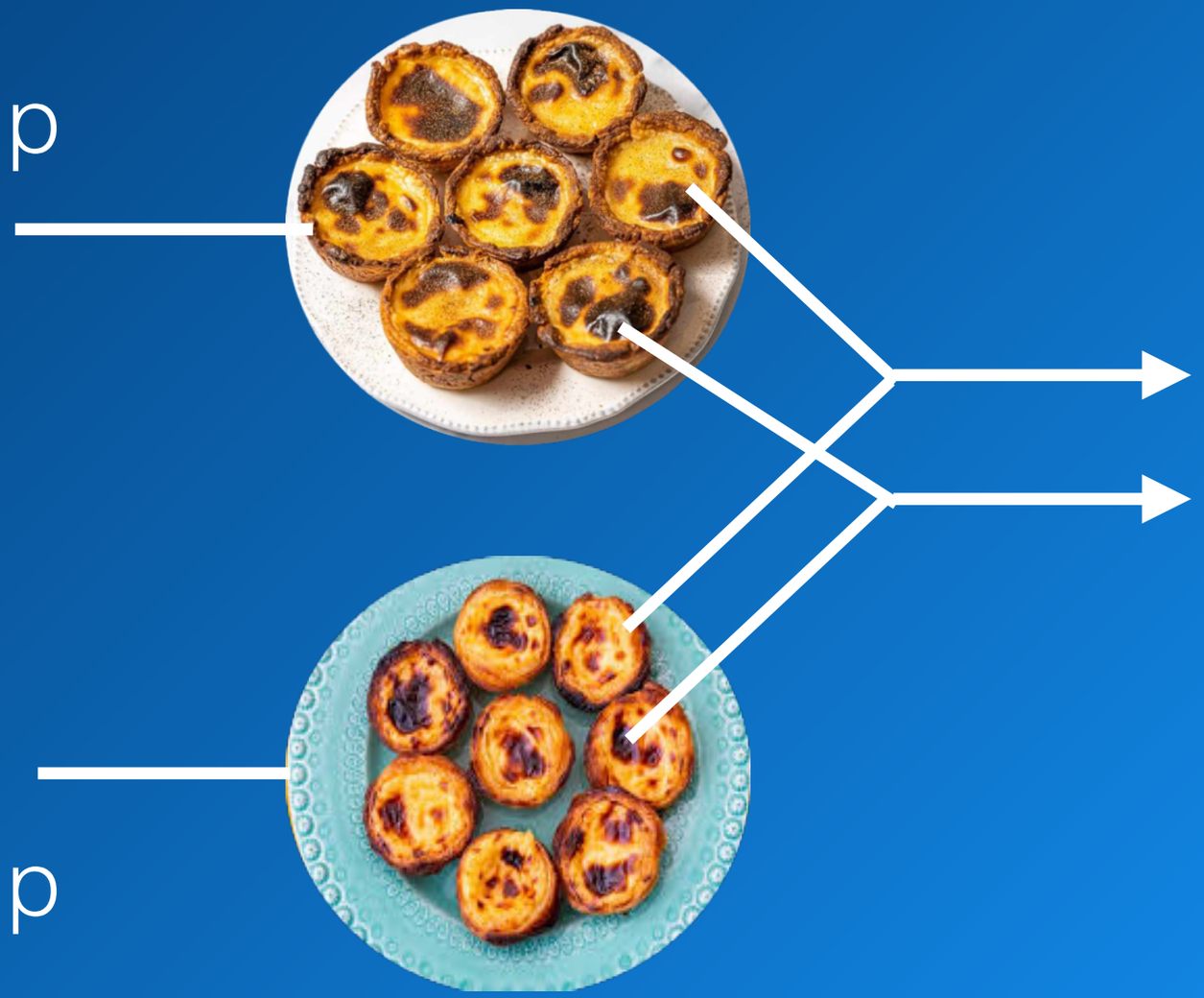
WG2 (DPS) Summary

MPI@LHC2021



Jonathan Hollar (LIP), Ankita Mehta (UHH), on behalf of WG2

Introduction

What is double parton scattering?

Definition

Double parton scattering (DPS) is a proton-proton scattering process in which two partons from each proton undergo **two separate hard interactions**.

Size comparison to SPS

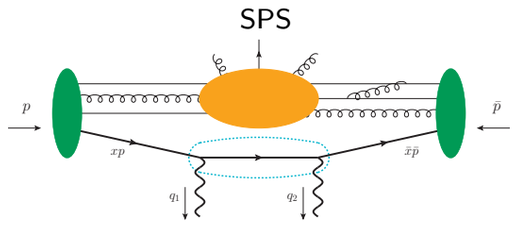
- integrated XS: $\dfrac{\sigma_{\text{DPS}}}{\sigma_{\text{SPS}}} \sim \mathcal{O}\left(\dfrac{\Lambda^2}{Q^2}\right)$
  $\Longrightarrow$ phase-space suppressed
- differential XS:
  $\dfrac{\mathrm{d}^2\sigma_{\text{SPS}}}{\mathrm{d}^2 q_1 \mathrm{d}^2 q_2} \sim \dfrac{\mathrm{d}^2\sigma_{\text{DPS}}}{\mathrm{d}^2 q_1 \mathrm{d}^2 q_2}$
  $\Longrightarrow$ same power counting!

hard scale is $Q \sim \min(Q_1, Q_2)$

transverse-momenta scale is Λ

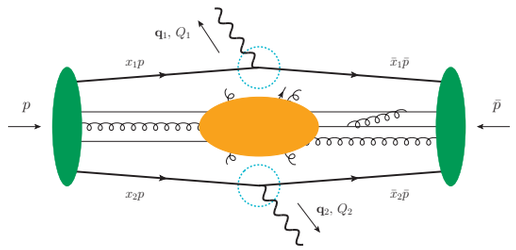
with $\Lambda_{\text{QCD}} \ll \Lambda \ll Q$

SPS



$$|\mathbf{q}_1^\perp + \mathbf{q}_2^\perp| \sim \Lambda \ll Q$$

DPS

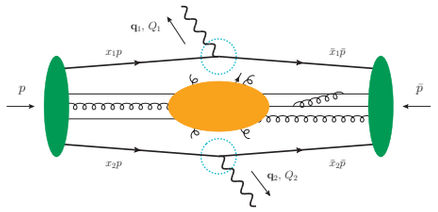


$$|\mathbf{q}_1^\perp| \sim \Lambda \ll Q$$
$$|\mathbf{q}_2^\perp| \sim \Lambda \ll Q$$

DPS cross section

For colorless final states, an analogous factorized form to the SPS case can be derived

- $\hat{\sigma}^{(i)}$ are regular partonic cross sections
- F_{ab} are double parton distributions (DPDs)
- y [GeV^{-1}] is inter-parton transverse separation



here neglecting color indices and $x_i, \bar{x}_i$ dependence in the functions

C is a symmetry factor

Collinear factorization:

$$\mathrm{d}\sigma_{\text{DPS}} = \frac{1}{C} \sum_{a_1 a_2 b_1 b_2} \hat{\sigma}^{(1)}_{a_1 b_1} \otimes \hat{\sigma}^{(2)}_{a_2 b_2} \otimes \int \mathrm{d}^2 y \, F_{a_1 a_2}(y) \otimes F_{b_1 b_2}(y)$$

In collinear factorization, $F_{ab}(y)$ are the collinear DPDs in position space.

Assuming no inter-partonic correlations whatsoever, obtain convenient XS formula (the **DPS pocket formula**)

$$\sigma_{\text{DPS}} = \frac{1}{C} \frac{\sigma_1^{\text{SPS}} \sigma_2^{\text{SPS}}}{\sigma_{\text{eff}}}$$

σ_{eff} used as a "measure" of DPS in exp's

R. Nagar

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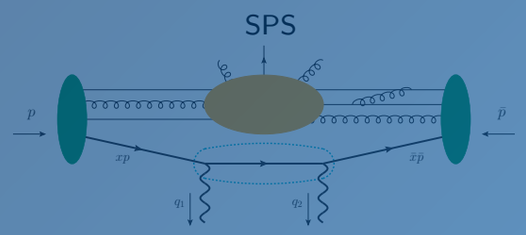

$$|\mathbf{q}_1^\perp + \mathbf{q}_2^\perp| \sim \Lambda \ll Q$$

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- differential XS: $\frac{\mathrm{d}^2\sigma_{\text{DPS}}}{\mathrm{d}^2 q_1 \mathrm{d}^2 q_2} \sim \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)\frac{\mathrm{d}^2\sigma_{\text{SPS}}}{\mathrm{d}^2 q_1 \mathrm{d}^2 q_2}$

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σ_{eff} used as a "measure" of DPS in exp's

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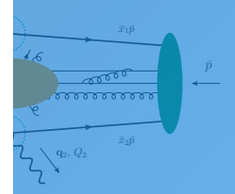
This assumption can't literally be true

Major theory effort on more rigorous QCD calculations including realistic correlation effects

But still a useful benchmark

Major experimental/pheno effort to make many measurements, understand where this fails

R. Nagar



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σ_{eff} used as a "measure" of DPS in exp's

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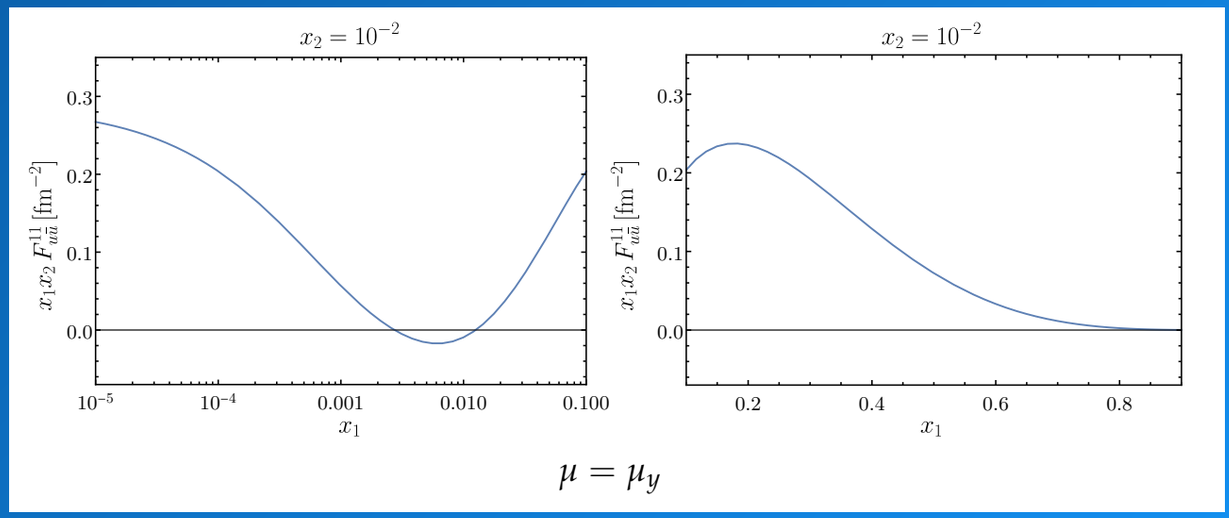
Double Parton Distributions: theory state of the art

A **formal all-order proof** of the factorization formulae in perturbative QCD **has been achieved for DPS** in the case of a **colorless final state**, both for the TMD and the collinear case. Current status is at the **same level as for the SPS** counterpart.

Diehl et al. JHEP 03 (2012) 089, JHEP 01 (2016) 076
Vladimirov JHEP 04 (2018) 045
Buffing et al. JHEP 01 (2018) 044
Diehl, RN JHEP 04 (2019) 124

- **Many-year effort to obtain formal all-order proof of factorization in pQCD**

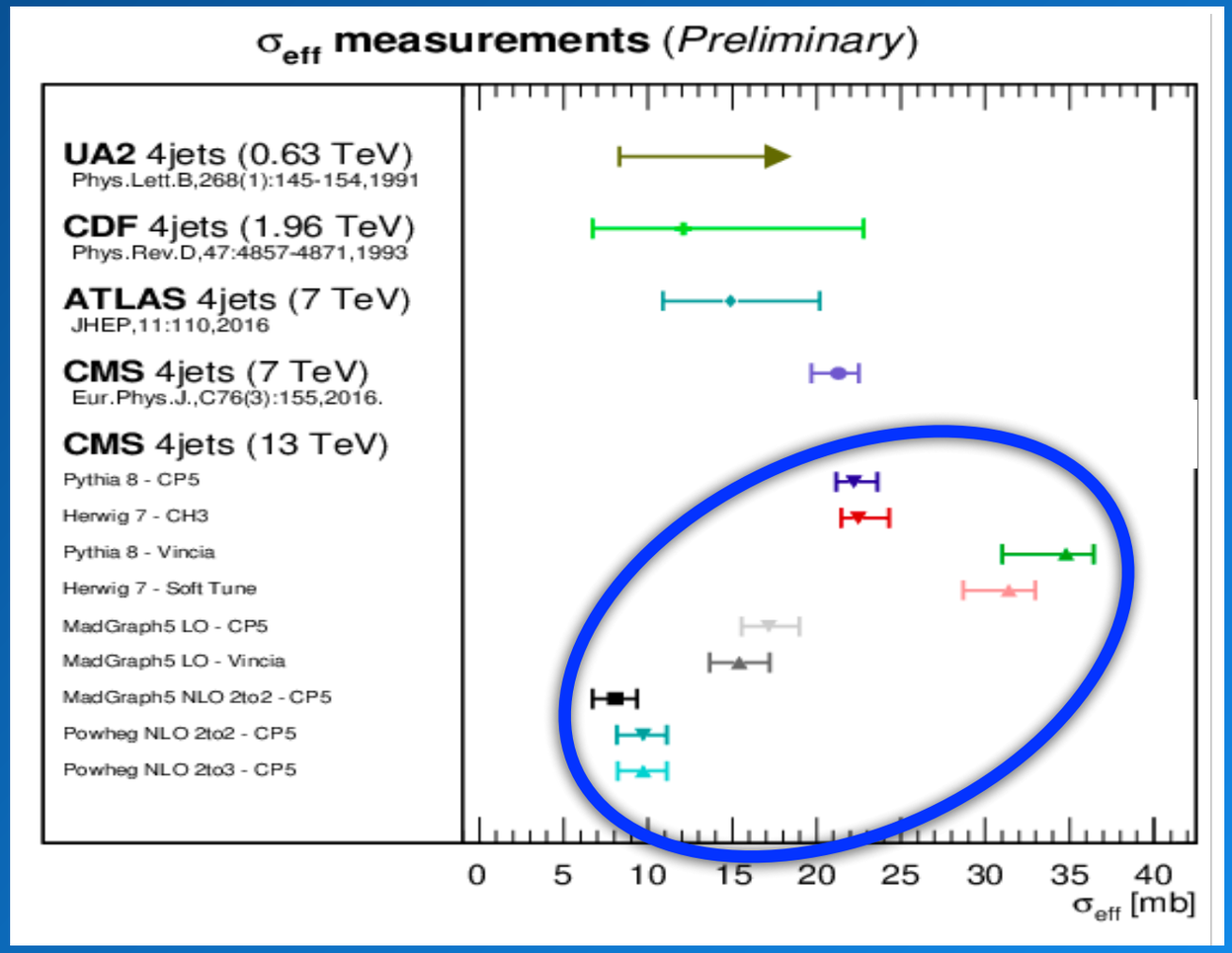
- **Properties of DPDs now being explored in great detail**
  - Color structure and correlations in the small-y limit
  - Impact of NLO corrections in non-singlet splitting DPDs
  - Derivation of positivity bounds, and investigation of violations in NLO DPDs



P. Plößl, R. Nagar

Experimental challenges

- **Very difficult to cleanly separate DPS from large SPS backgrounds in some channels**
- Example of the “classic” 4-jet final state: measurement at 7 TeV (ATLAS+CMS), and new measurement at 13 TeV (CMS)
  - **Same data can give very different DPS fraction depending on SPS MC/model assumptions**

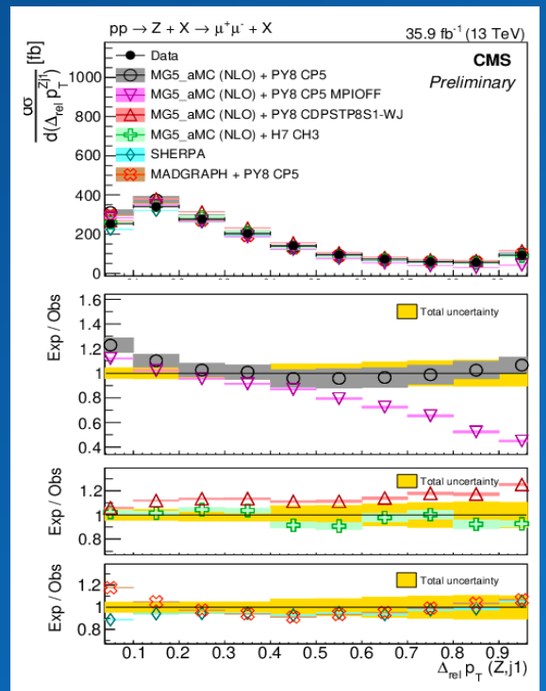


- => Motivation to focus on channels with lower cross sections but cleaner DPS signatures/suppressed SPS contributions

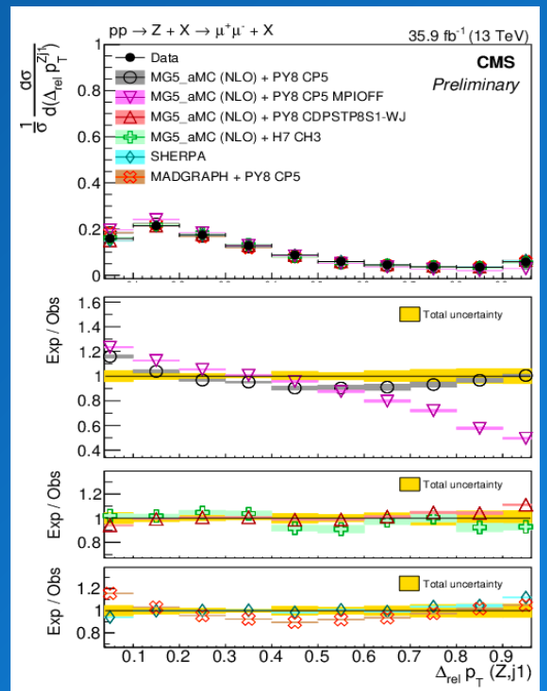
R. Nayak, R. Gupta

DPS in Z+jets

- **Differential cross sections measured as a function of DPS-sensitive observables**
  - Data is not described without MPIs
  - Varying levels of agreement with different MCs used for MPI modeling (Pythia8/Herwig++/Sherpa)

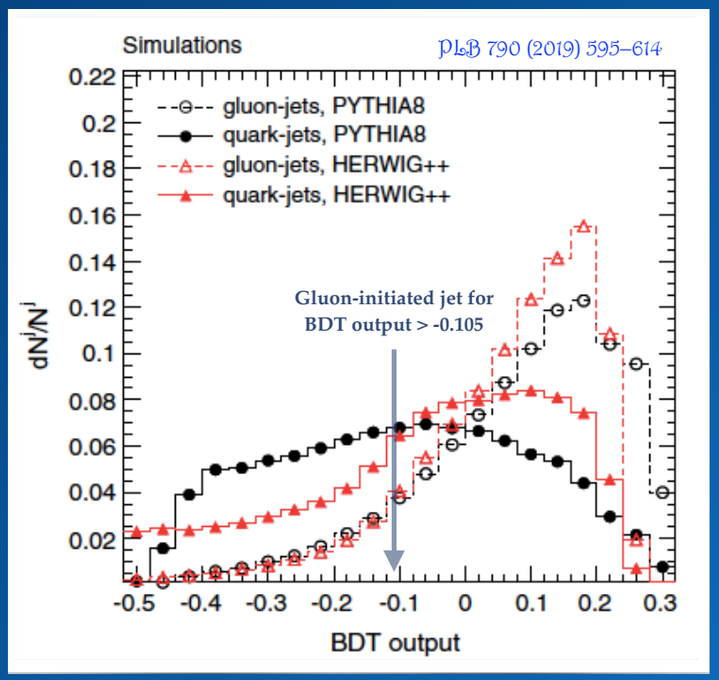


Differential cross-section



Area-normalized distribution

R. Gupta



R. Kumar

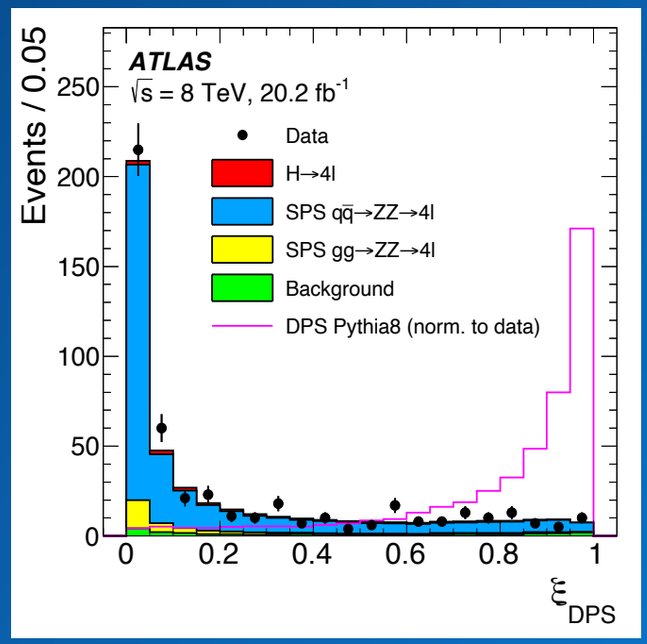
- **Prospects for significant improvements using quark/gluon tagging with MVA's**
  - **50%** improvement in DPS fraction vs. analysis without tagging in simulation

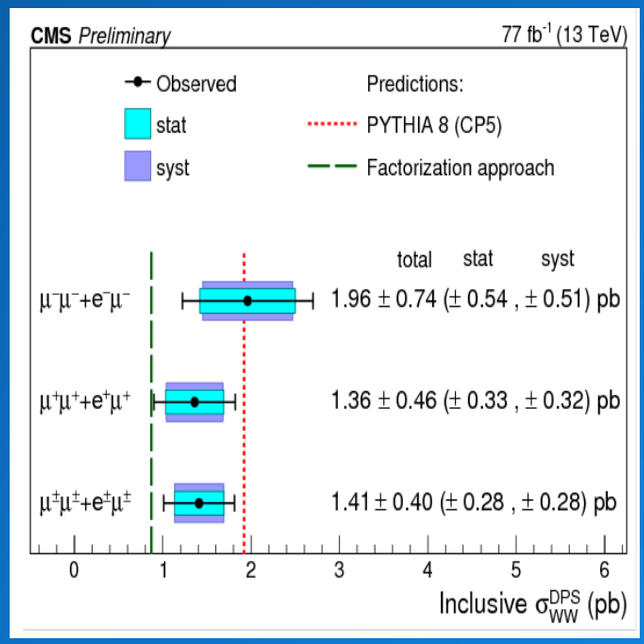
DPS in weak di-bosons

- **Even di-boson production with fully leptonic decays can be studied at the LHC**

- ***ZZ→l±l∓l±l∓***
  - ATLAS limit at 8 TeV (σ_{Eff} > 1 mb)

- **Same-sign *W±W±→l±νl±ν***
  - First evidence from CMS at 13 TeV ($\sigma_{Eff} = 12.7^{+5}_{-2.9}$ mb)





- **Di-boson processes implemented in dShower MC**
  - Based on full DPDs, taking care of SPS/DPS double counting in parton shower

R. Nayak, R. Gupta

J. Gaunt (slides)

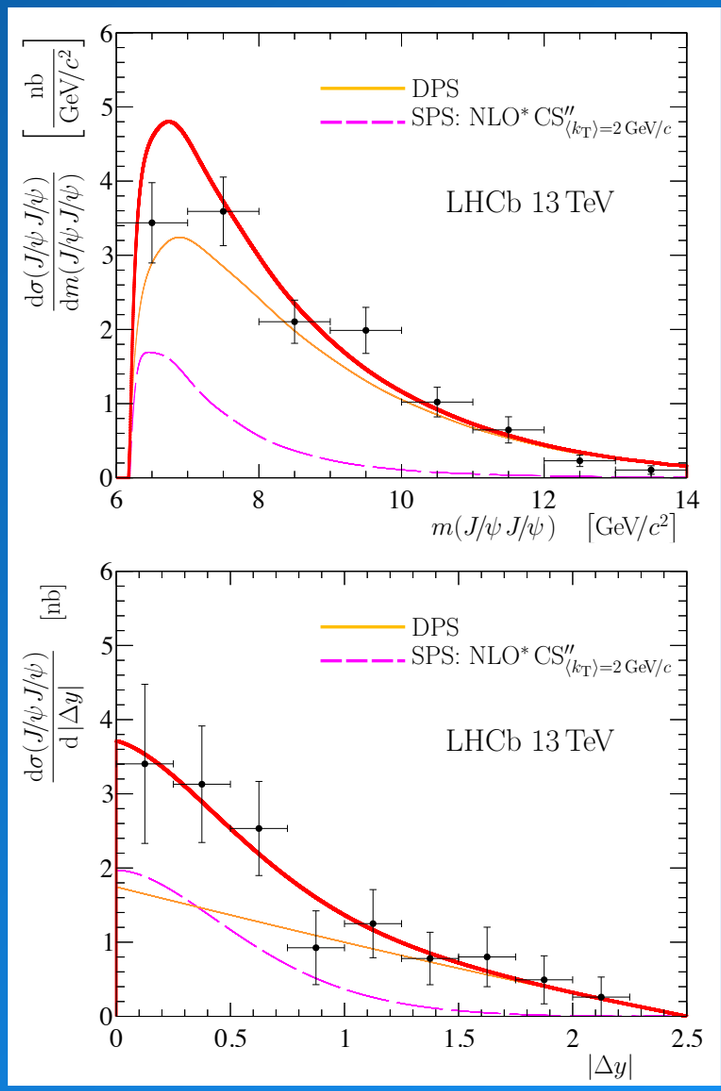
DPS with quarkonium

- ATLAS & D0 found values of ~5-6 mb for J/ψ+J/ψ at mid-rapidity, with 30-50% uncertainties

- LHCb finds ~[10-12] mb for J/ψ+J/ψ, depending on SPS model assumptions

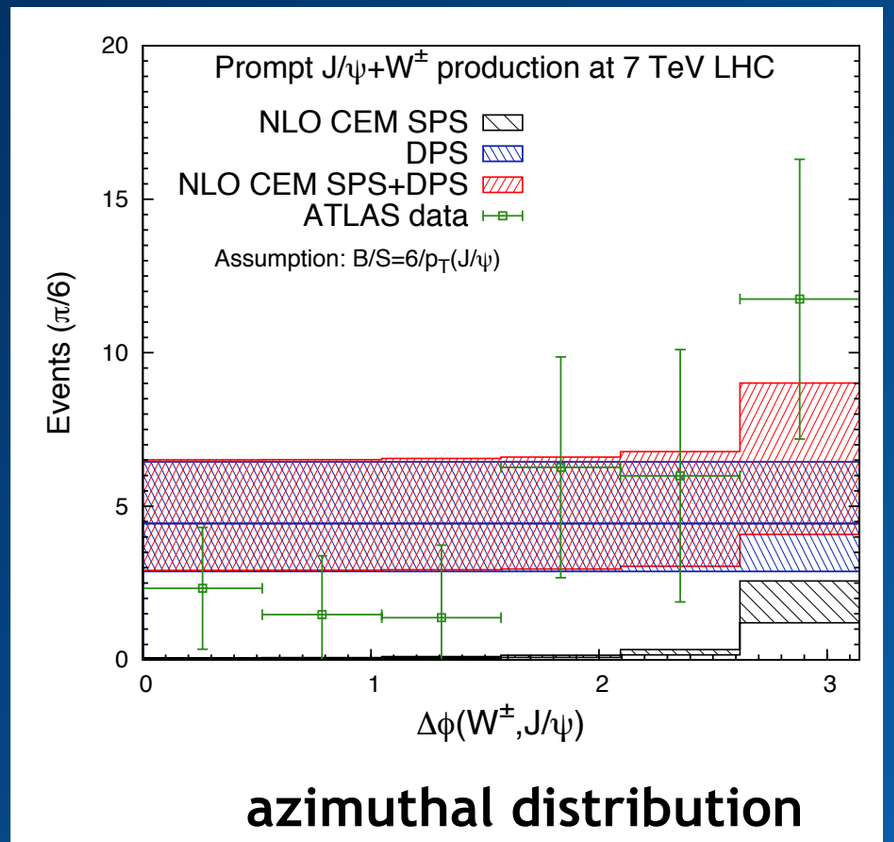
- LHCb measures J/ψ+charm and Y+charm, reporting σ_{eff} in the range of ~13-19 mb, assuming 0 SPS

- **Can information about DPS be extracted from other quarkonium measurements?**



N. Yamanaka, A. Bursche, D. d'Enterria

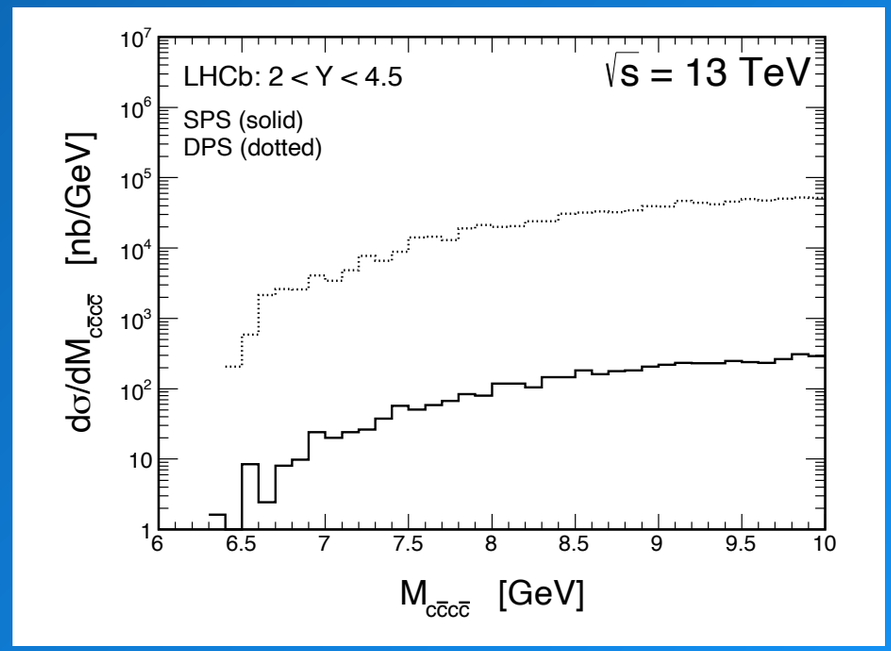
DPS with quarkonium (and friends)



N. Yamanaka

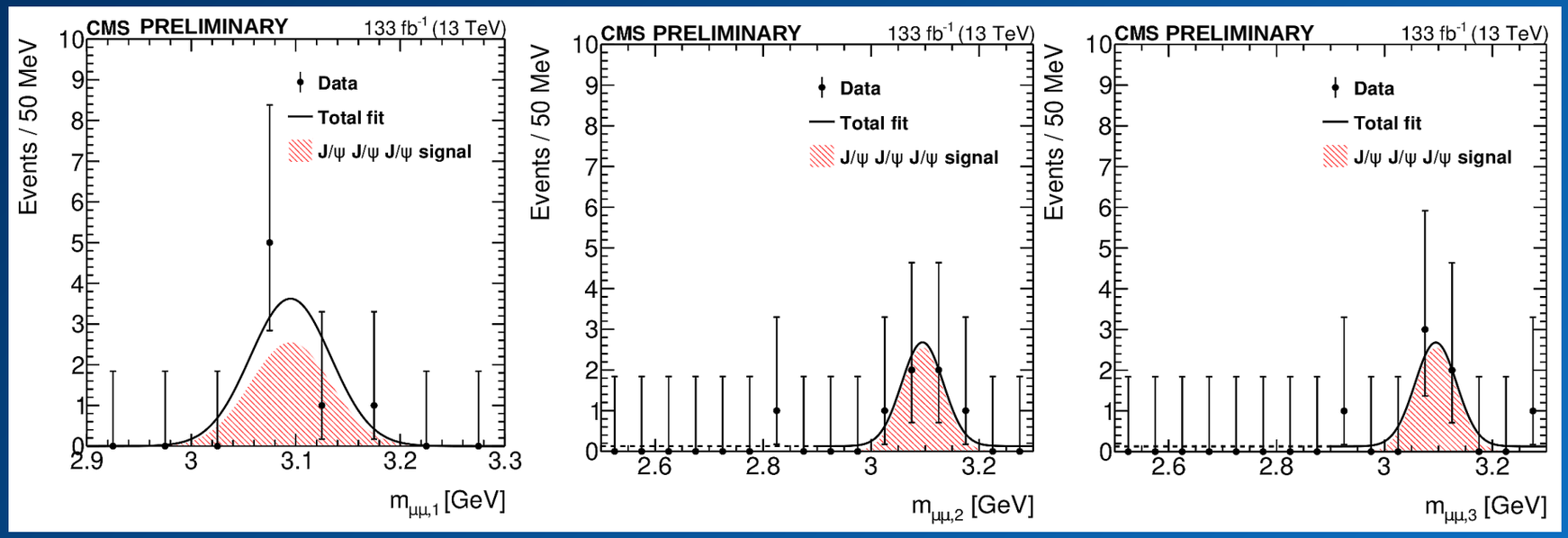
- **Yes! Re-analysis of W+J/ψ, Z+ψ, J/ψ+J/ψ differential cross sections from ATLAS+CMS**
  - Large DPS component (=small σ_{eff}) also preferred for this data, with conservative assumptions for SPS

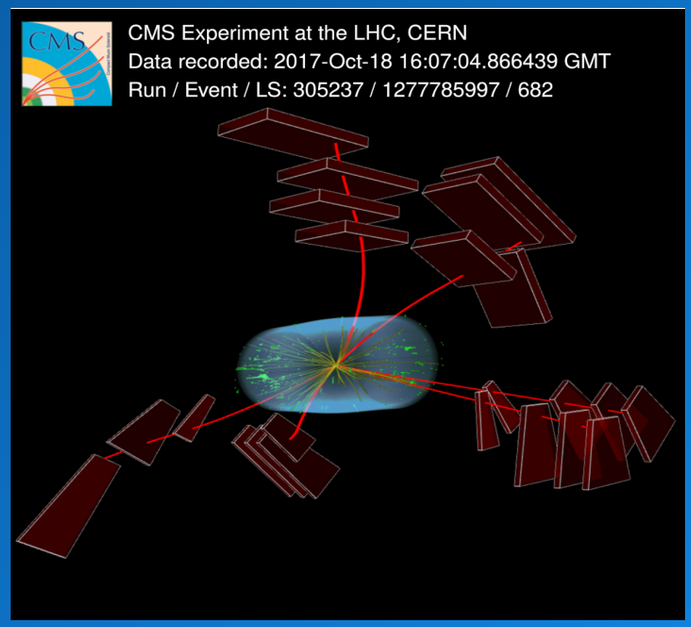
- **"Exotic"/tetraquark states promising in the future**
  - Predict DPS>>SPS for new LHCb T4c, and hypothesized bottom-charm tetraquarks



A. Szczurek

Triple-parton scattering





- **First observation of Triple-parton scattering via *J/ψ J/ψ J/ψ*→ *μ⁺μ⁻μ⁺μ⁻μ⁺μ⁻* in CMS**
  - Very rare process, but very clean: expect ~95% DPS+TPS
- **Significant signal, plus $\sigma_{eff,DPS}$ and $\sigma_{eff,TPS}$, extracted using full Run 2 data**
  - $\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}{}^{+1.5}_{-1.0}$ mb

D. d'Enterria

Triple parton distribution functions

- **Generalization of DPDs, derivation of sum rules for triple parton scattering**
  - Pythia8 sPDF machinery used to construct tPDFs at different stages of generation

Let's check momentum rule first

x_1	x_2	j_1	j_2	PYTHIA tPDFs	"Naive" tPDFs
10^{-6}	10^{-4}	u	u	0.996	0.996
10^{-3}	10^{-4}	u	u	0.997	0.997
10^{-1}	10^{-4}	u	u	1.007	1.096
0.2	10^{-4}	u	u	1.008	1.195
0.4	10^{-4}	u	u	1.007	1.390
0.8	10^{-4}	u	u	1.002	1.626

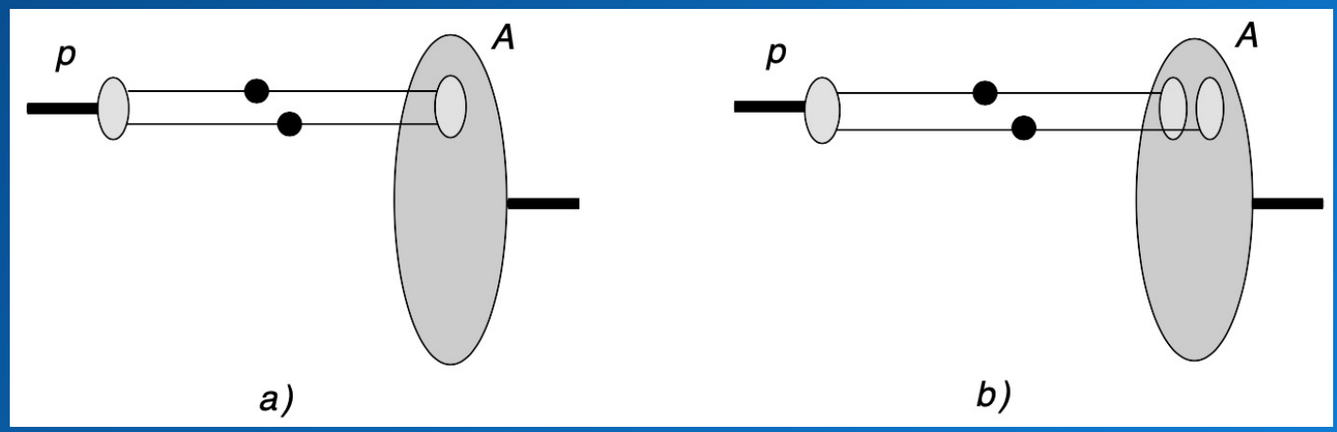
Test of the momentum sum rule for the tPDFs.

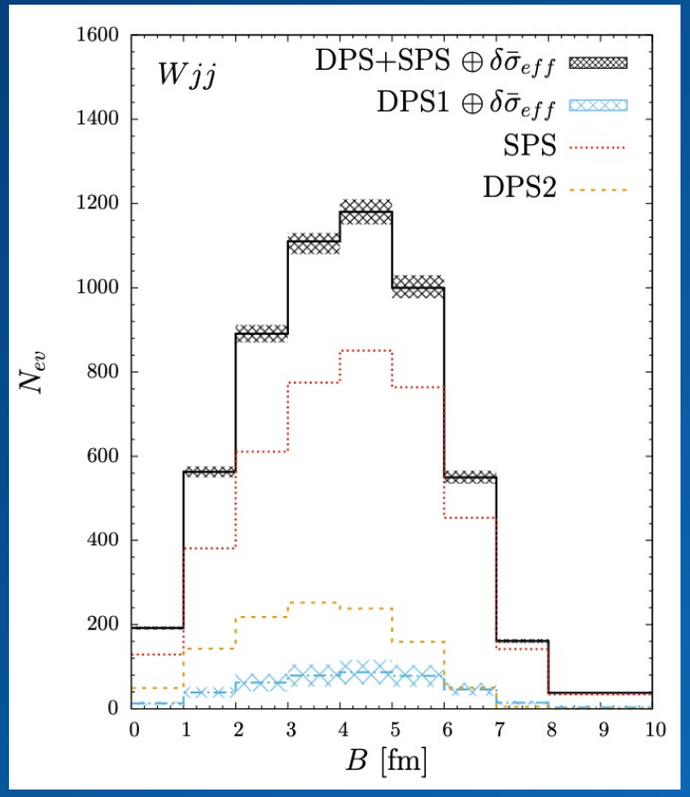
- In some regions of phase space, differences from "naive" tPDFs can be significant

- Some challenges to be resolved in future work: symmetric PDFs, s-quark PDFs, phenomenology of TPS processes

DPS in p-A: theory

- **Two types of DPS in p-Pb collisions: 1 or 2 protons in the target nucleus involved**

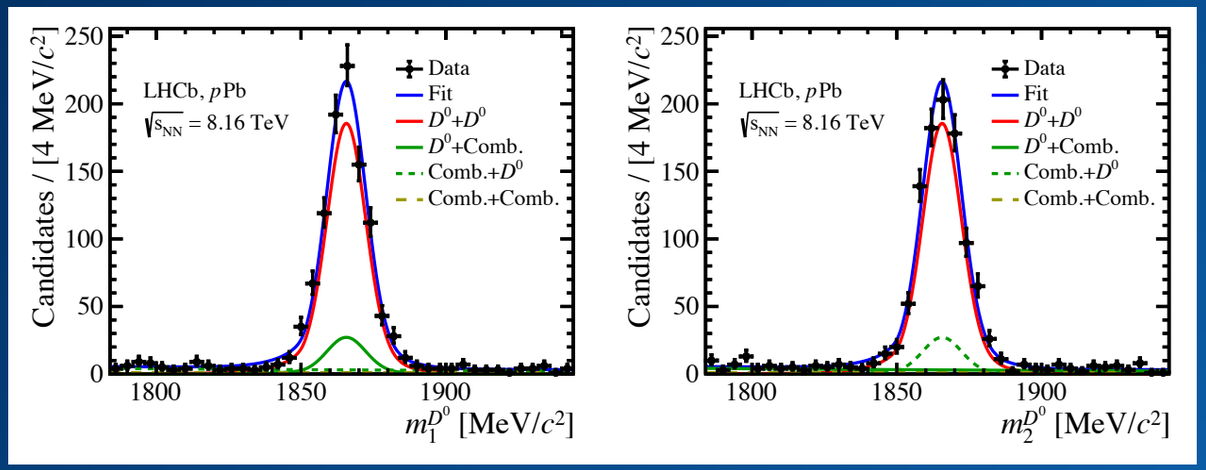




- Different impact parameter dependence can distinguish the 2nd DPS process (“DPS2”) from the 1st DPS process (“DPS1”) and SPS

- Existing ATLAS+CMS p-Pb data should be sufficient to study DPS with 4-jets, W+jets, Z+jets…

DPS in p-A: experiment



- **First measurement of DPS in proton-ion collisions already performed by LHCb**
  - p-Pb→ double open charm and J/ψ + open charm

- **Enhancement of DPS fraction over p-p**
  - Connected to p-p σ_{eff} via Glauber approach

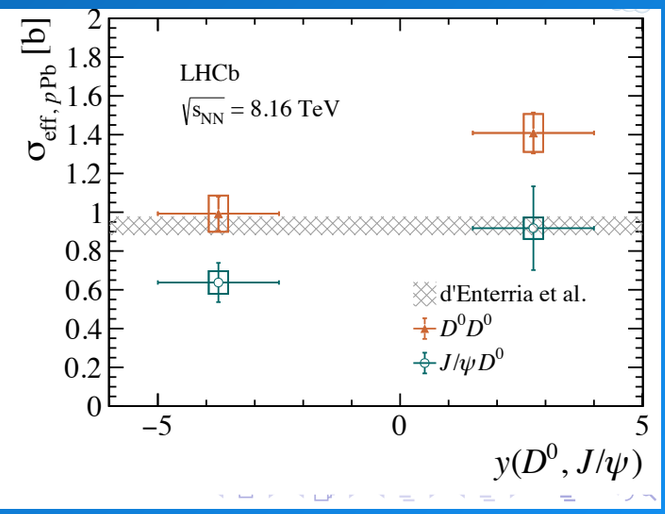
$$R^{D_1D_2}_{forward} = \frac{\sigma_{D_1D_2}}{\sigma_{D_1\bar{D}_2}} = 0.308 \pm 0.015 \pm 0.010$$

$$R^{D_1D_2}_{backward} = 0.391 \pm 0.019 \pm 0.025$$

$$R^{D^0D^0}_{pp} = 0.109 \pm 0.008$$

Like sign charm fraction tripled!

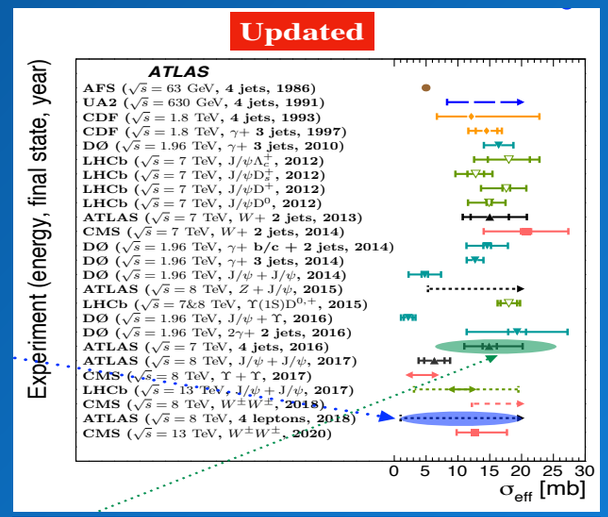
$\sqrt{s_{NN}} = 8.2$ TeV *Phys. Rev. Lett. 125 (2020) 212001*

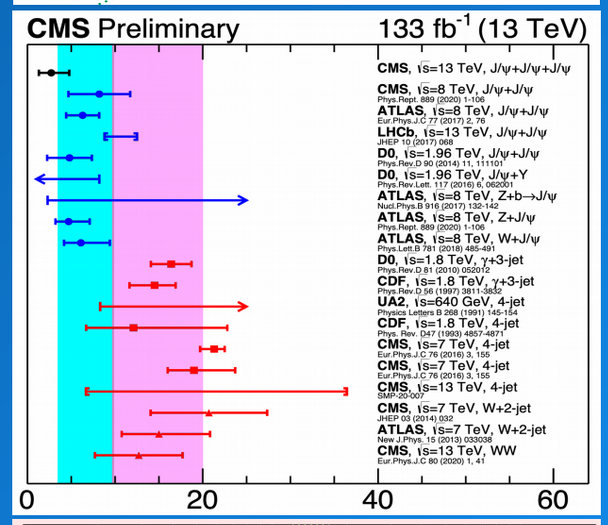


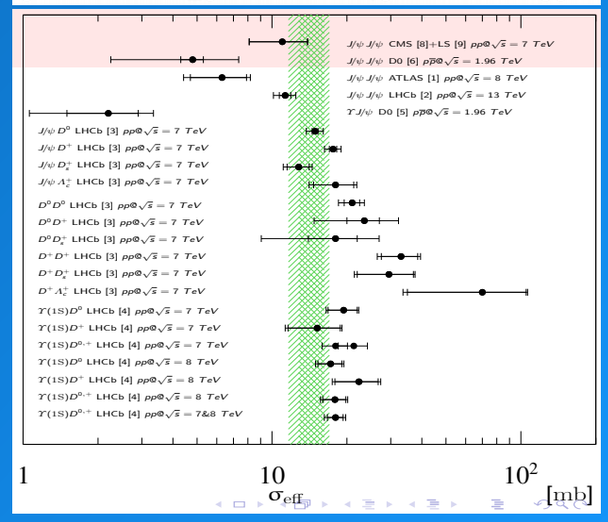
A. Bursche

Overall picture (p-p experiment)

- **“Pocket formula”/naive approach has 1 free parameter σ_{eff}...**







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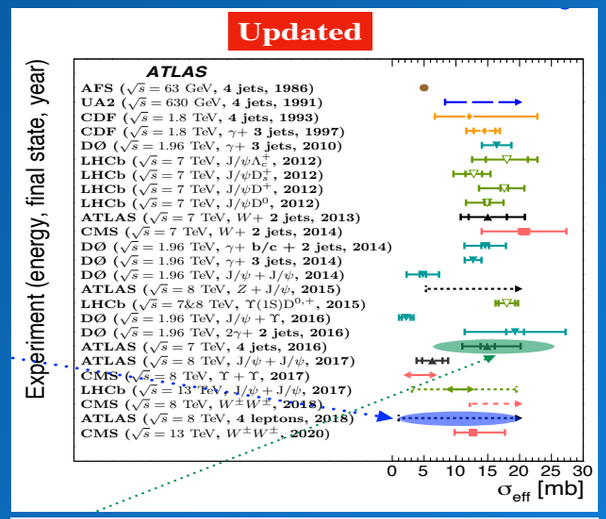
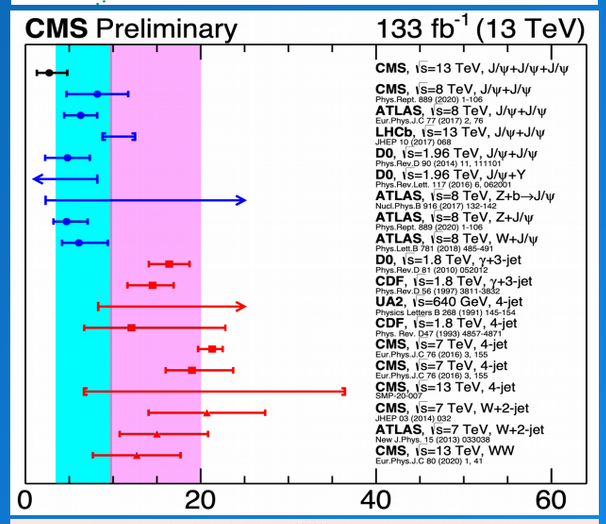
- **“Pocket formula”/naive approach has 1 free parameter σ_{eff}...**
- **By now >30 different experimental/reinterpretation results quoting σ_{eff}**
- **(Not counting σ_{eff} determinations from UE/minbias tunes within Pythia/Herwig)**
- **Too many summary plots to fit on one page!**





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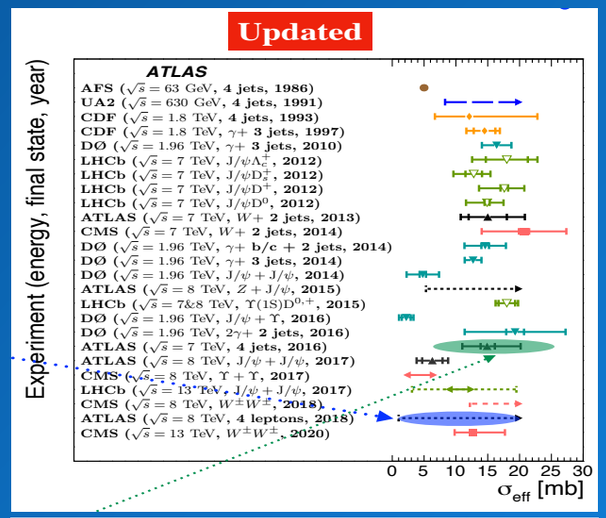
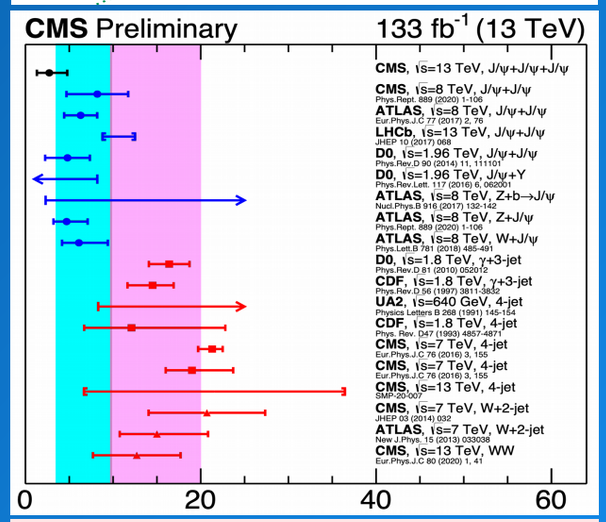
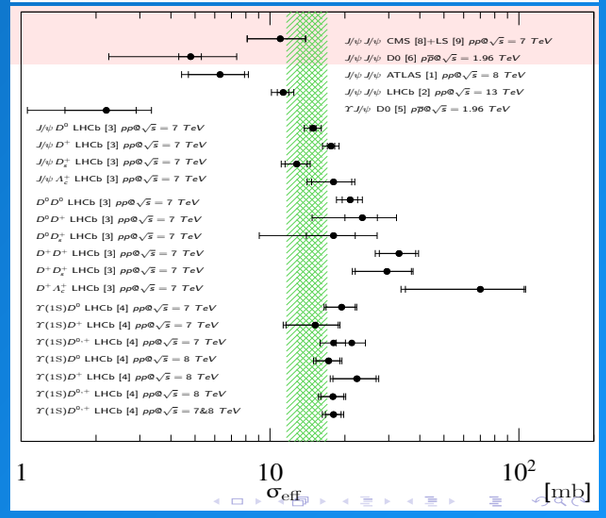
- **Very (very) over-constrained "model"**

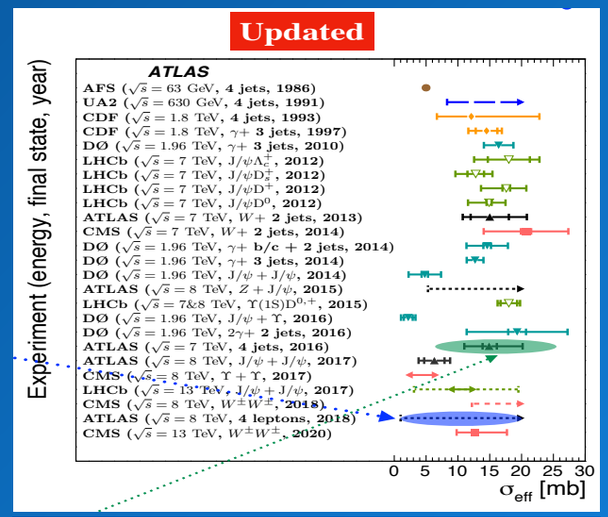


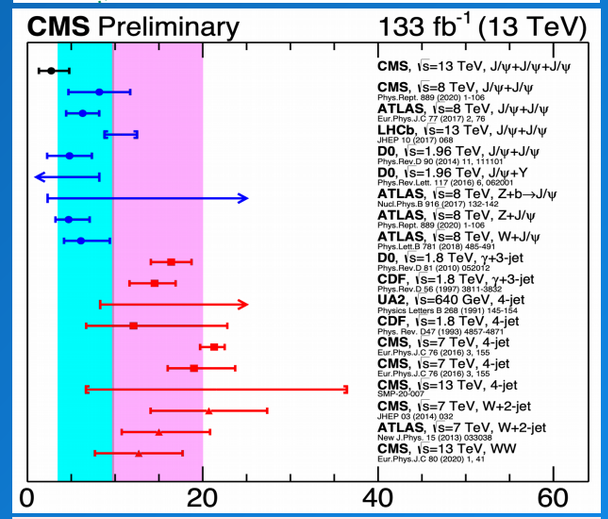


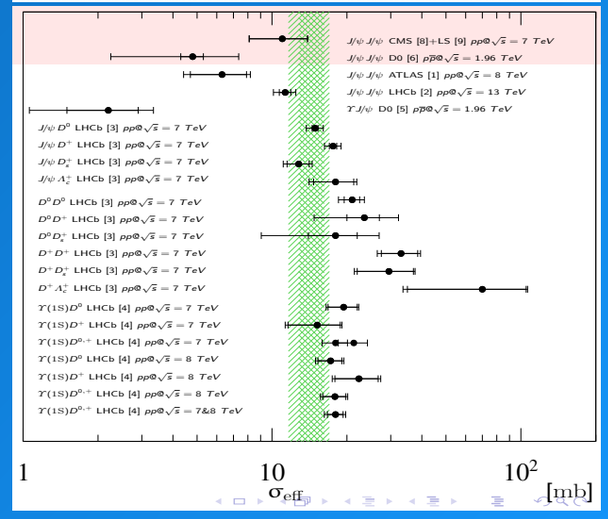


Overall picture (p-p experiment)

- **4-jets, vector boson+jets, di-boson**
  - ~10-20 mb, compatible with mean ~15 mb
- **LHCb quarkonium+ open charm**
  - Compatible with 10-20 mb
- **Double and triple quarkonium (mid-rapidity), J/ψ + W/Z**
  - ~2-10 mb, mean well below 10 mb
- **Taking error bars at face value, no longer possible to describe all data with a single value of σ_{eff}**







Frequent discussion points

- **Experimentally, DPS(+TPS) ≈ 1 - SPS**
  - Some channels can be quite sensitive to modeling of SPS background: CMS 4-jets, LHCb charm/J/ψ…
    - Possible improvements? (already some ideas in this workshop involving quark/gluon tagging, MVAs/machine learning)
  - Do experimental error bars (esp. in older results) cover these effects?

- **Huge progress in sophistication of DPS theory**
  - How to connect all of this work to experiment+phenomenology?
  - Incorporation of DPDs in MC generators like dShower an important bridge
    - Plans to include newer developments (color or spin correlations, TPDs…)?

Frequent discussion points

- **Given apparent deviations from constant σ_{eff}, what are the (most) relevant degrees of freedom**
  - Rapidity coverage, x dependence in quark- vs. gluon-dominated processes?
  - Flavor dependence?
  - Other?

- **What measurements with LHC Run 2/3 data would have the biggest impact**
  - More differential measurements of existing channels?
  - New channels?
    - Tetraquarks, DPS in p-Pb proposed in this workshop - others?

Summary of the summary

- **Remarkable progress since the last edition of MPI**

  - **1st measurements of triple-parton scattering, DPS in p-Pb, DPS in same-sign WW…**

  - **Closing proof of factorization formulae in pQCD, detailed understanding of color correlations and NLO splitting effects in DPDs, first extension to TPDs, development of MC/parton shower algorithms based on DPDs…**

- **Exciting times ahead**

Extra

DPS in 4-jets

- Earliest final state in which DPS was studied by AFS/UA2/CDF
  - Still quite active at LHC: measured at 7 TeV (ATLAS+CMS), and recently at 13 TeV (CMS)

- Now understood to be very challenging: small signal in tails of SPS background distribution
- => Strong dependence on MC/models for SPS