lessons learnt at HERMES on technical aspects of TMD measurements

- the devil is in the detail -

Gunar.Schnell @ desy.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Disclaimers

- contains a number of trivial, but hopefully still useful, statements
- can not offer a general recipe, though hopefully some guidance

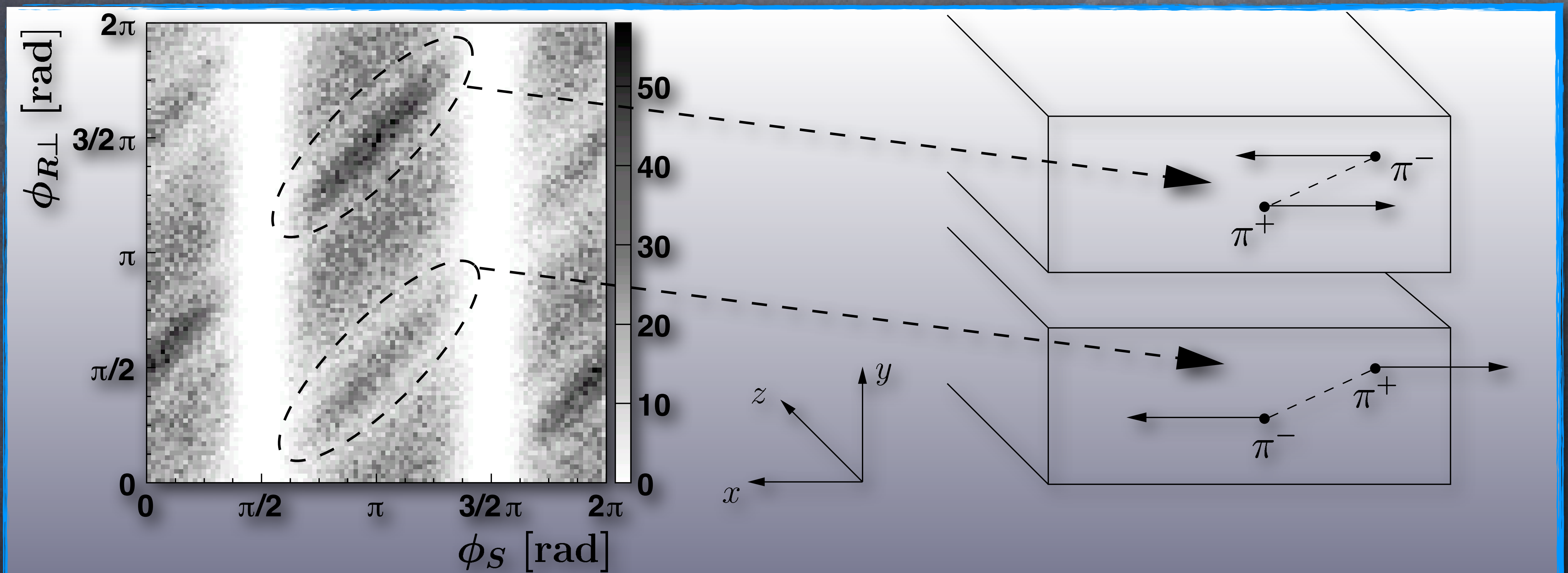
Prelude: role of acceptance in experiments

an unfortunate Lemma

- "No particle-physics experiment has a perfect acceptance!"

  - obvious for detectors with gaps/holes
  - but also for "4π", especially when looking at complicated final states

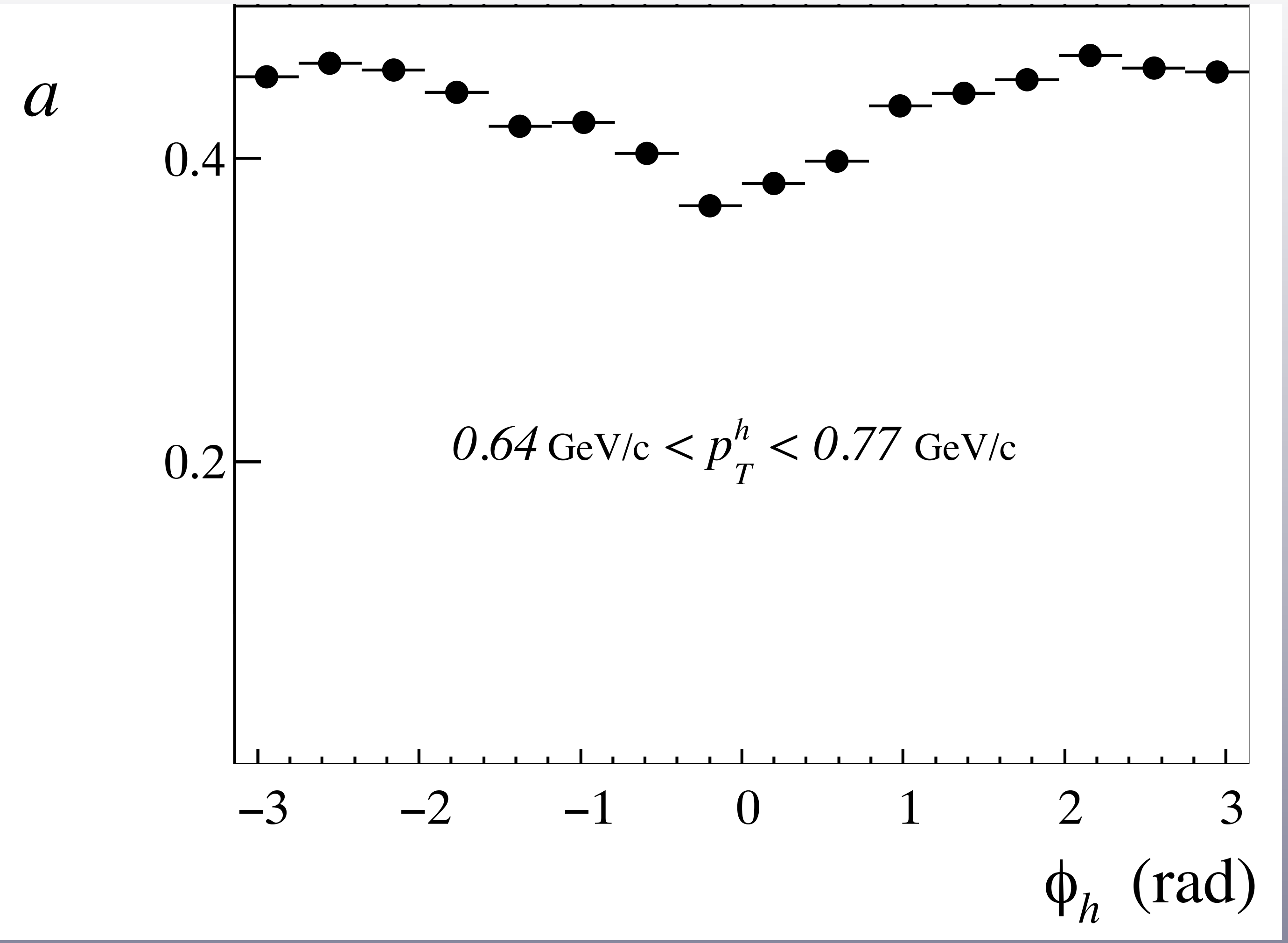
an unfortunate Lemma



HERMES azimuthal acceptance for 2-hadron production

[P. van der Nat, Ph.D. thesis, Vrije Universiteit (2007)]

an unfortunate Lemma

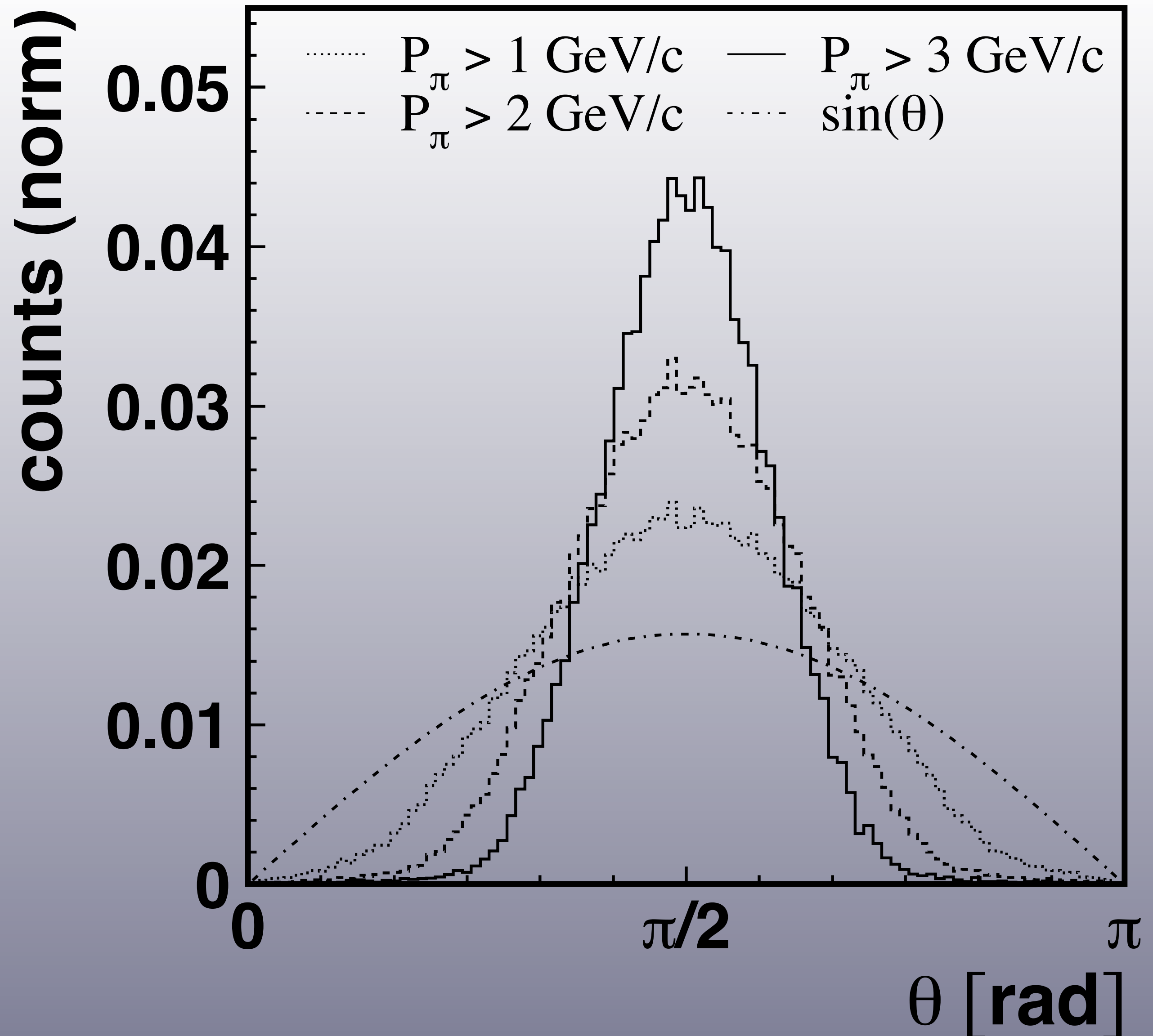


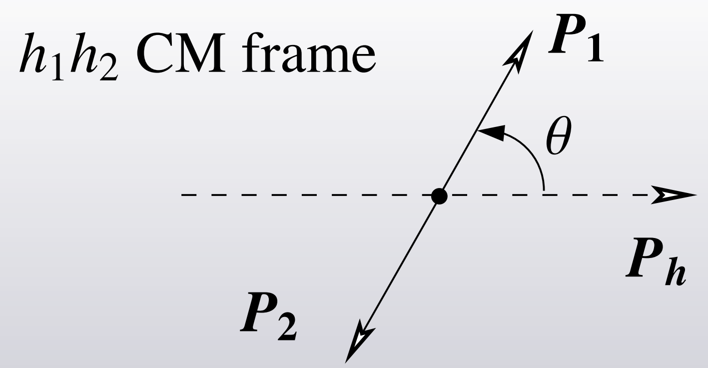
[C. Adolph, arXiv:1401.6284]

maybe "2π" around beam axis, but not around virtual-photon axis because of lower limit on θ

[see also A. Bianconi et al., Eur.Phys.J. A49 (2013) 42]

an unfortunate Lemma





momentum requirements strongly distort kinematic distributions even for "4π" acceptance

[P. van der Nat, Ph.D. thesis, Vrije Universiteit (2007)]

an unfortunate Lemma

- "No particle-physics experiment has a perfect acceptance!"
    - obvious for detectors with gaps/holes
    - but also for "4π", especially when looking at complicated final states
- How acceptance effects are handled is one of the essential questions in experiments!

some acceptance effects

- acceptance in kinematic variable studied, e.g., azimuthal coverage in extraction of azimuthal moments
- acceptance in kinematic variables integrated over, e.g., due to limited statistics not being able to do fully differential analysis
- event migration due to smearing

a common misconception

- “acceptance cancels in asymmetries”

a common misconception

- "acceptance cancels in asymmetries"

$$A_{UT}(\phi,\Omega) = \frac{\sigma_{UT}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} \qquad \Omega = x, y, z, \ldots$$

$$= \frac{\sigma_{UT}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)} \qquad \epsilon : \textbf{detection efficiency}$$

$$\neq \frac{\int \mathrm{d}\Omega\,\sigma_{UT}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\,\sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)} \neq \frac{\int \mathrm{d}\Omega\,\sigma_{UT}(\phi,\Omega)}{\int \mathrm{d}\Omega\,\sigma_{UU}(\phi,\Omega)} \equiv A_{UT}(\phi)$$

Acceptance does **not cancel** in general when **integrating** numerator and denominator over (large) ranges in kinematic variables!

… geometric acceptance

extract acceptance from Monte Carlo simulation? …

$$\epsilon(\phi,\Omega) = \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} \qquad \Omega = x, y, z, ..$$

simulated acceptance

simulated cross section

… geometric acceptance

extract acceptance from Monte Carlo simulation? …

$$\epsilon(\phi,\Omega) = \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)}$$

$$\neq \frac{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)\, \epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)}$$

$$\Omega = x, y, z, \ldots$$

"Aus Differenzen und Summen
kürzen nur die Dummen."

… geometric acceptance

extract acceptance from Monte Carlo simulation? …

$$\epsilon(\phi,\Omega) = \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)}$$

$$\neq \frac{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)\, \epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)}$$

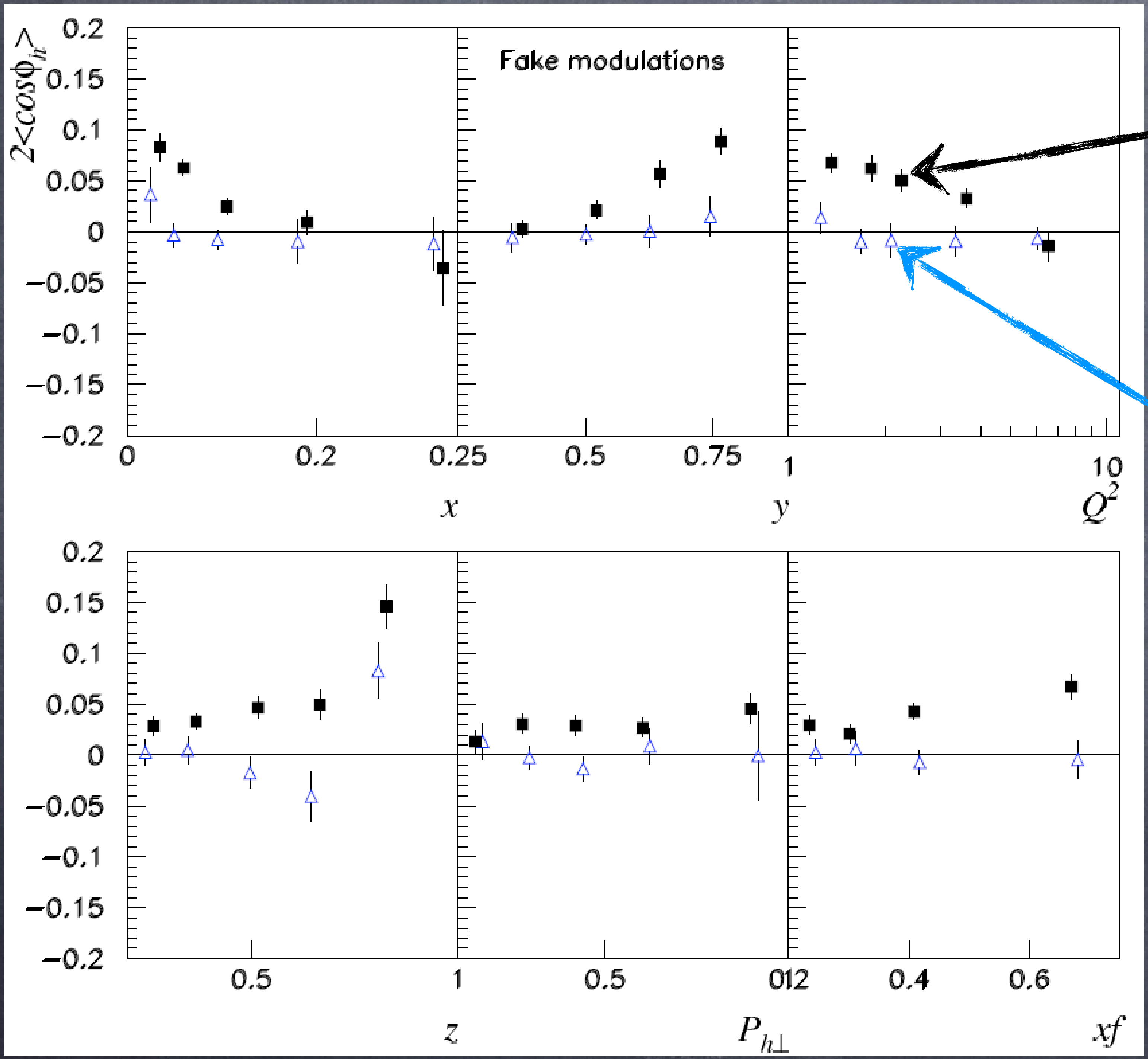
$$\neq \int \mathrm{d}\Omega\, \epsilon(\phi,\Omega) \equiv \epsilon(\phi)$$

$$\Omega = x, y, z, \ldots$$

"Aus Differenzen und Summen kürzen nur die Dummen."

Cross-section model does NOT CANCEL in general when integrating numerator and denominator over (large) ranges in kinematic variables!

"Classique" Example: $\langle \cos\phi \rangle_{UU}$



1D correction

(input: MC without azimuthal modulation)

5D correction

[F. Giordano, Transversity 2008, Ferrara]

… averaging …

often enough one has to average observables over available phase space:

$$\langle A(\Omega)\rangle_\epsilon = \int \mathrm{d}\Omega\, A(\Omega)\epsilon(\Omega)$$

properly normalized for simplicity

… averaging …

often enough one has to average observables over available phase space:

$$\langle A(\Omega)\rangle_\epsilon \equiv \int \mathrm{d}\Omega\, A(\Omega)\epsilon(\Omega)$$

$$\neq \int \mathrm{d}\Omega\, A(\Omega) \equiv \langle A(\Omega)\rangle_{\text{“}4\pi\text{”}}$$

… averaging …

often enough one has to average observables over available phase space:

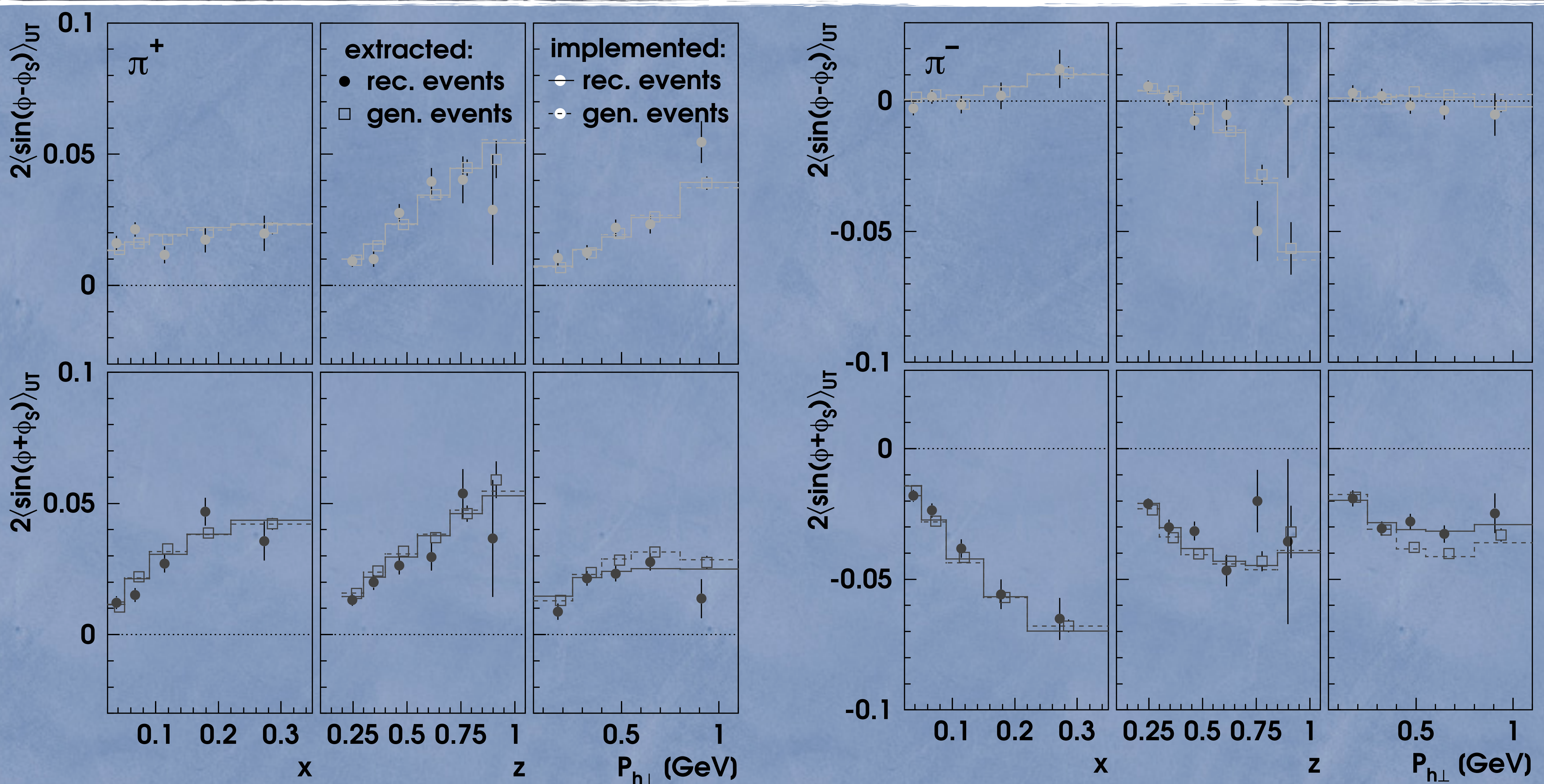
$$\langle A(\Omega)\rangle_\epsilon \equiv \int \mathrm{d}\Omega\, A(\Omega)\epsilon(\Omega)$$

$$\neq \int \mathrm{d}\Omega\, A(\Omega) \equiv \langle A(\Omega)\rangle_{\text{“}4\pi\text{”}}$$

life (of the experimentalist) simplifies if asymmetries are weakly (i.e. not more than linearly) dependent on kinematics:

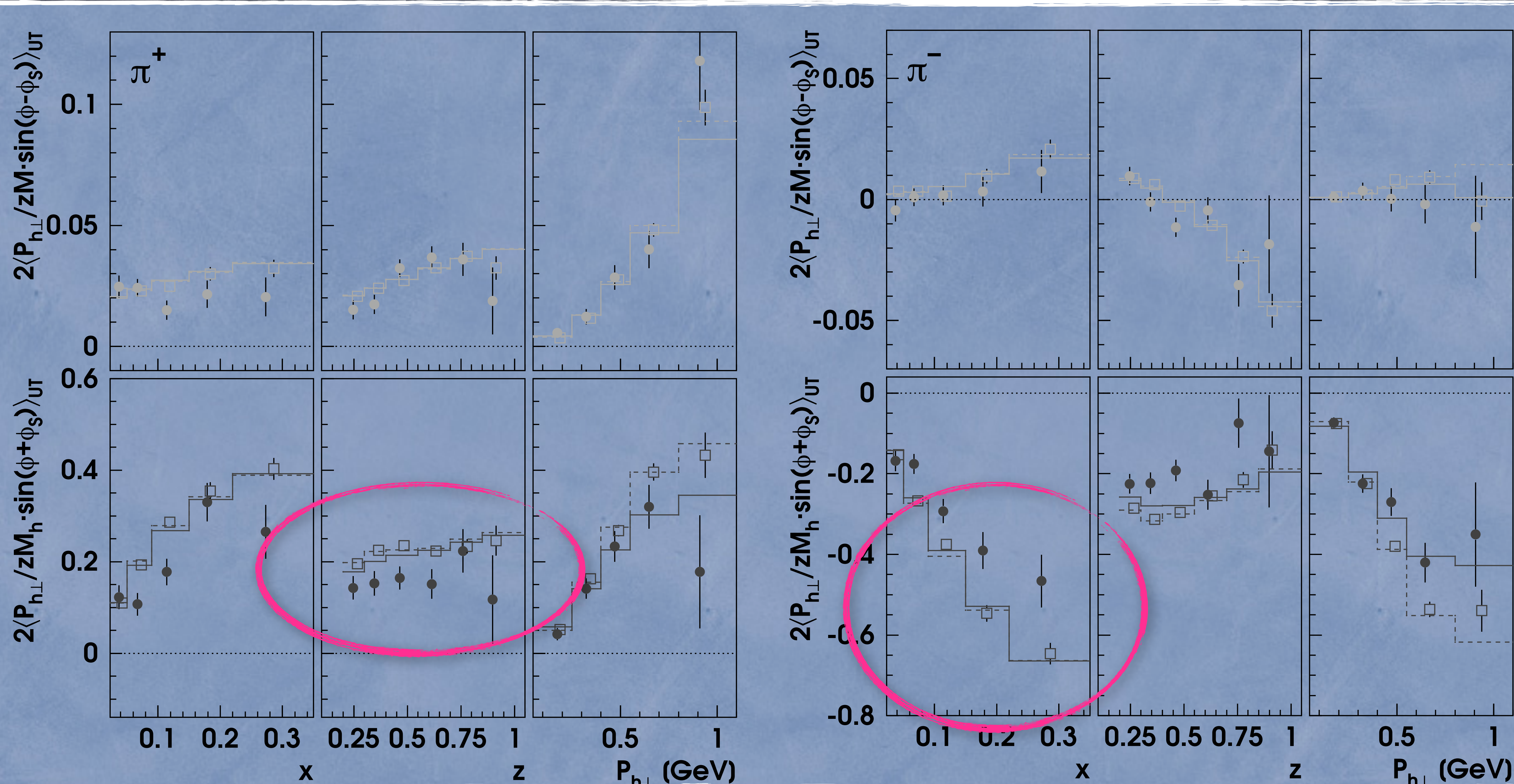
$\langle A(\Omega)\rangle_\epsilon = A(\langle\Omega\rangle_\epsilon)$ for $A(\Omega) = A_0 + A_1\Omega$

generated vs. extracted A_{UT}



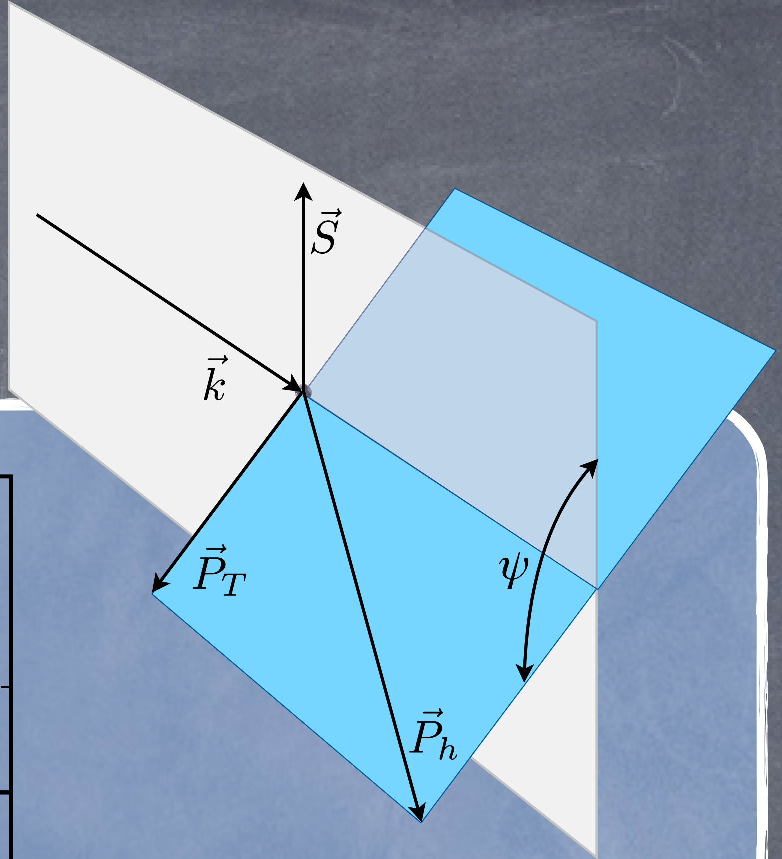
Extraction method works well!

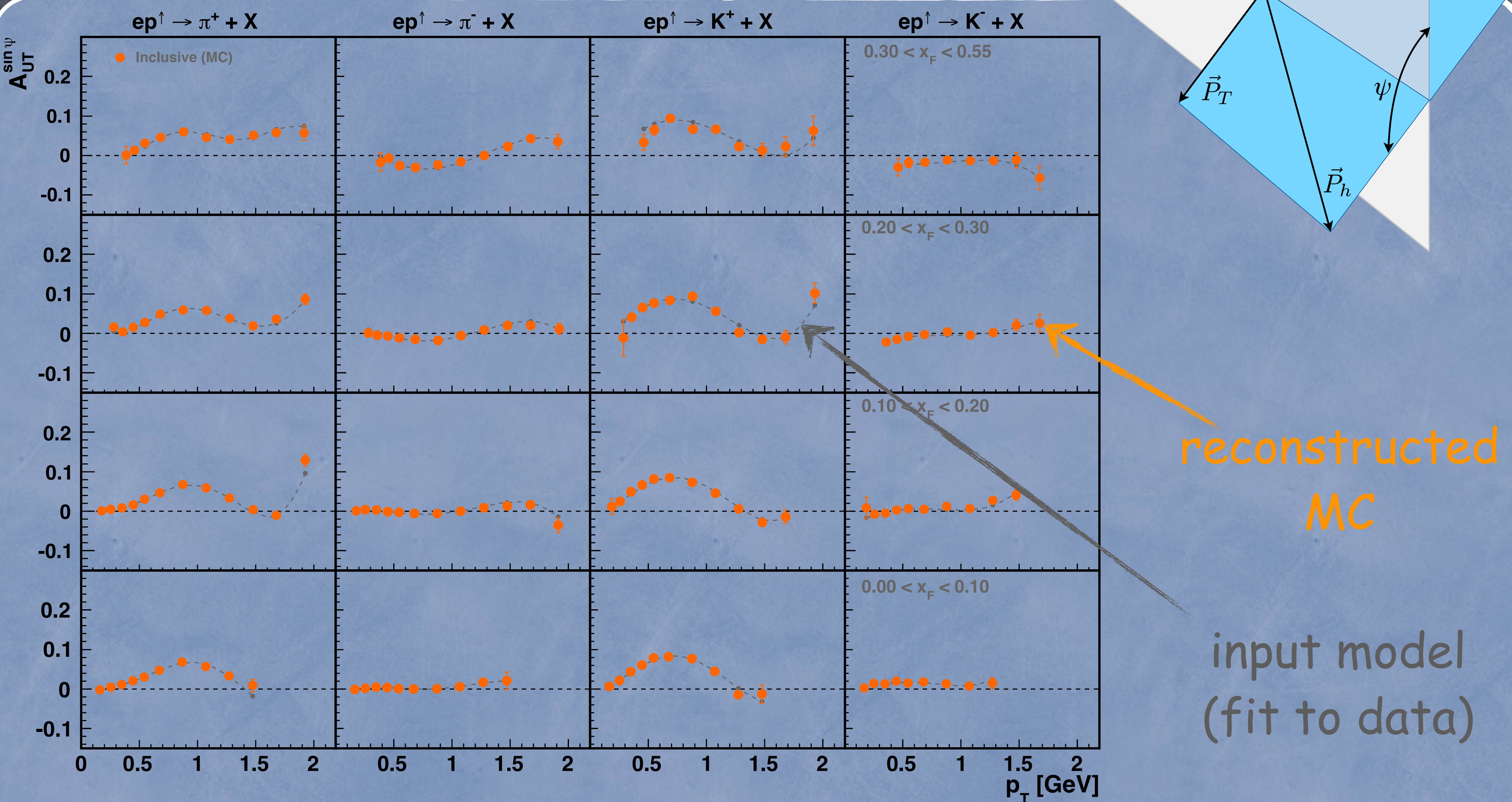
what about weighted moments



Not so good news for weighted moments!

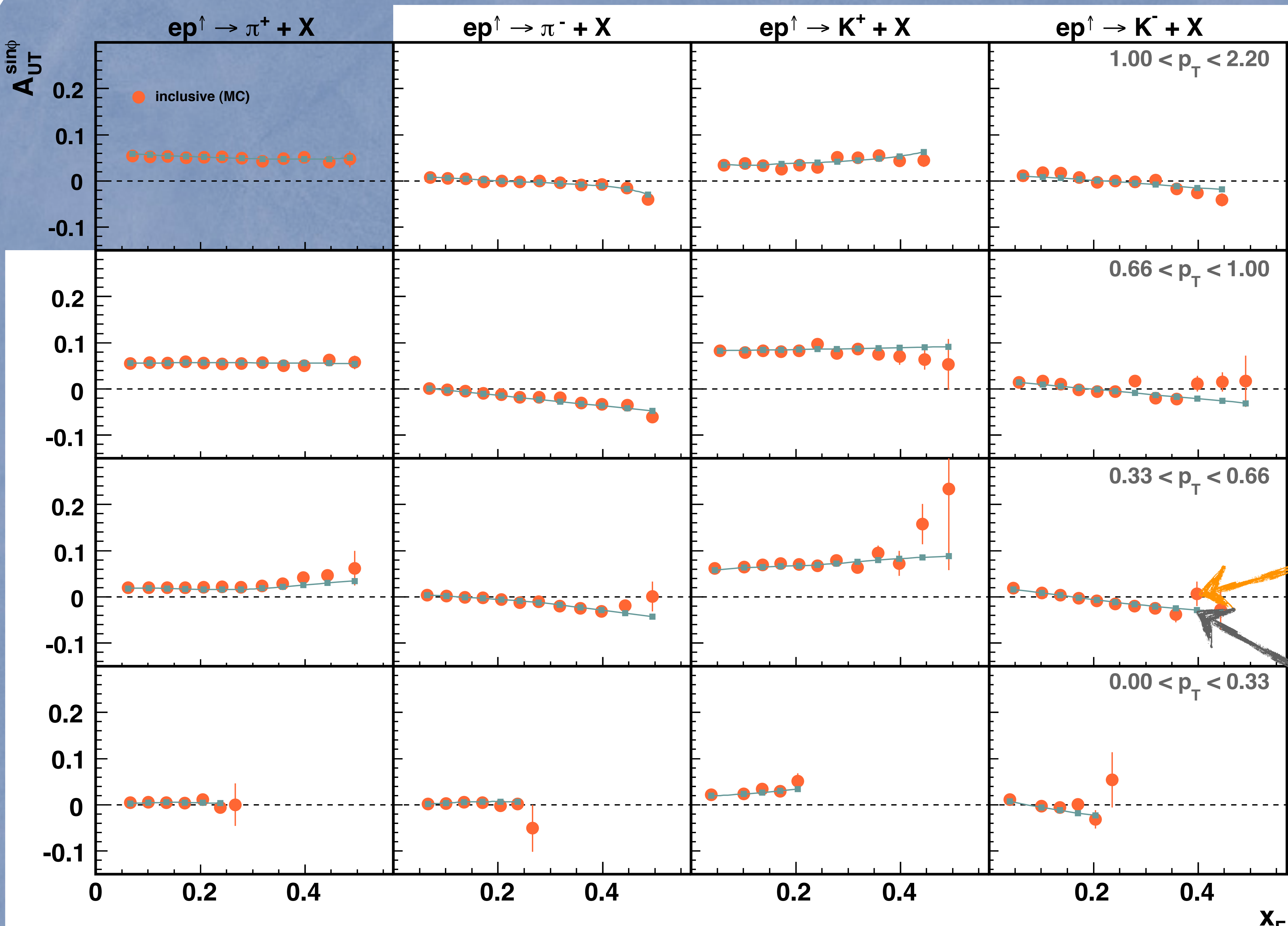
A_{UT} inclusive hadrons

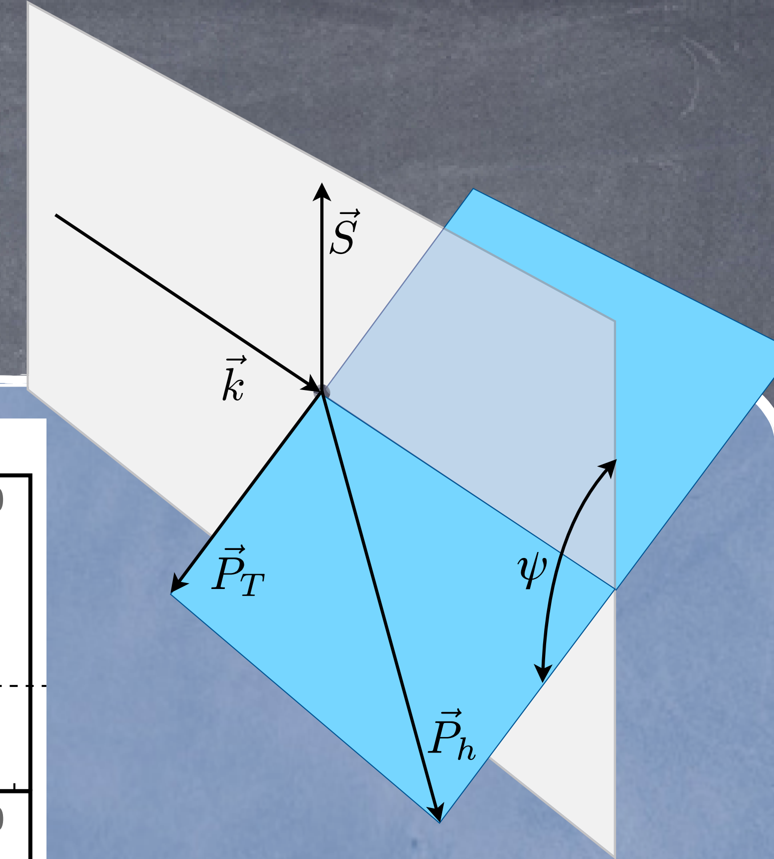




small detector effects in fully differential analysis

A_{UT} inclusive hadrons



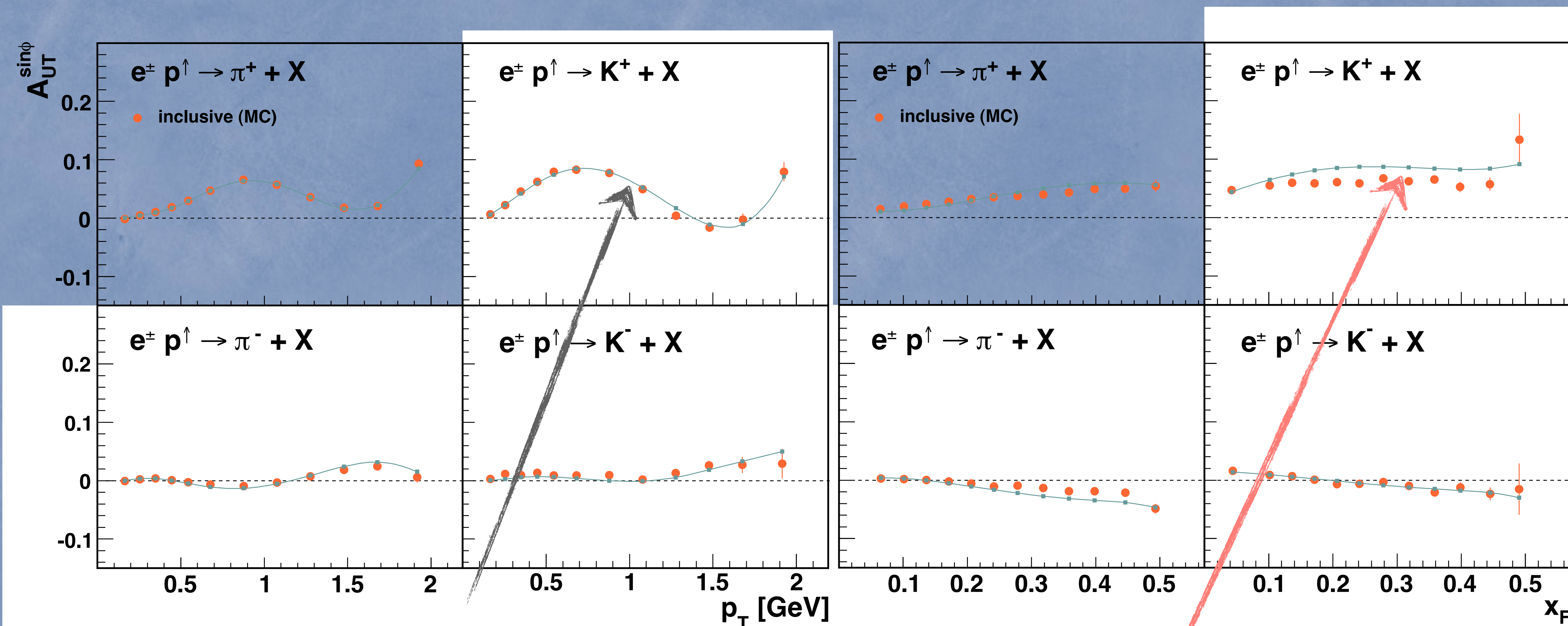


reconstructed MC

input model (fit to data)

small detector effects in fully differential analysis

A_{UT} inclusive hadrons



strong kinematic dependence can lead to large systematic effects if integrated over

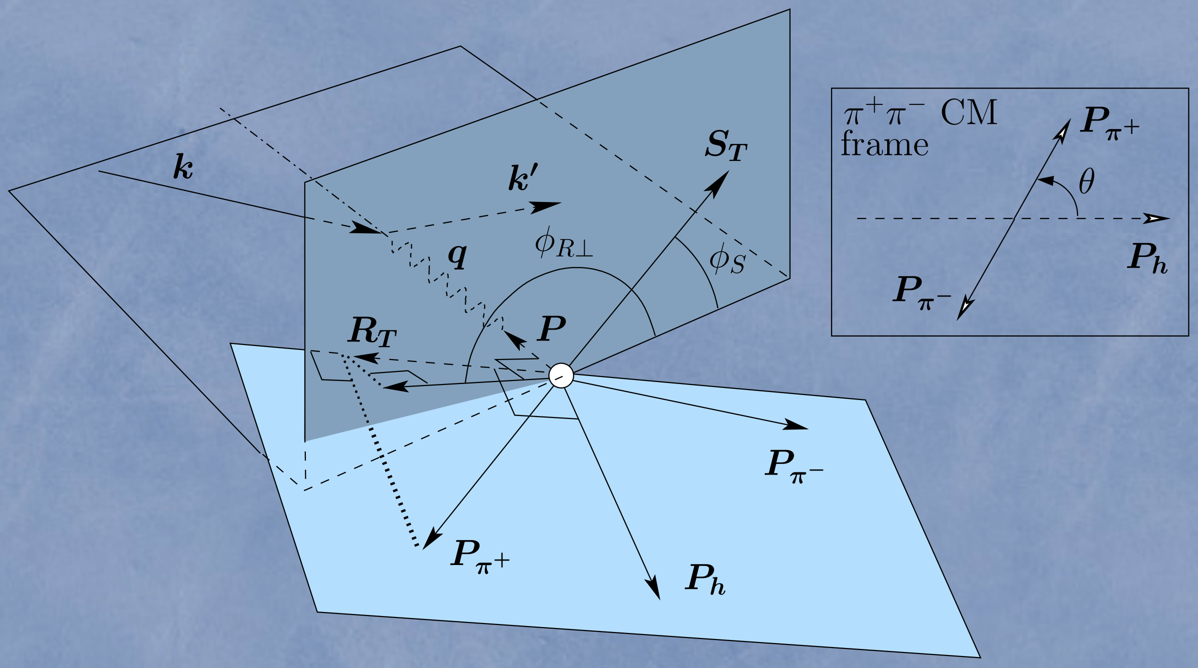
not so small detector effects in 1D analysis

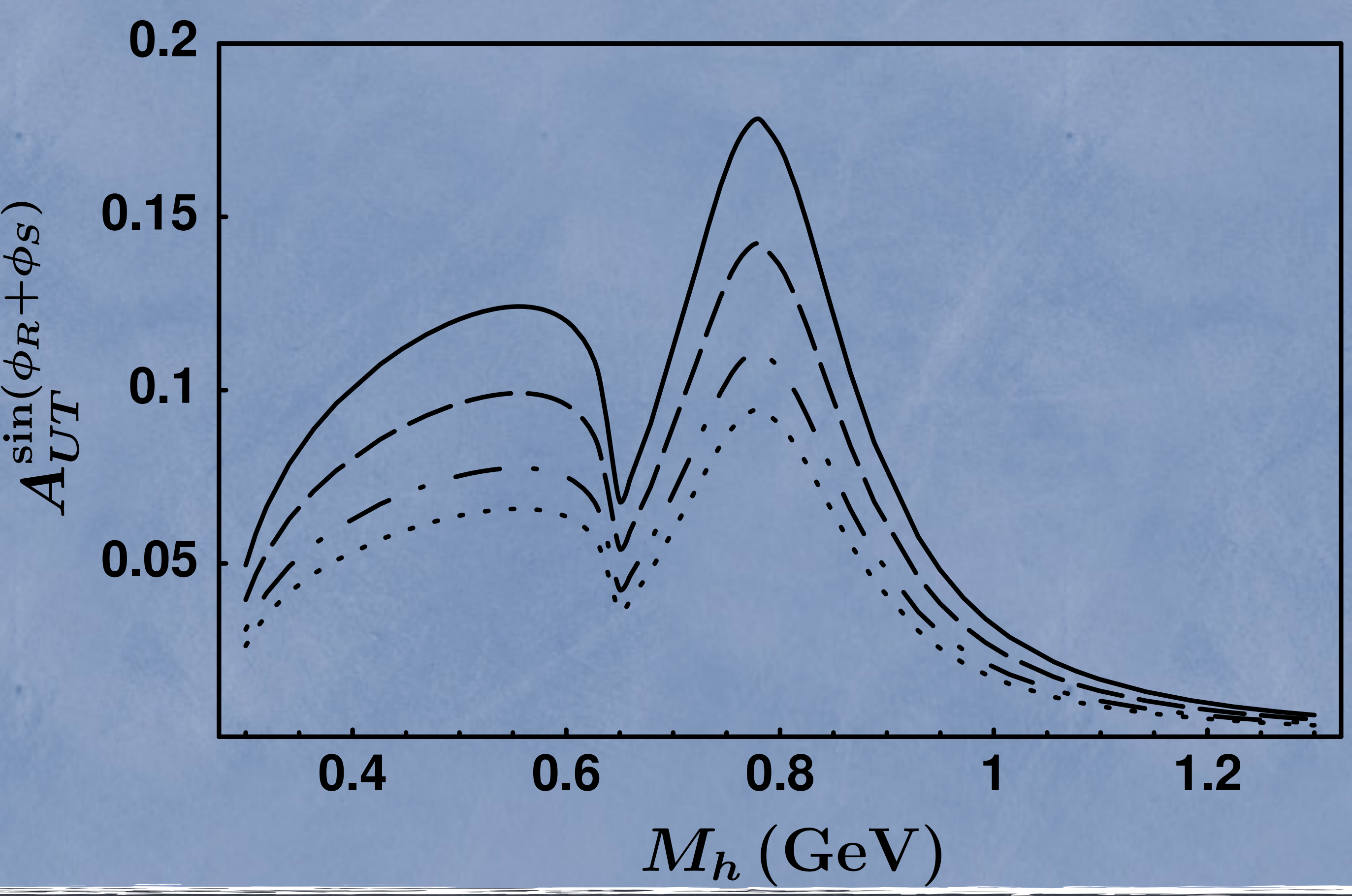
similar problem: di-hadron A_{UT}

$$N^{\uparrow(\downarrow)}(\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}) \propto \int \mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}^2\boldsymbol{P_{h\perp}}\,\epsilon(x,y,z,\boldsymbol{P_{h\perp}},\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}) \times \\ \times\ \sigma_{U\uparrow(\downarrow)}(x,y,z,\boldsymbol{P_{h\perp}},\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}),$$

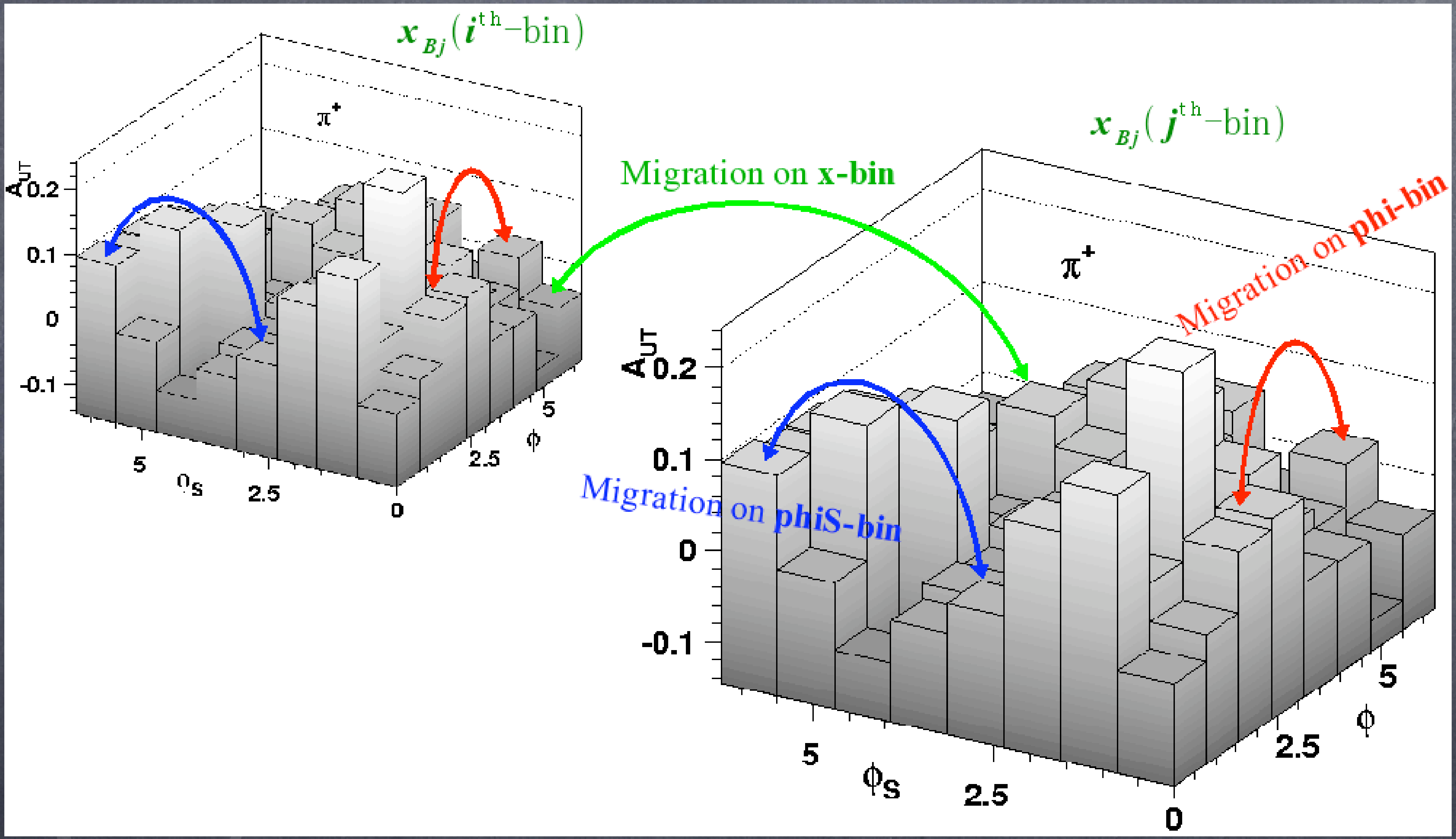
- many kinematic variables needed to describe process
- at least for one of them strong dependence expected:

[A. Bacchetta and M. Radici, Phys. Rev. D74 (2006) 114007]





… event migration …



- migration correlates yields in different bins
- can't be corrected properly in bin-by-bin approach

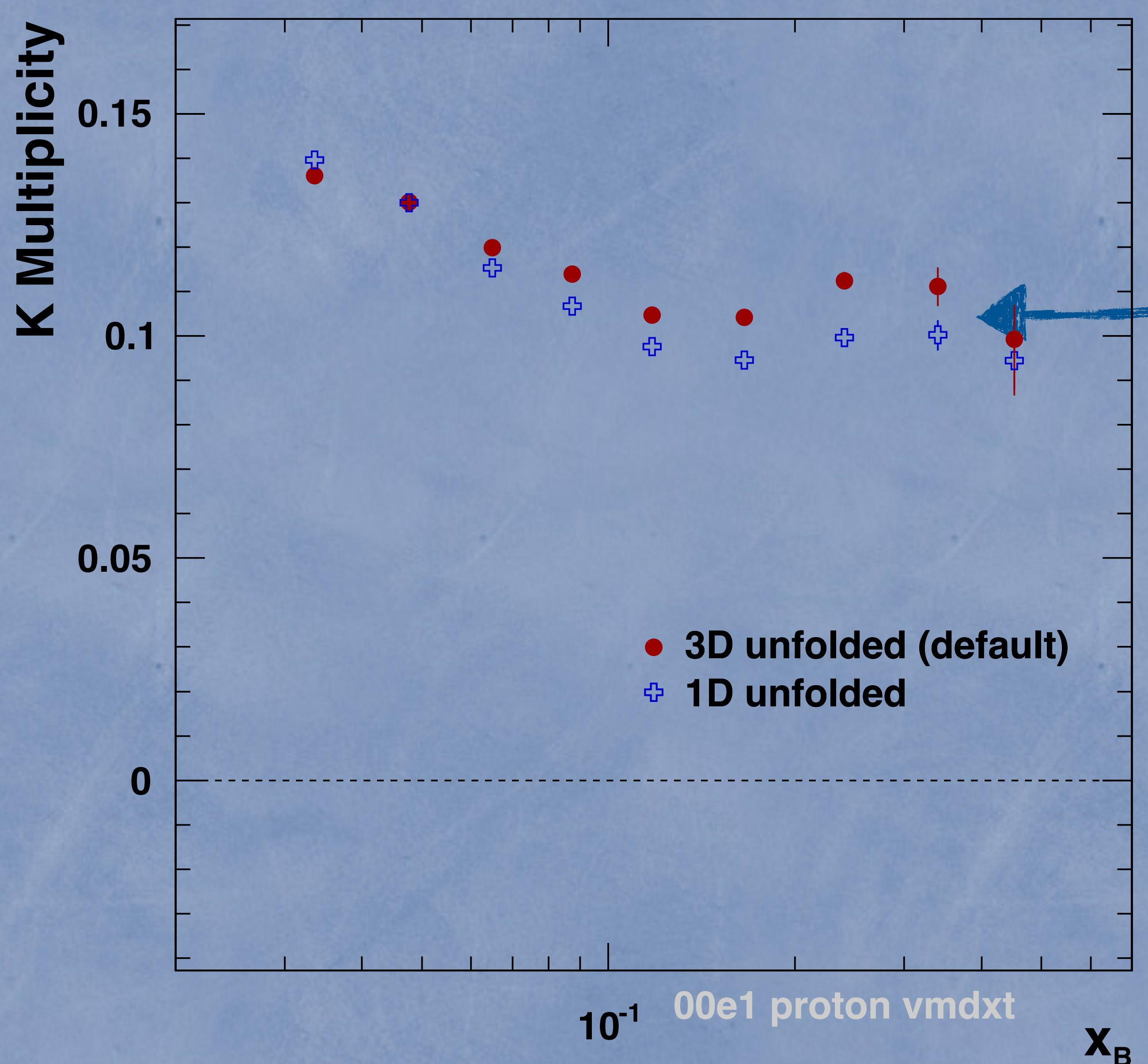
… event migration -> unfolding

$$\mathcal{Y}^{\mathrm{exp}}(\Omega_i) \propto \sum_{j=1}^{N} S_{ij} \int_j d\Omega \, d\sigma(\Omega) + \mathcal{B}(\Omega_i)$$

- experimental yield in i^{th} bin depends on all Born bins j …
- … and on BG entering kinematic range from outside region
- smearing matrix S_{ij} embeds information on migration
  - determined from Monte Carlo - independent of physics model in limit of infinitesimally small bins and/or flat acceptance/cross-section in every bin
  - in real life: dependence on BG and physics model due to finite bin sizes
- inversion of relation gives Born cross section from measured yields

Multi-D vs. 1D unfolding

[S.J. Joosten, PhD thesis UIUC (2013)]

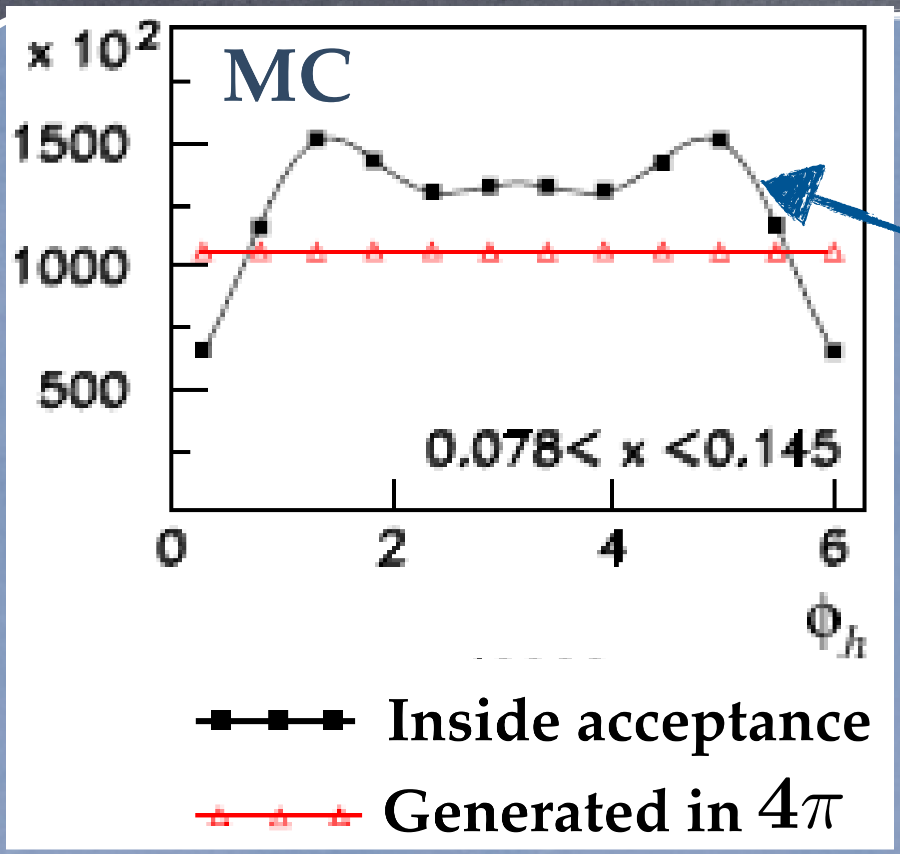


Neglecting to unfold in z changes x dependence dramatically

➡ 1D unfolding clearly insufficient

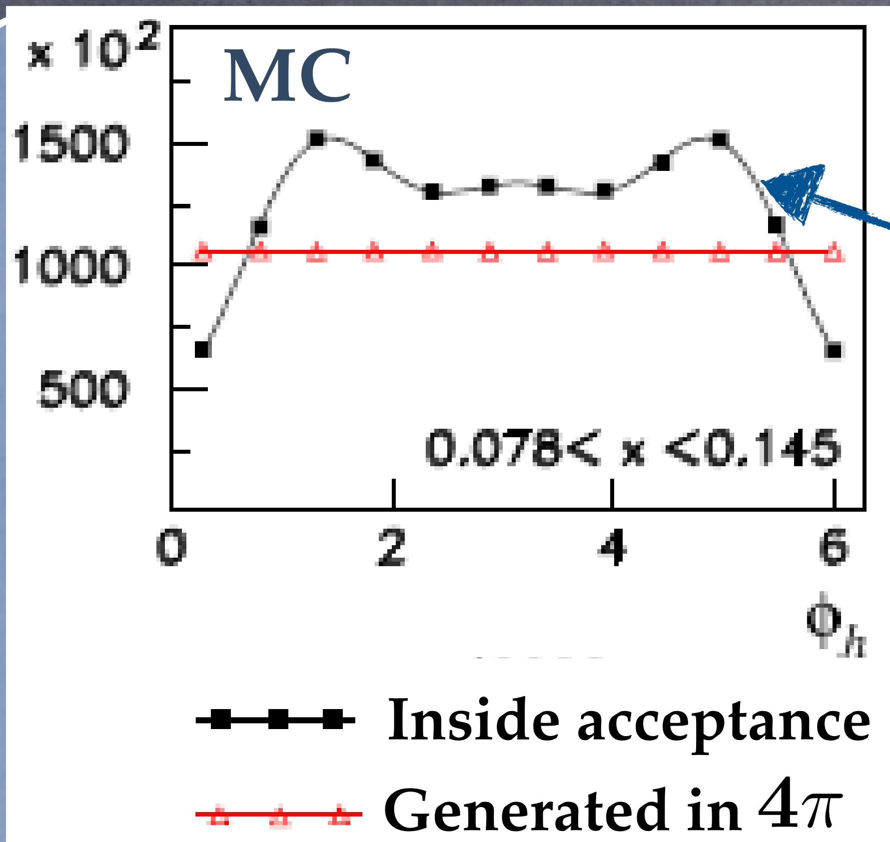
even though only interested in collinear observable, need to carefully consider transverse d.o.f.

Multi-D vs. 1D unfolding

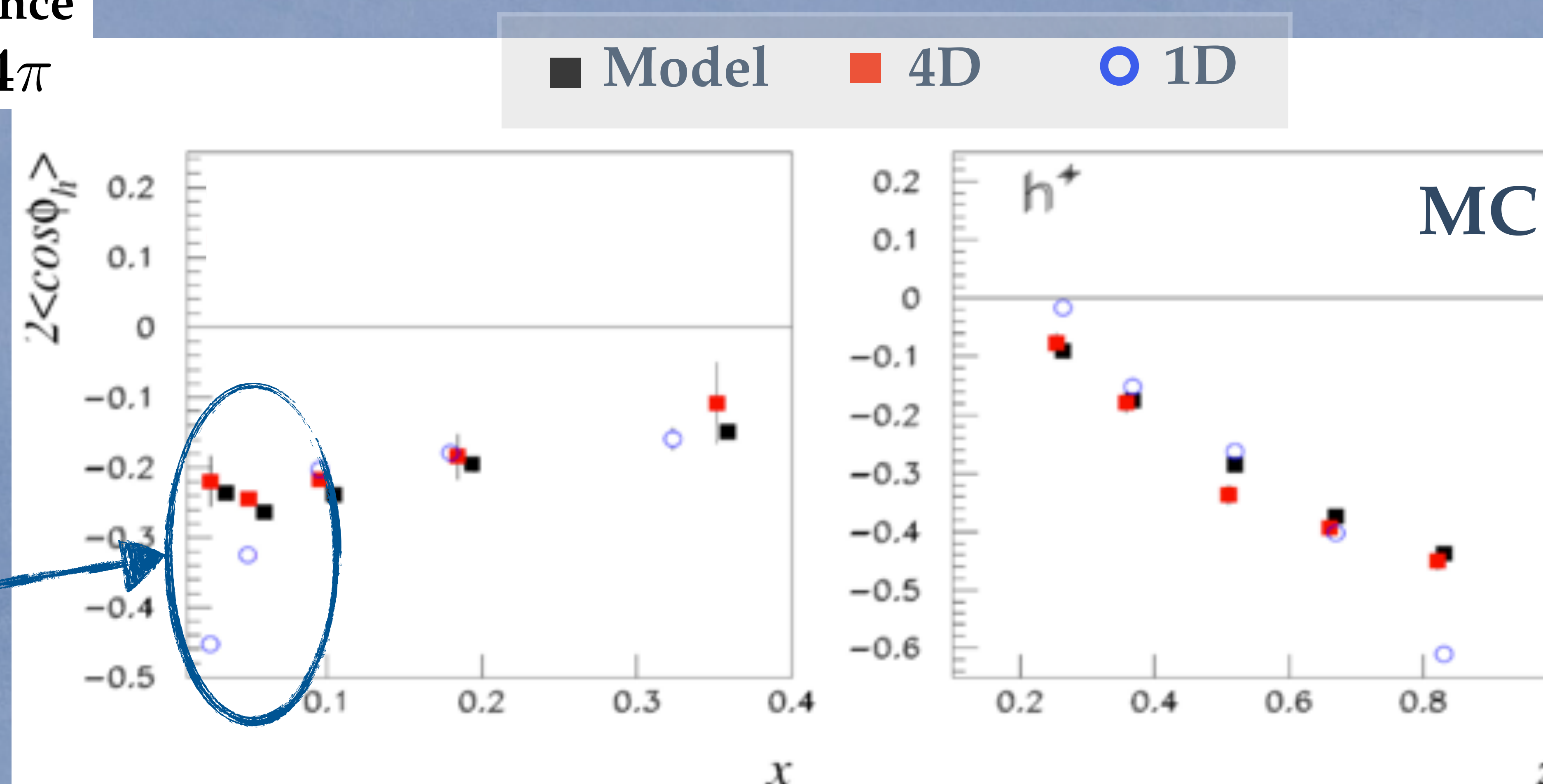


fully simulated yield with clear cosine modulations from migration and acceptance

Multi-D vs. 1D unfolding



fully simulated yield with clear cosine modulations from migration and acceptance

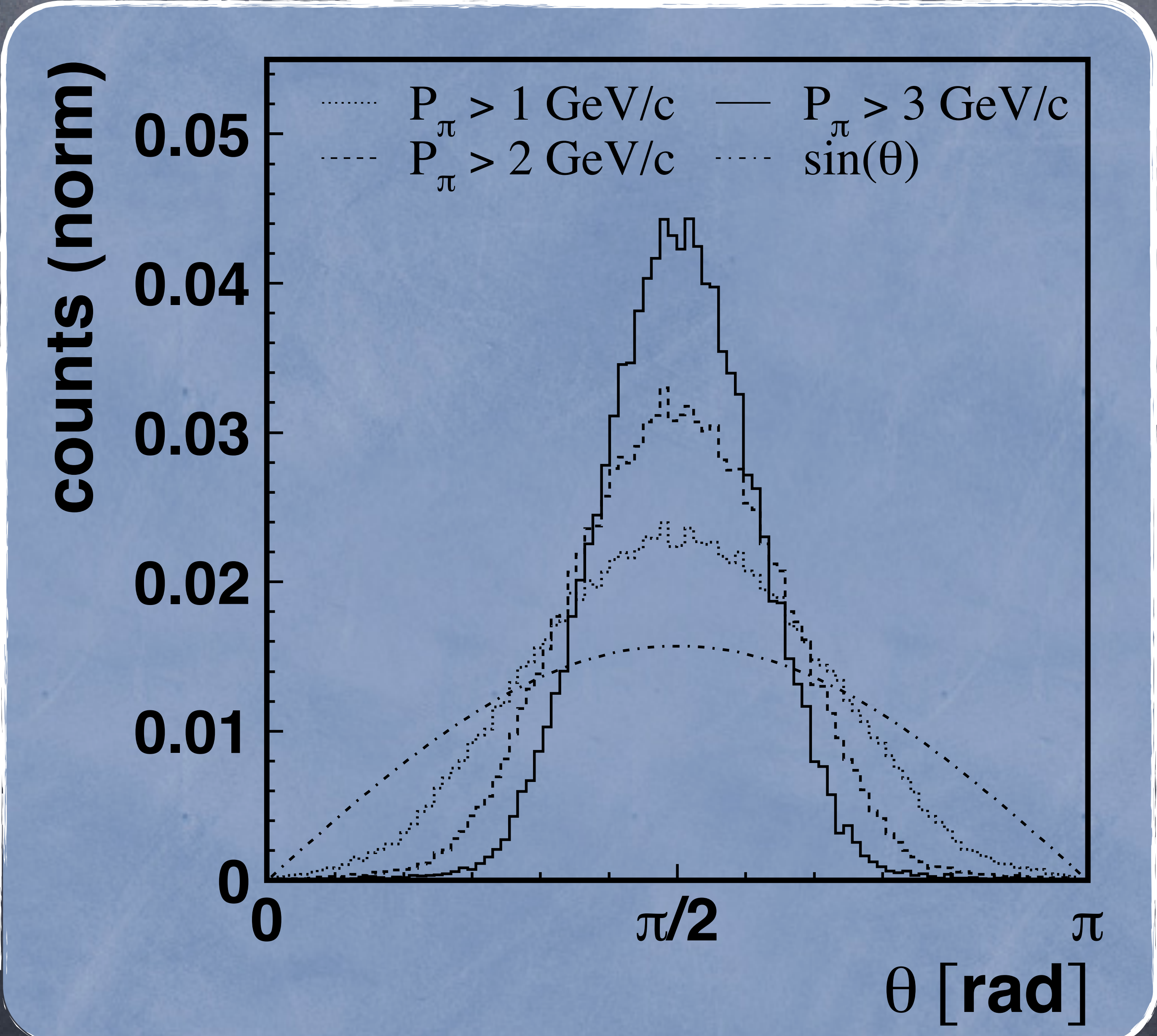


1D clearly not sufficient

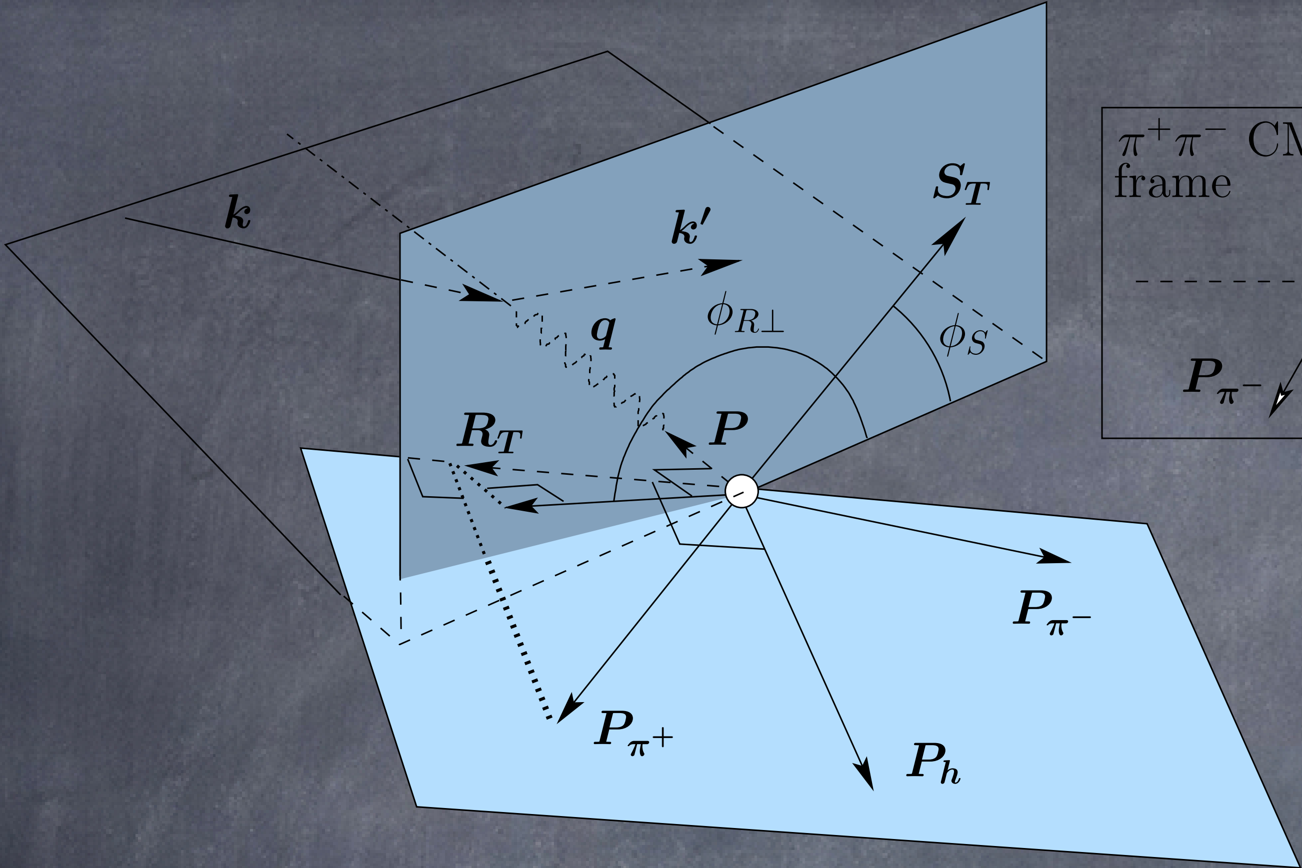
define your measurement wisely and clearly!

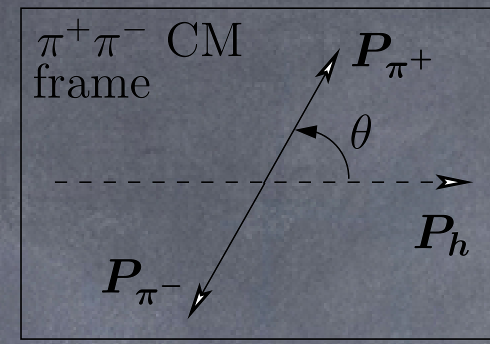
- data point interpreted as asymmetry/multiplicity
  - at the average kinematics given
  - integrated over kinematic ranges
- results in different systematics -> select the one with smallest systematics?
- try to go fully differential to minimize biases

more “pitfalls” in dihadron fragmentation



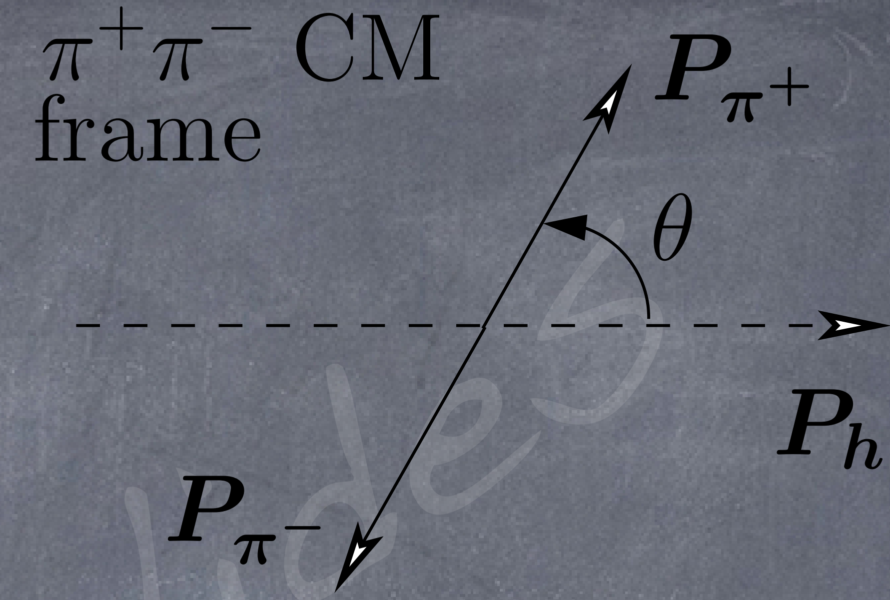
“appetizer”





- dihadron FFs: alternative path to extract (collinear) transversity
  - exploit orientation of hadron's relative momentum, correlate with target polarization
- complication: SIDIS cross section now differential in 9(!) variables
- integration over polar angle eliminates, in theory, a number of contributing FFs (partial waves)
- experimental constraints limit acceptance in polar angle, most prominently the minimum-momentum requirements

simple case study



basic assumptions:

- dihadron pair with equal-mass hadrons; here: pions
- e^+e^- annihilation, thus energy fractions z translates directly to energy/momentum of particles/system as primary energy is "fixed"
  (-> simplifies Lorentz boost)
- without loss of generality, focus on B factory and use primary quark energy E_0 = 5.79GeV
- minimum energy of each pion in lab frame: 0.1 E_0
  (i.e., z_{min} = 0.1)

application of Lorentz boost

- can easily apply Lorentz boost using the invariant mass of the dihadron M and its energy zE_0 to arrive at condition on θ, e.g., polar angle of pions in center-of-mass frame:

$$\cos\theta \leq \frac{z - 2z_{\min}}{\sqrt{[(zE_0)^2 - M^2)(M^2 - 4m_\pi^2)]}} E_0 M$$

- as both pions have to fulfill the constraint on the minimum energy:

$$\cos(\pi - \theta) = -\cos\theta \leq \frac{z - 2z_{\min}}{\sqrt{[(zE_0)^2 - M^2)(M^2 - 4m_\pi^2)]}} E_0 M$$

thus:

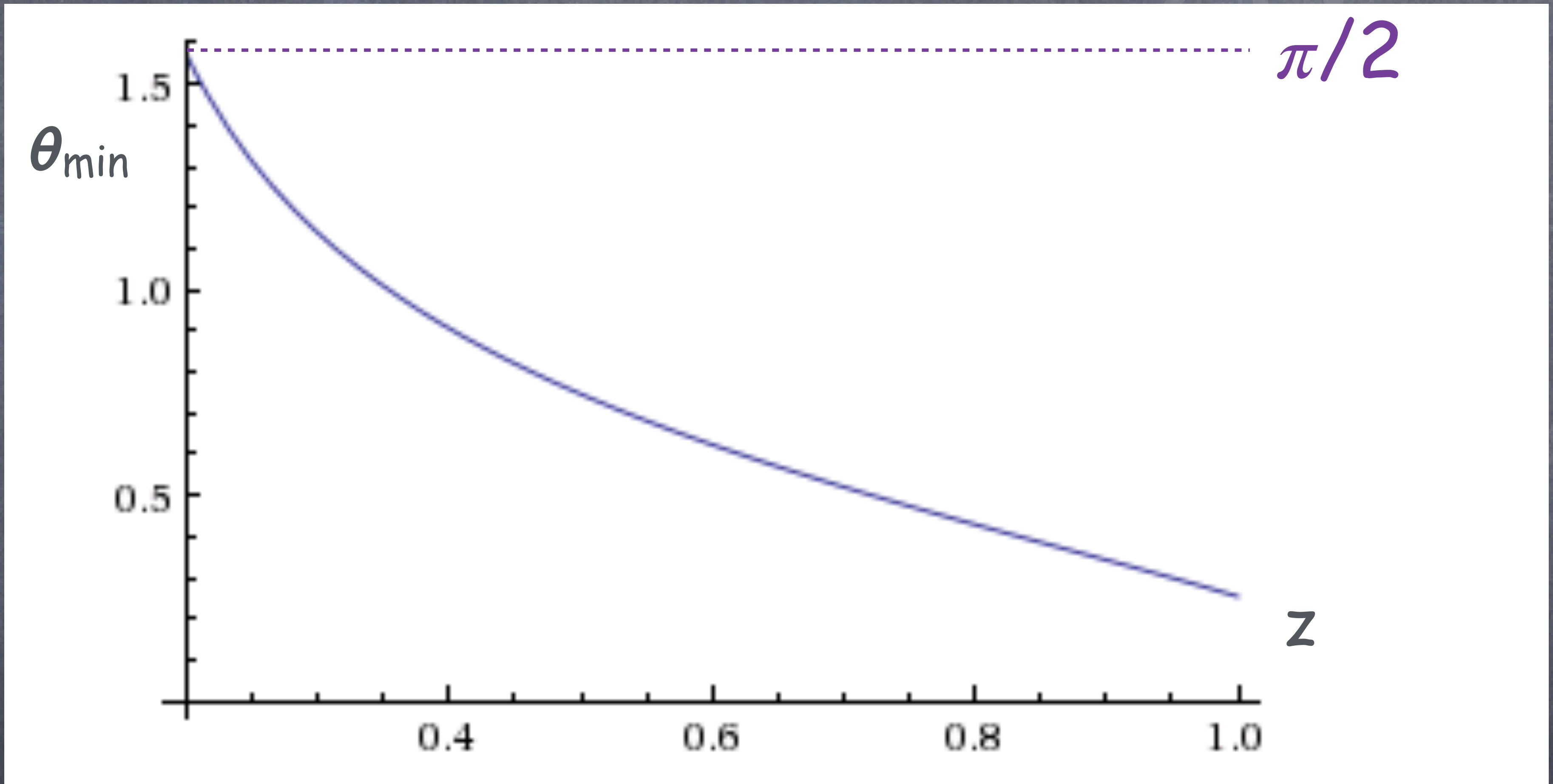
$$|\cos\theta| \leq \frac{z - 2z_{\min}}{\sqrt{[(zE_0)^2 - M^2)(M^2 - 4m_\pi^2)]}} E_0 M$$

- translates to a symmetric range around $\pi/2$

(can be easily understood because at $\pi/2$ the pions will have both the same energy in the lab and easily pass the z_{min} requirement, while in the case of one pion going backward in the CMS, that pion will have less energy in the lab frame ... and maybe too little)

impact of z_{min}=0.1 on accepted polar range

- (again without loss of generality) let's assume M=0.5 GeV :



- all theta below curve (and above its mirror curve relative to dashed line) are excluded
- clearly limited, especially at low z

partial-wave expansion

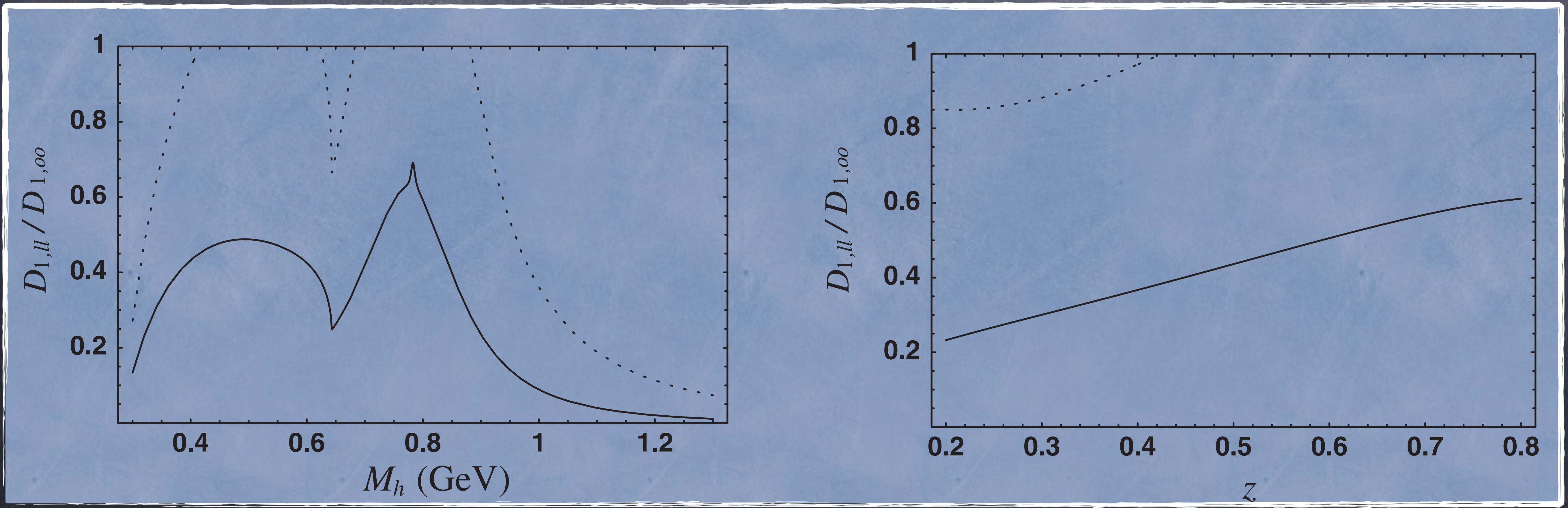
- partial-wave expansion worked out in Phys. Rev. D67 (2003) 094002
- for the particular case here, use Phys. Rev. D74 (2006) 114007, in particular Eq. (12), and (later on) Figure 5:

$$D_1^q(z, \cos\theta, M_h^2) \approx D_{1,oo}^q(z, M_h^2) + D_{1,ol}^q(z, M_h^2)\cos\theta + D_{1,ll}^q(z, M_h^2)\tfrac{1}{4}(3\cos^2\theta - 1), \qquad (12)$$

- it is the first contribution ($D_{1,oo}$) that is used in "collinear extraction" of transversity (and subject of a current Belle analysis)
  - it is also the only one surviving the integration over θ
- the $D_{1,ol}$ contribution vanishes upon integration over θ as long as the theta range is symmetric around $\pi/2$ (as it is the case here)
- the $D_{1,ll}$ term, however, will in general contribute in case of only partial integration over θ — the question is how much?

$D_{1,ll}$ contribution to DiFF

- $D_{1,ll}$ is unknown and can't be calculated using first principles
- it can not be extracted from cross sections integrated over θ
- upon (partial) integration there is no way to disentangle the two contributions
- in PRD74 (2006) 114007, a model for dihadron fragmentation was tuned to PYTHIA and used to estimate the various partial-wave contributions
- its Figure 5 gives an indication about the relative size of $D_{1,ll}$ vs. $D_{1,oo}$:



effect of partial integration

- as both contributions — $D_{1,ll}$ and $D_{1,oo}$ — will be affected by the partial integration, look at relative size of the $D_{1,ll}$ to $D_{1,oo}$ modulations when subjected to integration:

$$\frac{D_{1,ll}}{D_{1,oo}} \, \frac{\int_{\cos(\pi-\theta_0)}^{\cos\theta_0} \mathrm{dcos}\,\theta \, \frac{1}{4}(3\cos^2\theta - 1)}{\int_{\cos(\pi-\theta_0)}^{\cos\theta_0} \mathrm{dcos}\,\theta} = -\frac{1}{4}(1-\cos^2\theta_0)\,\frac{D_{1,ll}}{D_{1,oo}}$$

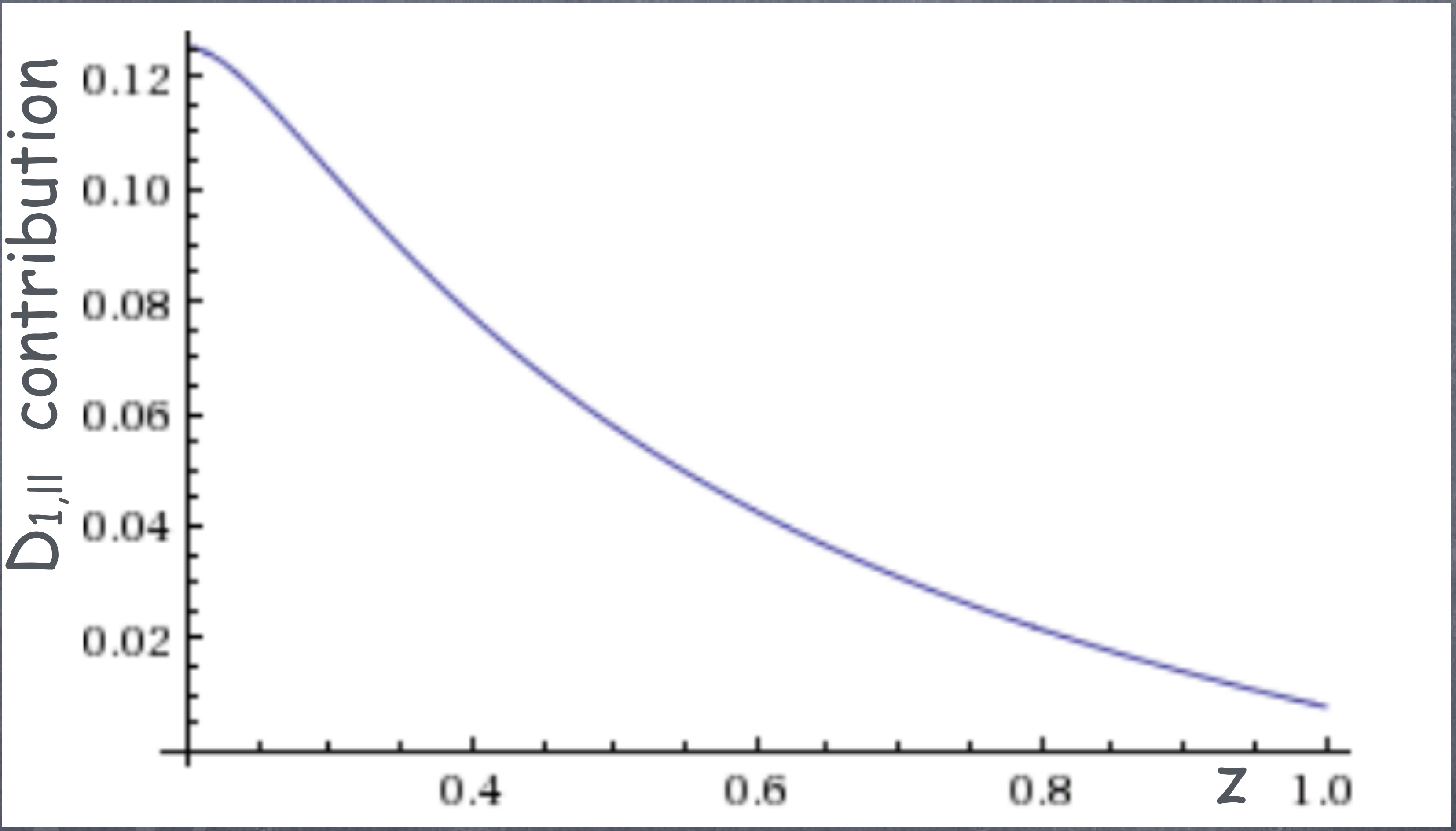
- without limit in the polar-angular range (θ_0 =0) -> no contribution from $D_{1,ll}$ (sanity check!)

- the relative size of the partial integrals reaches a maximum of 25% for z=0.2 (i.e., pions at 90 degrees in center-of-mass system)

- in order to estimate the $D_{1,ll}$ contribution, one "just" needs the relative size of $D_{1,ll}$ vs. $D_{1,oo}$, e.g., Figure 5 of PRD74 (2006) 114007
  - let's take for that size 0.5 (rough value for M=0.5 GeV)

effect of partial integration

- ... $D_{1,ll}$ / $D_{1,oo}$ ~0.5 results in an up to O(10%) effect on the measured cross section:

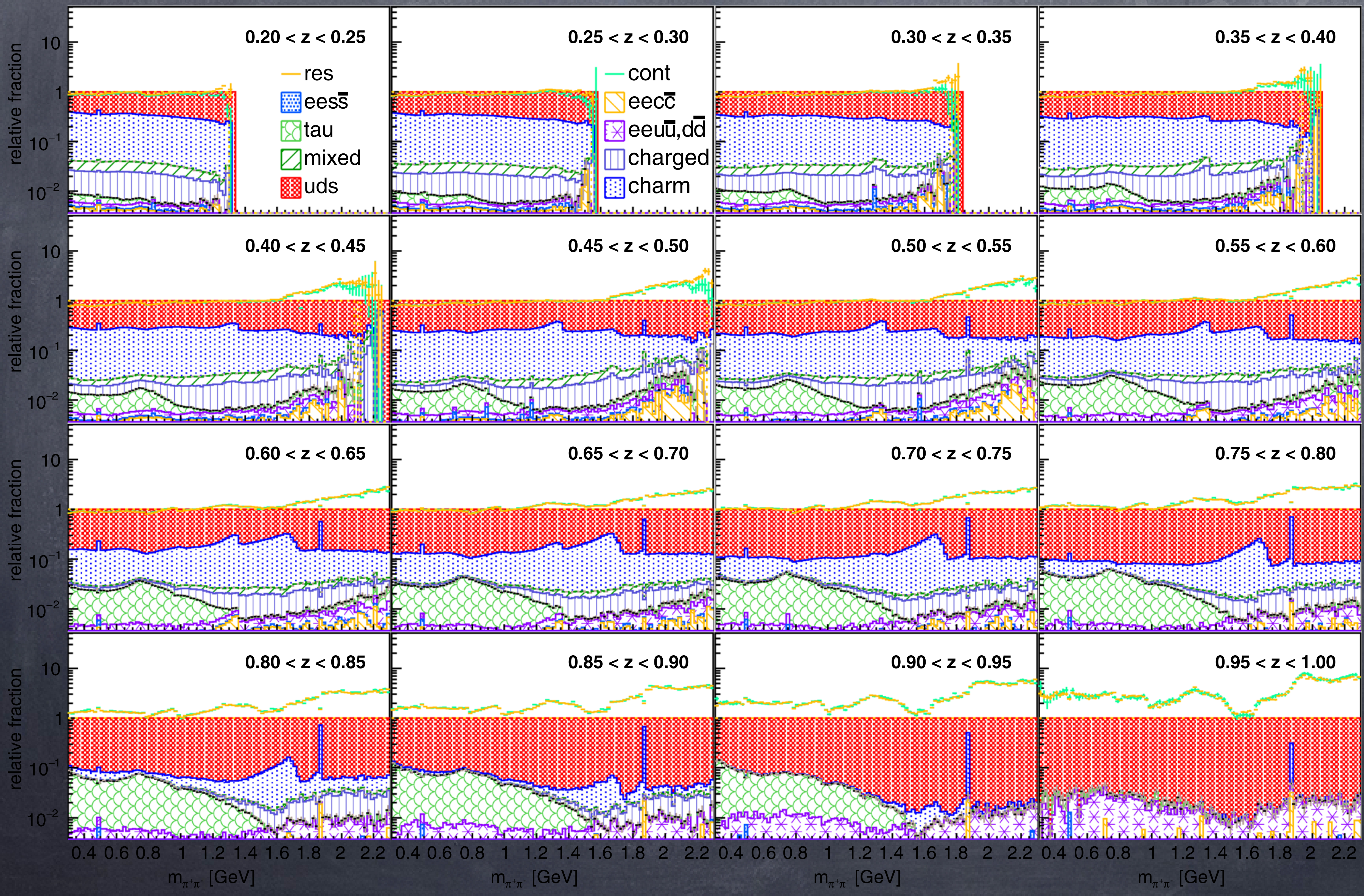


- depending on the sign of $D_{1,ll}$, the partial integration thus leads to a systematic **underestimation** (positive $D_{1,ll}$) or **overestimation** (negative $D_{1,ll}$) **of the "integrated" dihadron cross section**
  - **leads to overestimate/underestimate of extracted transversity**

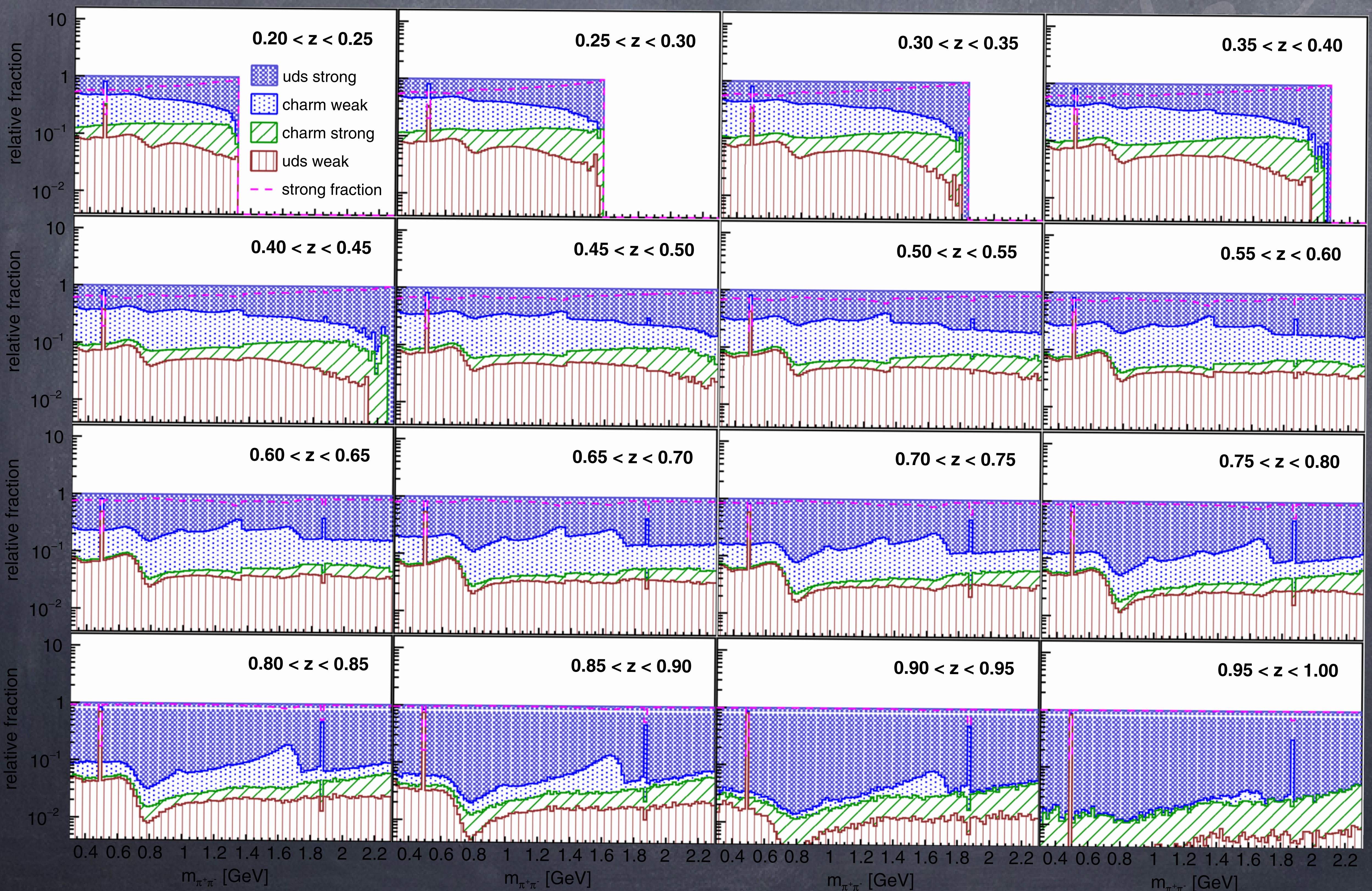
back to experiment

- how precisely can we measure FFs, e.g., how precisely can we deal with other-than-uds contributions

subprocess contributions



weak contributions



resonance contributions