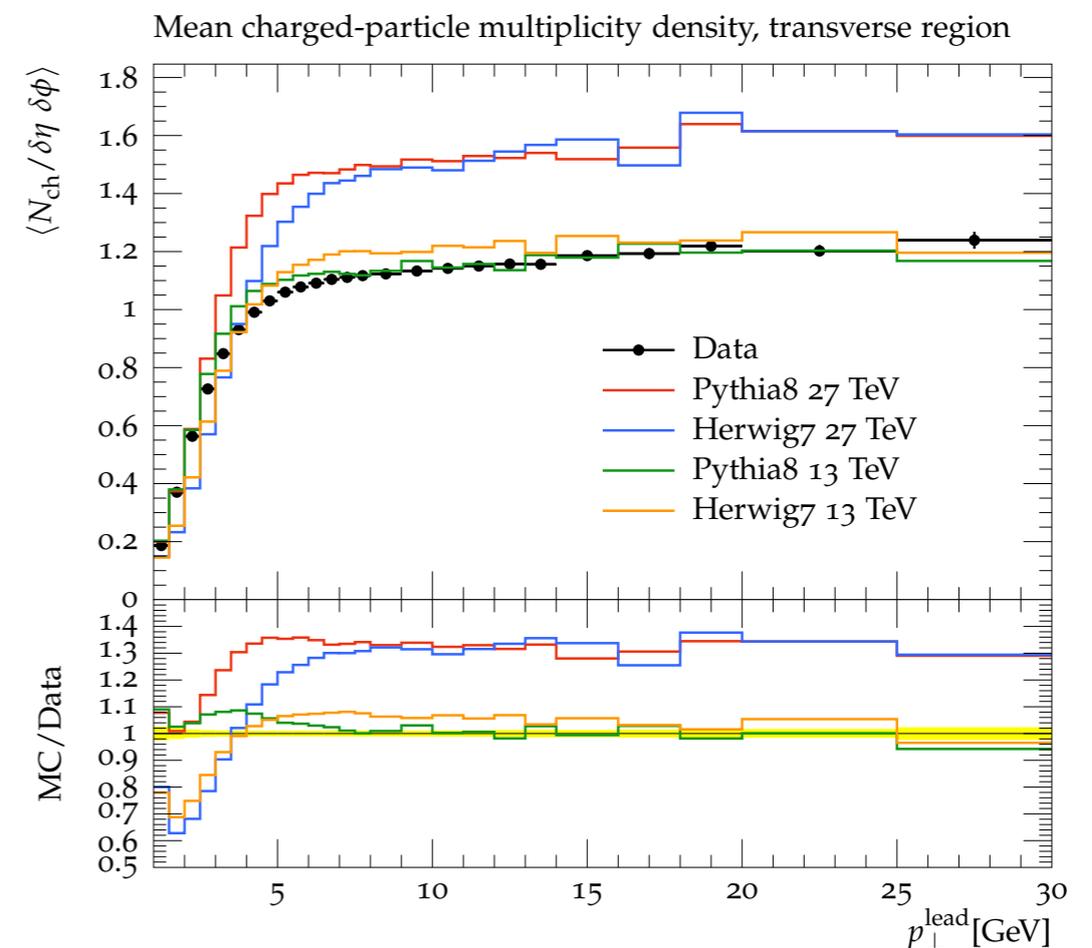
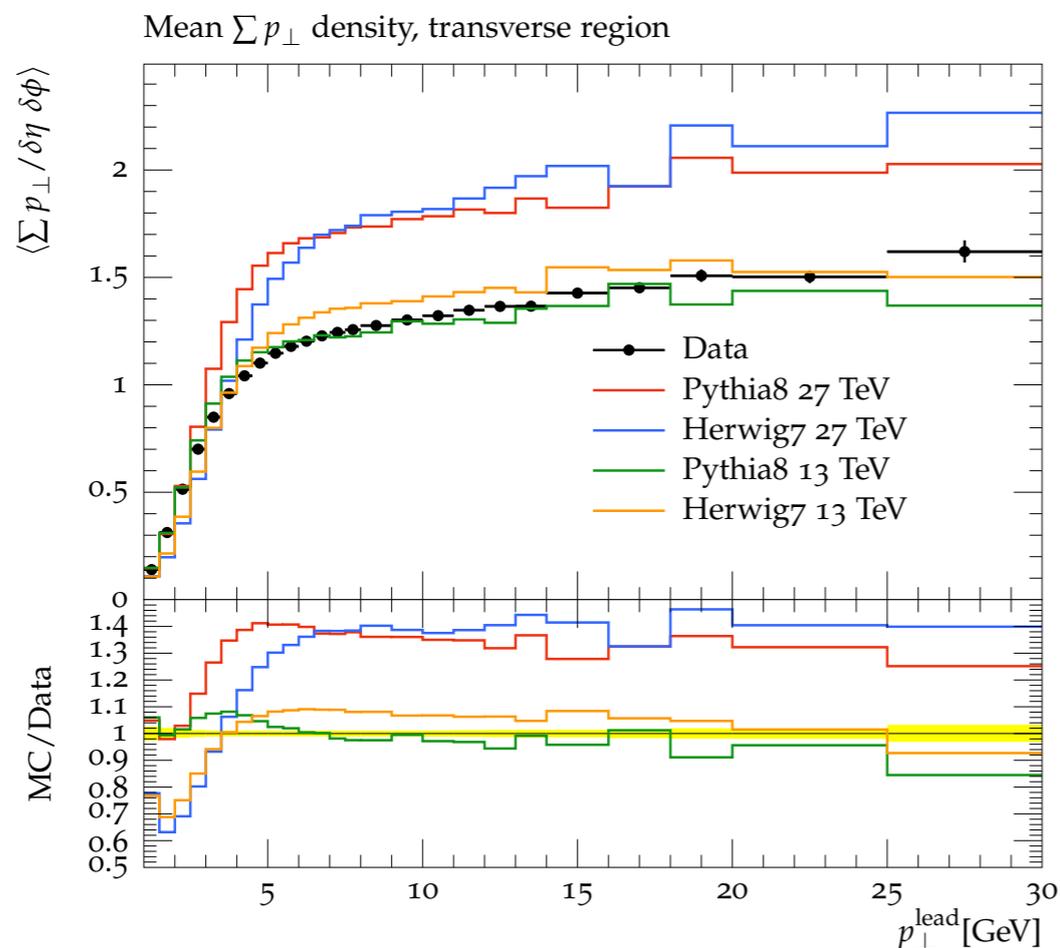
- **Significant error reduction**, with little dependence assumptions about projected systematics.
- LHAPDF sets publicly available for use.

[https://data.nnpdf.science/HLLHC\\_YR/PDF4LHC15\\_nnlo\\_hllhc\\_scen1.tgz](https://data.nnpdf.science/HLLHC_YR/PDF4LHC15_nnlo_hllhc_scen1.tgz)  
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# Underlying Event and MPI

# Underlying Event at HE-LHC

- Predictions for UE require MC tuning. MC predictions for MPI from Tevatron did not describe LHC, with MC predictions varying wildly.
- How about from **LHC** to **HE-LHC**? Dedicated study indicates:
  - ★ Increased UE (as expected) at HE-LHC:  $\sim 25\text{-}30\%$  more activity.
  - ★ Welcoming **stability** between latest Pythia/Herwig predictions.

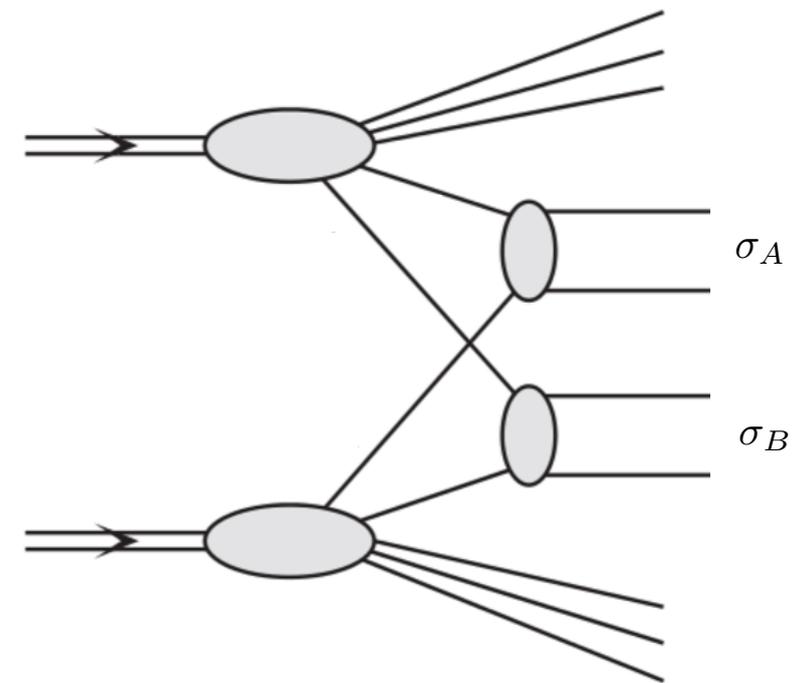


# Double Parton Scattering

- **DPS**: production of some final state  $AB$  by two distinct hard scatters. Generally suppressed, but can be important where SPS cross section low, e.g. same sign  $WW$ .
- Under certain assumptions, have simple ‘pocket’ formula

$$\sigma_{\text{DPS}}^{AB} \simeq \frac{\sigma_{\text{SPS}}^A \sigma_{\text{SPS}}^B}{\sigma_{\text{eff}}}$$

- Assumes no cross-talk/correlation between initiating partons for processes  $A$ ,  $B$ . Known to be false, but data so far insensitive to this.
- Potential to probe correlations and QCD nature of DPS differentially for the **first time** at **HL/HE-LHC**: subject of detailed study.

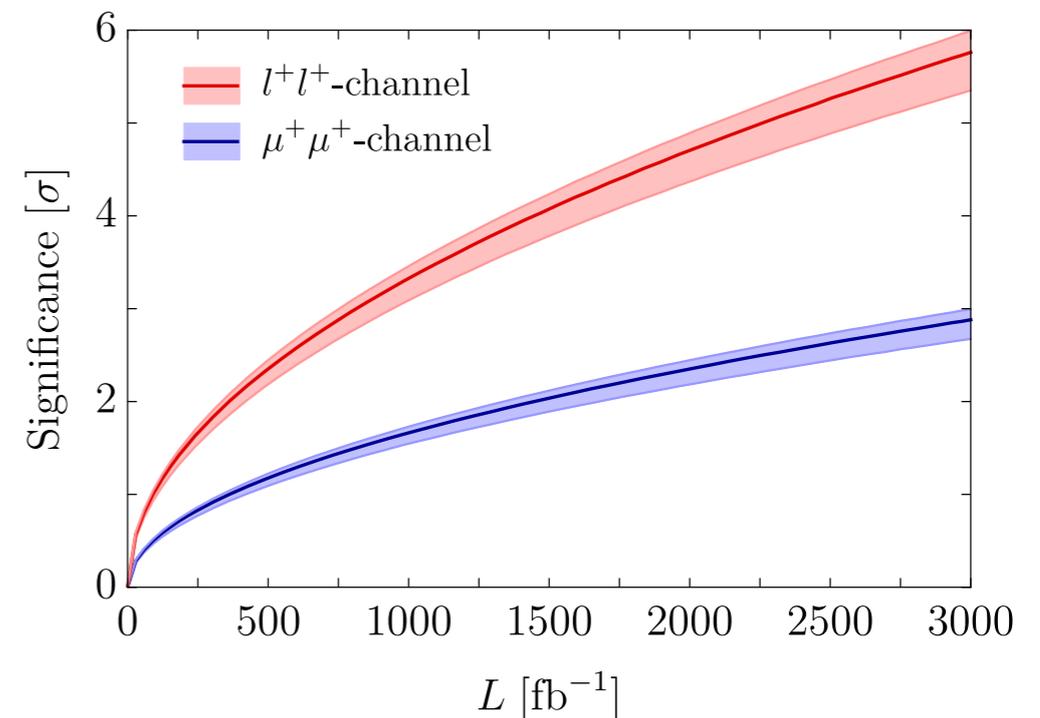
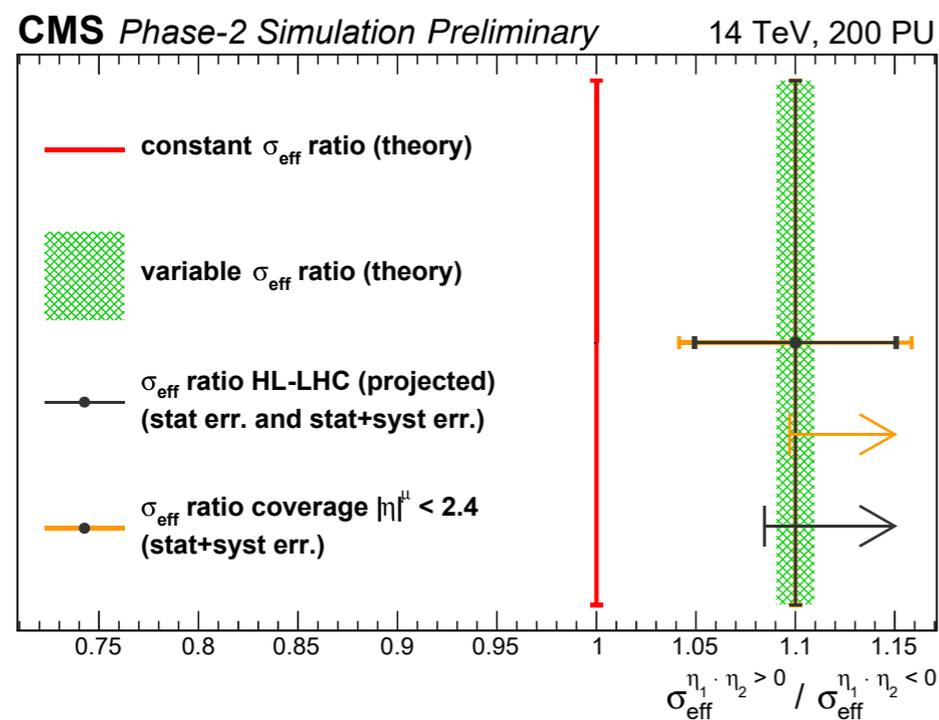


- Test case: **same sign W** pair production. Consider asymmetry:

$$a_{\eta_l} = \frac{\sigma(\eta_1 \cdot \eta_2 < 0) - \sigma(\eta_1 \cdot \eta_2 > 0)}{\sigma(\eta_1 \cdot \eta_2 < 0) + \sigma(\eta_1 \cdot \eta_2 > 0)},$$

which by construction is zero in absence of correlations. Range of more realistic scenarios considered:  $a_{\eta_l} \sim 10\%$ .

- Anticipated sensitivity at **HL-LHC** studied. Find this percent level effect can be measured for the first time: a completely **new** and so-far unobserved QCD phenomenon.

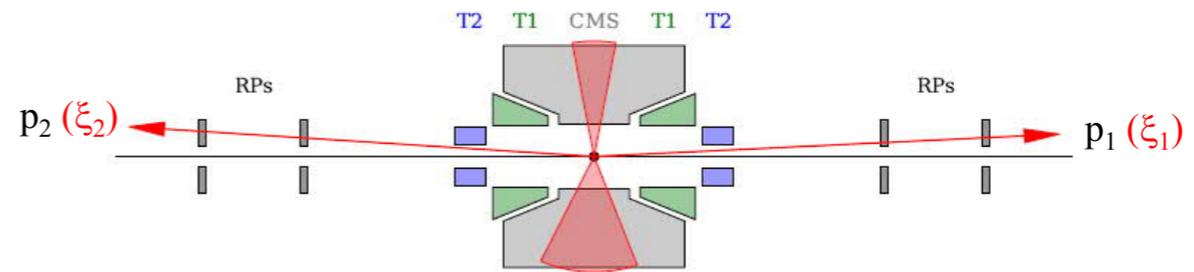


# Forward Physics

# Central Exclusive Production

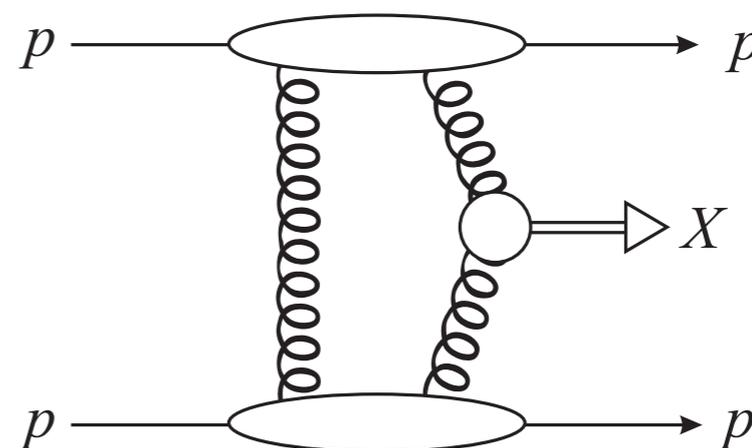
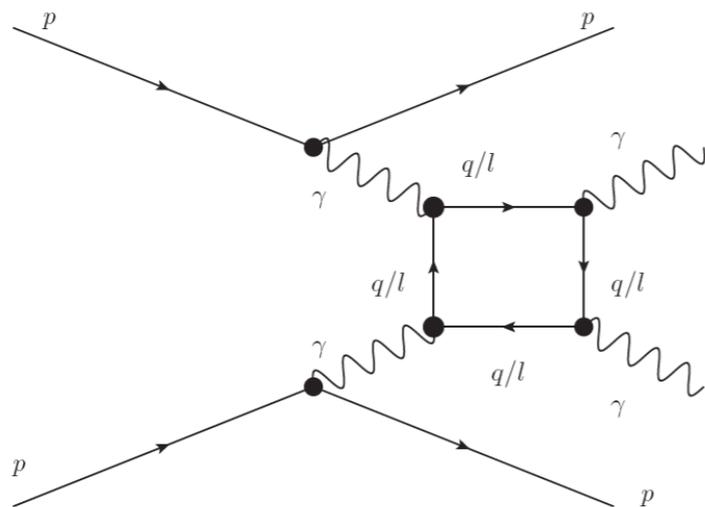
- Potential for extended studies of **CEP**: production of object  $X$  + nothing else:

$$pp \rightarrow p + X + p$$



$X$  = all products except the 2 leading protons

- Ongoing experimental programme of measurements at LHC, with protons tagged by dedicated forward detectors in association with ATLAS (**AFP**) and CMS (**CT-PPS**).
- Exciting possibility to continue this into **HL-LHC**.



# Physics with tagged protons - QED

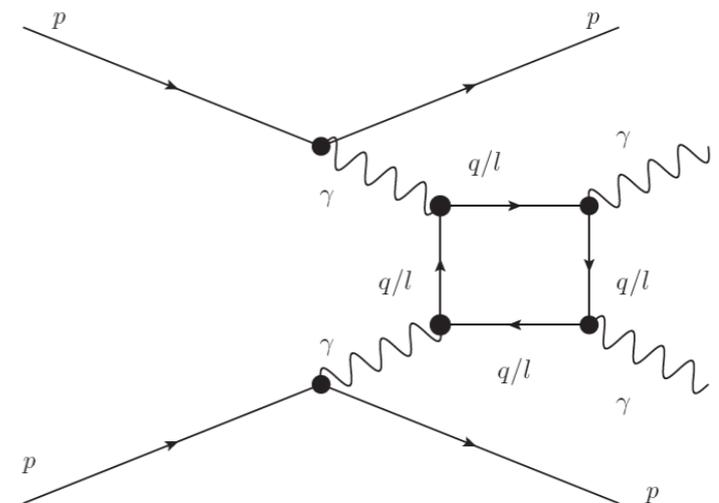
- Exclusive photon-initiated production of particular interest for **BSM**-clean and well understood  $\gamma\gamma$  initial state (prob. of  $pp$  MPI interactions low).

→ LHC as a (high energy)  $\gamma\gamma$  collider!

★ Relatively rare EW processes  $\Rightarrow$  gain from increased HL-LHC dataset clear.

★ Relevant to various BSM channels (ALPs, SUSY...).

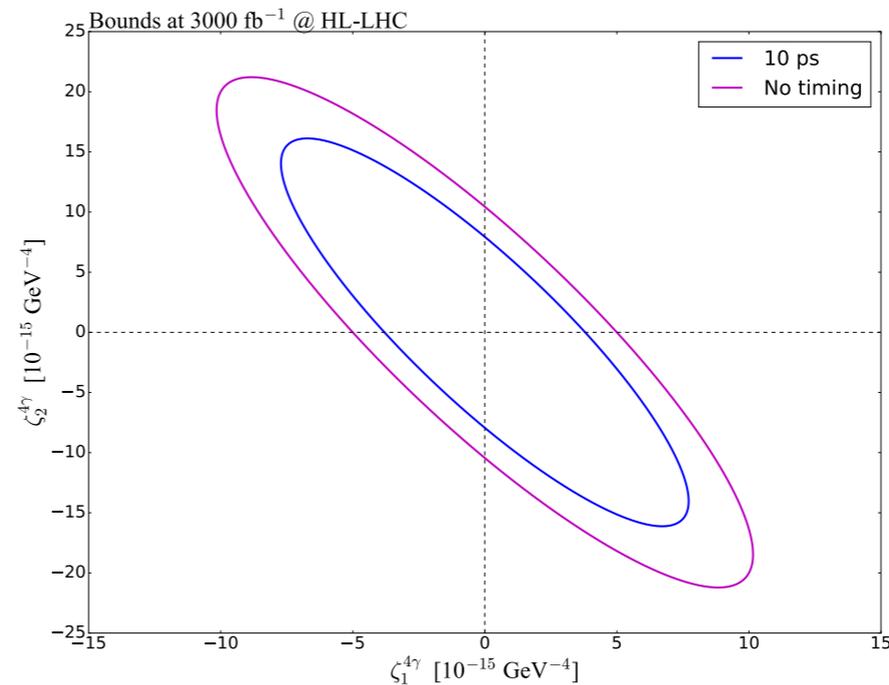
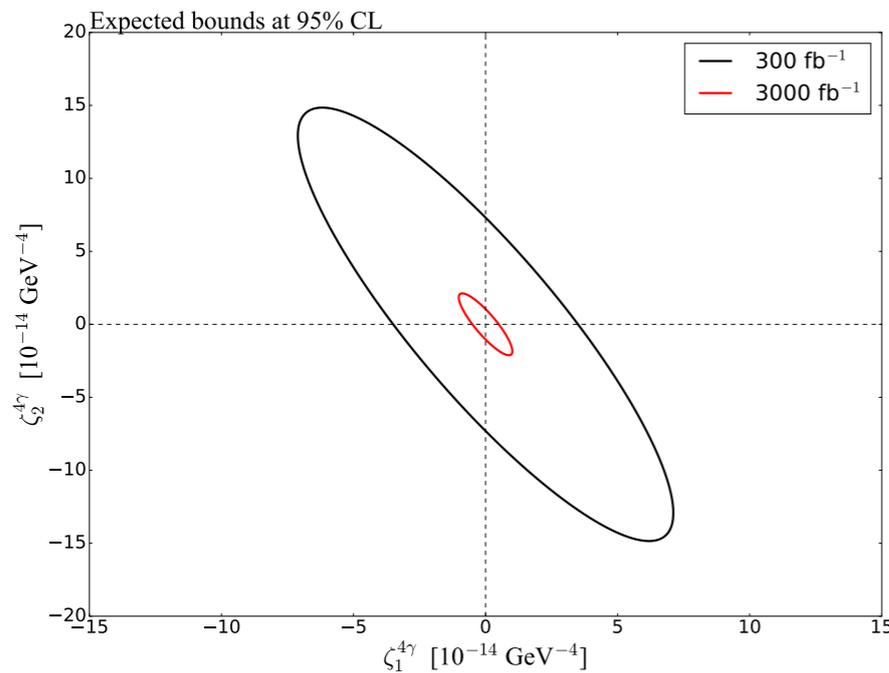
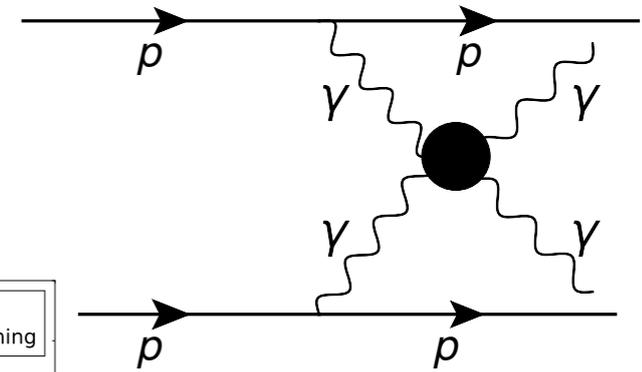
★ **Benchmark study** in report: assessment of discovery potential for **anomalous gauge couplings** under realistic experimental conditions.



# Anomalous couplings - $4\gamma$

- Model interaction via EFT, two dimension 8 operators:

$$\mathcal{L}_{\gamma\gamma\gamma\gamma} = \zeta_1^{4\gamma} F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} + \zeta_2^{4\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

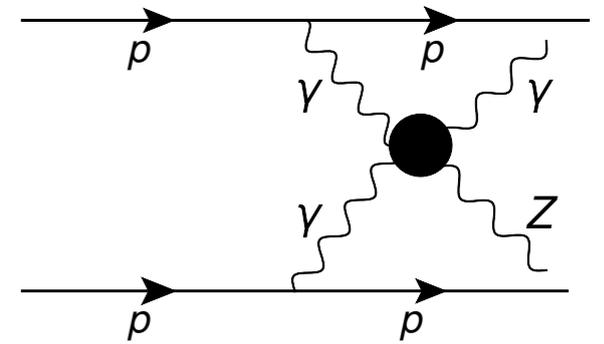


**Left:** comparison between  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$ . **Right:** (zooming-in, see change of scale in X-Y axis) comparison between the use of timing and  $\delta t = 10 \text{ ps}$  (not much difference if 5 ps and 2 ps are used).

- HL-LHC** can improve bound on EFT operators by  $\sim$  an **order of magnitude**. Little sensitivity to precise level of timing precision.

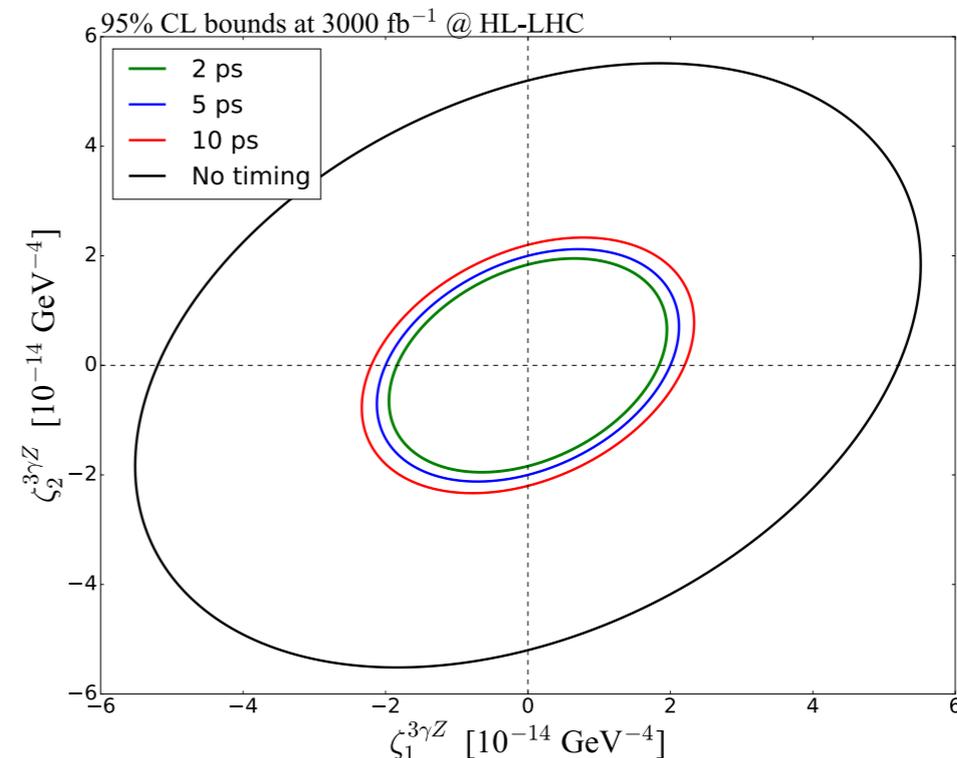
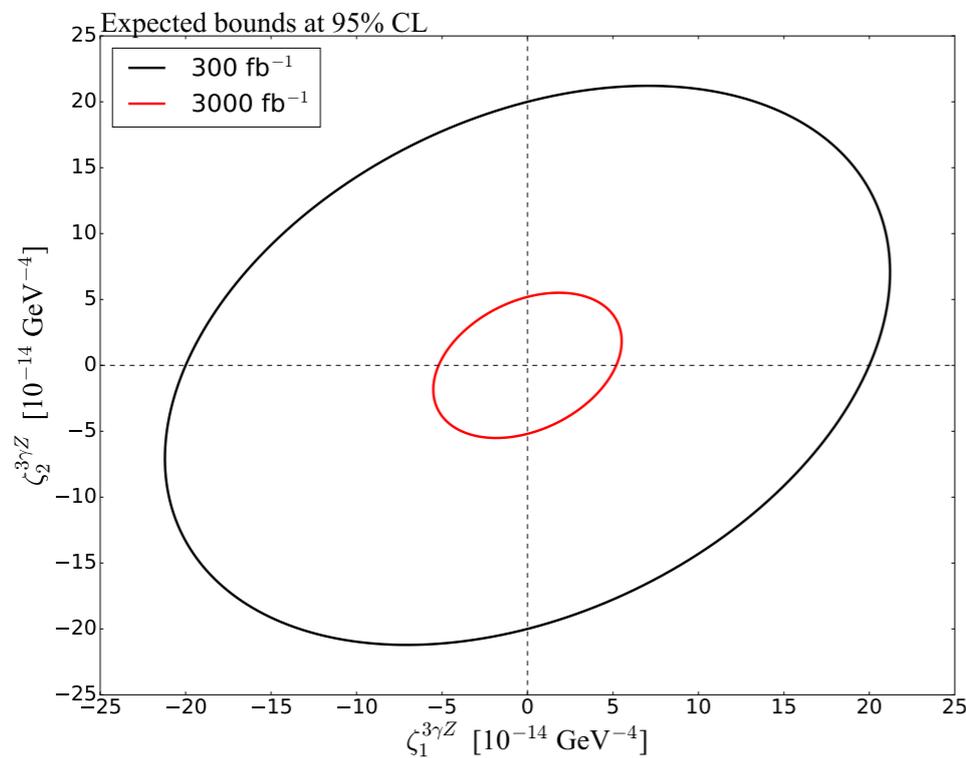
$$\sqrt{48\zeta_1^2 + 11\zeta_2^2 + 40\zeta_1\zeta_2} \leq 2.4 \cdot 10^{-13} \text{ GeV}^{-4} \rightarrow 4.2 \cdot 10^{-14} \text{ GeV}^{-4}$$

# Anomalous couplings - $\gamma Z$



- Again set limits via EFT operators:

$$\mathcal{L}_{\gamma\gamma\gamma Z} = \zeta_1^{3\gamma Z} F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \zeta_2^{3\gamma Z} F^{\mu\nu} \tilde{F}_{\mu\nu} F^{\rho\sigma} \tilde{Z}_{\rho\sigma}$$



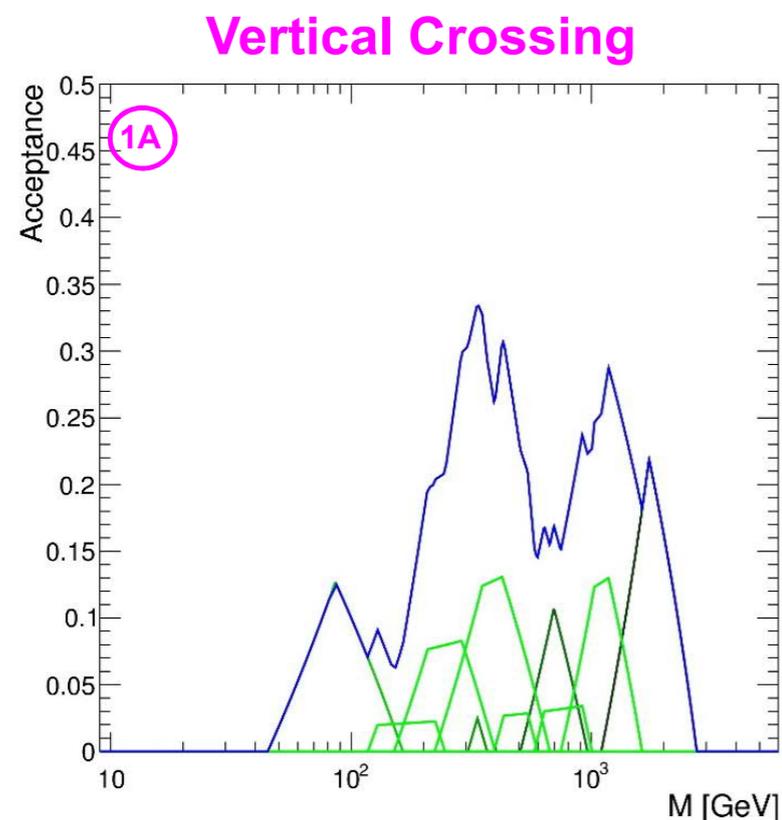
**Left:** Comparison between  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$ . **Right:** (Zoomed-in; change of scale in X-Y axis) comparison between the use of timing  $\delta t = 2, 5, 10 \text{ ps}$ .  $Z\gamma \rightarrow \text{hadrons} + \gamma$  benefits the most from the use of timing.

- Once again, expected **improvements** from HL-LHC impressive  $\sim$  an **order of magnitude** ( $\sim 5$  orders of magnitude better than current best inclusive limits).

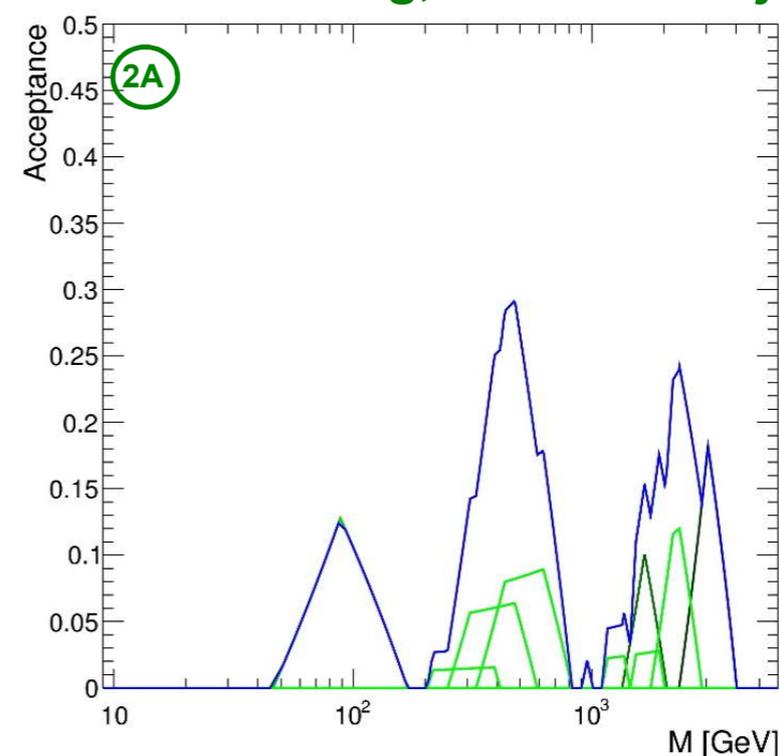
# Proton Tagging at HL-LHC: Experimental Prospects

- Dedicated study of proton tagging possibilities at **HL-LHC**:
  - ★ Best-suited detector positions identified, and proton tagging ( $\Rightarrow$  mass  $M_X$ ) acceptance evaluated for these (**CT-PPS** study, though ATLAS  $\sim$  similar).
  - ★ Study based on present-day assumptions about beam optics, collimation scheme etc, with both **horizontal** and **vertical** crossing considered.
  - ★ Range of positions feasible, from  $\sim 200$  m ( $M_X \gtrsim 300$  GeV) to  $\sim 400$  m ( $M_X \gtrsim 20 - 50$  GeV). **Physics potential**: wide range of masses probed.

**XRPs @ 196 m, 220 m, 234 m, 420 m**



**Horizontal Crossing, Baseline Trajectory**

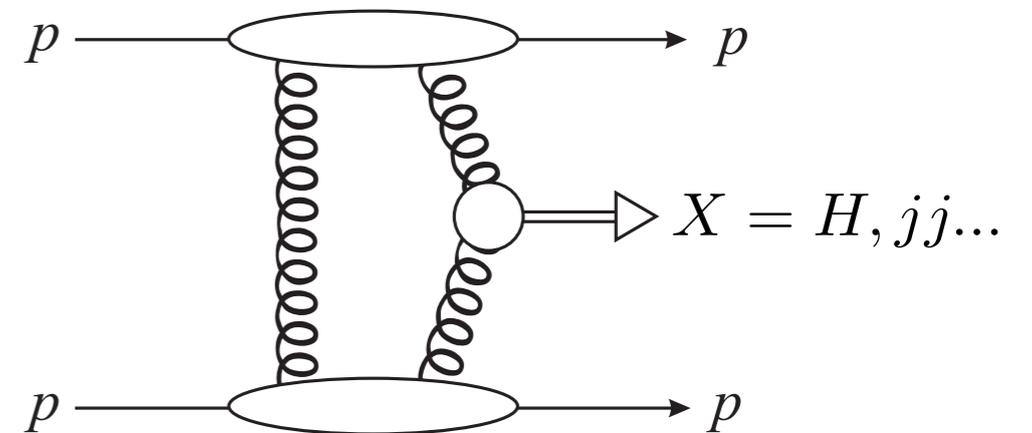


# Other CEP prospects

LHL

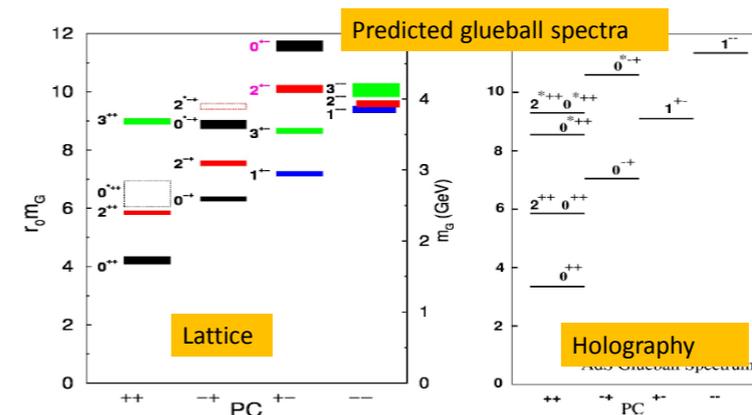
❖ QCD-initiated production: potential for e.g. exclusive jet and Higgs studies analysed (though there are more).

- ★ **Jets**:  $gg$  colour-singlet initial state range of unique QCD studies.
- ★ **Higgs**: completely unseen mode, Higgs properties (CP, couplings) via independent method.



❖ **ALICE** prospects: expect  $\sim 200 \text{ pb}^{-1}$  in  $pp$  in run 4. All **low pile-up** broad programme lower mass QCD studies/spectroscopy anticipated:

- ★ Meson spectroscopy.
- ★ **Glueball** searches.
- ★ Jets, monopoles...



E. Kryshen, C. Mayer

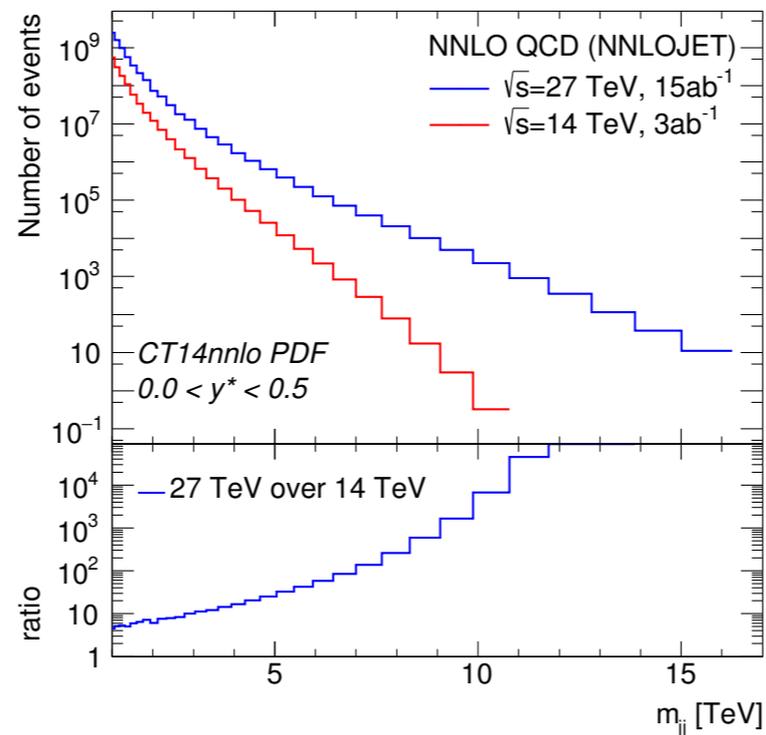
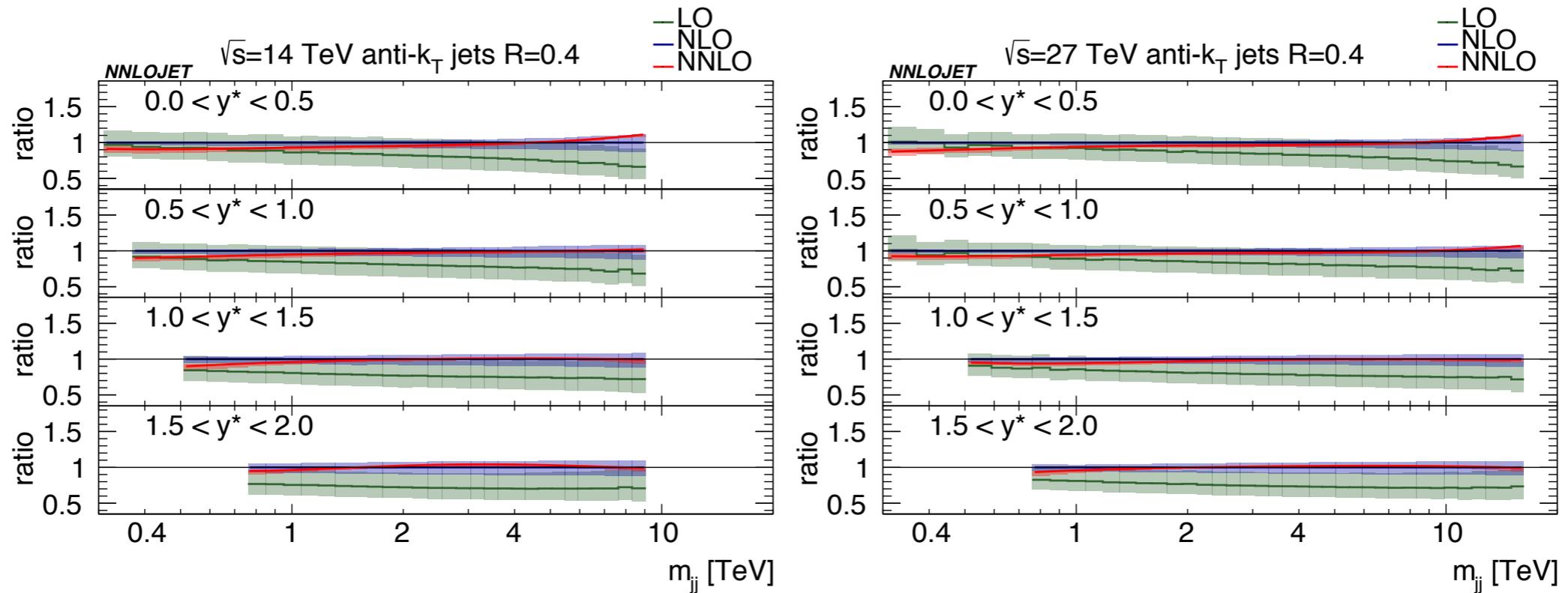
# Summary

- Exciting and broad theoretical and experimental programme for strong interactions and forward physics at the **HL** and **HE-LHC**:
  - ★ High precision data in jets/photons, with multi-TeV energy reach, and potential for various multi-differential studies.
  - ★ High precision NNLO theory can be put to the test.
  - ★ Potential for significant constraints on PDFs quantified.
  - ★ Not just about precision: new QCD effects in e.g. DPS.
  - ★ Potential to extend successful ongoing forward physics programme to HL-LHC with dedicated tagging detectors.
  - ★ Test case of anomalous couplings shows dramatic increase in sensitivity at HL-LHC.

*Thank you for listening!*

# Backup

# Dijet Production: Prospects



# Proton Tagging: Mass Acceptance

