Exclusive QCD measurements at LHC and their relevance for EIC

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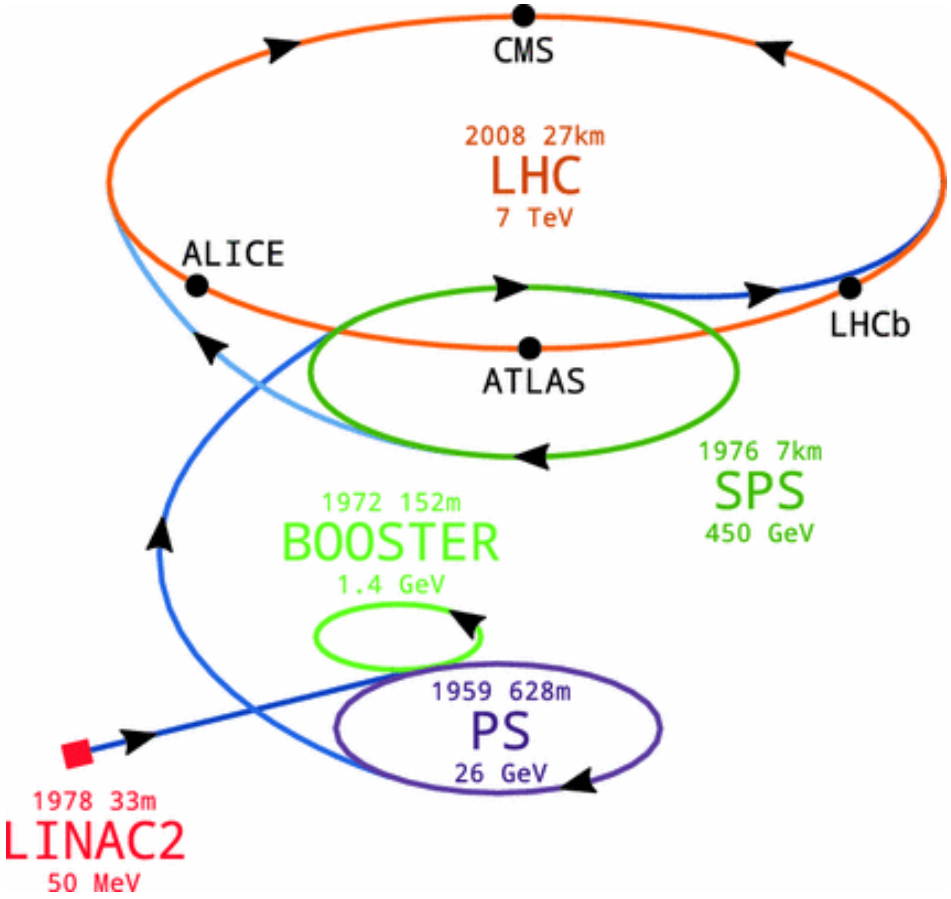
Outline:

- *LHC (+ its physics goals)*
- *Exclusive Processes*
- *Detectors*
- *Results*

Large Hadron Collider (LHC)



LHC has associated experiments to study the collision outputs

LHC provided rich data with different collision system and energy to explore phase-space to new extreme

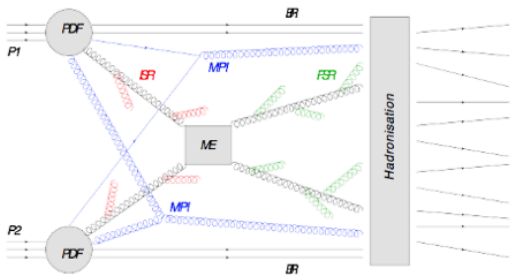
Collision System	Approx. Lumi (collision energy)
p-p	150 fb^{-1} (13 TeV), 20 fb-1 (8 TeV), 5 fb^{-1} (7 TeV) 5 pb^{-1} (2.76 TeV) Other low stat data with specific run conditions i.e. reference run, pileup, detector
p-Pb	180 nb^{-1} (8 TeV/nucleon) 35 nb^{-1} (5 TeV/nucleon)
Pb-Pb	25 nb^{-1} (5 TeV/nucleon) 150 μb^{-1} (2.76 TeV/nucleon)
Xe-Xe	13 mb^{-1} (5.44 TeV/nucleon)

Physics terrain with LHC

- ✓ SM and Higgs Physics
- ✓ Direct & Indirect signature of physics beyond SM
- ✓ Quark-gluon plasma
- ✓ B-Physics
- ✓ **Low-x and Forward Physics**

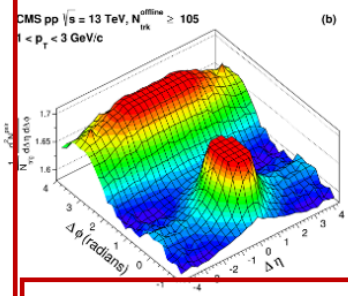
Soft QCD

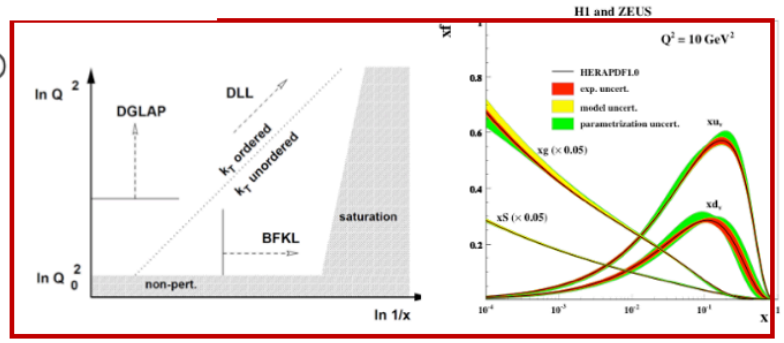
(particle spectra; underlying event)



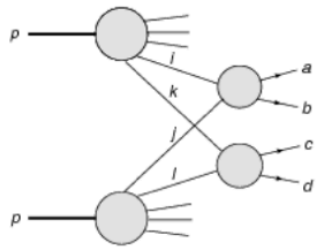
Small-x QCD

(forward jets)

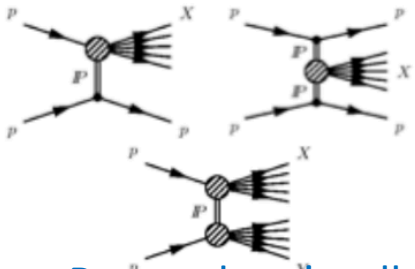




Double parton scattering

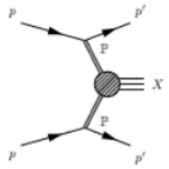


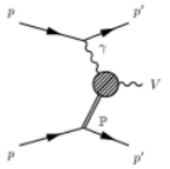
Diffraction



Ramandeep's talk

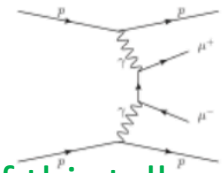
Central exclusive production





Low mass

High mass

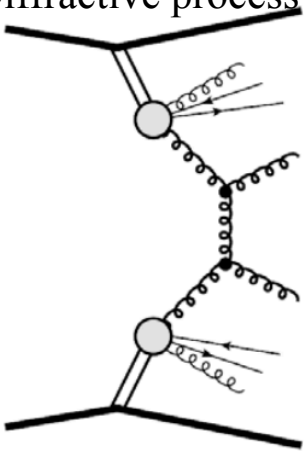


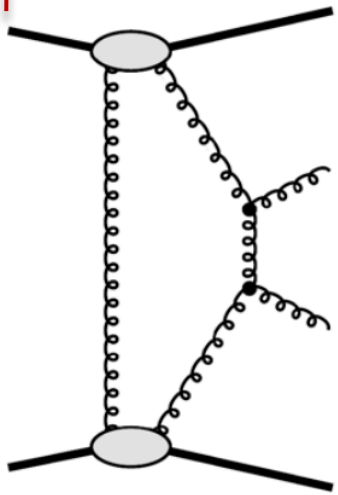
Scope of this talk

Exclusive Processes: incoming particles (one or both) are intact (and usually pass through undetected), interactions happen between radiated particles; t-channel exchange.

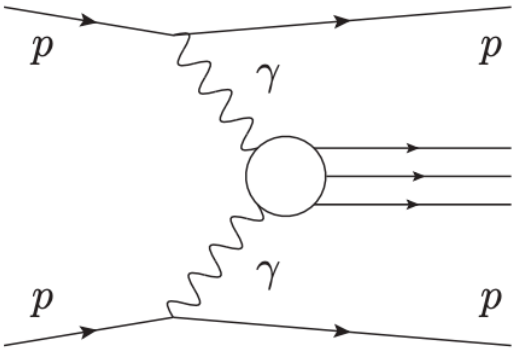
Exclusive/semi-exclusive processes

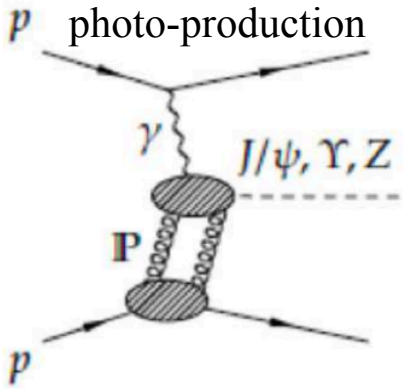
Double-pomeron exchange/ Diffractive process





QED

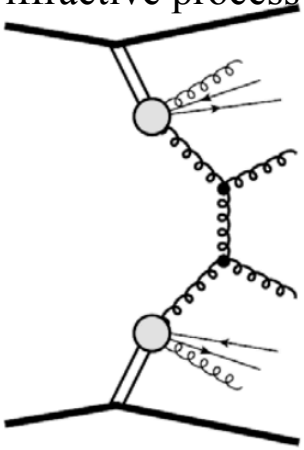


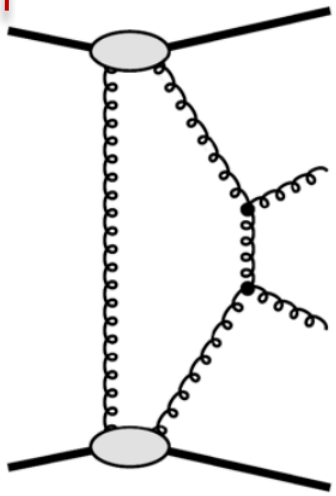


Exclusive Processes: incoming particles are intact (and usually pass through undetected), interactions happen between radiated particles; t-channel exchange of a colorless objects such as pomeron, photons

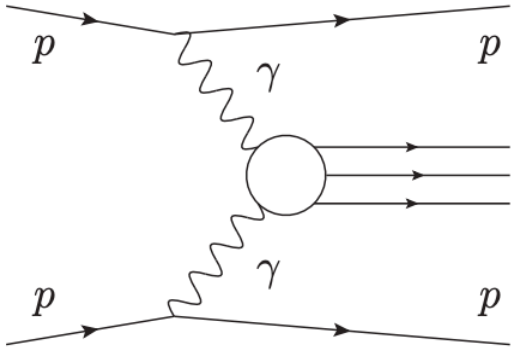
Exclusive/semi-exclusive processes

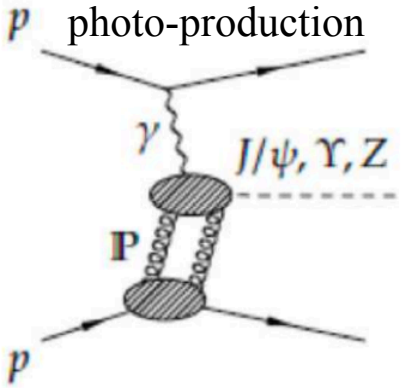
Double-pomeron exchange/ Diffractive process





QED



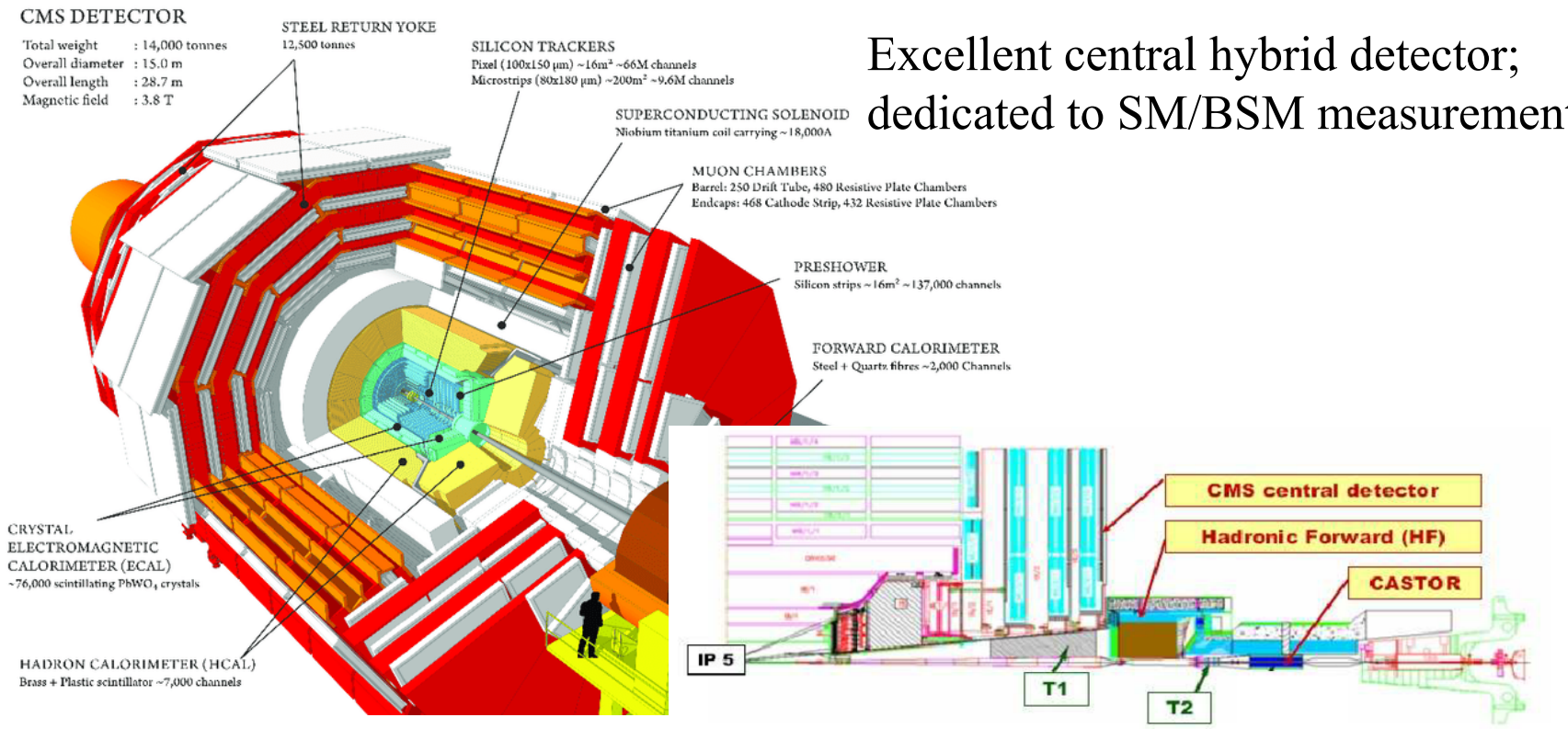


- QED "standard candle" process.
- Test of QCD, hadron spectroscopy.
- Sensitive to PDF at low-x

- Access to scalar and tensor glueballs.
- Constraining (indirectly) BSM phase-space

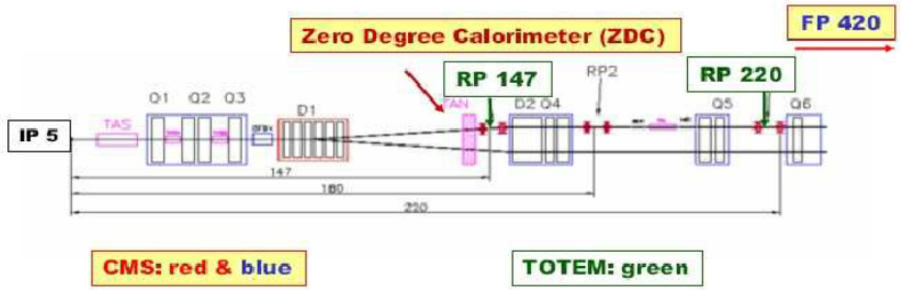
Need excellent central and forward detectors

CMS

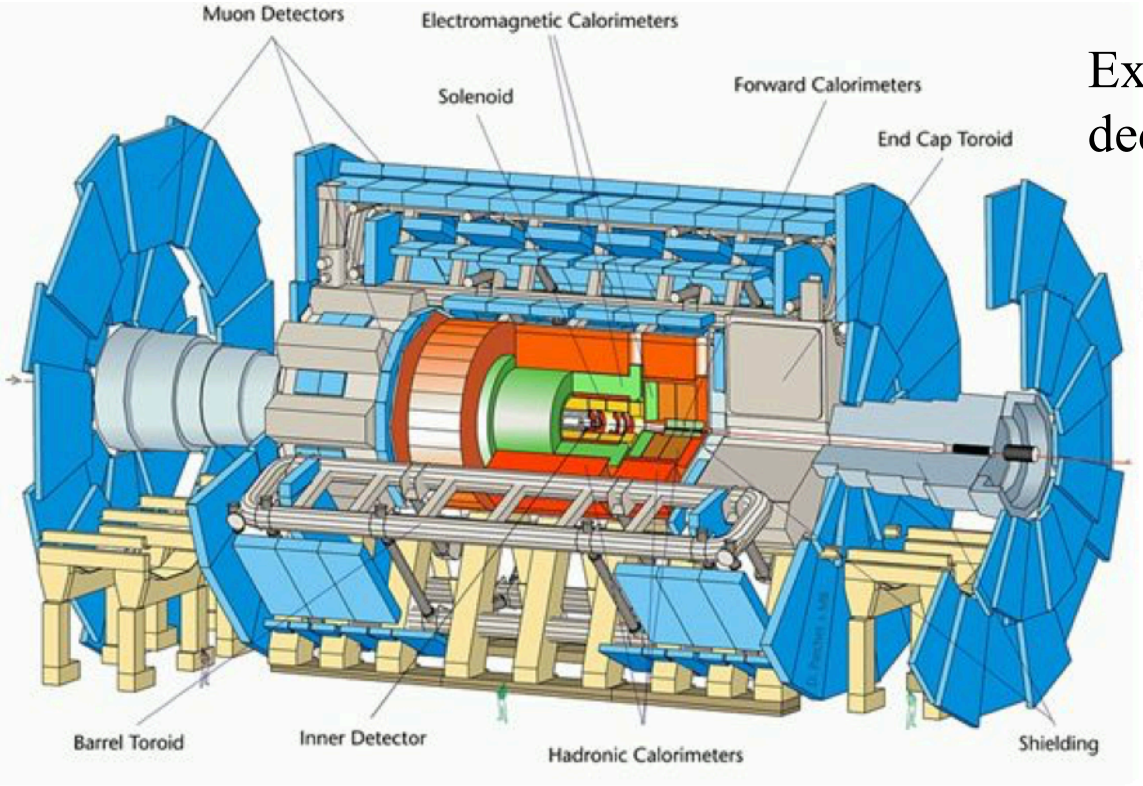


Excellent central hybrid detector; dedicated to SM/BSM measurements

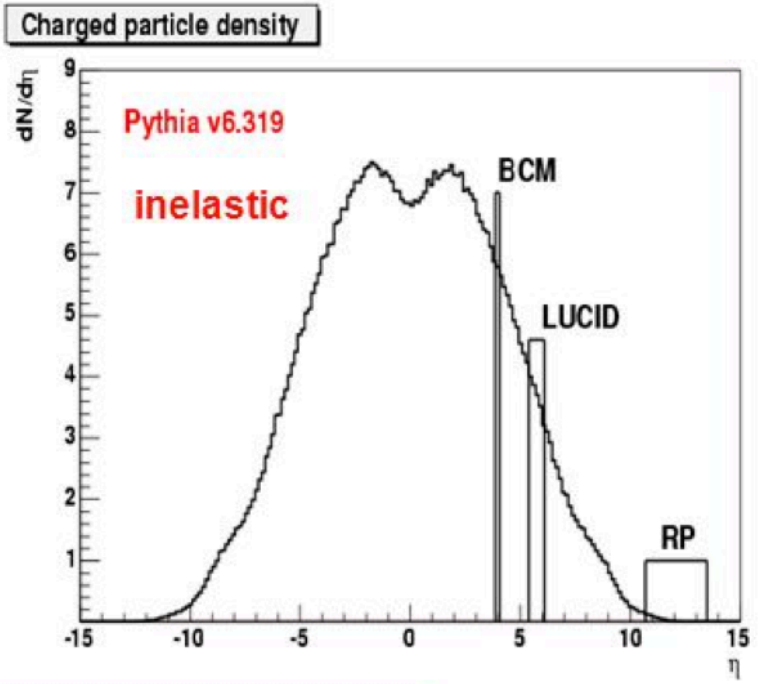
- ✓ HF, CASTOR add in forward acceptance but with limitations
- ✓ CT-PPS recent addition to tag scattered protons.

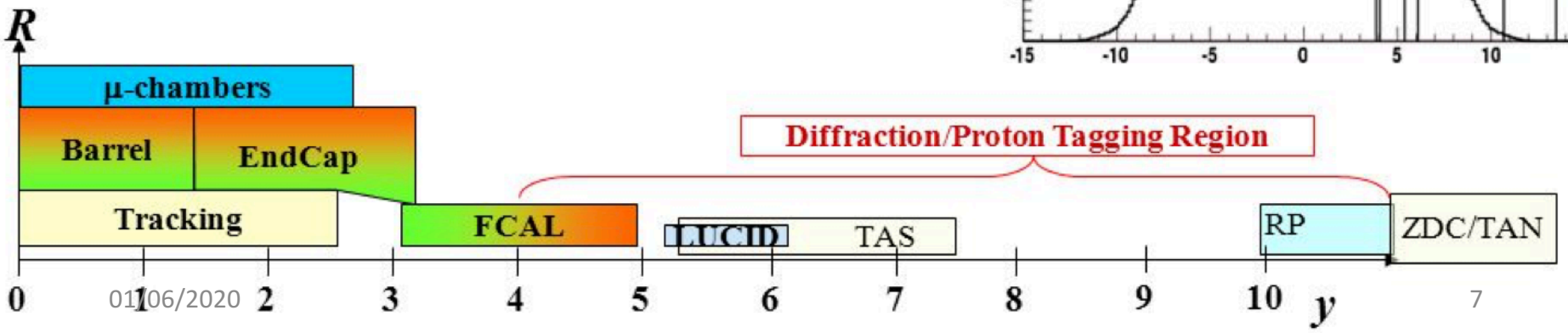


ATLAS

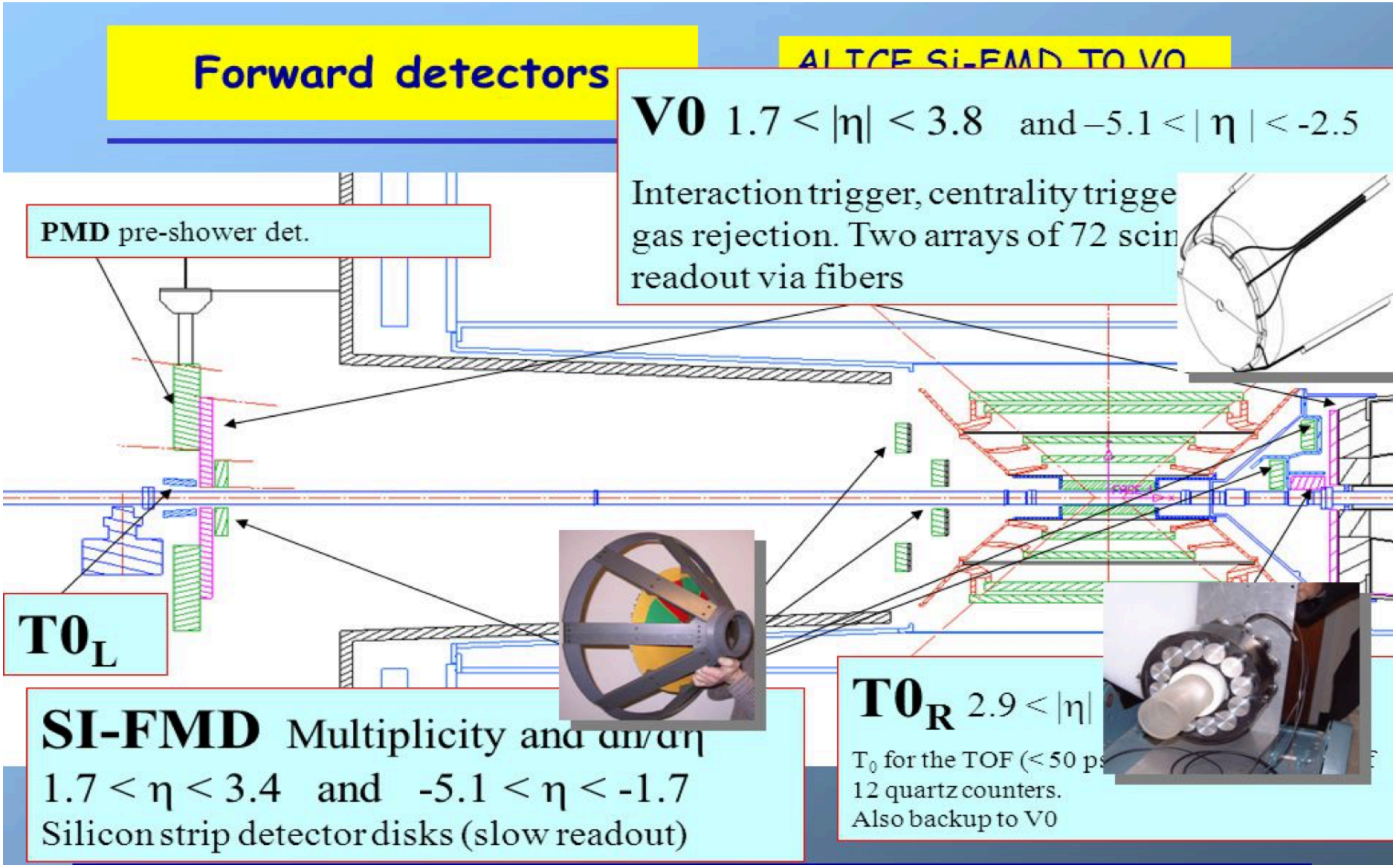


Excellent central hybrid detector; dedicated to SM/BSM measurements

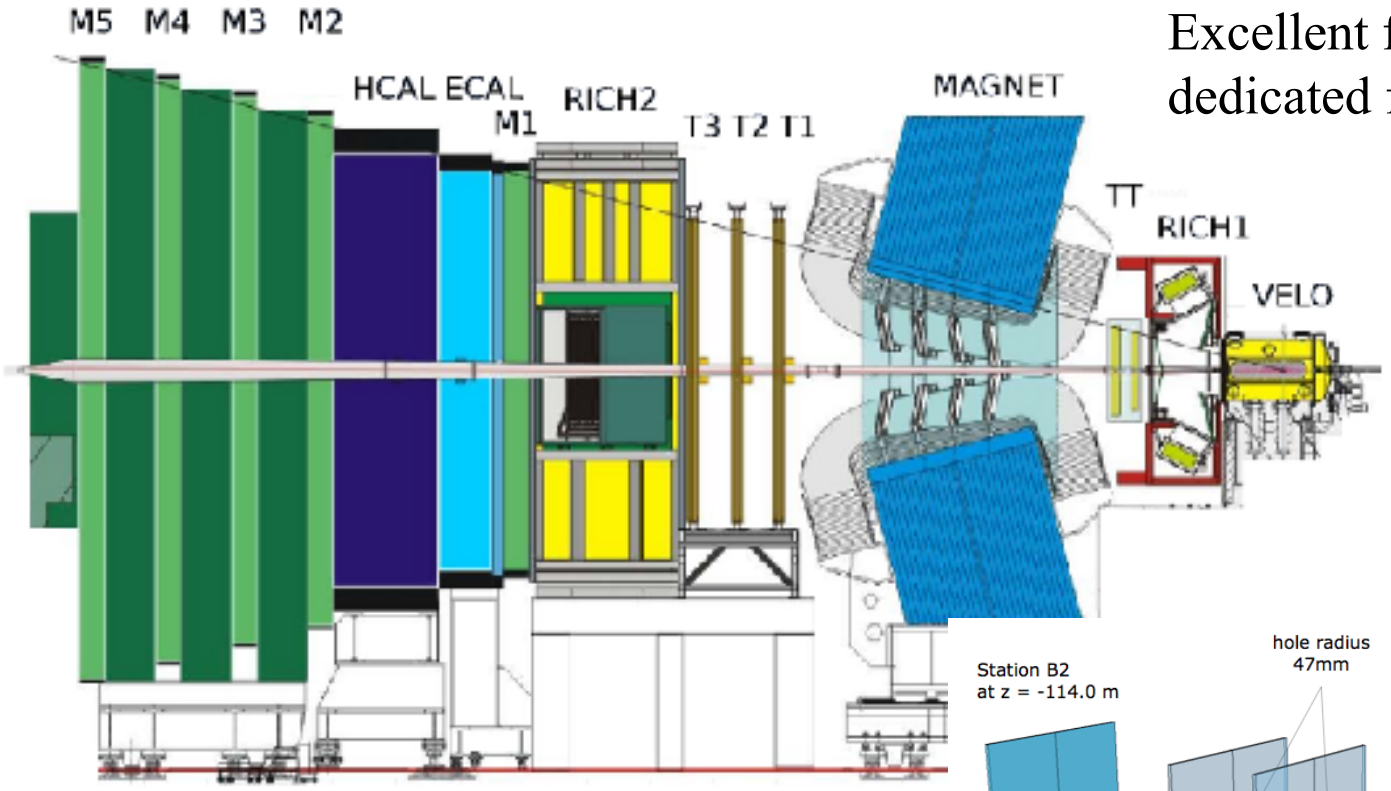




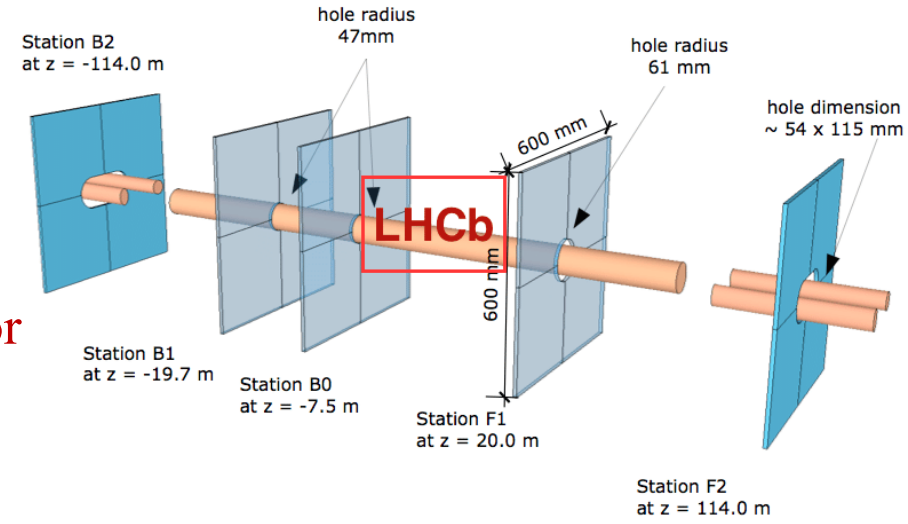
ALICE


Forward detectors
ALICE Si-FMD T0 V0
V0 1.7 < |η| < 3.8 and –5.1 < | η | < -2.5
Interaction trigger, centrality trigge
gas rejection. Two arrays of 72 scin
readout via fibers
PMD pre-shower det.
T0L
T0R 2.9 < |η|
T0 for the TOF (< 50 ps
12 quartz counters.
Also backup to V0
SI-FMD Multiplicity and dn/dη
1.7 < η < 3.4 and -5.1 < η < -1.7
Silicon strip detector disks (slow readout)

LHCb

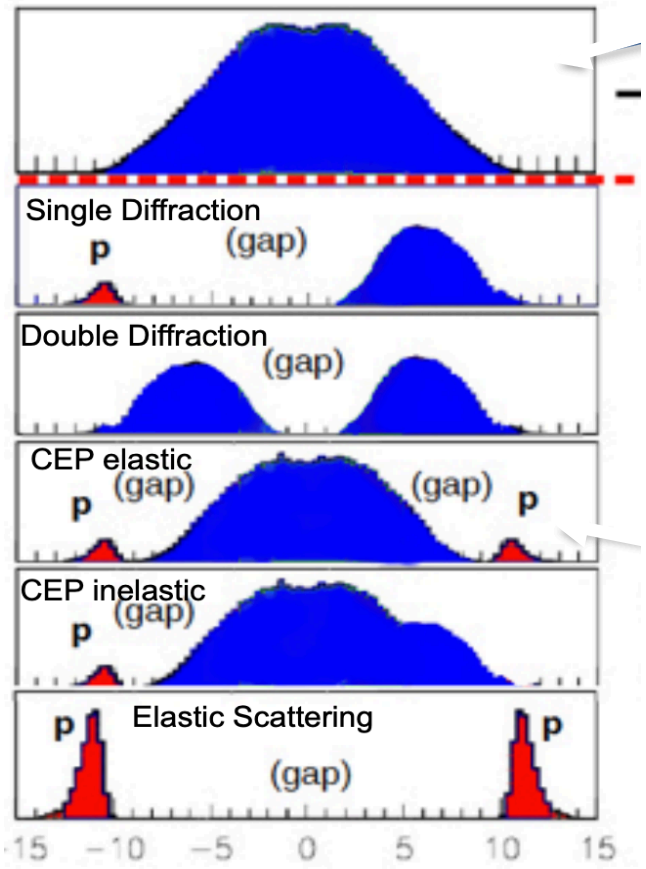


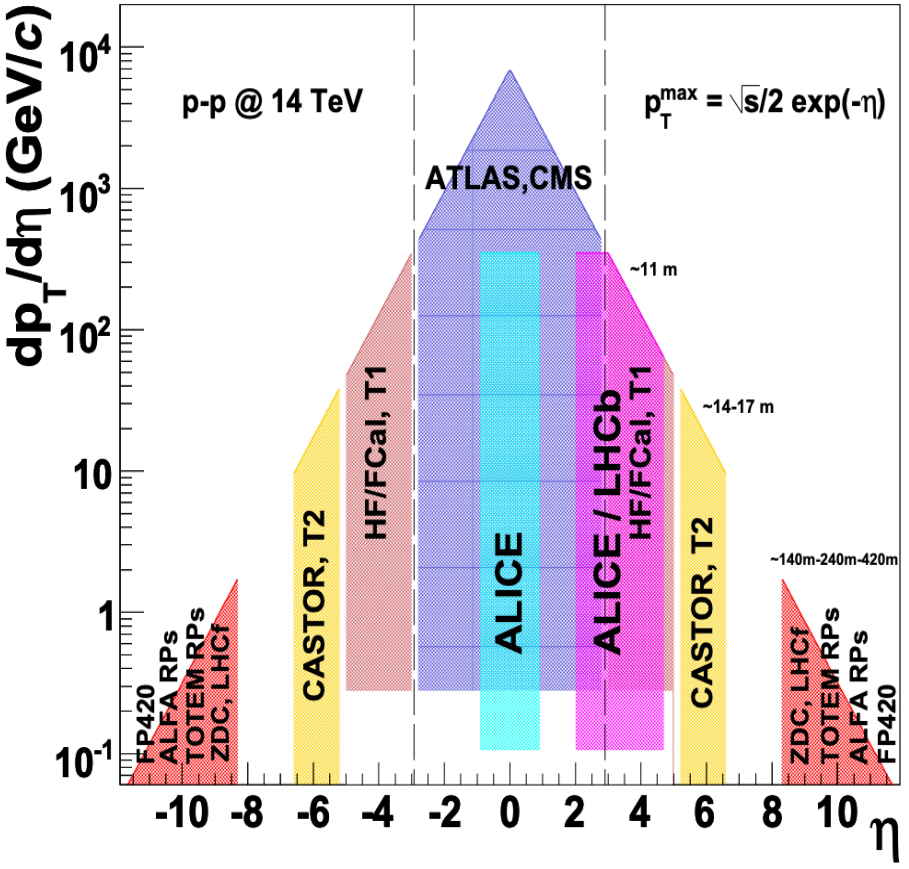
Excellent forward coverage; dedicated for b-physics



HeRSChel forward detector installed recently

Forward Physics and LHC acceptance

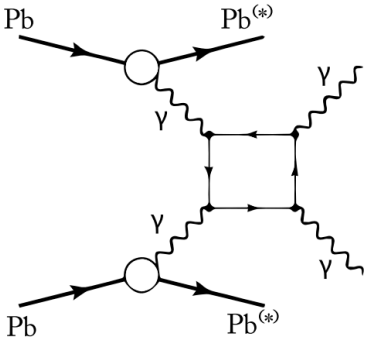




Measurement of exclusive processes require;

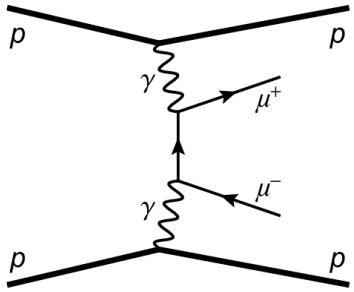
- ✓ tagging of proton (limited availability of detectors)
- ✓ look for gap (small activity)

Measurements covered



- Light-By-Light Scatterings
- Exclusive J/ψ production

  (other measurements of low mass resonances are not covered)



- Exclusive dilepton (low and high mass) production

  (with and without proton-tagging)

- Measurements sensitive to gluons saturation (BFKL vs DGLAP)

Disclaimer: this talk contains only selected results

Light-By-Light Scattering

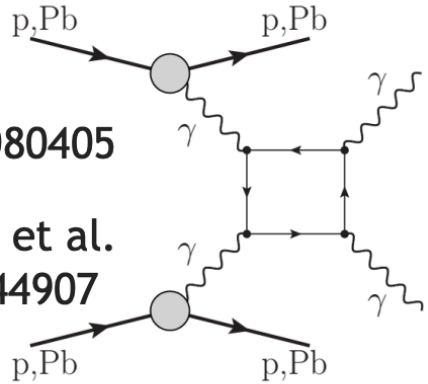
- **Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering**
  - Forbidden at tree-level
  - Tested indirectly in **electron/muon g-2** measurements
  - Another examples: **Delbruck scattering** and **photon splitting** processes

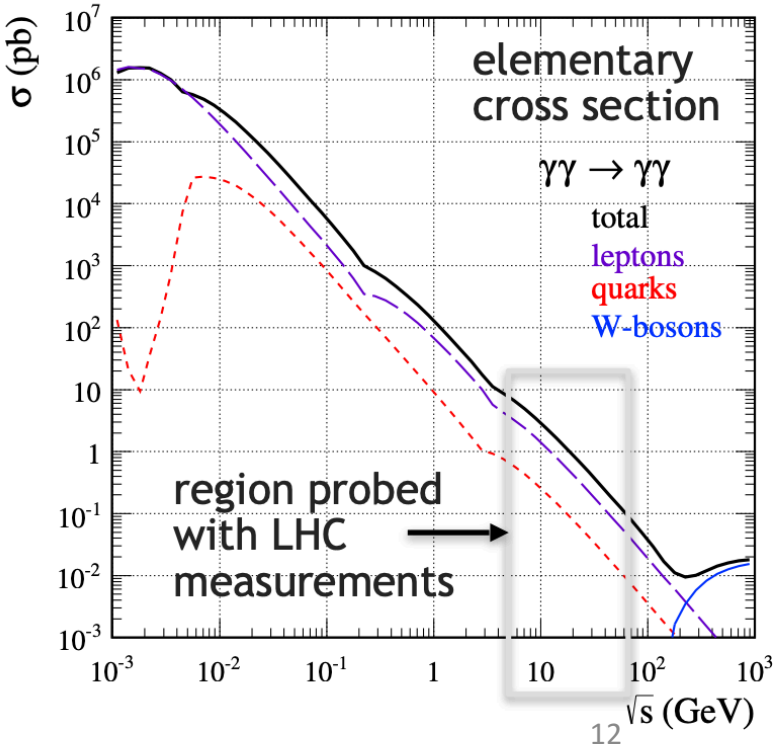
- **This reaction is accessible in Pb+Pb collisions at the LHC**
  - Cross-section scales ~with Z^4
  - Initial photon-photon system has very soft p_T (< 0.1 GeV)

- **At high energies, proposed as a clean channel to study:**
  - Anomalous gauge couplings
  - Contributions from BSM particles

d'Enterria et al.
PRL 111 (2013) 080405

Klusek-Gawenda et al.
PRC 93 (2016) 044907



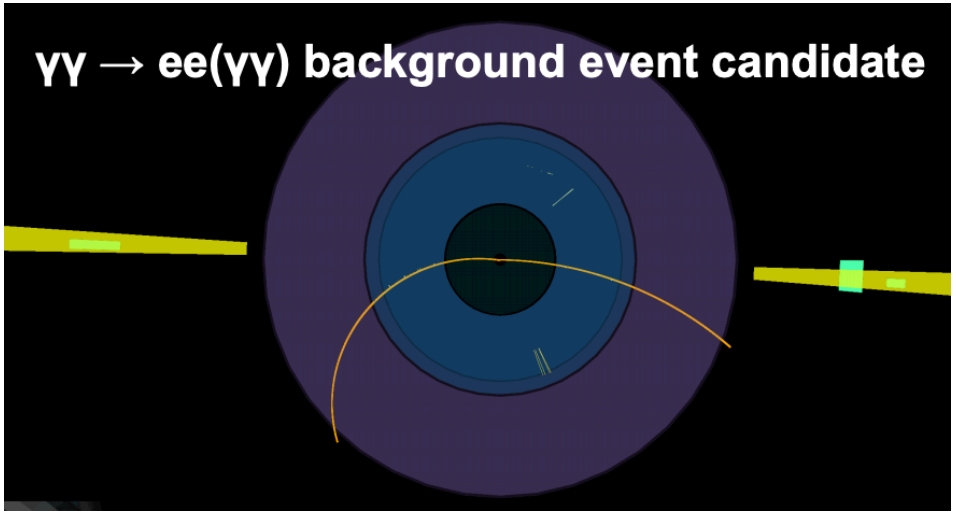


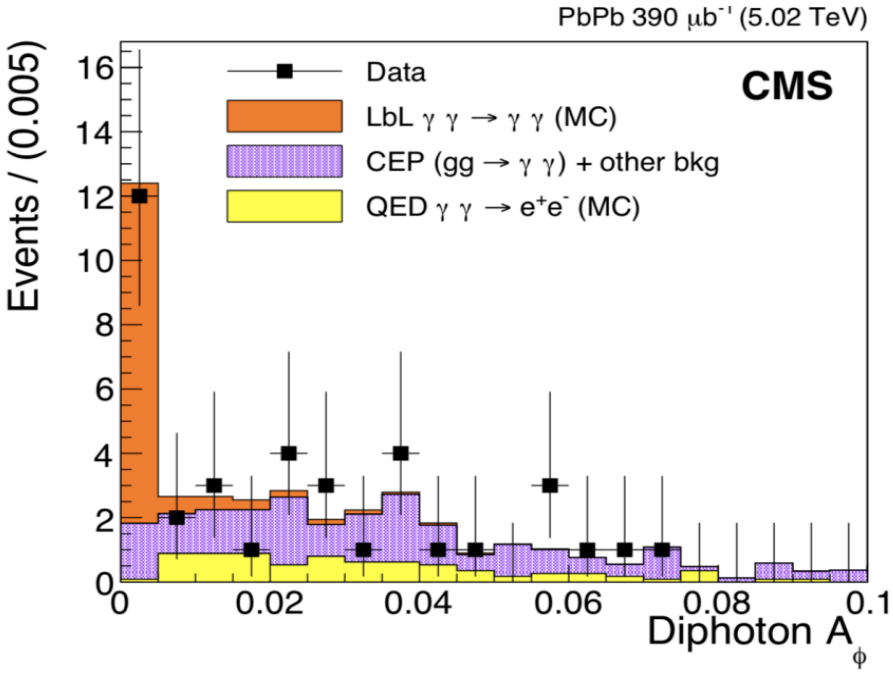
Light-By-Light Scattering

- Simple event topology

✓ Back-to-Back photons:
$E_T > 3$ (2) GeV
$p_T^{\gamma\gamma} < 2$ (1) GeV
Acc. < 0.01

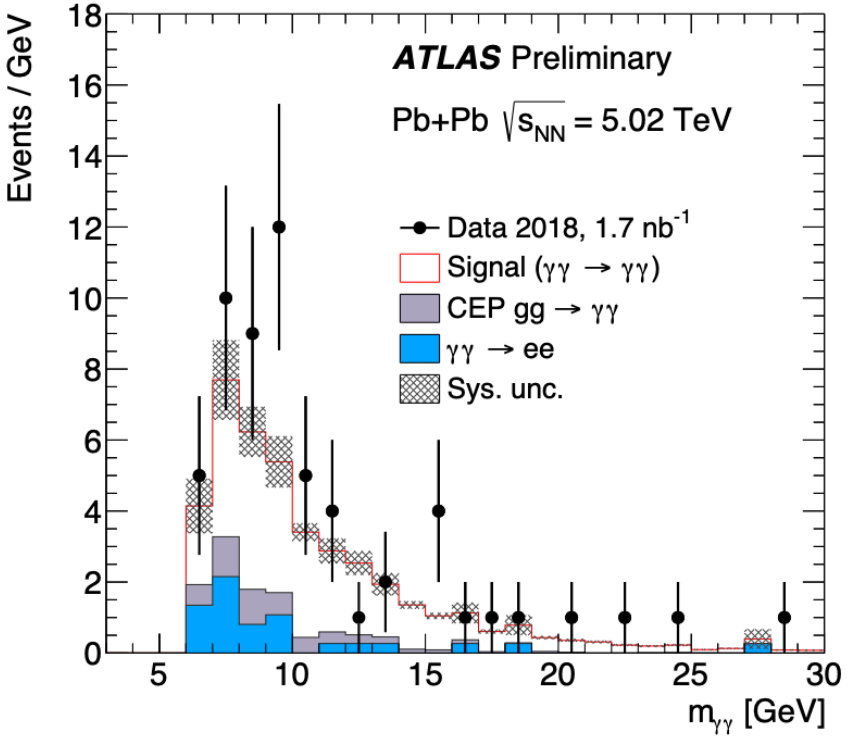
✓ Veto on Extra activity:
- No tracks with $p_T > 0.2$ GeV
- No calorimeter tower above noise threshold

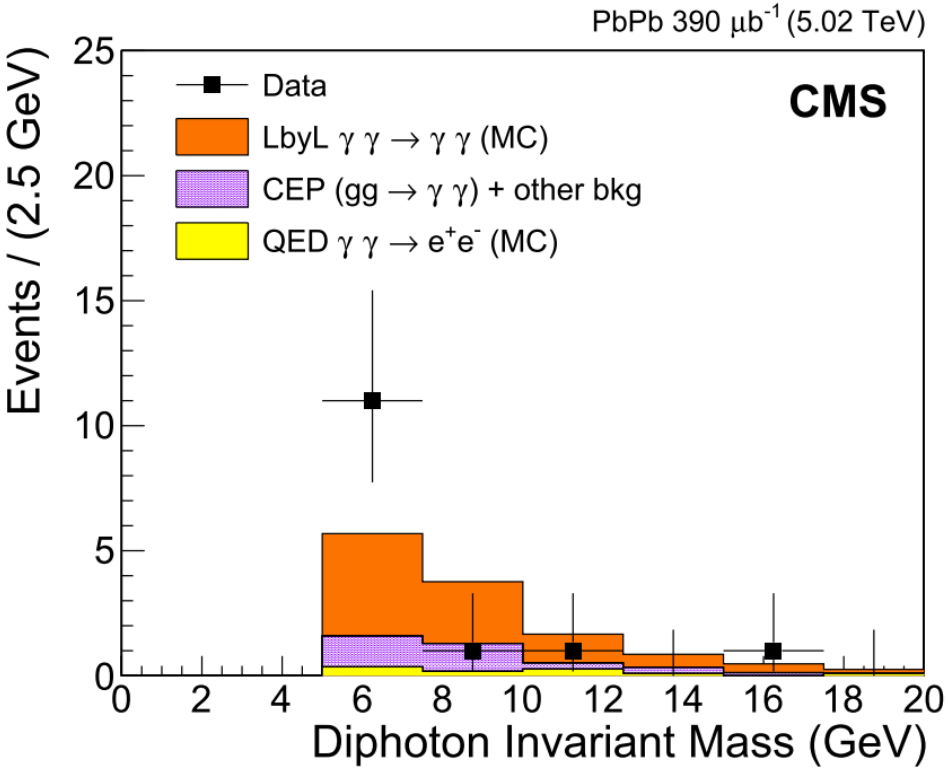




Light-By-Light Scattering

Experiment	Significance Observed (Expected)	Measured Cross-section (SM pred.)
ATLAS	8.2 (6.2) σ	78 $\pm$ 13 (stat.) $\pm$ 7 (syst.) $\pm$ 3 (lumi) nb (50 $\pm$ 5 nb)
CMS	4.1 (4.4) σ	120 $\pm$ 46 (stat.) $\pm$ 28 (sys) $\pm$ 4 (th.) nb (138 $\pm$ 14 nb)

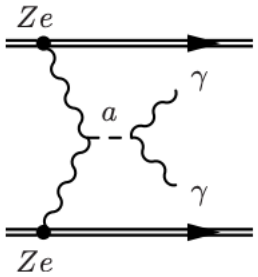


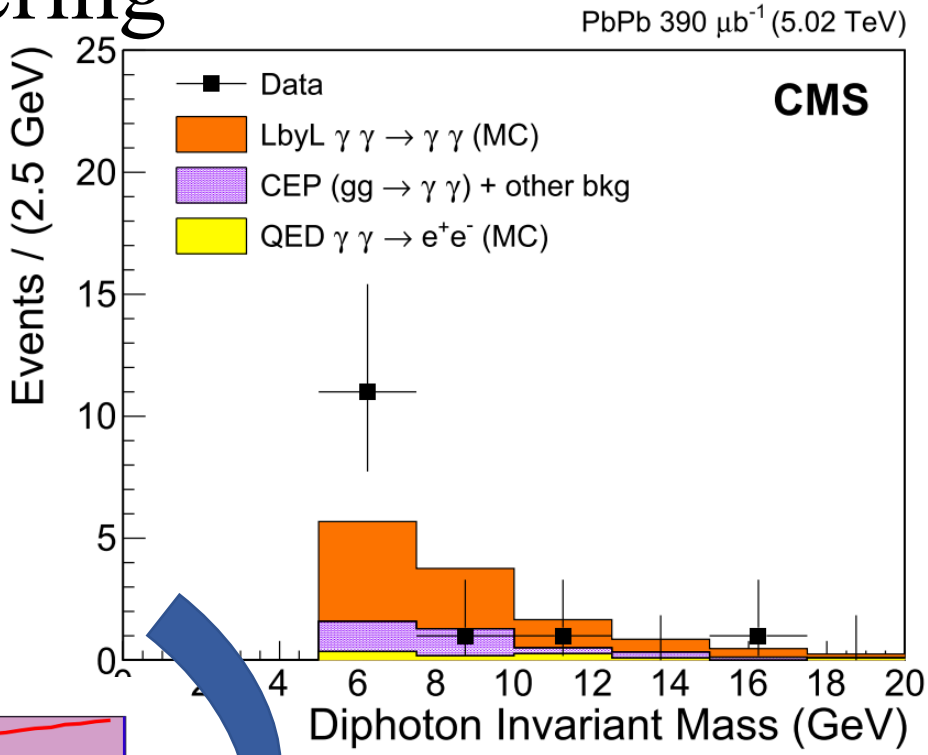


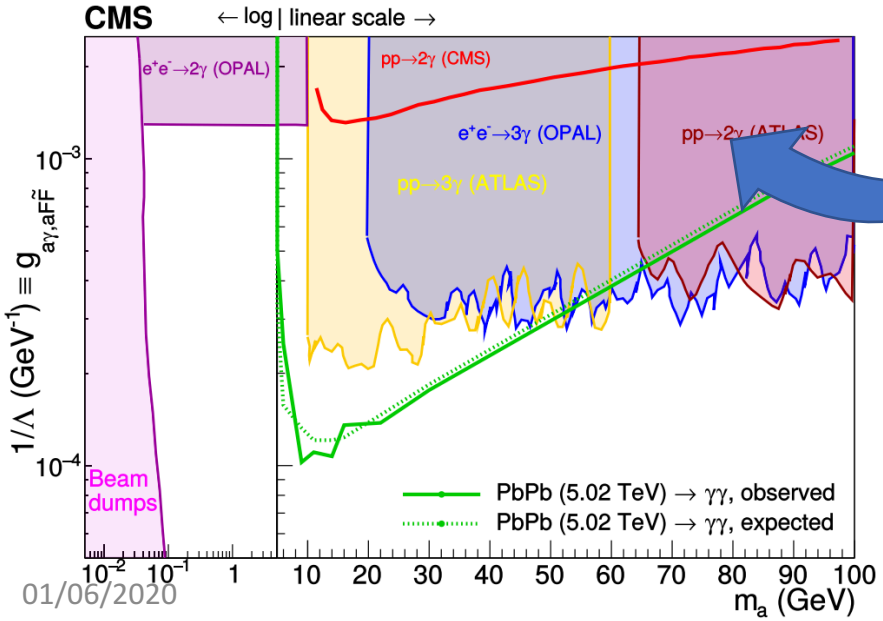
Light-By-Light Scattering

Axion-like particles

(see e.g. Knapen et al., PRL 118 (2017) 171801)







Constrained additional phase-space at low mass (5-90 GeV)

Ref.:

Nature Physics 13, 852–858(2017)

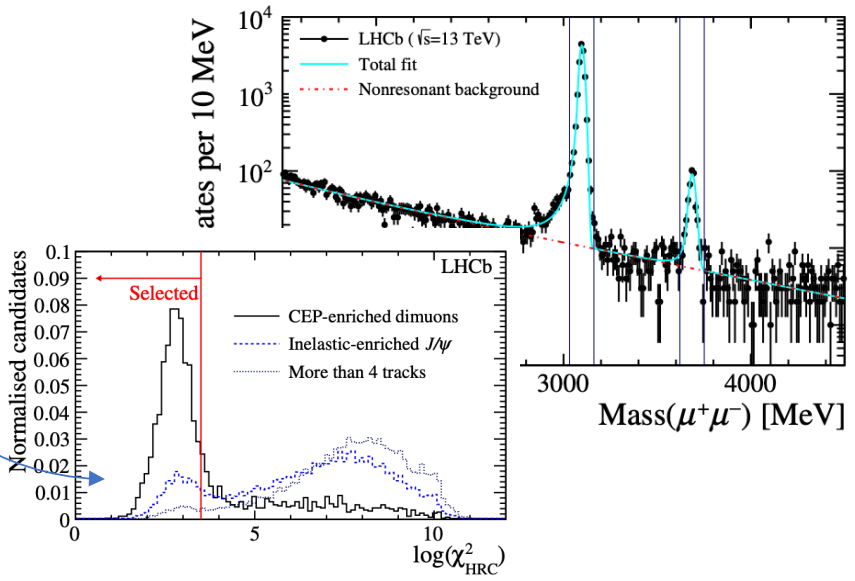
PRL 123, 052001 (2019)

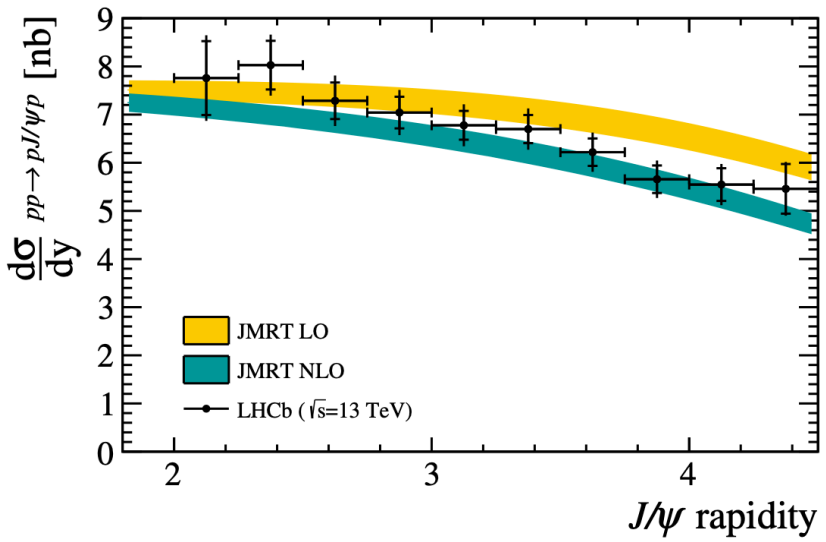
PLB 797, 134826 (2019)

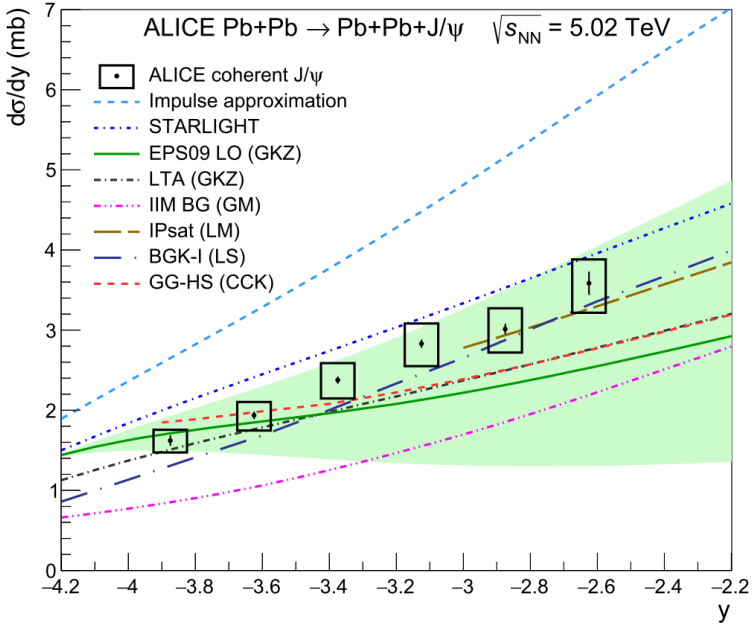
Exclusive J/ψ

- ✓ Exclusively two muon events
- ✓ Exclusivity conditions
  - Herschel detector (LHCb)
  - Veto on the V0A, ADA, ADC (ALICE)

- ✓ Cross-section falls at forward rapidities, reproduced by NLO calculations
- ✓ None of the calculation equally describe the central and forward measurements; indicate scope of improvements.



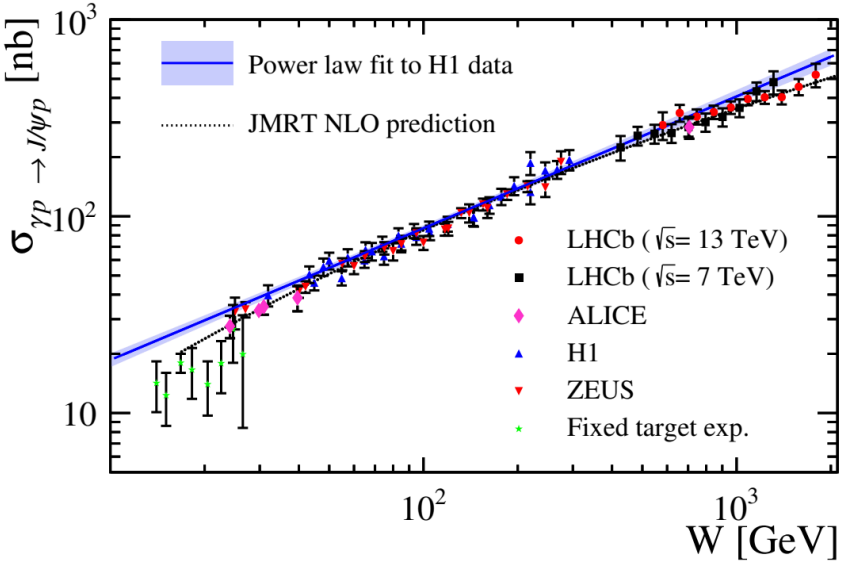


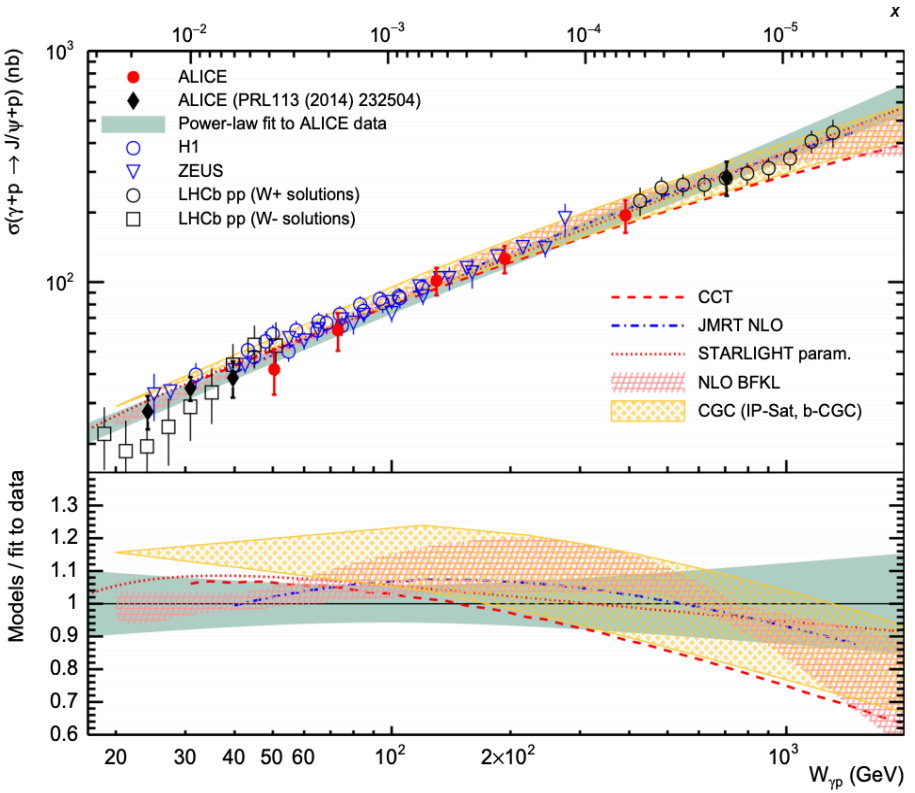


Exclusive J/ψ

- ✓ Photoproduction cross-section as a function of W (γp energy), explores kinematic range 1-2 TeV
- ✓ Models provide good description at low W but fails at high W.

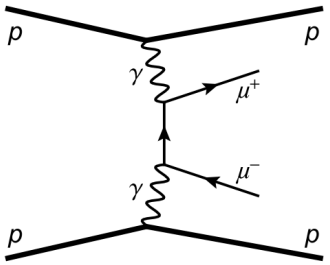
W varies with gluon density



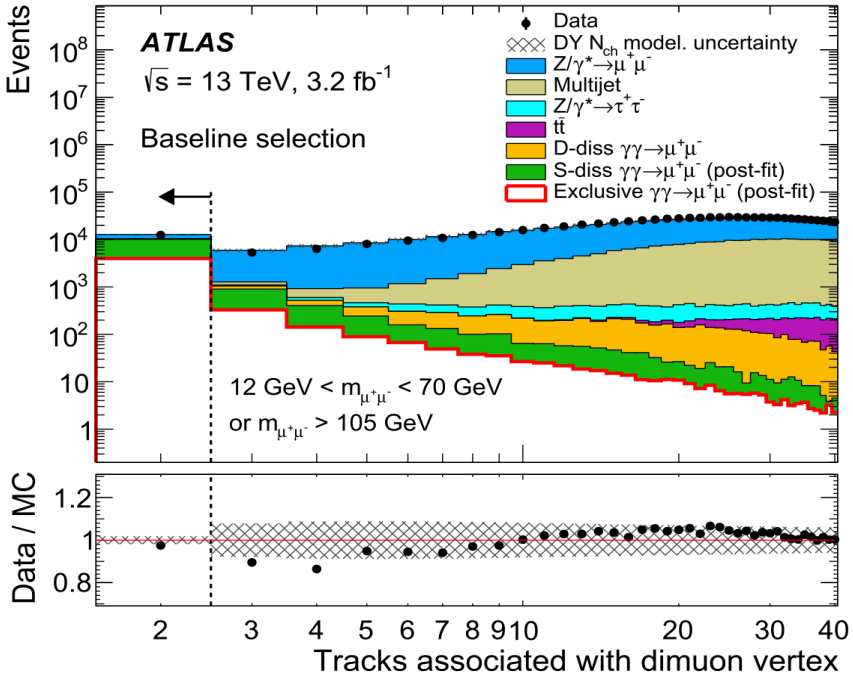


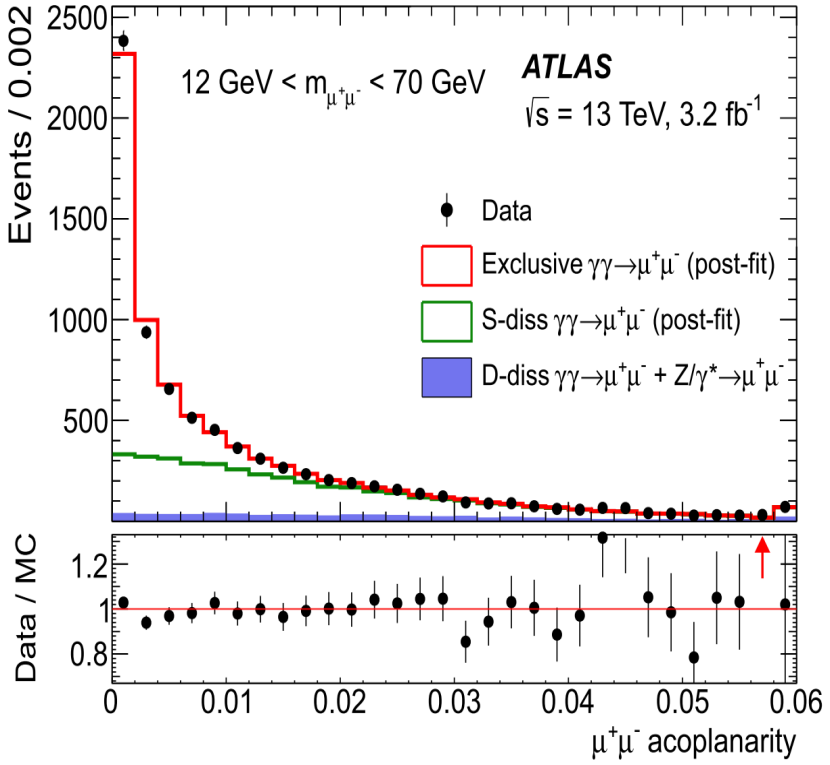
There are many other results with different system and resonances not discussed here

Exclusive dilepton



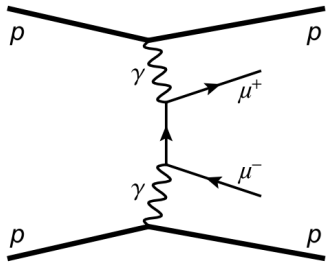
- ✓ Dilepton events with mass off Z-peak
- ✓ Exclusivity conditions: track veto & acoplanarity cut
- ✓ Single- and double dissociation background is irreducible: estimated with template fit.



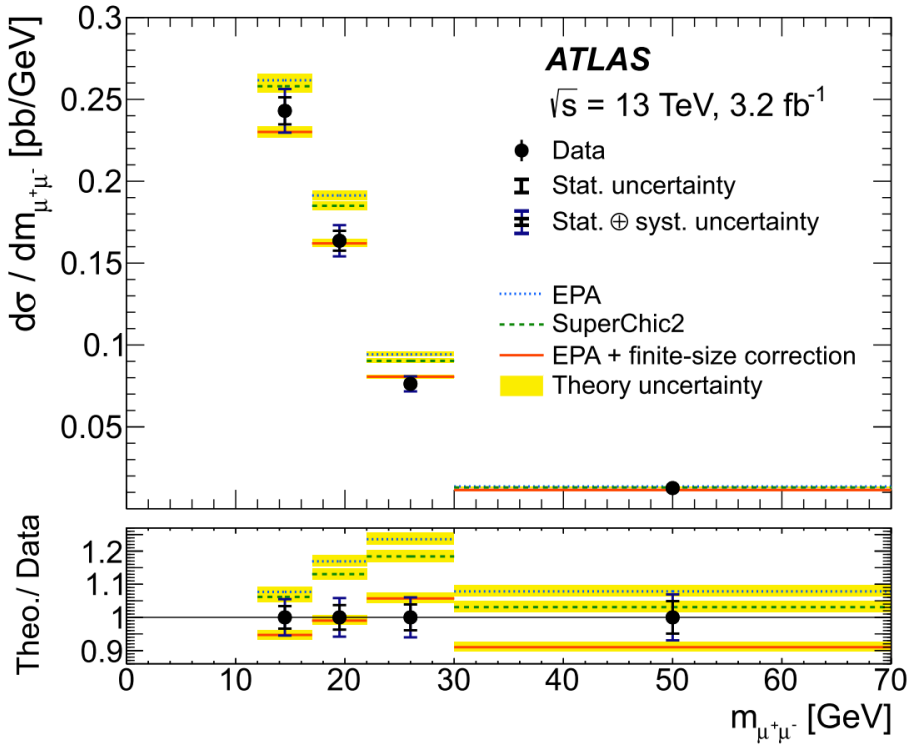


PLB 777 (2018), 303-323
PLB 749 (2015) 242-261
JHEP 01 (2012) 52

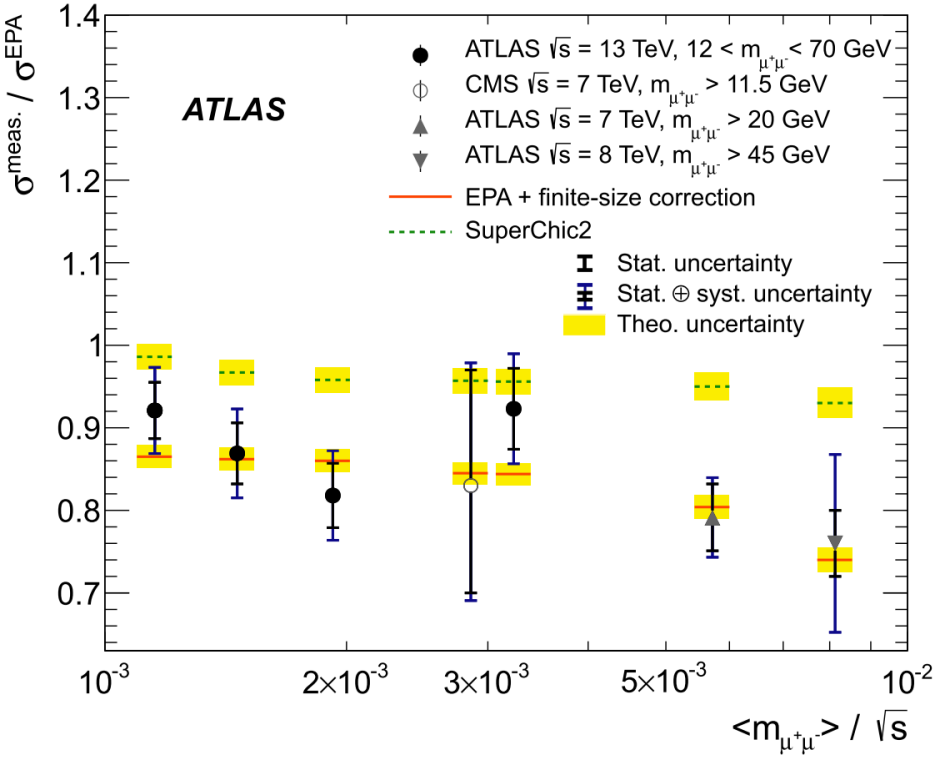
Exclusive dilepton



✓ Measured exclusive dilepton cross-section below the Z-peak; underestimated by simulations



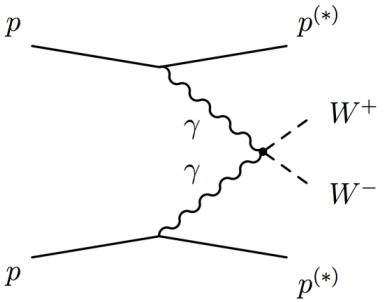
Survival factor



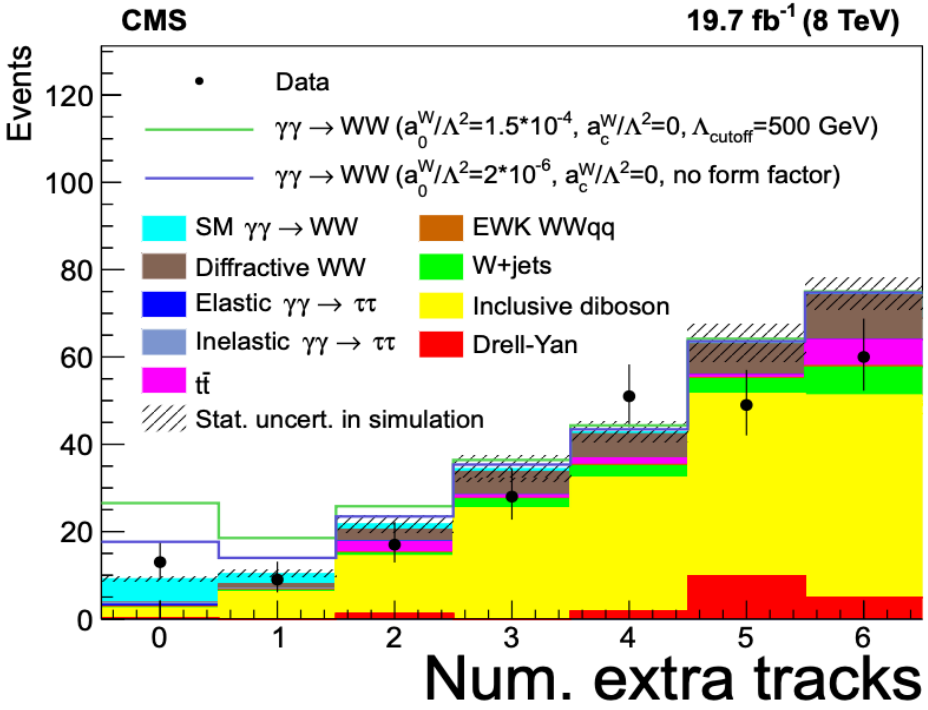
✓ Absorptive Correction factor increases with mass.

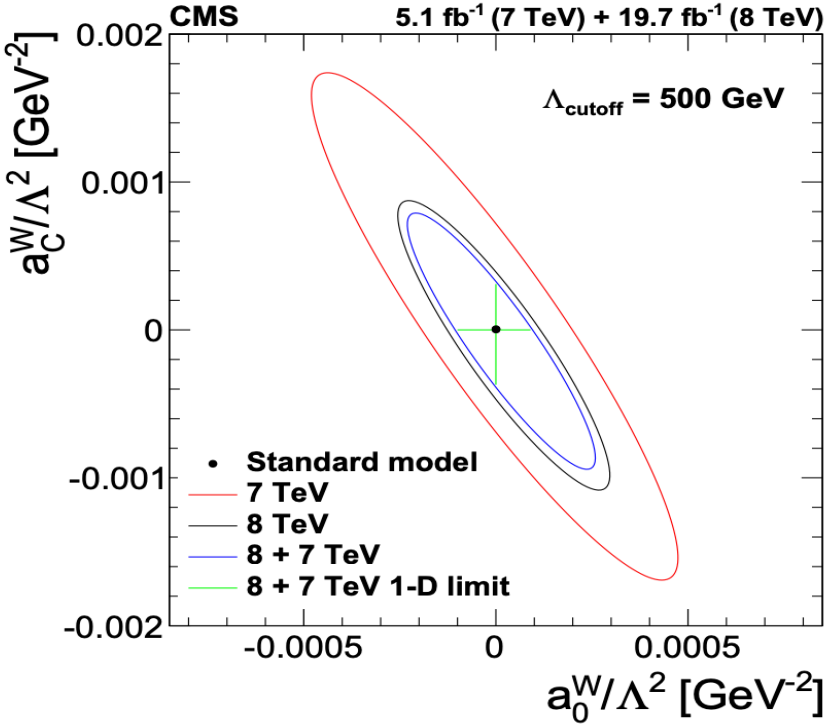
✓ Finite size parameterization correctly describe the measurements but SuperChic2 mis-model by 10-20%

Exclusive WW



- ✓ $\gamma\gamma \rightarrow$ WW production gives a handle to measure aQGC
- ✓ e + μ final state is experimentally clean final state
- ✓ Exclusivity condition is met with veto on extra tracks.





- ✓ First evidence of $\gamma\gamma \rightarrow$ WW with 3.4 σ consistent with SM predictions.
- ✓ Used to constrain aQGC parameter space.

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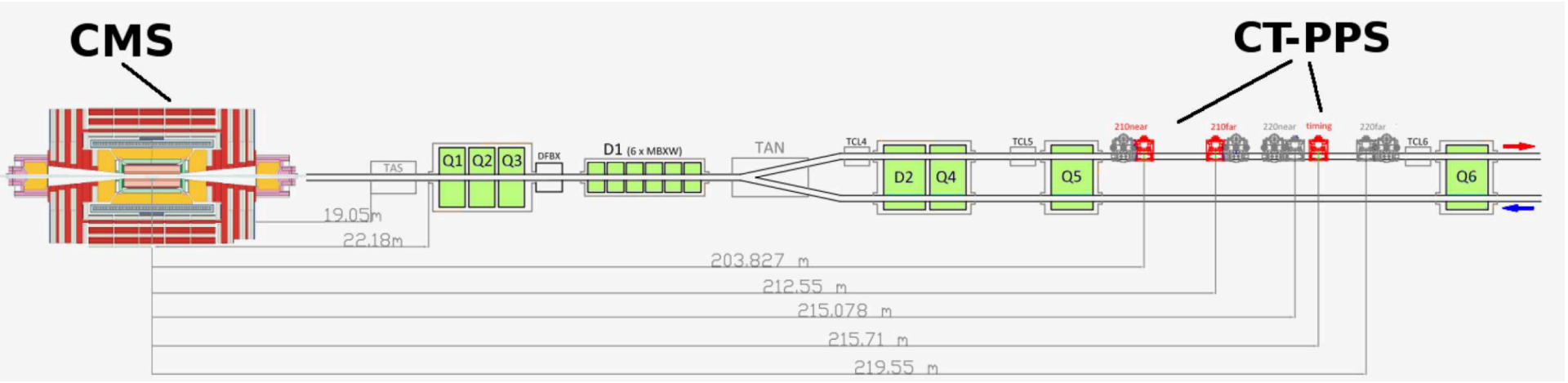
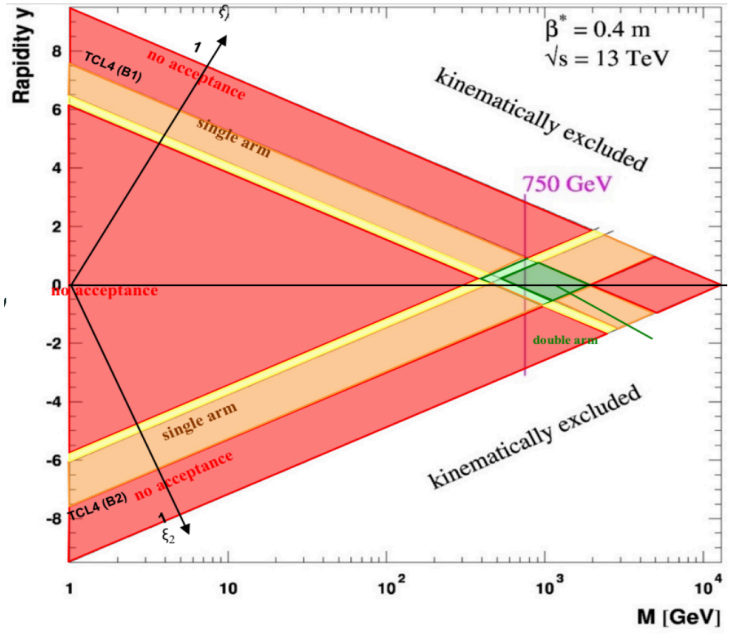
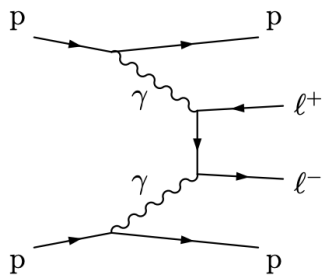
Exclusive dilepton (CT-PPS)





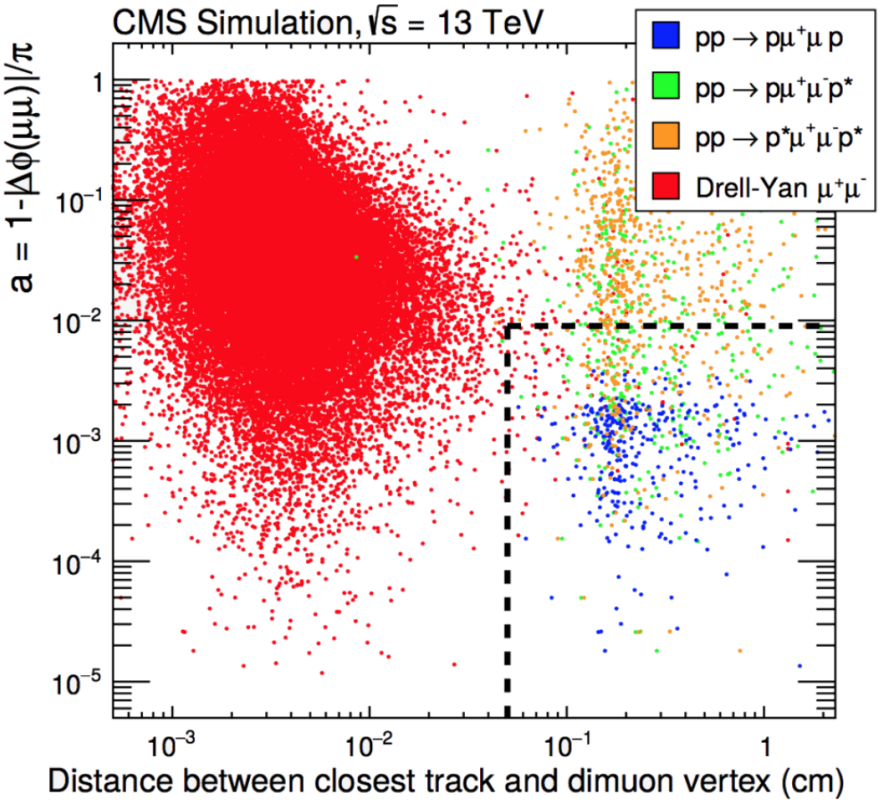
CT-PPS detects scattered proton at ~200 m from interaction point: interesting possibility to look for actual exclusive processes (with medium to high mass)

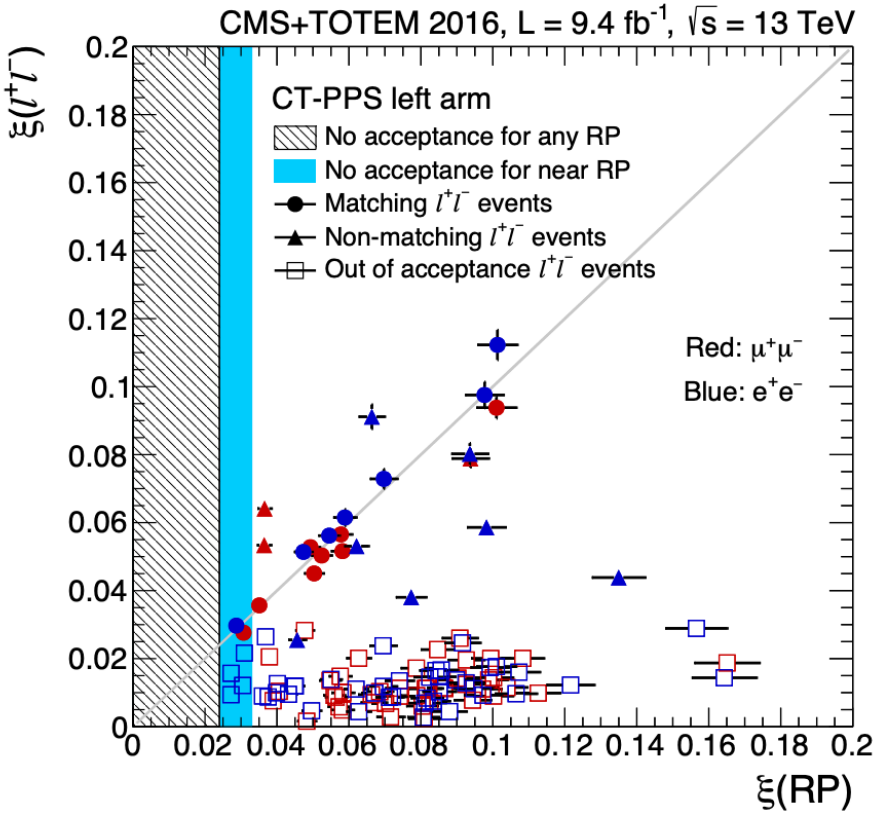
❖ Low mass coverage need special run with high β* (limited data available)



Ref.:
JHEP 07 (2018) 153

Exclusive dilepton (CT-PPS)





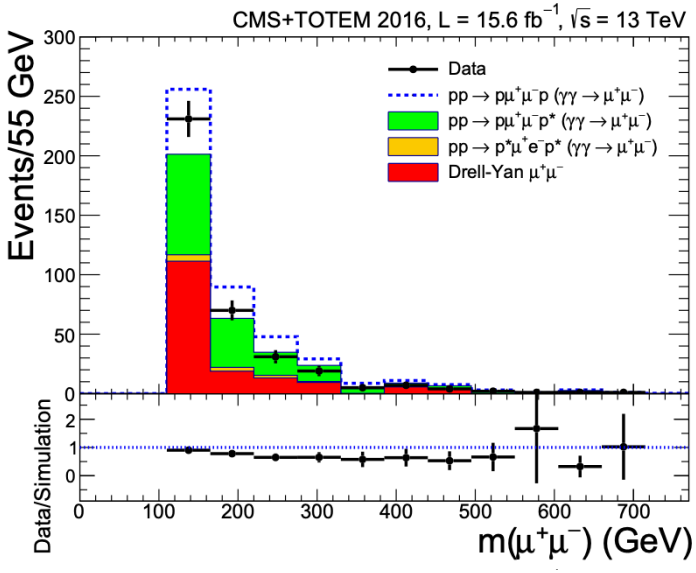
Exclusive selection:

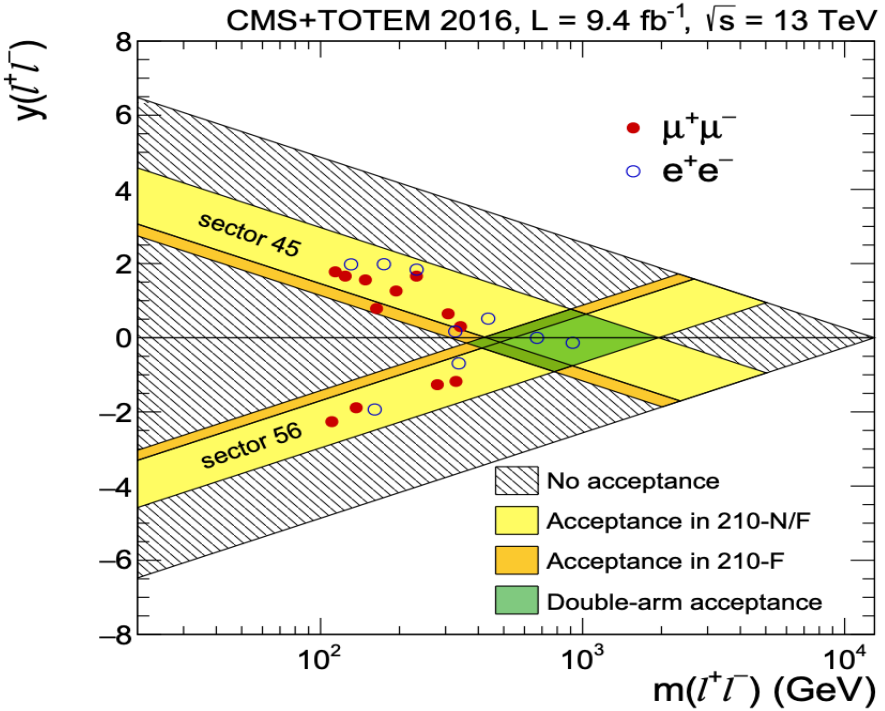
- track veto (CMS only)
- proton-tagging (CMS + CT-PPS)

Fractional Momentum loss

$$\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}}\left[p_T(\ell^+)e^{\pm\eta(\ell^+)} + p_T(\ell^-)e^{\pm\eta(\ell^-)}\right]$$

Exclusive dilepton (CT-PPS)



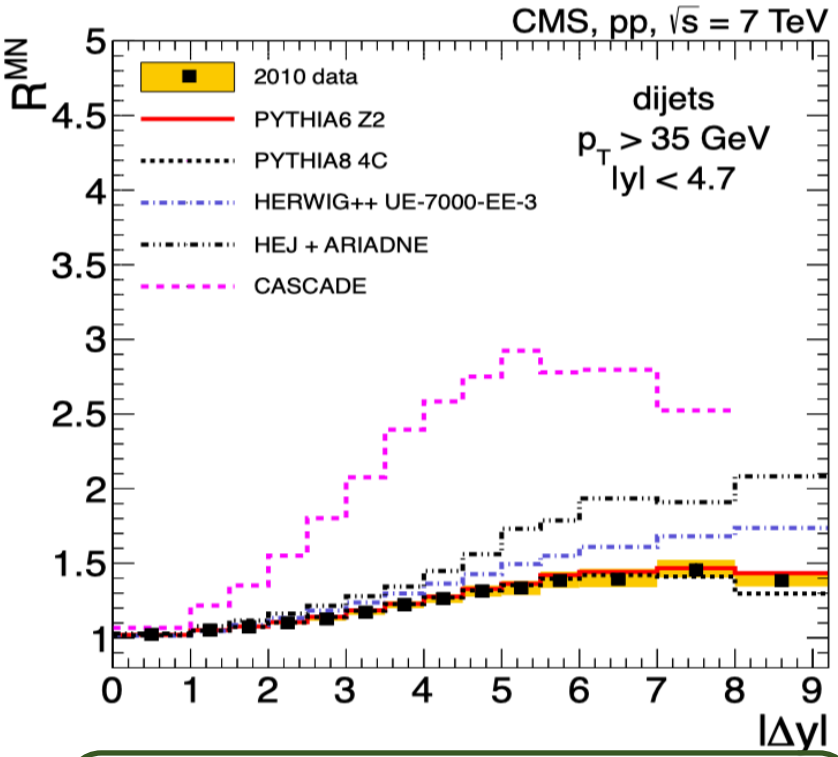


- 12 events have $\xi(\mu\mu)$ consistent with RP acceptance[3] and matching with the proton kinematics
- 8 events have ξ(ee) consistent with RP acceptance and matching with the proton kinematics
- Background: 1.49±0.07(stat)± 0.53(syst) $\mu\mu$; 2.36± 0.09(stat)±0.47(syst) ee
- Combined events $> 5.1\sigma$ over background

Jets Correlations

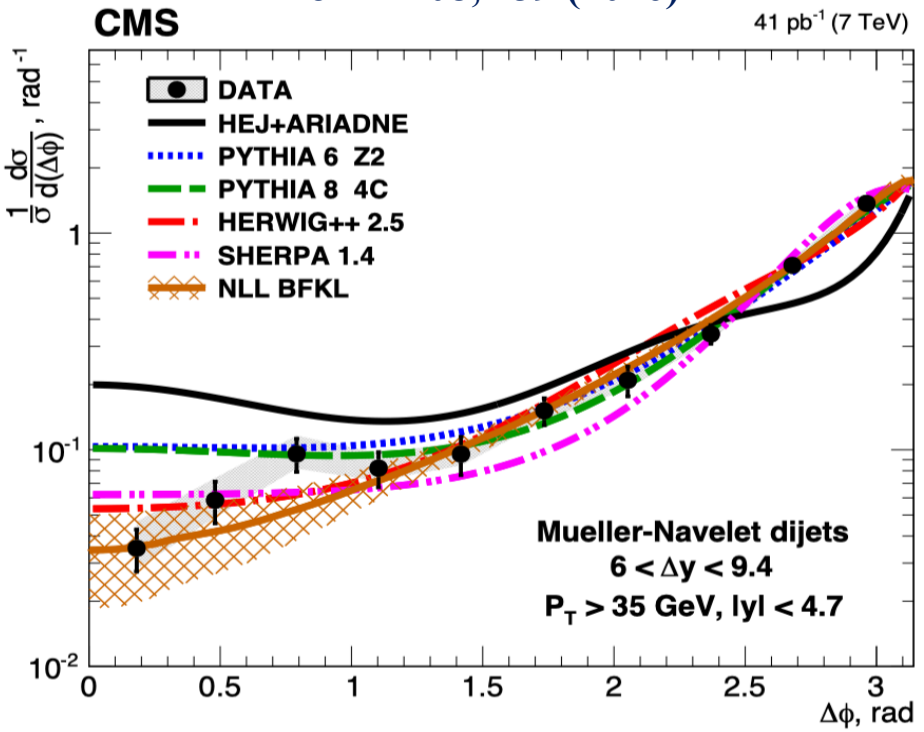
Mueller-Navelet jets (Forward-Backward jets): sensitivity to shower evolution and BFKL/DGLAP at larger rapidity gap

Eur. Phys. J. C72, 2216 (2012)



Pythia (DGLAP) describe well but non-DGLAP predictions fails at higher rapidity

JHEP 08, 139 (2016)

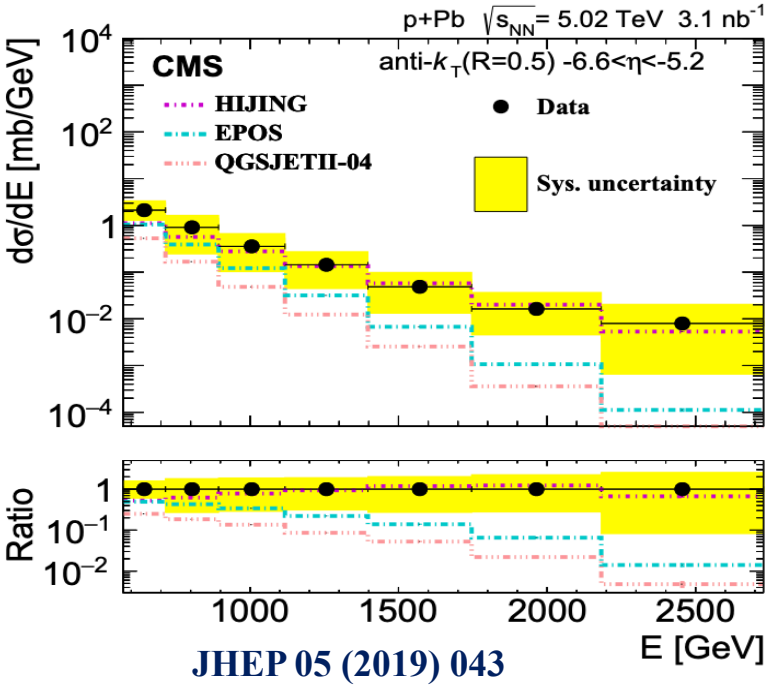


NLL BFKL gives best description: hints of transitions to BFKL regions?

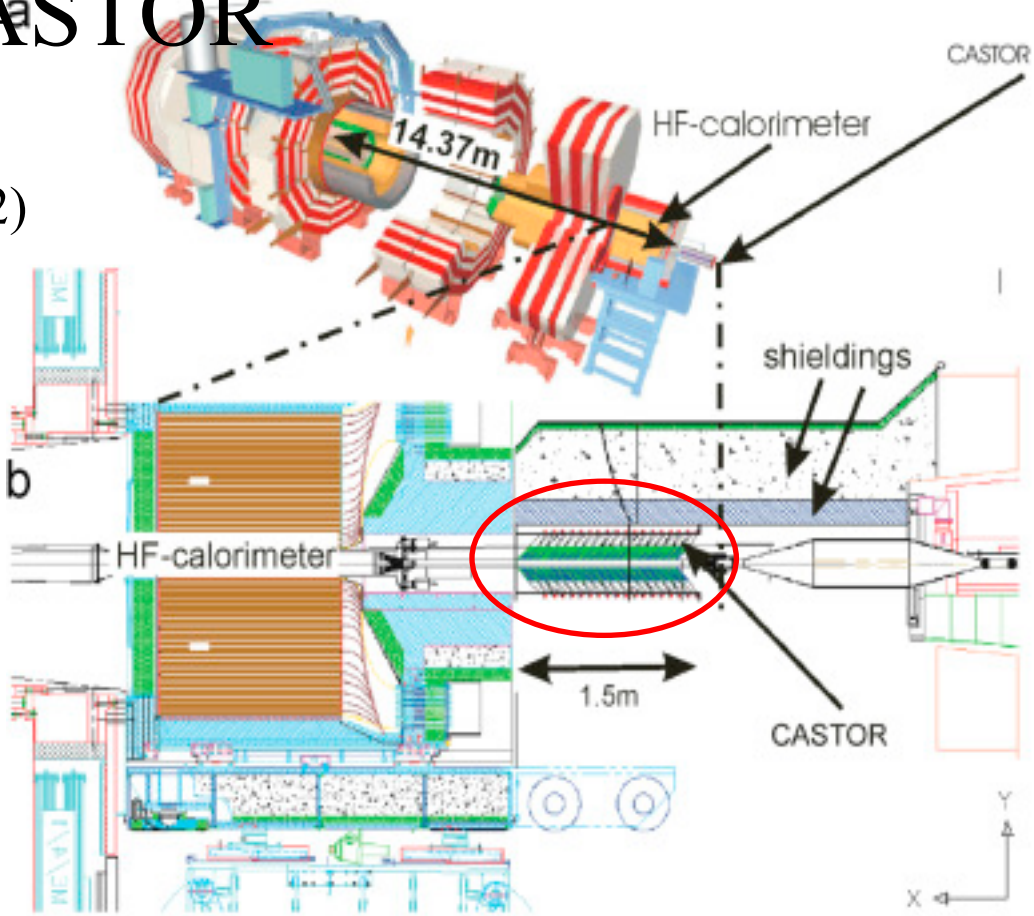
Gluon density with CASTOR

CASTOR: very forward ($-6.6 < \eta < -5.2$) calorimeter, (no tracking)

- ✓ Can explore very low x ~ 10^{-5} – 10^{-6}
- ✓ But limited availability
- ✓ Results on particle production/ correlations, jet cross-section



JHEP 05 (2019) 043



HIJING (DGLAP with shadowing effect) gives best description; other fails by a factor 2 at higher energies

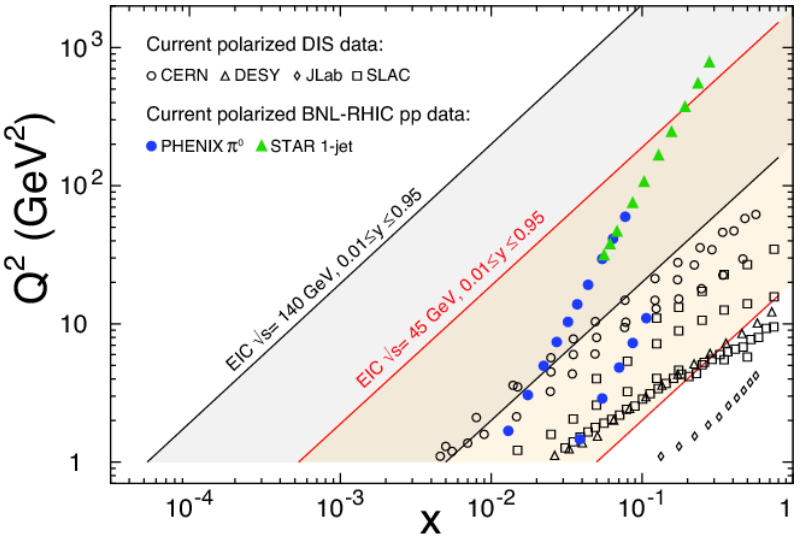
No clear support/rejection of BFKL

Context with EIC

- ✓ LHC explore low-x phase space upto 10^{-6} with range of collision energies and system.
  - Collective behavior at large multiplicities → gluon saturation
  - Azimuthal anisotropy and correlations as flow distributions which increases with PbPb system
  - Exclusive productions with the usage of forward detectors

- ✓ EIC will complement LHC with new collision system eA.
- ✓ Clean and controlled environment to extract x and Q^2

- ✓ Forward detectors of EIC can explore the phase-space uncovered by the limitation of the LHC experiments



Summary & Outlook

- LHC: rich dataset for extensive physics programs including low-x measurements
- A flavor of the LHC physics program on the exclusive processes is presented
- Looking forward to all success for EIC
  → to have robust understanding of nucleon and nuclei

Thanks!!