# *Long-range Correlations in Massive Jets*

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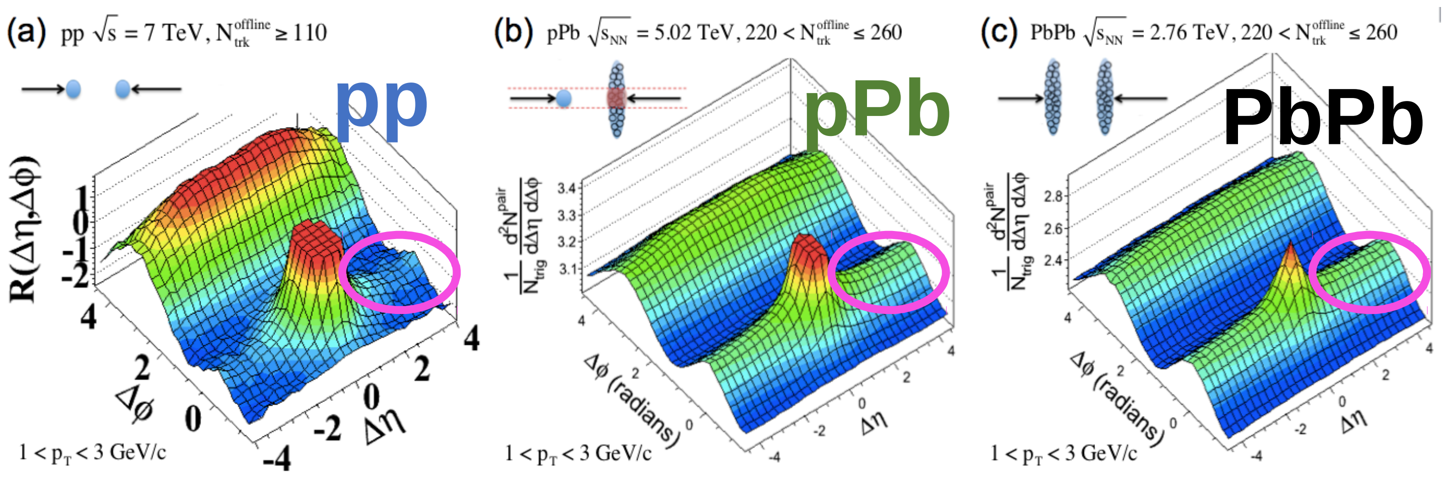
# Motivation

- People are looking for collectivity in pp and ee as a possible sign of QGP

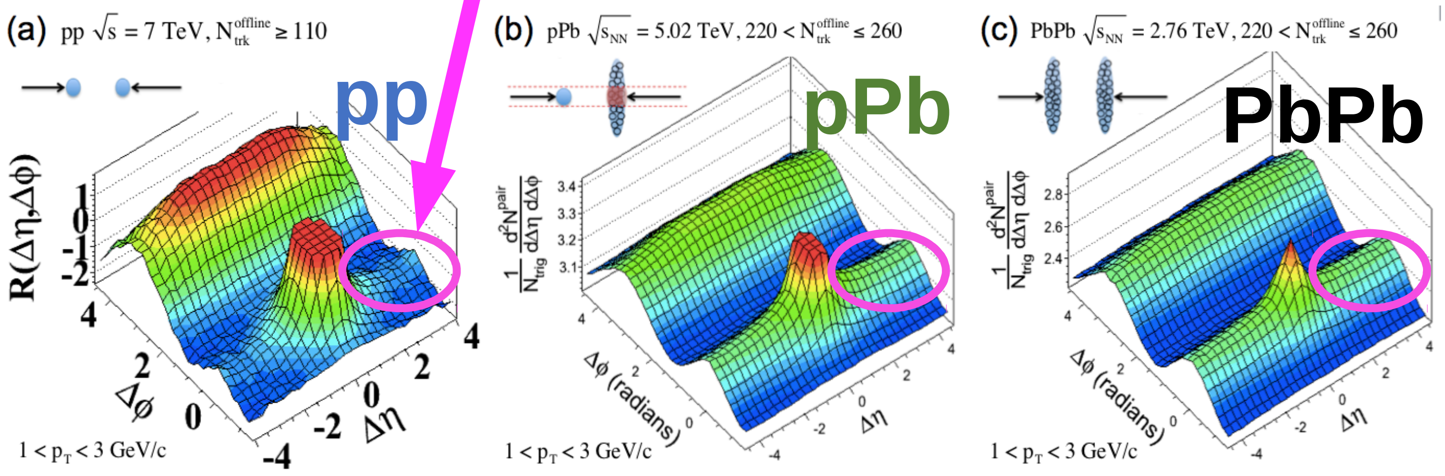
- long range $\Delta Y$ correlations are the signal of collectivity




- Is the near-side ridge in high-multiplicity pp events due to QGP or massive jets?

# *Motivation*

***Long-range $\Delta Y$ correlations may emerge due to highly virtual partons (massive jets) in the hard process***



# Motivation

***To get long range $\Delta Y$ correlations, we need massive jets***

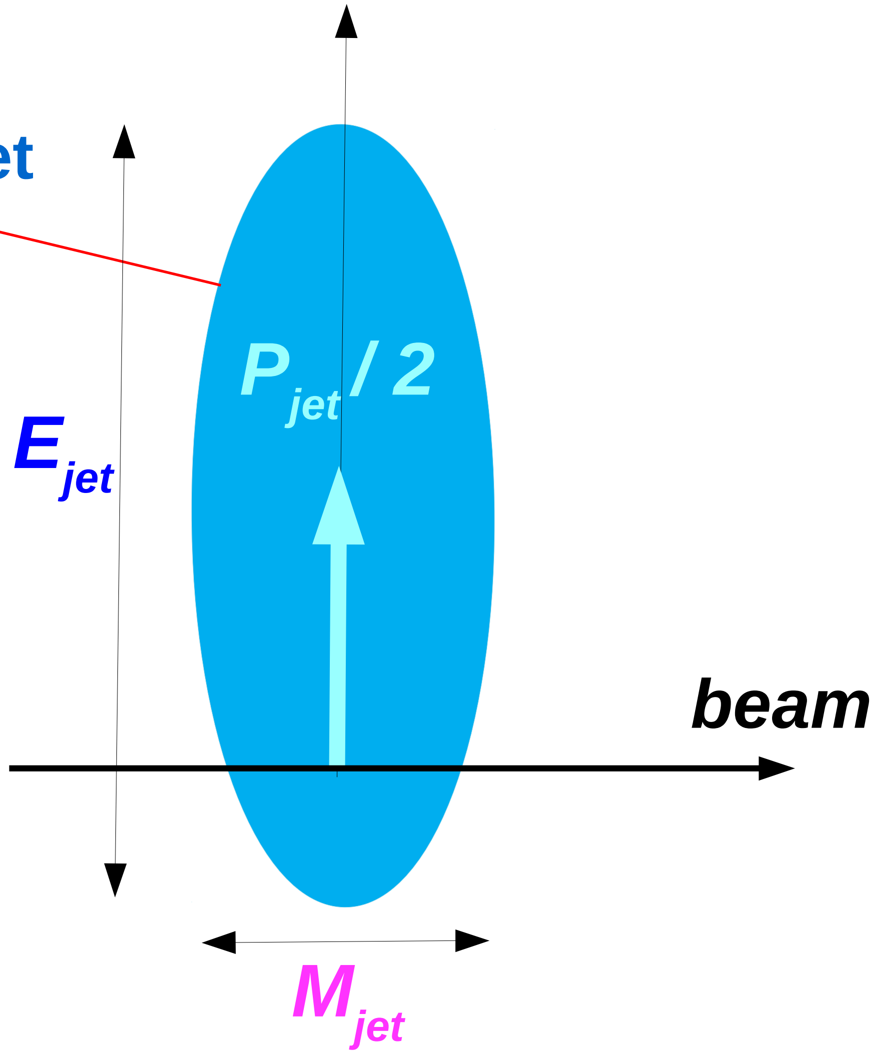
**phasespace of hadrons in a jet**

**initiated by a leading parton of**

**momentum** $P_\mu = (E_{jet}, \vec{P}_{jet})$

**is an ellipsoid of width** $M_{jet}$

**and length** $E_{jet}$

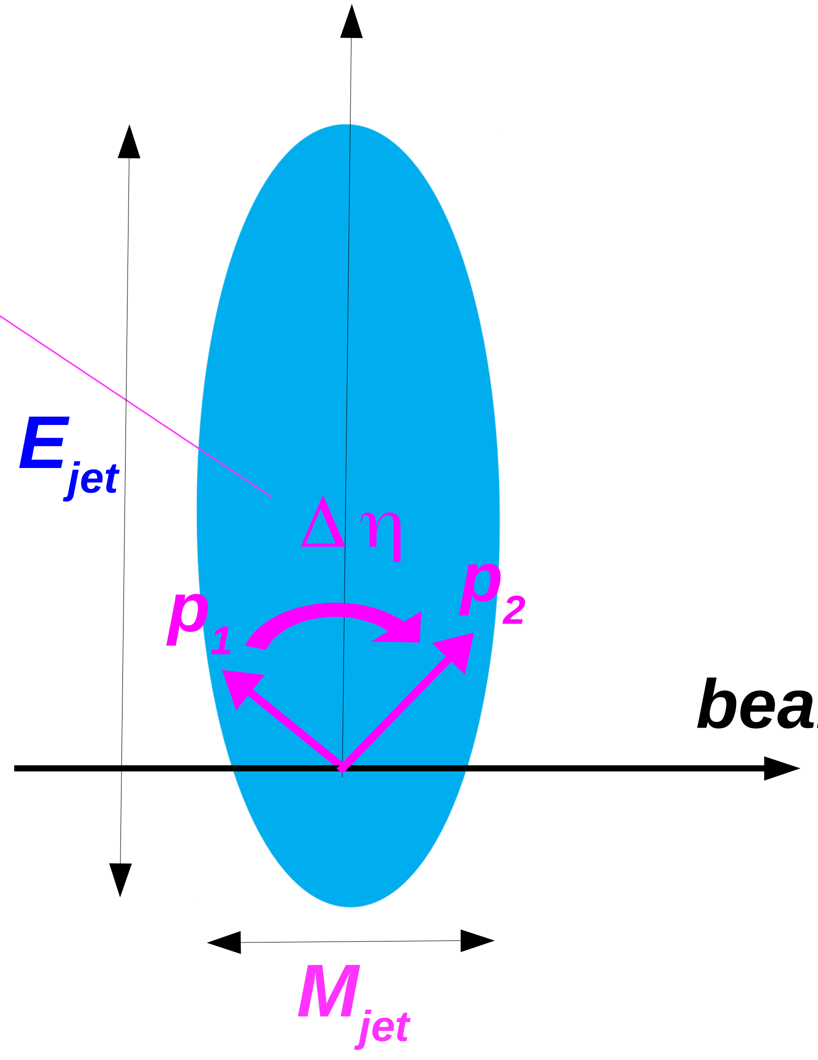


# *Motivation*

***To get long range ΔY correlations, we need massive jets***

**We can have hadrons with large ΔY**

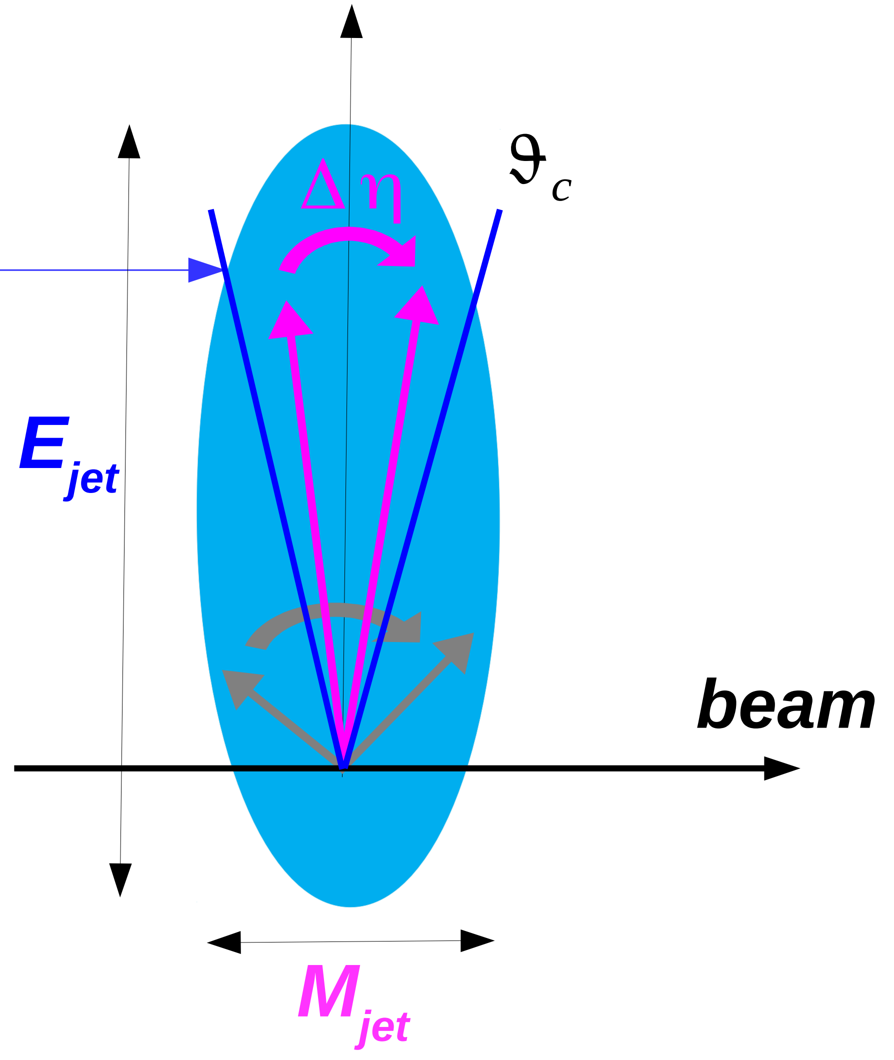
***if $p_1$ and $p_2$ are small enough***



# *Motivation*

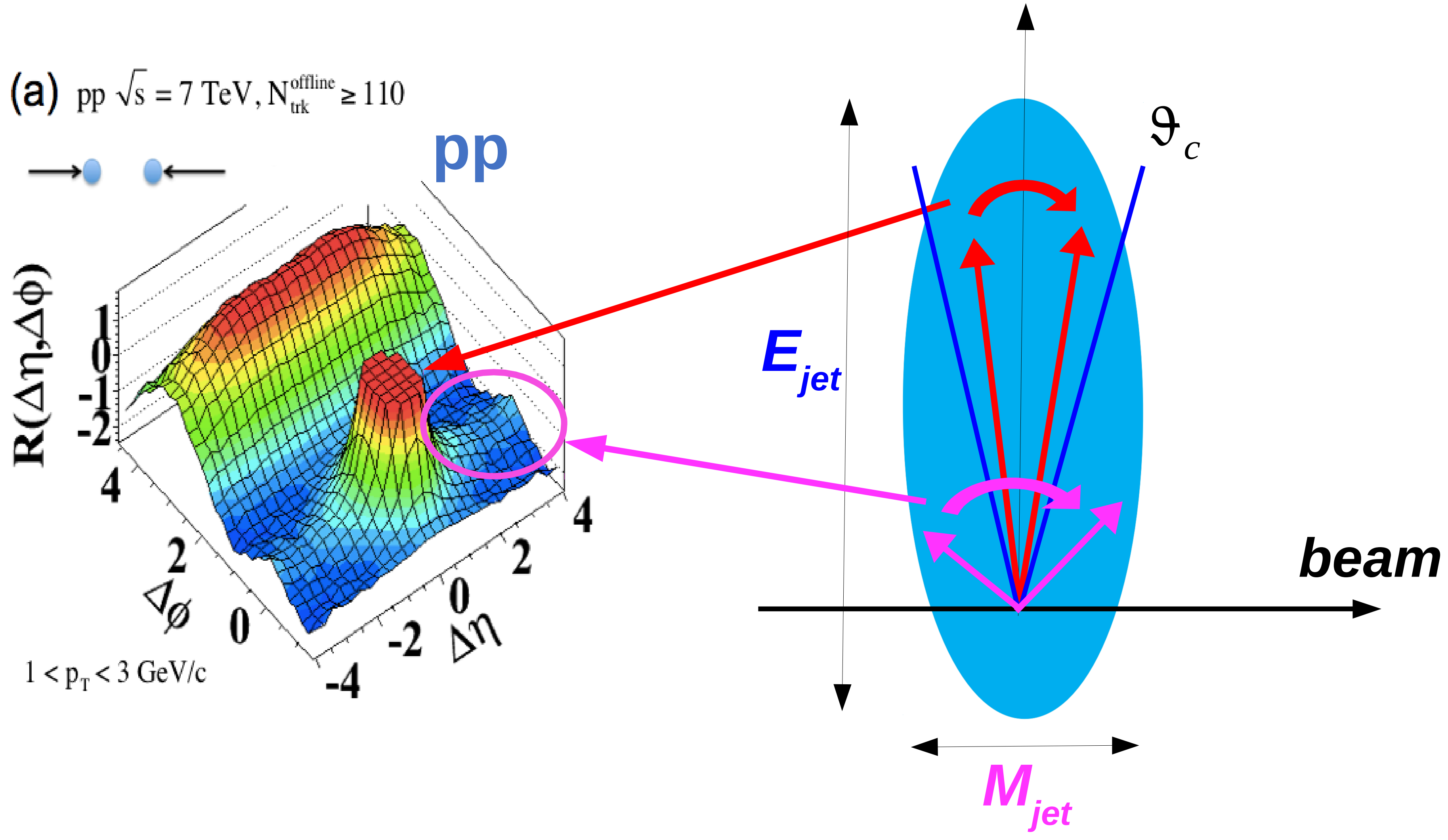
***To get long range ΔY correlations, we need massive jets***

**But, the jet cone might *exclude* hadrons with large *ΔY***



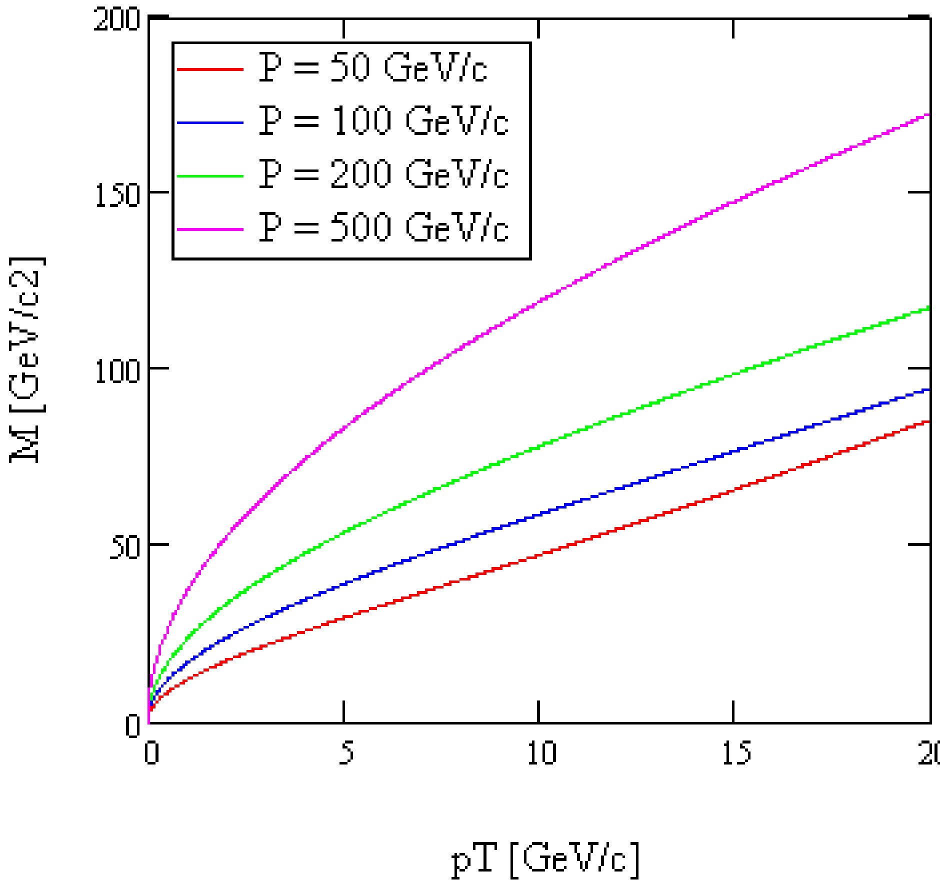
# *Motivation*

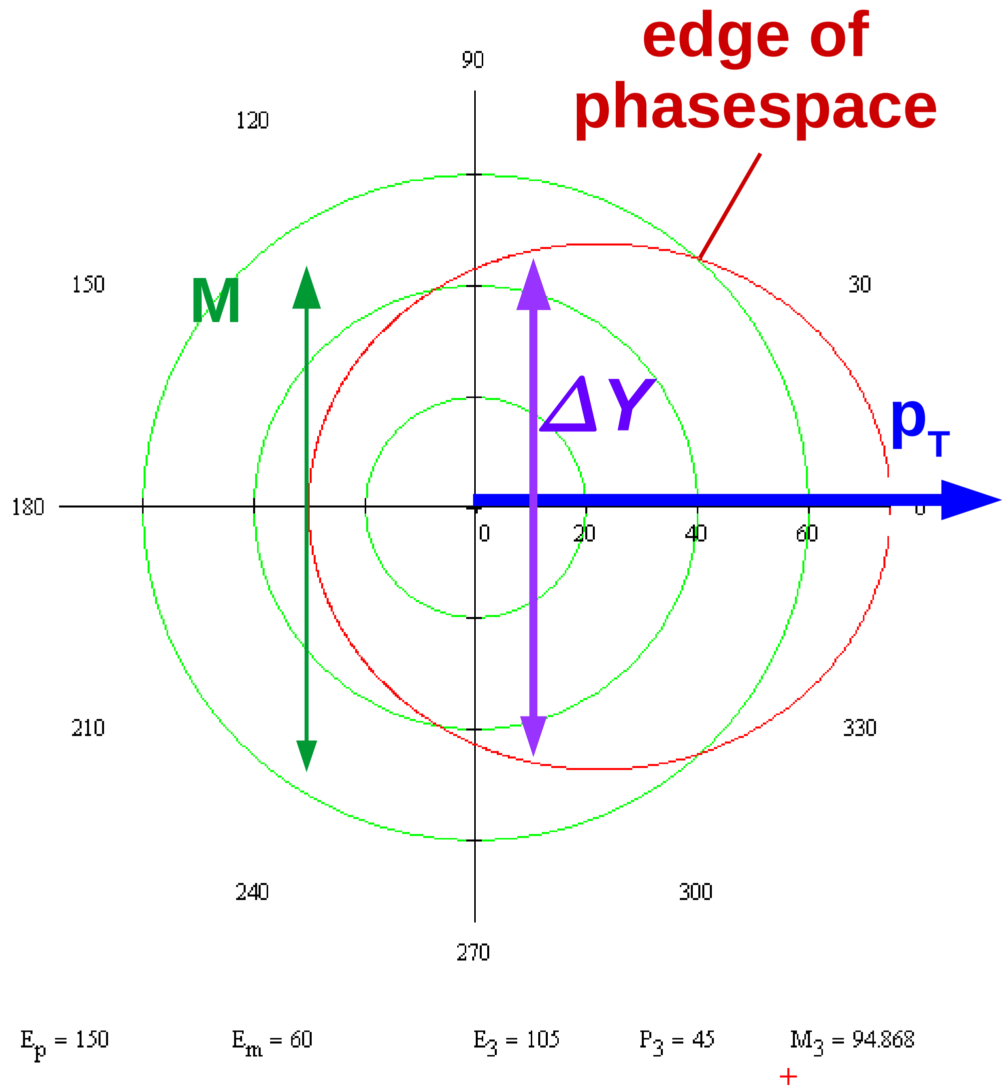
***To get long range ΔY correlations, we need massive jets***



# How large $M_{jet}$ do we need?

**Lets say, we calculate $v_2(p_T)$ from hadron pairs with $\Delta Y = 3$**



# Outline

- Off-shell fragmentation and scale evolution

- Long-range correlations of hadrons stemming from highly-virtual leading partons

- v2 in fix multiplicity jets

# *Outline*

- ***Off-shell fragmentation and scale evolution***

- ***Long-range correlations of hadrons stemming from highly-virtual leading partons***

- ***v2 in fix multiplicity jets***

# *Off-shell fragmentation function*

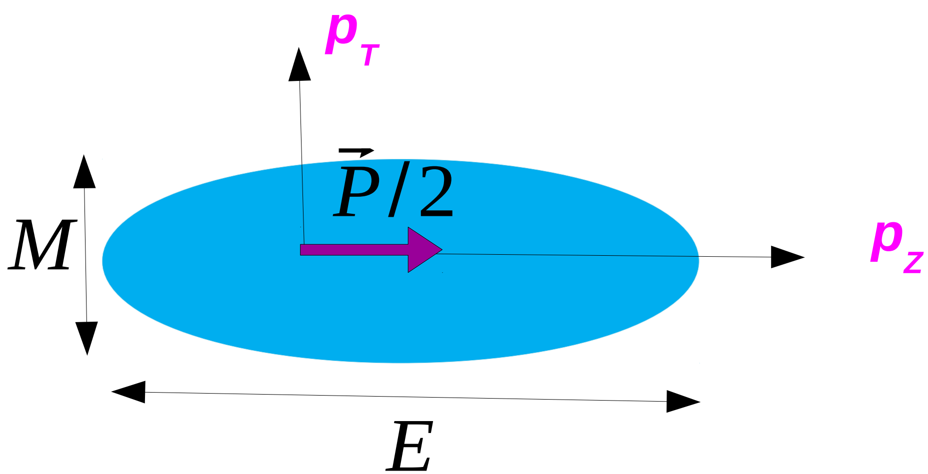
- ***Initial function** at starting scale $Q_0$*

- ***Scale evolution***

# Model for a jet at $Q_0$

- ***Statistical model* for the *initial FF* at starting scale:**

**The haron distribution in a jet of *n* hadron with total momentum *P***




$$p^0 \frac{d\sigma}{d^3 p}^{n=fix} \propto \left(1 - x_1\right)^{\boxed{n-3}}$$

$$p_1^0 p_2^0 \frac{d\sigma}{d^3 p_1 d^3 p_2}^{n=fix} \propto \left(1 - x_1 - x_2 + x_{12}\right)^{\boxed{n-4}}$$

$$x_1 = 2 P_\mu p_1^\mu / M^2, \qquad x_{12} = 2 p_{1\mu} p_2^\mu / M^2$$

- ***Averaging over multiplicity fluctuations of the form of*** $\boxed{P(n) = \binom{n+r-1}{r-1} \tilde{p}^n (1-\tilde{p})^r}$

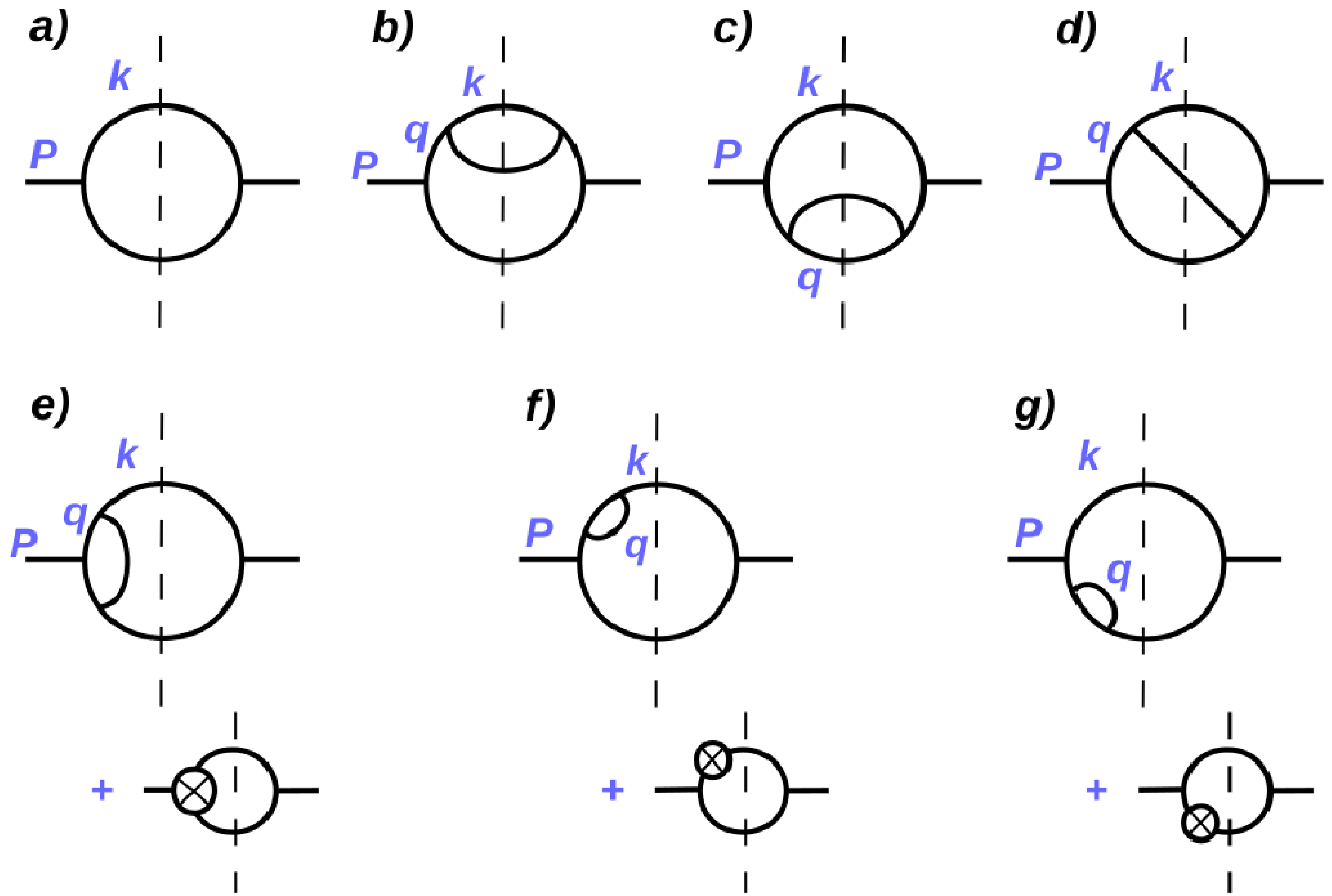
***results in an initial FF of the form of***

$$\boxed{p^0 \frac{d\sigma}{d^3 p} = A\left[1 + \frac{q-1}{\tau} x\right]^{-1/(q-1)}}$$

***Urmossy et.al,*** *Eur. Phys. J. A (2017) 53: 36 ; PLB*, **701**: 111-116 (2011) ; *PLB*, **718**, 125-129, (2012)

# Off-shell Scale-evolution (in the $\varphi^3$ theory)

**Difference from the standard way: the leading parton is off-shell**



# Thus, the fragmentation scale is the jet mass

**Hadron spectrum: leading parton (of momentum *P*) emits on-shell daughter partons (of momentum *k*) that fragment to hadrons at low virtuality $m_0$**

$$D\left(x,P^2\right) = \int \frac{dz}{z} \left\{\delta(1-z)+g^2 A\left(z,P^2\right)\right\} D_0\left(\frac{x}{z},m_0^2\right)$$

**Which can be inverted (up to O(g²))**

$$D_0\left(x,m_0^2\right) = \int \frac{dz}{z} \left\{\delta(1-z)-g^2 A\left(z,P^2\right)\right\} D\left(\frac{x}{z},P^2\right)$$

**Differentiate wrt ln(P²)** → ***DGLAP equation***

$$\frac{\partial}{\partial \ln P^2} D\left(x,P^2\right) = \int \frac{dz}{z} D\left(\frac{x}{z},P^2\right) g^2 \boxed{\frac{\partial}{\partial \ln P^2} A\left(z,P^2\right)} \longrightarrow \textit{splitting function } P(z)$$

$$\frac{\partial}{\partial \ln P^2} \tilde{D}\left(\omega,P^2\right) = \tilde{D}\left(\omega,P^2\right) g^2 \tilde{P}(\omega) \quad \leftarrow \quad \tilde{f}(\omega)=\int_0^1 dx\, x^{\omega-1} f(x)$$

$$\tilde{D}\left(\omega,P^2\right) = \tilde{D}_0\left(\omega,m_0^2\right) \exp\left[\tilde{P}(\omega)\, b\left(P^2\right)\right]$$

# Model for a jet

- **Scale evolution of the parameters of the model:**

  - ***approximation:***

$$D(x,t) \;=\; \int_x^1 \frac{dz}{z} f(z,t)\left(1+\frac{q_0-1}{\tau_0}\frac{x}{z}\right)^{1/(q_0-1)} \neq \left(1+\frac{q(t)-1}{\tau(t)}x\right)^{1/(q(t)-1)}$$

  - **Prescription for a few moments of D:**

$$t=\ln\left(\;M_{jet}^2\;/\;\Lambda^2\;\right)$$

$$\int D_{apx}(x,t) \;=\; \int D(x,t)$$

$$\int x\,D_{apx}(x,t) \;=\; \int x\,D(x,t) \;=\; 1$$

(by definition)

$$\int x^2 D_{apx}(x,t) \;=\; \int x^2 D(x,t)$$

$$\Rightarrow$$

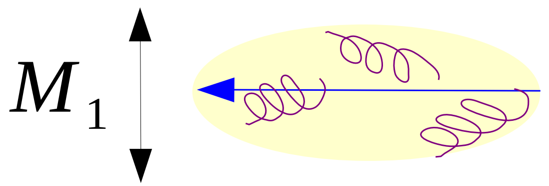
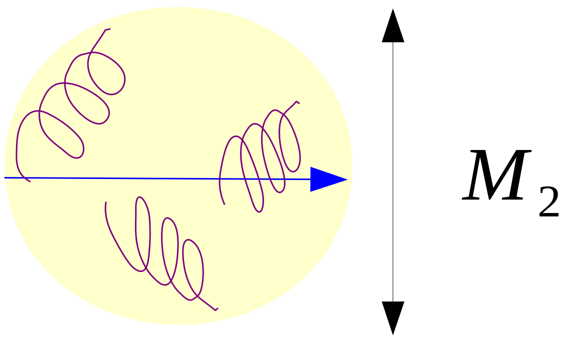
$$q(t)=\frac{\alpha_1(t/t_0)^{a1}-\alpha_2(t/t_0)^{-a2}}{\alpha_3(t/t_0)^{a1}-\alpha_4(t/t_0)^{-a2}}$$

$$\tau(t)=\frac{\tau_0}{\alpha_4(t/t_0)^{-a2}-\alpha_3(t/t_0)^{a1}}$$

$$a_1=\tilde{P}(1)/\beta_0,\quad a_2=\tilde{P}(3)/\beta_0$$

Urmossy, Eur. Phys. J. A (2017) 53: 36

## ***Scale = jet mass!!!***

| | **Inside *light jets*** | **Inside *heavy jets*** |
|---|---|---|
| |  |  |
| **The *fragmentation function:*** | $D(x) \approx \exp\{-x/\tau\}$ | $D(x) \approx \left(1+\frac{q-1}{\tau}x\right)^{-1/(q-1)}$ |
| **The *multiplicity distribution:*** | $P(n) \approx \frac{(1/\tau)^n}{n!}e^{-1/\tau}$ | $P(n) \approx \binom{n+r-1}{r-1}\tilde{p}^n(1-\tilde{p})^r$ |

$$\tilde{p} = (q-1)/(\tau+q-1)$$
$$r = 1/(q-1)-3$$

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# *Evolution of multiplicity*

**Evolution of the mean *multiplicity* and its *dispersion:***

$$\langle n \rangle \;=\; \frac{4-3\mathrm{q}_0}{\tau_0}\left(t/t_0\right)^{-a2} \;\sim\; \ln^a\left(M_{jet}\right)$$

$$\langle n^2 \rangle - \langle n \rangle^2 \;=\; \langle n \rangle \left[\frac{3-2\mathrm{q}_0}{\tau_0}\left(t/t_0\right)^{a1} \;+\; 1 \;-\; \langle n \rangle\right]$$

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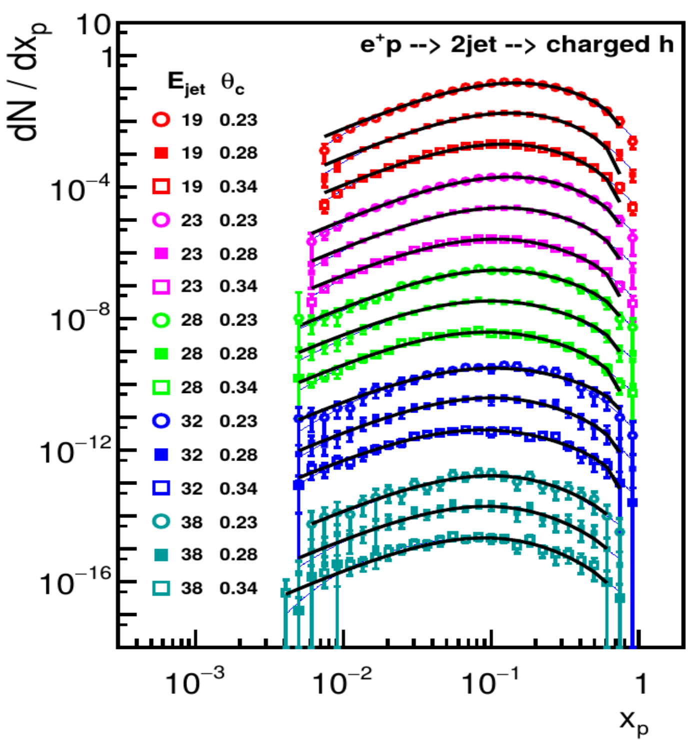
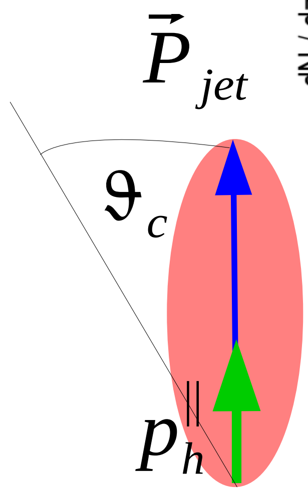
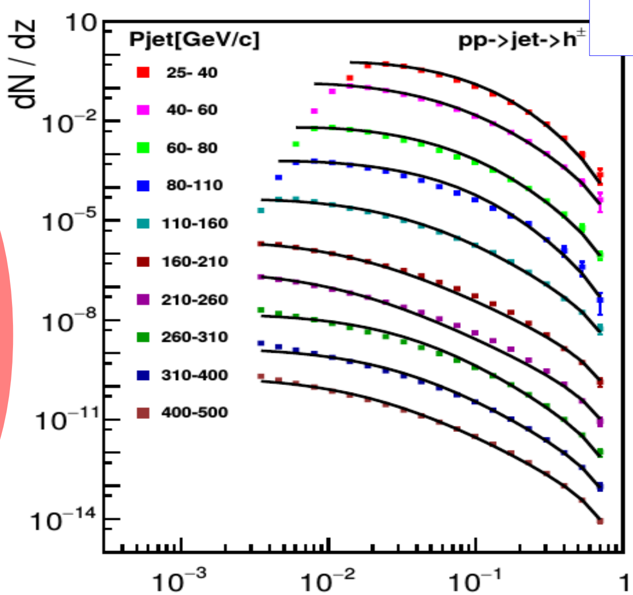
# The *model works* for *longitudinal* and *transverse* momentum *distributions* in jets

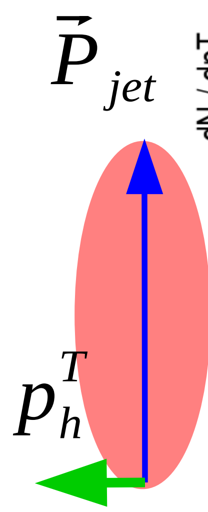
**$e^+P \rightarrow$ 2 jets**

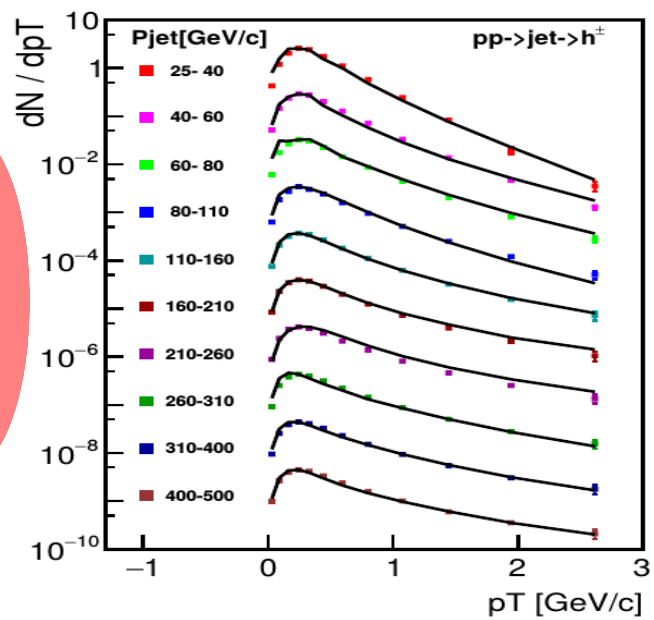



**PP**



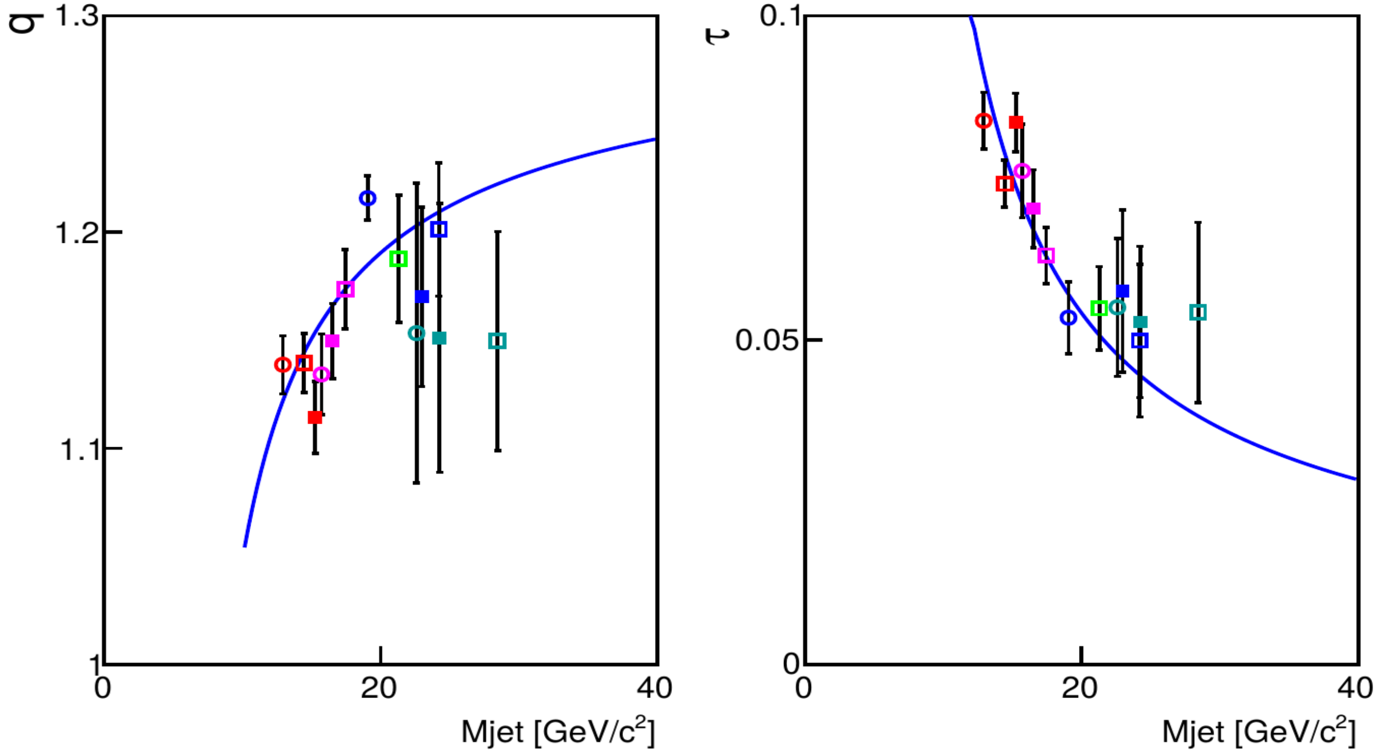





Urmossy, Eur. Phys. J. A (2017) 53: 36
proc. of conf.: ***DIS2016***, arXiv:1605.06876

# Scale evolution of the fit parameters




$$q(t)=\frac{\alpha_1(t/t_0)^{a1}-\alpha_2(t/t_0)^{-a2}}{\alpha_3(t/t_0)^{a1}-\alpha_4(t/t_0)^{-a2}} \qquad \tau(t)=\frac{\tau_0}{\alpha_4(t/t_0)^{-a2}-\alpha_3(t/t_0)^{a1}}$$

$$t=\ln\left(M_{jet}^2/\ \Lambda^2\right)$$

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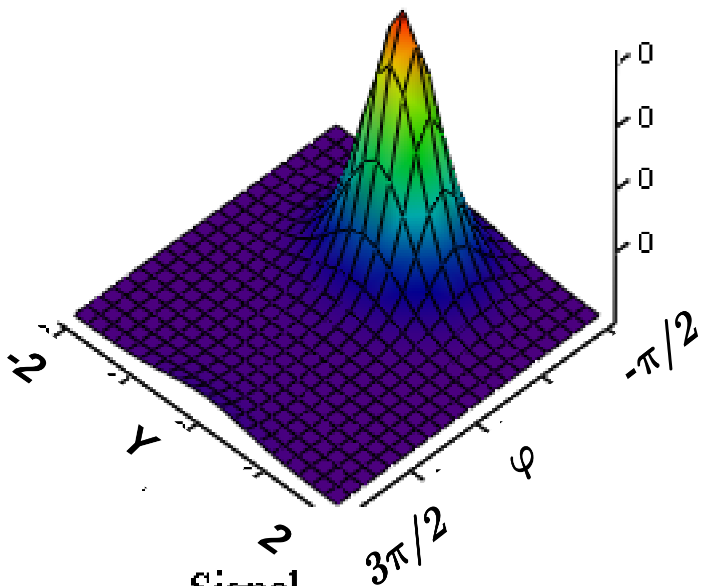
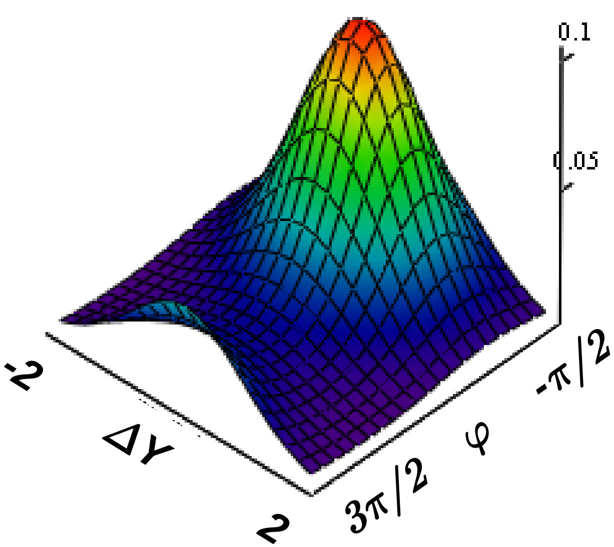
# Long-range correlations in fat jets

1-particle distribution

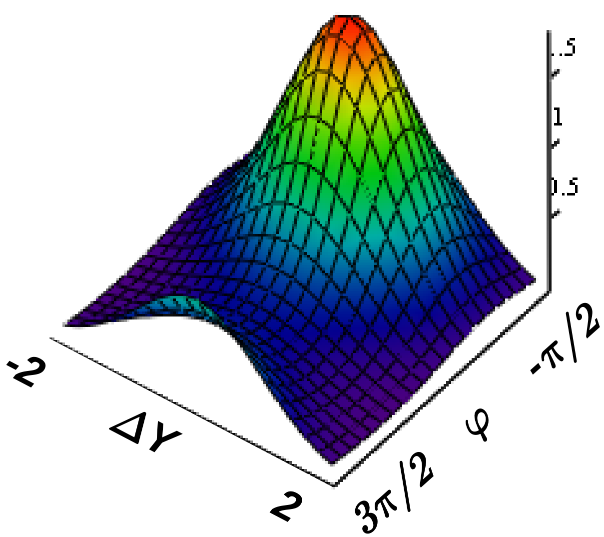



***E* = *110*** GeV
***P* = *85*** GeV/c
***M* = *70*** GeV/c²

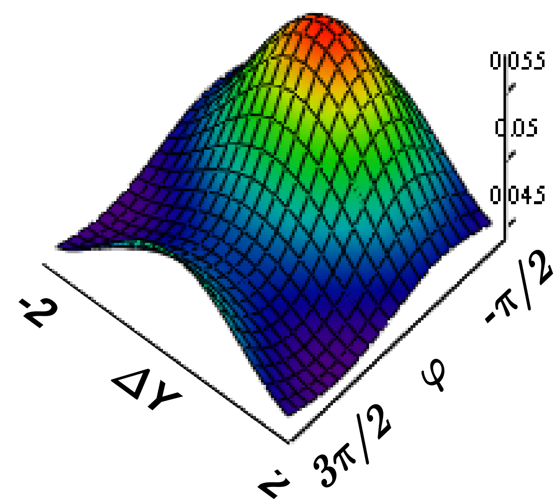
Signal



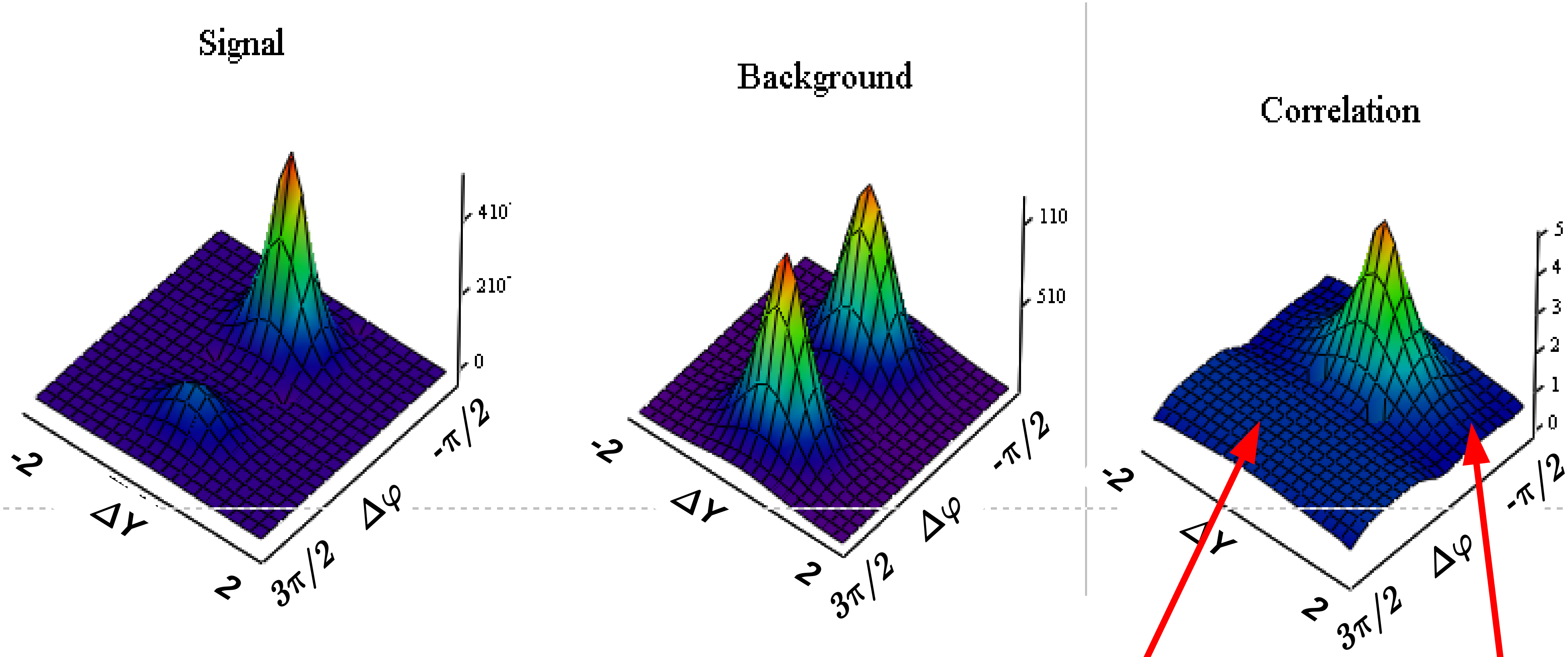

Background




Correlation

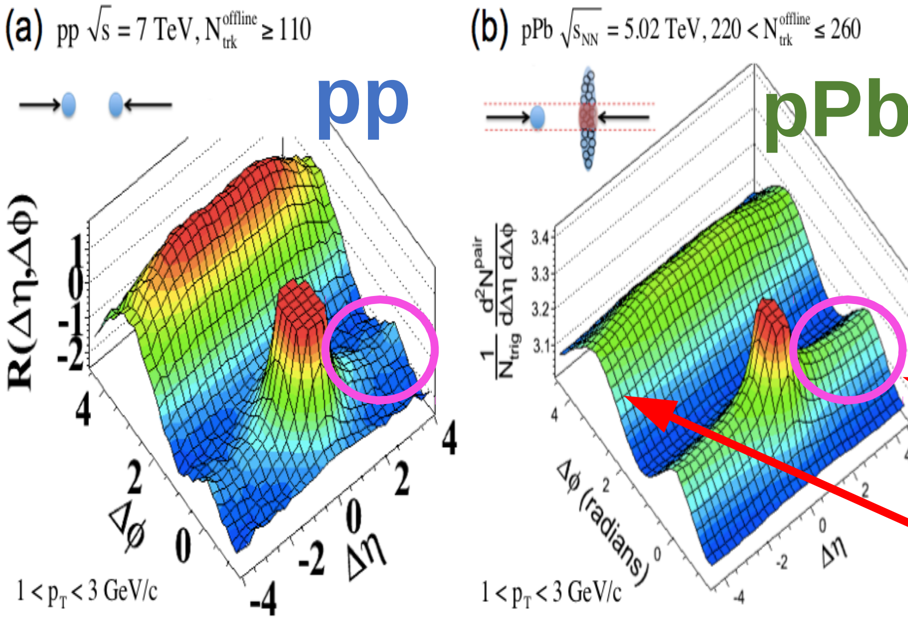


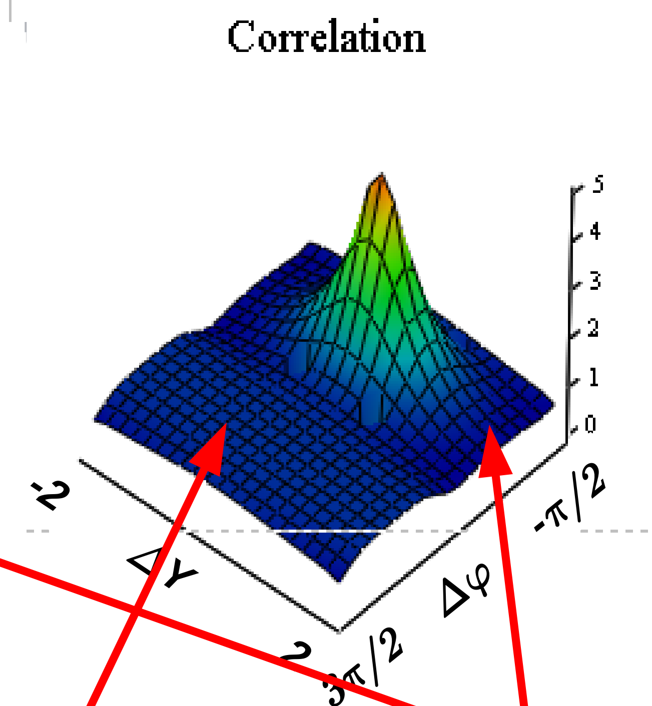
# *Long-range correlations in fat jets*




***away* and *near-side***
***ridge-like structure***

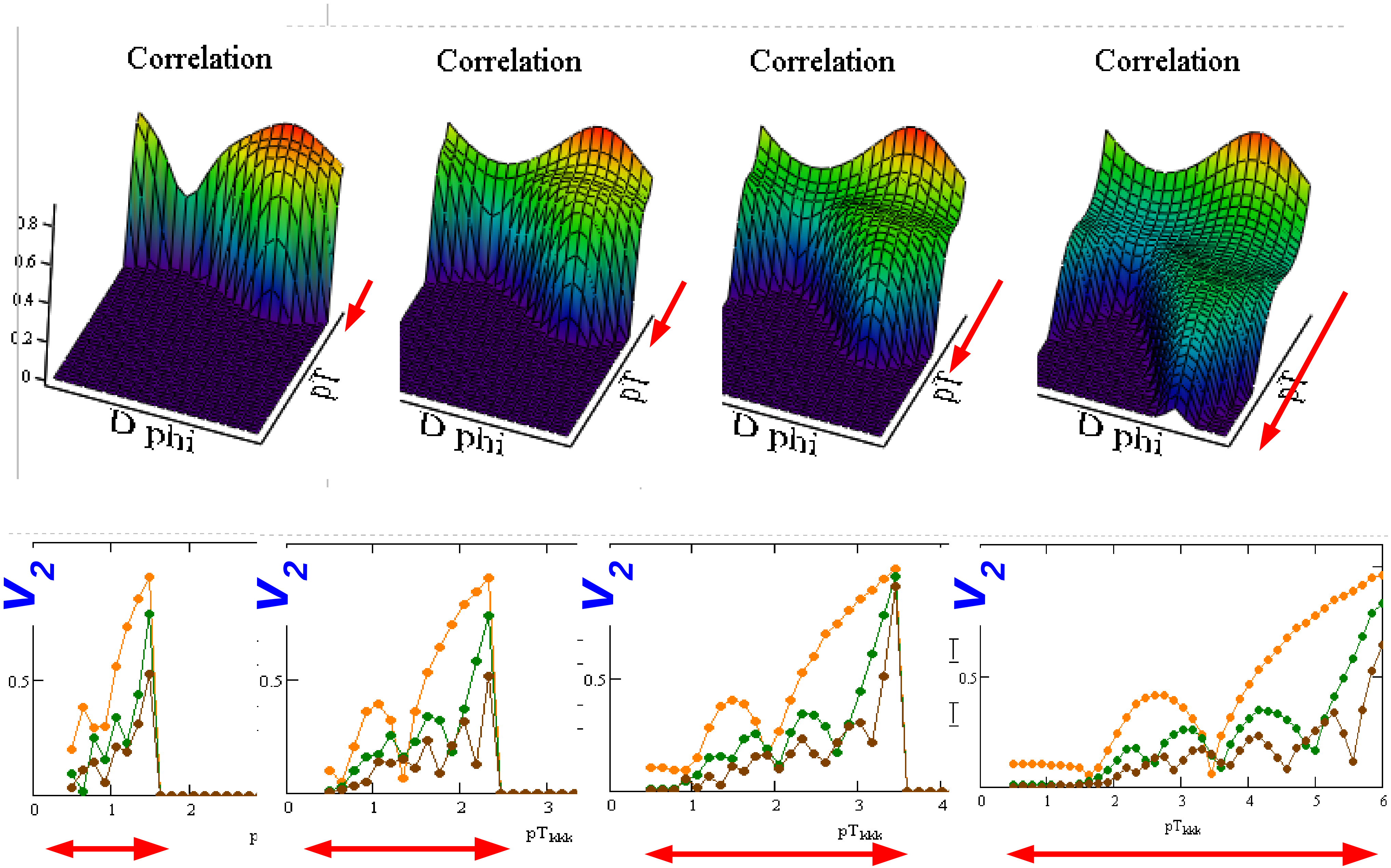
# Long-range correlations in fat jets



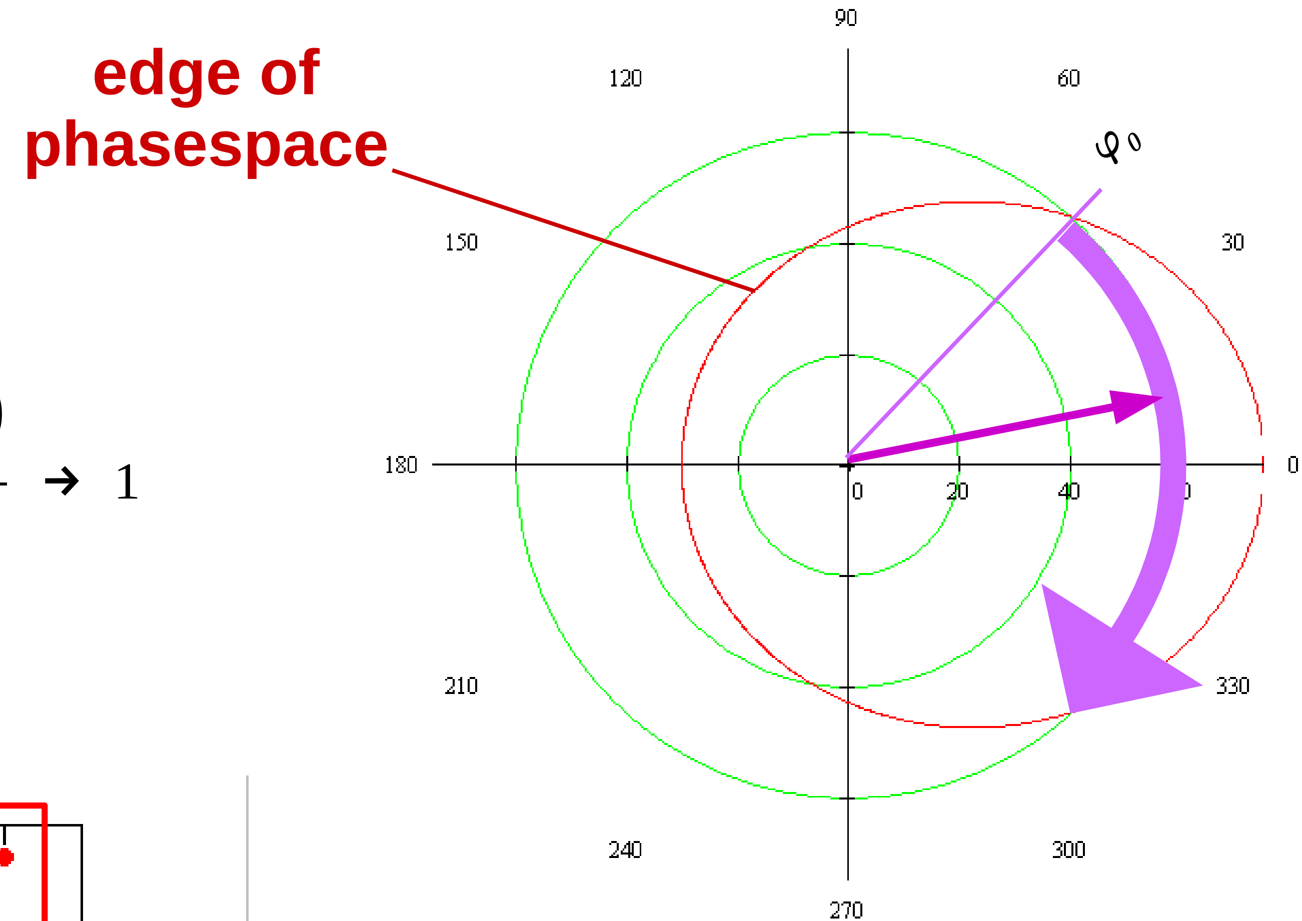




**away and near-side**
**ridge-like structure**

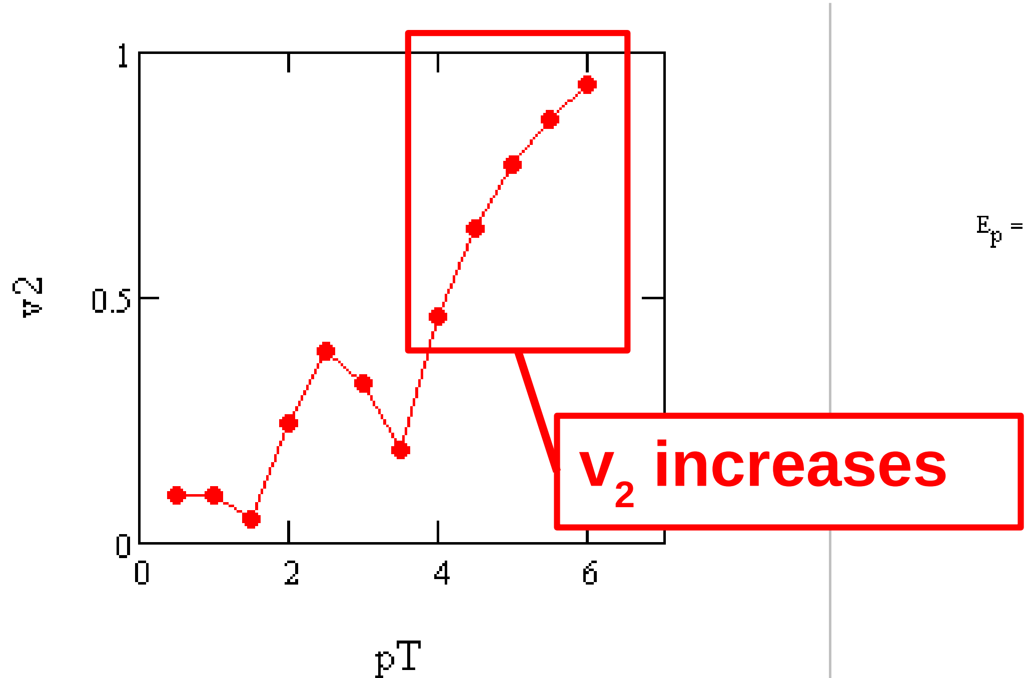
# v2 from large $2<|\Delta\eta|<4$ correlations



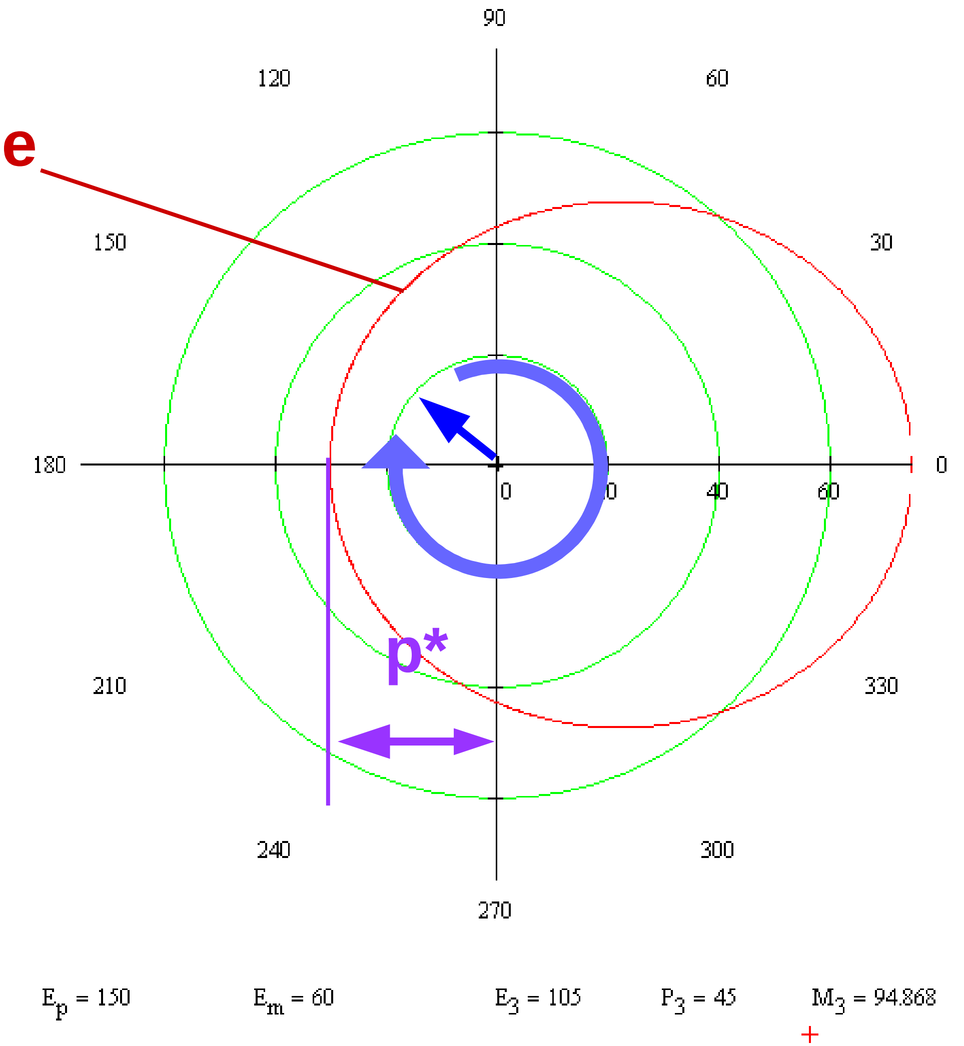
$$v_2 = \frac{\int_{-\varphi_0}^{\varphi_0} d\varphi\, f(\varphi) \cos(n\varphi)}{\int_{-\varphi_0}^{\varphi_0} d\varphi\, f(\varphi)} \rightarrow 1$$




$E_p = 150$ $E_m = 60$ $E_3 = 105$ $P_3 = 45$ $M_3 = 94.868$

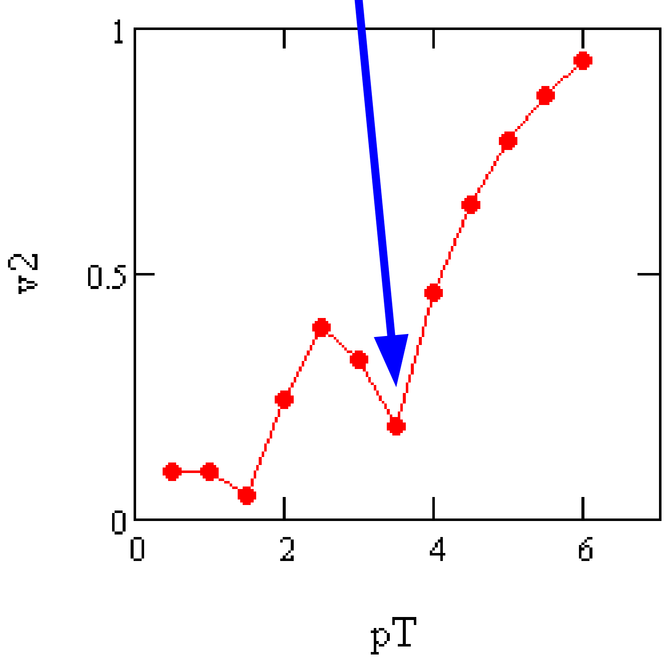


**edge of phasespace**

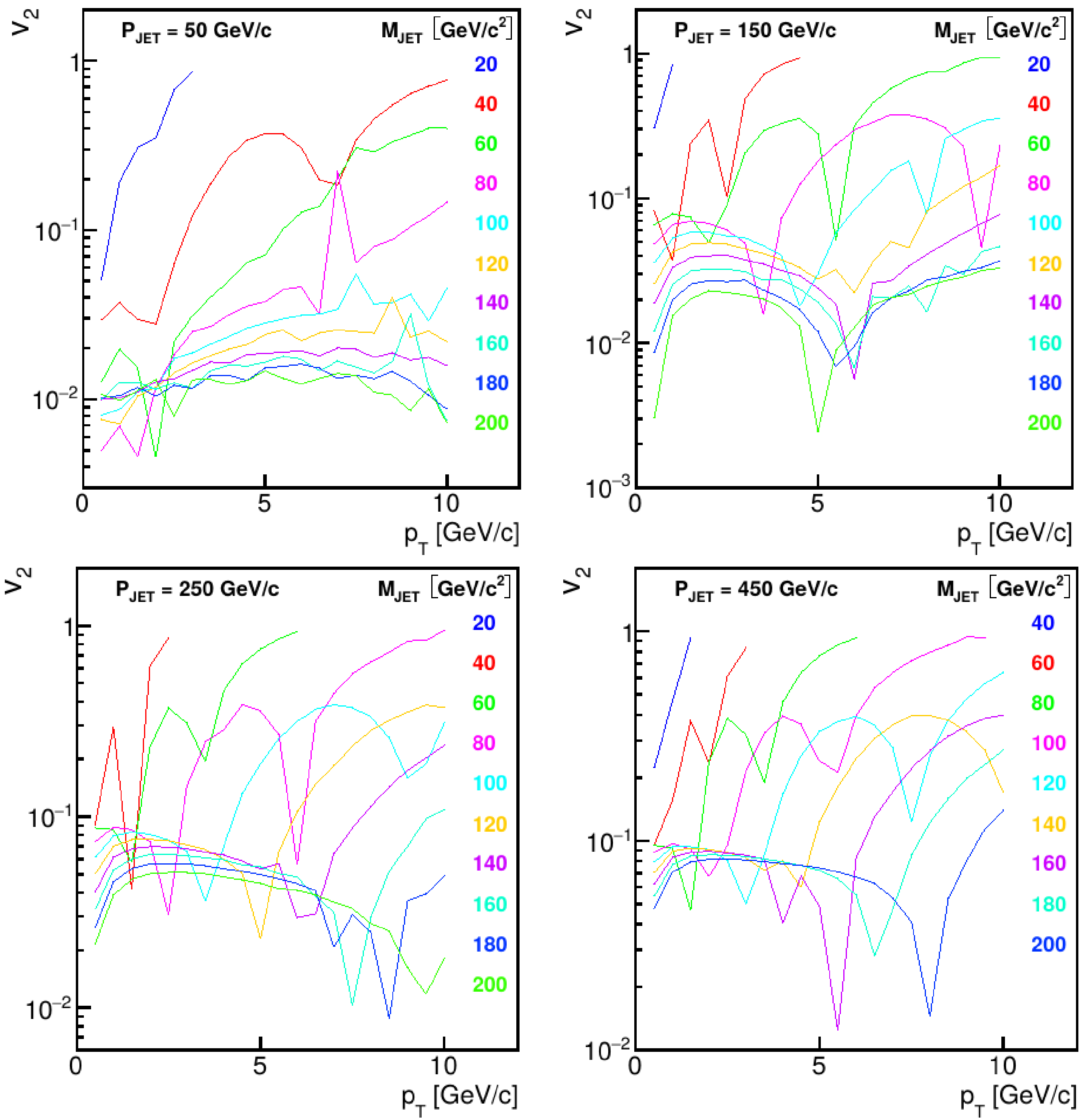



$$p^* = \frac{E_{JET} - P_{JET}}{2}$$

**position of this minimum**

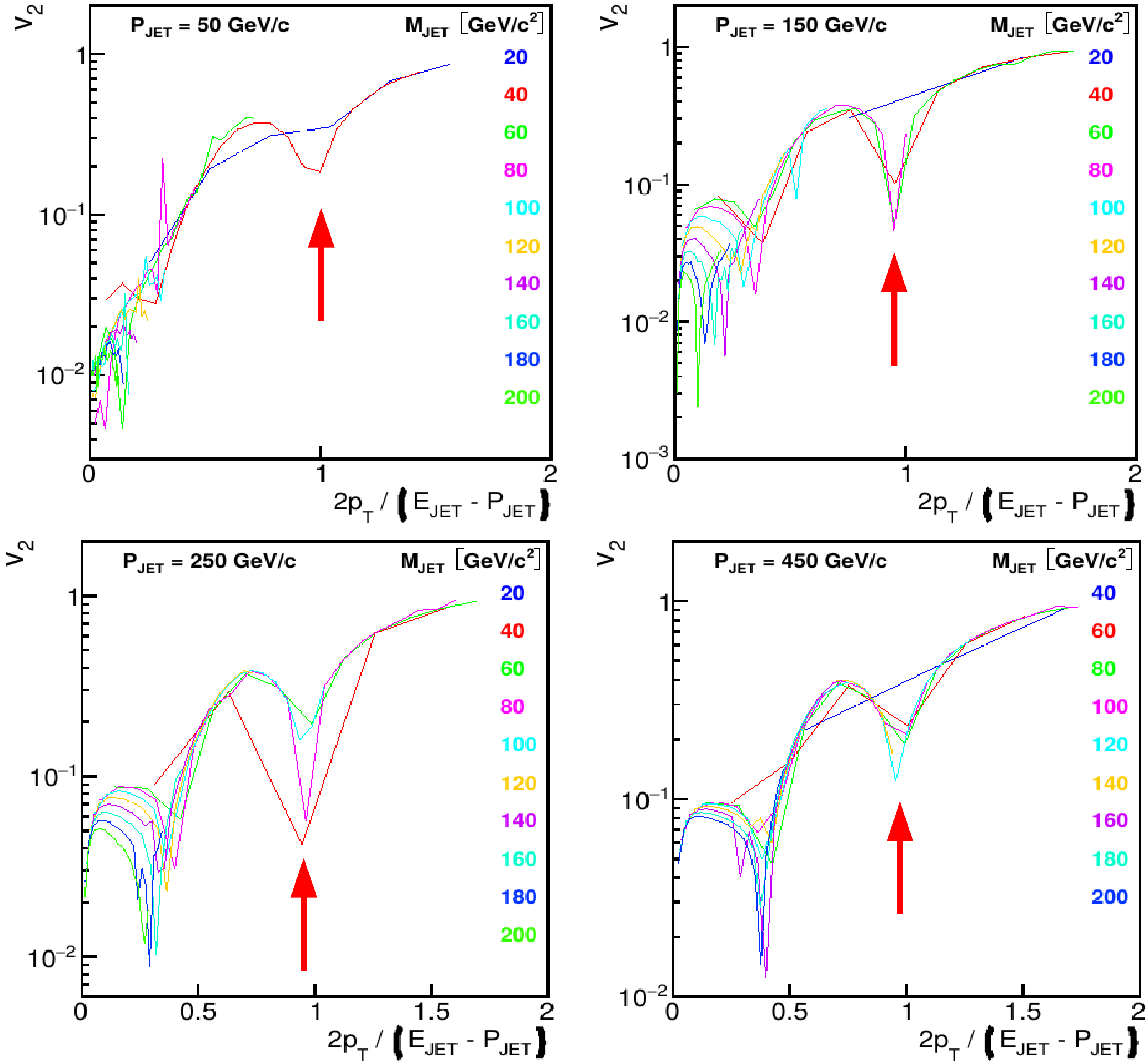


# $v_2$ in 1 jet

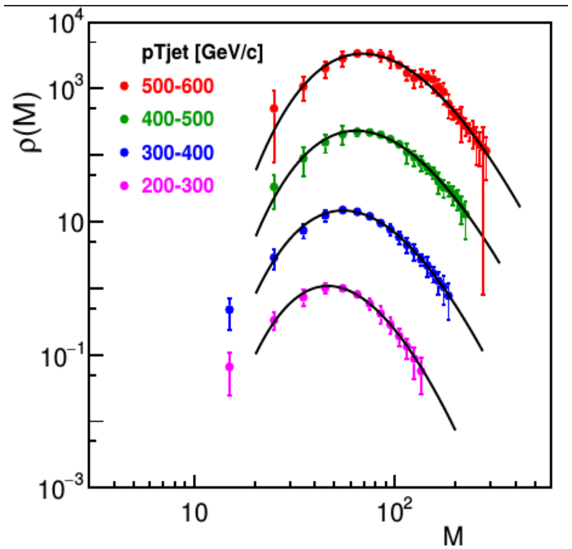


$P_{JET}$ = 50 GeV/c
$M_{JET}$ [GeV/$c^2$]
20
40
60
80
100
120
140
160
180
200
$P_{JET}$ = 150 GeV/c
$M_{JET}$ [GeV/$c^2$]
20
40
60
80
100
120
140
160
180
200
$P_{JET}$ = 250 GeV/c
$M_{JET}$ [GeV/$c^2$]
20
40
60
80
100
120
140
160
180
200
$P_{JET}$ = 450 GeV/c
$M_{JET}$ [GeV/$c^2$]
40
60
80
100
120
140
160
180
200
$v_2$
$p_T$ [GeV/c]

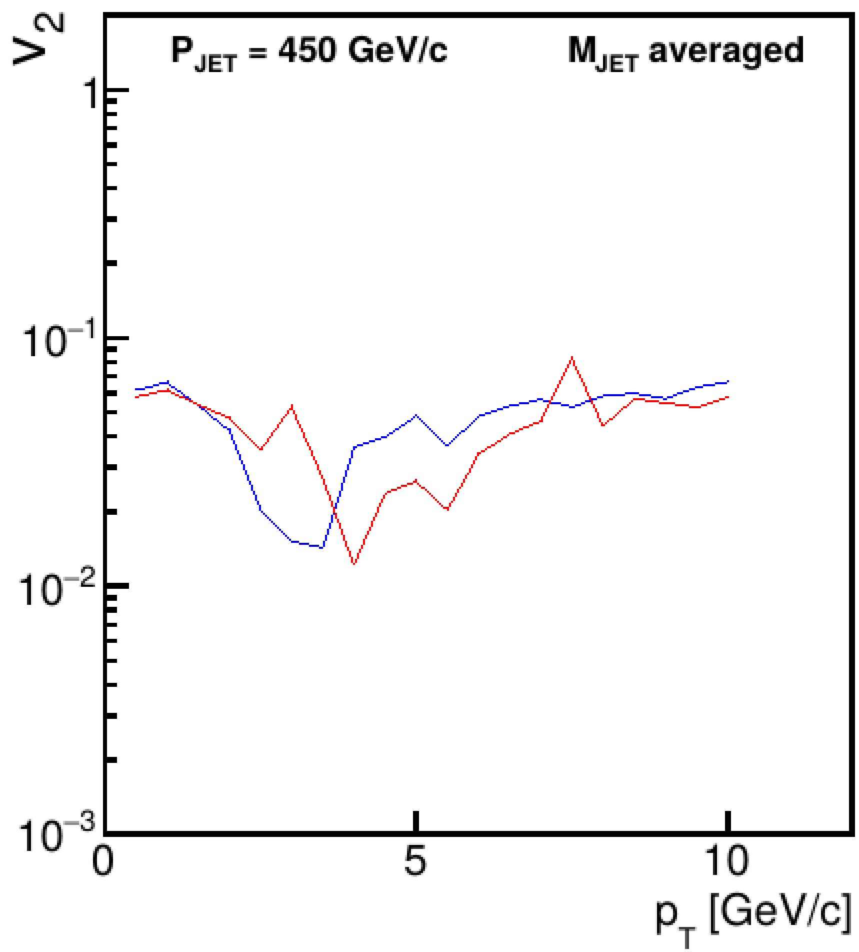
# $v_2$ in 1 jet scaled by $p^* = \frac{E_{JET} - P_{JET}}{2}$



# Averaging over jet mass fluctuations




$$\rho(M_{jet}) \sim \ln^{b}(M_{jet}/M_{0})/M_{jet}^{c}$$




***Averaging reduces fluctuations in $v_2$***

# *Outline*

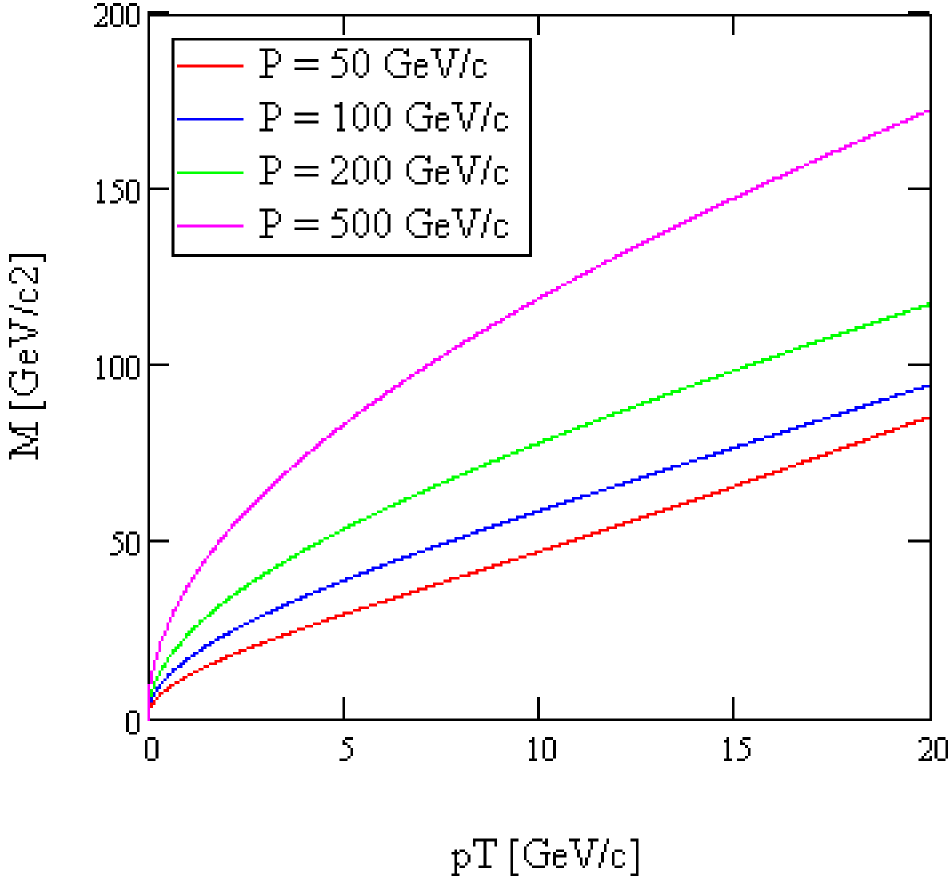
*- Off-shell fragmentation and scale evolution*

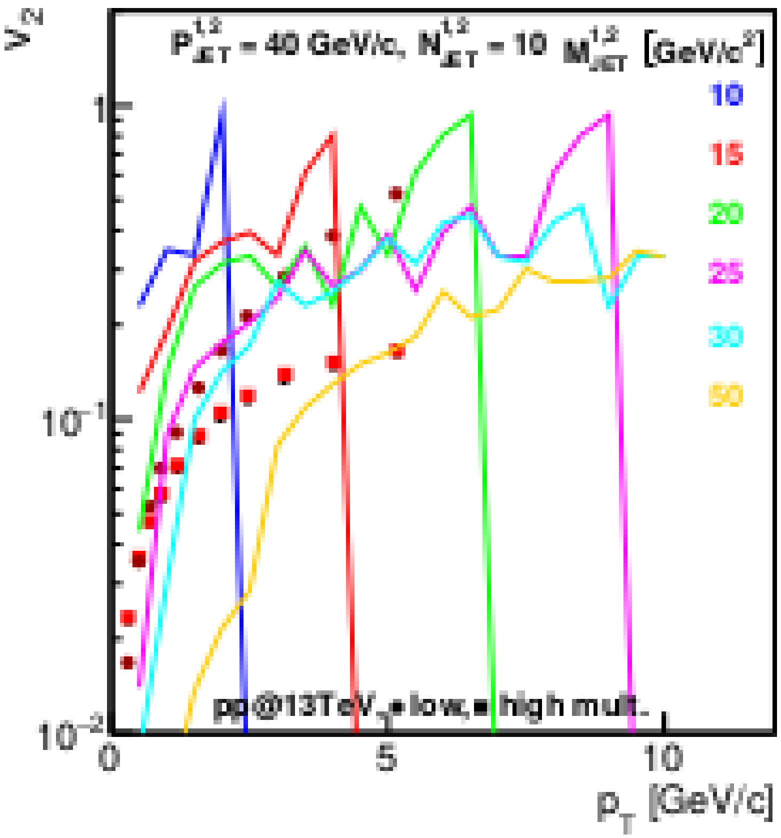
*- Long-range correlations of hadrons stemming from highly-virtual leading partons*

***- v2 in fix multiplicity jets***

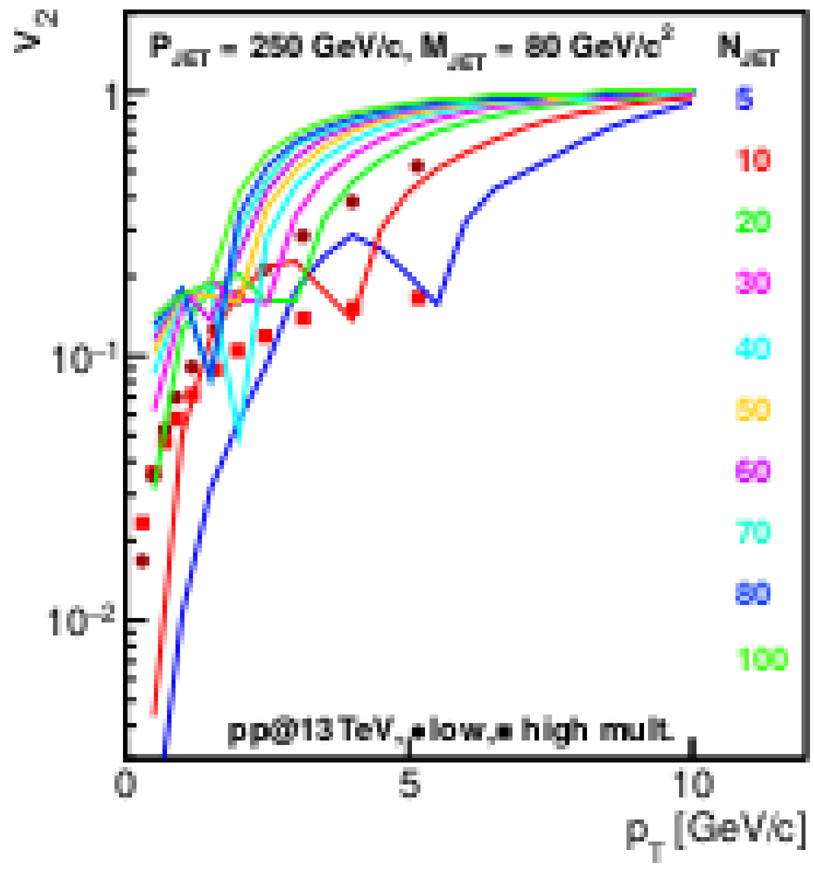
## *Fix Multiplicity Events*

# *Jet Mass dependence*



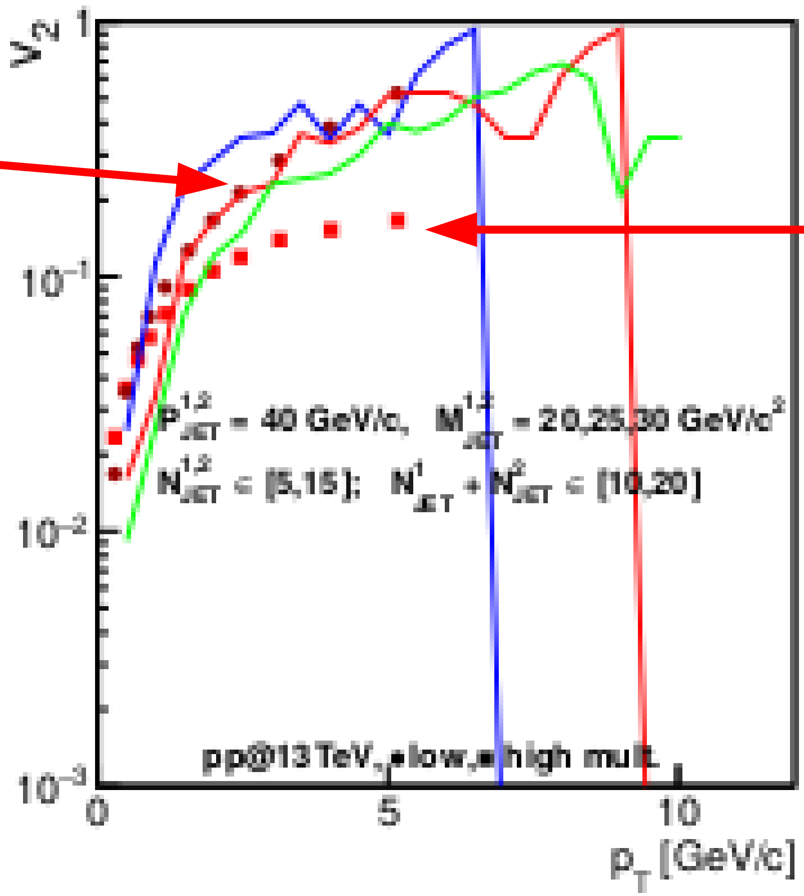



# Multiplicity dependence



# Fix multiplicity v2

„peripheral” pp
10 < N < 20




„central” pp
105 < N < 150

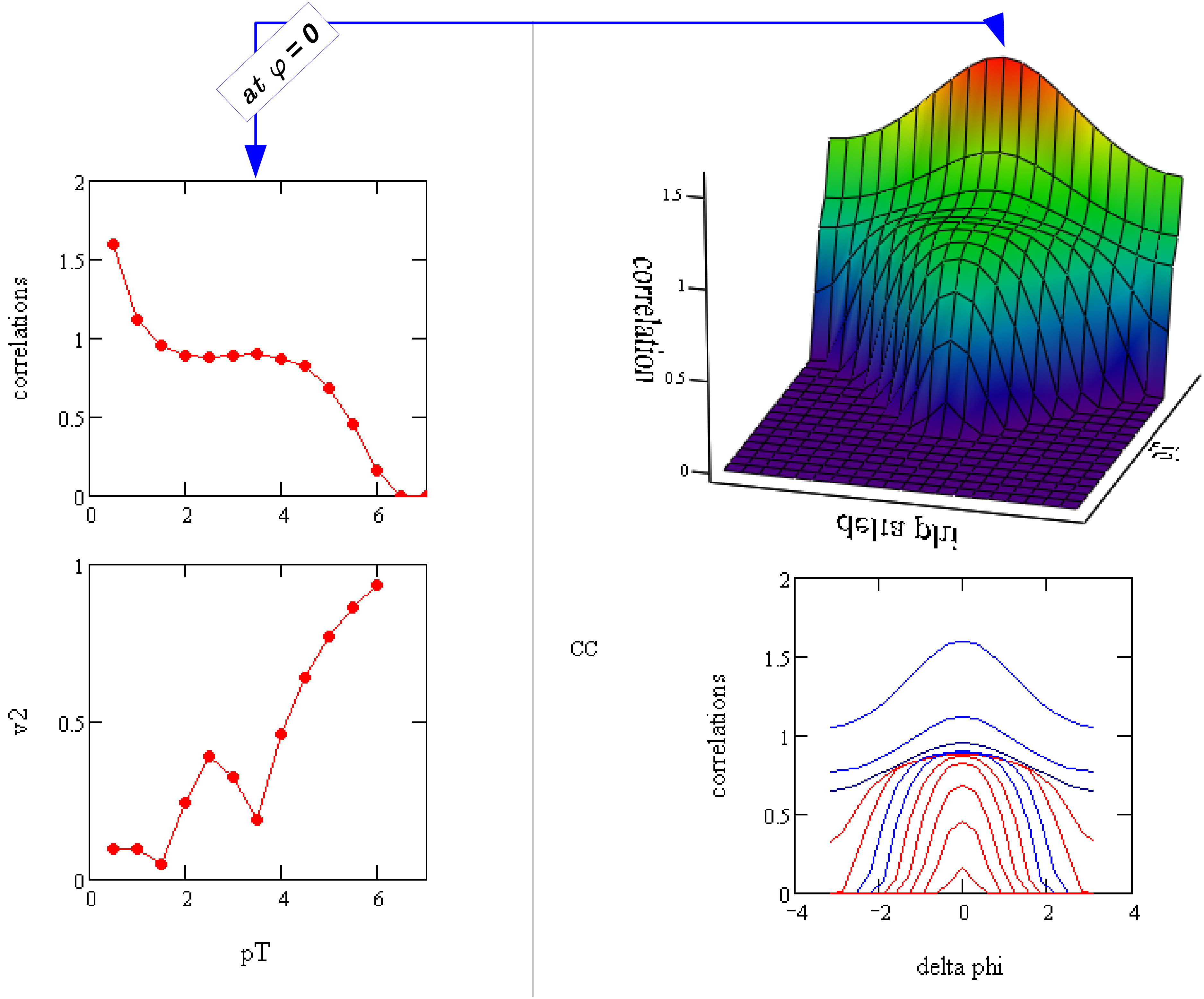
# Conclusions

***We have a fragmentation function for highly virtual partons. The frag.scale is the jet mass***

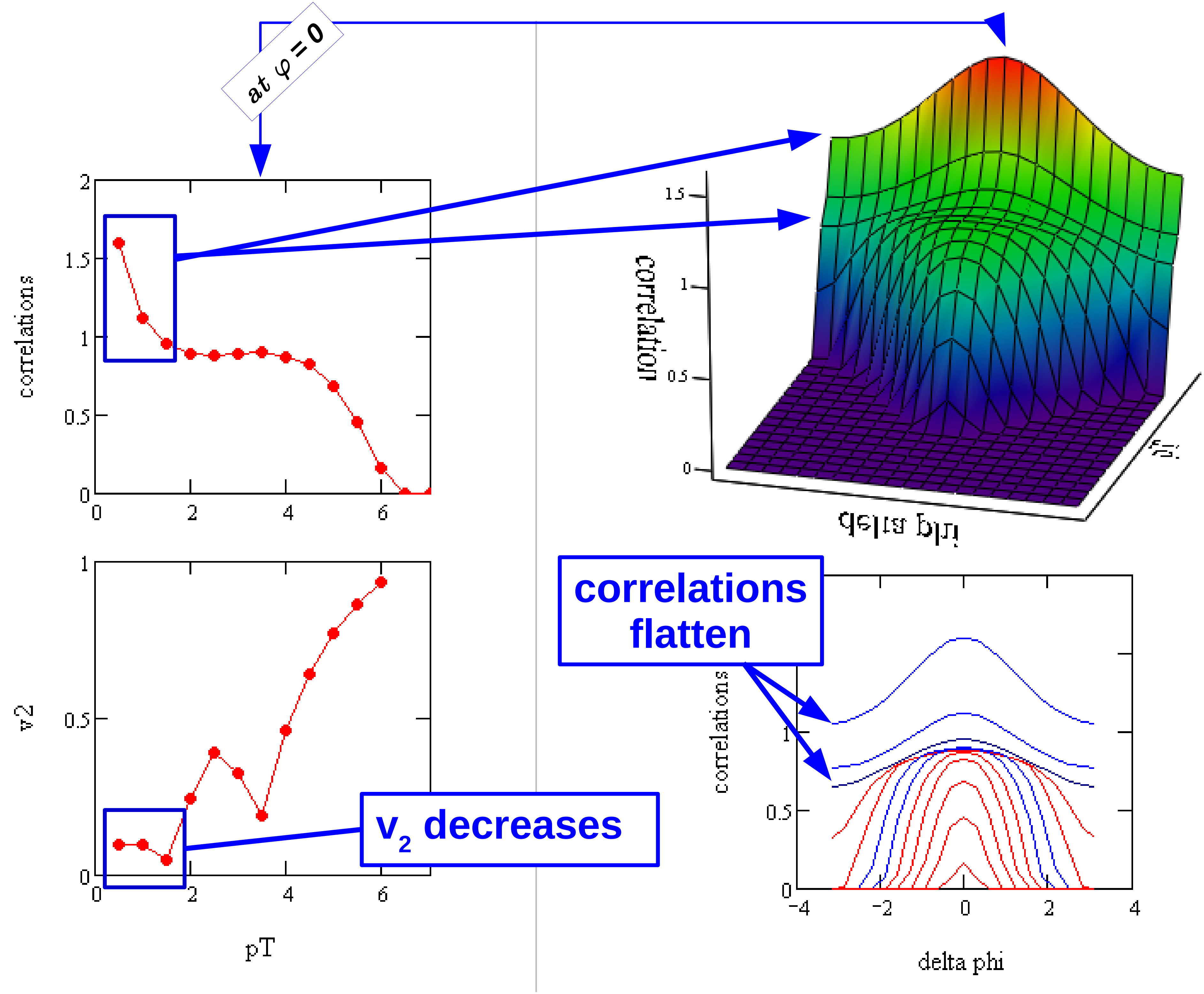
***We have a FF for jets of fix multiplicity***

***v2 of large $\Delta$Y hadrons seems to be discribable by fragmentation of off-shell leading partons***

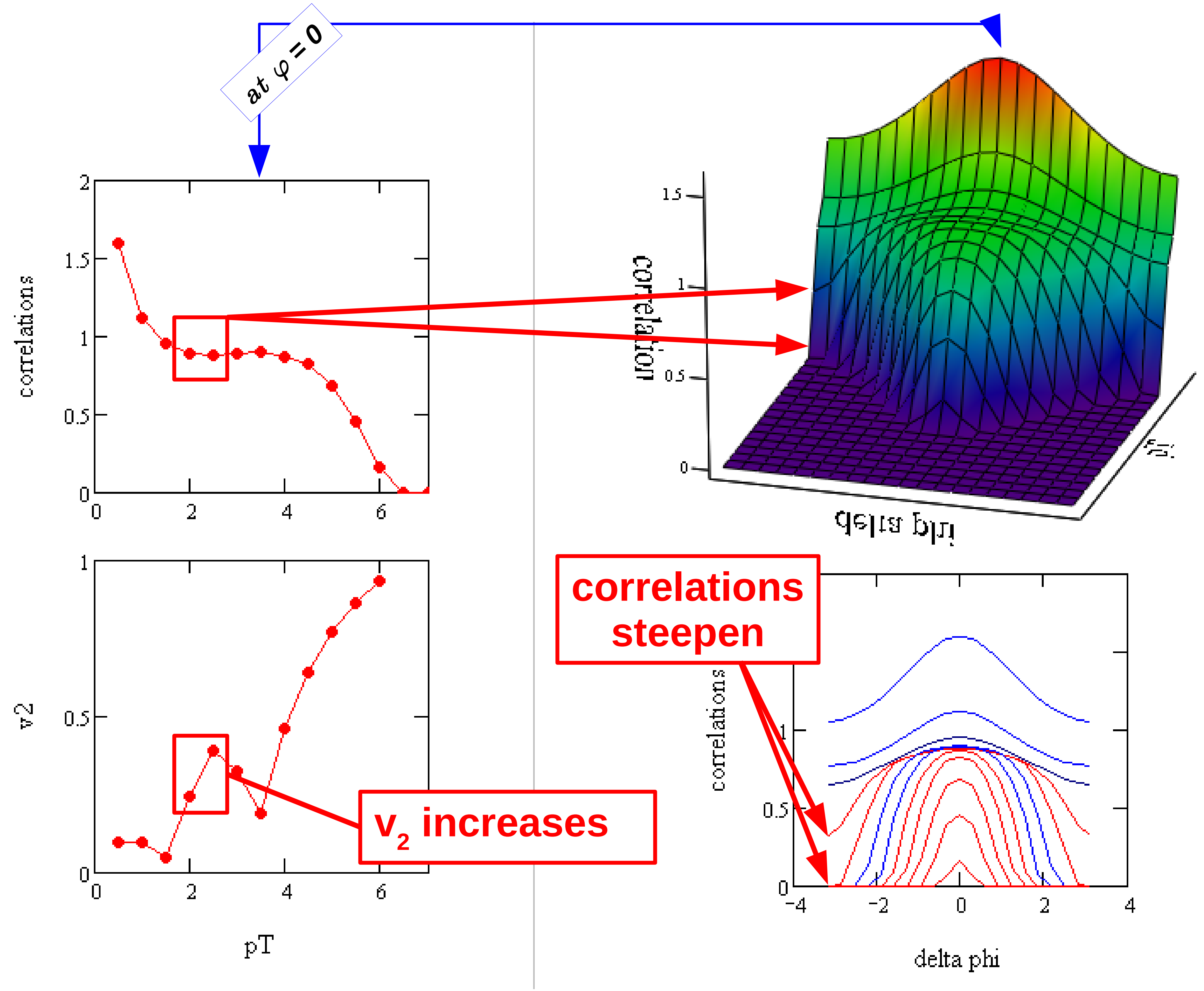
# ***Back-up Slides***



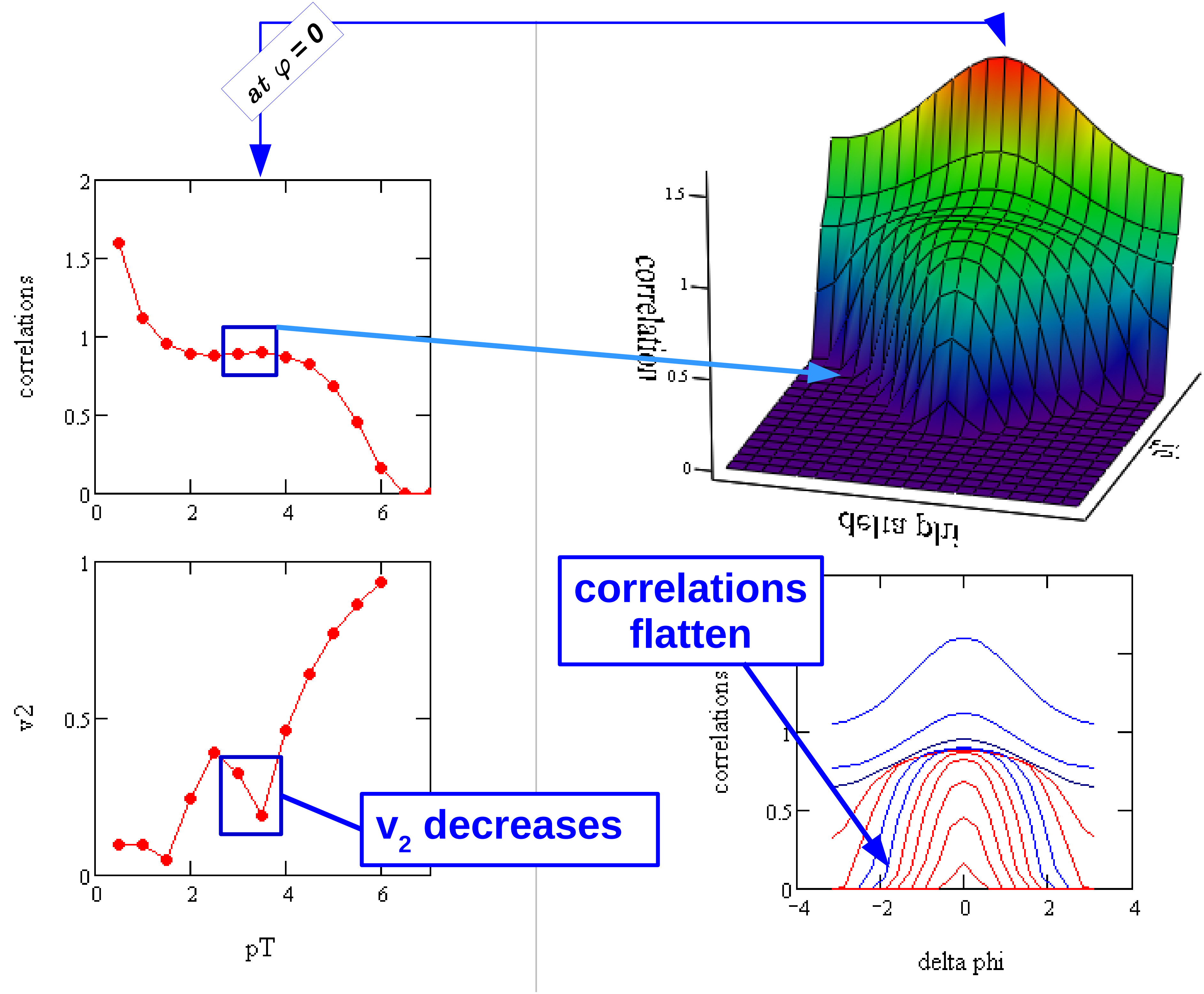
at φ = 0
correlations
v2
pT
correlation
delta phi
CC
correlations
delta phi



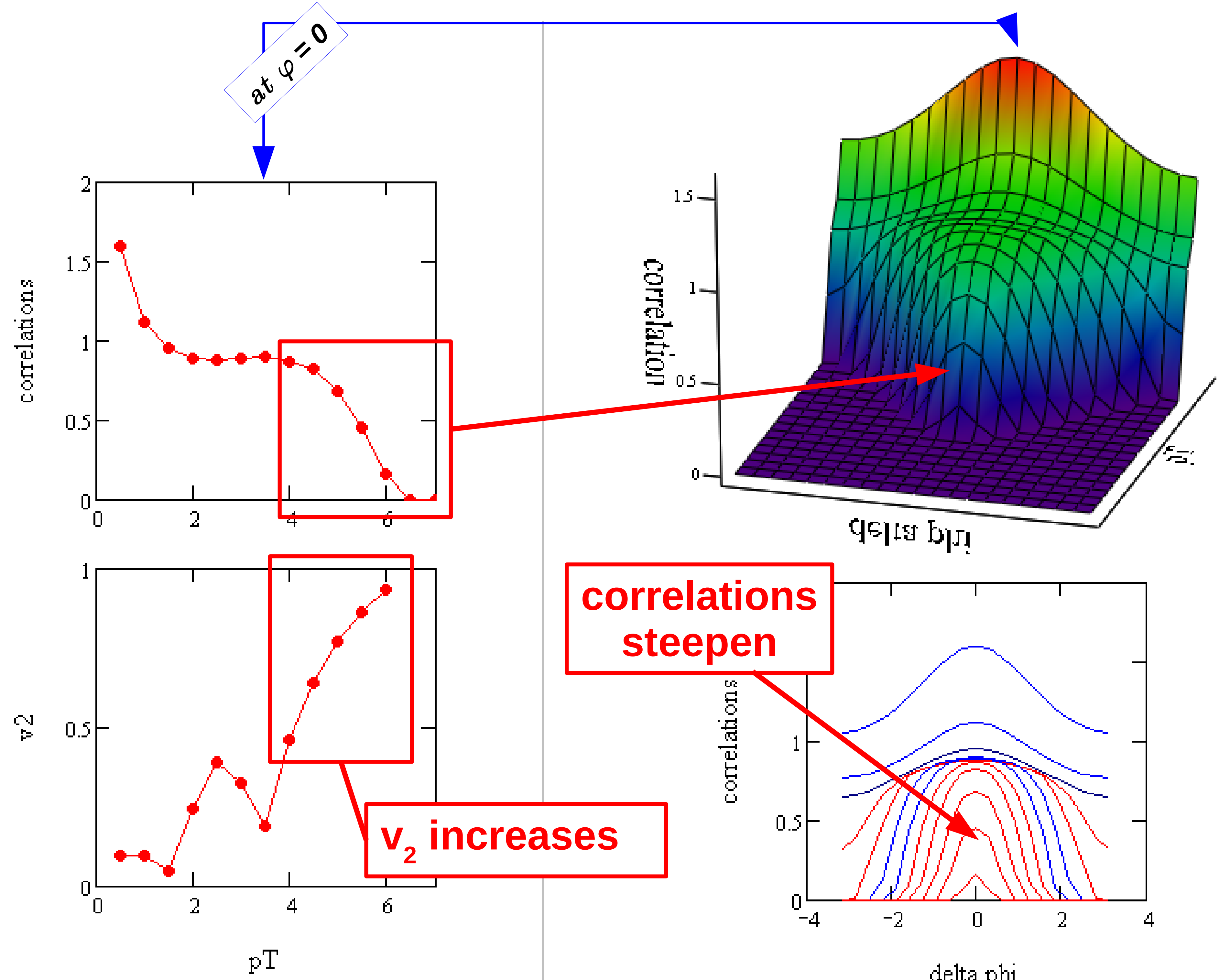
at φ = 0
correlations
pT
v2
correlation
correlations
delta phi
correlations flatten
v2 decreases



at φ = 0
correlations
pT
v2
v2 increases
correlation
delta phi
correlations steepen
correlations
delta phi

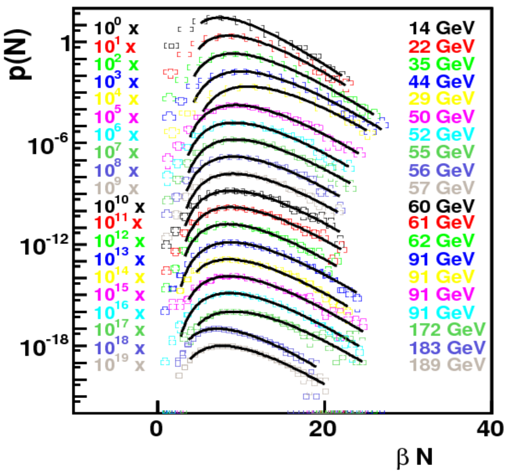


at $\varphi = 0$
correlations
v2
pT
correlation
delta phi
correlations
flatten
$v_2$ decreases
correlations
delta phi

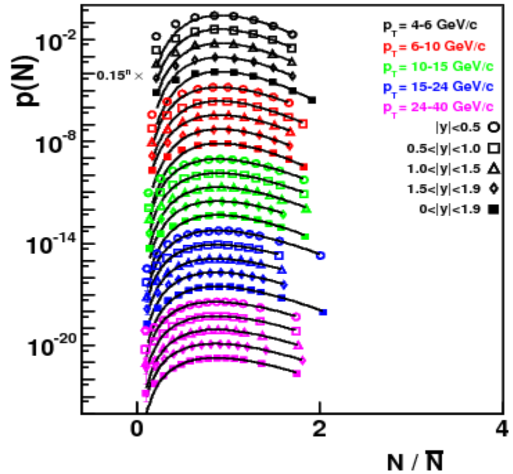

at $\varphi = 0$
correlations
v2
pT
correlation
delta phi
correlations
delta phi
correlations steepen
$v_2$ increases

# *Particle Multiplicity fluctuates according to the Negative-binomial distribution*

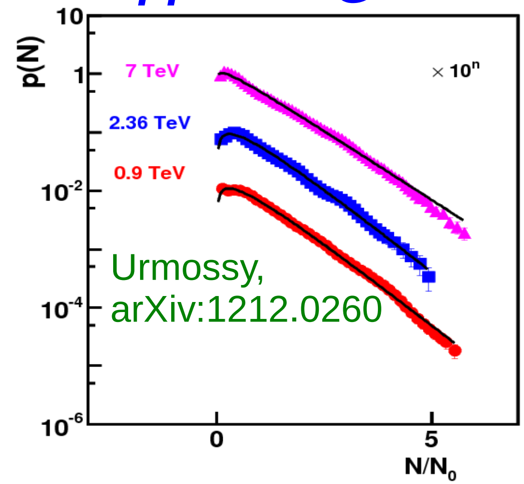
***$e^-e^+ \rightarrow h^\pm$***



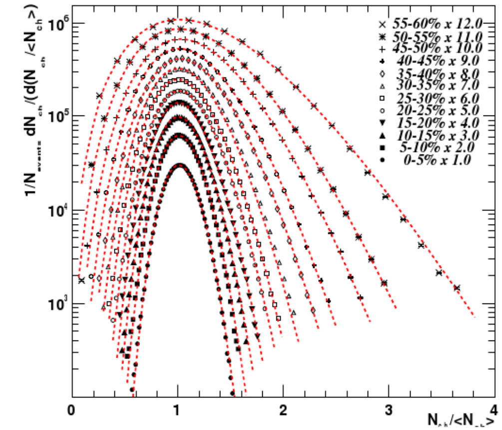

***pp → jets @ 7 TeV***



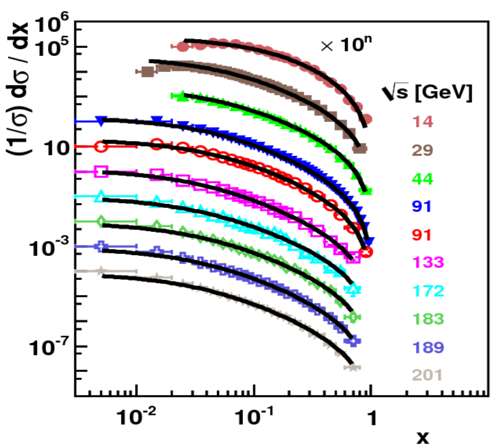

***pp*** **→ $h^\pm$ @ LHC**



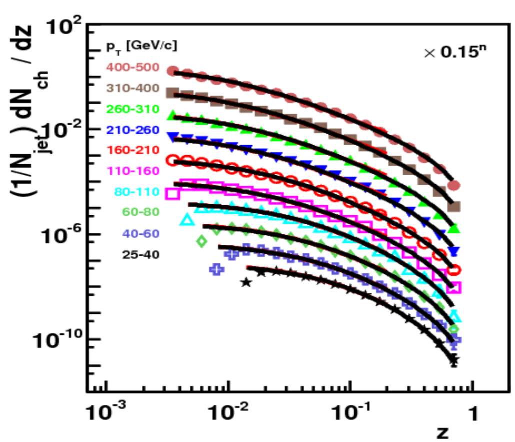

***AuAu*** **→ $h^\pm$ @RHIC**



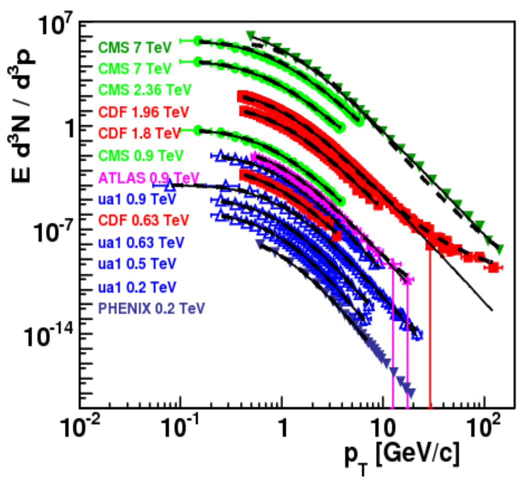

# *Power-law hadron spectra*



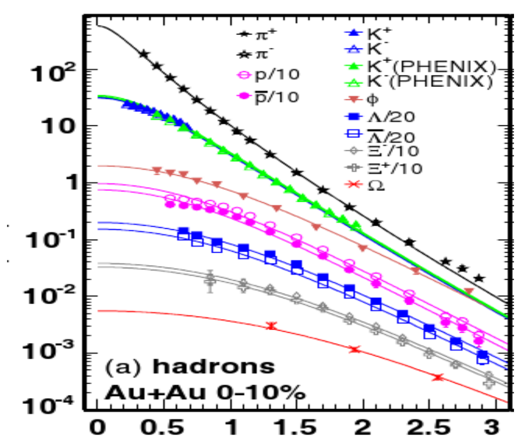

Urmossy et.al.,*PLB*, **701**: 111-116 (2011)




Urmossy et. al., *PLB*, **718**, 125-129, (2012)



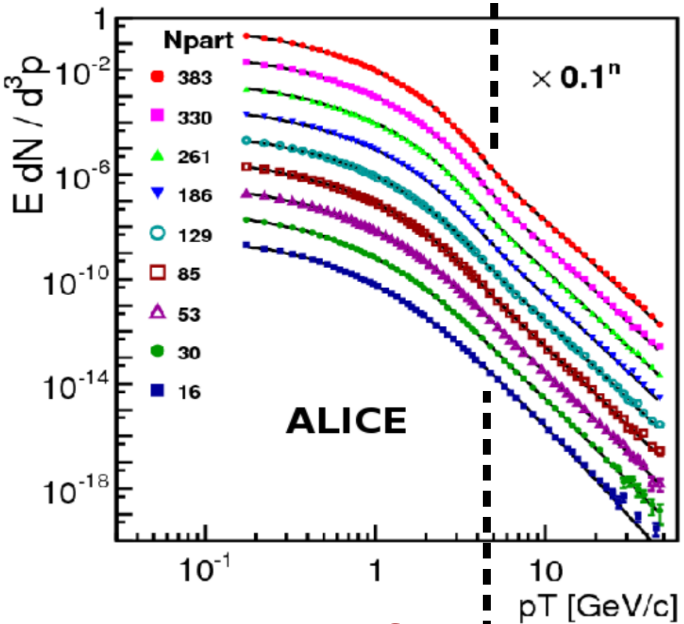

Barnaföldi etal, *J. Phys.: Conf. Ser.*, **270,** 012008 (2011 )



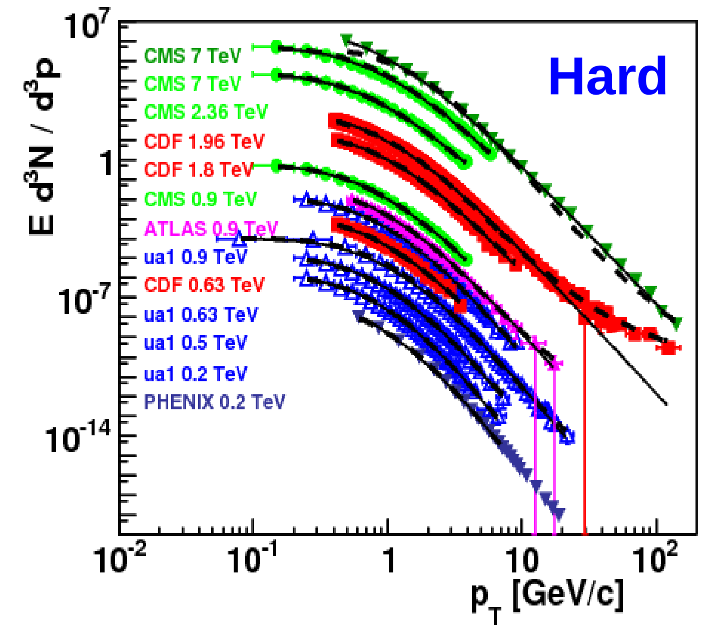

*J. Phys. G: Nucl. Part. Phys.* **37** 085104 (2010),

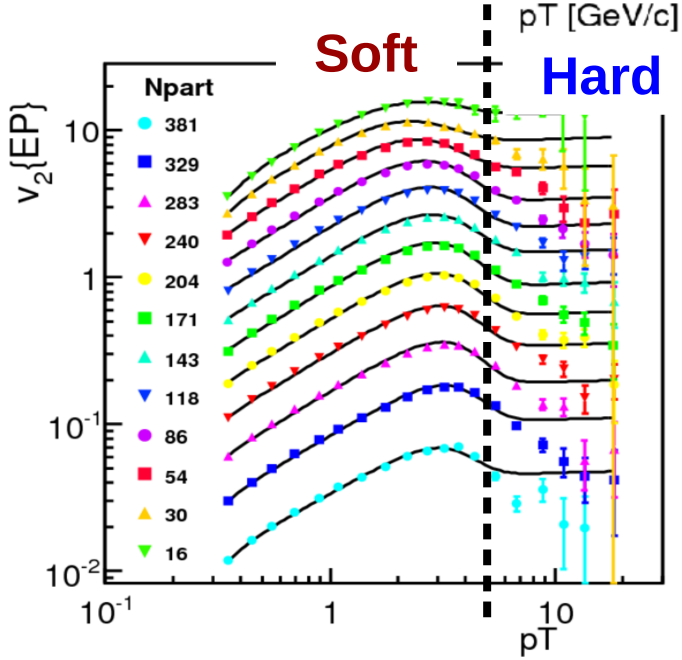
# Spectrum and v2

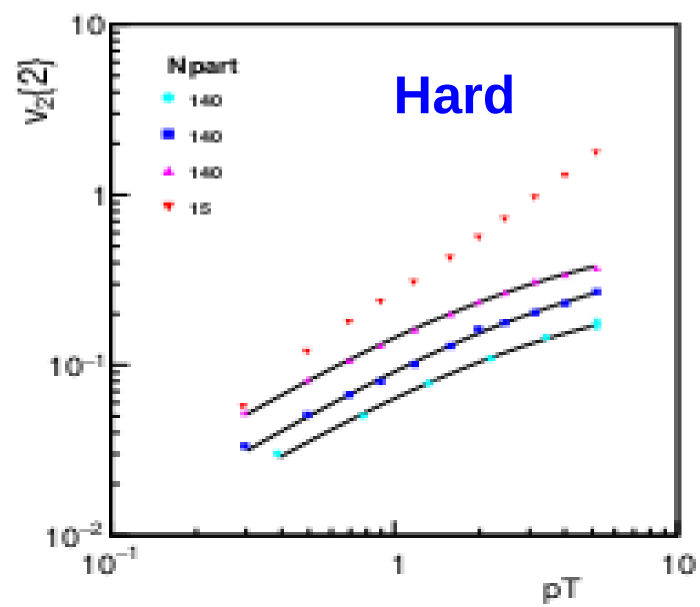
**PbPb**




**PP**




(Hot Quarks 2014) J. Phys. Conf. Ser. 612 (2015) 1, 012048; (WPCF 2014) arXiv:1501.05959, Conference: C14-08-25.8; (High-pT 2014), arXiv:1501.02352, arXiv:1405.3963

# v2 in pp and PbPb