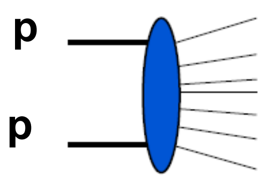
Diffraction with the ALICE detector

- Classification of diffractive processes
- Theoretical description (Pomeron exchange)
- Single and double diffractive dissociation
- Central exclusive production
- Summary

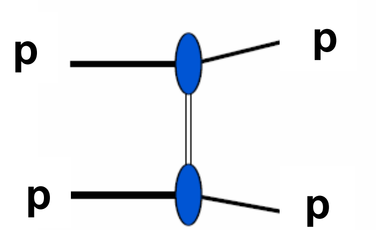
High energy pp collisions: about 40% of σ_{TOT} comes from diffractive processes

Diffraction: protons emerge intact or are excited to higher mass states

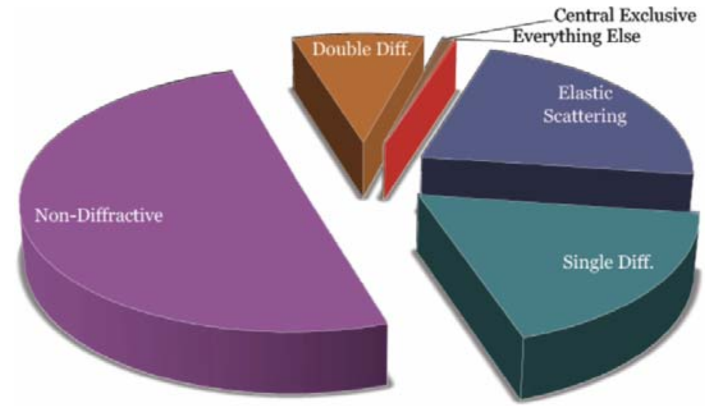
$\sigma_{TOT} = \sigma_{ND} + \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{CD}$



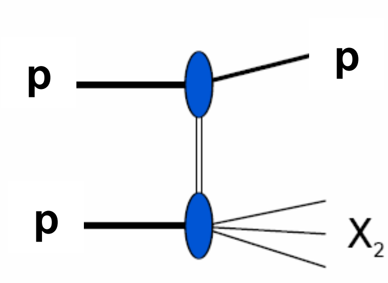
non-diffr. process

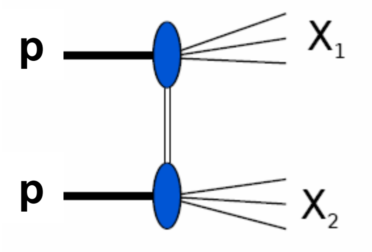


elastic scattering (~26%)



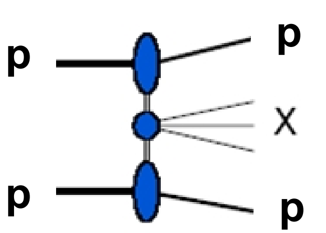
$\sqrt{s}$ = 7 TeV, $\sigma_{TOT} \approx$ 100 mb

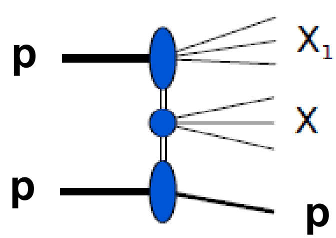


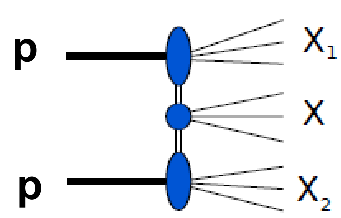


single and double diffractive dissociation

$pp \rightarrow pX_2$ (~12.5%) **$pp \rightarrow X_1X_2$** (~6.5%)





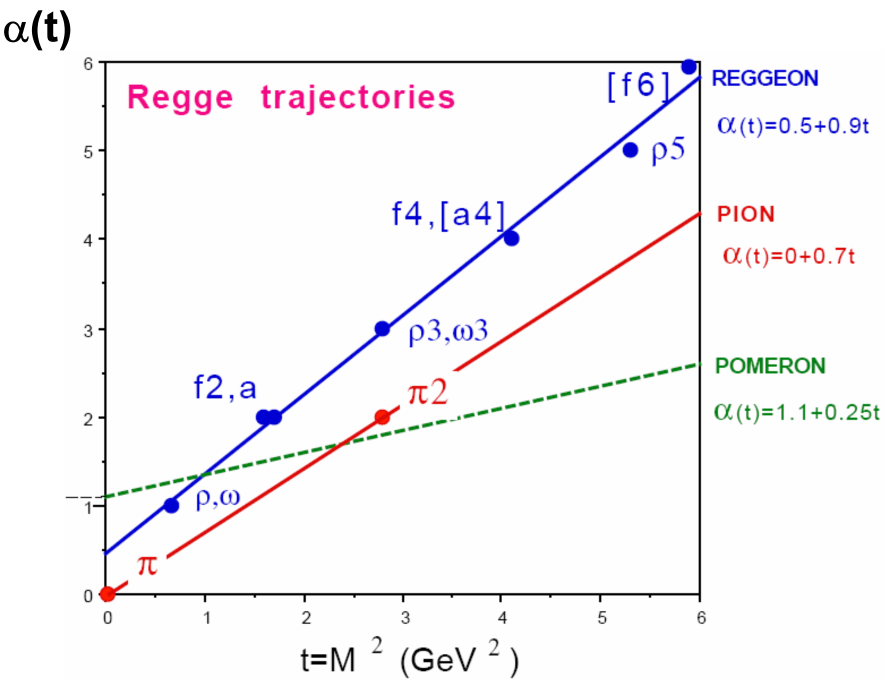


central diffraction & CD with single /double diffr. dissociation (≤ 1%)

$pp \rightarrow p + X + p$

Regge theory (Regge, Chew & Frautschi,1959-1962)

- describes soft hadron processes in high energy hadron-hadron and γ-hadron collisions: elastic scattering, soft diffraction, behaviour of σ_{TOT}
- general methods of Regge theory are based on the unitarity, analicity and crossing symmetry of the scattering amplitudes
- t-channel exchange of "reggeons" (IR) including the Pomeron (IP)

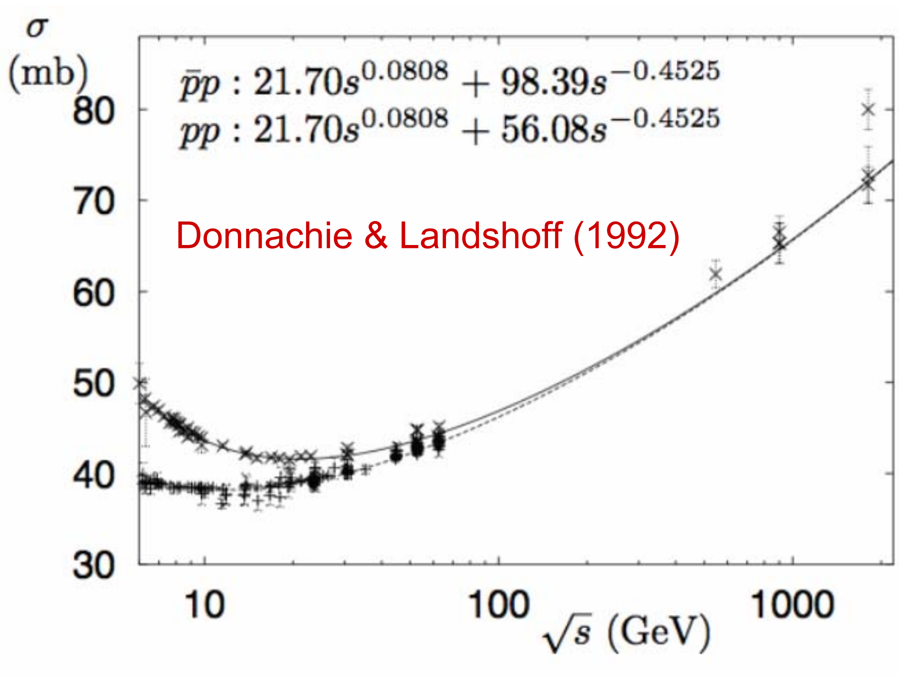


- a generalization of a particle exchange in the t-channel: an exchange of a state of "spin" $\alpha(t)$ which coincides with particles of spin J for $t = M^2_J$
- Regge trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$
- scattering amplitude : $T(s,t) \approx (s/s_0)^{\alpha(t)}$

t = (4-momentum transfer)^2

Pomeron

$\sigma_{TOT}(pp)$ and $\sigma_{TOT}(p\bar{p})$ vs. $\sqrt{s}$ in the energy range of ISR, Sp$\bar{p}$S and Tevatron



σ_{TOT} is rising with $\sqrt{s}$

$\sigma_{TOT}(s) \sim s^{\,\alpha(0) - 1}$

Reggeon exchange:

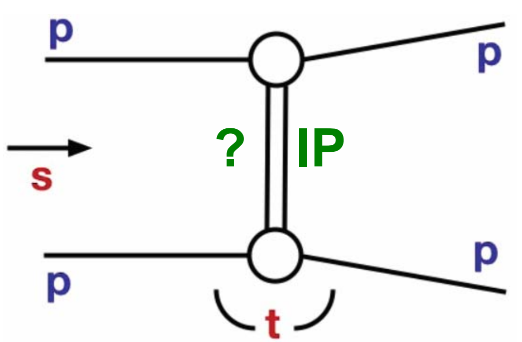
$\alpha_{IR}(0) < 1 \quad \sigma_{TOT}(s) \sim 1/\sqrt{s}$

initial decrease of σ_{TOT} with rising energy, contribution negligible at the very high energy limit

Pomeron exchange:

$\alpha_{IP}(0) > 1$

σ_{TOT} is rising with energy in agreement with data



- Pomeron trajectory:

  $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP}' \cdot t \approx 1.085 + 0.25 \cdot t$ (soft Pomeron)

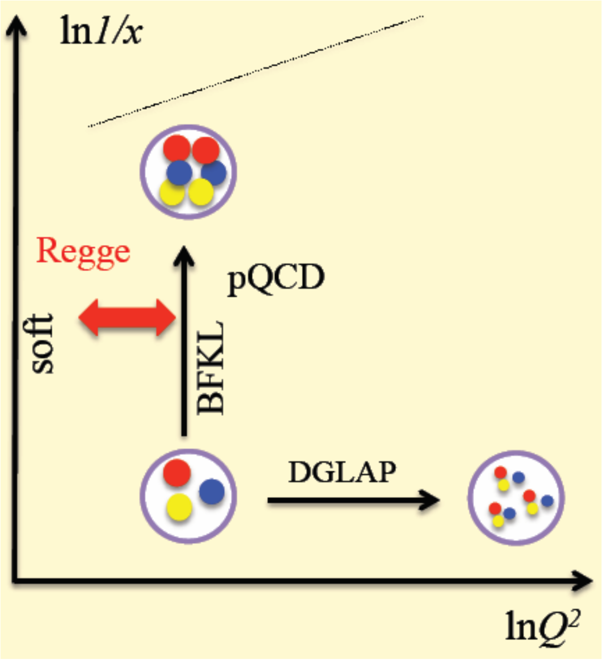
- Pomeron exchange dominates at high energy
- Pomeron has quantum numbers of vacuum: $I^{PC} = 0^{++}$

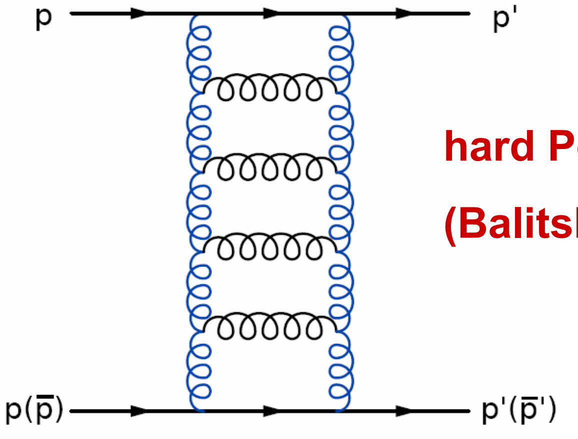
Pomeron was introduced by V. Gribov and named after I. Pomeranchuk, who studied the behaviour of vacuum exchange in Regge theory

QCD and Pomeron

Soft diffraction is described by phenomenolgical models based on Regge theory
It is a non-perturbative QCD process – a lot of unsolved problems

Properties of Regge poles partially emerge from QCD →
IP is interpreted in terms of exchange of at least two gluons in a colour singlet state





hard Pomeron, BFKL Pomeron

(Balitsky- Fadin-Kuraev-Lipatov)

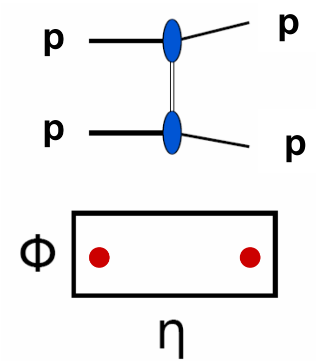
Complicated dynamic structure of a gluon ladder →
in the high energy limit development of the QCD cascade results from BFKL evolution equations

Diffractive reactions with an intrinsic hard scale are described by perturbative QCD

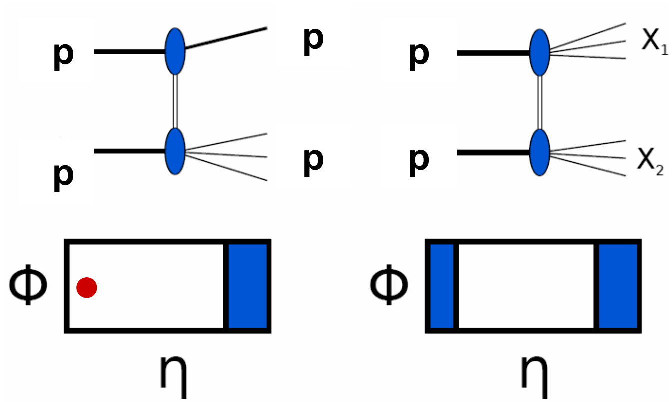
Theoretical definition of diffraction in HEP: any process involving Pomeron exchange

Topology of diffractive events

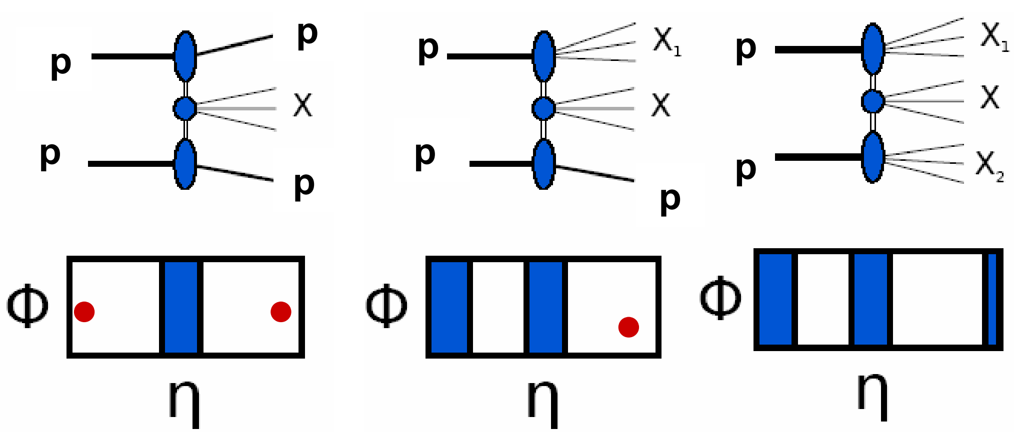
elastic scattering



SD and DD



central diffraction



Two methods for selecting diffractive events:

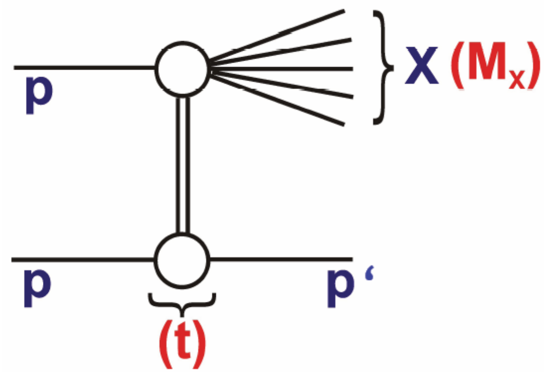
- **proton tagging**
- **rapidity gap detection**

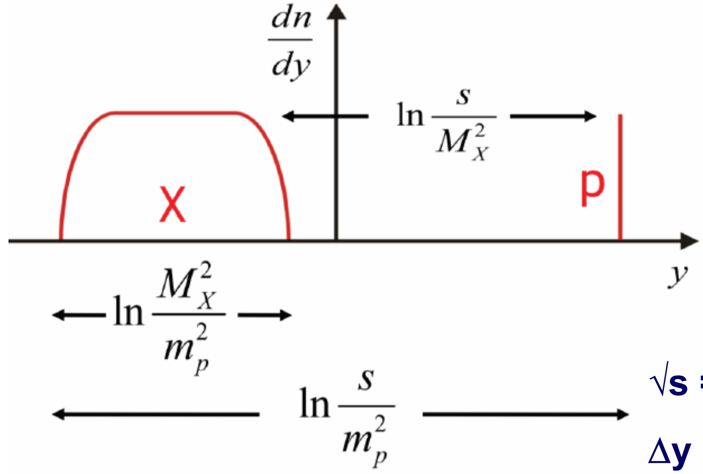
$\eta = -\ln(\tan(\theta/2))$

Exchange of colour singlet object → Large ranges in (pseudo) rapidity without particle activity ($\Delta\eta \geq 3$) → large rapidity gap (LRG) events

LRG due to multiplicity fluctuations in non-diffractive events are exponentially suppressed

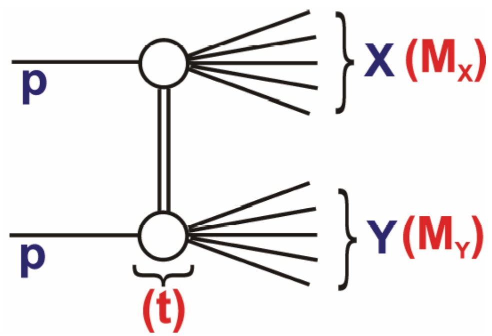
Rapidity gap kinematics





$\sqrt{s}$ = 14 TeV

Δy ~19.2



SD $$\Delta\eta \approx \ln\left(\frac{s}{M_X^2}\right) = \ln\left(\frac{1}{\xi}\right)$$, $\xi = 1 - E_{p'}/E_p$

DD $$\Delta\eta \approx \ln\left(\frac{s s_0}{M_X^2 M_Y^2}\right)$$

At LHC, in soft diffractive processes Mx, My can be in the range from ($m_p + m_\pi$) to ~ 1 TeV

Survival factors

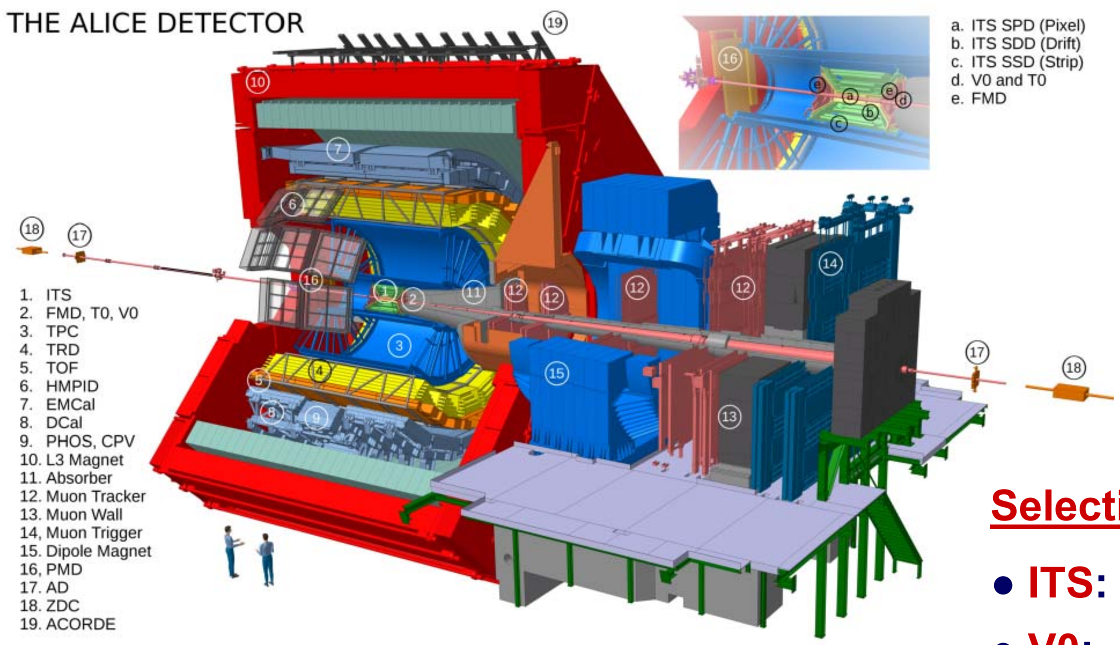
pp scattering : large probability that a rapidity gap produced in a single parton chain will be filled by partons produced in another chain

→ complicated structure of multiple interactions → suppression of diffractive cross section encoded in the survival factor $S^2 < 1$

Why is diffraction interesting at LHC ?

- large fraction of σ_{TOT}, important to understand its composition and behaviour
- study of complicated structure of multiple interactions, event structure in pp
- interplay of soft and hard processes
  overlap of Regge theory and perturbative QCD
- nature of Pomeron (spin ?, partonic structure, soft/hard Pomeron, …)
- information on the proton (ion) structure and interaction mechanism

Diffraction with the ALICE detector



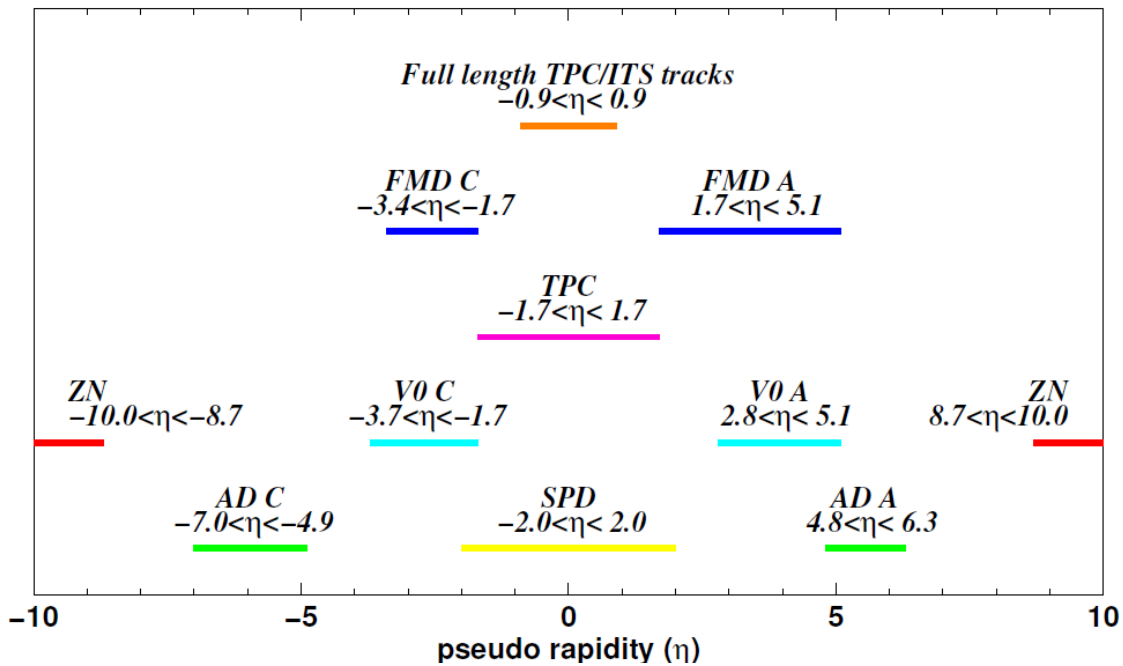
- high granularity
- very good tracking (ITS, TPC)
- good acceptance for p_T down to 100 MeV/c
- good particle identification efficiency (ITS, TPC, TOF)

Selection of diffractive events:

- **ITS**: six layers of silicon detectors
- **V0**: scintillator hodoscopes
- **FMD** (Forward Multiplicity Detector): silicon strips
- **AD** (ALICE Diffractive detector) : scintillator pads (since Run 2)
- **ZDC**: Zero Degree Calorimeters for neutron and proton
- **Muon arm**: production of vector mesons in ultra- peripheral PbPb and pPb collisions

Selection of diffractive events:

- **SPD**: Silicon Pixel Detector
- **V0**: scintillator hodoscopes
- **FMD**: silicon strips
- **AD** : scintillator pads
- **ZDC**: Zero Degree Calorimeters for neutron and proton

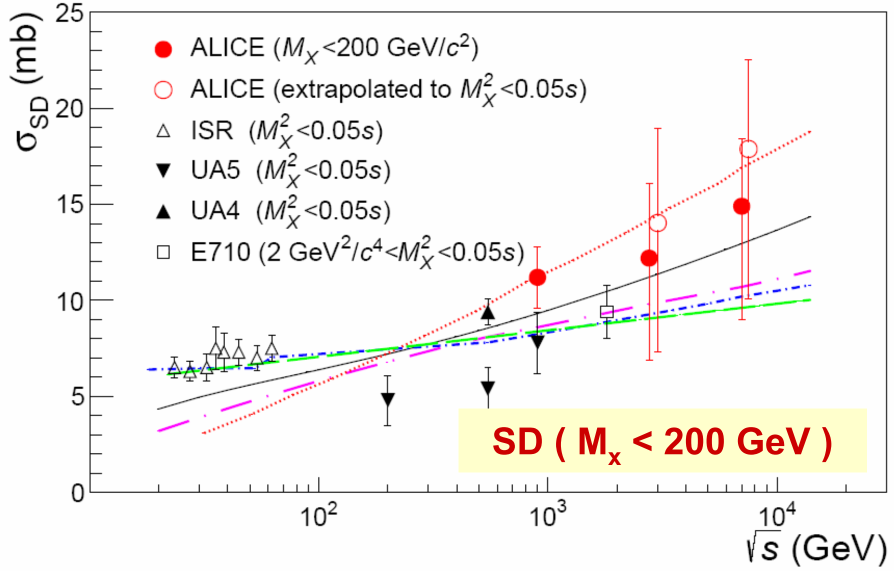


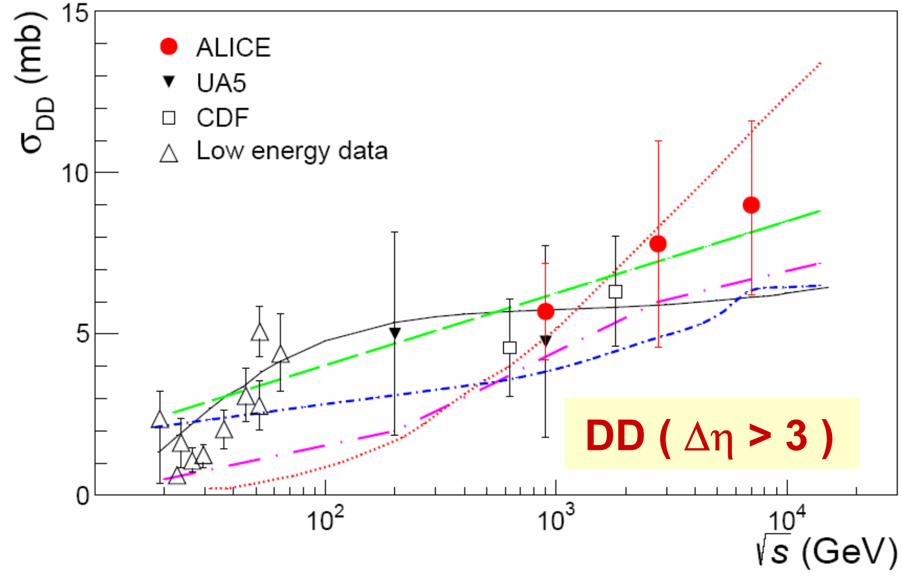
Pseudorapidity coverage with forward detectors V0 and AD:

V0C – V0A : $\Delta\eta \approx 8.8$ (run 1)

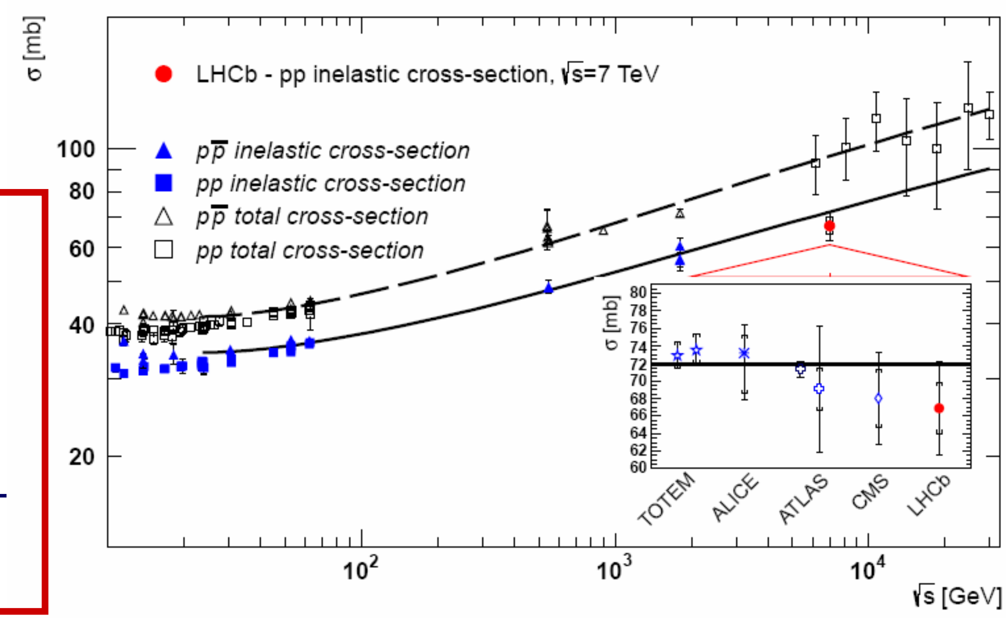
ADC – ADA : $\Delta\eta \approx 13$ (run 2)

Single and double diffraction cross sections, √s = 0.9, 2.76 and 7 TeV





ALICE SD & DD data [EPJC78(2013)2456]
– good agreement with data at lower energy and with theory predictions



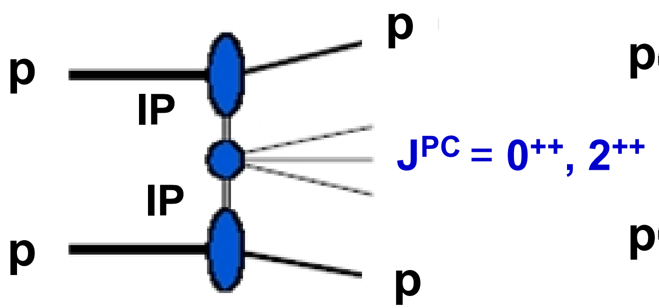
σ_{INEL} @ √s=7 TeV
Results of ALICE, ATLAS, CMS, LHCb and TOTEM experiments in agreement.

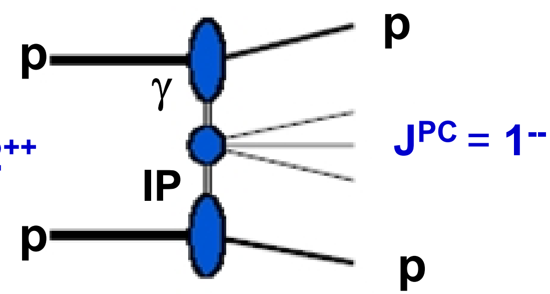
ALICE and TOTEM (larger η coverage) closer to precise measurements of σ_{INEL} using elastic scattering and optical theorem.

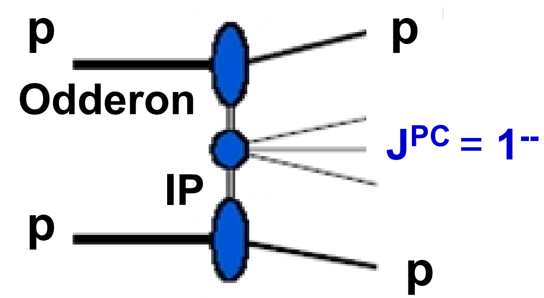
Central exclusive production: pp $\rightarrow$ p + X + p

Topology of events : production of state X in the central region + 2 rapidity gaps

Contributions from double Pomeron exchange (DPE) and γIP, Odderon IP, Oderon γ and $\gamma\gamma$ processes







Theoretical predictions:

Model KRM / Durham

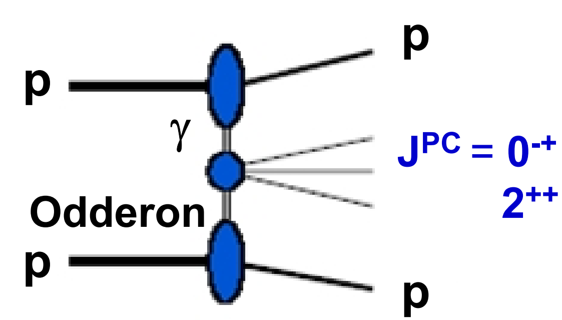
V.Khoze, A. Martin, M. Ryskin et al.

BFKL Pomeron + absorptive corrections …

Tensor Pomeron Model

P. Lebiedowicz, O. Nachtmann, A. Szczurek

Phys. Rev. D93 (2016) 054015



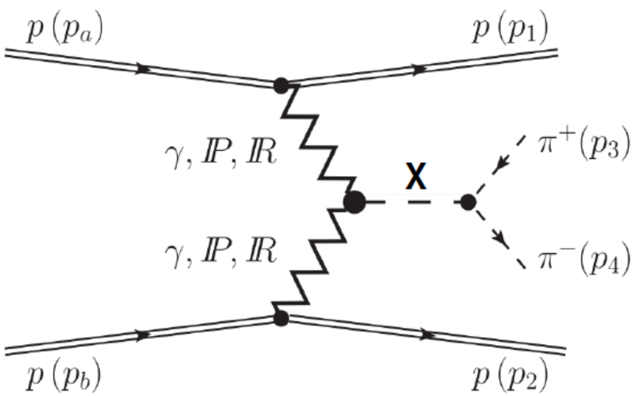
Odderon ≡ 3 gluons

Strong QCD prediction,

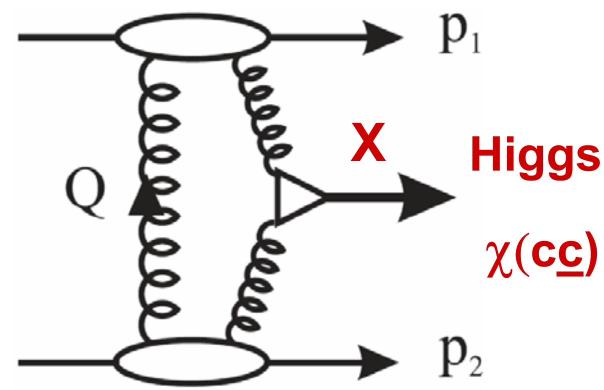
C=”– ” partner of Pomeron

Central exclusive production $pp \to p + X + p$

Production of low mass system M_X by DPE (2 soft IP), contributions from reggeon and photon exchanges



Production of high mass system M_X by DPE in pQCD (fusion of 2 gluons)



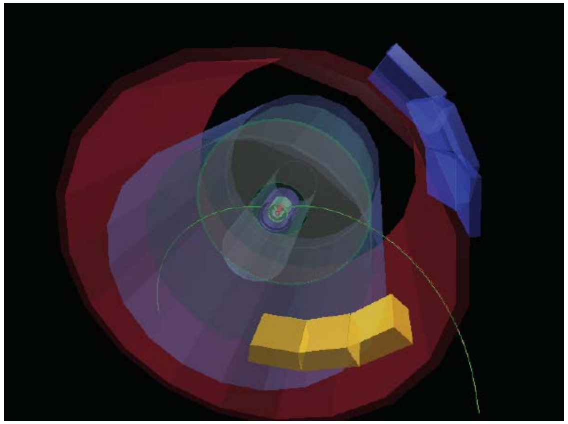
- Central exclusive production of X – dominance of DPE at high energy IP + IP → X
  → formation of new states from pure gluons – glueballs or mixed glueball and $q\underline{q}$ states ?
- $I^G J^{PC} = 0^+ \text{(even)}^{++}$ → quantum number filter → studies of light scalar mesons $J^{PC} = 0^{++}$, identification of scalar mesons ($M \leq 2$ GeV) is still a puzzle

  $f_0(1500)$ and $f_0(1710)$ 0++ are glueball candidates
  Lattice QCD: $M(0^{++})$ glueball 1600-1700(±100) MeV
- Open questions: nature of IP, σ_{CD}, gap-survival factors
- Constrain Pomeron structure in terms of quark and gluons (hard processes)
- Production of beyond-standard-model objects ? High M_X, tagging of intact protons allows for a clean spin-parity analysis

CEP in ALICE

- **select CEP events in pp collisions by double gap (DG) detection**
  veto on signals in forward detectors (V0, FMD, AD)
  (CD with single/double proton dissociation included)

- **investigate centrally produced 2/4 track events with net charge = 0**
  $\pi\pi$, KK , $p\bar{p}$, 4π, 4K, $\pi\pi$KK channels
  ITS-TPC track reconstruction within the range $|\eta| < 0.9$



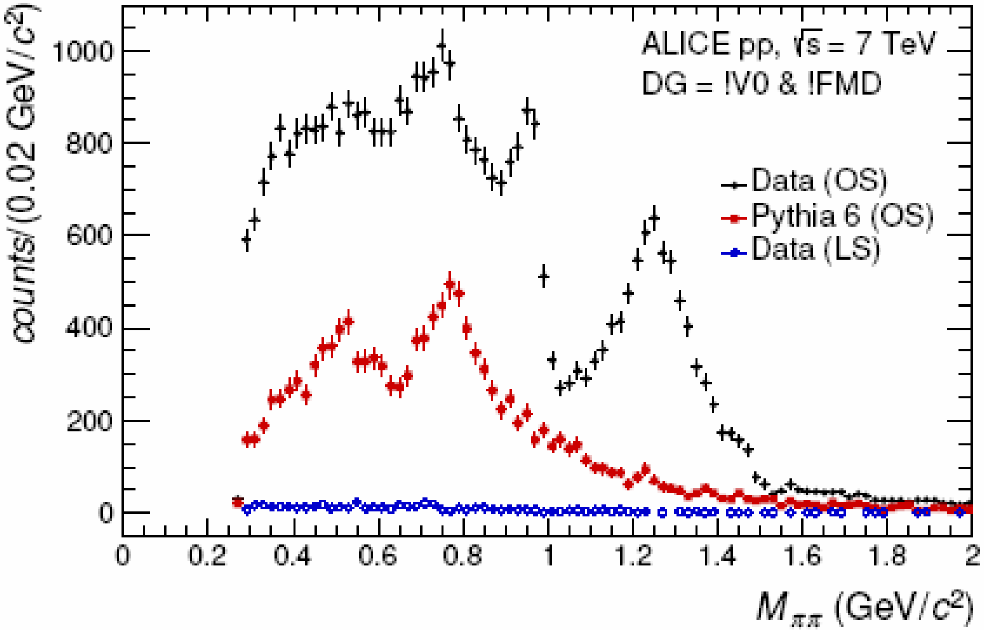
$\pi^+\pi^-$ event candidate

Data sets

Period	Trigger	Approx. number of 2π DG events
7 TeV	**minimum bias trigger**	
2010	MBOR SPD || V0	0.6 M
13 TeV	**dedicated DG trigger**	
$\geq$2016	CCUP13 $\geq$2 online tracklets & !V0	1 M
$\geq$2017	CCUP25 $\geq$2 online tracklets & !V0 & $\geq$2 TOF hits	5 M

Analysis of centrally produced $\pi^+\pi^-$ system

In preparation paper on "Partial wave analysis of the $\pi^+\pi^-$ system produced in double-gap proton-proton collisions at $\sqrt{s}$ = 7 TeV" (ALICE – Ana – 4187, May 2018)



Raw $\pi^+\pi^-$ invariant mass spectrum for V0 + FMD DG condition (black)

Background from like-sign (LS) $\pi\pi$ pairs

Pythia 6 with non-CD processes does not describe data (red)

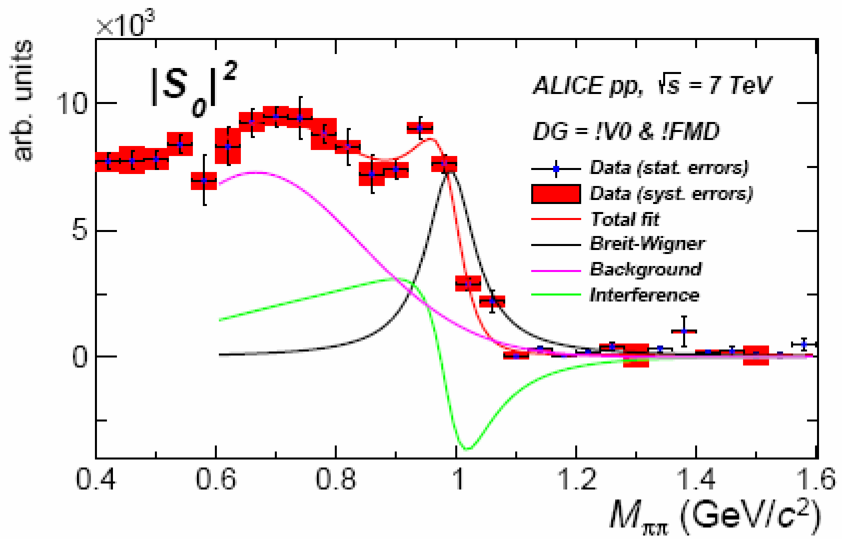
PWG-UD internal plot

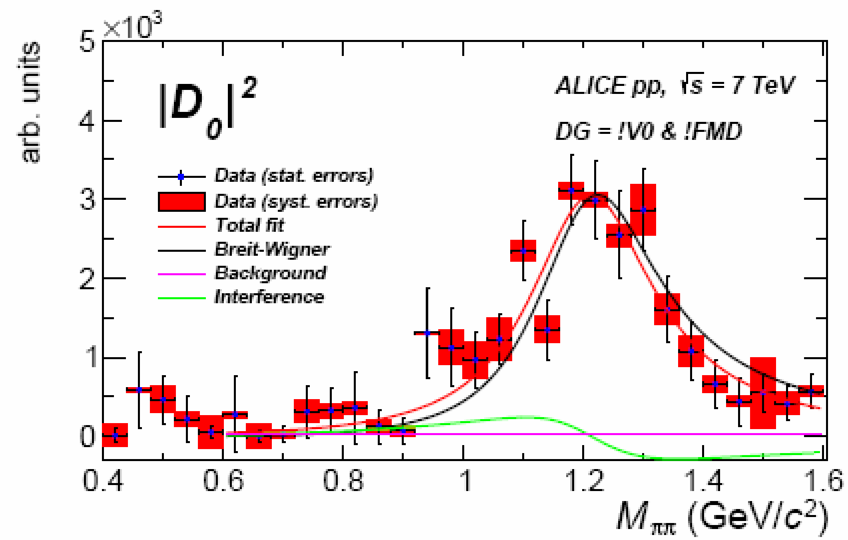
$M_{\pi\pi}$: continuum + peaks in the mass region of vector resonance ρ^0(770), scalar resonance f_0(980) and tensor resonance f_2(1270)

Spin and parity of states contributing to $\pi\pi$ spectrum disentangled using partial wave analysis (PWA).
States with spin up to 2 included: S-, P- and D- waves.
Finally, P- wave (here one expects ρ^0) found to be negligible and neglected.

PWA of centrally produced $\pi^+\pi^-$ system

PWG-UD internal plots





Mass-dependent fits of S- and D-waves with contributions from resonant, non-resonant and interference terms.

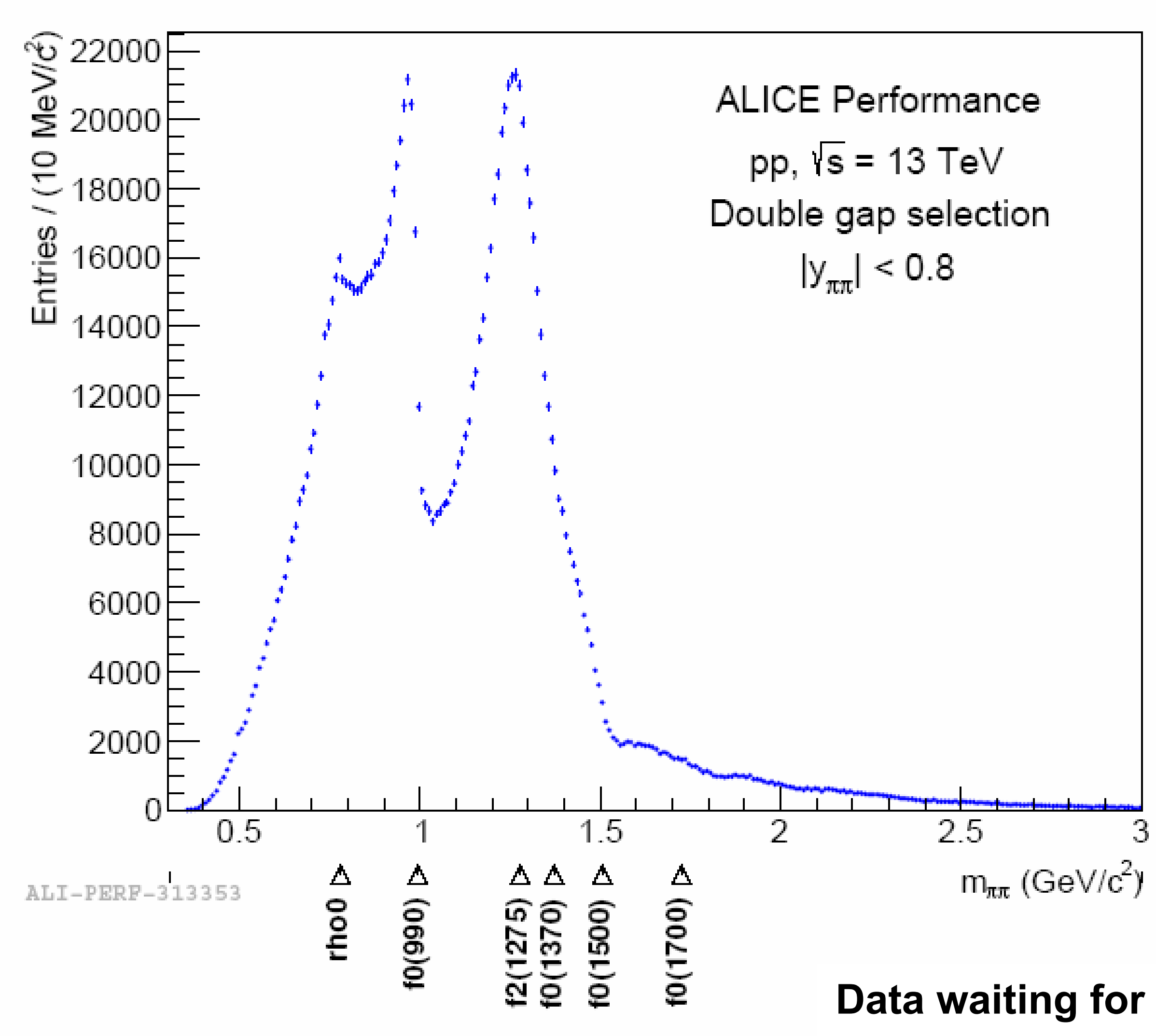
The observed peaks in S- and D-waves are $f_0(998)$ and $f_2(1270)$, respectively. Production cross sections of resonances and their parameters (mass, width) are measured.

The total $\pi^+\pi^-$ cross section for DG events ($|y_{\pi\pi}| < 0.9$) :

$$\boxed{\sigma_{\pi\pi} = 31.4 \pm 0.4(stat) \pm 2.7(sys) \pm 1.1(lumi)\mu b.}$$

Invariant mass distribution of CEP events at $\sqrt{s}$ = 13 TeV

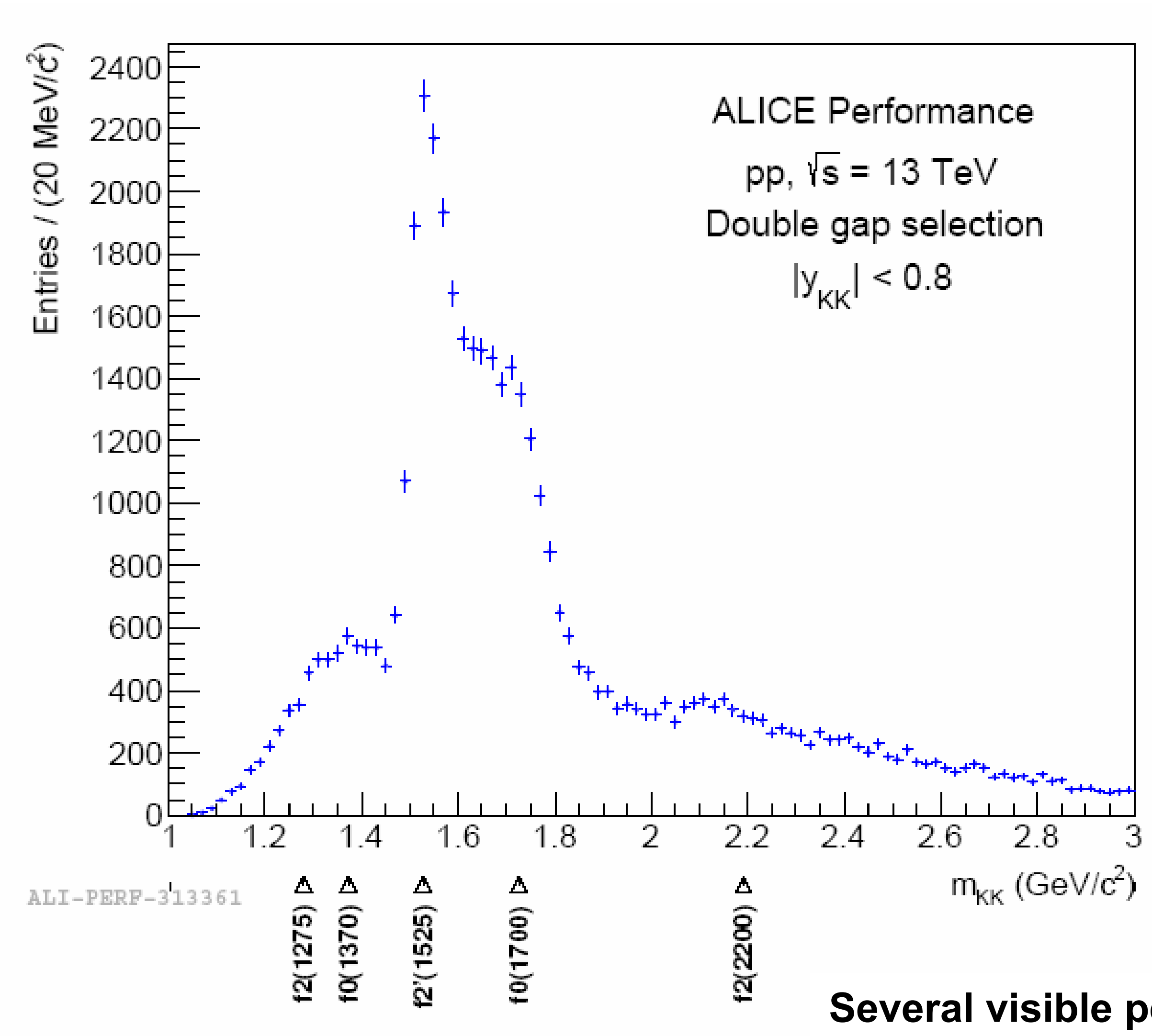
ALICE 2017/2018 (~8.2 pb^{-1}), uncorrected $\pi\pi$ data



Data waiting for more detailed analysis …

Invariant mass distribution of CEP events at $\sqrt{s}$ = 13 TeV

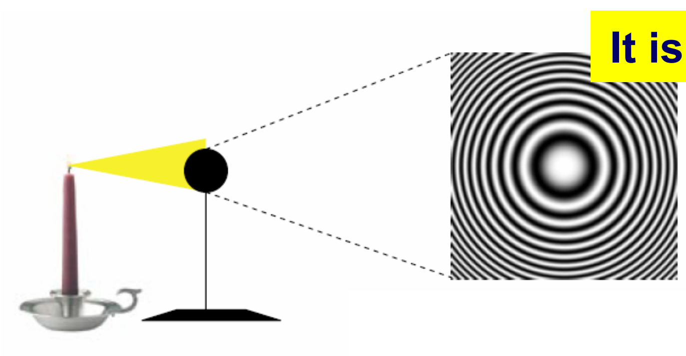
ALICE 2017/2018 (~8.2 pb^{-1}), uncorrected KK data



Several visible peaks to be disentangled using PWA …

Summary

- Advantages of the ALICE detector for performing diffractive studies: very good track reconstruction and PID efficiency down to low p_T , large pseudorapidity coverage
- ALICE exploits large rapidity gap detection to select diffractive processes
- Central exclusive production of low mass resonances promising for investigation of scalar resonances and search for glueballs
- Invariant mass spectra of $\pi\pi$ and KK systems in CEP show interesting structures which need to be further investigated
- It would be interesting to investigate the high invariant mass region in CEP with increased statistcs in Run 3 and 4



It is worthwhile to study diffraction !!

NZ23 members of PWG-UD:
Jan Figiel, Lidia Görlich - Central Exclusive Production in pp
Christoph Mayer – production of vector mesons in ultra-peripheral pPb&PbPb collisions, AD expert & very active in the FDD (Forward Diffraction Detector) Collaboration

Additional slides …

M. G. Albrow, „Hadron Spectroscopy in Double Pomeron Exchange Experiments", arXiv: 1701.09092

Light meson states allowed in DPE. Branching fractions are in % (DPG 2016)

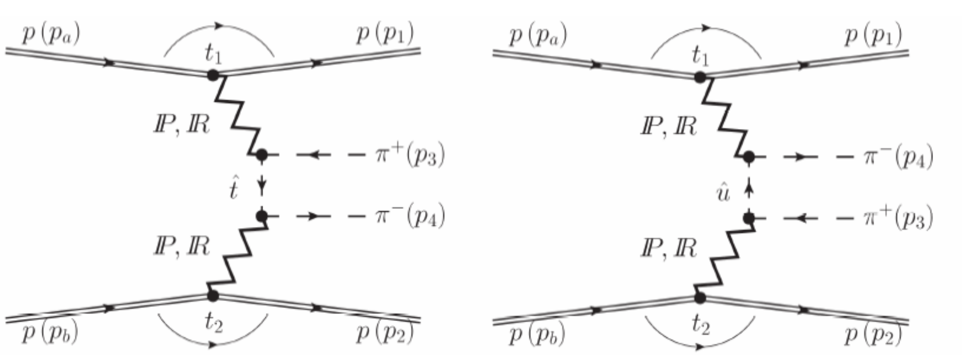
Name	M(MeV)	Γ(MeV)	$I^G J^{PC}$	$\pi\pi$	$K\bar{K}$	Other modes
$f_0(500)/\sigma$	400-550	400-700	0^+0^{++}	$\sim$100	-	-
$f_0(980)$	990±20	10-100	0^+0^{++}	dominant	seen	$\gamma\gamma$ seen
$f_2(1270)$	1275.5±0.8	$186.7^{+2.2}_{-2.5}3$	0^+2^{++}	$84.2^{+2.9}_{-0.9}$	$4.6^{+0.5}_{-0.4}$	$4\pi \sim 10\%$
$f_0(1370)$	1200-1500	200-500	0^+0^{++}	seen	seen	$\rho\rho$ dominant
$f_0(1500)$	1504±6	109±7	0^+0^{++}	34.9±2.3	8.6±1.0	4π 49.5±3.3
$f_2'(1525)$	1525±5	73^{+6}_{-5}	0^+2^{++}	0.8±0.2	88.7±2.2	$\eta\eta$ 10.4±2.2
$f_0(1710)$	1723^{+6}_{-5}	139±8	0^+0^{++}	seen	seen	$\eta\eta$ seen
$f_2(1950)$	1944±12	472±18	0^+2^{++}	seen	seen	$\eta\eta$ seen
$f_2(2010)$	2011^{+60}_{-80}	202±60	0^+2^{++}	-	seen	$\phi\phi$ seen
$f_4(2050)$	2018±11	237±18	0^+4^{++}	17%	$\sim$0.7%	$\eta\eta$ 0.2%
$f_2(2300)$	2297±28	149±40	0^+2^{++}	-	seen	$\phi\phi$ seen
$f_2(2340)$	2345^{+50}_{-40}	322^{+70}_{-60}	0^+2^{++}	-	-	$\phi\phi, \eta\eta$ seen

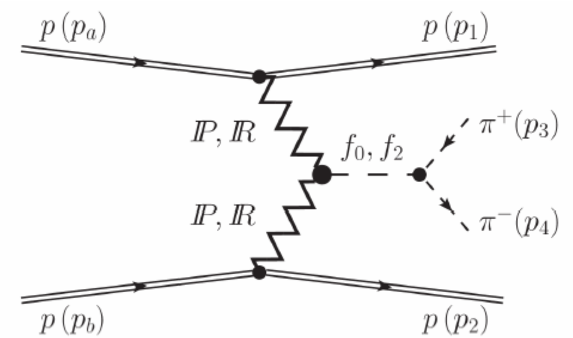
Tensor Pomeron Model

- **P. Lebiedowicz, O. Nachtmann, A. Szczurek**

„Extracting the pomeron-pomeron-f_2(1270) coupling in the pp → pp$\pi^+\pi^-$ reaction through angular distributions of the pions”, arXiv: 1901.07788

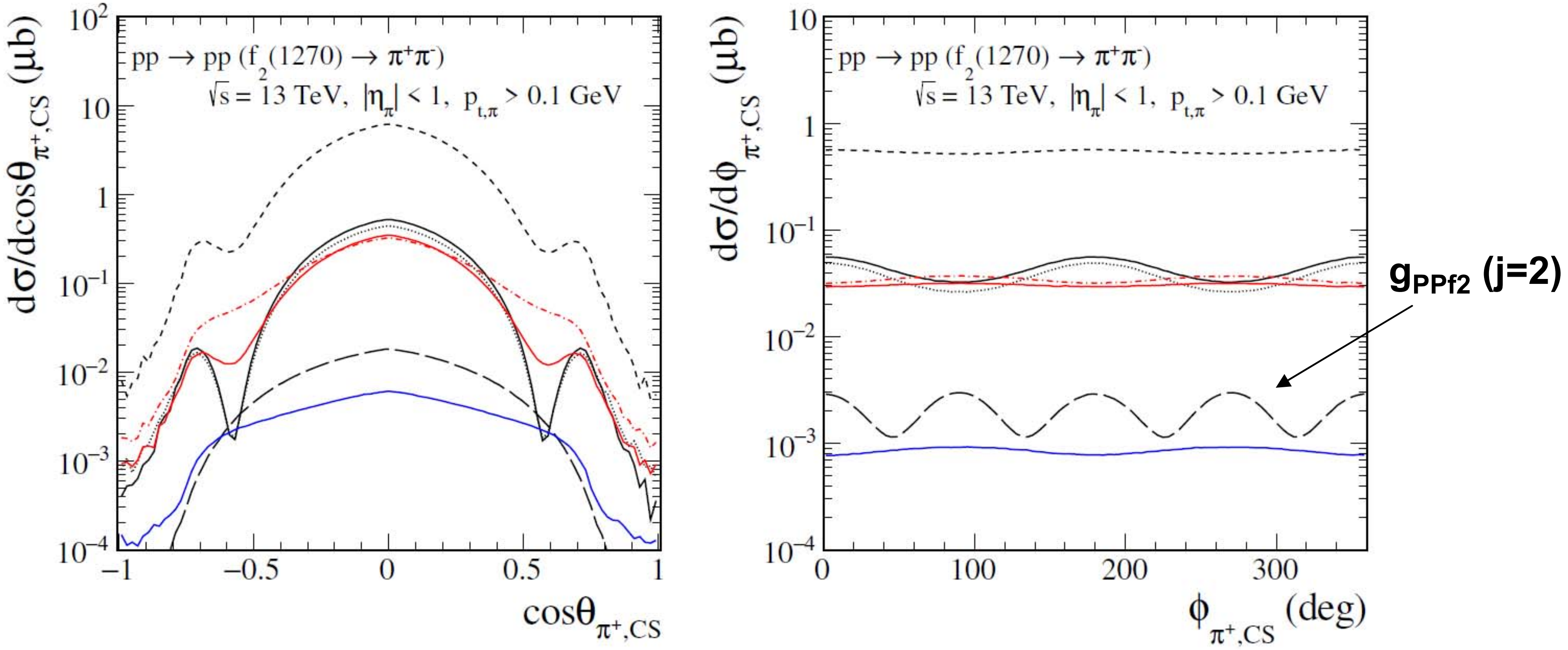
- **Analysis of pion angular distributions, $\cos\theta_{\pi+}$ and $\phi_{\pi+}$, in the Collins-Soper system of reference**
- **Azimuthal angle distributions are sensitive to the choice of PPf_2 coupling**
- **One of the PPf_2 couplings ($g_{PPf2}(j=2)$) leads to four-oscillations in $\phi_{\pi+}$ compared to two-oscillations for the six other tensorial couplings**
- **Influence of experimental cuts**





pp → p + (resonance → $\pi^+\pi^-$) + p

continuum pp → p + $\pi^+\pi^-$ + p



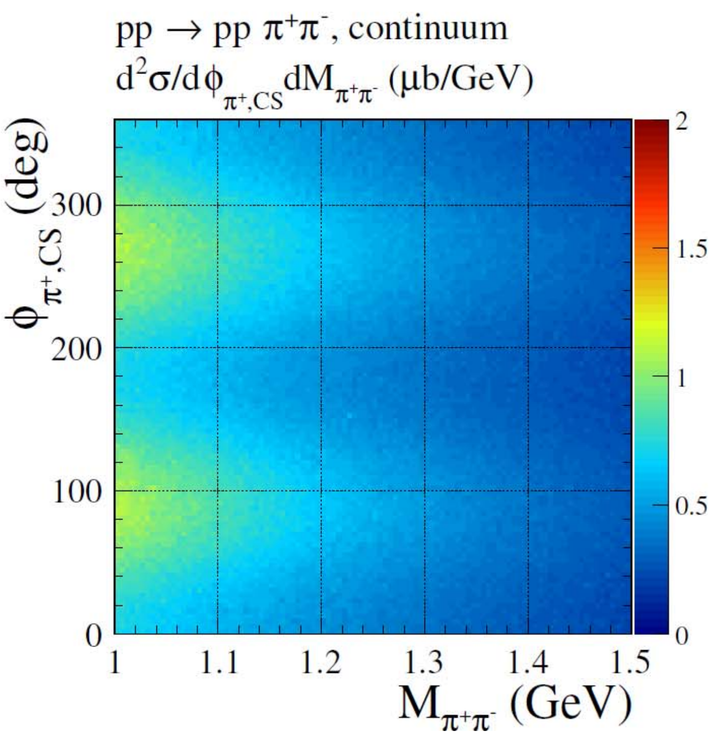
Angular distributions for seven PPf$_2$(1270) couplings

Absorption effects not included

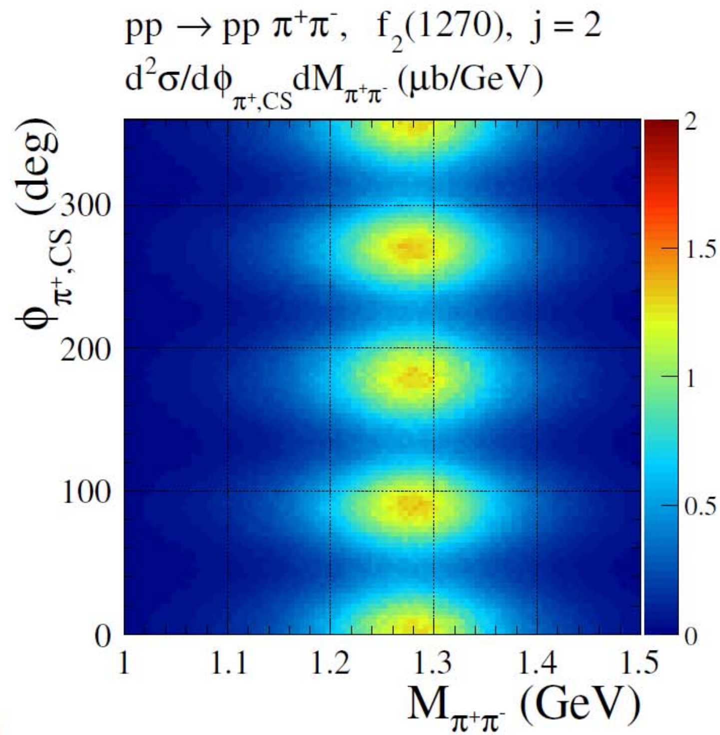
$$d\sigma/d\phi_{\pi^+,CS} \approx A \pm B\cos(n\,\phi_{\pi^+,CS})$$

The shape of the azimuthal angle distributions depends on the choice of the PPf$_2$ coupling

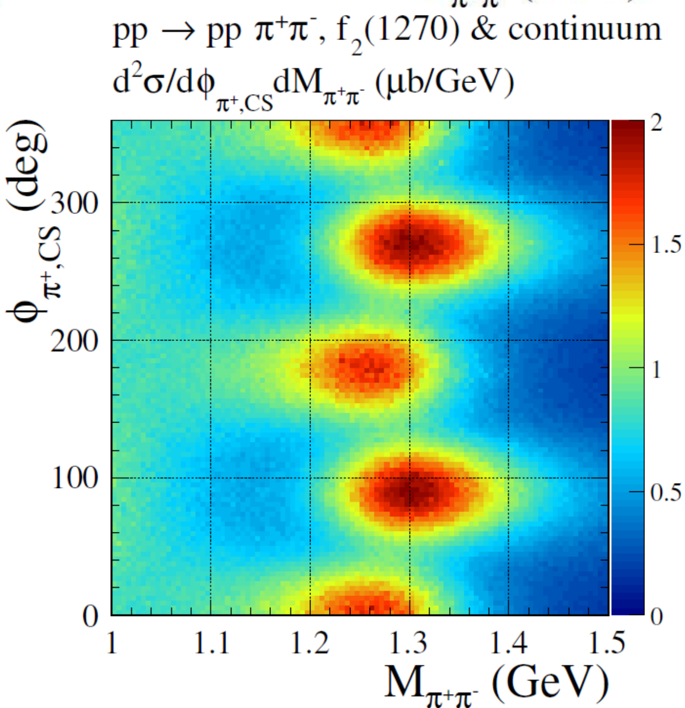
n = 2 for most of the couplings but for the j = 2 coupling n = 4



(a)



(b)



Tensor Pomeron Model

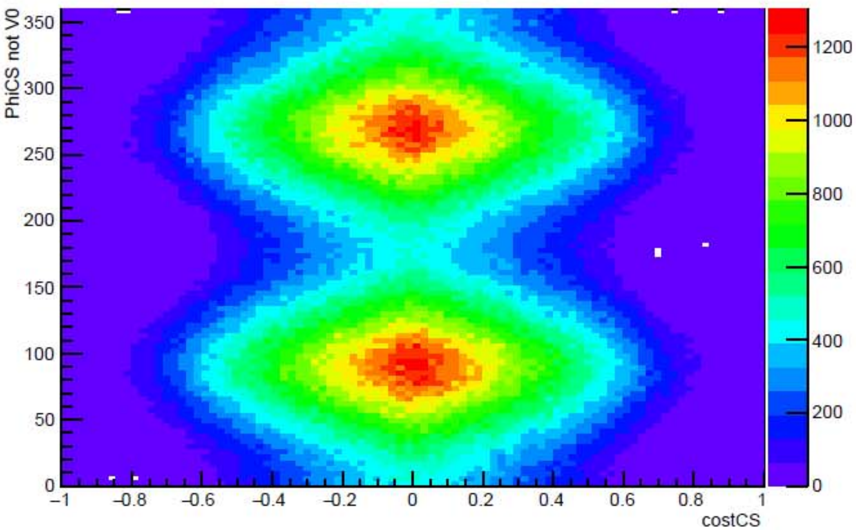
$\phi_{\pi+}$ vs. $M_{\pi\pi}$

$\sqrt{s}$ = 13 TeV, $|\eta_\pi| < 1$, $p_{t,\pi} > 0.1$ GeV

Absorption effects not included

ALICE data (2017, $\sqrt{s}$ = 13 TeV)

$\phi_{\pi+}$ vs. $\cos\theta_{\pi}$

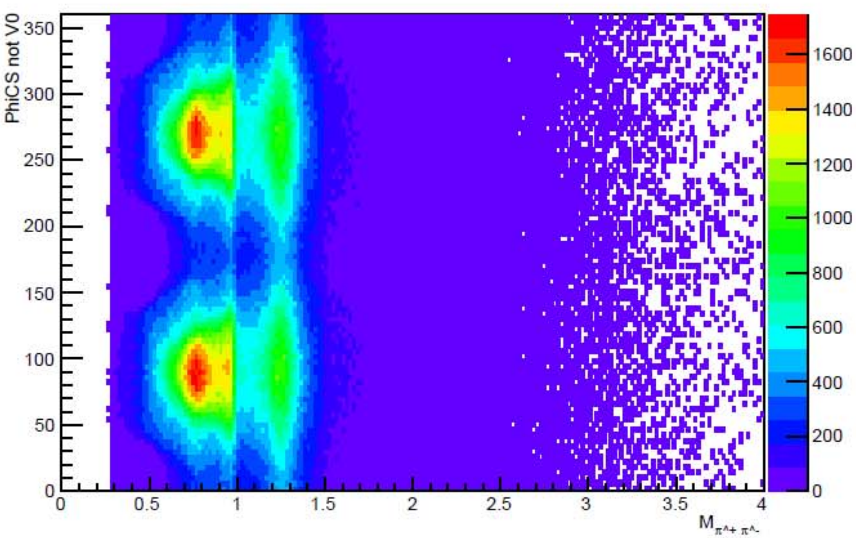


V0 gap

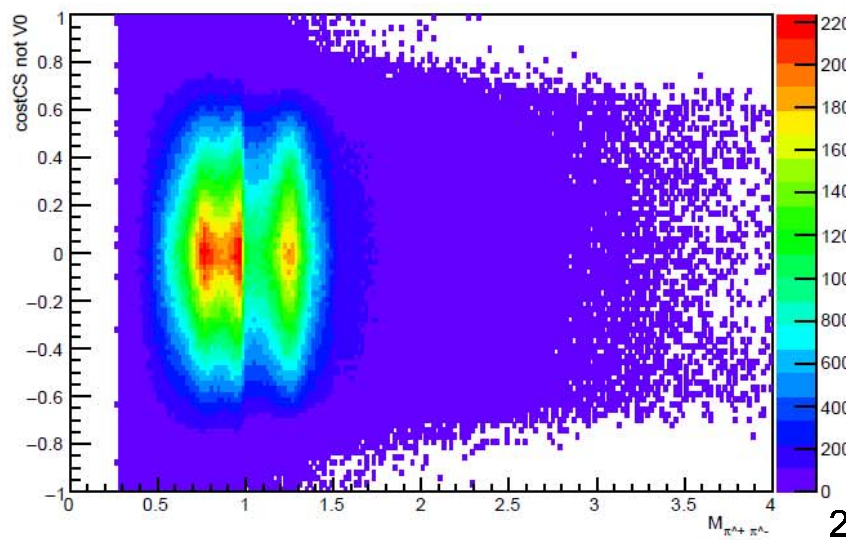
(similar distributions for V0AD Double Gap events)

Two oscilations in the pion azimuthal angle distribution

$\phi_{\pi+}$ vs. $M_{\pi\pi}$



$\cos\theta_{\pi}$vs. $M_{\pi\pi}$

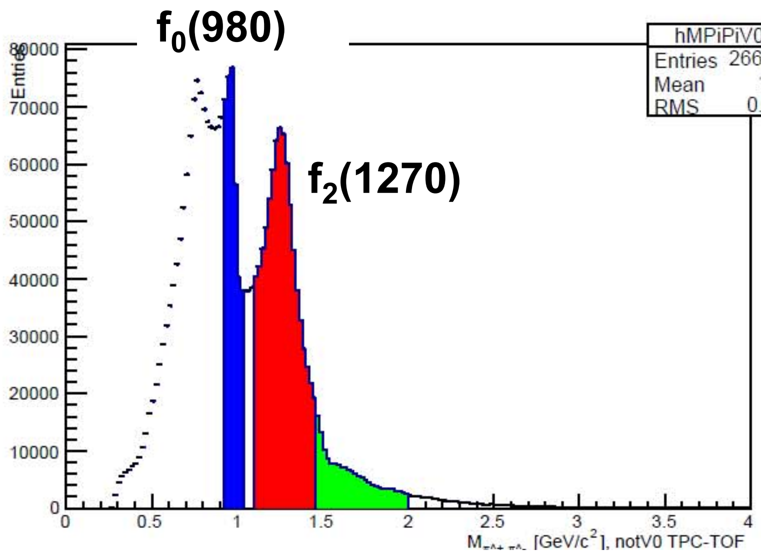


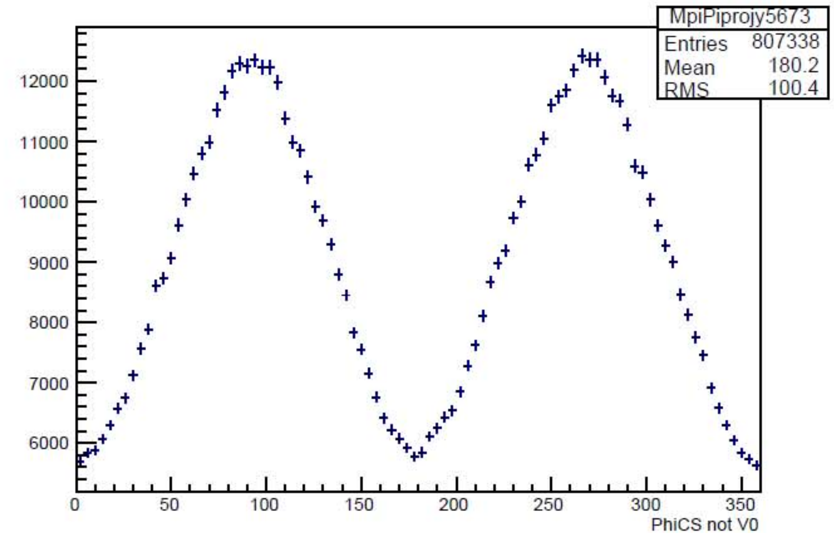
ALICE data - $\phi_{\pi+}$ distributions

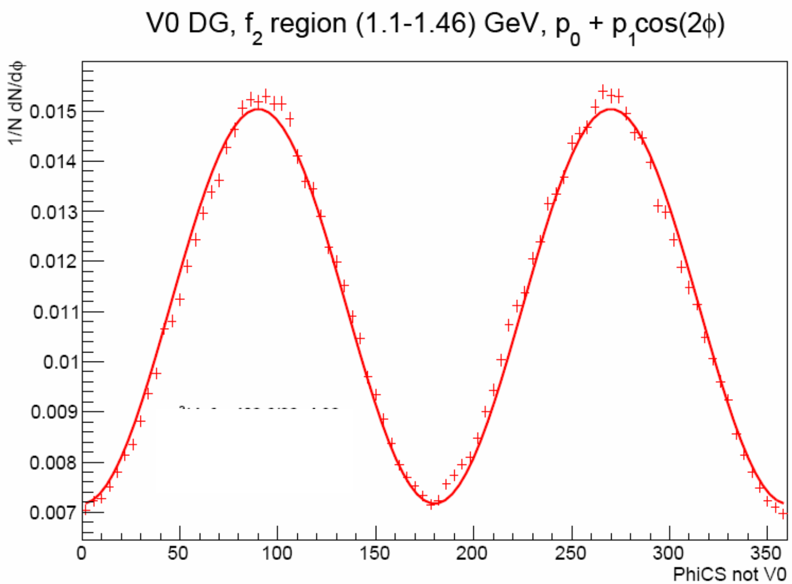
$M_{\pi\pi}$ **V0 gap**

$f_2(1270)$ region

$M_{\pi\pi}$: (1.10 – 1.46) GeV







Fit of 1/N dN/dϕ distributions

$p_0 + p_1 \cdot \cos(n\phi)$

n = 2 (fixed),χ^2 = 4.93