INTRODUCTION: Sumit Basu

Lund University, Department of Physics,
Division of Particle Physics,
Box 118, SE-221 00, Lund, Sweden
email: sumit.basu@cern.ch

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- I am from India
- Ph.D (2016) (VECC &

  ALICE Expt. CERN)
- Post-Doctoral Fellow

  (Wayne State University, USA)

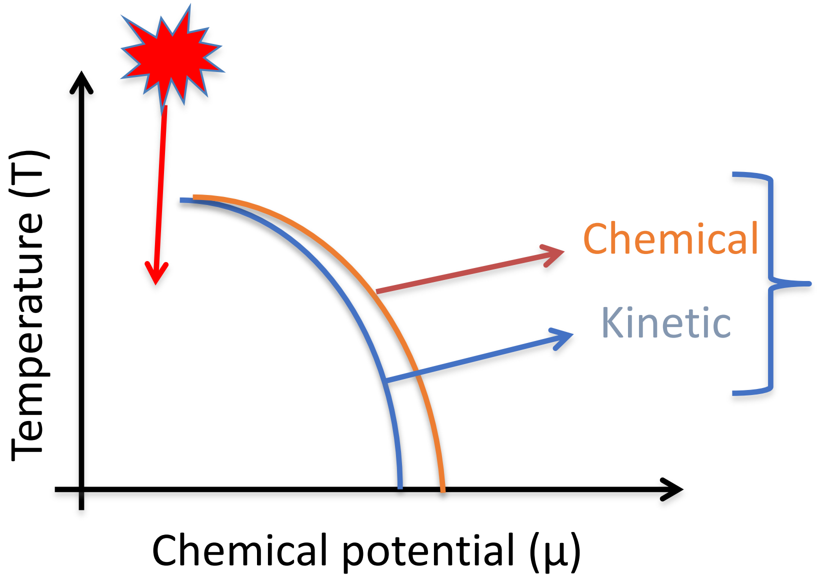
  (Dec 2016 – Mar 2020)

  and Now,
- Post-Doctoral Fellow

  (Lund University, Sweden)

2018 → Sumit V2.0

Ph.D.: Temperature Fluctuations

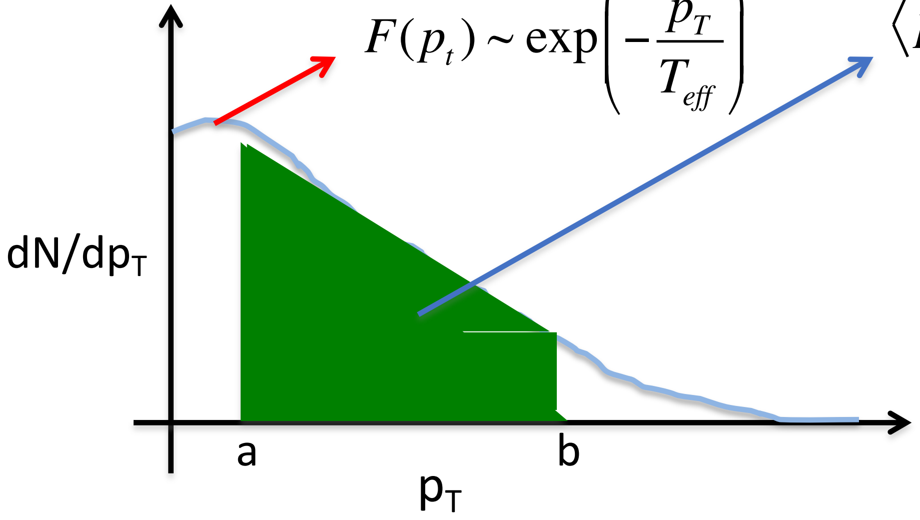


Sources

1. Initial State fluctuations (L. Stodolsky, Phys. Rev. Lett. 75, 1044 (1995))
2. Thermodynamical fluctuations
3. Statistical fluctuations

$$C^{-1} = \frac{(\Delta T)^2}{T^2}$$

$$\langle \Delta p_t \Delta p_t \rangle \approx \left[\frac{d\langle p_t \rangle}{dT} \right]^2 \Delta T^2$$

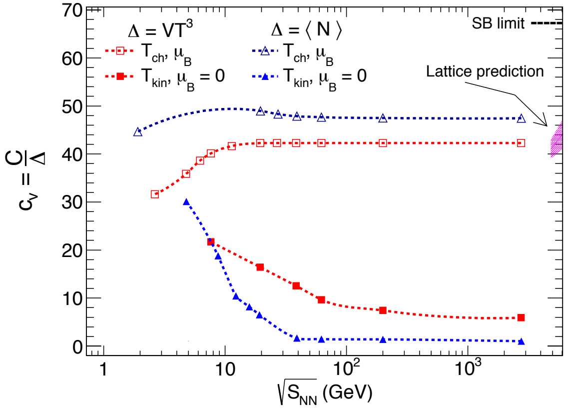


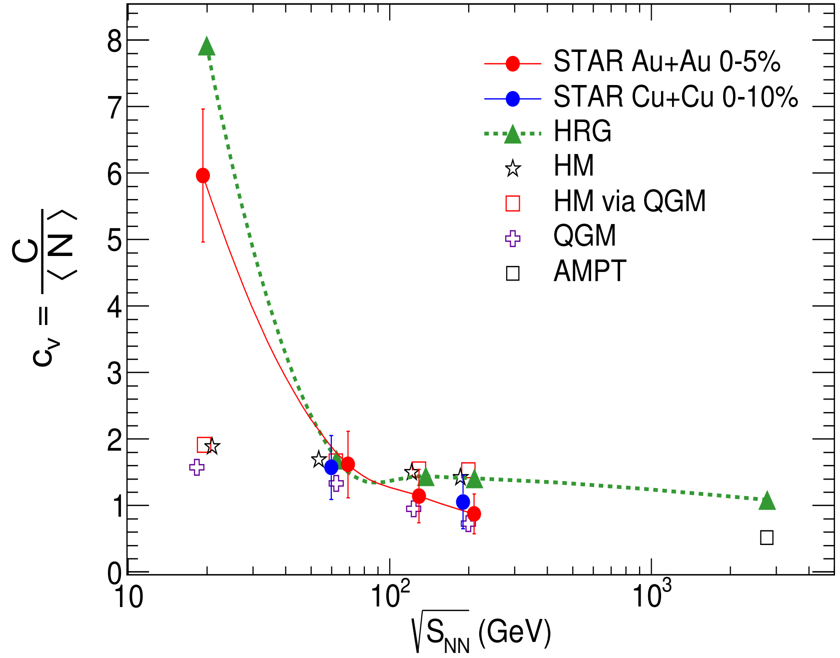
$$F(p_t) \sim \exp\left(-\frac{p_T}{T_{eff}} \right)$$

$$\langle p_T \rangle = \frac{\int_a^b p_T^2 F(p_t) dp_T}{\int_a^b p_T F(p_t) dp_T}$$

Sp. Heat $c_v = \frac{C}{\langle n \rangle} = \frac{C}{VT^3}$

Phy. Rev. C **94** 034909 (2016)

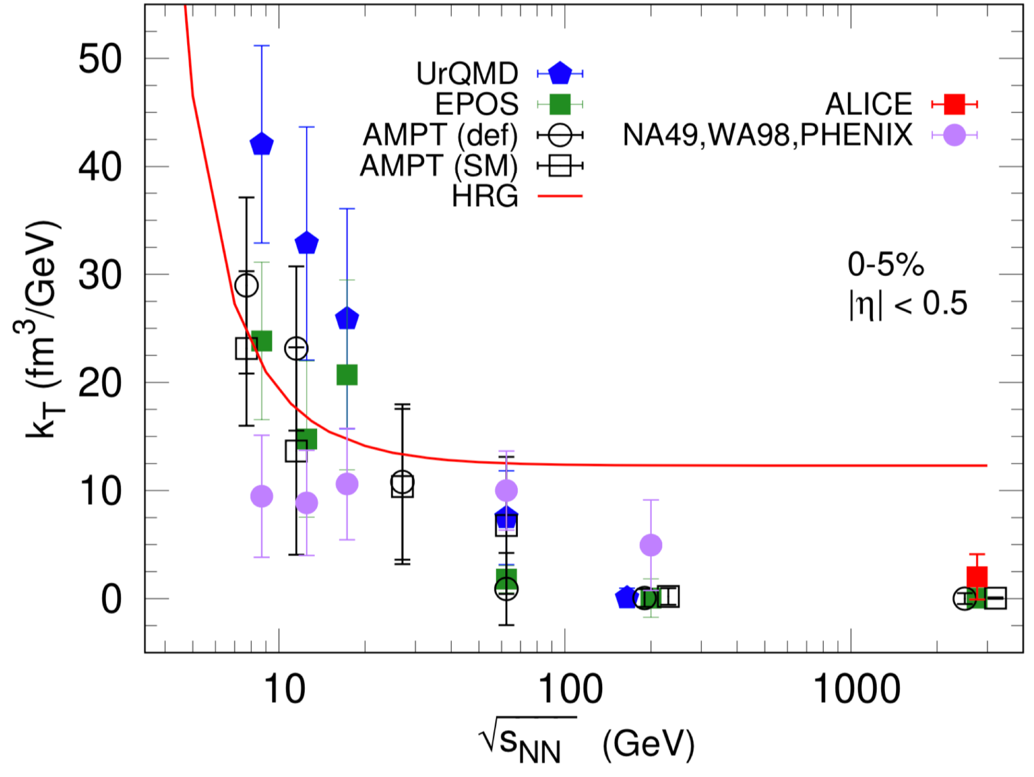


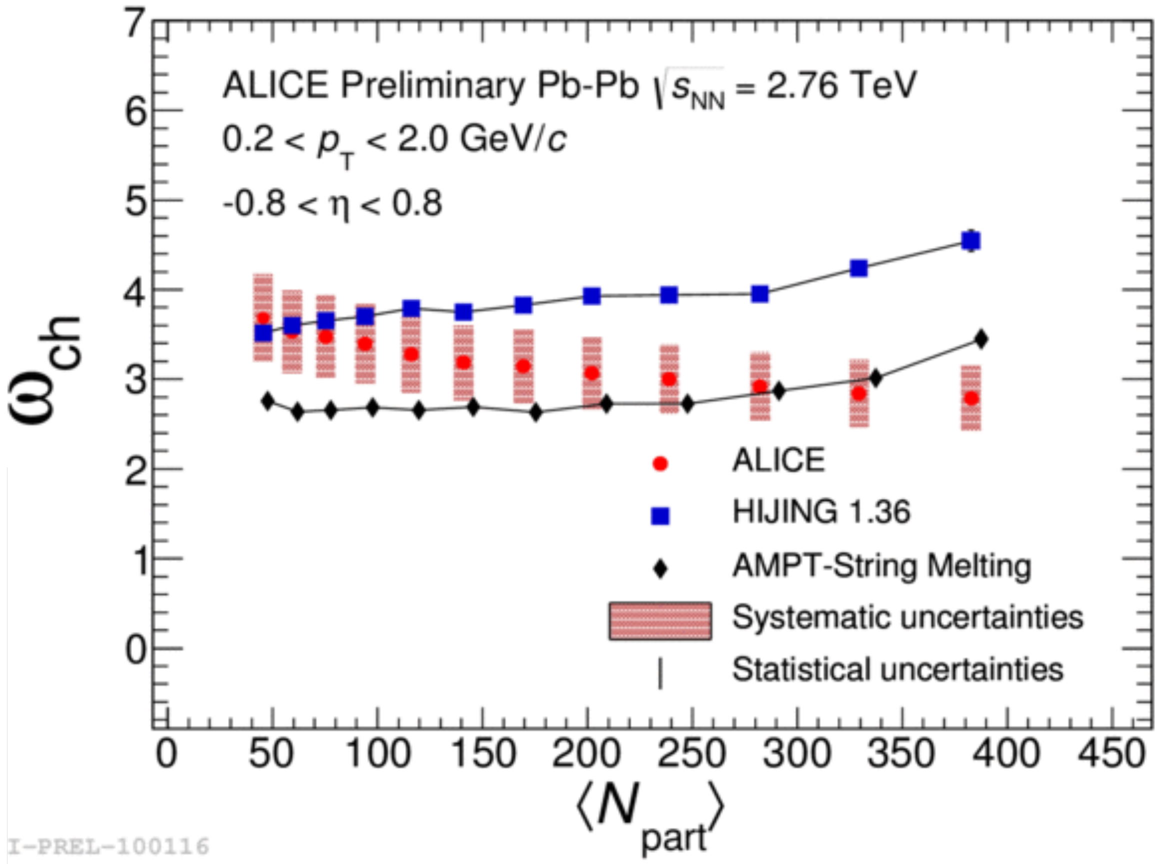


$$\omega_{ch} = \frac{\langle N_{ch}^2\rangle - \langle N_{ch}\rangle^2}{\langle N_{ch}\rangle} = \frac{\sigma^2}{\mu}$$

k_T expressed in $fm^3\ GeV^{-1}$

Phys. Lett. B784 (2018) 1-5





$$k_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

$$k_T = \frac{\sigma^2}{<N>^2}\frac{V}{k_B T} = \frac{\omega_{ch}}{<N>}\frac{V}{k_B T}$$

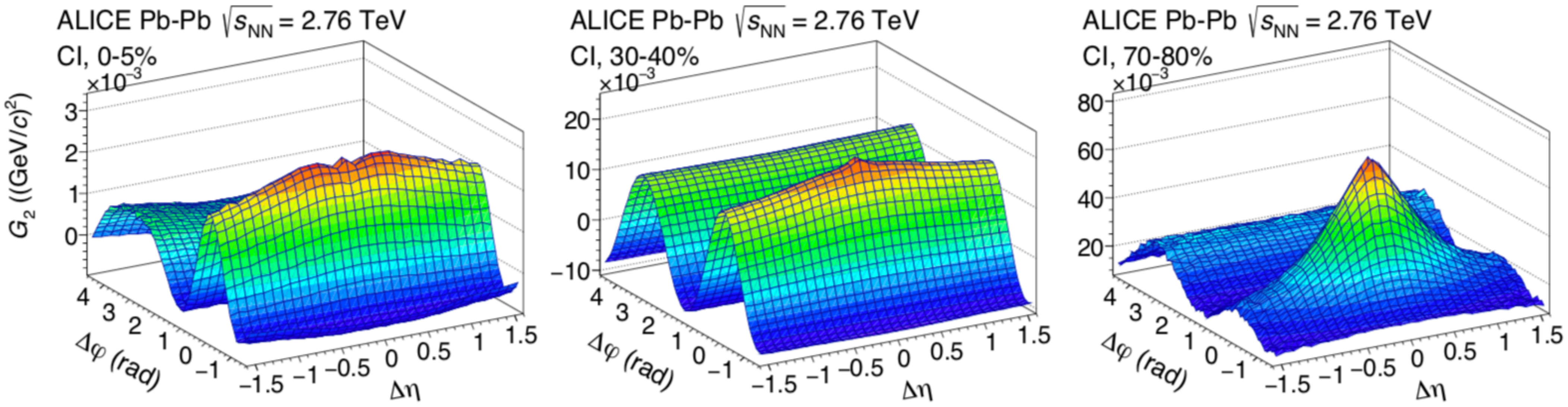
Two-particle transverse momentum correlations

$$G_2(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{1}{\langle p_{T,1}\rangle\langle p_{T,2}\rangle}\left[\frac{\int_\Omega p_{T,1}p_{T,2}\,\rho_2(\vec{p}_1,\vec{p}_2)\,\mathrm{d}p_{T,1}\mathrm{d}p_{T,2}}{\int_\Omega \rho_1(\vec{p}_1)\,\mathrm{d}p_{T,1}\otimes\int_\Omega \rho_1(\vec{p}_2)\,\mathrm{d}p_{T,2}} - \langle p_{T,1}\rangle(\eta_1,\varphi_1)\langle p_{T,2}\rangle(\eta_2,\varphi_2)\right]$$

Sean Gavin et. Al
PRL 97 162302 (2006)
PRC 94 024921 (2016)

Experimentally

$$G_2(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{1}{\langle p_{T,1}\rangle\langle p_{T,2}\rangle}\left[\frac{\left\langle \sum_{\mathrm{i}}^{n_{1,1}}\sum_{\mathrm{j}\neq\mathrm{i}}^{n_{1,2}} p_{T,\mathrm{i}}\,p_{T,\mathrm{j}}\right\rangle}{\langle n_{1,1}(\eta_1,\varphi_1)\rangle\langle n_{1,2}(\eta_2,\varphi_2)\rangle} - \langle p_{T,1}\rangle(\eta_1,\varphi_1)\langle p_{T,2}\rangle(\eta_2,\varphi_2)\right]$$



Two-particle transverse momentum correlations

Sean Gavin et. Al
PRL 97 162302 (2006)
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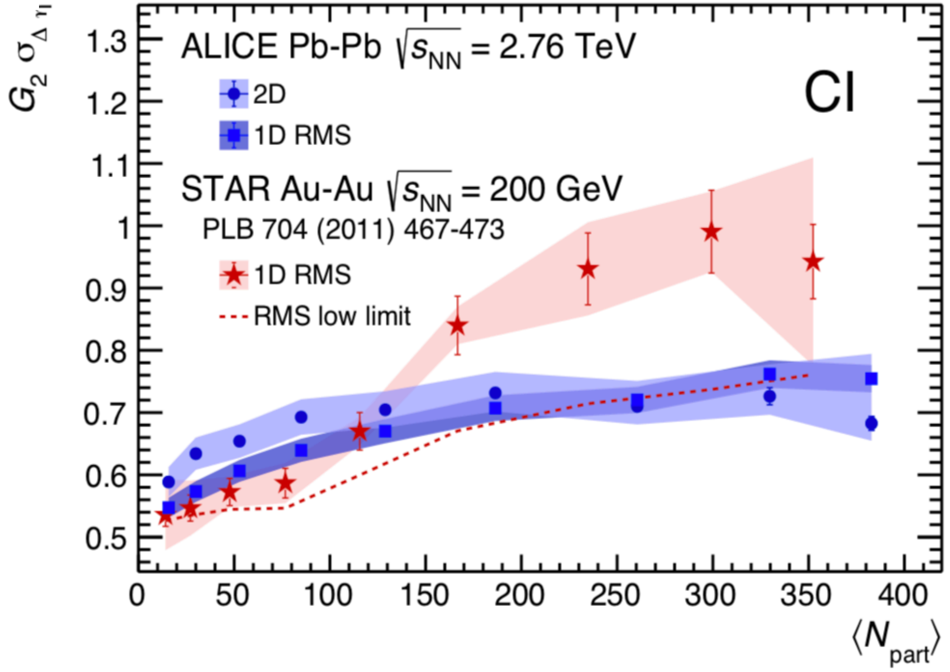
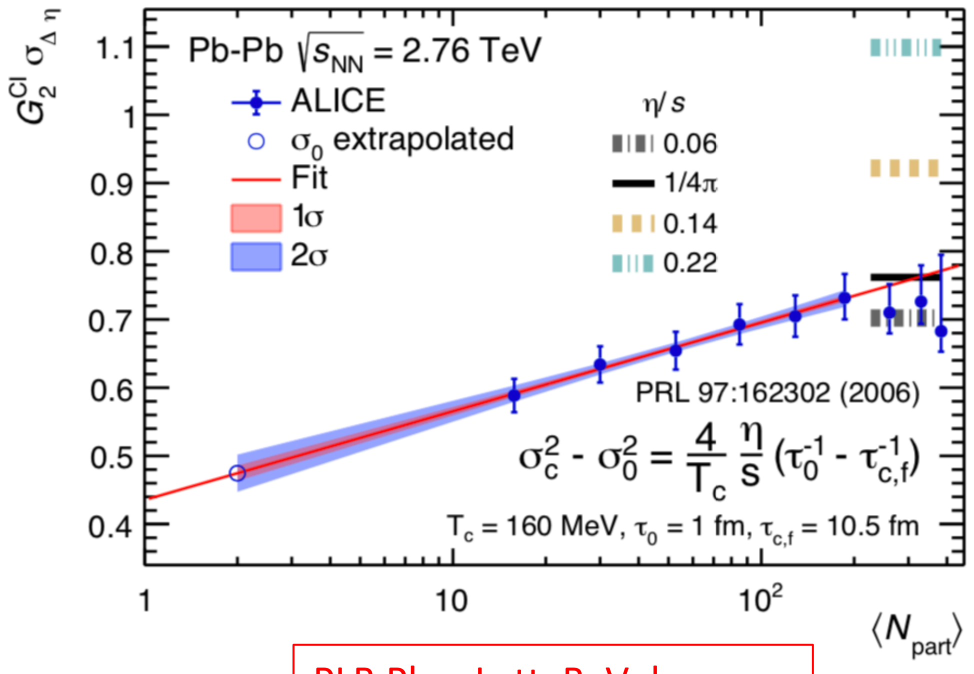
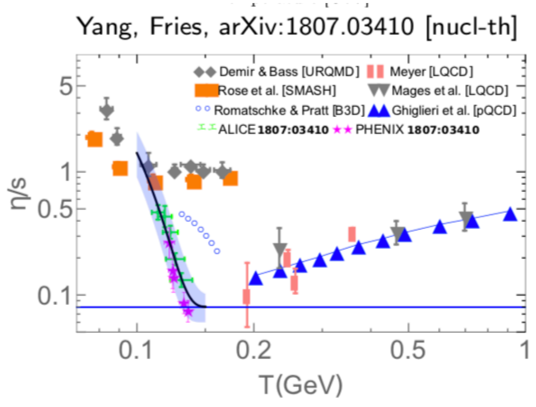






PLB Phys Lett. B, Volume 804 (2020) 135375

Ongoing further developments: Extend this study for pp and pPb and study the variation of G2 observable with dNch/dη

Promising results, soon will be reported from ALICE, about System size dependence of G2 (Momentum Correlator)

General Definition of Balance Functions

Cumulant $C_2(x_1,x_2) = \rho_2(x_1,x_2) - \rho_1(x_1)\rho_1(x_2)$

$x \equiv \{y, \varphi, p_T\}$ $\rho(x) = \frac{1}{\sigma}\frac{d\sigma}{dx}$

Normalized Cumulant $$R_2(x_1,x_2) = \frac{C_2(x_1,x_2)}{\rho_1(x_1)\rho_1(x_2)}$$

R_2 is a robust observable!
Single track efficiencies cancel out of the ratio

4 different charge combinations for R_2:
(+ -), (- +), (+ +), and (- -)

$$LS = \frac{1}{2}\{(++) + (--)\}$$

$$US = \frac{1}{2}\{(+-) + (-+)\}$$

Charge Independent (CI) combinations $CI = \frac{1}{2}\{LS + US\}$

Charge Dependent (CD) combinations $CD = \frac{1}{2}\{US - LS\}$

R_2^{CD} is proportional to the Balance Function

$$B(\Delta x) \approx \frac{dN_{ch}}{dx} R_2^{CD} = \frac{dN_{ch}}{dx}\frac{1}{2}\left[R_2^{+-} - R_2^{++} + R_2^{-+} - R_2^{--}\right]$$

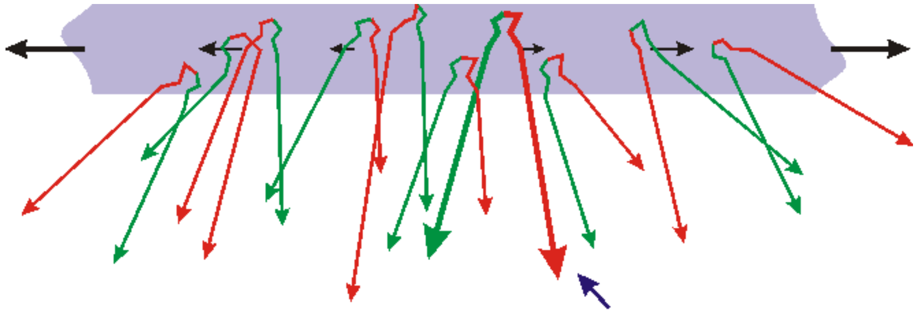
For Charged particle, Signs (+) & (-) represents charge.

For Λ's being neutral particle, we define (+) for baryon number & (-) for antibaryon number.

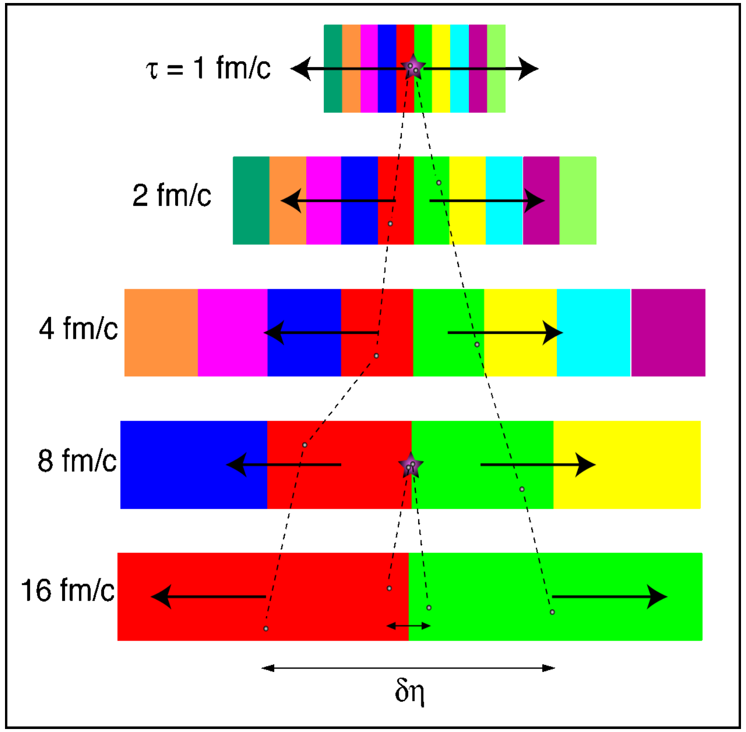
Similary, LS means same-type Baryonic number and US means opposite-type Baryonic number

Importance of Studying Balance Functions

Conservation of quantum numbers.
-> for each positive general charge, a negative balancing charge produced at approx. the same space-time.



The width of the BF was initially proposed to be related to the time of hadronization.



$$B(\Delta y) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_{+}} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_{-}}\right\}$$

Bass, Danielewicz, Pratt PRL 85 2689 (2000)

Understand / Probe

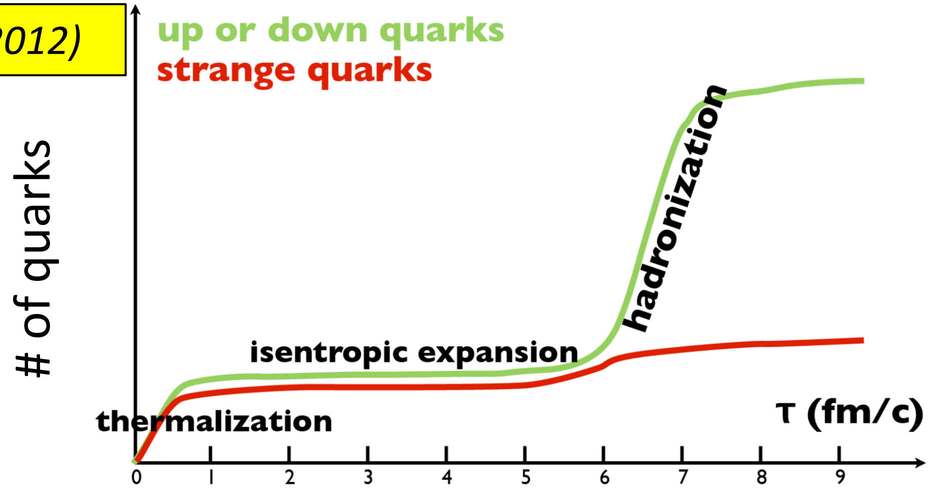
1. Two-wave quark production model:
- $\pi^{\pm}$ $p(\overline{p})$: predominantly produced at late stage
- $K^{\pm}$: predominantly produced at early stage

2. Collision dynamics, e.g., radial flow

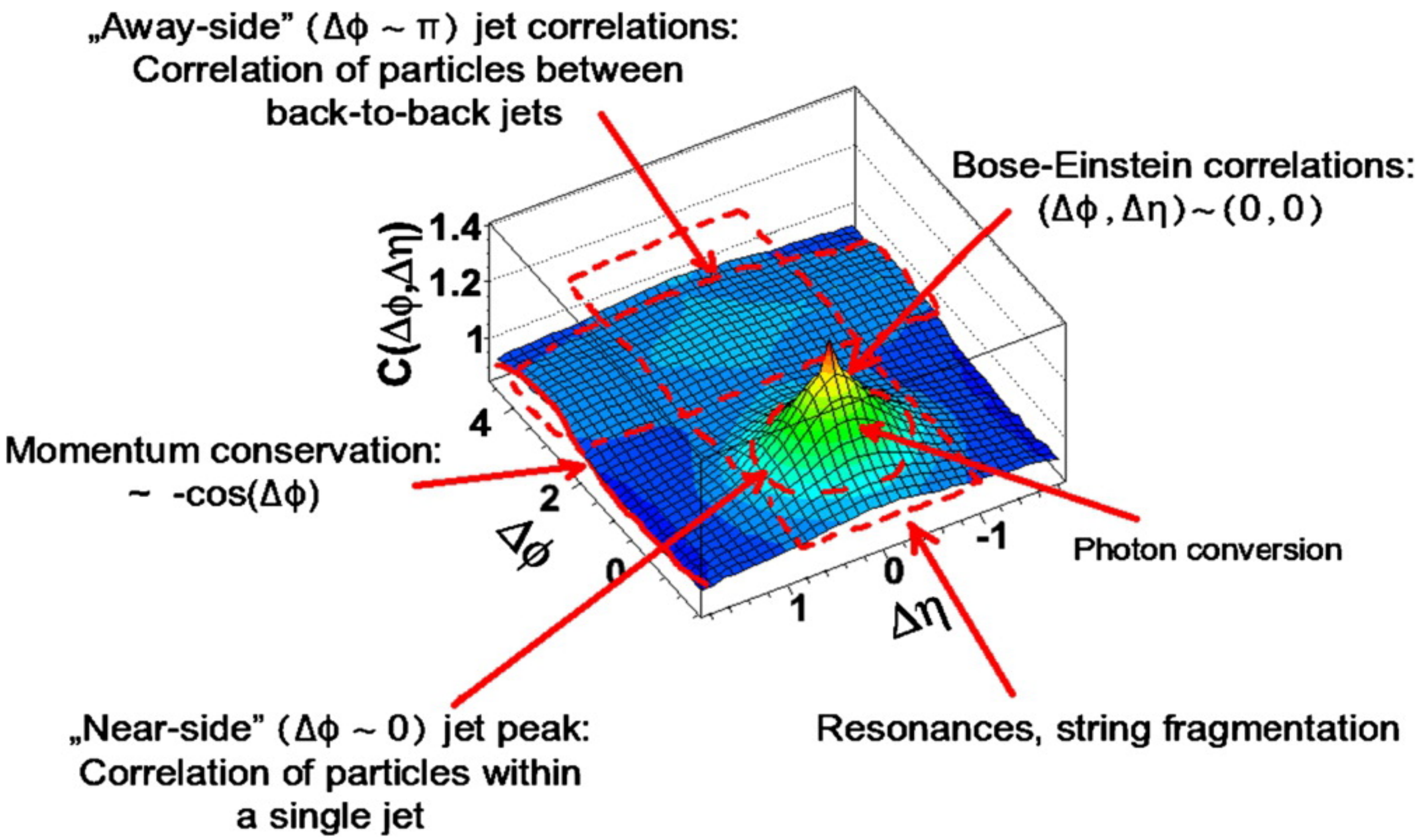
3. Hadro-chemistry – Charge / Strangeness / Baryon / Resonance production

Pratt PRL. 108, 212301 (2012)

Scott Pratt - CPOD 2013

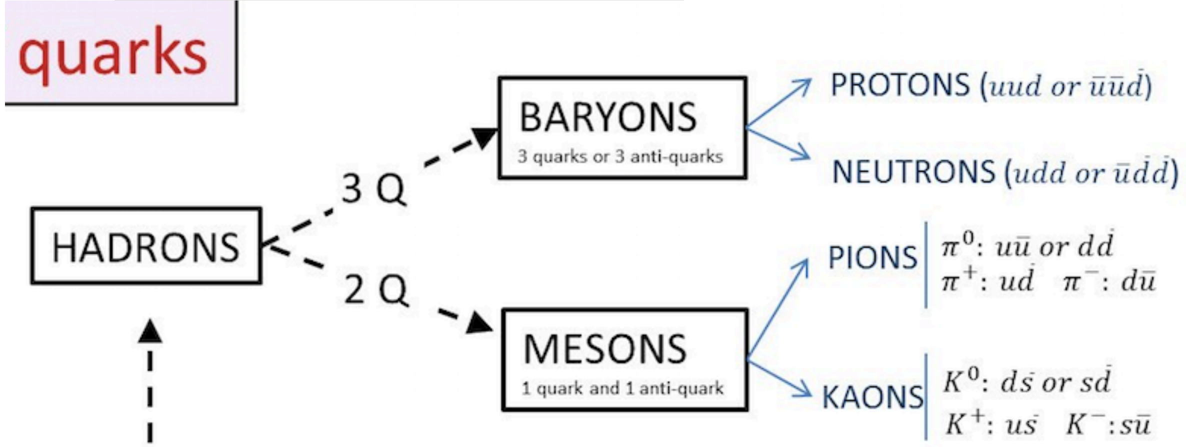


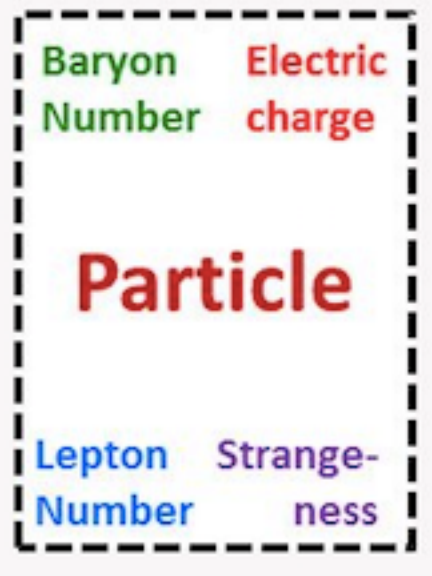
Two-particle Number **(Δ*η*,Δ*φ*)** Correlations

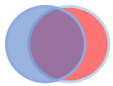


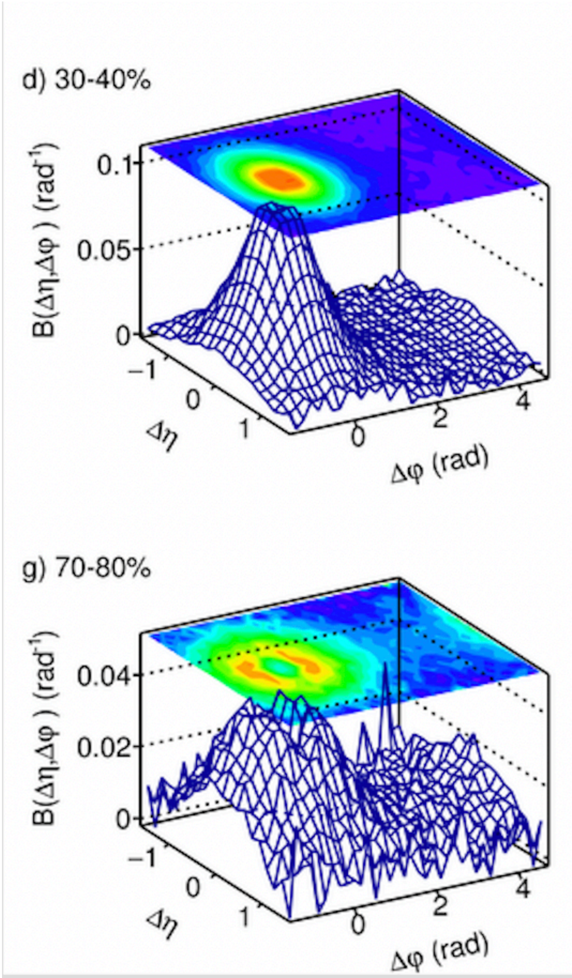
Motivation:

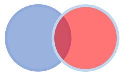
		h
Q	h	✓

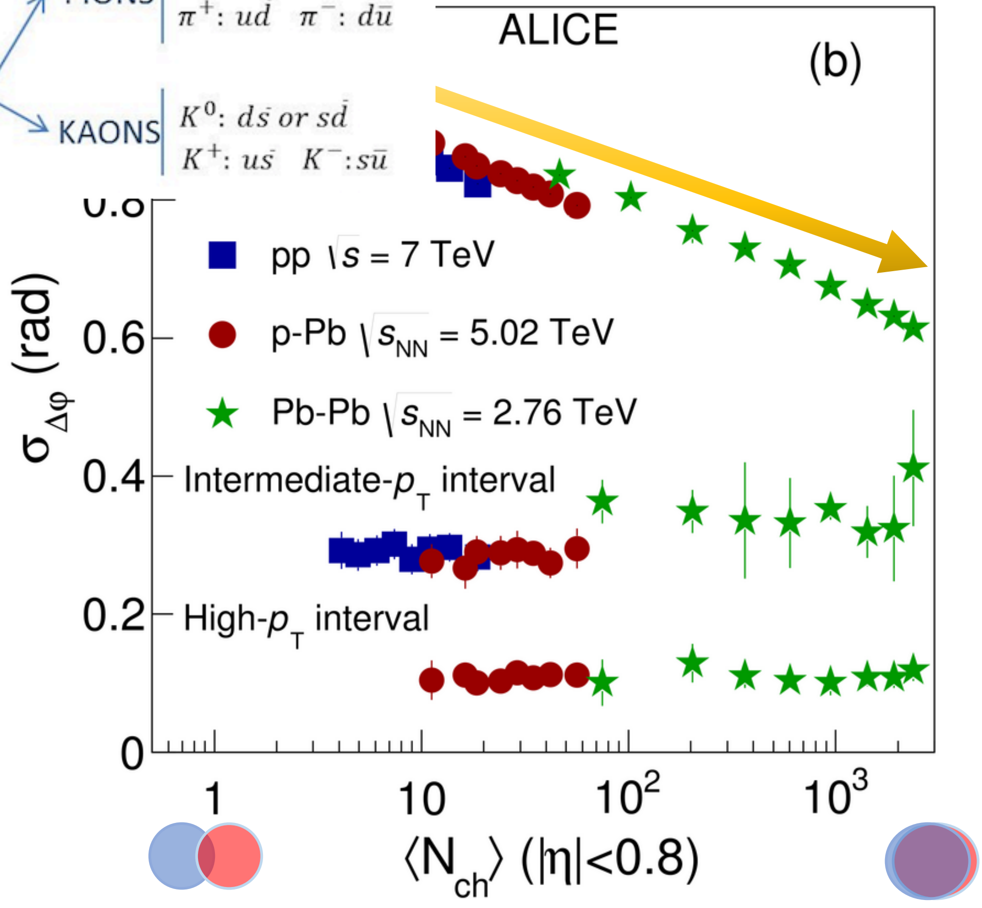








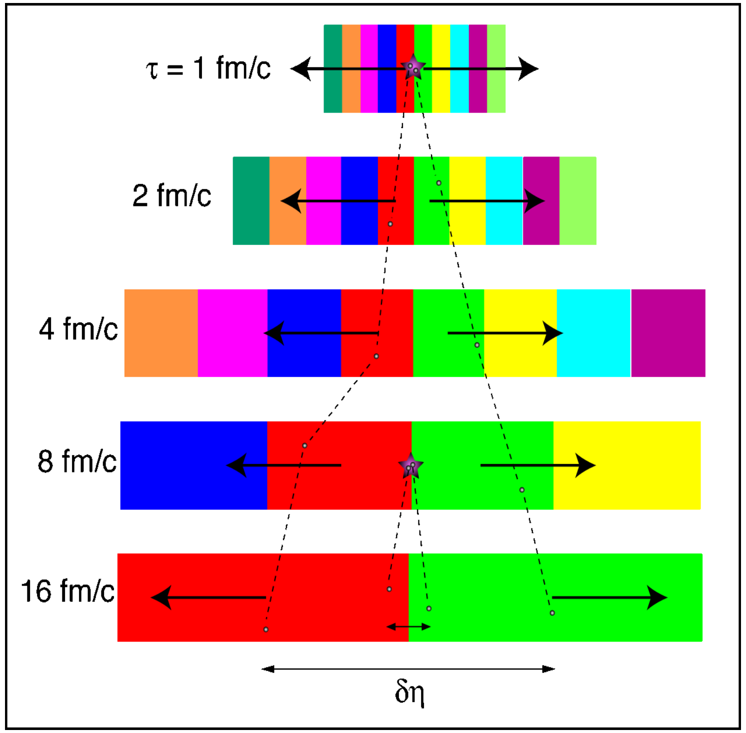




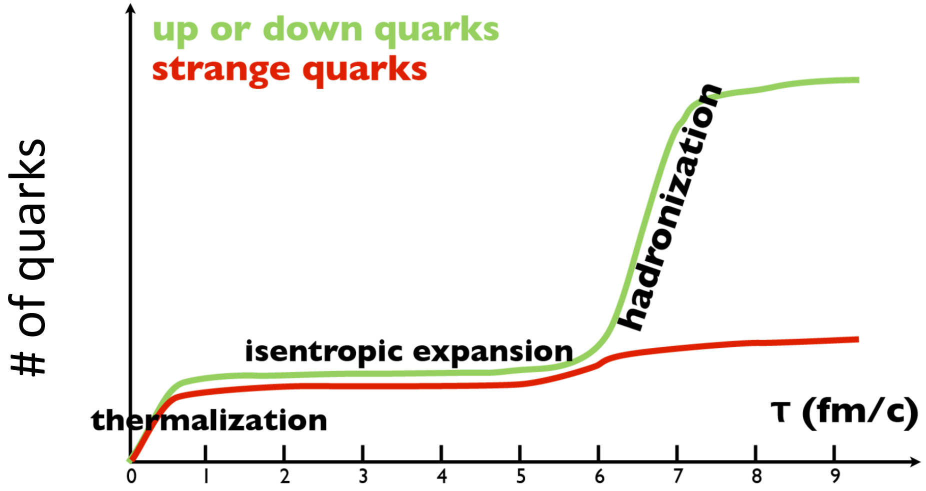
Motivation: π K p Balance Functions

		h	π	k	p
Q	h	✓			
Q	π		?	?	?
Q S	k		?	?	?
Q B	P		?	?	?

Run I : Pb+Pb @ 2760 GeV



Scott Pratt - CPOD 2013



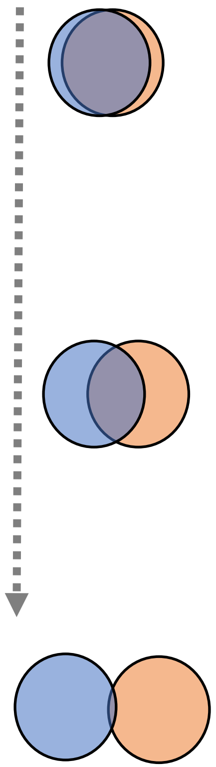
Charged Hadrons = Strange(■)+ Non-Strange(■ ■)

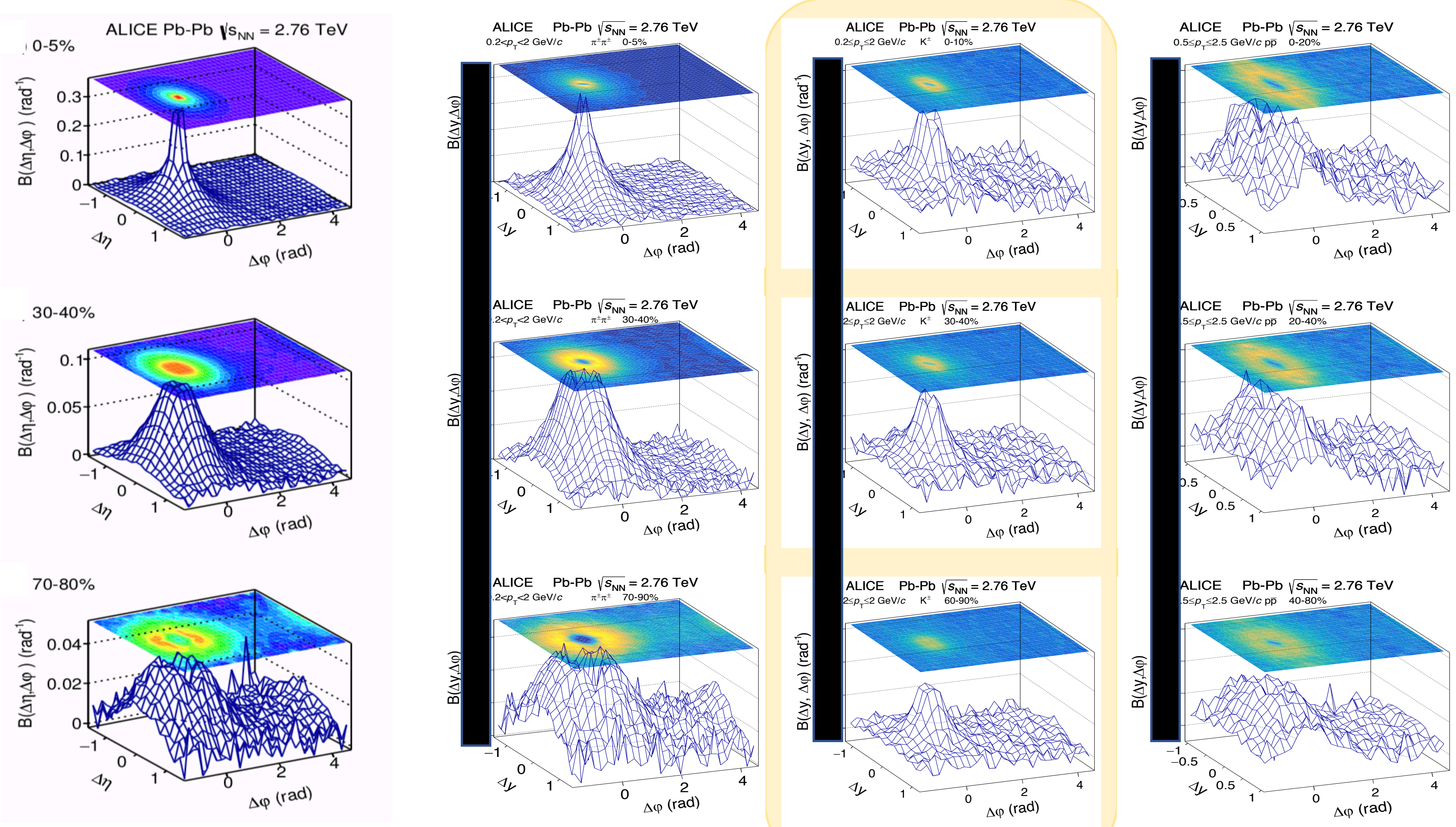
Non-Strange Meson = Pion (π±) ■

Strange Meson = Kaon (K±) ■

Non-Strange Baryon = Proton (p($\bar{p}$)) ■

Centrality

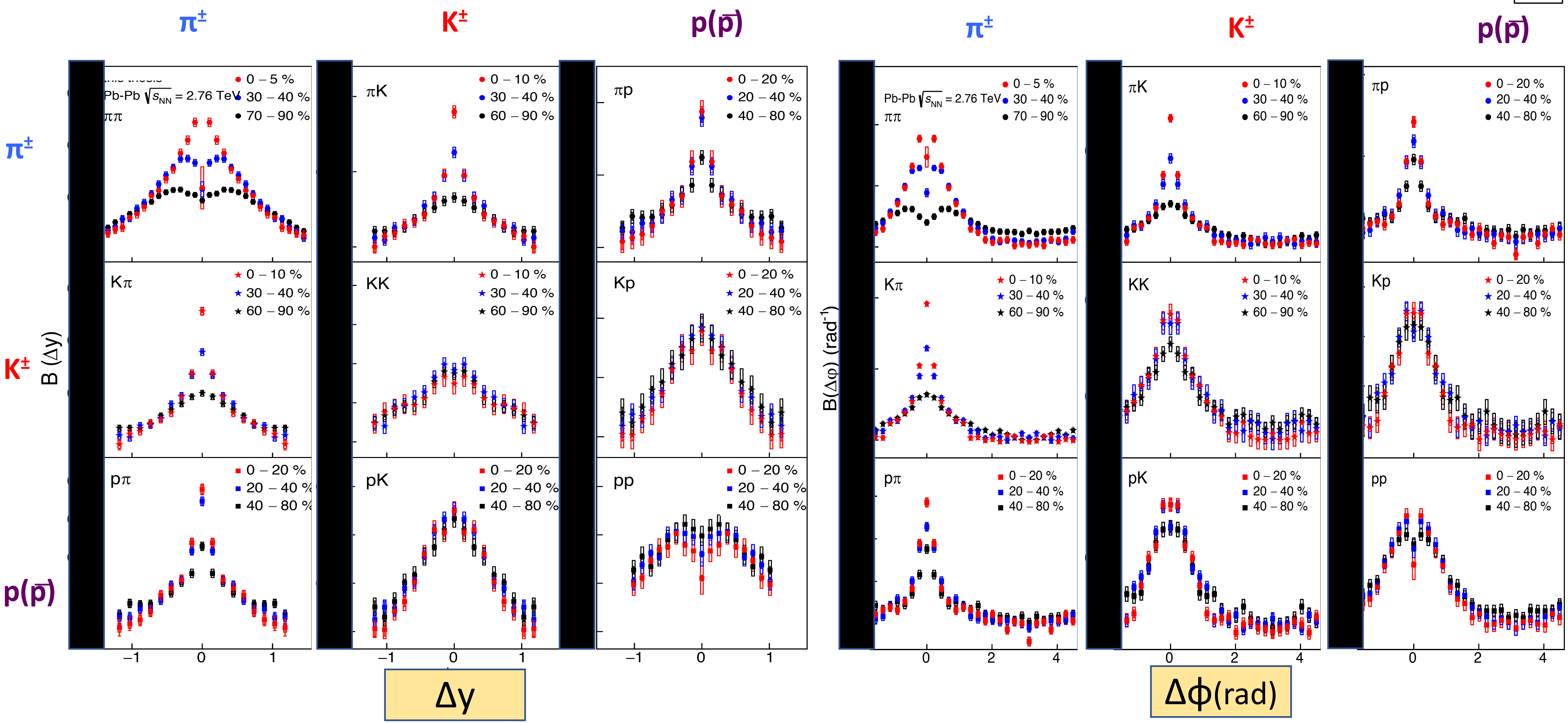




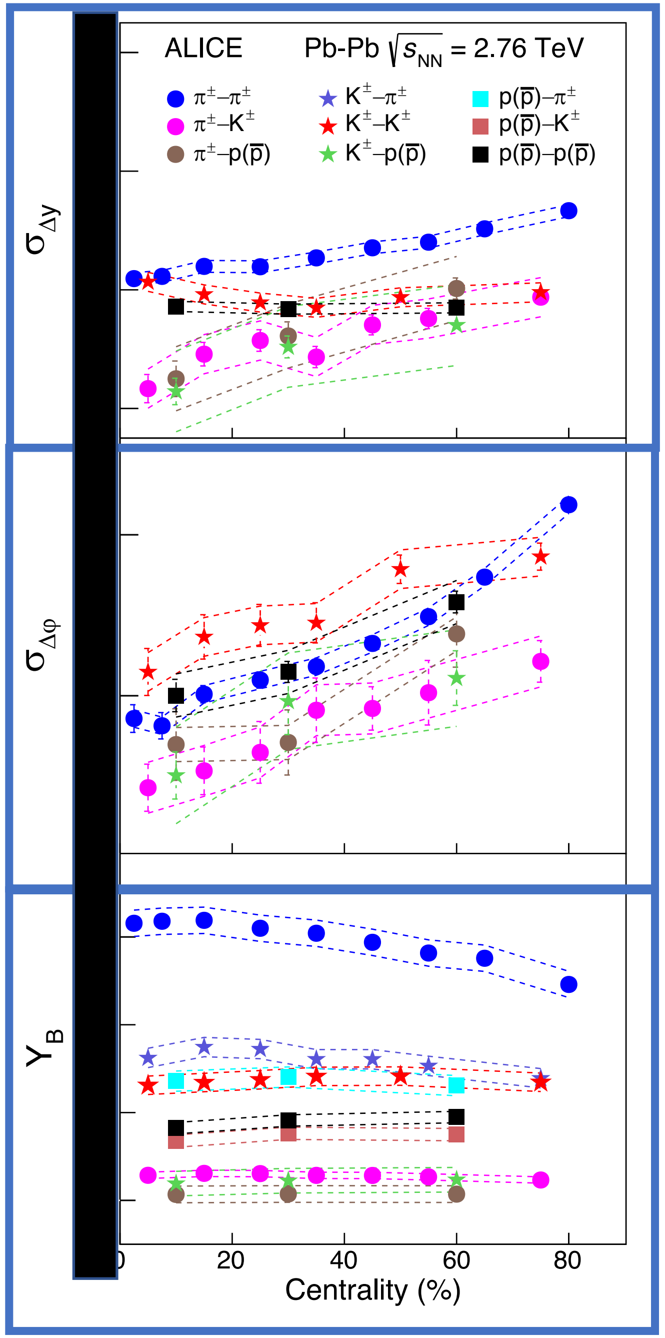
Increasing Mass (MeV) 139 496 938

1. **What about Λ Strange Baryon ??**
2. **Strange Baryons: Lambda Cascade Omega**
3. **Strangeness-Dependent Net Baryon?**

B(Δy) Projections & Widths

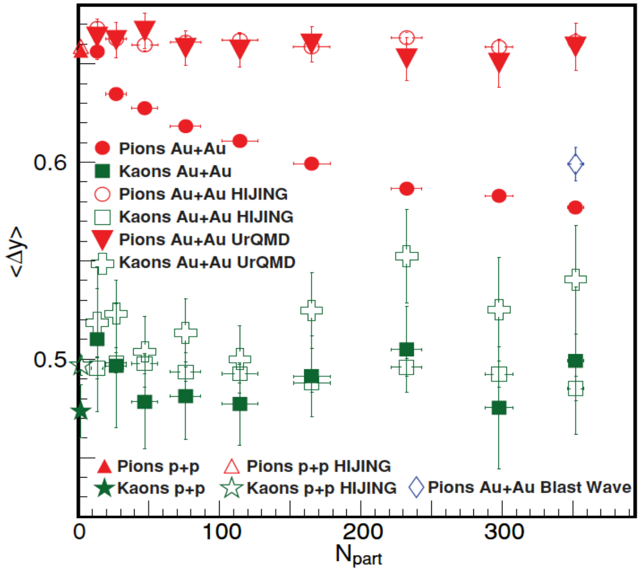


BF Widths and Integrals



$0.2 < p_T(\pi^{\pm}, K^{\pm}) < 2.0$ GeV/c

$0.5 < p_T(p(\bar{p})) < 2.5$ GeV/c

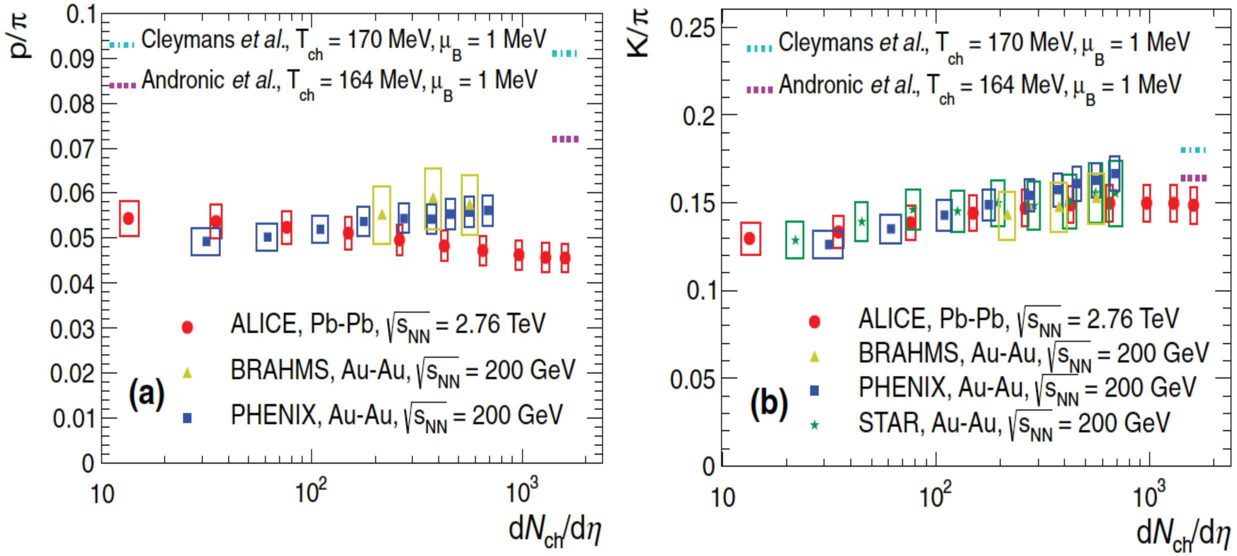


STAR PRC 82, 024905 (2010)

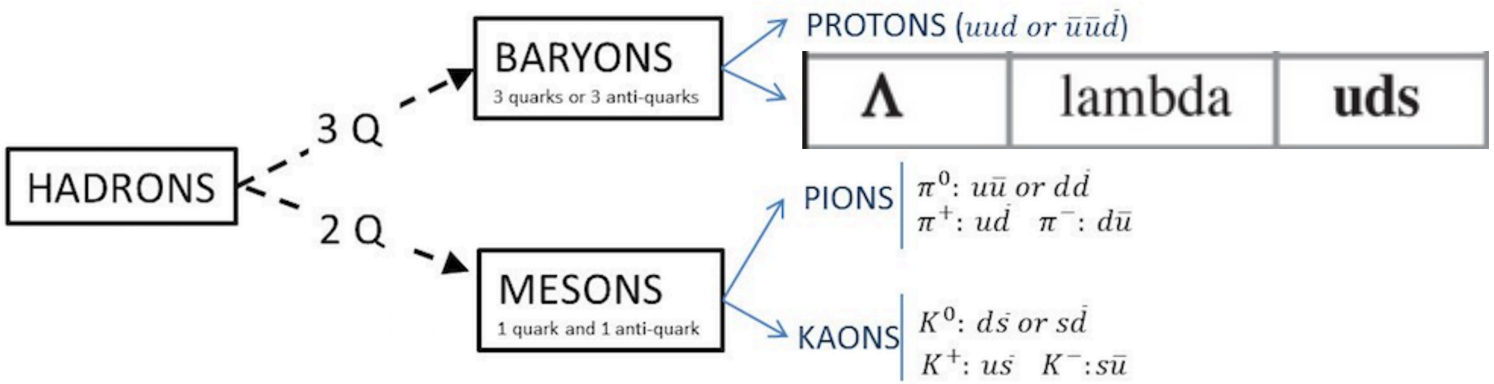
Au-Au @ 200 GeV

$0.2 < p_T < 0.6$ GeV/c

ALICE, PRC 88, 044910 (2013)



Motivation:



Baryon Number | Electric charge

Particle

Lepton Number | Strangeness

		h	π	k	p	Λ
Q	h	✓				
Q	π		✓	✓	✓	
Q S	k		✓	✓	✓	
Q B	P		✓	✓	✓	
B S	Λ					

Work in Progress

Run I : Pb+Pb @ 2760 GeV

Run II : Pb+Pb @ 5020 GeV

Results: R2

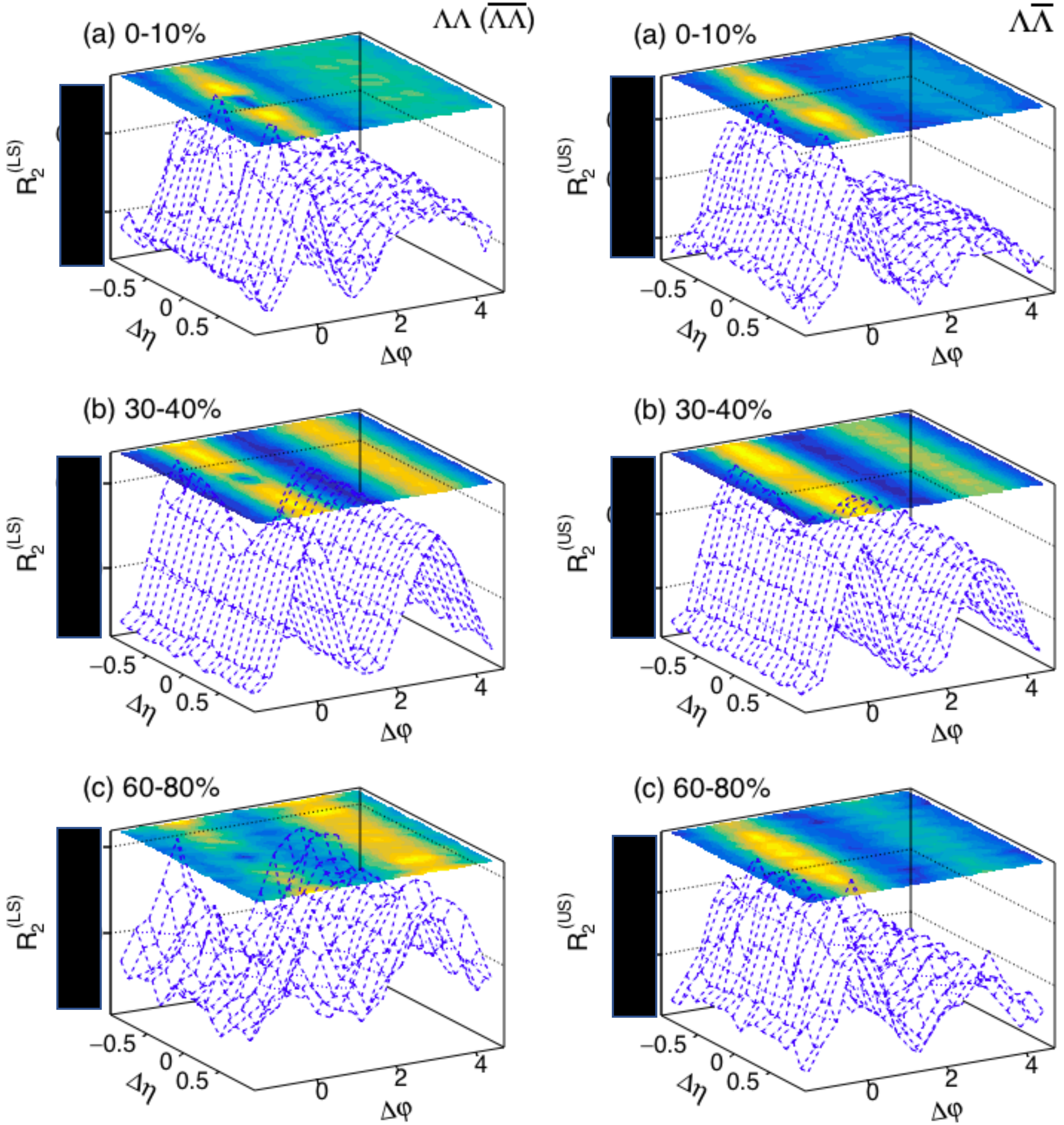
0-10%

Same Baryon/Strange

$\Lambda\Lambda + \bar{\Lambda}\bar{\Lambda}$

Opposite Baryon/Strange

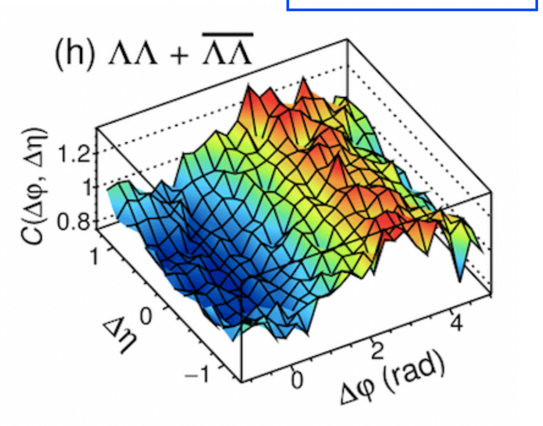
$\Lambda\bar{\Lambda}$



30-40%

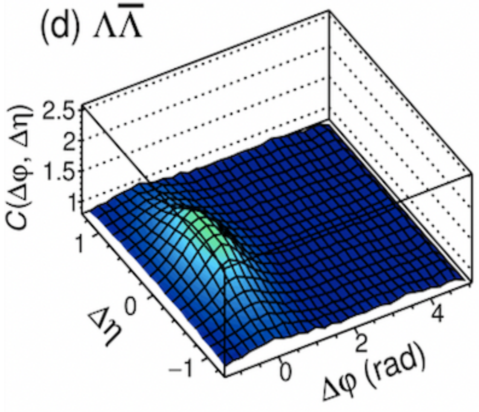
$$R_2(x_1, x_2) = \frac{C_2(x_1, x_2)}{\rho_1(x_1)\rho_1(x_2)}$$

60-80%

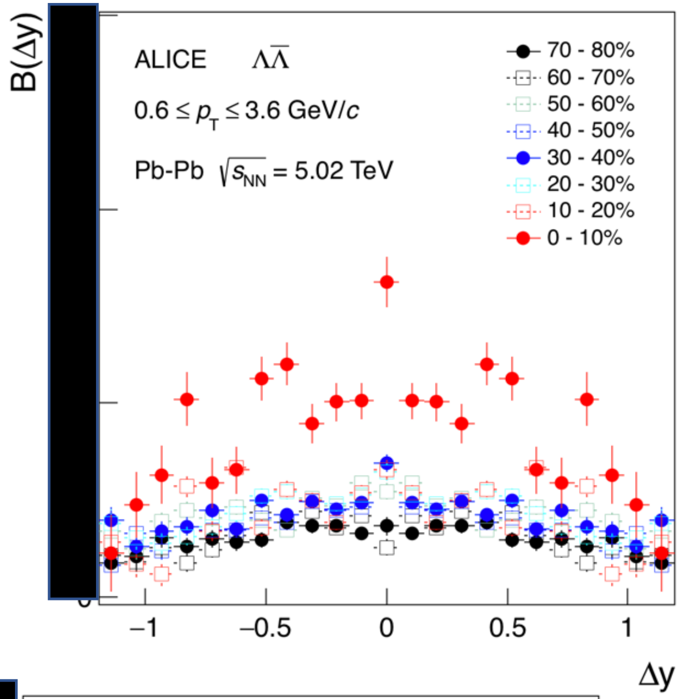


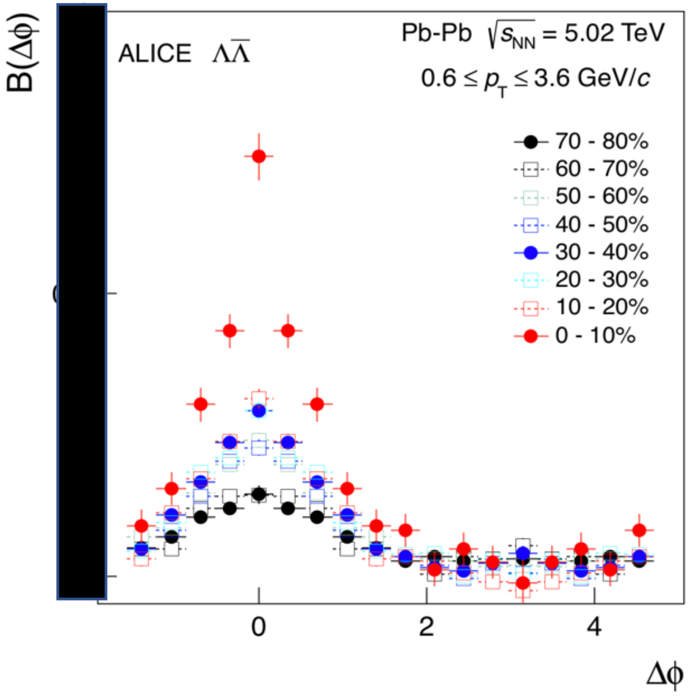
Ref: Eur.Phys.J. C77 (2017) 569

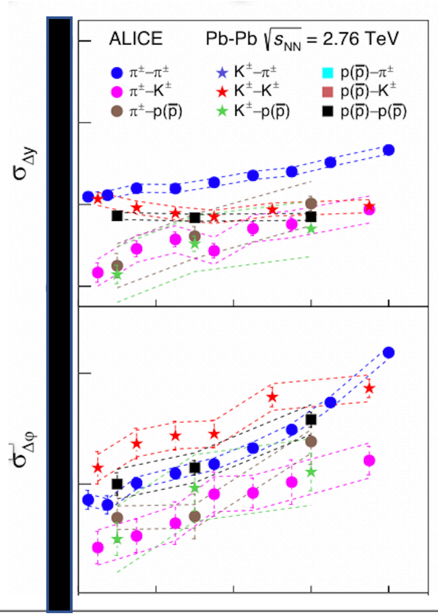
p+p @ √s =7 TeV

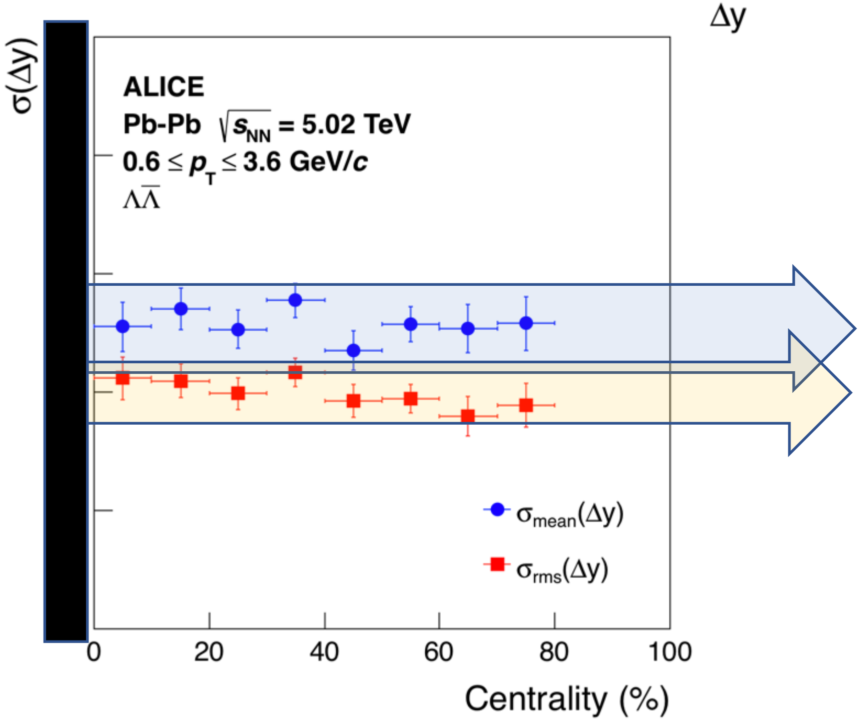


Results: B



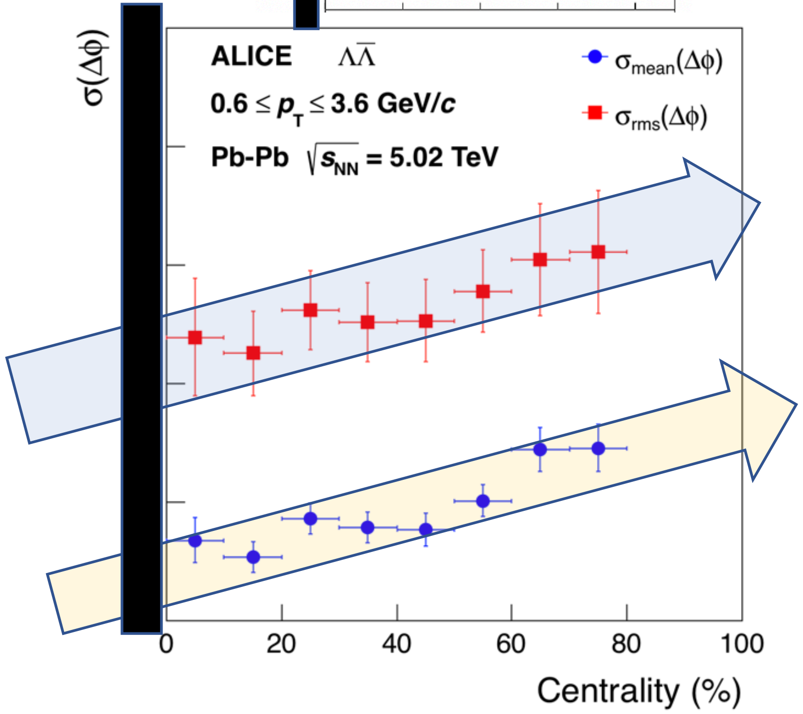






Two Wave quark Production???

Radial Flow effect???



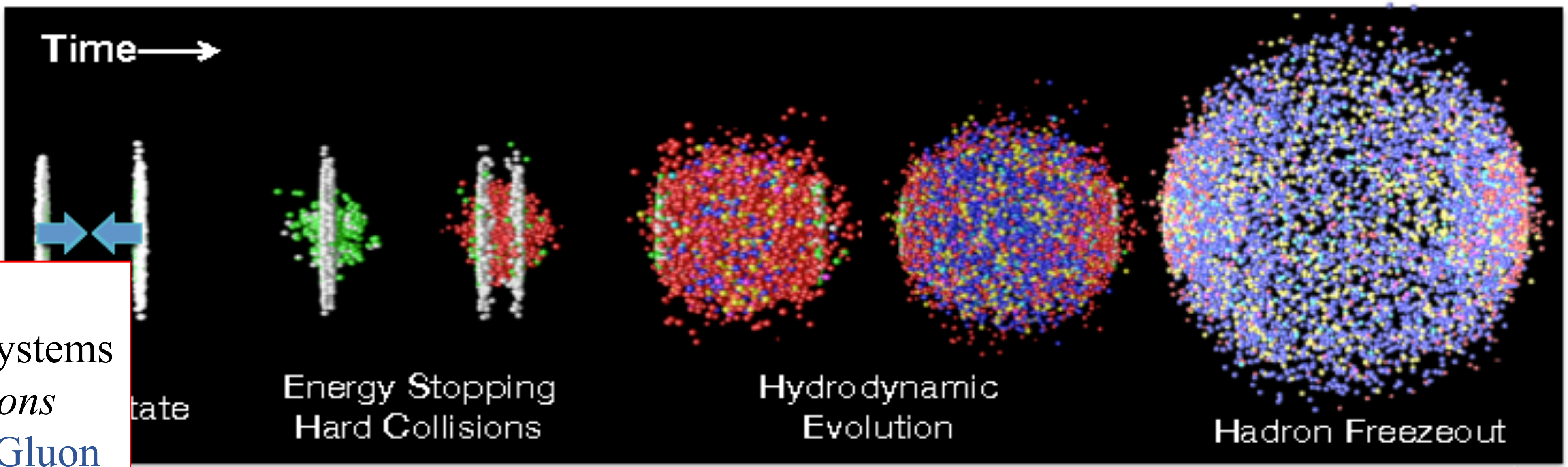
At Lund:

1. Make a multiplicity dependent RT & SO analysis for $\Lambda\bar{\Lambda}$ analysis and make a connection Between Balance Function & Per Trigger Yield analysis
2. Extend Jonatan's study of **Ξ Ξ** correlation to **Ω Ω** Correlation
3. Grid MC: for Rope Tune CD based CR
4. Pythia ANTAGYR Study and Make a comparison with QCD-QGP(EPOS) approach to regular PYTHIA MPI model(Lund string model), Strange (Rope Hadronization framework/ **Flavour Ropes**) and Flow(Rope Hadronization framework/ **String shoving)**
5. **…**

Thank You

Back-up Slides

Introduction: Relativistic Heavy Ion Collisions

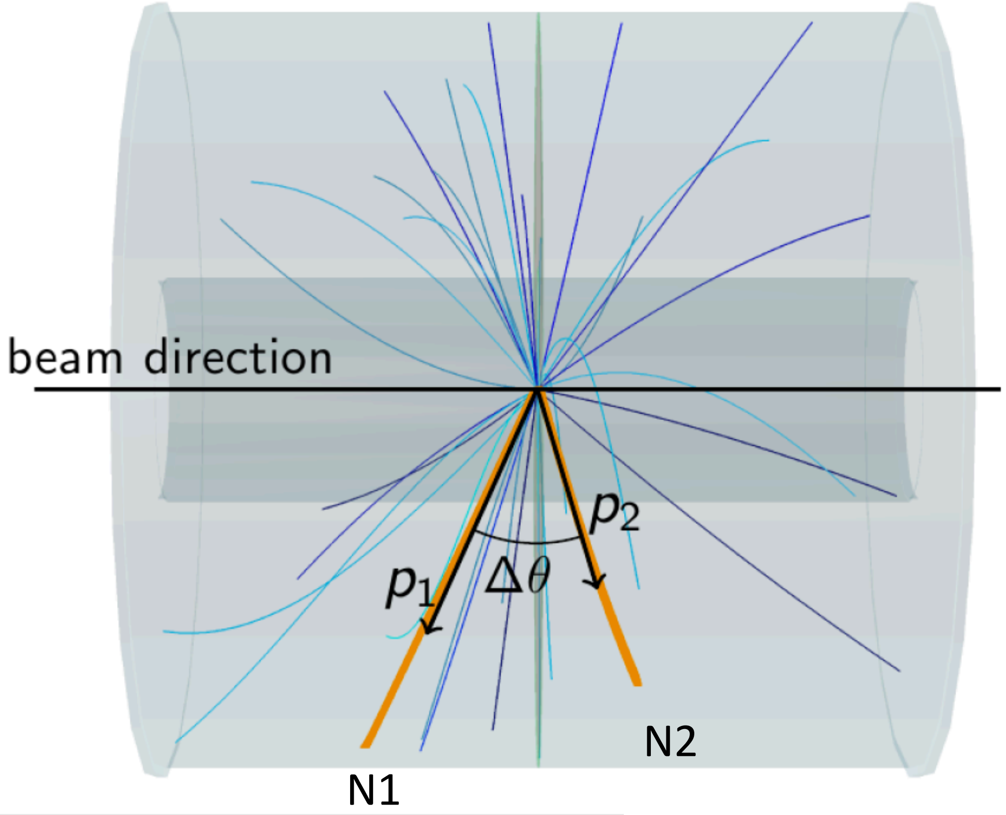


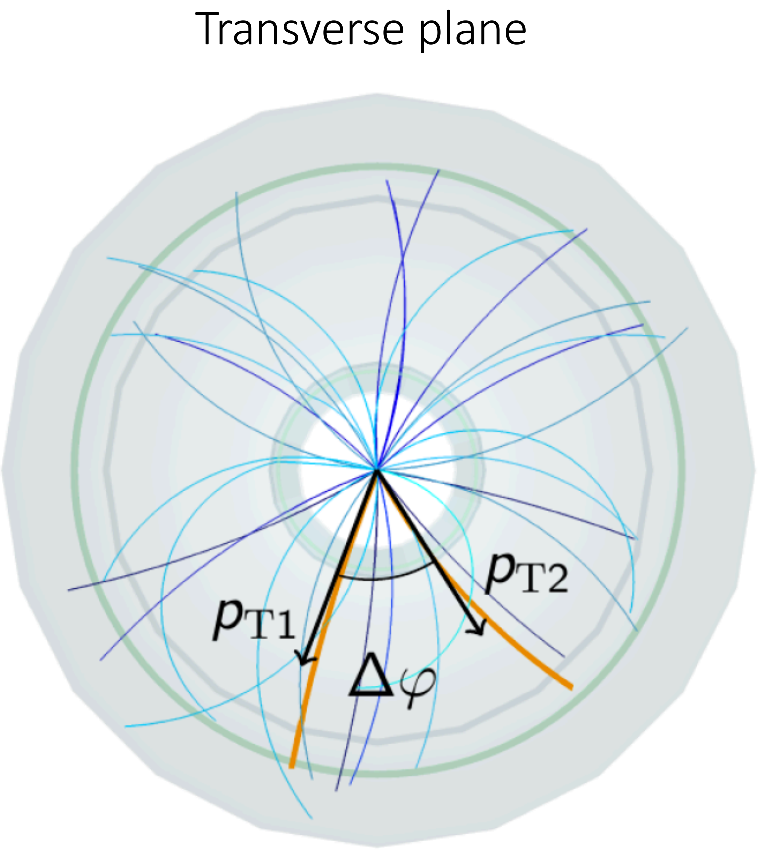
- These collisions produce "large" systems of *quarks* and *gluons* called the Quark-Gluon Plasma (our universe up to a few μs after BB)
- nearly perfect fluid (surprise!)
- Briefly ~100,000 times hotter than the core of the Sun.
- Thousands of particles are produced in every event.

We want to study the Quark Gluon Plasma (QGP)

We measure the correlations between identified particles

Correlation Variables





p — particle momentum
p_T — transverse momentum
φ — azimuthal angle
θ — polar angle
η — pseudorapidity
y — rapidity

$$p_T^2 = p_x^2 + p_y^2$$

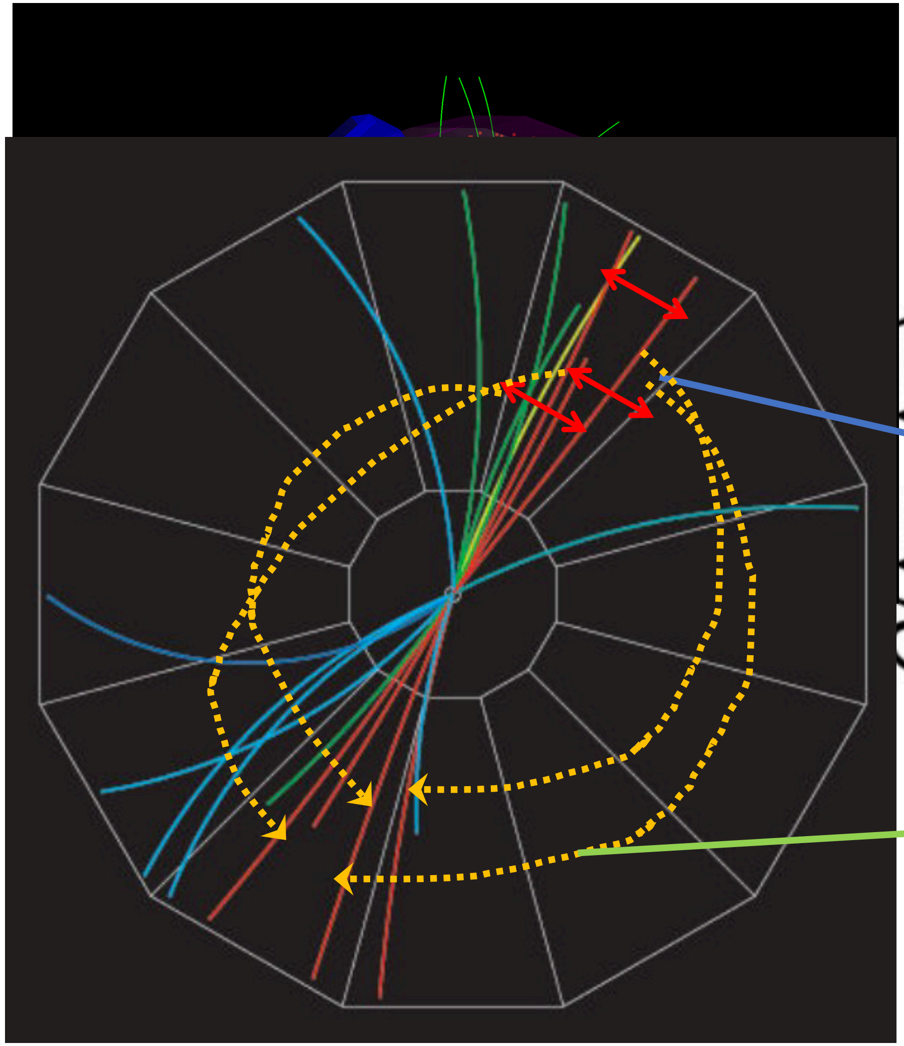
$$\eta \equiv -\ln\left[\tan(\frac{\theta}{2})\right] = \frac{1}{2}\ln\frac{|p| + p_z}{|p| - p_z}$$

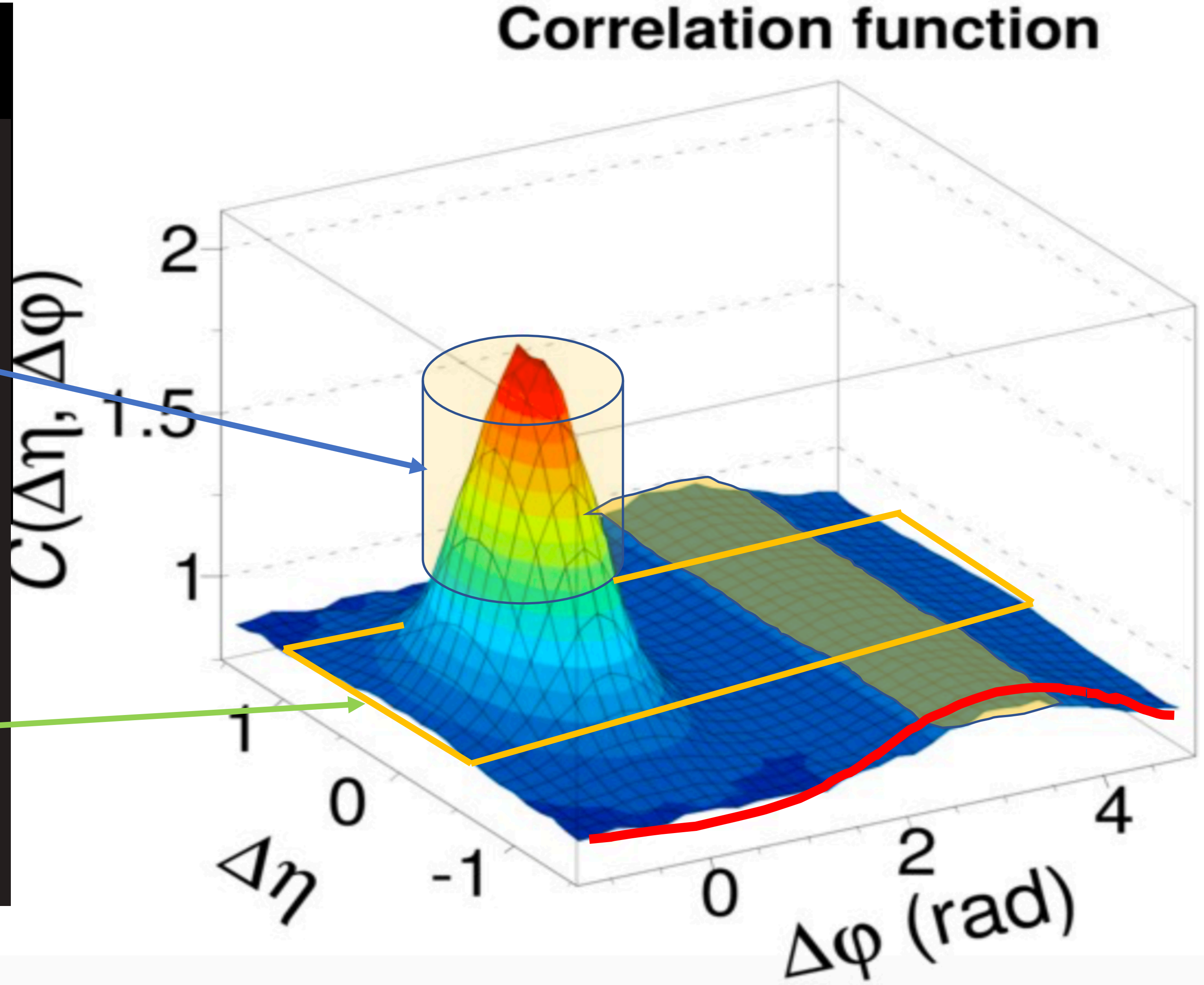
$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

Lorentz invariant

Two-particle Number **(Δ*η*,Δ*φ*)** Correlations

B3





Large Hadron Collider @ CERN

B4

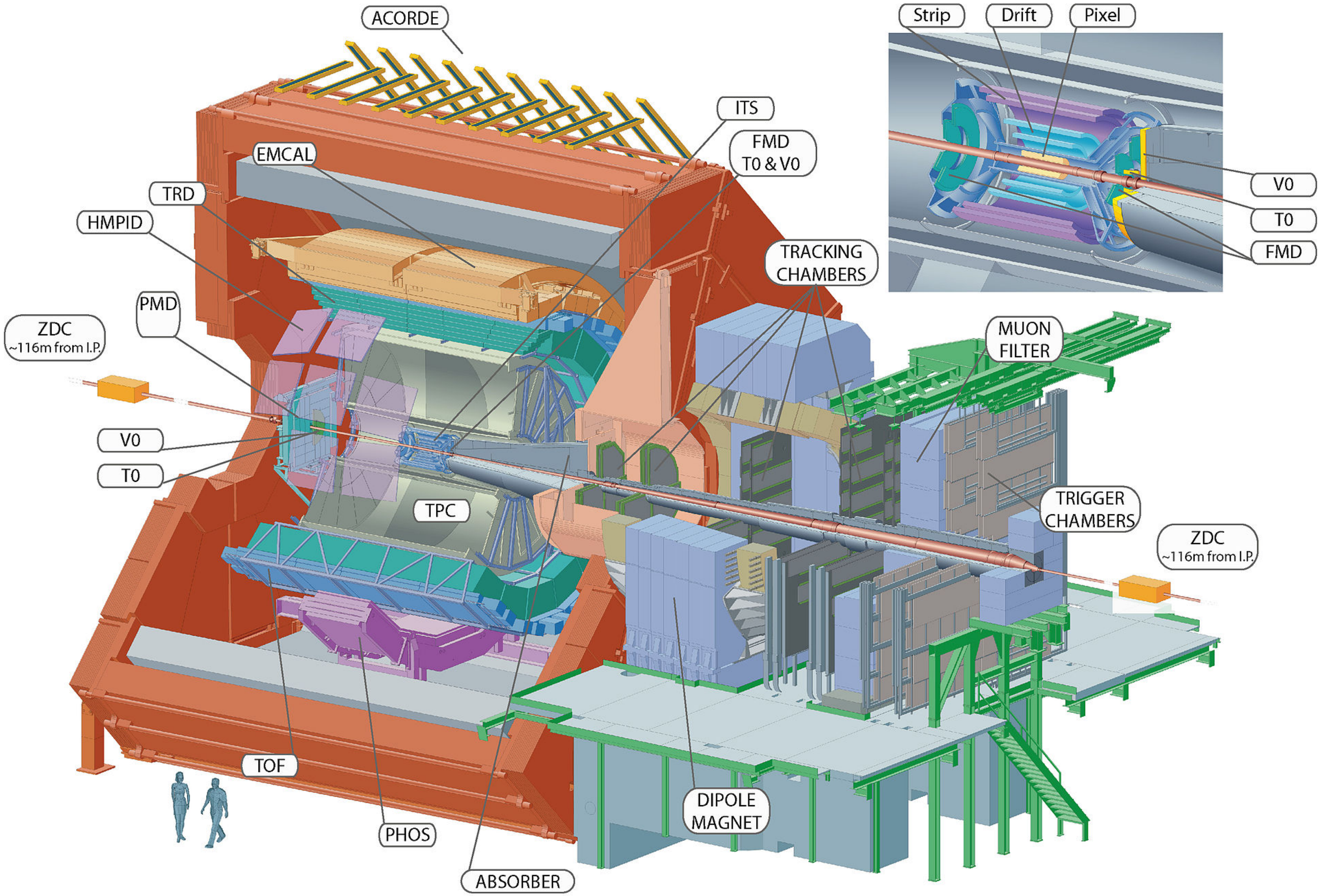
- Largest machinery ever built by human with the highest energy of collisions

27 kilometers (17 mi) in circumference ~ 100 meters (328 ft) underground

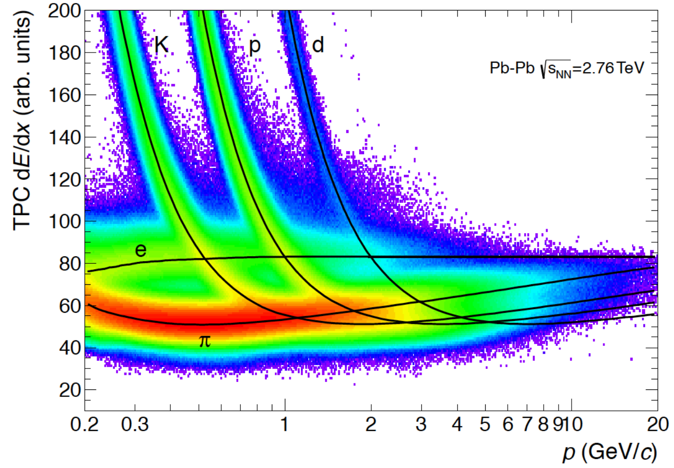
Lead ions are accelerated to more than 99.9999% of the speed of light and collide.

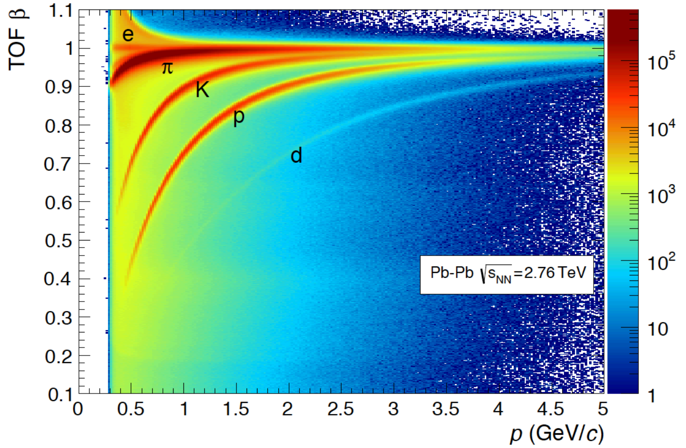
ALICE (A Large Ion Collider Experiment)

B5



Excellent particle identification capability





	$\pi^{\pm}$	$K^{\pm}$	p(p)
Purity	>97 %	>95%	~ 94%

Analysis Details

B6

Analysis done separately for ++ & -- magnetic field polarities, then averaged the BF results.

Event selection:
2.76 TeV Pb-Pb 2010
Production: LHC10h — AOD160
Accepted events: $14*10^6$,
Trigger: Minimum Bias,
Centrality selection: VZERO-M,
Longitudinal event vertex position range: |Vz|< 6 cm,

Common track selection:
TPC Only Tracks (filterBit = 1),
$N_{TPCclusters}$>70 out of a maximum of 159.

Track selection:
$\pi^{\pm}$: $0.2<p_T<2.0$ GeV/*c*,
$|y|<0.8$ in $\pi^{\pm}-\pi^{\pm}$; $|y|<0.7$ in cross-species BF.
$K^{\pm}$: $0.2<p_T<2.0$ GeV/*c*,
$|y|<0.7$.
$p(\bar{p})$: $0.5<p_T<2.5$ GeV/*c*,
$|y|<0.6$ in $p(\bar{p})-p(\bar{p})$; $|y|<0.7$ in cross-species BF.

PID	$\pi^{\pm}$	$K^{\pm}$	$p(\bar{p})$
TPC $0.2<p_T, p<0.8$ GeV	$n\sigma_{\pi}<2$, $n\sigma_{K,p}>3$, $n\sigma_e>1$	$n\sigma_K<2, n\sigma_{\pi,p}>3$, $n\sigma_e>1$	
TPC $0.5<p_T, p<1.0$ GeV			$n\sigma_p<2, n\sigma_{\pi,K}>3$, $n\sigma_e>1$
TOF $0.8<p, p_T<2.5$ GeV	$n\sigma_{\pi}<2$, $n\sigma_{K,p}>3$		
TPC + TOF $0.8<p, p_T<2.5$ GeV		$n\sigma_K<2$, $n\sigma_{\pi,p}>3$	
TOF $1.0<p, p_T<2.5$ GeV			$n\sigma_p<2$, $n\sigma_{\pi,K}>3$
DCAz	*< 2 cm*	*< 2 cm*	*< 2 cm*
DCAxy	*< 0.04 cm*	*< 2 cm*	*< 0.04 cm*
MisID	~ 1.2%	~ 4.7%	< 1%
Secondaries from weak decays	~ 1.4%	< 0.1%	< 5%
Secondaries from material	~ 0	~ 0.2%	<1 %
Purity Primary Particles	>97 %	>95%	~ 94%

Analysis Details:

Data sets LHC18q & LHC18r pass1

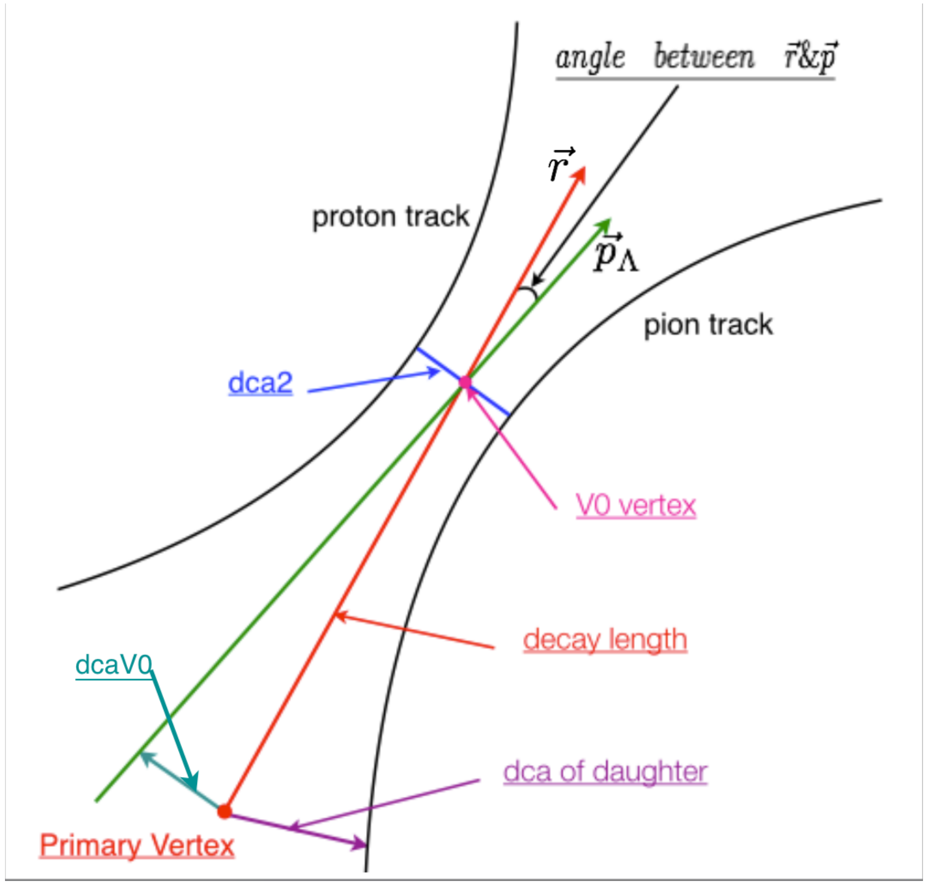
New

Runlist MagFieldMinus: RunList_LHC18q_pass1_CentralBarrelTracking_hadronPID.txt SSD SPD SDD V0 TPC TOF T0 ZDC 126 runs

Runlist MagFieldPlus: RunList_LHC18r_pass1_CentralBarrelTracking_hadronPID.txt SSD SPD SDD V0 TPC TOF T0 ZDC 90 runs

[anti]Λ cuts

Selection	Value
DCA proton to PV (cm)	>0.1
DCA pion to PV (cm)	>0.2
DCA V0 daughters (σ)	<0.8
Cosine of PA (signal loss)	5 %
V0 radius (cm)	>5
Proper lifetime (τ)	<2.5



Event SelecLon: V0M, |Vz| < 10 cm. Pile up cut
Track SelecLon: TPC Only Tracks (filterBit= 128)
$-0.7 < y < 0.7$
$0.6 < pT < 3.6$ GeV/c
nCluster >=70
$0 \leqq \phi \leqq 2\pi$