Tsallis-thermometer: a QGP indicator for large and small collisional systems

20th Zimányi School Winter Workshop on Heavy Ion Physics

Gábor Bíró

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Wigner Research Centre for **Physics**
Eötvös Loránd **University**

Collaborators:

Gergely Gábor Barnaföldi
Tamás Sándor Biró

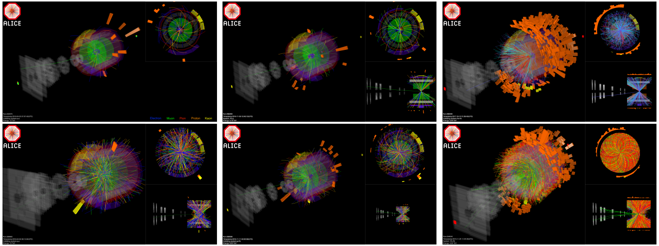
Talk based on:
G. Bíró, **G.G. Barnaföldi**, **T.S. Biró**, **J. Phys. G**, 47.10 (2020), 105002.

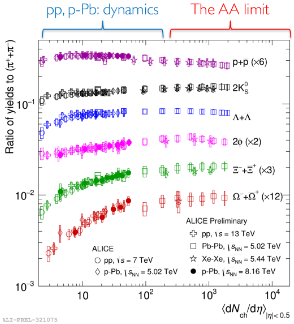
Related publications:
G. Bíró, **G.G. Barnaföldi**, **K. Ürmössy**, **T.S. Biró**, **Á. Takács**, **Entropy**, 19(3), (2017), 88
G. Bíró, **G.G. Barnaföldi**, **T.S. Biró**, **K. Shen**, **EPJ Web Conf.**, 171, (2018), 14008

Motivation

Ratio of identified hadrons in small to large systems...

...but what is small?





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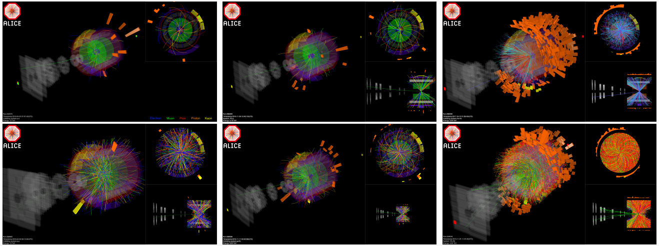
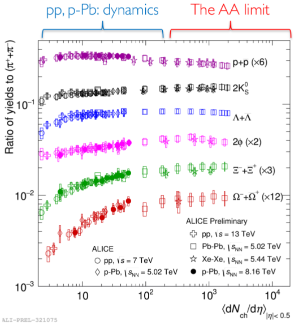
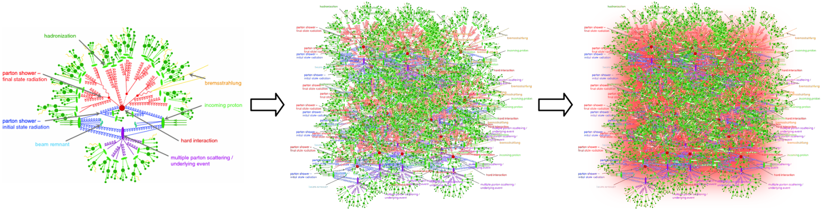


Small systems can have **large** multiplicities too…





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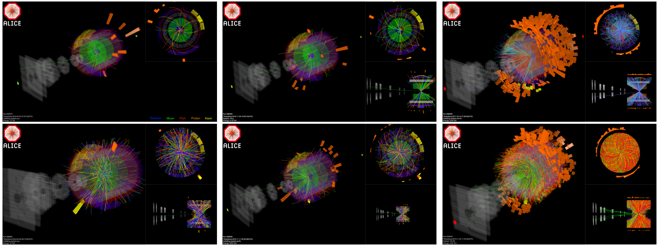
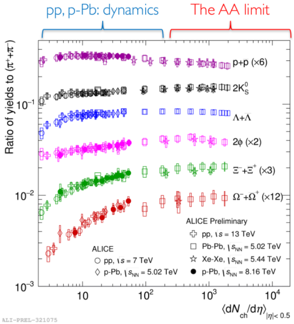
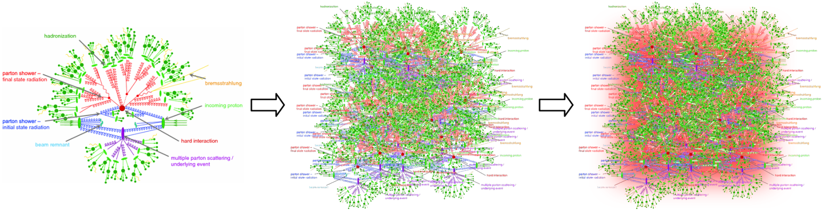
Where does the quark-gluon plasma start in **multiplicity**?







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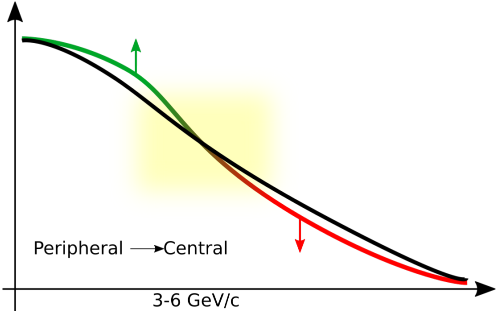

$$\frac{d^2N}{2\pi p_T dp_T dy} = A m_T \left[1 + \frac{q-1}{T}(m_T - m)\right]^{-\frac{q}{q-1}}$$

Entropy 16(12), (2014), 6497-651, **Eur.Phys.J.A** 55 (2019) 8, 126

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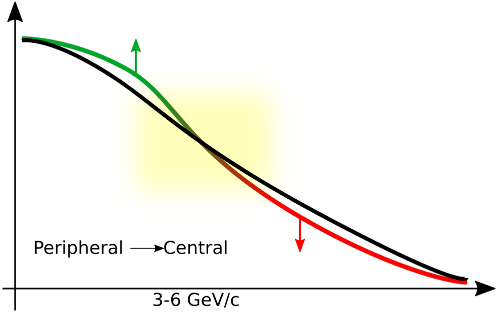
$$\lim_{q \to 1} S_q = S_{BG}$$



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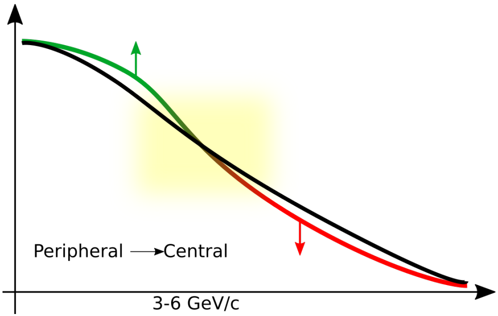
$$P = Ts + \mu n - \varepsilon$$

$$P = g\int \frac{\mathrm{d}^3p}{(2\pi)^3}\, Tf \qquad s = g\int \frac{\mathrm{d}^3p}{(2\pi)^3}\left[\frac{E-\mu}{T} f^q + f\right]$$

$$N = nV = gV\int \frac{\mathrm{d}^3p}{(2\pi)^3} f^q \qquad \varepsilon = g\int \frac{\mathrm{d}^3p}{(2\pi)^3} E f^q$$



$$\frac{\mathrm{d}^2N}{2\pi p_T \mathrm{d}p_T \mathrm{d}y} = A m_T \left[1 + \frac{q-1}{T}(m_T - m)\right]^{-\frac{q}{q-1}}$$

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Final size effects:

$$T = \frac{E}{\langle n\rangle} \qquad q = 1 - \frac{1}{\langle n\rangle} + \frac{\Delta n^2}{\langle n\rangle^2}$$

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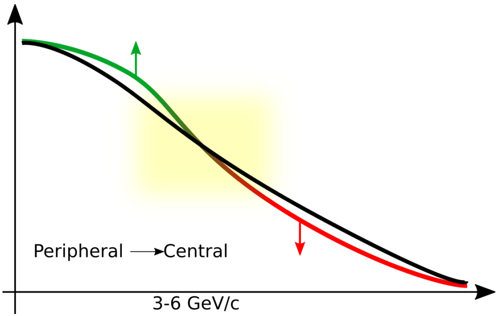

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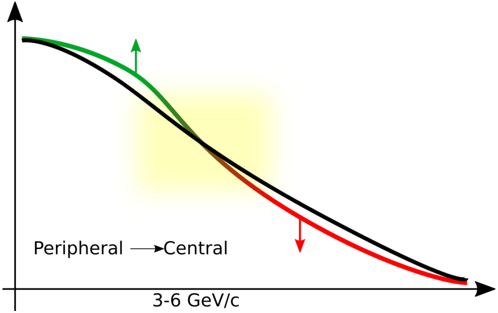

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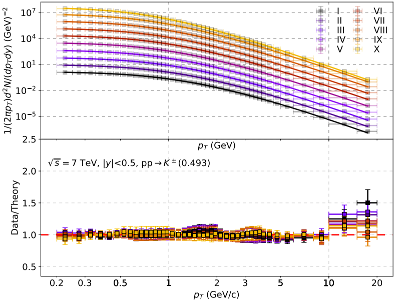

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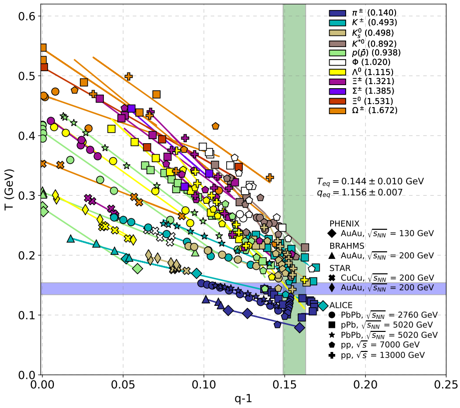
The q and T parameters can track down the size evolution!

Phenomenological approach:

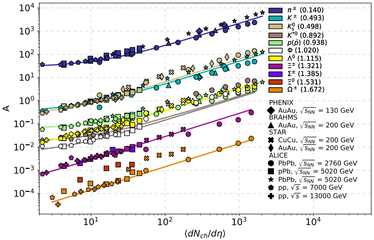
Map the thermodynamically consistent non-extensive parameter space of the available experimental data and compare it with theoretical QCD calculations

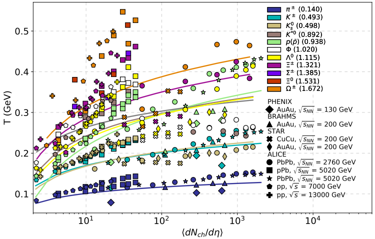
- 11 identified hadron species: from $\pi^{\pm}$ to Ω
- Various collision systems: proton-proton, proton-nucleus, nucleus-nucleus
- Wide range of multiplicities: $2.2 \leq \langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle \leq 2047$
- Wide range of CM energies: $130 \leq \sqrt{s_{NN}} \leq 13000$ GeV
- **More than 30** published experimental datasets

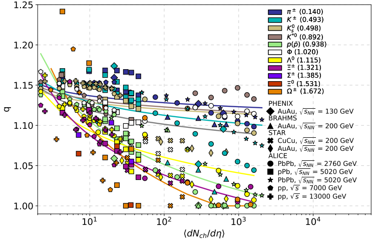


EPJ Web Conf. 171, (2018), 14008

Goal: calibrate the Tsallis-thermometer







Parametrizations:

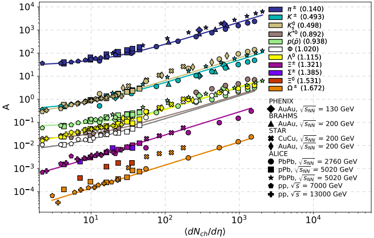
$$A = A_0 + A_1 \ln \frac{\sqrt{s_{NN}}}{m} + A_2 \left\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \right\rangle$$

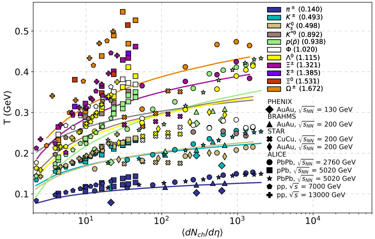
$$T = T_0 + T_1 \ln \frac{\sqrt{s_{NN}}}{m} + T_2 \ln \ln \left\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \right\rangle$$

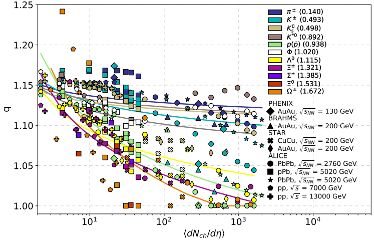
$$q = q_0 + q_1 \ln \frac{\sqrt{s_{NN}}}{m} + q_2 \ln \ln \left\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \right\rangle$$

1. The **A**, **q** and **T** parameters characterize the collision
2. Strong **grouping:** $T_{eq} \approx 0.144$ GeV, $q_{eq} \approx 1.156$

Results







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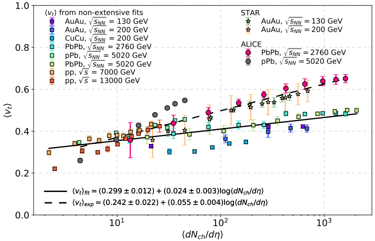
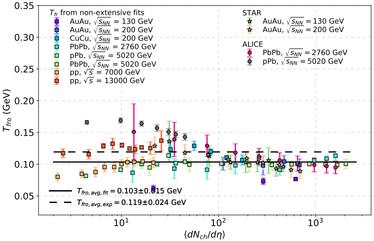
Radial flow:

$$T = T_{fro} + m \left\langle u_t \right\rangle^2$$

$$\left\langle v_t \right\rangle = \frac{\left\langle u_t \right\rangle}{\sqrt{1 + \left\langle u_t \right\rangle^2}}$$



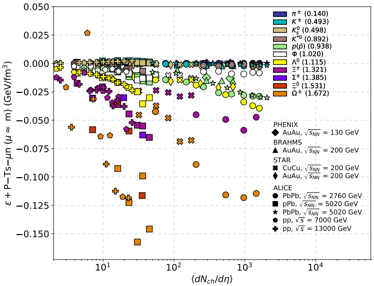


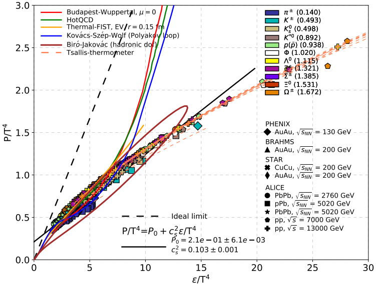
1. The **A**, **q** and **T** parameters characterize the collision
2. Strong **grouping:** $T_{eq} \approx 0.144$ GeV, $q_{eq} \approx 1.156$
3. **Test:** results are comparable with experiments (**Phys. Rev. C 83 (2011), 064903**)

Thermodynamical consistency: ✓

$$P = Ts + \mu n - \varepsilon$$

Comparison of the thermodynamical variables with theoretical calculations





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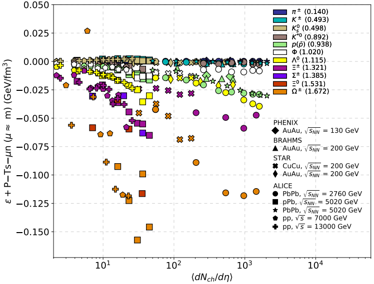

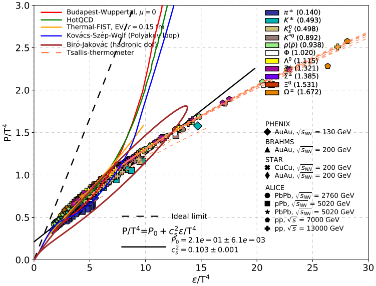

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1. Overlapping region with theoretical QCD calculations $\rightarrow$ **presence of hot QCD matter** just before the hadronization?

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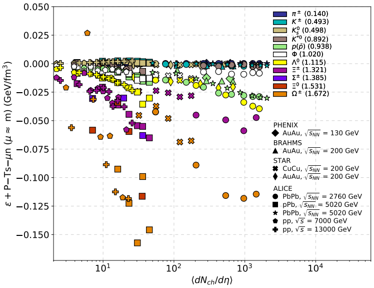

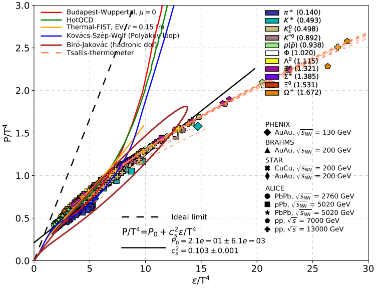

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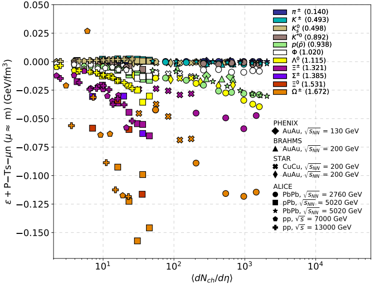

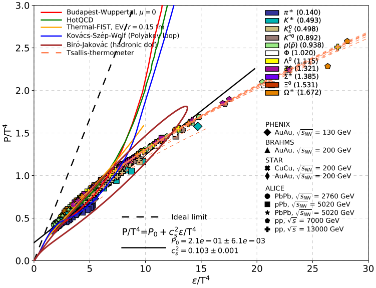

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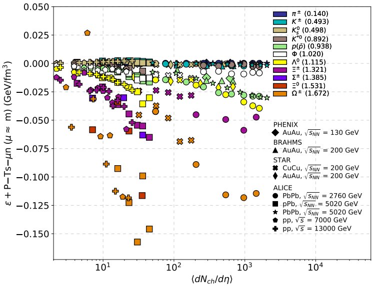

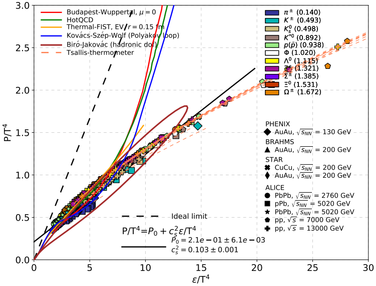

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With the **parametrizations:** $\sqrt{s}$ and $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle$ regions:

- $\sqrt{s} \gtrsim 7000$ GeV: $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle \gtrsim 130$
- $\sqrt{s} \gtrsim 13000$ GeV: $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle \gtrsim 90$

Summary

- Consistent non-extensive analysis of a **very large set** of experimental data
- $q \neq 1$ for all hadron spectra: dependency on the size of the collisional system through **multiplicity** fluctuations
- **Various checks** of the non-extensive framework
- Grouping of the **T** and **q** parameters, **comparison** with theoretical QCD calculations
- **Tsallis-thermometer:** final state hadrons may originate from a previously present strongly interacting QCD matter at event multiplicities as low as $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle \sim 100$

Support

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Thank you for your attention!

Backup

Experimental data

System, $\sqrt{s_{NN}}$ (GeV)	η or y	Hadron	Mult. classes	p_T range (GeV/c)
AuAu, 130	$\|\eta\| < 0{,}35$	$\pi^{\pm}$	3, [21,3; 622]	[0,25; 2,2]
		$K^{\pm}$		[0,45; 1,65]
		$p(\bar{p})$		[0,55; 3,42]
CuCu, 200	$\|y\| < 0{,}5$	K_s^0	5, [32; 175]	[0,5; 9,0]
		Λ^0		[0,5; 7,0]
		$\Xi^{\pm}$		[0,7; 6,0]
		$\Omega^{\pm}$		[1,0; 4,5]
		Φ	6, [24; 175]	[0,45; 4,5]
AuAu, 200	$\|y\| < 0{,}2$	$\pi^{\pm}$	3, [111; 680]	[0,2; 2,0]
		$K^{\pm}$		[0,4; 2,0]
		$p(\bar{p})$		[0,3; 3,0]
	$\|y\| < 0{,}5$	K_s^0	5, [27; 680]	[0,5; 9,0]
		Λ^0		[0,5; 8,0]
PbPb, 2760	$\|y\| < 0{,}5$	$\pi^{\pm}$	10, [13,4; 1601]	[0,1; 3,0]
		$K^{\pm}$		[0,2; 3,0]
		K_s^0	7, [55; 1601]	[0,4; 12,0]
		K^{*0}	6, [261; 1601]	[0,3; 20,0]
		$p(\bar{p})$		[0,3; 4,6]
		Λ^0		[0,6; 12,0]
		Φ		[0,5; 21,0]
		$\Xi^{\pm}$	5, [55; 1601]	[0,6; 8,0]
		$\Omega^{\pm}$		[1,2; 7,0]
pPb, 5020	$-0{,}5 < \|y\| < 0{,}0$	$\pi^{\pm}$	7, [4,3; 45]	[0,1; 20,0]
		$K^{\pm}$		[0,2; 20,0]
		K^{*0}	5, [4,3; 45]	[0,0; 16,0]
		$p(\bar{p})$		[0,35; 20,0]
		Φ		[0,4; 20,0]
		Ξ^0	4, [7,1; 35,6]	[0,8; 8,0]

System, $\sqrt{s_{NN}}$ (GeV)	η or y	Hadron	Mult. classes	p_T range (GeV/c)
pPb, 5020	$-0{,}5 < \|y\| < 0{,}0$	$\pi^{\pm}$	7, [4,3; 45]	[0,1; 20,0]
		$\Sigma^{\pm}$	3, [7,1; 35,6]	[1,0; 6,0]
		$\Xi^{\pm}$	7, [4,3; 45]	[0,6; 7,2]
		$\Omega^{\pm}$		[0,8; 5,0]
	$0{,}0 < \|y\| < 0{,}5$	$\pi^{\pm}$	7, [4,3; 45]	[0,1; 3,0]
		$K^{\pm}$		[0,2; 2,4]
		K_s^0		[0,0; 8,0]
		$p(\bar{p})$		[0,3; 4,0]
		Λ^0		[0,6; 8,0]
PbPb, 5020	$\|y\| < 0{,}5$	$\pi^{\pm}$	10, [19,5; 2047]	[0,1; 10,0]
		$K^{\pm}$		[0,1; 10,0]
		$p(\bar{p})$		[0,1; 10,0]
pp, 7000	$\|y\| < 0{,}5$	$\pi^{\pm}$	10, [2,2; 21,3]	[0,1; 20,0]
		$K^{\pm}$		[0,2; 20,0]
		K_s^0	10, [2,2; 21,3]	[0,0; 12,0]
		K^{*0}	9, [2,2; 21,3]	[0,0; 10,0]
		$p(\bar{p})$	10, [2,2; 21,3]	[0,3; 20,0]
		Φ	9, [2,2; 21,3]	[0,4; 10,0]
		Λ^0	10, [2,2; 21,3]	[0,4; 8,0]
		$\Xi^{\pm}$		[0,6; 6,5]
		$\Omega^{\pm}$	5, [2,2; 21,3]	[0,9; 5,5]
pp, 13000	$\|y\| < 0{,}5$	K_s^0	10, [2,52; 25,72]	[0,0; 12,0]
		Λ^0		[0,4; 8,0]
		$\Xi^{\pm}$		[0,6; 6,5]
		$\Omega^{\pm}$	5, [3,58; 22,8]	[0,9; 5,5]