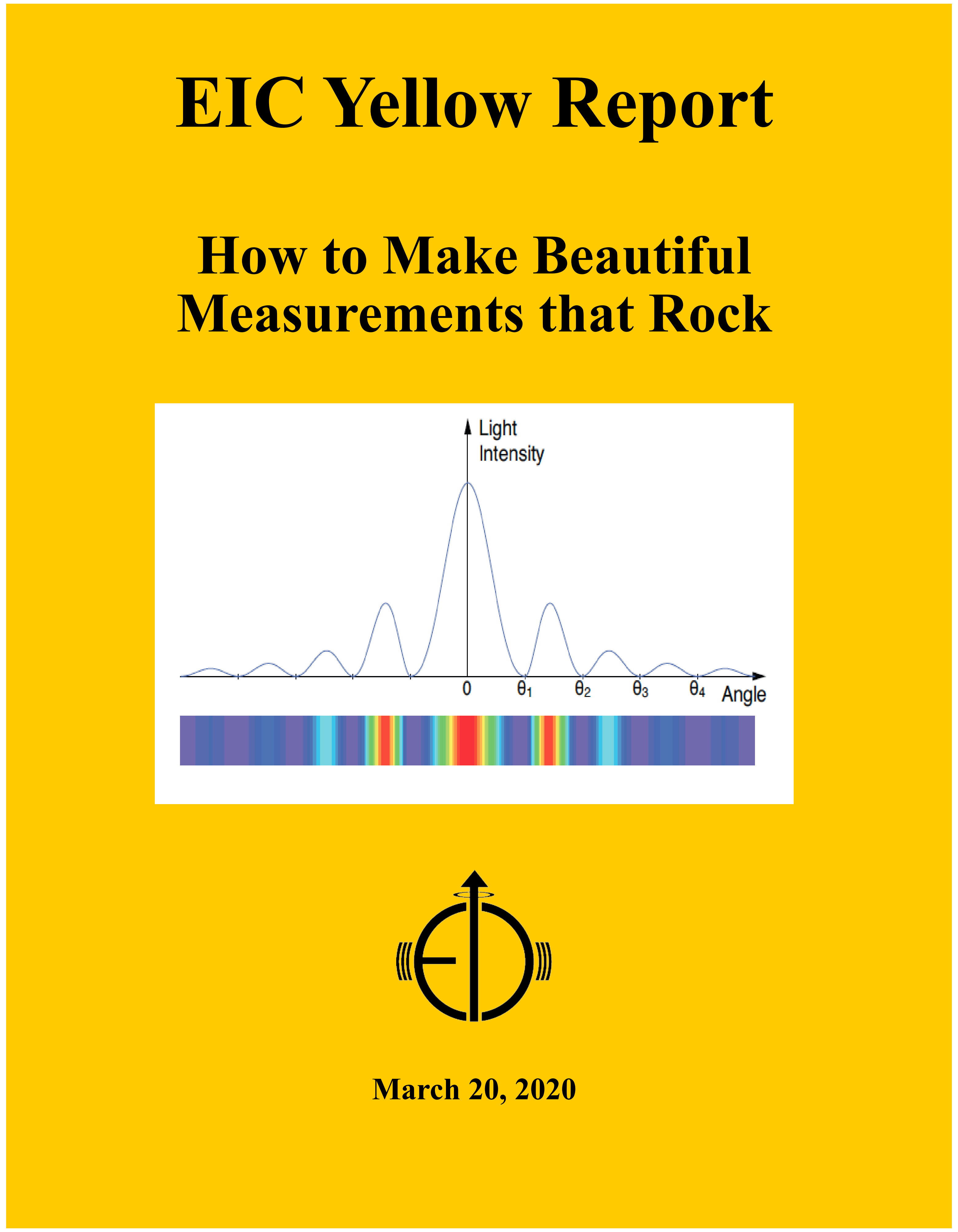



# Diffractive Exclusive Vector Meson Production in e+A

## Status of Studies and First Detector Constraints

*Thomas Ullrich*
Exclusive Processes WG

1st Yellow Report Workshop (aka Temple Meeting)
March 20, 2020

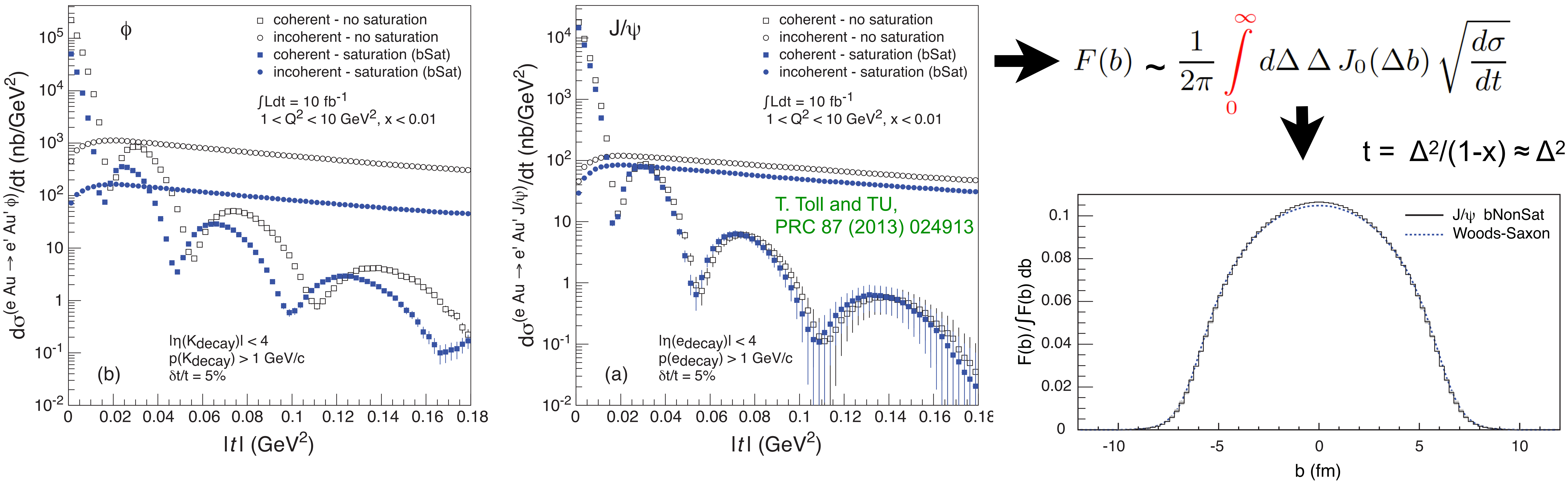
BROOKHAVEN NATIONAL LABORATORY

# The Importance of Diffraction for the EIC

- Diffractive physics will be a *major* component of the e+A program at an EIC
  - High sensitivity to gluon density: $\sigma \propto g(x, Q^2)^2$ due to color-neutral exchange
  - Many (most) key measurements on gluon saturation are in the diffractive program (inclusive & exclusive)

- Central role: Exclusive vector meson production
  $e + A \rightarrow e' + A' + \Upsilon, J/\psi, \phi, \rho$
  - Only process to allows to measure momentum transfer $t$ in e+A
    - In general, cannot detect the outgoing nucleus and it's momentum
  - Momentum transfer $t = |p_{\mathrm{A}} - p_{\mathrm{A}'}|^2$ conjugate to $b_T$
    - Measurement of spatial gluon distribution in nuclei

# EIC White Paper: Vector Meson Production: $d\sigma/dt$




$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

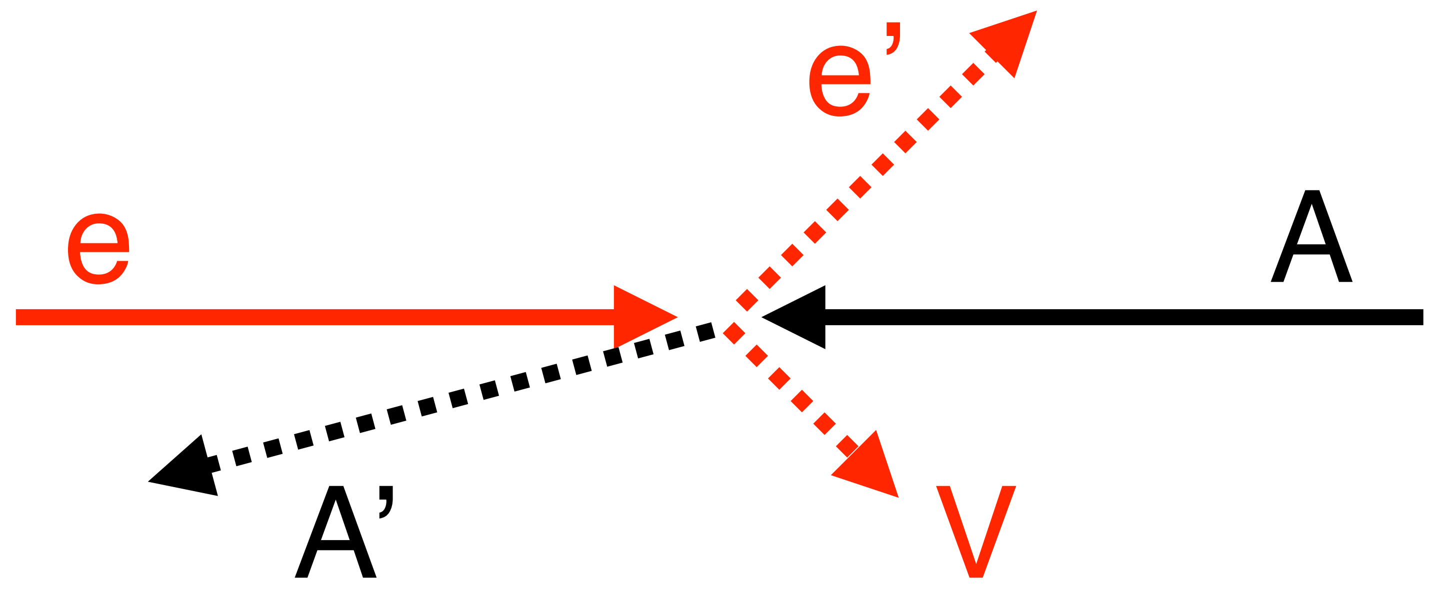
$t = \Delta^2/(1-x) \approx \Delta^2$

- Studies performed with diffractive ep/eA generator Sar*t*re based on color dipole model. Features saturation and non-saturation models.
- Heavy mesons less affected by gluon saturation than lighter ones
- Can reconstruct $F(b)$ with remarkable precision from coherent $d\sigma/dt$
- For WP study assumed: $d\sigma/dt \approx 5\,\%$ (taken from HERA)

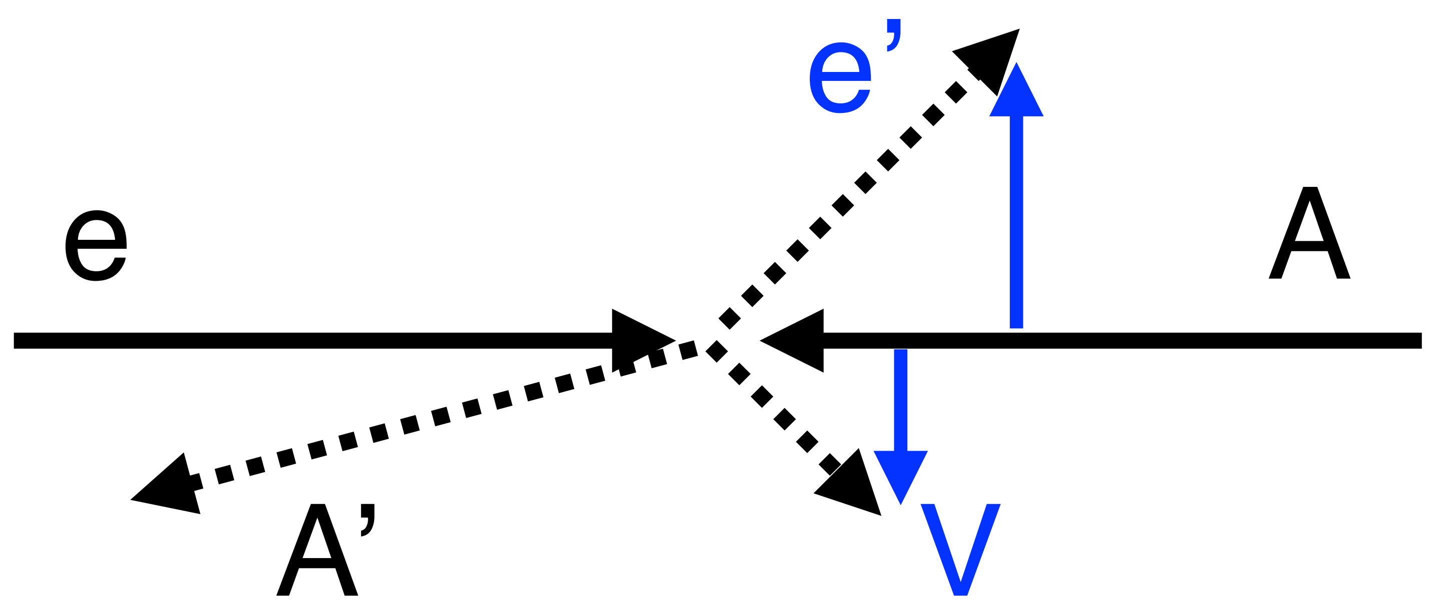
# Measuring $t$ in $e + A \rightarrow e' + A' + V$

- Note: A' cannot be measured directly

- Exact Method (E):
  - $t = (p_A - p_{A'})^2 = (p_V + p_{e'} - p_e)^2$
  - Matches original $t$ used to generate Sartre event
  - Note for later: details of A and A' are not relevant in this method



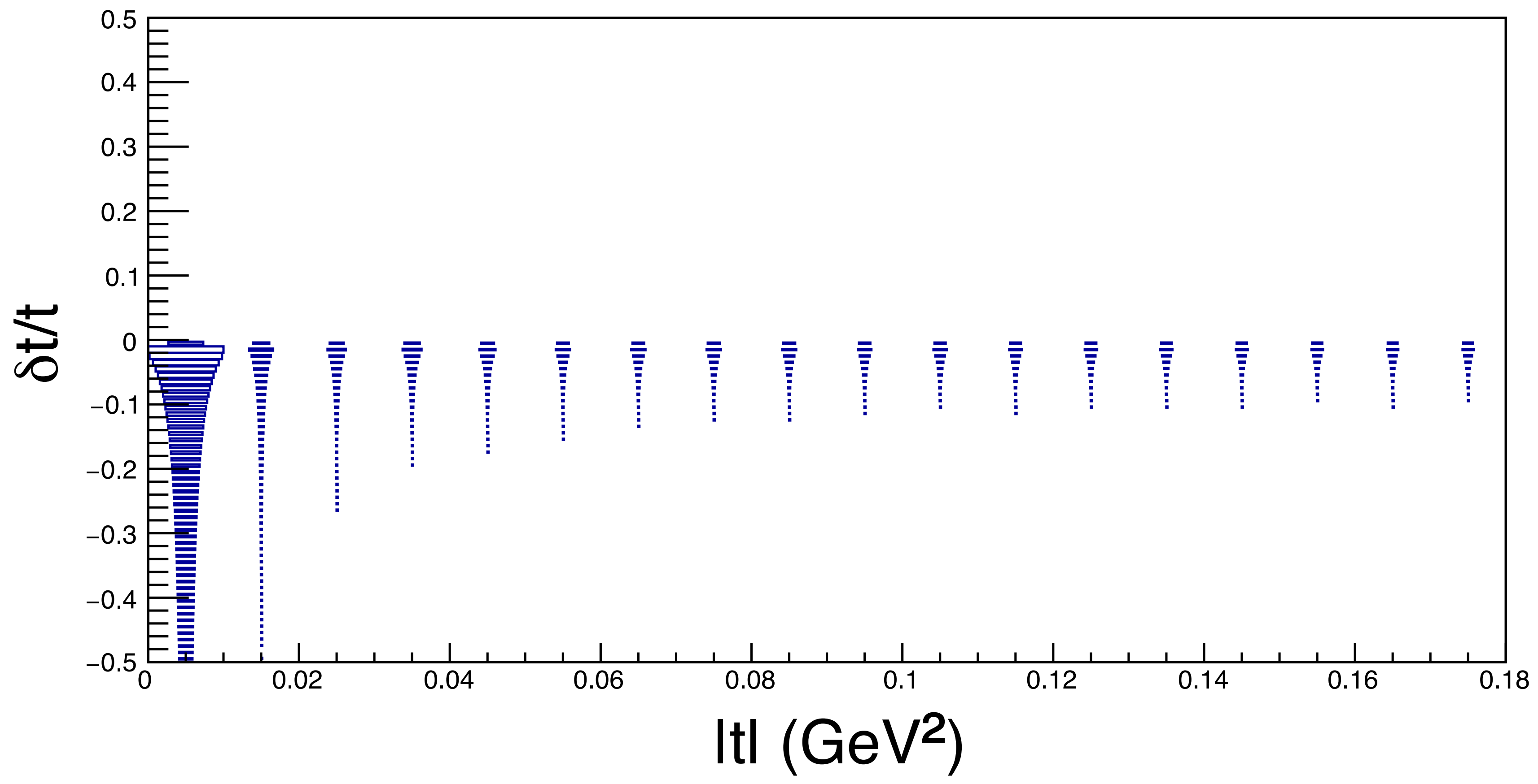

- Approximative Method (A):
  - $t = |\vec{p}_T(e') + \vec{p}_T(V)|^2$
  - Ignores any longitudinal momenta
  - Method used in HERA
  - This formula is valid for small $t$ and for small $Q^2$

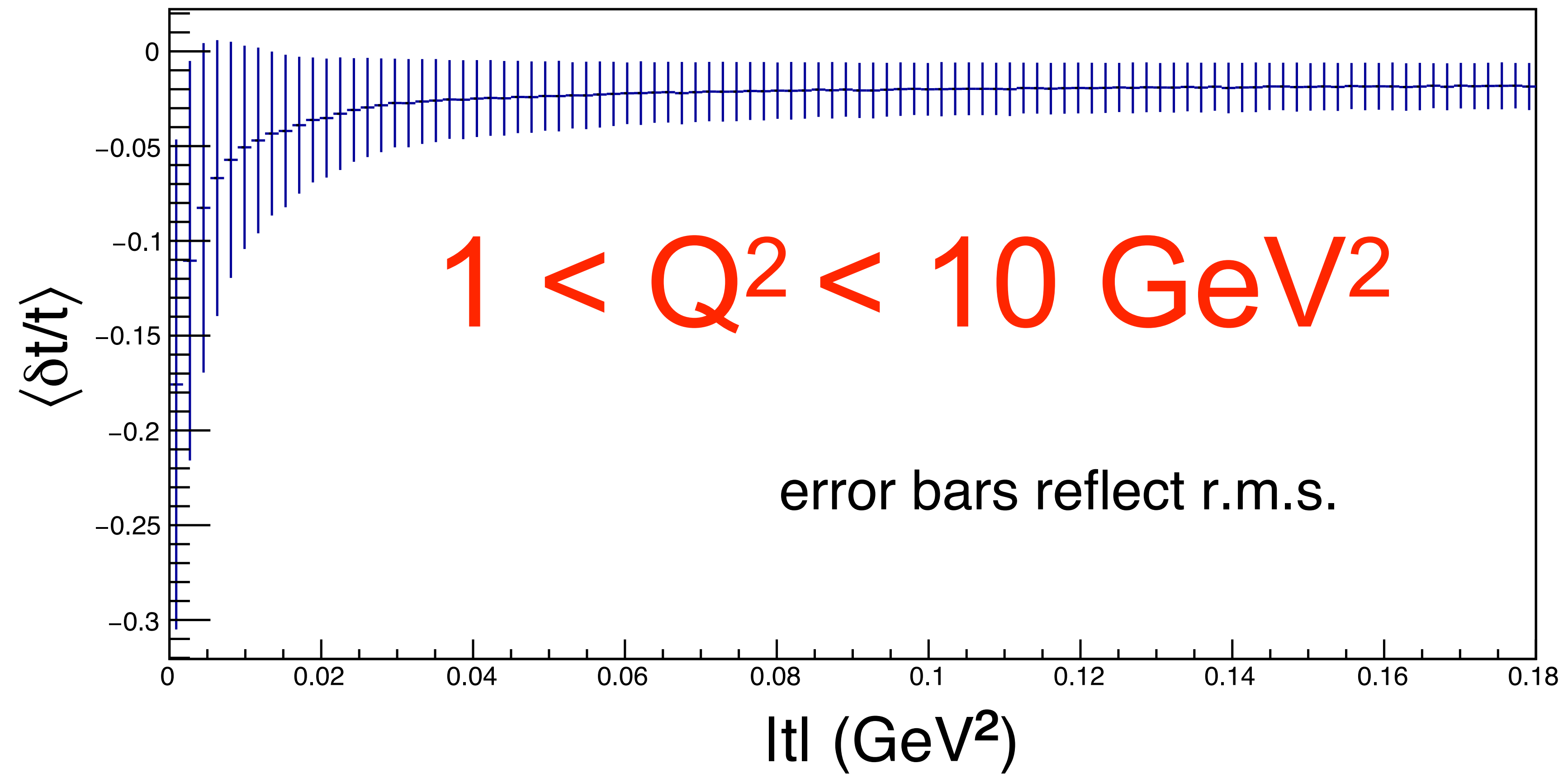


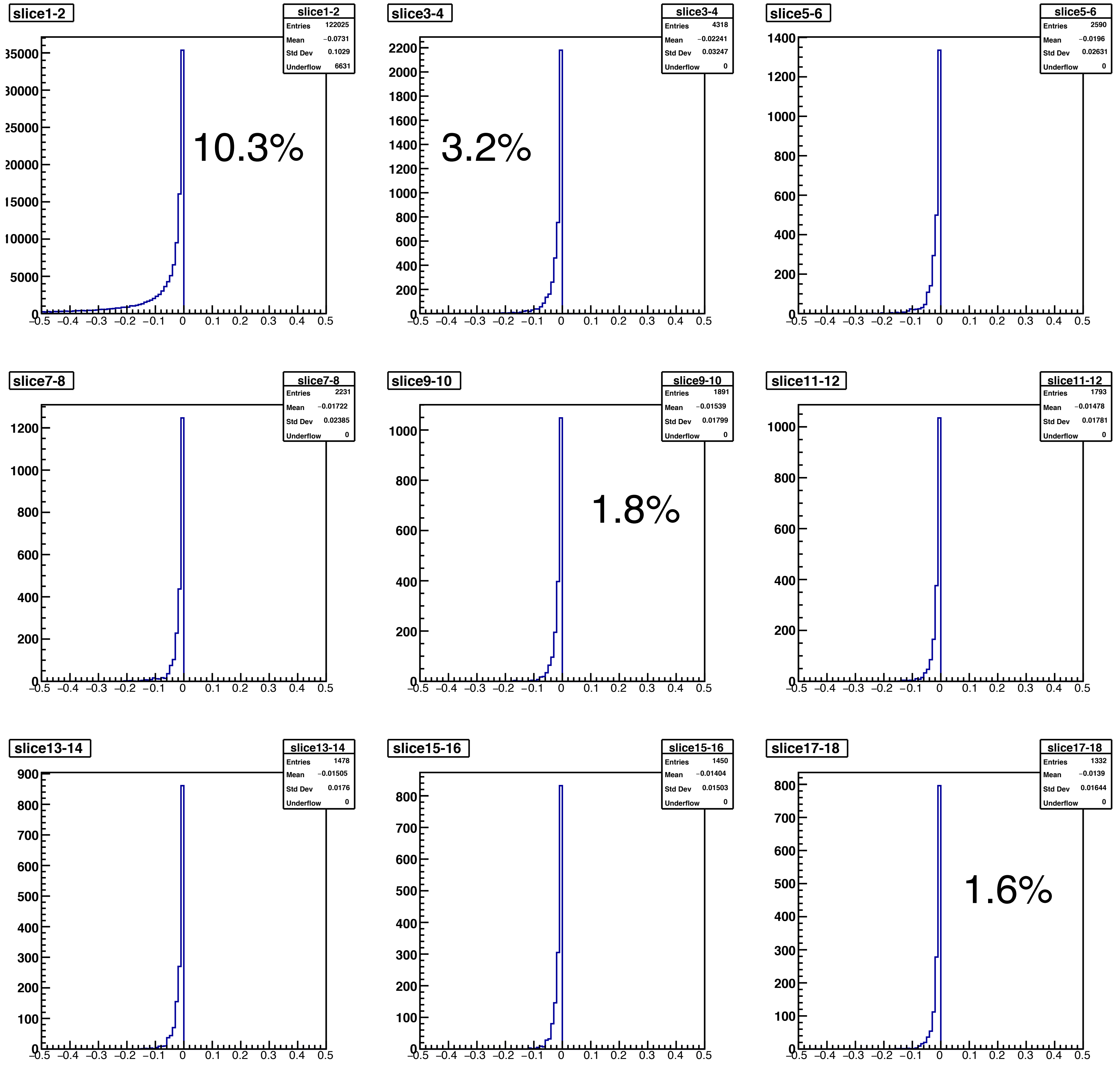
# Simulation Parameters

- Data from Sartre with KWM bSat/bNonSat parameters (same as WP)
  - all with $x < 0.01$
- Energy 18+110 GeV
  - $\sqrt{s} = 89$ GeV
- $V = J/\psi$ from here on

# How Good is Method A (no beam/detector effects)




Here and in what follows: Slices from left to right edge of left side 2D histo

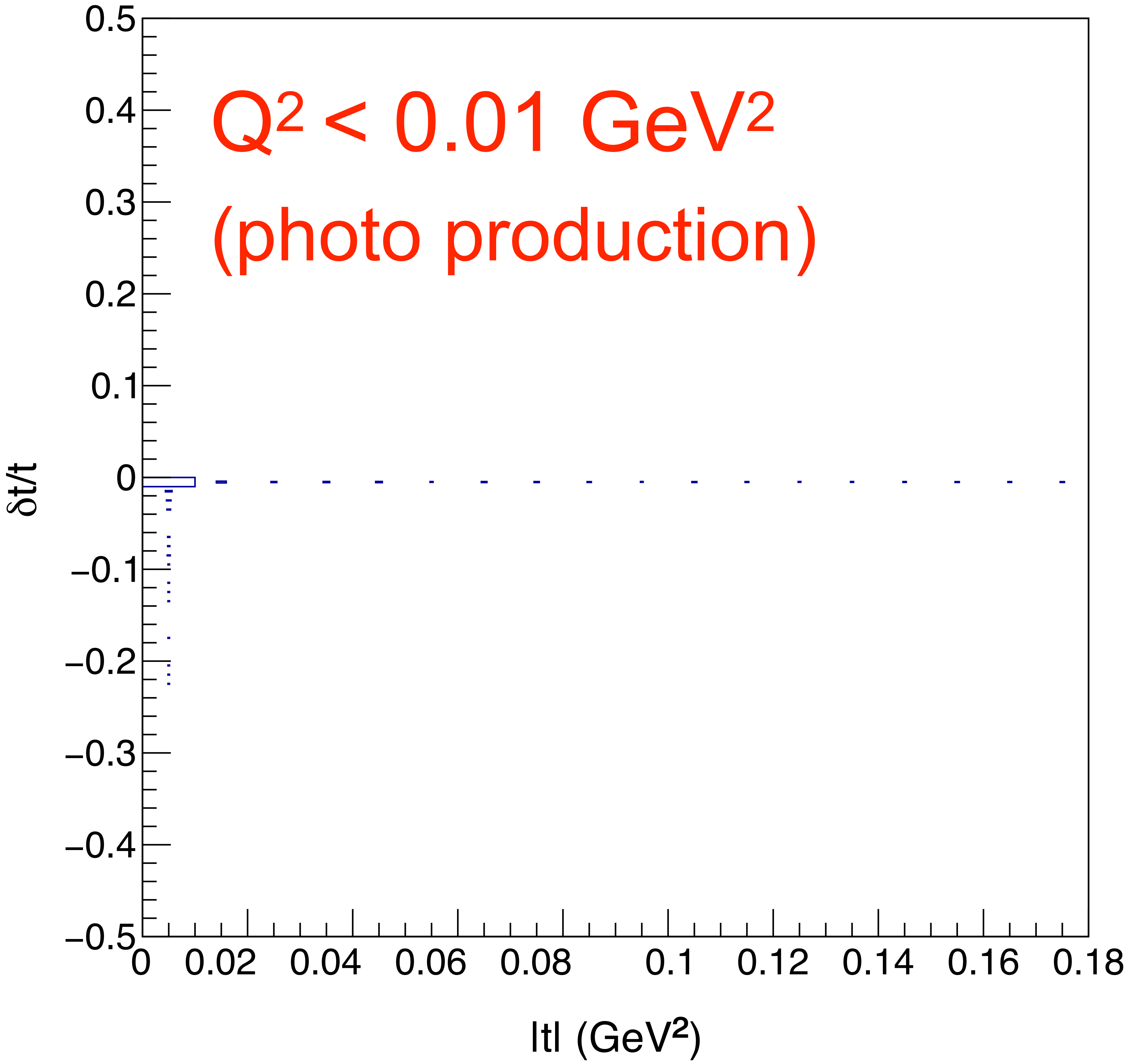
Method A appears to underestimate *t*

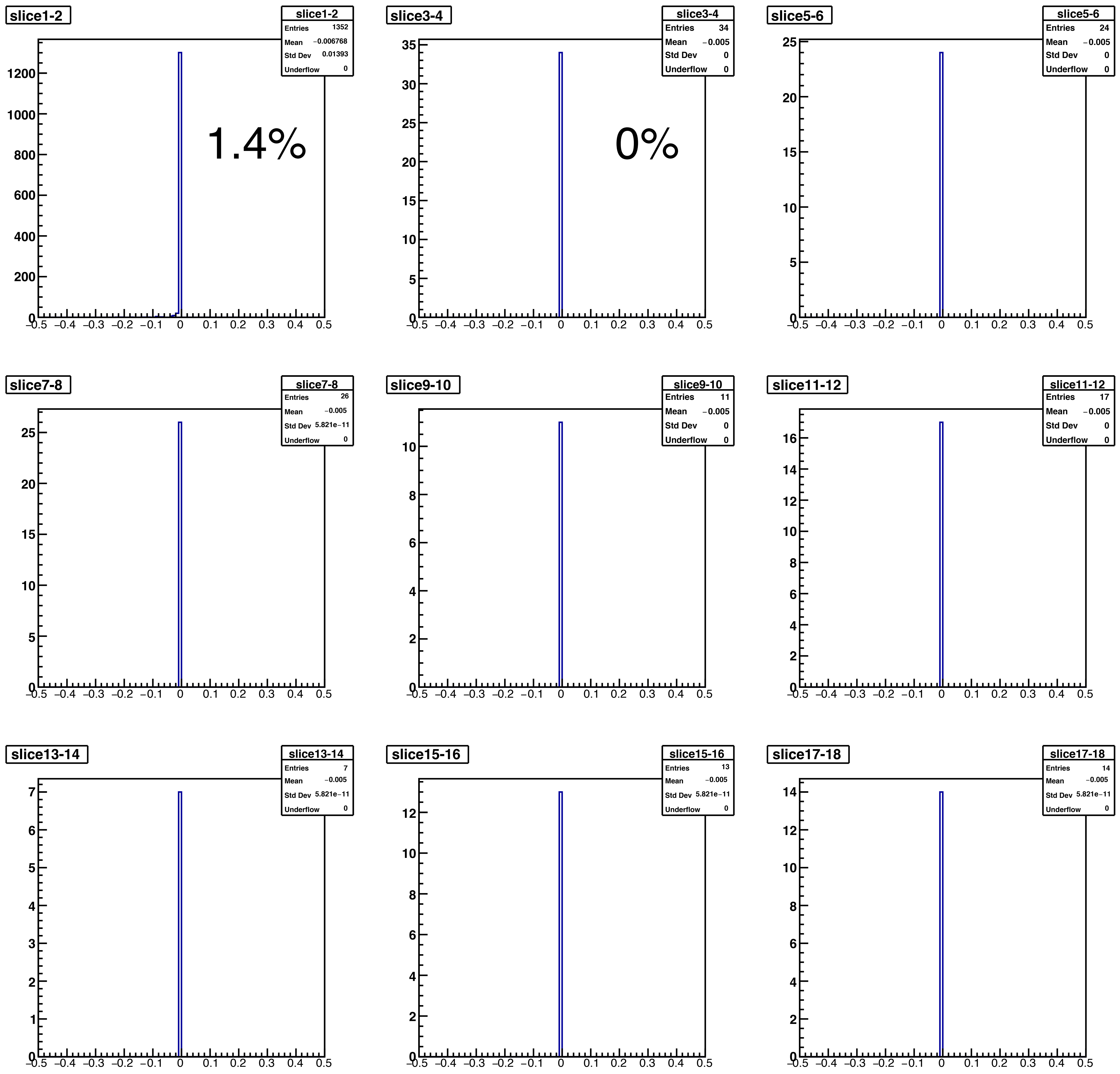
$t < 0.01 \quad \delta t/t \sim 10\%$

$t \sim 0.16 \quad \delta t/t \sim 1.6\%$

$\delta t = |t(\text{from A}) - |t(\text{Sartre})|$

# How Good is Method A (no beam/detector effects)



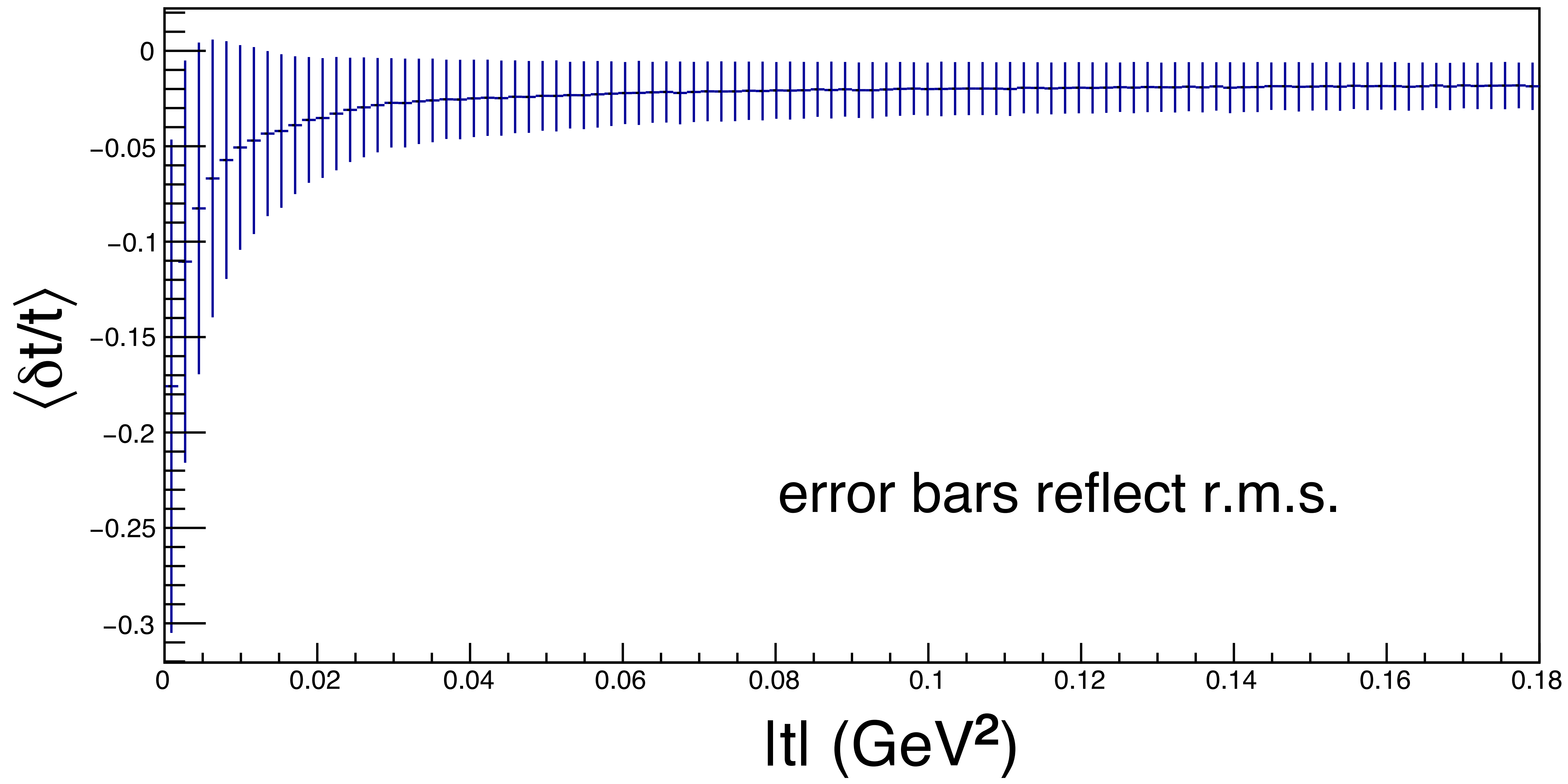




Method A works very well at $Q^2 \sim 0$

t < 0.01 $\delta t/t \sim 1.3\%$

t ~0.16 $\delta t/t \sim 0\%$

# $Q^2$ dependent correction for Method A?




$t > 0.04\ \mathrm{GeV}^2$

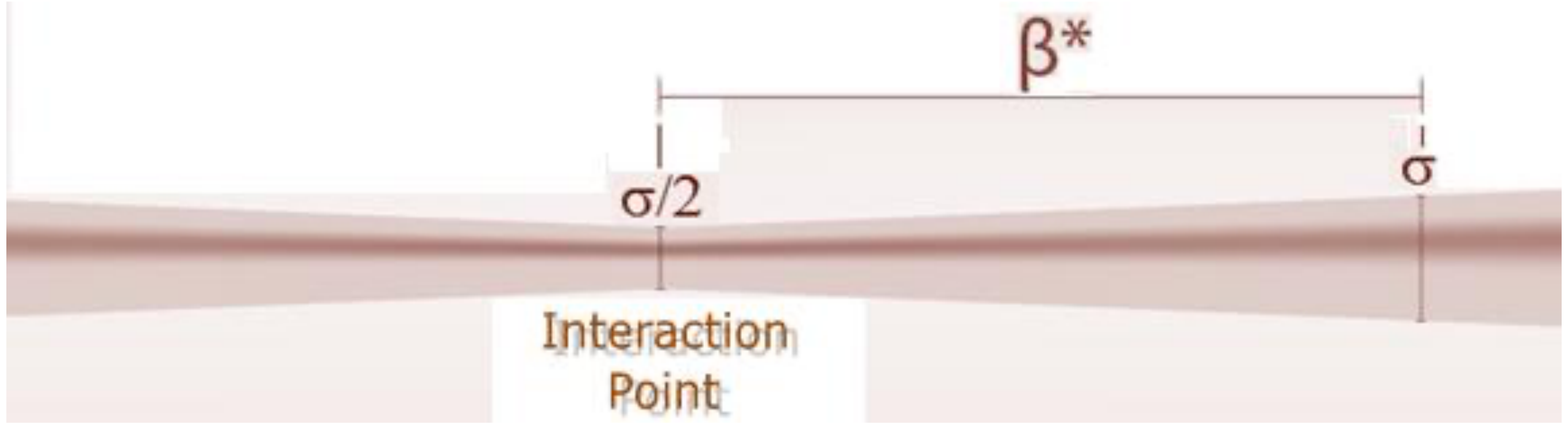
| $Q^2$ range (GeV) | offset | error |
|---|---|---|
| < 0.01 | -0.00135311 | 9.03428E-06 |
| 1-2 | -0.018309 | 0.00288668 |
| 2-3 | -0.0148724 | 0.00182143 |
| 3-4 | -0.0130223 | 0.00140125 |
| 4-5 | -0.0117659 | 0.0011486 |
| 5-6 | -0.0110839 | 0.000993935 |
| 6-7 | -0.0105928 | 0.000887688 |
| 7-8 | -0.010177 | 0.000800267 |
| 8-9 | -0.00990677 | 0.000734945 |
| 9-10 | -0.00976082 | 0.000687827 |

- This offset is $Q^2$ dependent - vanishes at $Q^2 \sim 0$
- Can this be corrected for? Unfolding, Monte Carlo
- HERA - couldn't find any attempts to do so
- First studies by Tuomas Lappy (Thanks!)

Offset in the ranges looked at here:
Highest at low $Q^2$ and then gets less for larger $Q^2$ but disappears for photo production $Q^2 \to 0$

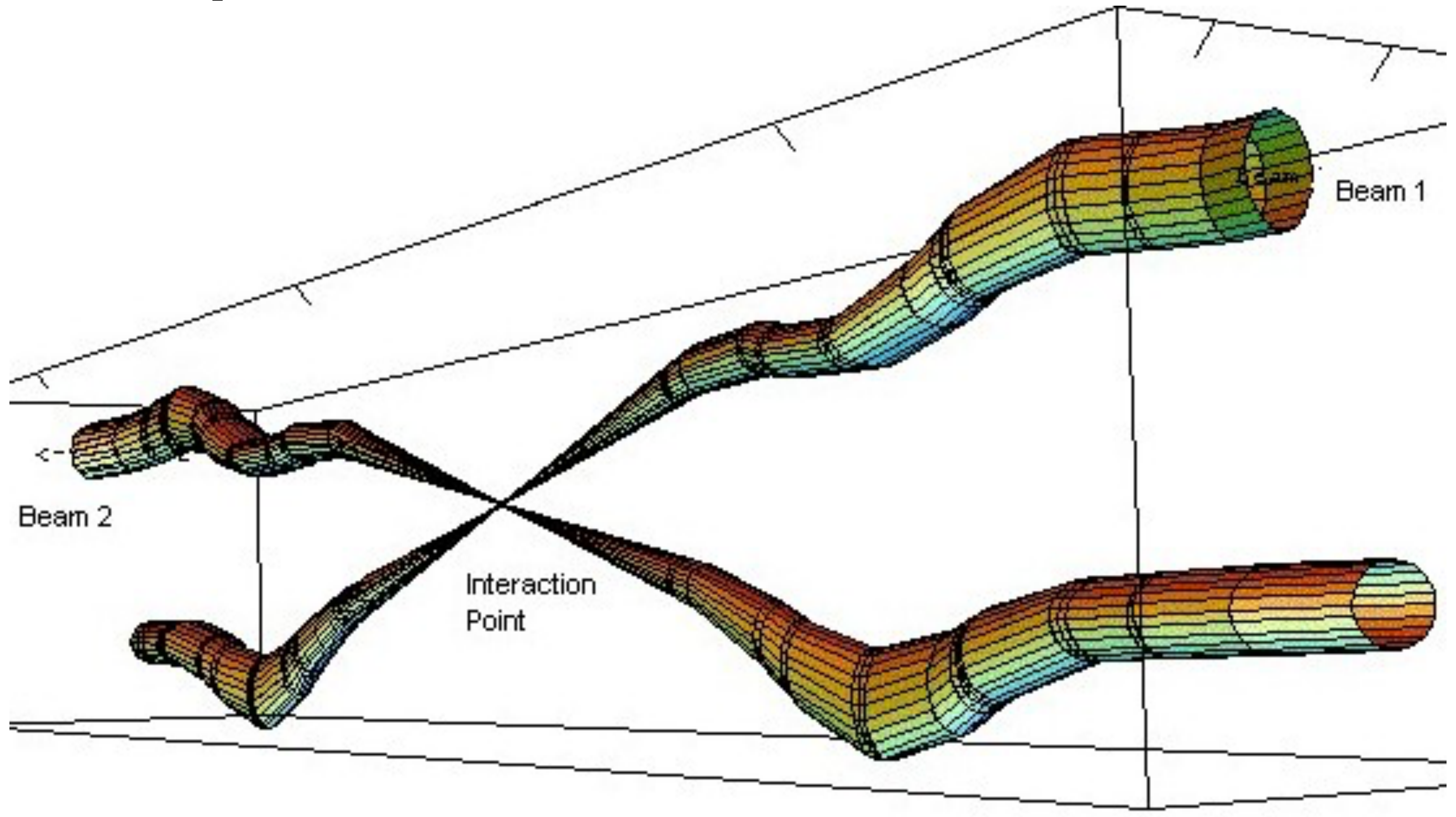
# Beam & Machine Properties Affecting Measurements

- The beam size can be expressed in terms of two quantities, one termed the transverse emittance, ε , and the other, the amplitude function, β.
- Emittance, ε ,can be defined as the smallest opening you can squeeze the beam through, and can also be considered as a measurement of the parallelism of a beam. It has units of length.
- The amplitude function, β , is determined by the accelerator magnet configuration. Of particular significance is the value of the amplitude function at the interaction point, β*.
- Sometimes β is referred as the distance from the focus point where the beam width is twice as wide as a the focus point. β has units of length.
- If β is low, the beam is narrower, "squeezed". If β is high, the beam is wide and straight.



# Beam & Machine Properties Affecting Measurements

- Clearly one wants  to be as small as possible; how small depends on the capability of the hardware to make a near-focus at the interaction point.
- This leads to **divergence** of the beam.
  - Horizontal and vertical divergence
    - $\sigma_x = \sqrt{\epsilon_x/\beta^*_x}, \sigma_y = \sqrt{\epsilon_y/\beta^*_y}$
    - Typical few hundred $\mu$rad
- Note: $\mathscr{L} \propto 1/\beta^*$




Note that $\sigma_x$ and $\sigma_y$ are different so the beam profile and divergence is an ellipse

Possibly even more important is **spread of beam momentum** $\delta p/p$

- This is a beam effect (not a machine effect)
- Typical values are few $10^{-4}$

e+p



**Table 3.3:** eRHIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

| Species | proton | electron | proton | electron | proton | electron | proton | electron | proton | electron |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy [GeV] | 275 | 18 | 275 | 10 | 100 | 10 | 100 | 5 | 41 | 5 |
| CM energy [GeV] | 140.7 | | 104.9 | | 63.2 | | 44.7 | | 28.6 | |
| Bunch intensity [$10^{10}$] | 20.5 | 6.2 | 6.9 | 17.2 | 6.9 | 17.2 | 4.7 | 17.2 | 2.6 | 13.3 |
| No. of bunches | 290 | | 1160 | | 1160 | | 1160 | | 1160 | |
| Beam current [A] | 0.74 | 0.227 | 1 | 2.5 | 1 | 2.5 | 0.68 | 2.5 | 0.38 | 1.93 |
| RMS norm. emit., h/v [$\mu$m] | 4.6/0.75 | 845/72 | 2.8/0.45 | 391/24 | 4.0/0.22 | 391/25 | 2.7/0.27 | 196/20 | 1.9/0.45 | 196/34 |
| RMS emittance, h/v [nm] | 16/2.6 | 24/2.0 | 9.6/1.5 | 20/1.2 | 37/2.1 | 20/1.3 | 25/2.6 | 20/2.0 | 44/10 | 20/3.5 |
| $\beta^*$, h/v [cm]] | 90/4.0 | 59/5.0 | 90/4.0 | 43/5.0 | 90/4.0 | 167/6.4 | 90/4.0 | 113/5.0 | 90/7.1 | 196/21.0 |
| IP RMS beam size, h/v [$\mu$m] | 119/10 | | 93/7.8 | | 183/9.1 | | 150/10 | | 198/27 | |
| $K_x$ | 11.8 | | 11.9 | | 20.0 | | 14.9 | | 7.3 | |
| RMS $\Delta\theta$, h/v [$\mu$rad] | 132/253 | 202/202 | 103/195 | 215/156 | 203/227 | 109/143 | 167/253 | 133/202 | 220/380 | 101/129 |
| BB parameter, h/v [$10^{-3}$] | 3/2 | 100/100 | 14/7 | 73/100 | 10/9 | 75/57 | 15/10 | 100/66 | 15/9 | 53/42 |
| RMS long. emittance [$10^{-3}$, eV·sec] | 36 | | 36 | | 21 | | 21 | | 11 | |
| RMS bunch length [cm] | 6 | 0.9 | 6 | 2 | 7 | 2 | 7 | 2 | 7.5 | 2 |
| RMS $\Delta p/p$ [$10^{-4}$] | 6.8 | 10.9 | 6.8 | 5.8 | 9.7 | 5.8 | 9.7 | 6.8 | 10.3 | 6.8 |
| Max. space charge | 0.006 | neglig. | 0.003 | neglig. | 0.028 | neglig. | 0.019 | neglig. | 0.05 | neglig. |
| Piwinski angle [rad] | 5.6 | 0.8 | 7.1 | 2.4 | 4.2 | 1.2 | 5.1 | 1.5 | 4.2 | 1.1 |
| Long. IBS time [h] | 2.1 | | 3.4 | | 2 | | 2.6 | | 3.8 | |
| Transv. IBS time [h] | 2 | | 2 | | 2.3/2.4 | | 2/4.8 | | 3.4/2.1 | |
| Hourglass factor $H$ | 0.86 | | 0.86 | | 0.85 | | 0.83 | | 0.93 | |
| Luminosity [$10^{33}$cm$^{-2}$sec$^{-1}$] | 1.65 | | 10.05 | | 4.35 | | 3.16 | | 0.44 | |



preCDR Numbers, see https://wiki.bnl.gov/eic/upload/EIC.Design.Study.pdf e+p

**Table 3.4:** eRHIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High acceptance configuration.

| Species | proton | electron | proton | electron | proton | electron | proton | electron | proton | electron |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy [GeV] | 275 | 18 | 275 | 10 | 100 | 10 | 100 | 5 | 41 | 5 |
| CM energy [GeV] | 140.7 | | 104.9 | | 63.2 | | 44.7 | | 28.6 | |
| Bunch intensity [$10^{10}$] | 19.53 | 6.248 | 6.9 | 17.2 | 6.9 | 17.2 | 4.7 | 17.2 | 2.6 | 13.3 |
| No. of bunches | 290 | | 1160 | | 1160 | | 1160 | | 1160 | |
| Beam current [A] | 0.71 | 0.227 | 1 | 2.5 | 1 | 2.5 | 0.68 | 2.5 | 0.38 | 1.93 |
| RMS norm. emit., h/v [$\mu$m] | 4.9/0.62 | 845/42.3 | 2.8/0.45 | 391/22 | 3.5/0.25 | 391/27 | 2.7/0.27 | 196/20 | 1.9/0.45 | 196/34 |
| RMS emittance, h/v [nm] | 16.7/2.1 | 24.0/1.2 | 9.6/1.5 | 20/1.1 | 33/2.4 | 20/1.4 | 25/2.6 | 20/2.0 | 44/10 | 20/3.5 |
| $\beta^*$, h/v [cm]] | 395/4.0 | 274/7.0 | 227/4.0 | 109/5.5 | 102/4.0 | 169/6.8 | 90/4.0 | 113/5.0 | 90/7.1 | 196/21 |
| IP RMS beam size, h/v [$\mu$m] | 256/9.2 | | 148/7.8 | | 184/9.7 | | 150/10 | | 198/27 | |
| $K_x$ | 0.036 | | 18.9 | | 18.9 | | 14.9 | | 7.3 | |
| RMS $\Delta\theta$, h/v [$\mu$rad] | 65/229 | 94/131 | 65/196 | 135/143 | 180/243 | 109/143 | 167/253 | 133/202 | 220/380 | 101/129 |
| BB parameter, h/v [$10^{-3}$] | 3/1 | 100/71 | 14/5 | 75/71 | 11/8 | 75/57 | 15/10 | 100/66 | 15/9 | 53/42 |
| RMS long. emittance [$10^{-3}$, eV·sec] | 36 | | 36 | | 21 | | 21 | | 11 | |
| RMS bunch length [cm] | 6 | 0.9 | 6 | 2 | 7 | 2 | 7 | 2 | 7.5 | 2 |
| RMS $\Delta p/p$ [$10^{-4}$] | 6.8 | 10.9 | 6.8 | 5.8 | 9.7 | 5.8 | 9.7 | 6.8 | 10.3 | 6.8 |
| Max. space charge | 0.006 | neglig. | 0.003 | neglig. | 0.027 | neglig. | 0.019 | neglig. | 0.05 | neglig. |
| Piwinski angle [rad] | 2.6 | 0.4 | 4.5 | 1.5 | 4.2 | 1.2 | 5.1 | 1.5 | 4.2 | 1.1 |
| Long. IBS time [h] | 2 | | 3.4 | | 2 | | 2.6 | | 3.8 | |
| Transv. IBS time [h] | 2 | | 2 | | 2.0/3.0 | | 2/4.8 | | 3.4/2.1 | |
| Hourglass factor $H$ | 0.88 | | 0.87 | | 0.85 | | 0.83 | | 0.93 | |
| Luminosity [$10^{33}$cm$^{-2}$sec$^{-1}$] | 0.83 | | 6.4 | | 4.07 | | 3.16 | | 0.44 | |

e+Au



**Table 3.5:** eRHIC beam parameters for e-Au operation for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling.

| Species | Au ion | electron | Au ion | electron | Au ion | electron | Au ion | electron |
|---|---|---|---|---|---|---|---|---|
| Energy [GeV] | 110 | 18 | 110 | 10 | 110 | 5 | 41 | 5 |
| CM energy [GeV] | 89.0 | | 66.3 | | 46.9 | | 28.6 | |
| Bunch intensity [$10^{10}$] | 0.08 | 7.29 | 0.05 | 17.2 | 0.05 | 17.2 | 0.036 | 17.2 |
| No. of bunches | 290 | | 1160 | | 1160 | | 1160 | |
| Beam current [A] | 0.23 | 0.26 | 0.57 | 2.50 | 0.57 | 2.50 | 0.41 | 2.50 |
| RMS norm. emit., h/v [$\mu$m] | 5.1/0.7 | 705/20 | 5.0/0.4 | 391/20 | 5.0/0.4 | 196/20 | 3.0/0.3 | 196/20 |
| RMS emittance, h/v [nm] | 43.2/5.8 | 20.0/0.6 | 42.3/3.0 | 20.0/1.0 | 42.3/3.0 | 20.0/2.0 | 68.1/5.7 | 20.0/2.0 |
| $\beta^*$, h/v [cm]] | 91/4 | 196/41 | 91/4 | 193/12 | 91/4 | 193/6 | 90/4 | 307/11 |
| IP RMS beam size, h/v [$\mu$m] | 198/15 | | 196/11 | | 197/11 | | 248/15 | |
| $K_x$ | 0.077 | | 0.057 | | 0.056 | | 0.061 | |
| RMS $\Delta\theta$, h/v [$\mu$rad] | 218/379 | 101/37 | 216/274 | 102/92 | 215/275 | 102/185 | 275/377 | 81/136 |
| BB parameter, h/v [$10^{-3}$] | 1/1 | 37/100 | 3/3 | 43/47 | 3/2 | 86/47 | 5/4 | 61/37 |
| RMS long. emittance [$10^{-3}$, eV·sec] | 16 | | 16 | | 16 | | 16 | |
| RMS bunch length [cm] | 7 | 0.9 | 7 | 2 | 7 | 2 | 11.6 | 2 |
| RMS $\Delta p/p$ [$10^{-4}$] | 6.2 | 10.9 | 6.2 | 5.8 | 6.2 | 6.8 | 10 | 6.8 |
| Max. space charge | 0.007 | neglig. | 0.008 | neglig. | 0.008 | neglig. | 0.038 | neglig. |
| Piwinski angle [rad] | 4.4 | 1.1 | 4.5 | 1.2 | 4.5 | 1.5 | 5.8 | 1.2 |
| Long. IBS time [h] | 0.33 | | 0.36 | | 0.36 | | 0.85 | |
| Transv. IBS time [h] | 0.81 | | 0.89 | | 0.89 | | 0.16 | |
| Hourglass factor $H$ | 0.85 | | 0.85 | | 0.85 | | 0.71 | |
| Luminosity [$10^{33}$cm$^{-2}$sec$^{-1}$] | 0.59 | | 4.76 | | 4.77 | | 1.67 | |

# e+Au

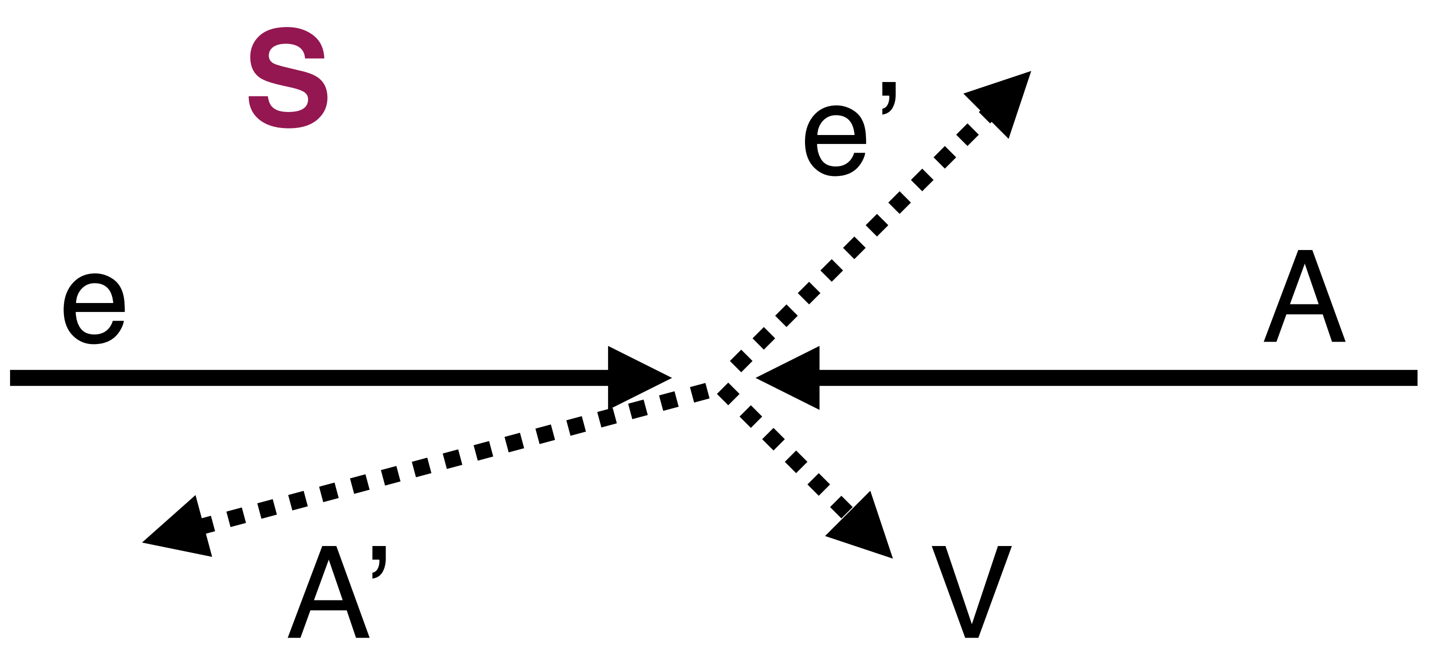


**Table 3.6:** eRHIC beam parameters for e-Au operation for different center-of-mass energies $\sqrt{s}$, with stochastic cooling.

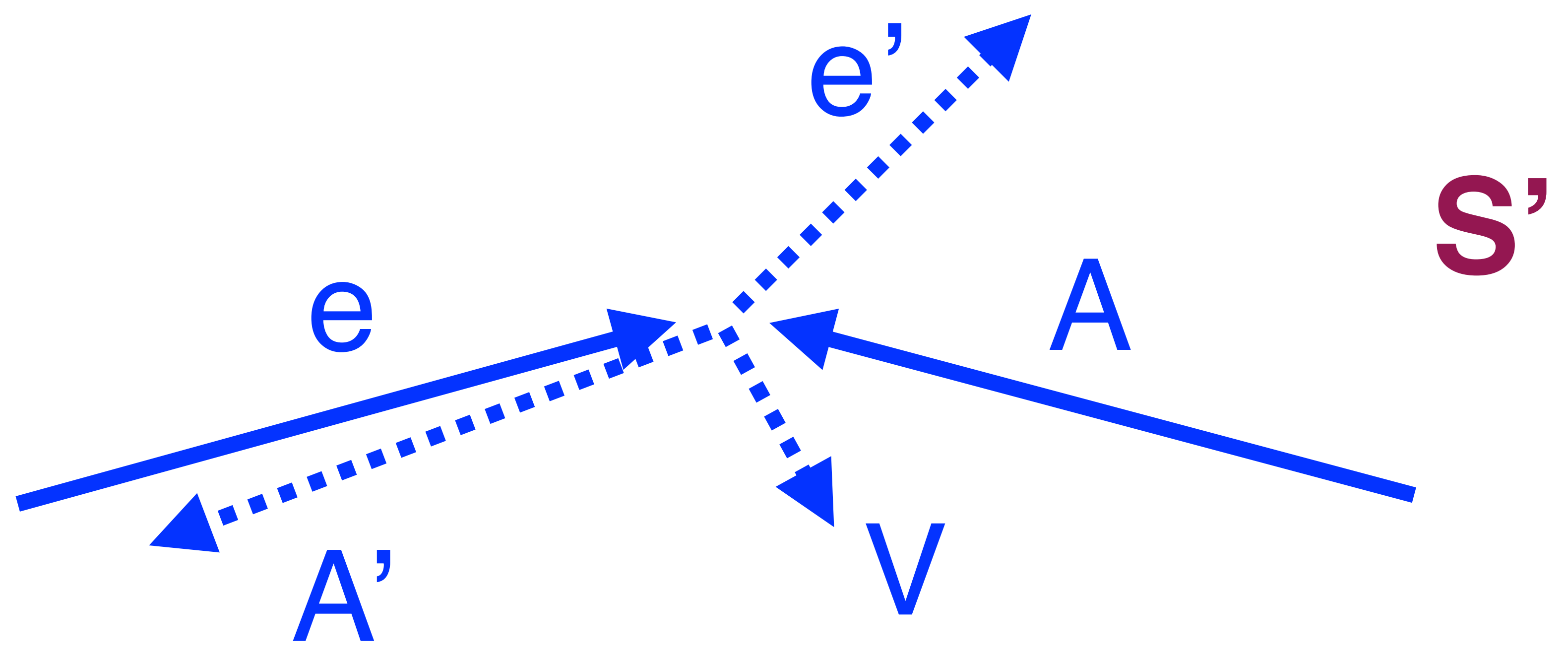
| Species | Au ion | electron | Au ion | electron | Au ion | electron | Au ion | electron |
|---|---|---|---|---|---|---|---|---|
| Energy [GeV] | 110 | 18 | 110 | 10 | 110 | 5 | 41 | 5 |
| CM energy [GeV] | 89.0 | | 66.3 | | 46.9 | | 28.6 | |
| Bunch intensity [$10^{10}$] | 0.10 | 7.29 | 0.10 | 30 | 0.08 | 30 | 0.09 | 30 |
| No. of bunches | 290 | | 580 | | 580 | | 580 | |
| Beam current [A] | 0.29 | 0.26 | 0.57 | 2.18 | 0.44 | 2.18 | 0.50 | 2.18 |
| RMS norm. emit., h/v [$\mu$m] | 2.0/2.0 | 845/60 | 2.0/2.0 | 391/102 | 2.0/2.0 | 196/63 | 2.0/2.0 | 196/113 |
| RMS emittance, h/v [nm] | 16.9/16.9 | 24.0/1.7 | 16.9/16.9 | 20.0/5.2 | 16.9/16.9 | 20.0/6.4 | 45.4/45.4 | 20.0/11.5 |
| $\beta^*$, h/v [cm]] | 288/12 | 203/116 | 91/12 | 77/39 | 146/12 | 113/31 | 149/50 | 339/196 |
| IP RMS beam size, h/v [$\mu$m] | 221/45 | | 124/45 | | 157/45 | | 261/150 | |
| $K_x$ | 0.202 | | 0.363 | | 0.284 | | 0.577 | |
| RMS $\Delta\theta$, h/v [$\mu$rad] | 77/380 | 109/38 | 136/376 | 161/116 | 108/380 | 127/144 | 174/302 | 77/77 |
| BB parameter, h/v [$10^{-3}$] | 3/1 | 35/100 | 11/4 | 66/93 | 11/3 | 100/96 | 9/5 | 100/100 |
| RMS long. emittance [$10^{-3}$, eV·sec] | 64 | | 64 | | 64 | | 64 | |
| RMS bunch length [cm] | 15 | 0.9 | 18 | 2 | 18 | 2 | 18 | 2 |
| RMS $\Delta p/p$ [$10^{-4}$] | 10 | 10.9 | 10 | 5.8 | 10 | 6.8 | 13 | 6.8 |
| Max. space charge | 0.001 | neglig. | 0.001 | neglig. | 0.001 | neglig. | 0.007 | neglig. |
| Piwinski angle [rad] | 8.5 | 0.5 | 18.1 | 2.0 | 14.3 | 1.6 | 8.6 | 1.0 |
| Long. IBS time [h] | 2.65 | | 2.65 | | 3.39 | | 2.02 | |
| Transv. IBS time [h] | 1.02 | | 0.80 | | 1.32 | | 0.93 | |
| Hourglass factor $H$ | 0.54 | | 0.54 | | 0.54 | | 0.65 | |
| Luminosity [$10^{33}$cm$^{-2}$sec$^{-1}$] | 0.14 | | 2.06 | | 1.27 | | 0.31 | |

# How to simulate (I)

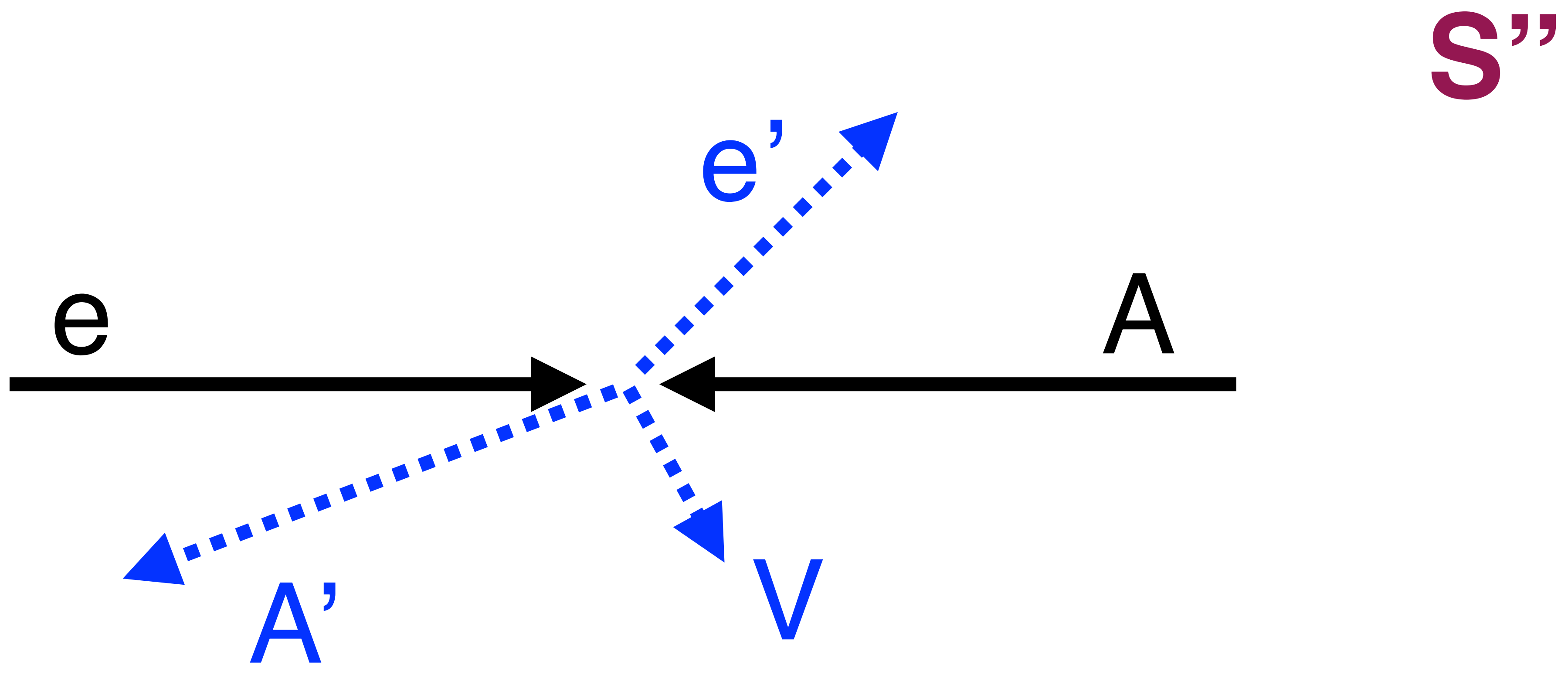
- Most generators, including Sartre, have only beams with 0 crossing angle




Ideal case
Generator does this



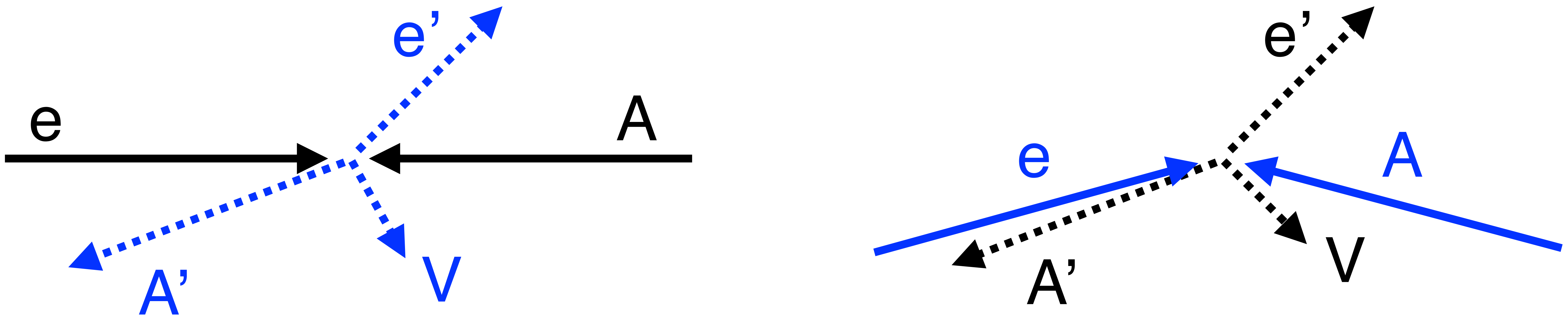

Nature & collider do this but we don't know the details and assume it looks like this:




In the experiment this affects the way we calculate t. We can only assume nominal beam energy and 0 divergence. Depending on method this smears *t*.

# How to simulate (II)

- Issue
  - Cannot transform (via Lorentz boost) S → S’
  - The two system have different (Lorentz invariant) features, e.g. √*s* and *t*
- Strategy:




Instead of this | we use this scenario

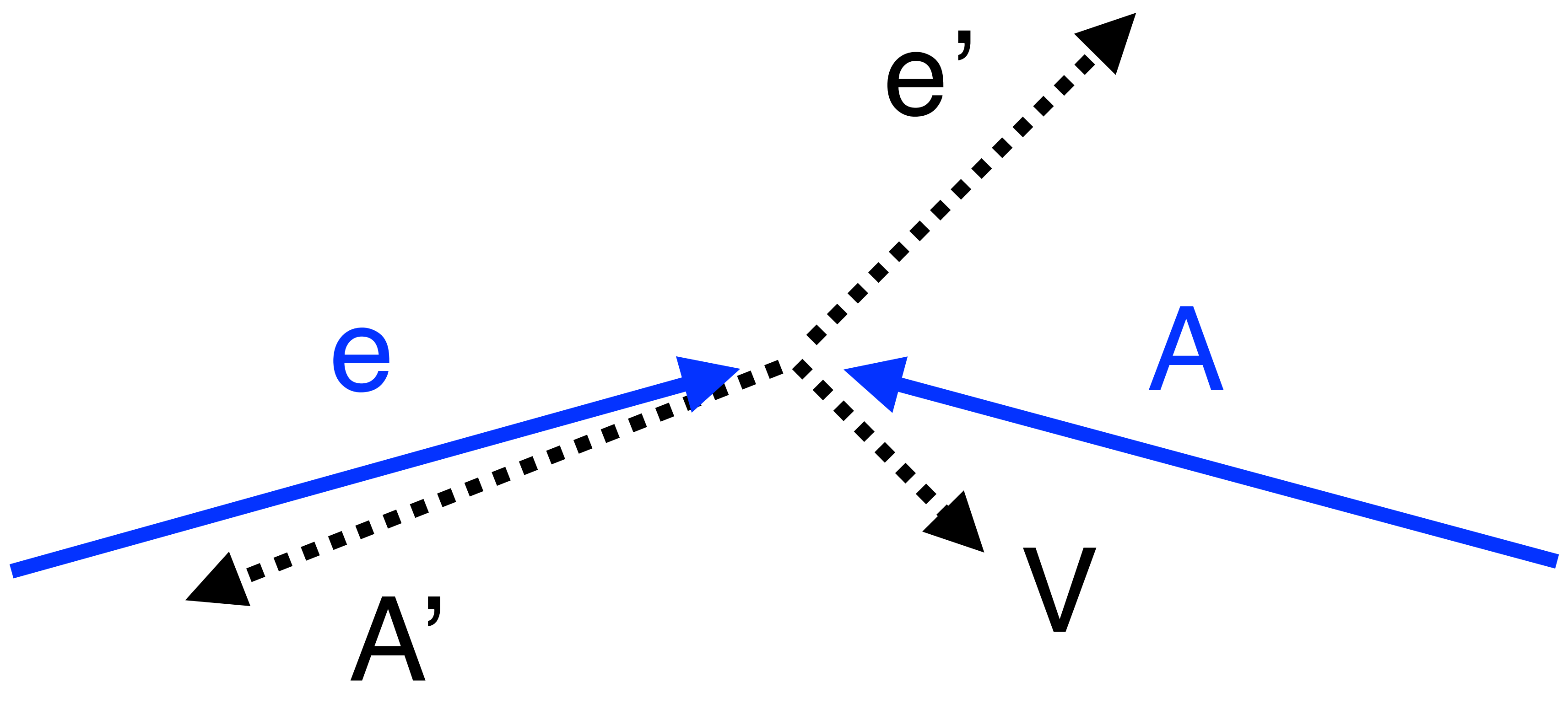
Instead of using the “*wrong” initial state* and the correct final state we are using the *correct initial state* but the “*wrong” final state*

- **Pros:** can use final state from generator which gives coherent physics picture and all variables are known
- **Cons:** does not give the most precise smearing numbers

# How to simulate (III)

How are the different methods affected?

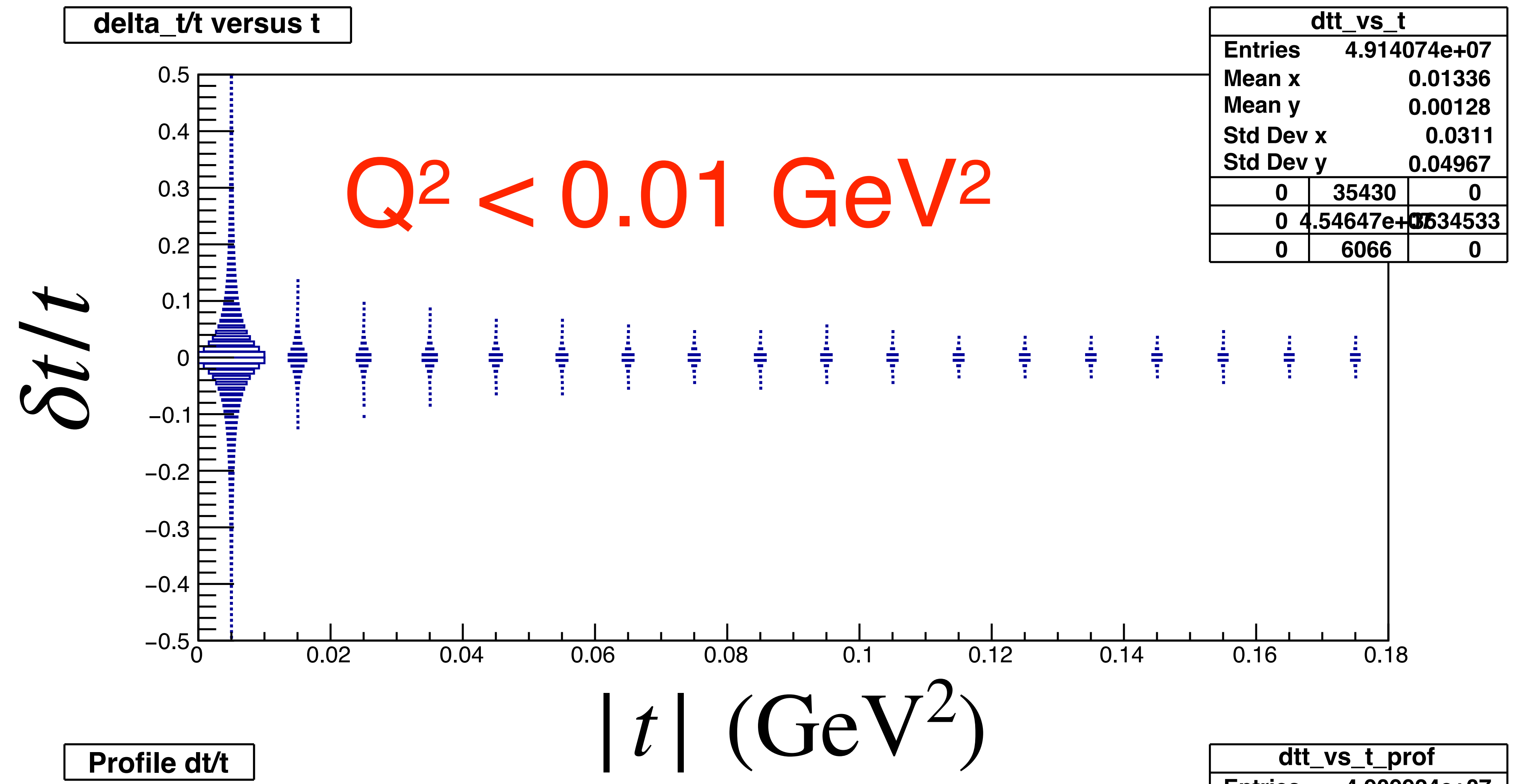
- Method E
  - $t = (p_V + p_{e'} - p_e)^2$
  - $p_V$ is taken from generator
  - $p_{e'}$ is staken from generator
  - $p_e$ is smeared using divergence and beam momentum spread
- Method A
  - $t = (\vec{p}_T(e') + \vec{p}_T(V))^2$
  - $\vec{p}_T(e')$ is taken from generator
  - $\vec{p}_T(V)$ is taken from generator
  - In **S** and **S'** this method is *not* affected by smearing
  - Despite it's shortcoming it is more robust

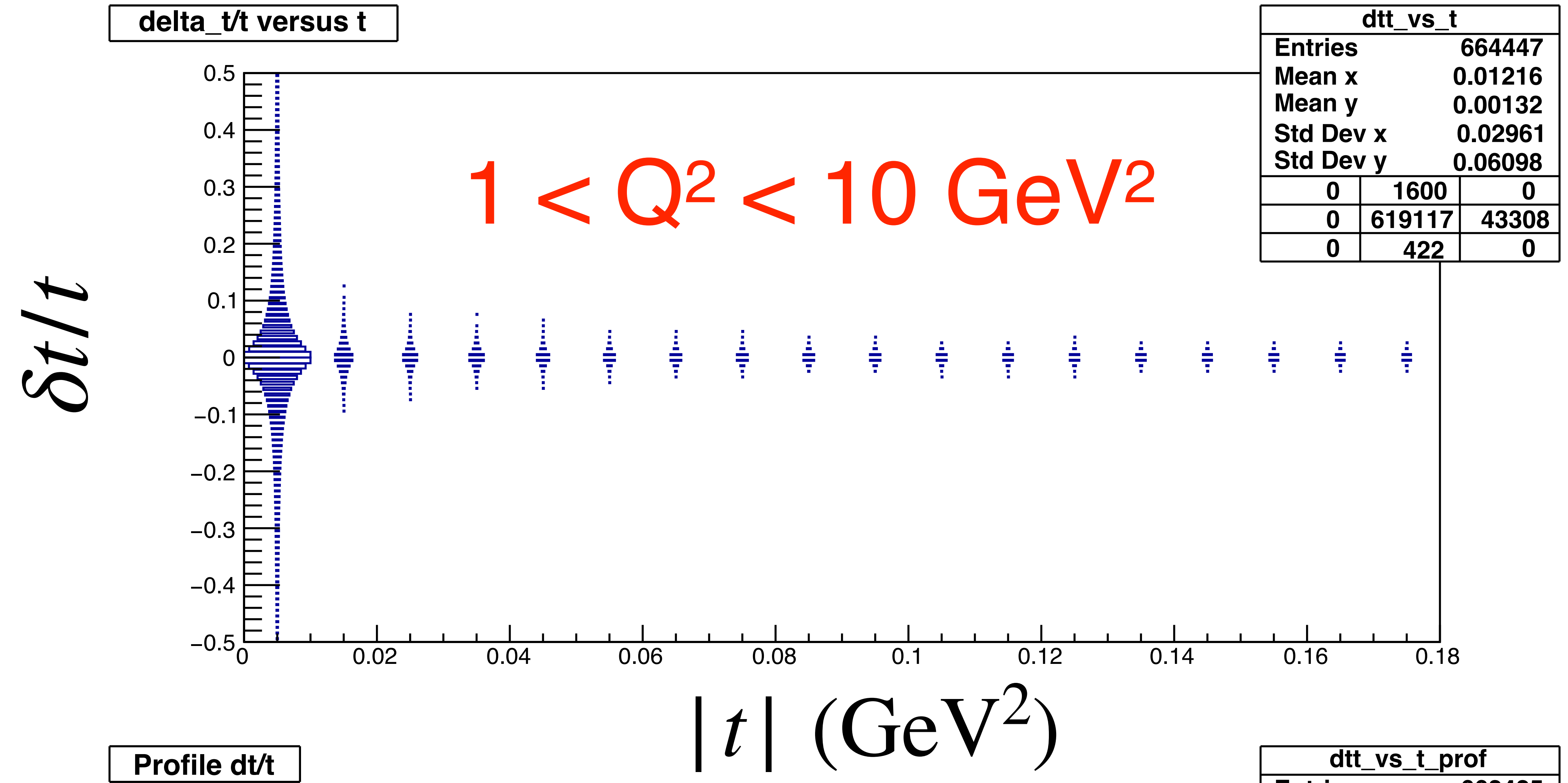


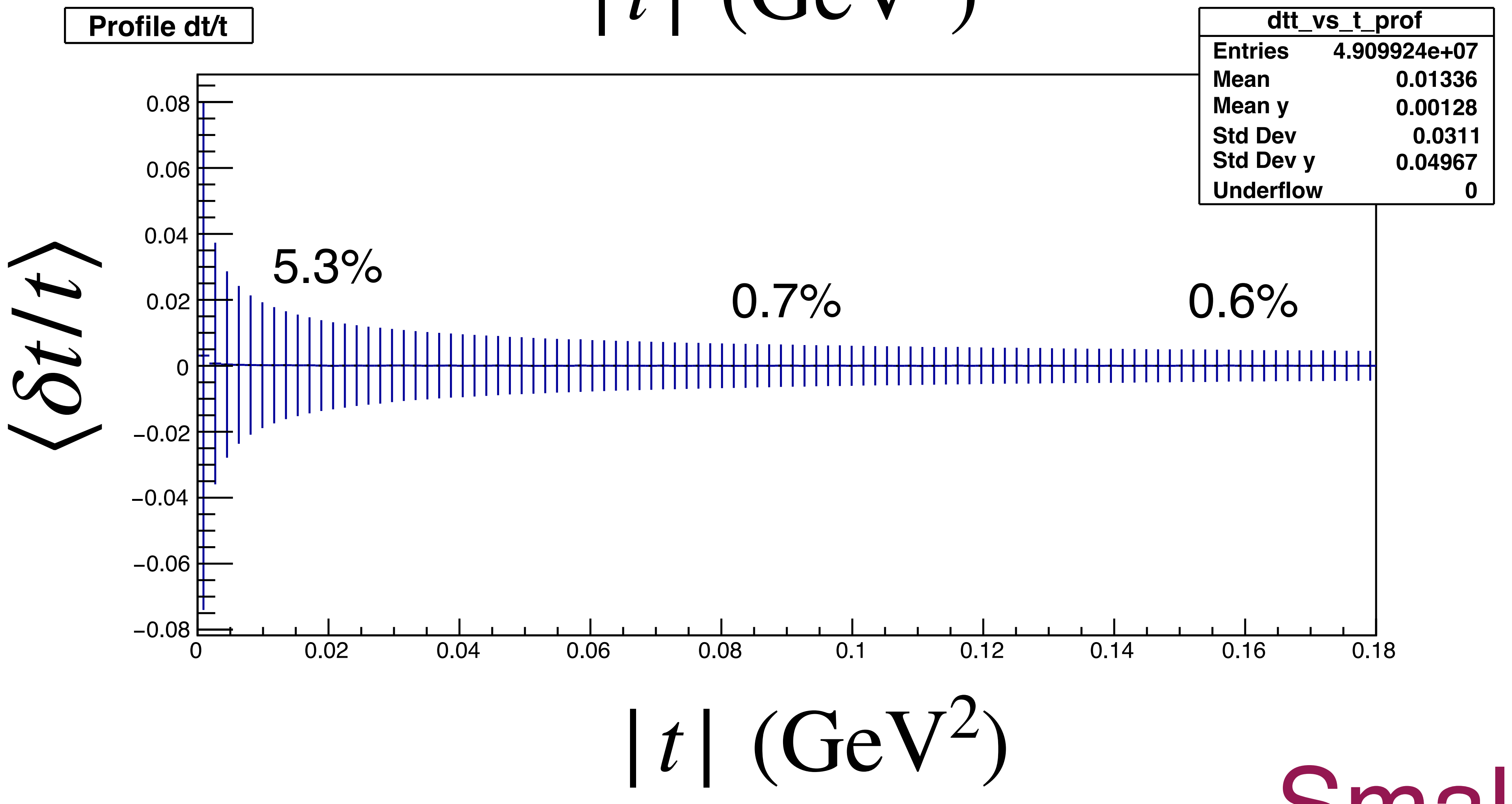
# Effect of beam smearing on method E

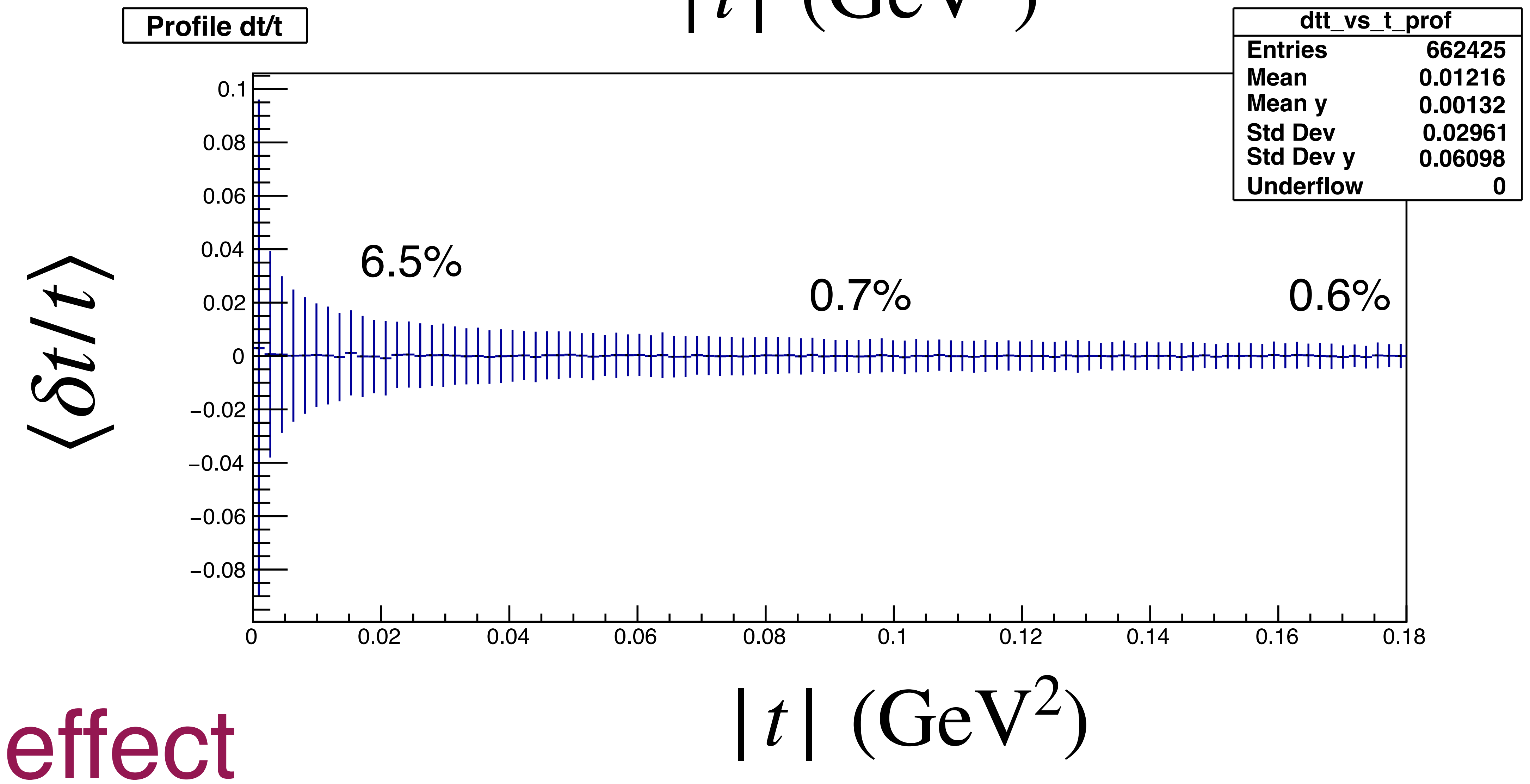
Here divergence only

$$t = (p_V + p_{e'} - p_e)^2$$



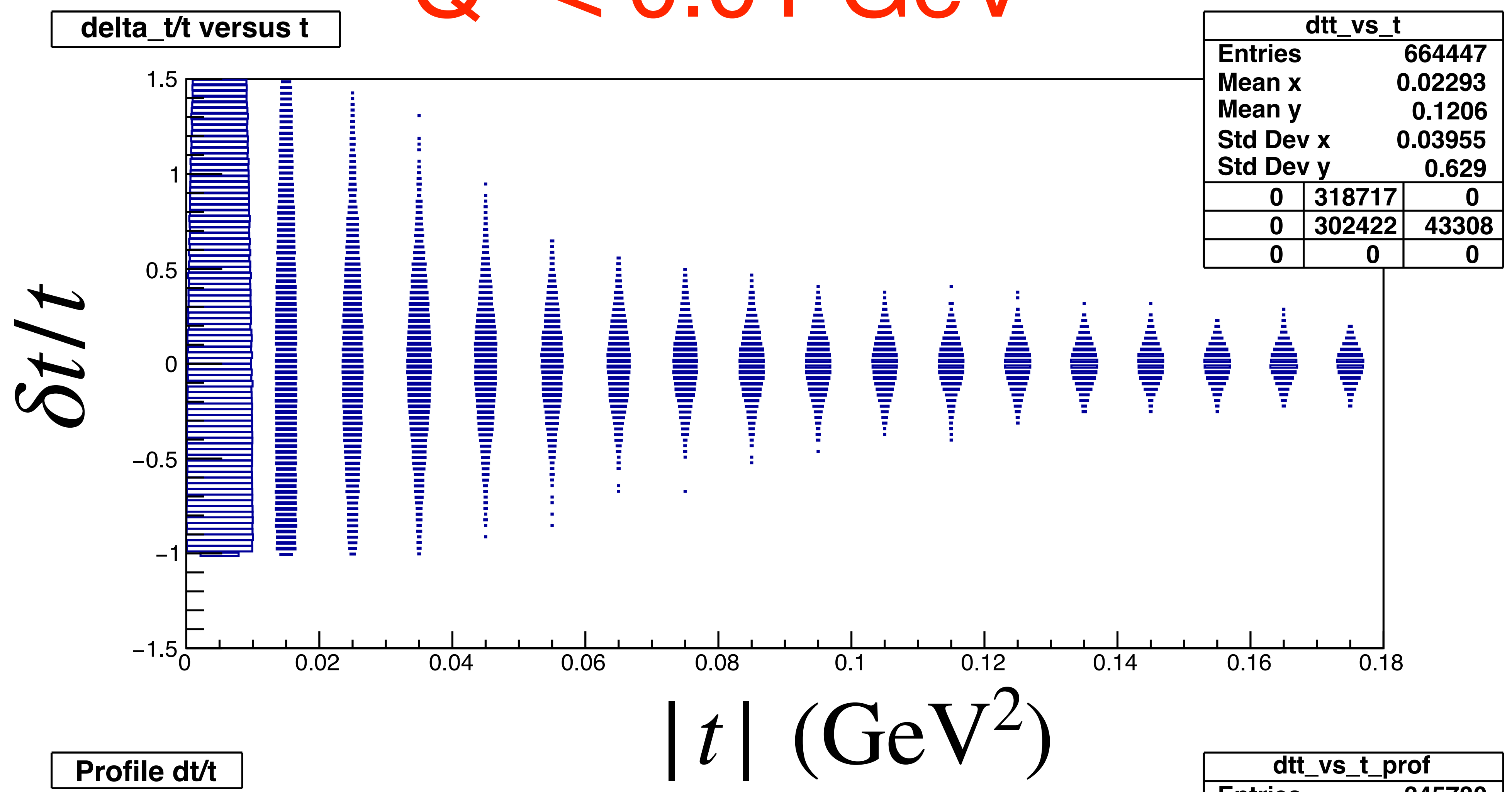

Small/moderate effect

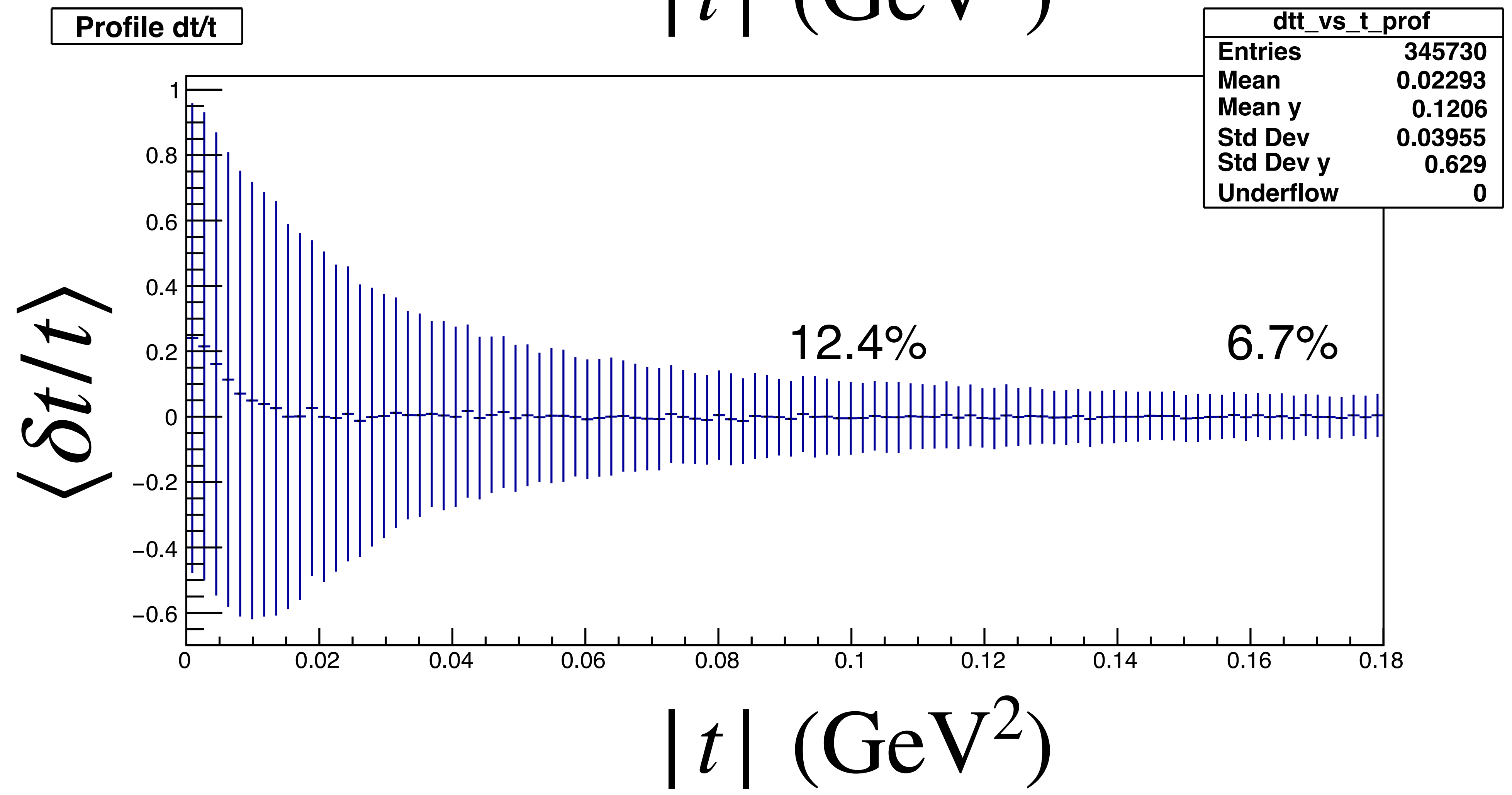
# Effect of beam smearing on method E

Here beam smearing only

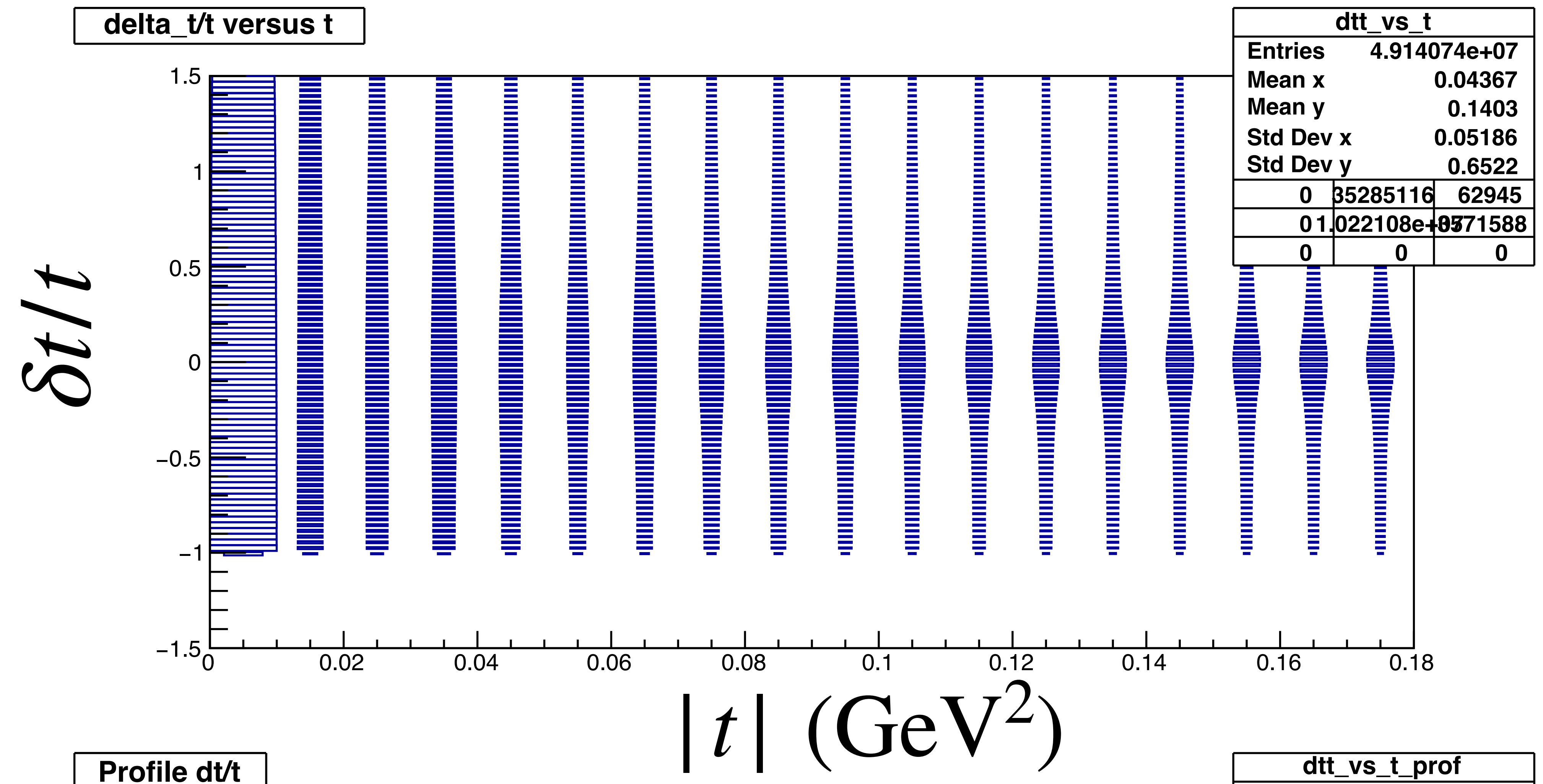
$$t = (p_V + p_{e'} - p_e)^2$$

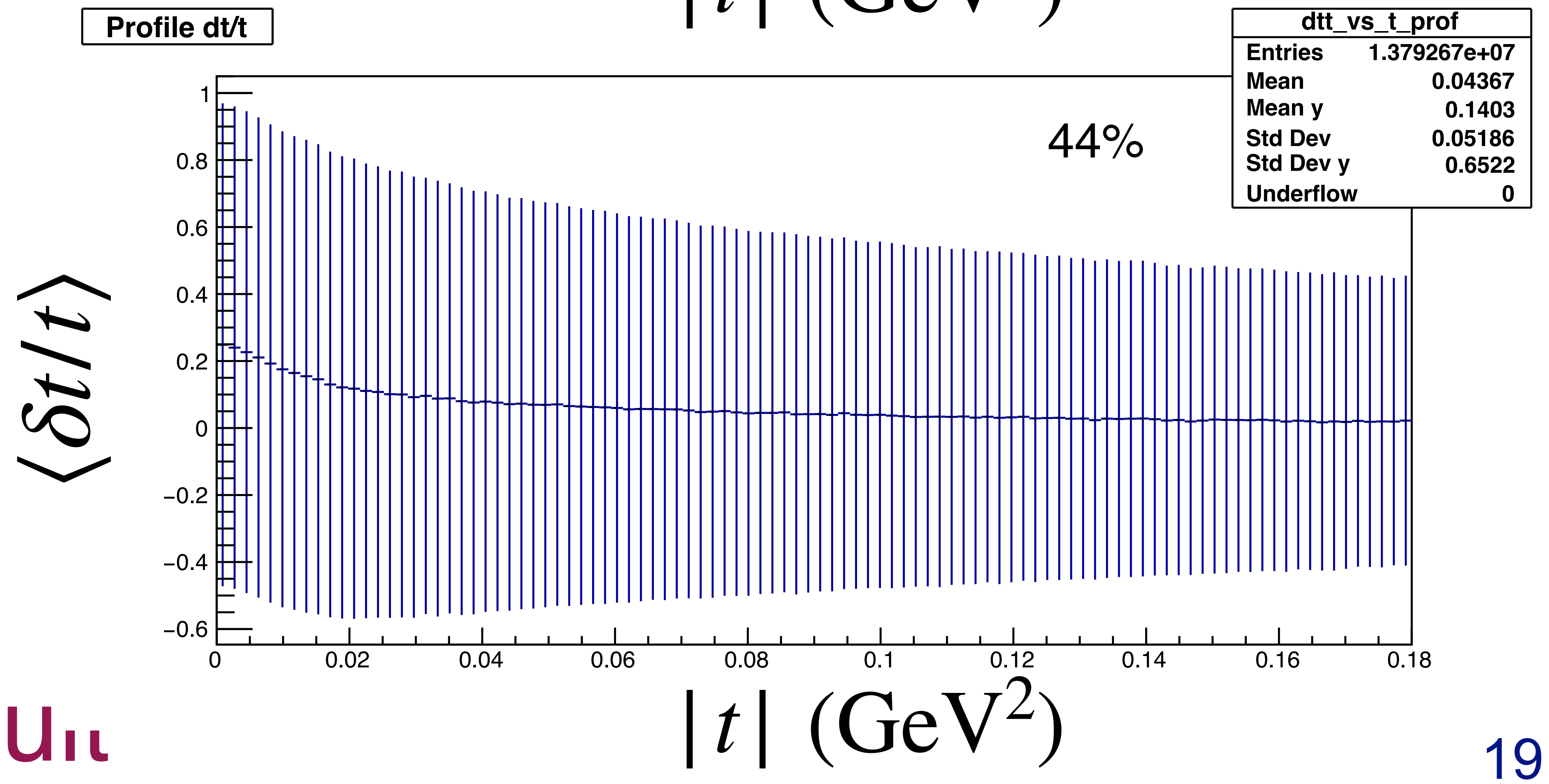
$Q^2 < 0.01$ GeV$^2$




$1 < Q^2 < 10$ GeV$^2$



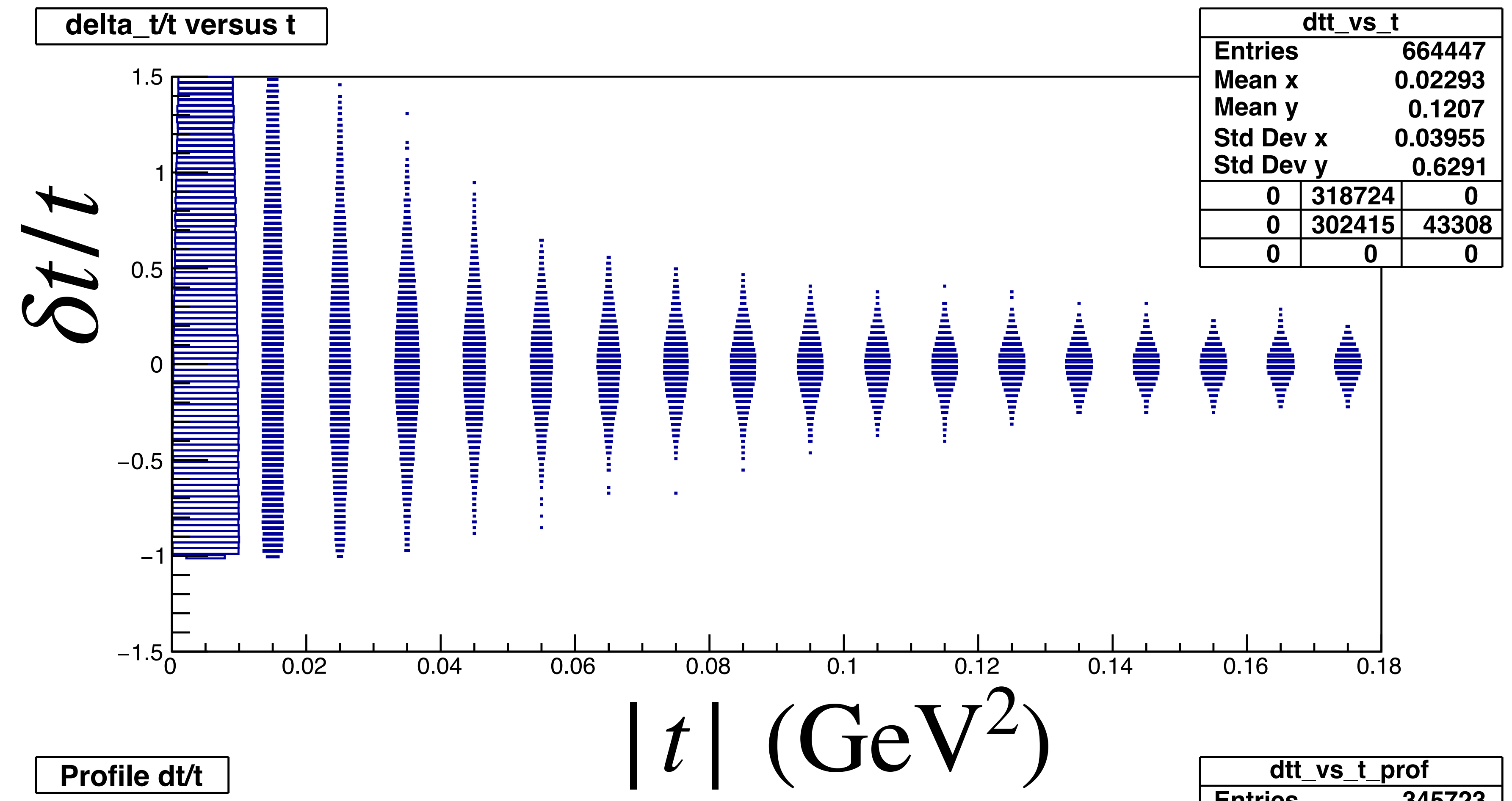

Devastating Resu...

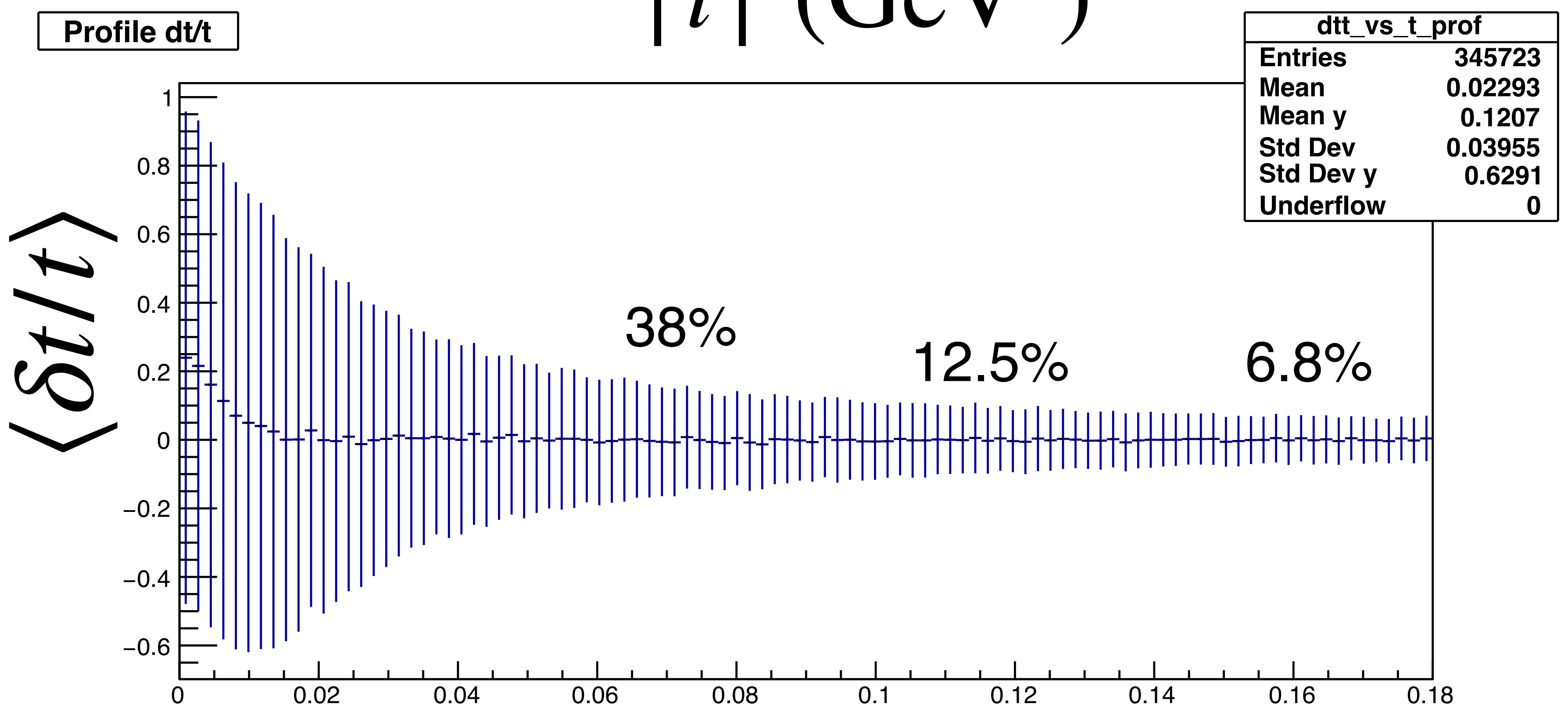
# Effect of beam smearing on method E

Here beam smearing and divergence

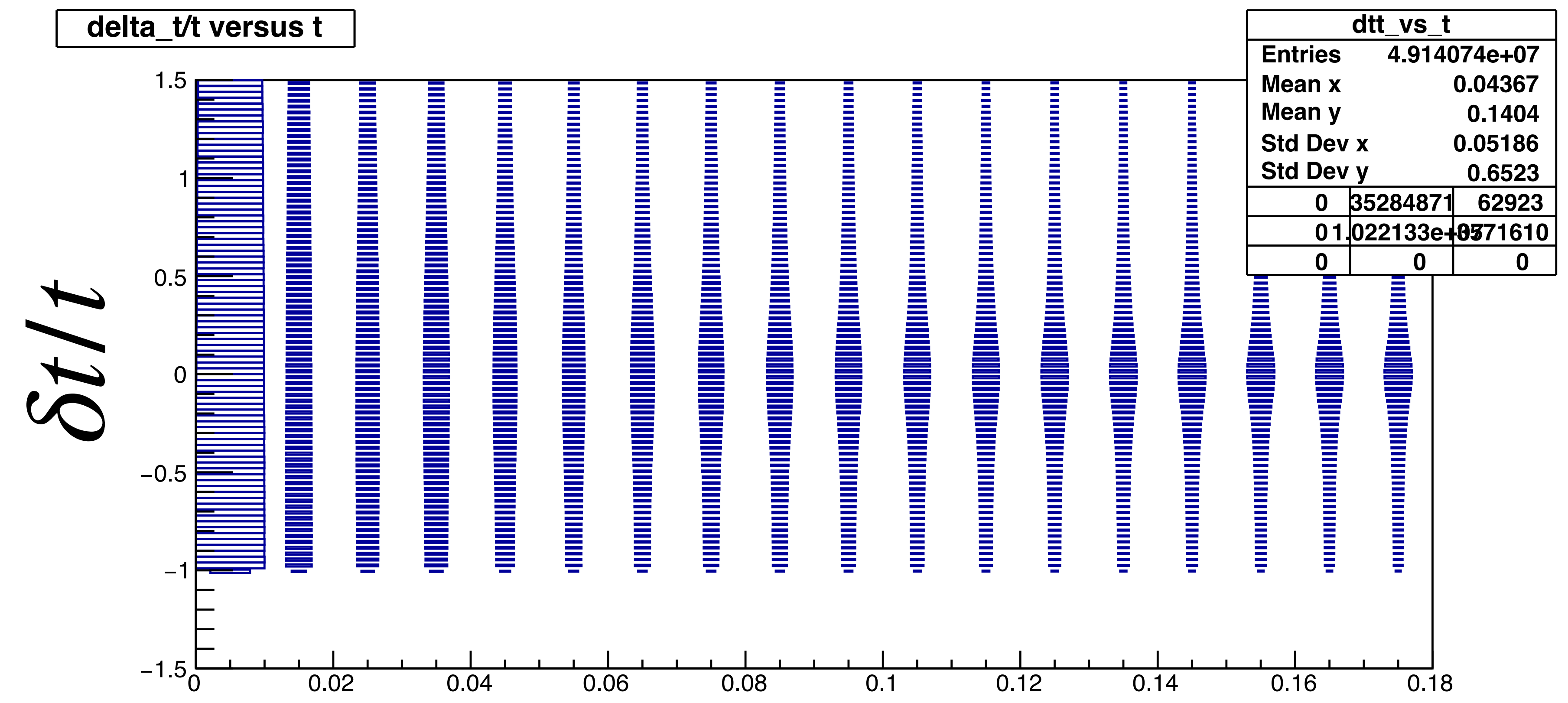
$$t = (p_V + p_{e'} - p_e)^2$$

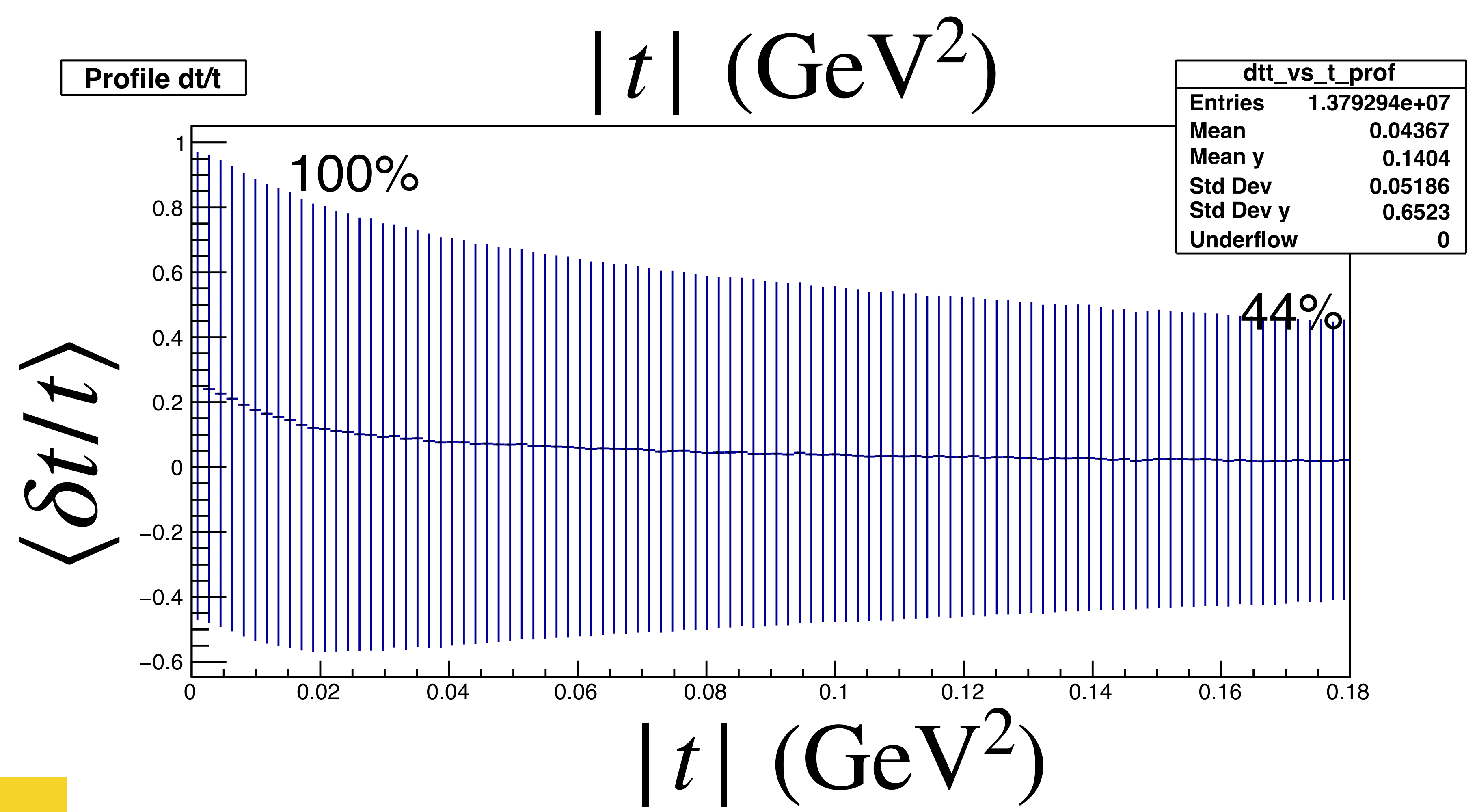
$Q^2 < 0.01$ GeV$^2$




$1 < Q^2 < 10$ GeV$^2$



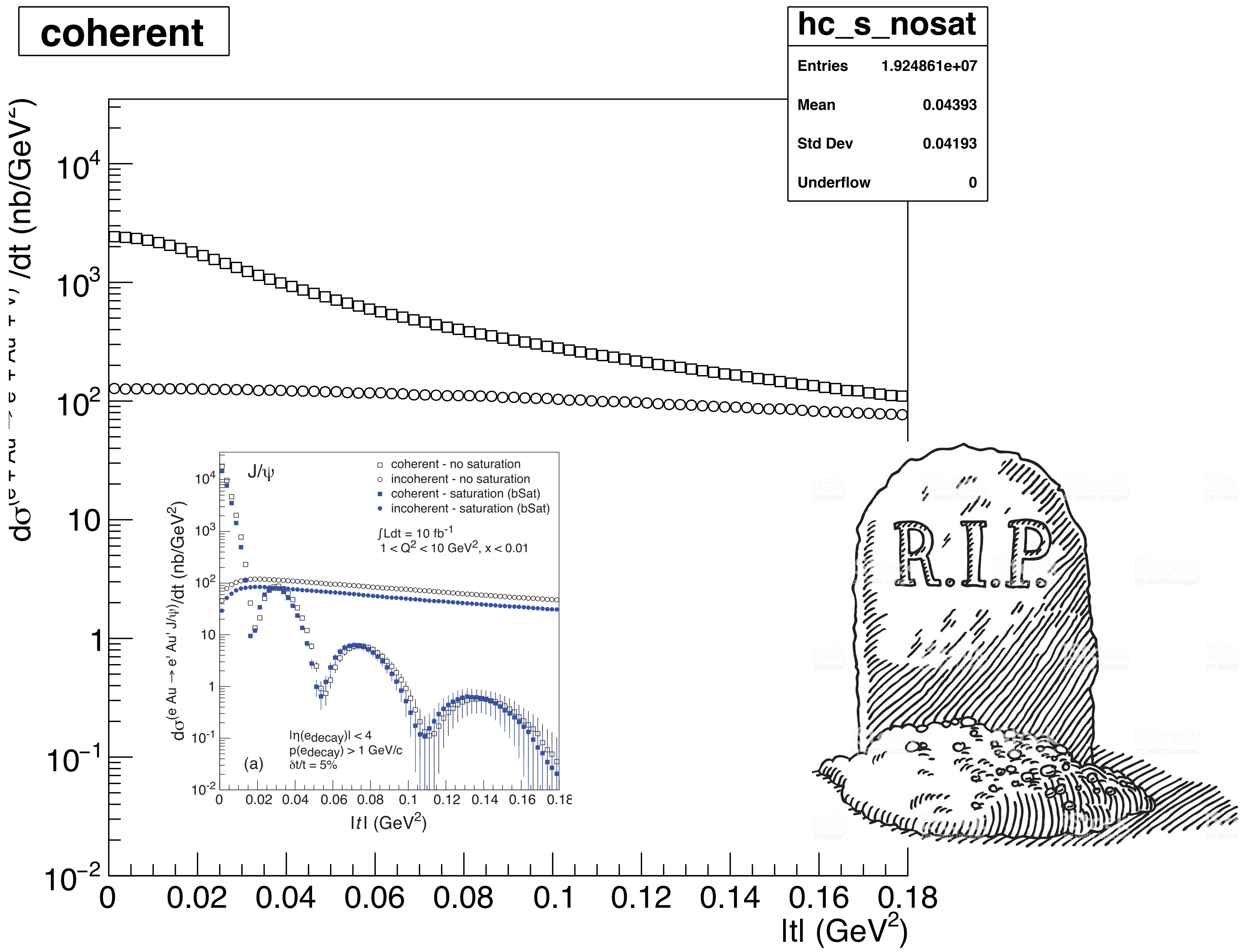




Method E does **not** work!!!

Results are so bad it takes method E off the table

# Why is Method E Failing?

- $t = (p_A - p_{A'})^2 = (p_V + p_{e'} - p_e)^2$
- we are subtracting large numbers
- even little fluctuations have large effects since $t$ is small
- The effect of the momentum spread is the overwhelming cause of the devastating $t$ resolution. Divergence is a minor problem for $t$ with method E.




**Method A to the rescue**
(not affected by any of the issues that kill E)

| at $|t|$ = 0.18 GeV$^2$ | $Q^2 < 0.01$ GeV$^2$ | $1 < Q^2 < 10$ GeV$^2$ |
|---|---|---|
| beam divergence | 0.6% | 0.6% |
| beam momentum spread | 6.7% | 44% |
| both | 6.8% | 44% |

# Tracking Resolution

Precision term: $$\left.\frac{\sigma_{p_T}}{p_T}\right|_{\rm meas} = \frac{p_T\ \sigma_{r_{\phi r}}}{0.3\ L^2\ B}\sqrt{\frac{720}{N+4}}$$

MS term: $$\left.\frac{\sigma_{p_T}}{p_T}\right|_{\rm MS} = \frac{0.05}{L\ B\ \beta}\sqrt{1.43\frac{L}{X_0}}\left[1+0.038\ \log\frac{L}{X_0}\right]$$

Total Track momentum resolution: $$\frac{\sigma_{p_T}}{p_T} = \left.\frac{\sigma_{p_T}}{p_T}\right|_{\rm meas} \oplus \left.\frac{\sigma_{p_T}}{p_T}\right|_{\rm MS}$$

where

- $\sigma_{r_{\phi r}}$ is point resolution in meter
- $L$ is lever arm in meter
- $B$ is magnetic field in Tesla
- $N$ are number of measurements (hits)
- $\beta$ velocity of particle
- $X_0$ is gas/material density in meter

# Start Values and Ballpark Numbers for Simulations

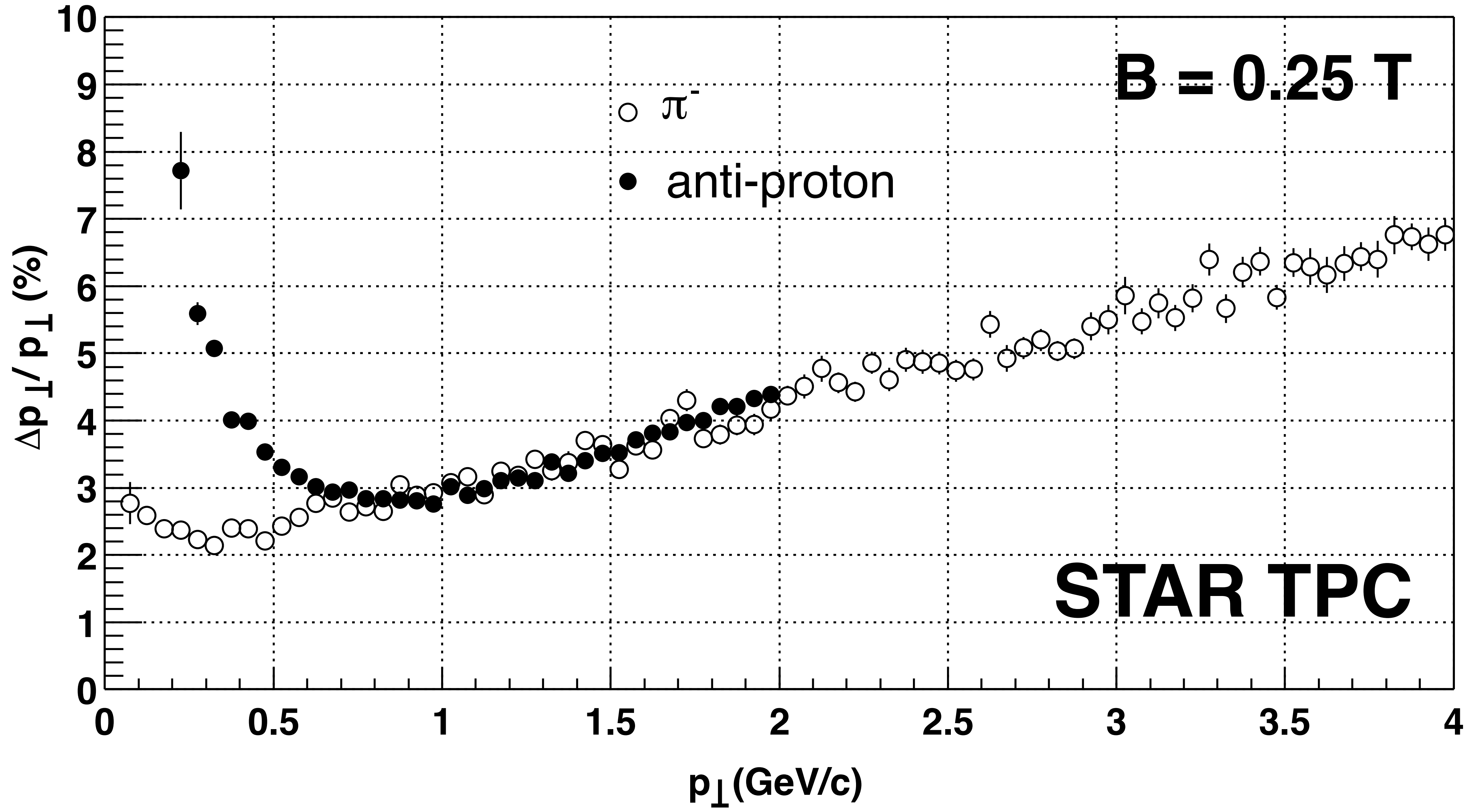
## Examples:

B=0.25 T (half field)

STAR TPC: $\frac{\sigma_{p_T}}{p_T}(\,\%\,) = 1.56\; p_T \oplus 2.74$

B=0.5 T (full field)

STAR TPC: $\frac{\sigma_{p_T}}{p_T}(\,\%\,) = 0.78\; p_T \oplus 1.37$




All EIC, B=3 T (full field)

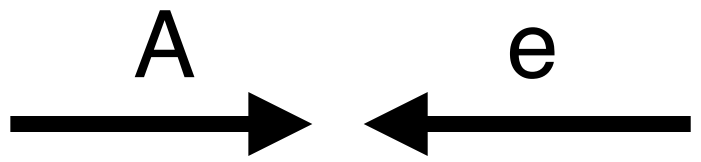
EIC Handbook $|\eta| < 1$ : $\frac{\sigma_{p_T}}{p_T}(\,\%\,) = 0.05\; p_T \oplus 0.5$

EIC Handbook $-2.5 < \eta < -1.0$ : $\frac{\sigma_{p_T}}{p_T}(\,\%\,) = 0.05\; p_T \oplus 1.0$

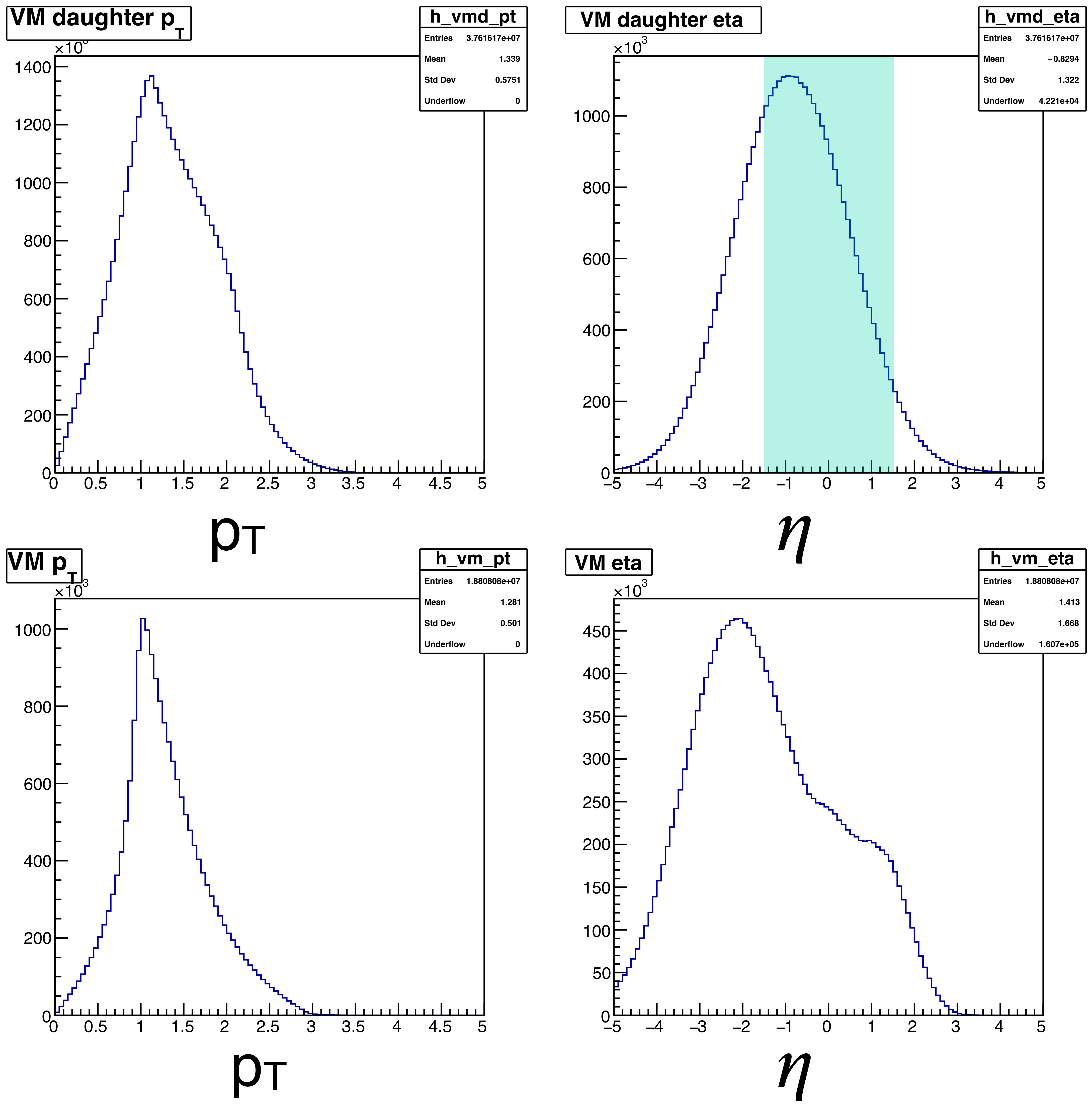
EIC Handbook $-3.5 < \eta| < -2.5$ : $\frac{\sigma_{p_T}}{p_T}(\,\%\,) = 0.1\; p_T \oplus 2.0$

N.B.
Important to consider if vertex is included or not (primary vs. global tracks)

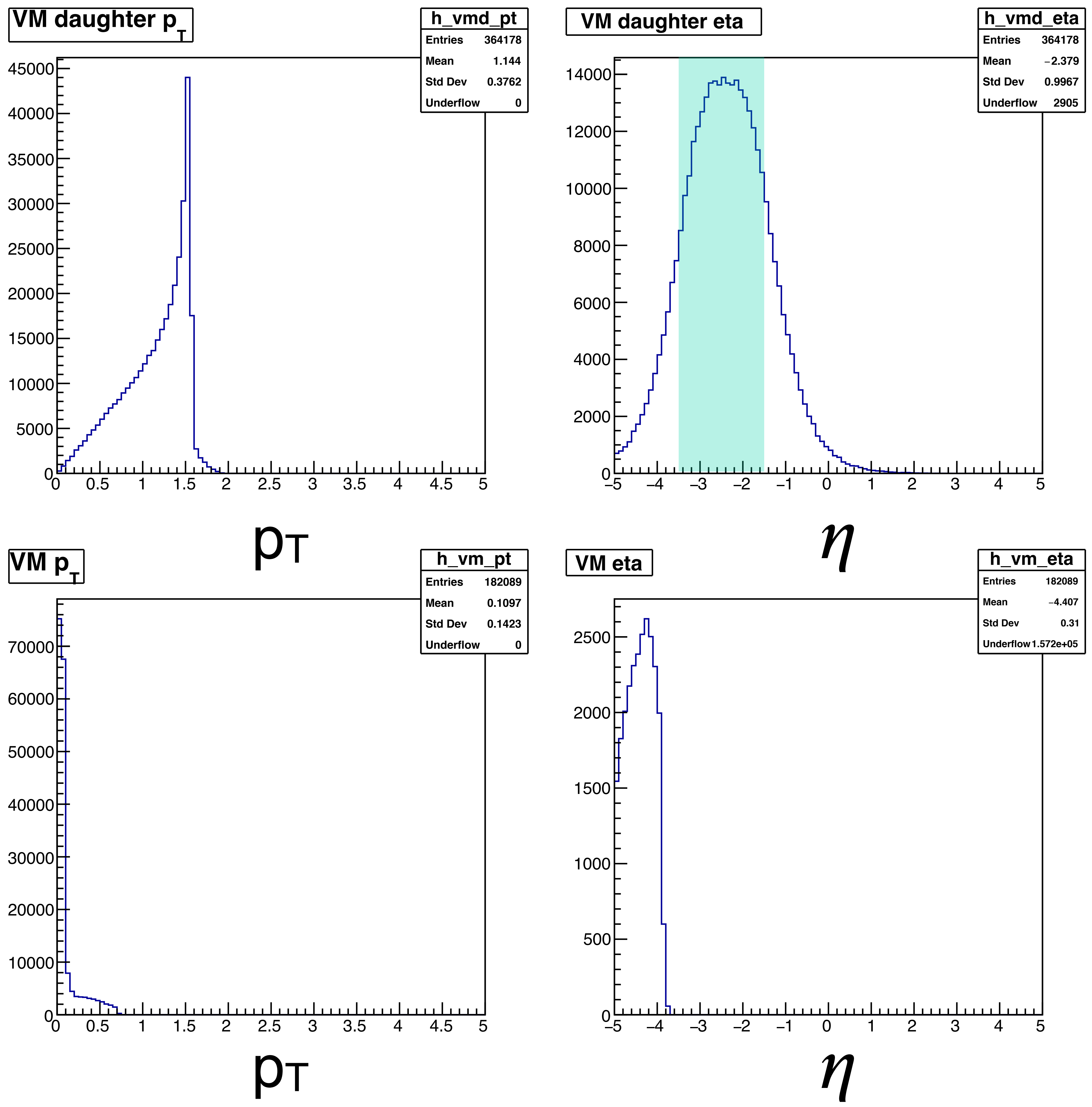
# Kinematics $J/\psi$




## $1 < Q^2 < 10$ GeV$^2$

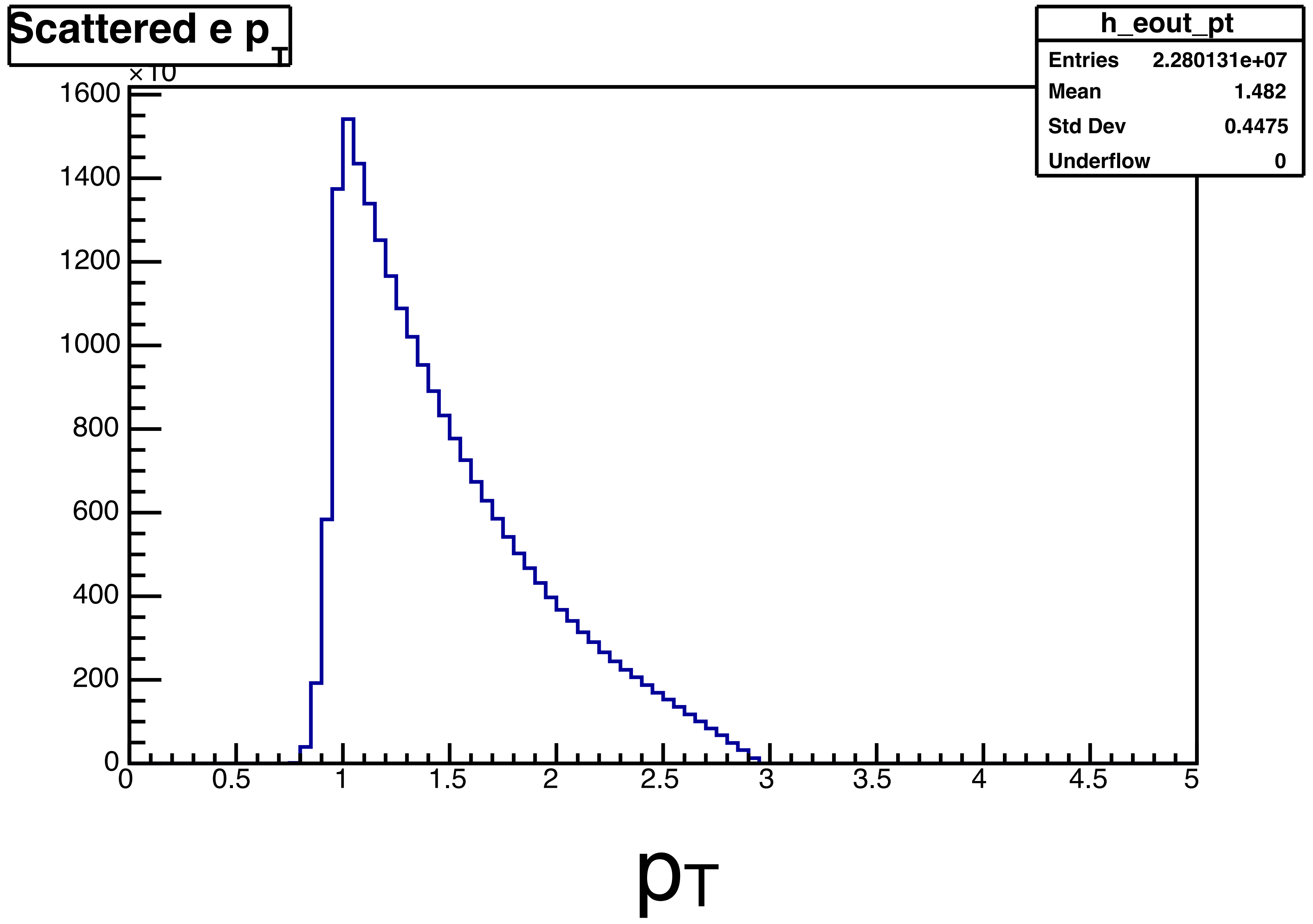


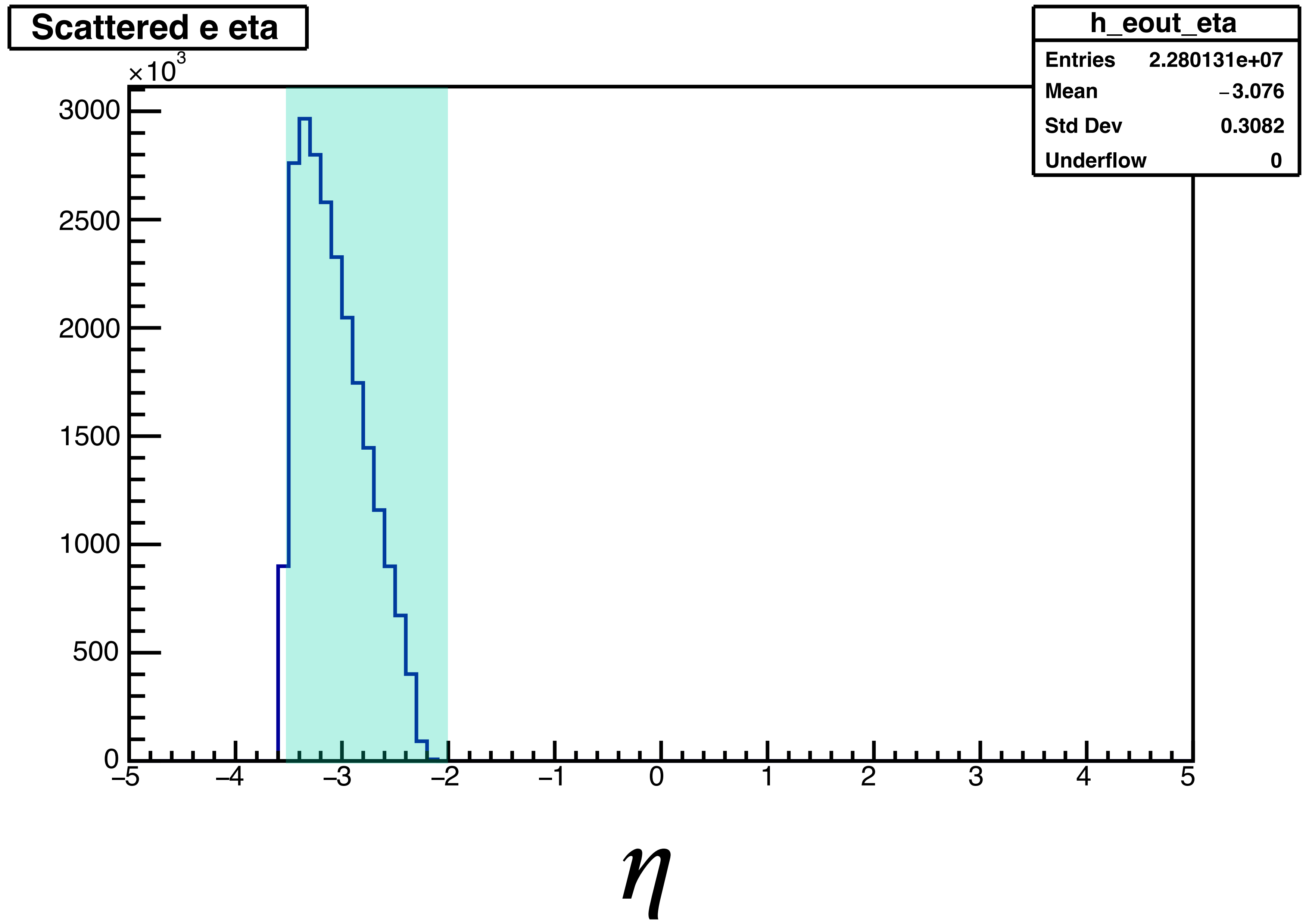

## $Q^2 < 0.01$ GeV$^2$



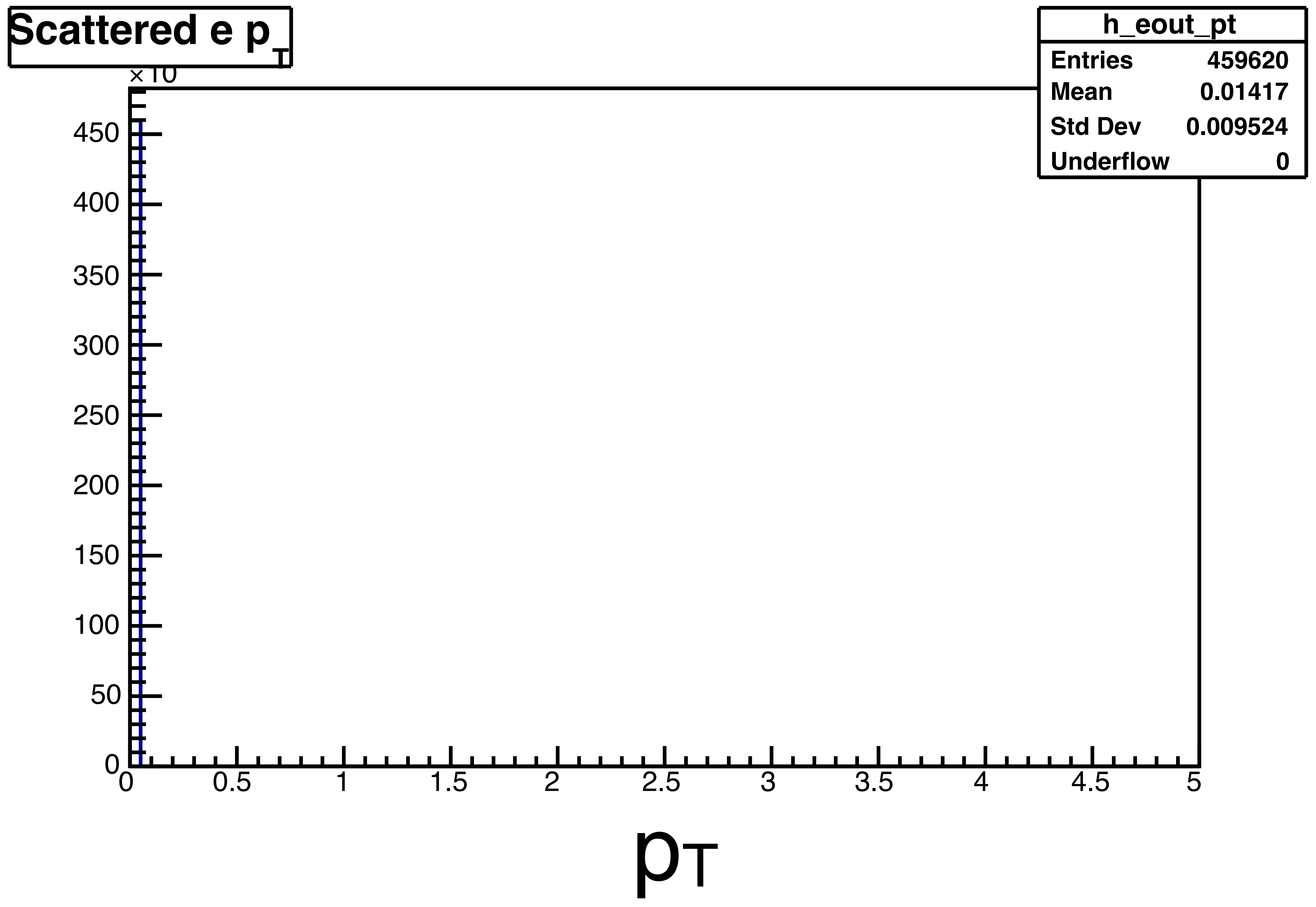
# Where do the scattered electrons go?

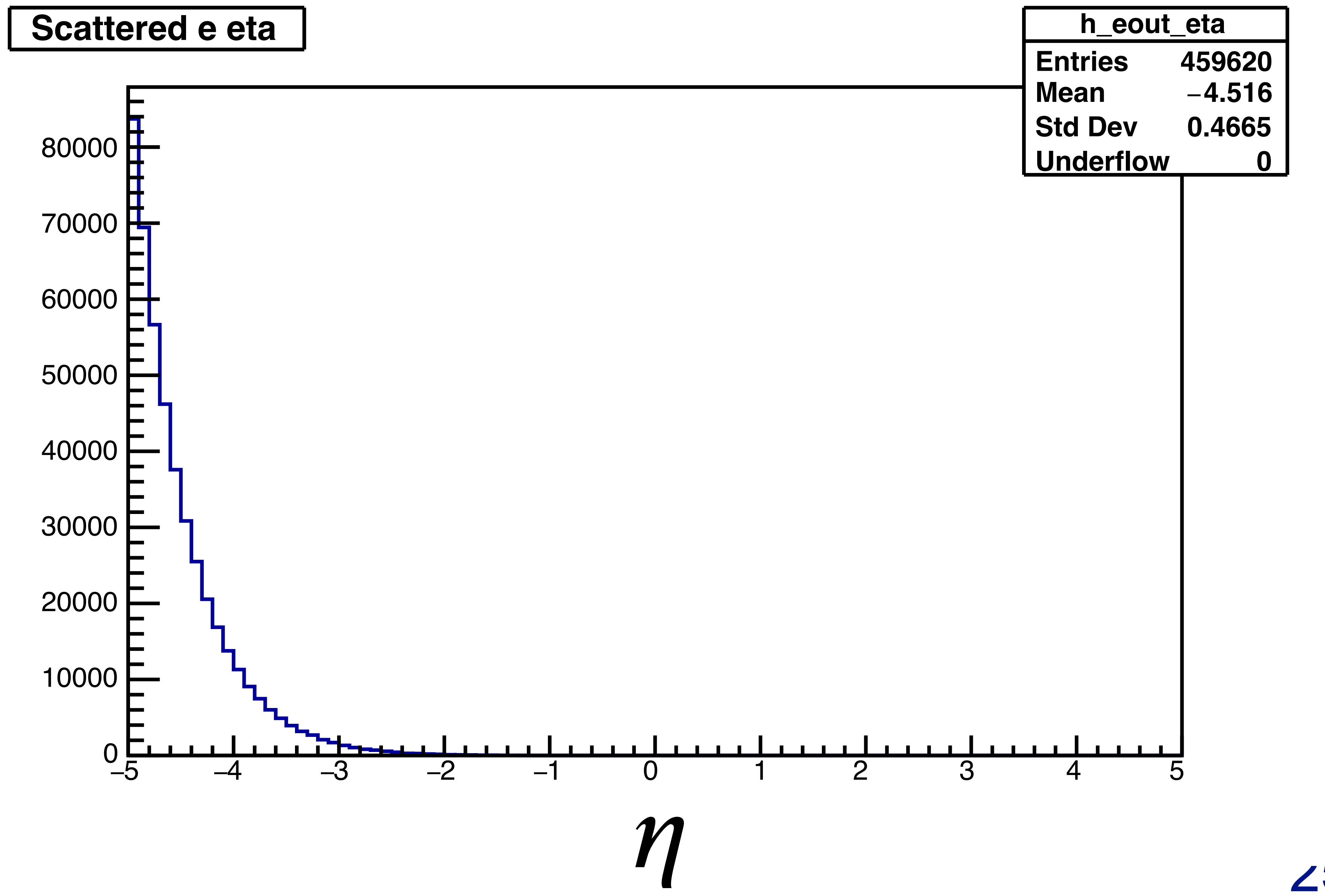
- $1 < Q^2 < 10\ \mathrm{GeV}^2$



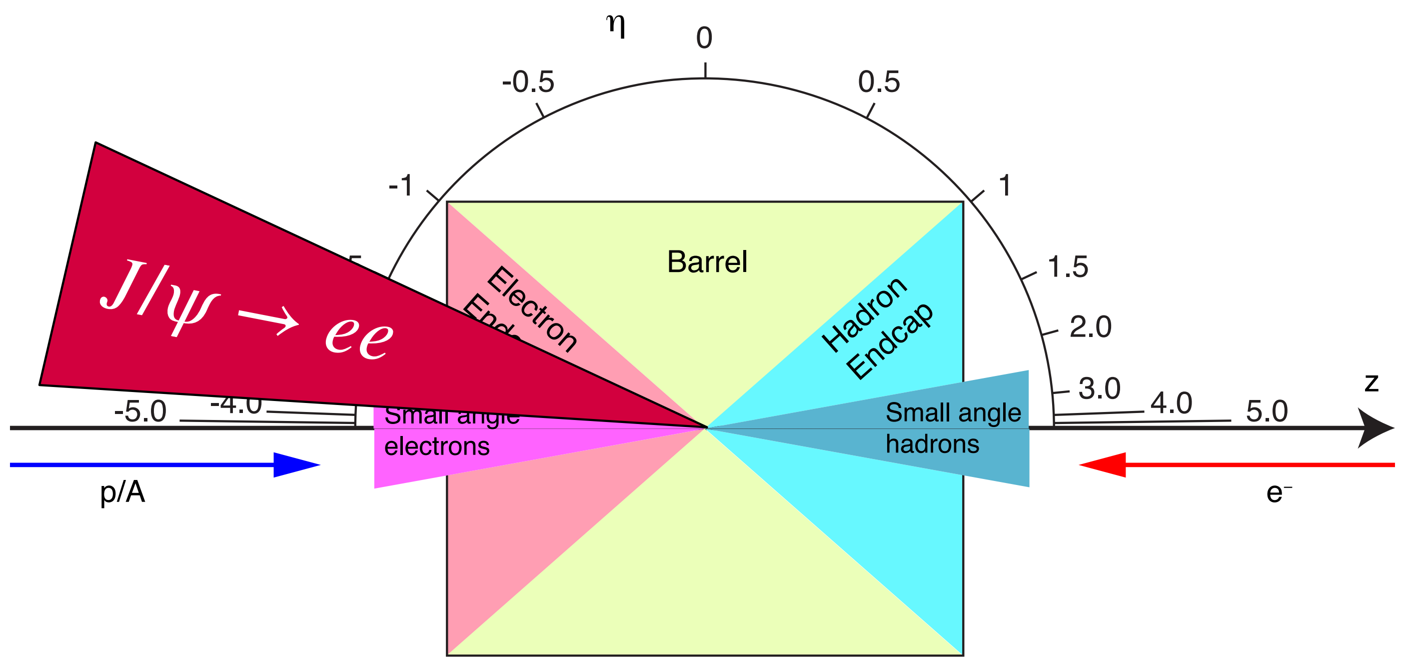

- $Q^2 < 0.01\ \mathrm{GeV}^2$



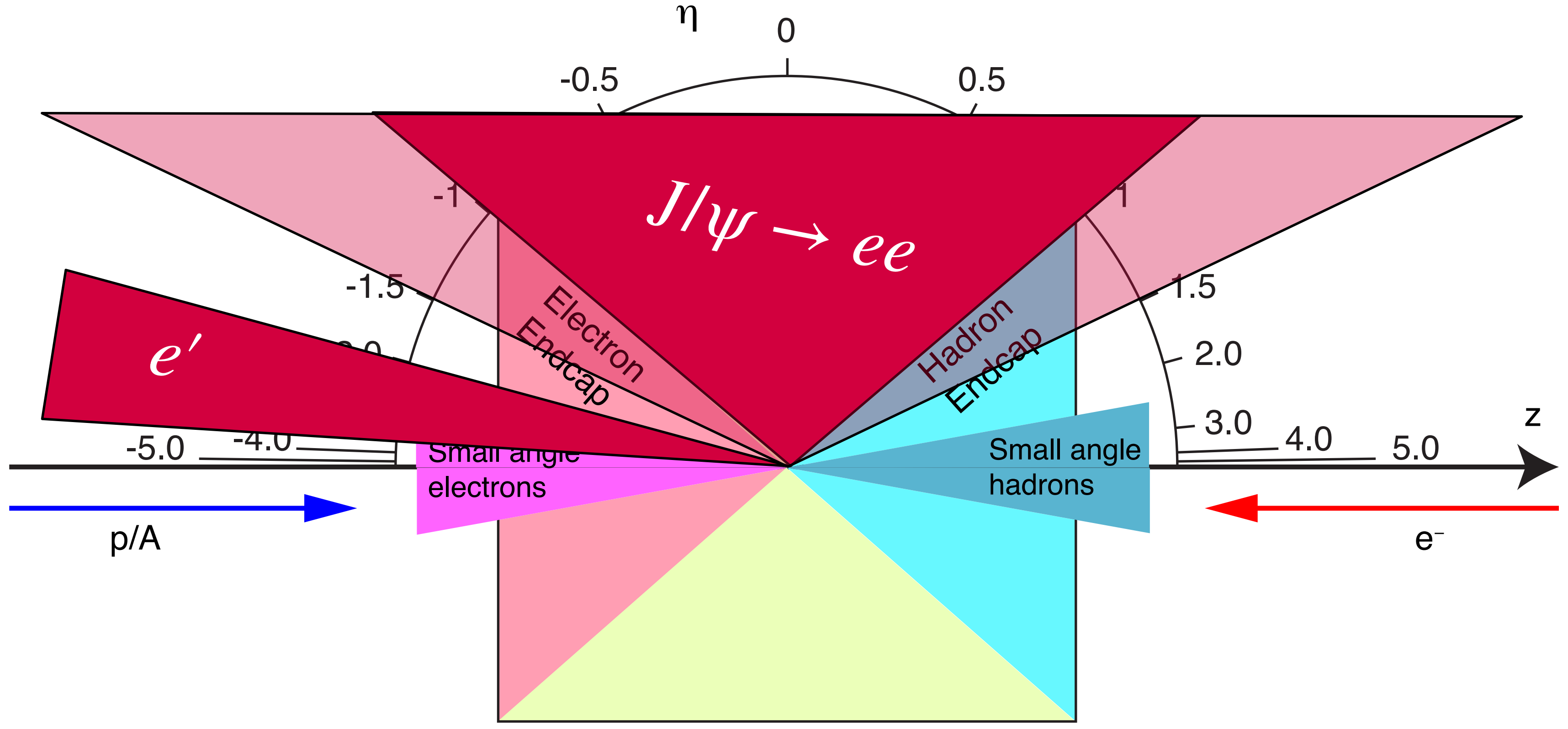



# Detector Constraints - Directions

- **$Q^2$ < 0.01 GeV$^2$ (Photoproduction)**
  - Constraints tracking in the backward (e-going) region
    - $-3.5 < \eta < -1.5$
    - $p_T > 0.5$
  - Smearing of scattered electron does not matter since $p_T \sim 0$




- **1 < $Q^2$ < 10 GeV$^2$**
  - $J/\psi$ Constraints tracking in the central (barrel) region
    - $|\eta| < \sim 1.5$
    - $p_T > 0.5$
  - Smearing of scattered electron does matter
    - $-3.5 < \eta < -2$
    - $p_T > 1$ GeV/c

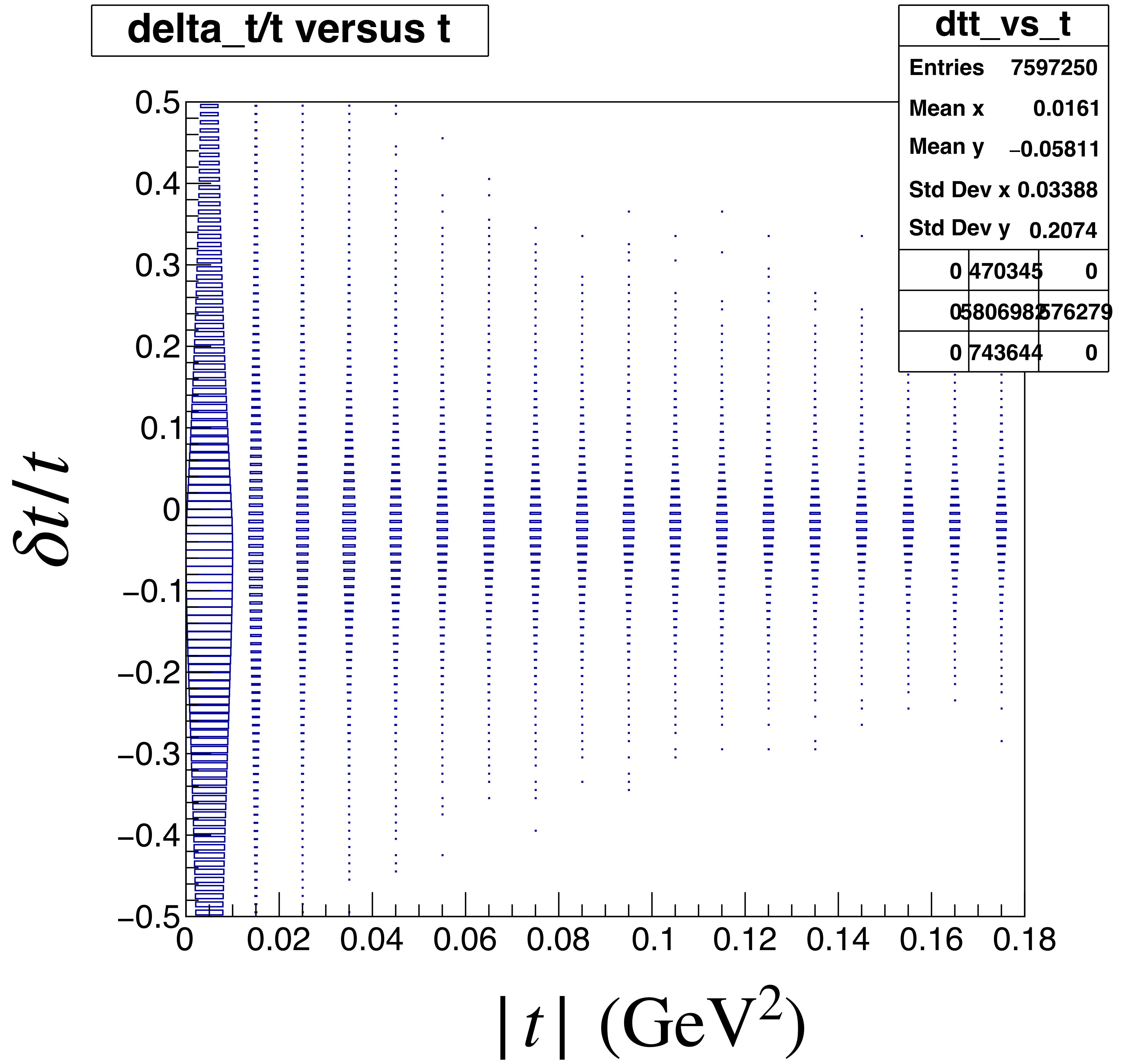


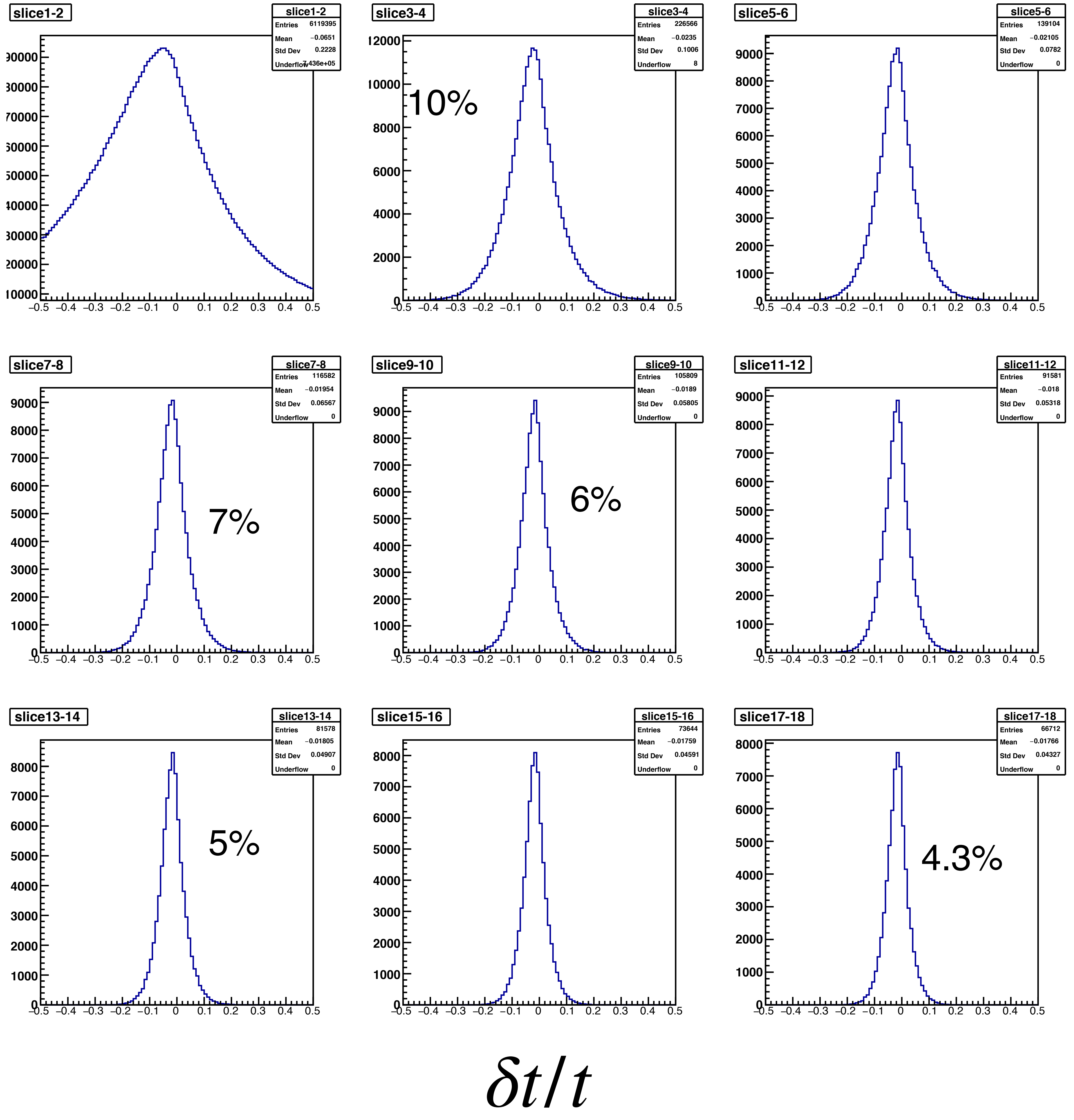
# Impact of Tracking Resolution on Method A

Start with: $\frac{\sigma_{p_T}}{p_T}(\%) = 0.05\ p_T \oplus 0.5$

1 < Q² < 10 GeV²

Handbook value for barrel region



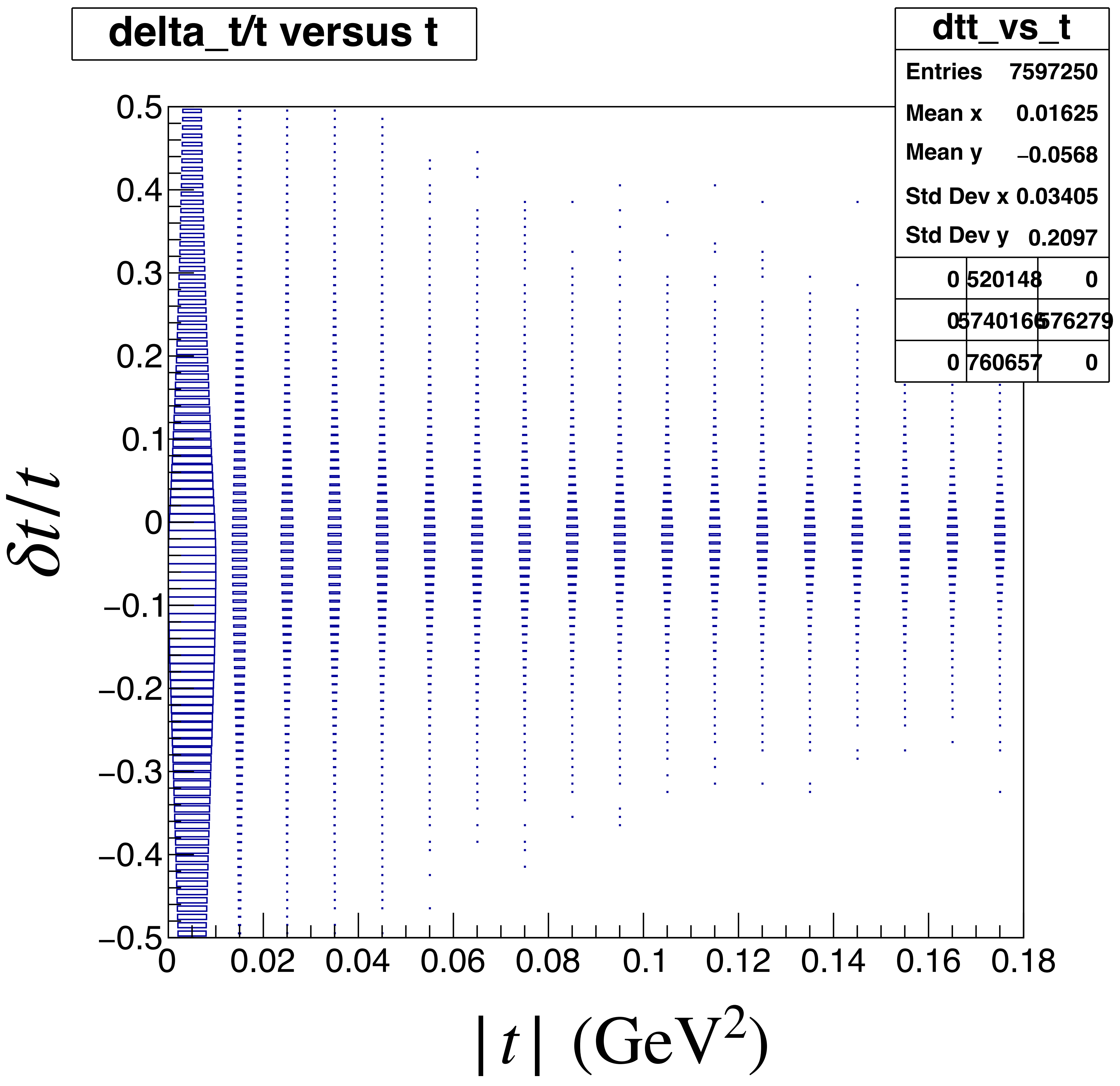



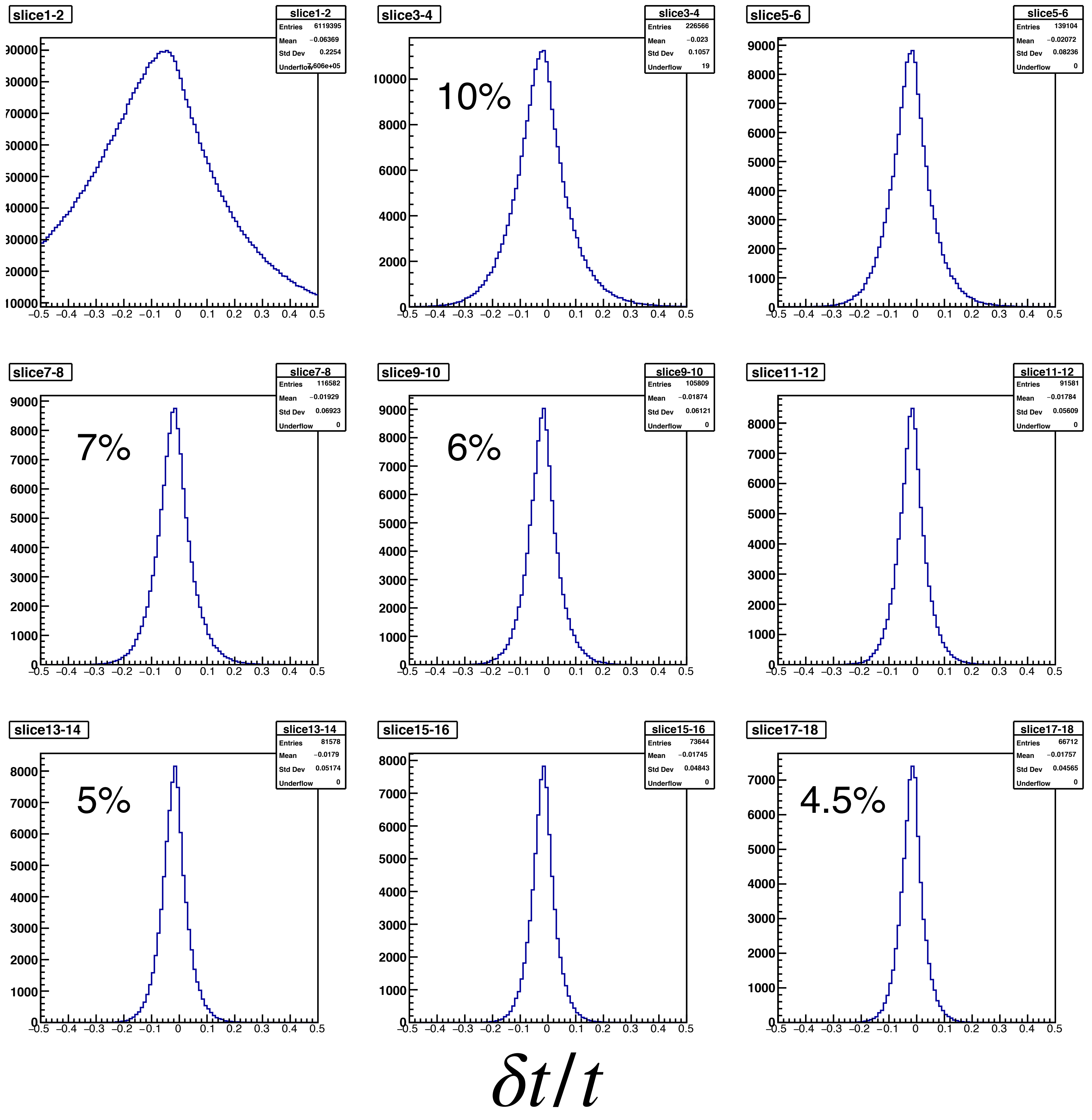
# Impact of Tracking Resolution on Method A

Start with: $\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.5$

$1 < Q^2 < 10$ GeV$^2$

Precision term seem not matter too much



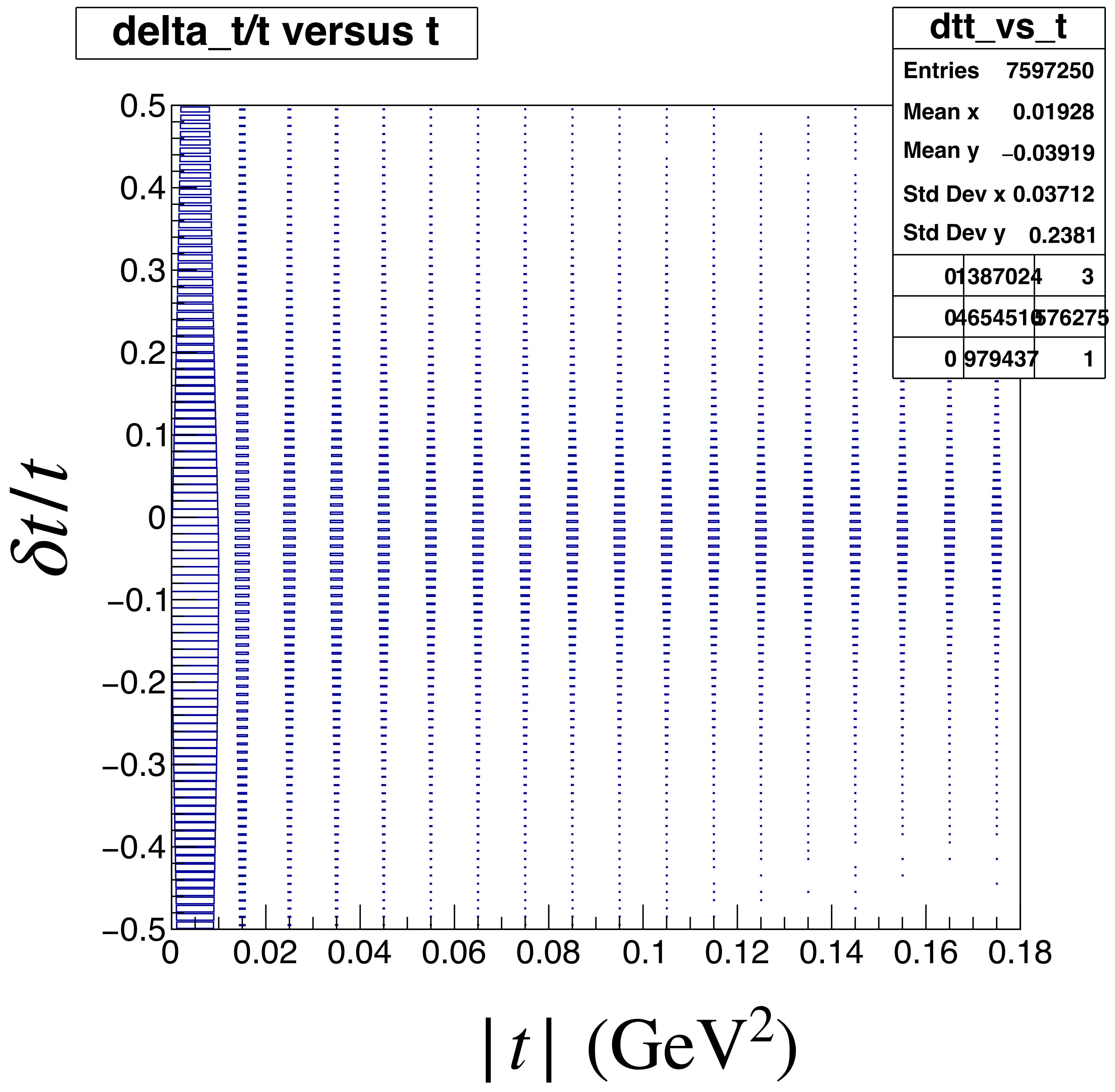



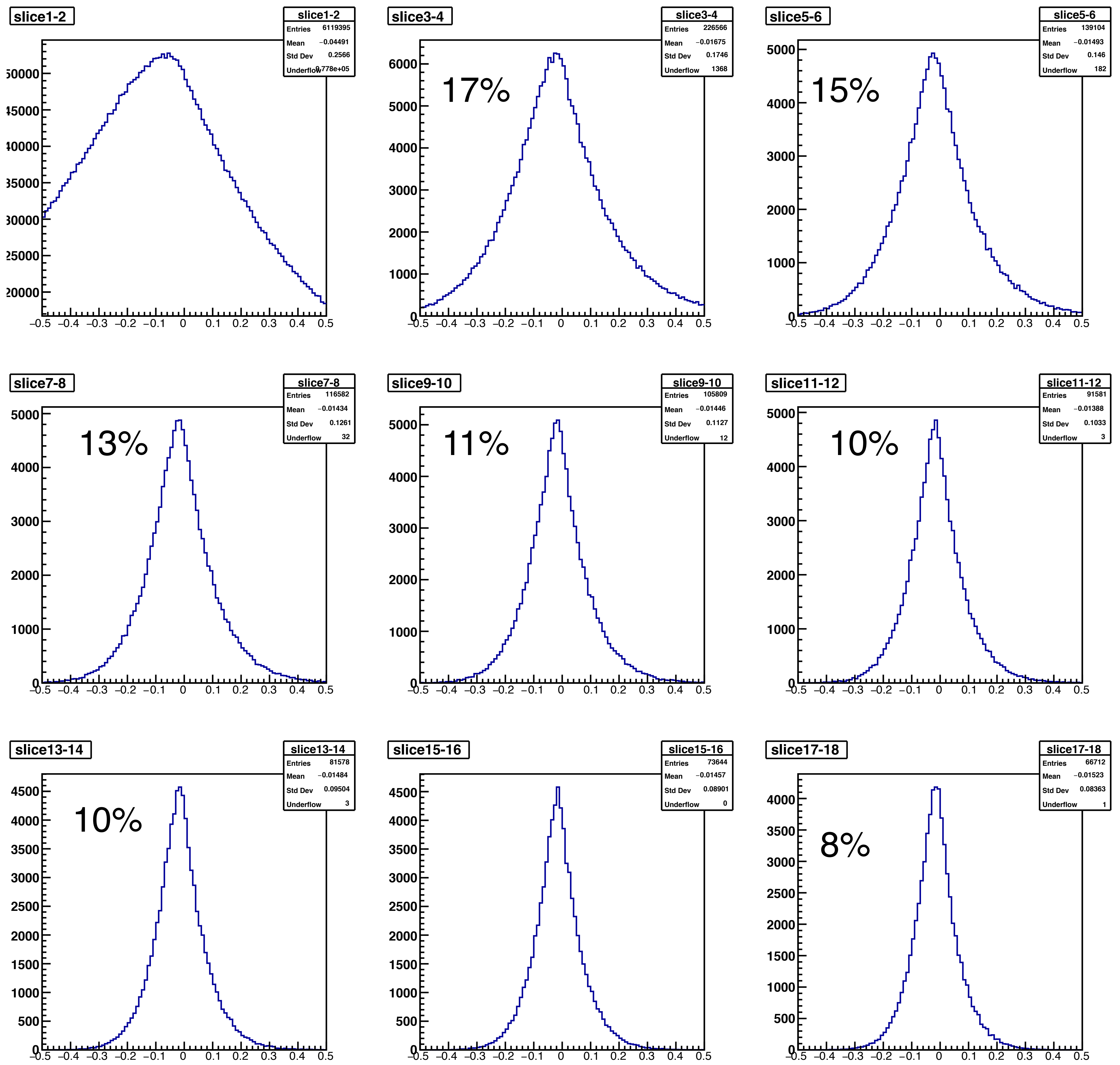
# Impact of Tracking Resolution on Method A

Start with: $\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 1.0$

$1 < Q^2 < 10$ GeV$^2$

MS term matters! dpt/ptl$_{MS}$ ~ dt/t

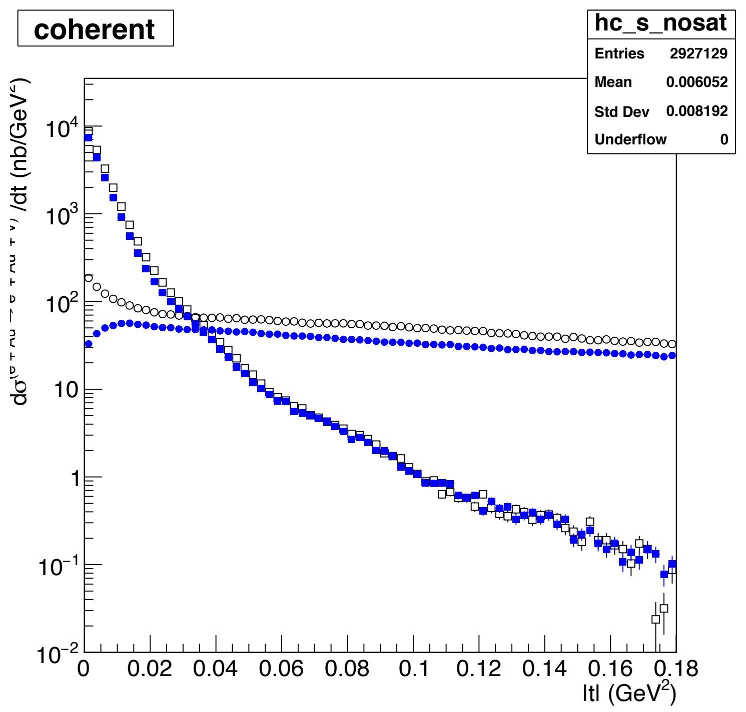


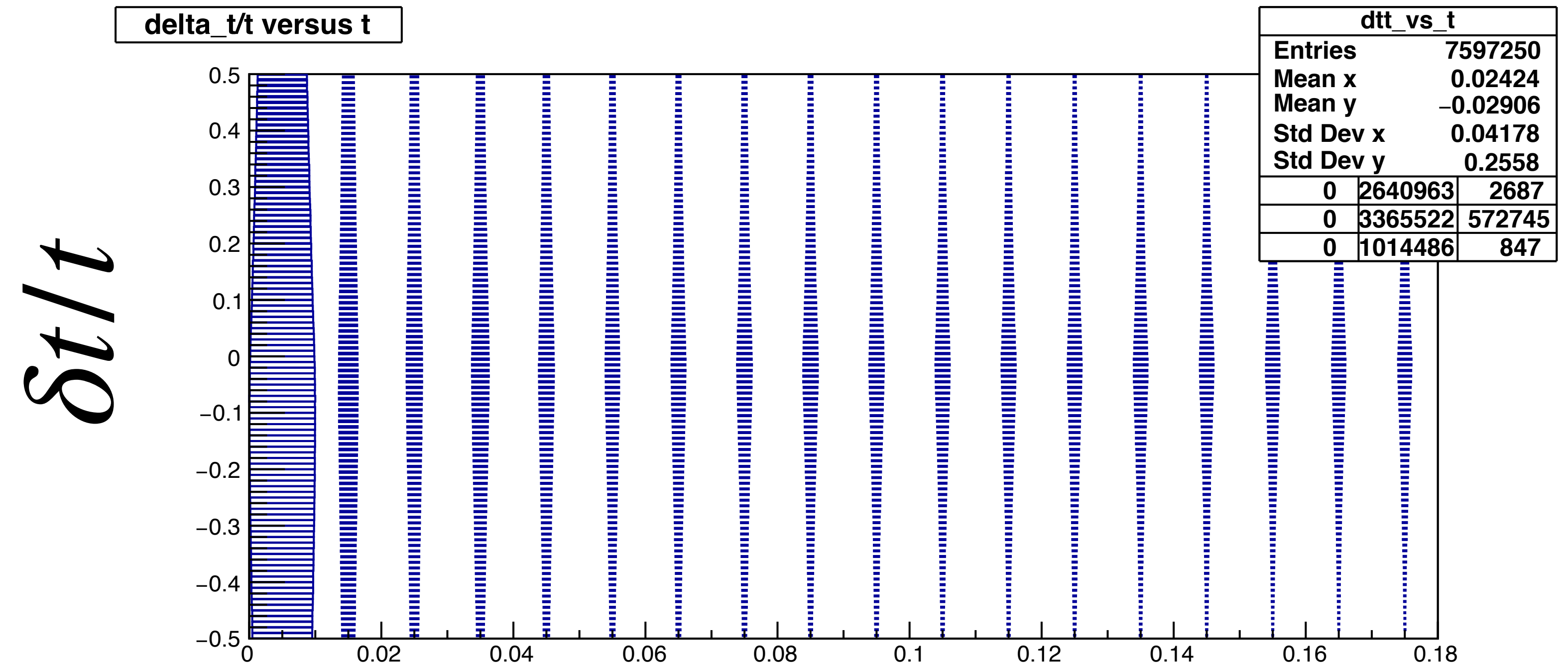



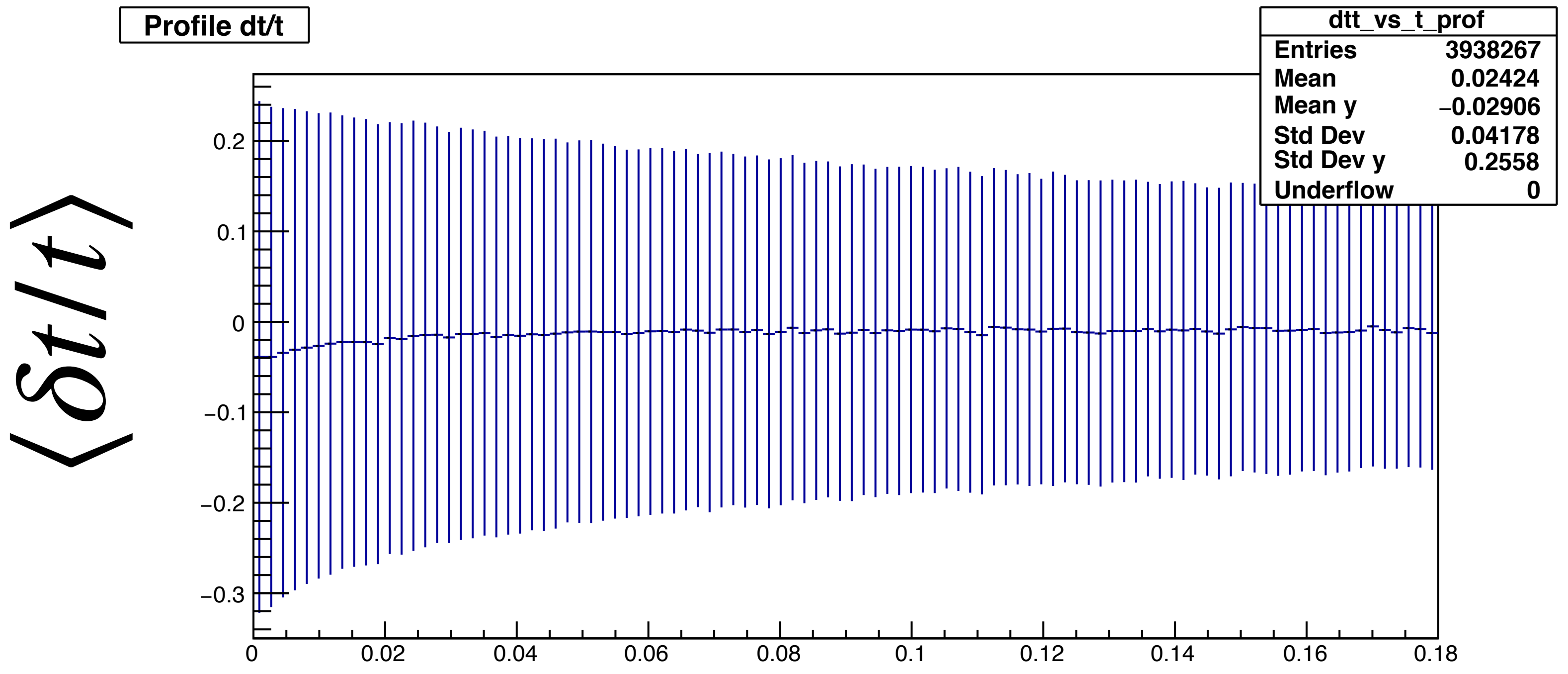
# Impact of Tracking Resolution on Method A

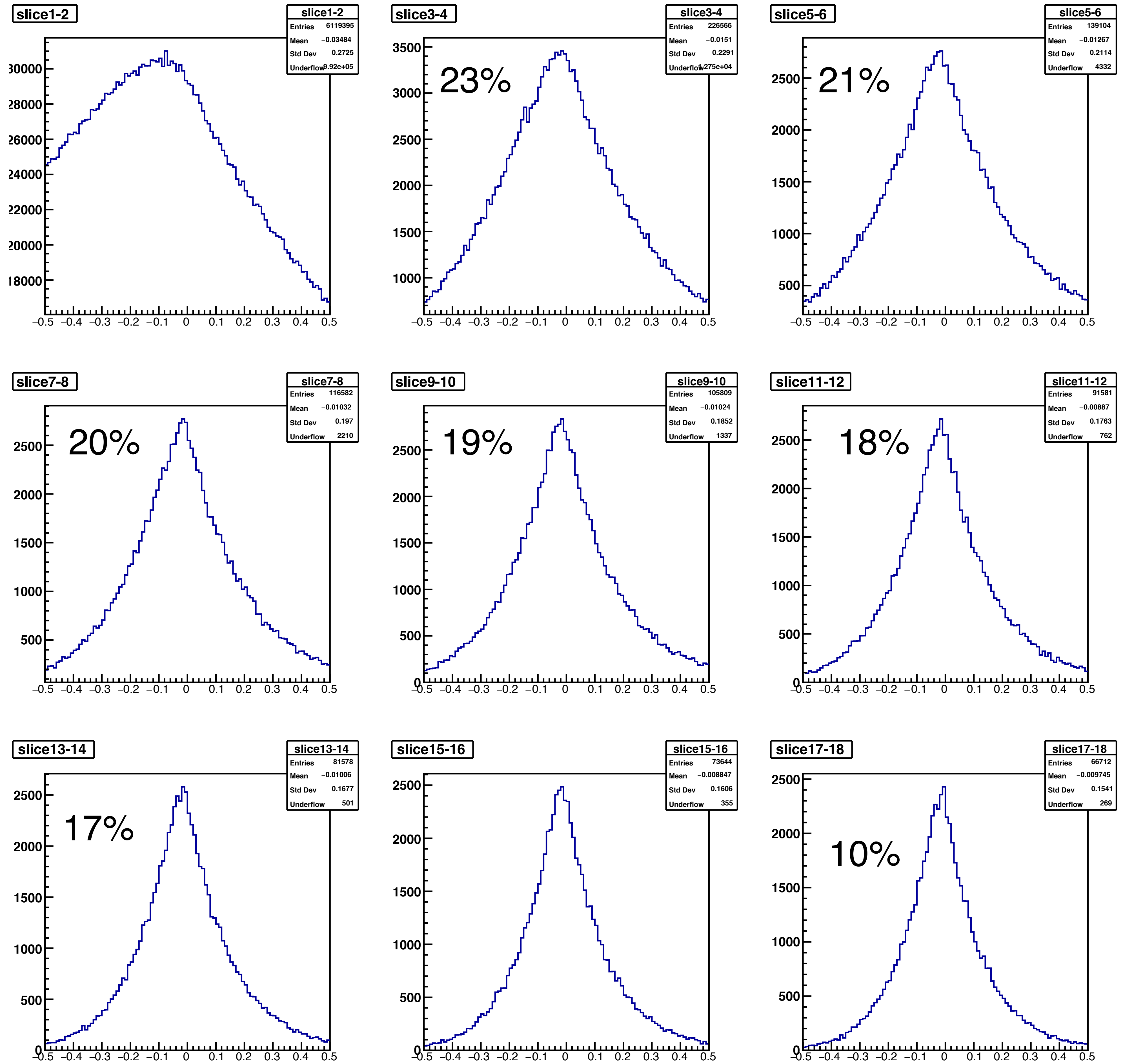
STAR TPC: $\frac{\sigma_{p_T}}{p_T}(\%) = 0.78\ p_T \oplus 1.37$

$1 < Q^2 < 10\ \mathrm{GeV}^2$



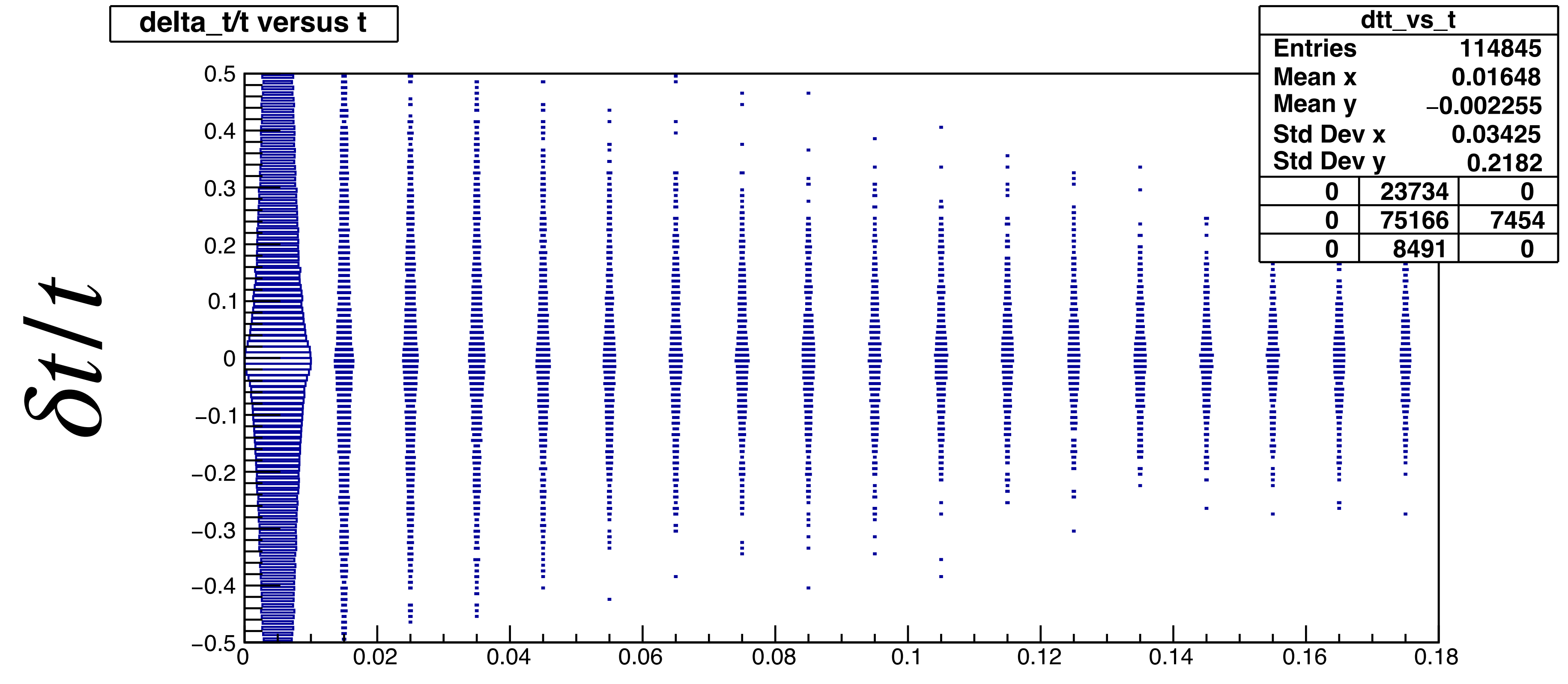

STAR TPC like resolution is NOT an option.
Minima gone!

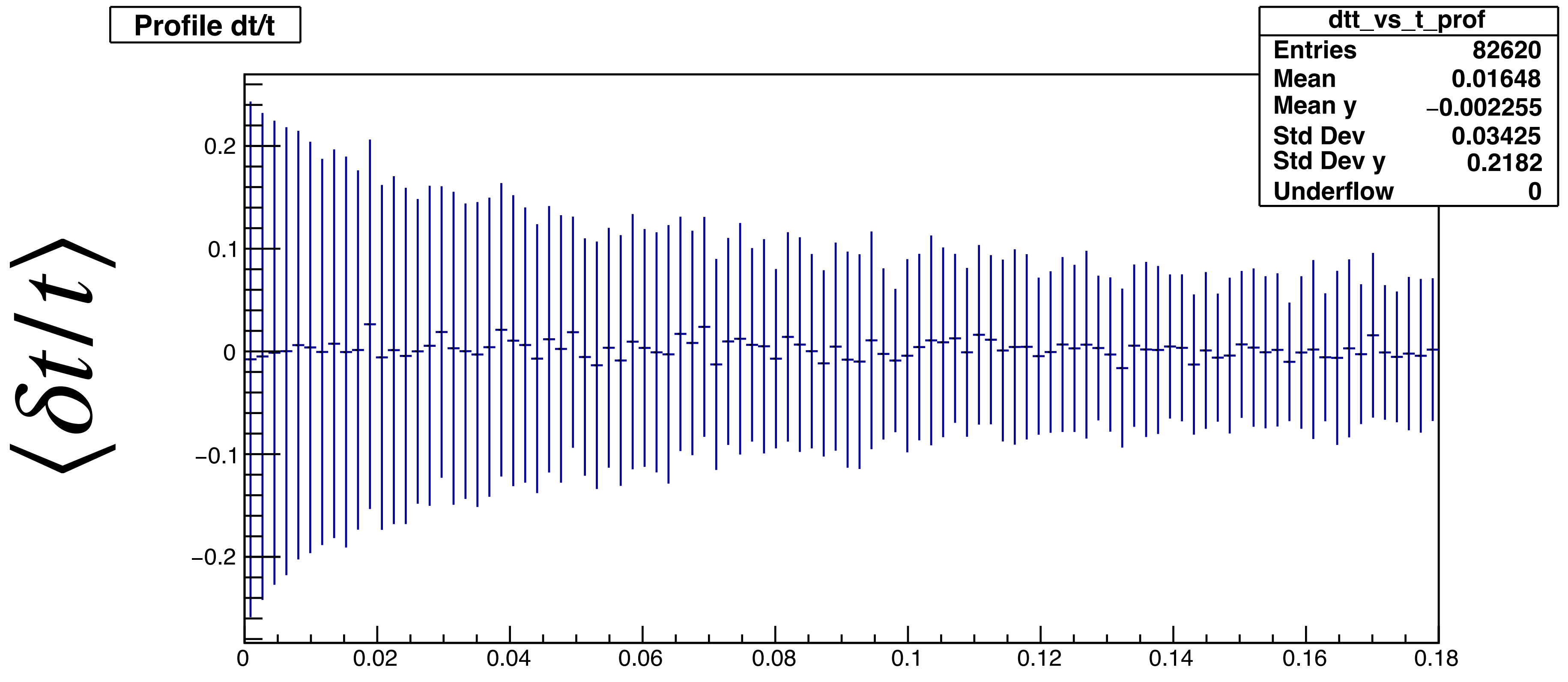
# Impact of Tracking Resolution on Method A

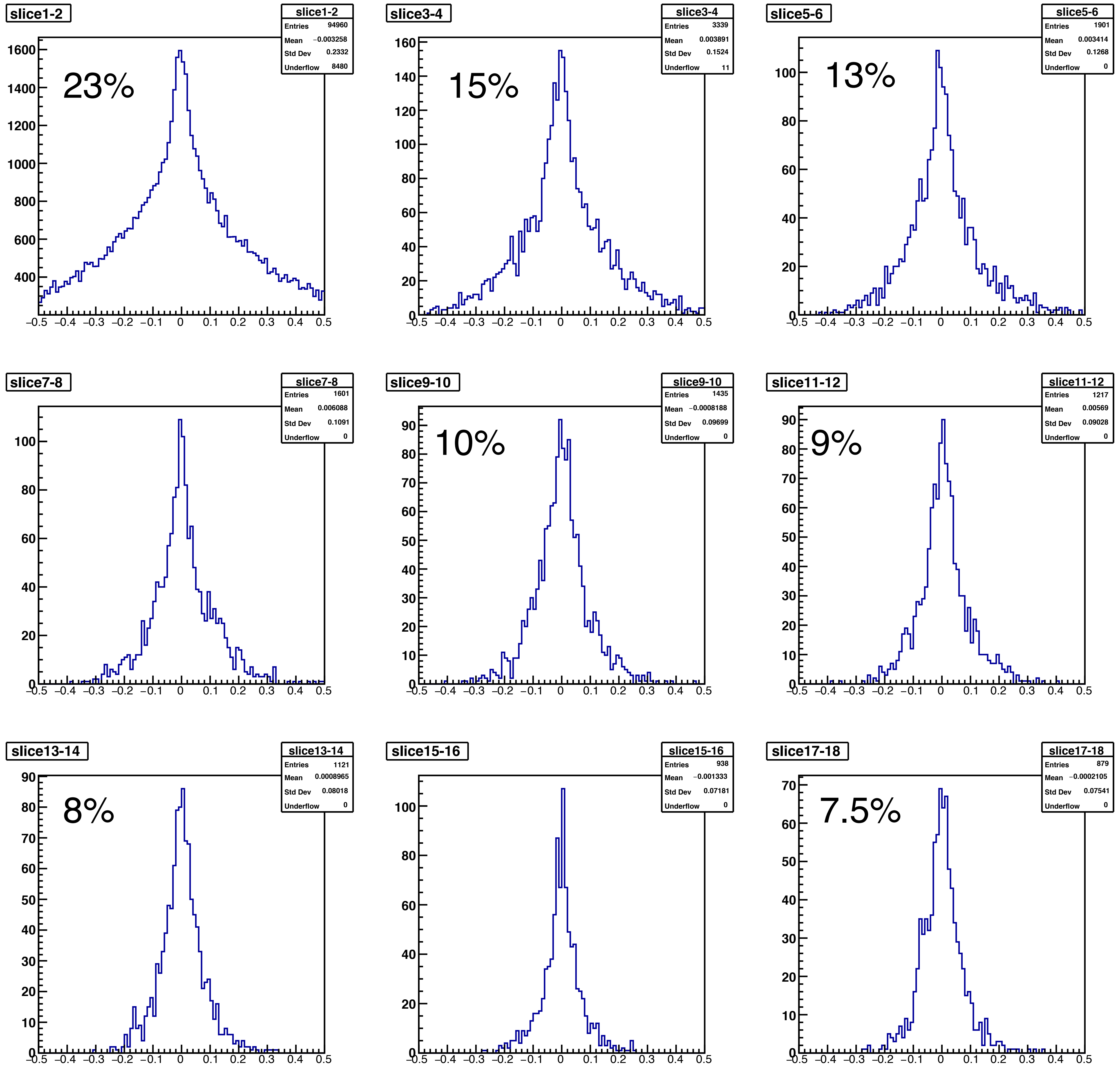
$$\frac{\sigma_{p_T}}{p_T}(\,\%\,) = 0.1\ p_T \oplus 1.0$$

$Q^2 < 0.01\ GeV^2$

Same ballpark as large $Q^2$



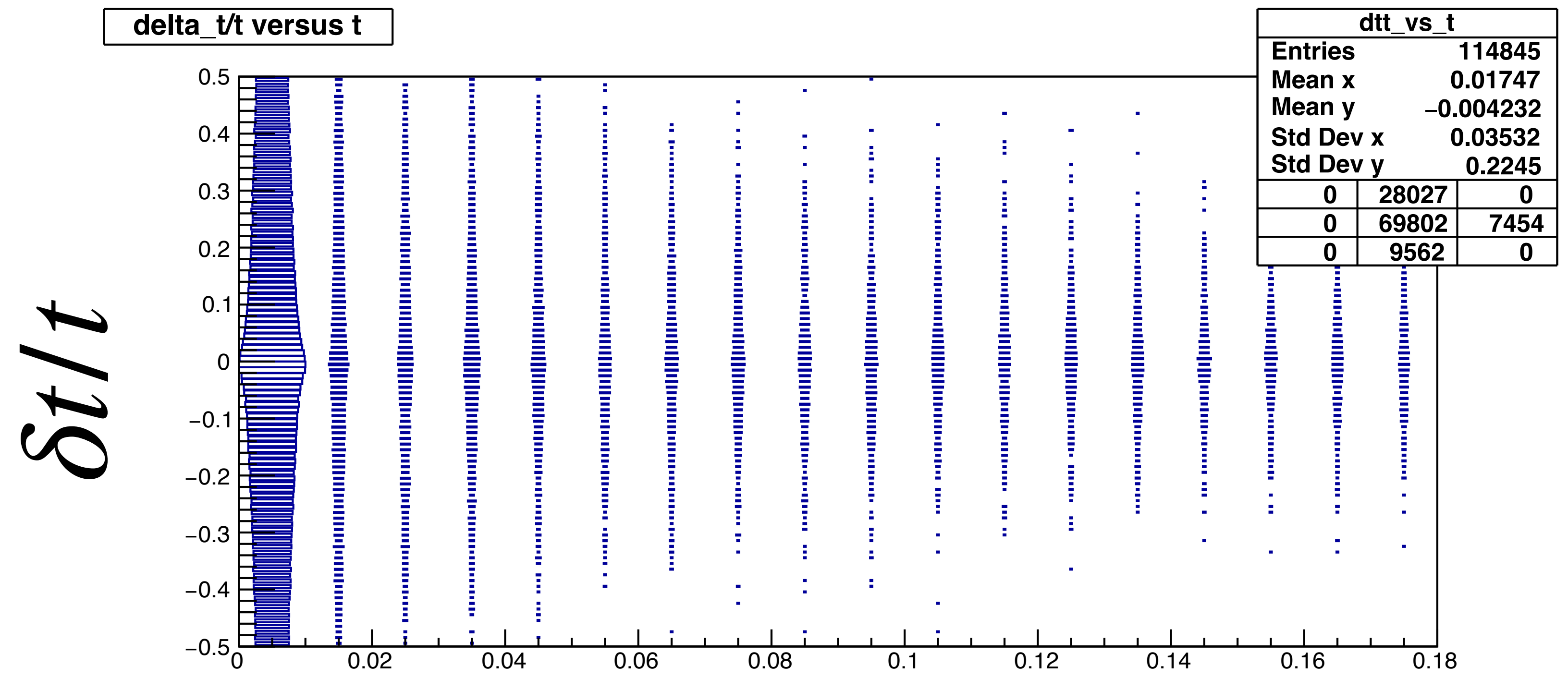



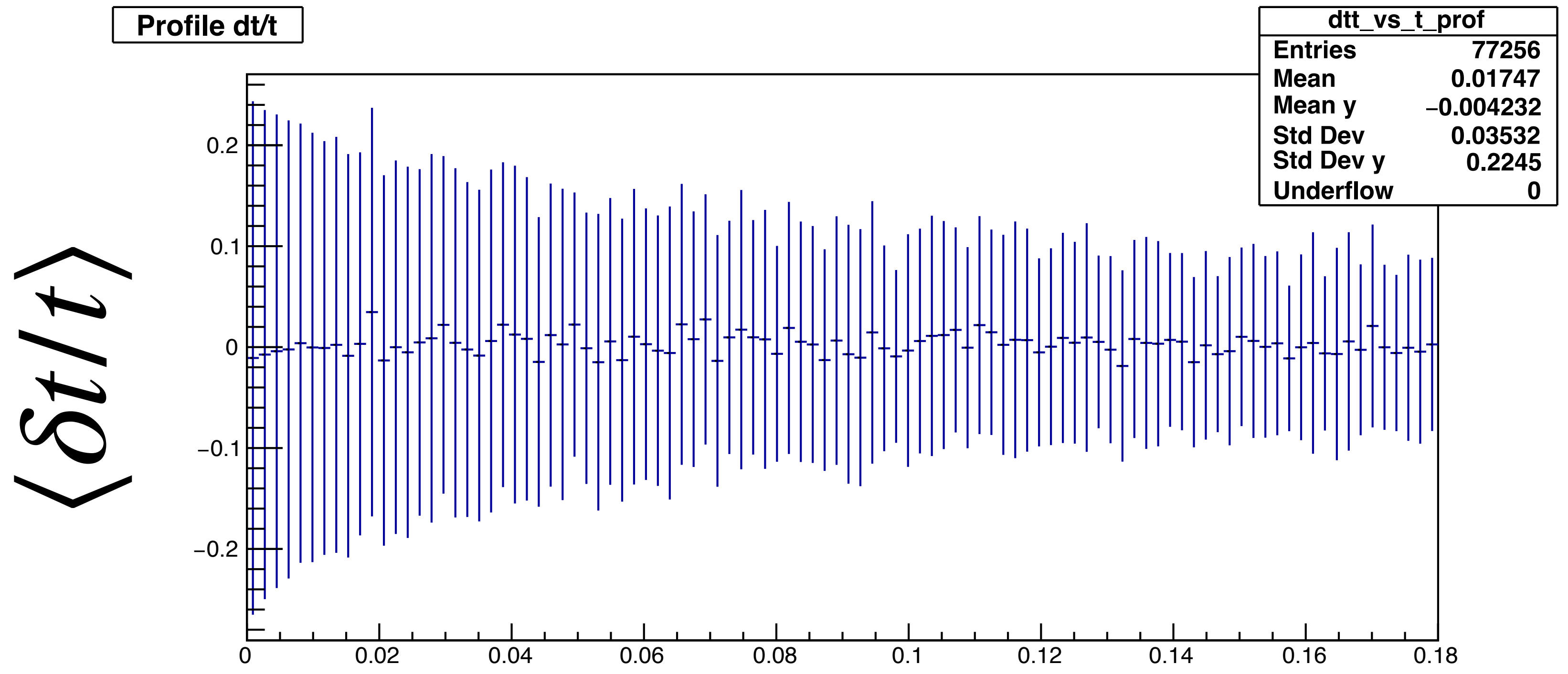
# Impact of Tracking Resolution on Method A

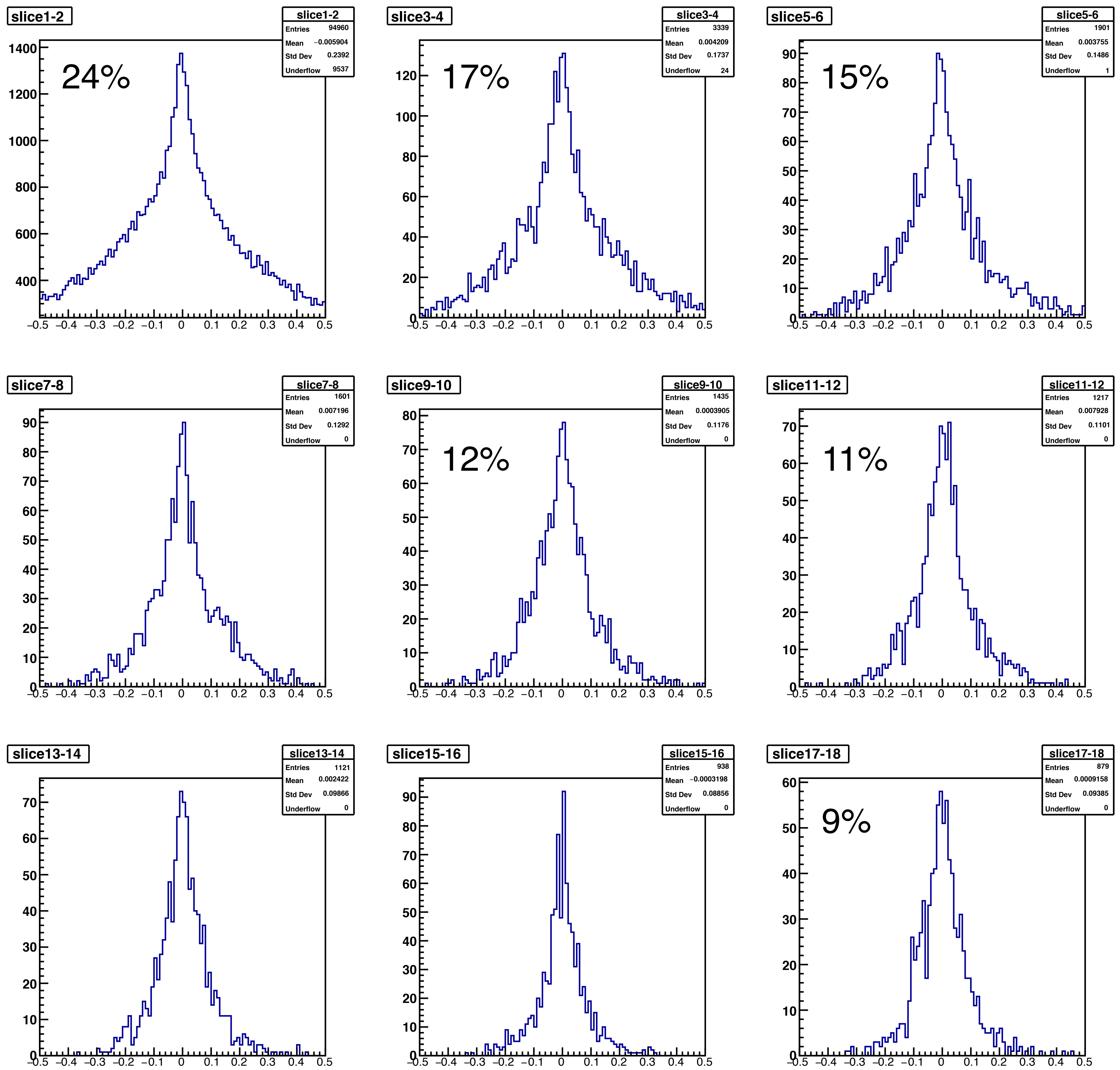
$$\frac{\sigma_{p_T}}{p_T}(\%) = 0.5\ p_T \oplus 1.0$$

Again weak impact of precisions term

$Q^2 < 0.01\ \mathrm{GeV}^2$



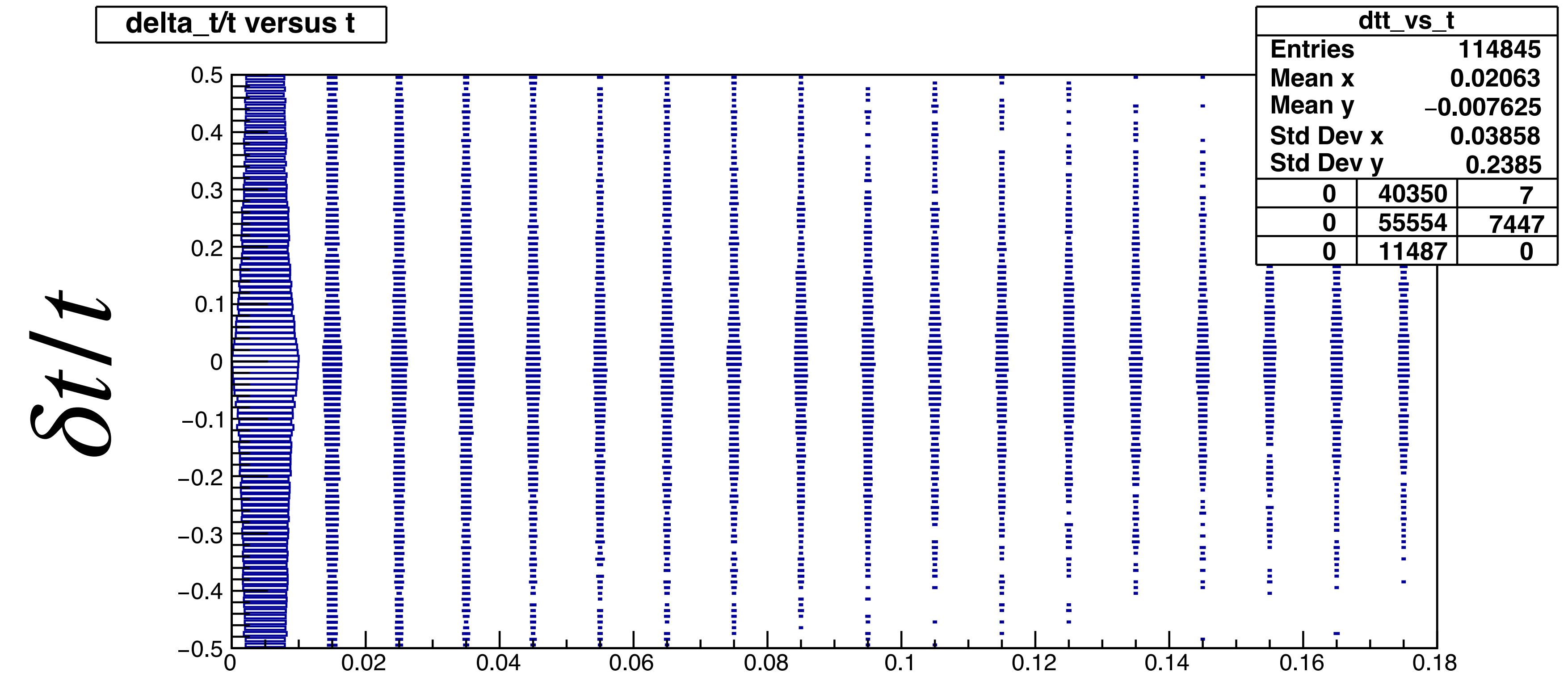



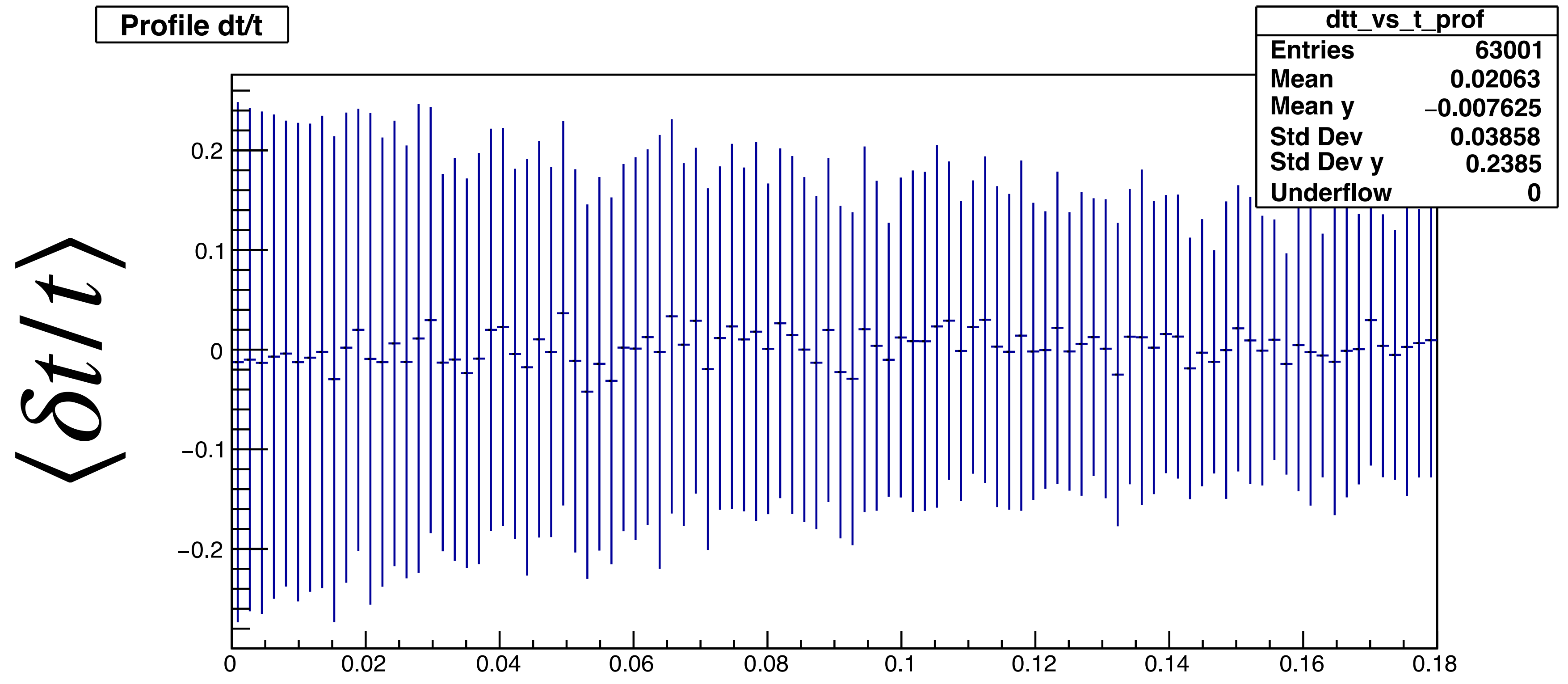
# Impact of Tracking Resolution on Method A

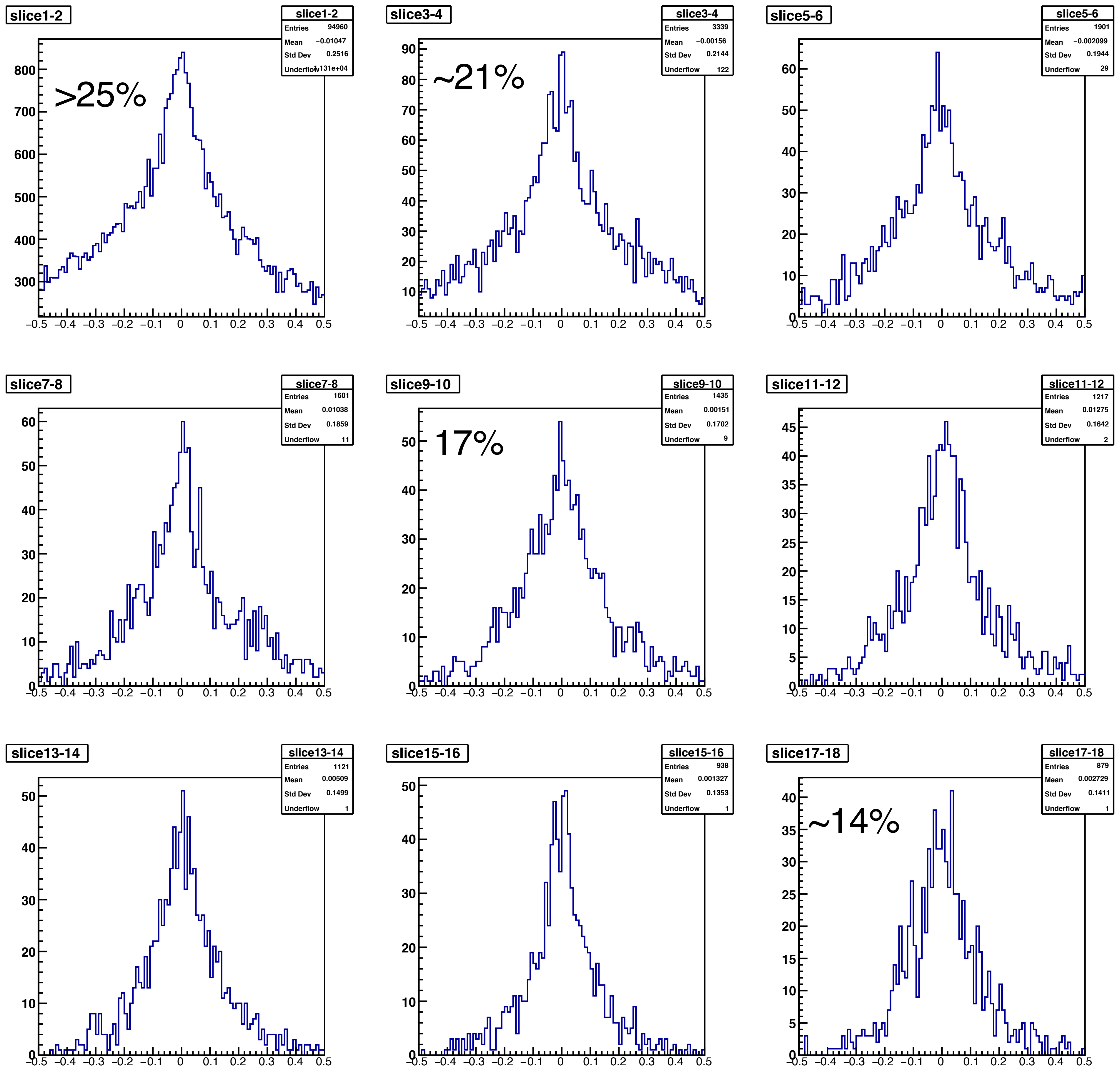
$$\frac{\sigma_{p_T}}{p_T}(\,\%\,) = 0.1\ p_T \oplus 2.0$$

MS term will be key

$Q^2 < 0.01\ \mathrm{GeV}^2$

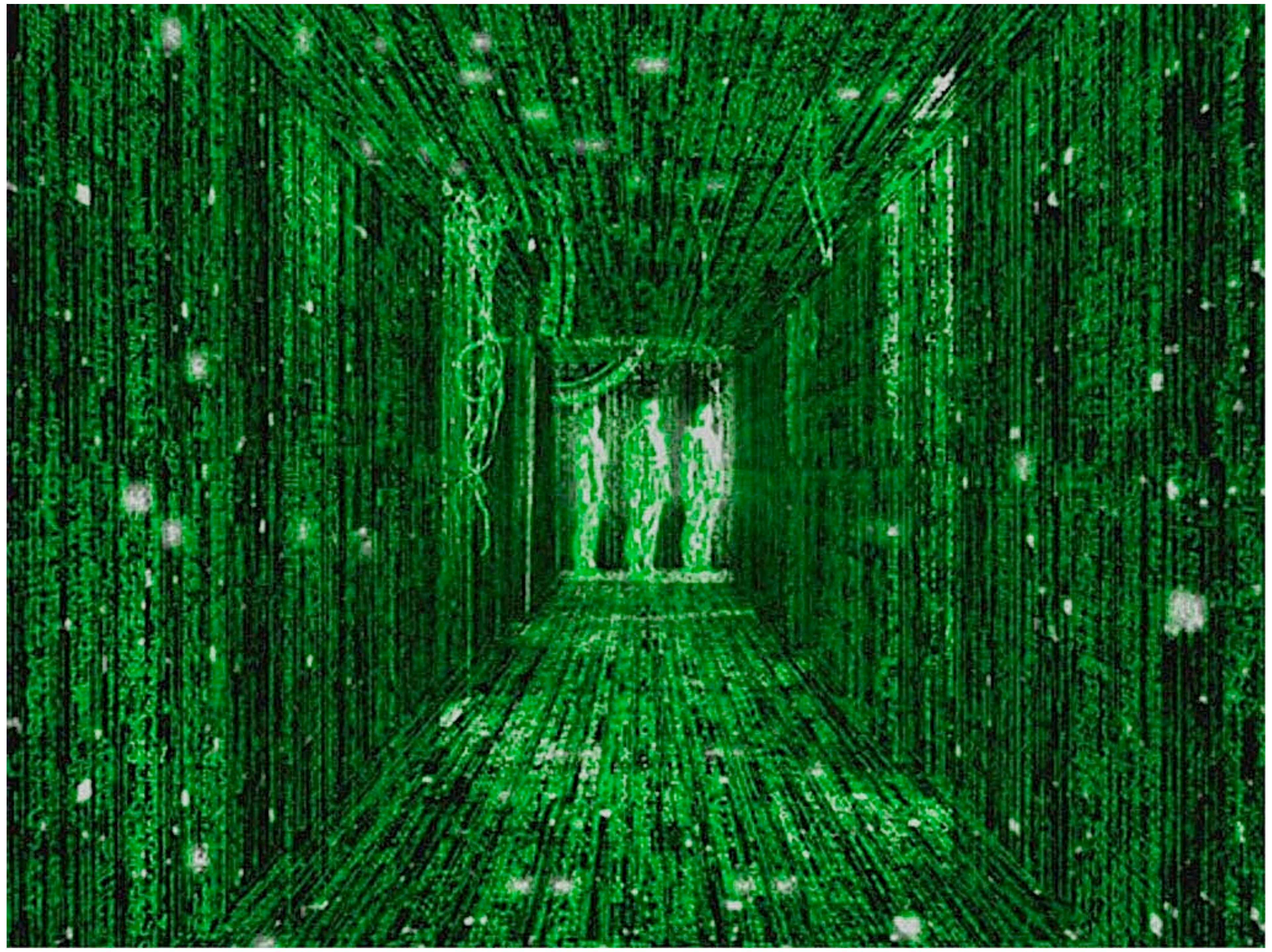


# The Raison d'etre for $d\sigma/dt$

- Finding the Source
  - Sartre used Wood-Saxon as input distribution
  - Basic Idea: Comparison of extracted WS with input WS is key to establishing when *t* resolution is not good enough
  - W/o that there's no point in measuring $d\sigma/dt$ at all
  - Note that with it all nDVCS studies disappear as well
  - VM production still useful for many saturation studies but there one can look at t integrated variables (e.g. $Q^2$, Mx, …)



# Getting Source Distribution from dσ/dt

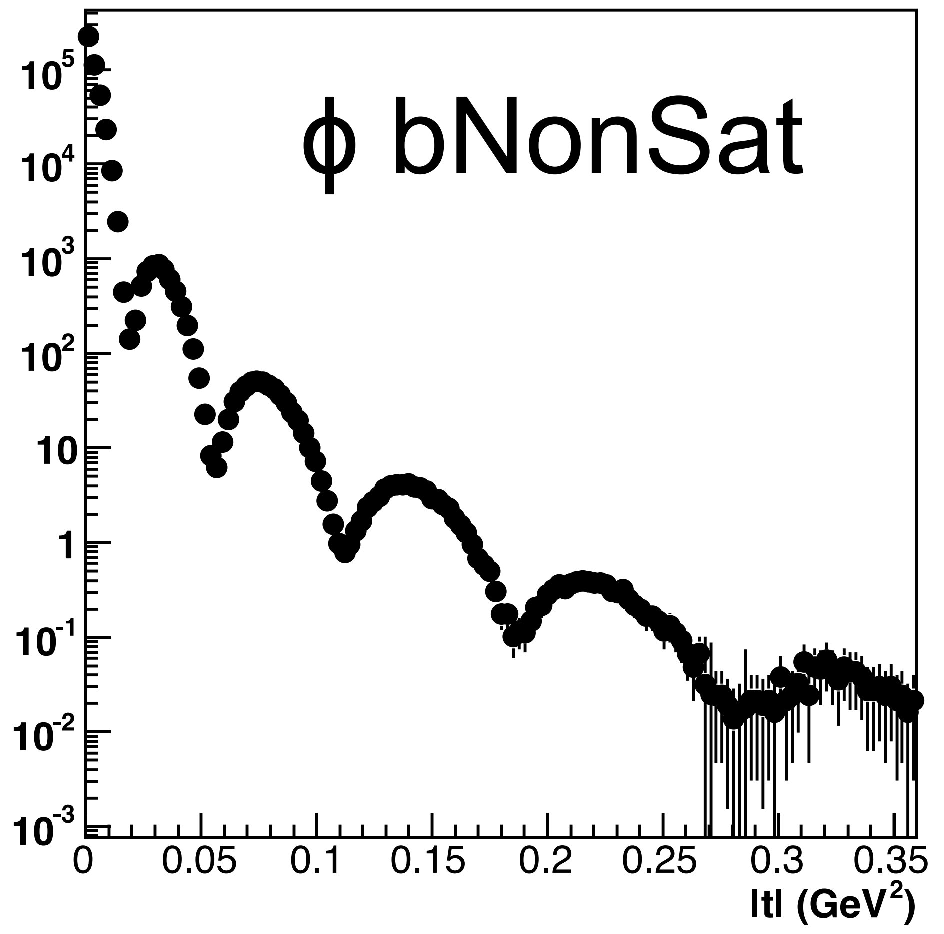
- Worked out in collaboration with Markus Diehl (INT '10):

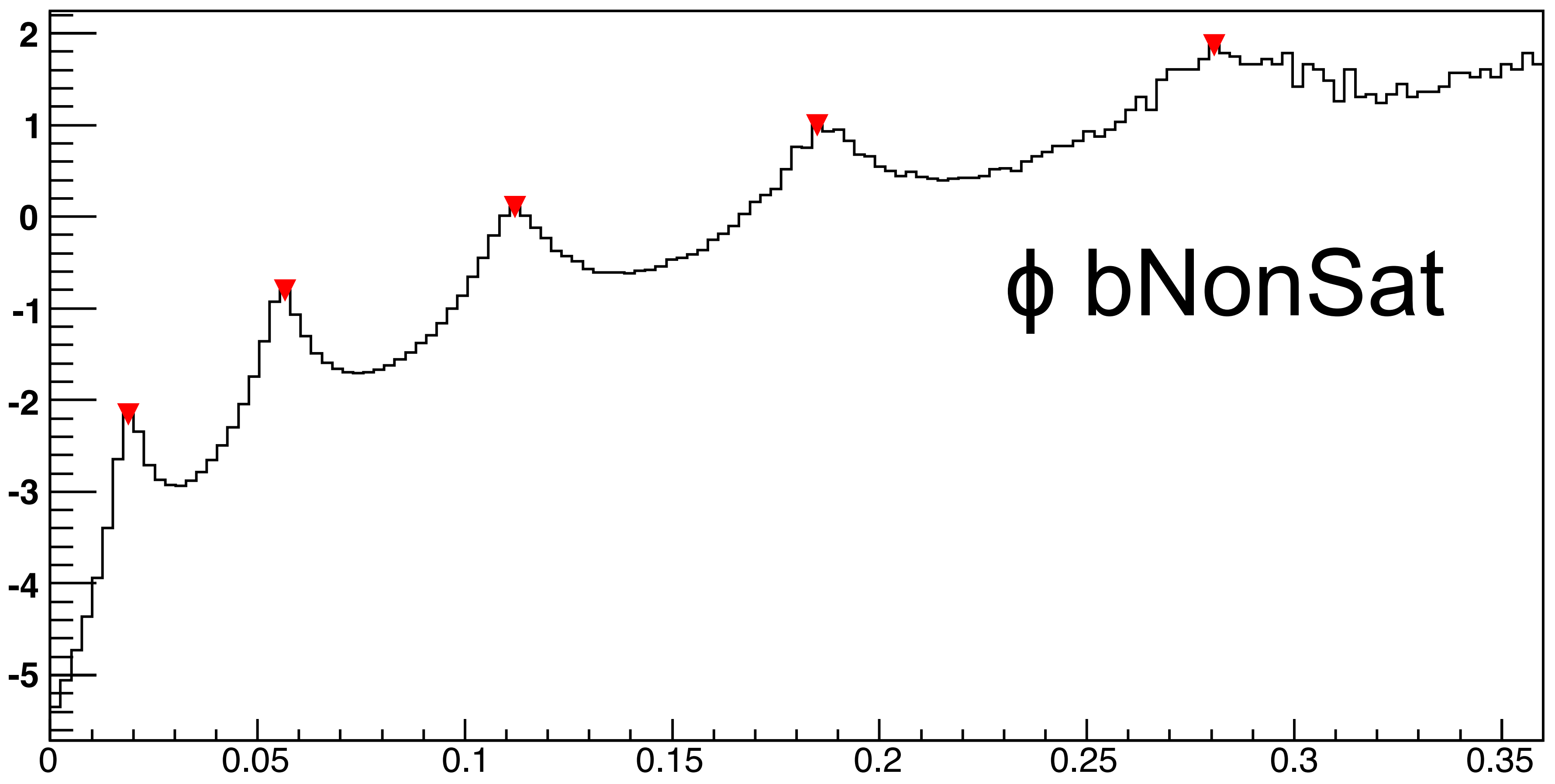
$$F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

http://www.int.washington.edu/talks/WorkShops/int_10_3/People/Diehl_M/Diehl1.pdf

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)

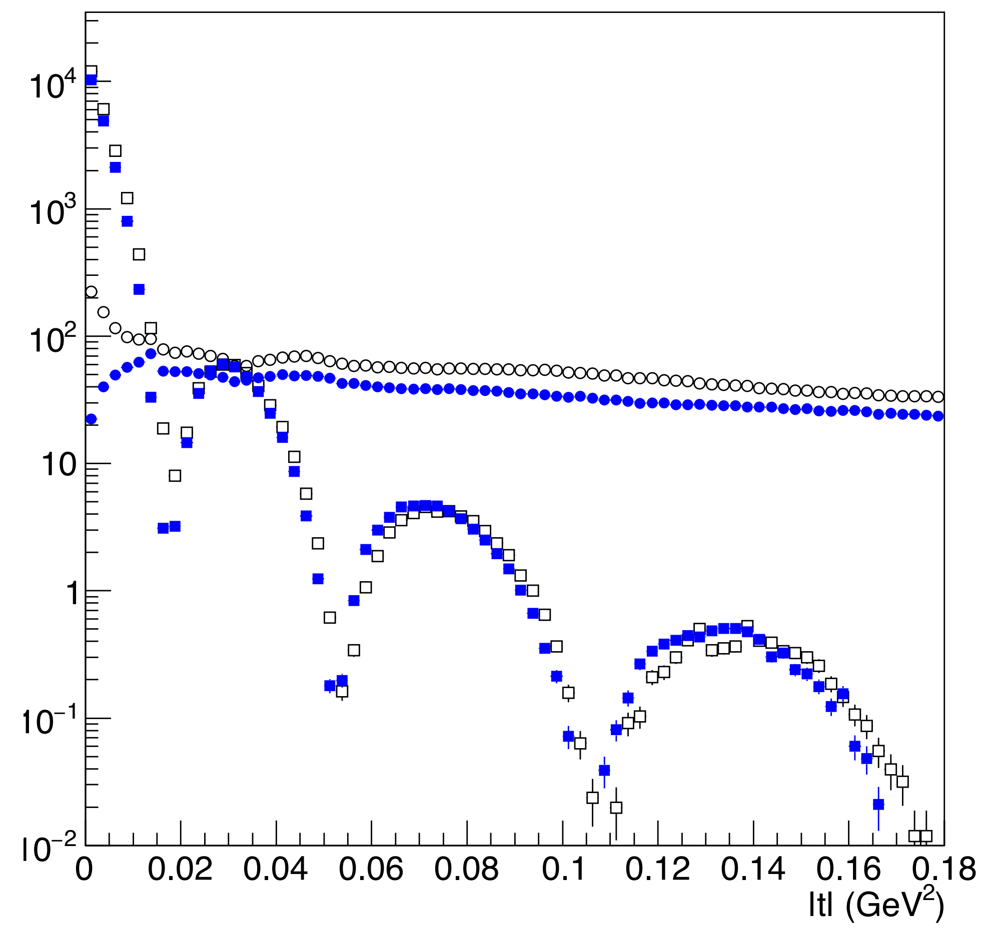
- Reach in e+A
  - So far dσ/dt for $t<0.18$ GeV$^2$ - sufficient for good result/extraction
  - Note that above 0.18 GeV$^2$ the incoherent background becomes enormously large
- Issues:
  - For integration: Sign flip in $J_0(\Delta b)$ - need precise position of minima (peaks)



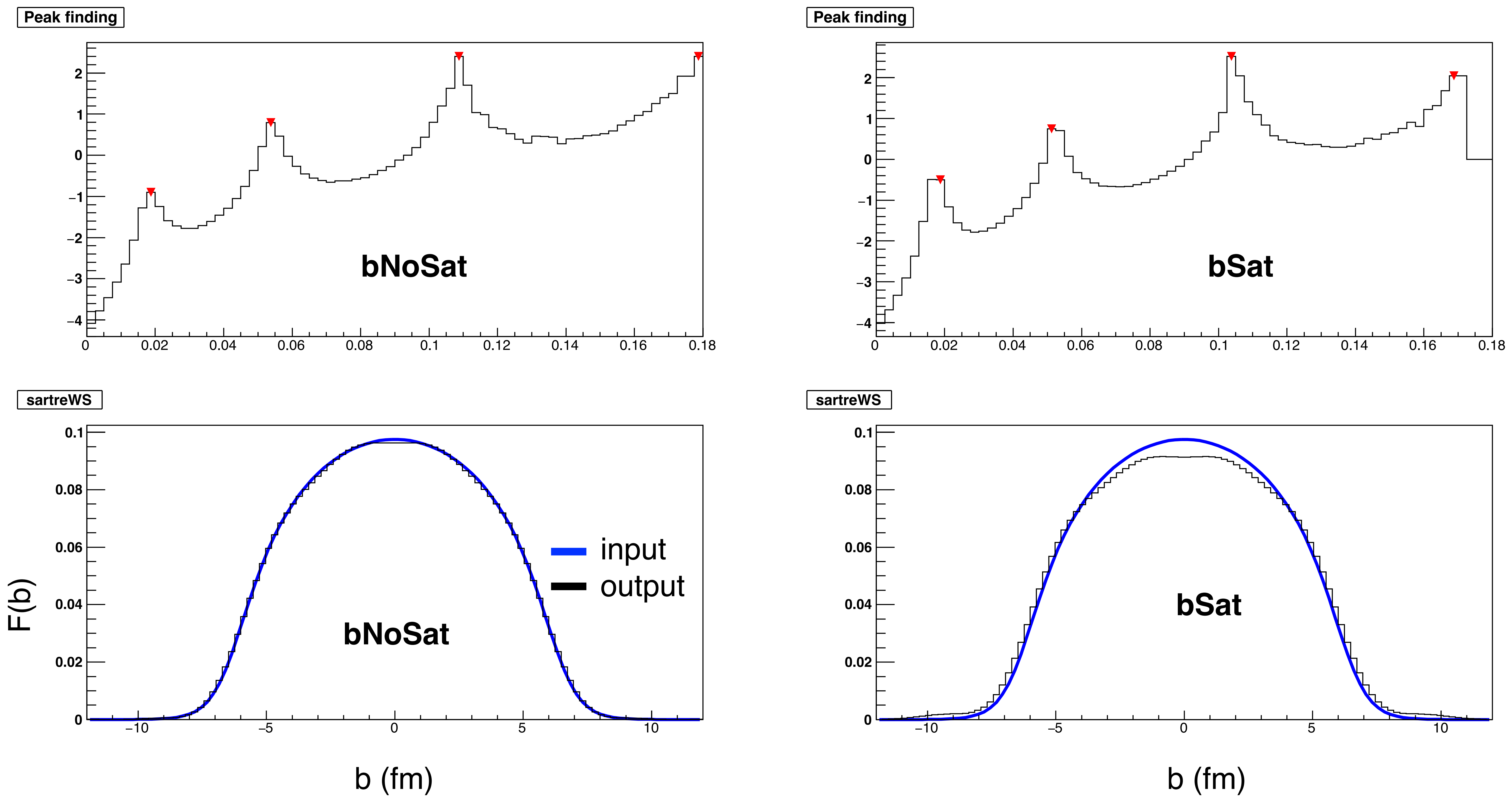



# Method A: $F(b)$ without any smearing

- bSat: method A seem good enough
- bNonSat: as usual slight indication of saturation around b ~0
- Use bSat only from now on




1 < Q$^2$ < 10 GeV$^2$



# What matters for $\delta t/t$

- $Q^2 < 0.01$ GeV$^2$

$$\frac{\delta t}{t} \approx \frac{\delta p_T^{e^-}}{p_T^{e^-}} \oplus \frac{\delta p_T^{e^+}}{p_T^{e^+}}$$

$$-3.5 < \eta < -1.5$$

- $1 < Q^2 < 10$ GeV$^2$

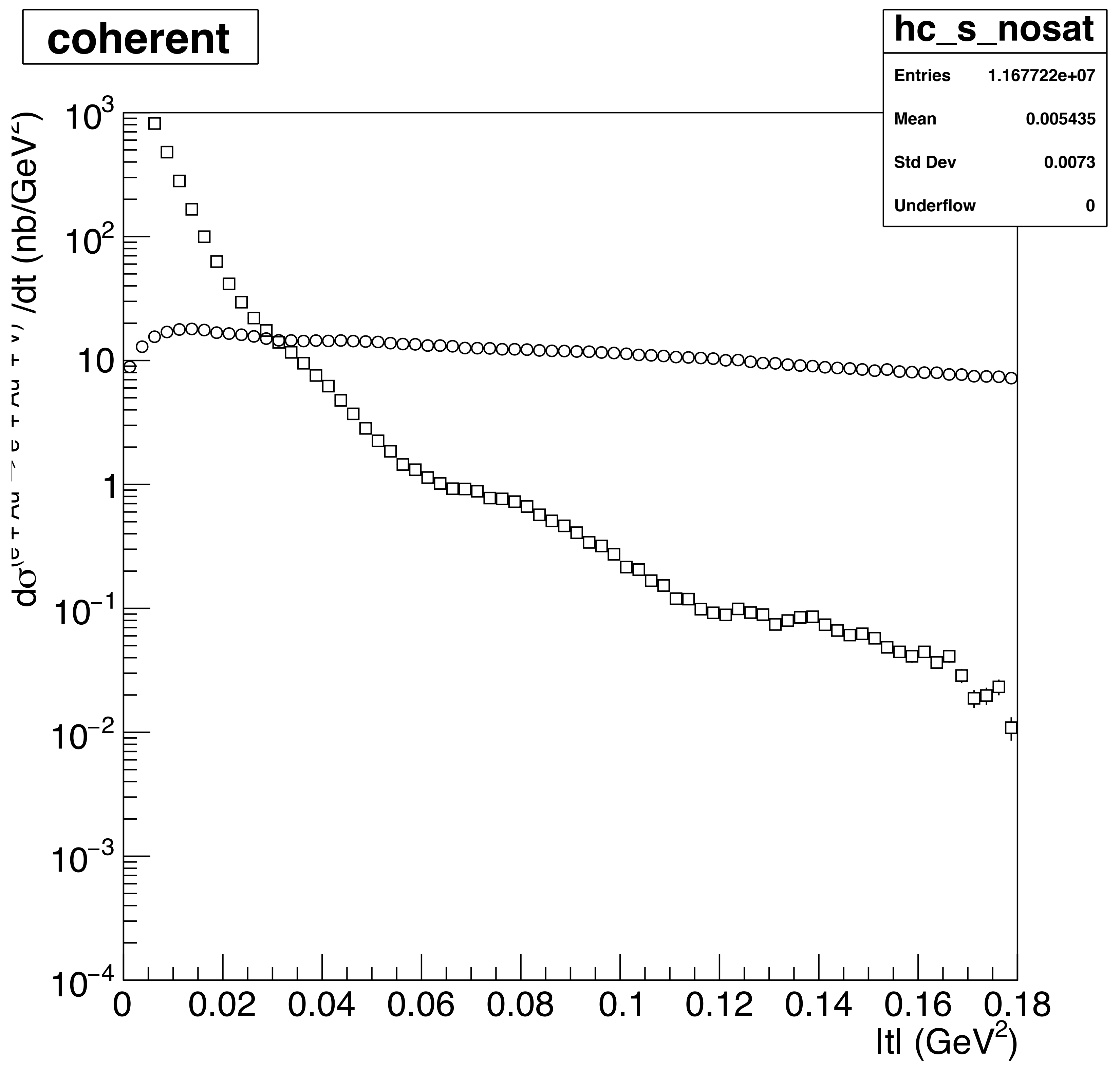
$$\frac{\delta t}{t} \approx \frac{\delta p_T^{e^-}}{p_T^{e^-}} \oplus \frac{\delta p_T^{e^-}}{p_T^{e^-}} \oplus \frac{\delta p_T^{e^+}}{p_T^{e^+}}$$

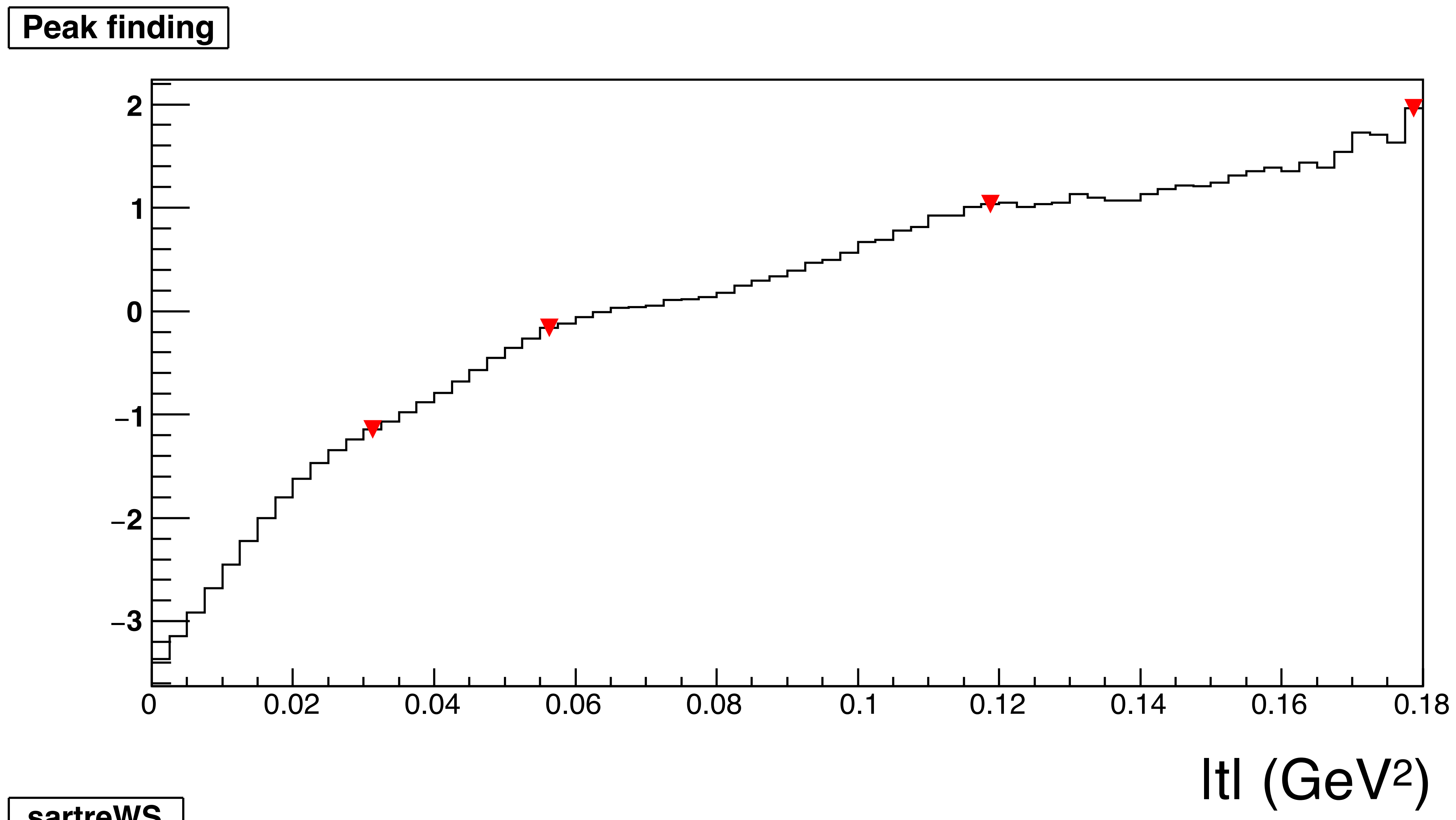
$$-3.5 < \eta < -2 \qquad |\eta| < 1.5$$

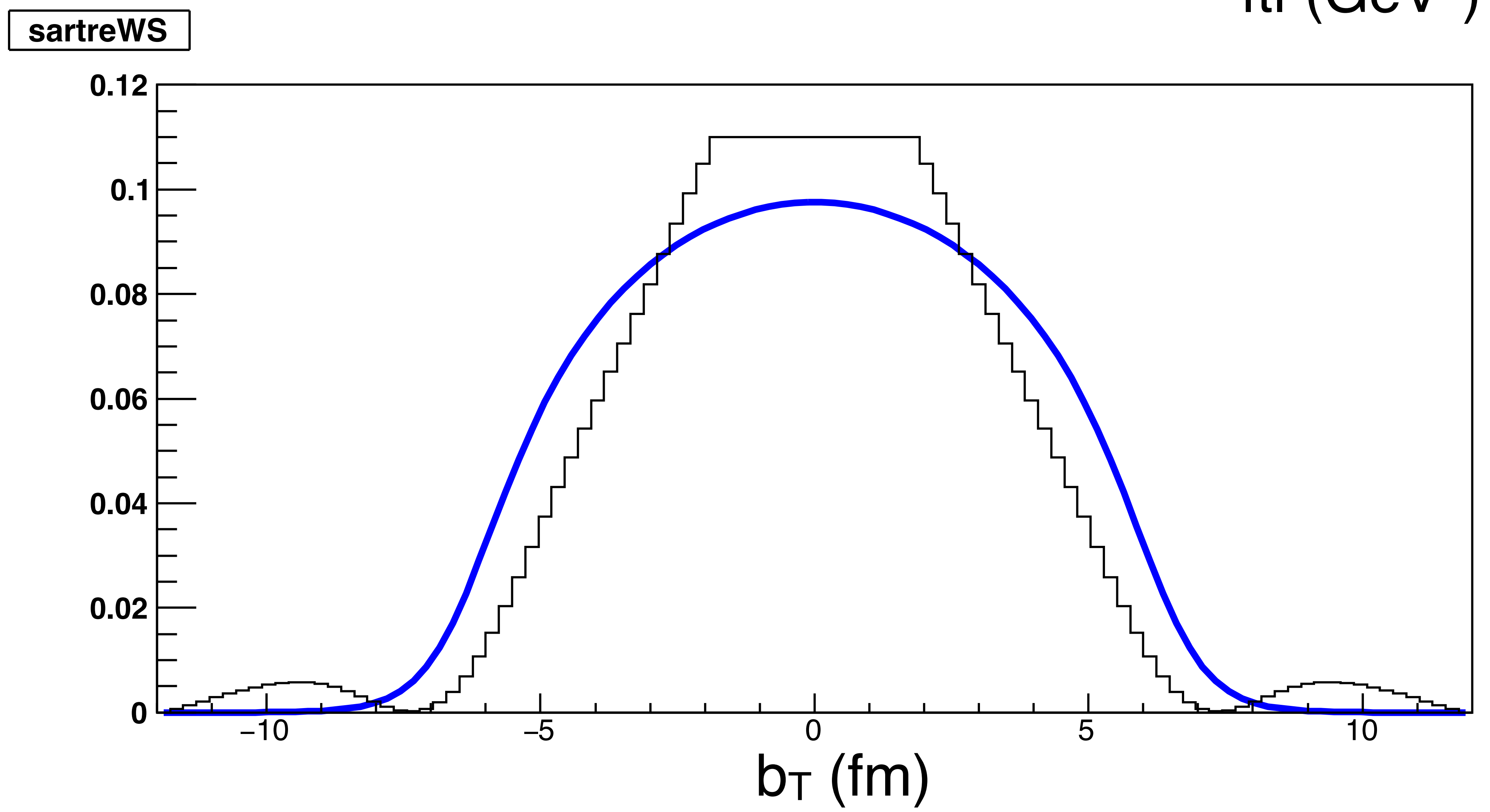
# Method A: Photoproduction $Q^2 < 0.01$ GeV$^2$

$$\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 2.0$$

Handbook value for -3.5 < $\eta$ < -2.5



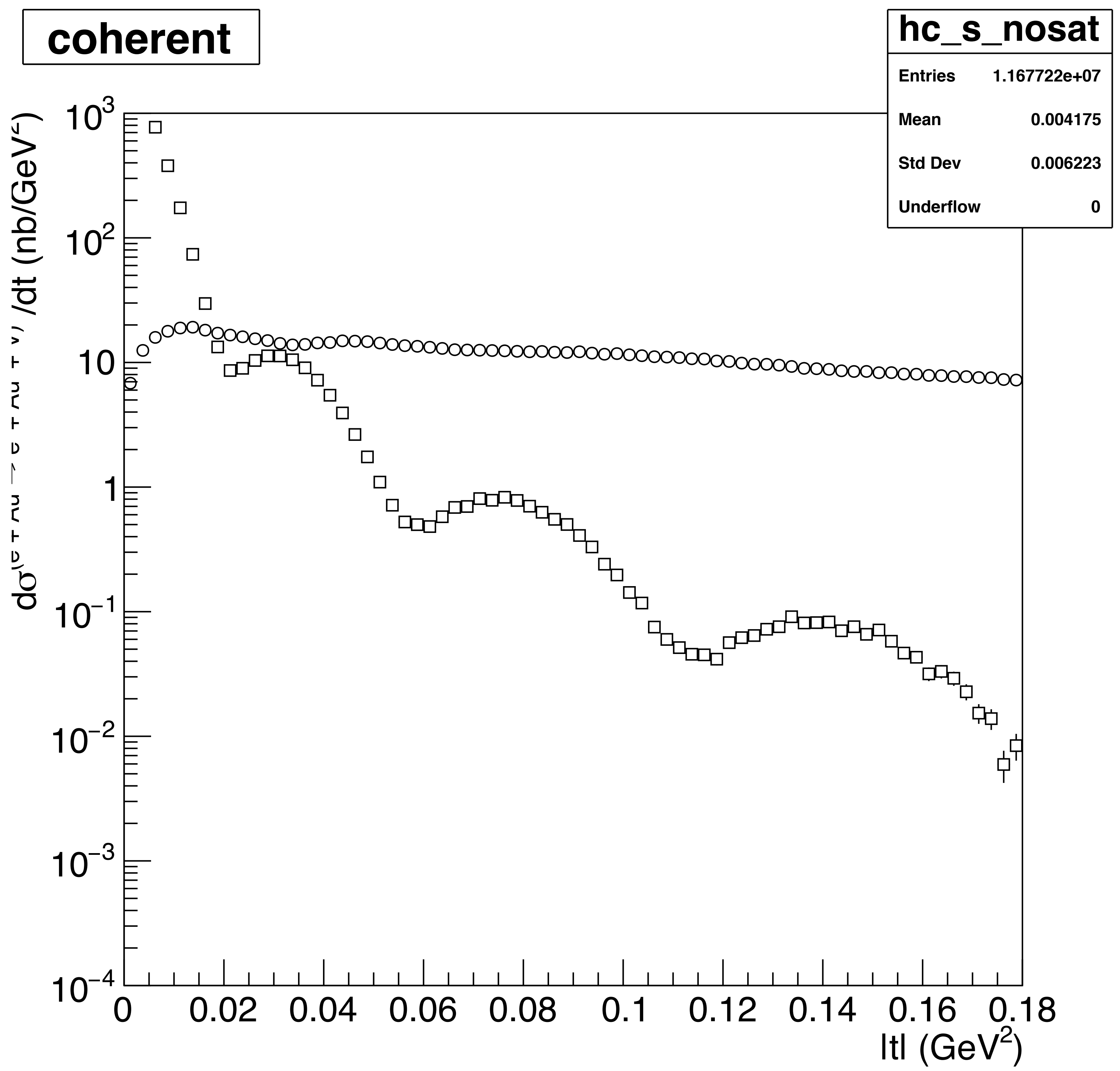




**Verdict: Not working**

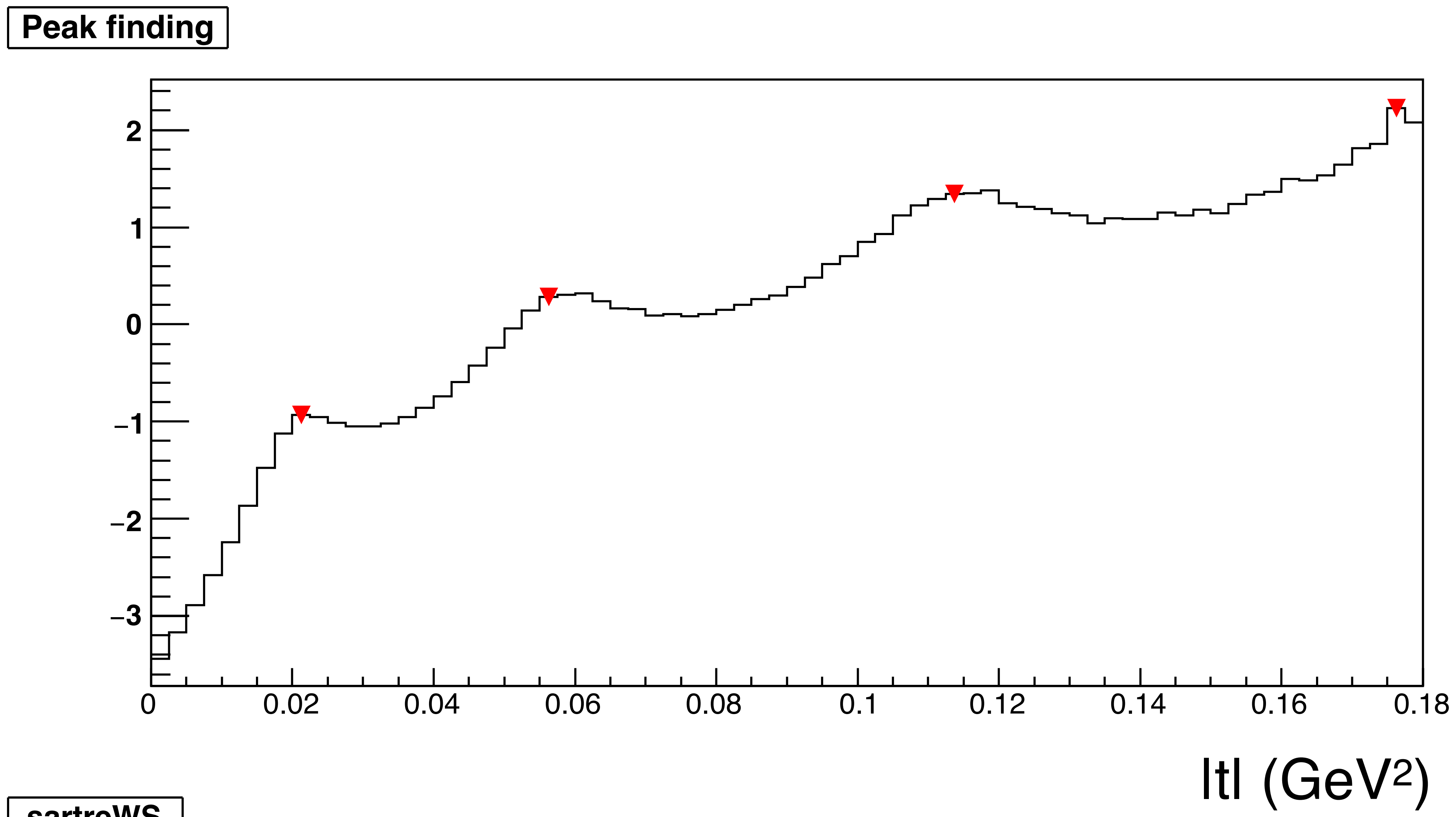
# Method A: Photoproduction $Q^2 < 0.01$ GeV$^2$

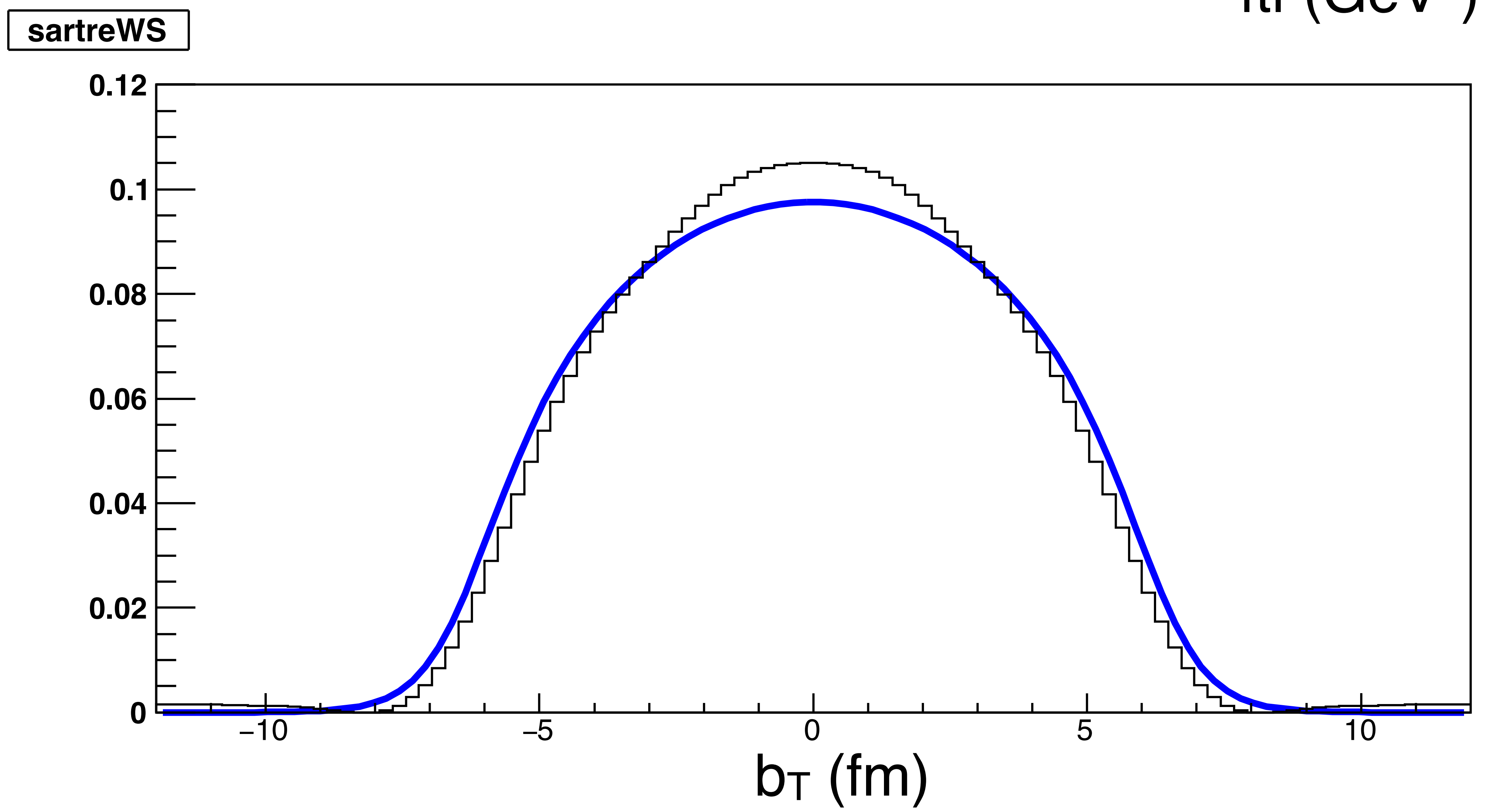
$$\frac{\sigma_{p_T}}{p_T}(\%) = 0.05\ p_T \oplus 1.0$$




**Verdict: Broadening of peaks affects extraction of shape**

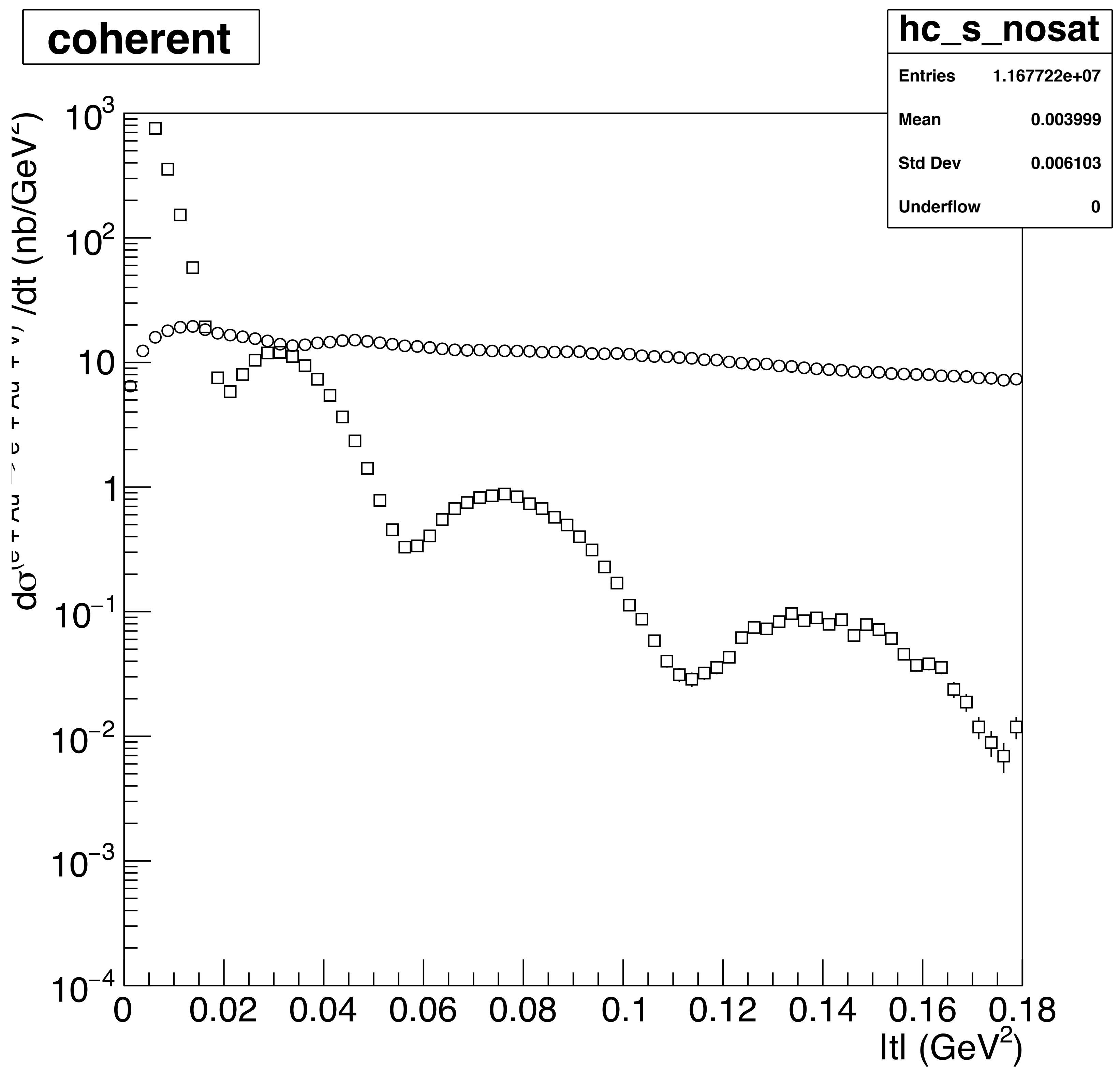
Handbook value for $-2.5 < \eta < -1.5$

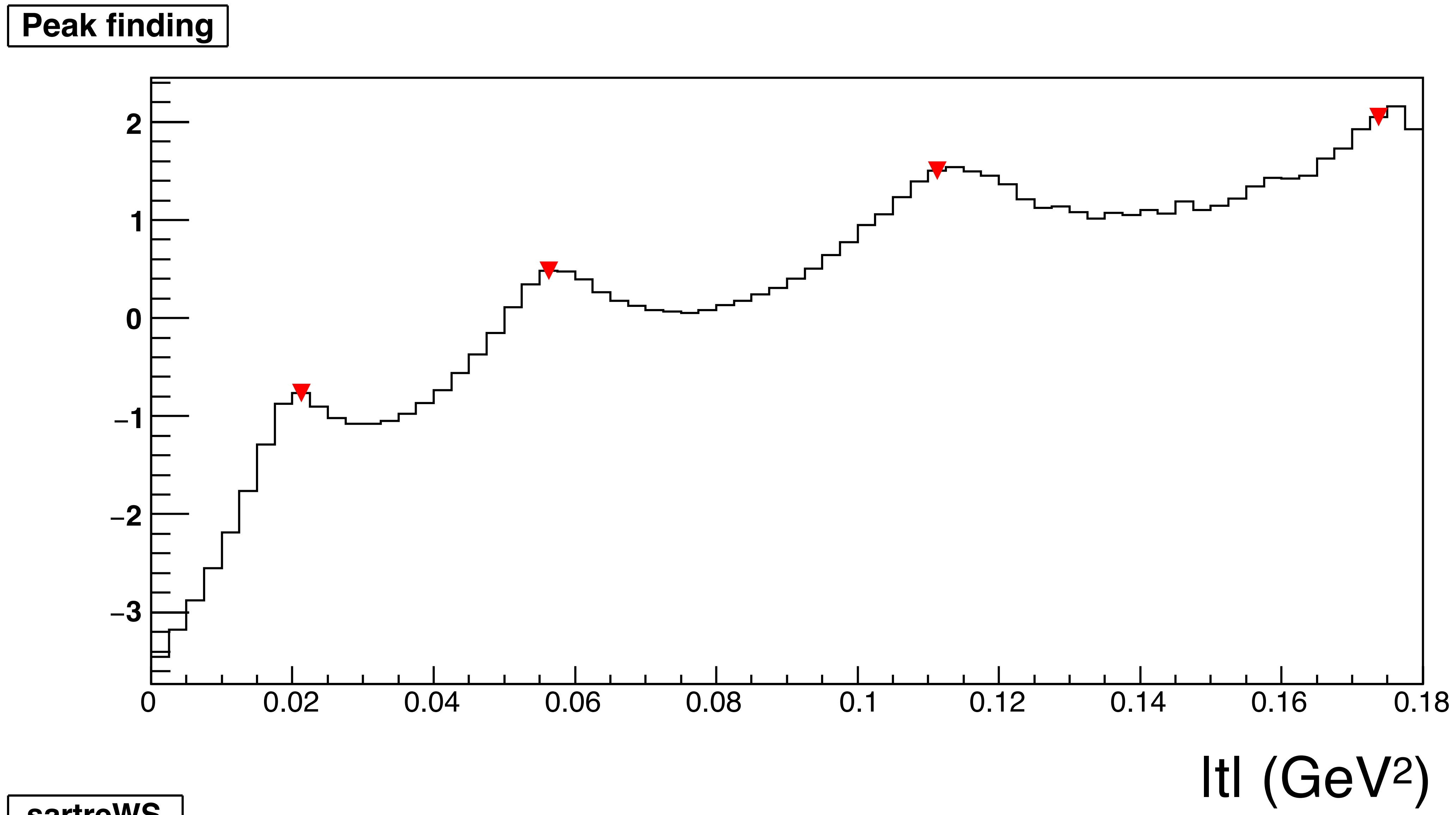


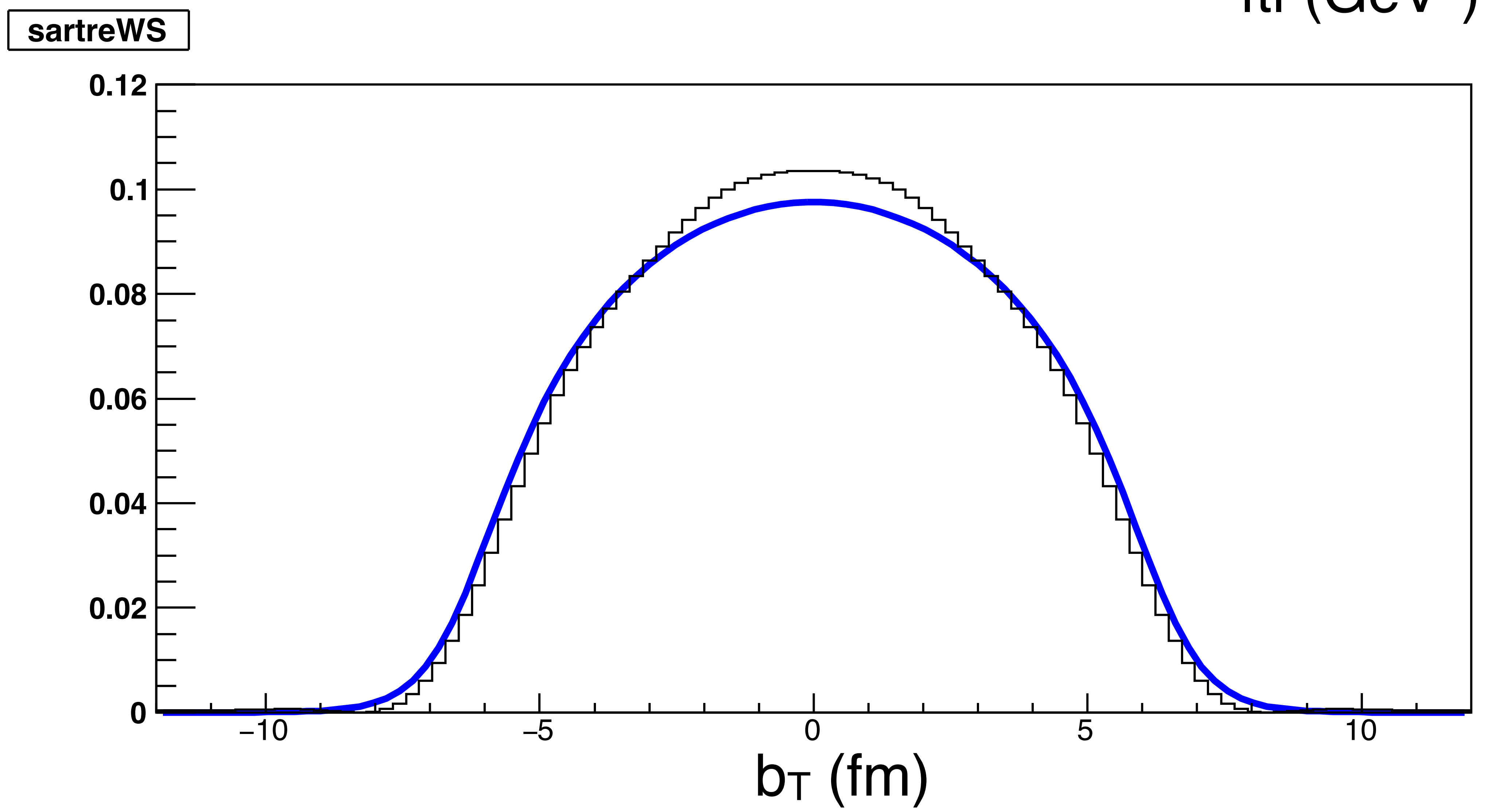



# Method A: Photoproduction $Q^2 < 0.01$ GeV$^2$

$$\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.75$$



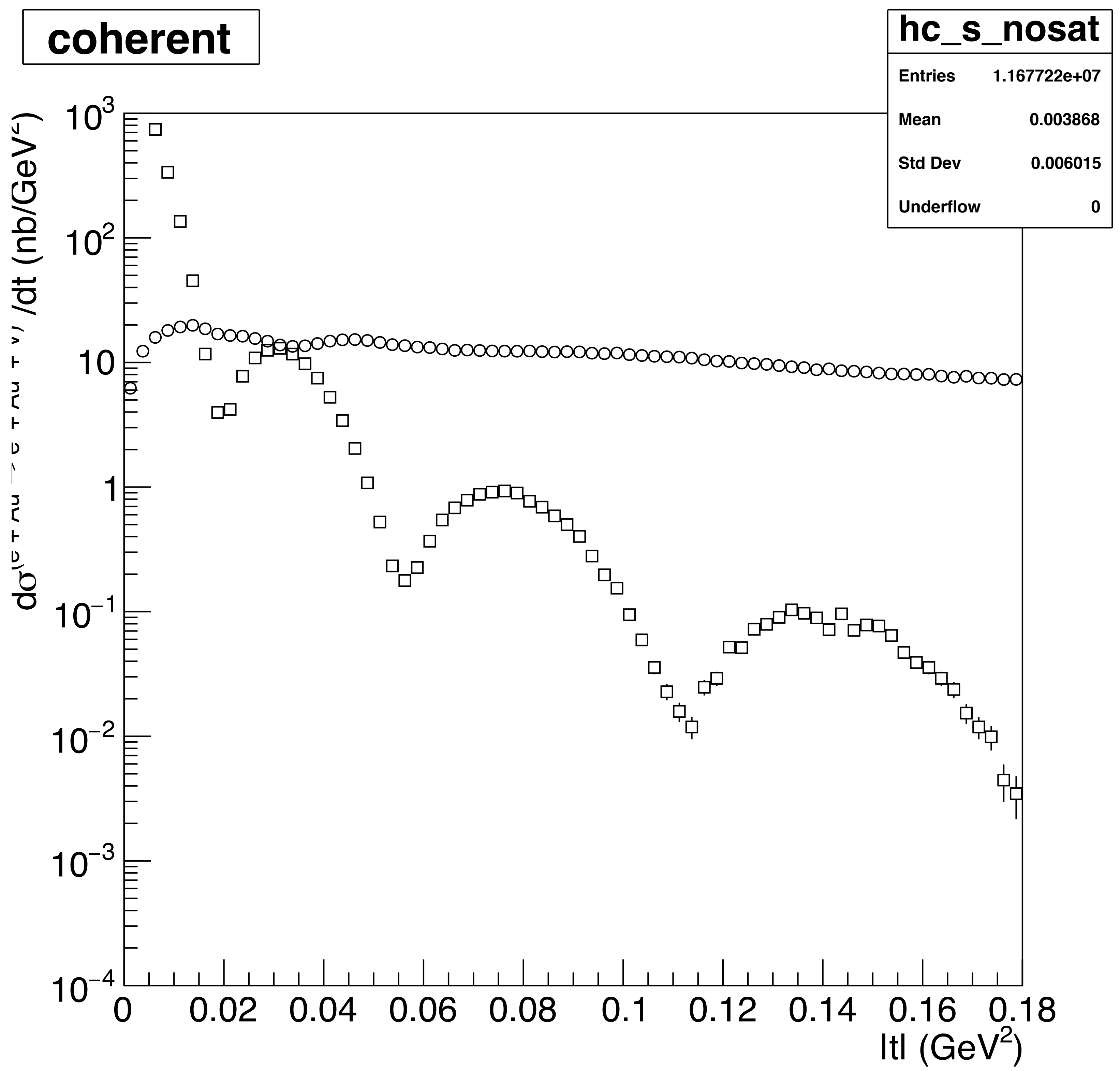



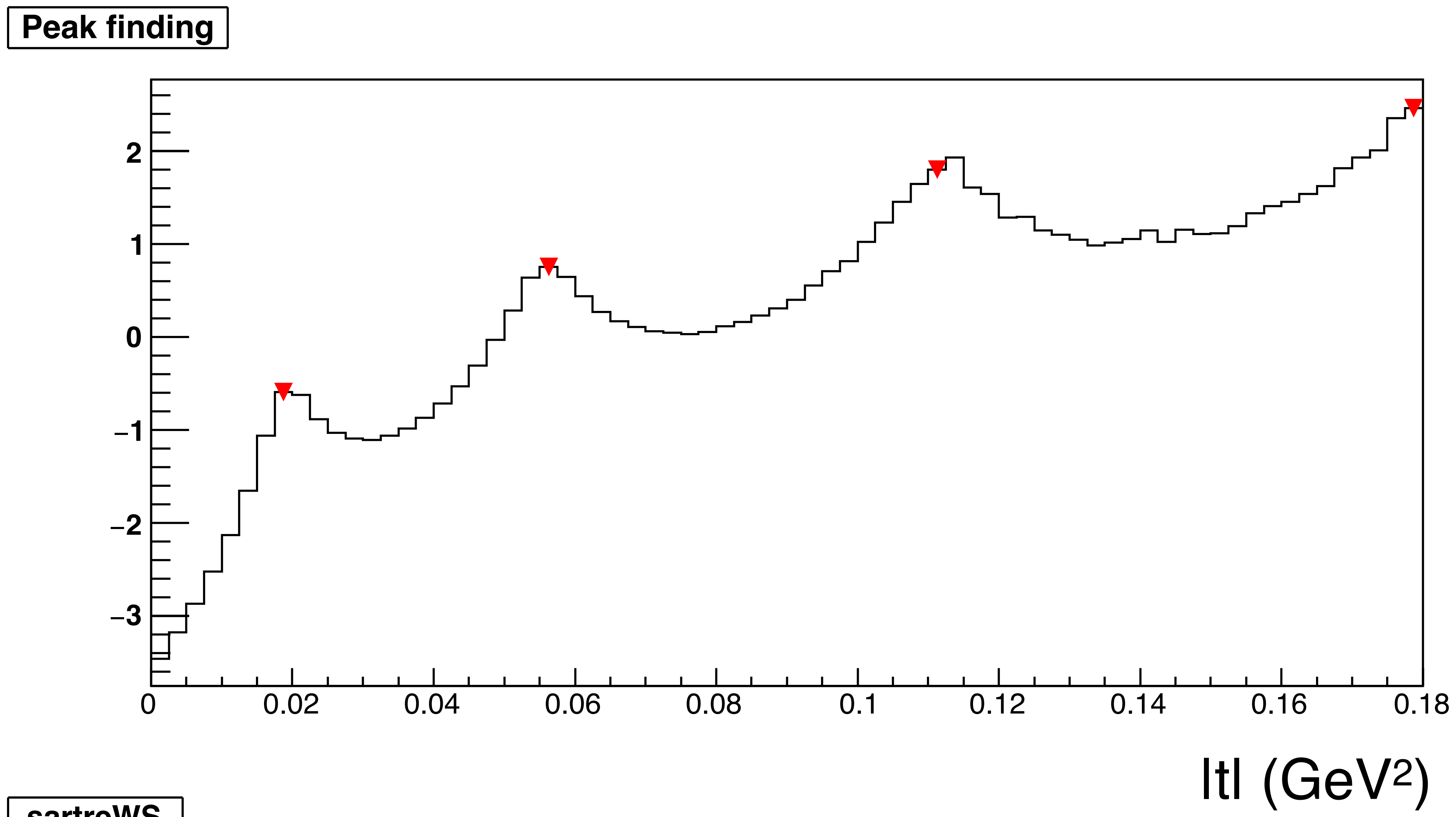



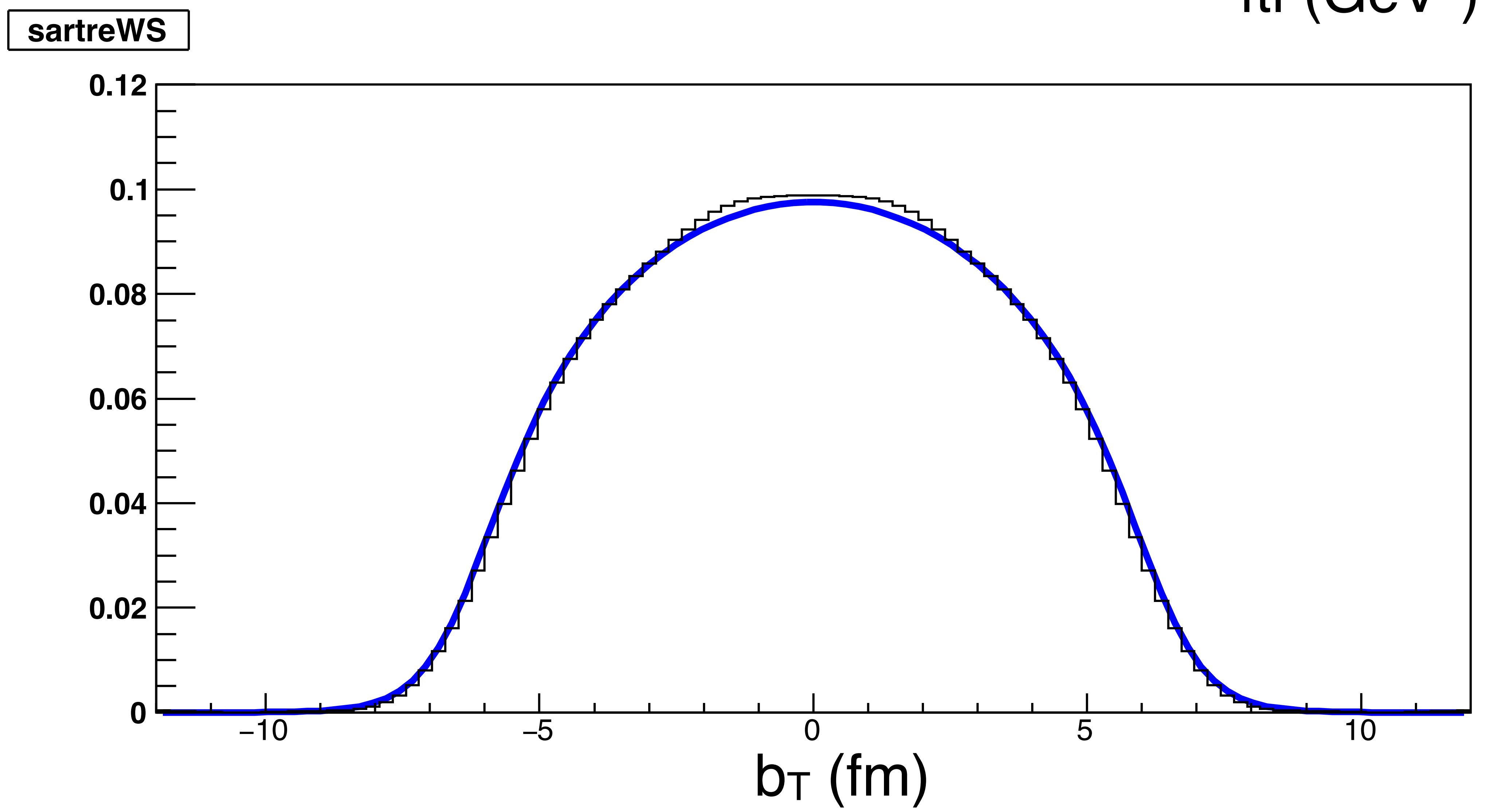

Verdict: Slightly better but still too broad peaks

# Method A: Photoproduction $Q^2 < 0.01$ GeV$^2$

$$\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.5$$



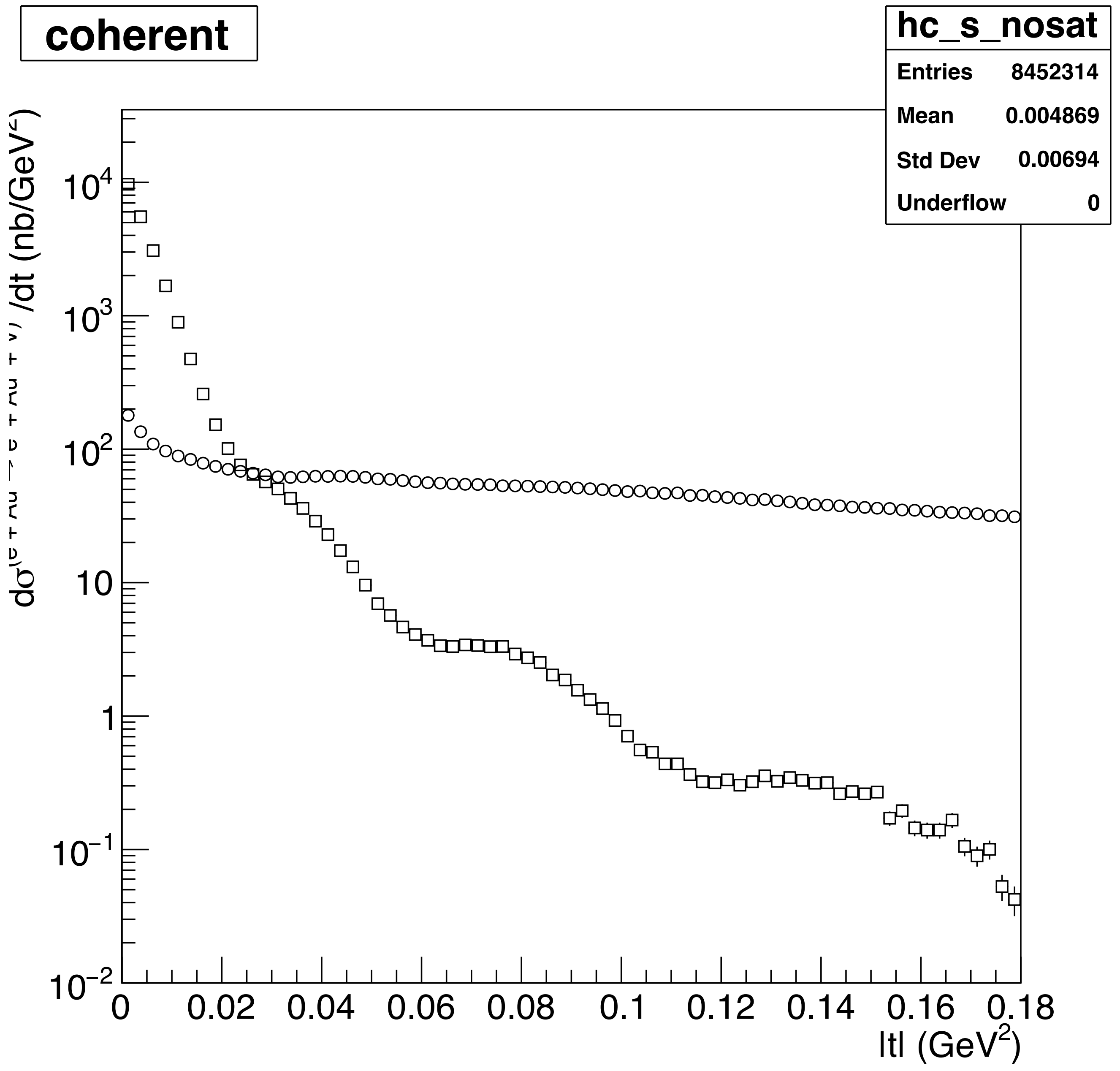



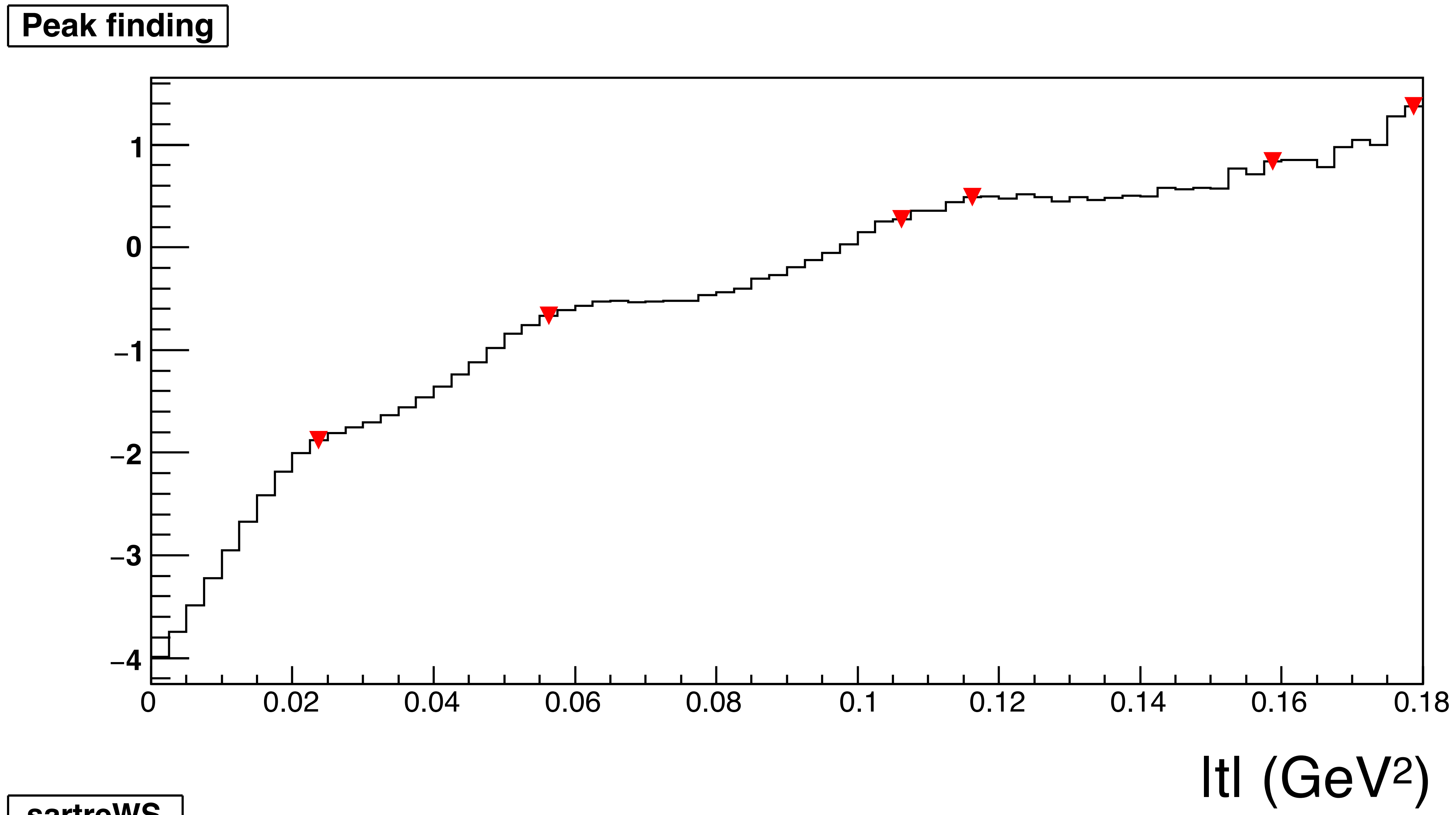

Verdict: That will do

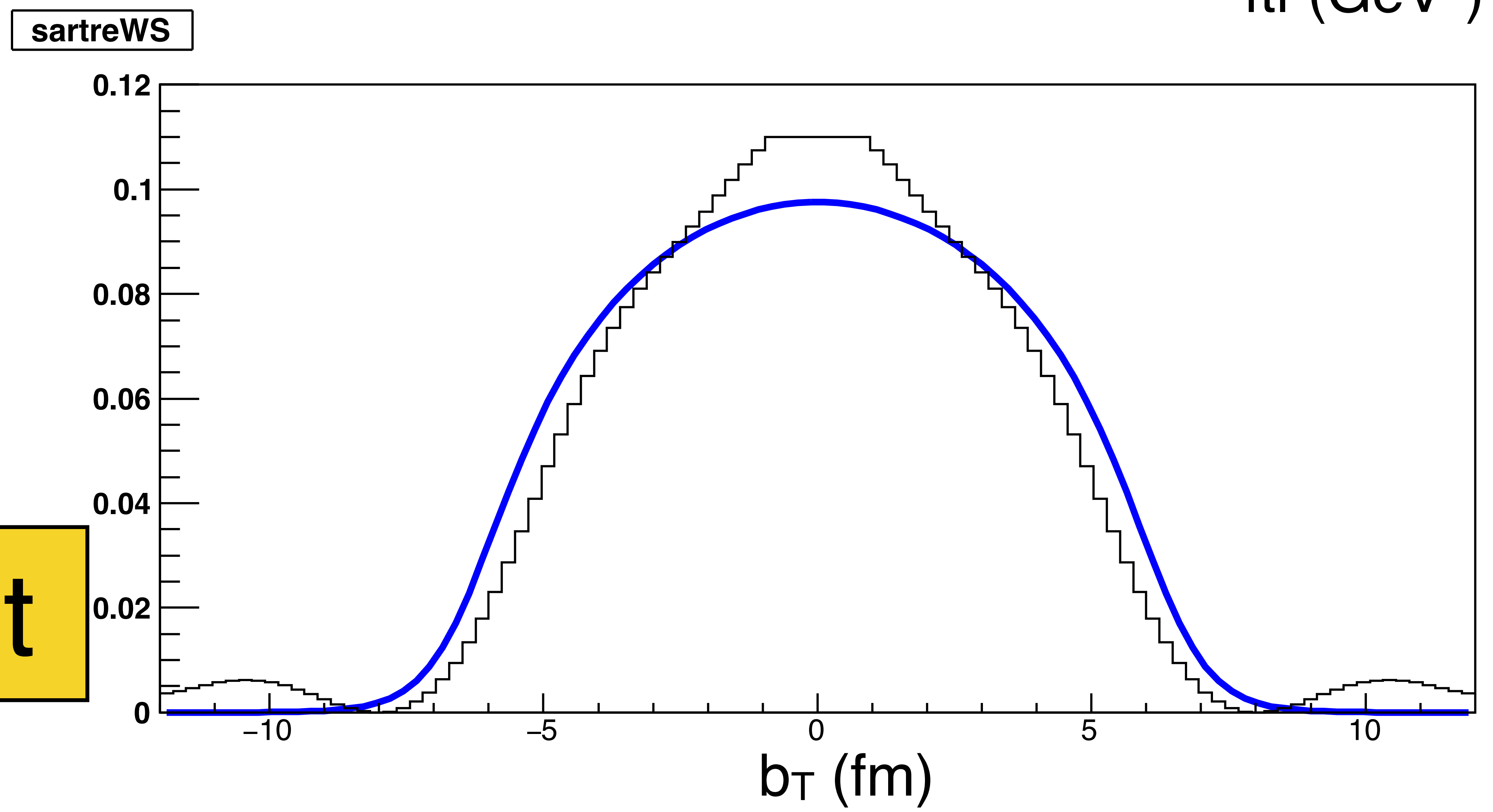
# Method A: $1 < Q^2 < 10$ GeV$^2$

e from J/$\psi$: $\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.5$

scattered e’: $\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 2.0$



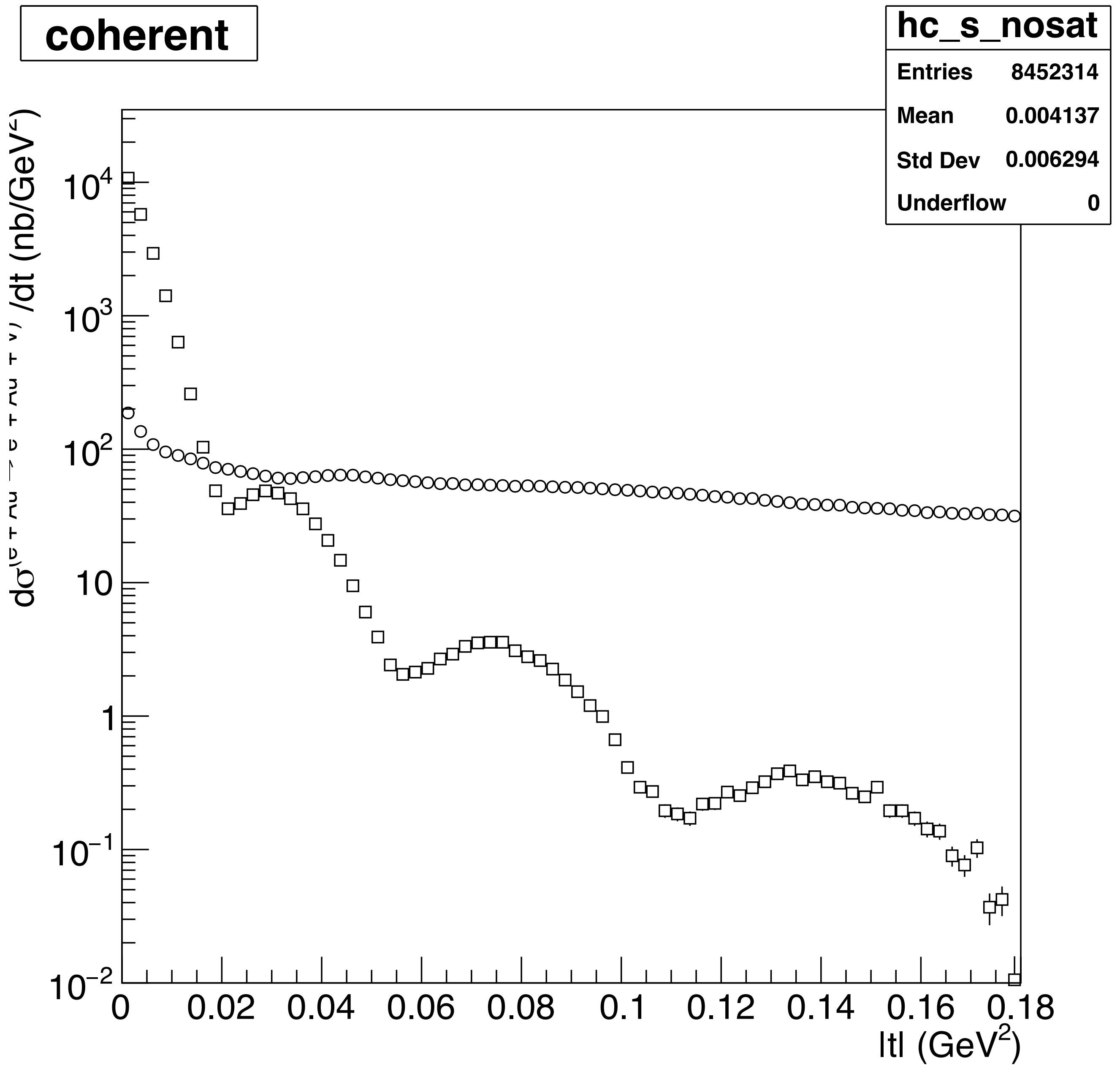



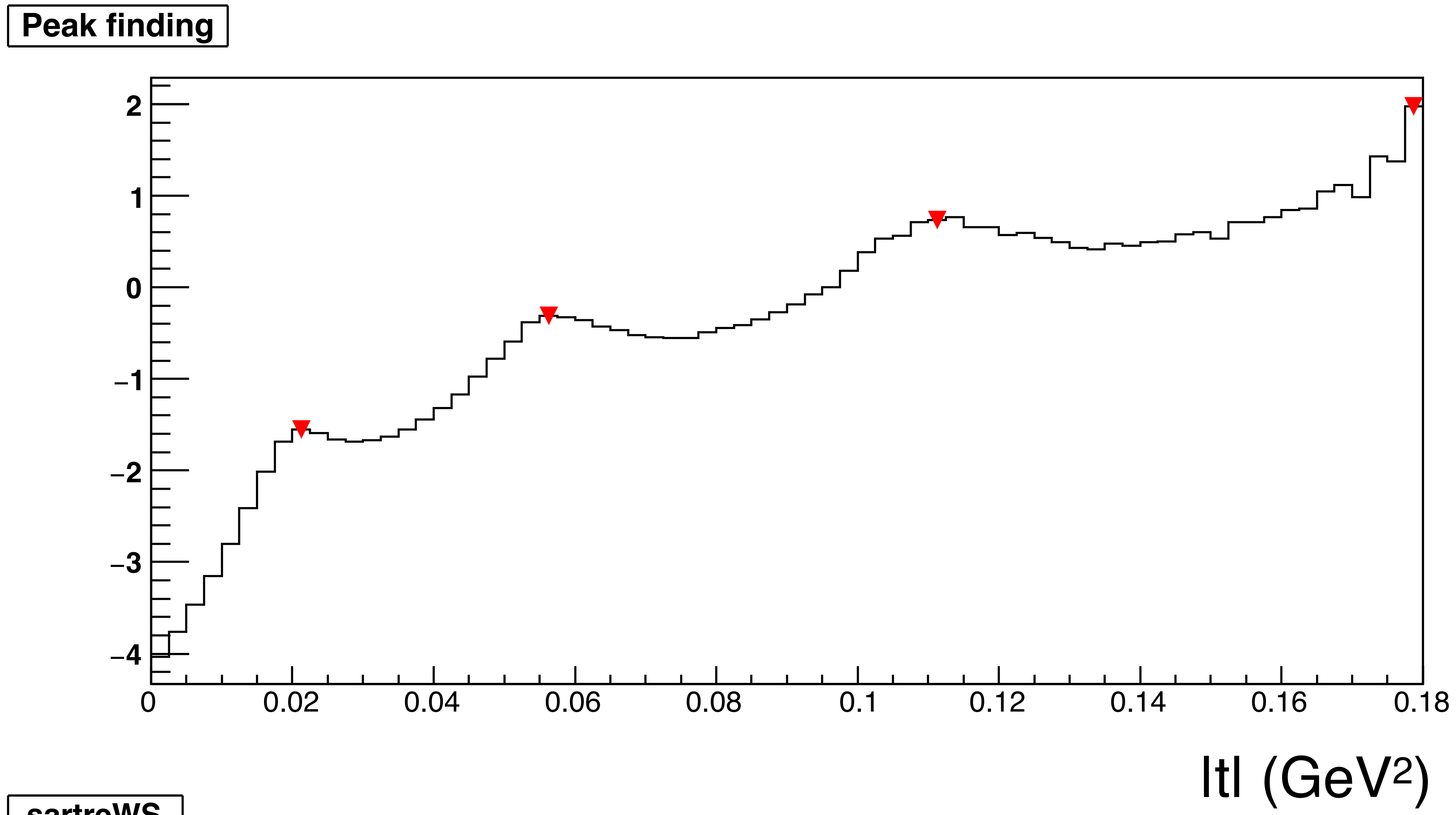

**Verdict: e’ MS term kills measurement**

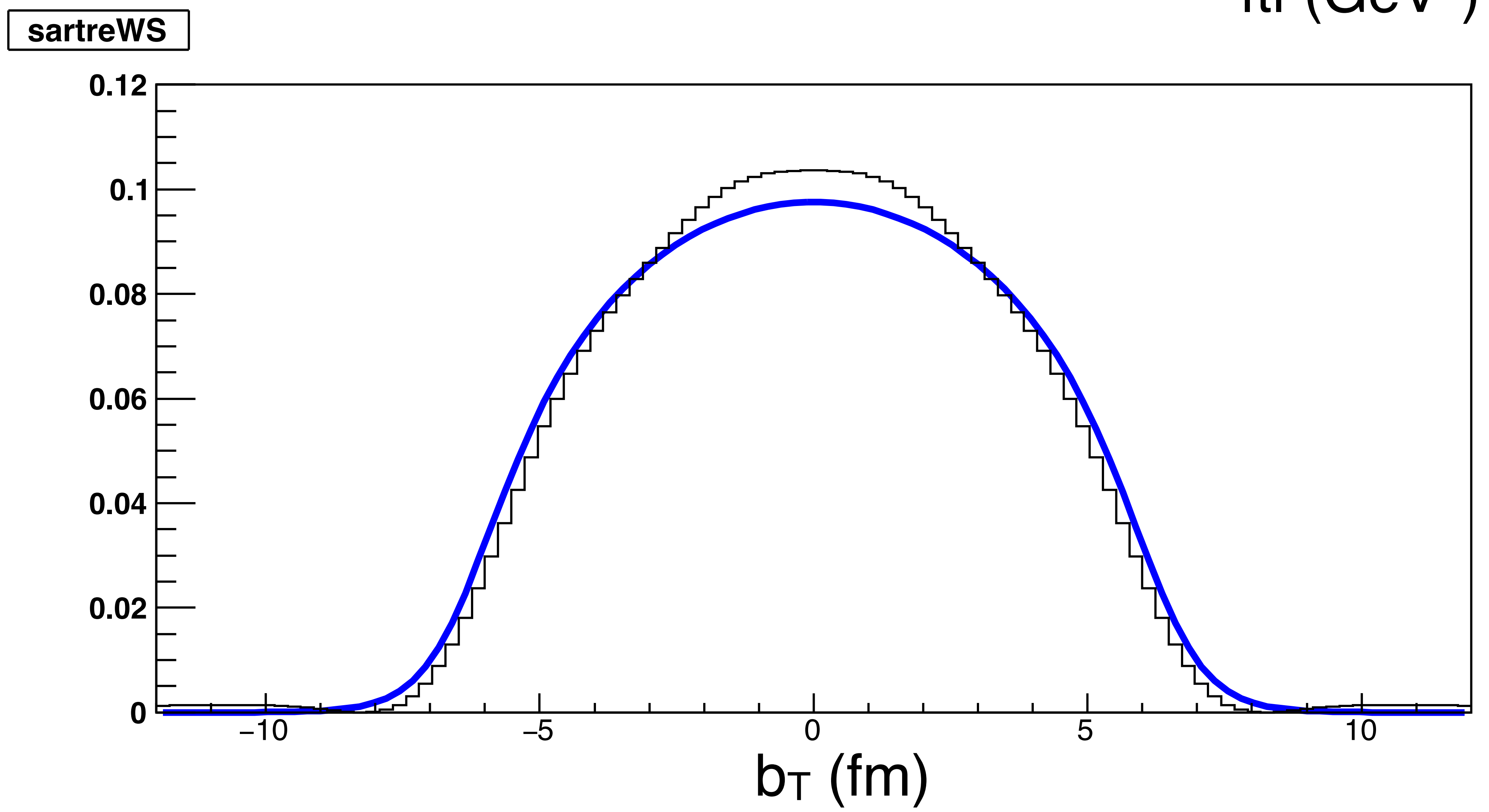
# Method A: $1 < Q^2 < 10$ GeV$^2$

e from J/$\psi$: $\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.5$

scattered e': $\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 1.0$



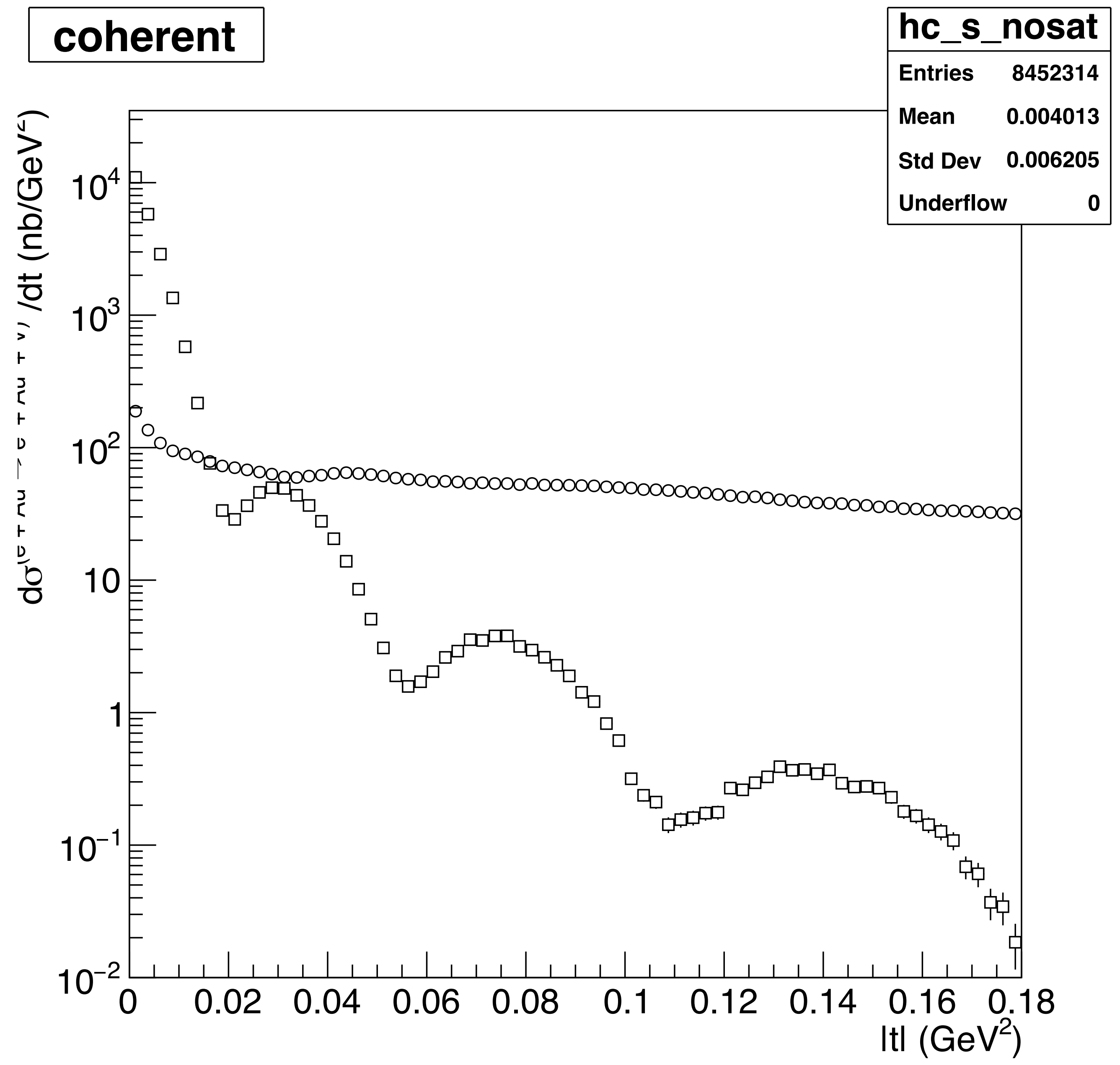



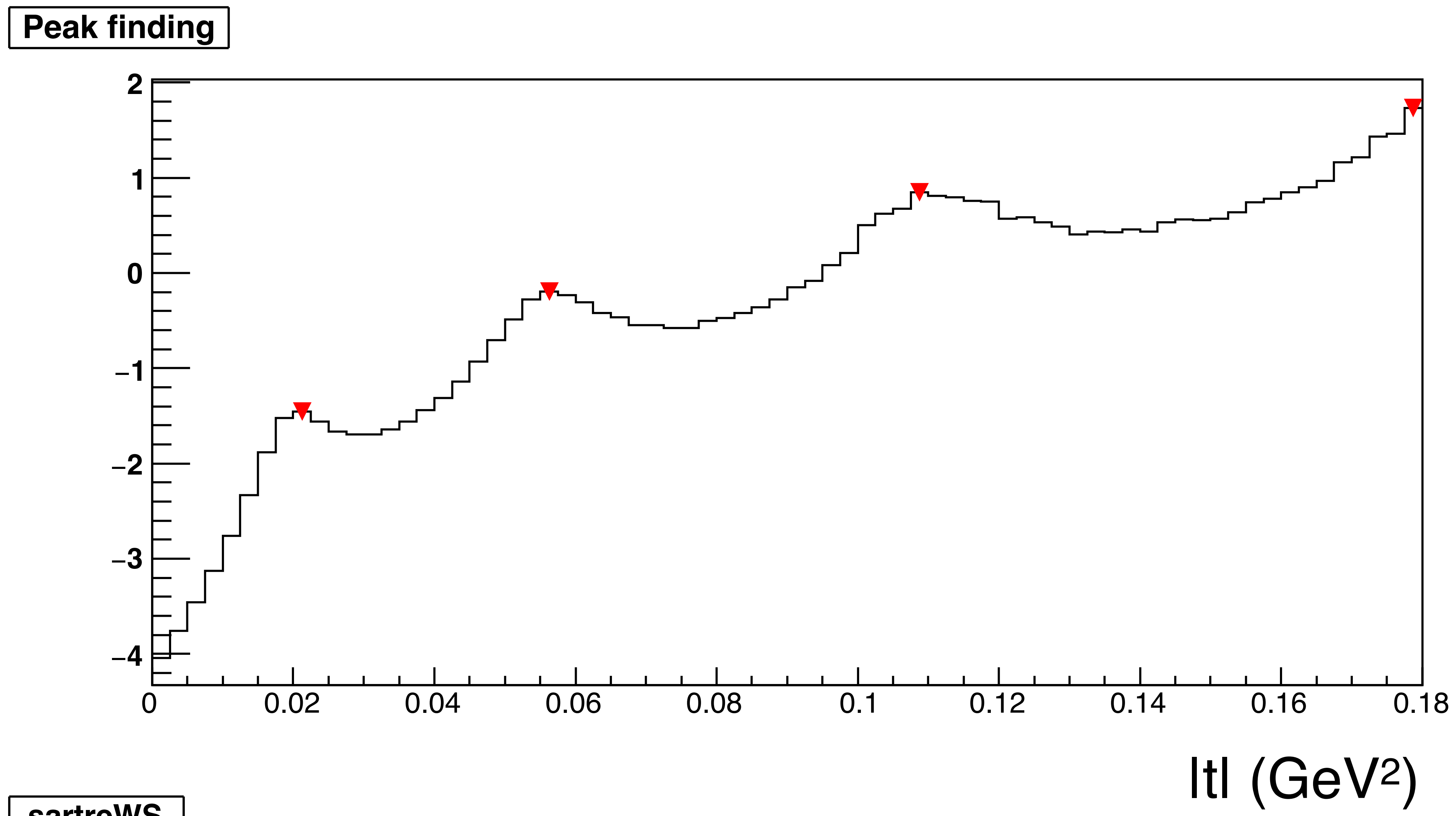

**Verdict: e' MS term still too big**

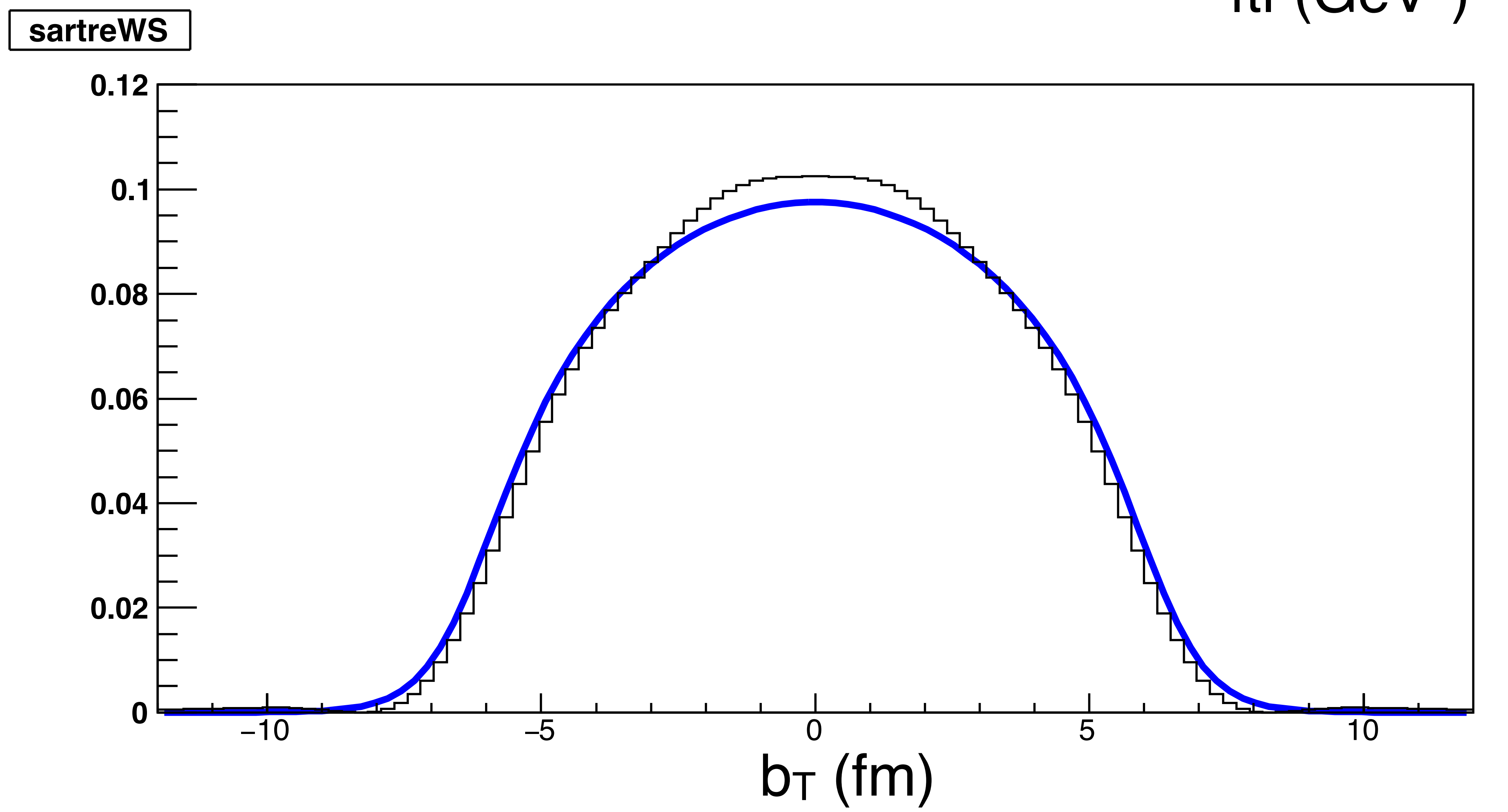
# Method A: 1 < Q² < 10 GeV²

e from J/$\psi$: $$\frac{\sigma_{p_T}}{p_T}(\%) = 0.05\ p_T \oplus 0.5$$

scattered e': $$\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.75$$



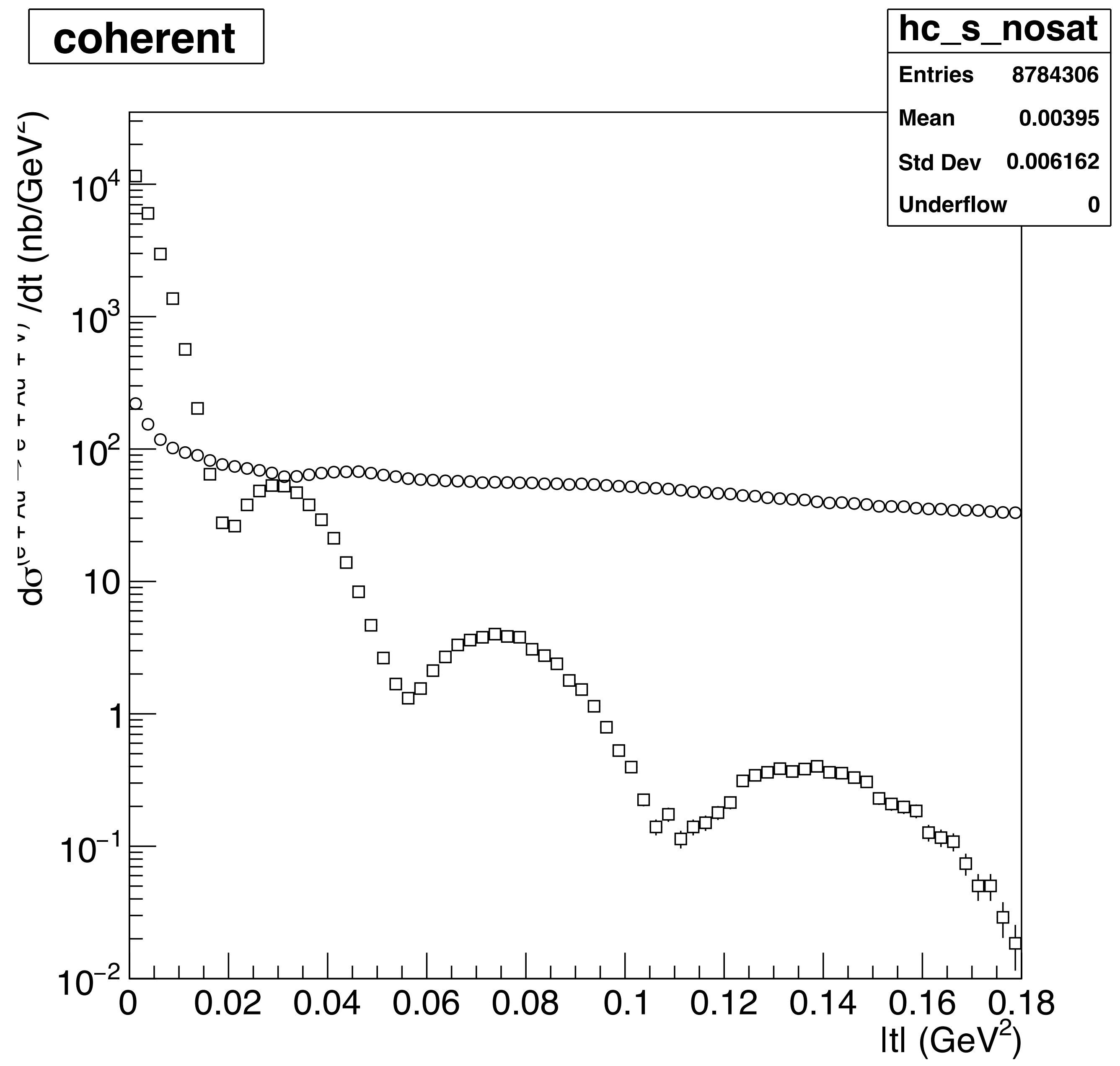



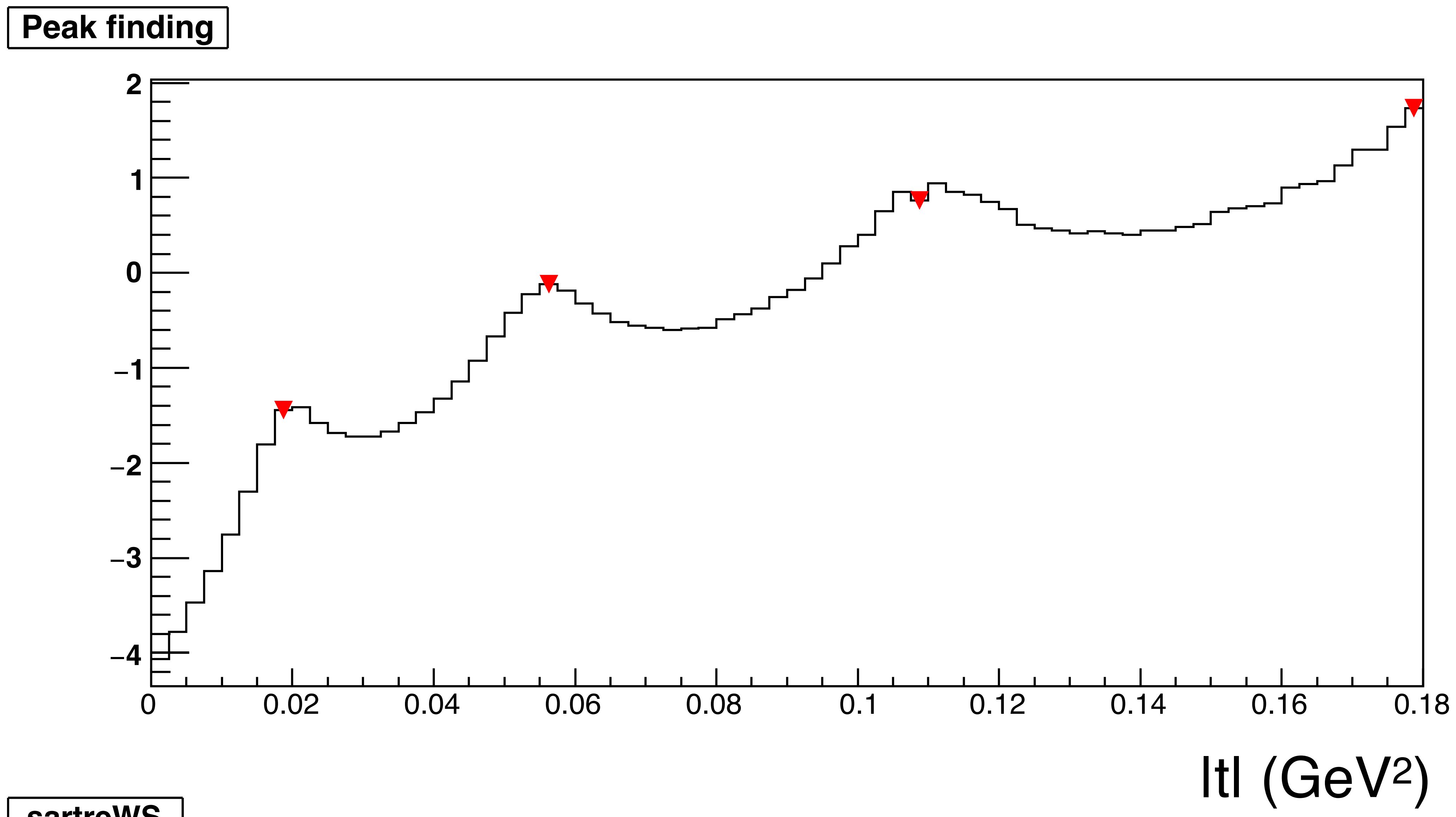

**Verdict: at the edge**

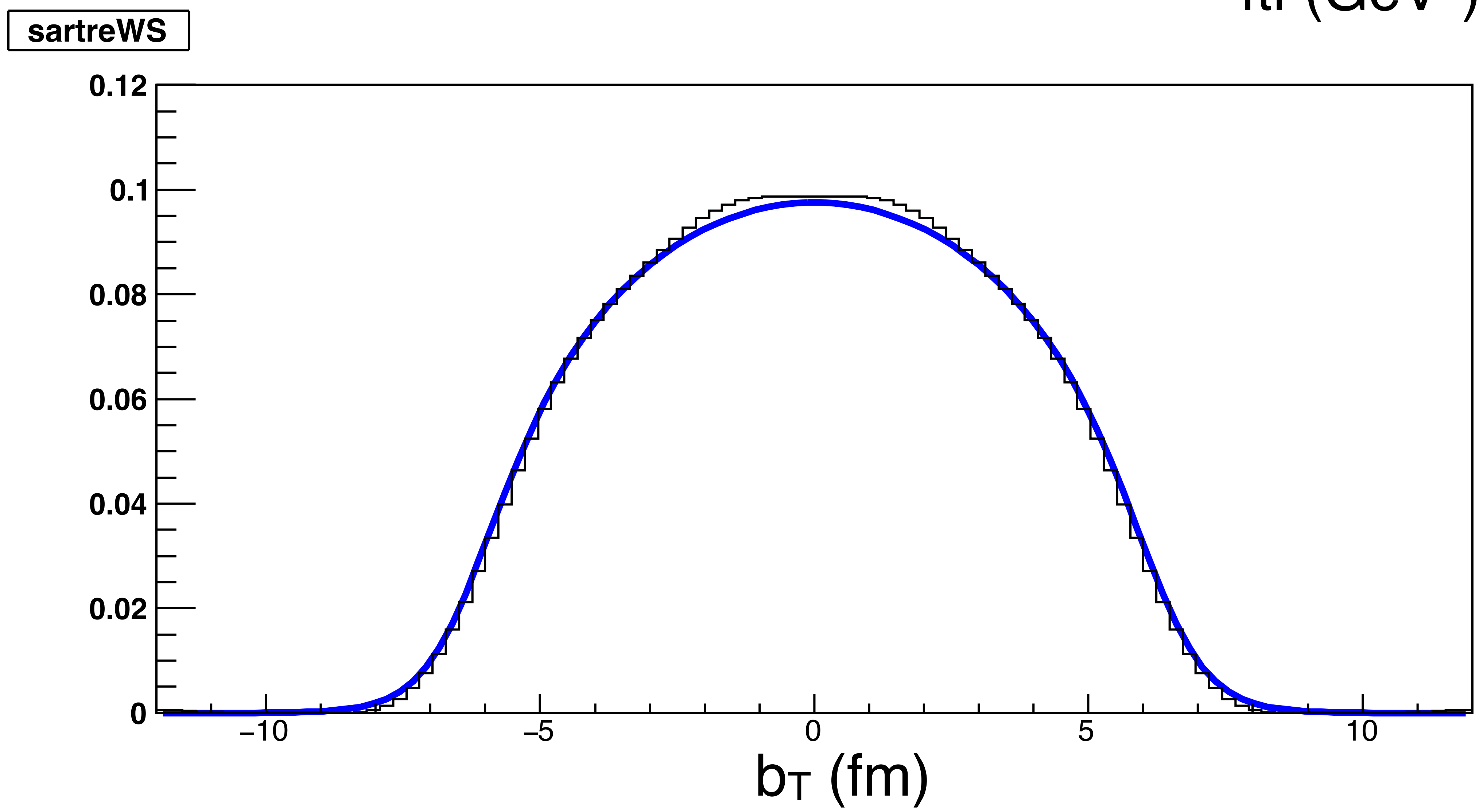
# Method A: $F(b)$

e from J/$\psi$: $$\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.5$$

scattered e’: $$\frac{\sigma_{p_T}}{p_T}(\%) = 0.1\ p_T \oplus 0.5$$




**Verdict: That will do!**

# Detector Requirements and Next Steps

- In order for this measurement to work:
  - The MS terms for the backward (e going) tracking requirements have to be smaller than the values listed currently in the Handbook
  - At least in some fraction of $-3.5 < \eta < -2$ the MS term needs to be $\leq 0.5\%$ and not 1.0% (2.0%) as currently assumed. That's quite a challenge!
  - Precision terms are less important but should not exceed 0.1% as in Handbook
  - In short everything worse than $\sigma_{p_T}/p_T(\%) = 0.1\ p_T \oplus 0.5$ in $-3.5 < \eta < 1$ can kill this measurement.
- Interesting note:
  - In PRC 81, 025203 (2010) the authors Kowalski and Caldwell studied diffractive J/$\psi$ photoproduction for the EIC in e+A and estimated $\sigma_{p_t}/p_t = 0.005 \cdot p_t \oplus 0.045/\beta\%$,
  - They envisioned $J/\psi \rightarrow \mu^+\mu^-$
- Next step: $\phi \rightarrow K^+K^-$