Vector meson photoproduction in ultra-peripheral heavy ion collisions at sqrt(s)=5.02 TeV

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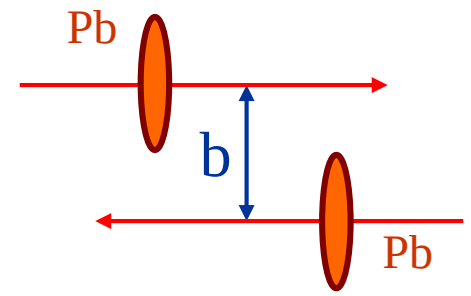
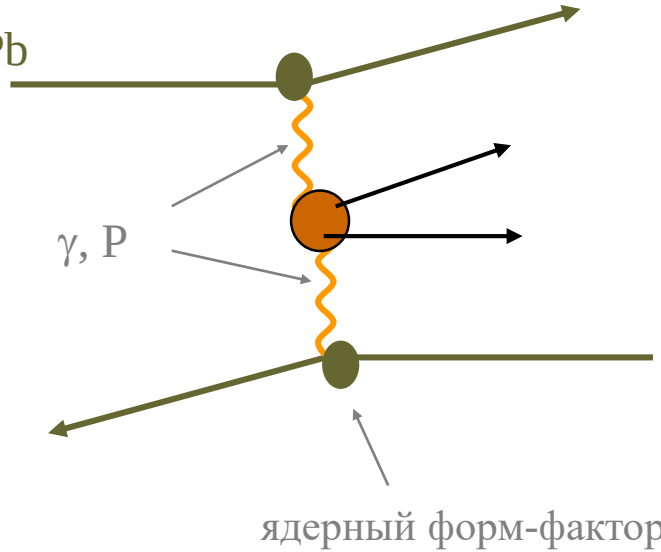
Ультрапериферические взаимодействия

- Ионы являются источником полей
  - фотонов
    - $\sigma_{\gamma\gamma} \sim Z^4$
  - померонов
    - $\sigma_{\gamma P} \sim Z^2 A^2$ - для тяжелых мезонов (J/psi)
    - $\sigma_{\gamma P} \sim Z^2 A^{4/3}$ - для легких мезонов (ρ, ω, φ)
- В когерентных полях:
  - ♦ Небольшой поперечный импульс:
  - ♦ $p_\perp < h/R_A \sim 90$ МэВ (для Pb)
  - ♦ Максимальная продольная компонента
  - ♦ $p_{||} < \gamma h/R_A \sim 100$ GeV $E_{\gamma max} \sim \gamma hc/b$





Baur G., J.Phys. G24 (1998) 1657

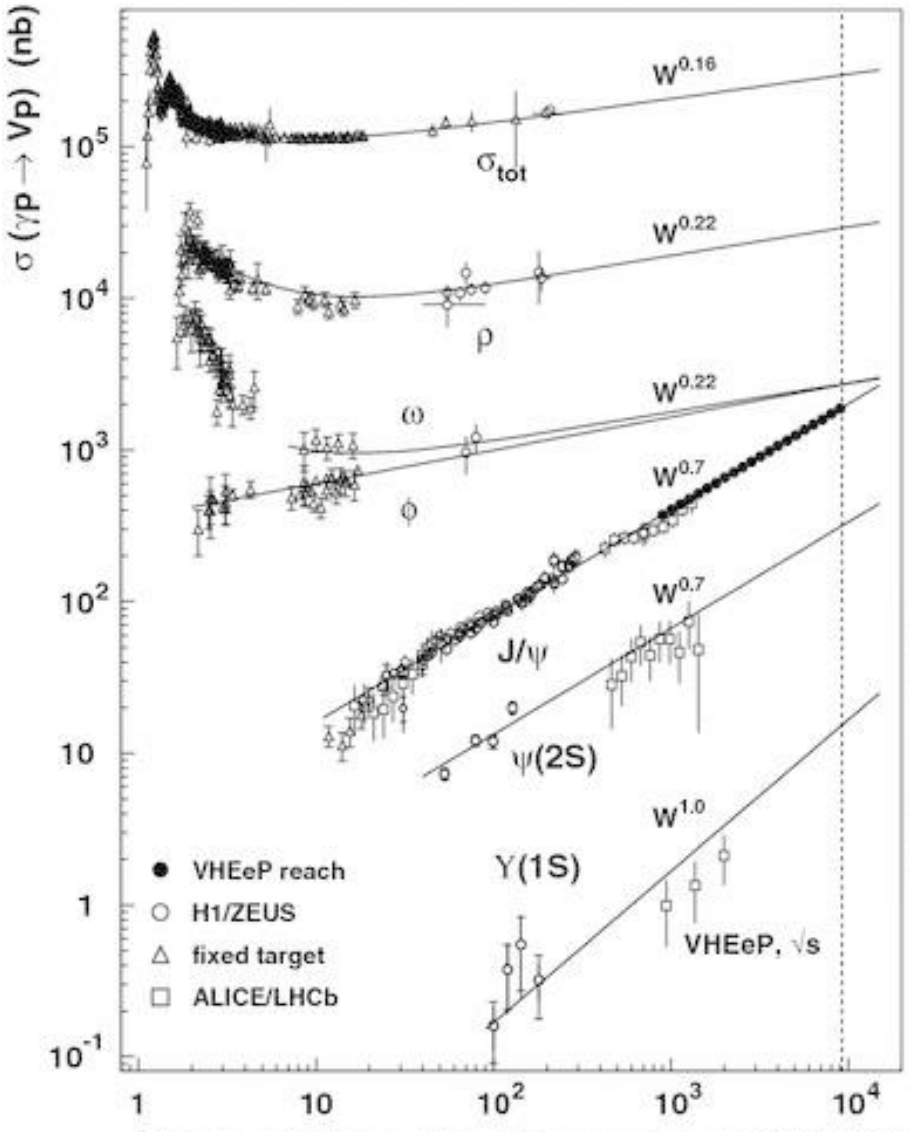
Energy	AuAu (RHIC)	PbPb (LHC)	pp (LHC)
CM Energy Wγp	24 GeV	700 GeV	~ 3000 GeV
Max γγ Energy	6 GeV	200 GeV	~ 1400 GeV

The $\pi^+\pi^-\pi^+\pi^-$ final states

- Study of the $\pi^+\pi^+\pi^-\pi^-$ photonuclear production in ultra-peripheral Pb+Pb collisions at 5.02 TeV
- The $\pi^+\pi^+\pi^-\pi^-$ has not yet been studied at such energies
- There are several inserting channels for the production of the $\pi^+\pi^+\pi^-\pi^-$ final states, for example:
  - Photon+pomeron$\rightarrow\rho'\rightarrow \pi^+\pi^-\pi^+\pi^-$
    - in paper arXiv:0912/0604v2[nucl-ex] the ρ' production cross section estimated ~13% of that of the $\rho^0(770)$ meson
  - Photon+pomeron$\rightarrow\rho^0\phi\rightarrow \rho K_L K_S \rightarrow \pi^+\pi^-\pi^+\pi^-$
    - $\sigma(\rho^0\phi)$~1,6 mb
  - Photon+pomeron$\rightarrow\rho^0\omega\rightarrow (\omega \rightarrow \pi^+\pi^-\pi^0) \rightarrow \pi^+\pi^-\pi^+\pi^-$
    - $\sigma(\rho^0\omega)$~1,6 mb
  - Photon+photon $\rightarrow \rho^0\rho^0\rightarrow \pi^+\pi^-\pi^+\pi^-$
    - $\sigma(\rho^0\rho^0)$~8,8 mb

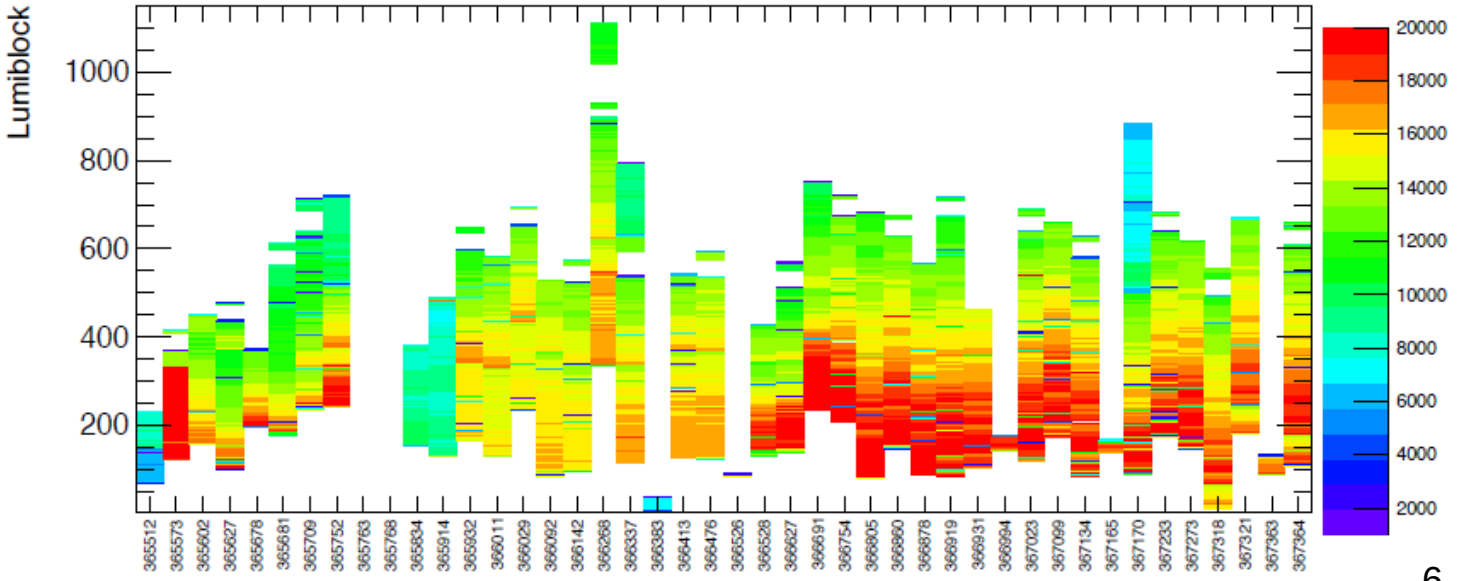
Reaction (Eγ, GeV)			exp(-bt)
$\gamma p \to p 4\pi$ (9,3)	$\sigma(\rho' \to \rho^0 \pi^- \pi^+) = 1{,}6$ μb	$R=(\rho' \to \pi^- \pi^+)/(\rho' \to \rho^0 \pi^- \pi^+)=0{,}2$	$b=5{,}6$ GeV^{-2}
$\gamma p \to p 4\pi$ (4,4) (7,1) (12,7)	$\sigma(\gamma p \to p\rho')= 1{,}3$ μb $= 1{,}0$ μb $= 1{,}6$ μb		$b=6{,}6$ GeV^{-2} $b=7{,}3$ GeV^{-2} $b=4{,}9$ GeV^{-2}
$\gamma d \to d 4\pi$ (7,5)	$\sigma(\gamma d \to d\rho')= 0{,}84$ μb $(t<0{,}2)$	$(f^2_{\rho'})/(f^2_{\rho})=6{,}0$	$b=7{,}5$ GeV^{-2}
$\gamma C \to p 4\pi$ (50)	$\sigma(\gamma C \to \rho' \to 2\pi)= 67$ nb/N $\sigma(\gamma C \to \rho' \to 4\pi)= 1$ μb/N		$b=64{,}6$ GeV^{-2}
$\gamma p \to p 4\pi$ (20-70)		$R=\sigma(\rho' \to \pi^- \pi^+)/\sigma(\rho^0)=0{,}01$ $R=(\rho' \to \pi^- \pi^+)/(\rho' \to \pi^- \pi^+ \pi^- \pi^+)=0{,}13$	
$AuAu \to Au^* Au^* 4\pi$		$R=(\rho' \to \pi^- \pi^+)/(\rho' \to \pi^- \pi^+ \pi^- \pi^+)=0{,}012$ $\frac{\sigma^{coh}_{4\pi,XnXn}}{\sigma^{coh}_{\rho,XnXn}} = \frac{\sigma^{coh}_{\rho',XnXn} \cdot B(\rho' \to \pi^+\pi^-\pi^+\pi^-)}{\sigma^{coh}_{\rho,XnXn}} = 16\%$ $\sigma^{coh}_{\rho',0n0n} = 53\text{mb}$	

for LHC approximately
5200mb*0.13 = 670mb

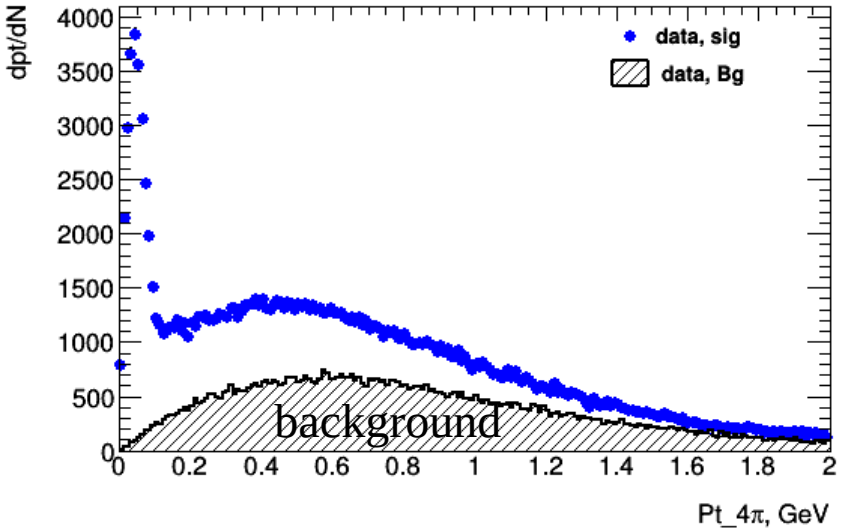


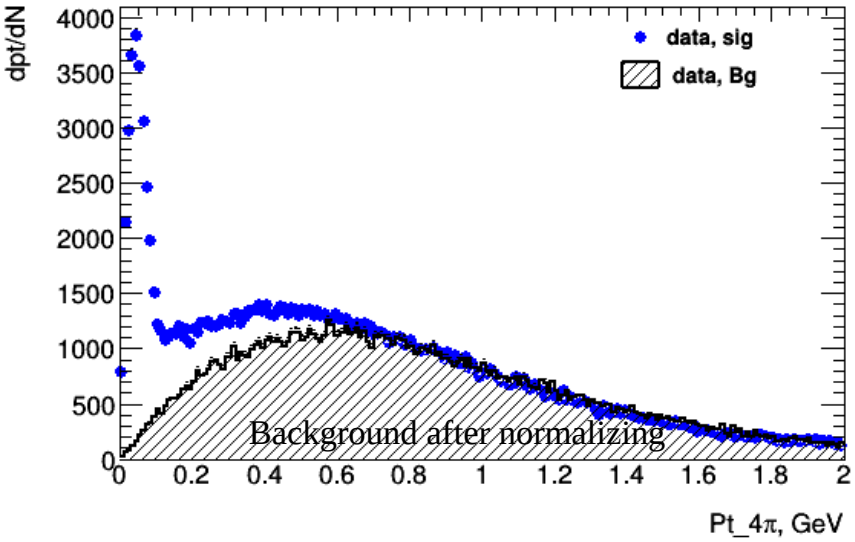
Набор данных

- Pb+Pb run 2018
- 39 good runs
- L_{int} = 1.44 nb^{-1}
- N_{tot} = 220 M
- Триггер
  - HLT_mb_sptrk_exclusiveloose_vetosp1500_L1VTE20
    - N ~ 50 M

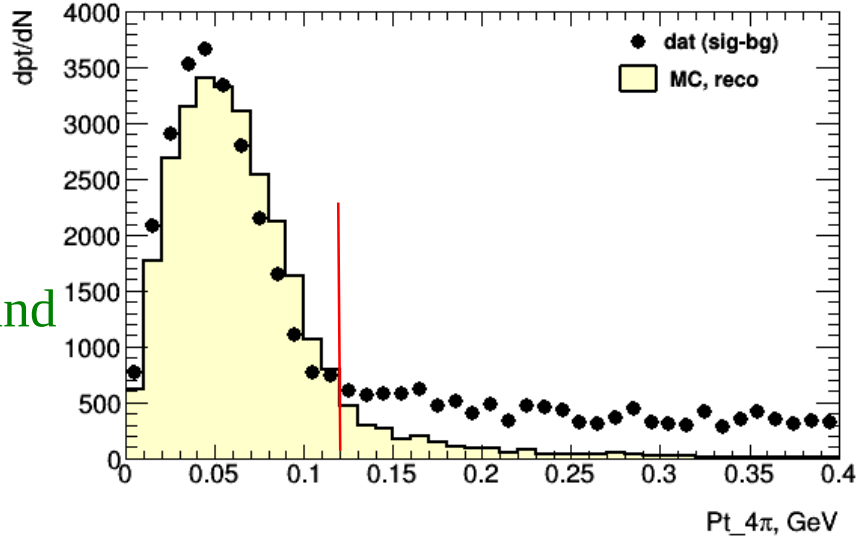


Pt (4π), data vs MC reco

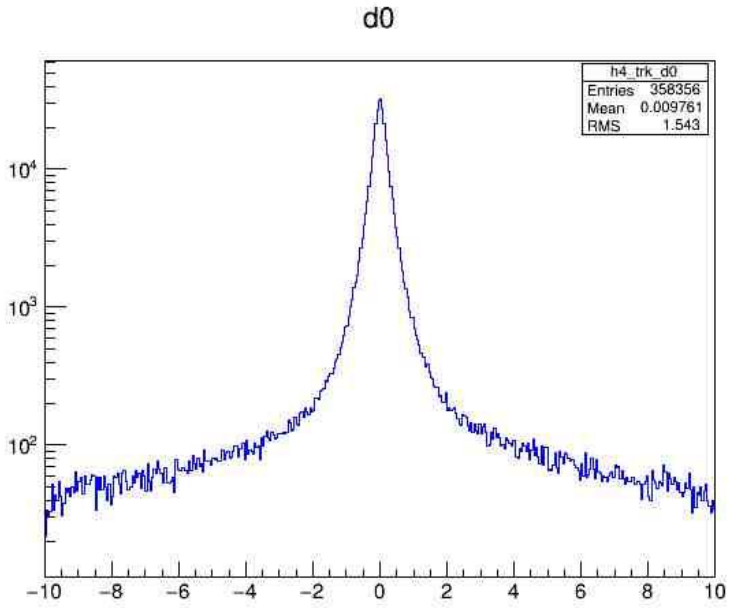


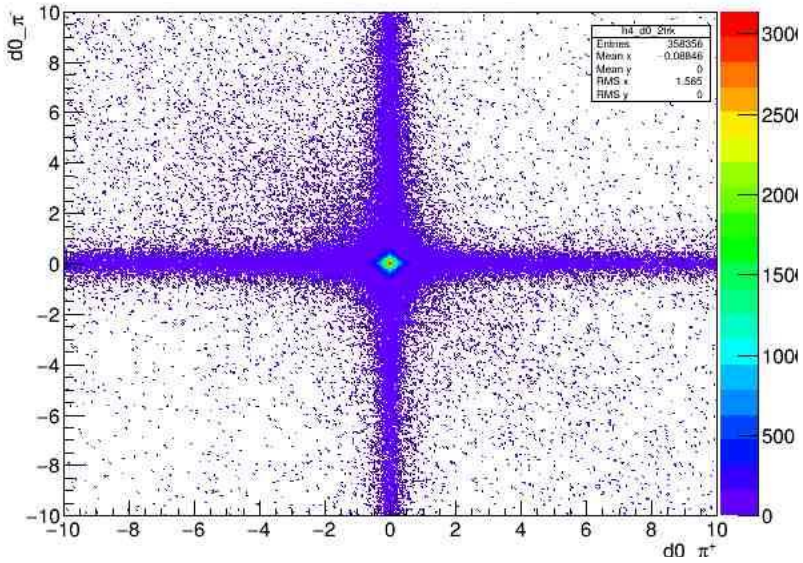


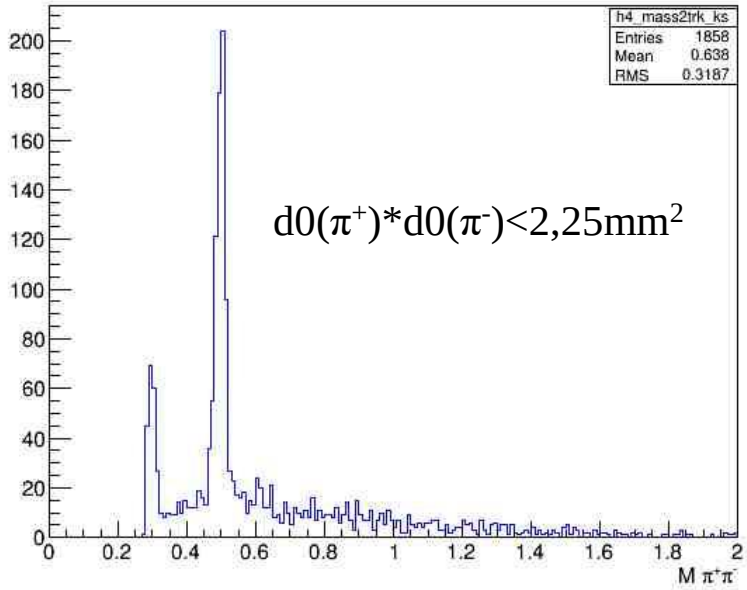
- Cuts:
  - Ntrack==4
  - $d_0 < 1,5$
  - Q=0 – signal; Q=+2 or -2 – background
  - Vertex > 0



d0



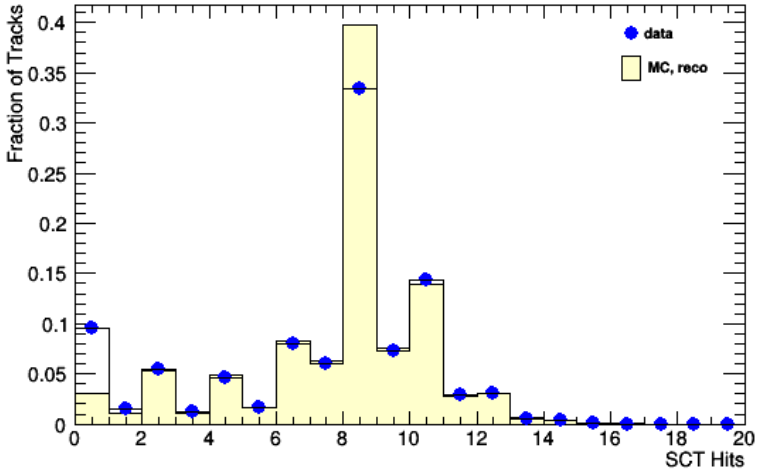


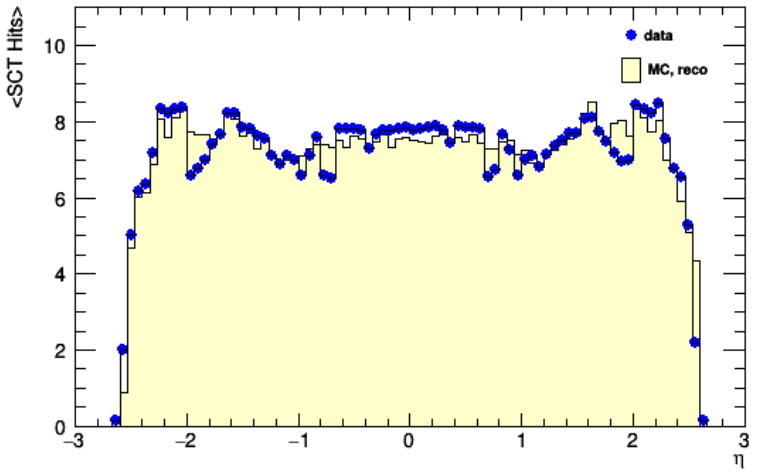


$d0(\pi^+)*d0(\pi^-)<2{,}25\text{mm}^2$

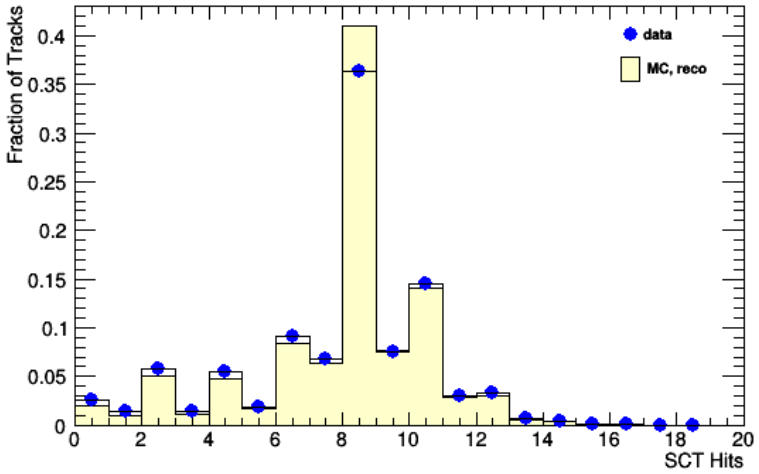
SCT: data vs MC reco

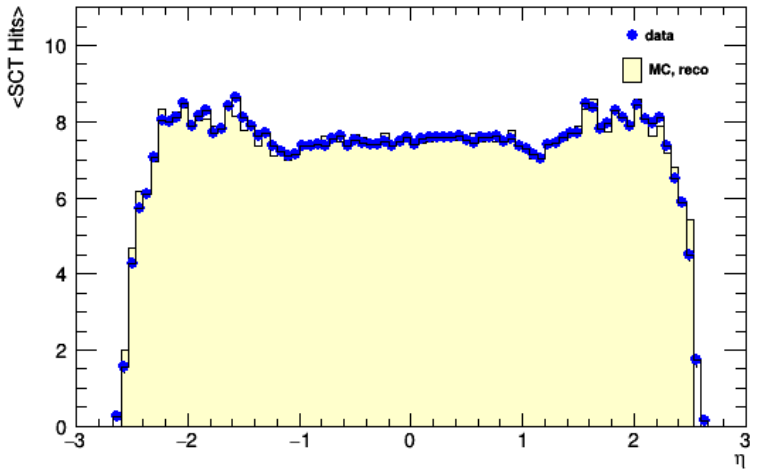
without cut





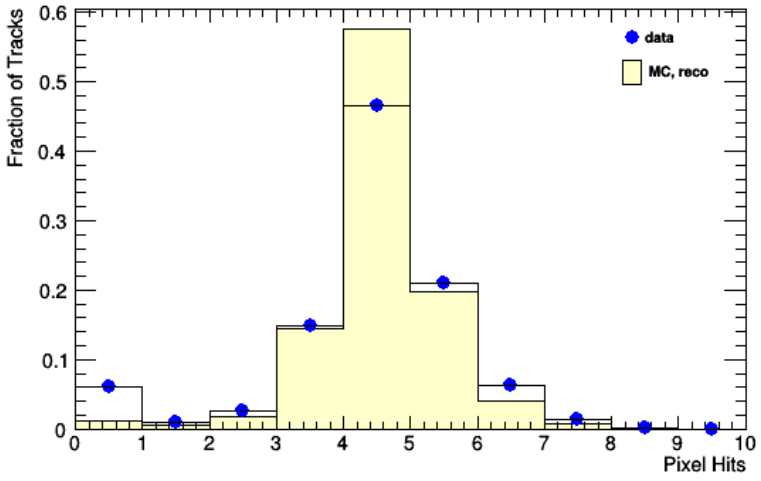
pt(4π)<0,12 GeV + d_0<1.5

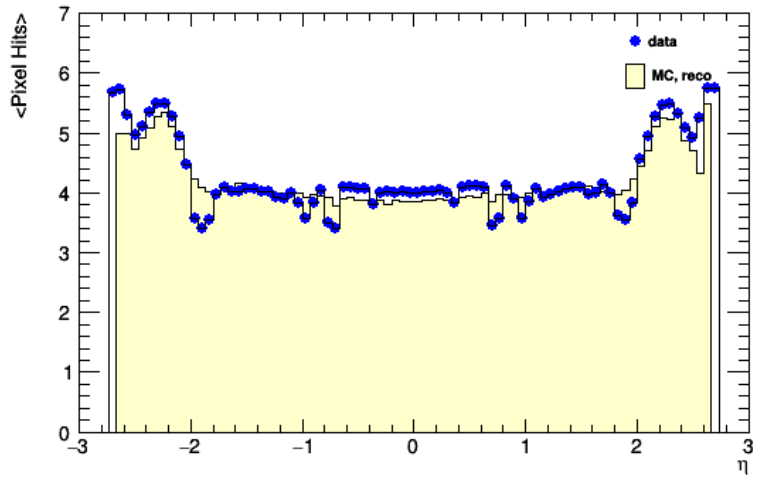




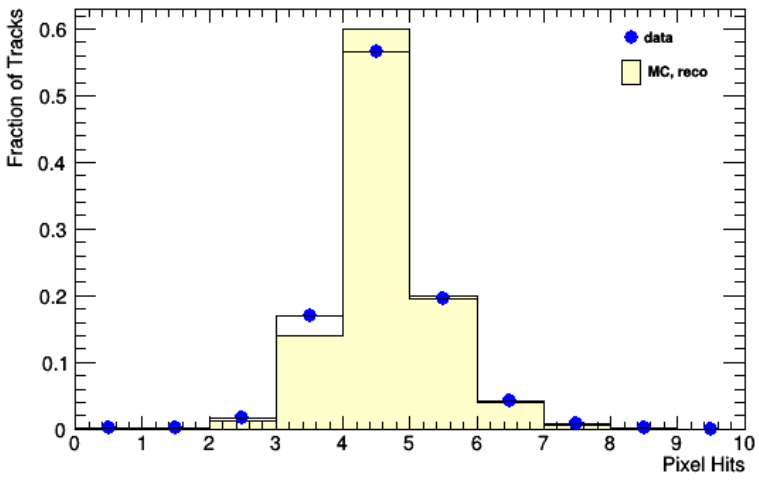
Pixel: data vs MC reco

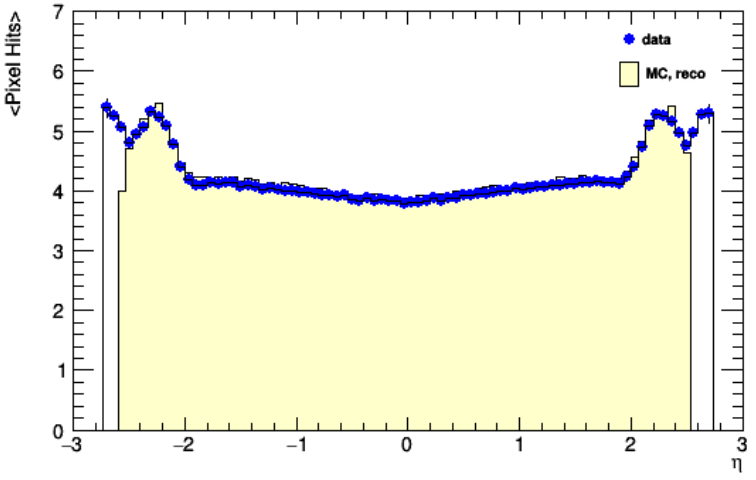
without cut





pt(4π)<0,12 GeV + d_0<1.5

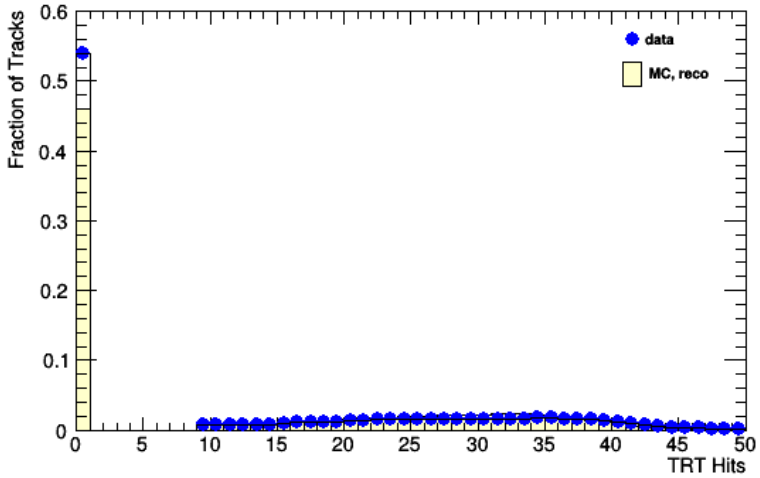


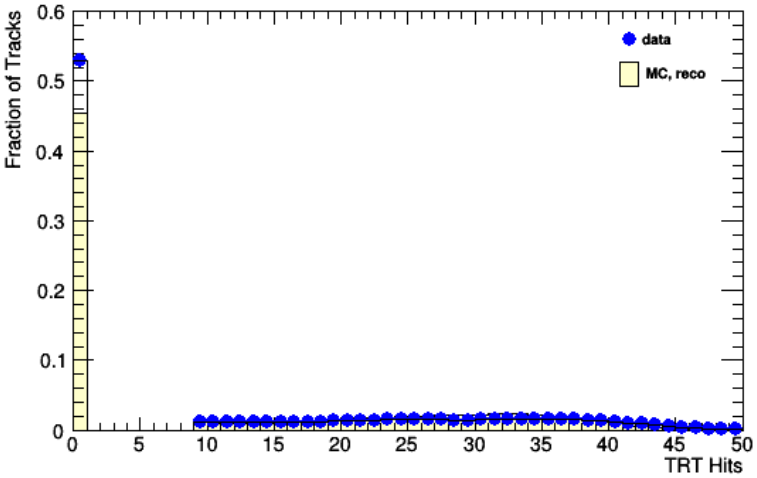


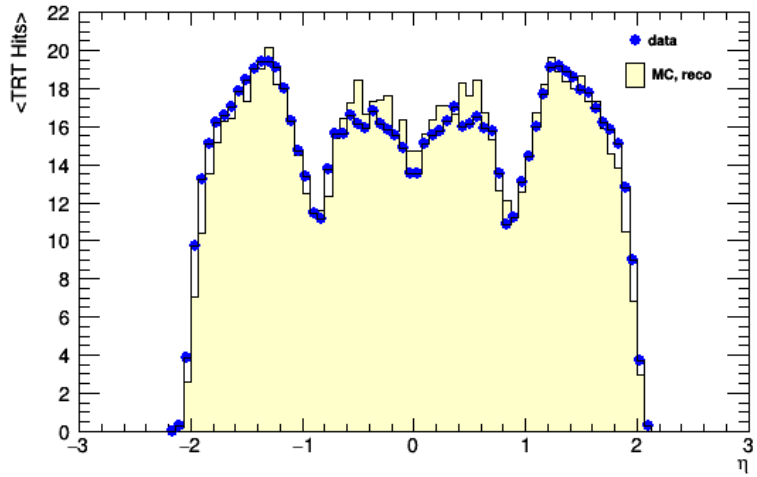
TRT: data vs MC reco

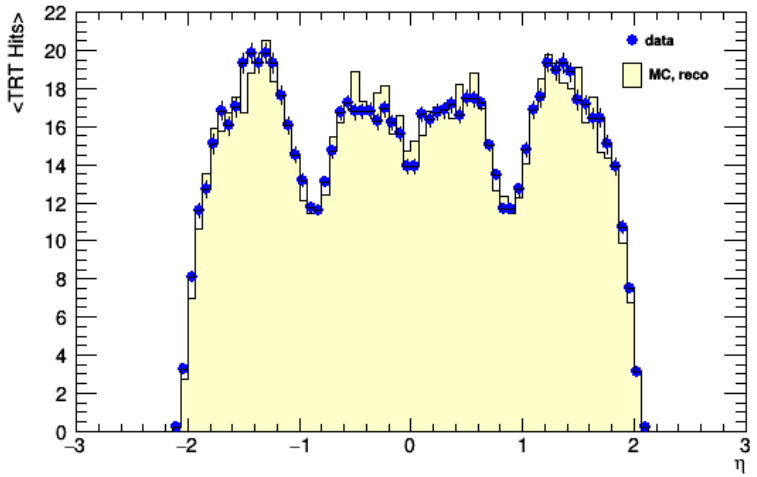
without cut

pt(4π)<0,12 GeV + d_0<1.5

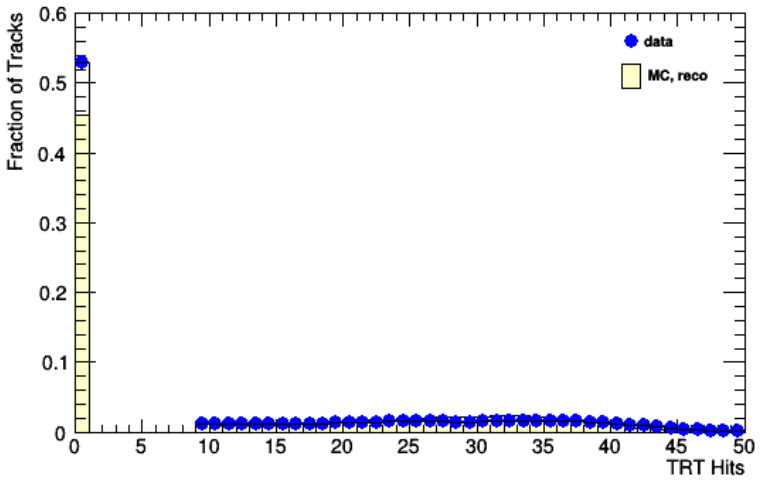


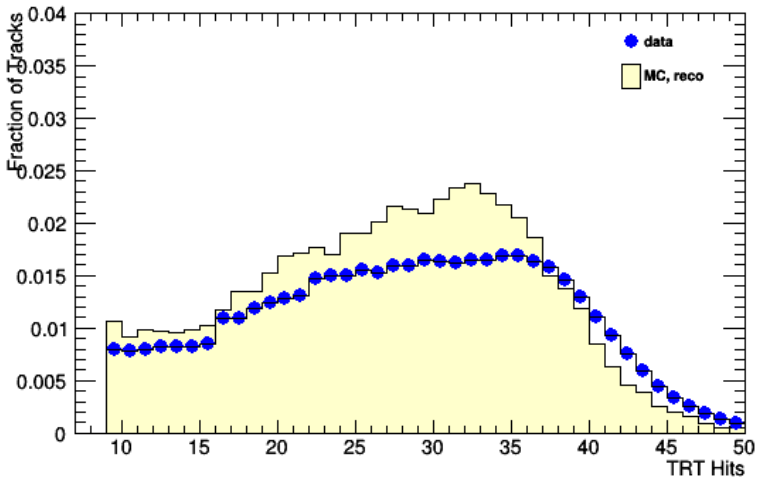




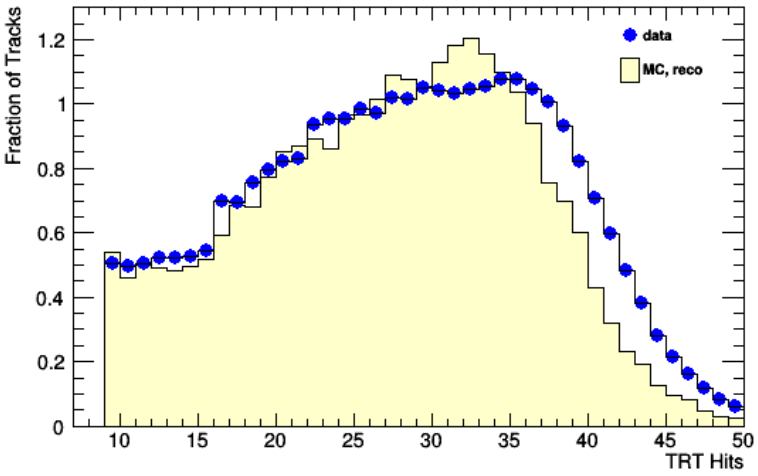


TRT: data vs MC reco

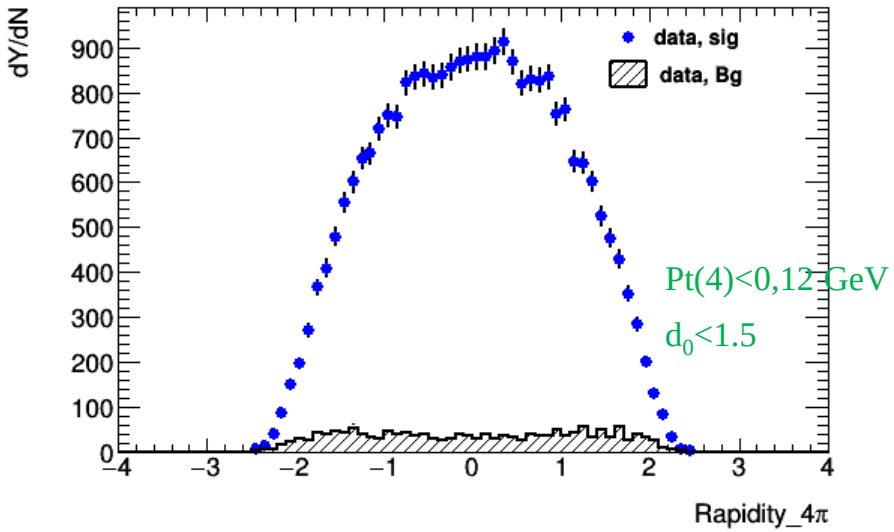




from 9 to 50

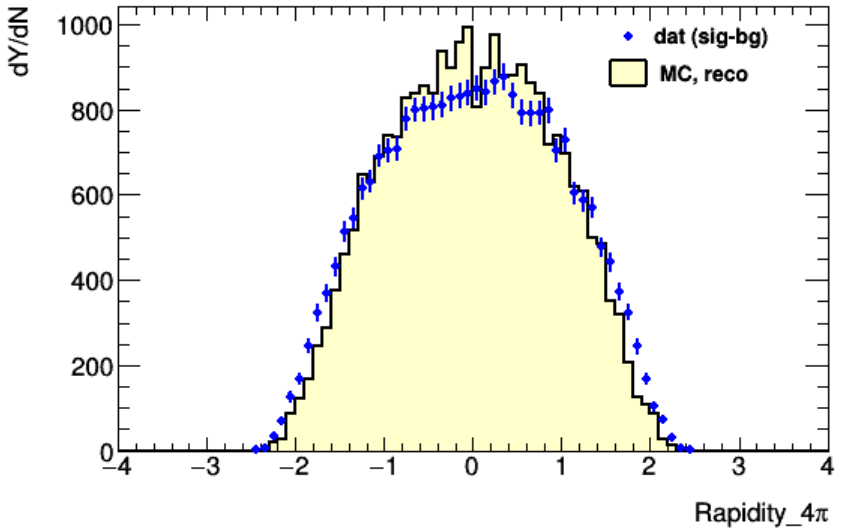


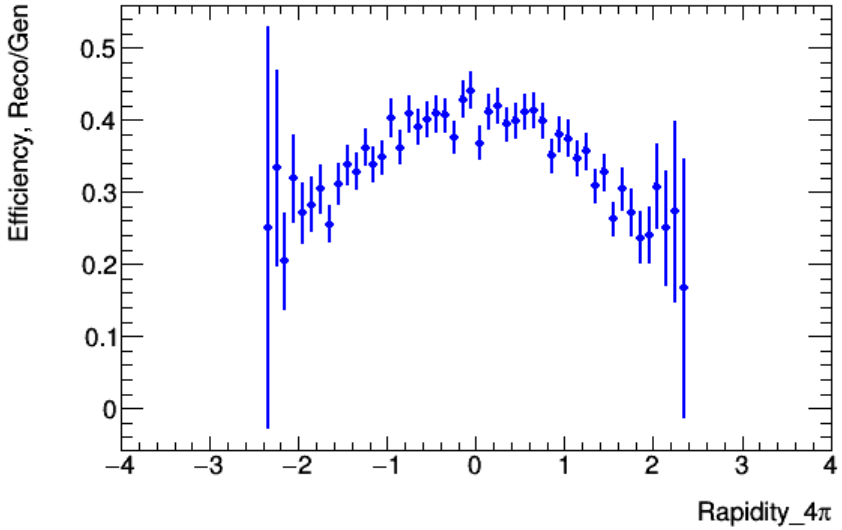
Rapidity (4π)



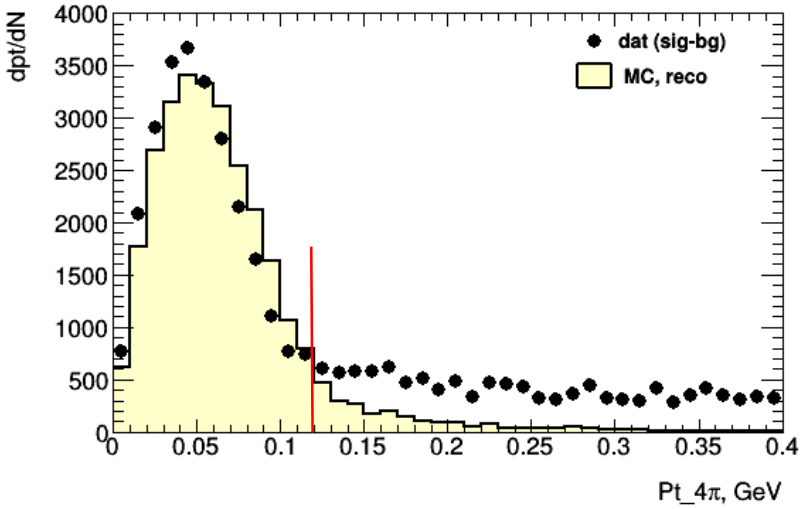
Pt(4)<0,12 GeV

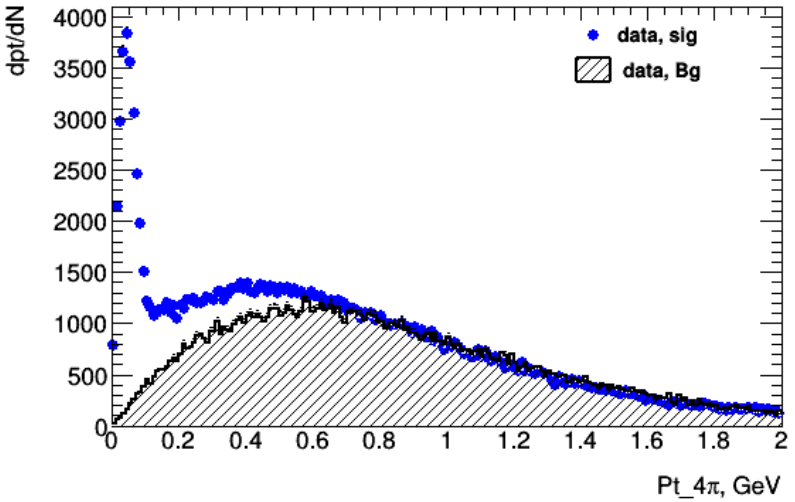
d_0<1.5

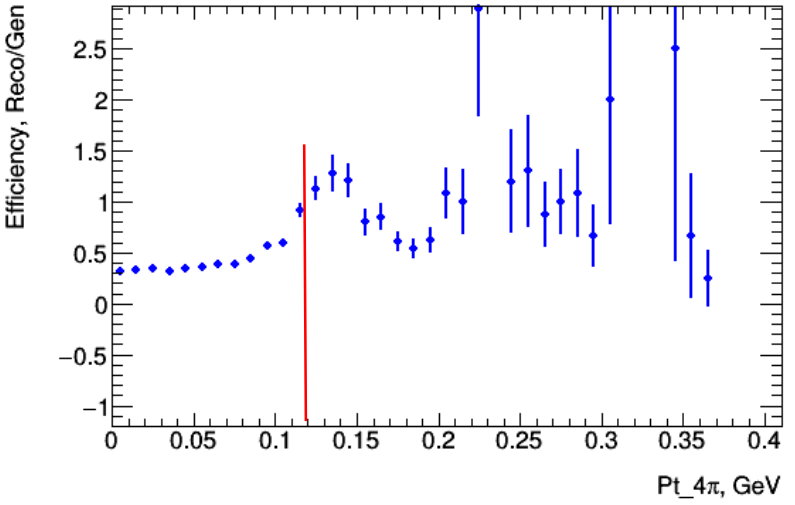




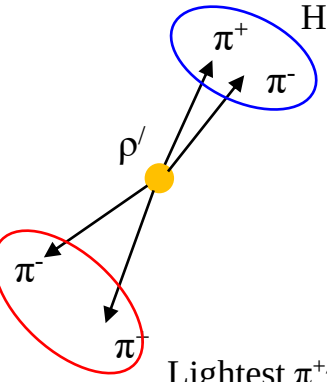
Pt (4π)

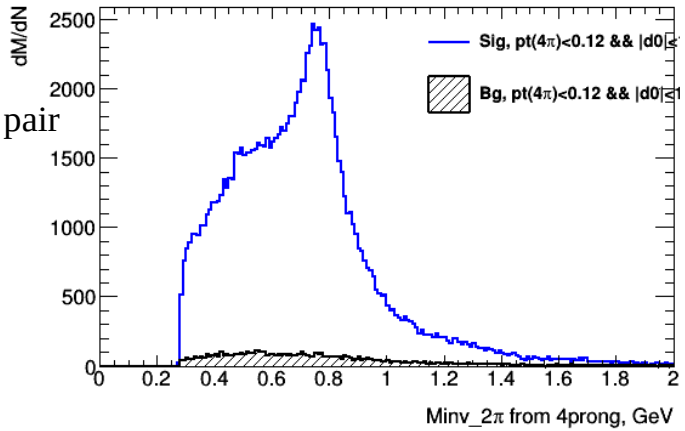

dpt/dN
dat (sig-bg)
MC, reco
Pt_4π, GeV

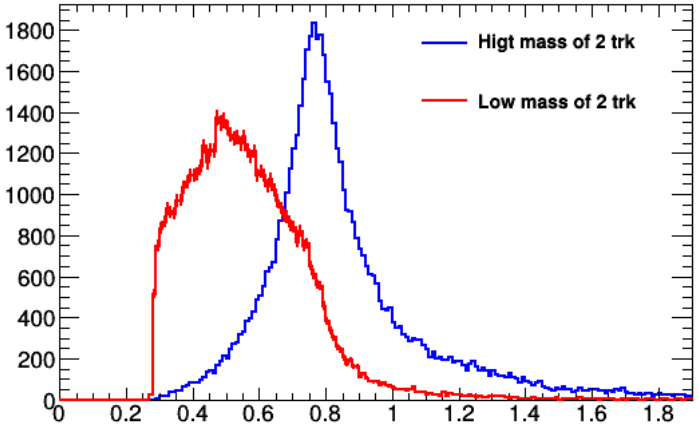

dpt/dN
data, sig
data, Bg
Pt_4π, GeV

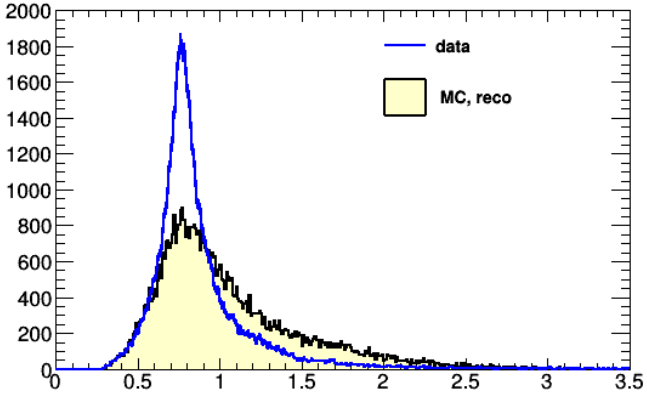

Efficiency, Reco/Gen
Pt_4π, GeV

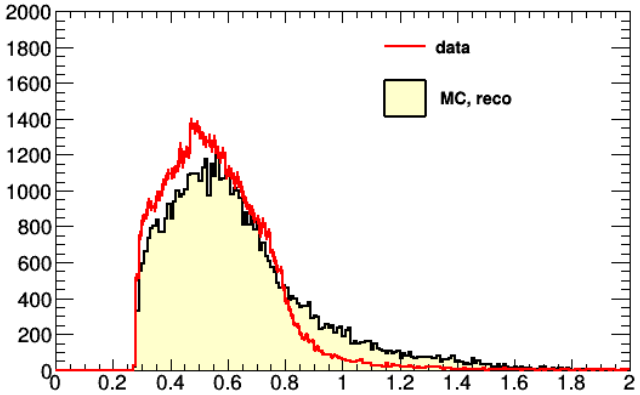
Distribution of $\pi^+\pi^-$ from 4π



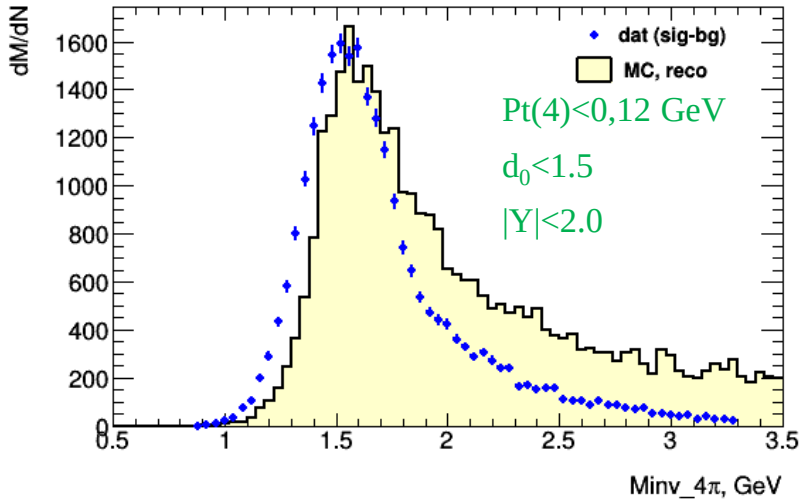




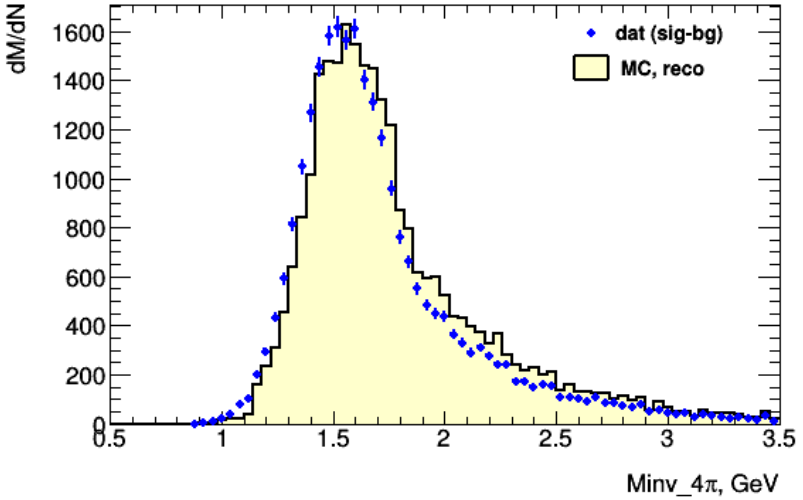


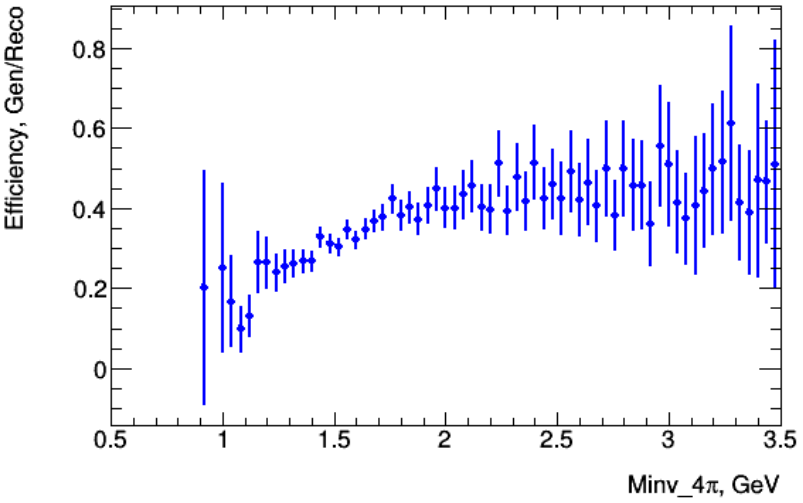


Mass (4π): data vs MC

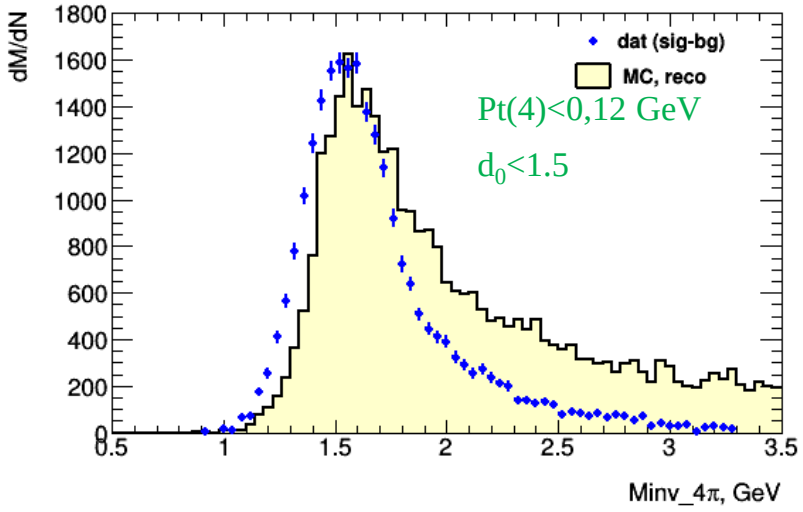


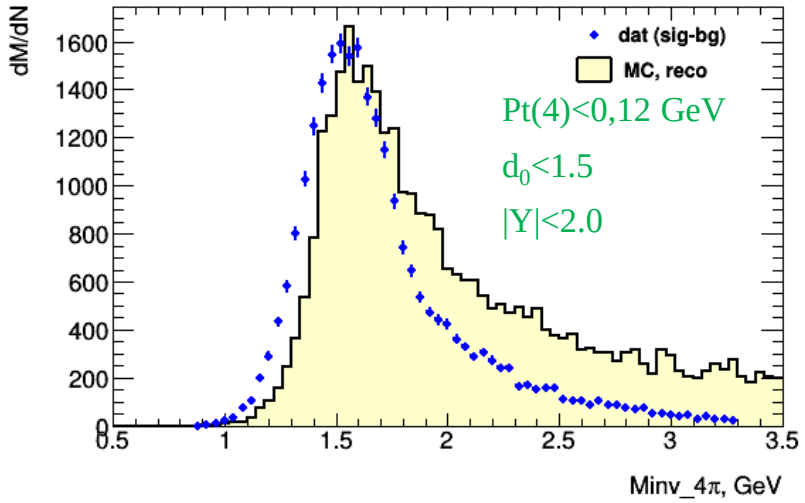
After reweighing

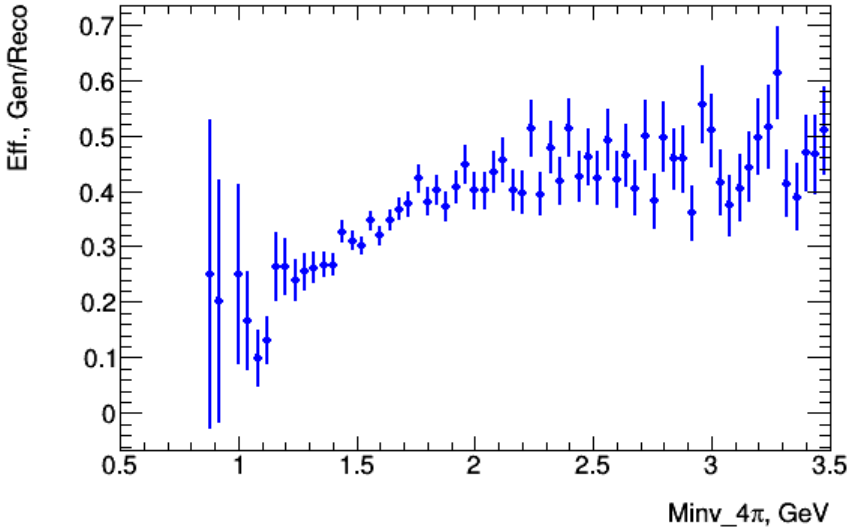


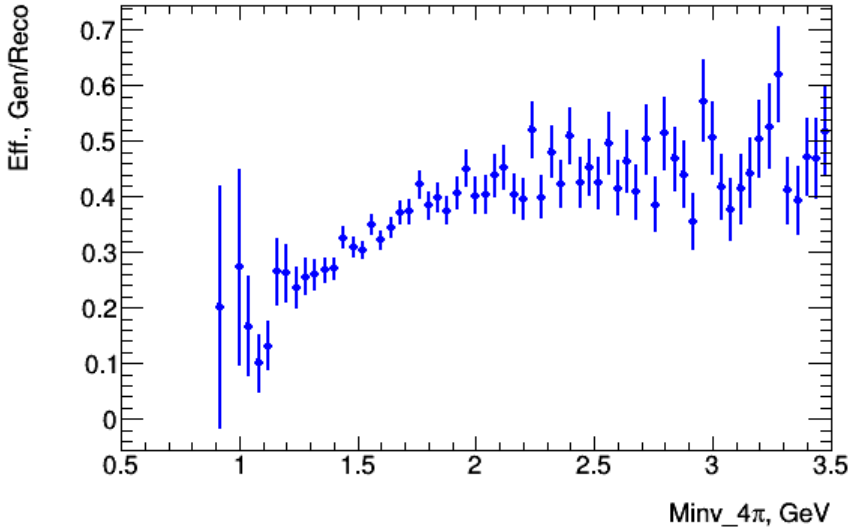


Mass (4π): data vs MC

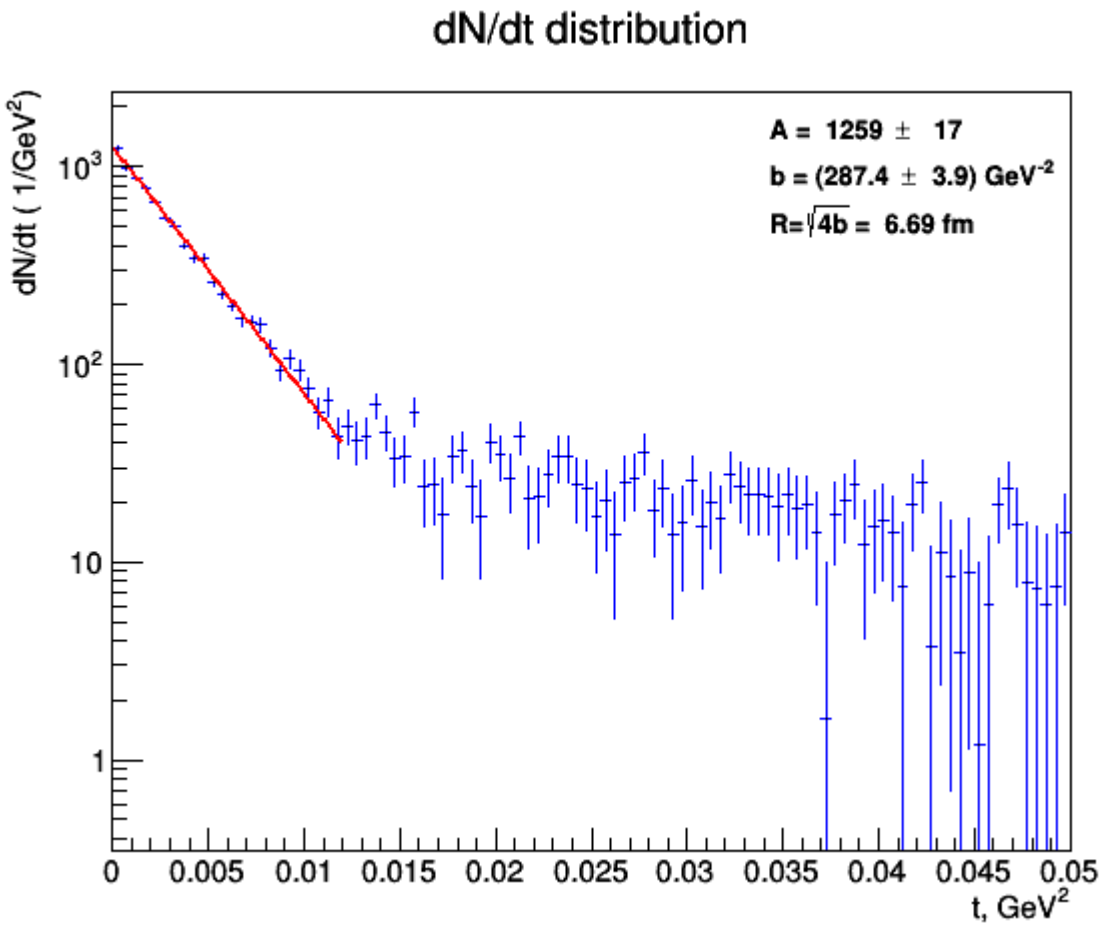








t distribution



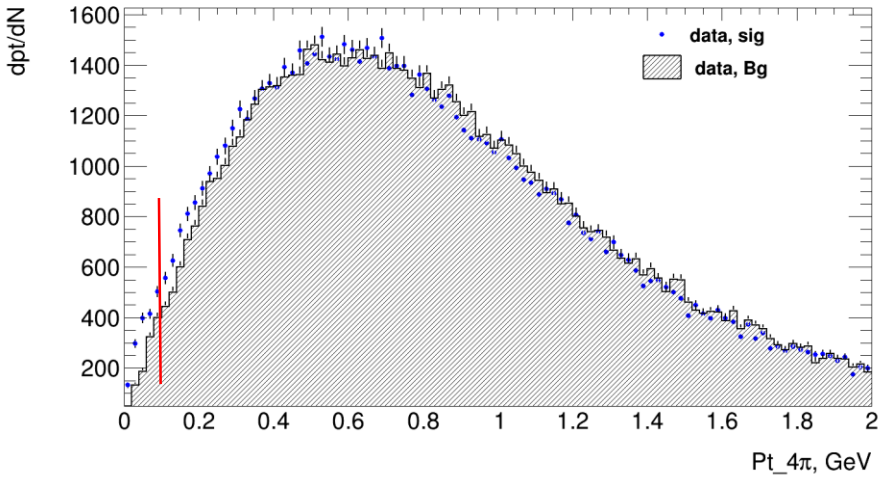
$$\frac{d\sigma}{dt} = A_V \exp(-bt)$$

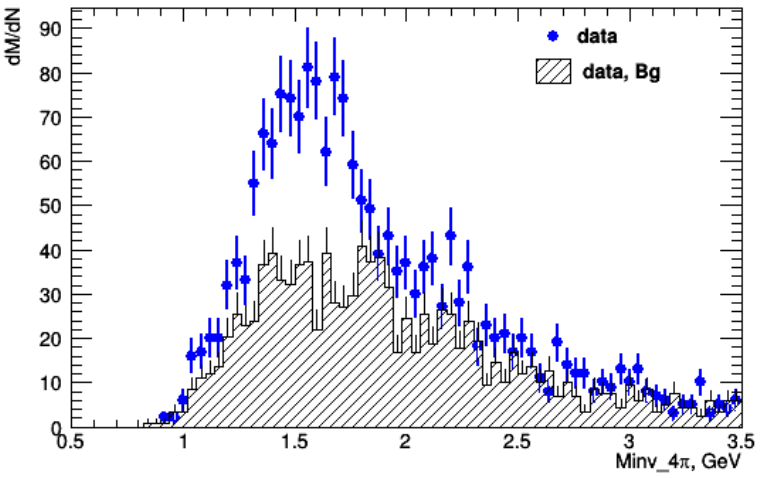
$$A_V = \left.\frac{d\sigma}{dt}\right|_{t=0}$$

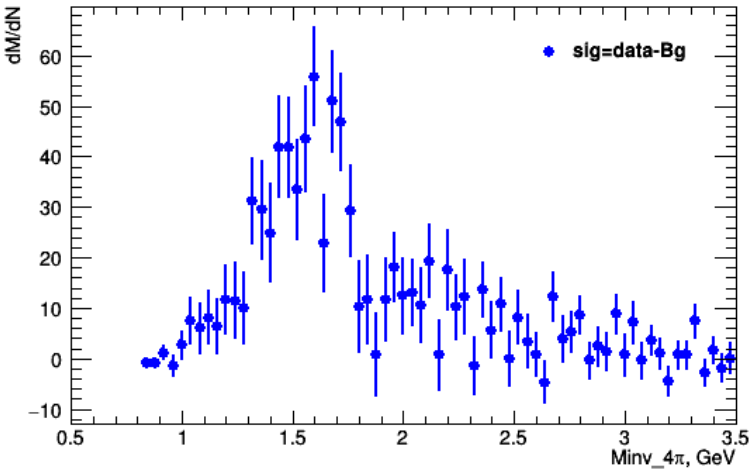
Systematic uncertainties

Source	Uncertainty
Luminosity	
Trigger efficiency	in progress
~~Extra material~~	
MC model (STARLight)	??? (STAR – 11%)
Event selection (pt cut, d0 cut)	pt - …, d0 – 1,2%
Fitting uncertainty	in progress
Background: • background subtraction, • 4prong from 5 tracks • other source	 0,4% (need to check) 2,5% (next slides) …
4π extrapolation	in progress
Tracking	…
MC detector description	???

5 track events to model contamination of 4 track event

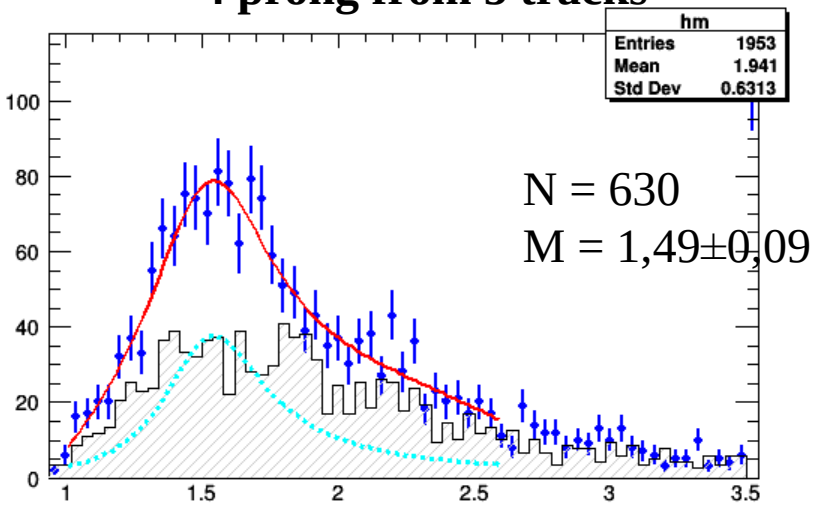




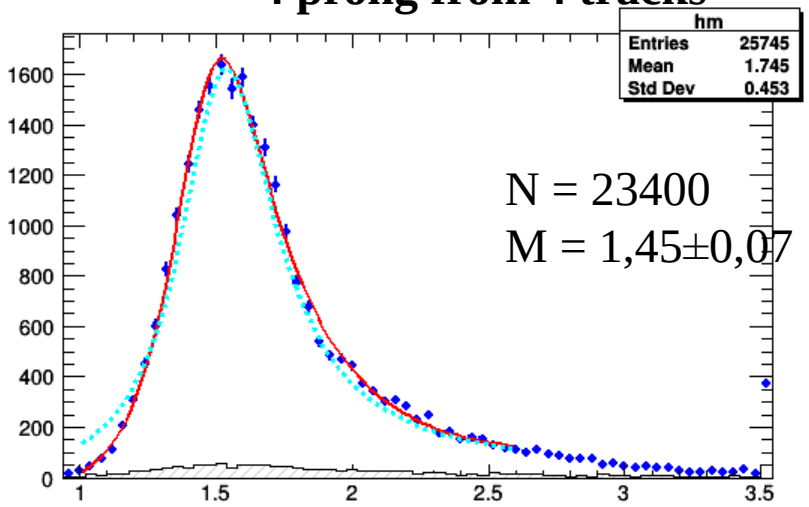


- Cuts:
  - Ntrack==5
  - d_0 < 1,5;
  - Q (4 trk) =0 – signal;
  - Pt(4 trk)<0.12

4 prong from 5 tracks



4 prong from 4 tracks



Other background processes

- According to the results from the article «Observation of pi+pi-pi+pi … STAR Detector» (0912.0604v2) one can see that the cross-section of the rhoPrime is 56 mb or 13% of that of the rho(770).
- So for LHC approximately 5200mb*0.13 = 670mb
- Next processes we could be consider as the background:

a) $\gamma A \rightarrow \rho^0\phi \rightarrow \rho K_L K_S \rightarrow \pi^+\pi^-\pi^+\pi$, $\sigma(\rho\phi)\sim 1{,}6$ mb

b) $\gamma A \rightarrow \rho^0\omega \rightarrow (\omega \rightarrow \pi^+\pi^-\pi^0) \rightarrow \pi^+\pi^-\pi^+\pi^-$, $\sigma(\rho\omega)\sim 1{,}6$ mb

c) $\gamma A \rightarrow \rho^0\rho^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$, $\sigma(\rho\rho)\sim 8{,}8$ mb

- Contribution < 1%

Analysis goal

- The invariant mass distribution for the coherent produced $\pi^+\pi^-\pi^+\pi^-$
  - ✓ mass and width
- The invariant mass distribution of two-pion subsystems
- Transverse momentum distribution of the $\pi^+\pi^-\pi^+\pi^-$
  - ✓ coherent and incoherent
- Momentum transfer squared *t* and rapidity *y* distributions
  - ✓ slope
- Correlation with ZDC (*0n0n*, *0nXn*, *XnXn*)
- Cross sections and comparisons with STAR
- ~~Decay angular distributions(cosTheta*, …)~~
- Ratios:
  - ~~$(\rho^{/} \rightarrow \pi^{\pm}\pi^{-})/(\rho^{/} \rightarrow \pi^{\pm}\pi^{-}\pi^{\pm}\pi^{-})$;~~
  - $(\rho^{/} \rightarrow \pi^{+}\pi^{-}\ \pi^{+}\pi^{-})/(\rho^{0} \rightarrow \pi^{+}\pi^{-})$

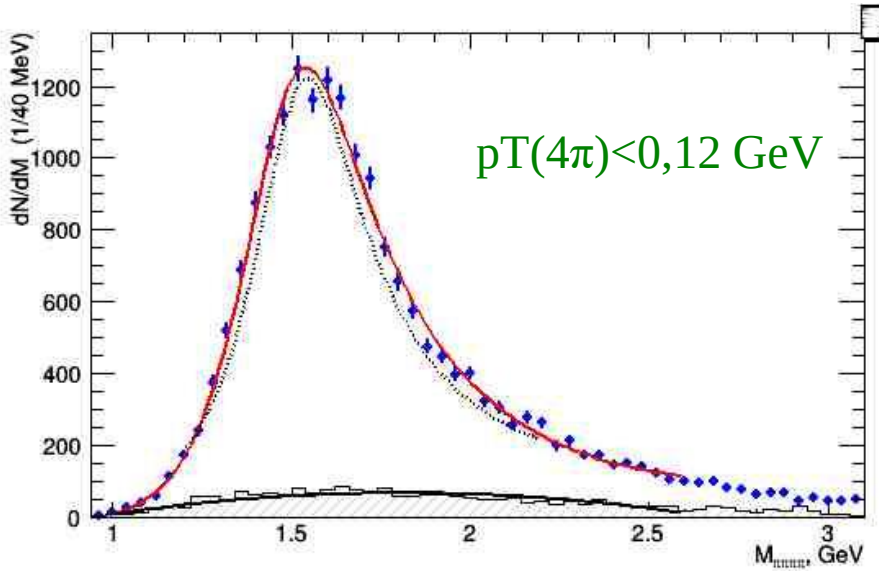
Back up

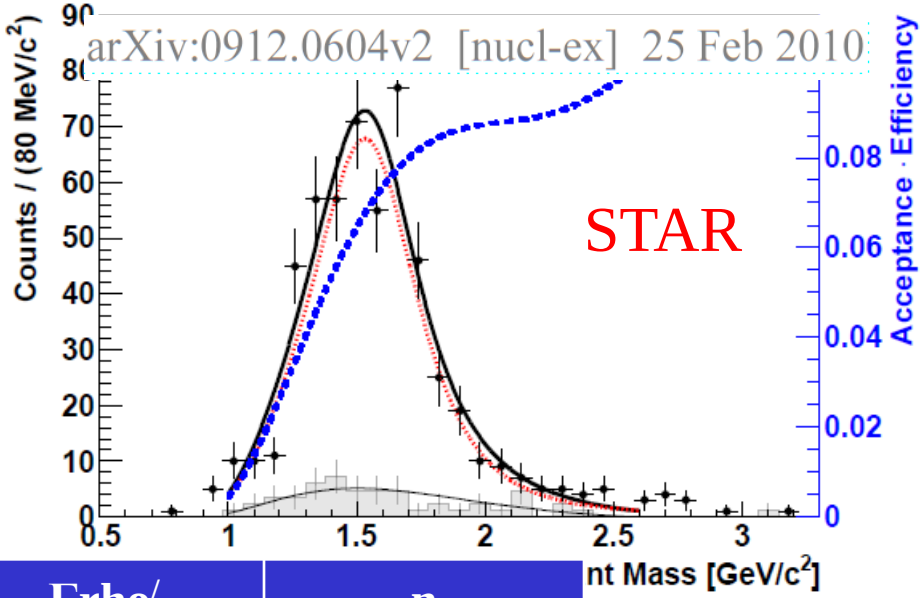
Распределение по инвариантной массе пппп

- Феменологическая параметризация (Ross and Stodolsky):

$$f(m) = f_{rho}\left(\frac{m_0}{m}\right)^n \frac{m_0^2\Gamma_0^2}{\left(m_0^2 - m^2\right)^2 + m_0^2\Gamma_0^2} + f_{bg}(m)$$

$$f_{bg}(m) - polynomial\ of\ a\ second\ order$$





	Mrho/	Γrho/	n
STAR	1540±40	570±60	2,4±0,7
ATLAS	1460±10	477±14	4,3±0,2
PDG	1465±25	400±60	

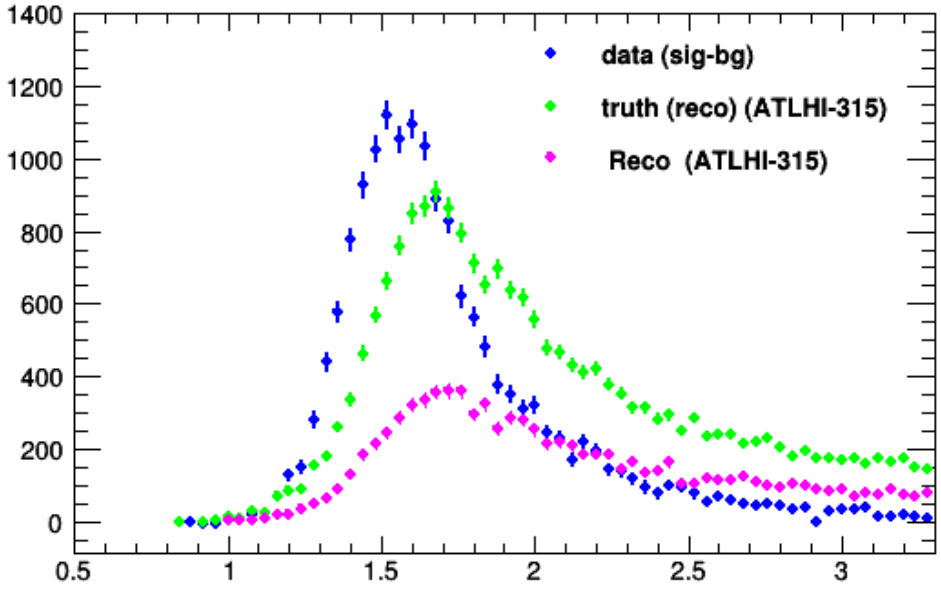
Simulation

- MC generator "Starlight" based on the KN-model:
  - photon-photon photon-pomeron interactions in UPCs

    (Klein S. and Nystrand J., Phys.Rev. C60, 014903 (1999) and Klein S. and Nystrand J., Phys.Rev.Lett. 84, 2330 (2000).
- Starlight v.3.13 – fixed bug
- In order to determine the acceptance corrections for the four-prong case, one assume a simple decay model, where an excited ρ^0 meson decays into $\rho^0(770)$ and $f_0(600)$, each in turn decaying into $\pi^+\pi^-$:

$$\rho' \rightarrow \rho^0(770)\ f_0(600) \rightarrow [\pi^+\pi^-]_{P\text{-wave}}\ [\pi^+\pi^-]_{S\text{-wave}}$$

Data vs Reco(ATLHI-315)



Default the input parameters of RhoPrime in STARlight r313

- Mass = 1540 MeV
- Width = 570 MeV

This parameters were used for STAR experiment.

http://pdg.lbl.gov/2019/listings/rpp2019-list-rho-1450.pdf

ρ(1450) MASS

ρ(1450) MASS

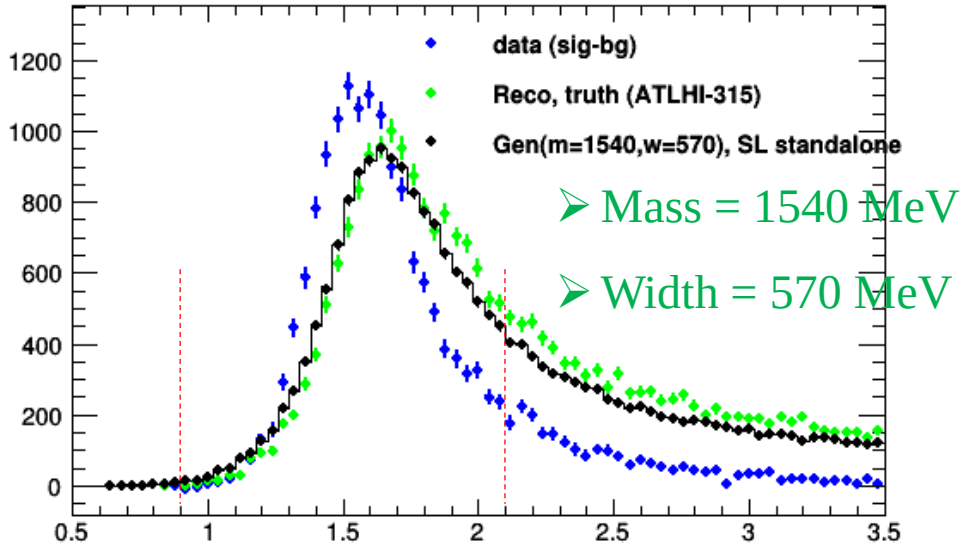
VALUE (MeV)	DOCUMENT ID
1465±25 OUR ESTIMATE This is only an educated guess; the error given is larger than the error on the average of the published values.	

ρ(1450) WIDTH

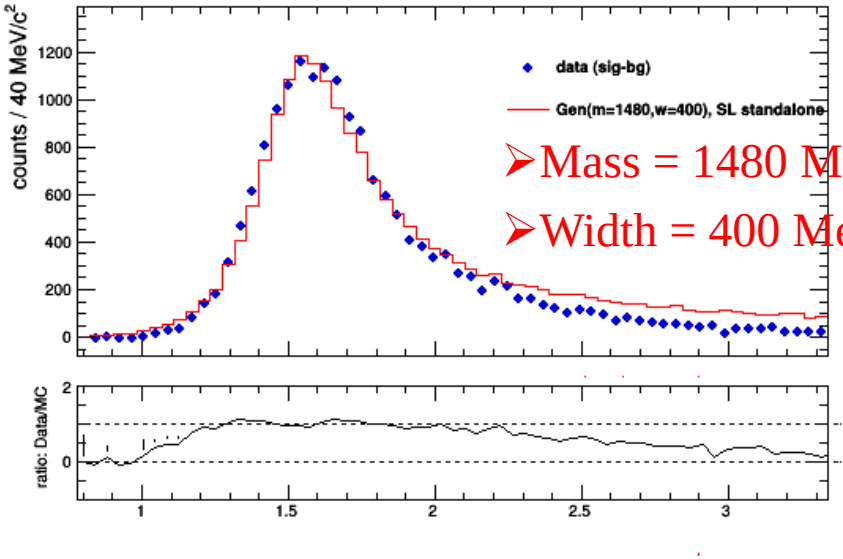
ρ(1450) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
400± 60 OUR ESTIMATE This is only an educated guess; the error given is larger than the error on the average of the published values.			

Data vs Reco(ATLHI-315) vs Gen(standalone)



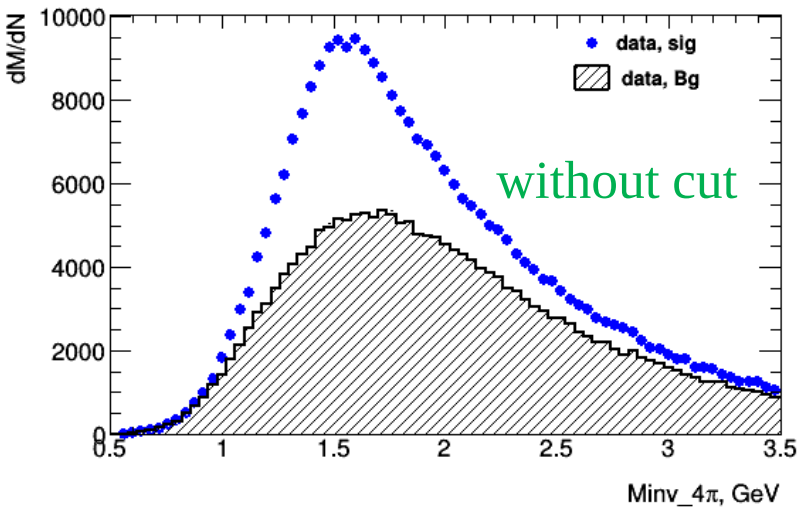
- Mass = 1540 MeV
- Width = 570 MeV

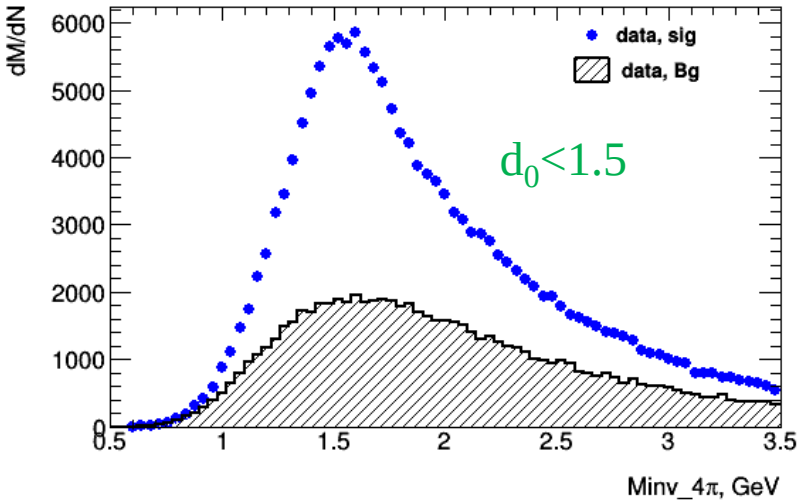


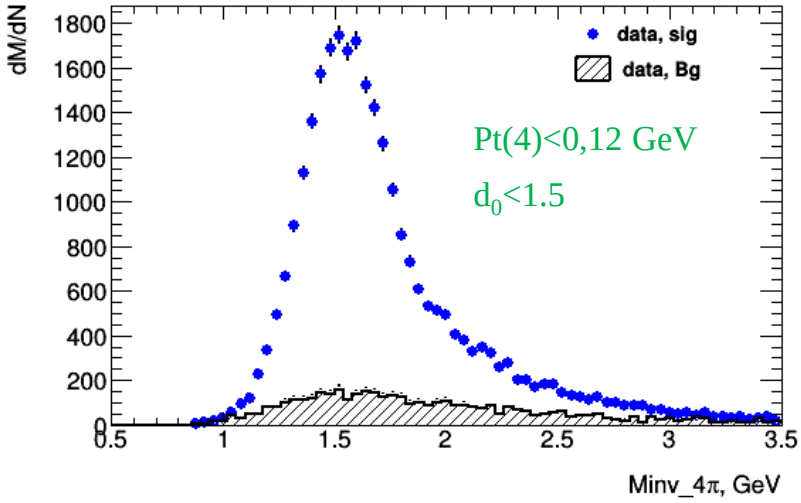
- Mass = 1480 MeV
- Width = 400 Mev

MC distributions and data were normalized in the range from 0.9 to 2.1

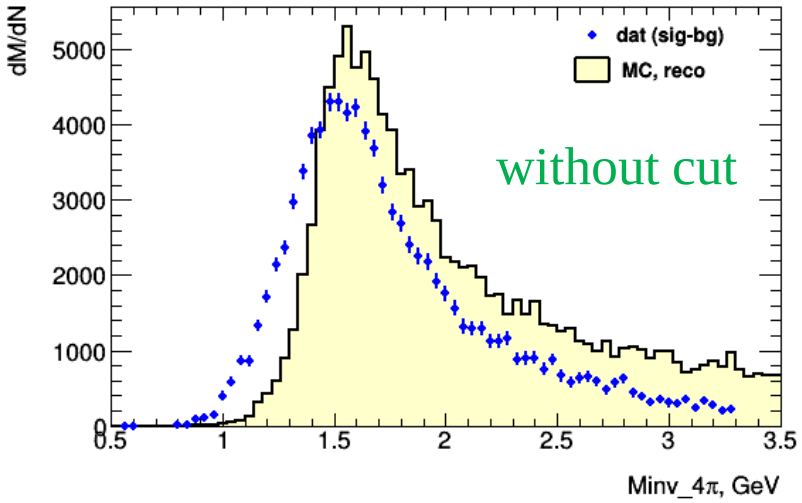
Mass (4π)

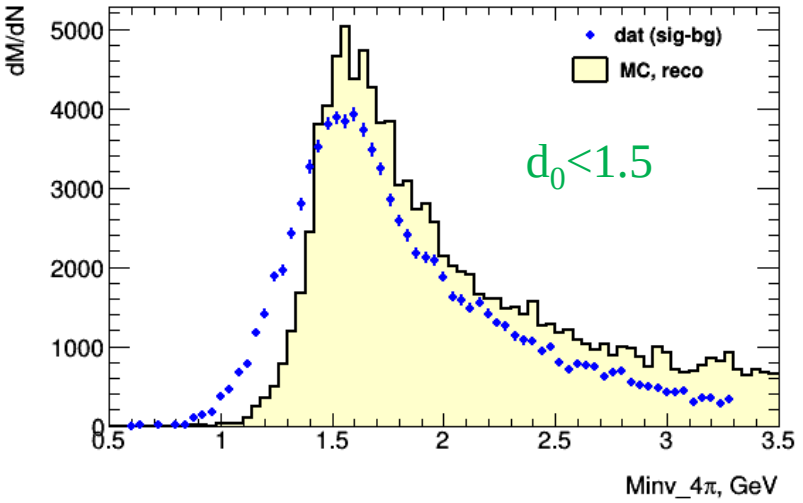

dM/dN
data, sig
data, Bg
without cut
Minv_4π, GeV

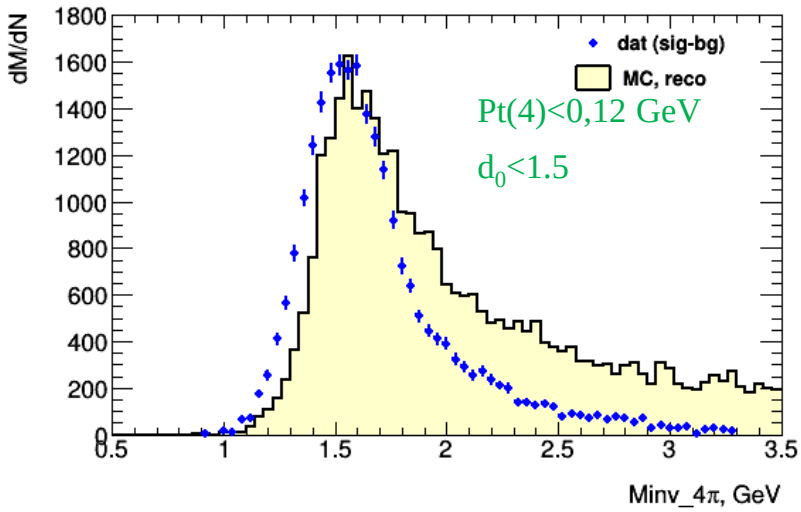

dM/dN
data, sig
data, Bg
d_0<1.5
Minv_4π, GeV

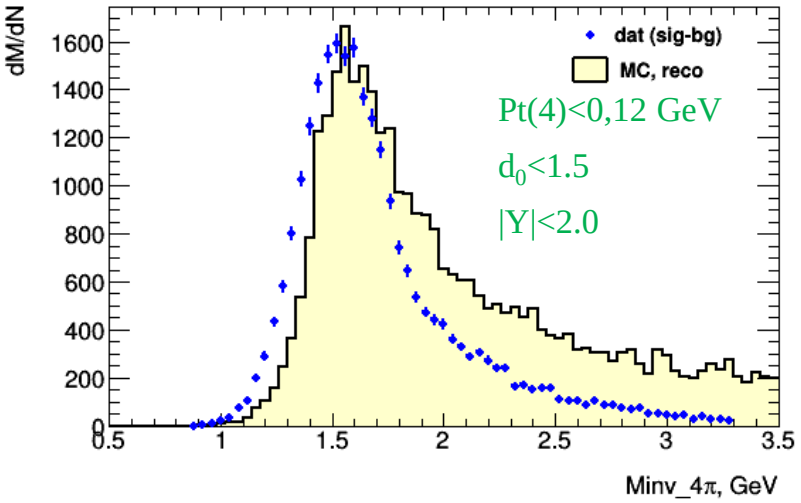

dM/dN
data, sig
data, Bg
Pt(4)<0,12 GeV
d_0<1.5
Minv_4π, GeV

Mass (4π): data vs MC

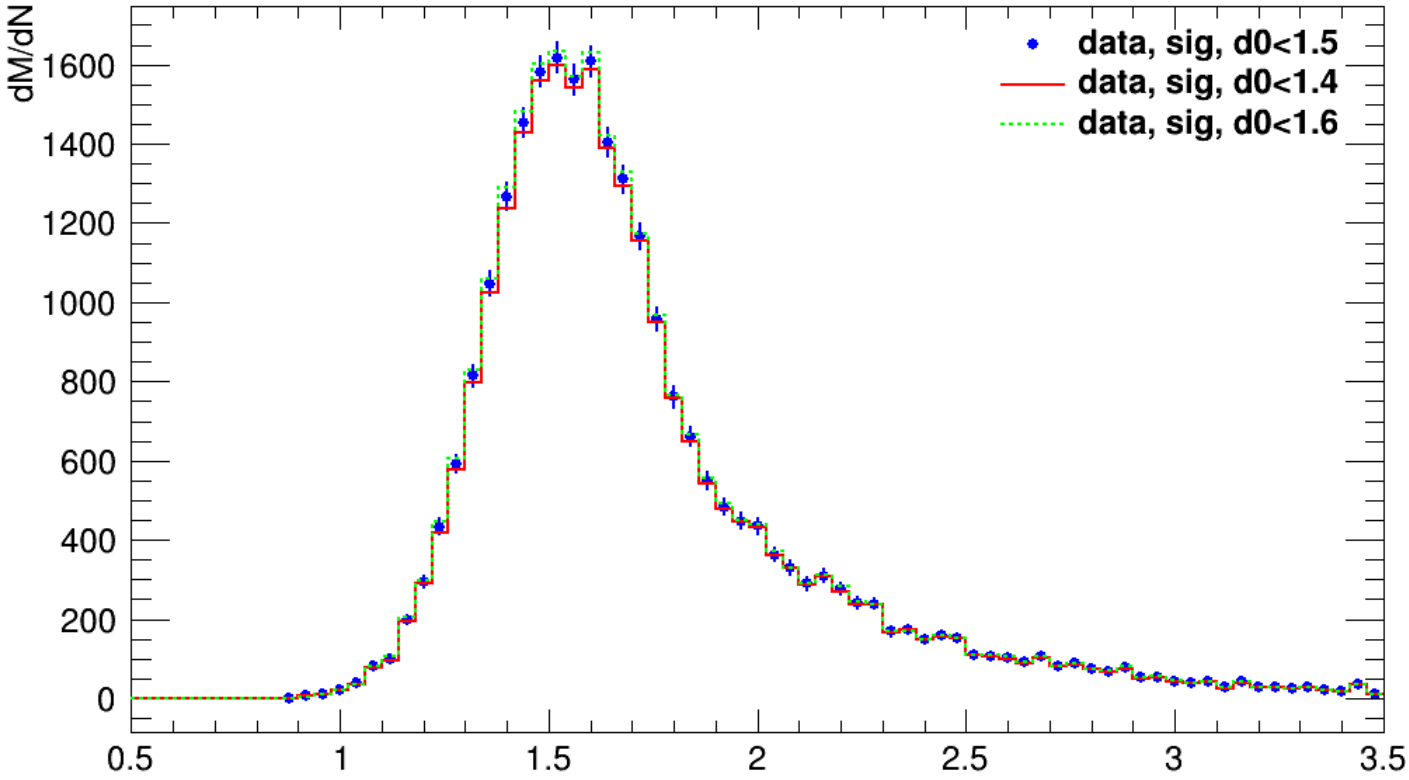




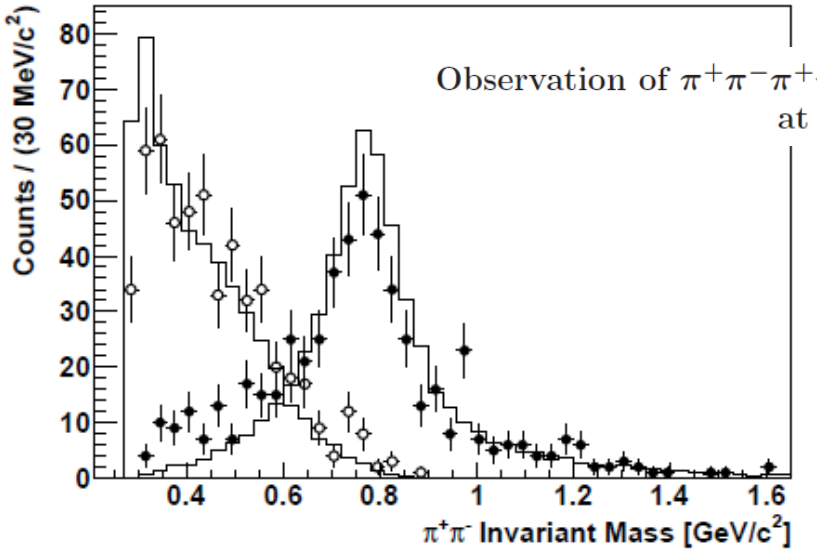




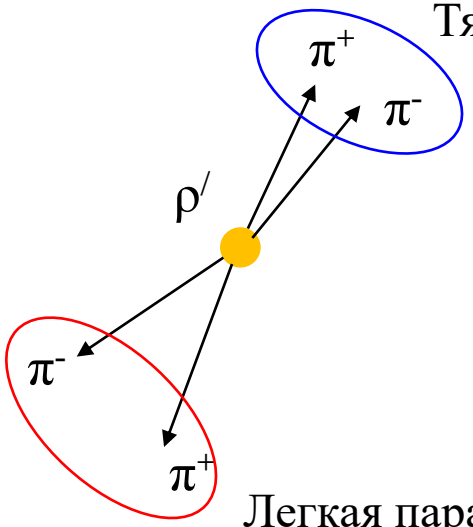
Mass (4π): for d0 cuts



Распределение $\pi^+\pi^-$ из системы 4-х π

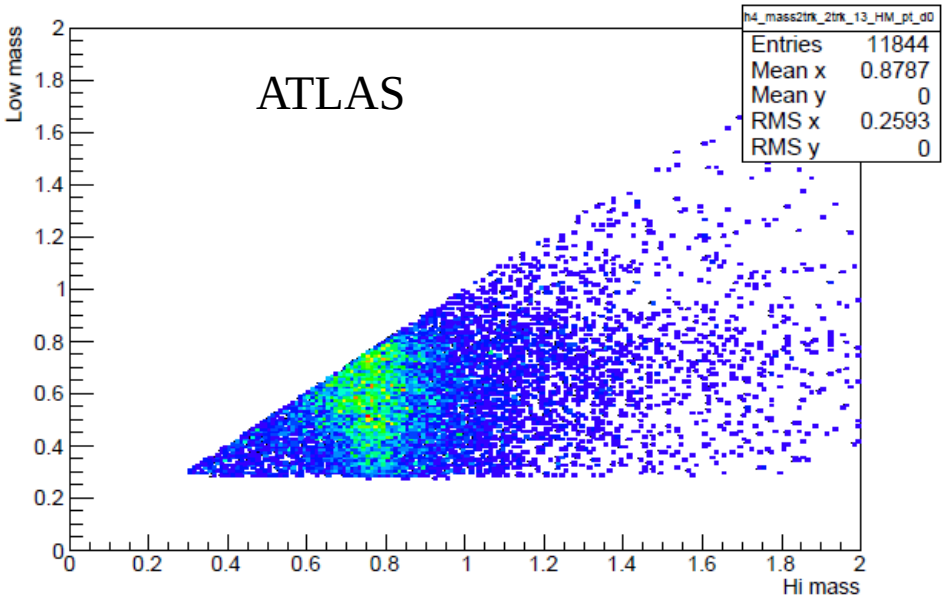


Observation of $\pi^+\pi^-\pi^+\pi^-$ Photoproduction in Ultra-Peripheral Heavy Ion Collisions at $\sqrt{s_{NN}} = 200$ GeV at the STAR Detector

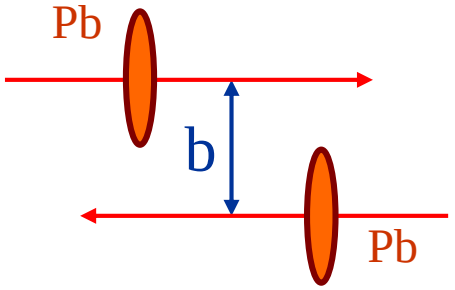


Тяжелая пара

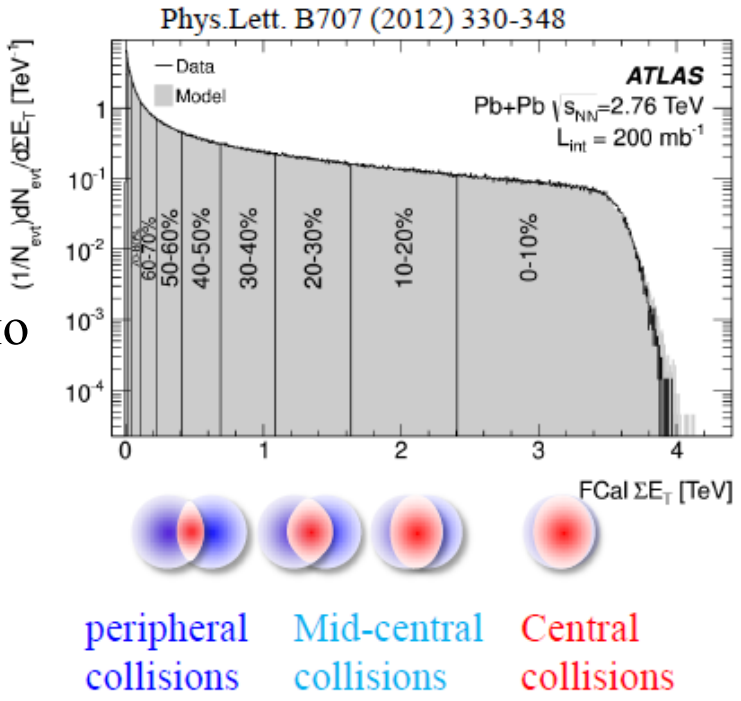
Легкая пара



Ультрапериферические взаимодействия



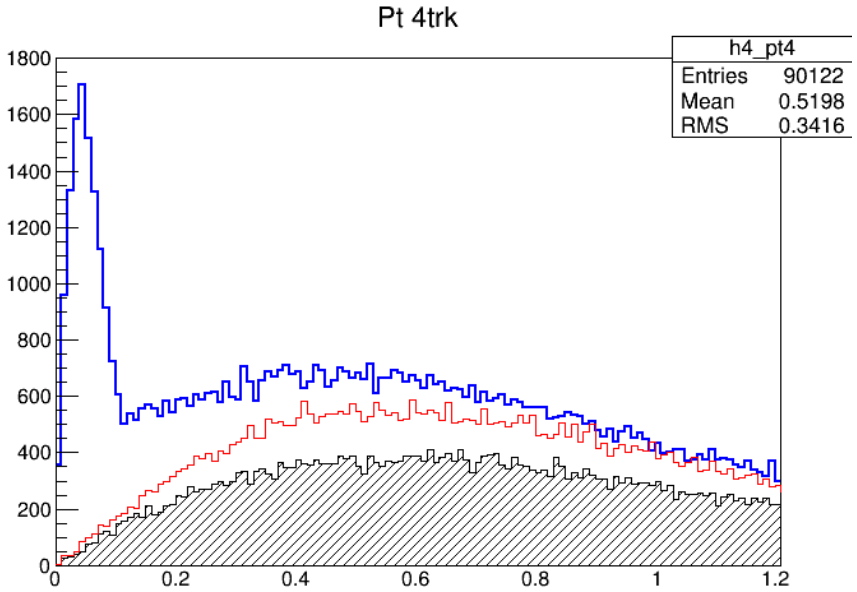
- b << R – центральные столкновения
  - плотности ядер перекрываются
  - сильные взаимодействия
- b > 1 fm – периферические столкновения
- b > $2R_A$ – ультрапериферические столкновения
  - Два ядра геометрически проходят мимо друг друга
    - электромагнитные взаимодействия доминируют над сильными
    - нет адронных взаимодействий
    - малая множественность
- Ионы являются источником полей
  - фотонов
  - померонов

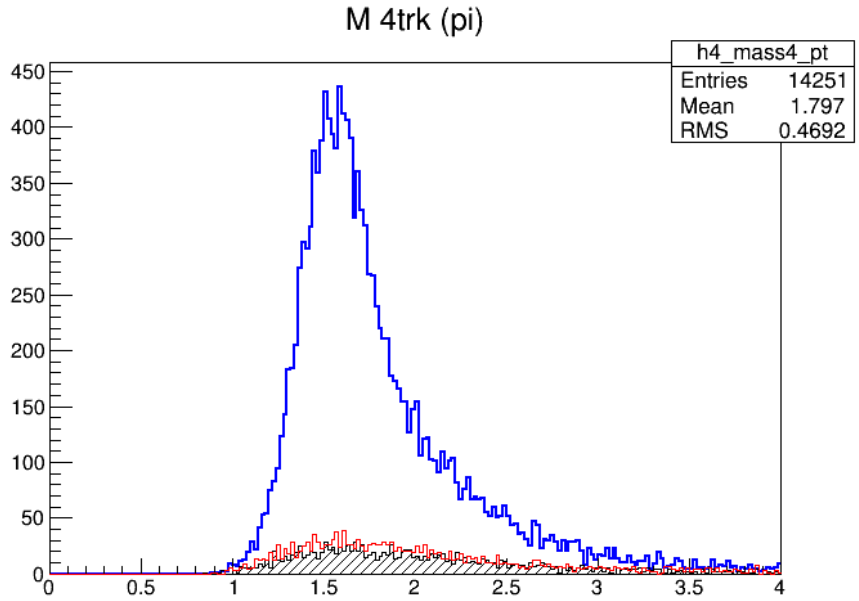


Померон - переносчик сильных взаимодействий, но бесцветный и имеет квантовый числа выкуума $J^P = 0^{++}$

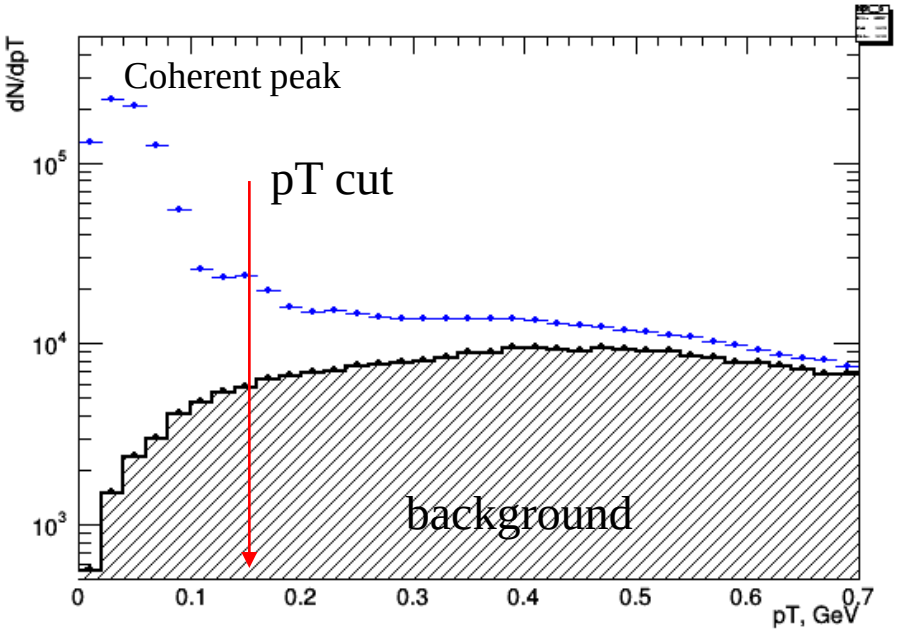
Compare 4 and 5 prong events

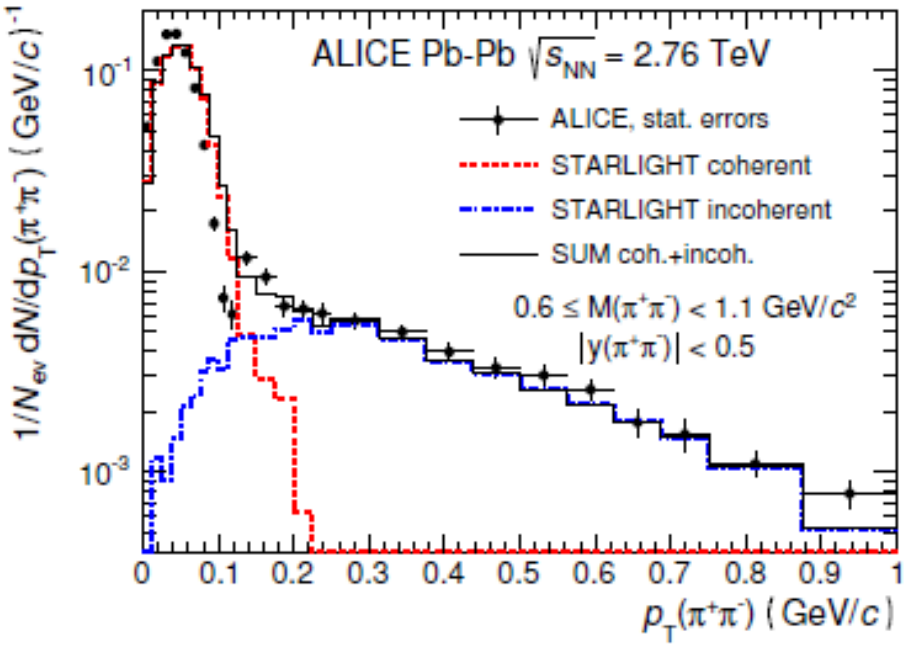
- Blue – 4 tracks, signal
- Hatched – 4 tracks, background
- Red – 4 tracks from 5, one tracks was missed.



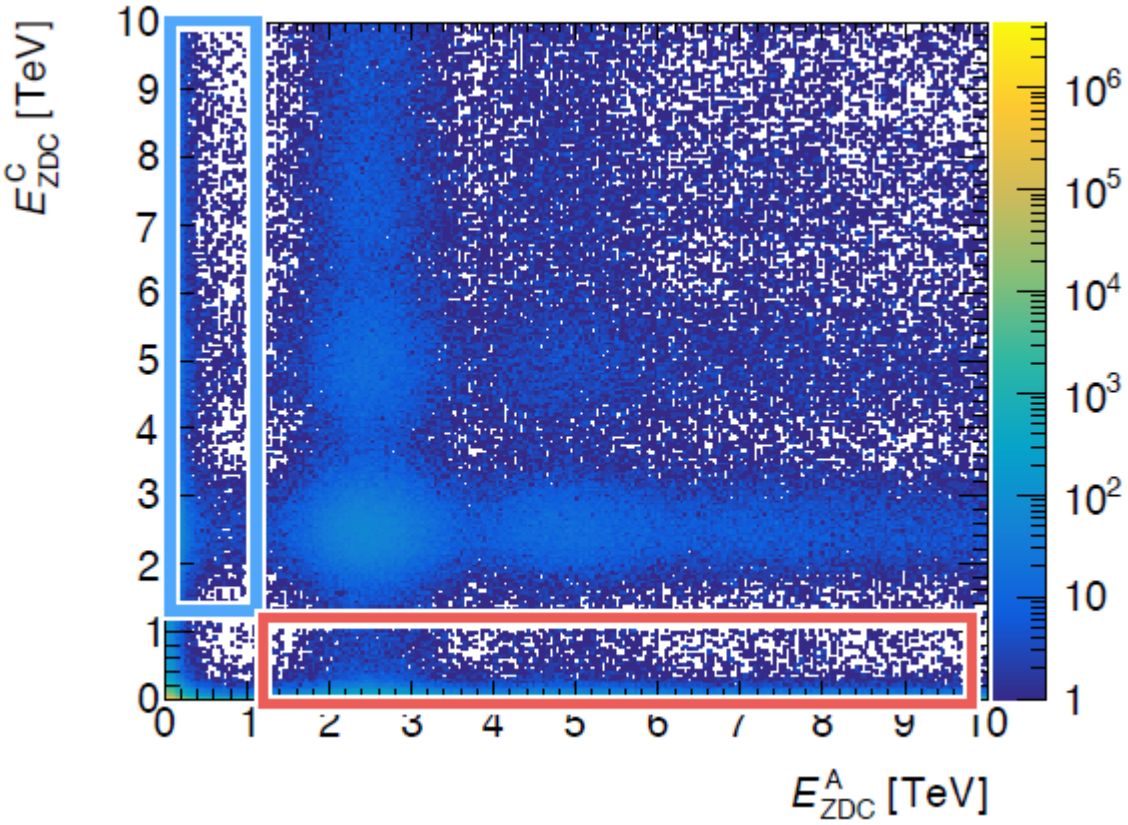


Распределение по поперечному импульсу $\pi^+\pi^-$

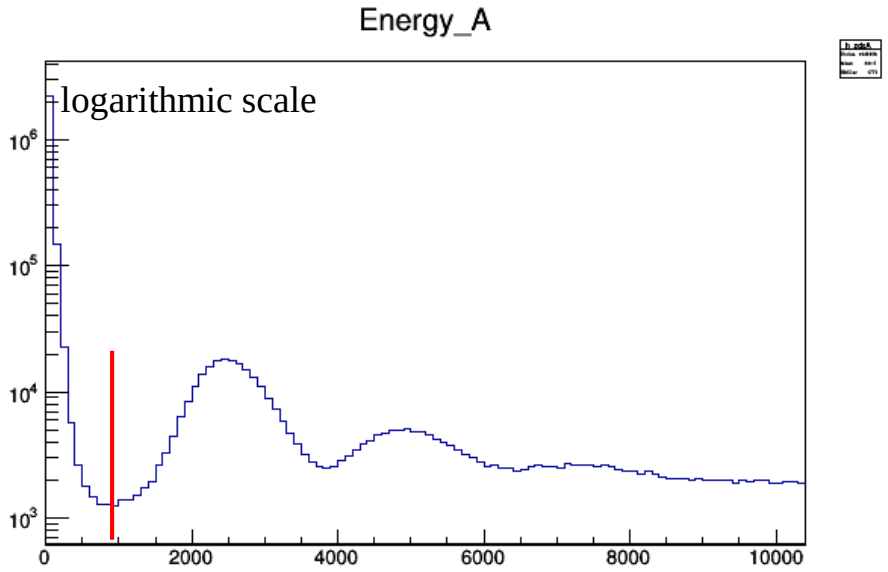


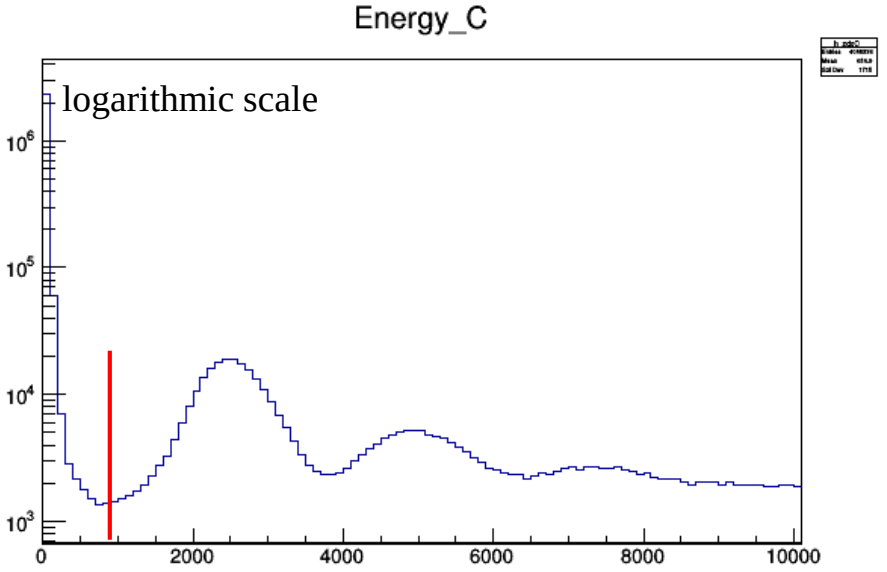


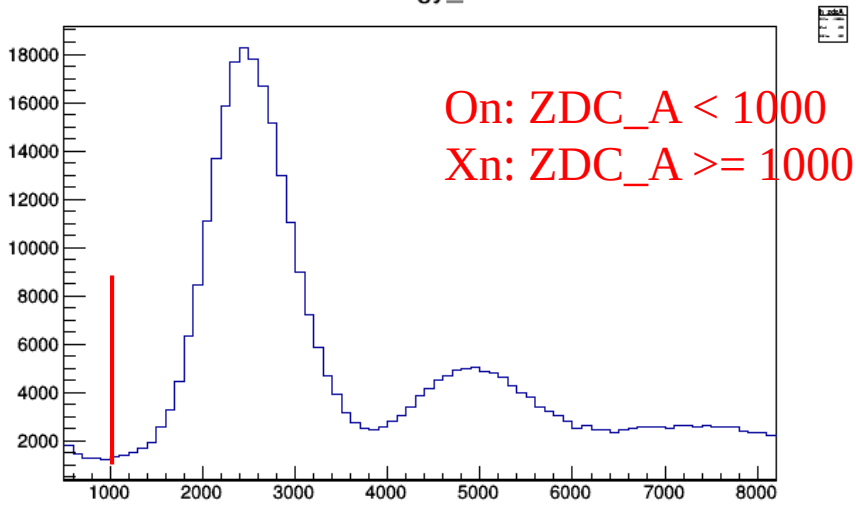
ZDC

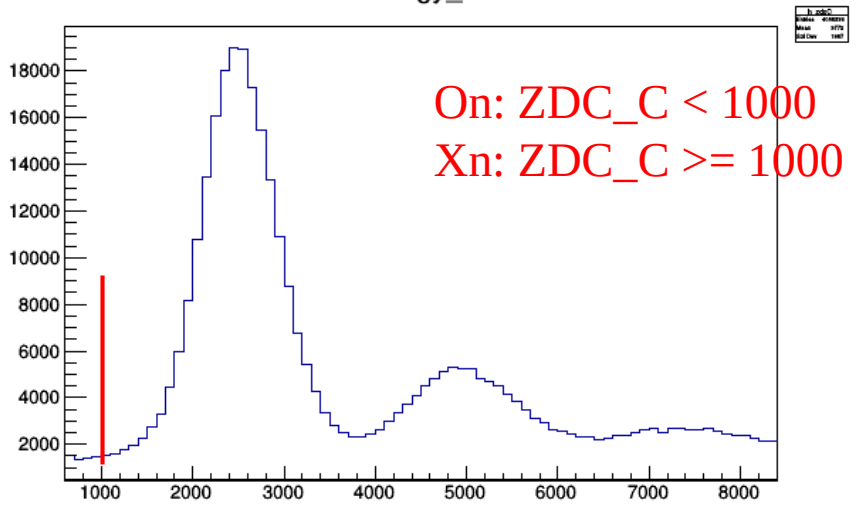


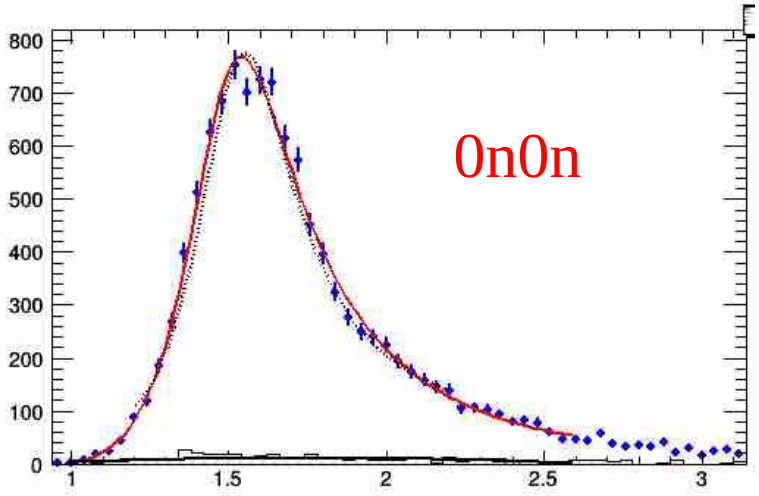
ZDC selection

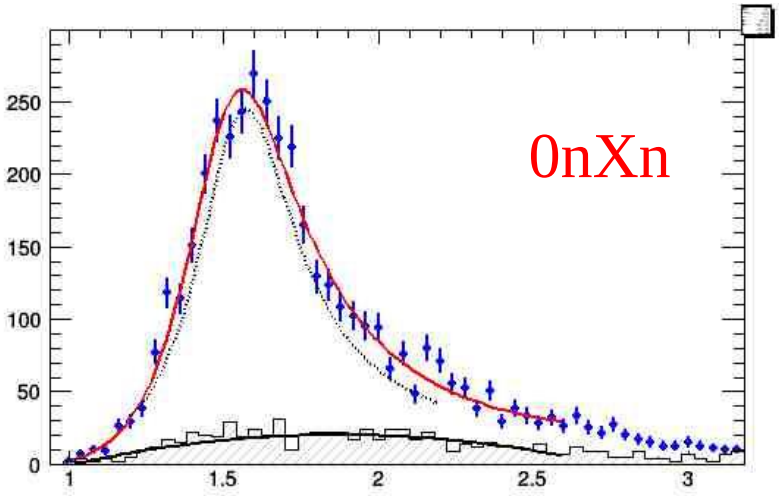


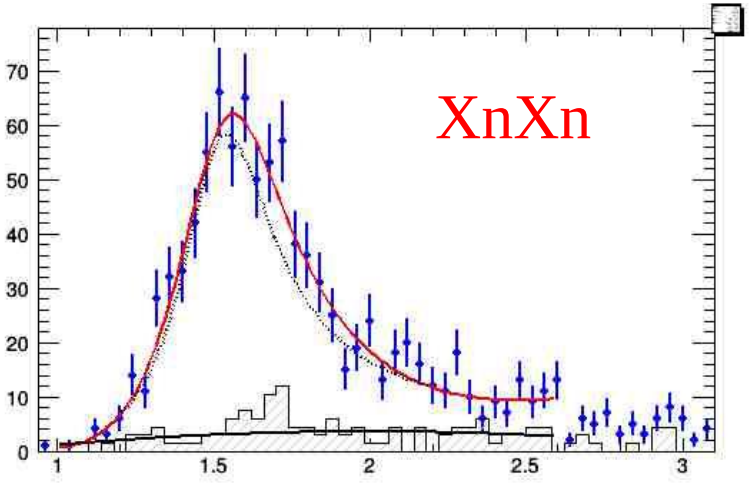










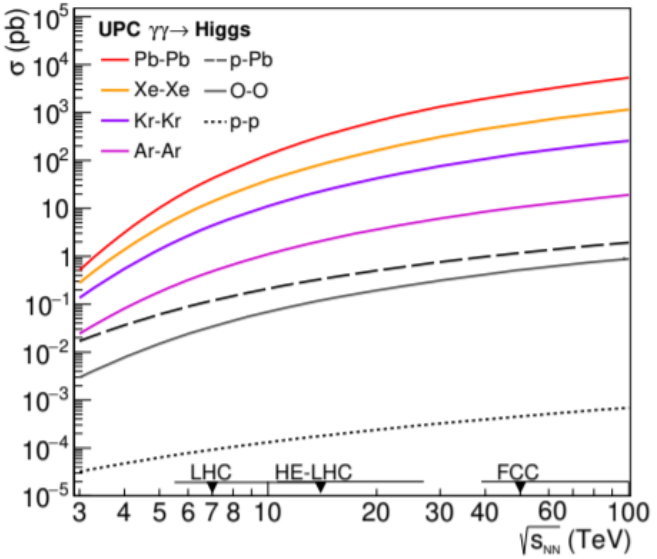


	0n0n	XnXn	0nXn
Nrho′	16400±300	1380±90	5730±180
Mrho′	1466±7	1490±30	1486±16
Γrho′	445±2	471±7	471±3
n	4,6±0,2	3,8±0,9	4,1±0,41

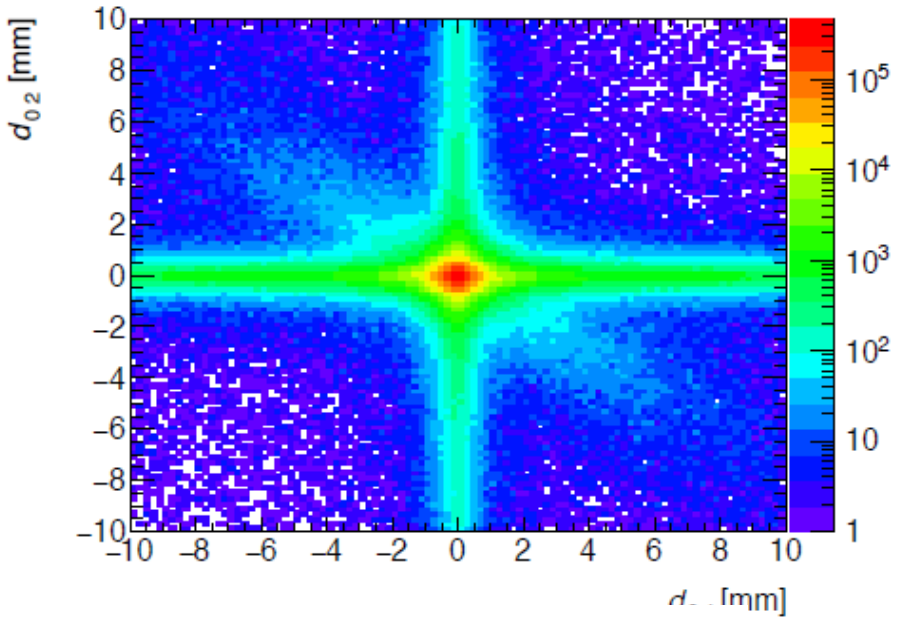
Образование векторных мезонов в UPC

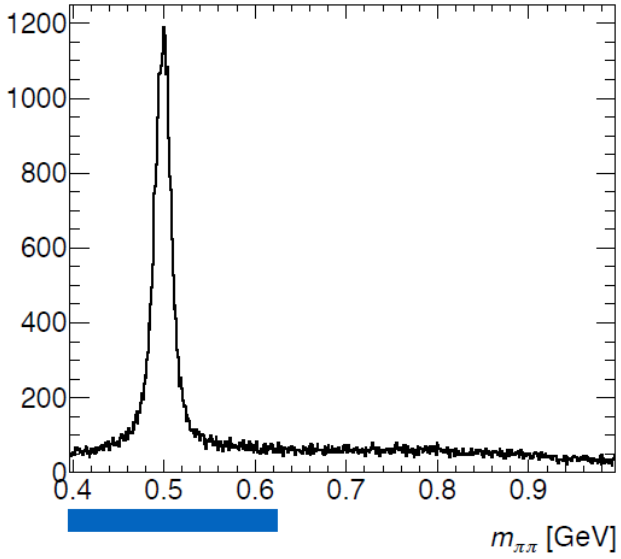
Meson	Au+Au, RHIC σ(mb)	Pb+Pb, LHC σ(mb)	Meson	Pb+Pb, LHC σ(mb)
			$\rho^0\rho^0$	8,8
ρ^0	590	5200	$\omega\omega$	0,073
ω	59	490	$\phi\phi$	0,076
ϕ	39	460	$\rho^0\omega$	1,6
J/ψ	0.29	32	$\rho^0\,\phi$	1,6
Y		150 μb	ρ^0J/ψ	0,2

Klein S. and Nystrand J.,
Phys. Rev. C 60 (1999) 014903

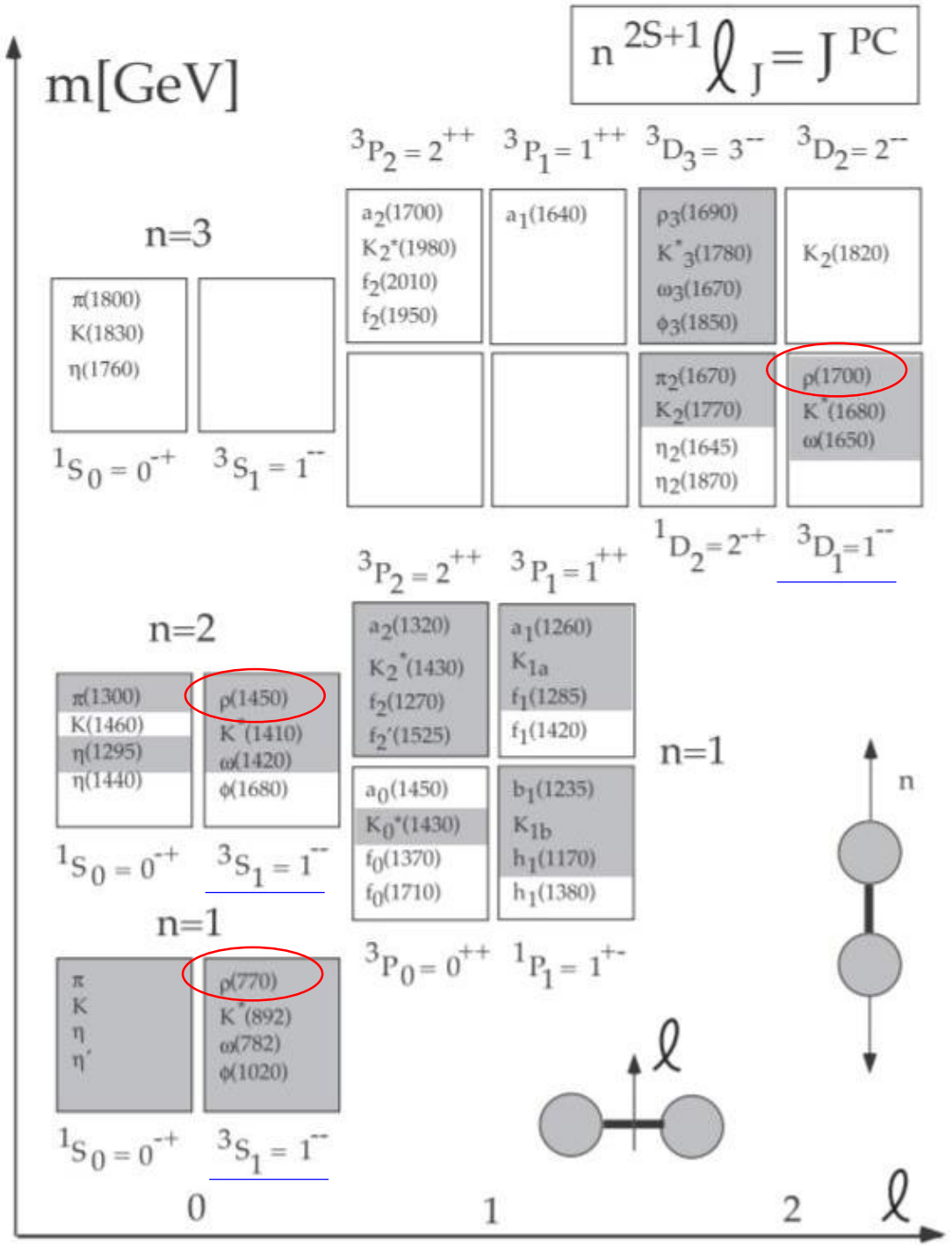


K_s in $\pi^+\pi^-$





$d_{01} \cdot d_{02} < 2.25\ mm^2$


m[GeV]
n 2S+1 ℓ J = J PC
3P2 = 2++
3P1 = 1++
3D3 = 3--
3D2 = 2--
n=3
π(1800)
K(1830)
η(1760)
a2(1700)
K2*(1980)
f2(2010)
f2(1950)
a1(1640)
ρ3(1690)
K*3(1780)
ω3(1670)
ϕ3(1850)
K2(1820)
π2(1670)
K2(1770)
η2(1645)
η2(1870)
ρ(1700)
K*(1680)
ω(1650)
1S0 = 0-+
3S1 = 1--
1D2 = 2-+
3D1 = 1--
n=2
π(1300)
K(1460)
η(1295)
η(1440)
ρ(1450)
K*(1410)
ω(1420)
ϕ(1680)
a2(1320)
K2*(1430)
f2(1270)
f2'(1525)
a1(1260)
K1a
f1(1285)
f1(1420)
a0(1450)
K0*(1430)
f0(1370)
f0(1710)
b1(1235)
K1b
h1(1170)
h1(1380)
n=1
3P0 = 0++
1P1 = 1+-
n=1
π
K
η
η'
ρ(770)
K*(892)
ω(782)
ϕ(1020)
n
ℓ
0
1
2
ℓ

$\pi^+\pi^-\pi^+\pi^-$ photoproduction

- The PDG currently lists two excited ρ^0 states
  - $\rho^0(1450)$ [$^3S_1$] – radially excited 2S state
  - $\rho^0(1700)$ [$^1D_1$] – orbitally excited 3D state

which are seen in various production modes and decay channels including two- and four-pion final states.

- The nature of these states is still an open question, because their decay patterns do not match quark model predictions.
- Little data exist on high-energy photoproduction of excited ρ^0 states in the four-pion decay channel.
  - Most of them are from photon-proton or photon-d(or C) fixed target experiments at photon energies in the range from 3.0 to 70 GeV.
  - Latest data is the photoproduction of $\pi^+\pi^-\pi^+\pi^-$ in UPC Au+Au at 200 GeV at the STAR

$\pi^+\pi^-\pi^+\pi^-$ photoproduction

- These experiments observe a broad structure in the four-pion invariant mass distribution at masses ranging from 1430± 50 MeV/c^2 to 1570 ± 60 MeV/c^2 and with widths between 340 ± 60 MeV/c^2 and 850 ± 200 MeV/c^2 that the PDG assigns to the $\rho^0(1700)$-(1450).

Mass (MeV)	Year	Reaction	Reference
1430±50	1972	9.3 $\gamma p \rightarrow p4\pi$	Bingham, Phys.Lett. 41B 635
1450±100	1974	9-18 $\gamma p \rightarrow p4\pi$	Schacht, Nucl.Phys. B81 205
1550±50	1974	5.5-19 $\gamma p \rightarrow p4\pi$	Schacht, Nucl.Phys. B81 205
1550±60	1974	$e^+e^- \rightarrow 2(\pi^+\pi^-)$	Conversi, Phys. Lett. 52B 493
1570±60	1975	7.5 $\gamma d \rightarrow d4\pi$	Alexander, Phys. Lett. 57B 487
1500	1979	50 $\gamma C \rightarrow p4\pi$	Atiya, Phys. Rev. Lett. 43 1691
1780	1980	11 $e^-p \rightarrow e^-p4\pi$	Killian, Phys. Rev. D21 3005
1666±39	1980	$e^+e^- \rightarrow 2(\pi^+\pi^-)$	Bacci, Phys. Lett. 95B 139
1654±25	1981	$\pi^+d \rightarrow pp4\pi$	DiBianca, Phys.Rev. D23 595
1520±30	1981	20-70 $\gamma p \rightarrow p4\pi$	Aston, Nucl. Phys. B189 15
1570±20	1982	$e^+e^- \rightarrow 2(\pi^+\pi^-)$	Cordier, Phys. Lett. 109B 129
1465±25; 1700±20	2001	(anti)$pd \rightarrow p\pi 4\pi$	Crystal BARREL Collaboration
1540±40	2007	$AuAu \rightarrow Au^*Au^*4\pi$	Abelev (STAR coll.), Phys.Rev.C81 044901

Reaction (Eγ, GeV)			exp(-bt)
γp→p4π (9,3)	σ(ρ′→ρ⁰π⁻π⁺) =1,6 μb	R=(ρ′→π⁻π⁺)/(ρ′→ρ⁰π⁻π⁺)=0,2	b=5,6 GeV^{-2}
γp→p4π (4,4) (7,1) (12,7)	σ(γp→pρ′)= 1,3 μb = 1,0 μb = 1,6 μb		b=6,6 GeV^{-2} b=7,3 GeV^{-2} b=4,9 GeV^{-2}
γd→d4π (7,5)	σ(γd→dρ′)= 0,84 μb (t<0,2)	$(f^2_{\rho'})/(f^2_{\rho})$=6,0	b=7,5 GeV^{-2}
γC→p4π (50)	σ(γC→ρ′→2π)= 67 nb/N σ(γC→ρ′→4π)= 1 μb/N		b=64,6 GeV^{-2}
γp→p4π (20-70)		R=σ(ρ′→π⁻π⁺)/σ(ρ⁰)=0,01 R=(ρ′→π⁻π⁺)/(ρ′→π⁻π⁺π⁻π⁺)=0,13	
AuAu→Au*Au*4π		R=(ρ′→π⁻π⁺)/(ρ′→π⁻π⁺π⁻π⁺)=0,012 $\frac{\sigma^{coh}_{4\pi,XnXn}}{\sigma^{coh}_{\rho,XnXn}} = \frac{\sigma^{coh}_{\rho',XnXn}\cdot B(\rho'\to\pi^+\pi^-\pi^+\pi^-)}{\sigma^{coh}_{\rho,XnXn}} = 16\%$ $\sigma^{coh}_{\rho',0n0n} = 53\text{mb}$	

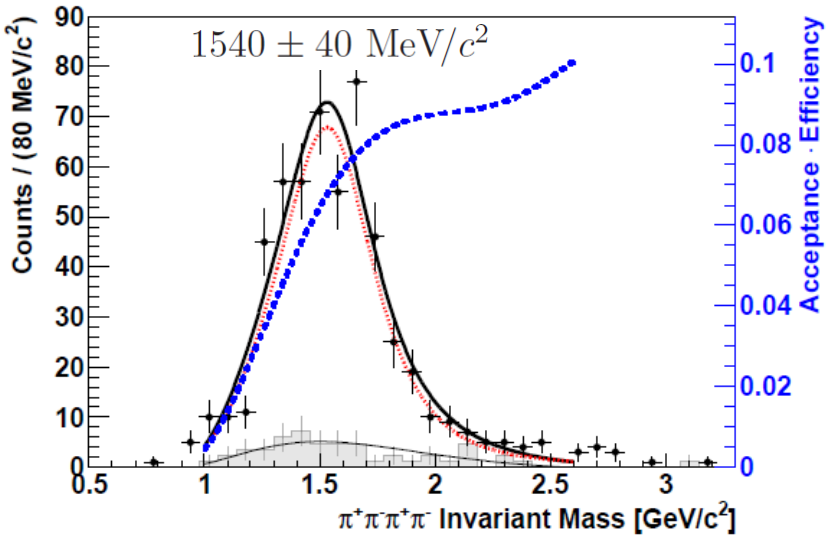
STAR results

Observation of $\pi^+\pi^-\pi^+\pi^-$ Photoproduction in Ultra-Peripheral Heavy Ion Collisions at $\sqrt{s_{NN}} = 200$ GeV at the STAR Detector

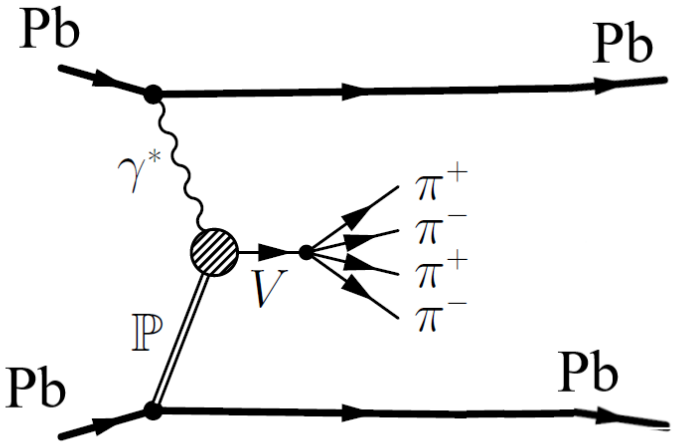
arXiv:0912.0604v2 [nucl-ex] 25 Feb 2010

$$\rho' \to \rho^0(770)\ f_0(600) \to [\pi^+\pi^-]_{P\text{-wave}}\ [\pi^+\pi^-]_{S\text{-wave}}$$

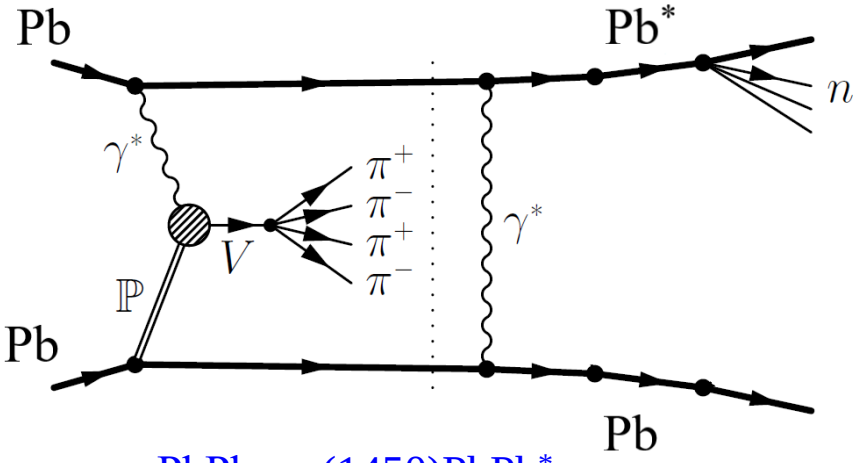
confidence level. The coherent ρ' production cross section is $13.4 \pm 0.8_{\text{stat.}} \pm 4.4_{\text{syst.}}\%$ of that of the $\rho^0(770)$ meson.



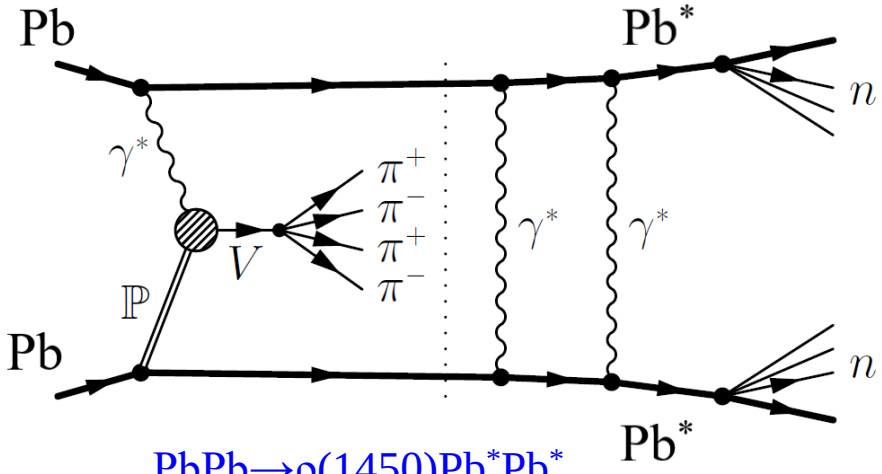
$\pi^+\pi^-\pi^+\pi^-$ photoproduction



PbPb→ρ(1450)PbPb



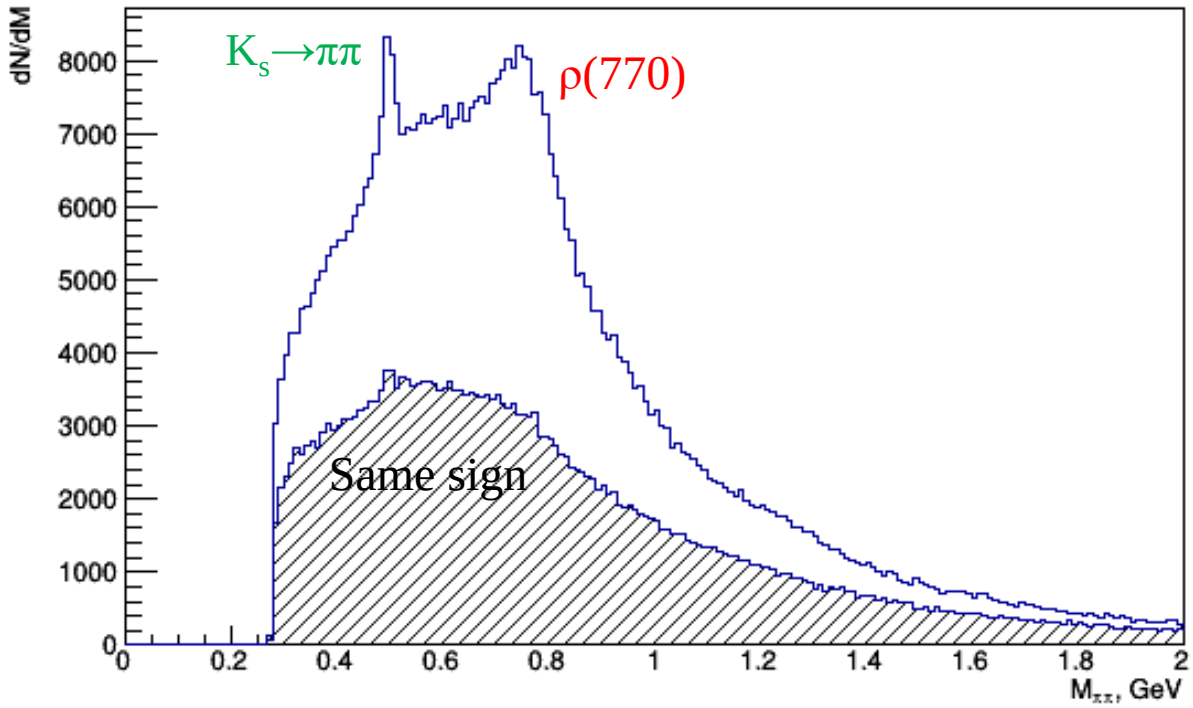
PbPb→ρ(1450)PbPb*



PbPb→ρ(1450)Pb*Pb*

Распределение $\pi^+\pi^-$ из системы 4-х π

- Распределение по инвариантной массе $\pi^+\pi^-$ в 4-х трековом событие



$\rho^0\phi \to \rho K_L K_S \to \pi^+\pi^+\pi^-\pi^-$???