PANDA collaboration meeting

June 15, 2021

GPD Measurements with Antiproton Scattering

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Stefan Diehl

Justus Liebig University Giessen

University of Connecticut

Introduction

Antiproton Annihilation: Study of GDAs (time like GPDs) $p\bar{p} \rightarrow \gamma M$

➔ Unique for annihilation experiments

see Faizas talk

Antiproton Scattering: Measure space like GPDs with PANDA as they are currently studied i.e. in hard exclusive electroproduction experiments

➔ Well developed theoretical framework

Physics content: spatial structure of the nucleon, pressure distributions, shear forces, …

Experimental method: Lepton-pair production in hard exclusive hadronic collisions

$$A\,B \rightarrow A\,B\,l^{+}\,l^{-}$$

➔ Exclusive analogue of the Drell-Yan process

Theoretical Description

Lepton-pair production in hard exclusive hadron-hadron collisions

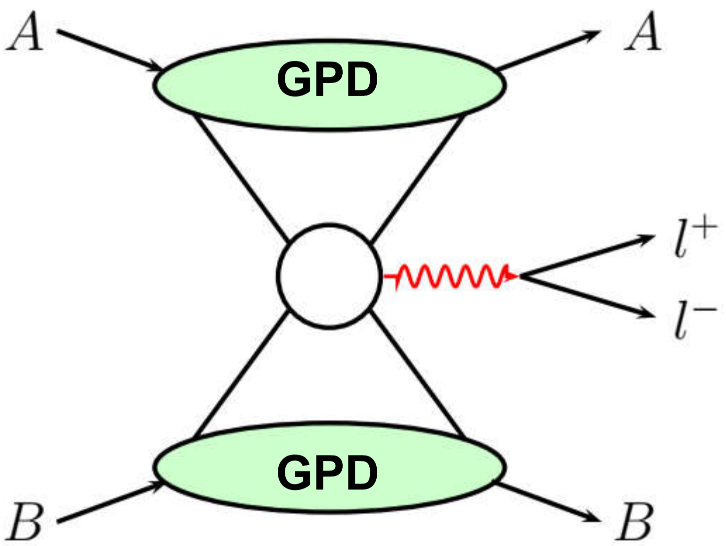
S.V. Goloskokov [§1], P. Kroll [†2] and O. Teryaev [§‡3]

§: *Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna 141980, Moscow region, Russia*
†: *Fachbereich Physik, Universität Wuppertal, D-42097 Wuppertal, Germany*
‡ : *Veksler and Baldin Laboratory of High Energy Physics, Dubna 141980, Moscow region, Russia*

arXiv:2008.13594v1 [hep-ph] 31 Aug 2020

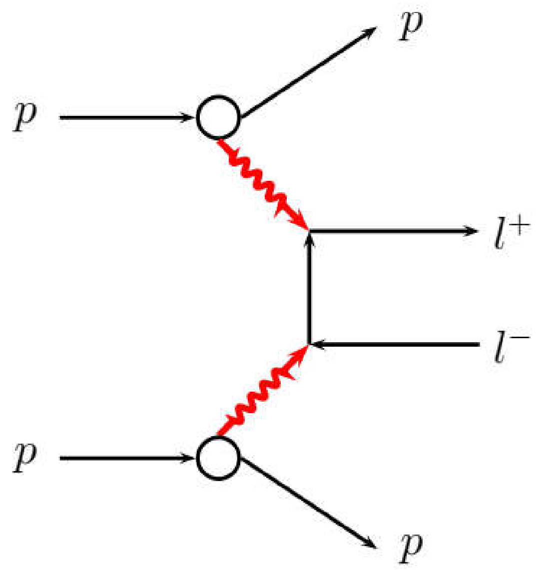
➔ Theoretical description based on the handbag approach

Theoretical Description



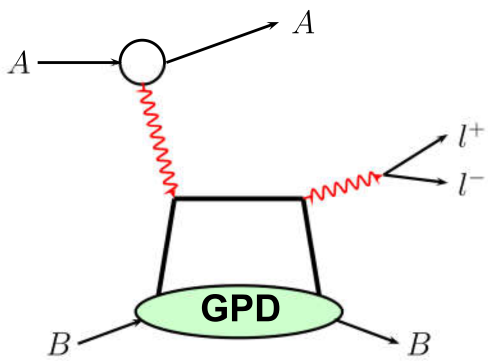
Double handbag for exclusive lepton-pair production in hadron-hadron collisions

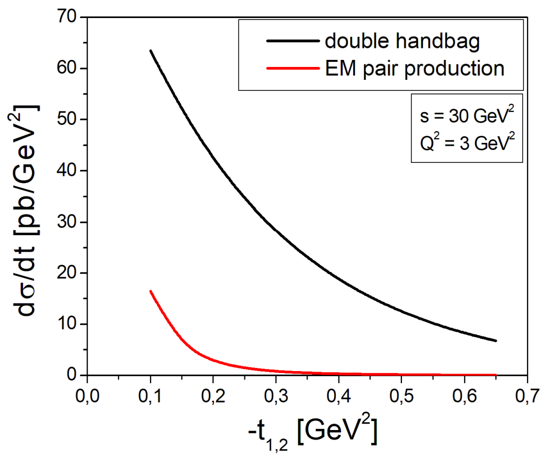
electromagnetic lepton pair poduction



TVCS process:

- much smaller cross section expected





➔ **Only relevant for -t < 0.2 - 0.3**

Theoretical Description and Physics Content

PANDA kinematic domain: Process dominated by helicity non-flip vertices

Vertices can be described by $H_{\text{eff}} = H - \frac{\xi_i^2}{1-\xi_i^2} E$

→ Contributions from the GPD E and other GPDs are epxted to be small

➔ **Process is dominated by the GPD H**

$$\frac{d\sigma(pp \to pp\, l^+ l^-)}{dt_1 dt_2 dQ^2} = \frac{1}{3(4\pi)^5} \frac{\alpha_{\text{em}}}{s^2 Q^2} \int \frac{ds_1 ds_2}{\sqrt{-\Delta_4}} |\mathcal{M}|^2$$

↳ **contains GPDs**

Expectation for particle vs antiparticle GPDs (universality):

$$H_{\bar{p}}^{\bar{a}}(x_2, \xi_2, t_2) = H^a(x_2, \xi_2, t_2), \qquad H_{\bar{p}}^{g}(x_2, \xi_2, t_2) = H^g(x_2, \xi_2, t_2).$$

What can we learn from the GPD *H* ?

- GPDs provide indirect access to mechanical properties of the nucleon (encoded in gravitational form factors of the energy-momentum tensor)

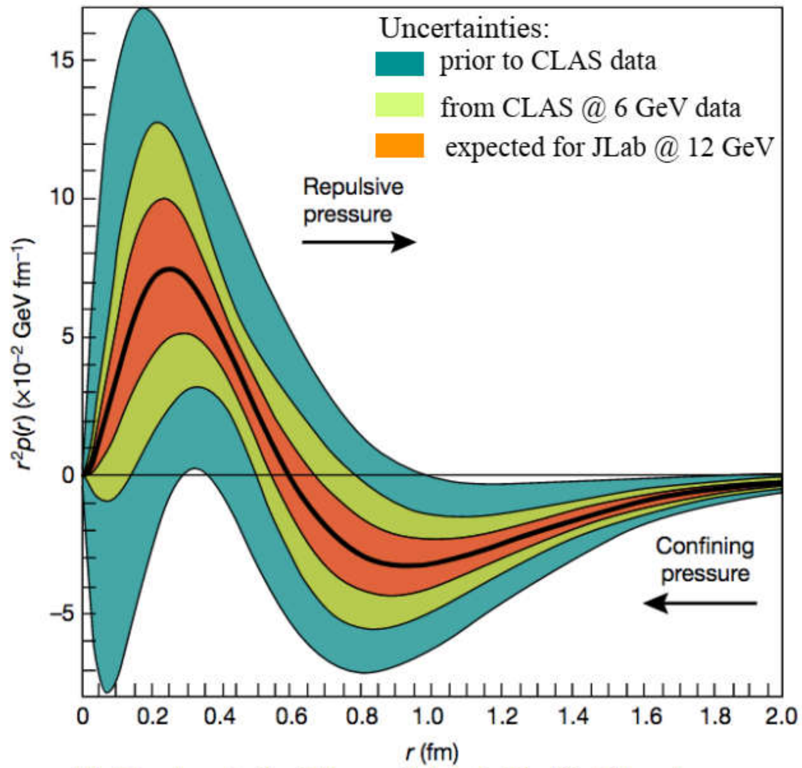
X. D. Ji, PRD **55**, 7114-7125 (1997) M. Polyakov, PLB **555**, 57-62 (2016)

<u>GFFs are related to GPDs via sum rules</u>:

$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,\mathrm{d}x = 2J(t)$$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t)+\frac{4}{5}\xi^2 d_1(t)$$

angular momentum (J), mass (M_2), pressure and shear forces (d_1)



V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature **557**, 396-399 (2018)

K. Kumerički, Nature **570**, E1-E2 (2019)

➔ Posibility to extract pressure distributions

➔ More data needed to constrain the d-term

➔ **Strongly model dependent!**

Goals for PANDA

1. Proove the factorisation of the proposed process and check where factorisation sets in (controversal in theory!)

$$\frac{d\sigma(pp \to pp\, l^+ l^-)}{dt_1 dt_2 dQ^2} = \frac{1}{3(4\pi)^5} \boxed{\frac{\alpha_{\rm em}}{s^2 Q^2}} \int \frac{ds_1 ds_2}{\sqrt{-\Delta_4}} |\mathcal{M}|^2 \quad \Big\} \sim 1/Q^2$$

➔ Investigate the Q^2 dependence of the cross section

2. Extract the GPD H from fits to the measured cross sections

➔ Proove the universality of GPDs (e^- vs $\bar{p}$ vs p scattering)

➔ Reduce model dependent aspects (double vs single handbag, ….)

➔ Provide additional constraints for the GPD parametrisation

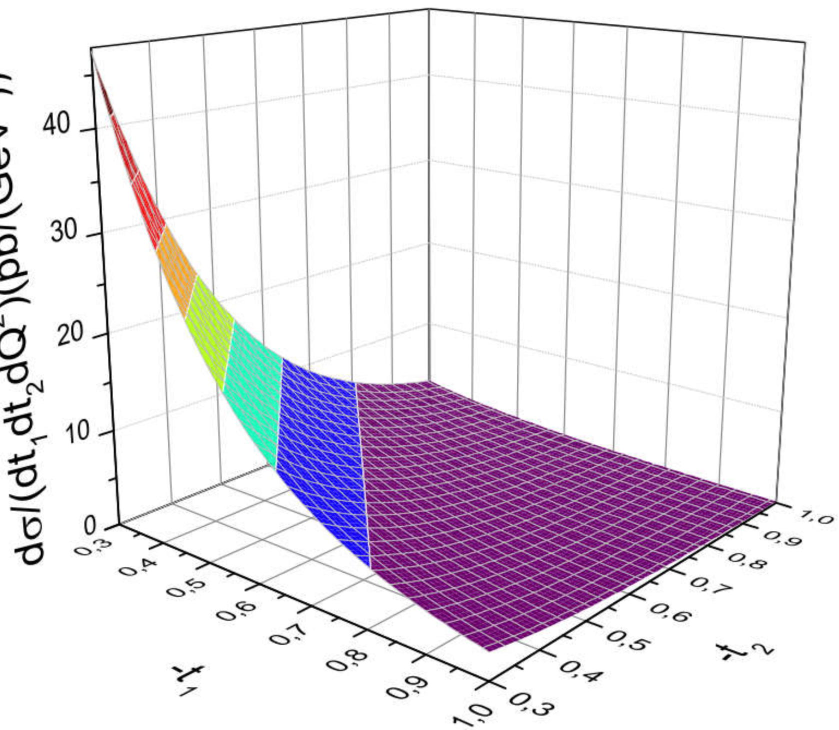
Observables

$$t_1 = (p_{target} - p'_p)^2$$

$$t_2 = (p_{beam} - p'_{\bar{p}})^2$$

$$Q^2 = p^2_{\gamma^*} = (p_{e^+} + p_{e^-})^2$$

factorisation for: $t_i / Q^2 << 1$



The $p\bar{p} \to p\bar{p}l^+l^-$ cross section in $pb/\ \mathrm{GeV}^6$ versus t_1 and t_2

$s = 30\ \mathrm{GeV}^2$, $Q^2 = 3\ \mathrm{GeV}^2$

Feasability Studies

➔ PANDAroot (latest dev version) simulations with a phase space event generator

2 final states have been studied: $p\bar{p} \rightarrow p\bar{p}\gamma^* \rightarrow \begin{cases} p\bar{p}e^+e^- \\ p\bar{p}\mu^+\mu^- \end{cases}$

3 beam momenta have been studied:

$s = 10\ GeV^2$	($p \sim 4.3$ GeV/c)	20M events
$s = 20\ GeV^2$	($p \sim 9.7$ GeV/c)	20M events
$s = 30\ GeV^2$	($p \sim 15$ GeV/c)	30M events

➔ Smaller beam momenta can not provide sufficiently high Q^2

Expected background and PID

Main background channel: $p\bar{p} \rightarrow p\bar{p}\pi^{+}\pi^{-}$

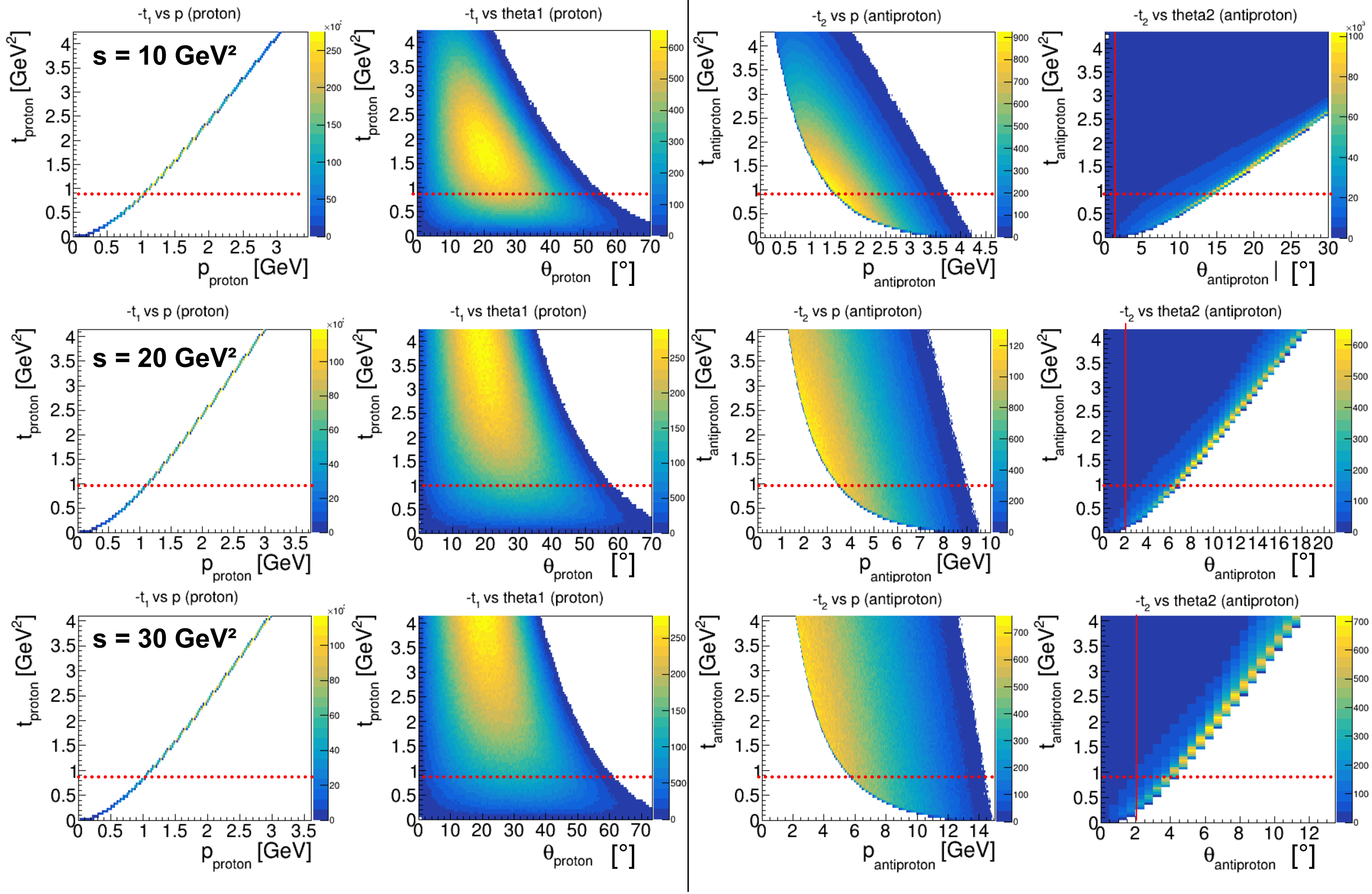
Signal: $p\bar{p} \rightarrow p\bar{p}\gamma^{*} \rightarrow \begin{cases} p\bar{p}e^{+}e^{-} \\ p\bar{p}\mu^{+}\mu^{-} \end{cases}$

A good lepton PID is essential!

The following PID algorithms have been applied and the strictness is set individually for each system:

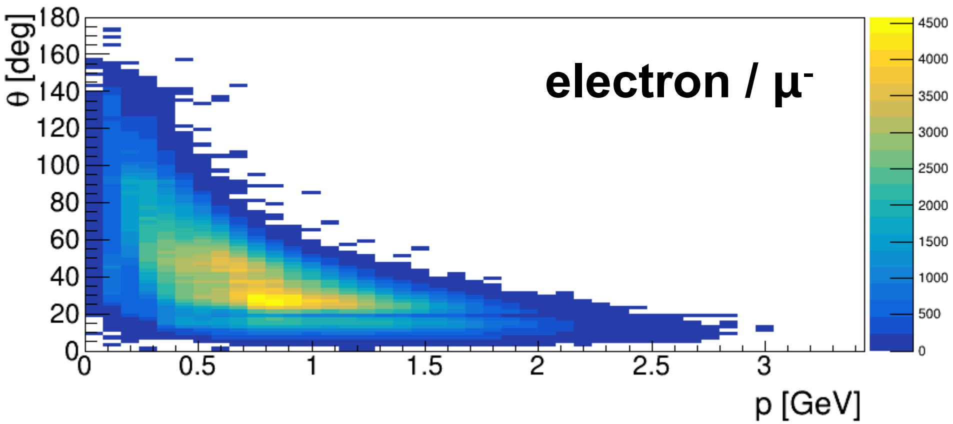
e^{-}, e^{+} and baryons	muons
PidAlgoMvd, PidAlgoStt, PidAlgoDrc, PidAlgoDisc, PidAlgoEMCBayes, PidAlgoSciT, PidAlgoRich, PidAlgoFtof	PidAlgoMdtHardCuts

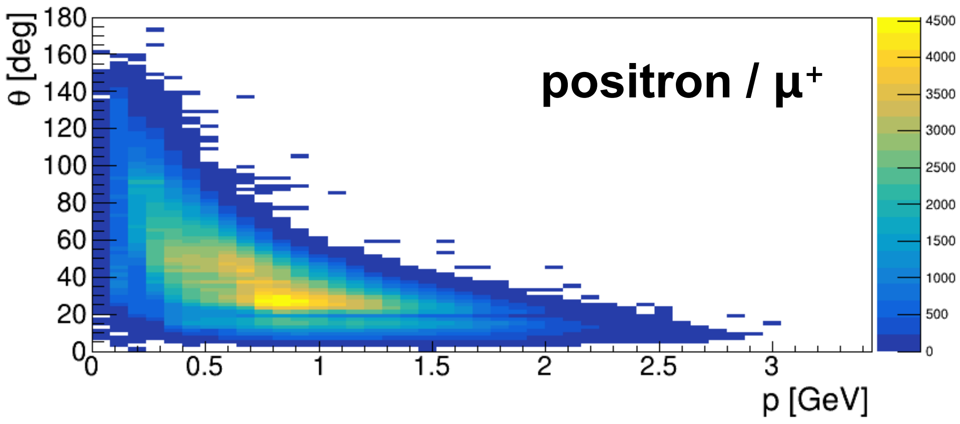
Generated Particle Distributions vs -t



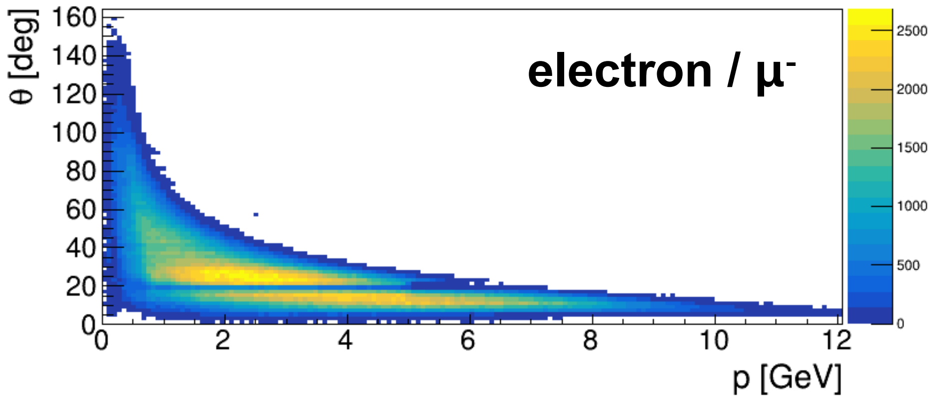
Generated Lepton Distributions

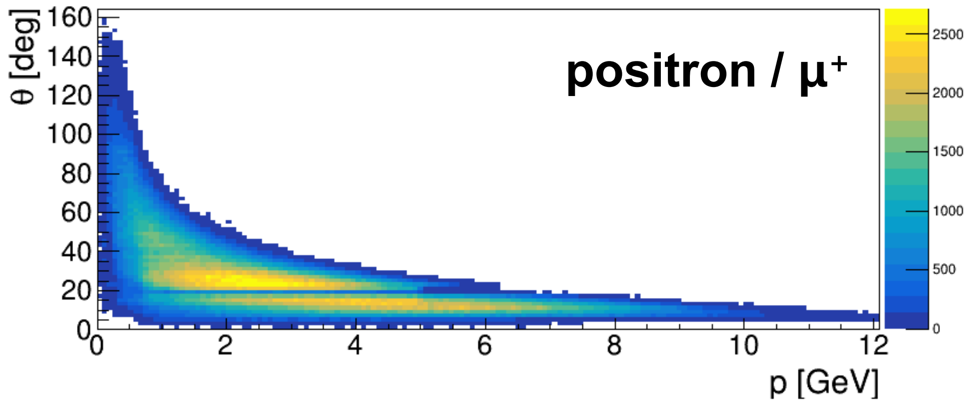
s = 10 GeV²





s = 30 GeV²





Topology 1

• All final state particles detected

➔ Event selection via a 4C kinematic fit (prob > 0.03)

➔ Especially at high beam momenta the detection of antiprotons is critical

➔ Two PID variants have been investigated

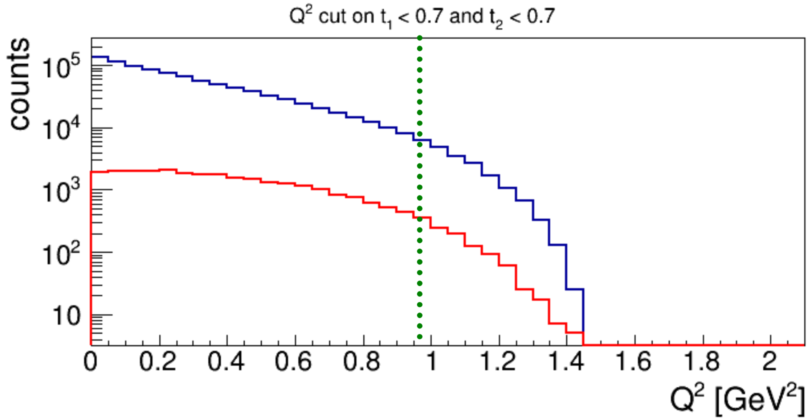
a) Loose PID for proton and antiprotons, tight PID for Leptons

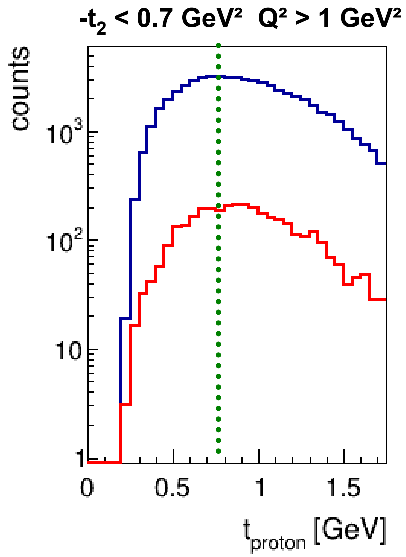
b) Tight PID for baryons and leptons

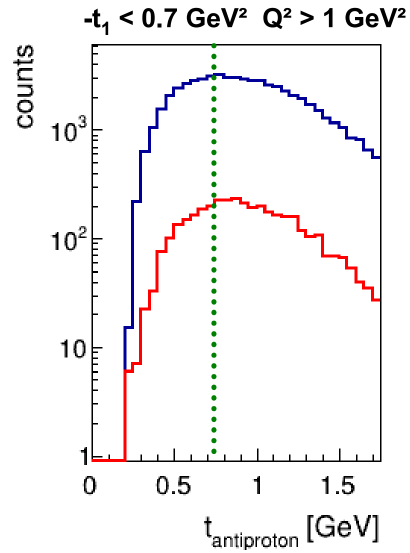
➔ **Version a)** was found to provide the best compromise between acceptance / PID capability for antiprotons and background rejection

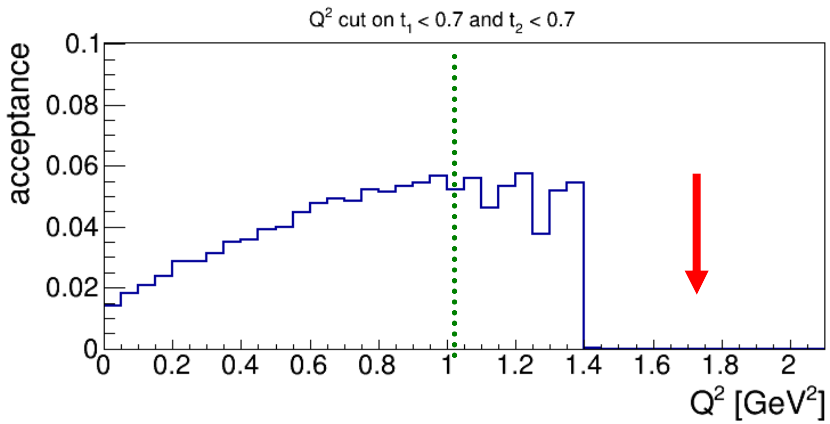
$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$ @ s = 10 GeV²

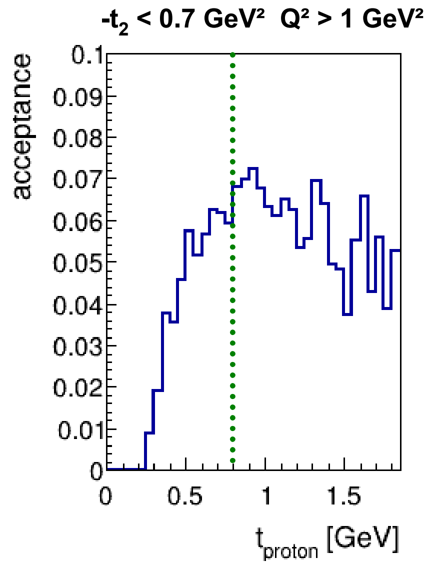
generated — reconstructed

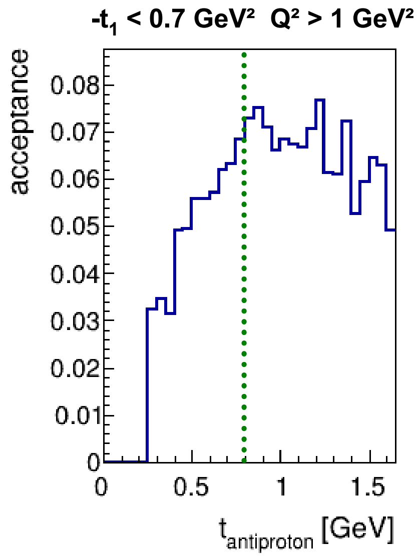




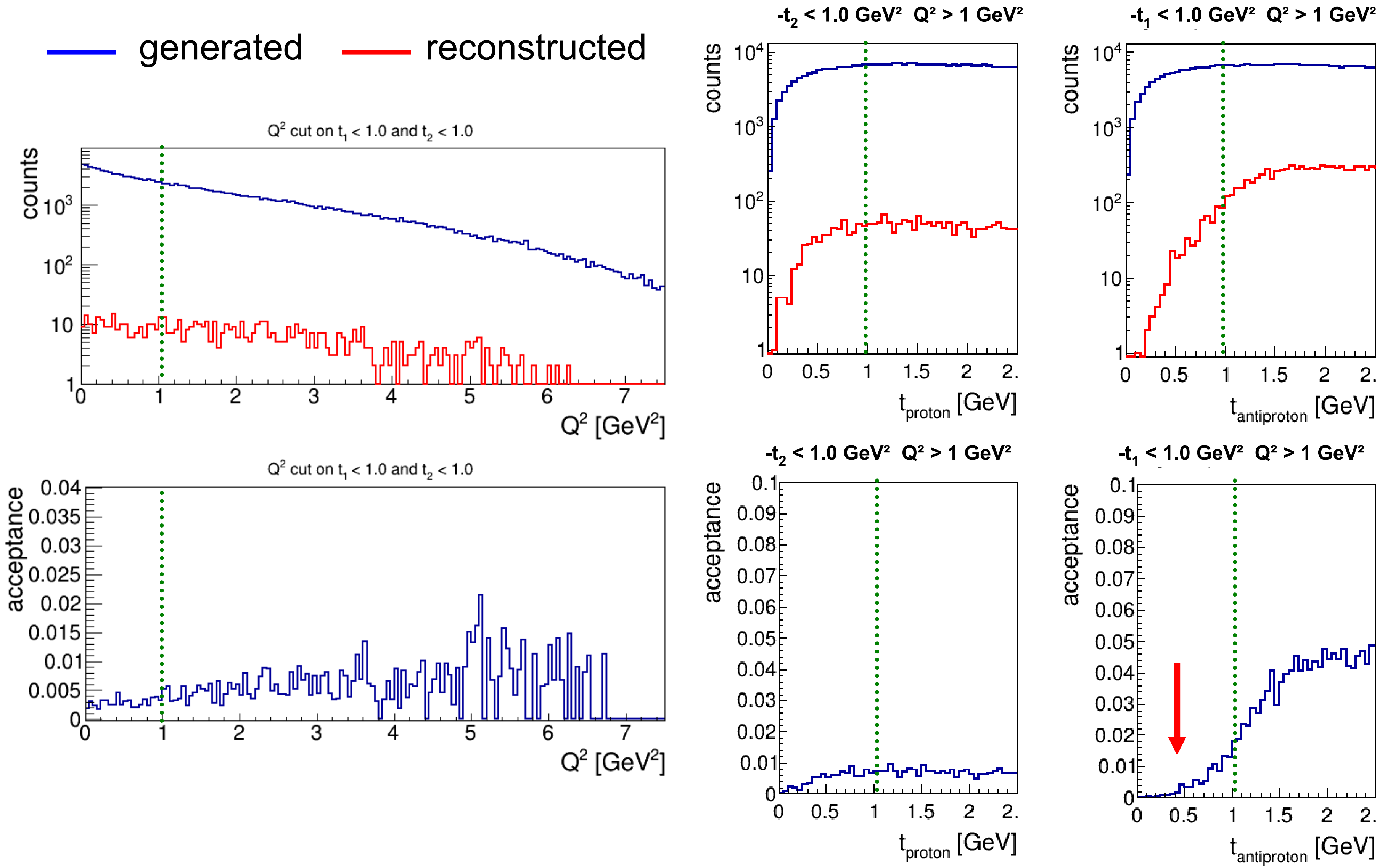




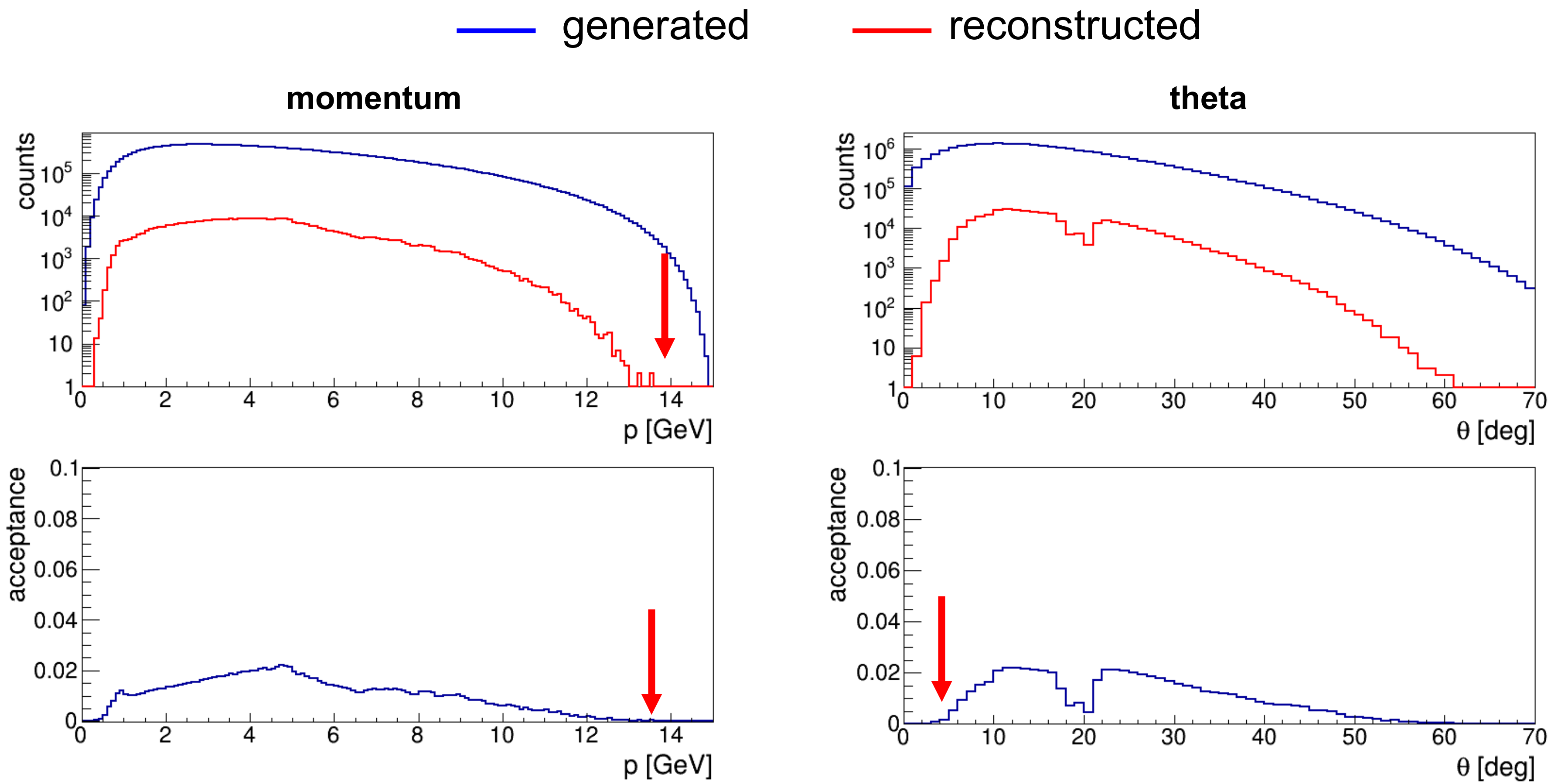




$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$ @ s = 30 GeV²



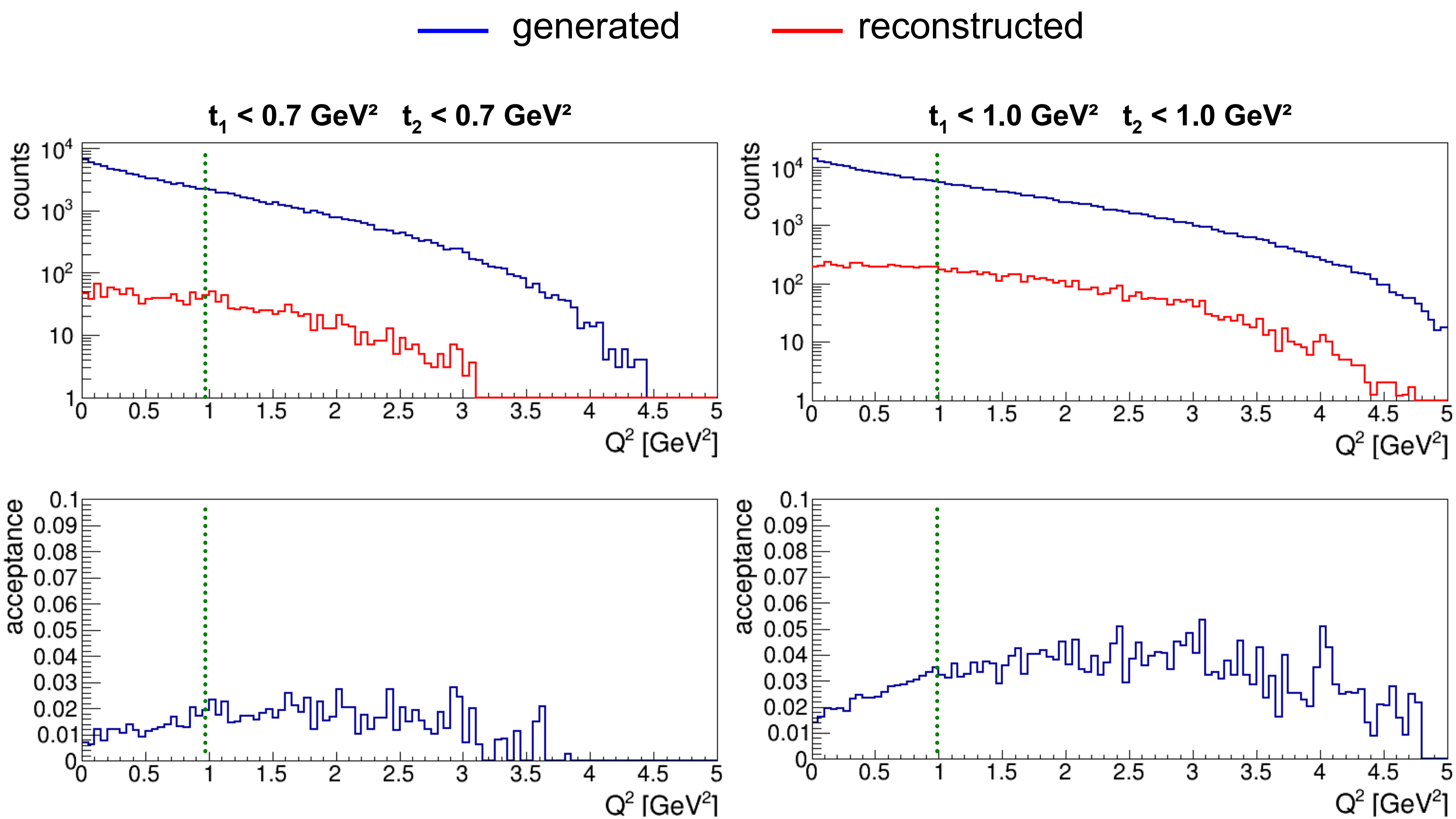
Antiproton Distributions @ s = 30 GeV²



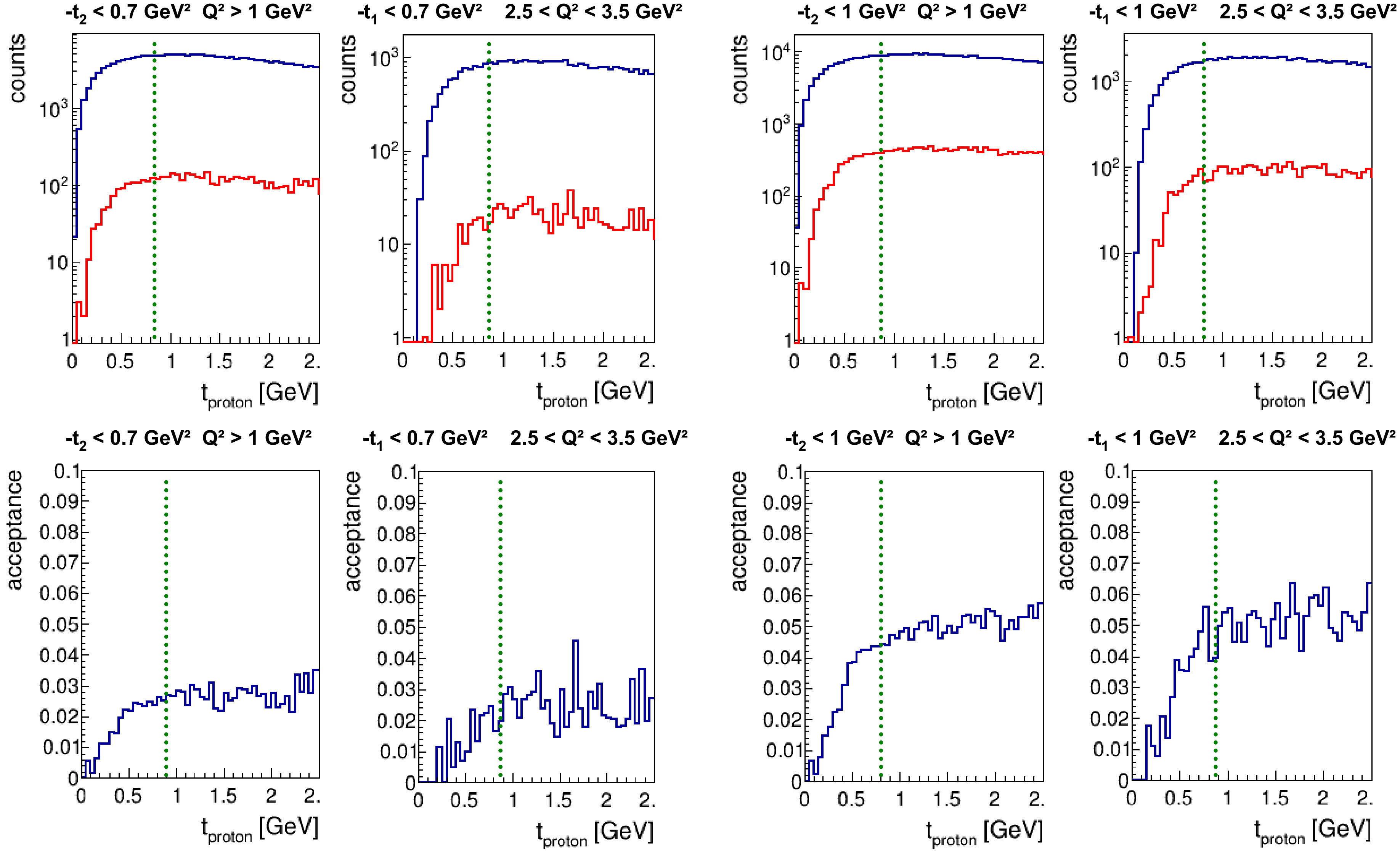
Problem: No / low acceptance for high momentum antiprotons under small angles even if they are only tagged

- Applying a PID for antiprotons > 10 GeV not fesable.

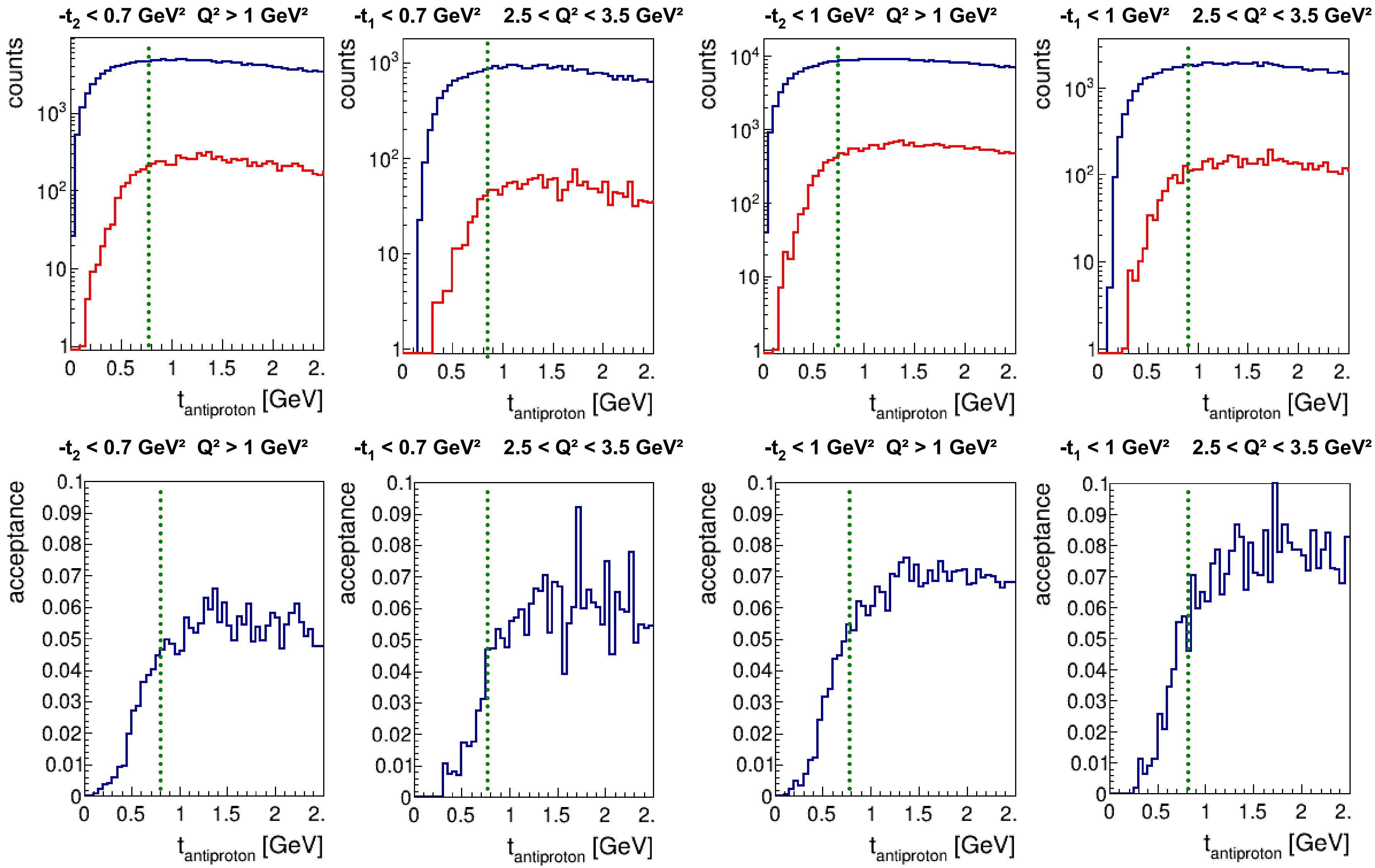
$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$ @ s = 20 GeV²



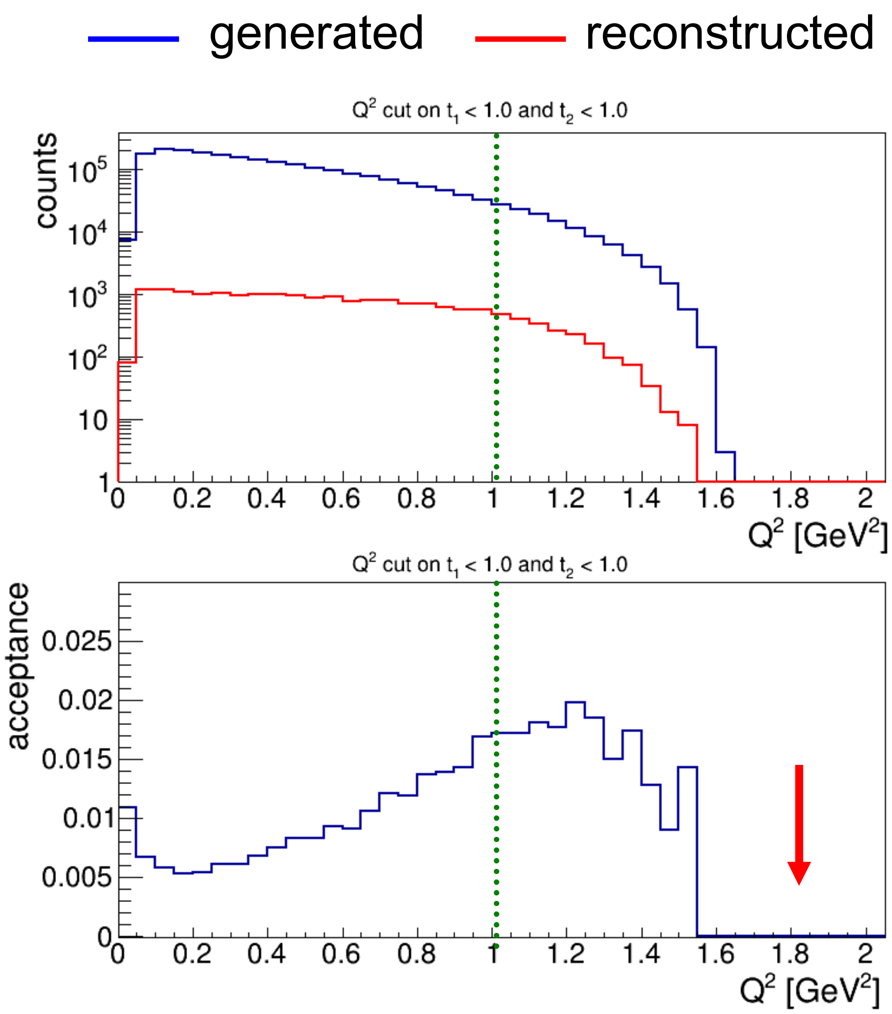
$p\bar{p} \to p\bar{p}e^+e^-$ @ s = 20 GeV²

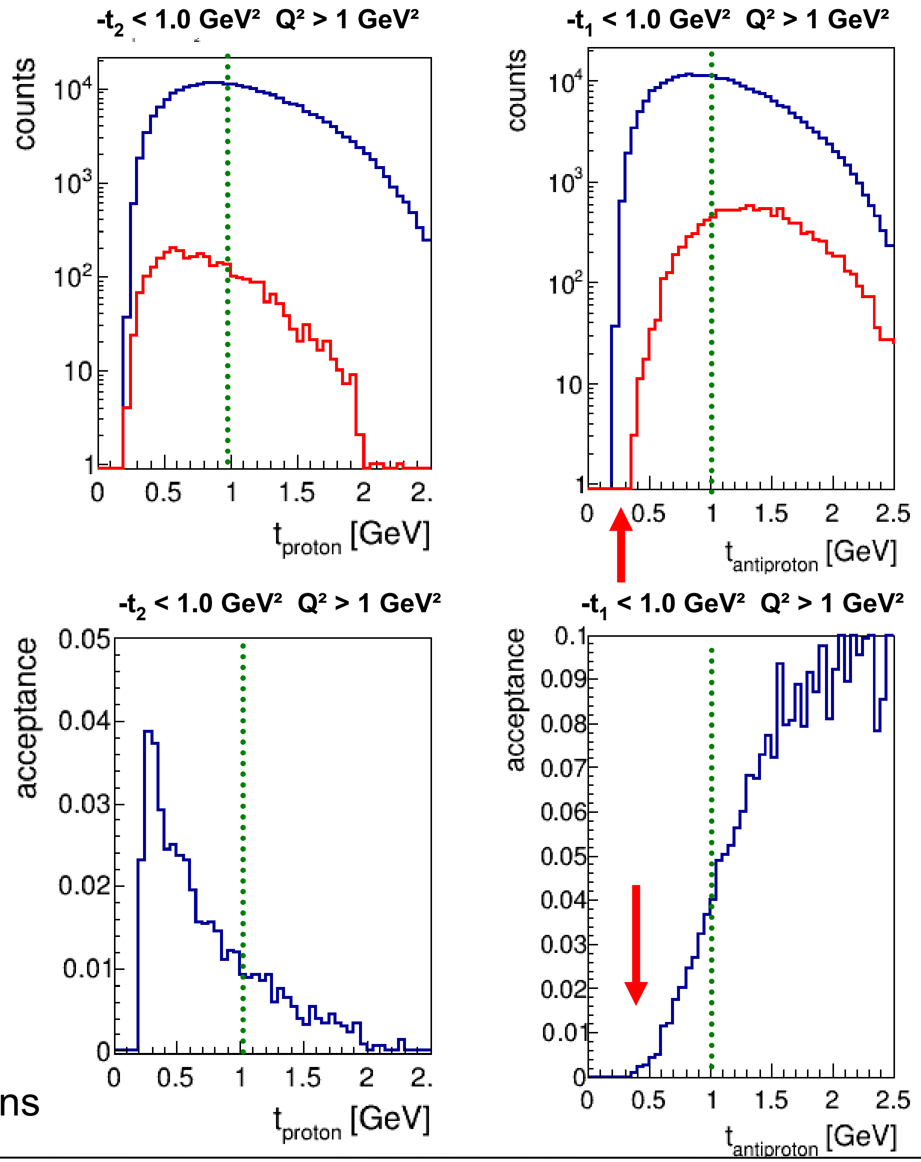


$p\bar{p} \rightarrow p\bar{p}e^+e^-$ @ s = 20 GeV²



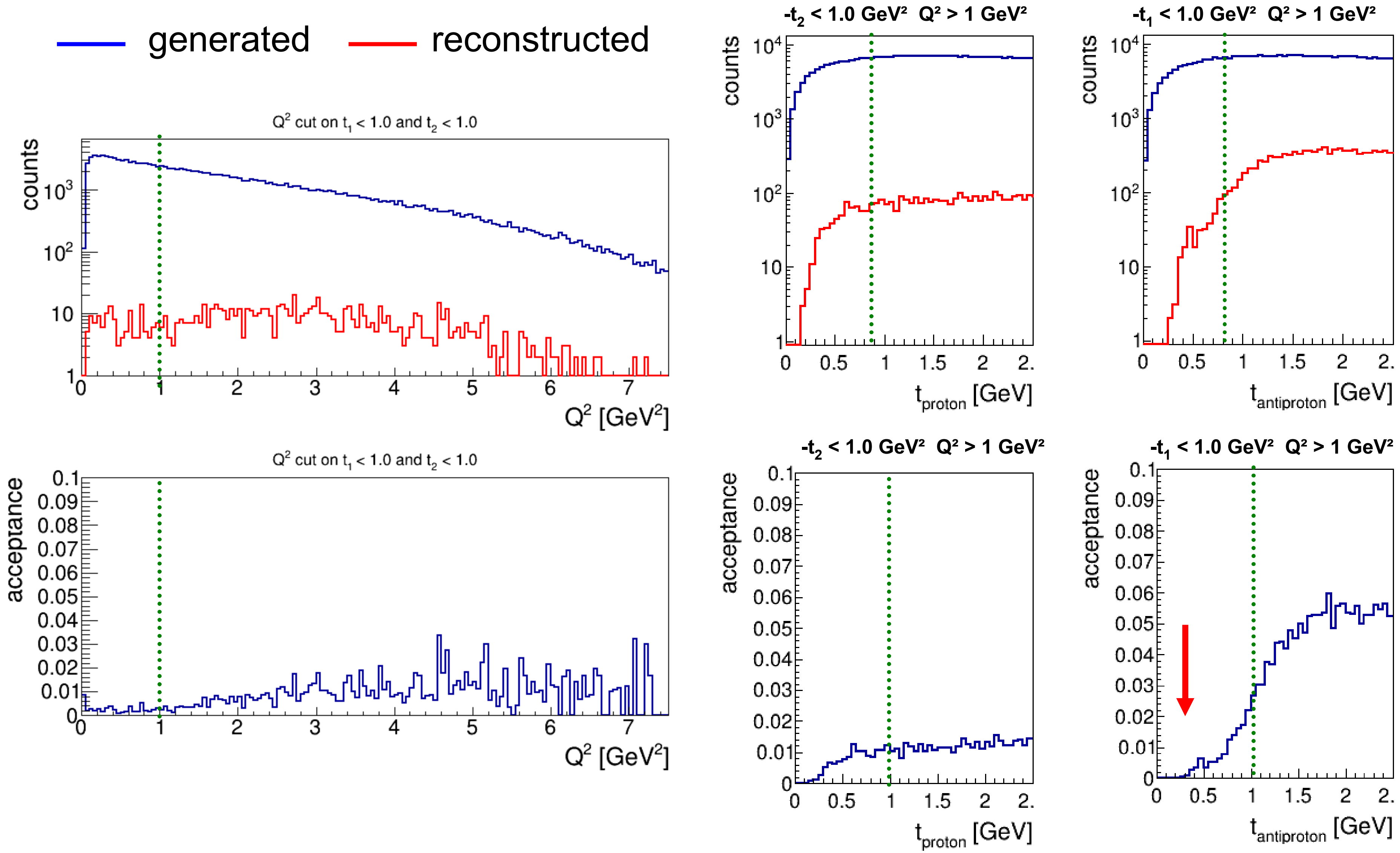
$p\bar{p} \rightarrow p\bar{p}\mu^{+}\mu^{-}$ @ s = 10 GeV²



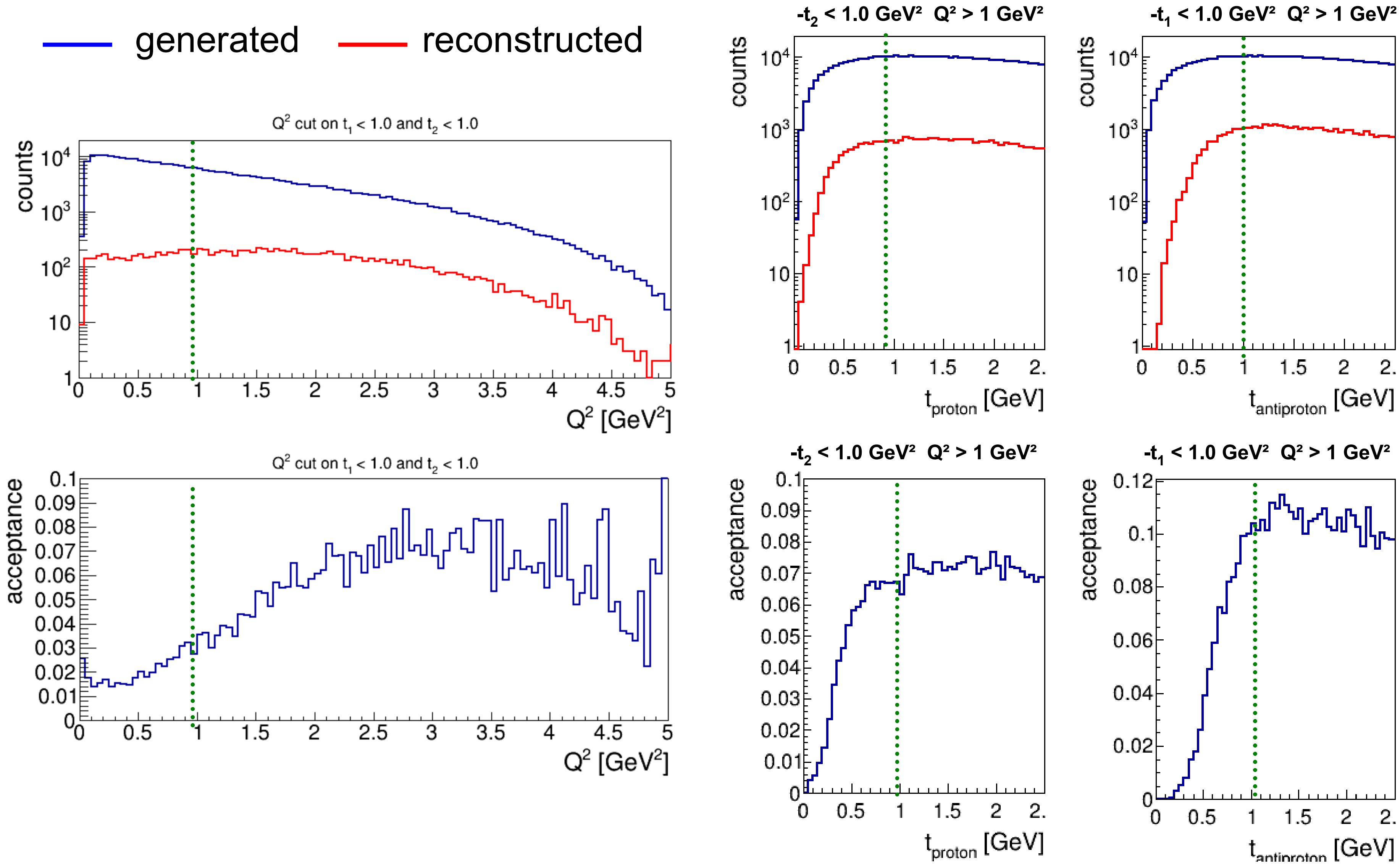


Limitation: Detection / PID of low momentum muons

$p\bar{p} \to p\bar{p}\mu^{+}\mu^{-}$ @ s = 30 GeV²



$p\bar{p} \to p\bar{p}\mu^+\mu^-$ @ s = 20 GeV²

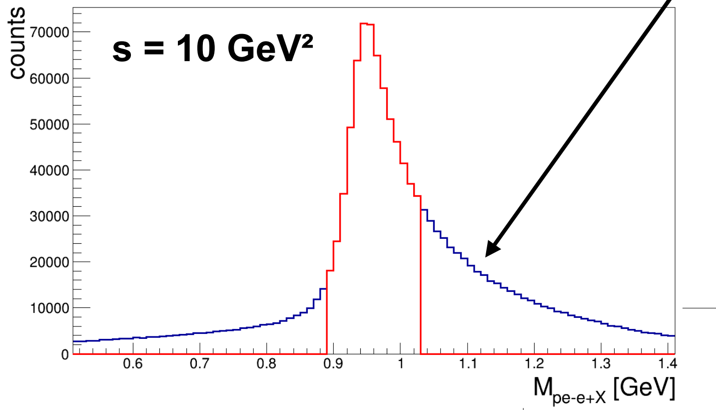


Topology 2

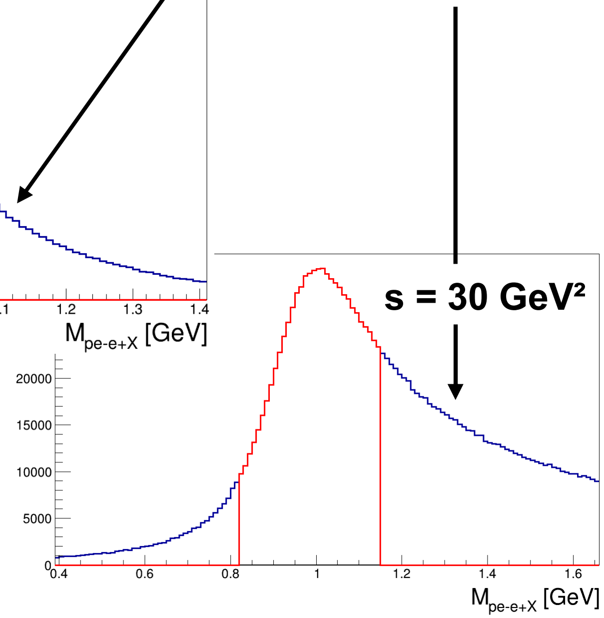
• Detection of the antiproton is not required

➔ Reconstruction via the missing antiproton mass:

➔ A tight PID for the detected particles is needed to reduce the background



radiative tail (also present for topology 1)



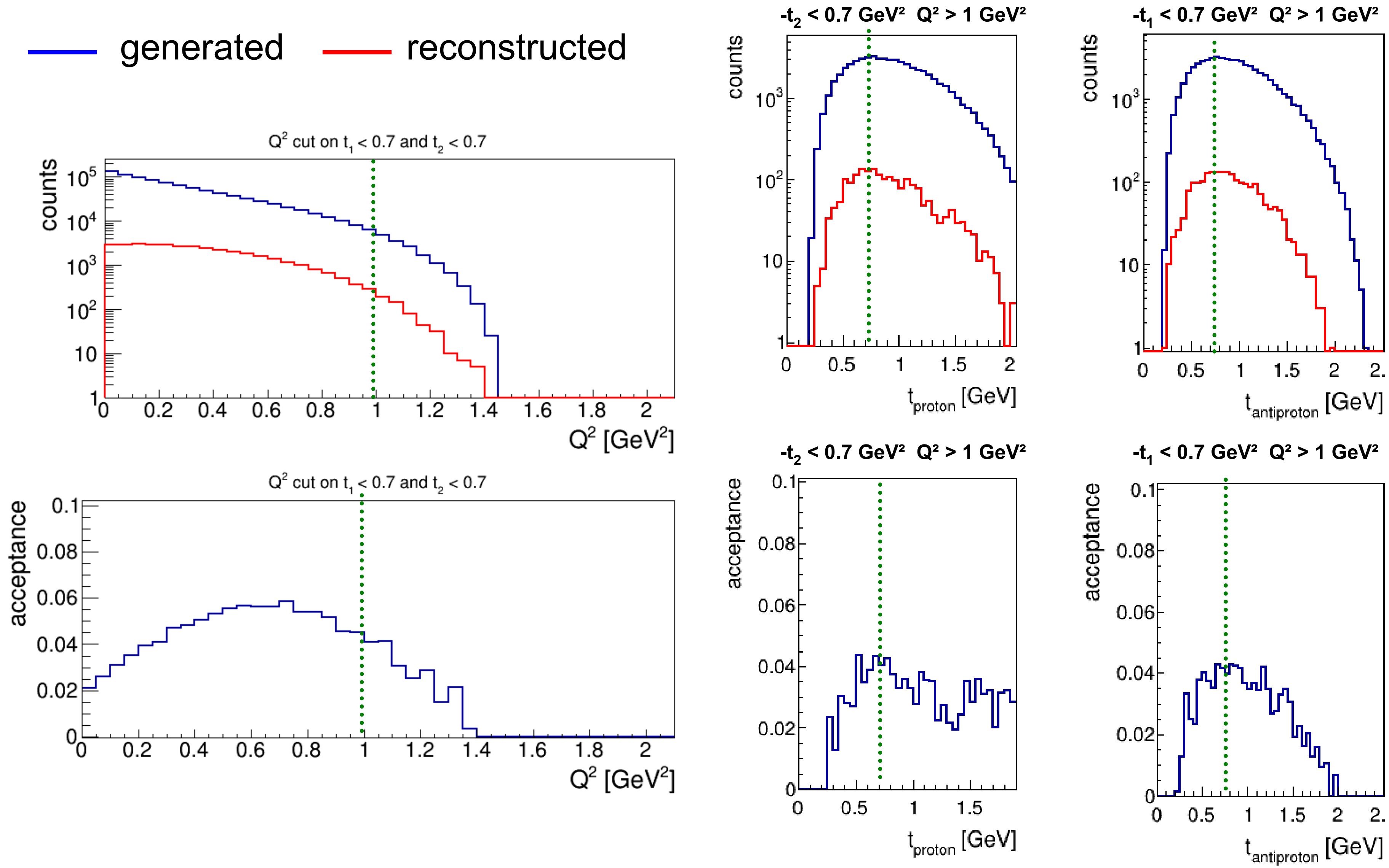
➔ Two PID variants have been investigated:

a) Tight PID for proton and leptons

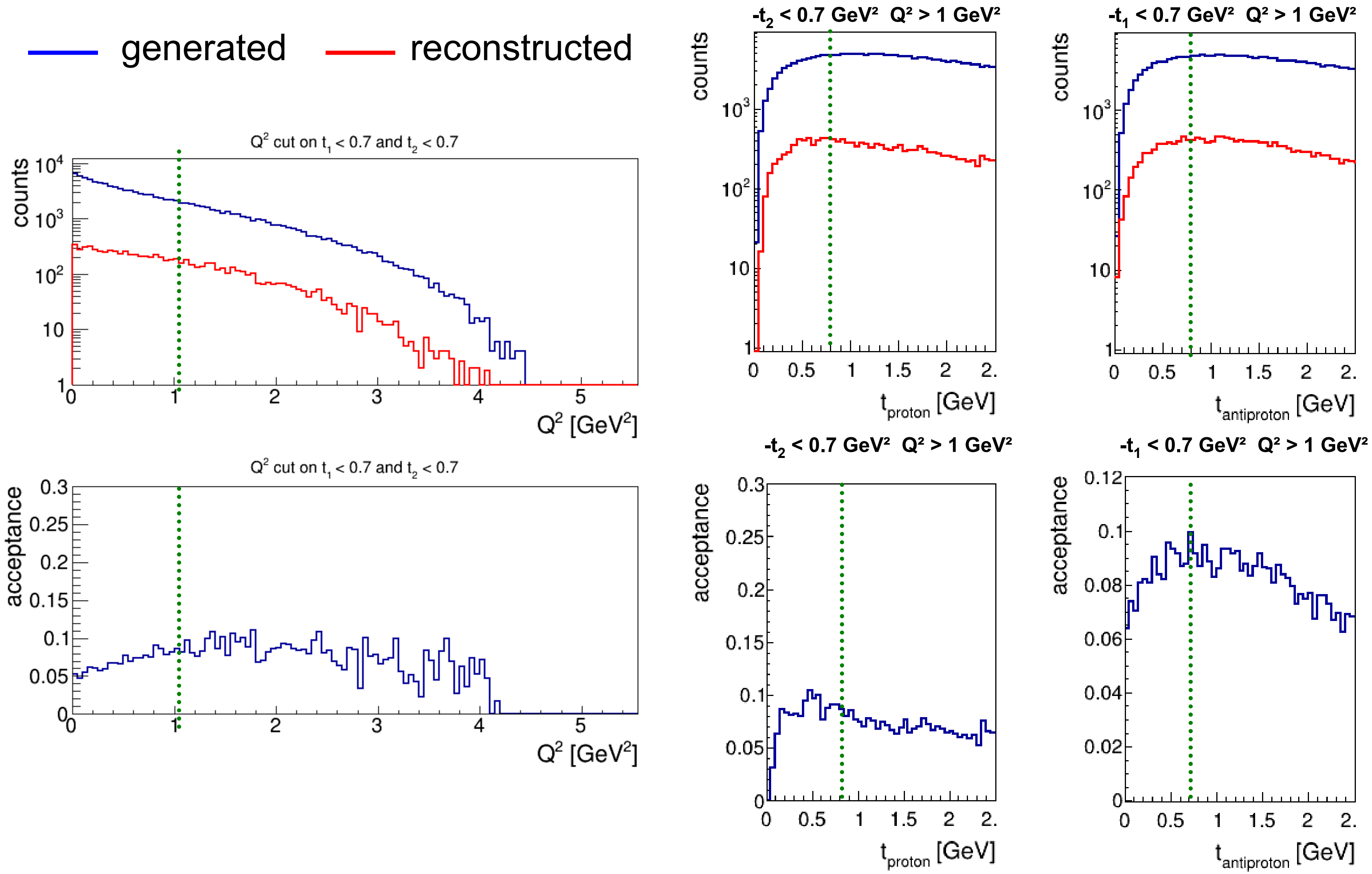
b) VeryTight PID for protons and leptons

➔ Version b) was found to provide still a sufficient statisics and a significantly better background rejection

$p\bar{p} \rightarrow p\bar{p}e^+e^-$ @ s = 10 GeV² topology 2

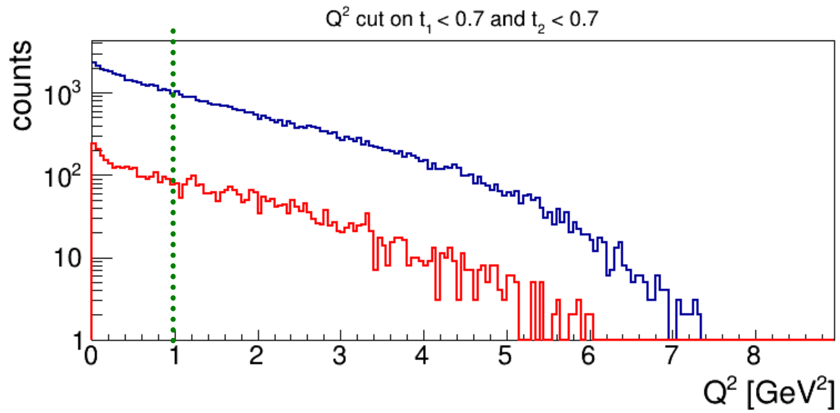


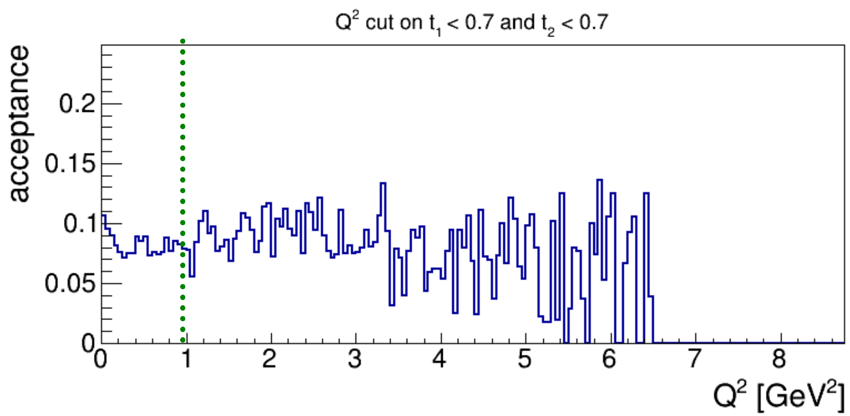
$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$ @ s = 20 GeV² topology 2

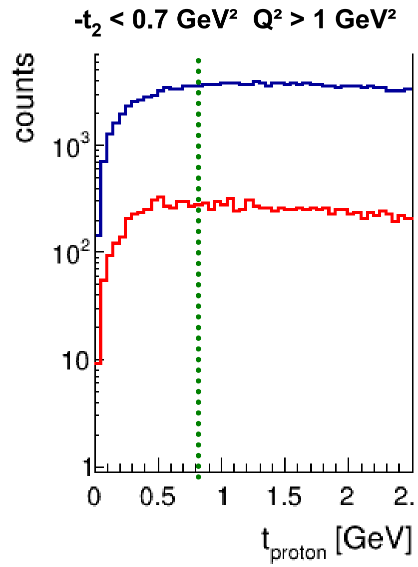


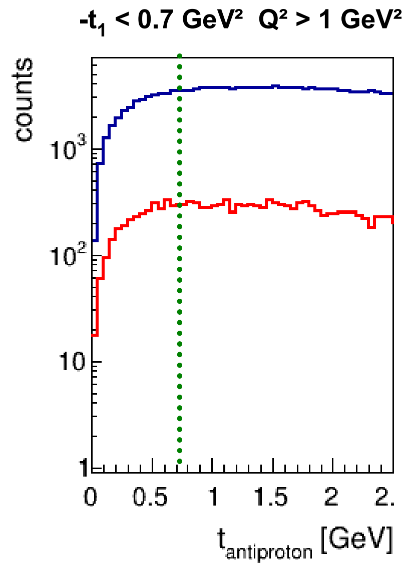
$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$ @ s = 30 GeV² topology 2

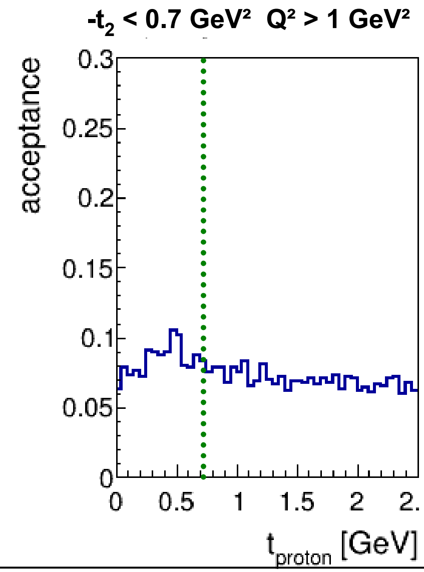
generated (blue) — reconstructed (red)

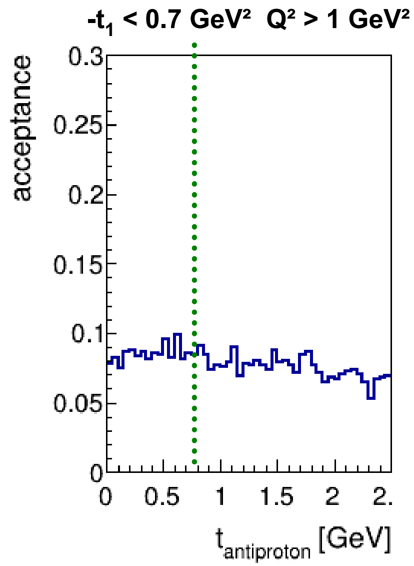




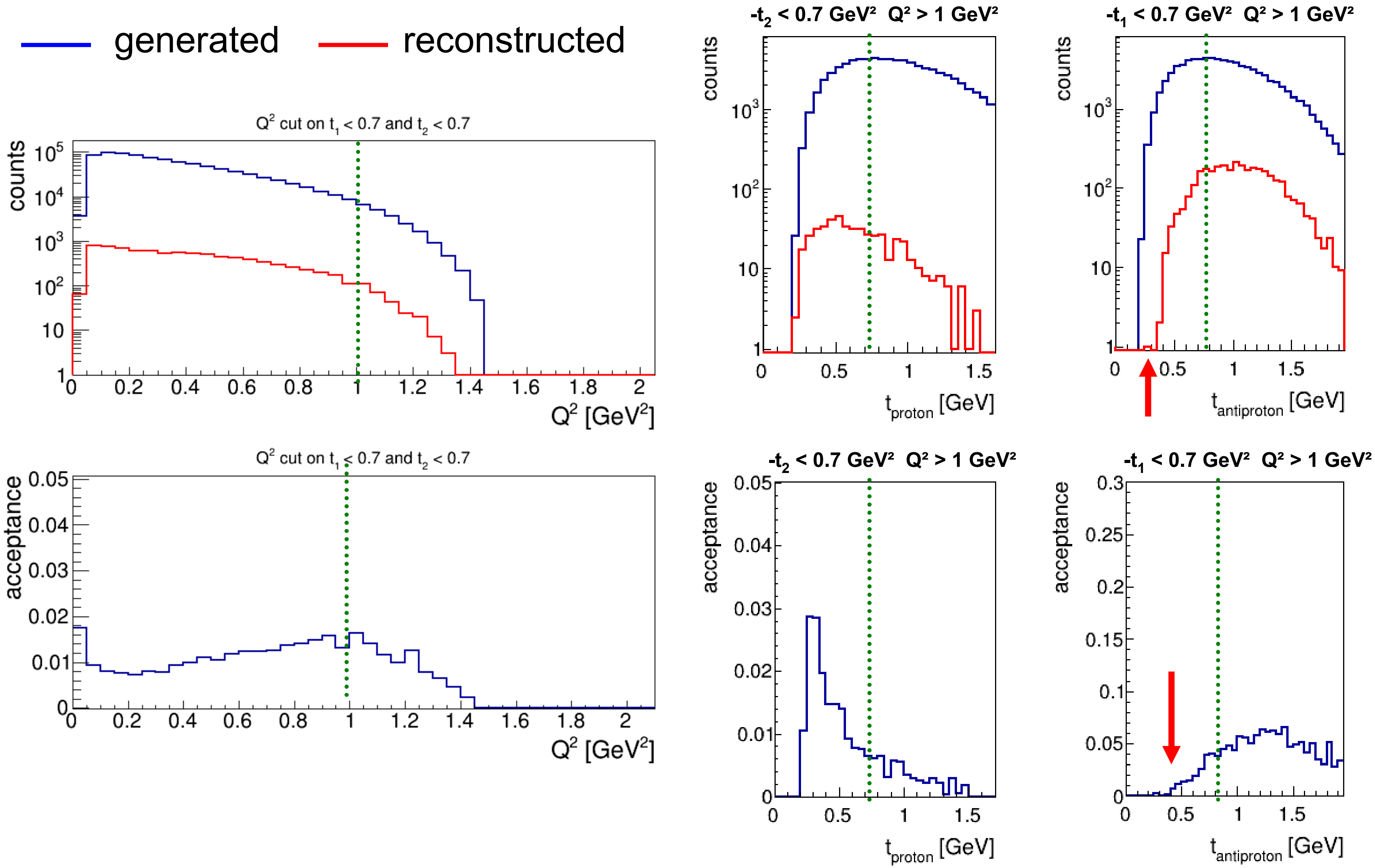




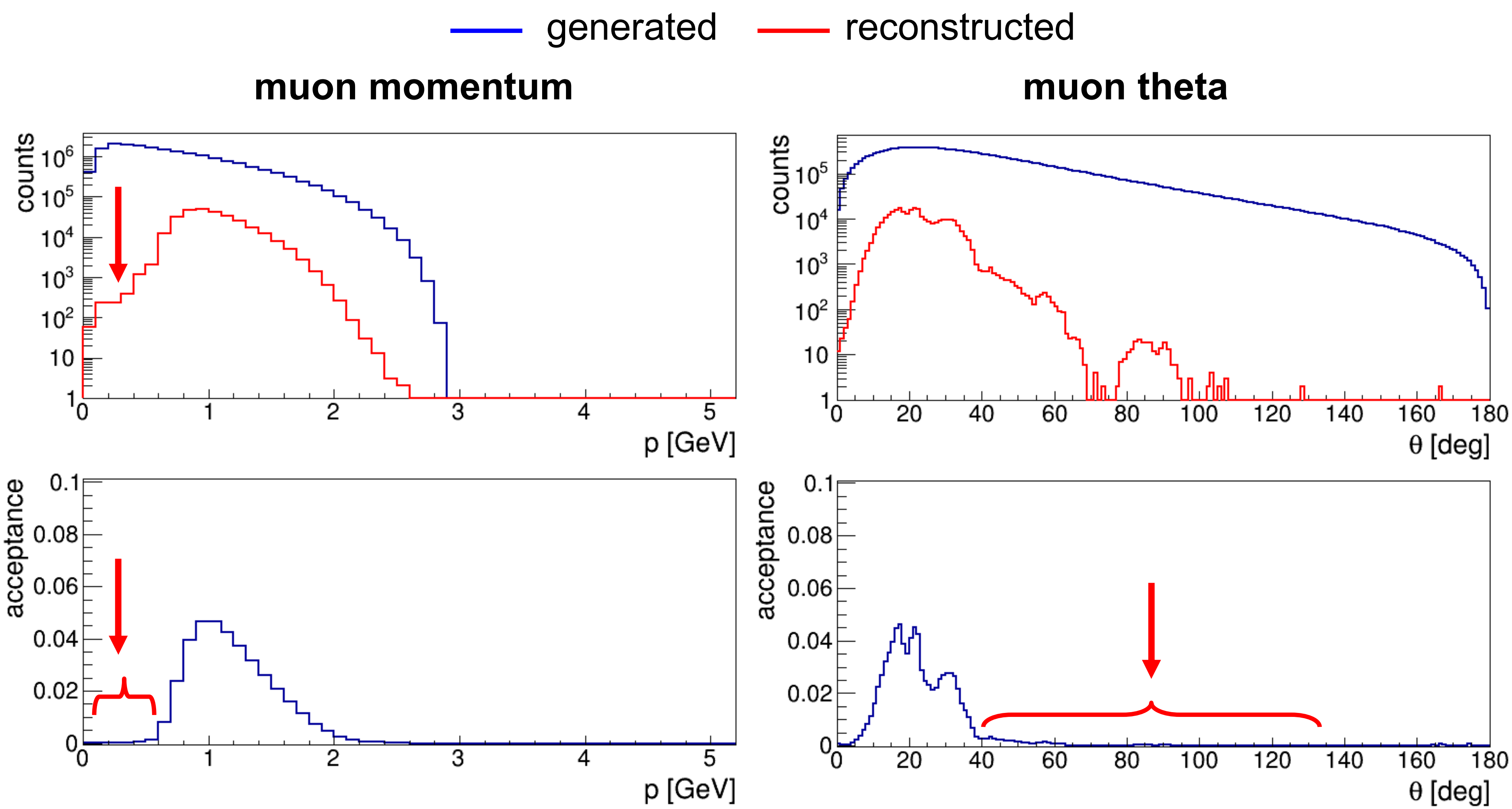




$p\bar{p} \rightarrow p\bar{p}\mu^+\mu^-$ @ s = 10 GeV² topology 2

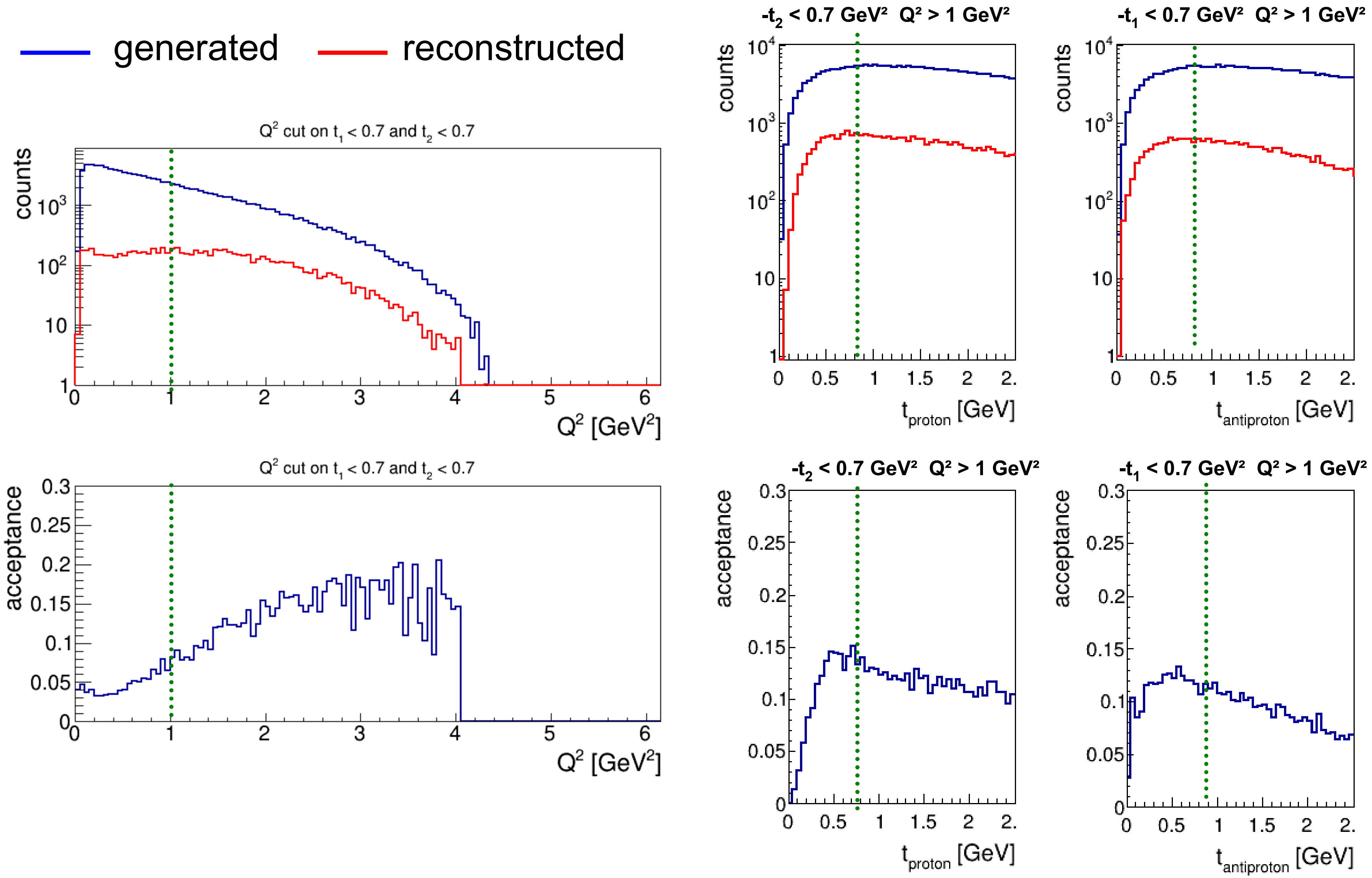


Muon Distribution @ s = 10 GeV² topology 2



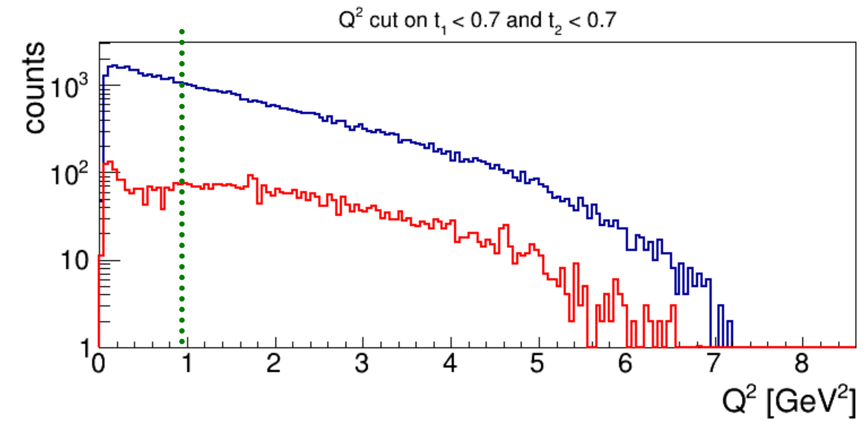
➔ Limitation from the detection / PID of low momentum muons / antimuons

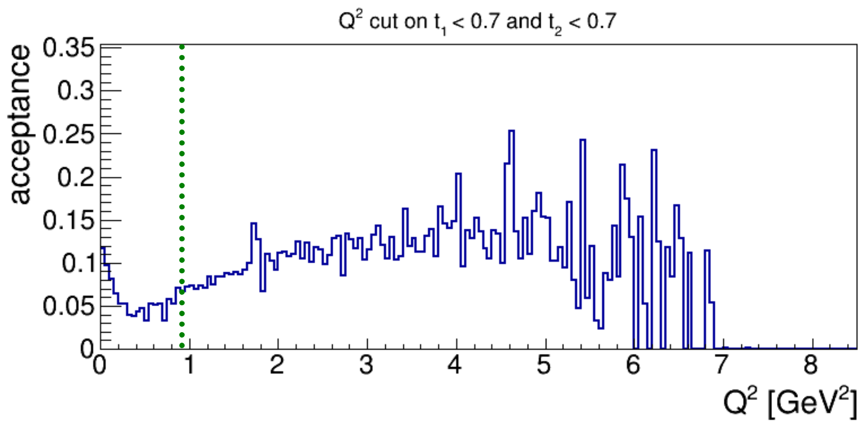
$p\bar{p} \rightarrow p\bar{p}\mu^+\mu^-$ @ s = 20 GeV² topology 2

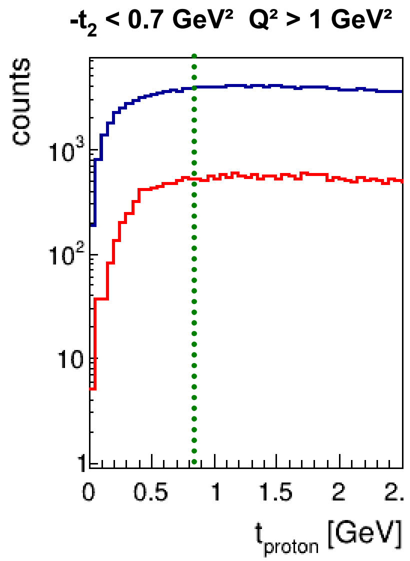


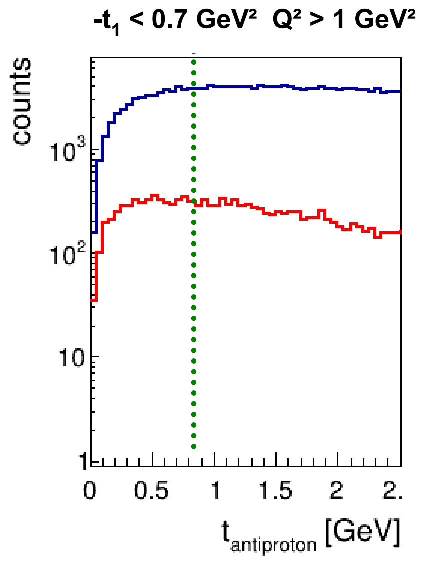
$p\bar{p} \rightarrow p\bar{p}\mu^{+}\mu^{-}$ @ s = 30 GeV²   topology 2

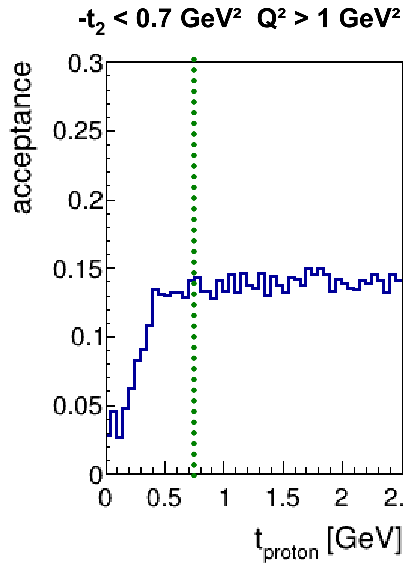
generated   reconstructed

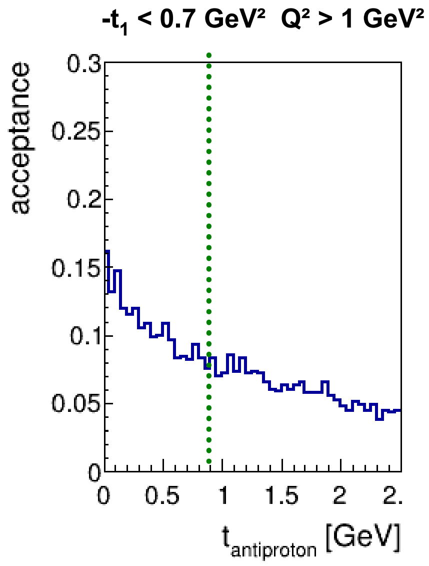












Background studies

Main background chanel: $p\bar{p} \rightarrow p\bar{p}\pi^+\pi^-$

➔ Phase space simulation for this channel and for the full DVMP background have been performed (20 – 30M events each)

Cross section estimates for the main background channel:

Physics Letters B 680 (2009) 459–465

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PHYSICS LETTERS B

Low-energy pion–pion scattering in the $pp \rightarrow pp\pi^+\pi^-$ and $p\bar{p} \rightarrow p\bar{p}\pi^+\pi^-$ reactions

P. Lebiedowicz [a], A. Szczurek [a,b,*], R. Kamiński [a]

Background studies

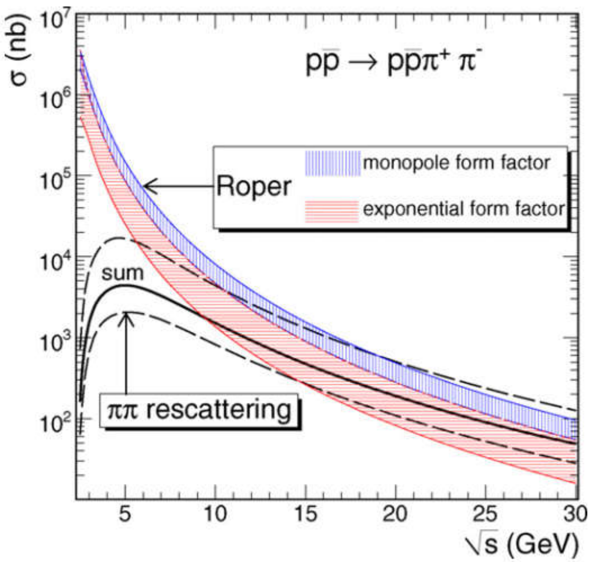
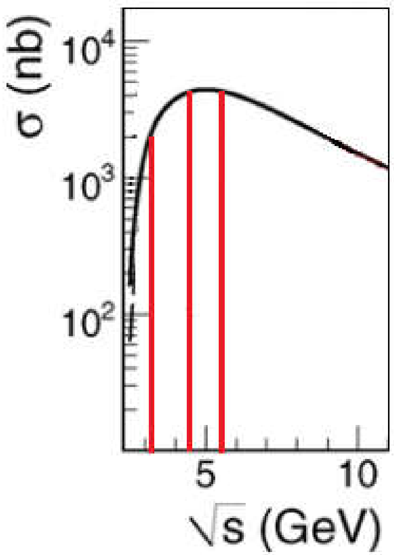


Fig. 6. The phase-space integrated cross section for the reaction $p\bar{p} \to p\bar{p}\pi^+\pi^-$ as a function of center of mass energy $\sqrt{s}$. We compare the pion–pion rescattering contribution and the Roper resonance contribution (only σ-meson exchange included). The uncertainty bands for both contributions are also shown. The area of uncertainties for the pion–pion rescattering contribution is indicated by the dashed lines. The pion–pion rescattering contribution is a coherent sum of all partial waves.



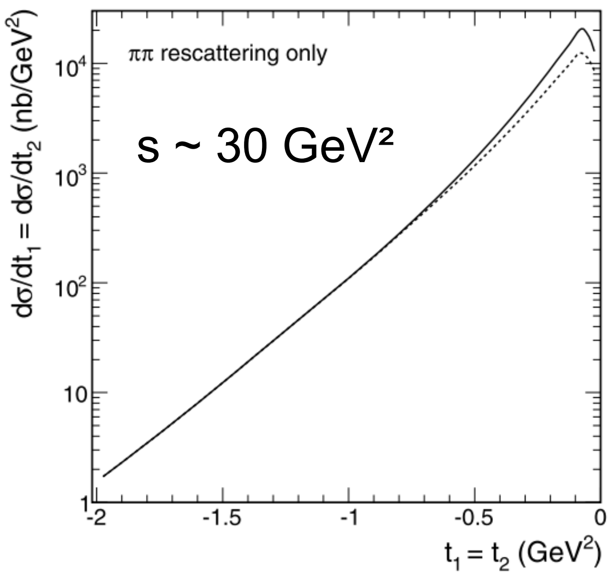


Fig. 7. Differential cross section $\frac{d\sigma}{dt_1} = \frac{d\sigma}{dt_2}$ for the $p\bar{p} \to p\bar{p}\pi^+\pi^-$ reaction at $\sqrt{s} =$ 5.5 GeV. The solid line is the cross section without cuts, the dashed line includes cuts to remove regions of Roper resonance and double-Δ excitations.

s = 30 GeV² -t = 0.5 GeV²: background: 10^3 - 10^5 nb/GeV²
signal: 11.6 pb/GeV²

➔ A background suppression of at least 10^5 (better 10^6) is required

➔ Similar to the e^+e^- final state of the annihilation process

Background studies

- Compare acceptance for generated pions after electron / muon ID with acceptance of generated electrons / muons

$p\,e^-e^+X$ $Q^2 > 1$ GeV² $t_1 < 0.675$ GeV² $t_2 < 0.675$ GeV²

Tight: Prob ≥ 0.5 **VeryTight**: P ≥ 0.9 set individually for each algorithm

	exp. S/B ratio elec.	exp. S/B ratio muons
s = 10 GeV² Tight PID	~ 20	~ 120
s = 10 GeV² VeryTight PID	~ 350	~ 70
s = 20 GeV² Tight PID	~ 20	~ 425
s = 20 GeV² VeryTight PID	~ 225	~ 433
s = 30 GeV² Tight PID	~ 25	~ 475
s = 30 GeV² VeryTight PID	~ 200	~ 300

➔ The applied simple PID is not sufficient.

Background studies

Similar situation as for $\bar{p}p \rightarrow e^+ e^-$

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Feasibility studies of time-like proton electromagnetic form factors at $\overline{\text{P}}$ANDA at FAIR

➔ $\pi^+\pi^-$ vs e^+e^- suppression was shown to reach 10^{-8}

p_{lab}	[GeV/c]	4.90	5.90	6.40
PID$_c$	[%]	> 99	> 99	> 99
PID$_s$	[%]	> 10	> 10	> 10
dE/dx_{STT}	[a.u.]	> 5.8	> 5.8	> 6.5
E_{EMC}/p_{reco}	[GeV/(GeV/c)]	> 0.8	> 0.8	> 0.8
EMC LM	–	< 0.75	–	–
EMC E1	[GeV]	> 0.35	> 0.35	> 0.35
$\lvert\theta + \theta' - 180\rvert$	[degree]		< 5	
$\lvert\phi - \phi' - 180\rvert$	[degree]		< 5	
M_{inv}	[GeV/c^2]	> 2.2	> 2.2	> 2.7

p_{lab} [GeV/c]	e^+e^-	$\pi^+\pi^-$
4.90	0.46	–
5.90	0.47	–
6.40	0.39	2.9×10^{-8}

p_{lab}	[GeV/c]	6.40
PID$_c$	[%]	> 99.5
PID$_s$	[%]	> 10
dE/dx_{STT}	[a.u.]	0 or > 6.5
E_{EMC}/p_{reco}	[GeV/(GeV/c)]	> 0.8
EMC LM	–	< 0.66
EMC E1	[GeV]	> 0.35
$\lvert\theta + \theta' - 180\rvert$	[degree]	< 5
$\lvert\phi - \phi' - 180\rvert$	[degree]	< 5
M_{inv}	[GeV/c^2]	> 2.7

p_{lab} [GeV/c]	$\epsilon(e^+e^-)$	$\epsilon(\pi^+\pi^-)$
6.4	0.41	1.9×10^{-8}

Background studies

- Background suppression for e^+e^- will be studied with these cuts
- For $\mu^+\mu^-$ a backround rejection of 10^{-5} was achieved in form factor studies
- A filtered generation of background events has to be performed to obtain enough statistics at small -t

➔ Full phase space simulation: 30M events

➔ ~ 10^4 events in the relvant region

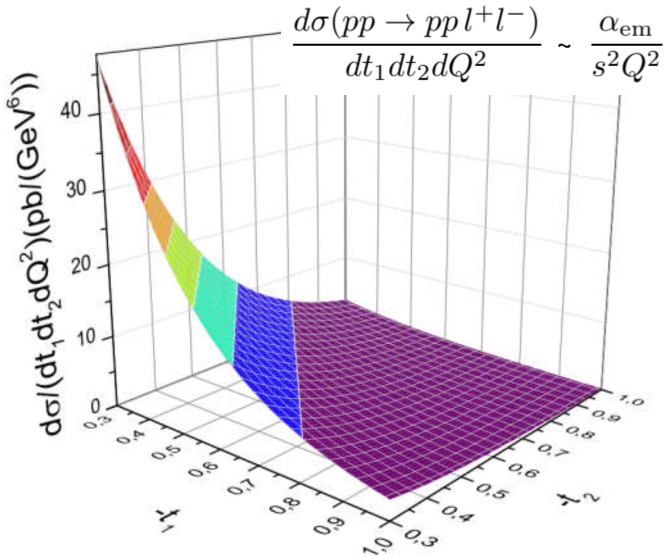
Estimate of the experimental count rates

- **Differential cross section available for s = 10 GeV², 20 GeV² and 30 GeV² @ Q² = 3 GeV²**

➔ Scaling is expected to follow 1/Q²

➔ Fix a Q² bin i.e. 2.5 GeV² < Q² < 3.5 GeV²

➔ ΔQ² = 1 GeV²



- Set the bin size in -t:
  i. e. $\Delta t_1 = \Delta t_2 = 0.05$ GeV² or 0.1 GeV²

- L = 2 fb^{-1} → 1/2 year at the design luminosity

- Acceptance based on MC simulations (without a detected antiproton – topology 2)

➔ A VeryTight (>0.9) PID is applied to ensure a reasonable background suppr. (PID tightness will impact the magnitude of the acceptance)

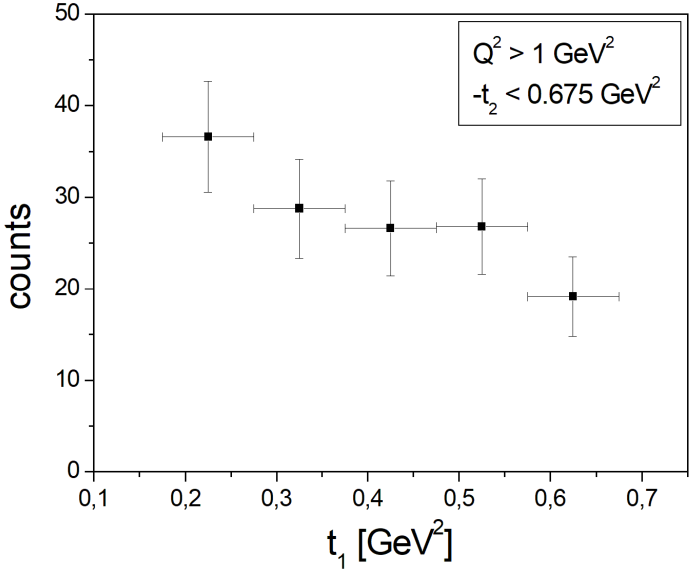
Rate estimate for s = 10 GeV²

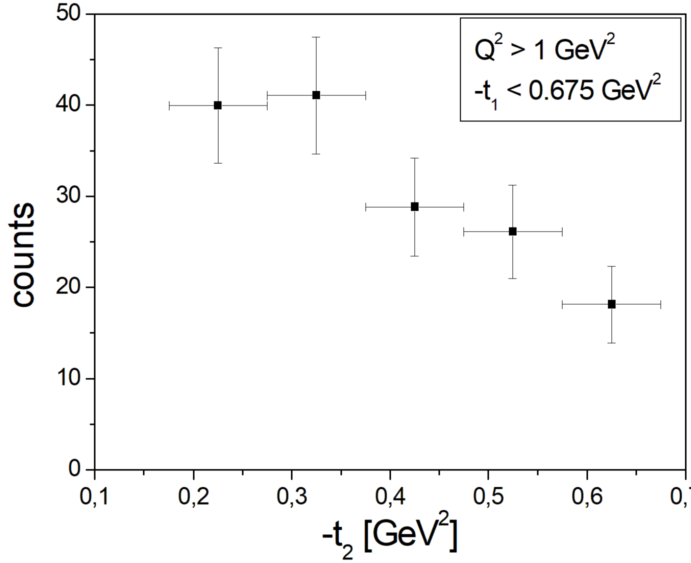
$$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$$

L = 2 fb^{-1}

Δt = 0.1 GeV²

➔ Low count rate due to Q² > 1 GeV²

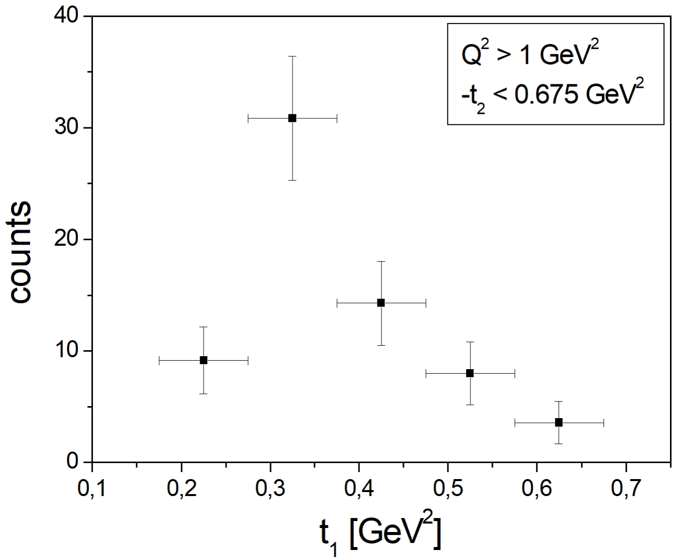


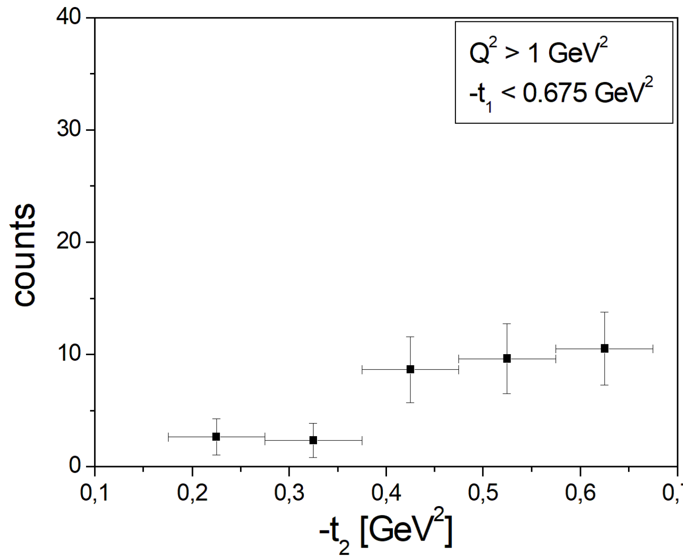


$$p\bar{p} \rightarrow p\bar{p}\mu^{+}\mu^{-}$$

L = 2 fb^{-1}

➔PID efficency of the muon detector limitted at low momenta



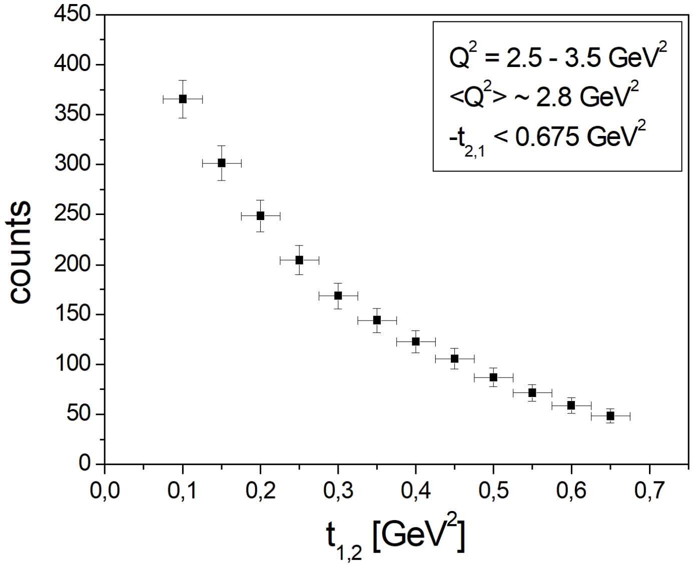


Rate estimate for s = 20 GeV²

$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$

L = 2 fb^{-1}

➔ Similar acceptance/ counts for t_1 and t_2



- flat Q² acceptance

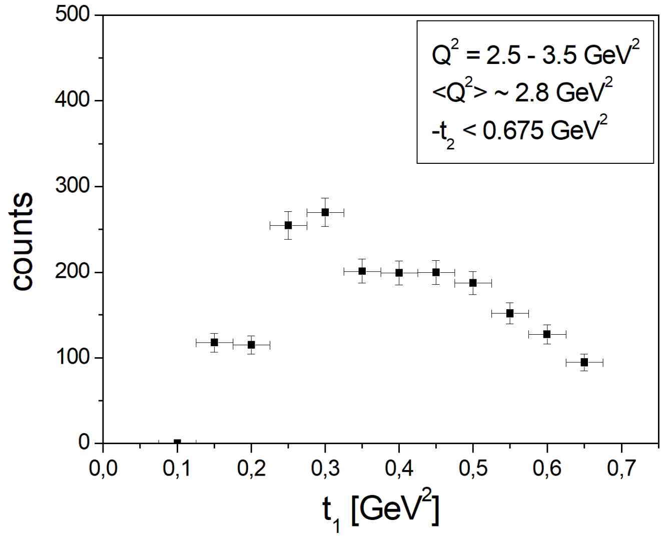
Q² = 1.5 – 2.5 GeV²
➔ counts * 1.5

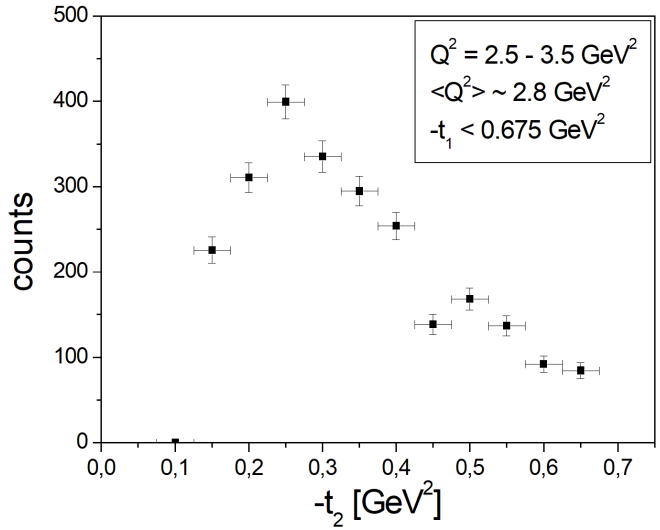
Q² > 1 GeV²
➔ counts * 4.9

$p\bar{p} \rightarrow p\bar{p}\mu^{+}\mu^{-}$

L = 2 fb^{-1}

➔Drop at small -t due to muon detection / PID





Rate estimate for s = 30 GeV²

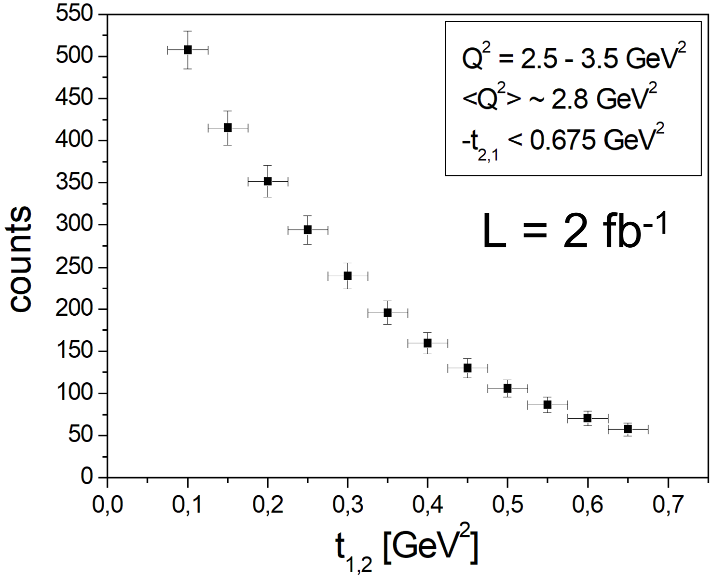
$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$

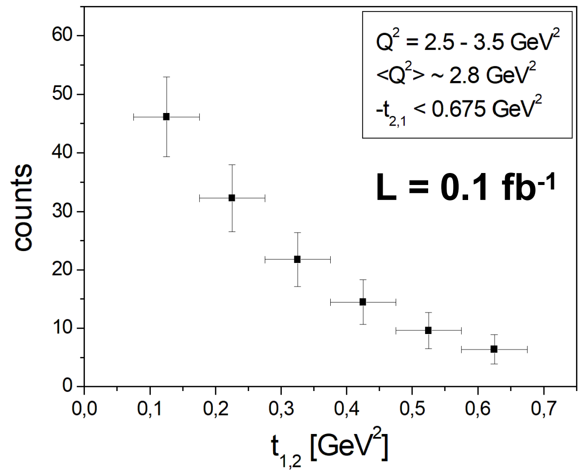
- flat Q^2 acceptance

  Q^2 = 1.5 – 2.5 GeV²
  counts * 1.5

  Q^2 = 4.5 – 5.5 GeV²
  counts * 0.6

  Q^2 > 1 GeV²
  counts * 4.9

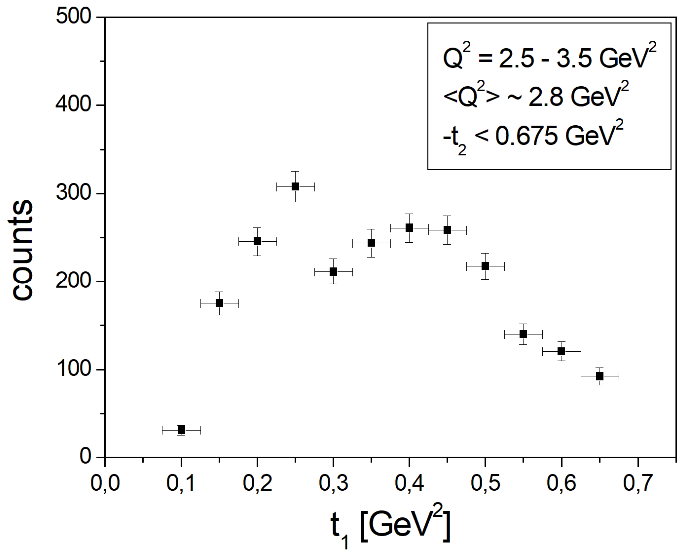


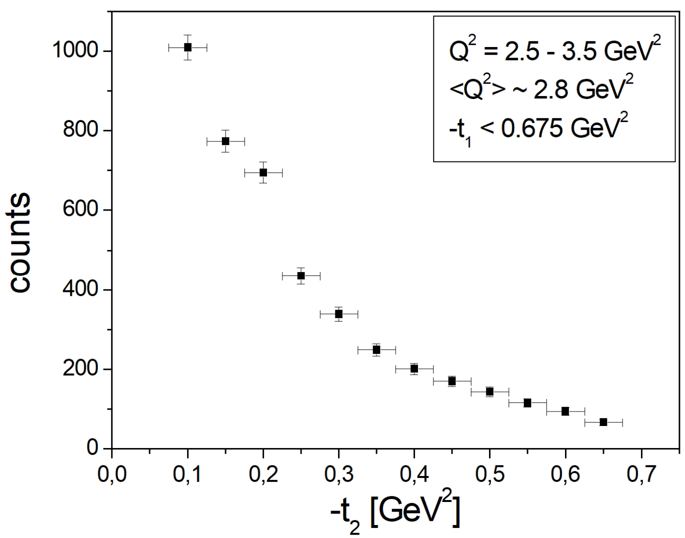


➔ Similar acceptance/counts for t_1 and t_2

$p\bar{p} \rightarrow p\bar{p}\mu^{+}\mu^{-}$

L = 2 fb^{-1}





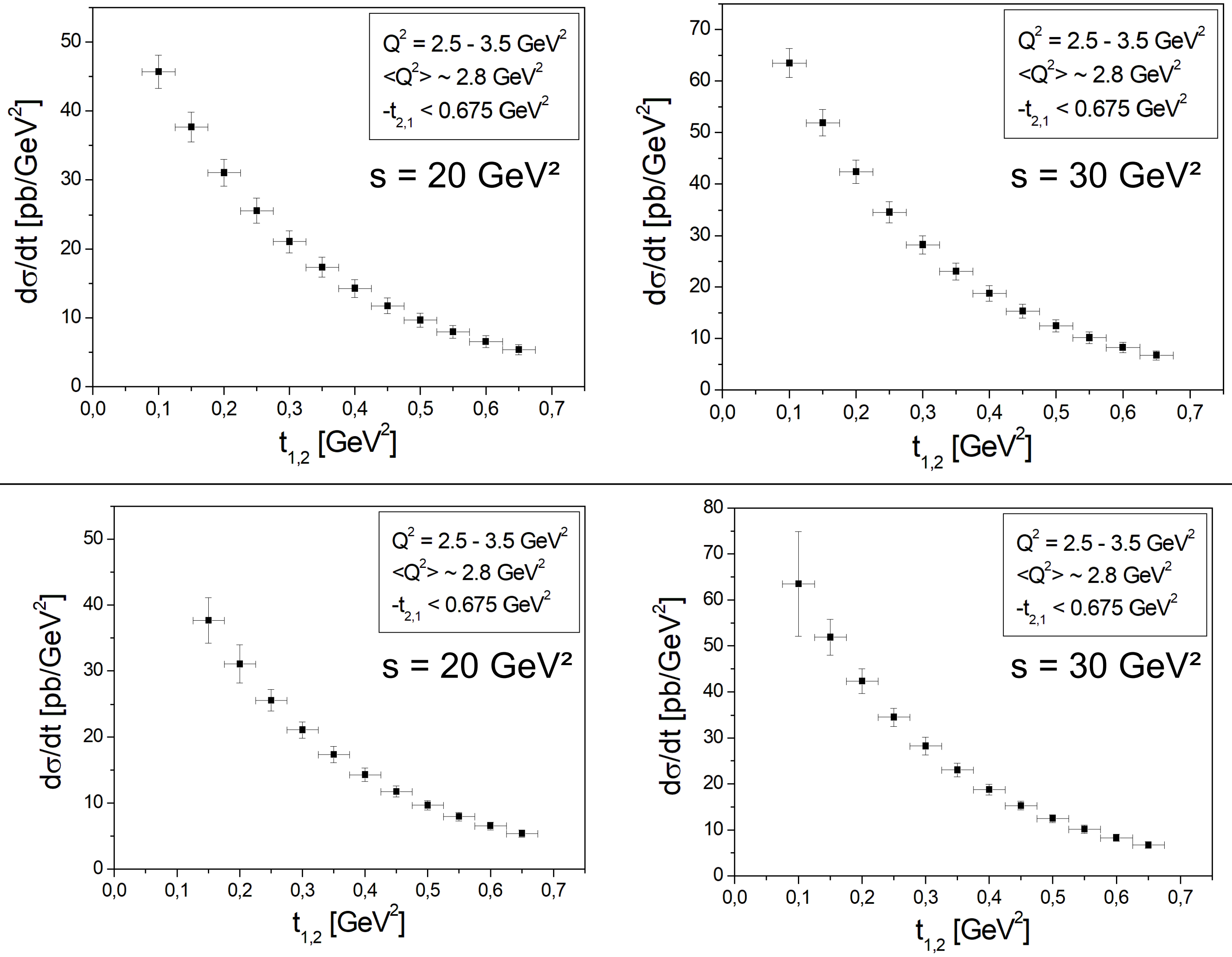
Reconstructed cross section and uncertainties

$p\bar{p} \rightarrow p\bar{p}e^+e^-$

L = 2 fb^{-1}

$p\bar{p} \rightarrow p\bar{p}\mu^+\mu^-$

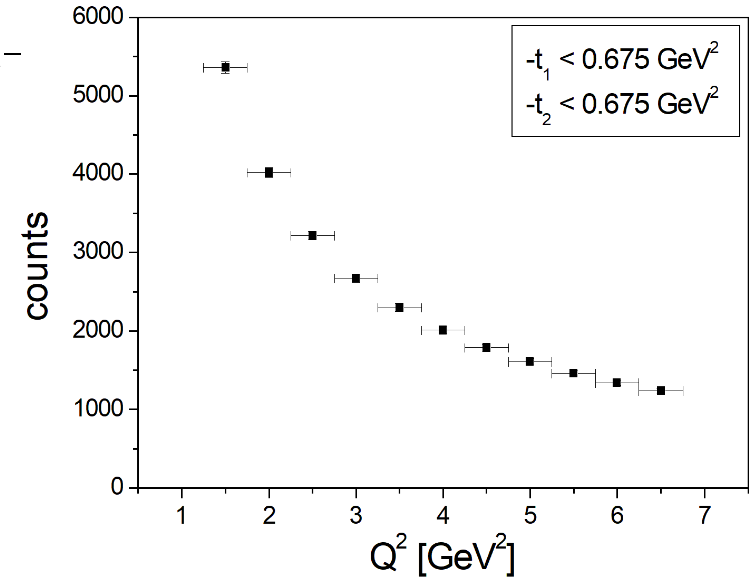
L = 2 fb^{-1}

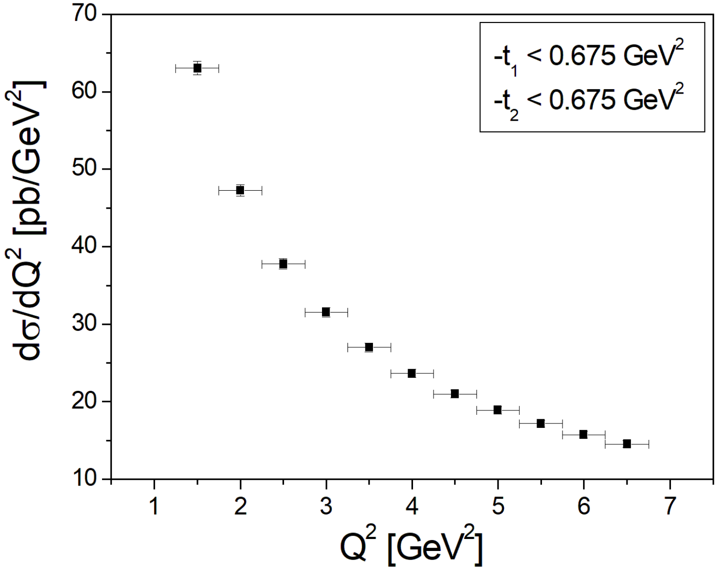


Q² dependence at s = 30 GeV²

$p\bar{p} \rightarrow p\bar{p}e^{+}e^{-}$

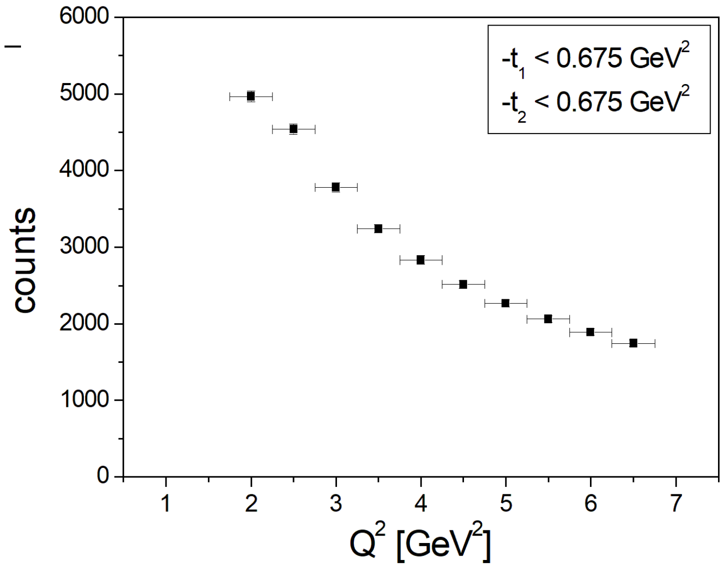
L = 2 fb^{-1}

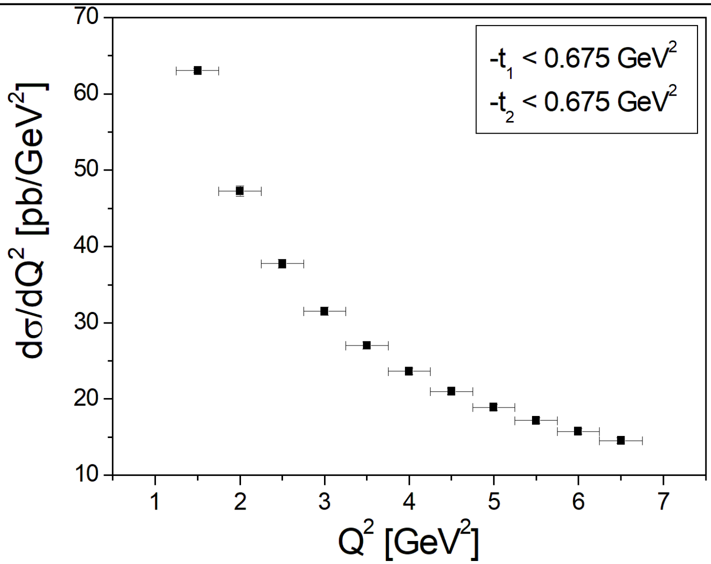




$p\bar{p} \rightarrow p\bar{p}\mu^{+}\mu^{-}$

L = 2 fb^{-1}

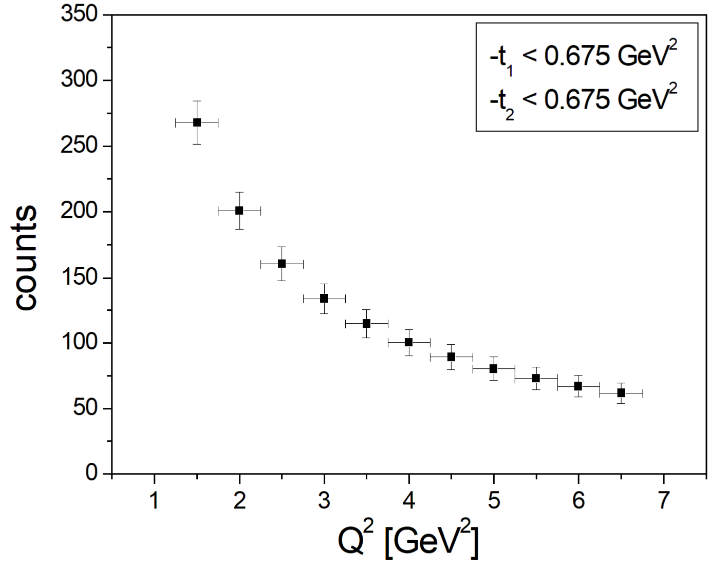


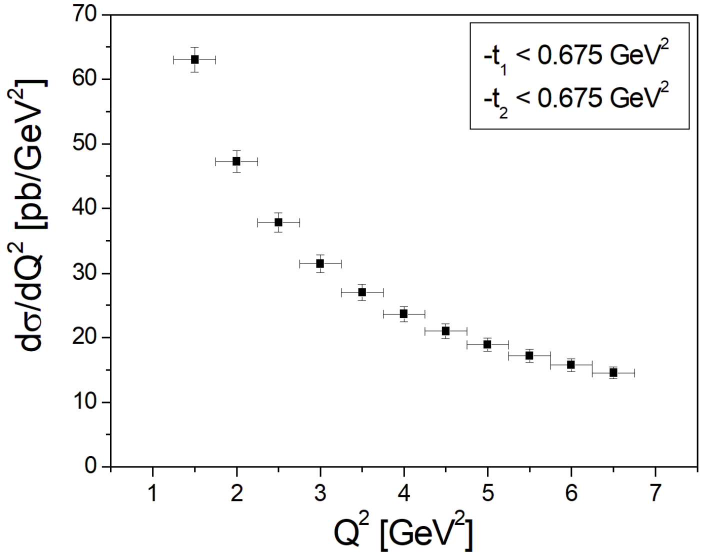


Q^2 dependence at s = 30 GeV²

$p\bar{p} \rightarrow p\bar{p}e^+e^-$

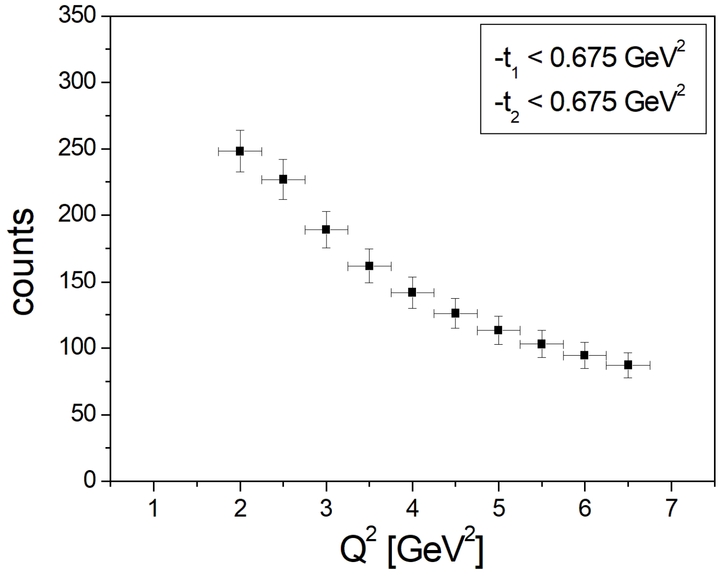
L = 0.1 fb^{-1}

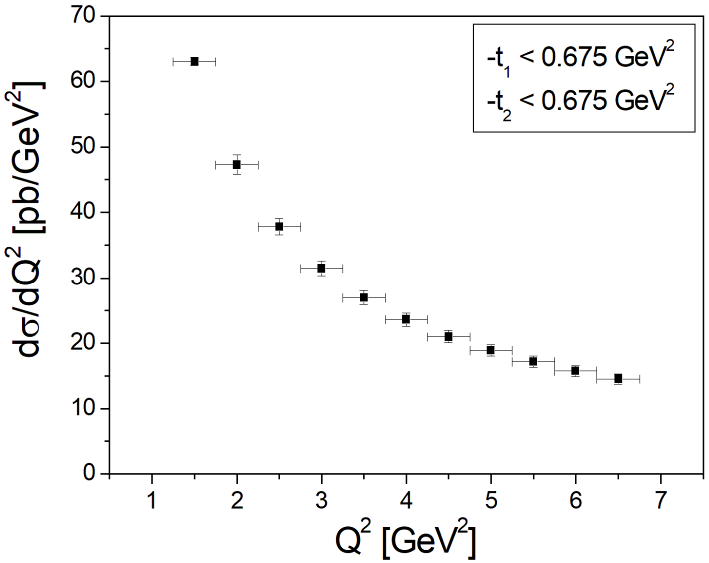




$p\bar{p} \rightarrow p\bar{p}\mu^+\mu^-$

L = 0.1 fb^{-1}





Summary

- GPDs can be well measured with PANDA
- Beam momenta between 5 GeV/c and 15 GeV/c (s = 10 – 30 GeV²) provide suitable kinematics
- Q^2_{max} = 1.3 – 1.4 GeV² (s = 10 GeV²)
- Q^2_{max} = 3.5 – 4.0 GeV² (s = 20 GeV²)
- Q^2_{max} = 6 – 7 GeV² (s = 30 GeV²)

} A beam momentum of at least 4.3 GeV/c, better 5 GeV/c is requied!

- **Two topologies have been investigated**

a) All particles detected:

- Intuitively cleaner event selection, but strict PID is still needed
- Significantly reduced acceptance, especially with strict PID
- Limitted capabilities for the detection / PID of high energetic antiprotons in the very forward region

b) Missing antiproton:

+ Increased acceptance
+ A tight PID can be / has to be applied
+ Small $-t_2$ can be accessed at all CM energies

Summary

Optimal settings:

pe-e+X s = 30 GeV² → p ~ 15 GeV/c can be well measured

→ Largest Q² range accessible

Also possible: All particles detected s ~ 20 GeV² → p ~ 10 GeV/c

→ Best compromise between Q² and $-t_2$ range

Next step:

Background and background suppression methods will be studied in more detail