Recent soft and diffractive QCD measurements at the LHC

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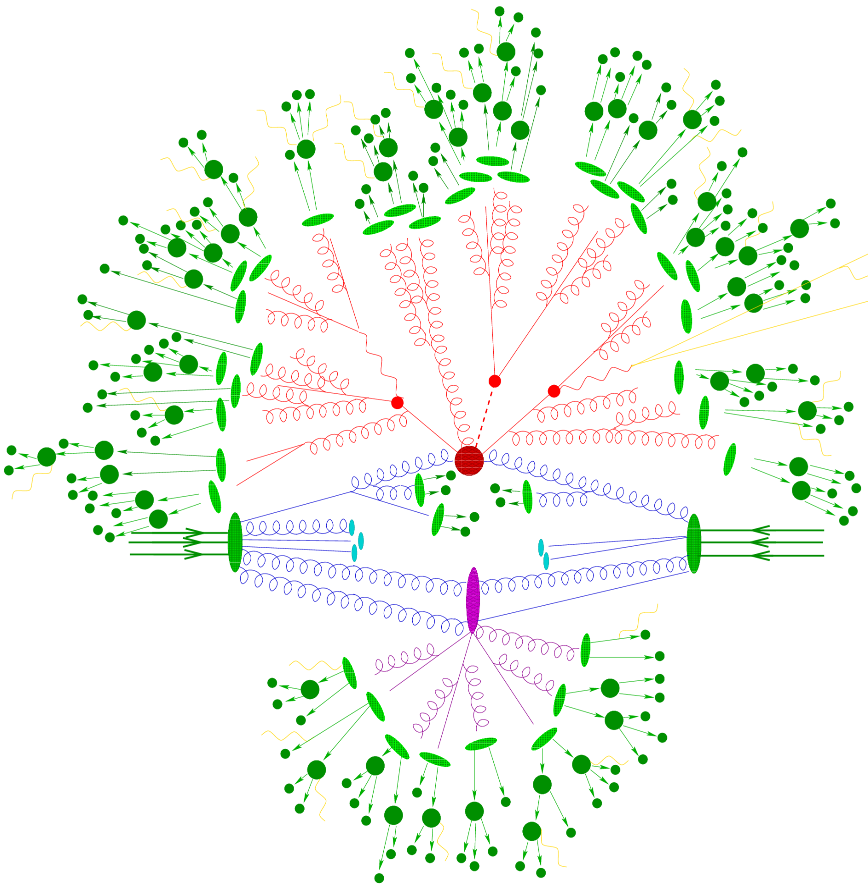
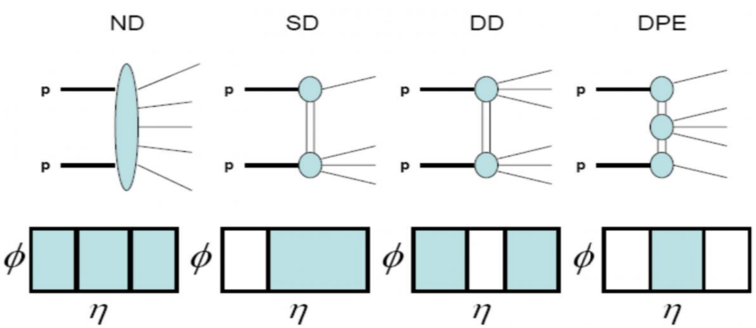
Introduction

- LHC collisions are complex due to sub-structure of protons
- QCD: theory of strong interactions between interacting quarks and gluons
  - Hard QCD – high p_T: PDFs, ISR & FSR, PS, perturbation theory
  - Soft QCD – low p_T: perturbative QCD approach not applicable
    - Minimum bias events, fragmentation and hadronisation
    - Radiation ISR/FSR
    - Underlying events (MPI)
    - Diffraction

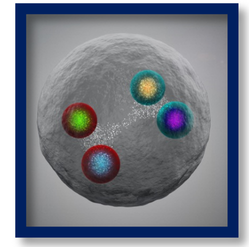
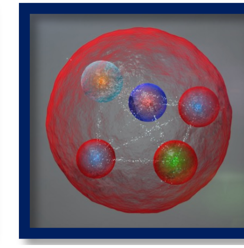


- pp collisions: elastic or inelastic
- Inelastic collisions: diffractive or non-diffractive
- Diffractive processes **dominate in forward regions**

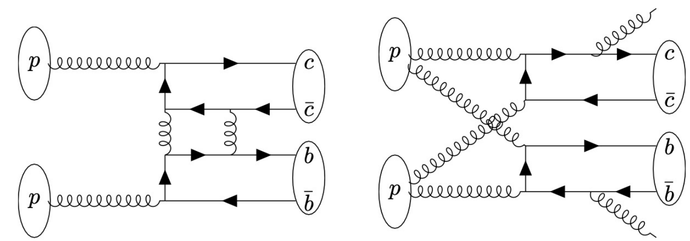


Outline

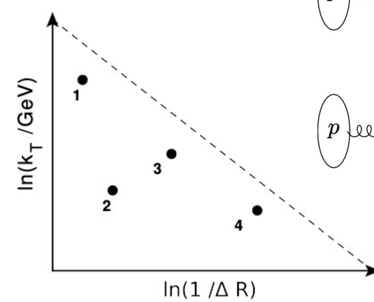
- The quark model towards tetraquark and pentaquark

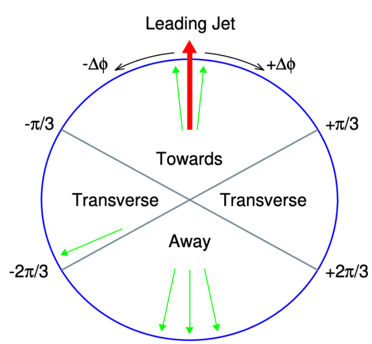
- Insight on multi-parton scattering with associated production



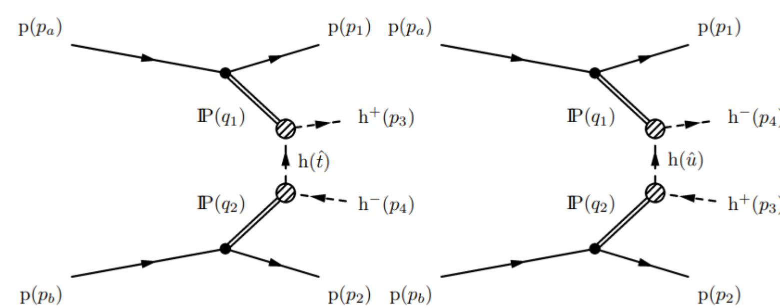
- Jet fragmentation and substructure



- Hadronisation in hadronic environment



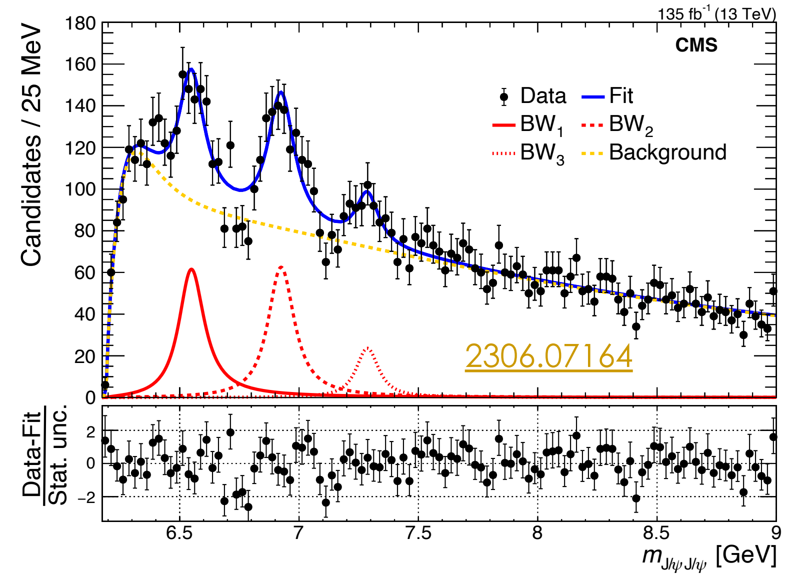
- Event shape modelling

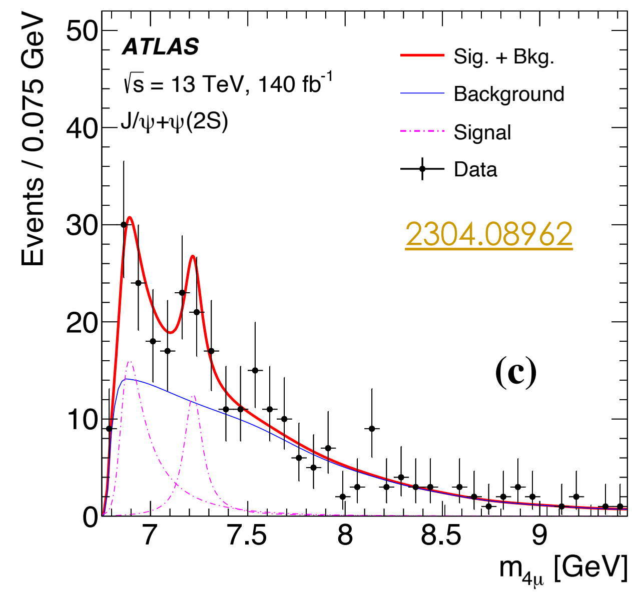


- Soft central exclusive production processes

Tetraquark with di-J/ψ spectrum

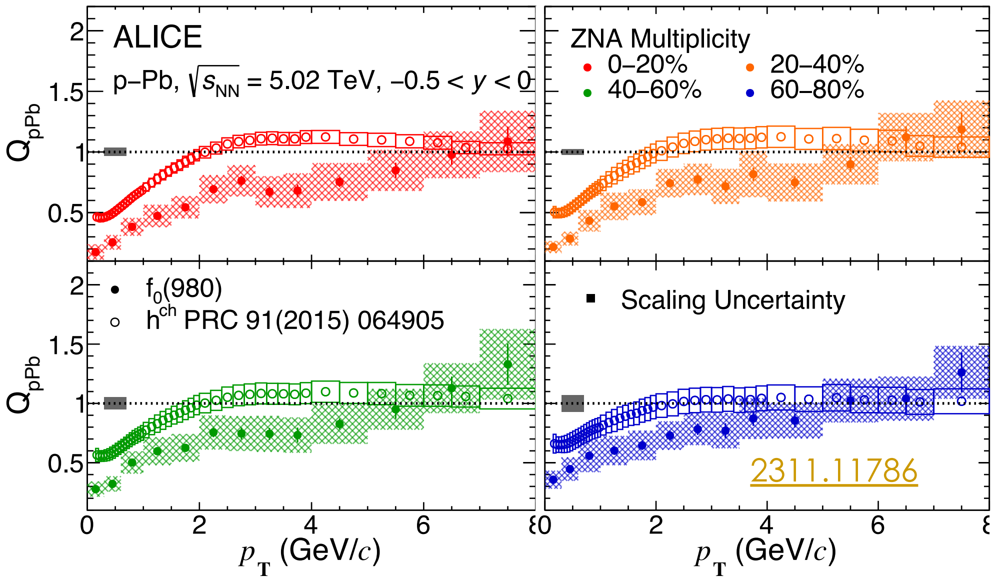
- Tetraquark candidate X(6900) first observed by LHCb in 2020 Sci. Bull. 65, 1983 (2020)
- X(6900) confirmed by CMS and ATLAS in channels $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\ J/\psi$ and $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\psi(2s)$
- Structure observed by CMS in $J/\psi\ J/\psi$ spectrum
- Hint for X(6600) and X(7100)
- **New charmed tetraquark candidates**

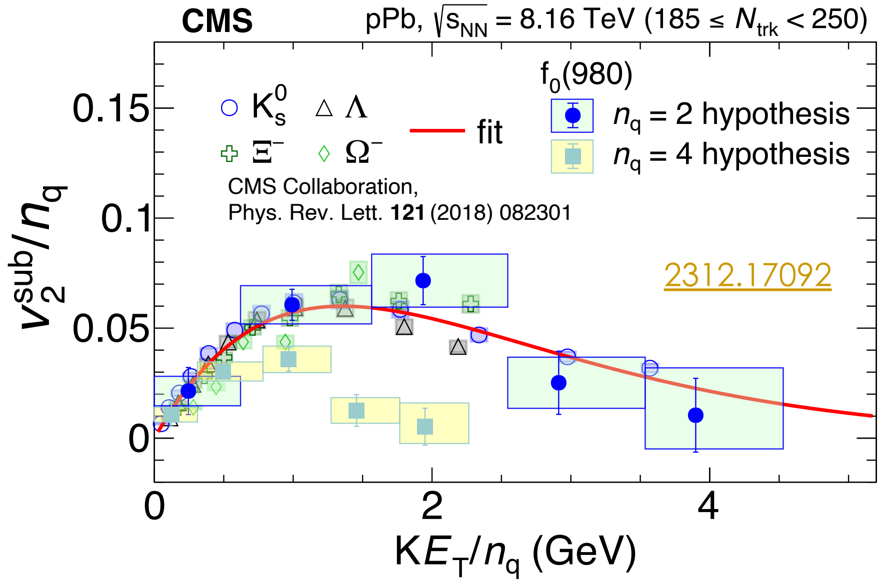




2-quark structure in p-Pb collisions

- Is the $f_0(980)$ a $q\bar{q}$ meson, a tetraquark state, a $K\bar{K}$ molecule or a $q\bar{q}$-gluon hybrid state?
- Study of the $f_0(980)$ production and dynamic in p-Pb collisions

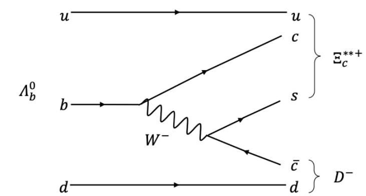




- **Clear suppression of the f_0 nuclear modification factor** suggests impact of final state scattering and meson-like structure
- $f_0(980)$ is found to be a $q\bar{q}$ meson (number-of-constituent-quarks scaling hypothesis) – other hypotheses ruled out

Search for pentaquarks

LHCb



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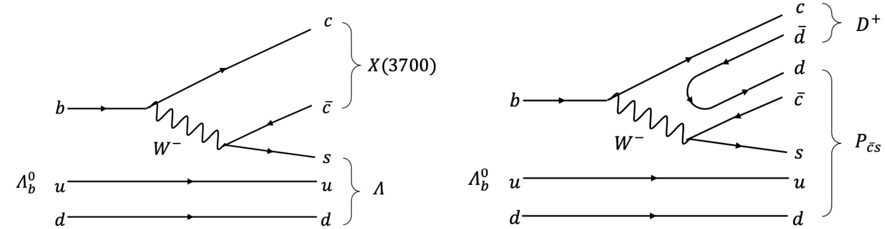
First observation of $\boldsymbol{\Lambda_b^0 \to D^+ D^- \Lambda}$



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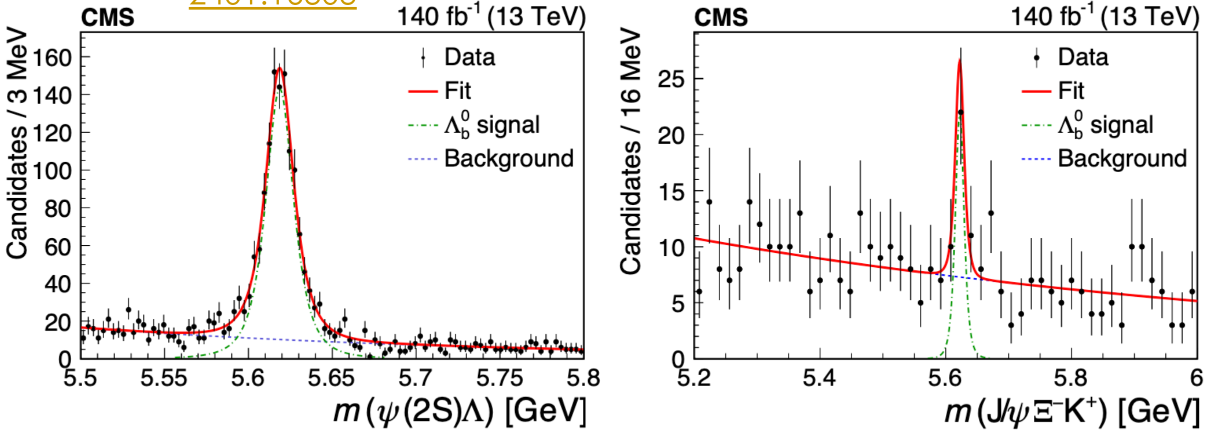
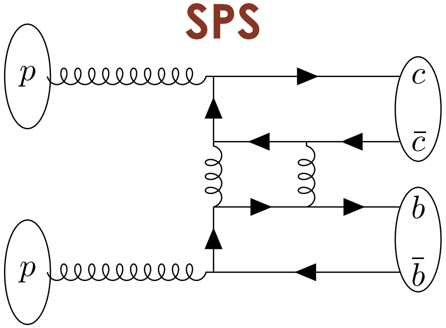


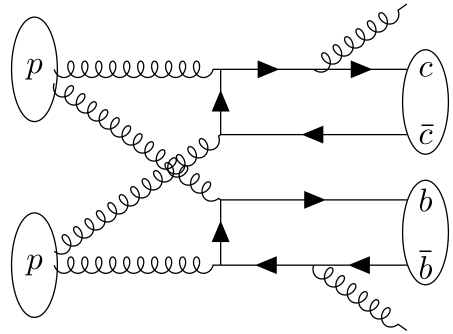
First observation of $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$

- Opens the possibility to search for **doubly-strange hidden-charm pentaquarks**

Double parton scattering

SPS





DPS

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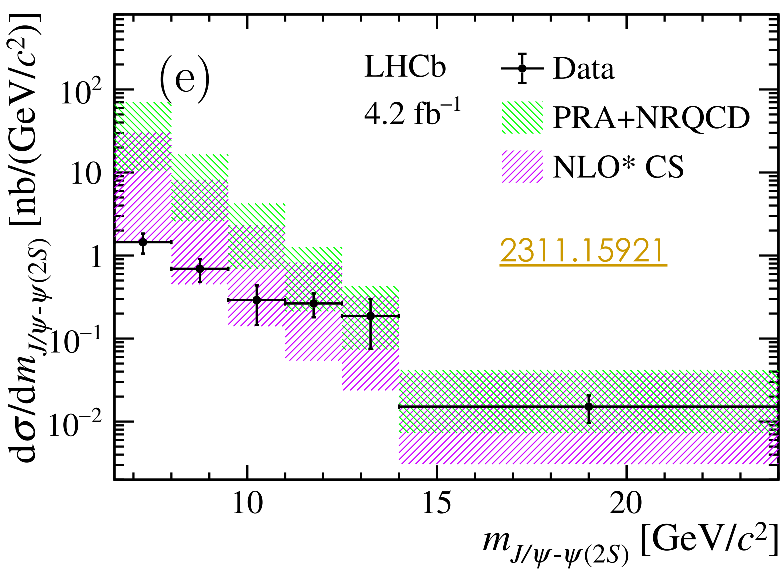
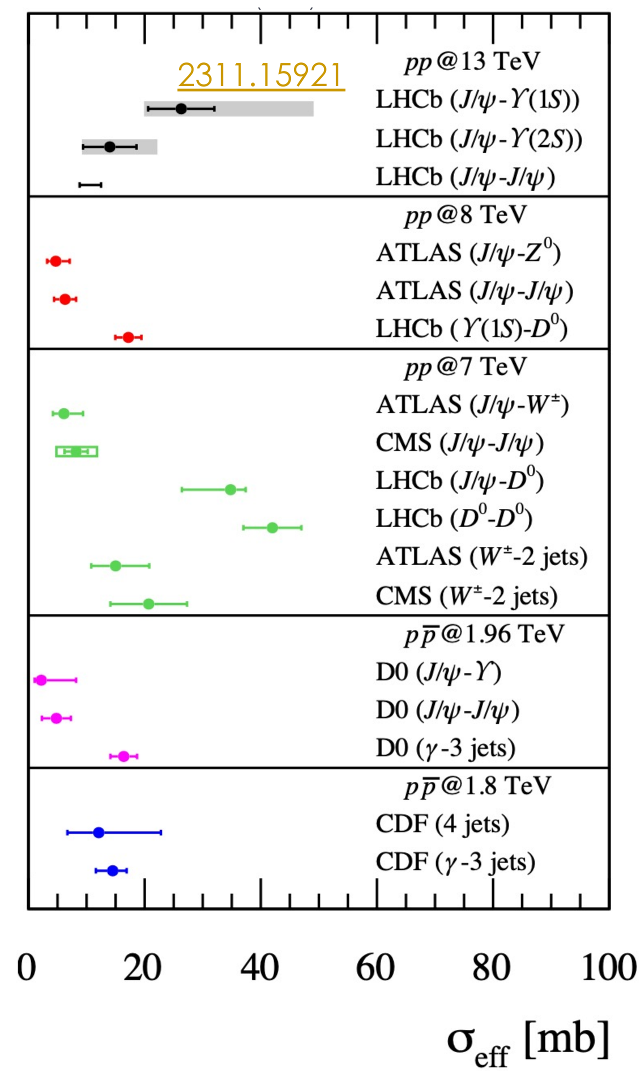
ALICE di-J/ψ

$\sigma_{eff} = 6.7 \pm 1.6(\text{stat}) \pm 2.7\ (\text{syst})\text{mb}$



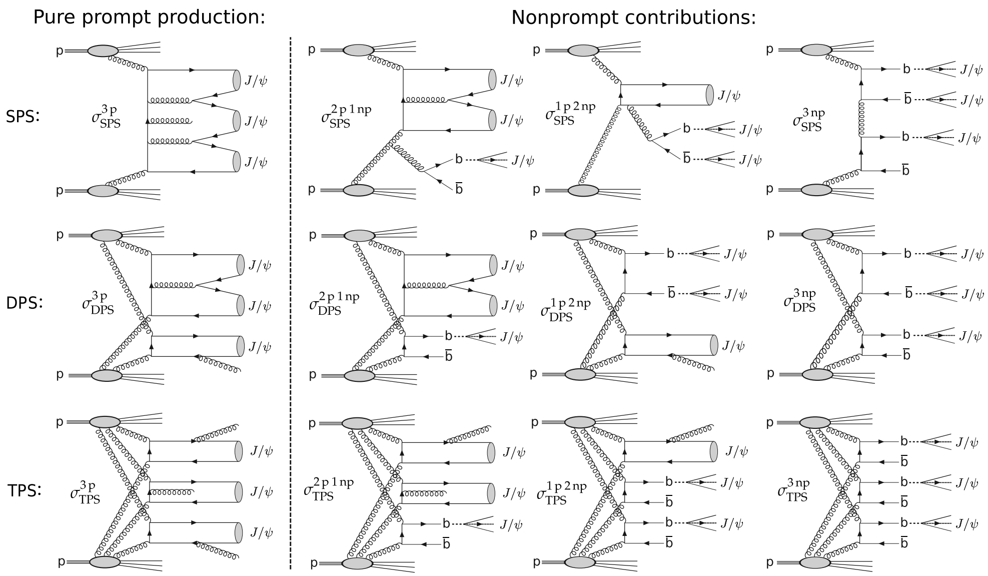
$$\sigma_{DPS}^{AB} = \frac{m}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{eff}}$$

m=2 when A and B are distinguishable
m=1 when indistinguishable

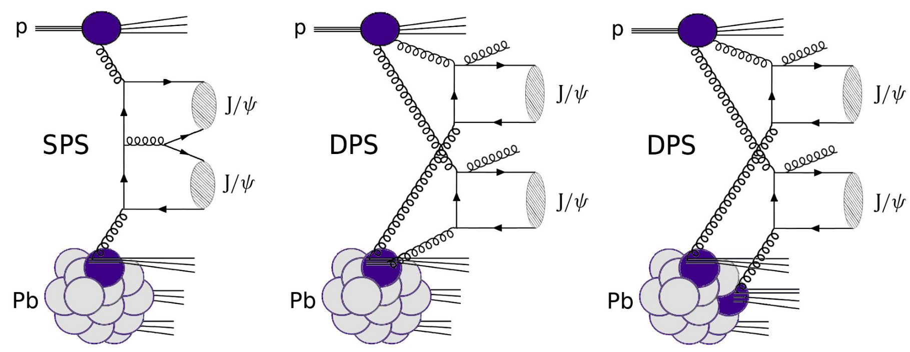


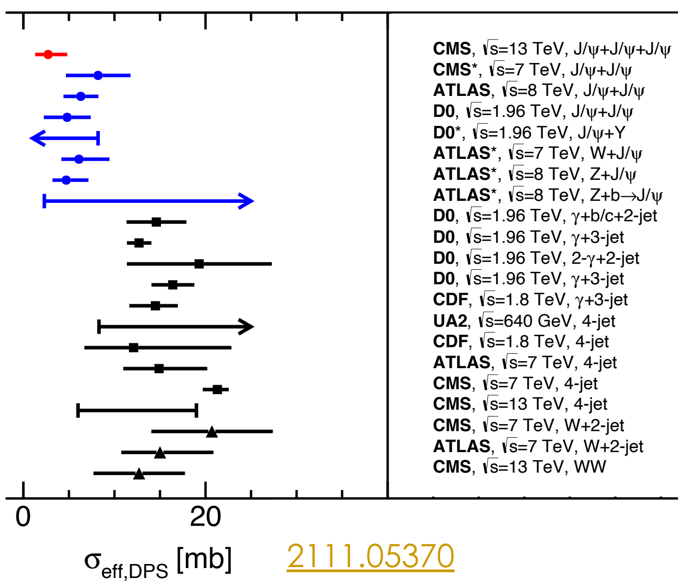
Expected properties	Observed properties
Collision energy independent	Energy dependent
Process independent	Process dependent
	Kinematic dependent

Next orders: tri-J/ψ in pp and di-J/ψ in pPb



Also extracted from p-Pb collisions





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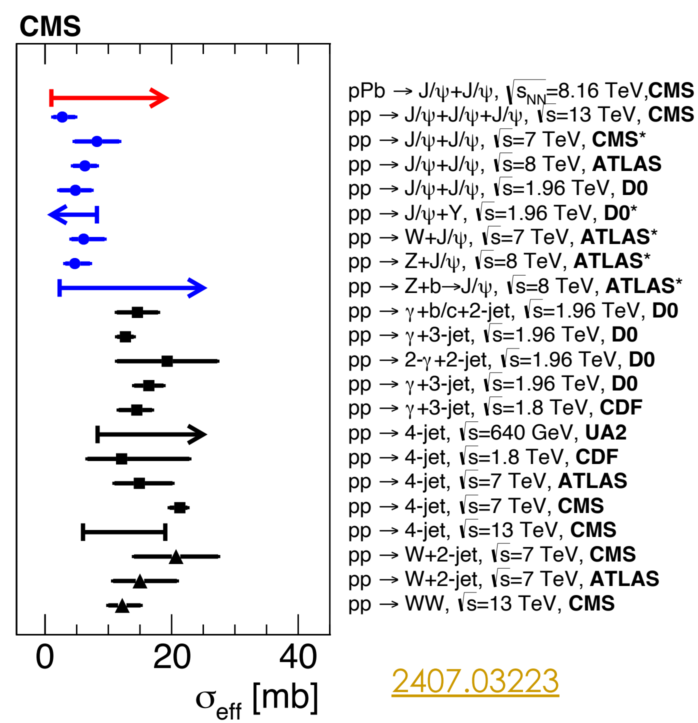
Dependence of the $\sigma_{eff,DPS}$ on the relevant parton species and x fractions probed



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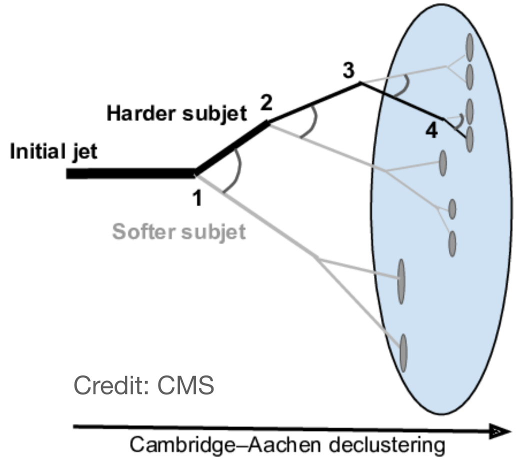
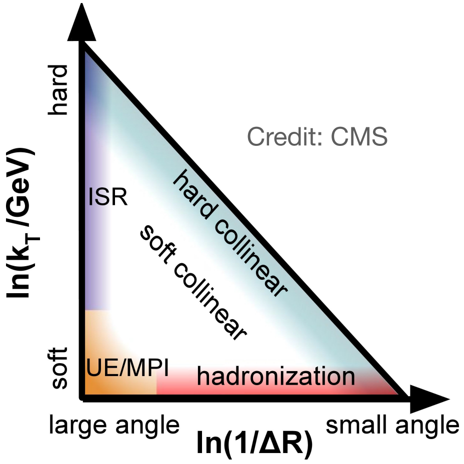
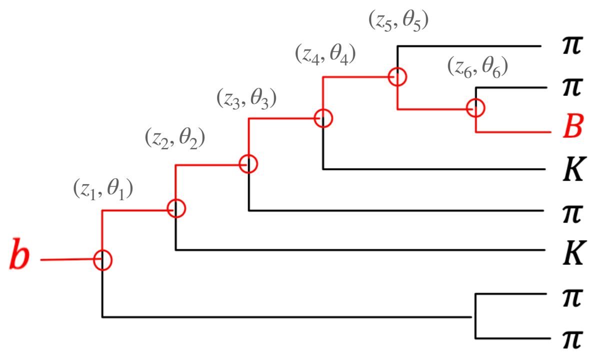
Lund sub-jet multiplicities

- Lund plane: theory tool used for many years, particularly by MC authors
  Z.Phys.C 43 (1989) 625
- Lund jet plane: applied to jet substructure, probe entire emission history of originating parton 1807.04758
- Two-dimensional representation of the phase space of emissions inside a jet
- Parameterize emissions of angle-ordered jet in terms of relative energies (z) and angles (ΔR)
- Allow to probe different mechanisms depending on kinematic

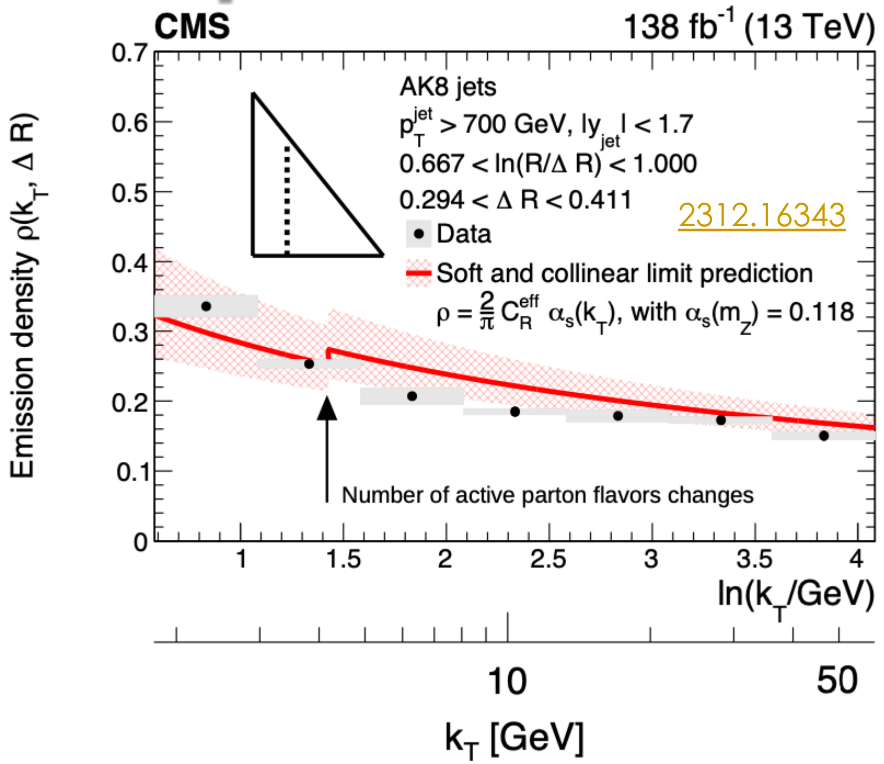


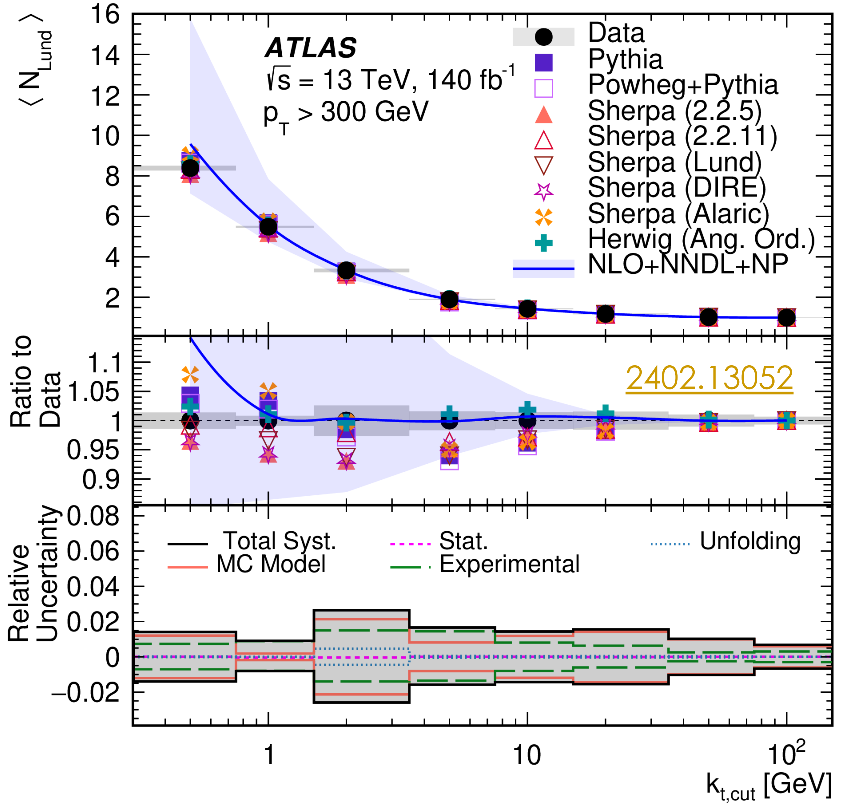




Lund sub-jet multiplicities

Running of α_S in the jet shower
dominant mechanism responsible for the rise of the LJP density at low k_T (characteristic energy scale in α_S evolution)

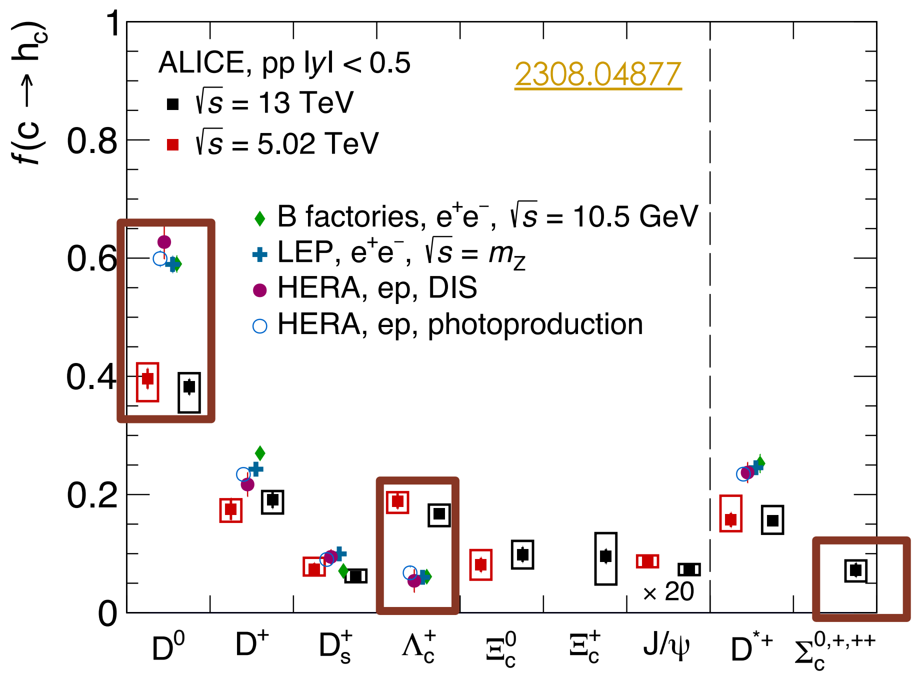


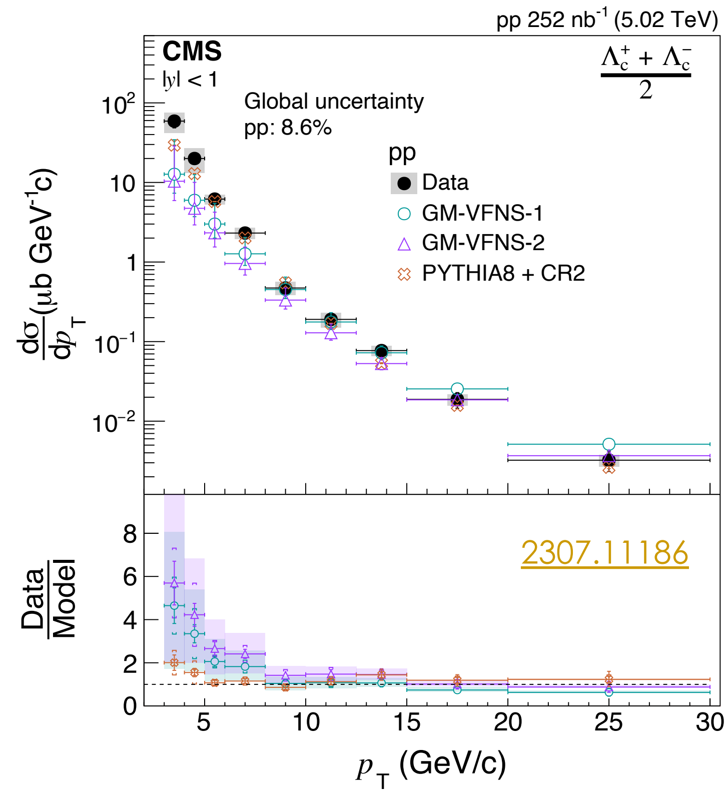


Measurement of average number of Lund subject multiplicities to constrained models

Charm fragmentation at the LHC

- **Λ_c^+-baryon yields much higher than predicted**
  - Breakdown of the universality of charm quark fragmentation functions
- **Prompt Λ_c^+-baryon FF in pp is ~3x larger than in e⁺e⁻ and ep**
  - Imply an overall reduction of the relative D-meson abundance (charm fragmentation function sum up to 1)



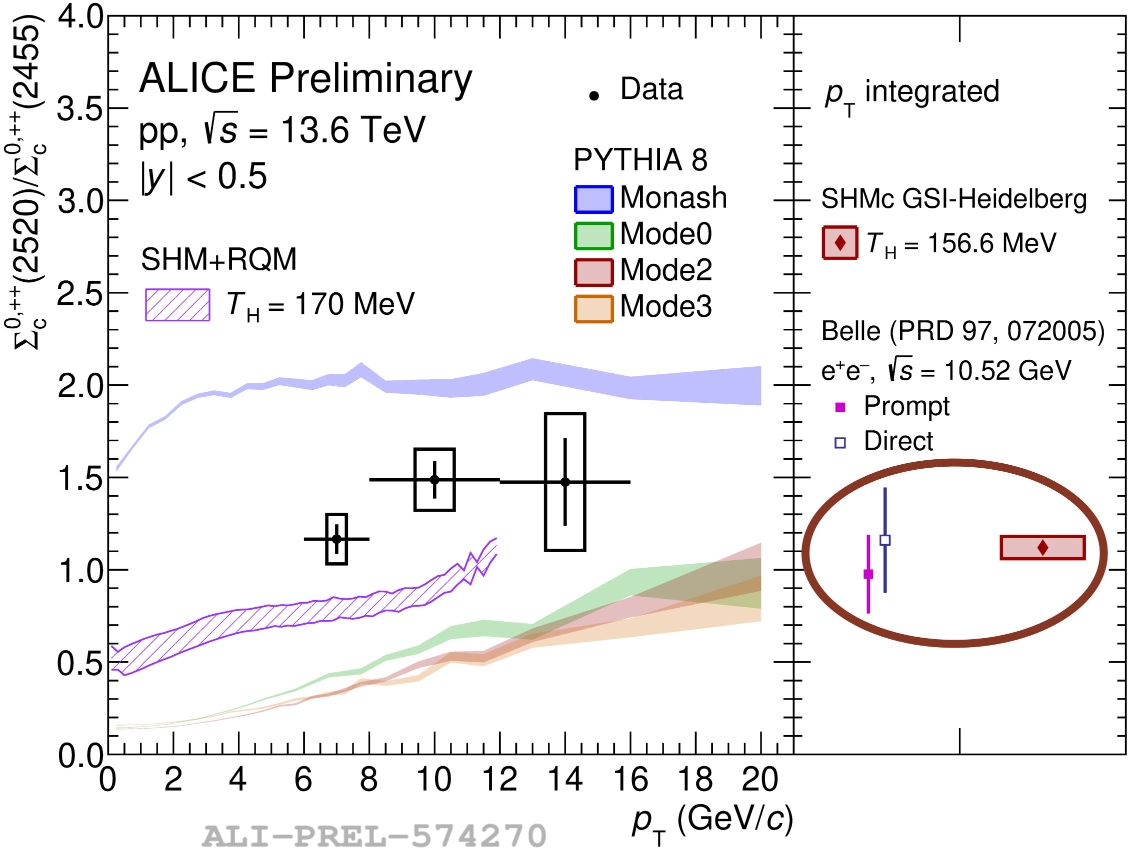


Charm hadronization is different in hadronic environment and in e⁺e⁻

Charm fragmentation at the LHC

- First measurement of the $\Sigma_c^{0,++}(2520)$ relative production at the LHC
- ALICE measurement in $6 < p_T < 14$ GeV compatible with e^+e^- p_T integrated withing uncertainties
- SHMc reproduces the p_T integrated ratio
- **PYTHIA8 and Statistical Hadronisation Model + RQM do not describe data**
- Feed-down from higher states under discussion

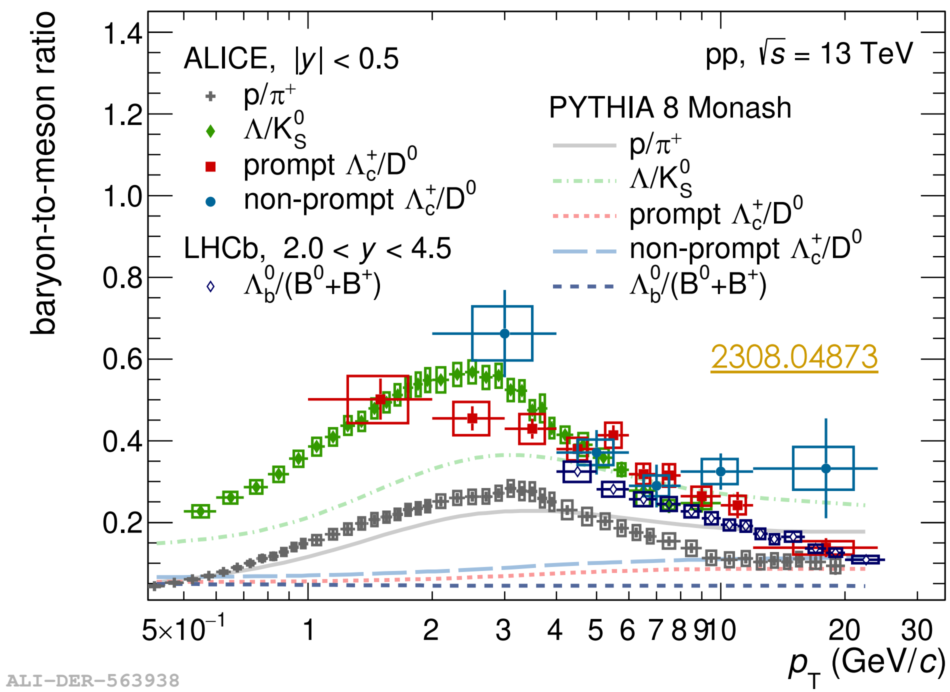
Charm abundance in pp under study

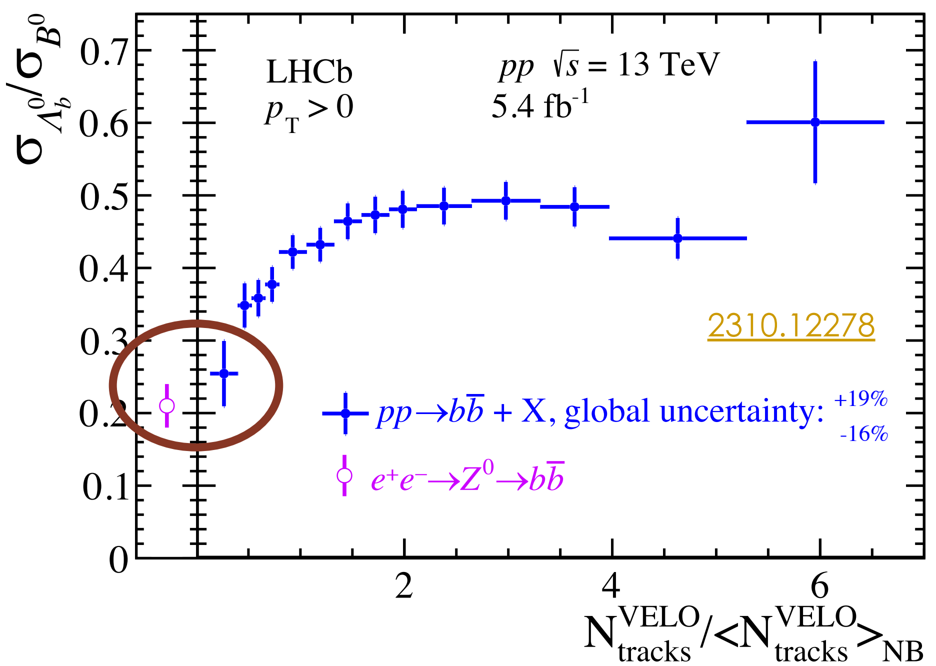


Beauty fragmentation at the LHC

Beauty, charm, and strange hadrons show a similar trend as a function of p_T

Lowest multiplicity bins:
pp data ~ e^+e^- data at LEP
(fragmentation in vacuum)



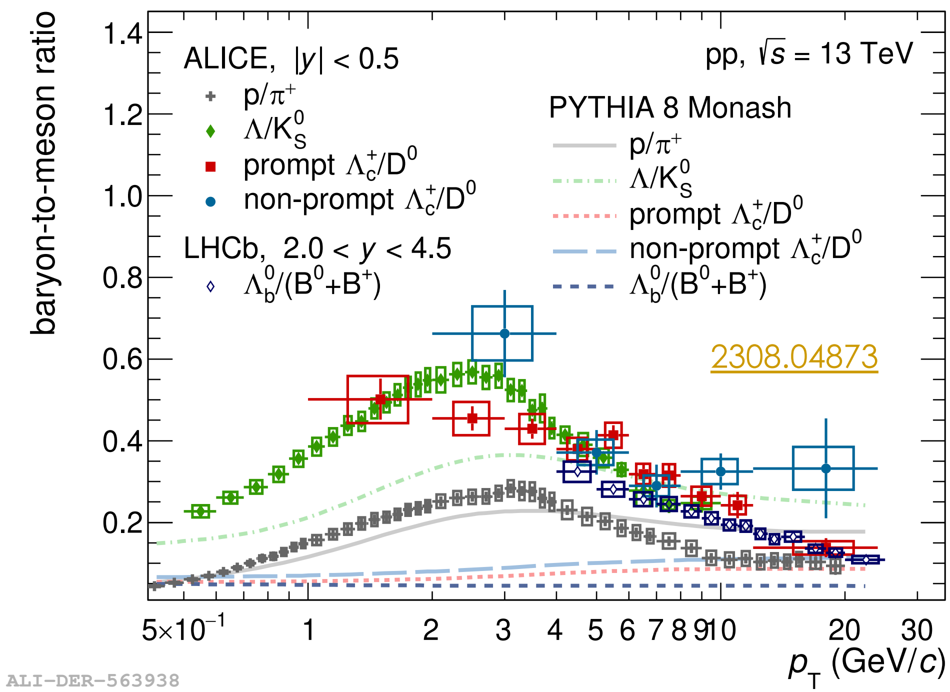


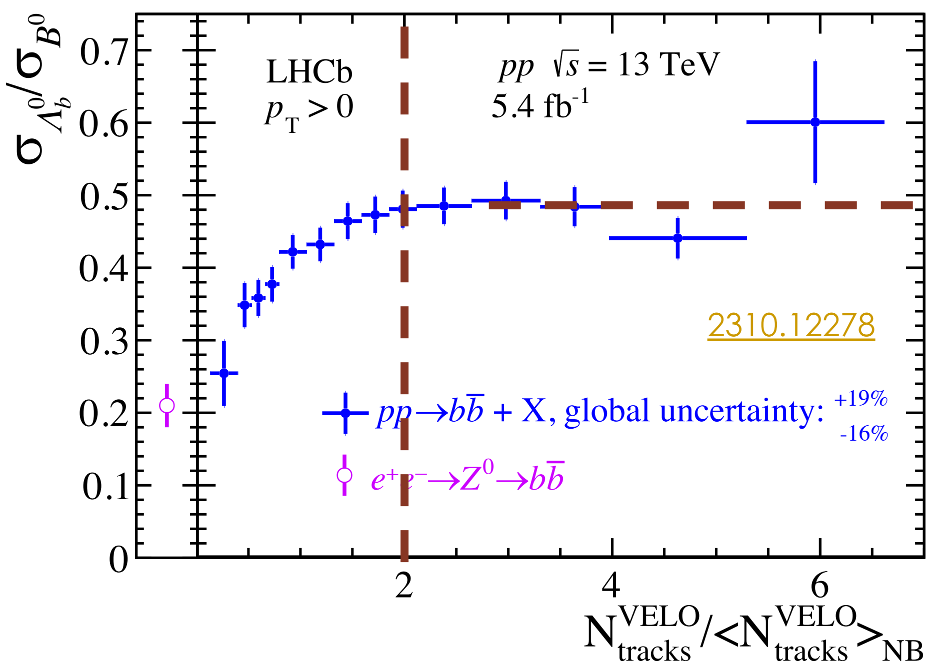
Beauty hadronization is different in hadronic environment and in e^+e^-

Beauty fragmentation at the LHC

Beauty, charm, and strange hadrons show a similar trend as a function of p_T

Rise of the baryon fraction with multiplicity, **plateau for collisions > 2x average number of VELO tracks**





Beauty hadronization is different in hadronic environment and in e^+e^-

Hadronization in and out of jets

- Strange baryon-to-meson and baryon-to baryon ratios **suppressed by a factor ~ 2** in jets w.r.t inclusive measurements

- **Deuteron coalescence probability in jets x 10 vs. underlying event**

- Nucleons have a smaller average phase-space distance

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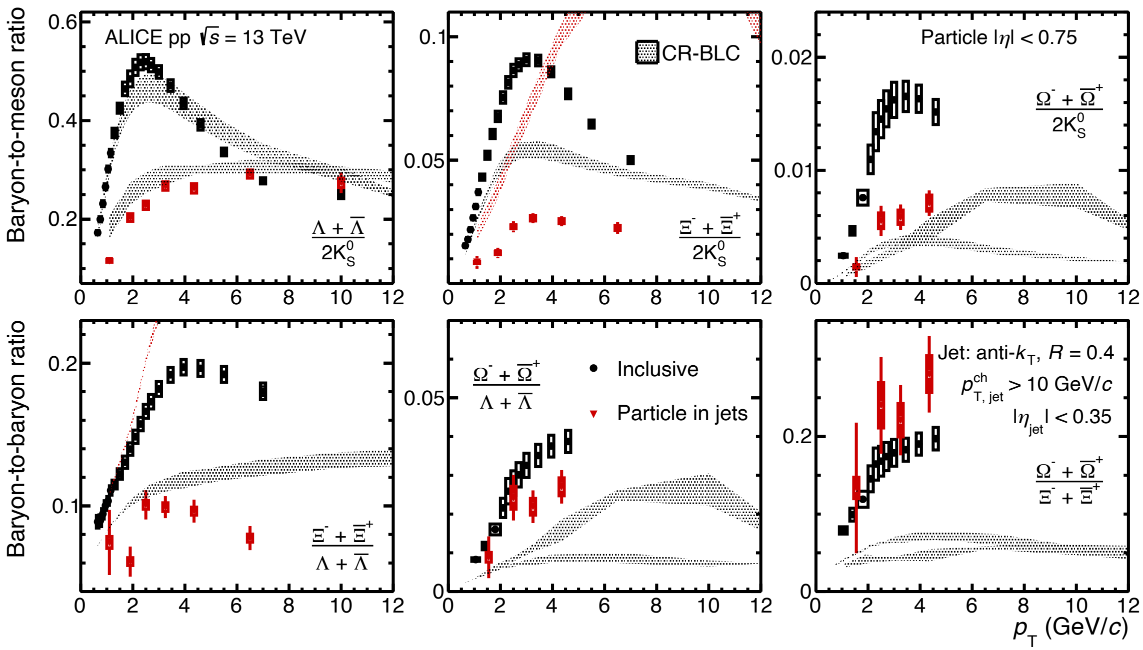
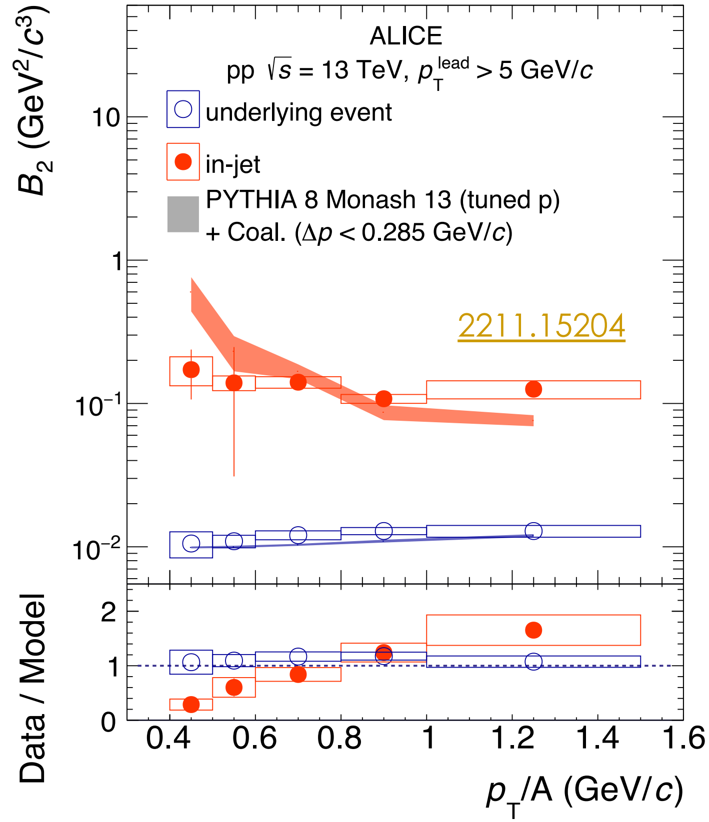
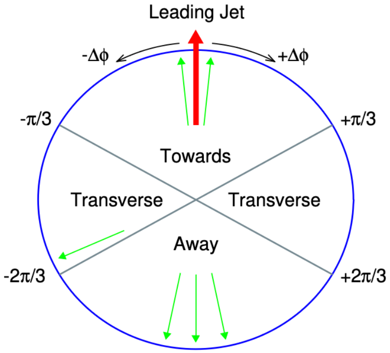


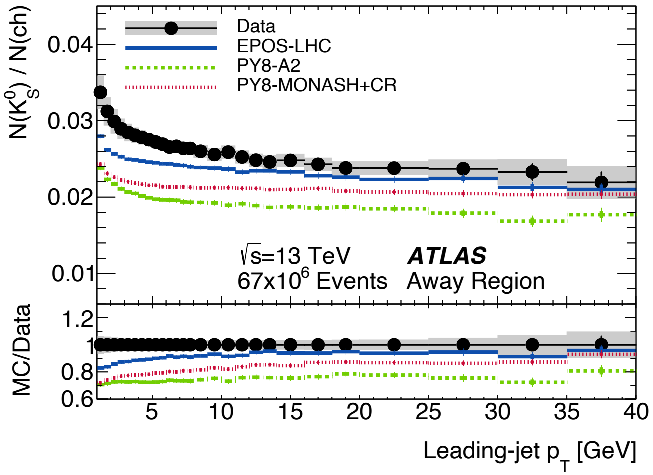


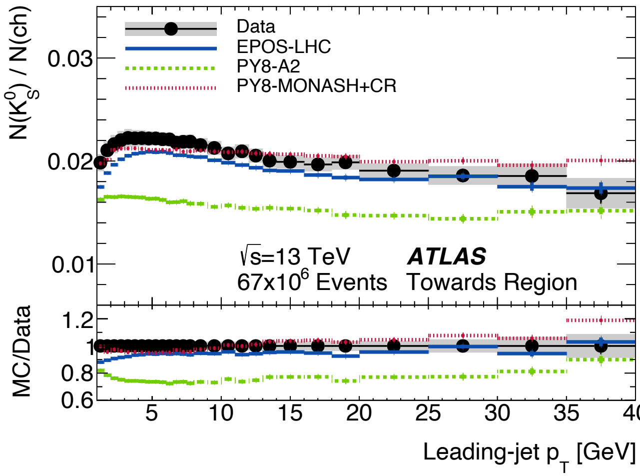
Hadronic environment (in jet vs. out of jet) impact hadronization

Underlying events with strangeness product

- Phase space divided in 3 regions:
  - Towards the leading jet: dominated by jet fragmentation
  - Away from the leading jet (back-to-back)
  - Transverse region: dominated by UE, MPI and soft processes







Strangeness production to study underlying event dynamic

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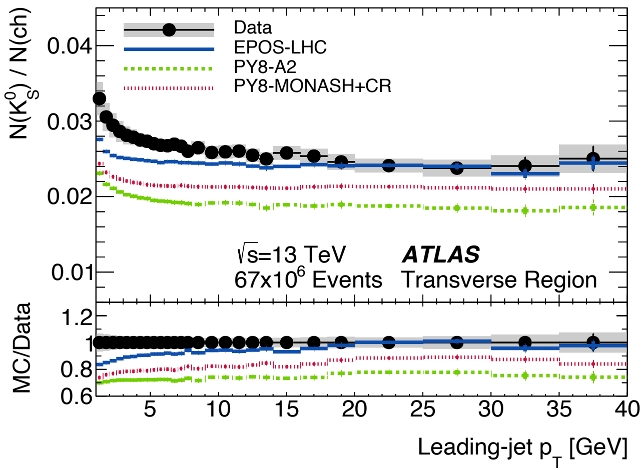
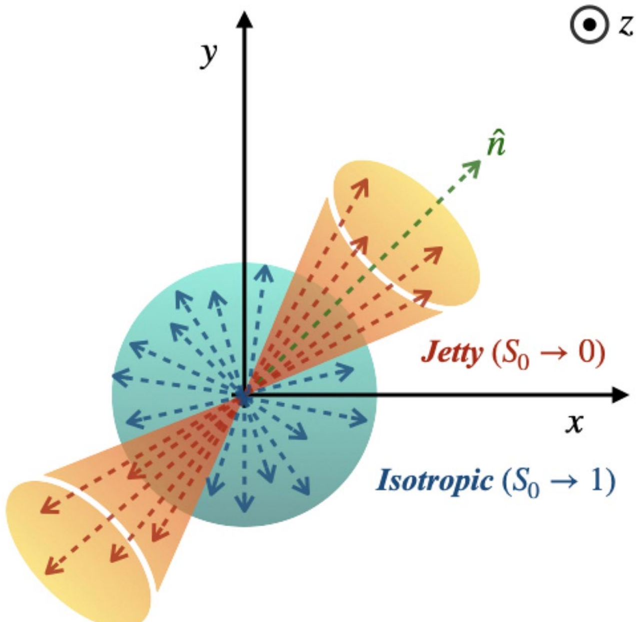


- Λ **and** K_s^0 production in 3 regions allow to understand **modelling of underlying event** from event generators

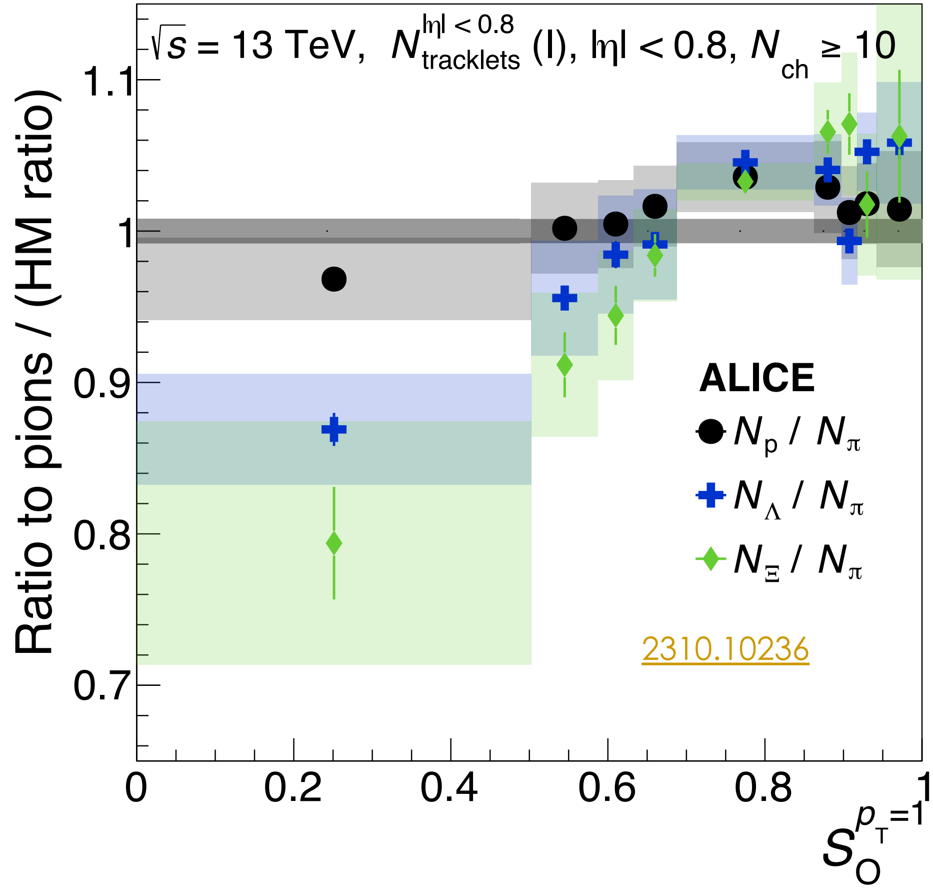
- None tested can reproduce all aspects

Event shape modelling

- Strangeness production
- Suppressed in events with jet-like topologies
- Slightly enhanced in softer, isotropic events topologies



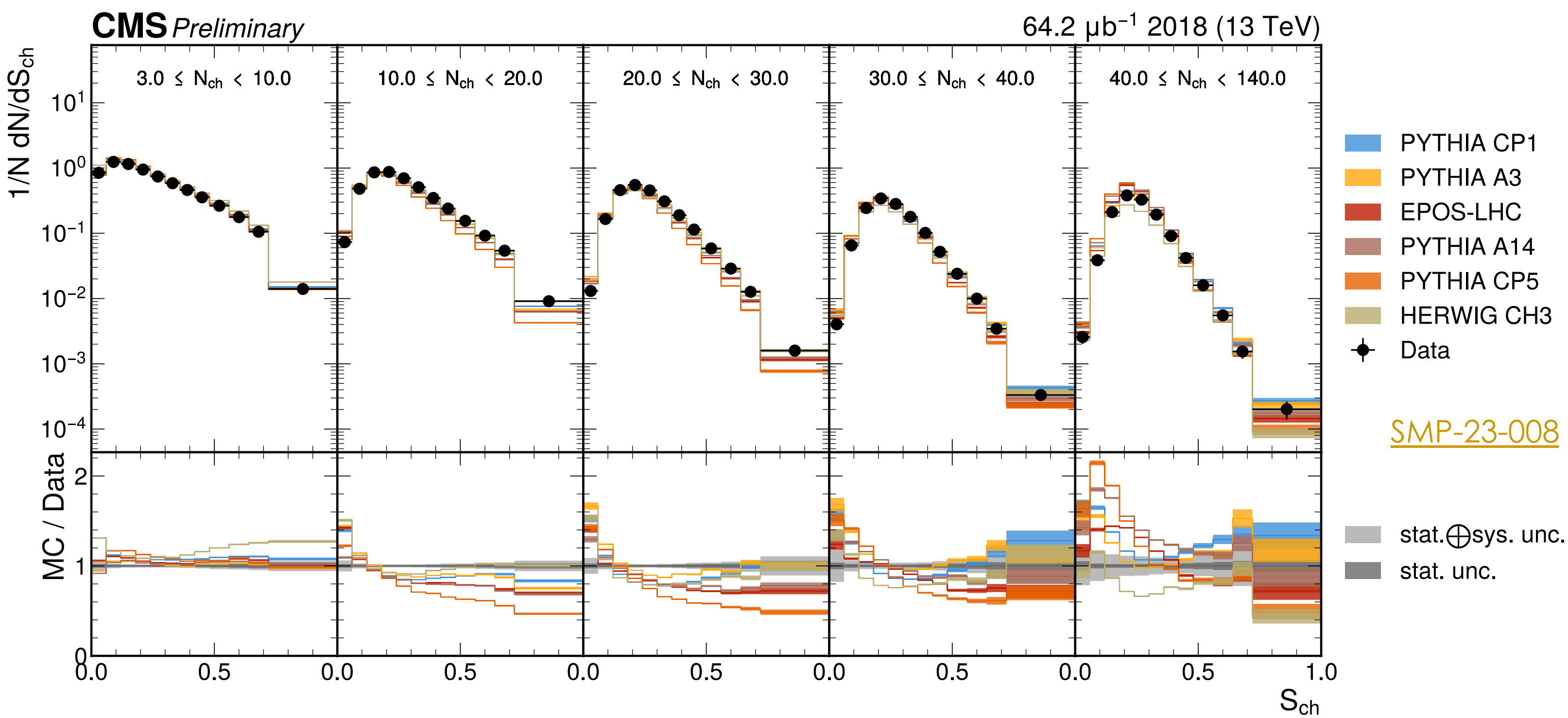
$$S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{T_i} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2$$



Event shape modelling to understand strangeness production in pp collisions

Event shape modelling

- The tensor $S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\overrightarrow{p_i}|^2}$ ($\alpha, \beta \in \{x, y, z\}$ refer to cartesian coordinates)
- i is the index for the final-state charged particles which passed the selections based on the detector acceptance
- Sphericity constructed from the two smallest eigenvalues $\mathcal{S} = \frac{3}{2}(\lambda_2 + \lambda_3)$



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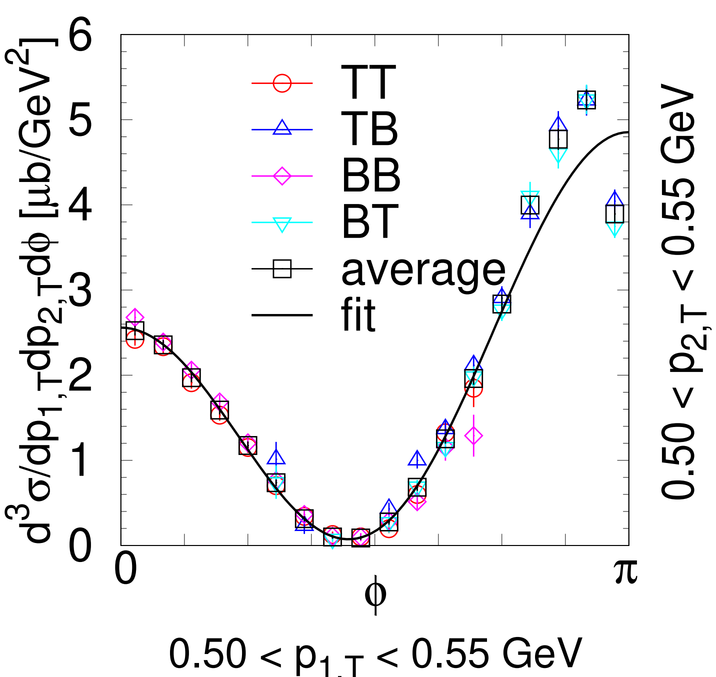
Data more isotropic than the modelling in event generators

Central exclusive production of charged pions

- Differential cross sections in bins of $[p_{1,T}, p_{2,T}]$ with $0.4 < p_{1/2,T} < 0.6$ GeV
- Azimuthal angle φ between the surviving protons
- **First observation of parabolic minimum in φ distribution**
- **First model tuning of pomeron related quantities**



Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
Empirical model				
a_{ore}[GeV]	—	0.735 ± 0.015	—	
$b_{exp/ore/pow}$[GeV$^{-2 \text{ or } -1}$]	1.084 ± 0.004	1.782 ± 0.014	1.356 ± 0.001	
$B_{\mathbb{P}}$ [GeV^{-2}]	3.757 ± 0.033	3.934 ± 0.027	4.159 ± 0.019	
χ^2/dof	9470/5796	10059/5795	11409/5796	
One-channel model				
σ_0[mb]	34.99 ± 0.79	27.98 ± 0.40	26.87 ± 0.30	
$\alpha_P - 1$	0.129 ± 0.002	0.127 ± 0.001	0.134 ± 0.001	
α'_P [GeV^{-2}]	0.084 ± 0.005	0.034 ± 0.002	0.037 ± 0.002	
a_{ore}[GeV]	—	0.578 ± 0.022	—	
$b_{exp/ore/pow}$[GeV$^{-2 \text{ or } -1}$]	0.820 ± 0.011	1.385 ± 0.015	1.222 ± 0.004	
$B_{\mathbb{P}}$ [GeV^{-2}]	2.745 ± 0.046	4.271 ± 0.021	4.072 ± 0.017	
χ^2/dof	7356/5793	7448/5792	8339/5793	
Two-channel model				
σ_0[mb]	20.97 ± 0.48	22.89 ± 0.17	23.02 ± 0.23	23 / 33
$\alpha_P - 1$	0.136 ± 0.001	0.129 ± 0.001	0.131 ± 0.001	0.13 / 0.115
α'_P [GeV^{-2}]	0.078 ± 0.001	0.075 ± 0.001	0.071 ± 0.001	0.08 / 0.11
a_{ore}[GeV]	—	0.718 ± 0.012	—	
$b_{exp/ore/pow}$[GeV$^{-2 \text{ or } -1}$]	0.917 ± 0.007	1.517 ± 0.008	0.931 ± 0.002	0.45
$\Delta\|a\|^2$	0.070 ± 0.026	-0.058 ± 0.009	0.042 ± 0.011	−0.04 / −0.25
$\Delta\gamma$	0.052 ± 0.042	0.131 ± 0.018	0.273 ± 0.023	0.55 / 0.4
b_1 [GeV^2]	8.438 ± 0.108	8.951 ± 0.041	8.877 ± 0.040	8.5 / 8.0
c_1 [GeV^2]	0.298 ± 0.012	0.278 ± 0.004	0.266 ± 0.006	0.18 / 0.18
d_1	0.472 ± 0.007	0.465 ± 0.002	0.465 ± 0.003	0.45 / 0.63
b_2 [GeV^2]	4.982 ± 0.133	4.222 ± 0.052	4.780 ± 0.060	4.5 / 6.0
c_2 [GeV^2]	0.542 ± 0.015	0.522 ± 0.006	0.615 ± 0.006	0.58 / 0.58
d_2	0.453 ± 0.009	0.452 ± 0.003	0.431 ± 0.004	0.45 / 0.47
χ^2/dof	5741/5786	6415/5785	7879/5786	

2401.14494

CMS

Summary

- Many results in the realm of soft and diffractive QCD

- Insight on multi-parton scattering with associated production
  - DPS with charm and beauty show non universal σ_{eff}
  - Next orders: Tri-J/ψ in pp and di- J/ψ in pPb collisions

- Jet fragmentation and substructure
  - Testing QCD with jet substruture

- Hadronization in hadronic environment
  - Charm and beauty hadronization are different in hadronic environment and in e^+e^-
  - Hadronic environment (in jet vs out of jet) impacts hadronization
  - Underlying event dynamic and event shape modelling under study

- Soft central exclusive production processes
  - Observation of parabolic minimum in φ distribution
  - First model tuning of pomeron related quantities

- We are now in the middle of LHC Run 3… More and more data to be analysed soon! Interesting time ahead… Stay tuned! ☺

THANKS FOR YOUR ATTENTION!