

Recent L3 results (and questions) on BEC at LEP

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BEC Introduction

$$R_2 = \frac{\rho_2(p_1, p_2)}{\rho_1(p_1)\rho_1(p_2)} = \frac{\rho_2(Q)}{\rho_0(Q)}$$

Assuming particles produced incoherently with spatial source density $S(x)$,

$$R_2(Q) = 1 + \lambda |\tilde{S}(Q)|^2$$

where $\tilde{S}(Q) = \int dx e^{iQx} S(x)$ – Fourier transform of $S(x)$

$\lambda = 1$ — $\lambda < 1$ if production not completely incoherent

Assuming $S(x)$ is a Gaussian with radius $r \implies$

$$R_2(Q) = 1 + \lambda e^{-Q^2 r^2}$$

▶ intro



Elongation Results

Results in LCMS frame:

▶ LCMS

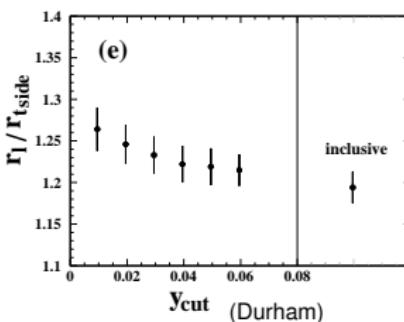
	r_L/r_{side}
L3	$1.25 \pm 0.03^{+0.36}_{-0.05}$
OPAL	$1.19 \pm 0.03^{+0.08}_{-0.01}$

(ZEUS finds similar results in ep)
~25% elongation along thrust axis

OPAL:

Elongation larger for narrower jets

- Conclusion: Elongation, but it is relatively small.
- So: Ignore it. — Assume spherical.



Results on Q from L3 Z decay

$$R_2 = \gamma \cdot [1 + \lambda G] \cdot (1 + \delta Q)$$

- Gaussian
 $G = \exp(-(rQ)^2)$

$$G = \exp(-(rQ)^2) \cdot \left[1 + \frac{\kappa}{3!} H_3(rQ)\right]$$

Gaussian if $\kappa = 0$

$$\kappa = 0.71 \pm 0.06$$

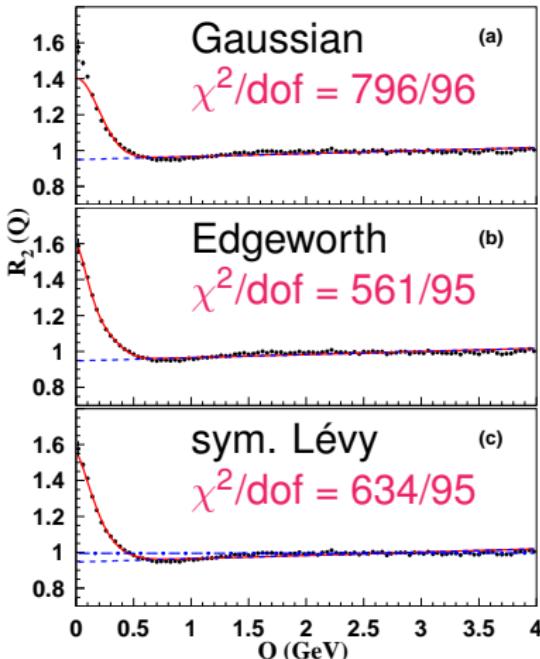
- symmetric Lévy

$$G = \exp(-|rQ|^\alpha)$$

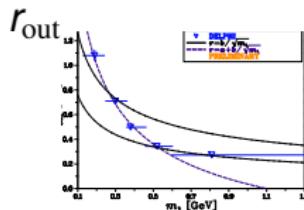
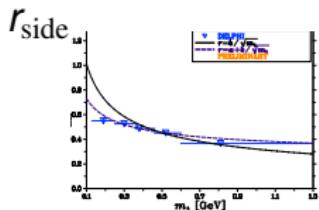
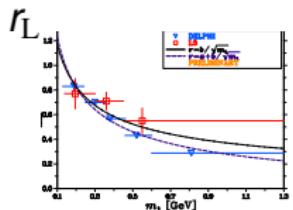
$$0 < \alpha \leq 2$$

$$\alpha = 1.34 \pm 0.04$$

Poor χ^2 . Edgeworth and Lévy better than Gaussian, but poor.
 Problem is the dip of R_2 in the region $0.6 < Q < 1.5$ GeV

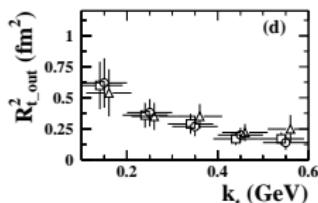
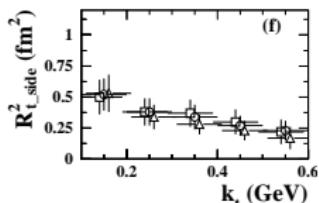
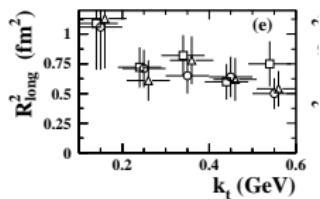


Transverse Mass dependence of r



Smirnova&Lörstad, 7th Int. Workshop on Correlations and Fluctuations (1996)

Van Dalen, 8th Int. Workshop on Correlations and Fluctuations (1998)



OPAL, Eur. Phys. J C52 (2007) 787

r decreases with m_t (or k_t) for all directions



Conclusions

- BEC depend (approximately) only on Q , not its components.
- BEC depend on m_t .

Turn now to a model providing such dependence.

The τ -model

T.Csörgő, W.Kittel, W.J.Metzger, T.Novák, Phys.Lett.**B663**(2008)214
 T.Csörgő, J.Zimányi, Nucl.Phys.**A517**(1990)588

- Assume momentum is related to avg. production point:

$$\bar{x}^\mu(p^\mu) = a_\tau p^\mu$$

where for 2-jet events, $a = 1/m_t$

$\tau = \sqrt{\vec{t}^2 - \vec{r}_z^2}$ is the “longitudinal” proper time

and $m_t = \sqrt{E^2 - p_z^2}$ is the “transverse” mass

- Let $\delta_\Delta(x^\mu - \bar{x}^\mu)$ be dist. of prod. points about their mean, and $H(\tau)$ the dist. of τ . Then the emission function is

$$S(x, p) = \int_0^\infty d\tau H(\tau) \delta_\Delta(x - a_\tau p) \rho_1(p)$$

- In the plane-wave approx.

F.B.Yano, S.E.Koonin, Phys.Lett.**B78**(1978)556.

$$\rho_2(p_1, p_2) = \int d^4x_1 d^4x_2 S(x_1, p_1) S(x_2, p_2) (1 + \cos([p_1 - p_2] [x_1 - x_2]))$$

- Assume $\delta_\Delta(x - a_\tau p)$ is very narrow — a δ -function. Then

$$R_2(p_1, p_2) = 1 + \lambda \operatorname{Re} \tilde{H}\left(\frac{a_1 Q^2}{2}\right) \tilde{H}\left(\frac{a_2 Q^2}{2}\right), \quad \tilde{H}(\omega) = \int d\tau H(\tau) \exp(i\omega\tau)$$



BEC in the τ -model

- Assume a Lévy distribution for $H(\tau)$

Since no particle production before the interaction,
 $H(\tau)$ is one-sided.

Characteristic function is

$$\tilde{H}(\omega) = \exp \left[-\frac{1}{2} (\Delta\tau |\omega|)^{\alpha} \left(1 - i \operatorname{sign}(\omega) \tan \left(\frac{\alpha\pi}{2} \right) \right) + i\omega\tau_0 \right], \quad \alpha \neq 1$$

where

- α is the index of stability
- τ_0 is the proper time of the onset of particle production
- $\Delta\tau$ is a measure of the width of the dist.

- Assume $a_1 \approx a_2 \approx \bar{a}$

- Then,

$$R_2(Q, \bar{a}) = \gamma \left[1 + \lambda \cos \left(\bar{a}\tau_0 Q^2 + \tan \left(\frac{\alpha\pi}{2} \right) \left(\frac{\bar{a}\Delta\tau Q^2}{2} \right)^{\alpha} \right) \exp \left(- \left(\frac{\bar{a}\Delta\tau Q^2}{2} \right)^{\alpha} \right) \right] \cdot (1 + \delta Q)$$

BEC in the τ -model

$$R_2(Q, \bar{a}) = \gamma \left[1 + \lambda \cos \left(\bar{a} \tau_0 Q^2 + \tan \left(\frac{\alpha \pi}{2} \right) \left(\frac{\bar{a} \Delta \tau Q^2}{2} \right)^\alpha \right) \exp \left(- \left(\frac{\bar{a} \Delta \tau Q^2}{2} \right)^\alpha \right) \right] \cdot (1 + \delta Q)$$

Simplification:

- Particle production begins immediately, $\tau_0 = 0$
- effective radius, $R = \sqrt{\bar{a} \Delta \tau / 2}$

$$R_2(Q) = \gamma \left[1 + \lambda \cos \left[(R_a Q)^{2\alpha} \right] \exp \left[- (R Q)^{2\alpha} \right] \right] (1 + \delta Q)$$

where $R_a^{2\alpha} = \tan \left(\frac{\alpha \pi}{2} \right) R^{2\alpha}$

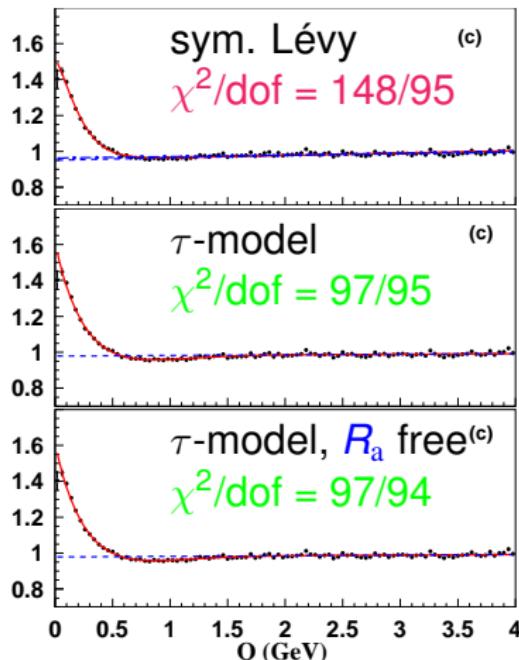
Compare to sym. Lévy parametrization:

$$R_2(Q) = \gamma \left[1 + \lambda \exp \left[- |r Q|^\alpha \right] \right] (1 + \delta Q)$$

2-jet Results on Simplified τ -model from L3 Z decay

2-jet events Durham $y_{\text{cut}} = 0.006$

- symmetric Lévy
does not describe dip or large Q
- $R_a^{2\alpha} = \tan\left(\frac{\alpha\pi}{2}\right) R^{2\alpha}$
good description
- R_a free
good description
Effective R works well



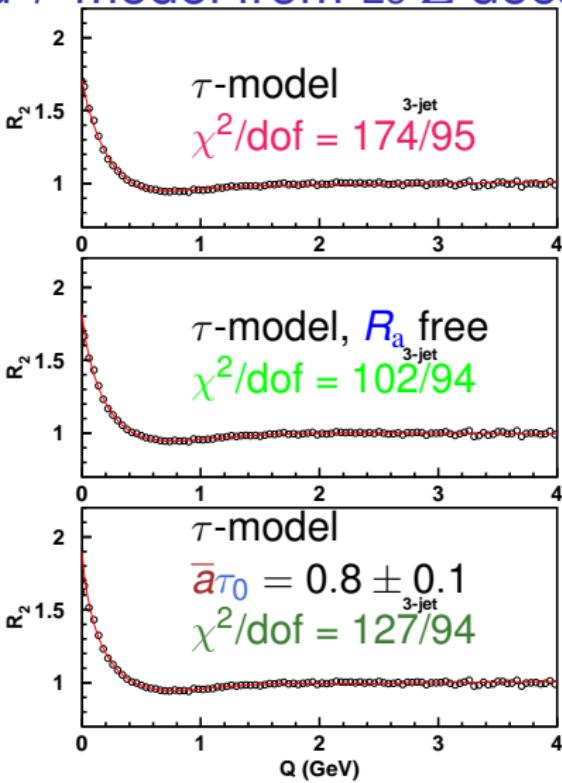
Simplified τ -model works better than sym. dists.

3-jet Results on Simplified τ -model from L3 Z decay

3-jet events Durham $y_{\text{cut}} = 0.006$

- $R_a^{2\alpha} = \tan\left(\frac{\alpha\pi}{2}\right) R^{2\alpha}$
poor description
- R_a free
good description
- $R_a^{2\alpha} = \tan\left(\frac{\alpha\pi}{2}\right) R^{2\alpha}$
pretty good description
(CL=1%)
 $\bar{a}_{\tau_0} > 0$
(VERY PRELIMINARY)

▶ all



Summary of Simplified τ -Model.

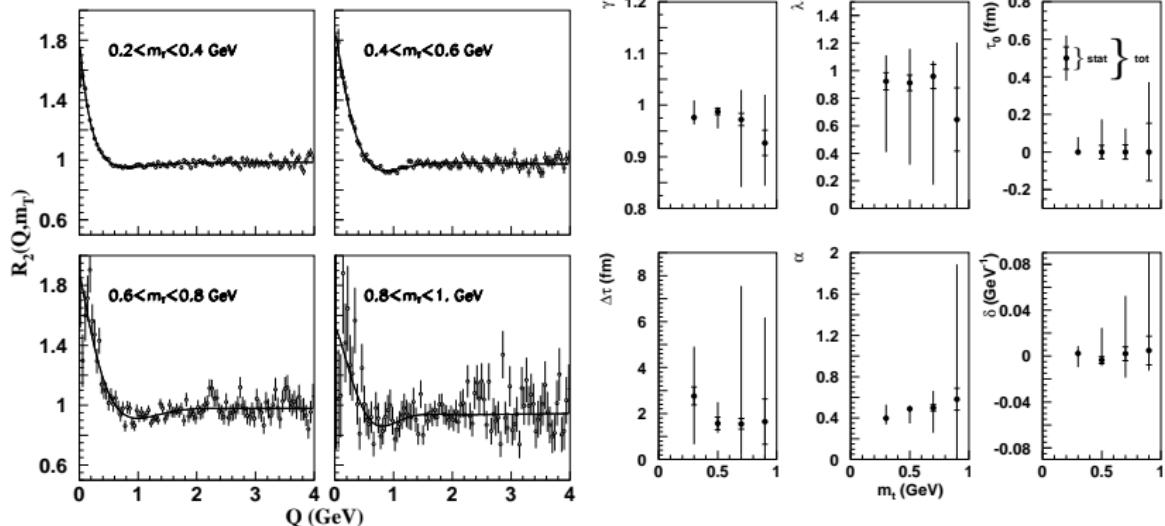
- Simplified τ -model works well
 - For 2-jet events including $R_a^{2\alpha} = \tan\left(\frac{\alpha\pi}{2}\right) R^{2\alpha}$
 - For 3-jet events
 - only if R_a a free parameter.
Possibly the assumption $a_1 \approx a_2 \approx \bar{a}$ is less valid.
 - or if $\tau_0 > 0$

Limit analysis to 2-jet events (Durham, $y_{\text{cut}} = 0.006$)

For 2-jet events, $a = 1/m_t$

Full τ -model for 2-jet events

$$R_2(Q, \bar{m}_t) = \gamma \left[1 + \lambda \cos \left(\frac{\tau_0 Q^2}{\bar{m}_t} + \tan \left(\frac{\alpha \pi}{2} \right) \left(\frac{\Delta \tau Q^2}{2 \bar{m}_t} \right)^{\alpha} \right) \exp \left(- \left(\frac{\Delta \tau Q^2}{2 \bar{m}_t} \right)^{\alpha} \right) \right] \cdot (1 + \delta Q)$$



- Parameters α , $\Delta \tau$, τ_0 are \sim independent of m_t
- Note: $\Delta \tau$ indep. of m_t equiv. to radius $r \propto 1/\sqrt{\bar{m}_t}$

Emission Function of 2-jet Events.

In the τ -model, the emission function in configuration space is

$$S(x) = \frac{d^4 n}{d\tau d^3 r} = \left(\frac{m_t}{\tau}\right)^3 H(\tau) \rho_1 \left(p = \frac{rm_t}{\tau}\right)$$

For simplicity, assume $S(r, z, t) = G(\eta)I(r)H(\tau)$
 $(\eta = \text{space-time rapidity})$

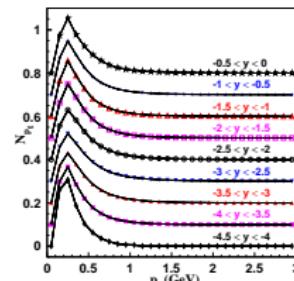
Strongly correlated $x, p \implies$

$$\eta = y \quad r = p_t \tau / m_t$$

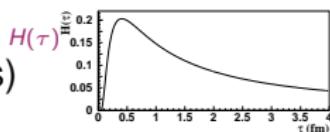
$$G(\eta) = N_y(\eta) \quad I(r) = \left(\frac{m_t}{\tau}\right)^3 N_{p_t}(rm_t/\tau) \quad H(\tau)$$

$(N_y, N_{p_t}$ are inclusive single-particle distributions)

So, using experimental N_y, N_{p_t} dists.
 and $H(\tau)$ from BEC fits,
 we can reconstruct S .



Factorization OK



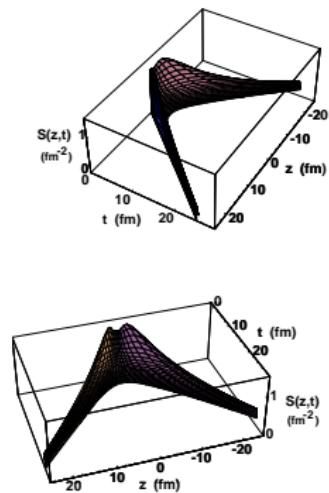
$$\alpha = 0.43$$

$$\Delta\tau = 1.8 \text{ fm}$$

$$\tau_0 = 0$$

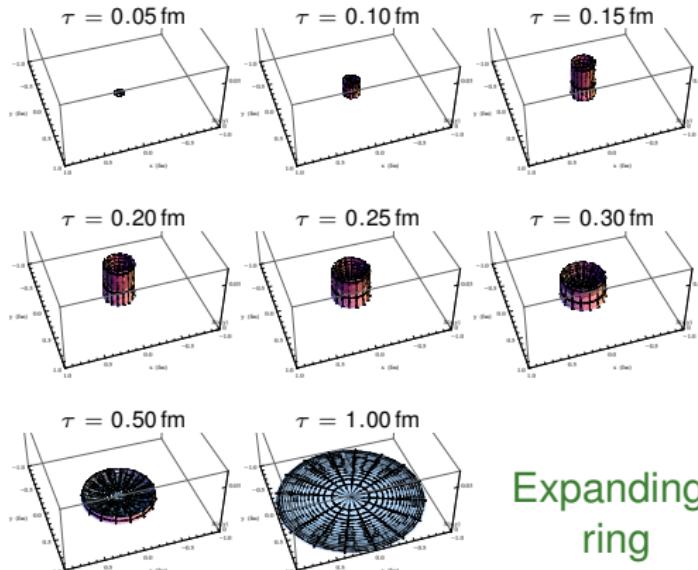
Emission Function of 2-jet Events.

Integrating over r ,



"Boomerang" shape

Integrating over z ,



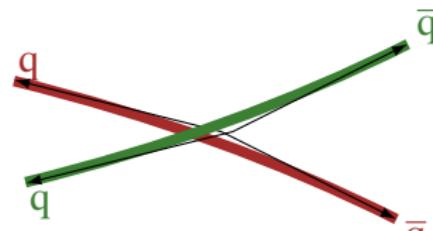
Expanding ring

Particle production is close to the light-cone

Inter-string BEC?

Recall $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$

- 2 strings, inter-string BEC?
- large syst. uncertainty on M_W
- No inter-string BEC found. BUT
 - low statistics
 - small overlap in \vec{p}
exasperated by expt. sel.
of 4 well-separated jets



Also 2 strings in $e^+e^- \rightarrow Z \rightarrow q\bar{q}g$

- high statistics
- larger overlap

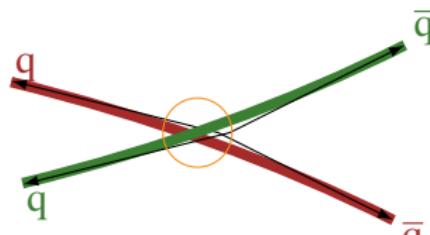


Nick van Remortel, Ph.D. thesis, Univ. Antwerpen, 2003
 Qin Wang, Ph.D. thesis, Radboud Univ., 4 Sep 2008

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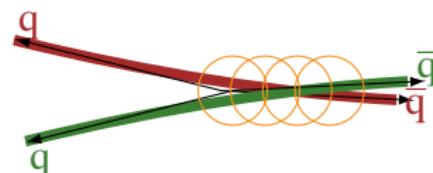
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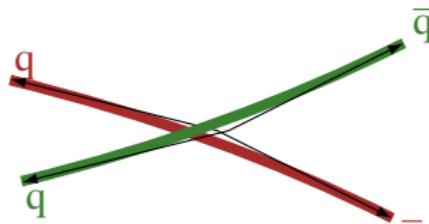
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Qin Wang, Ph.D. thesis, Radboud Univ., 4 Sep 2008

Signal of Inter-string BEC

Assuming $\lambda_{\text{inter-string}} = \lambda_{\text{intra-string}}$,

- momentum overlap, $f_{\text{str-1}}(\vec{p}) = f_{\text{str-2}}(\vec{p})$
- If no p overlap, can not detect inter-string BEC
no p overlap $\Rightarrow \lambda_2 = \lambda_1$ and $r_2 = r_1$
- spatial overlap, $f_{\text{str-1}}(\vec{r}) = f_{\text{str-2}}(\vec{r})$
- Assuming full p overlap and $\lambda_{\text{inter-string}} = \lambda_{\text{intra-string}}$,

	no spatial overlap	full spatial overlap
Inter-string BEC	$\lambda_2 = \lambda_1$ $r_2 > r_1$	$\lambda_2 = \lambda_1$ $r_2 = r_1$ (HBT) $r_2 > r_1$ (Lund)
No inter-str. BEC	$\lambda_2 < \lambda_1$ $r_2 = r_1$	$\lambda_2 < \lambda_1$ $r_2 = r_1$

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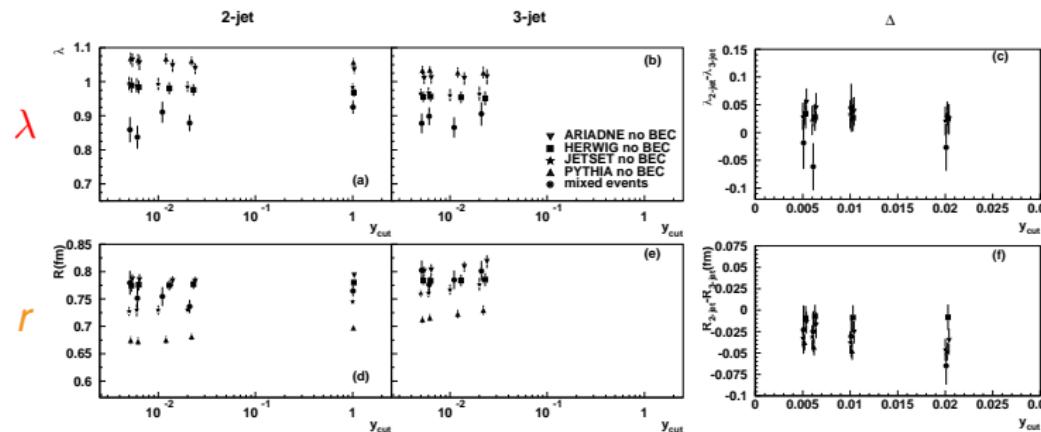
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2-jet / 3-jet fit with Edgeworth expansion parametrization:

$$R_2(Q) = \gamma(1 + \delta Q + \varepsilon Q^2) \left[1 + \lambda e^{-r^2 Q^2} \left(1 + \frac{\kappa}{3!} H_3(rQ) \right) \right]$$



- very weak dependence of λ , r on y_{cut}
- $\lambda_{2\text{-jet}} \gtrsim \lambda_{3\text{-jet}} \Rightarrow \lambda_{2\text{-str}} \gtrsim \lambda_{1\text{-str}} \Rightarrow$ no inter-str. BEC ?
- $r_{2\text{-jet}} \lesssim r_{3\text{-jet}} \Rightarrow r_{2\text{-str}} \gtrsim r_{1\text{-str}} \Rightarrow$ inter-str. BEC ?

q/g

fit with Edgeworth expansion parametrization:

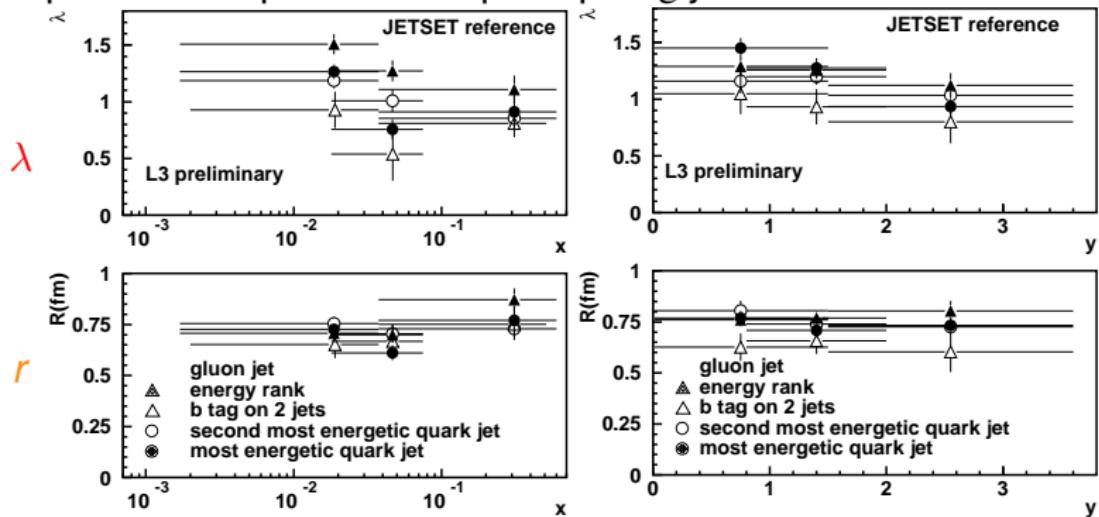
$$R_2(Q) = \gamma \left[1 + \lambda e^{-r^2 Q^2} \left(1 + \frac{\kappa}{3!} H_3(rQ) \right) \right]$$

Sample	g fract. (%)	$\langle E \rangle$ (GeV)	λ	r (fm)
dusc 2-jet	0	43	0.93 ± 0.05	0.75 ± 0.03
b-tag Yg g	32	40	0.96 ± 0.24	0.56 ± 0.10
dusc Merc.	33	29	1.25 ± 0.11	0.78 ± 0.05
dusc Yq	50	24	1.13 ± 0.09	0.78 ± 0.04
b-tag Merc. g	74	25	1.31 ± 0.50	0.96 ± 0.21
b-tag Yq g	75	19	0.83 ± 0.18	0.76 ± 0.09
average			1.01 ± 0.04	0.76 ± 0.02
			CL = 6%	CL = 37%

No evidence for q/g differences – Inter-String BEC (HBT) ?

q/g : x, y dependence

expect more spatial overlap in tip of g jet



- λ ↘, not const. with increasing x or y , but equally for q, g .
 λ_g of E -tag, b-tag inconsistent – systematics?
- r const., not decreasing with x and y – no inter-str. BEC ?

Summary 2

- 2-jet/3-jet: inconclusive.
- No evidence for different BEC in q, g.
 - No inter-string BEC?
 - or Inter-string BEC, but HBT rather than Lund?
 - or no sensitivity? - difficult to assess without a model

Inter-string BEC remains an open question.

Acknowl.: Qin Wang, Ph.D. thesis, Radboud Univ., 4 Sep 2008

Summary 1

- $R_2(Q)$, not $R_2(\vec{Q})$ is a reasonably good approximation
- **But** sym. Gaussian, Edgeworth, Lévy $R_2(Q)$ **do not fit well**
- τ -model with a one-sided Lévy proper-time distribution
 - Simplified, it provides a new parametrization of R_2 :
 - Works well with **eff.** R , R_a for all events;
 - with only **eff.** R for 2-jet events.
 - $R_2(Q, m_t)$ successfully fits R_2 for 2-jet events
 - both Q - and m_t -dependence described correctly
 - Note: we found $\Delta\tau$ to be **independent** of m_t
 $\Delta\tau$ enters R_2 as $\Delta\tau Q^2/m_t$
 In Gaussian parametrization, r enters R_2 as $r^2 Q^2$
 Thus $\Delta\tau$ independent of m_t corresponds to $r \propto 1/\sqrt{m_t}$
- Emission function shaped like a **boomerang** in z - t and an **expanding ring** in x - y
Particle production is close to the light-cone

L3 Data

- $e^+e^- \rightarrow$ hadrons at $\sqrt{s} \approx M_Z$
- about 10^6 events
- about $0.5 \cdot 10^6$ 2-jet events — Durham $y_{cut} = 0.006$
- use mixed events for reference sample in τ -model studies
use mixed events or MC for reference sample in inter-string BEC studies

BEC Introduction

q-particle density $\rho_q(p_1, \dots, p_q) = \frac{1}{\sigma_{\text{tot}}} \frac{d^q \sigma_q(p_1, \dots, p_q)}{dp_1 \dots dp_q}$

2-particle correlation: $\frac{\rho_2(p_1, p_2)}{\rho_1(p_1)\rho_1(p_2)}$

To study only BEC, not all correlations,

let $\rho_0(p_1, p_2)$ be the 2-particle density if no BEC
($= \rho_2$ of the ‘reference sample’) and define

$$R_2(p_1, p_2) = \frac{\rho_2(p_1, p_2)}{\rho_1(p_1)\rho_1(p_2)} \cdot \frac{\rho_1(p_1)\rho_1(p_2)}{\rho_0(p_1, p_2)} = \frac{\rho_2(p_1, p_2)}{\rho_0(p_1, p_2)}$$

Since 2- π BEC only at small Q

$$Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M_{12}^2 - 4m_\pi^2}$$

integrate over other variables:

$$R_2(Q) = \frac{\rho(Q)}{\rho_0(Q)}$$

LCMS

The usual parametrization assumes a symmetric Gaussian source

But, there is no reason to expect this symmetry in $e^+e^- \rightarrow q\bar{q}$.

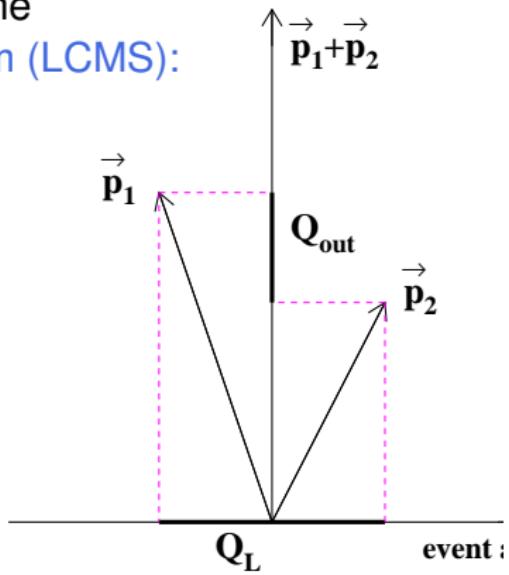
Therefore, do a 3-dim. analysis in the

Longitudinal Center of Mass System (LCMS):

Boost each π -pair along event axis
(thrust or sphericity) $\vec{p}_{L1} = -\vec{p}_{L2}$

$\vec{p}_1 + \vec{p}_2$ defines 'out' axis

$Q_{\text{side}} \perp (Q_L, Q_{\text{out}})$



▶ results

LCMS

Advantages of LCMS:

$$\begin{aligned} Q^2 &= Q_L^2 + Q_{\text{side}}^2 + Q_{\text{out}}^2 - (\Delta E)^2 \\ &= Q_L^2 + Q_{\text{side}}^2 + Q_{\text{out}}^2 (1 - \beta^2) \quad \text{where } \beta \equiv \frac{p_{\text{out}1} + p_{\text{out}2}}{E_1 + E_2} \end{aligned}$$

Thus, the energy difference,
and therefore the difference in emission time of the pions
couples only to the out-component, Q_{out} .

Thus,

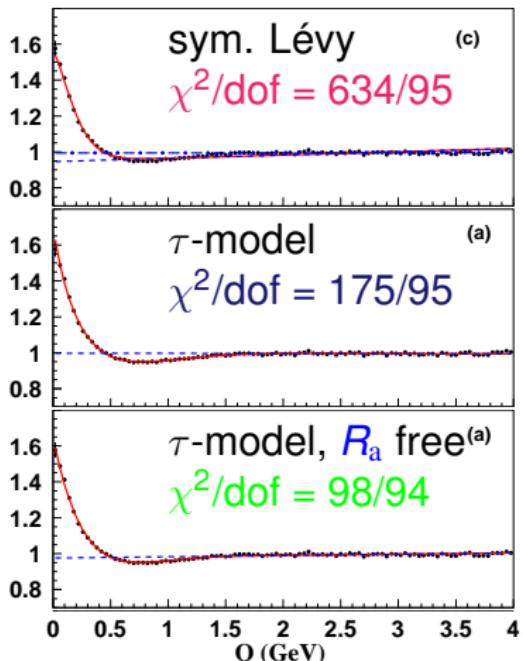
Q_L and Q_{side} reflect only spatial dimensions of the source
 Q_{out} reflects a mixture of spatial and temporal dimensions.

▶ results

Results on simplified τ -model from L3 Z decay

All events

- symmetric Lévy
does not describe dip or
large Q
- $R_a^{2\alpha} = \tan\left(\frac{\alpha\pi}{2}\right) R^{2\alpha}$
better description
- R_a free
good description



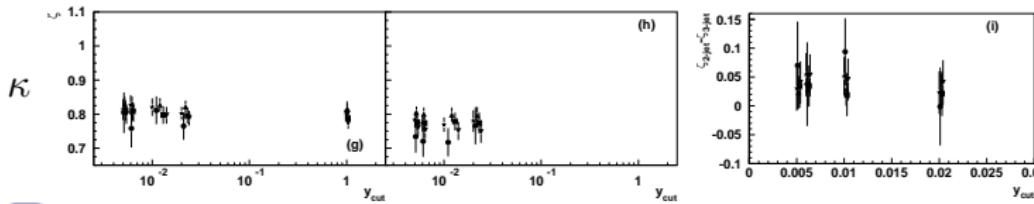
α_s

- LLA parton shower leads to a fractal in momentum space
fractal dimension is related to α_s *Gustafson et al.*
- Lévy dist. arises naturally from a fractal, or random walk,
or anomalous diffusion Metzler and Klafter, Phys.Rep.339(2000)1.
- strong momentum-space/configuration space correlation of
 τ -model \implies fractal in configuration space with same α
- generalized LPHD suggests particle dist. has same
properties as gluon dist.
- Putting this all together leads to *Csörgő et al.*

$$\alpha_s = \frac{2\pi}{3} \alpha^2$$

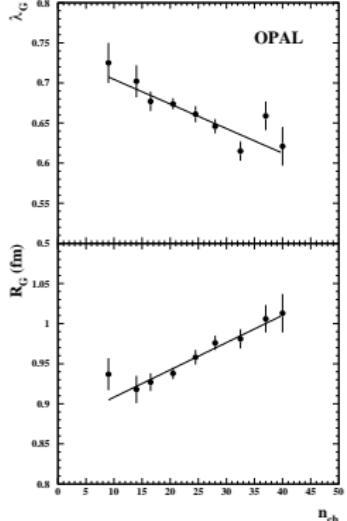
- Using our value of $\alpha = 0.43 \pm 0.03$ yields $\alpha_s = 0.39 \pm 0.05$
- This value is reasonable for a scale of 1–2 GeV,
where production of hadrons takes place
cf., from τ decays $\alpha_s(m_\tau \approx 1.8 \text{ GeV}) = 0.34 \pm 0.03$

2-jet / 3-jet

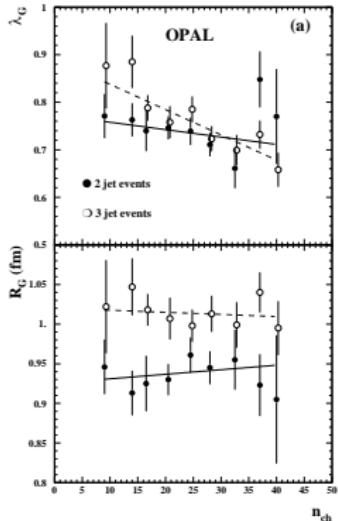
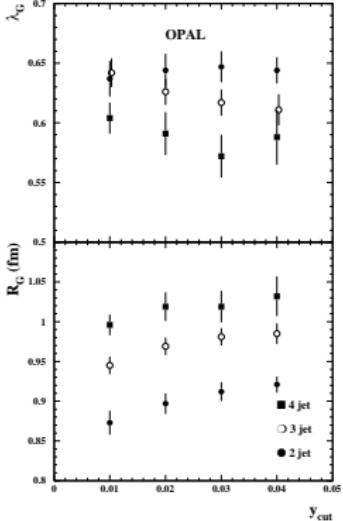


2-jet / 3-jet

λ



r



$\lambda \searrow$ with n_{ch}
 $r \nearrow$ with n_{ch}

$\lambda \searrow$ with n_{jet}
 $r \nearrow$ with n_{jet}

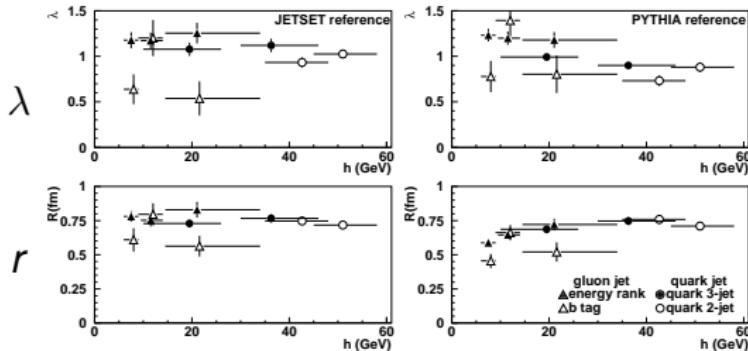
$\lambda_{n\text{-jet}} \approx$ indep. of n_{ch}
 $r_{n\text{-jet}}$ indep. of n_{ch}

Multiplicity dependence is largely due to number of jets.

q/g

fit with Edgeworth expansion parametrization:

$$R_2(Q) = \gamma \left[1 + \lambda e^{-r^2 Q^2} \left(1 + \frac{\kappa}{3!} H_3(rQ) \right) \right]$$

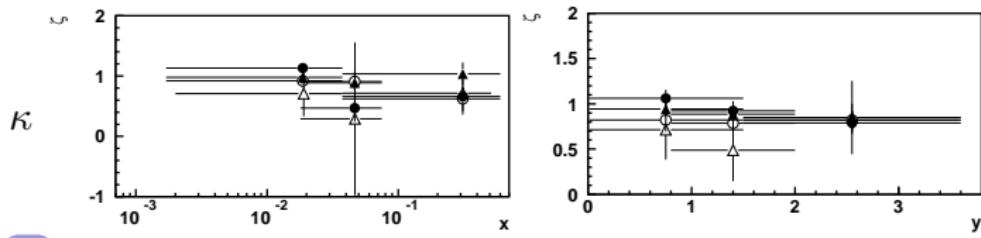


hardness,
 $h = E_{\text{jet}} \sin \left(\frac{\theta_{1,2}}{2} \right)$

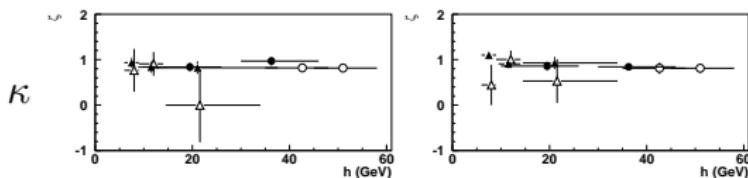
- no dependence on h

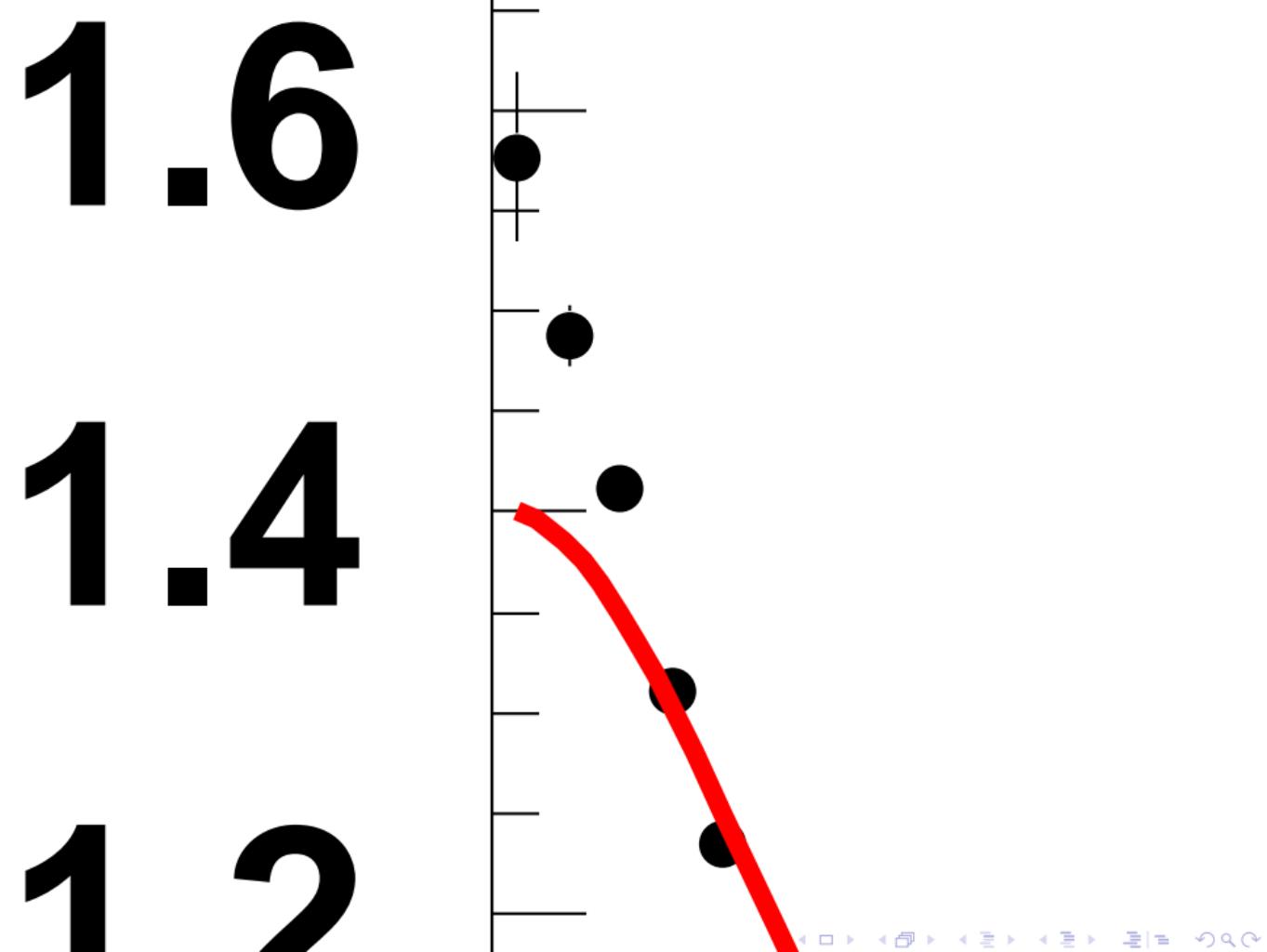


q/g: x, y dependence

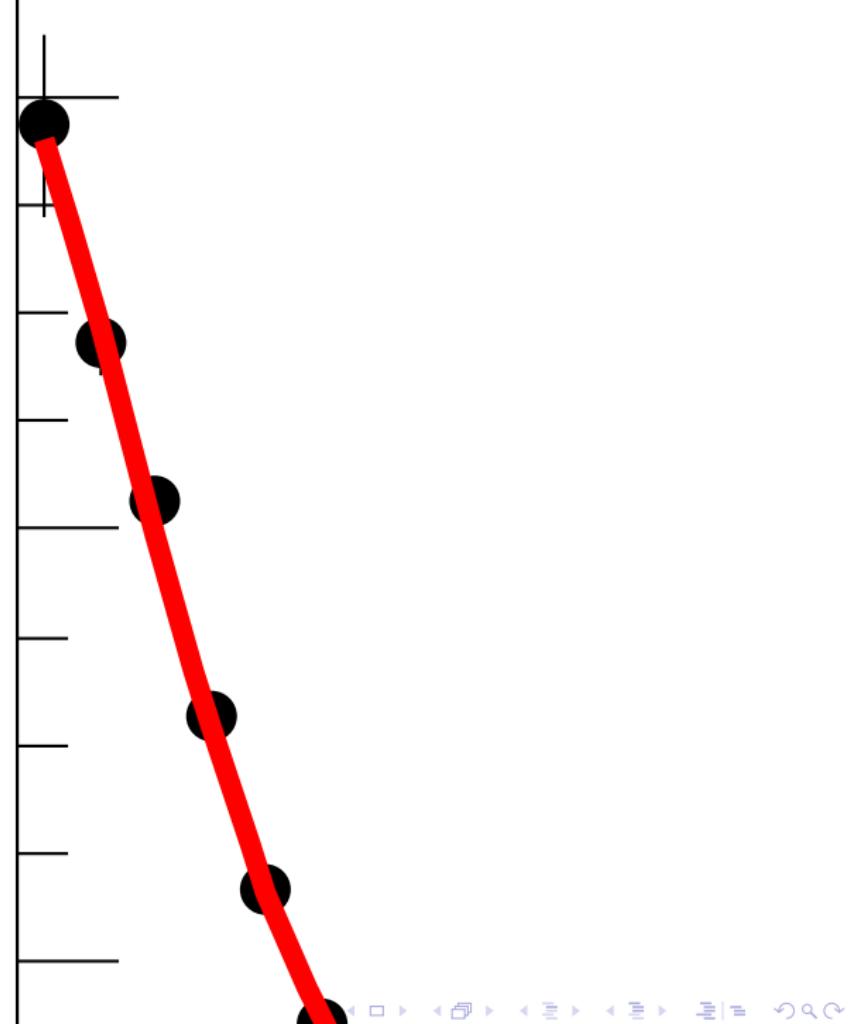


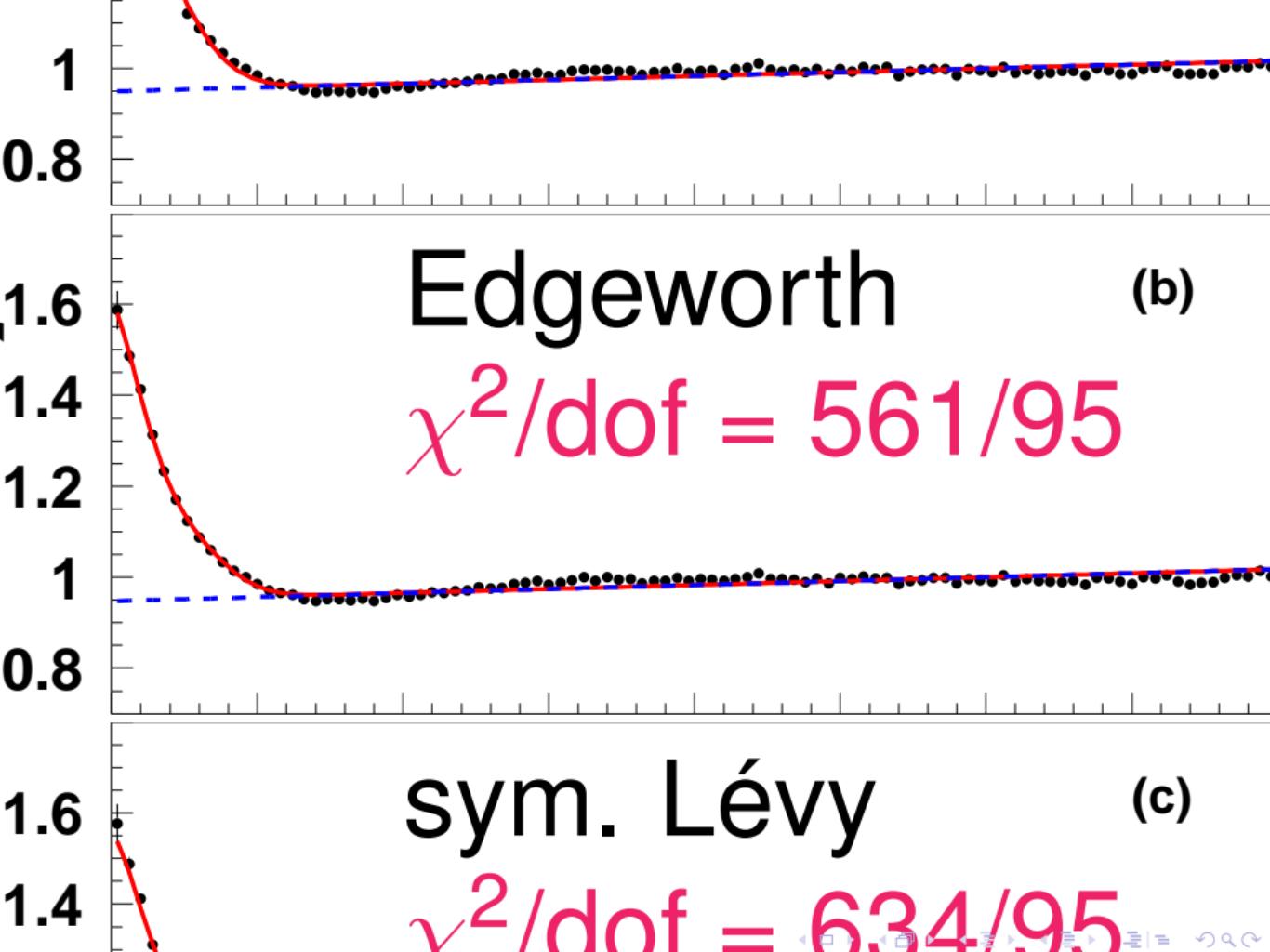
q/g

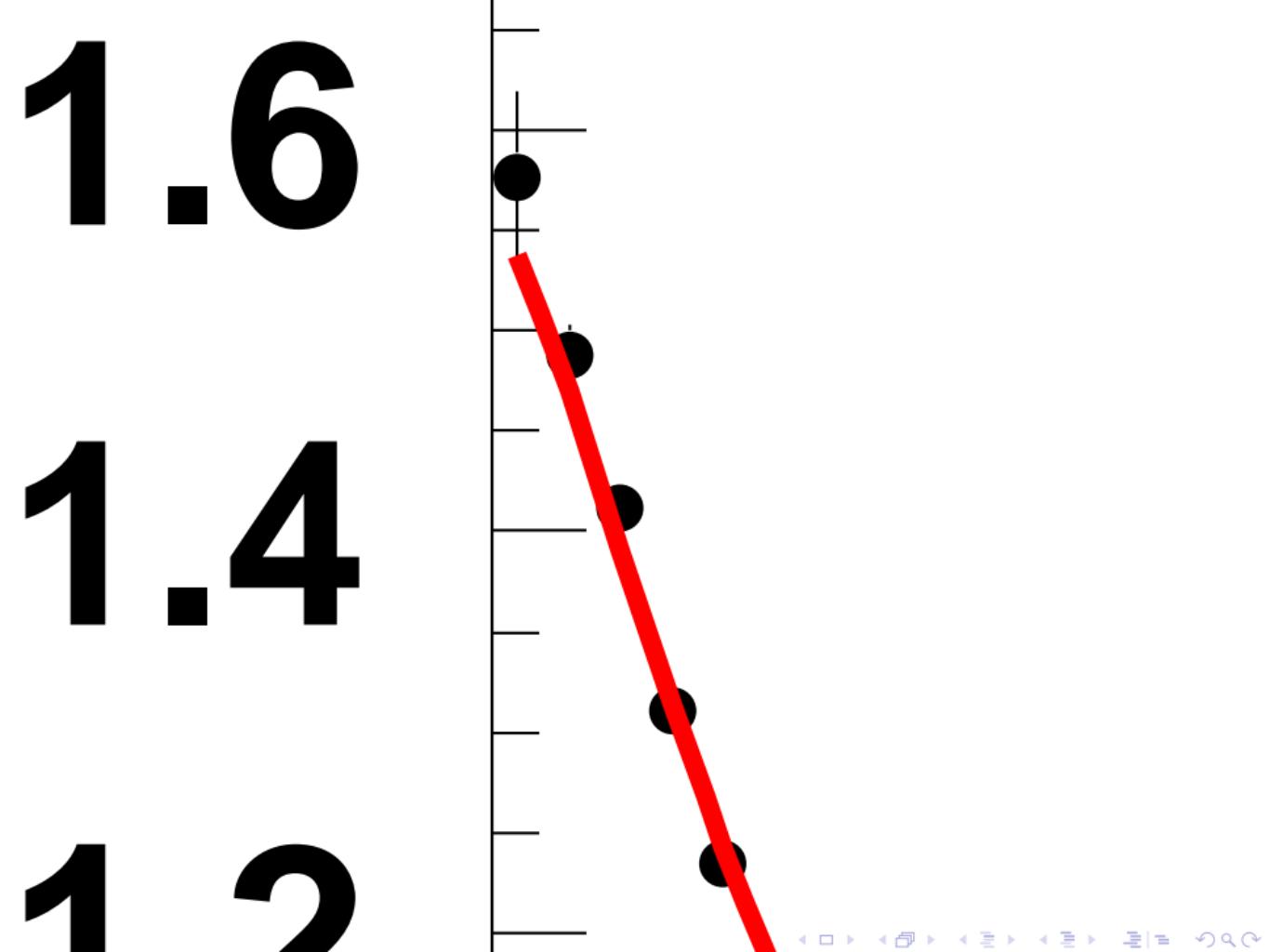




1.6
1.4
1.2

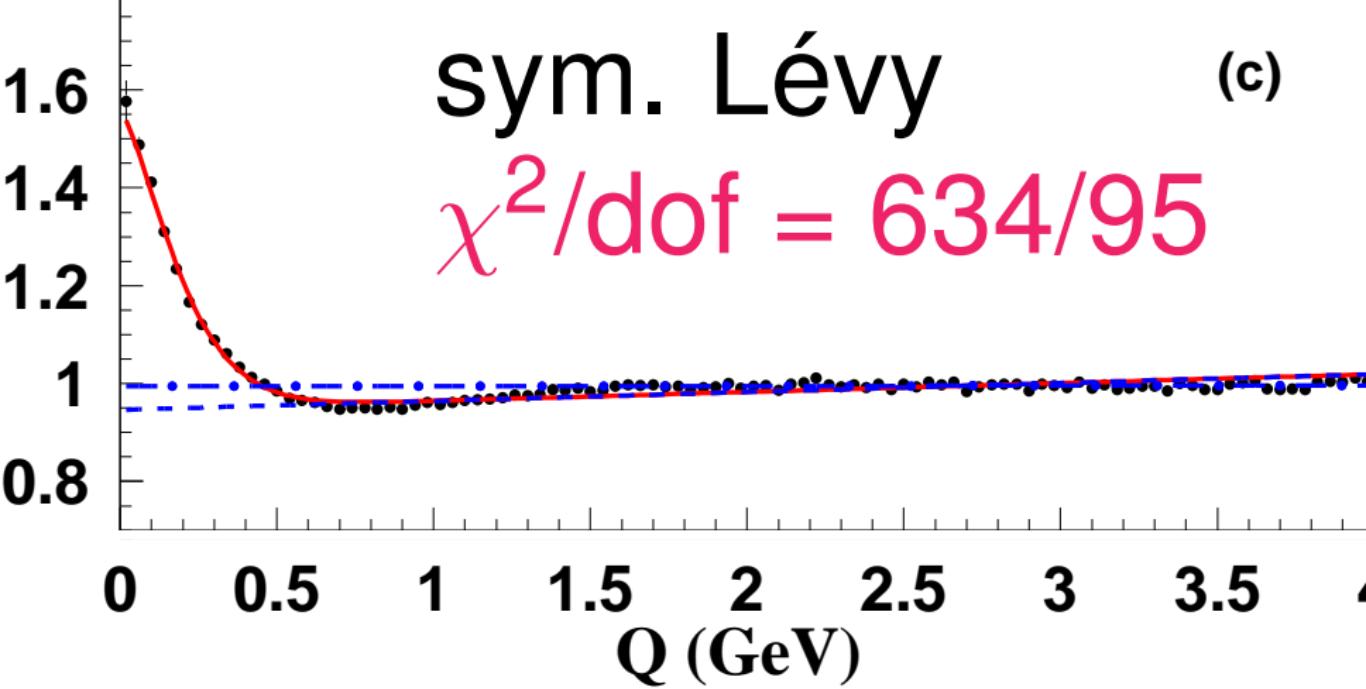




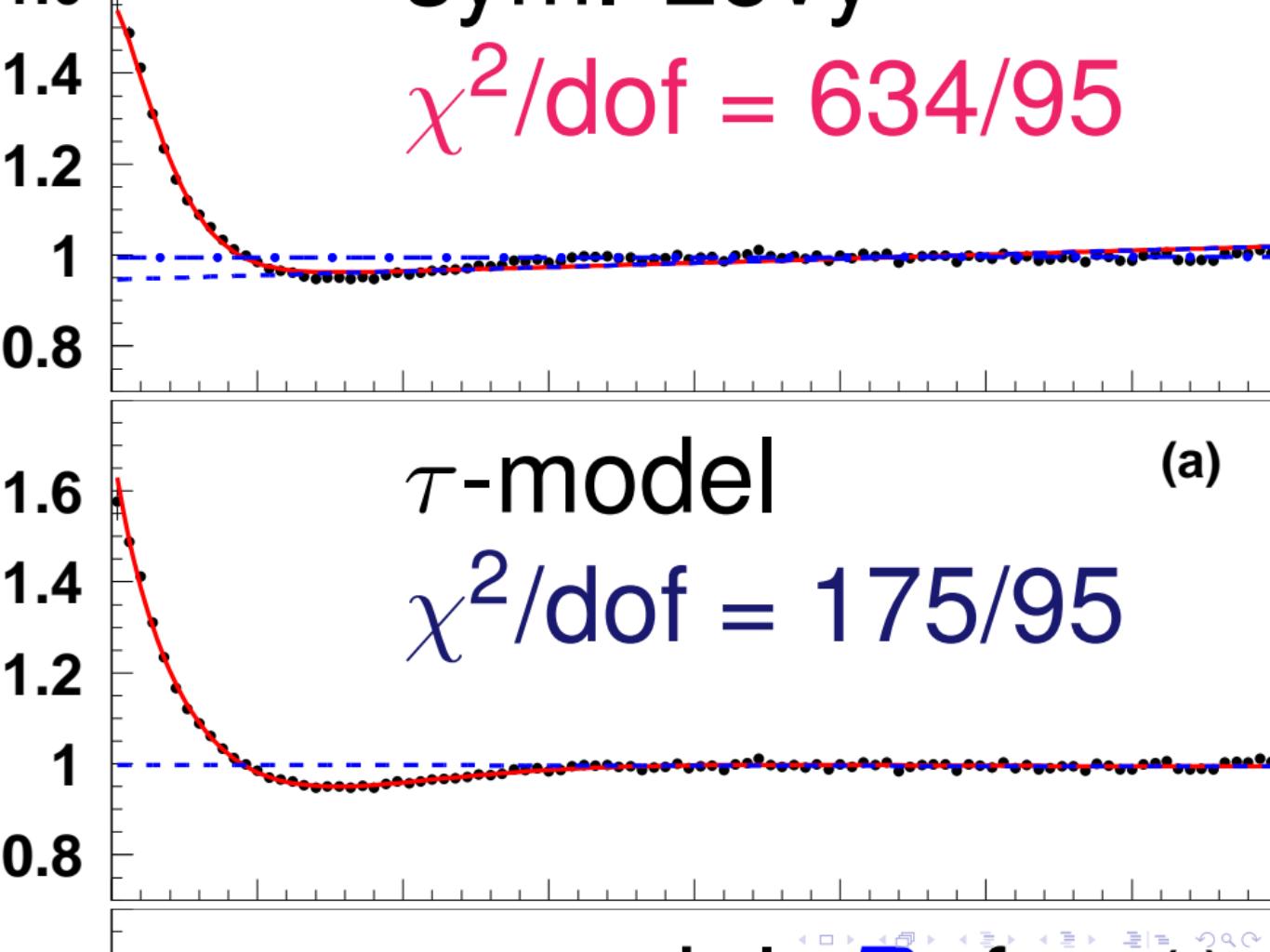


sym. Lévy (c)

$$\chi^2/\text{dof} = 634/95$$

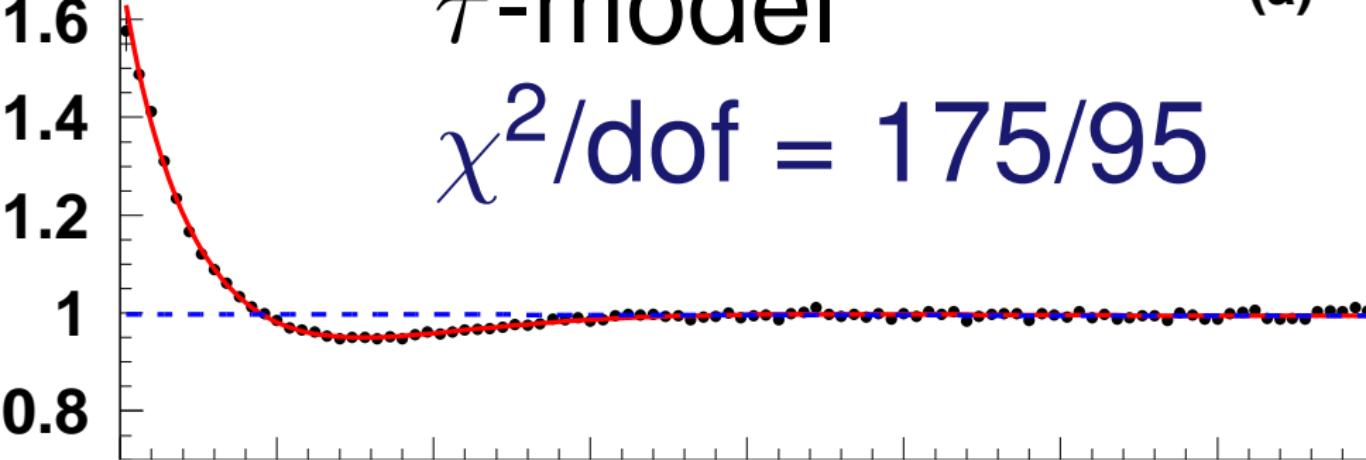


ter than Gaussian, but poor.
region $0.6 < Q < 1.5$ GeV



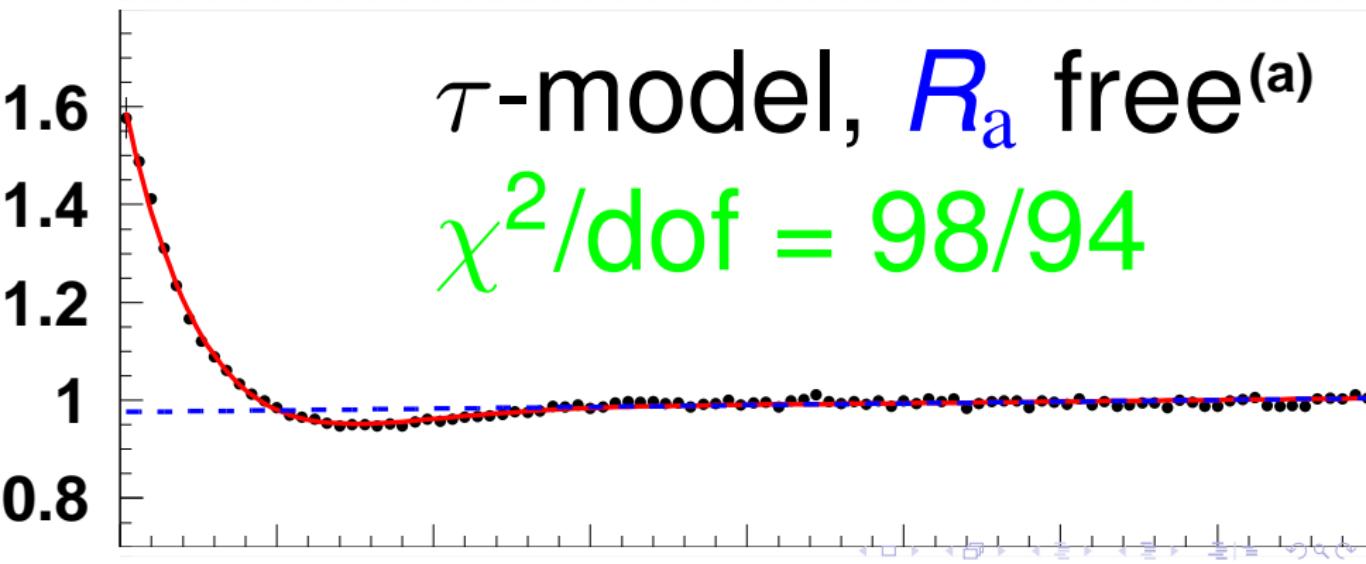
τ -model

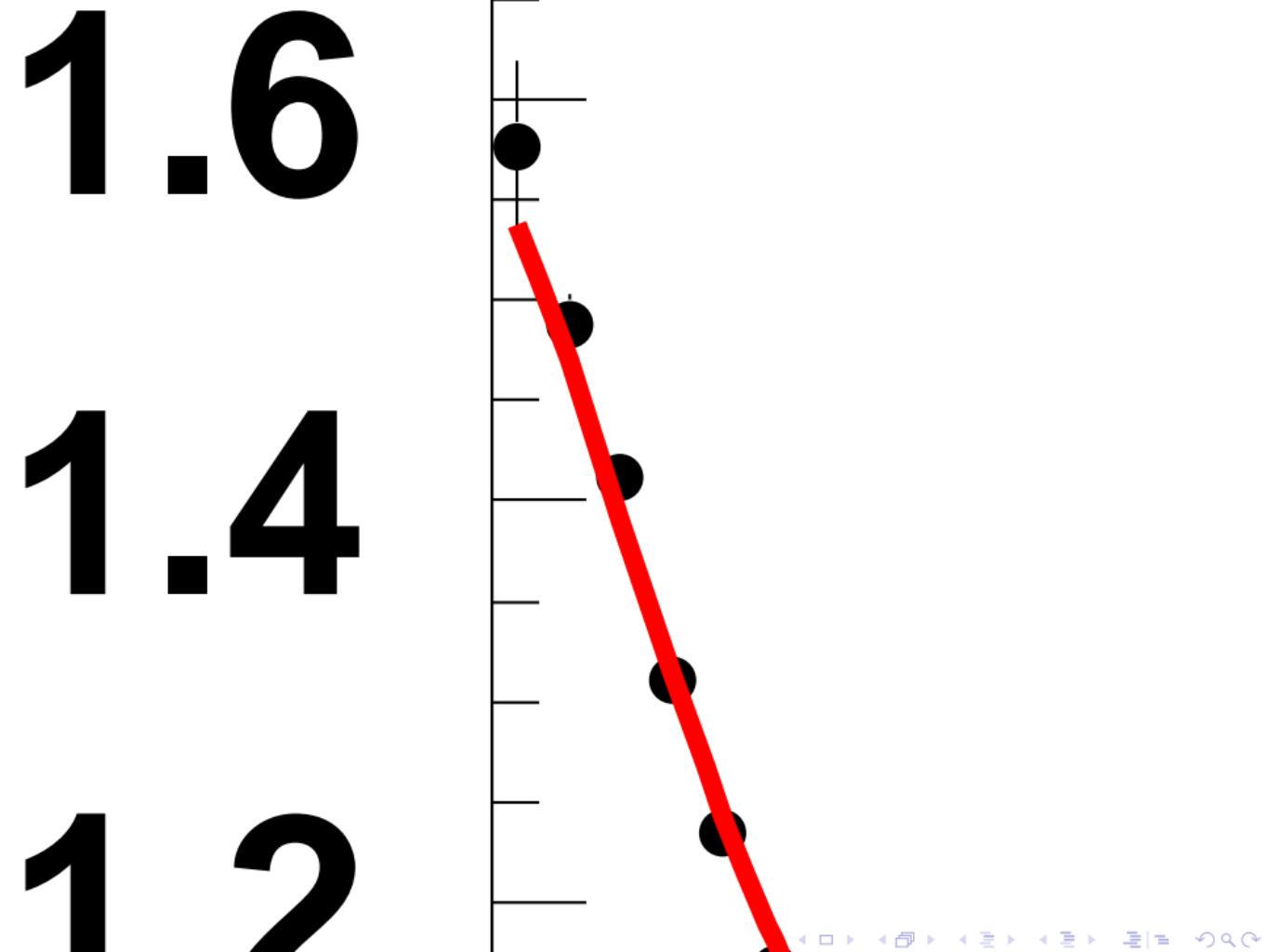
$$\chi^2/\text{dof} = 175/95$$



τ -model, R_a free^(a)

$$\chi^2/\text{dof} = 98/94$$

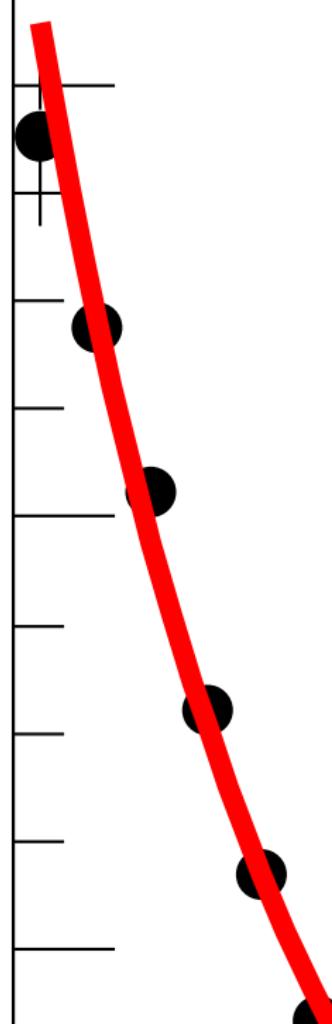


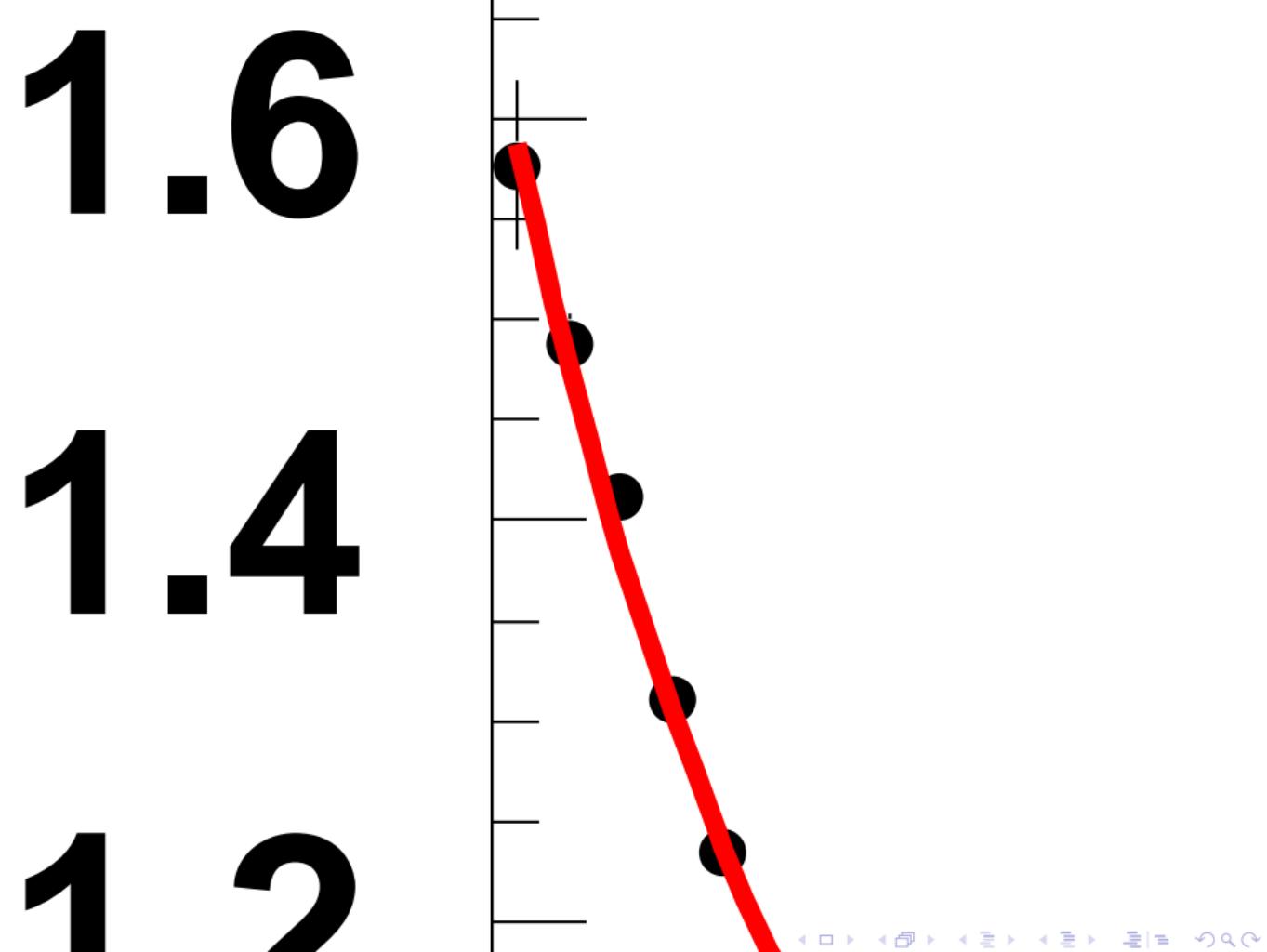


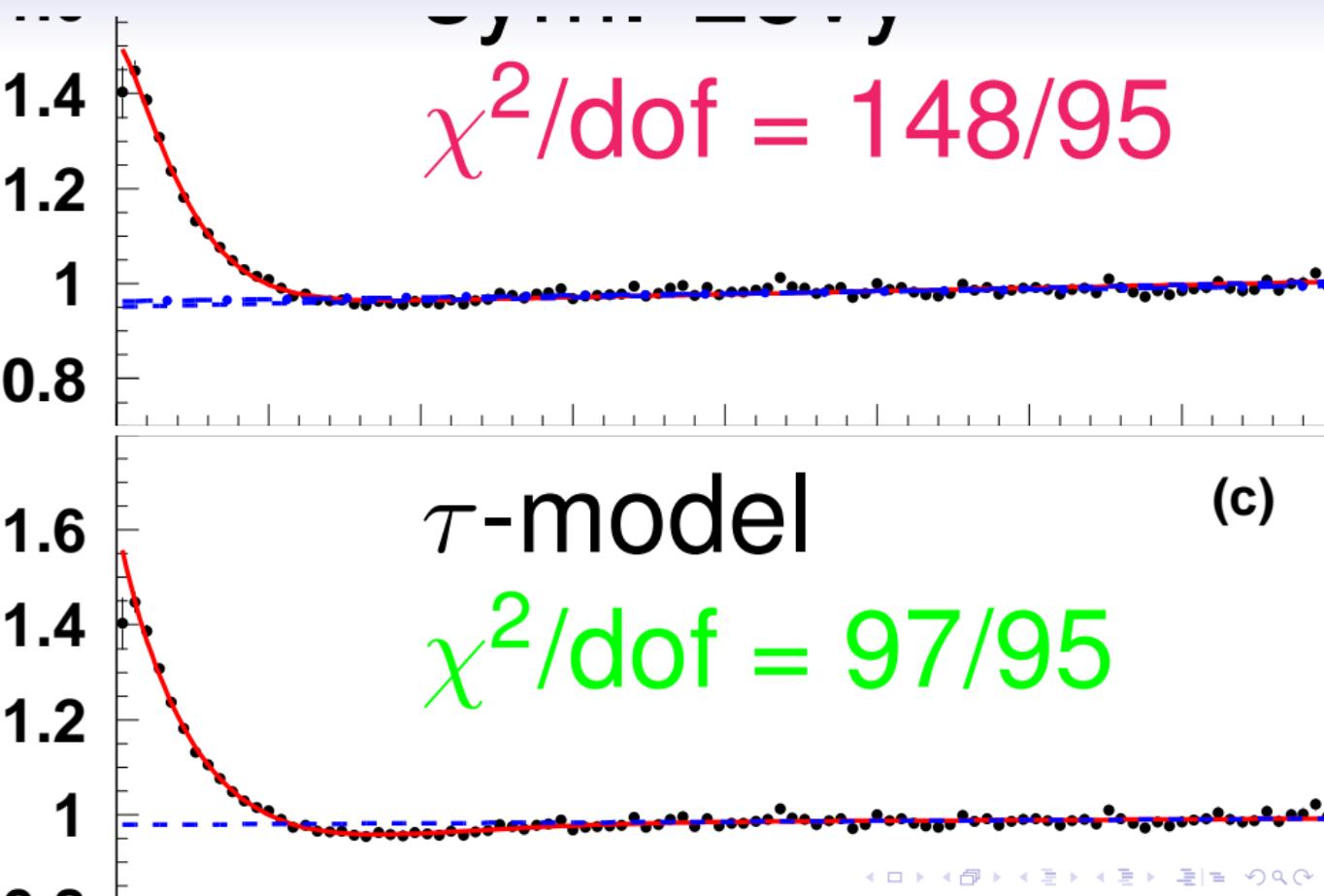
1.6

1.4

1.2

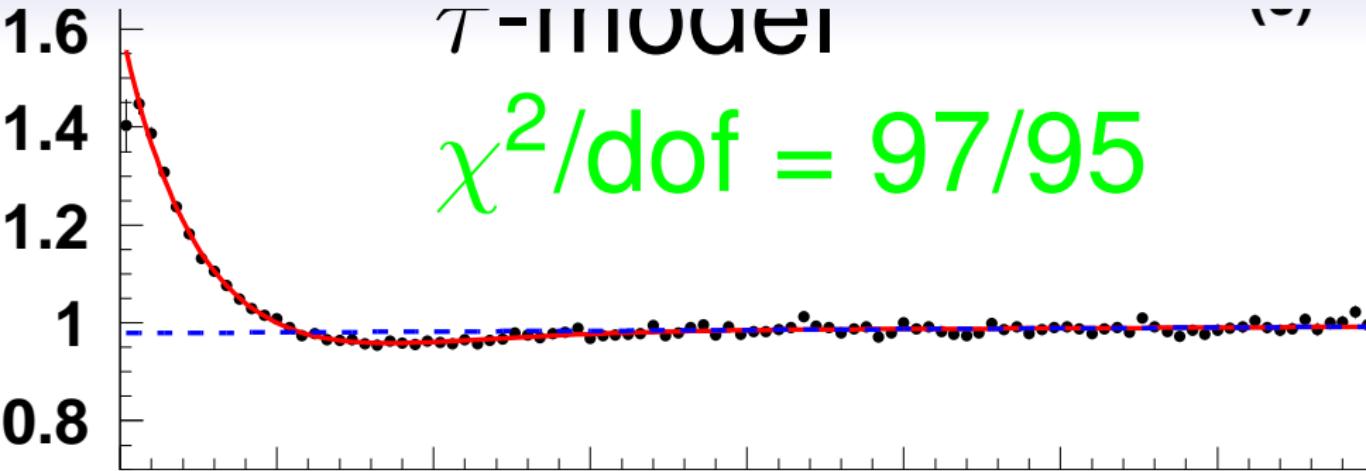






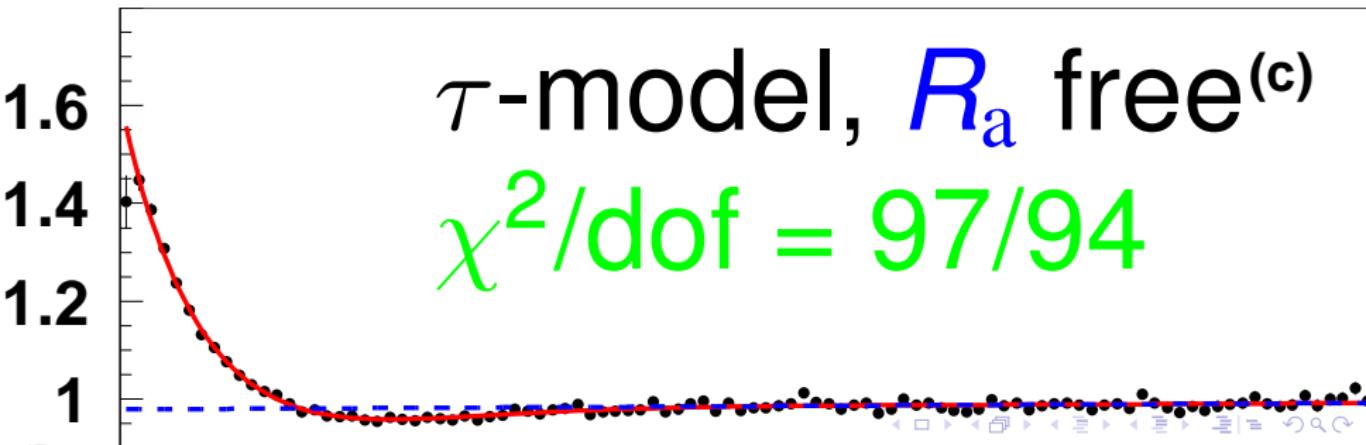
τ-THOMAS

$\chi^2/\text{dof} = 97/95$

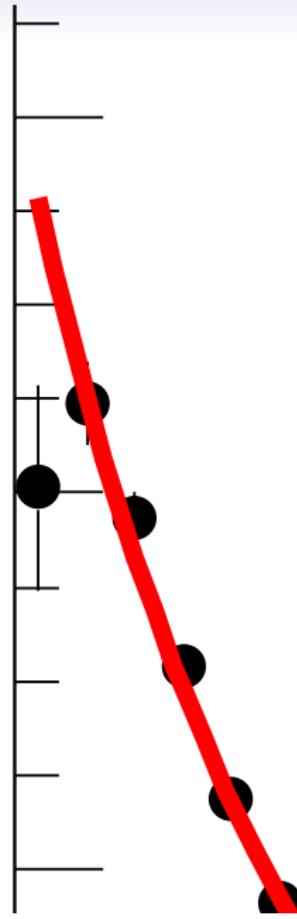


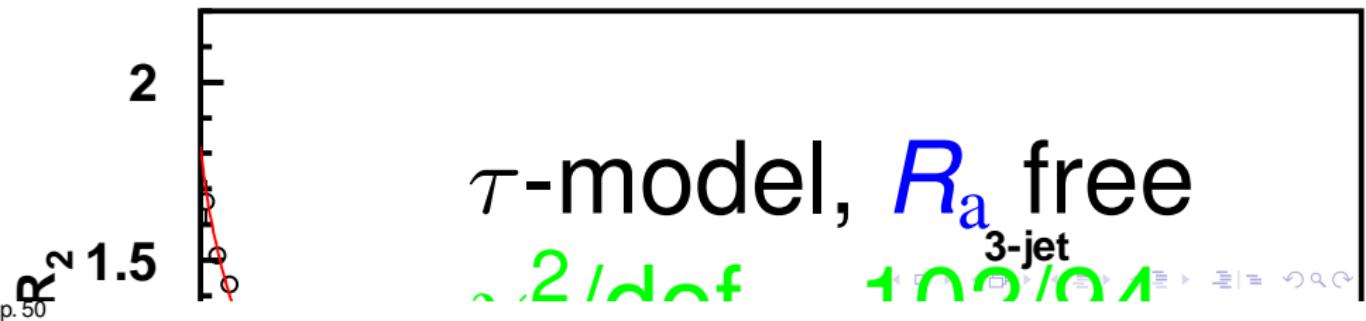
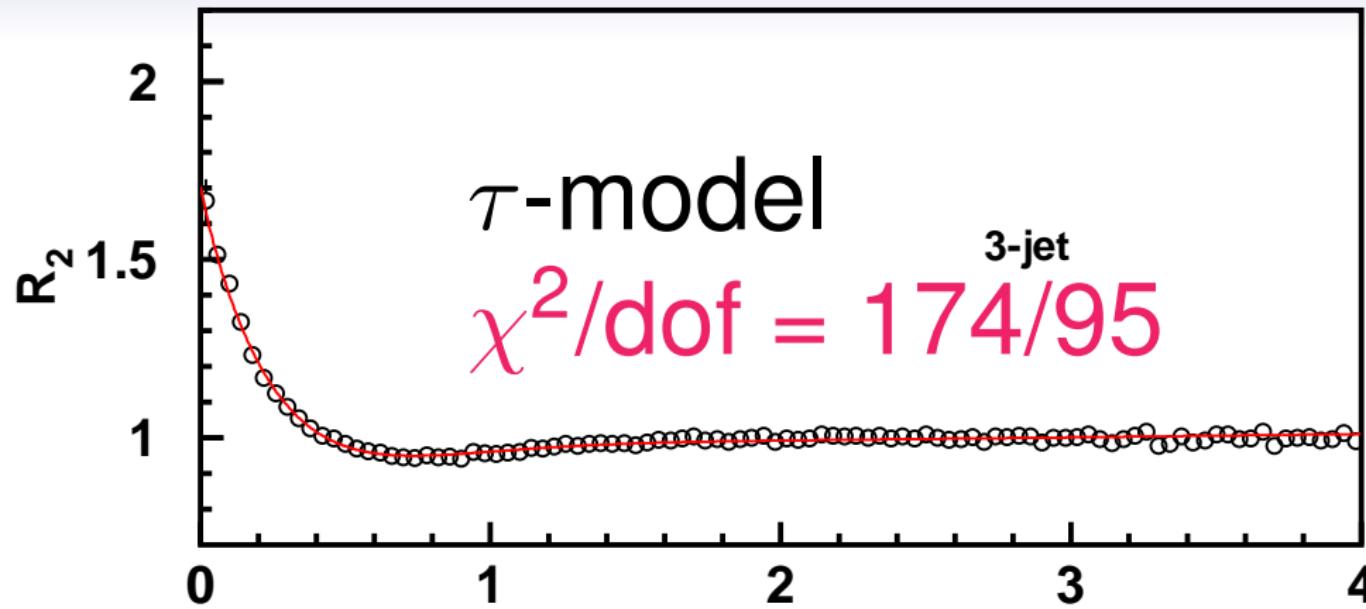
τ -model, R_a free^(c)

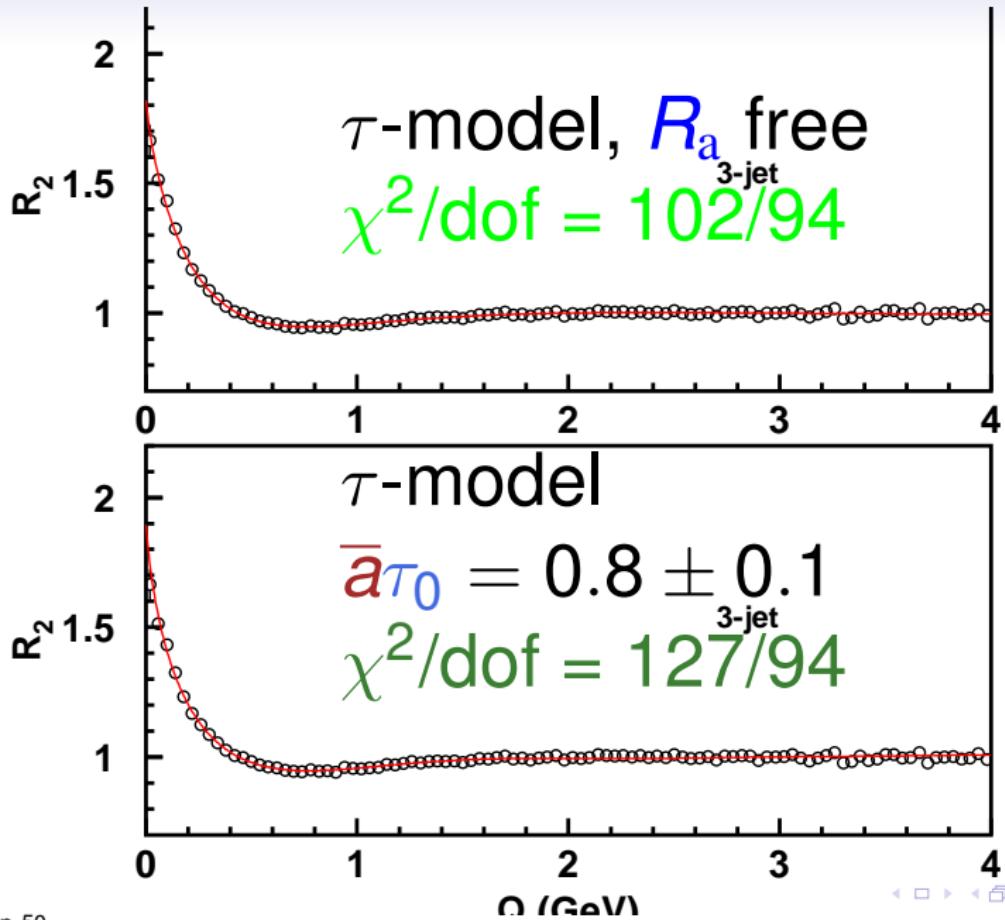
$\chi^2/\text{dof} = 97/94$

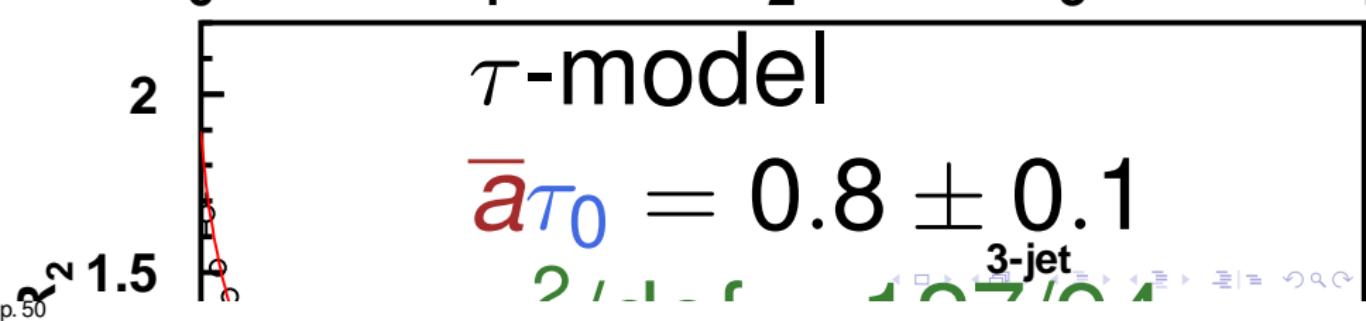
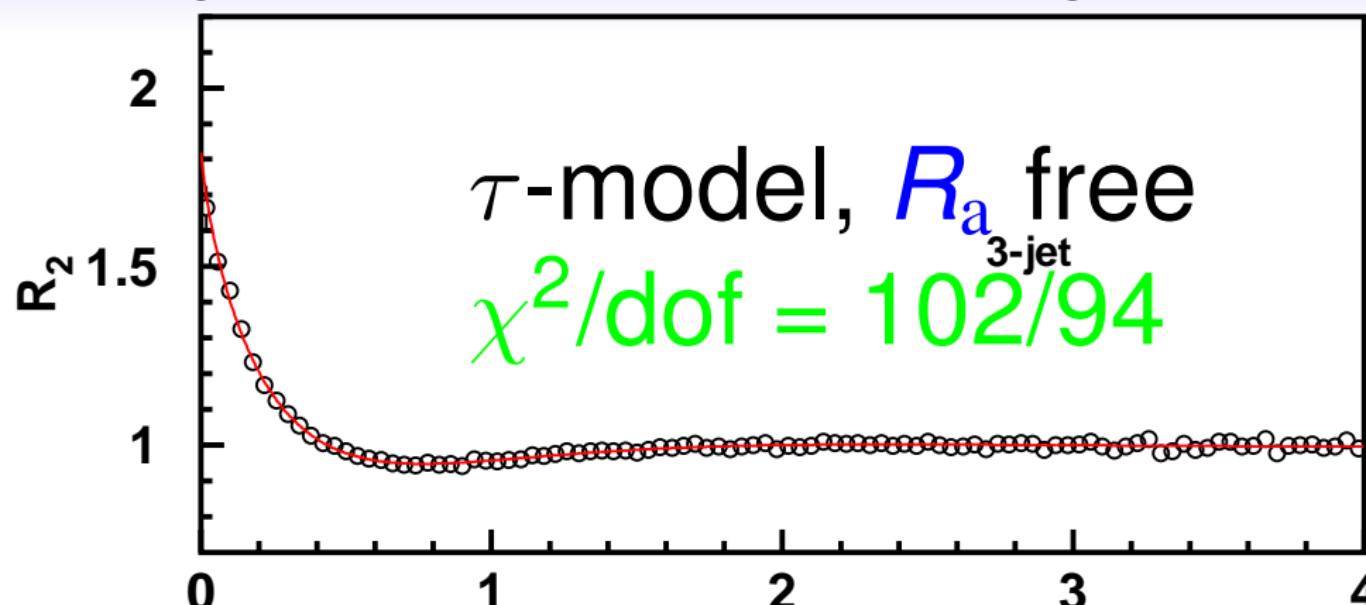


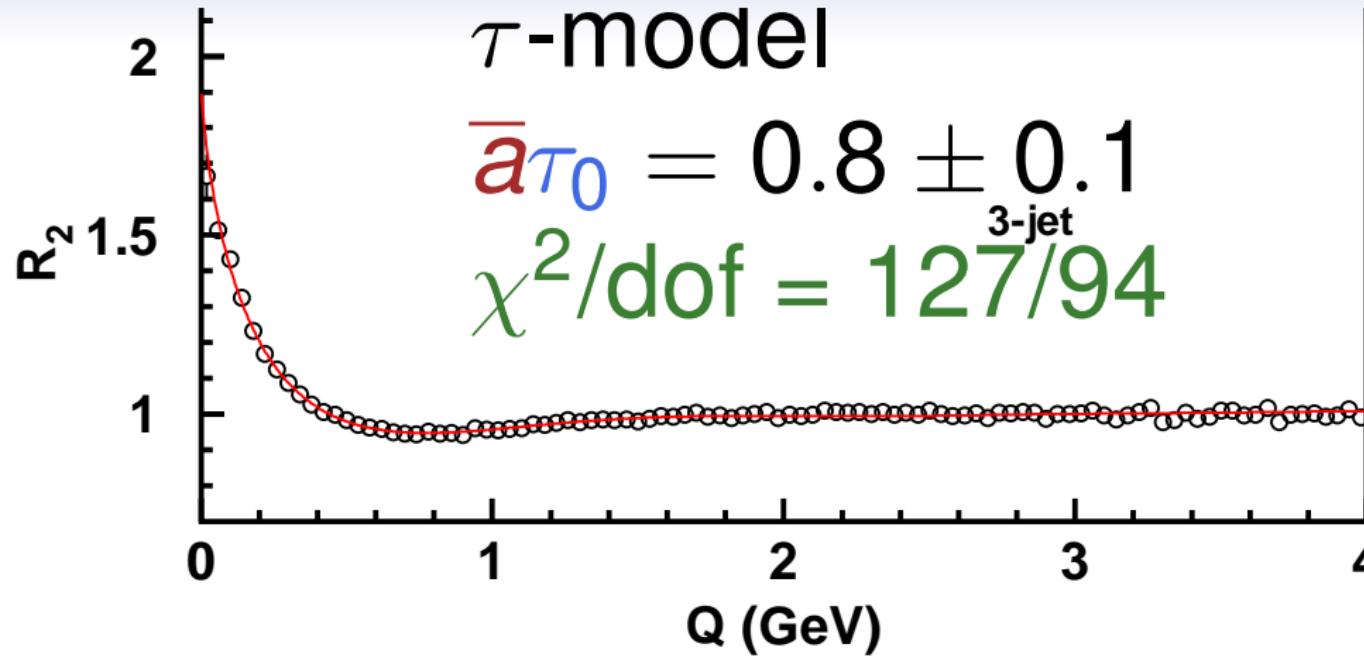
1.6
1.4
1.2

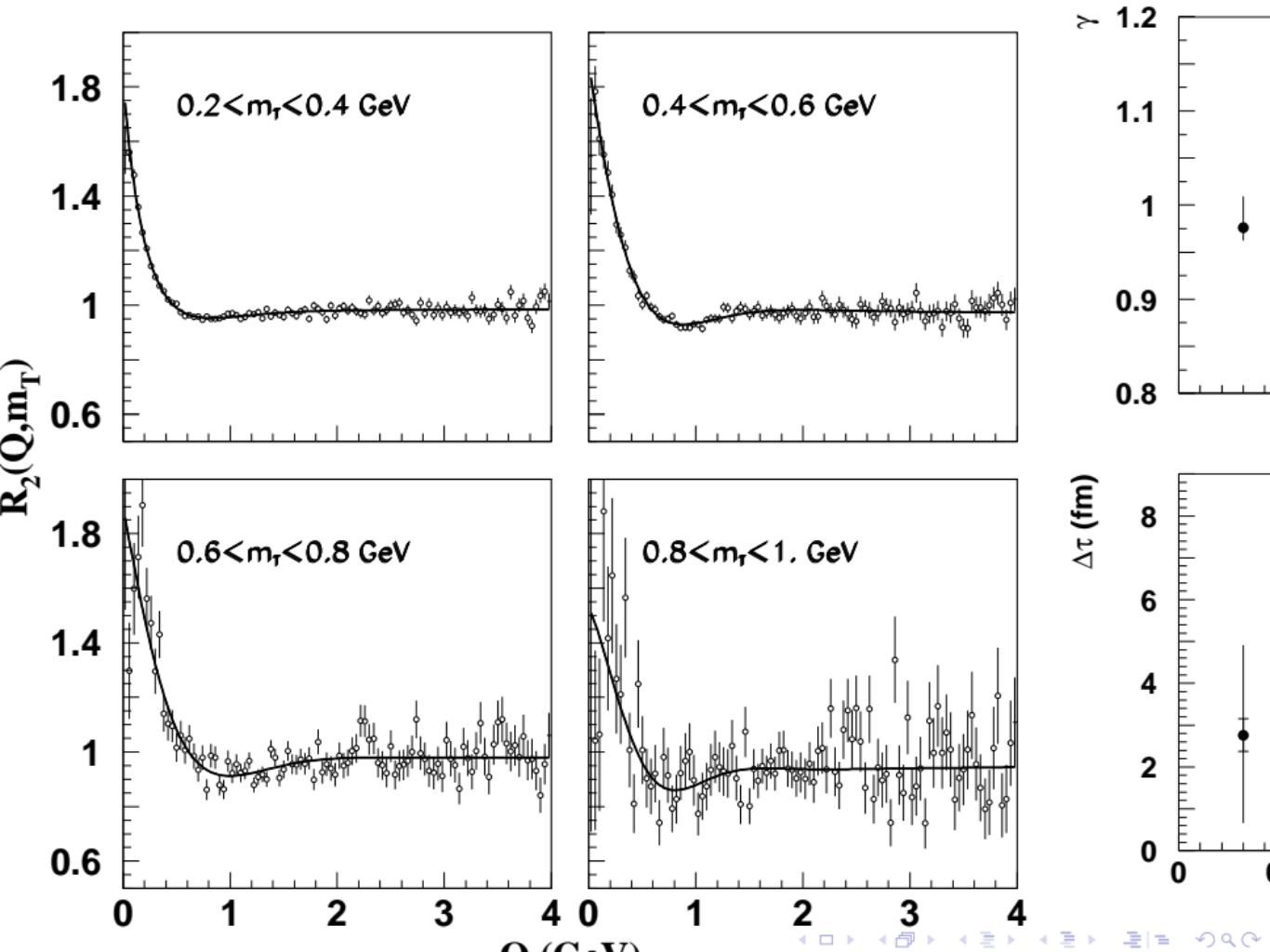


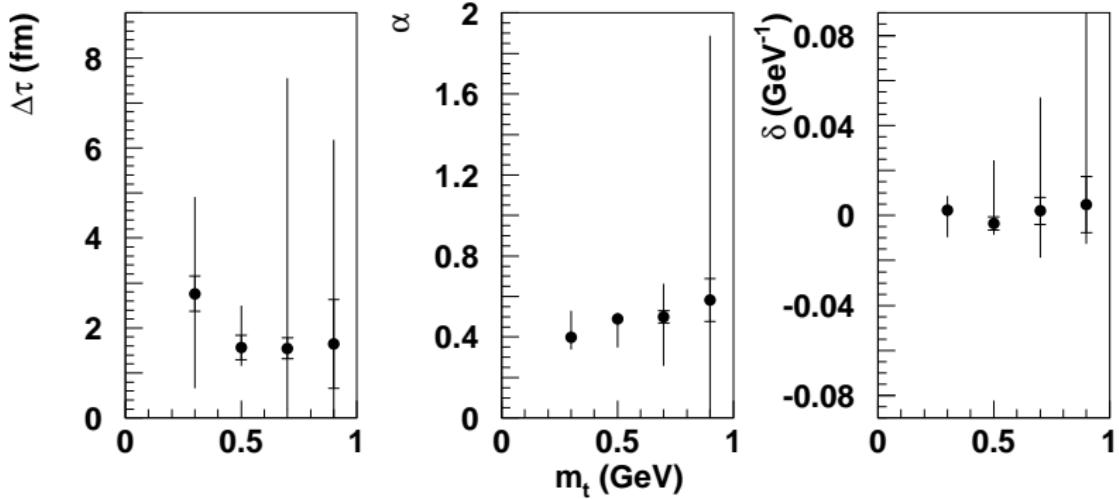
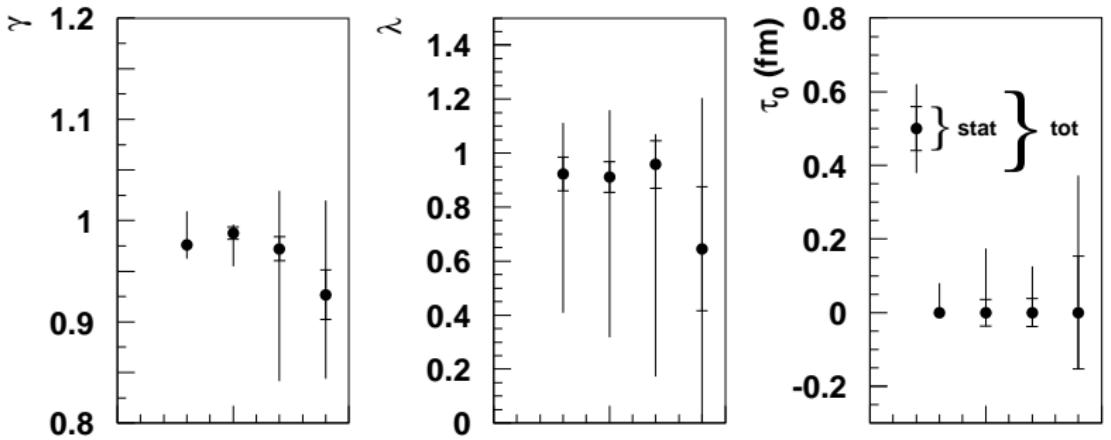




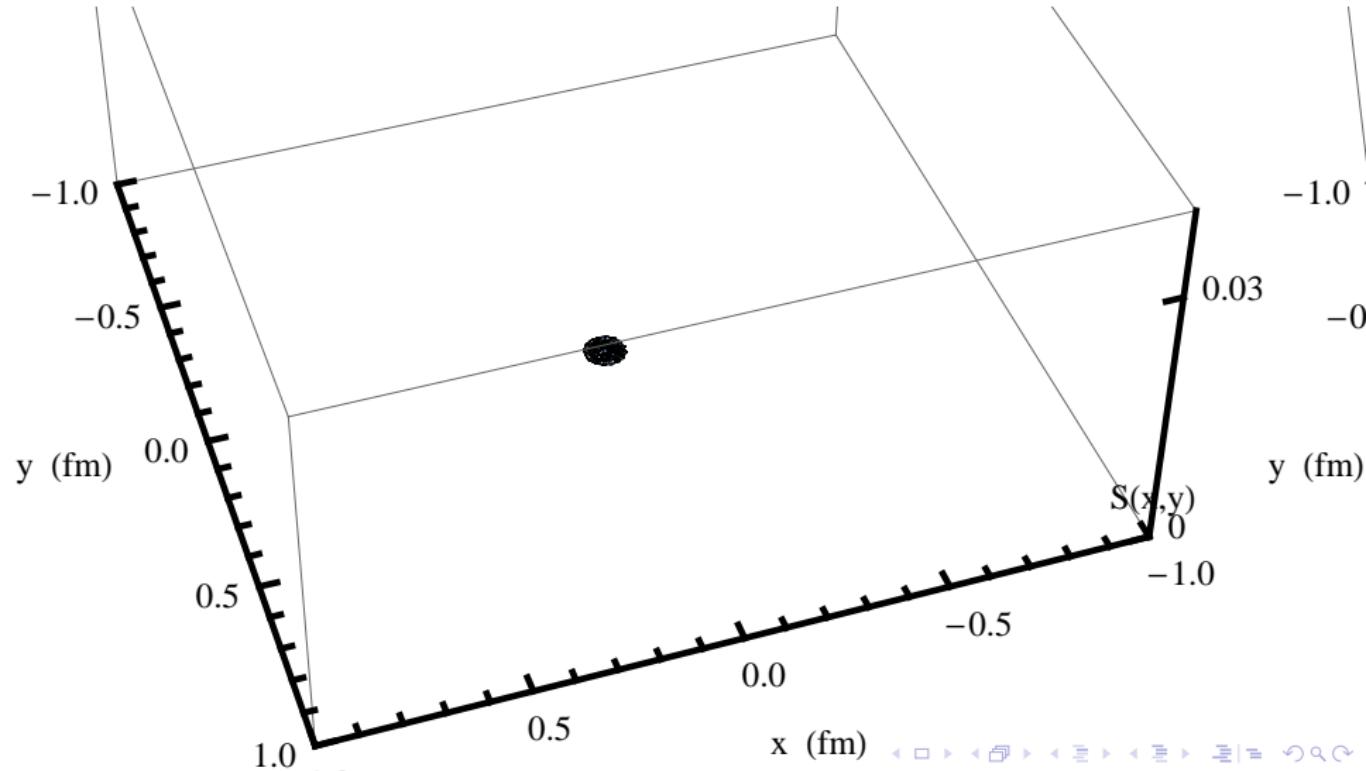




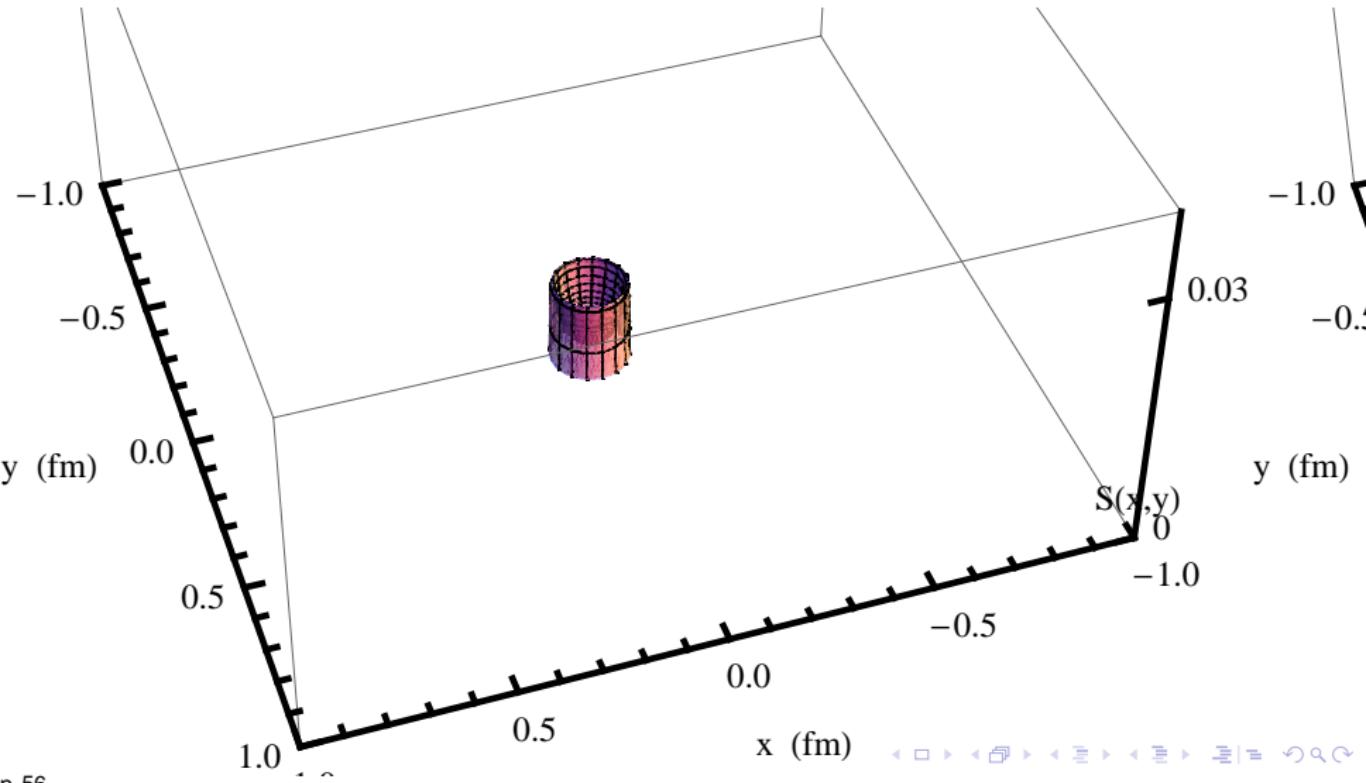




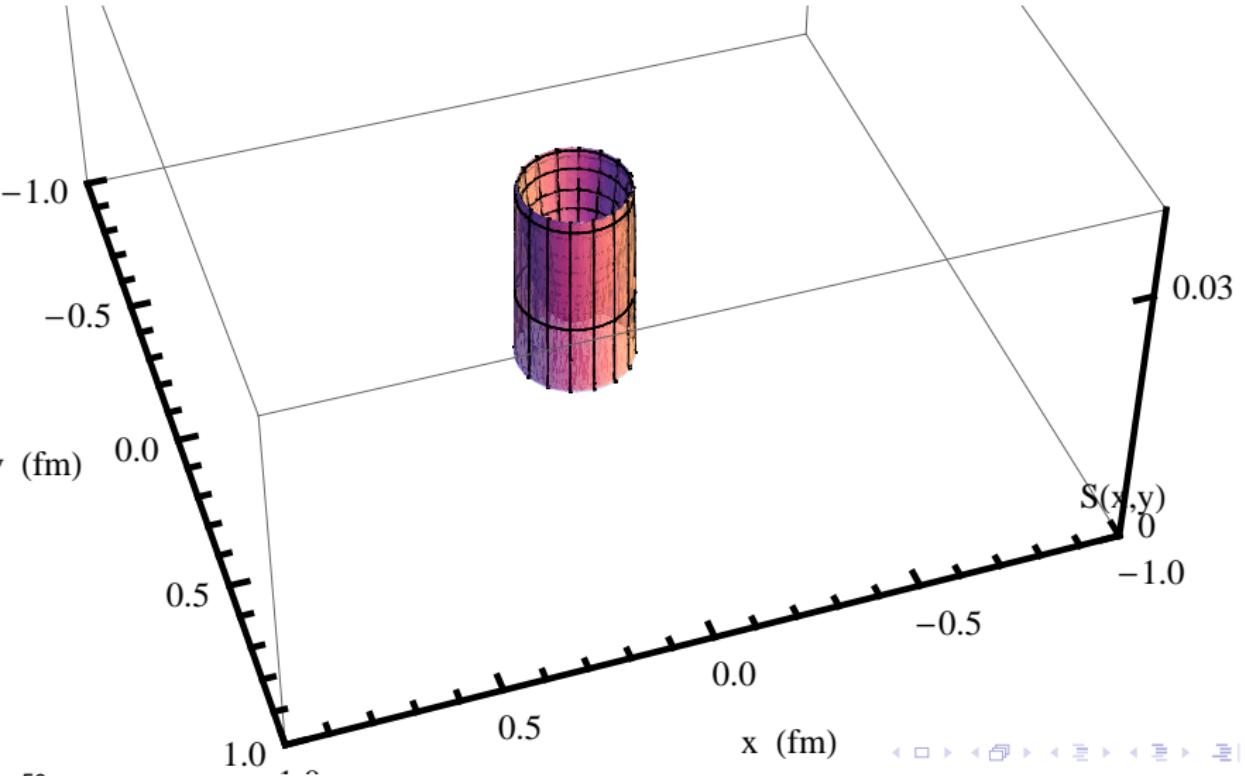
$\tau = 0.05 \text{ fm}$



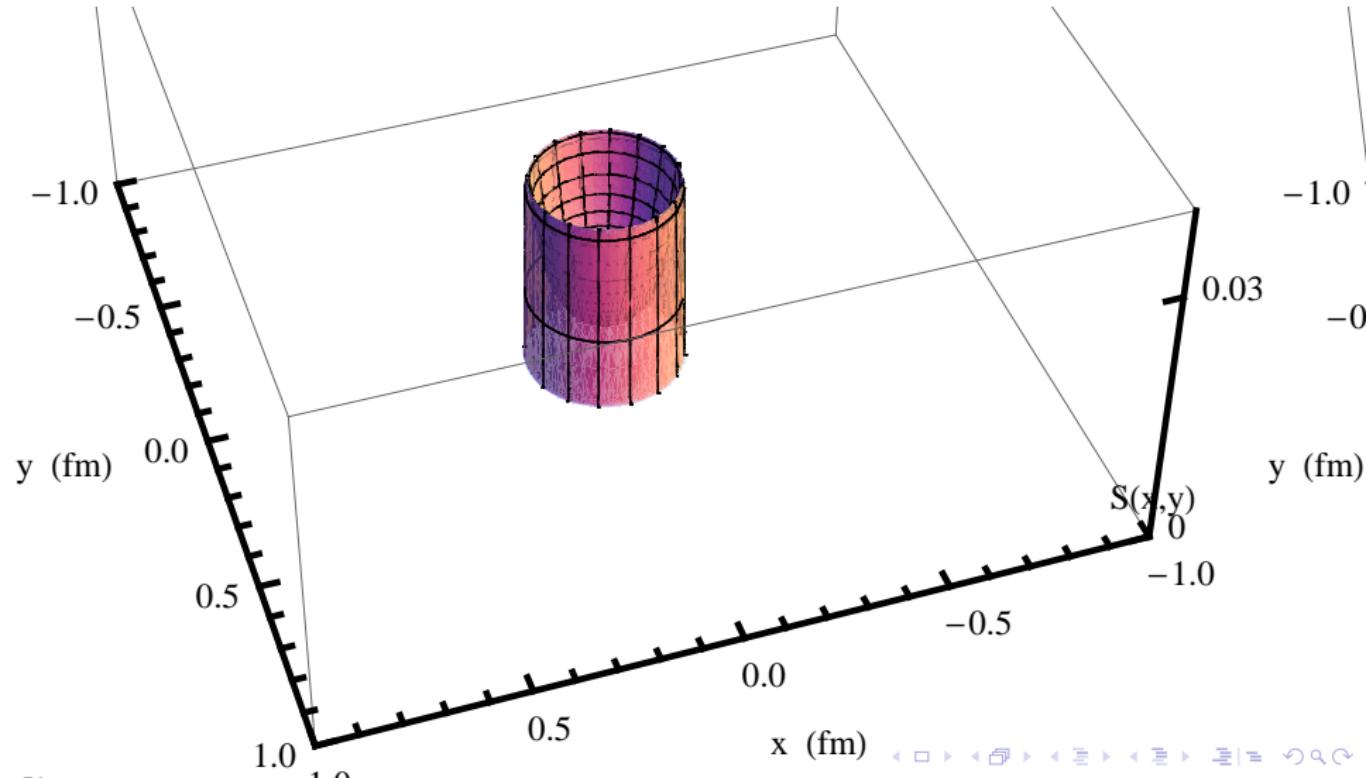
$\tau = 0.10 \text{ fm}$



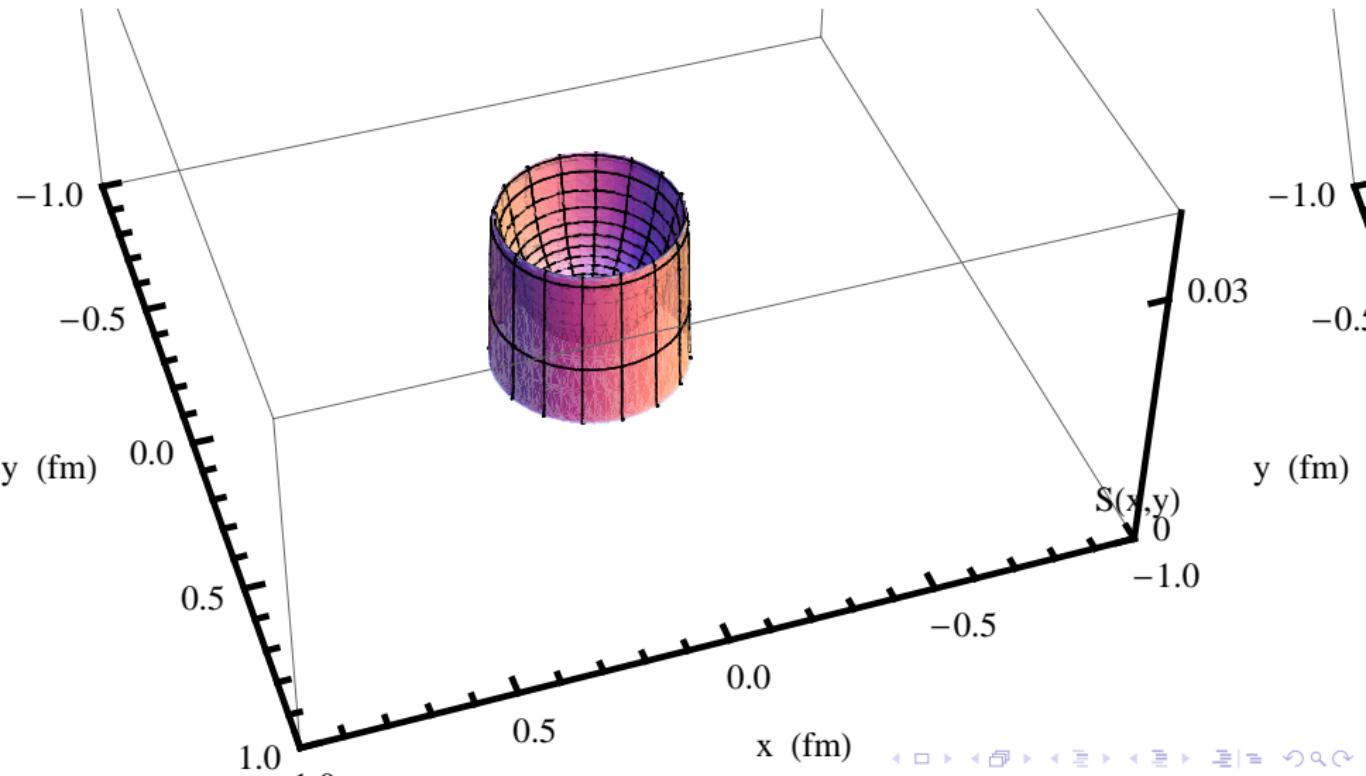
$\tau = 0.15 \text{ fm}$



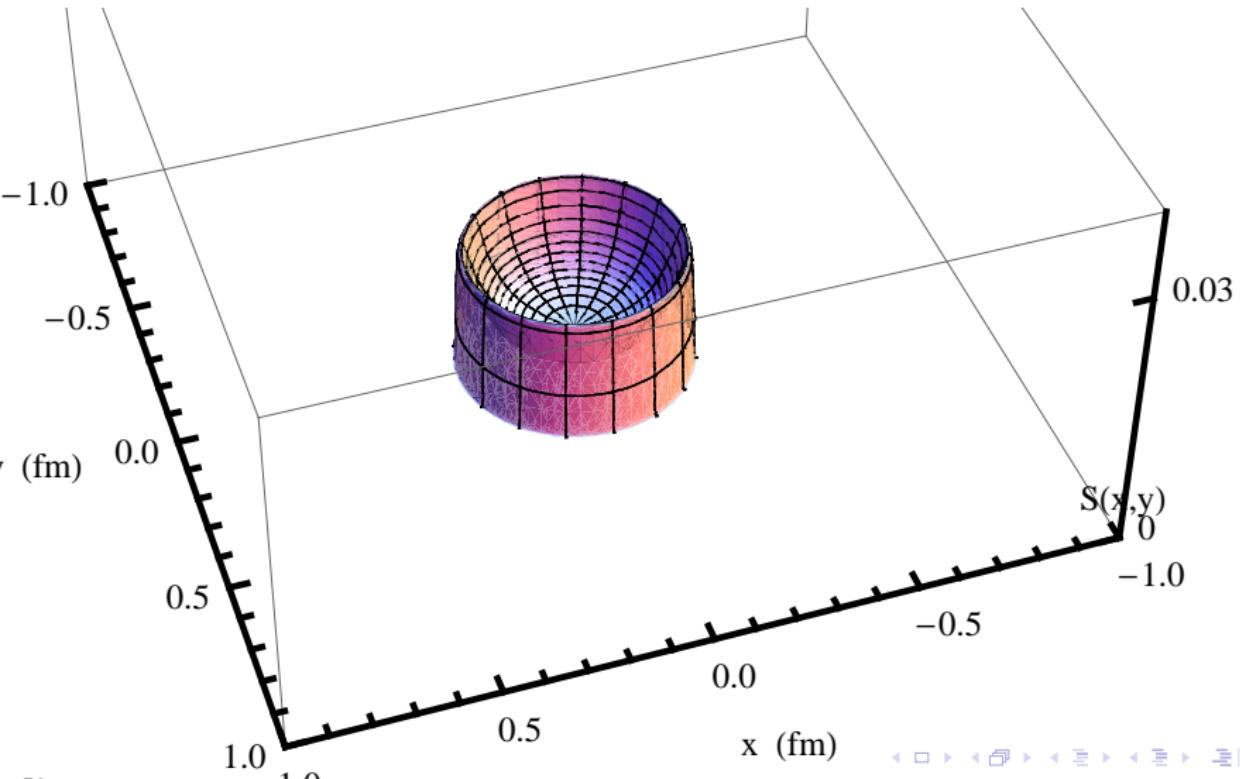
$\tau = 0.20 \text{ fm}$



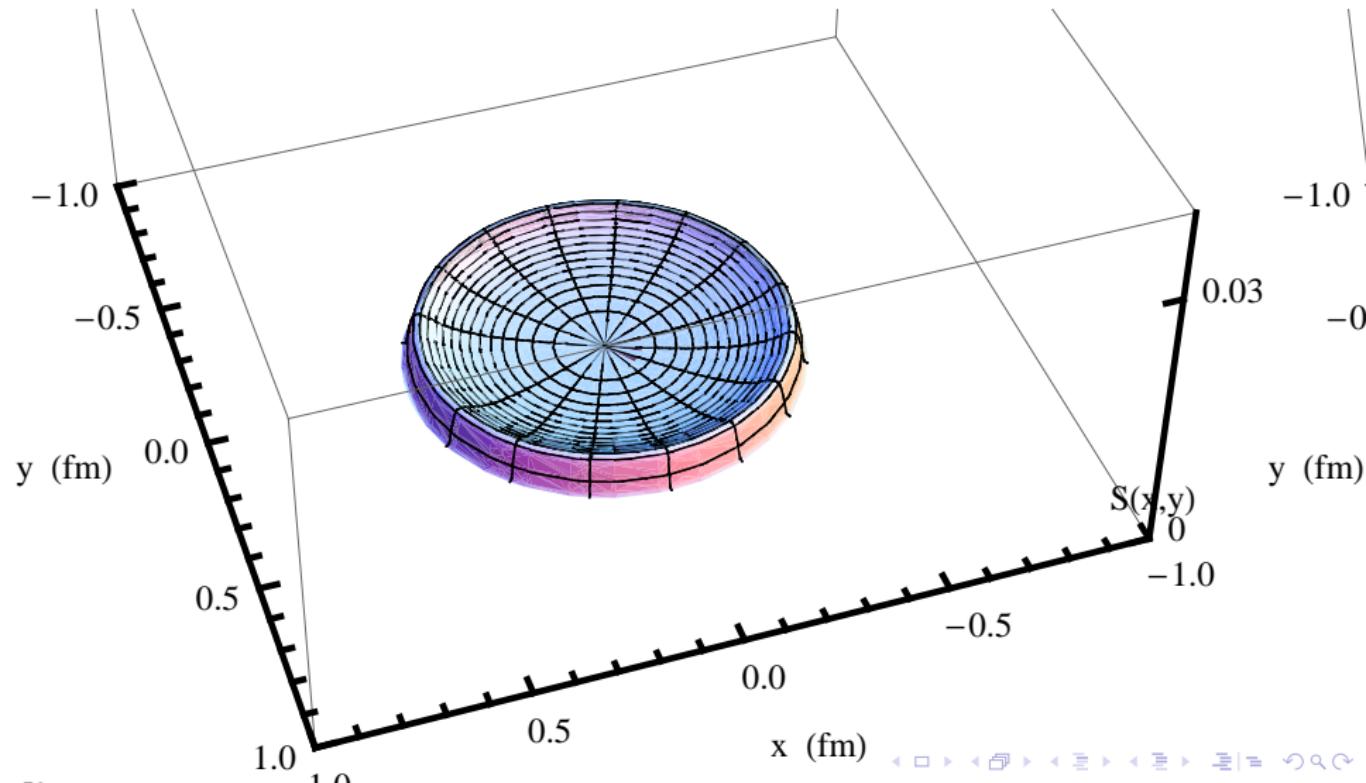
$\tau = 0.25 \text{ fm}$



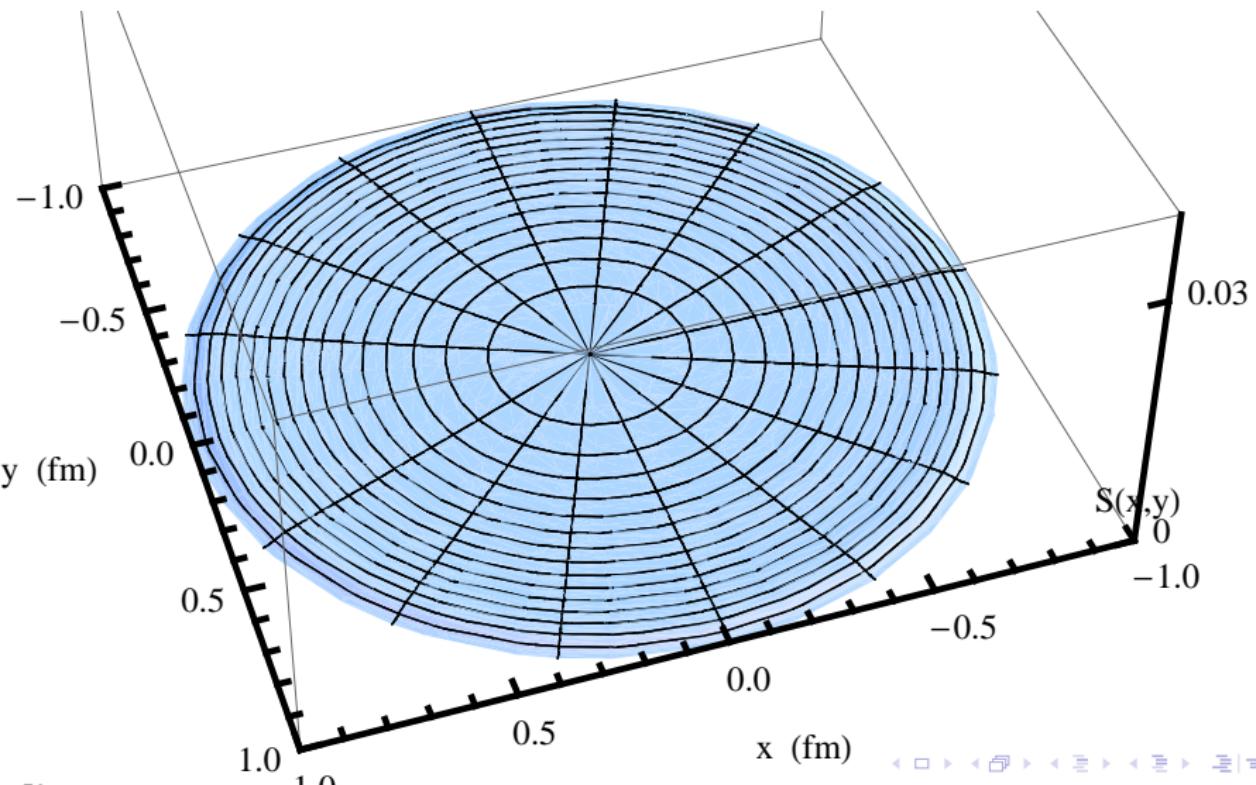
$\tau = 0.30 \text{ fm}$

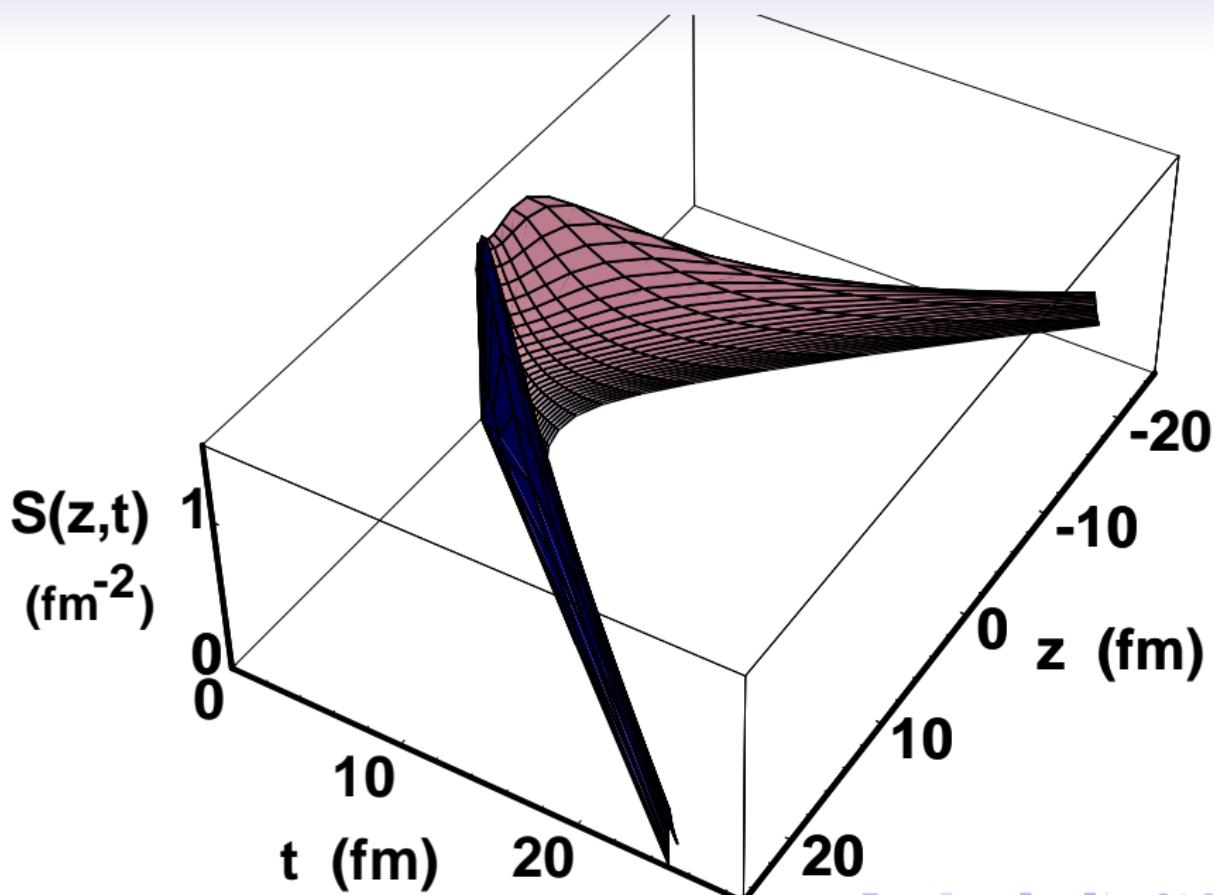


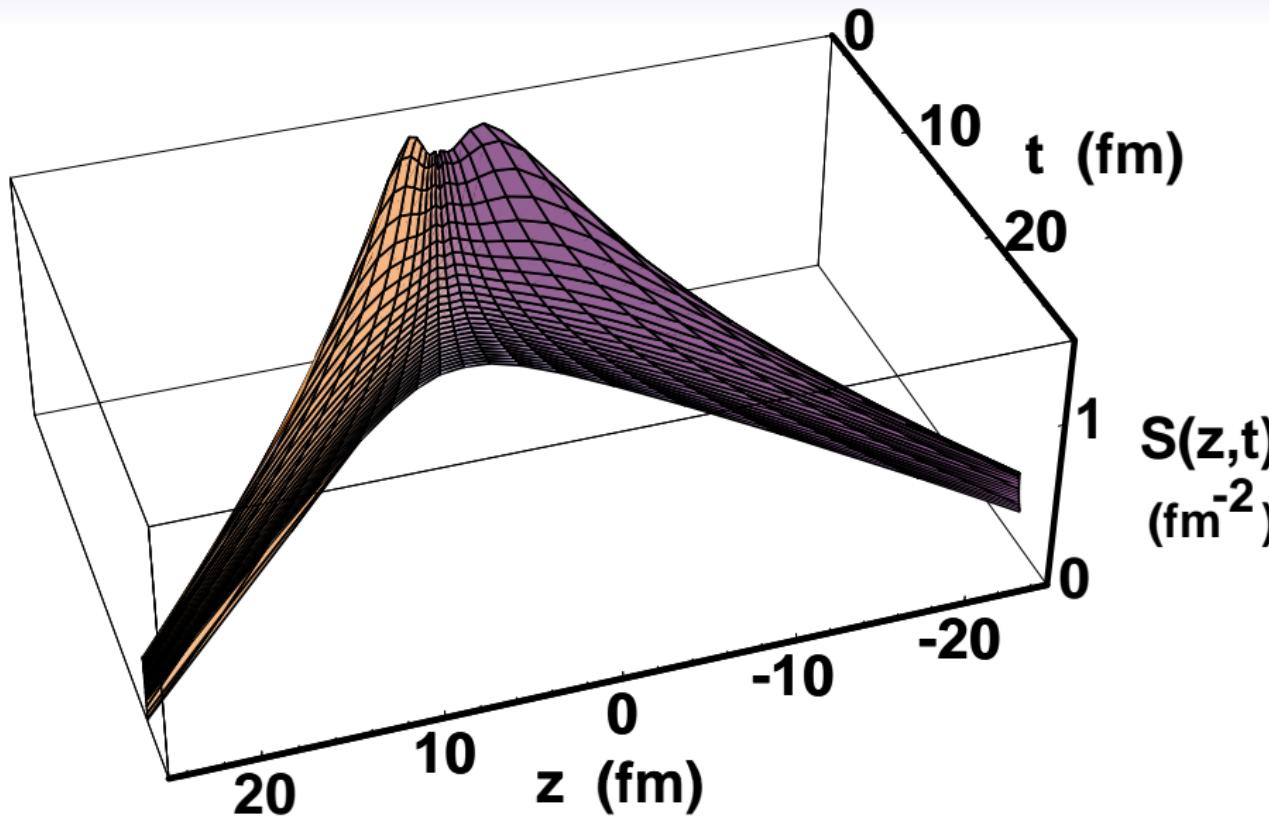
$$\tau = 0.50 \text{ fm}$$

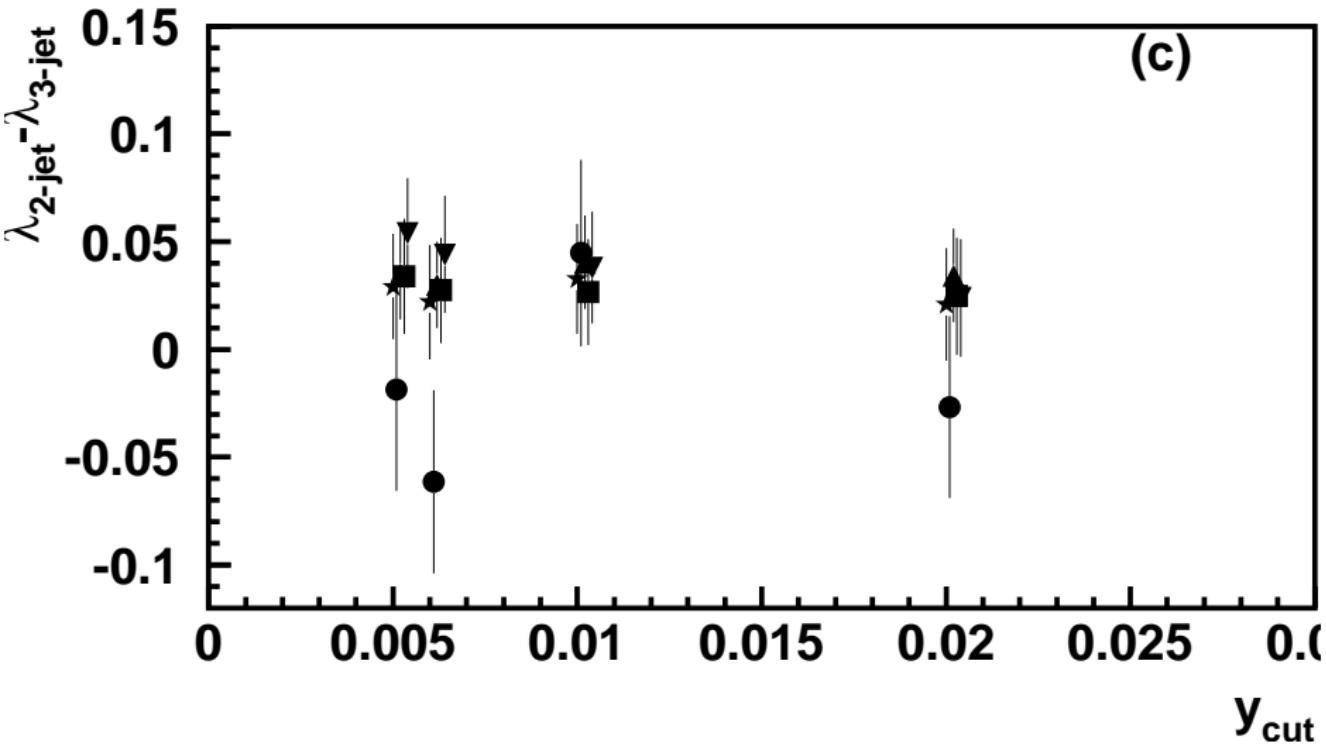


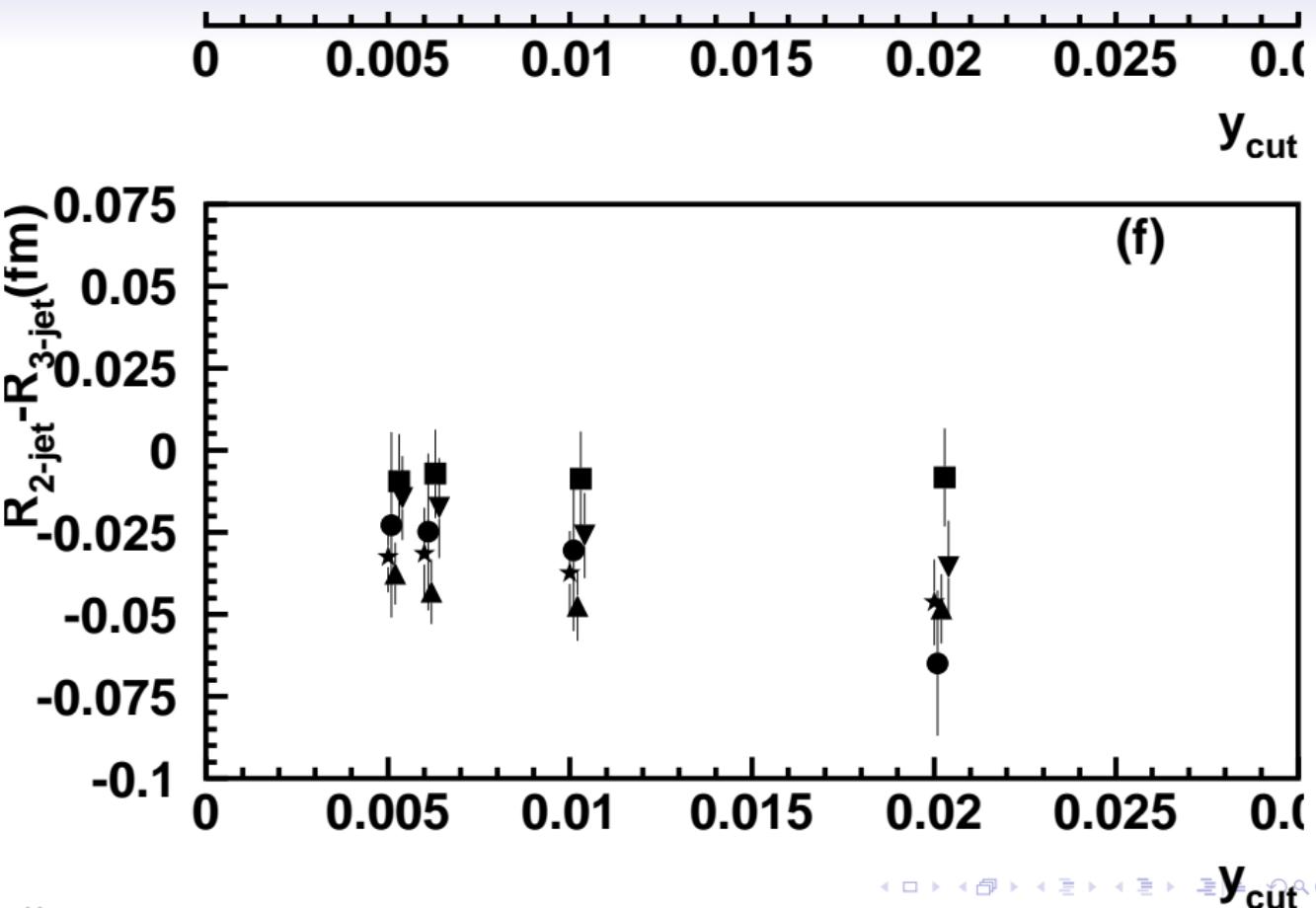
$\tau = 1.00 \text{ fm}$





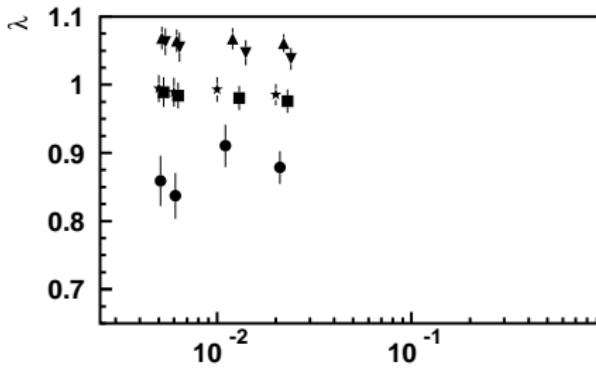


Δ 

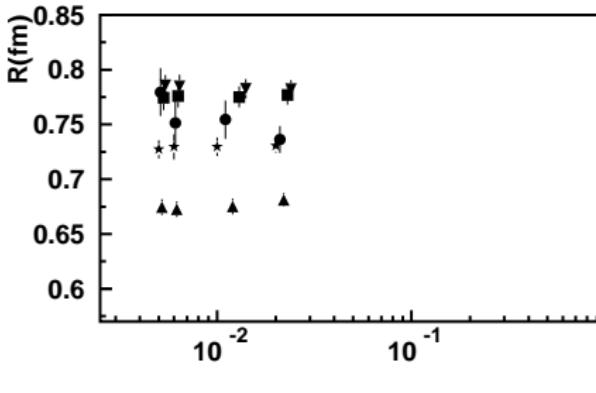
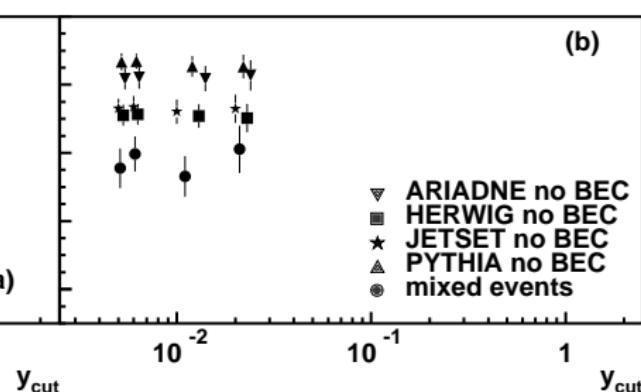


2-jet

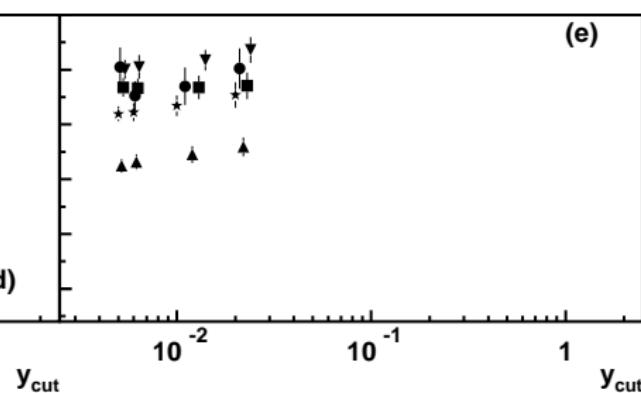
3-jet

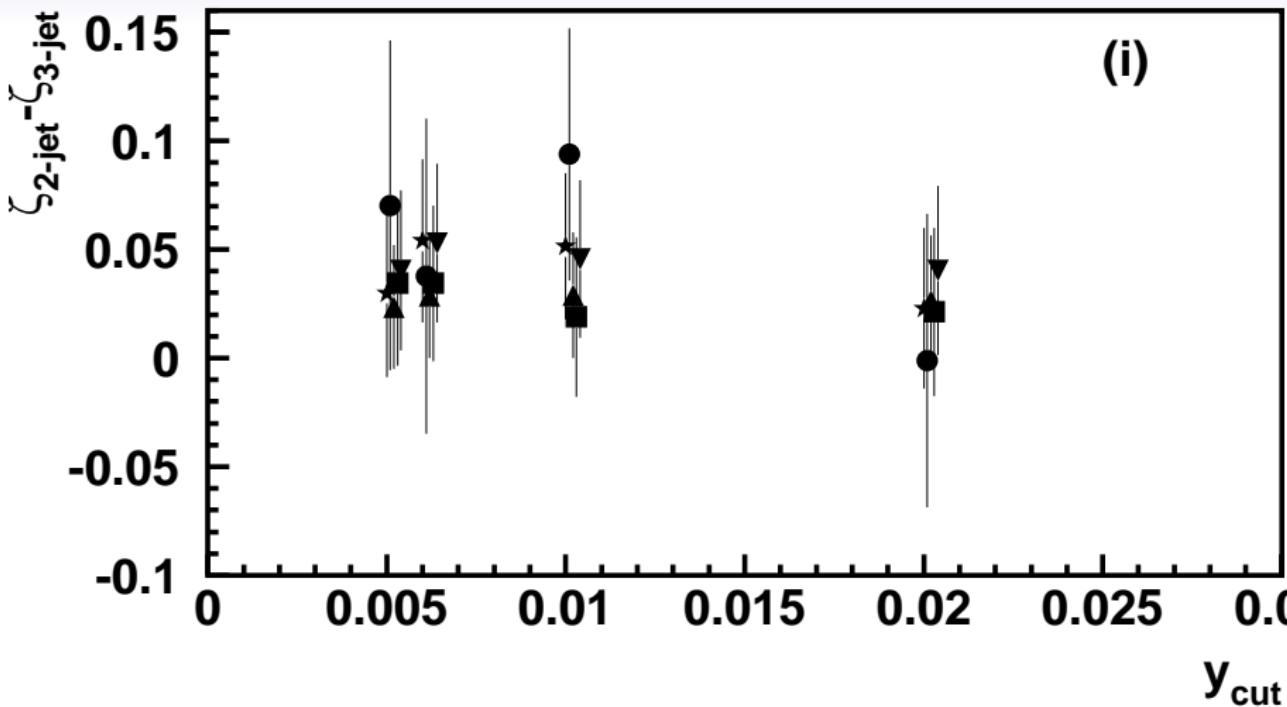


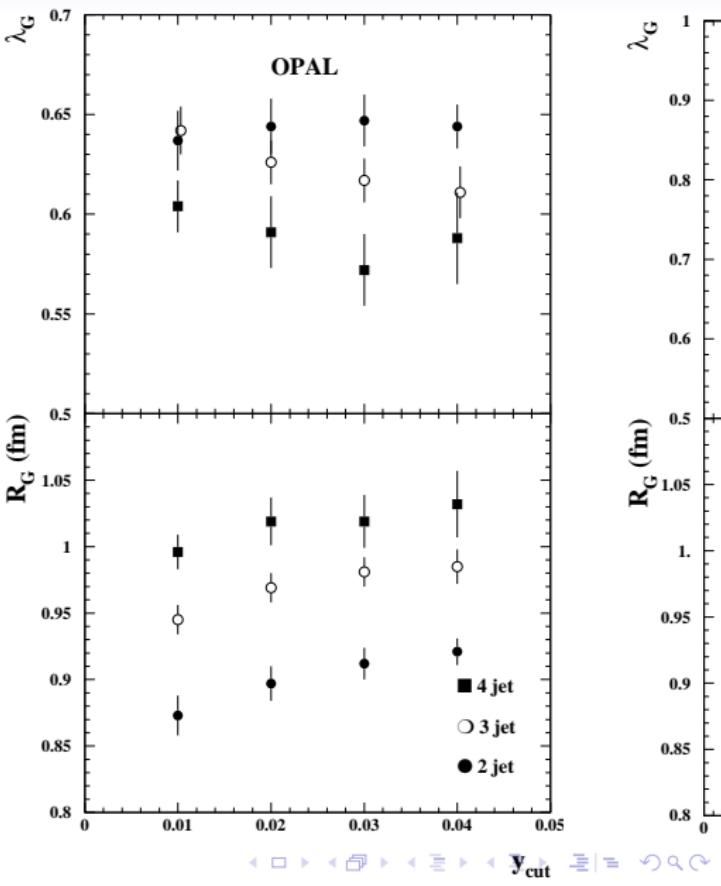
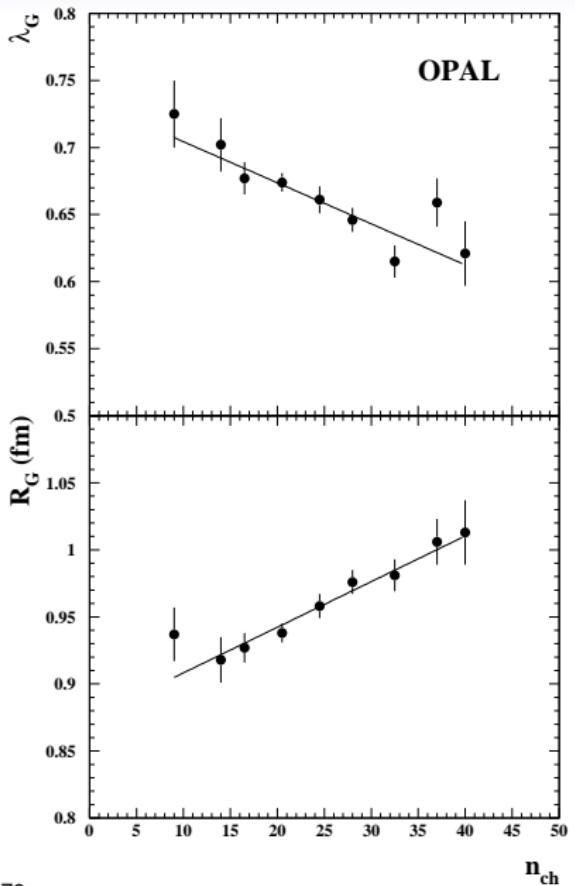
(b)

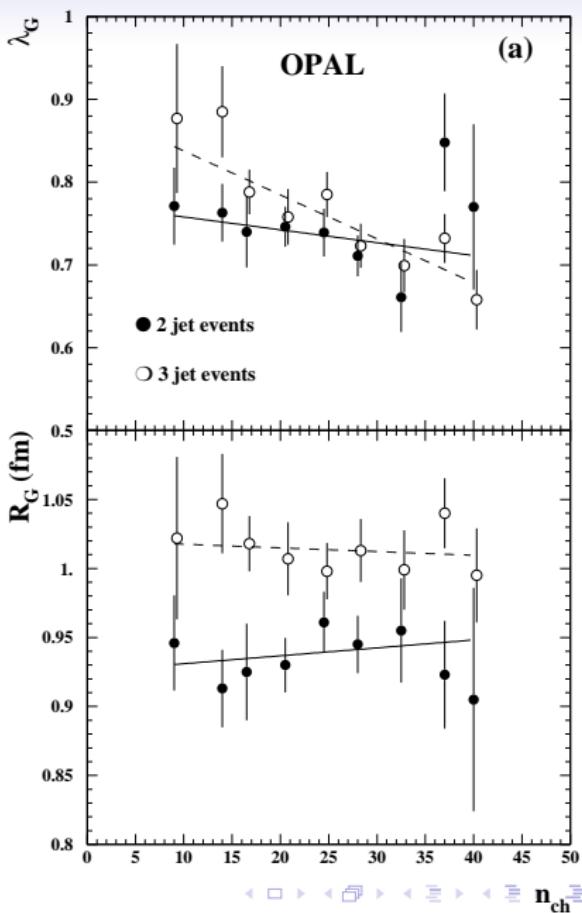
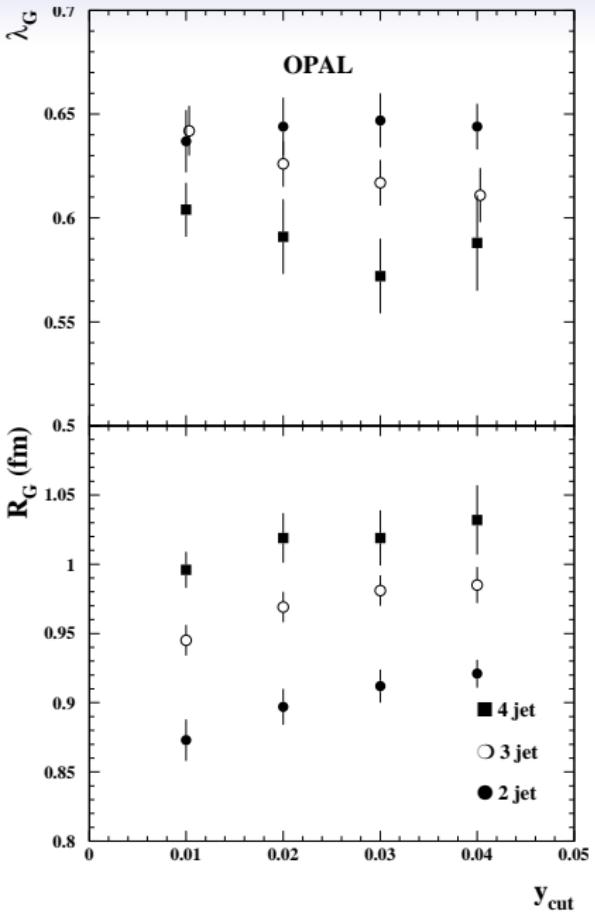


(e)

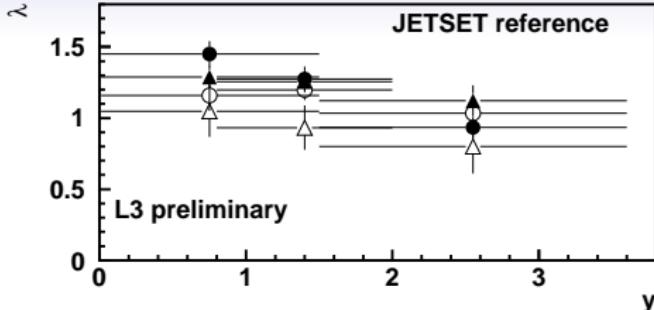
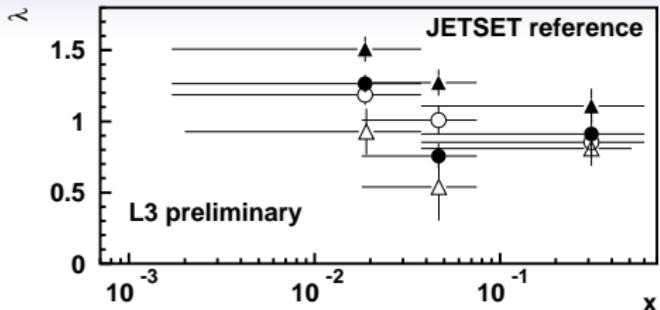




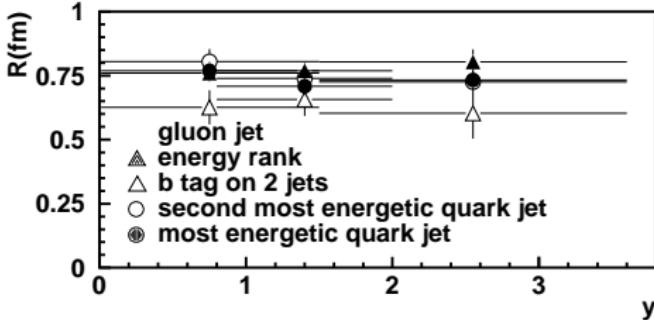
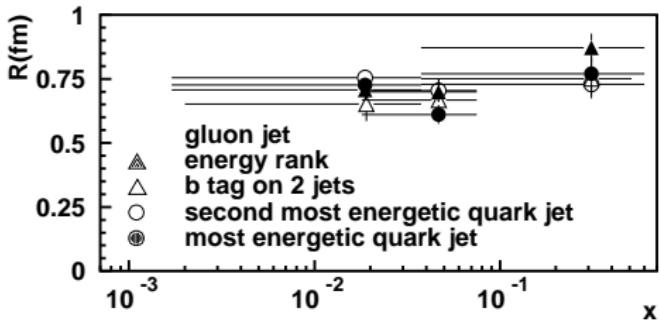




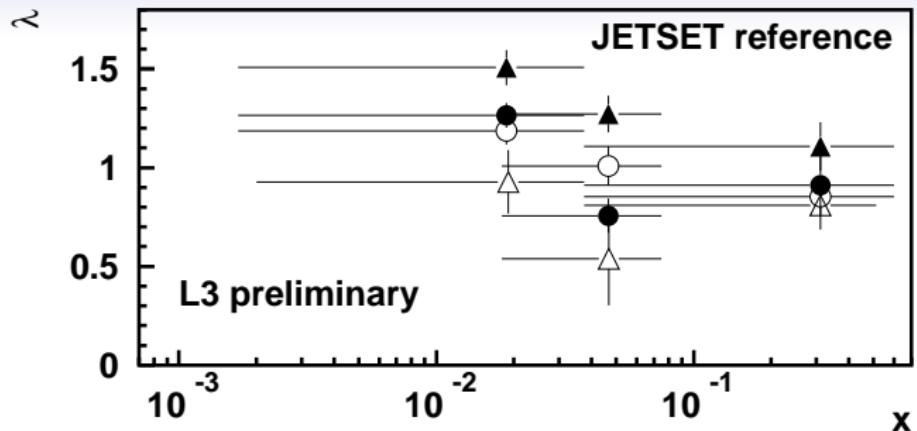
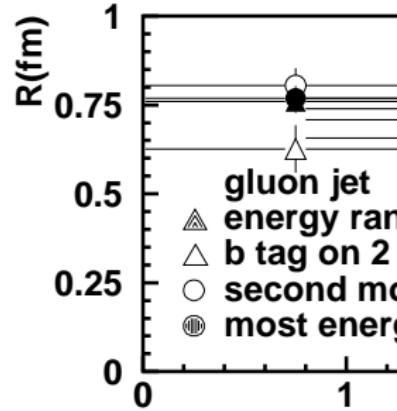
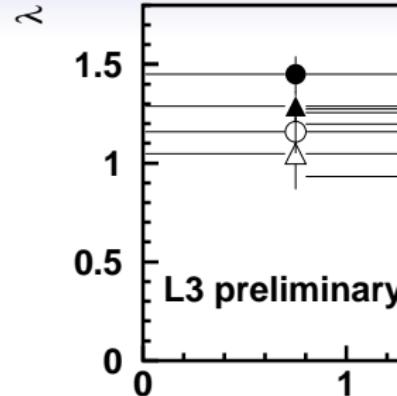
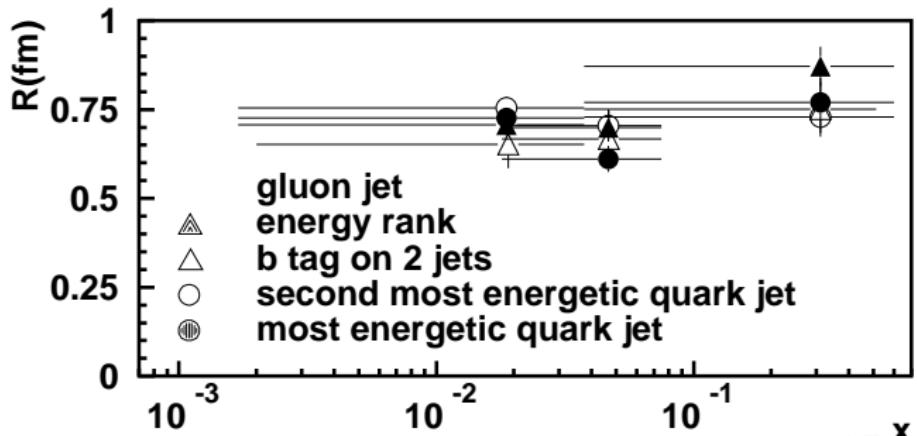
λ



r



- $\lambda \searrow$, not const. with increasing x or y , but equally for q , λ_g of E -tag, b-tag inconsistent – systematics?
- r const., not decreasing with x and y – no inter-str. BEC

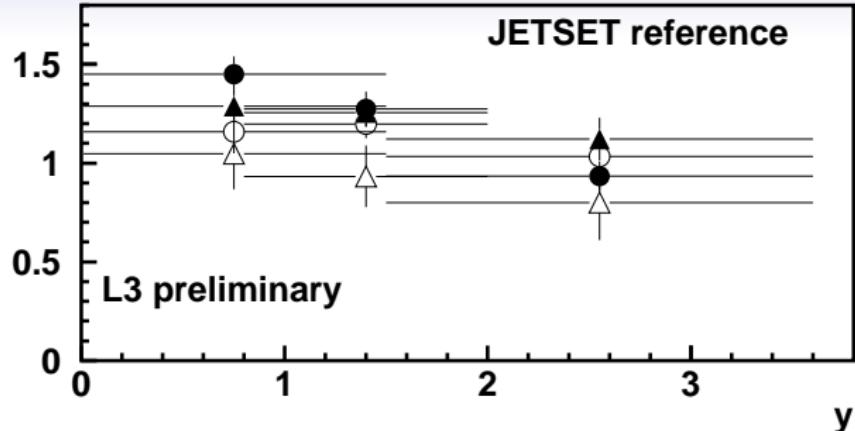
λ  r 

λ

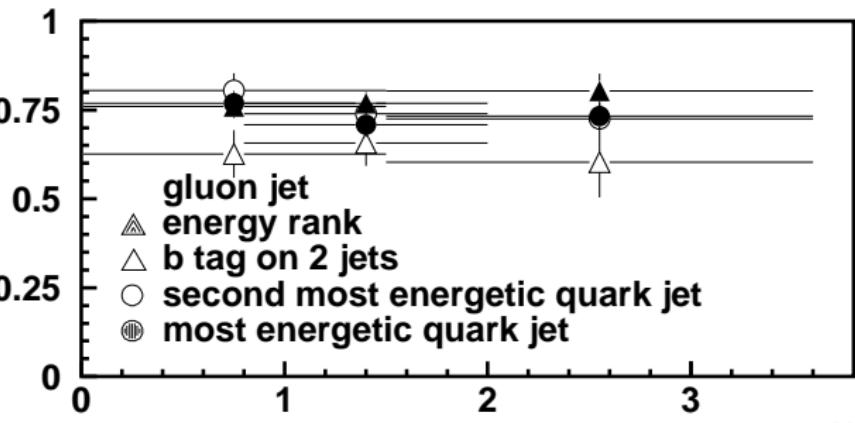
x

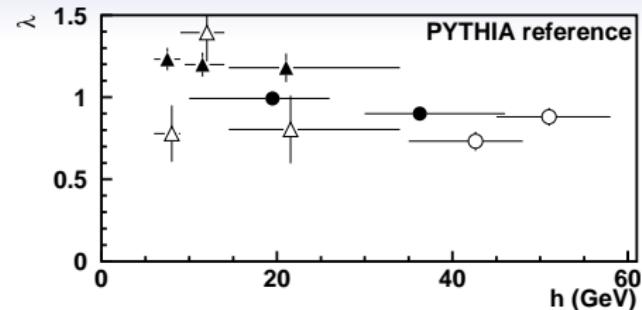
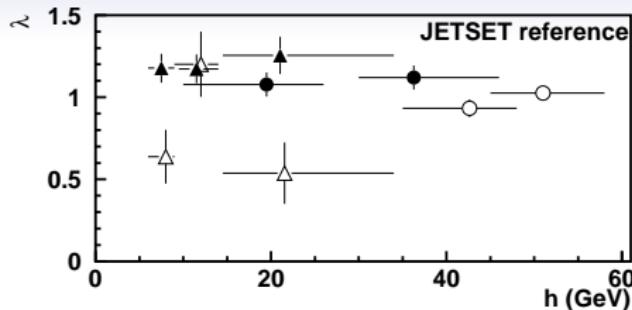
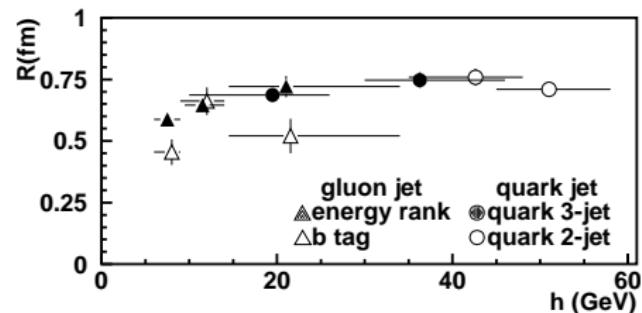
R (fm)

x



L3 preliminary



λ  r 

- no dependence on h

κ

