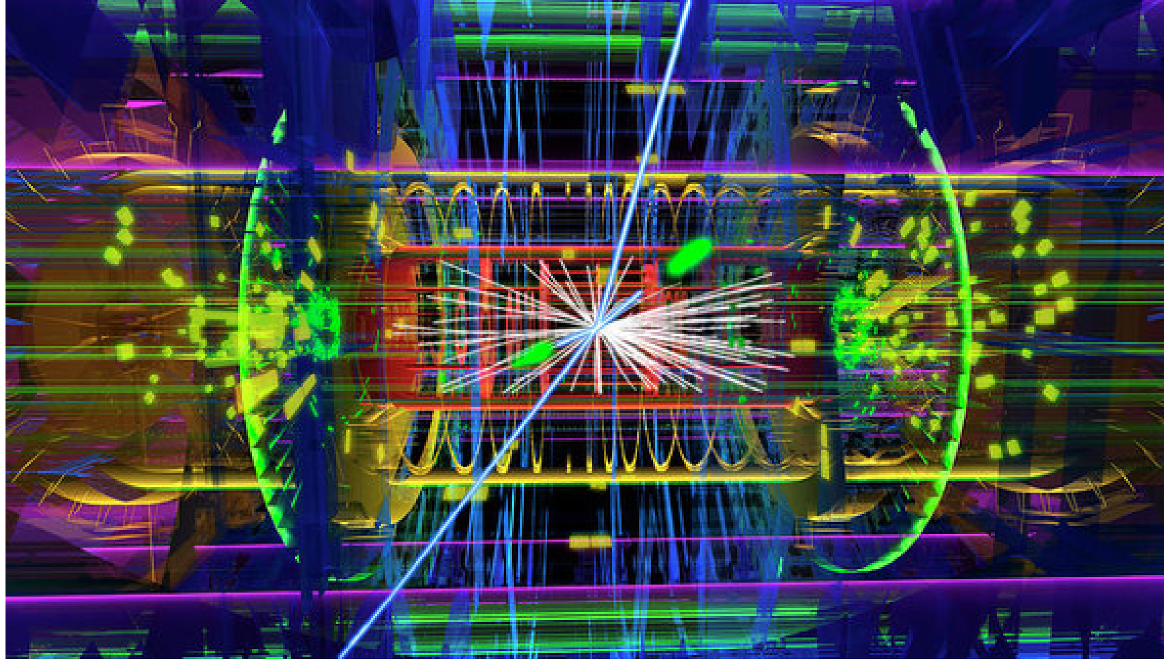

Anna Fehérkuti
ELTE, Physics Msc, II. Year
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ELTE TTK, Atomfizikai Tanszék

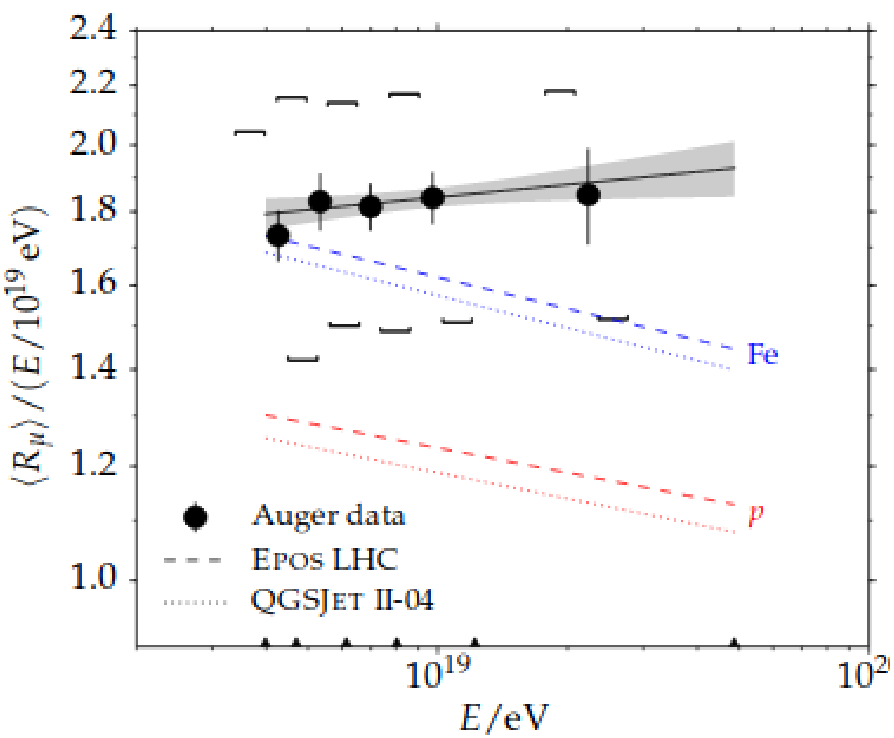
Feasibility studies of charge exchange measurements in pp collisions

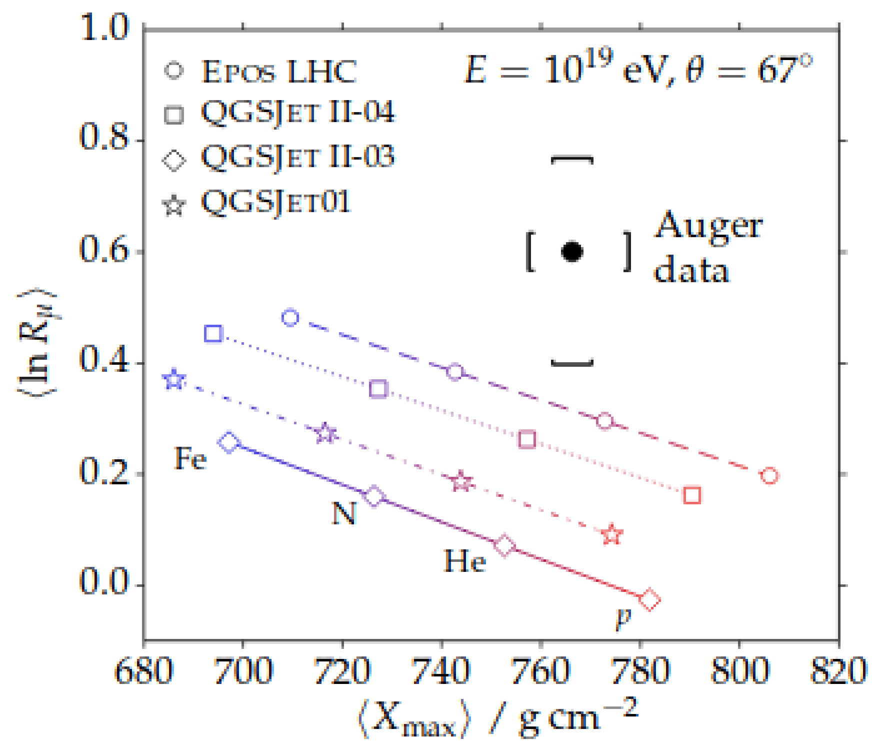
Zimányi School
9. 12. 2021.

Supported by the ÚNKP-20-2 and ÚNKP-19-1 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.
Further special thanks to NKFIH OTKA 128713 grant.

Muon Mystery

- Measurements of ultra high energy cosmic rays
  (eg. at Pierre Auger Observatory)
- Muon component / shower not reproduced by simulations

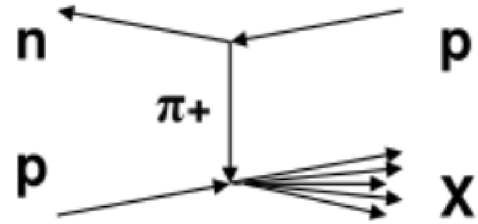




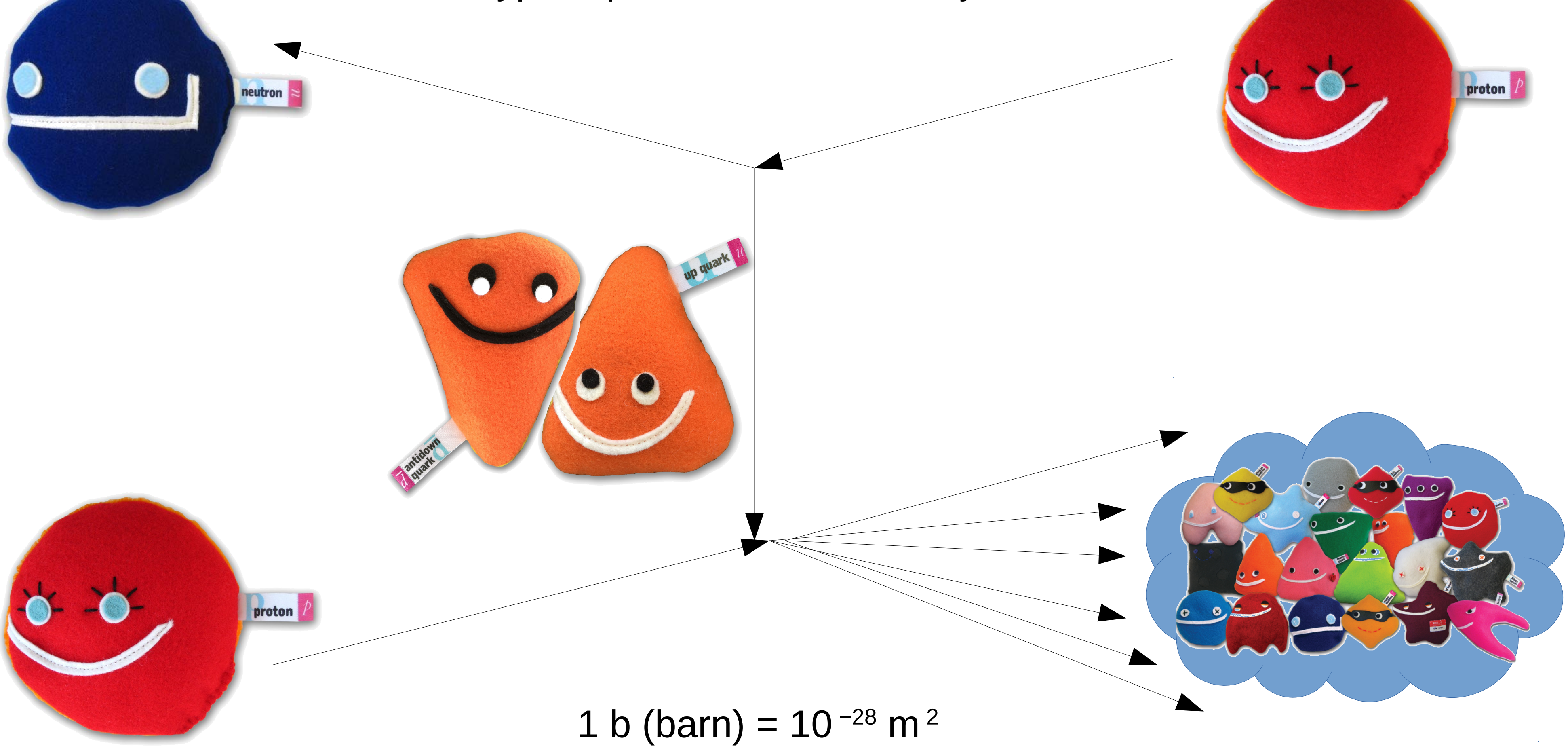
→ could this be measured in the laboratory (at LHC energies)?

- See whether simulations predict measured data well

Charge exchange



Typical process in cosmic rays

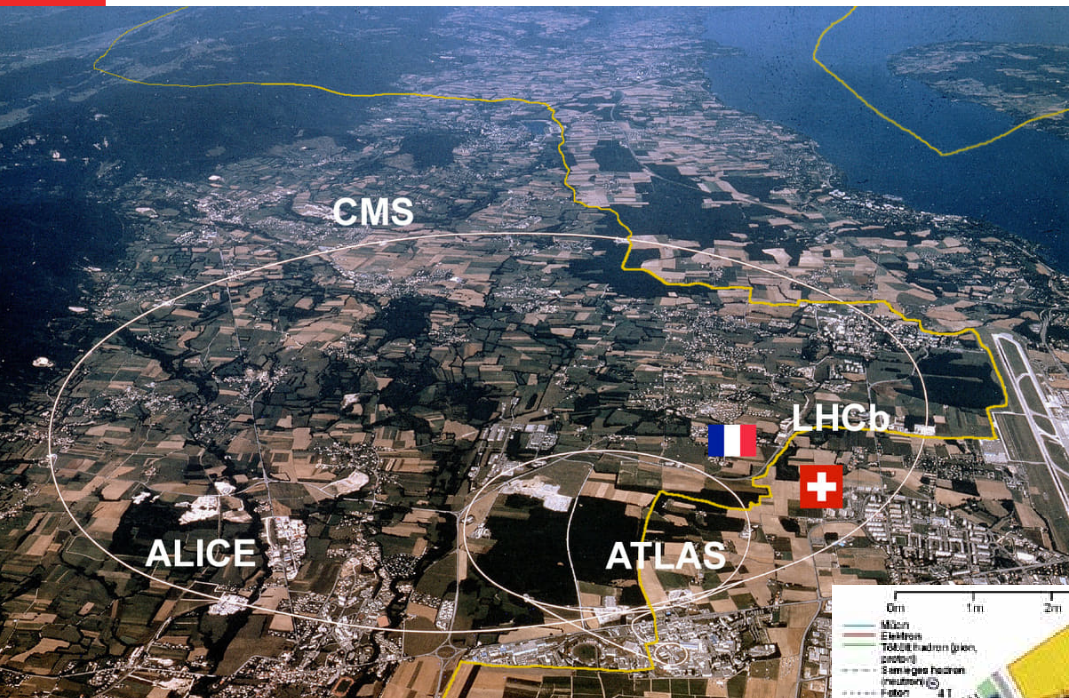


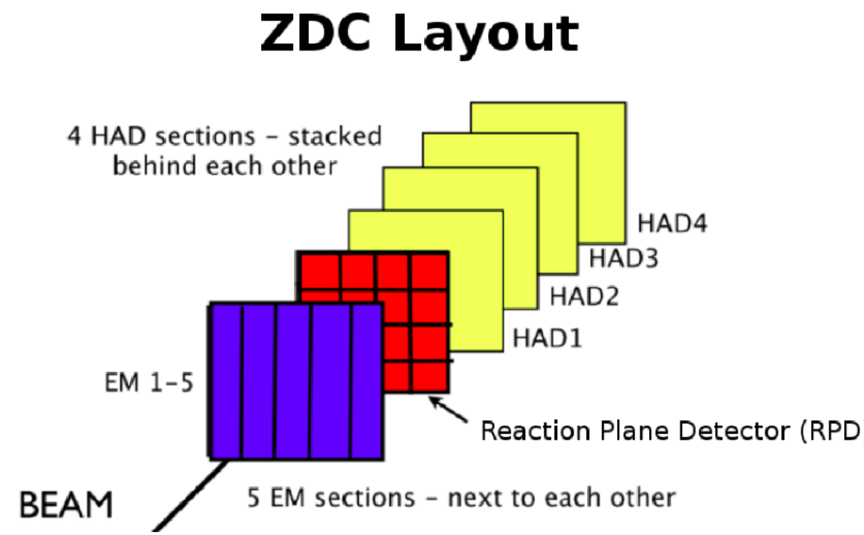
1 b (barn) = 10^{-28} m ^{2}

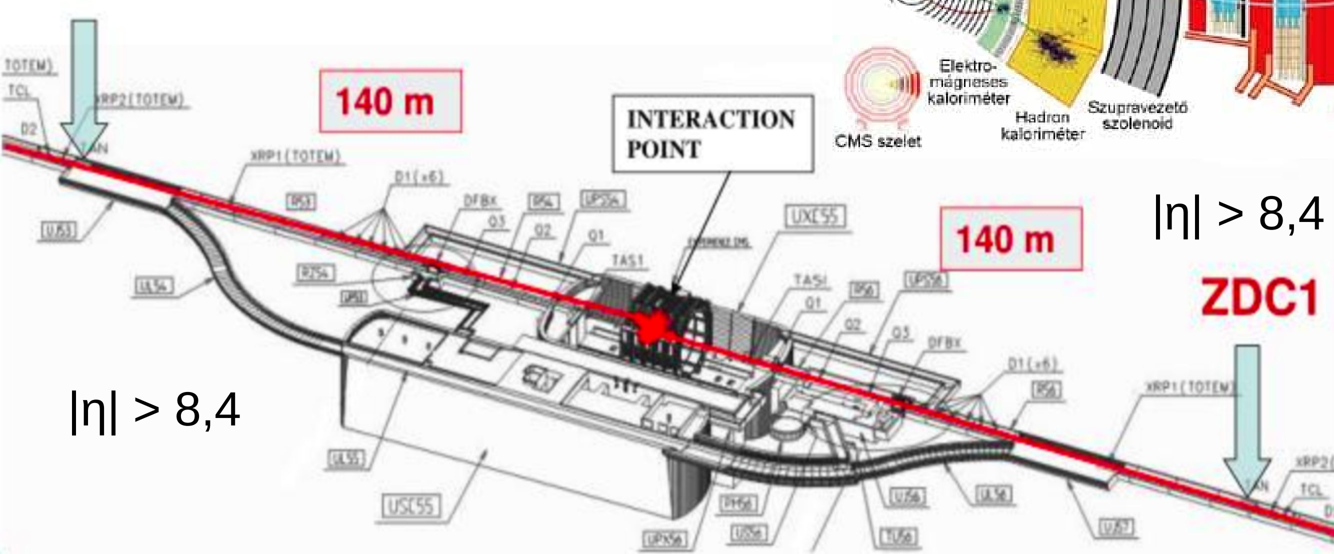
~mb order of magnitude cross-section

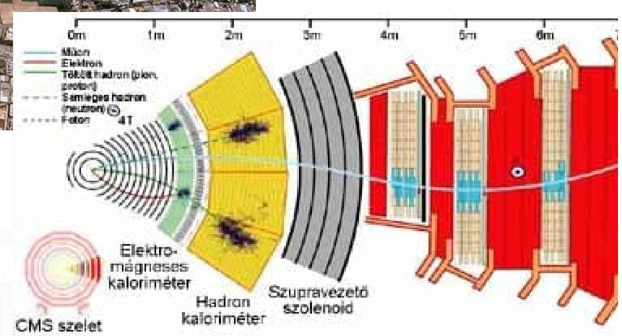
→ simulations with CRMC (pp collisions at $\sqrt{s}$ = 7 TeV)

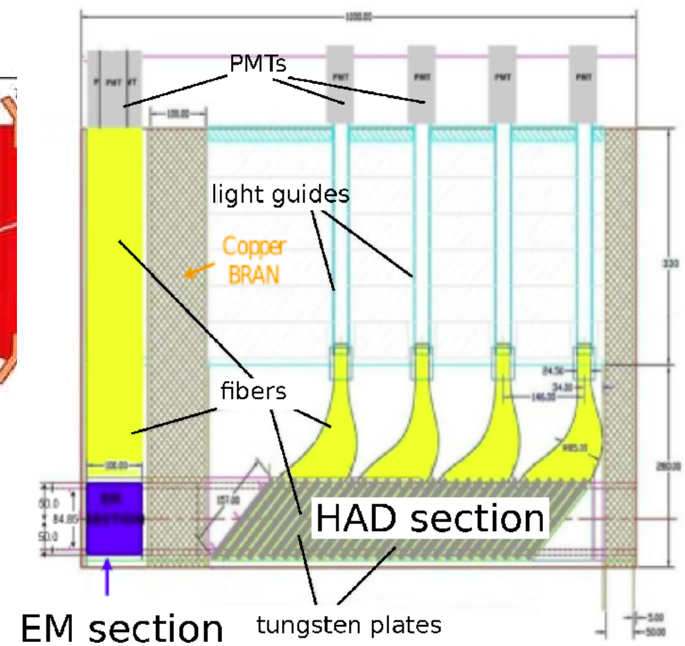
The ZDC at CMS



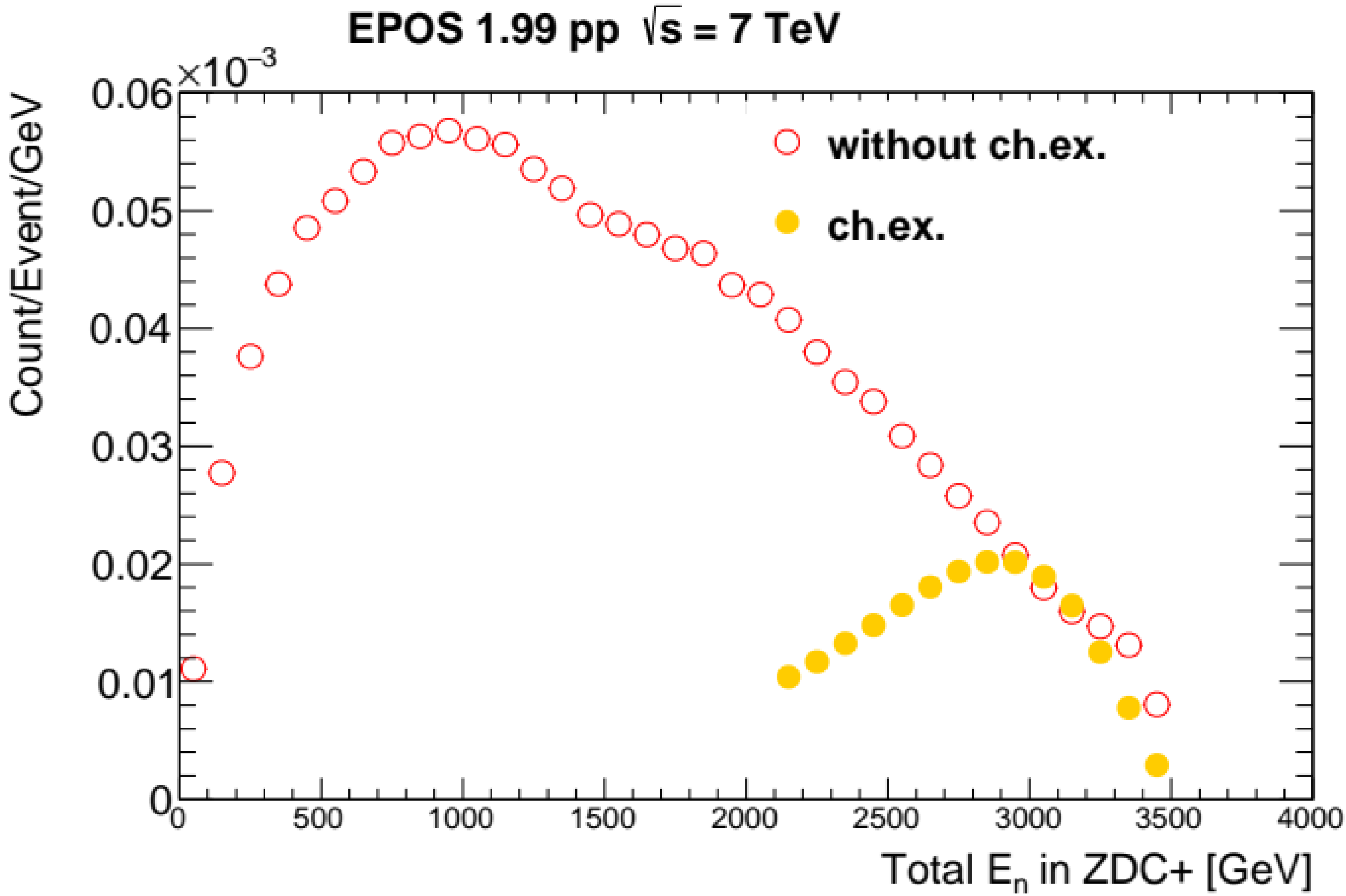








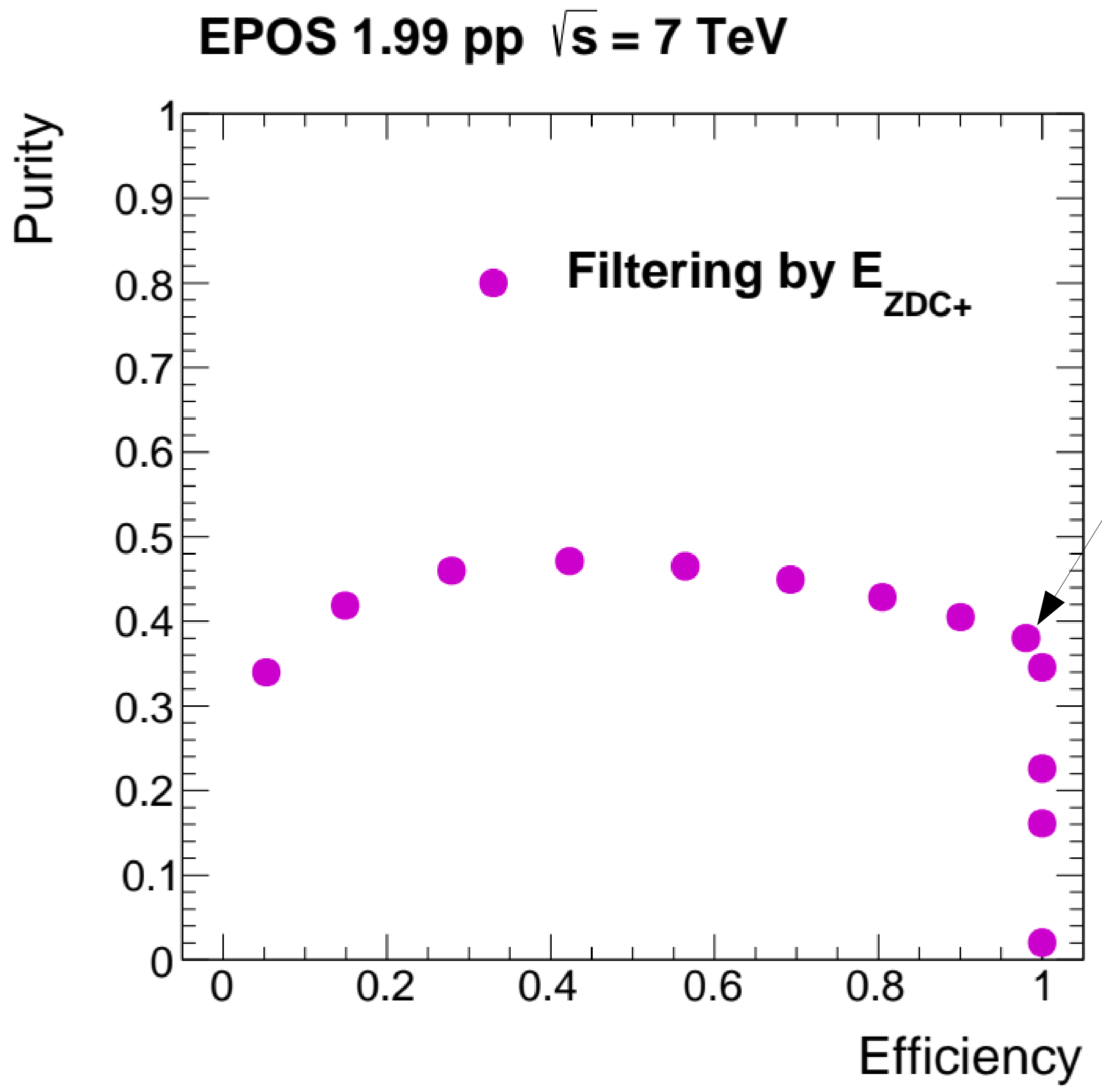
Energy distribution in the ZDC



- ch.ex.: characteristically high(er) energies
  → suitable quantity for selection

(nonphysical cut at 2100 GeV due to the MC for the p_{loss} of the initial proton)

ROC curve for the ZDC energy cut



$$\text{Purity} = \frac{\text{Ch.ex. In the range}}{\text{Everything in the range}}$$

Working point
(E_{ZDC} > 2140 GeV)

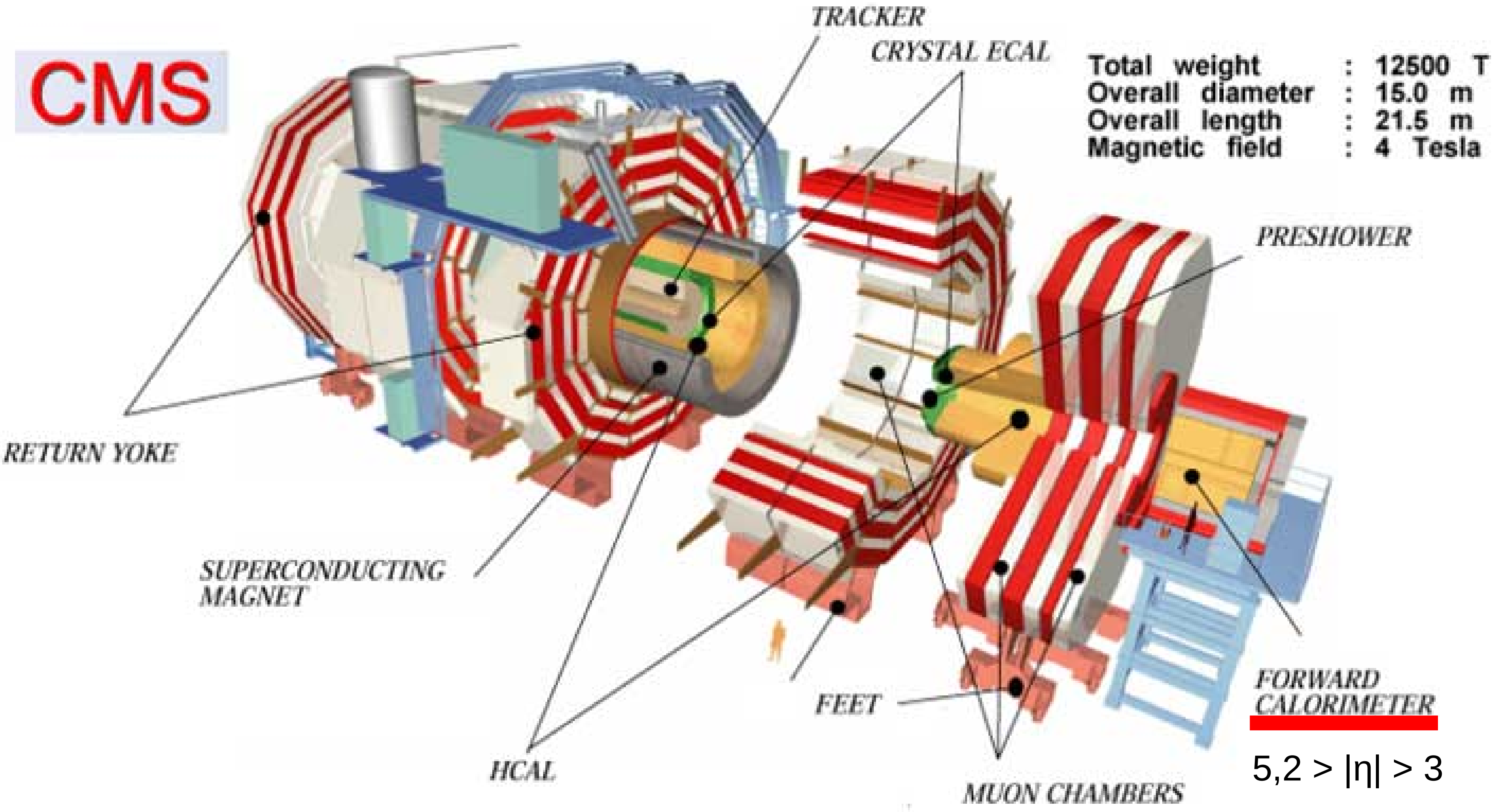
~38% purity

~98% efficiency

$$\text{Efficiency} = \frac{\text{Ch.ex. In the range}}{\text{All ch.ex.}}$$

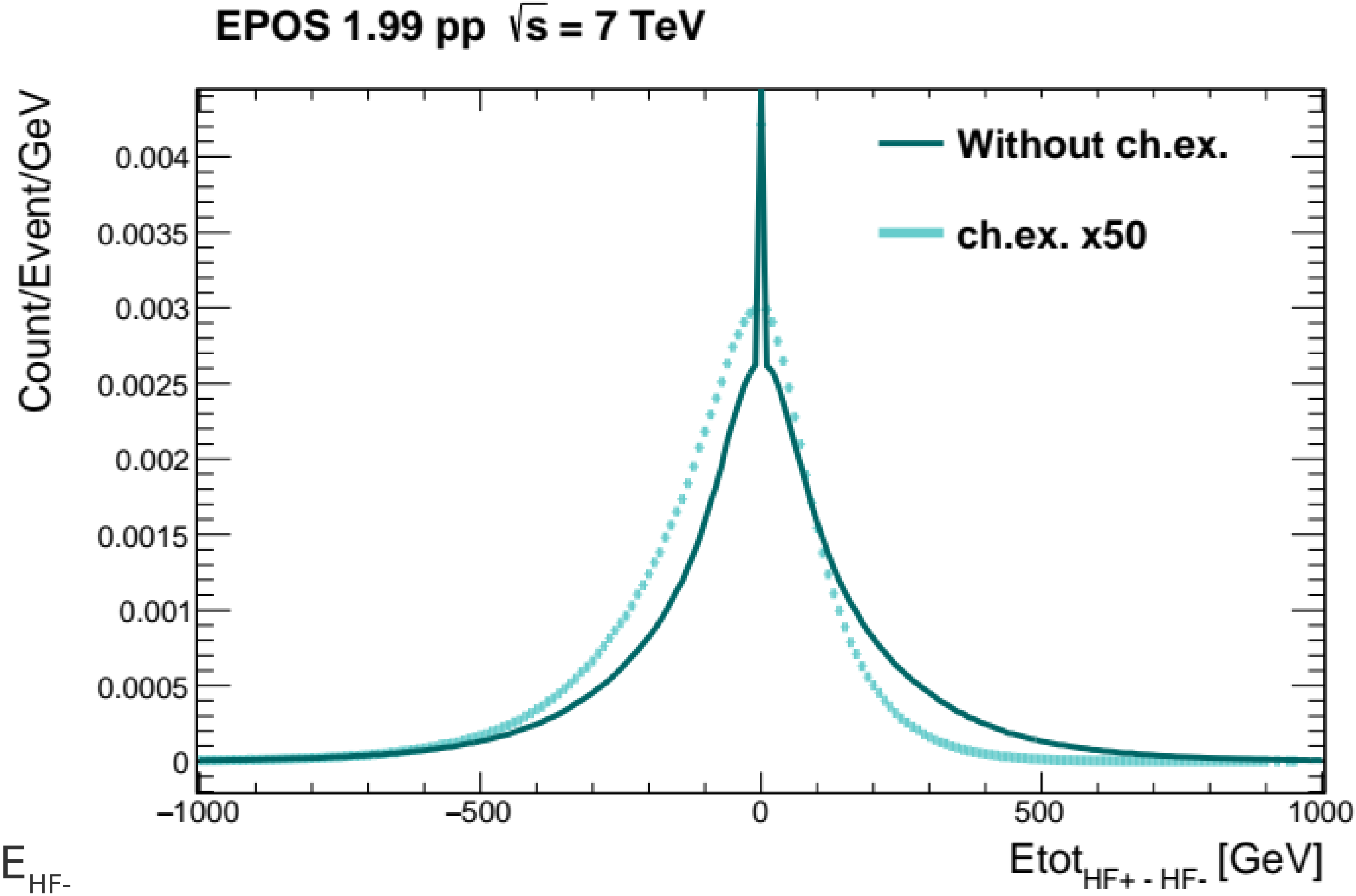
- (Remark: more dots because of the unphysical cut at 2100 GeV)

Further detectors of CMS



5,2 > |η| > 3

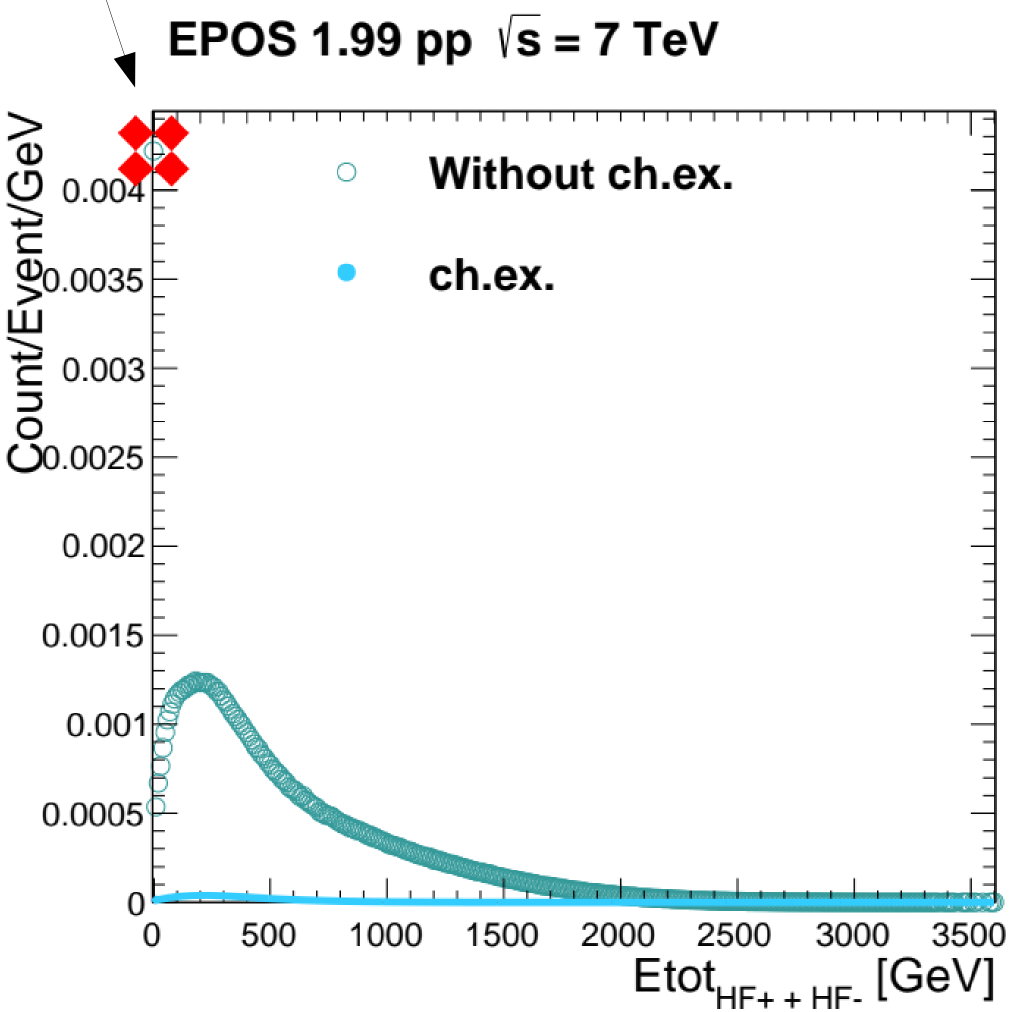
Energy asymmetry in the HF

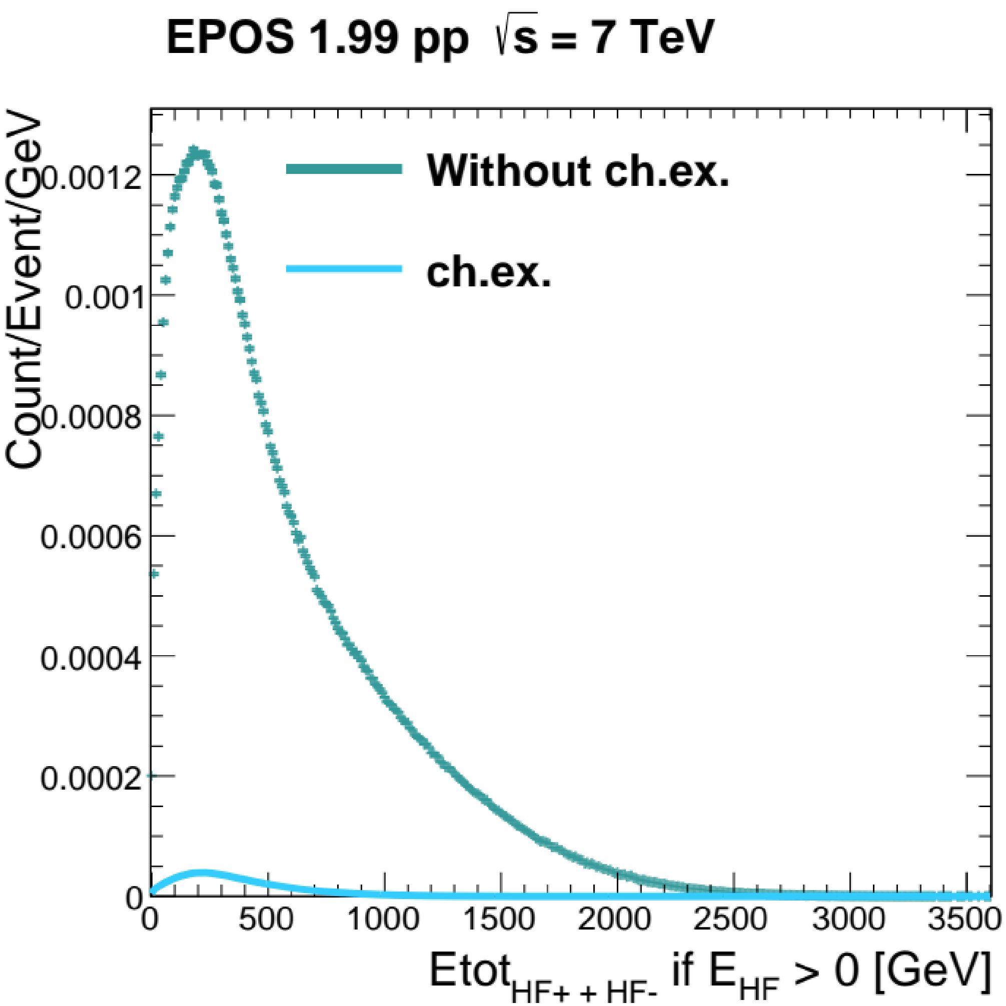


- E_{HF+}-E_{HF-}
- Asymmetric for charge exchange ← high energy neutron went to ZDC+
- Small effect→ selection used together with the E_{ZDC} cut

HF total energy distributions

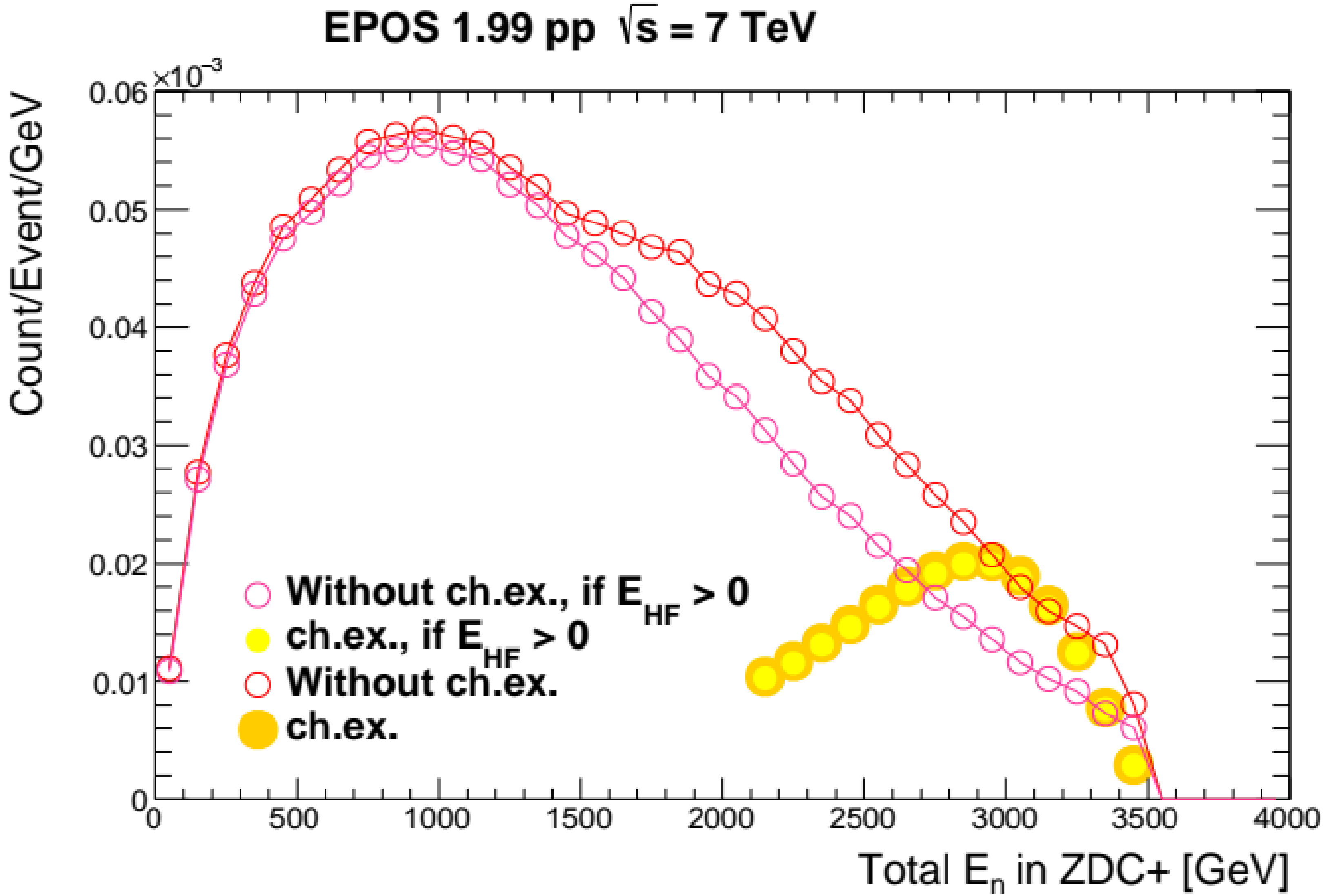
HF has not fired





No count in any of the HFs:
In 1.2% of the charge exchange
In 4.1% of others
→ new possibility of cut

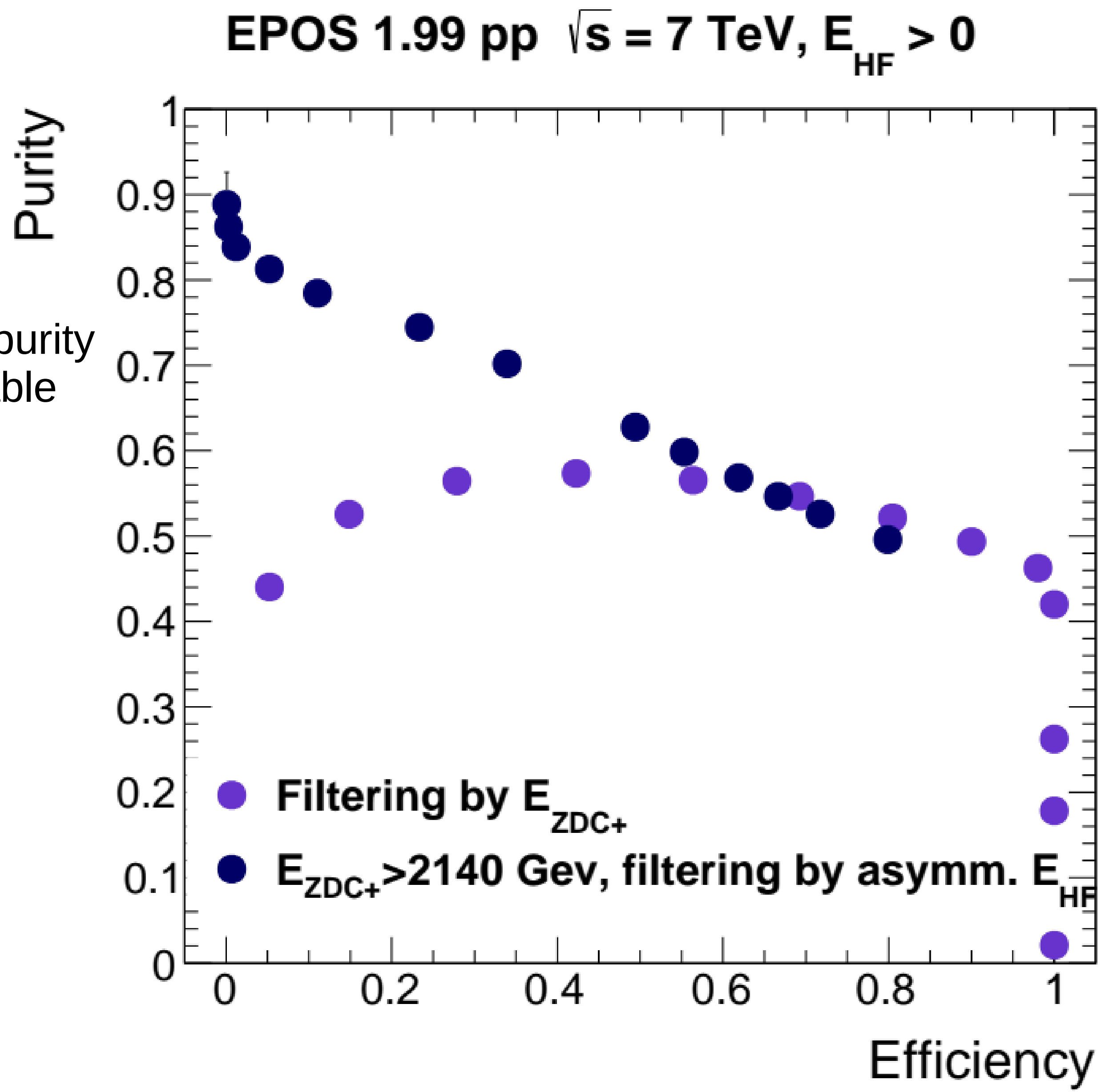
$E_{neutron}$ in ZDC for E_{HF}>0 events



- Rejecting many events without ch.ex, while ch.ex. barely changed

Comparing ROC curves

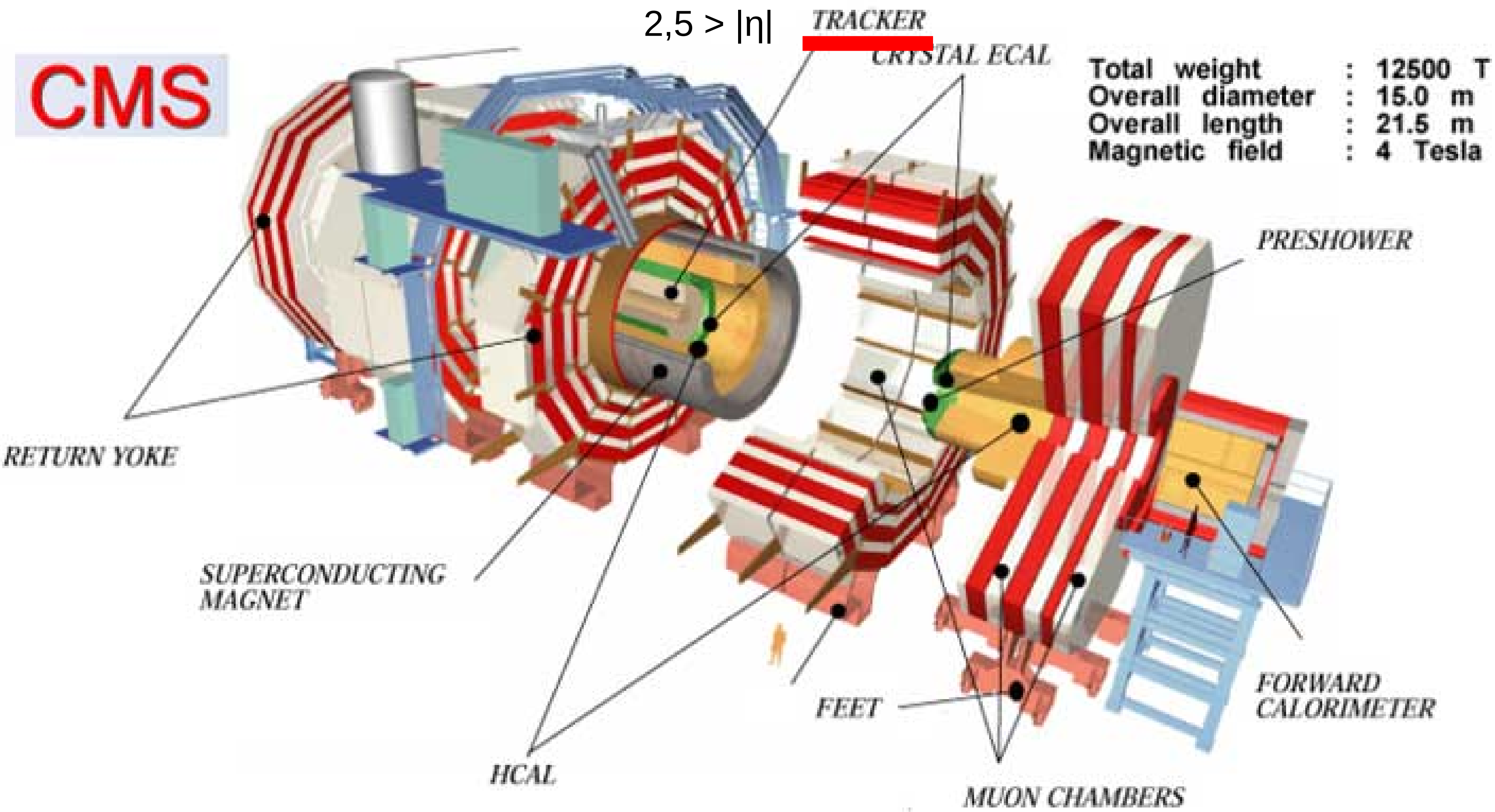
Higher purity achievable



Remark:
Efficiency redefined (defined on set of events that remained after E_{ZDC} & E_{min}^{HF} cut)

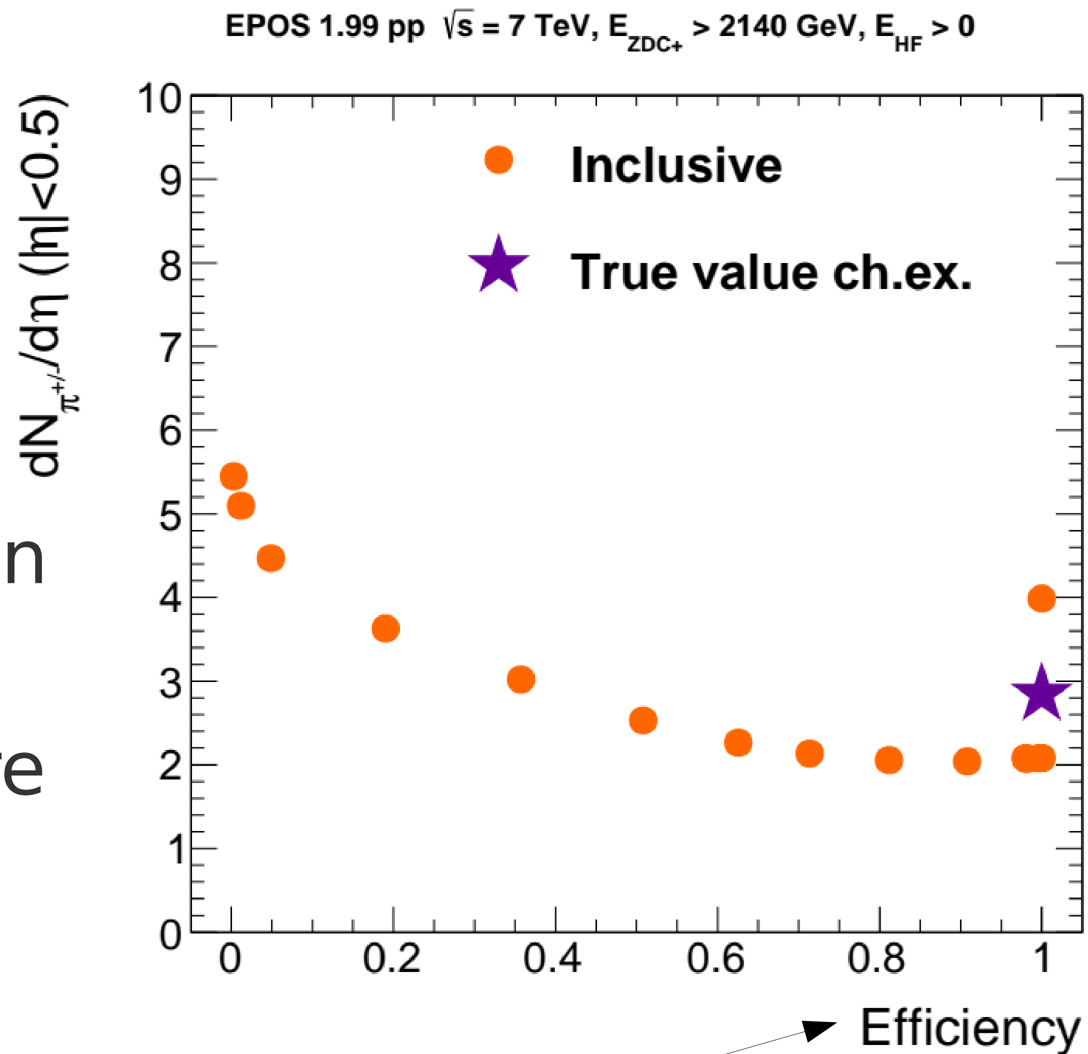
Further detectors of CMS

2,5 > |η|



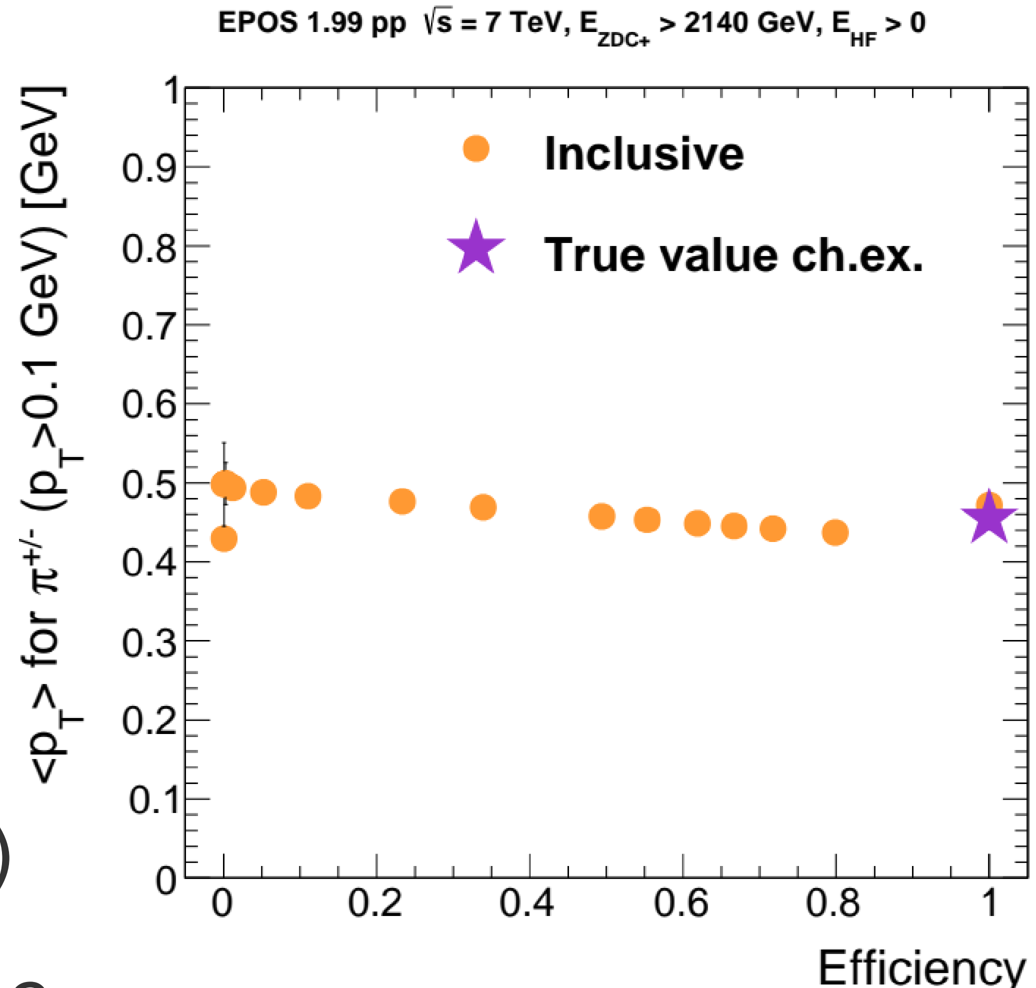
Bias test I.

- Tracker not used for event selection: no autocorrelation
- dN/dη in η<|0.5| region (midrapidity) for $\pi^{\pm}$
- Same quantity for pure charge exchange dataset: true value
- Greater asymmetry requires more particles → not independent



from the ROC curve for the HF asymmetry cut

Bias test II.



Acceptance of the Tracker
→ restriction on p_T

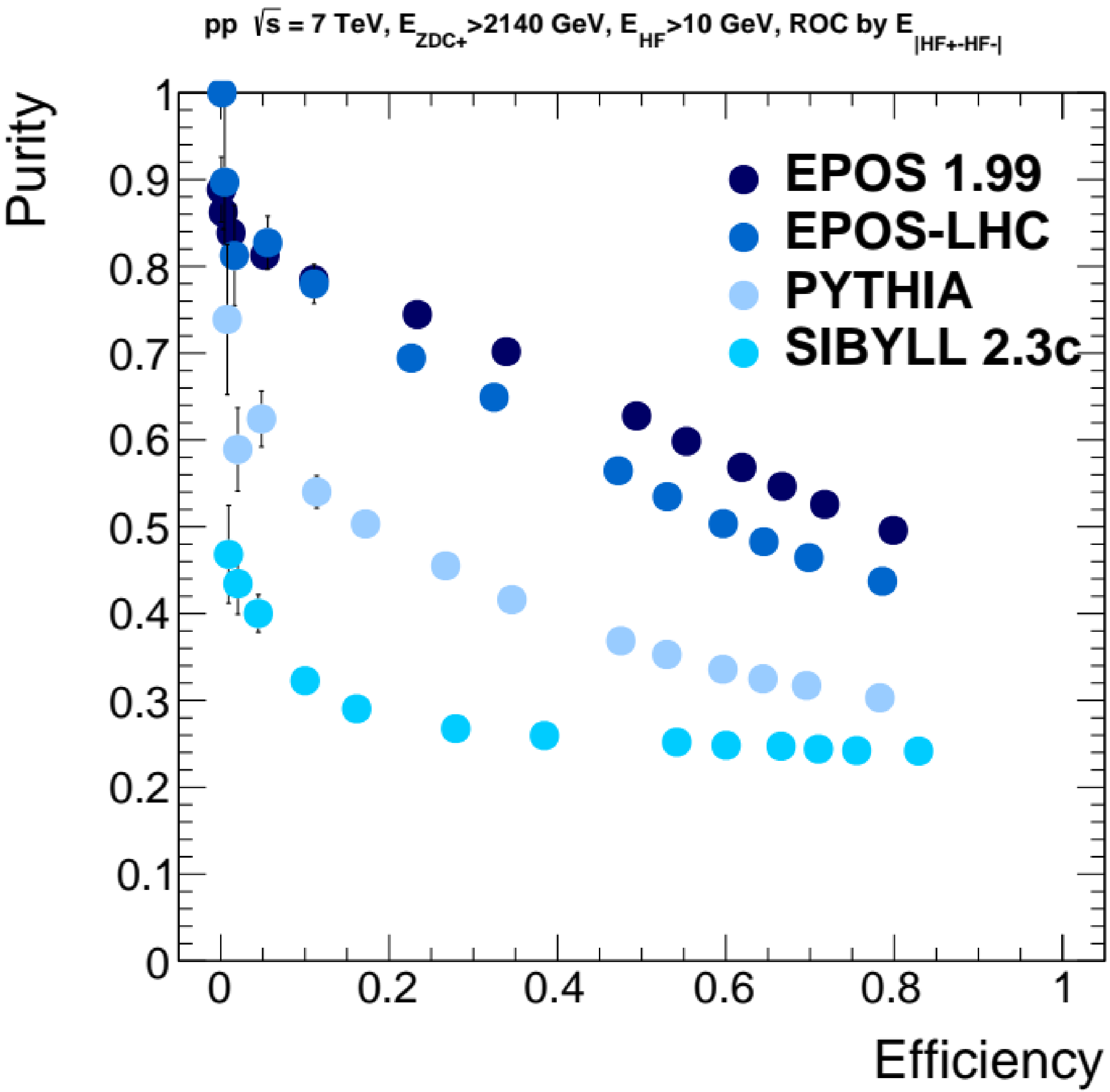
- $<p_T>$ for $\pi^{\pm}$

  (p_T>0.1 GeV ← detector)

- Weak dependence on the choice of the working point

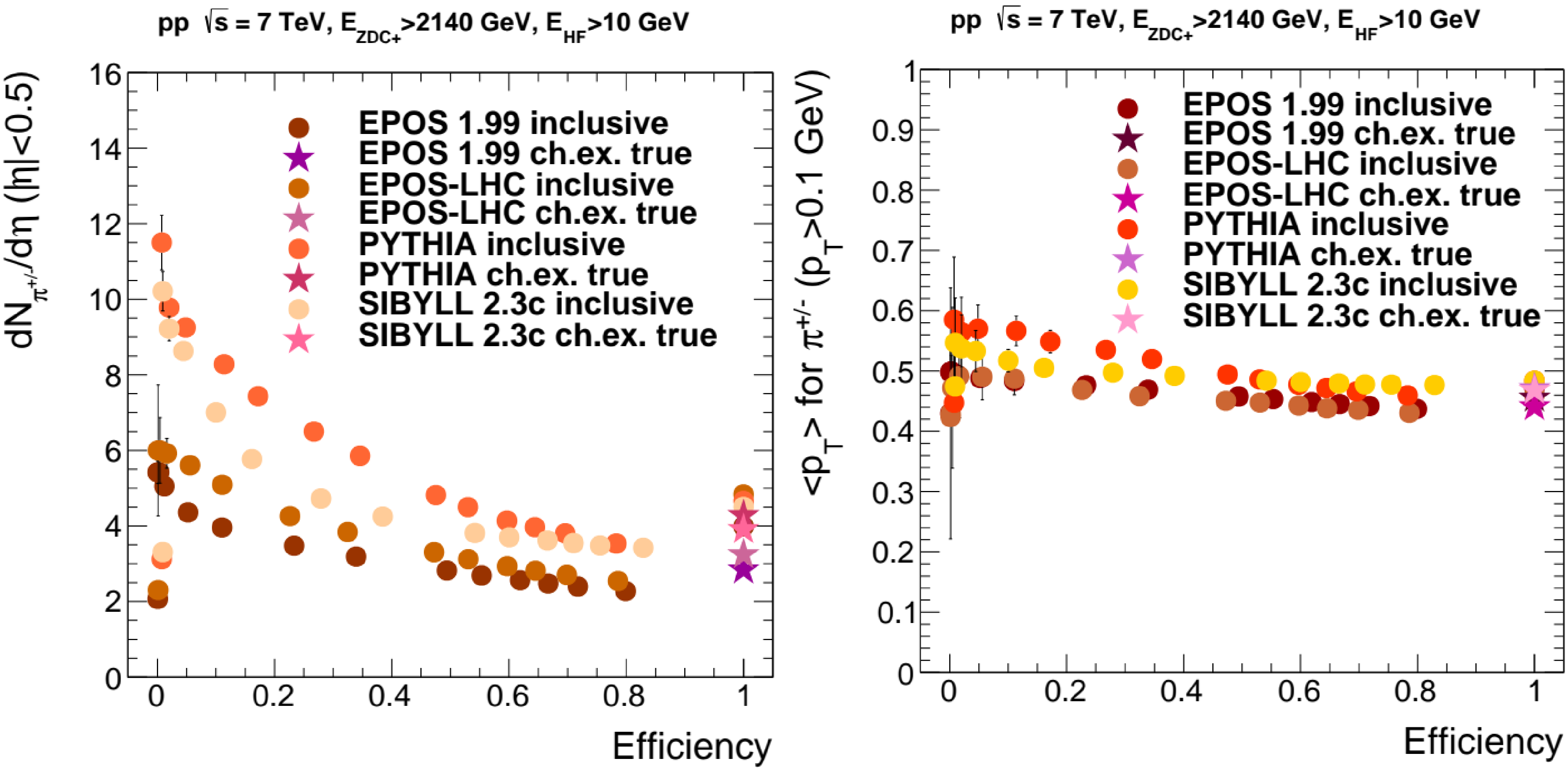
  → new working point chosen to match the midrapidity true value

More models: final ROC



- ROC for the asymmetry in the HF
- Huge difference in the predictions
- Need data for validation

More models: bias tests

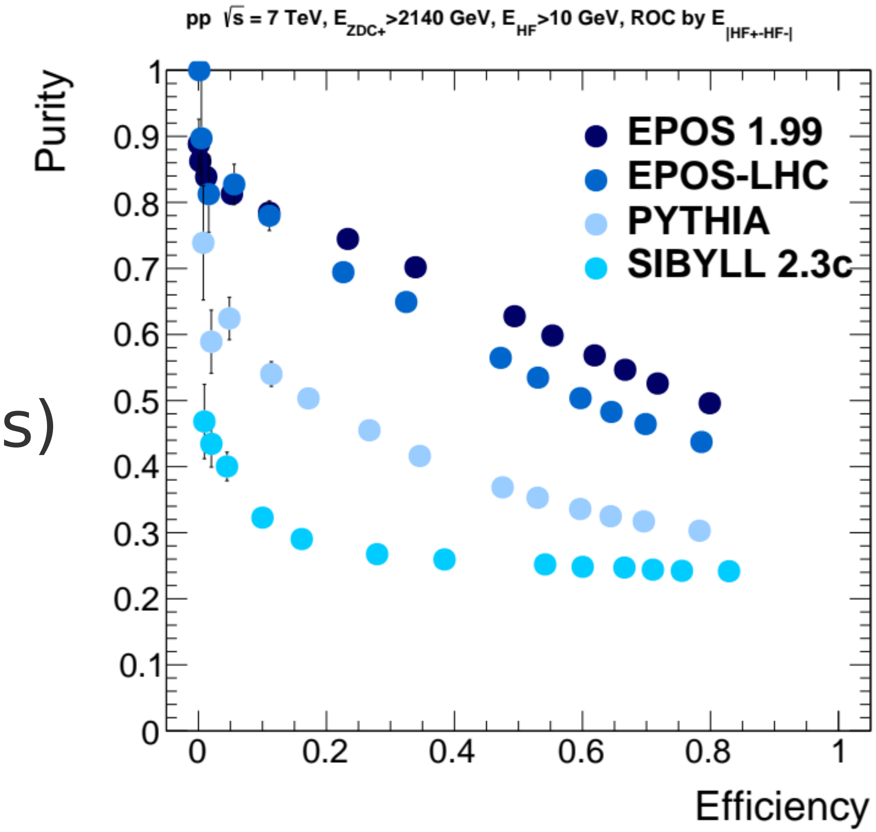


- Same tendencies
- Discrepancies between models

Predictions

- Working point for each model (obtained by the same matching method with appropriate bias tests)
- Really different predictions

  → very uncertain cut value



Quantity	EPOS 1.99	EPOS-LHC	PYTHIA	SIBYLL 2.3c	Average
Efficiency [%]	48.6	49.1	57.1	50.7	51.4 ± 5.7
Purity [%]	63.1	55.5	34.2	25.4	44.6 ± 18.6
ΔEnergy [GeV]	102.4	95.0	75.7	111.0	96.0 ± 14.9
Midrapidity vs true [%]	0.0	0.0	0.0	0.0	
Av. mom. vs true [%]	0.7	1.9	2.0	3.8	

Summary

Event selection for EPOS 1.99:

- Total energy in ZDC > 2140 GeV
- & E_{HF} > 10 GeV
- & $|E_{HF+} - E_{HF-}|$ > 102 GeV:
  - ~63% are charge exchange (purity)
  - ~49% of charge exchange accepted (efficiency)

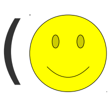
Using this cut for charged pions in Tracker:

- For dN/dη: reproduce the true value
- For $<p_T>$: agreement with the true value within 1%

- Very large discrepancies in predictions of different models

Main further plans

- Include CMS simulation
  → detector-specific effects

  (ongoing work)
- p+Pb analysis (ongoing work)
- Measured data
  - 2016 p+Pb [https://cds.cern.ch/record/2235235?]
  - Run3 pO, OO? ( ~collisions in the atmosphere)
- (+MultiVariate Analysis? → improve ROC)

Thank You for the attention!

Backups

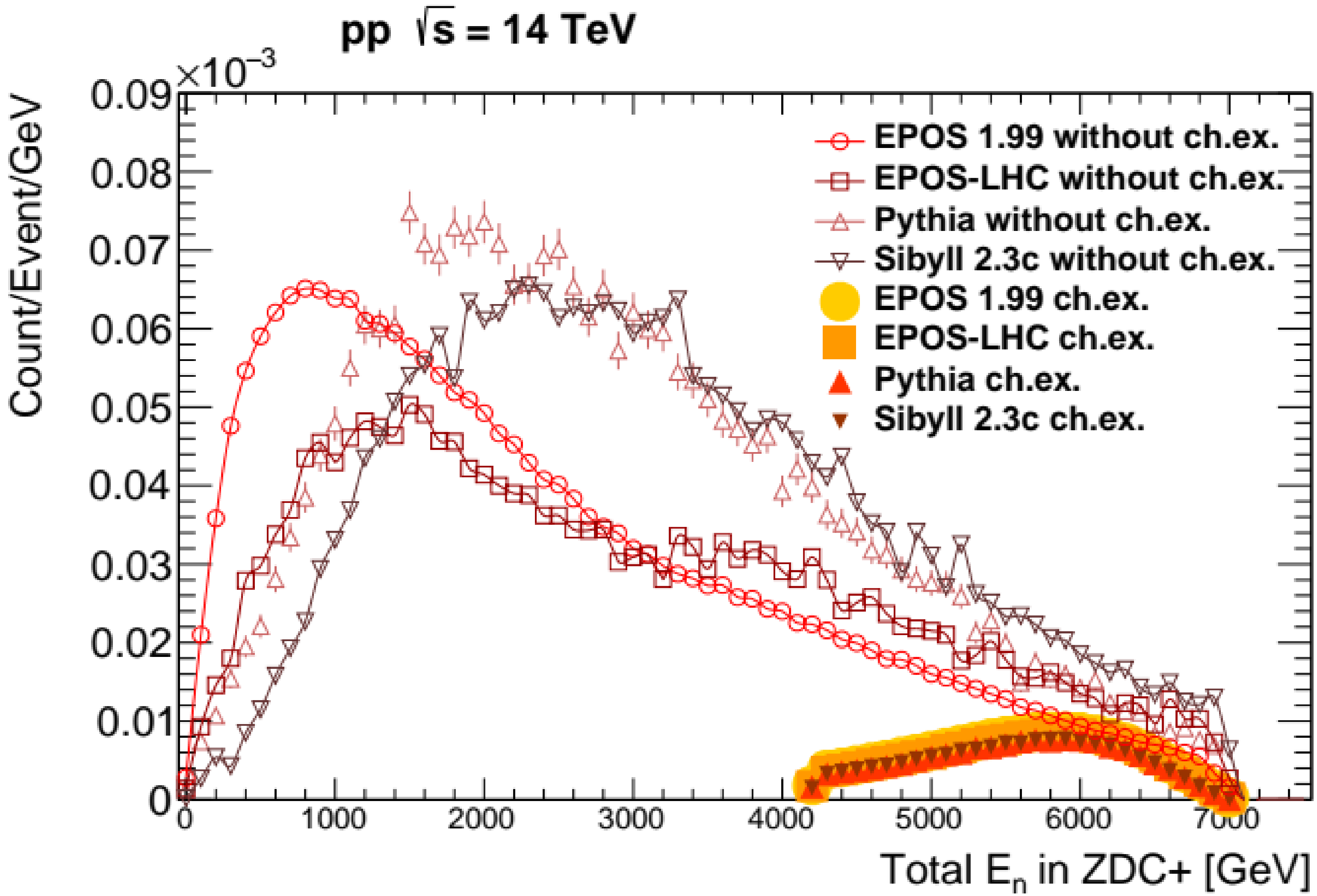
Supported by the ÚNKP-20-2 and ÚNKP-19-1 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.
Further special thanks to NKFIH OTKA 128713 grant.

Új Nemzeti Kiválóság Program

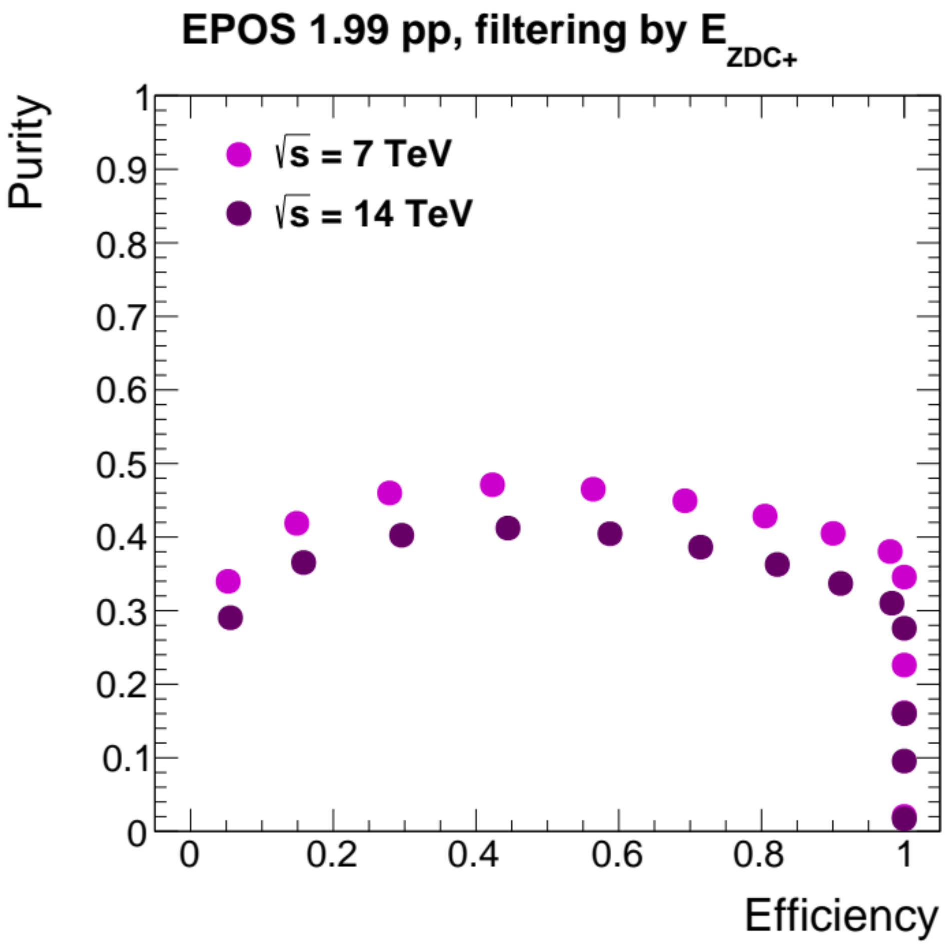
NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE
HUNGARY

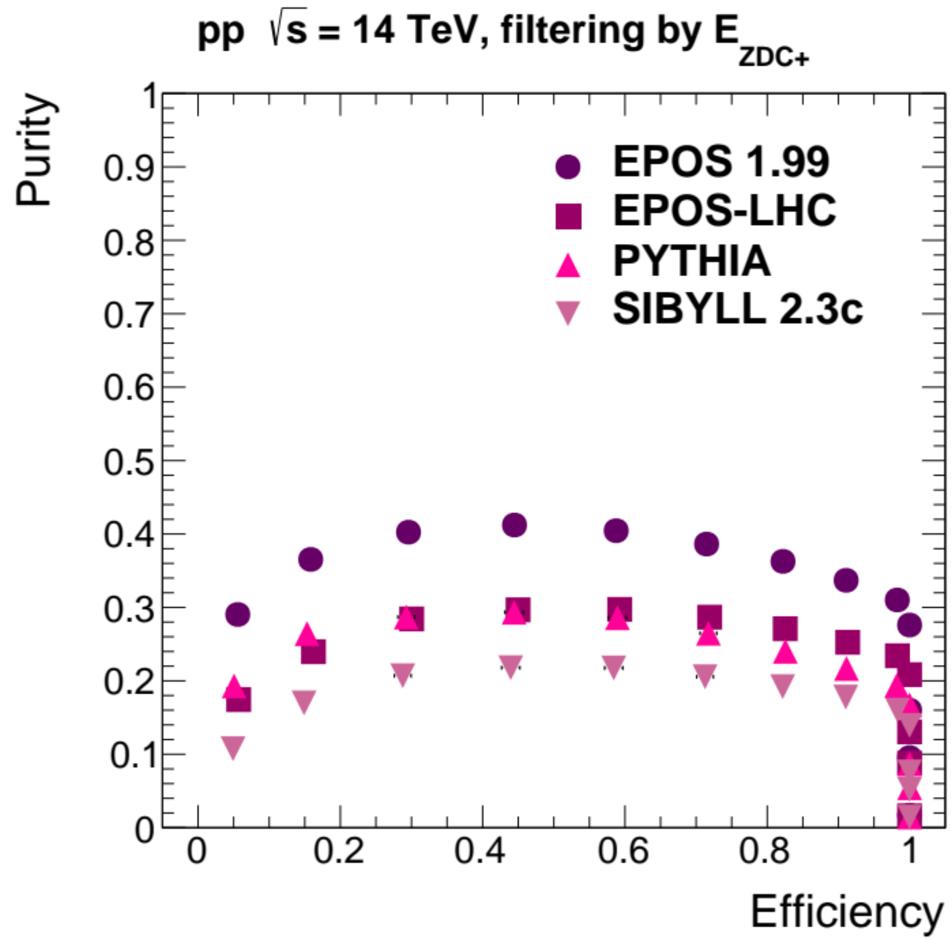
14 TeV: neutron energy

- Huge discrepancy between predictions of background by different models



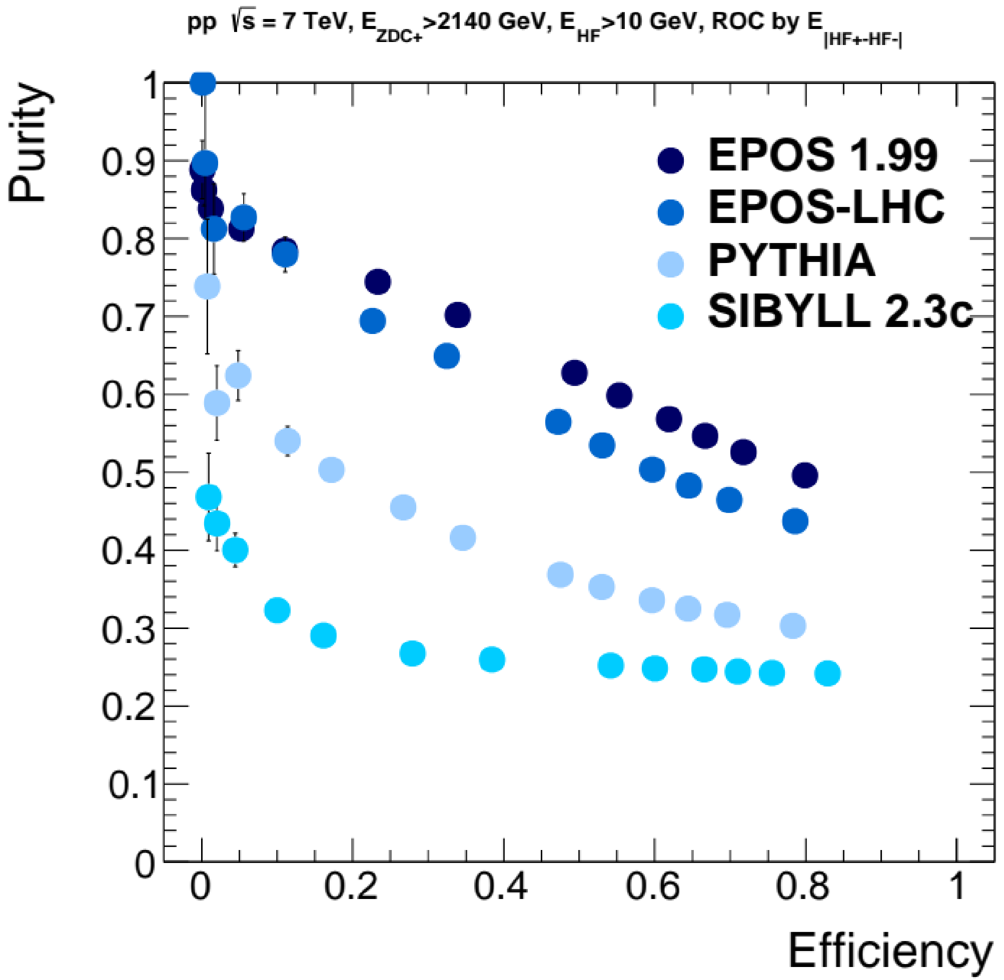
14 TeV: ROC for ZDC cut

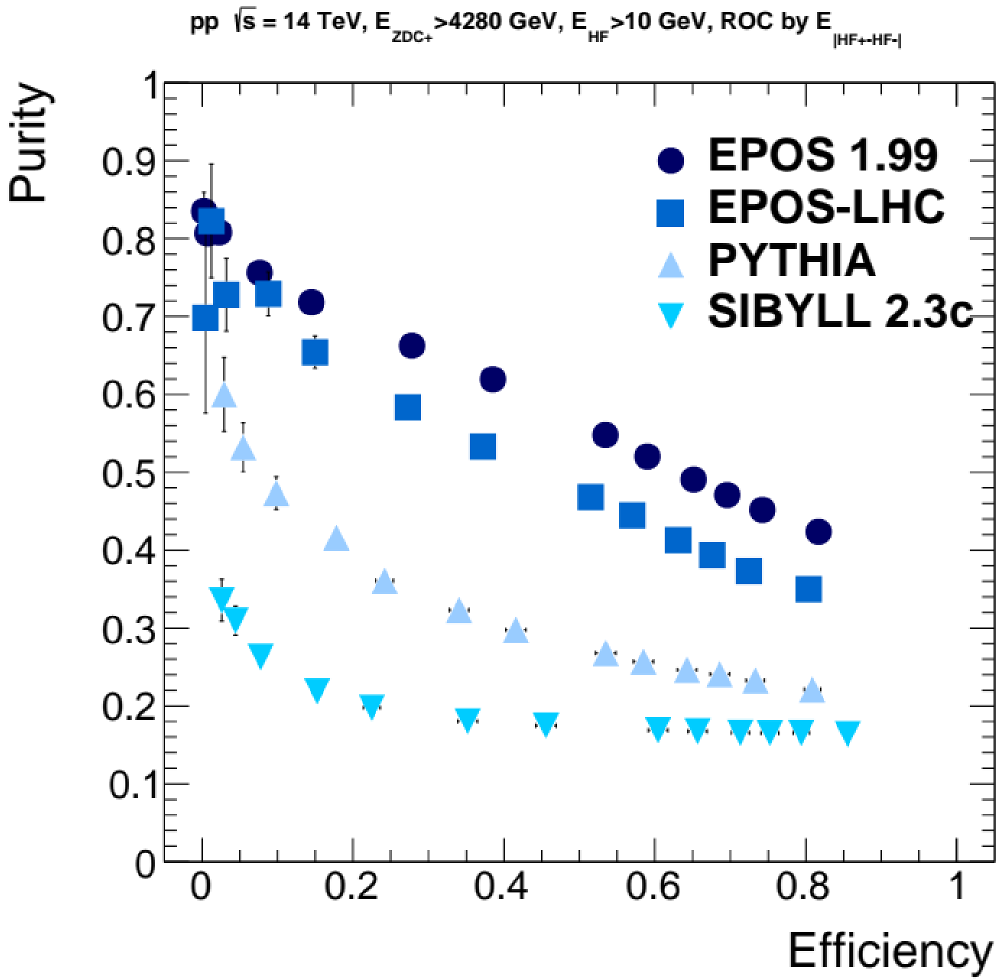




- Total inelastic cross section increases with energy
- Ch.ex. cross section considered as constant
  → net decrease in purity

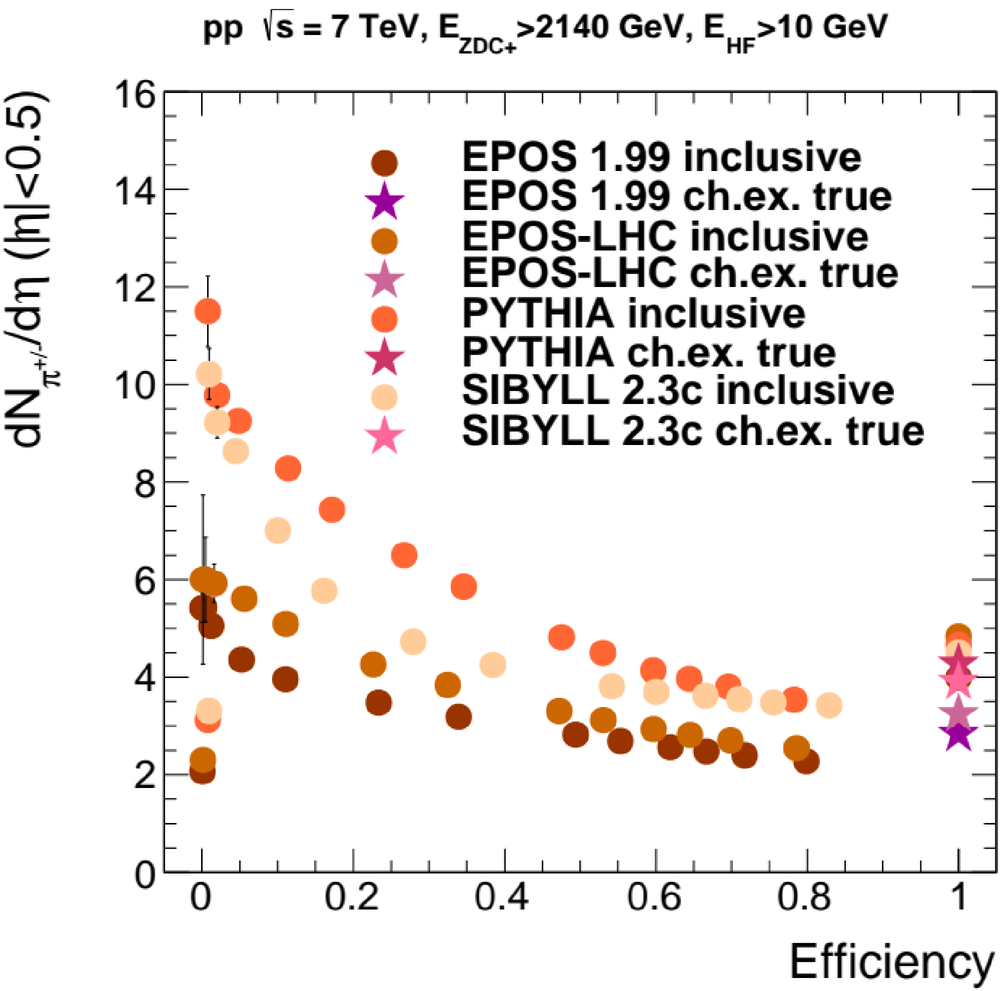
14 TeV: final ROC

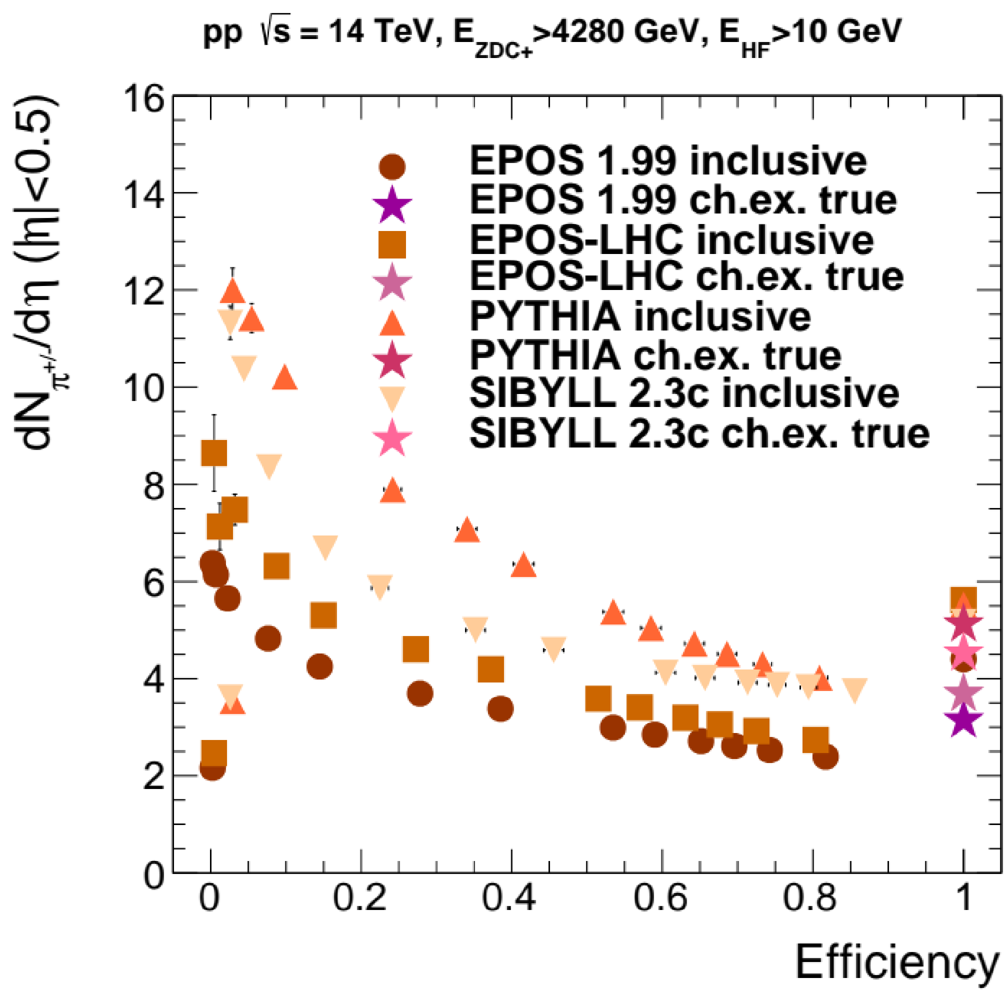




- Same tendency between models
- Lower purity reflected

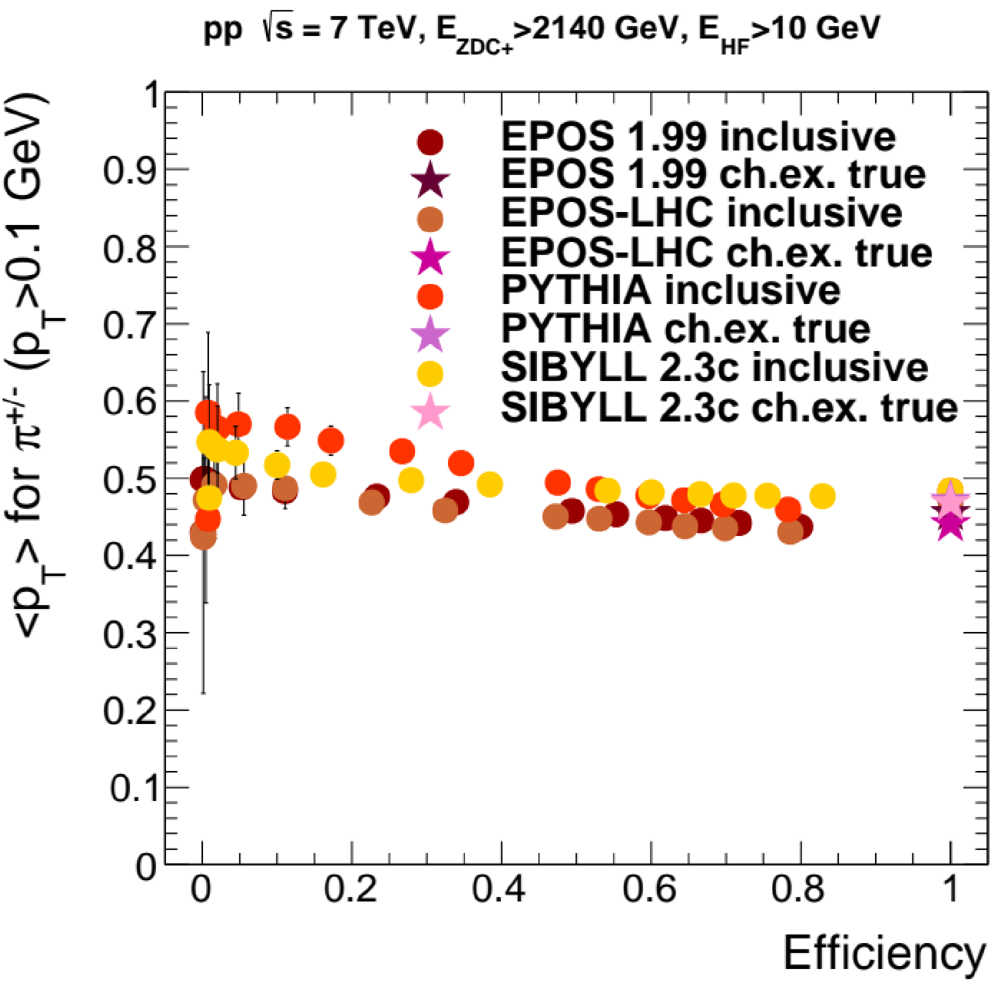
14 TeV: bias test I.

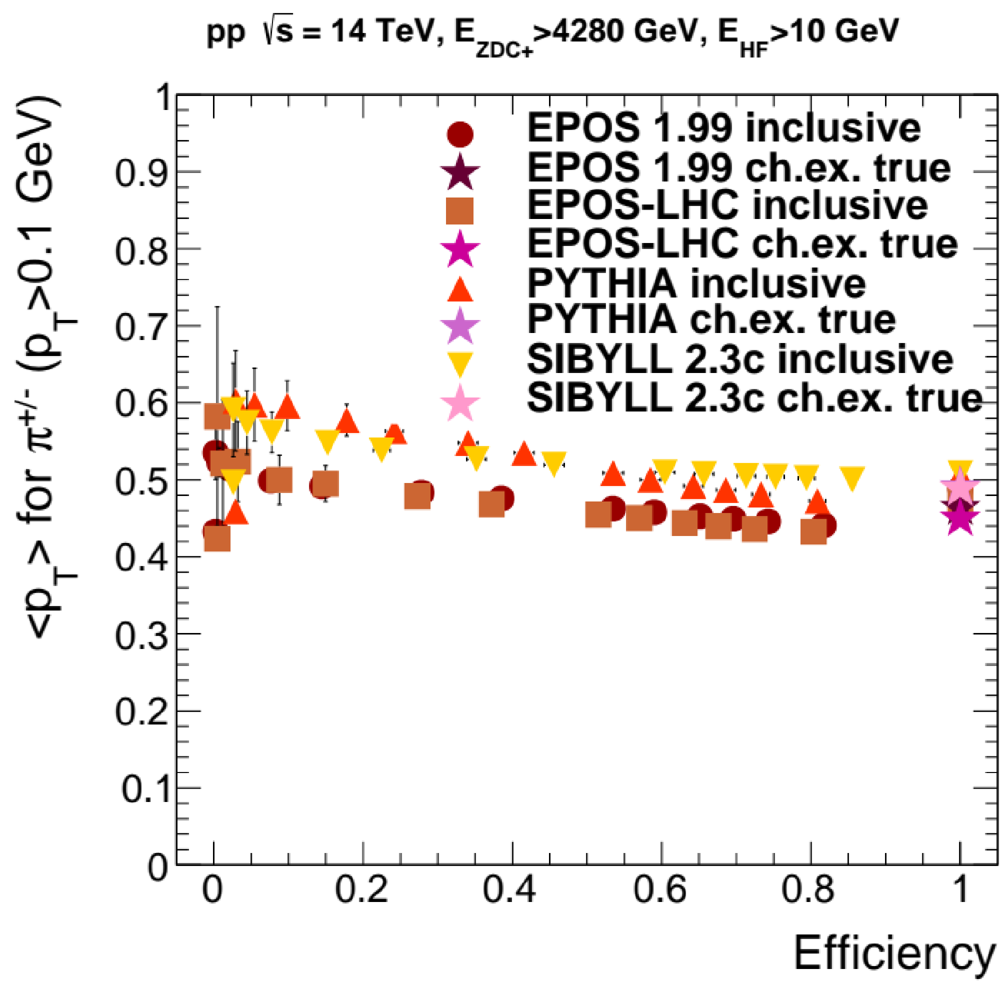




- Same tendencies

14 TeV: bias test II.





- Same tendencies

Charge exchange in the simulation

a) single pion exchange

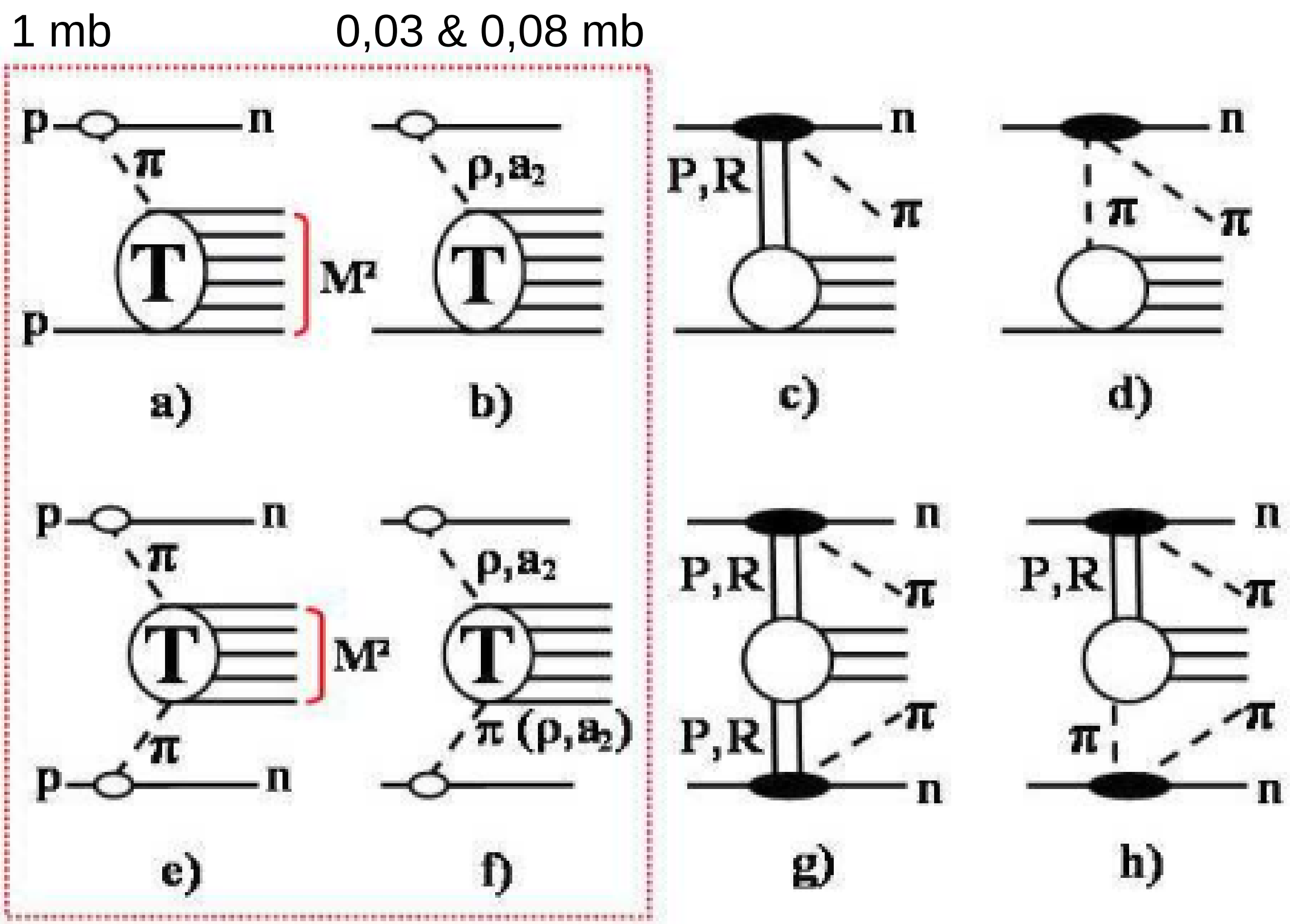
b) its background (instead of pion another reggeon)

c-d) double dissociative background

e) double pion exchange

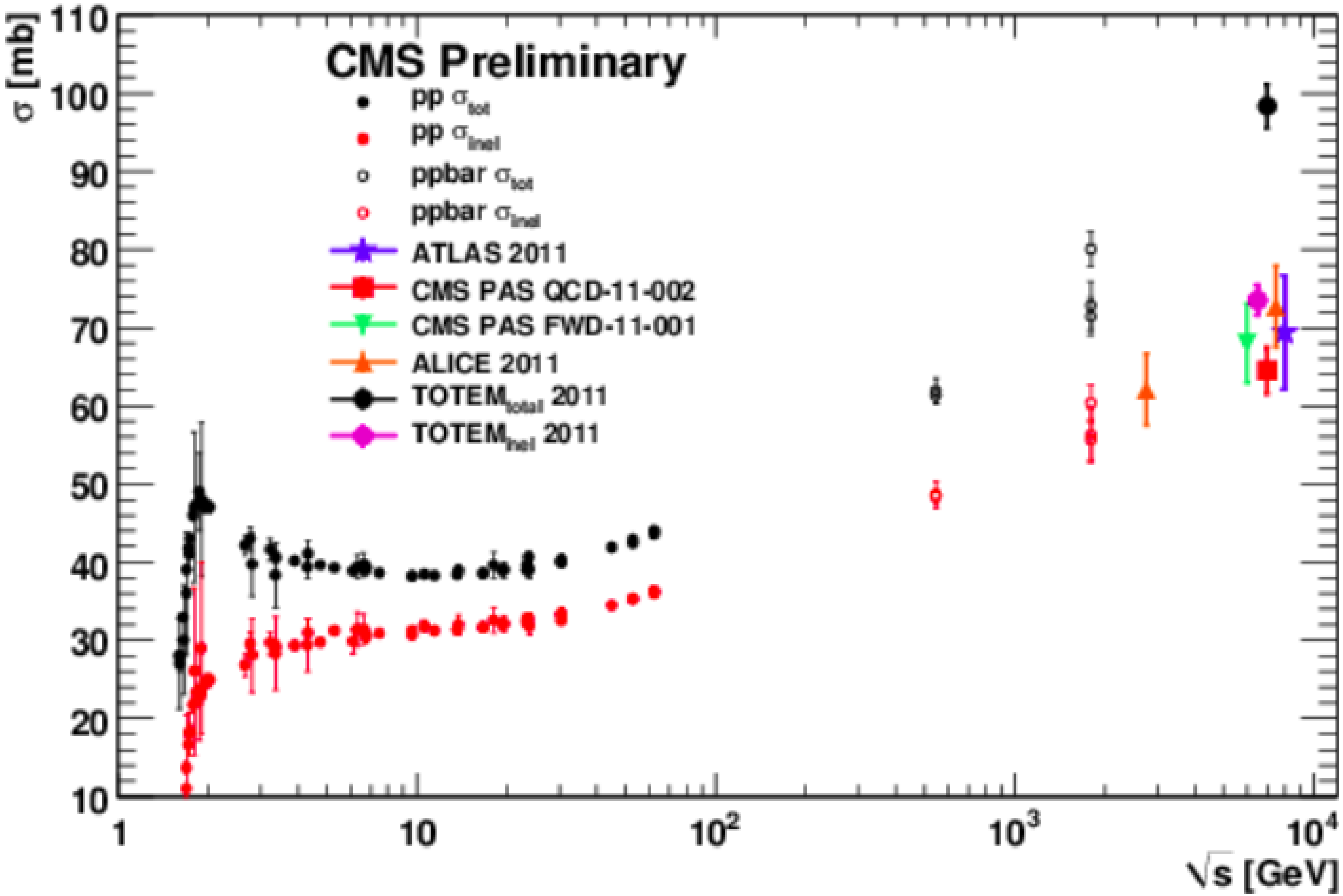
f) its background (dominance ~before)

g-h) central diffractive background

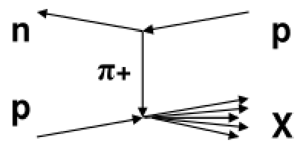
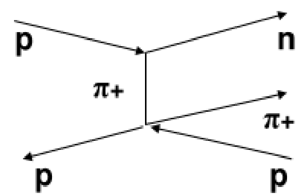
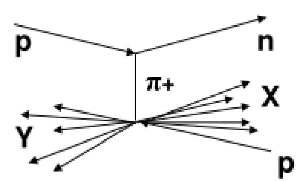
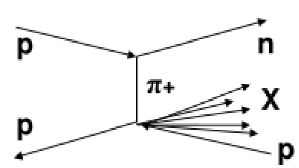
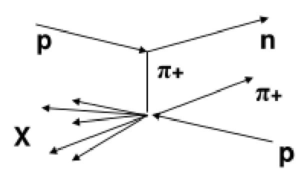


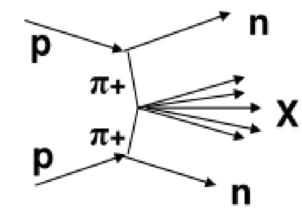
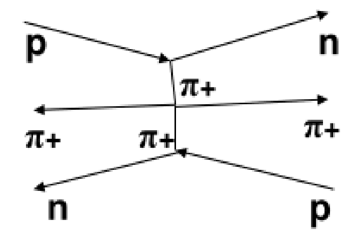
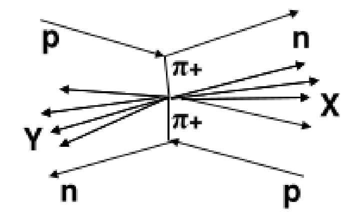
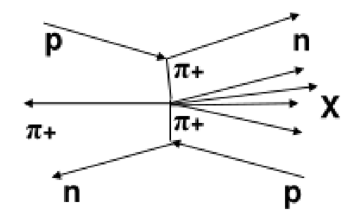
MonCher implemented into CRMC
Own analysis on the output

Total inelastic pp&p$\bar{p}$ cross-sections



Possible charge exchanges

Process	Type of π^+p interactions	Picture of the process
$pp \to nX$	minimum bias: $\pi^+p \to X$	
$pp \to n\pi^+p$	elastic scattering: $\pi^+p \to \pi^+p$	
$pp \to nXY$	double diffraction: $\pi^+p \to X + Y$	
$pp \to nXp$	single diffraction (π^+ dissociation): $\pi^+p \to X + p$	
$pp \to nX\pi^+$	single diffraction (p dissociation): $\pi^+p \to X + \pi^+$	

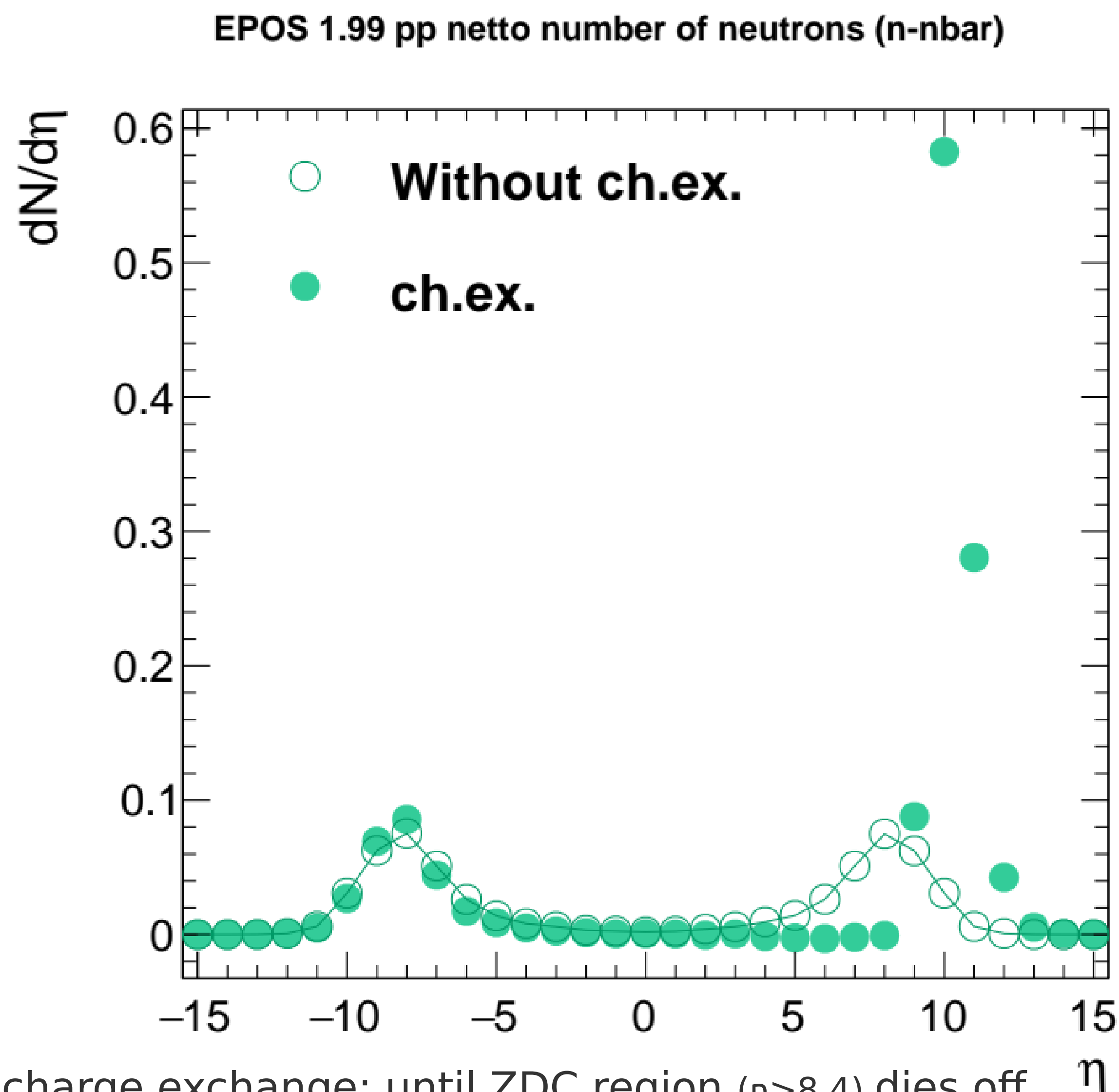
Process	Type of $\pi^+\pi^+$ interactions	Picture of the process
$pp \to nXn$	minimum bias: $\pi^+\pi^+ \to X$	
$pp \to n\pi^+\pi^+n$	elastic scattering: $\pi^+\pi^+ \to \pi^+\pi^+$	
$pp \to nXYn$	double diffraction: $\pi^+\pi^+ \to X + Y$	
$pp \to nX\pi^+n$	single diffraction: $\pi^+\pi^+ \to X + \pi^+$	

Used models in CRMC

MonCher implemented into CRMC
Own analysis on the output

- EPOS 1.99: all 3 reggeons
  - Parton model (originally for RHIC)
  - Cross-sections tuned to measurements (KASCADE)
  - QM multiple scattering approach
  - Collective effects for dense systems (flow)
- EPOS-LHC: all 3 reggeons
  - Improvements from the previous one
  - Tuned to LHC data + EPOS 2 morals
  - Fast, but simplified hydrodynamics
- PYTHIA: only pions
  - Various possibilities for particle decay (“updated decay data”)
  - Possibility for two selected hard interactions in same event
- SIBYLL 2.3c: pions & rhos
  - From CR model (most relevant aspects for the development of extensive air showers)
    - energy flow & particle production in the forward phase space region
  - Implementation of phenomenological model for charm particles formation
  - New fits to total & elastic x-sections for pp, πp, Kp ints → match LHC & fixed-target data

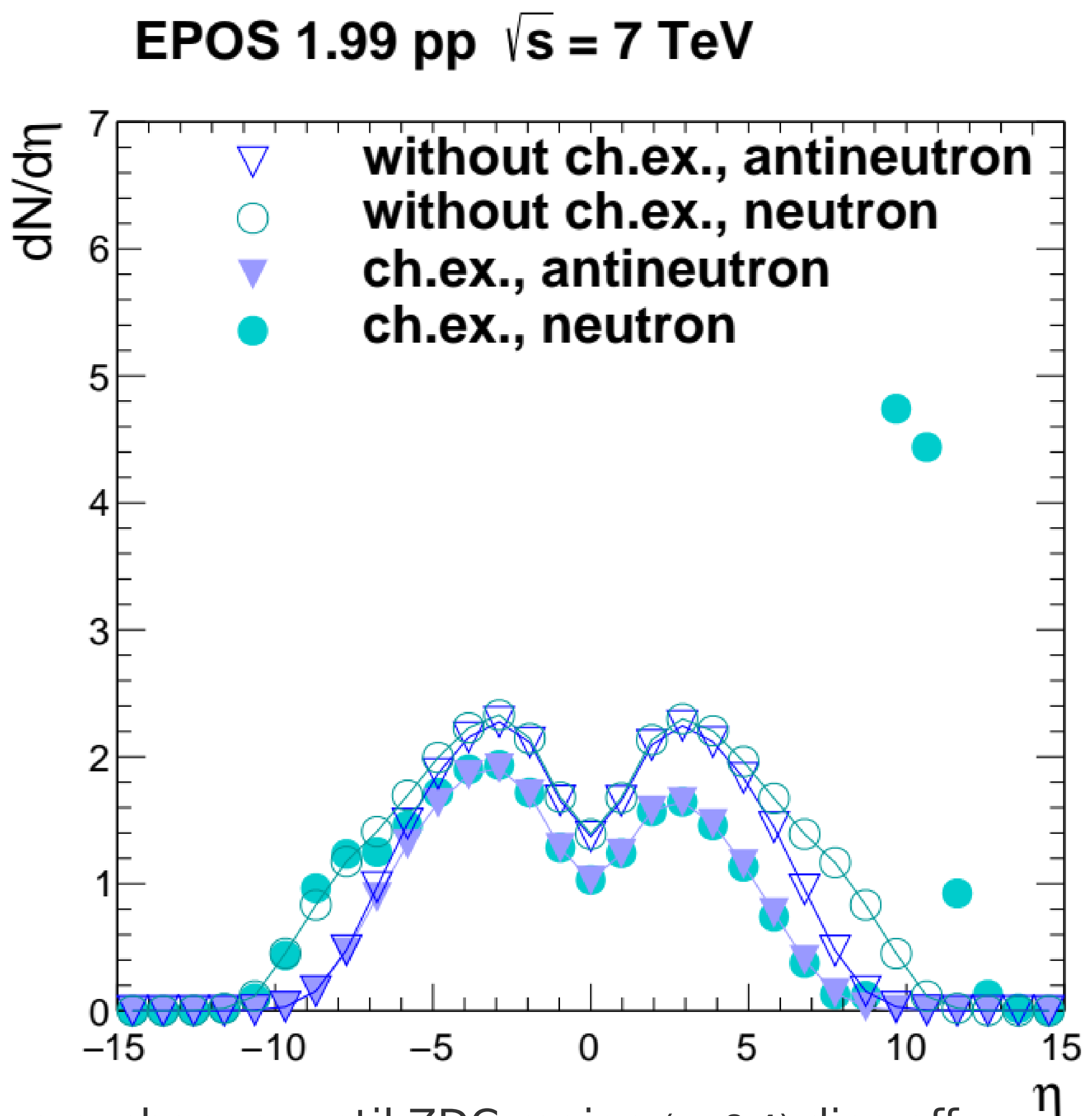
Pseudorapidity distribution of (anti)neutrons



Large charge exchange peak visible for Neutrons in the ZDC

- Without charge exchange: until ZDC region (η>8.4) dies off
- Charge exchange: in MC by definition always η>0 neutrons
- Ratios NOT in correspondance with cross-sections

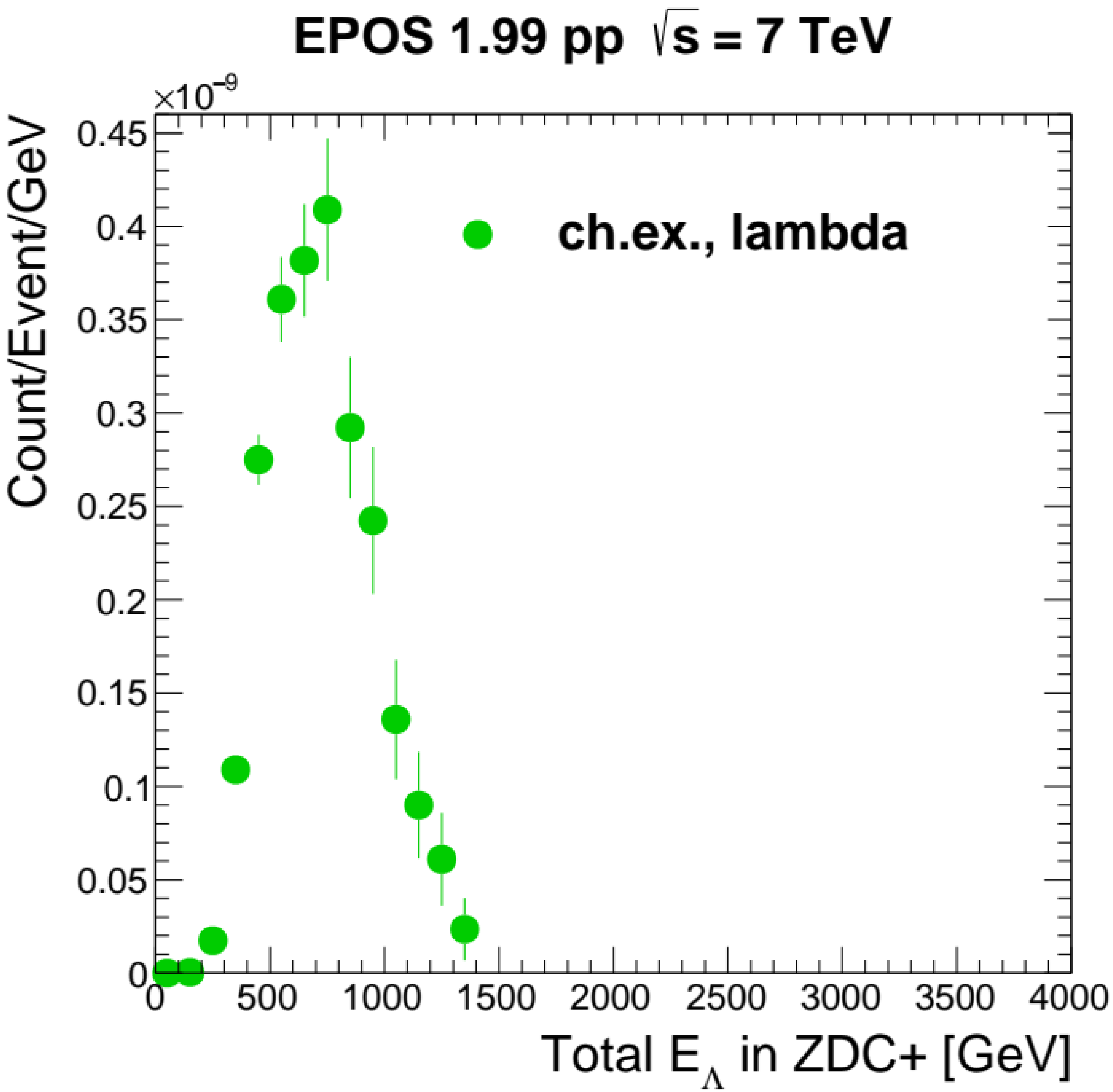
Pseudorapidity distribution of (anti)neutrons



Large charge exchange peak visible for Neutrons in the ZDC

- Without charge exchange: until ZDC region (η>8.4) dies off
- Charge exchange: in MC by definition always η>0 neutrons
- Ratios NOT in correspondance with cross-sections

Other neutral hadrons



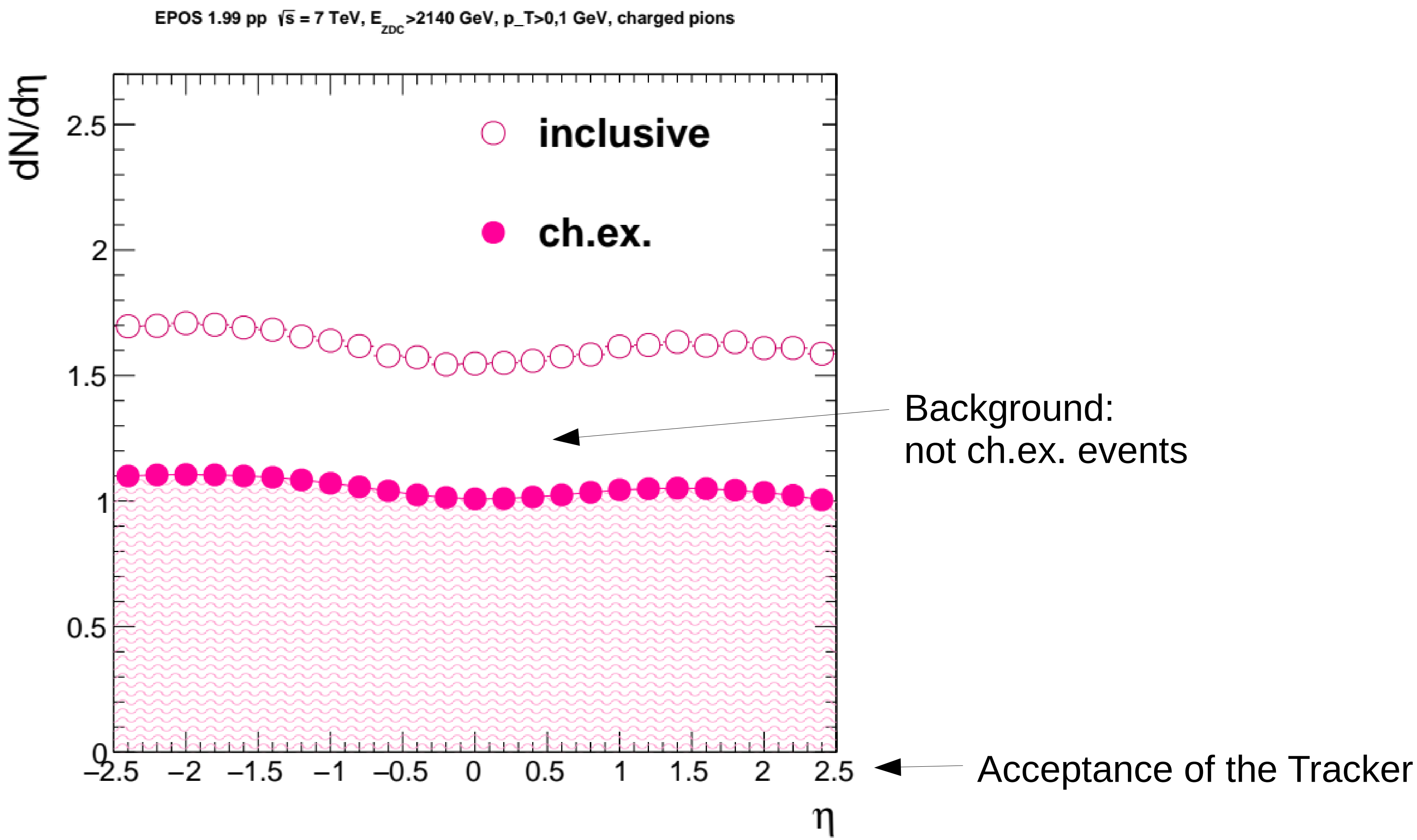
Neutral Λ: negligible contribution in region > 2140 GeV (cut)
(Neutral kaon: negligible contribution vs Λ)

Smaller than neutron energy distribution with 5 order of magnitude

Etot[Λ] distribution $\times e^{-\gamma \cdot c \cdot \tau}$

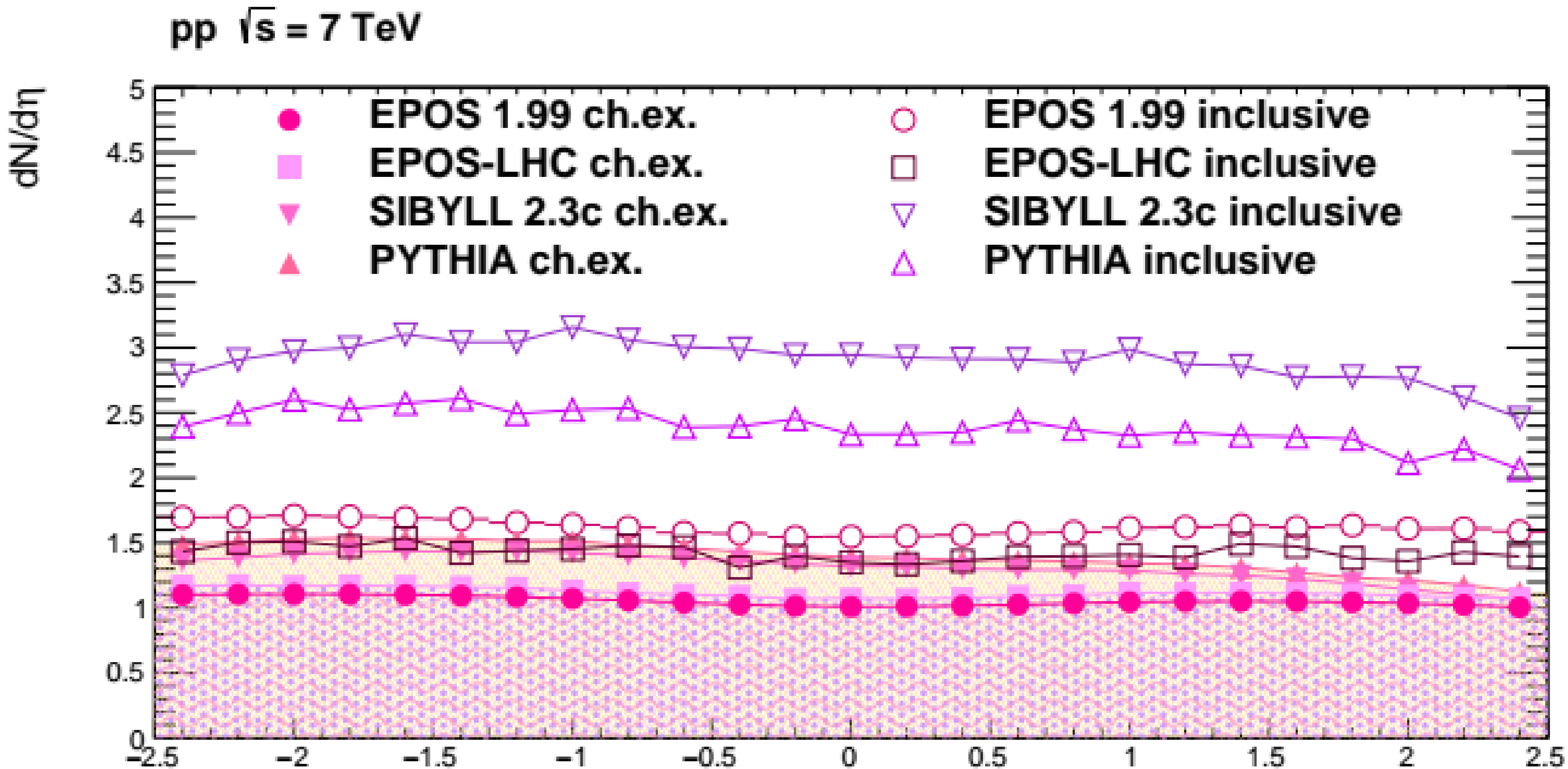
- γ: Lorentz-faktor
- c: speed of light (in vacuum)
- τ: mean lifetime of the particle

η distribution of $\pi^{\pm}$ after E_{ZDC}-cut



- In inclusive events after selections: more than half of the pions from ch.ex.

Same, comparing different models

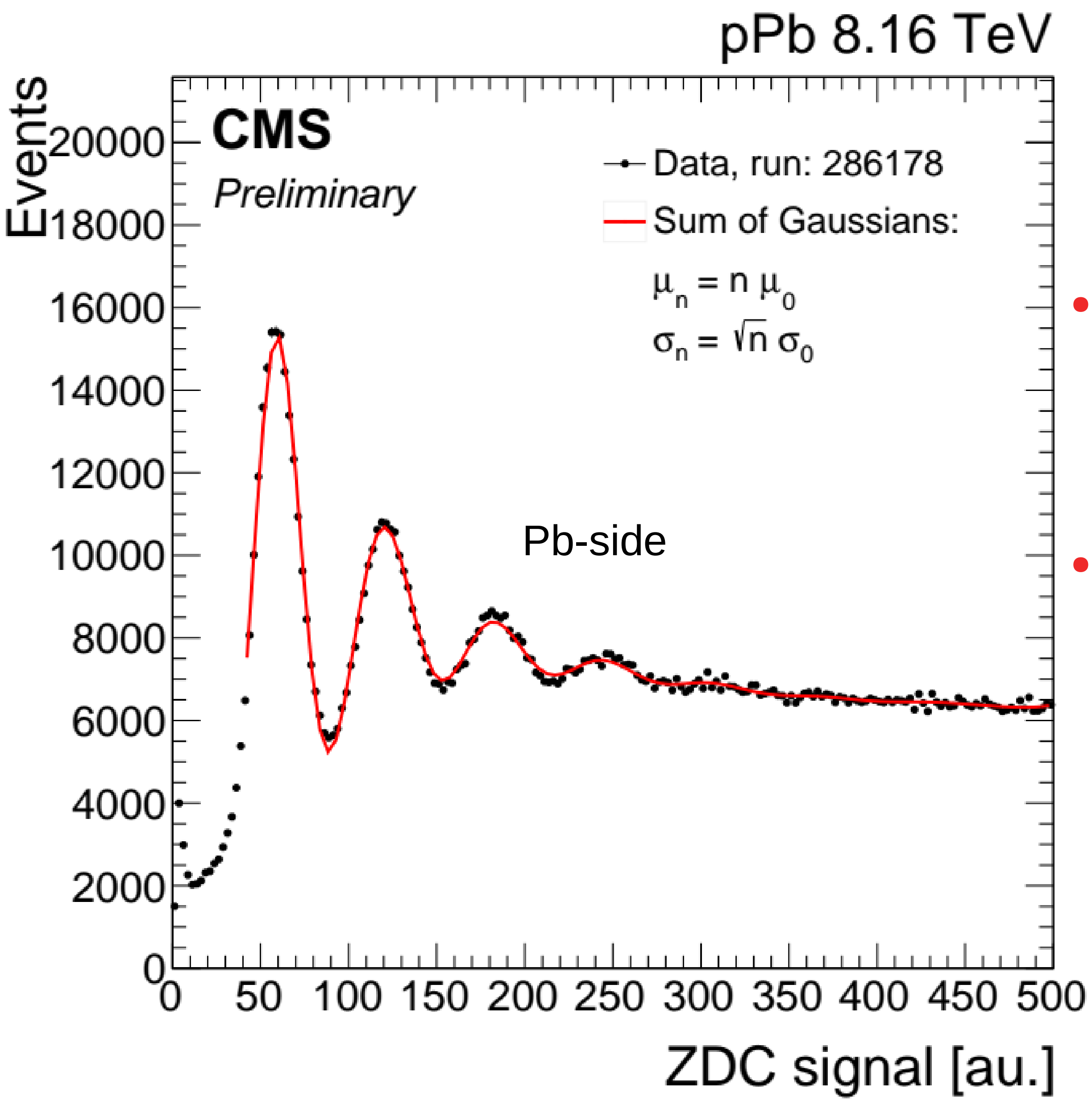


- Two tunes of EPOS: similar shape of the η distribution ~expectations
- PYTHIA & SIBYLL similar too
- signal/background ratio regarding different models: not consistent

  → in ch.ex. events distribution of pions not so model-dependent,

  but non-ch.ex. background strongly model-dependent :(/main difference/

Energy resolution of the ZDC



- Resolution ~25%

  (plot from another member of our research group)
- LHC accelerating voltage:

  6.5 TeV/proton
- Pb nucleus:

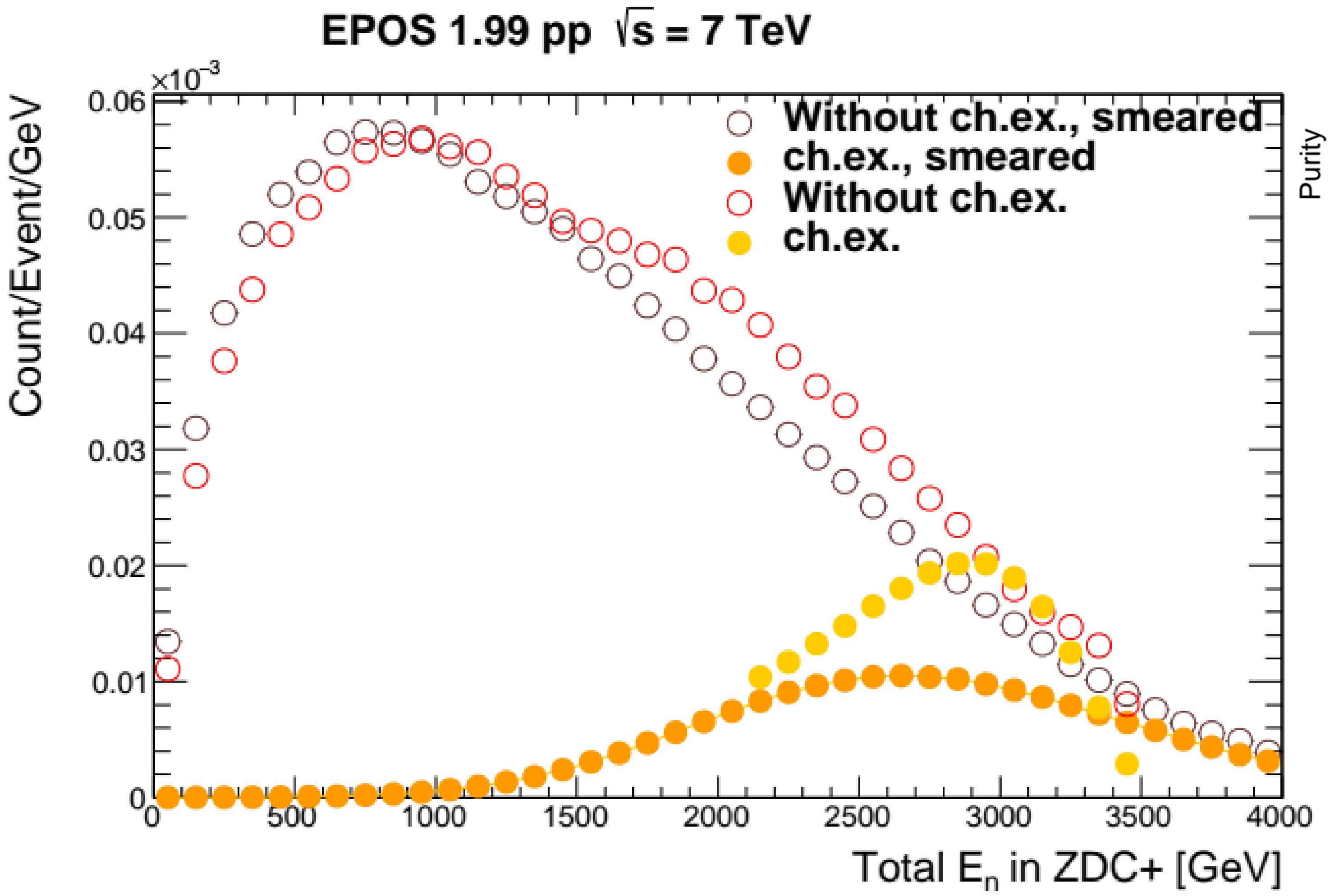
  82x charge

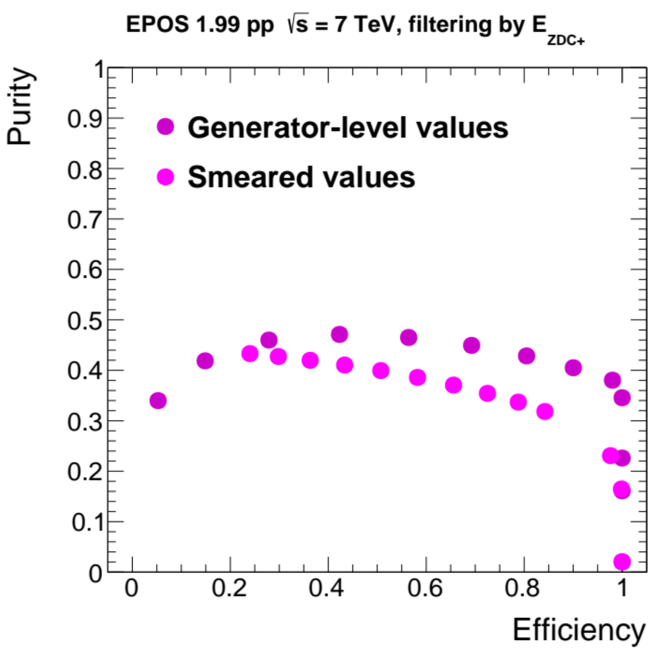
  208x massive

→ 6.5·82/208=2.56 TeV

(1st neutron peak)

Taking into account resolution of ZDC

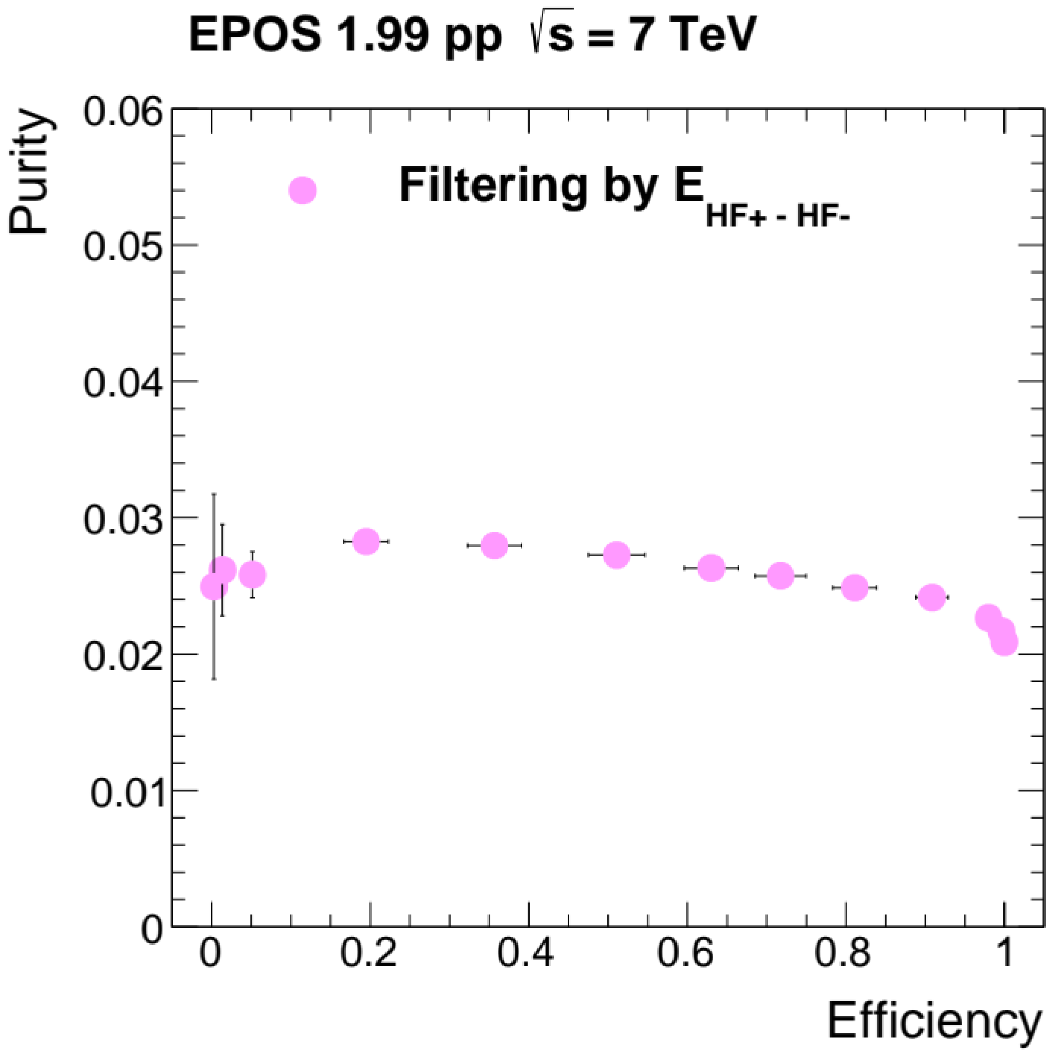


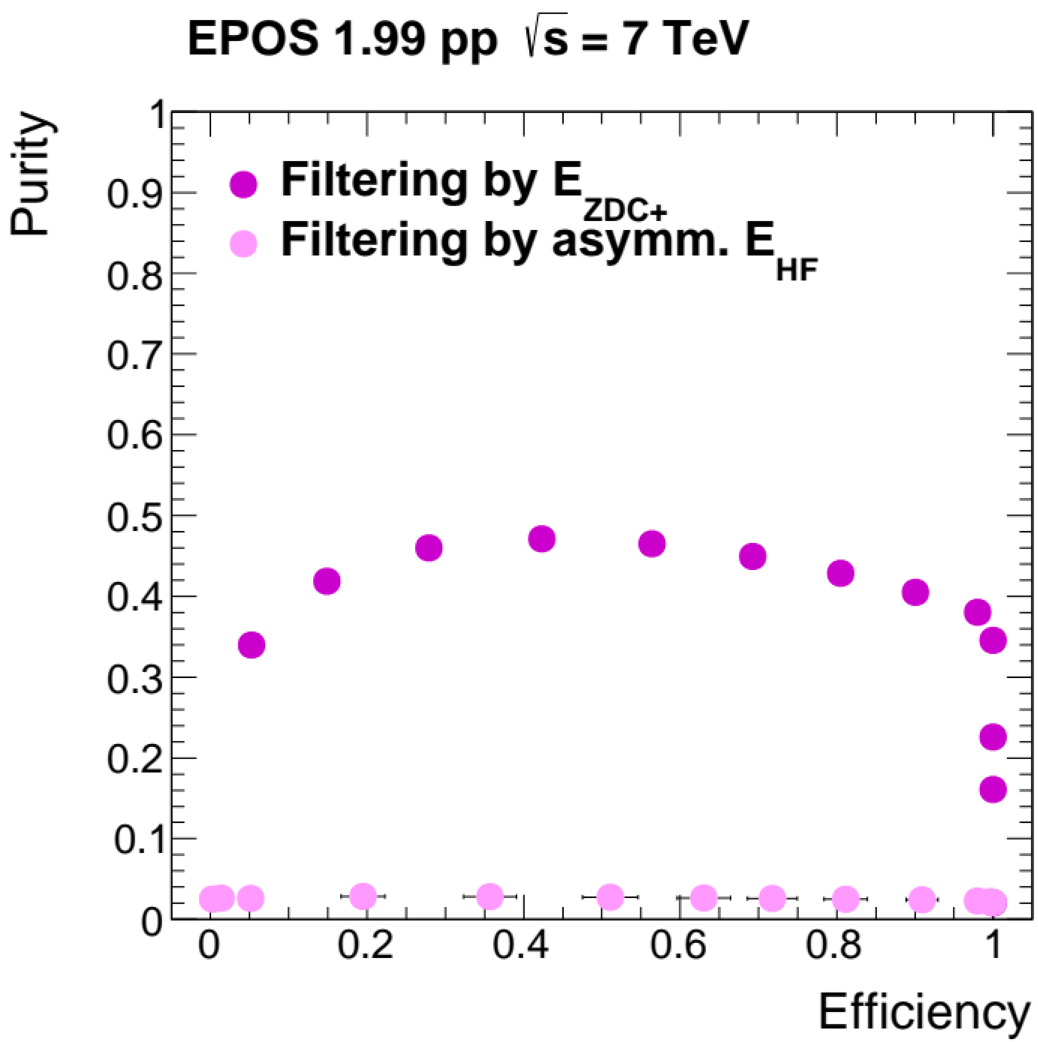


Relative energy resolution 25% → Gaussian:

- standard deviation: 25% of the generator level energy

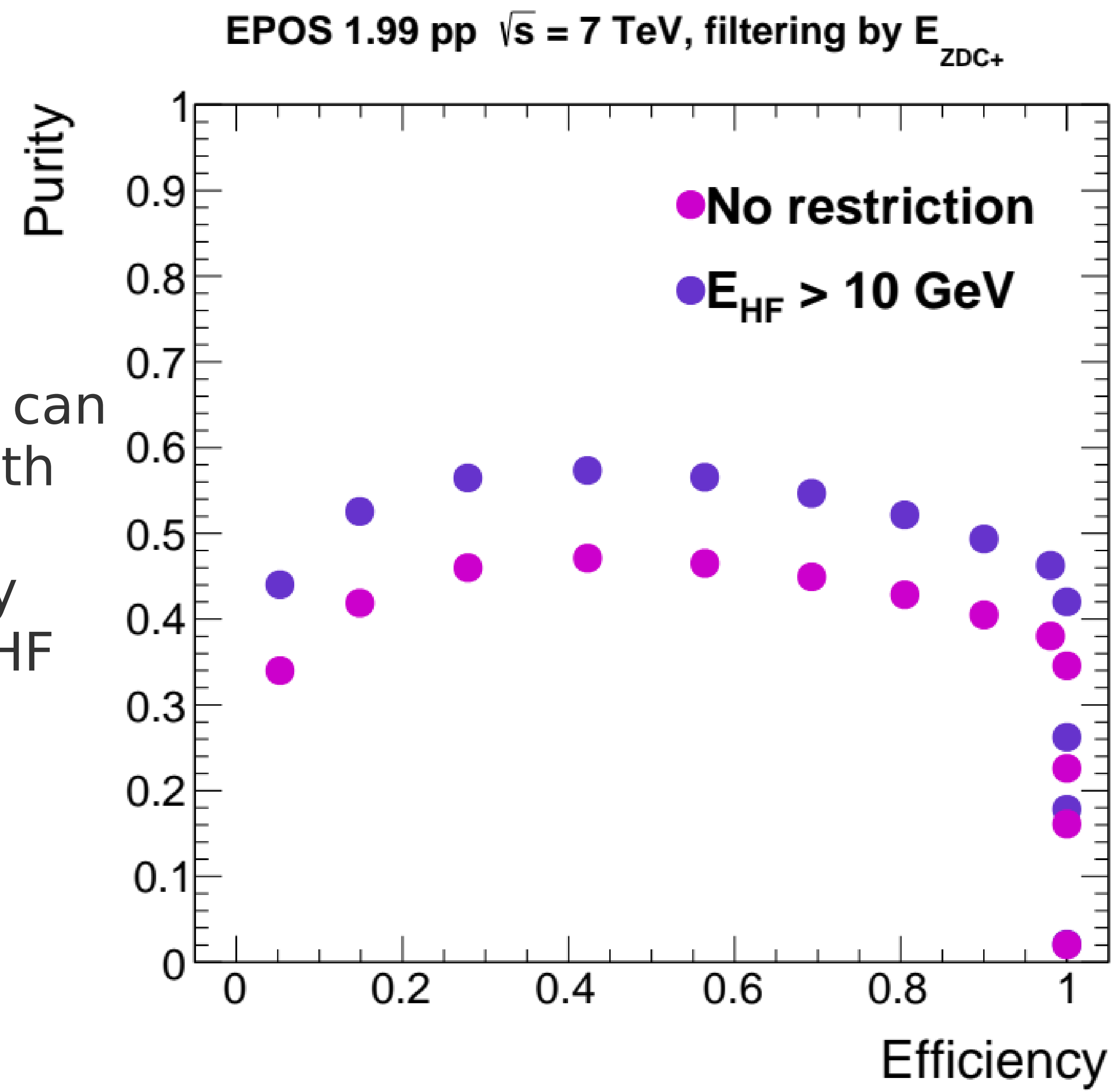
Selection only by ΔE_{HF}





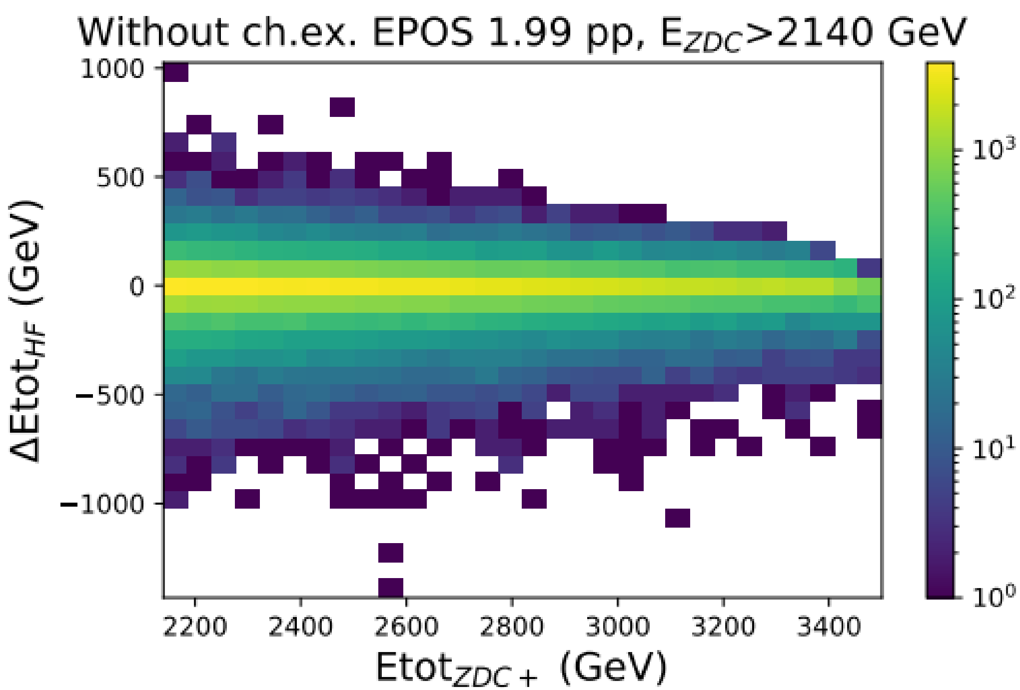
Minimal energy in HF

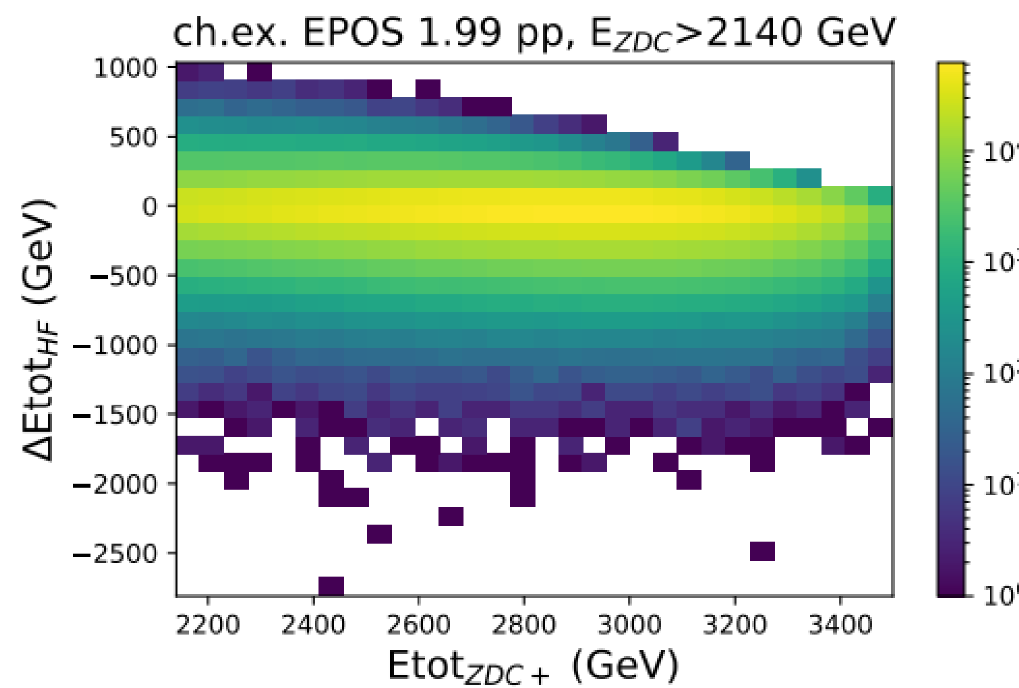
- Higher purities can be achieved with requiring a minimal energy deposit in the HF



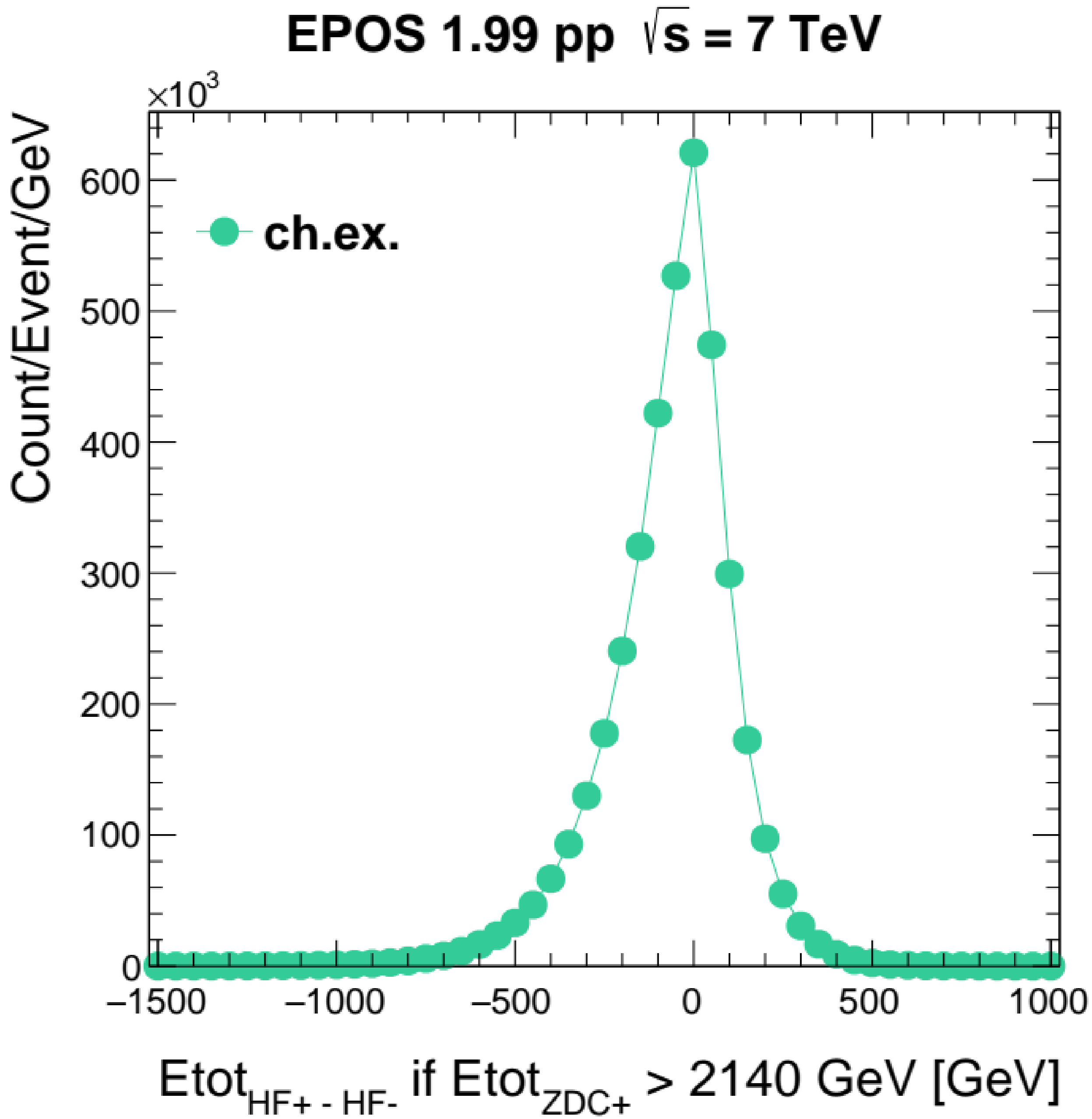
Deposited energy in different detectors

- Effect of asymmetry in ch.ex. versus without ch.ex. Events: energy-independent
- (E_{ZDC} working point: $Etot_{ZDC}$>2140 GeV)

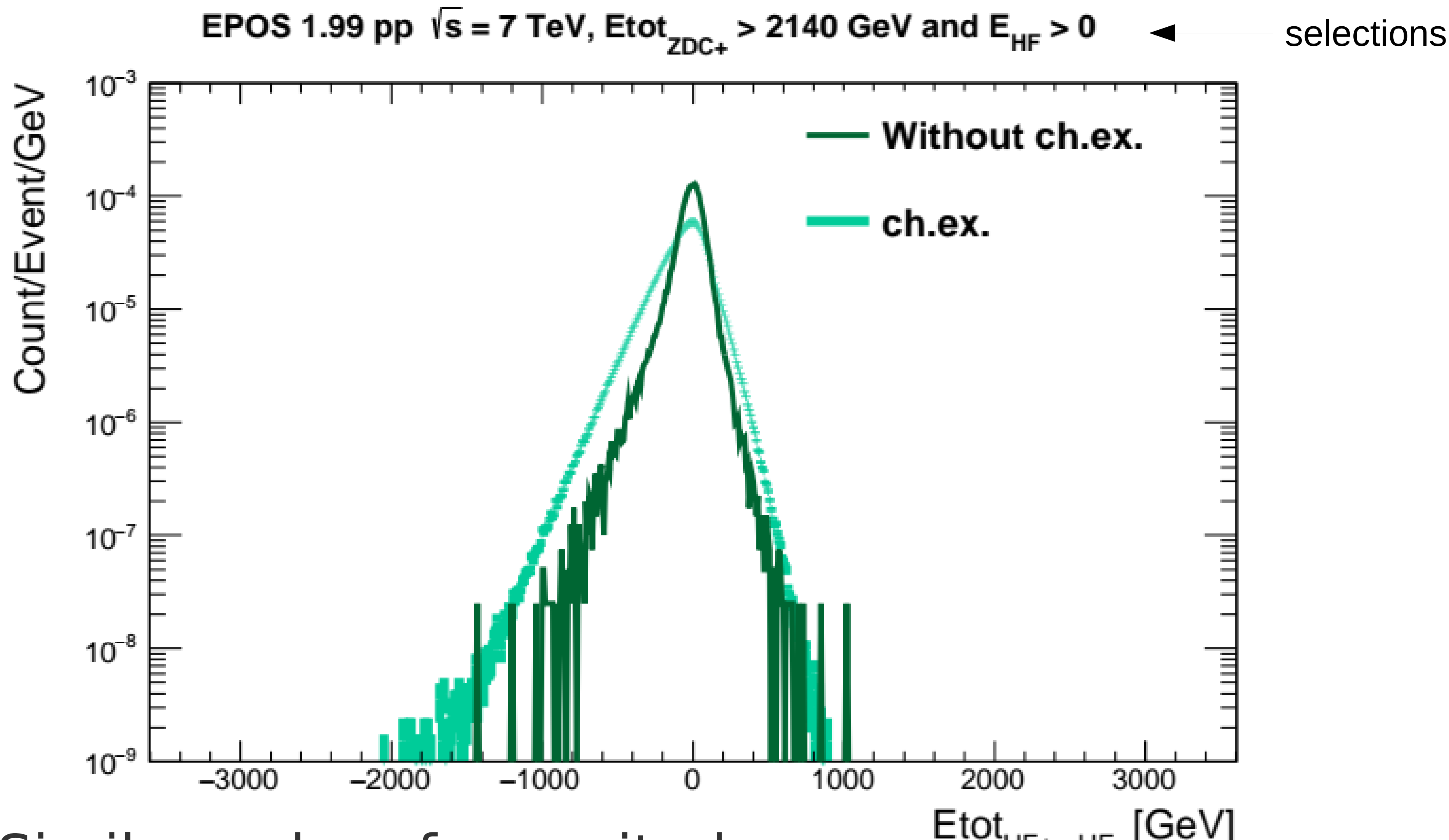




E_{ZDC} and ΔE_{HF}

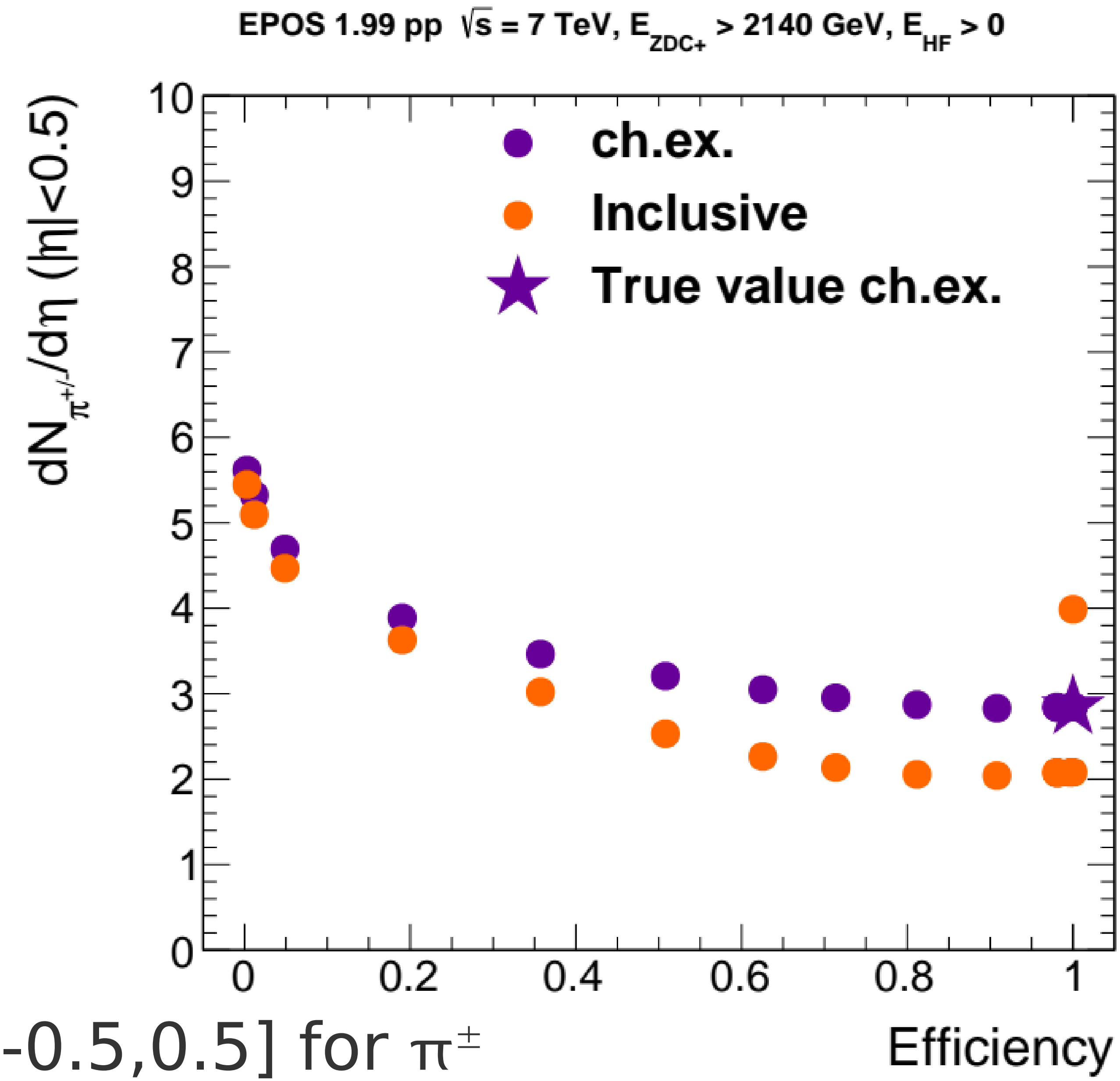


HF energy distribution for selected events



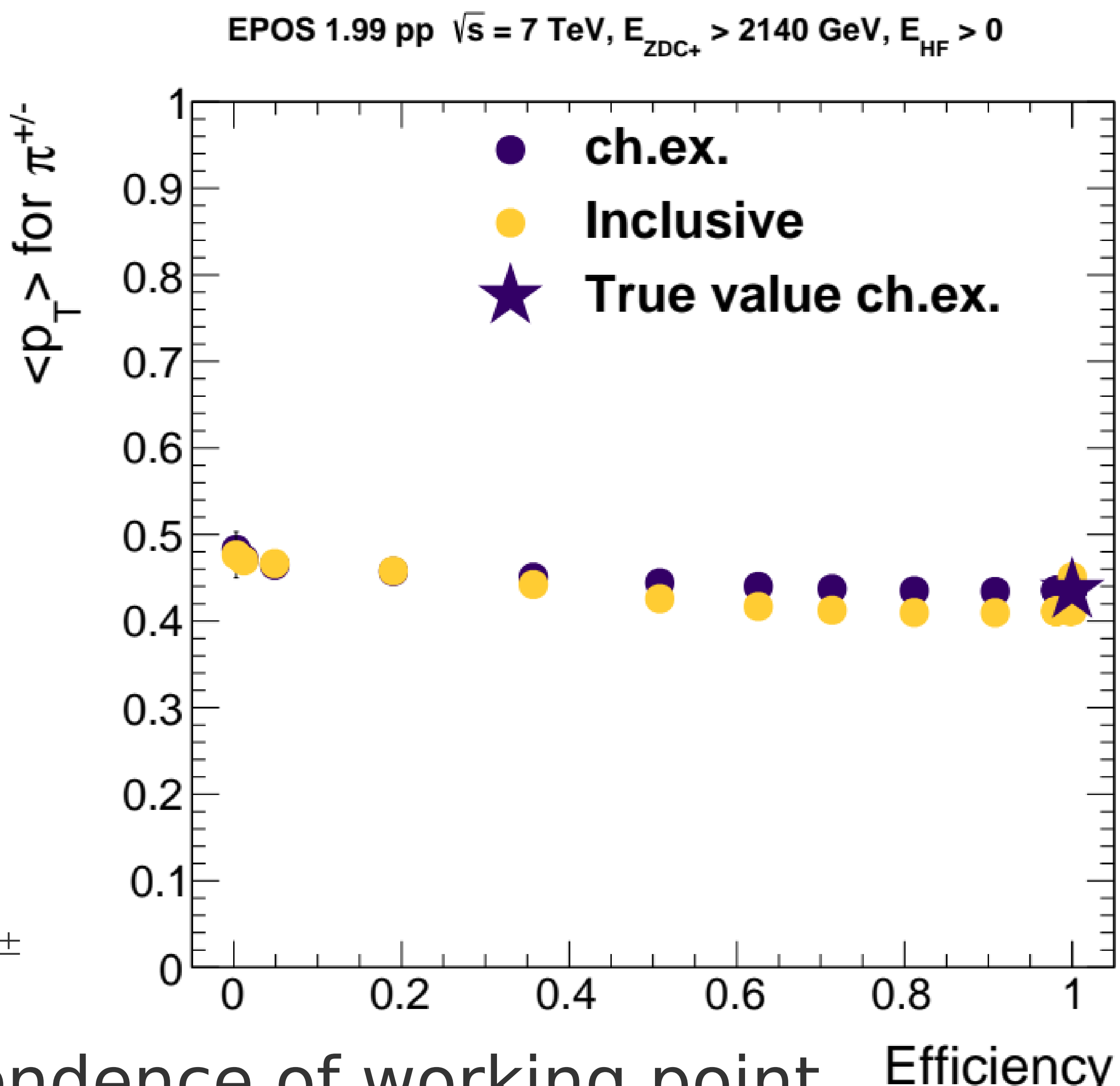
- Similar order of magnitude
- ch.ex. more asymmetric

Bias test I.



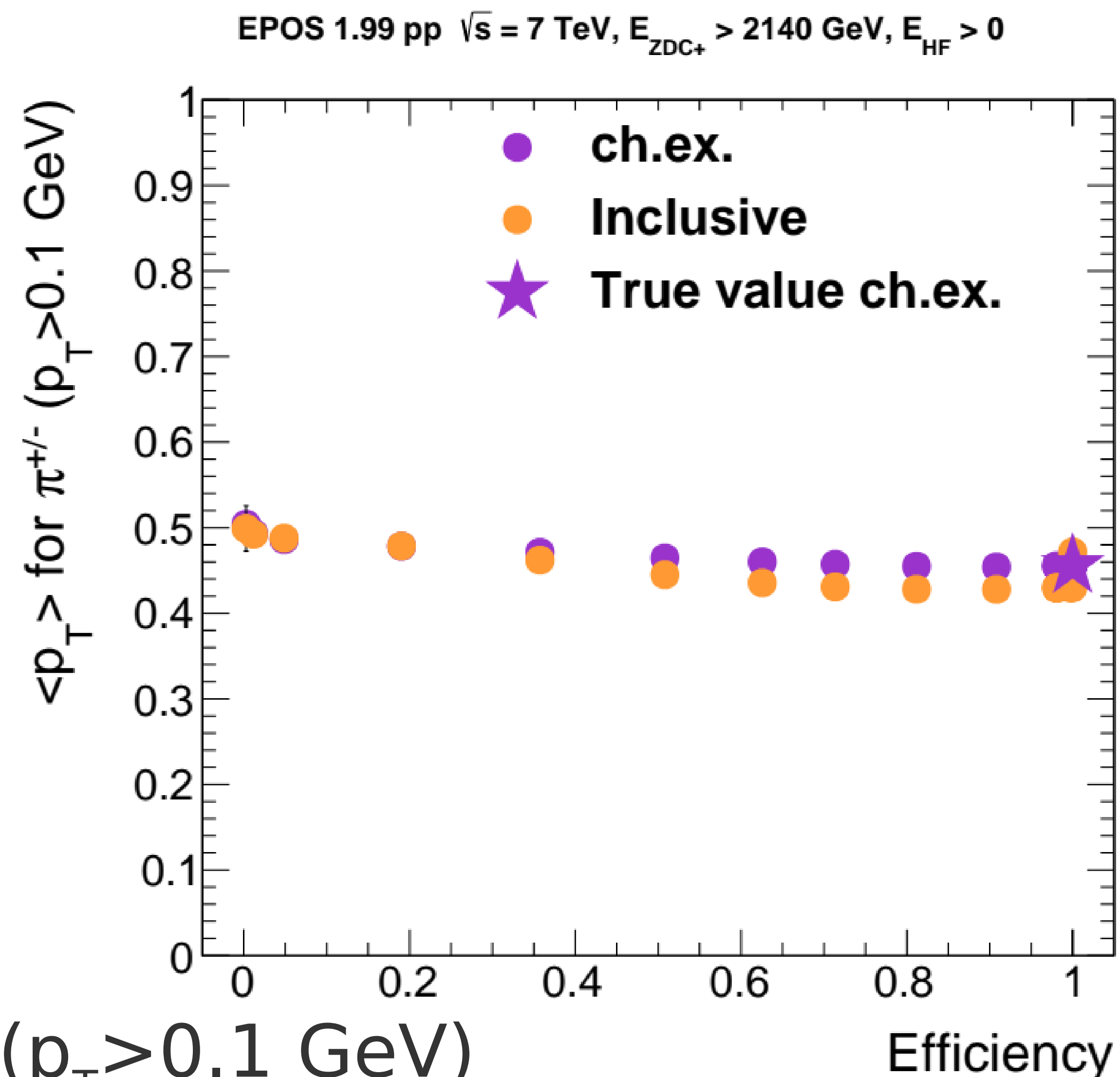
- dN/dη in [-0.5,0.5] for $\pi^{\pm}$

Bias test II./a



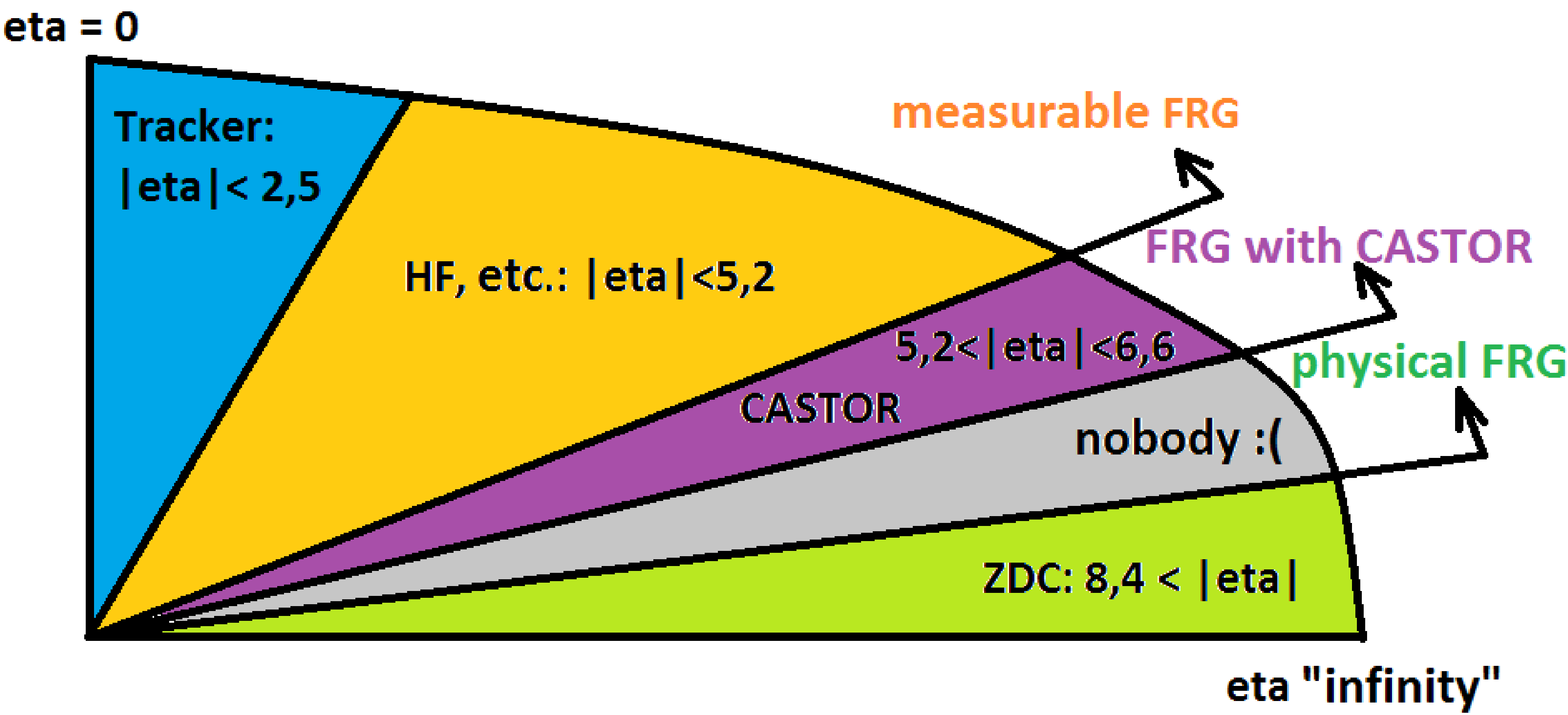
- $<p_T>$ for $\pi^{\pm}$
- Weak dependence of working point

Bias test II./b



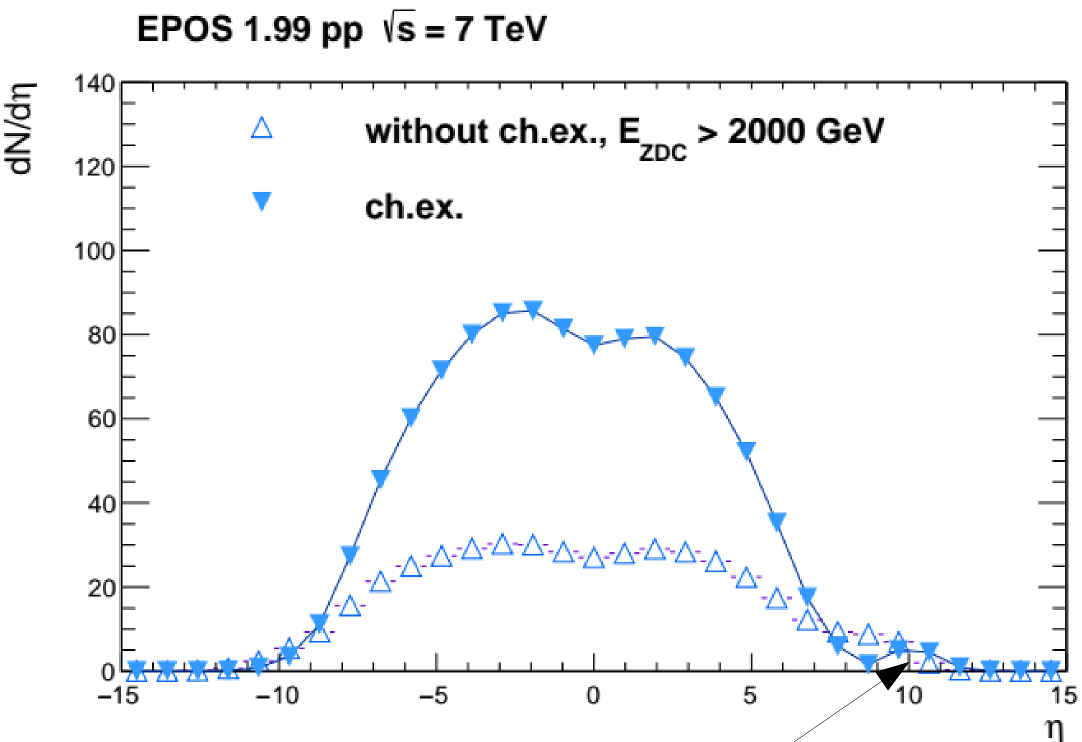
- $<p_T>$ for $\pi^{\pm}$ (p_T>0.1 GeV)
- Weak dependence of working point

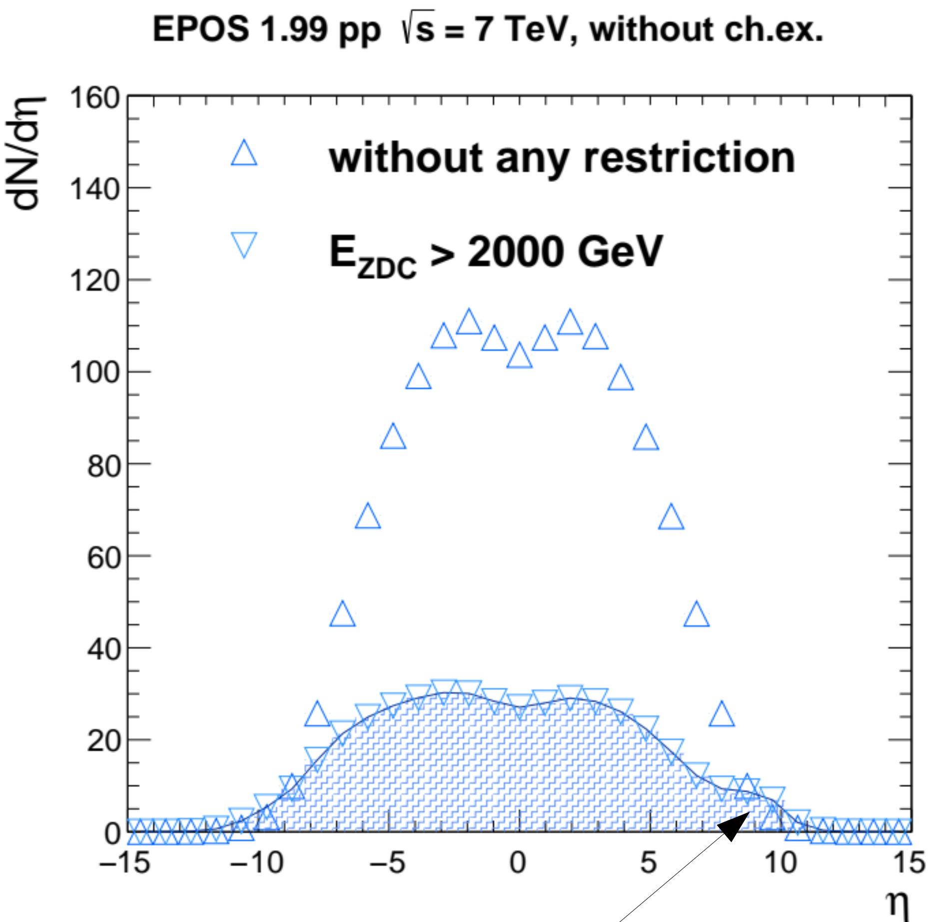
Forward rapidity gaps (FRGs)



- See extra pdfs

η distribution (E_{ZDC} > 2000 GeV)

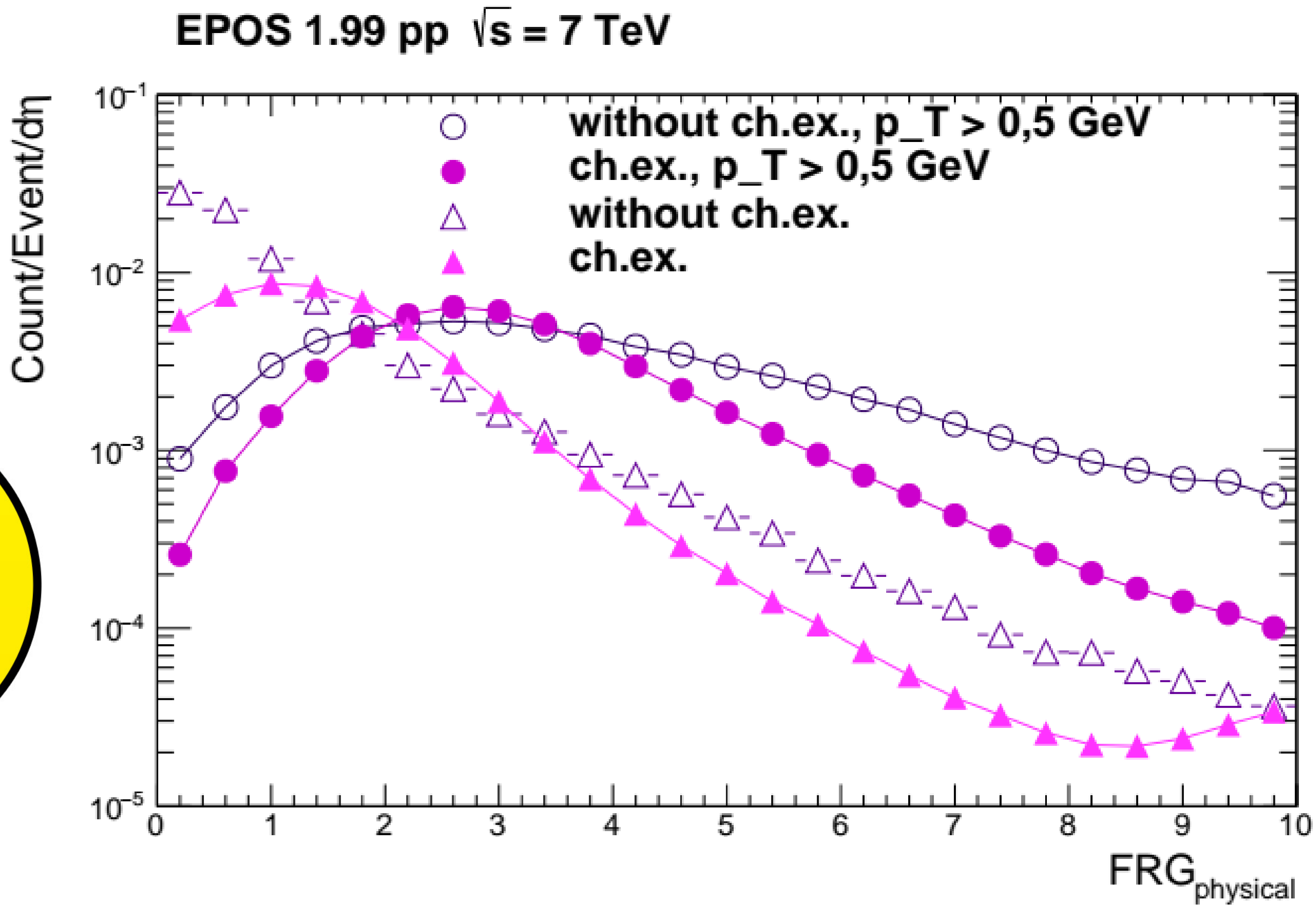




→ more alike to ch.ex. distribution

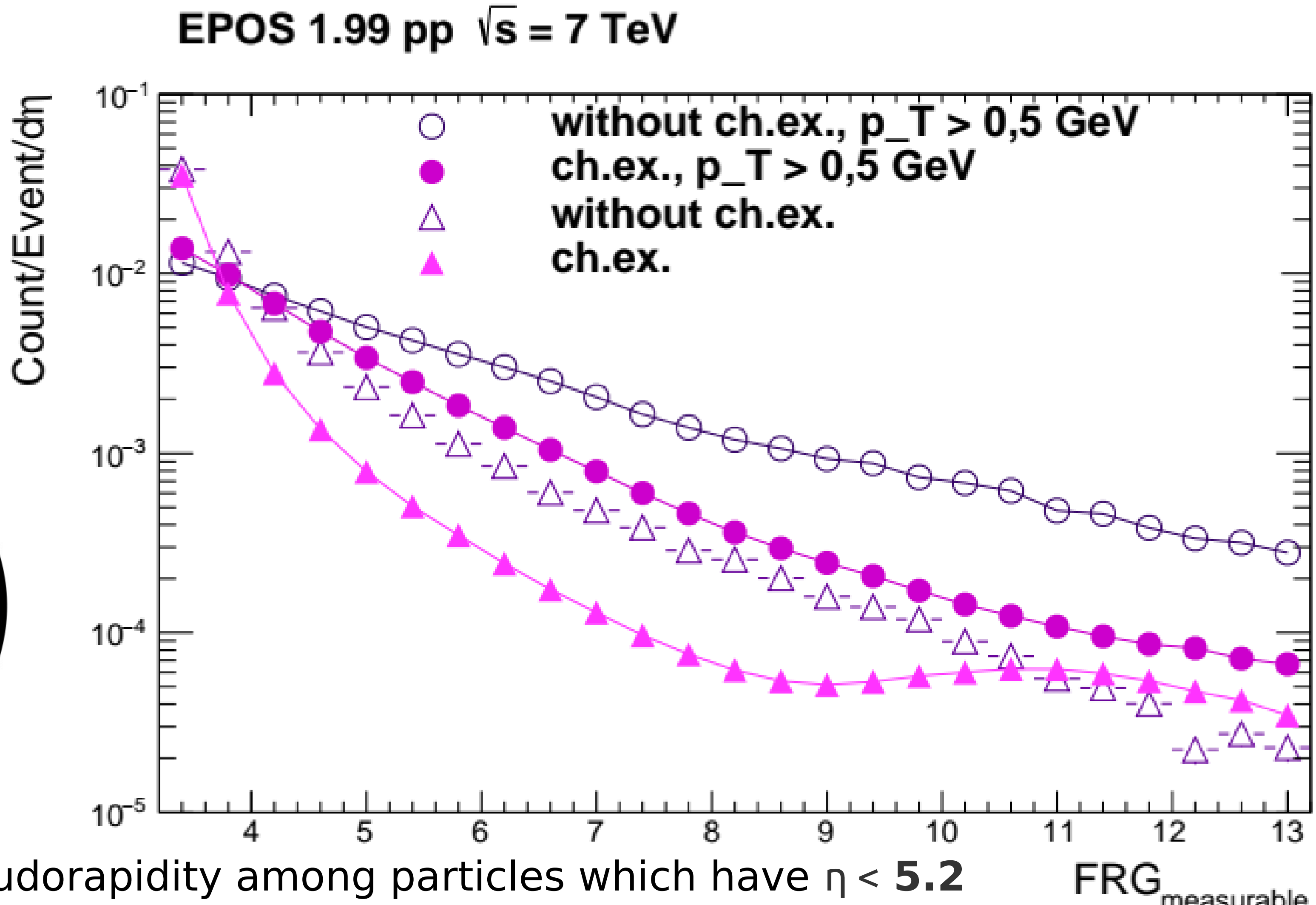
With E_{ZDC}-cut: the distribution becomes more forward

Forward rapidity gap (FRG) -physical



- FR: maximal pseudorapidity among particles which have η < 8.4
- Acceptance of ZDC: η > 8.4
  → FRG = 8.4 – FR

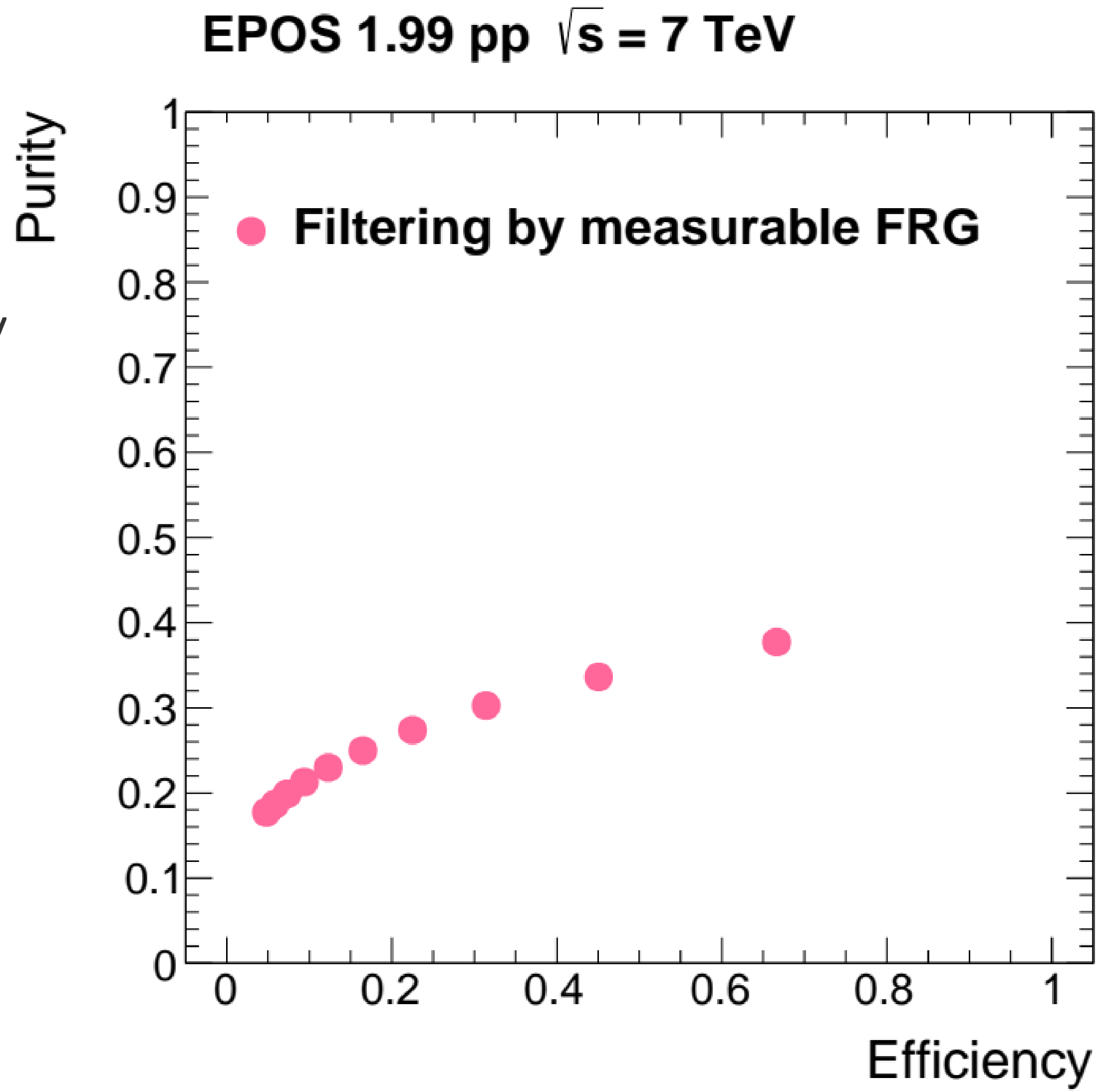
Forward rapidity gap -measurable



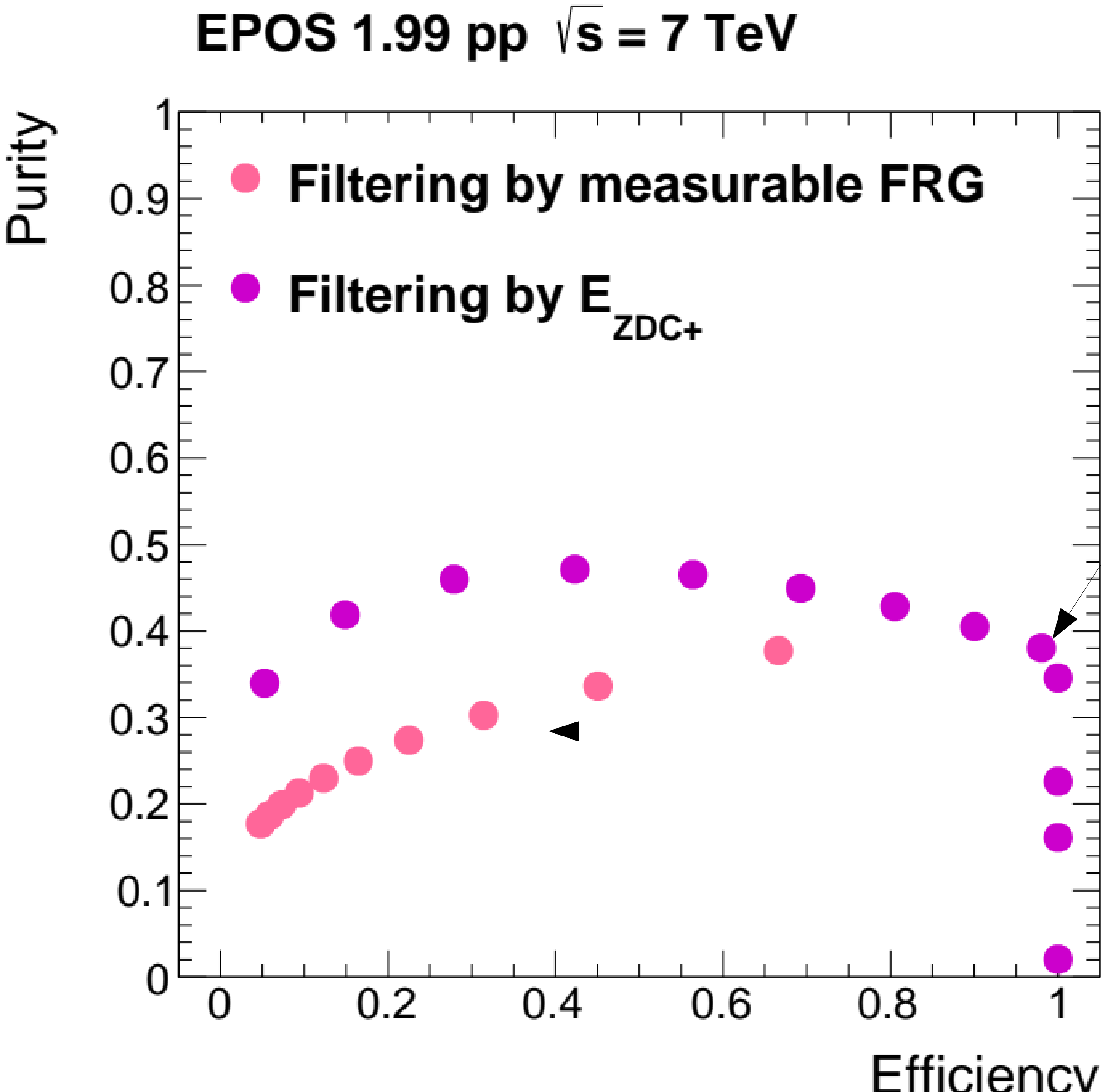
- FR: maximal pseudorapidity among particles which have η < **5.2**
- 5.2<η<8.4: no detector (HF)
  → FRG = 8.4 – FR
- Further: measurable FRG with p_T > 0.5 GeV

ROC curve of measurable FRG

- wider FRG ~ smaller probability
  to be ch.ex.
  → working point viaE_{ZDC}-cut



ROC curve of the FRG-cut, working point

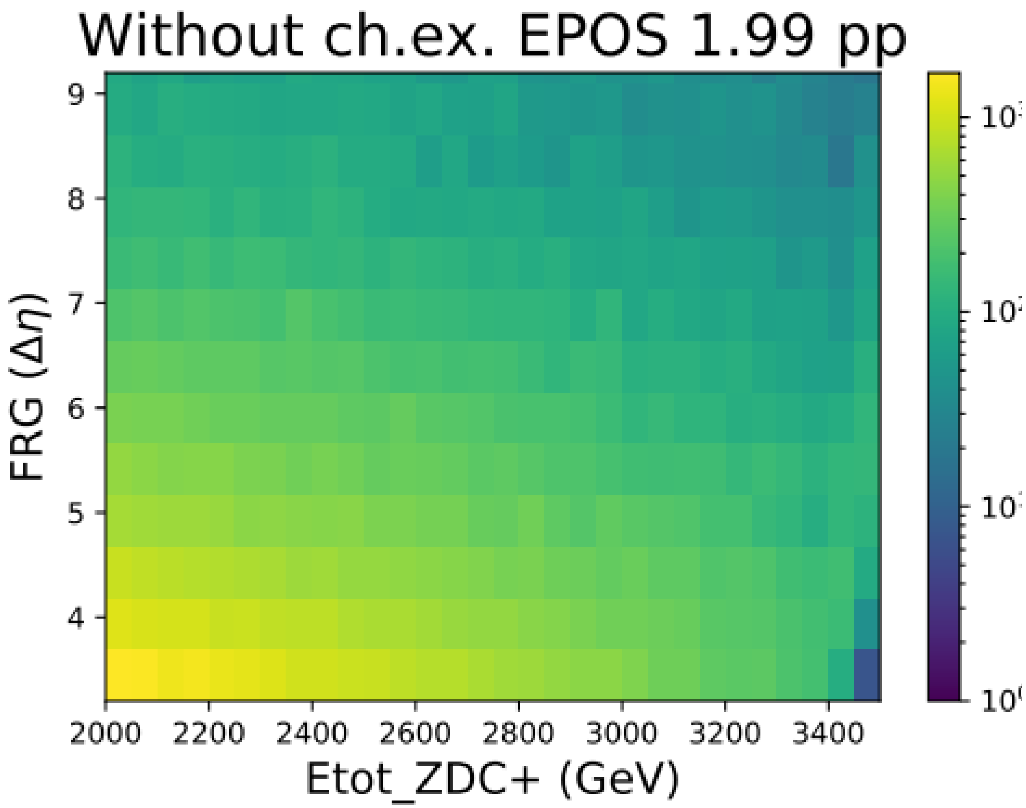


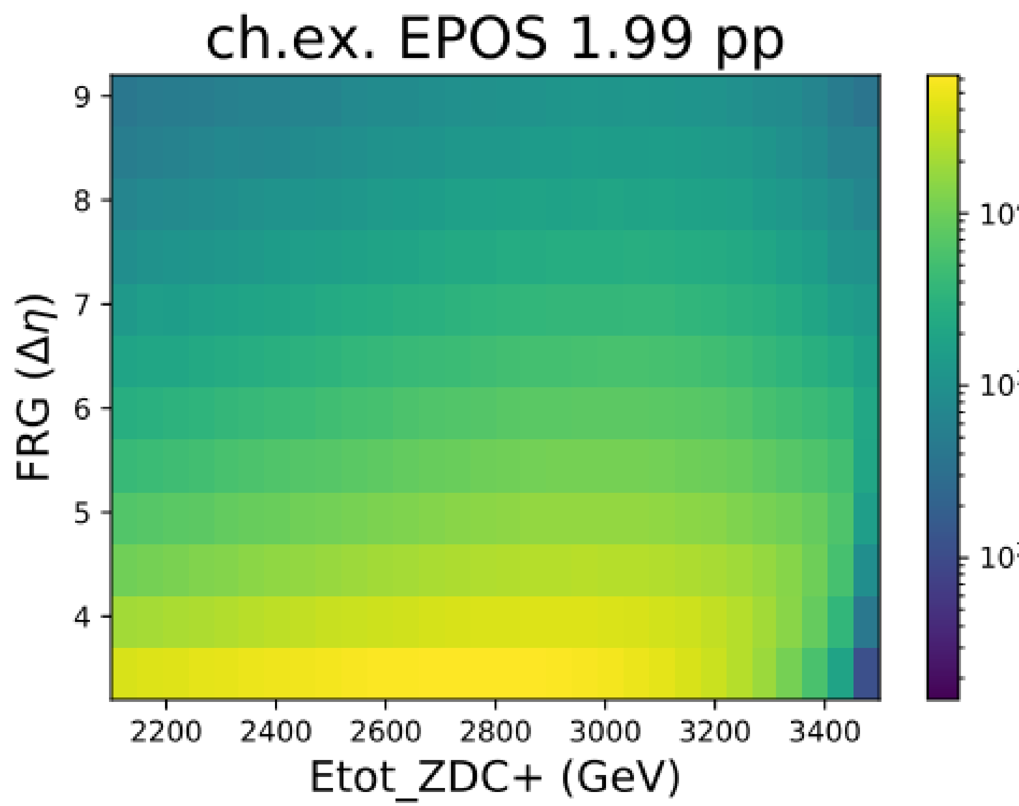
Working point:

- min 2140 GeV in ZDC:
  - ~38% purity
  - ~98% efficiency

FRG :(

Forward rapidity gap energy-correlation

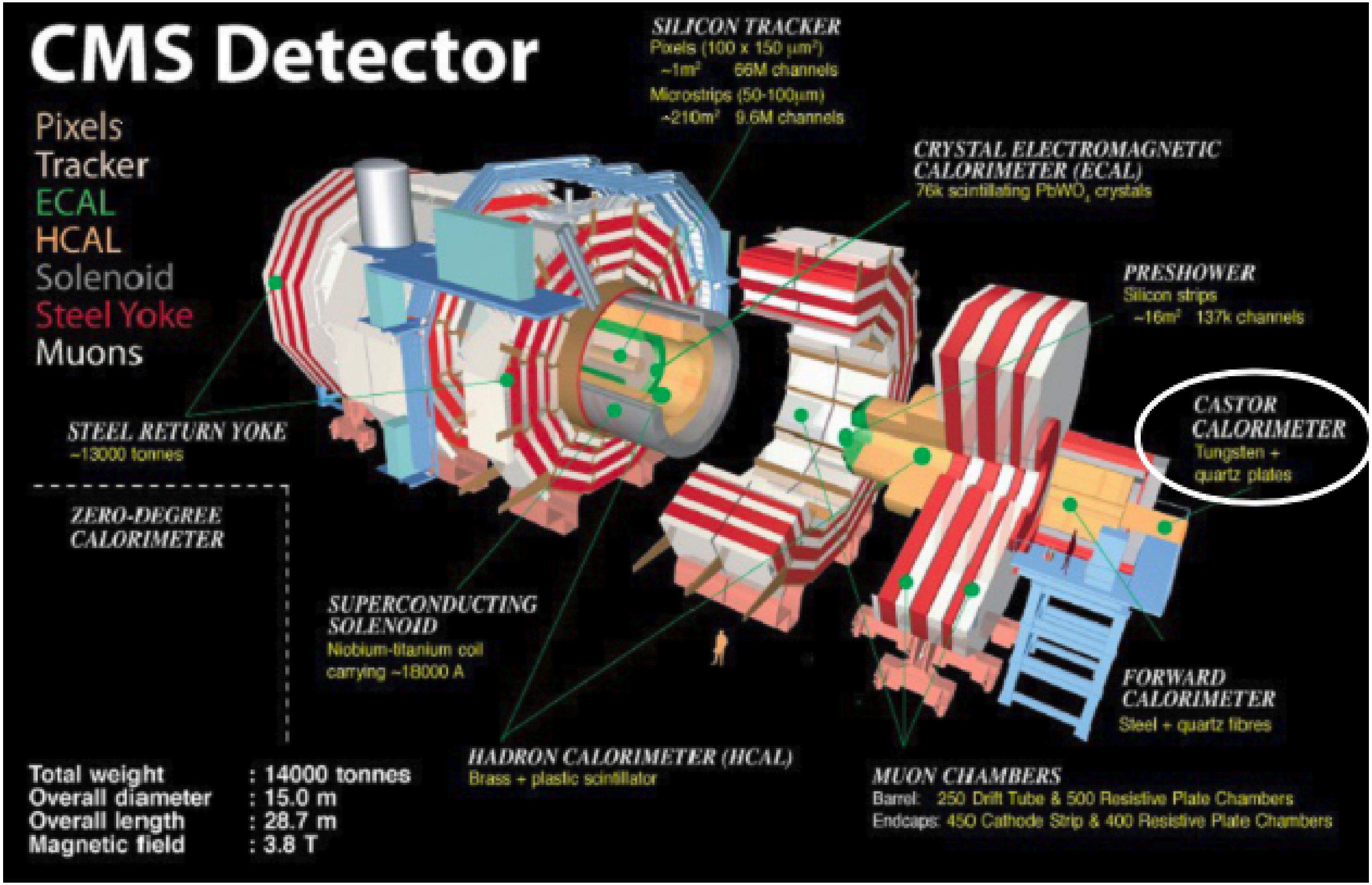




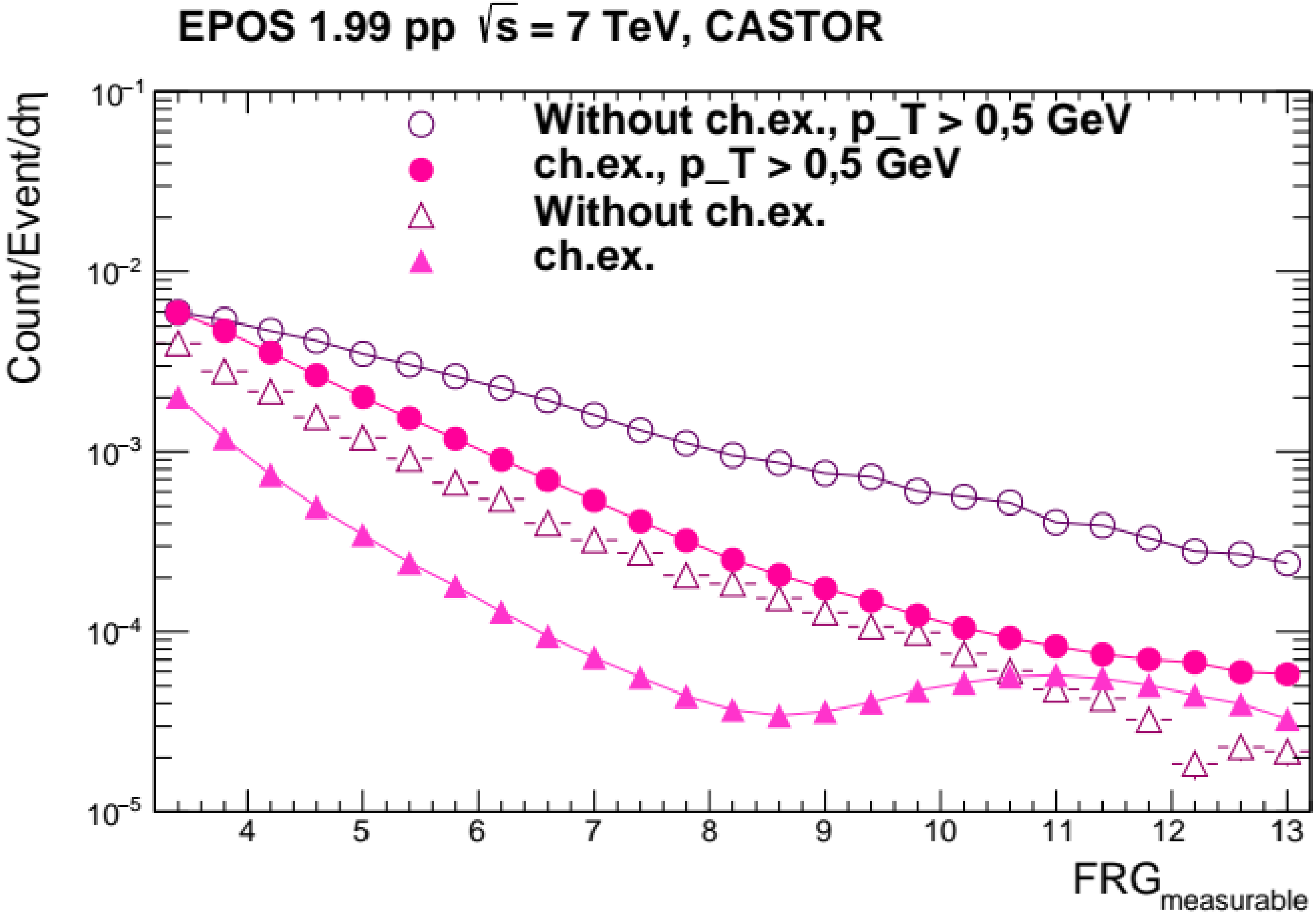
- Between the 2 type of event:
  in ZDC energy big difference

  but rapidity gap similarly distributed
- Weak correlation

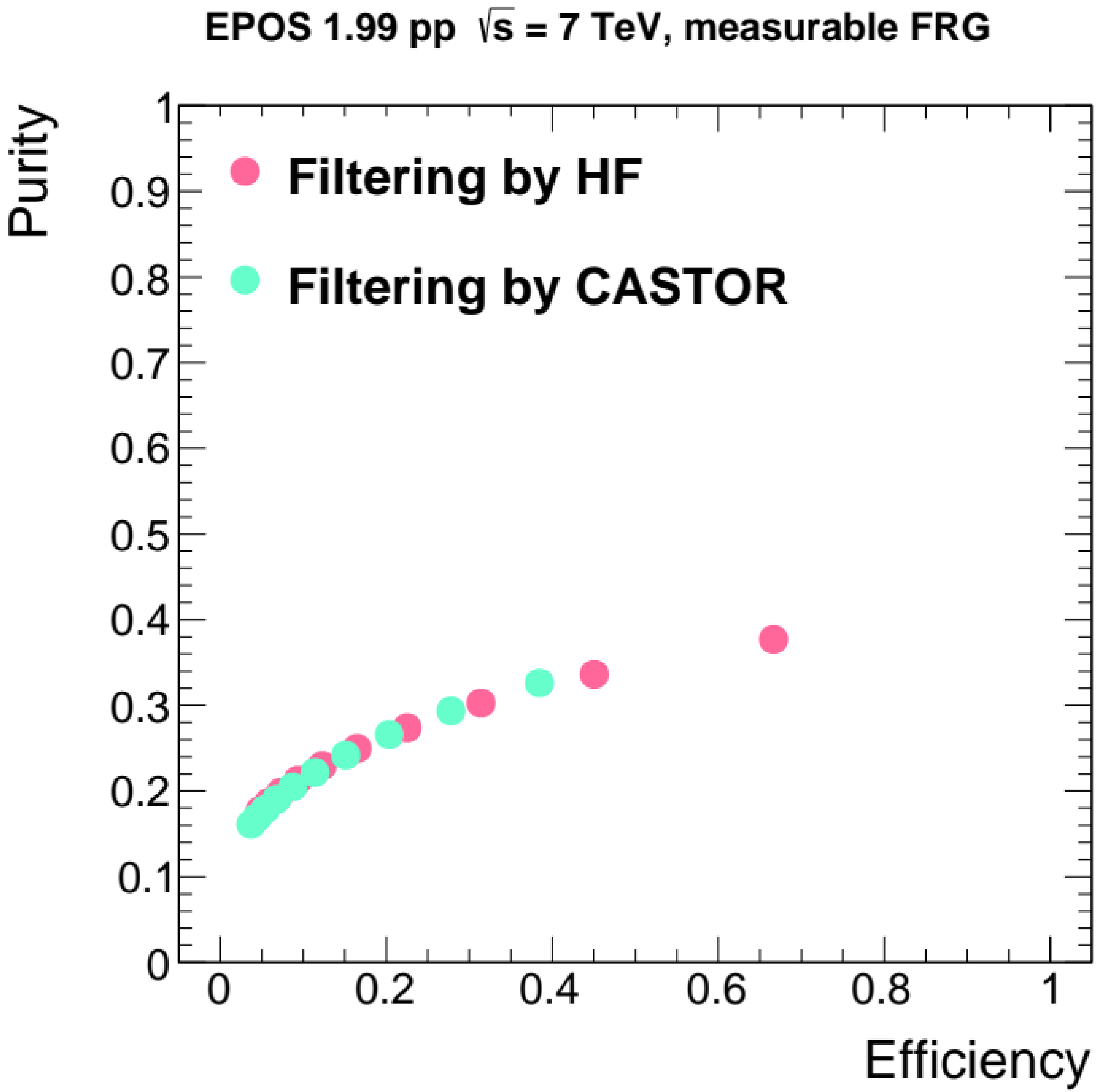
Further detectors of CMS: CASTOR



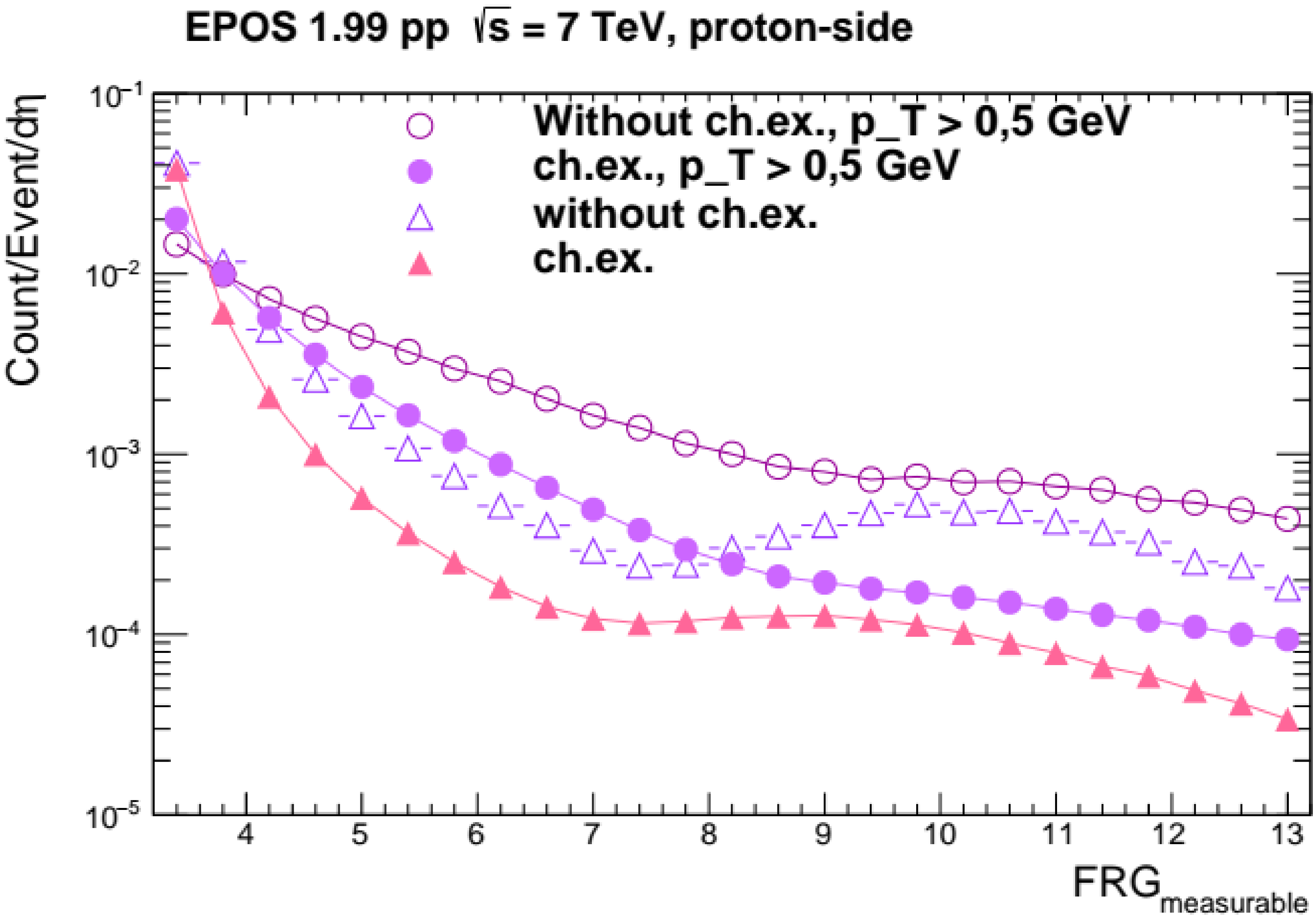
FRG with CASTOR



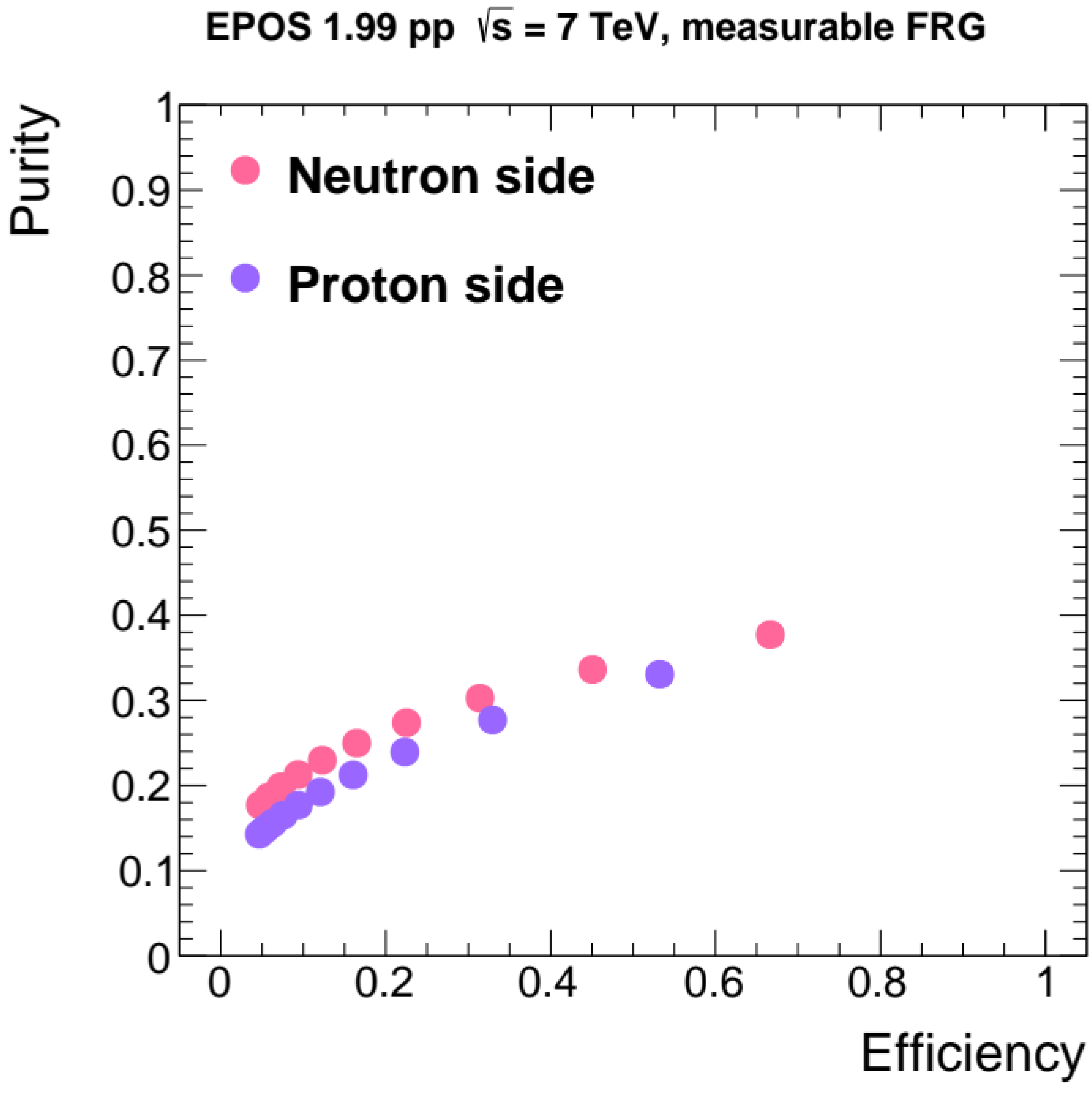
ROC curve of FRG_{CASTOR}



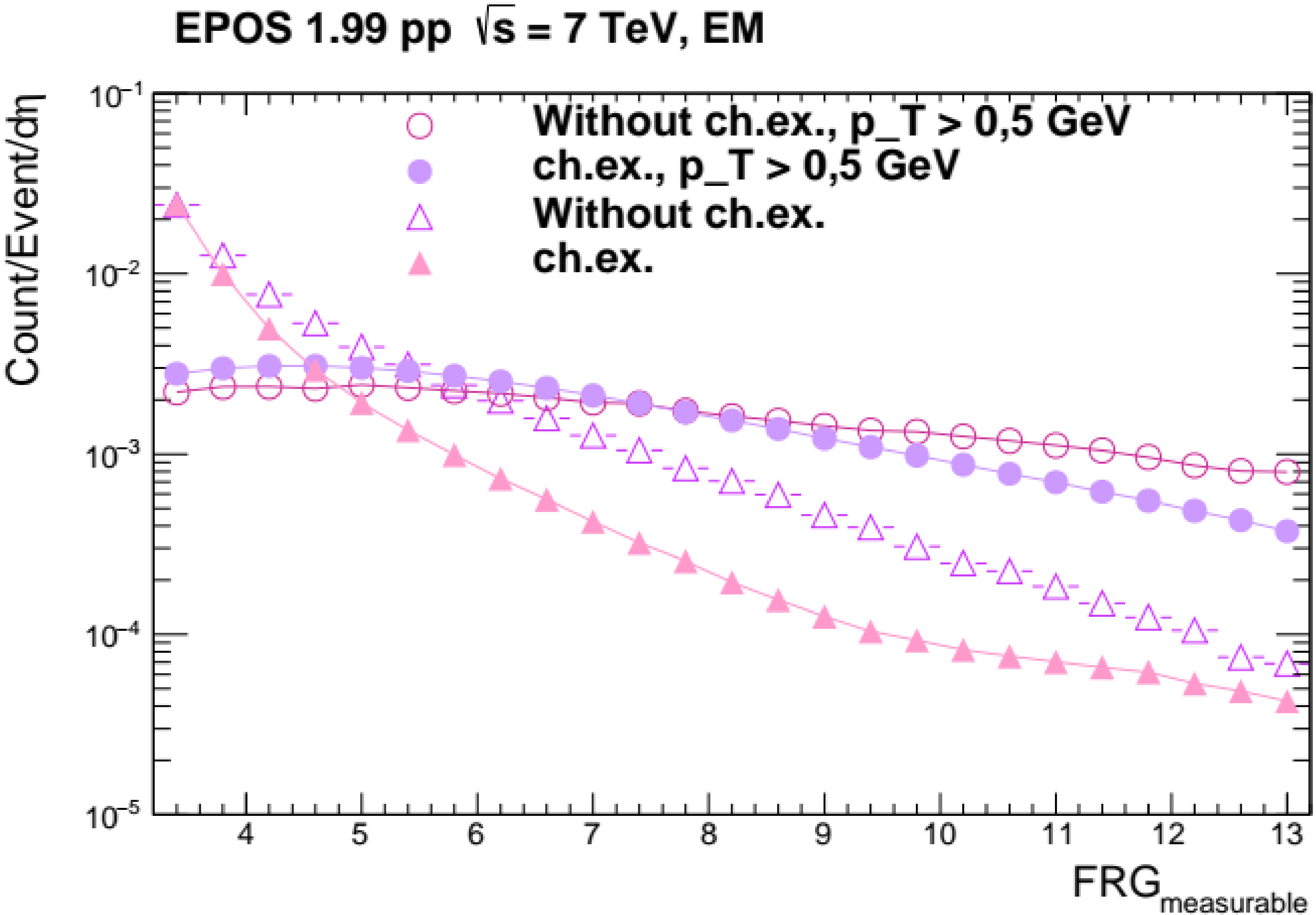
FRG on proton's side



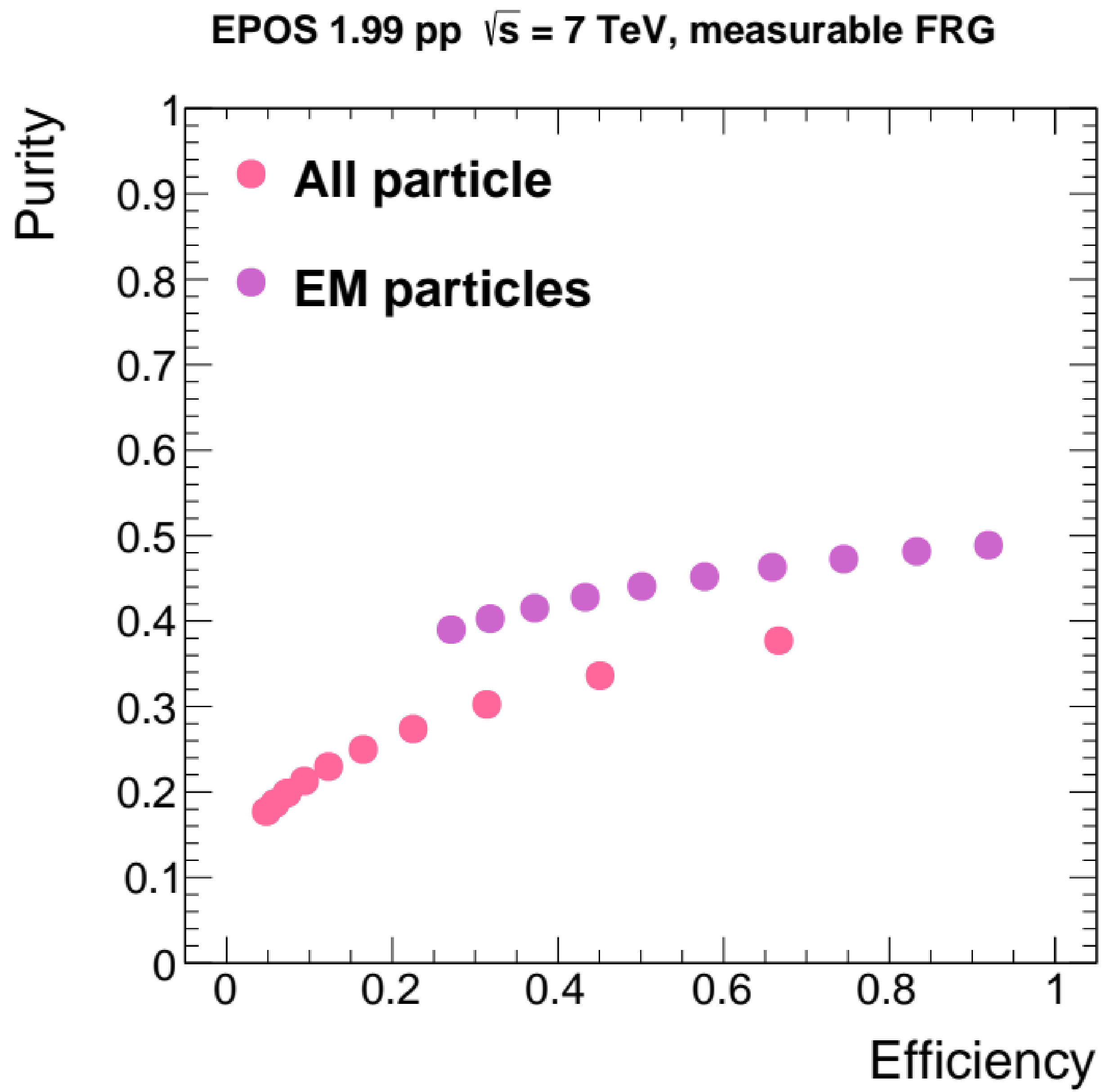
ROC curve of $FRG_{\text{proton side}}$



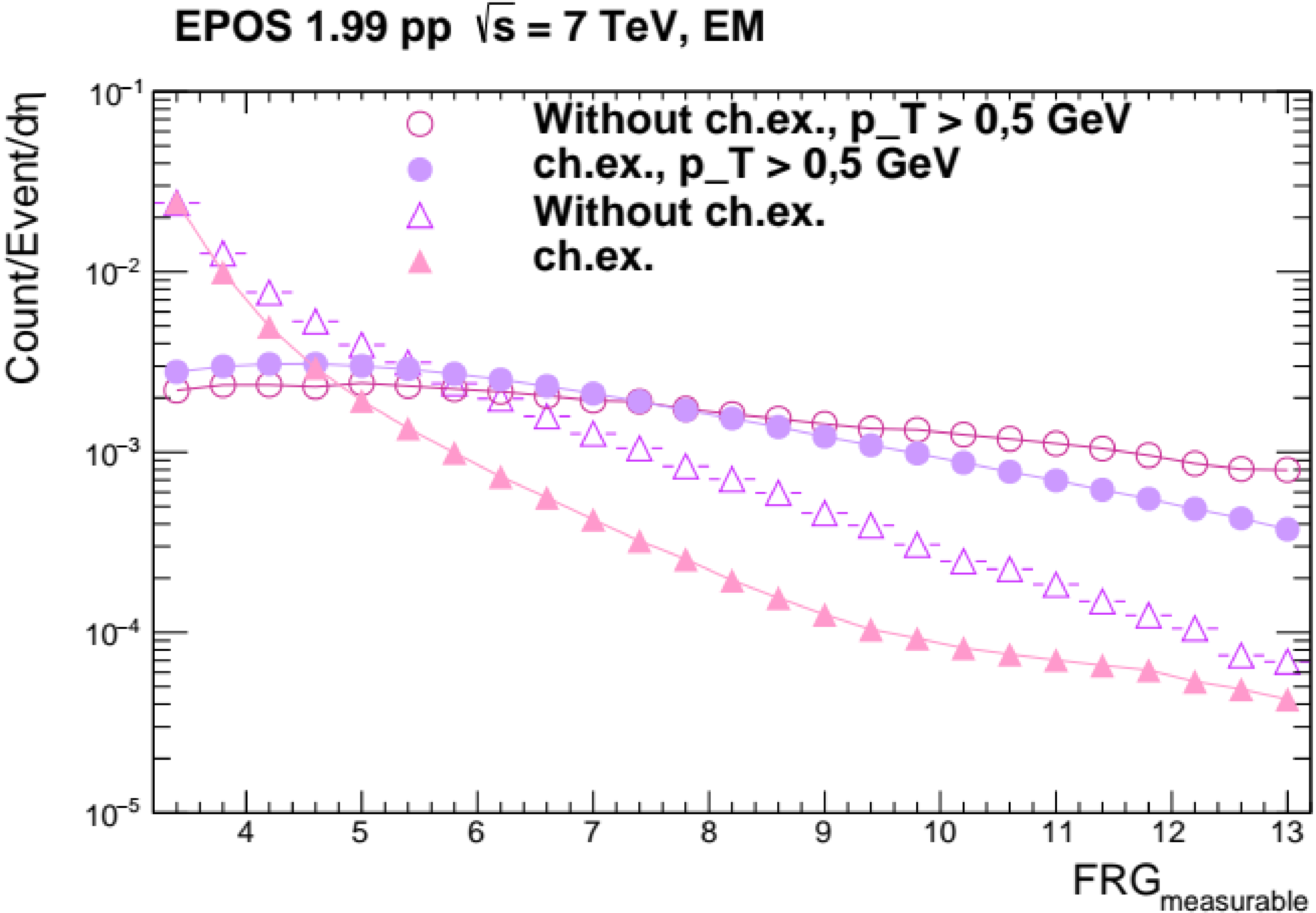
FRG for EM particles



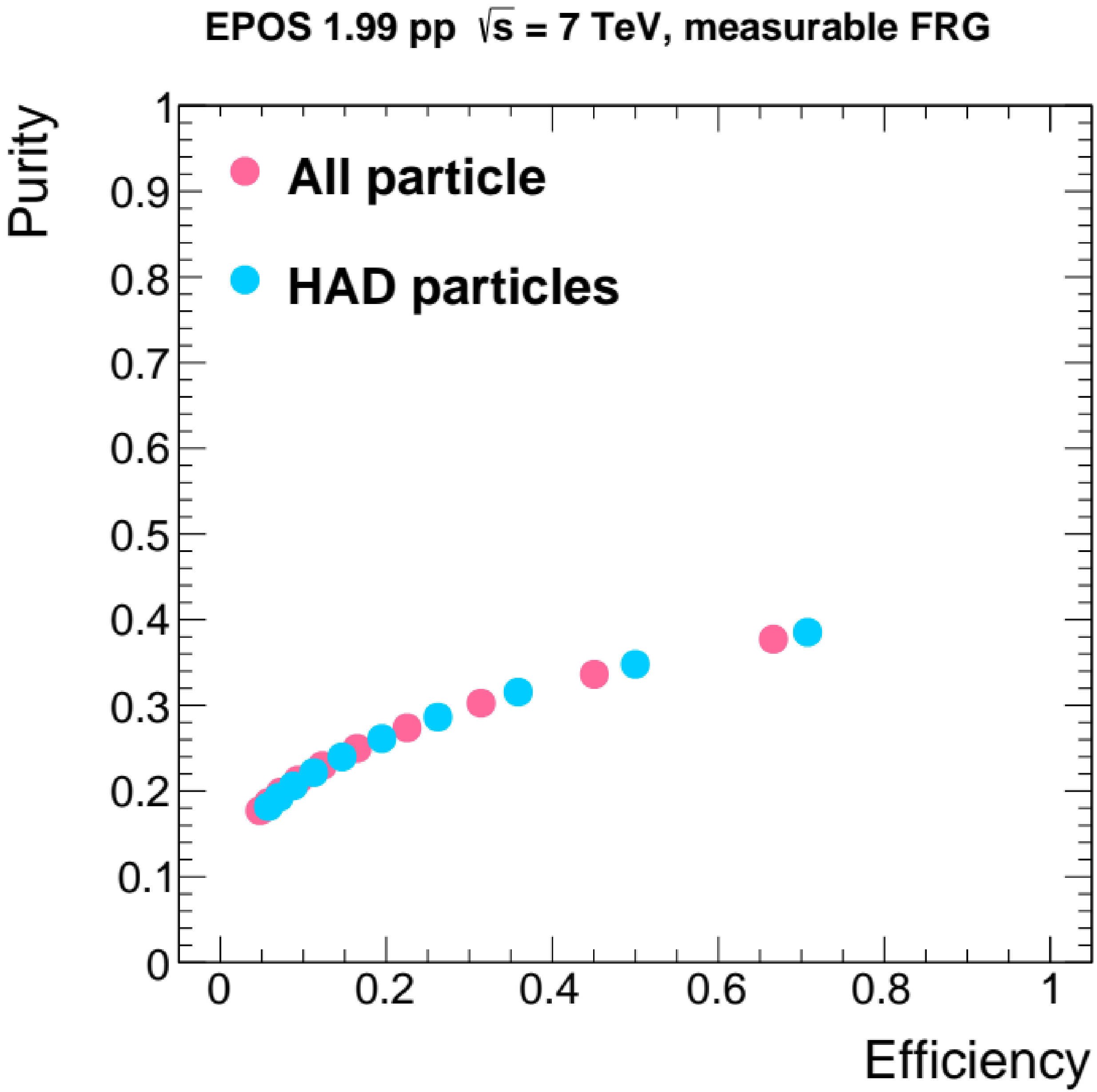
ROC curve of FRG$_{\text{EM particles}}$



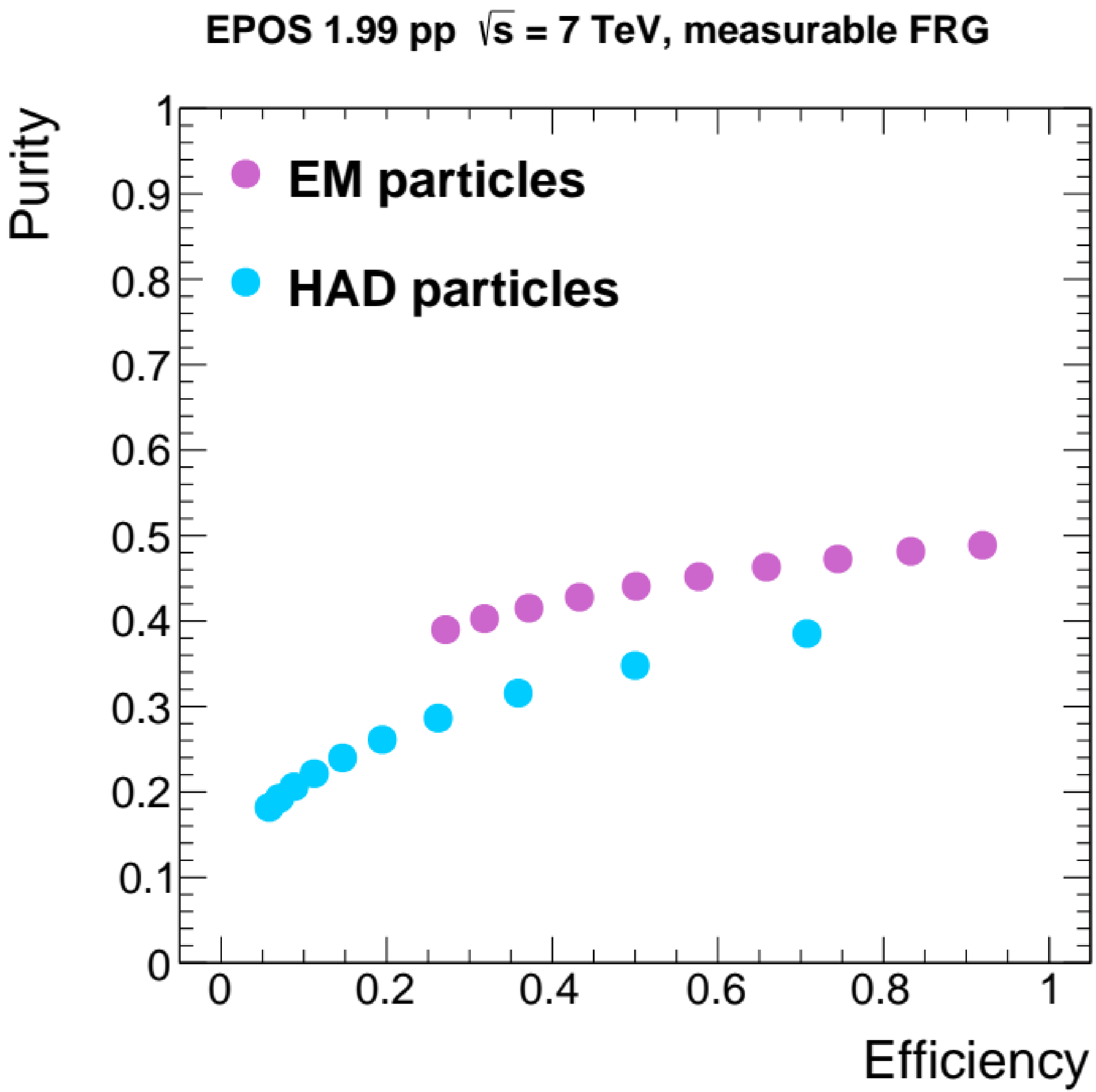
FRG for HAD particles



ROC curve for $FRG_{\text{HAD particles}}$

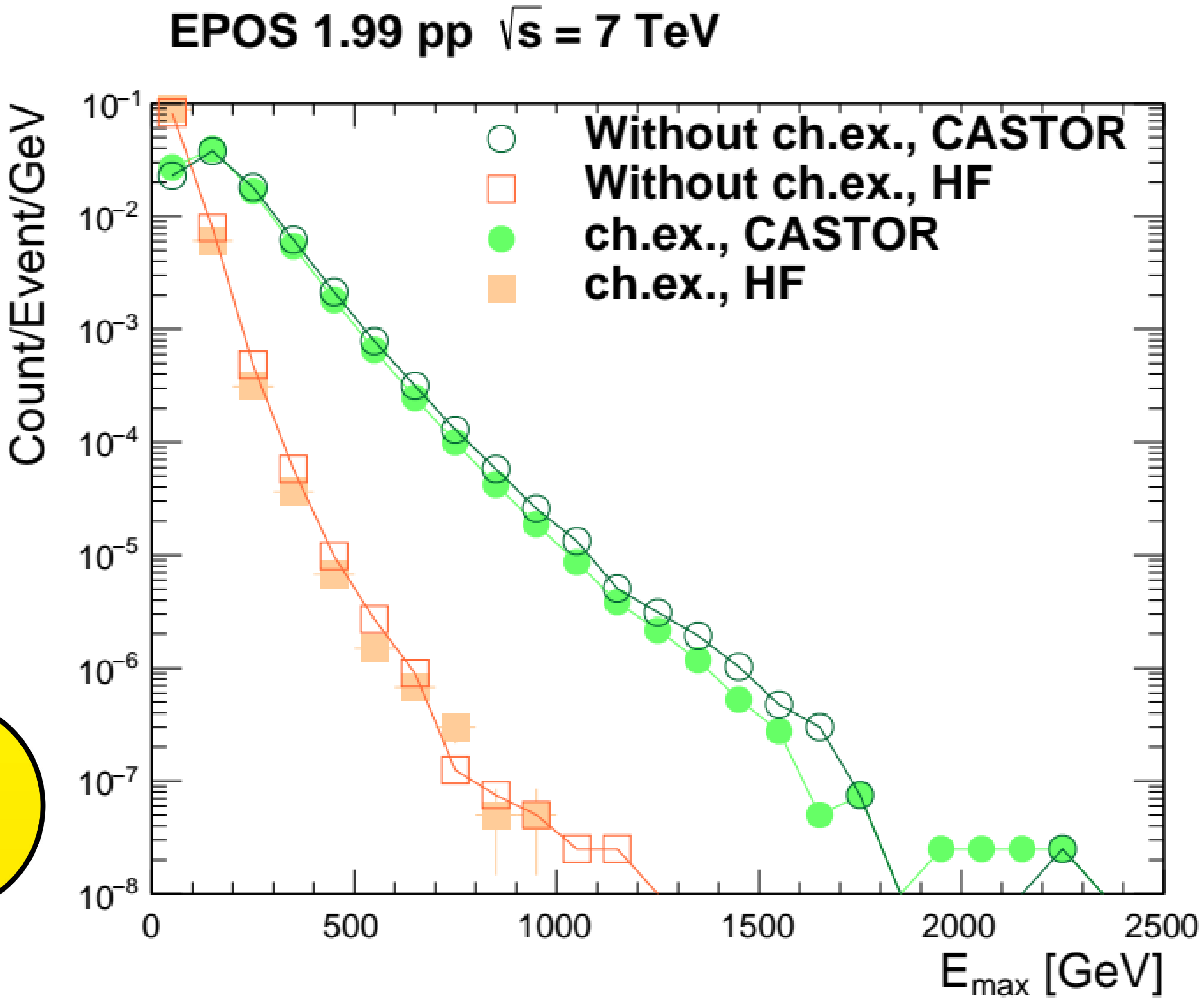


FRG: EM vs HAD

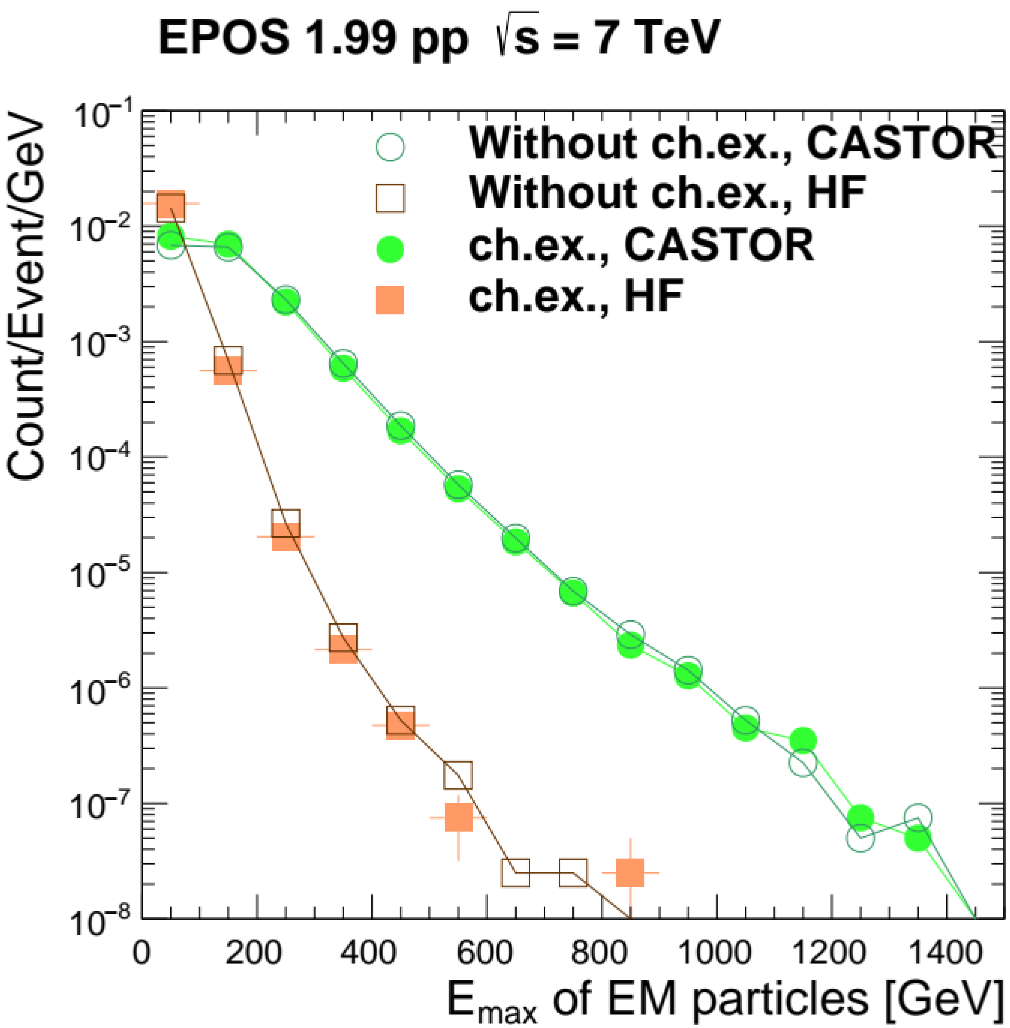


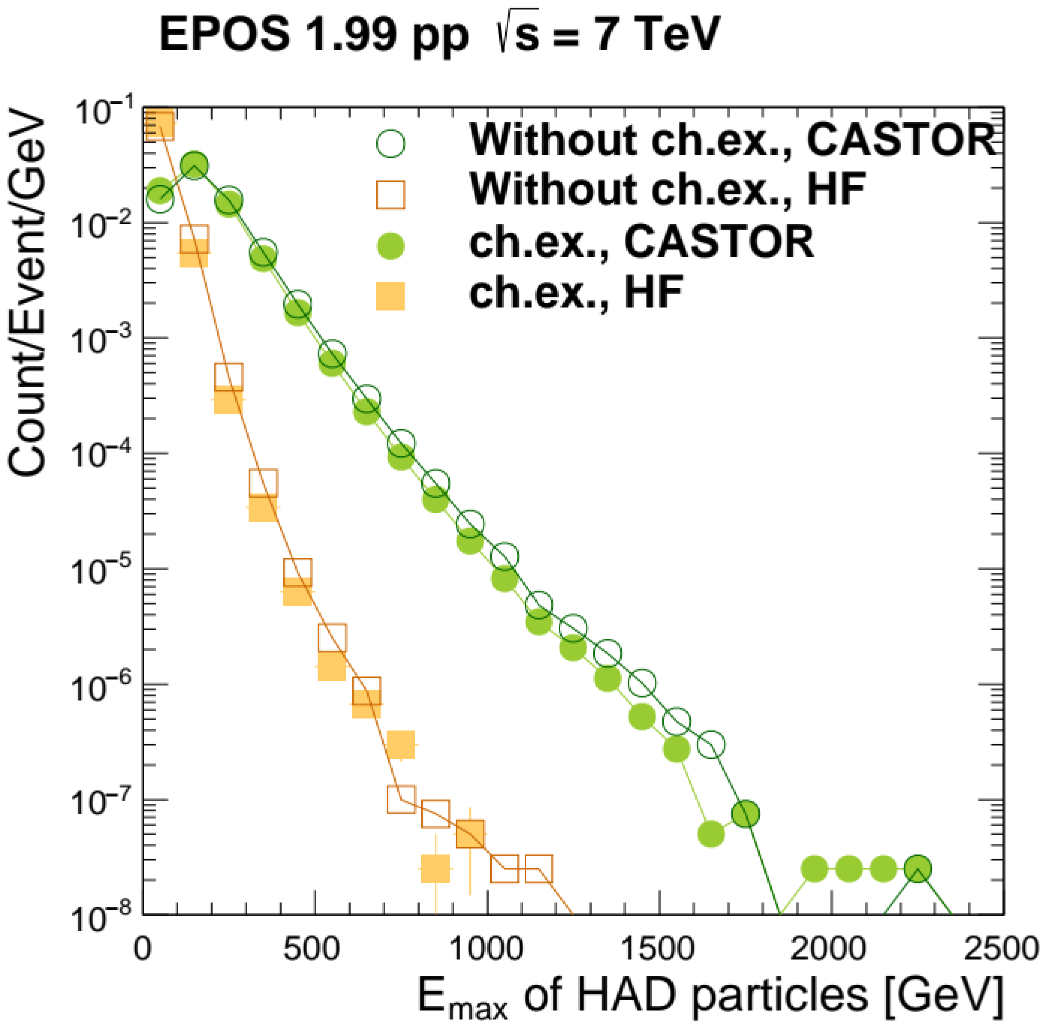
EPOS 1.99 pp $\sqrt{s}$ = 7 TeV, measurable FRG
Purity
Efficiency
EM particles
HAD particles
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1

Leading energy particles

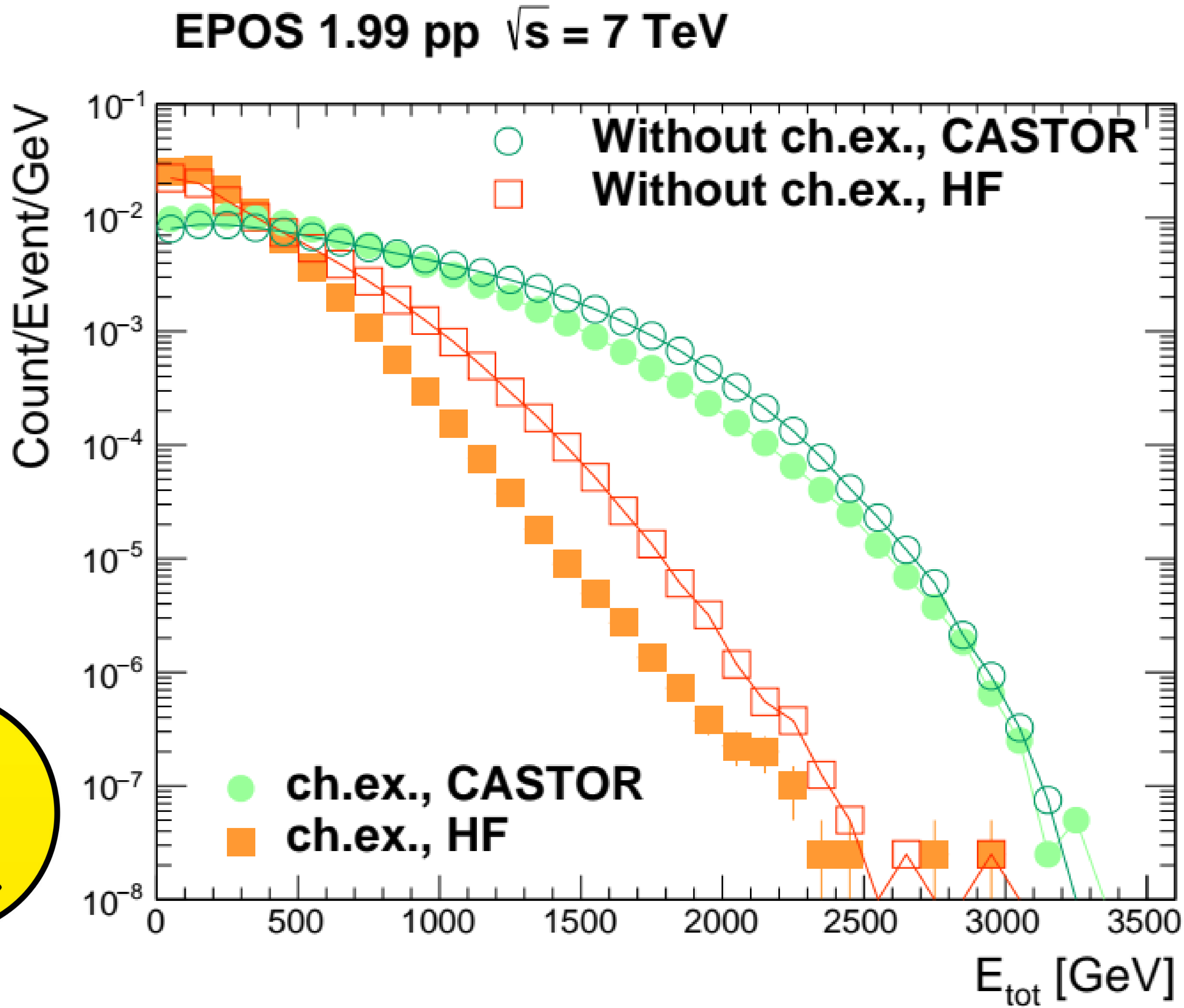


Emax: EM vs HAD

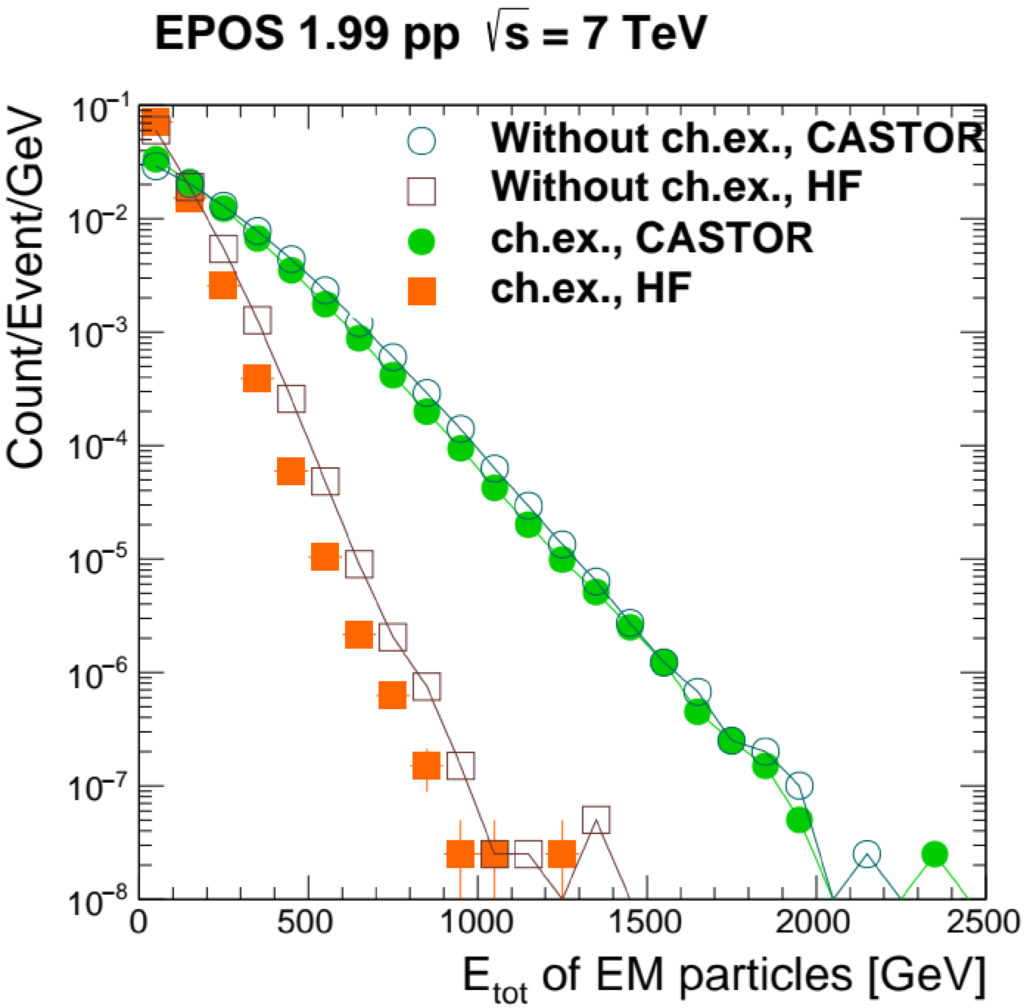


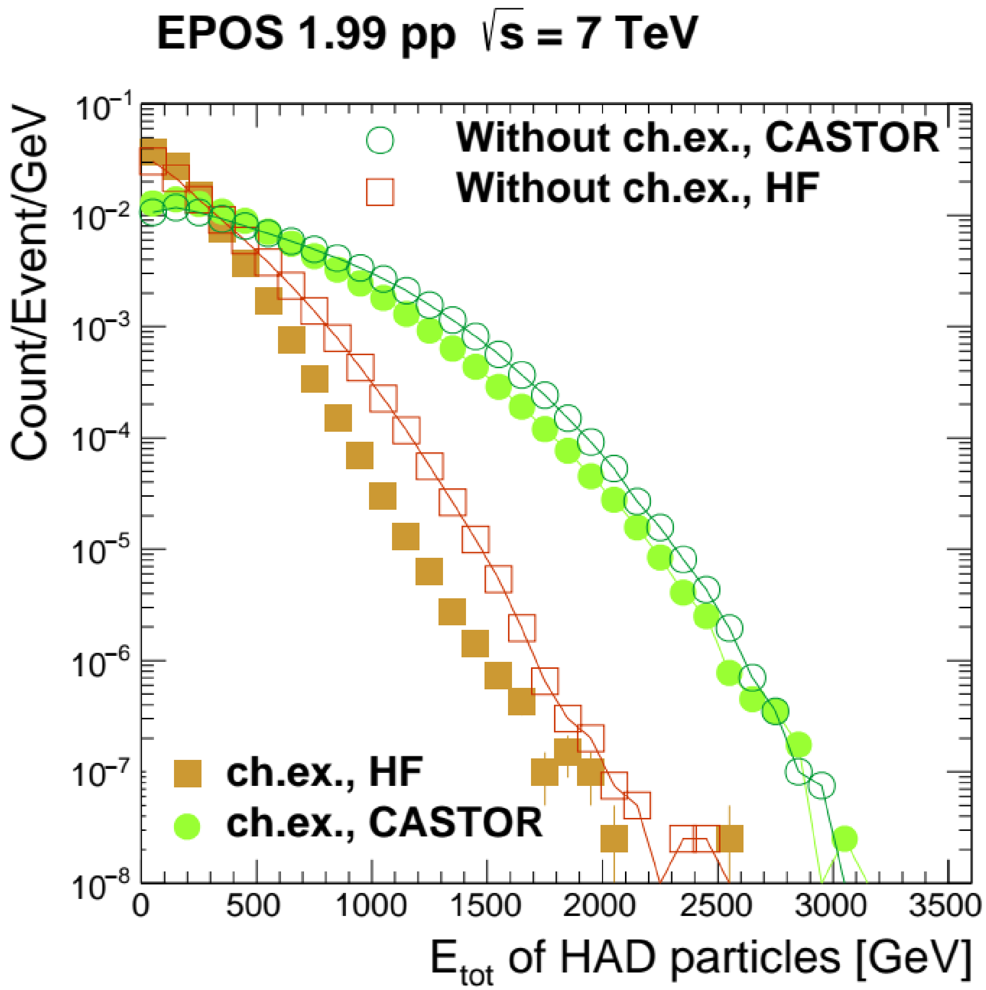


Total energy: HF vs CASTOR



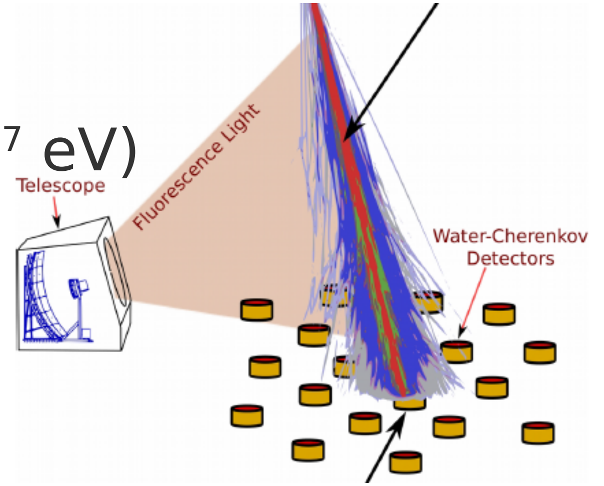
Etot: EM vs HAD

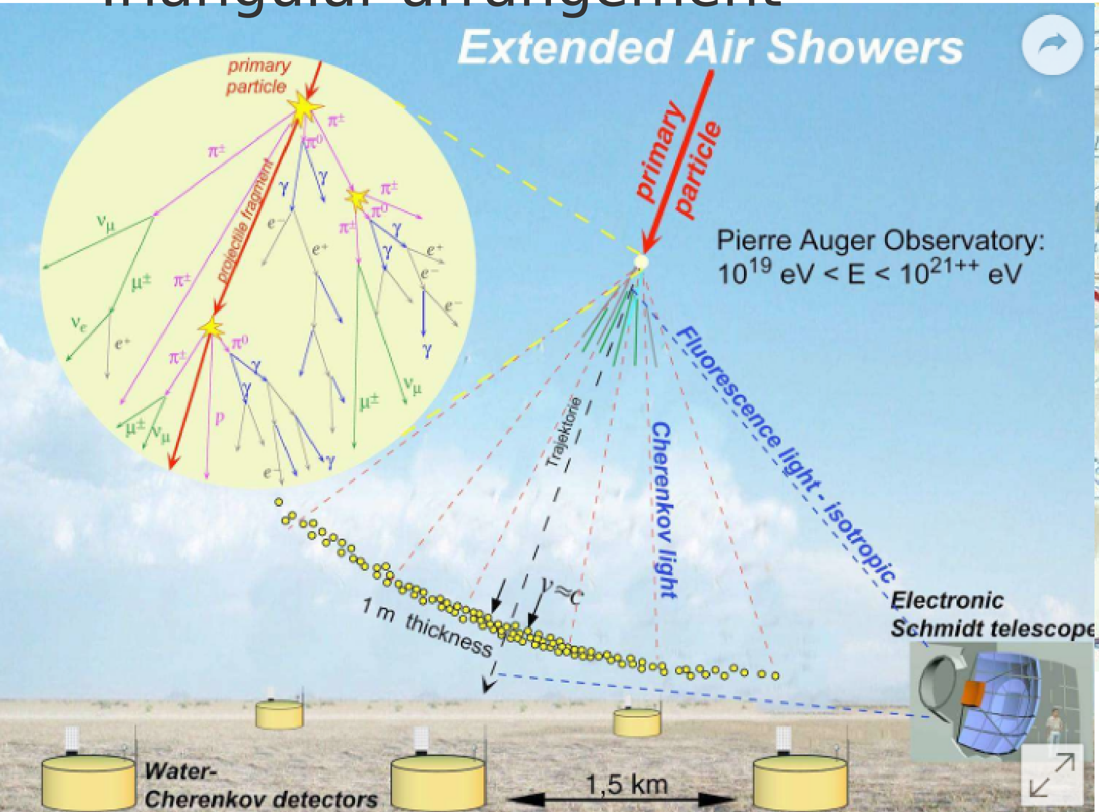


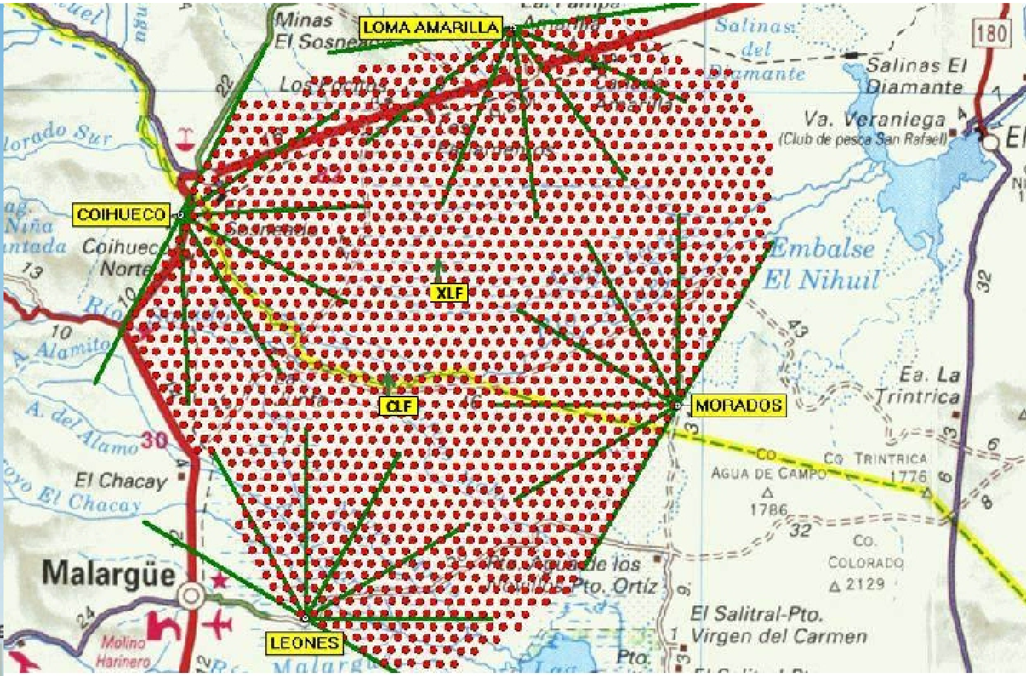


Pierre Auger Observatory

- Argentine, 18 countries
- Aim: origin + characteristic + interactions ($>10^{17}$ eV)
- 1660 surface H_2O-Čerenkov detector (3000 km^2)
- Surrounded with 32 telescopes (air fluoresce)
- Triangular arrangement

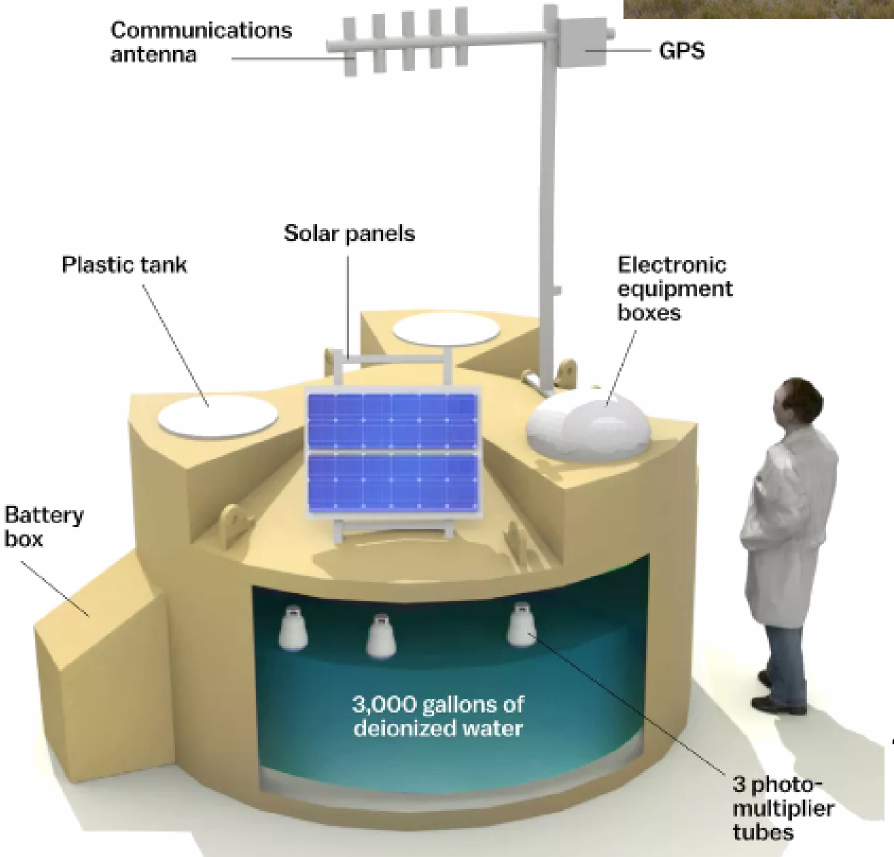






Detector system in PAO

- particles (EM & $\mu^{\pm}$): Čerenkov radiation, surface detectors
  - time + particle flux
- γs from collisions: fluorescent telescopes /UV/ (on dark nights)
  - time + dE/dX

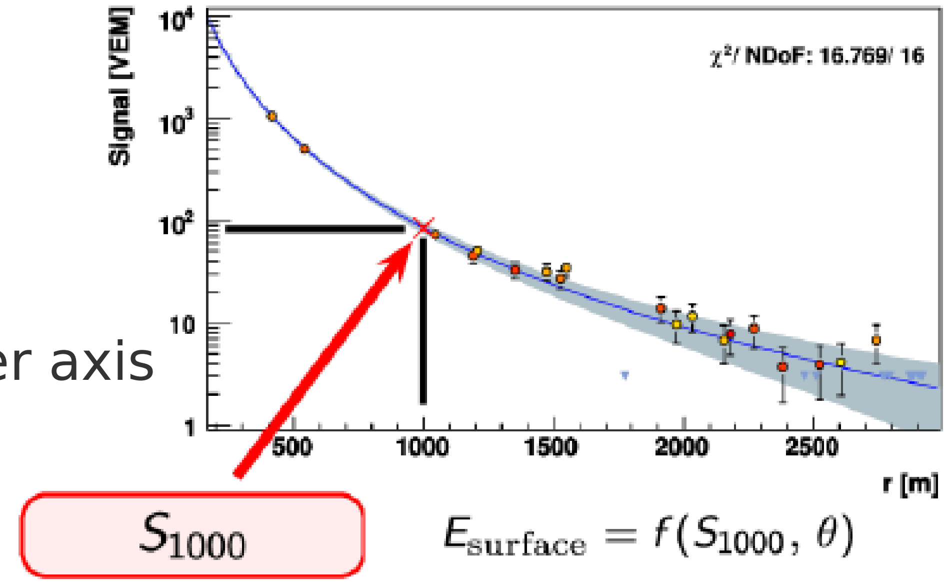


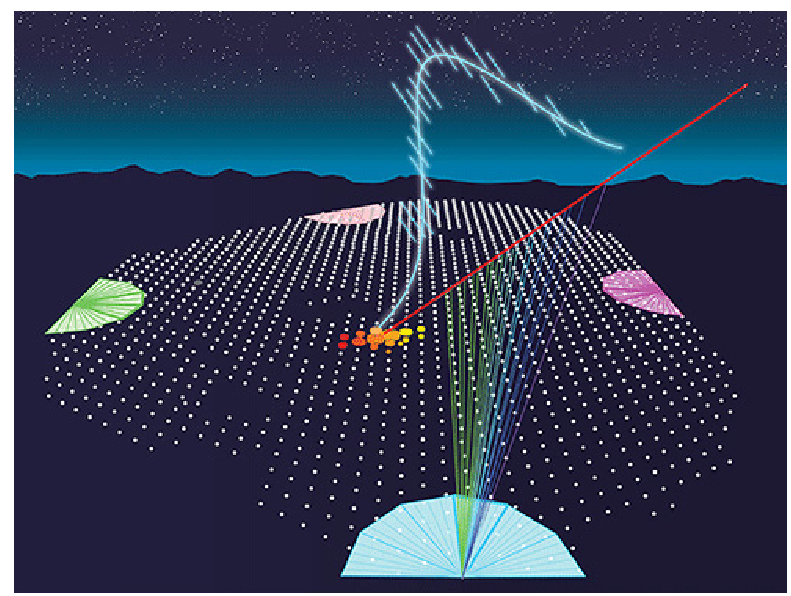
Measurements in the PAO

- X_{max}: projected coordinate
  of the maximum of the shower
  to the longitudinal axis of the shower
- S_{1000}: value of the signal
  from 1000 m trasversally of the shower axis

  → energy of the shower: $E_0 = E_{cal} + E_{inv}$
- $$E_{cal} = \int \mathrm{d}X \frac{\mathrm{d}E}{\mathrm{d}X}$$
- $E_0 \propto S_{1000}$
- Not detectable component of energy (E_{inv}):
  - neutrinos

    +heigh energy muons

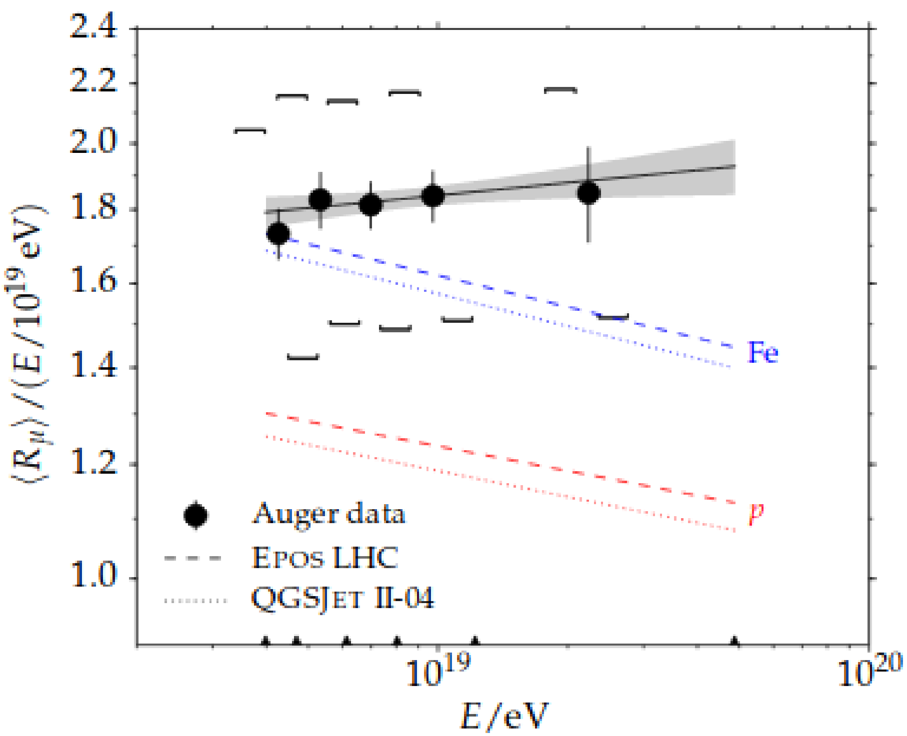


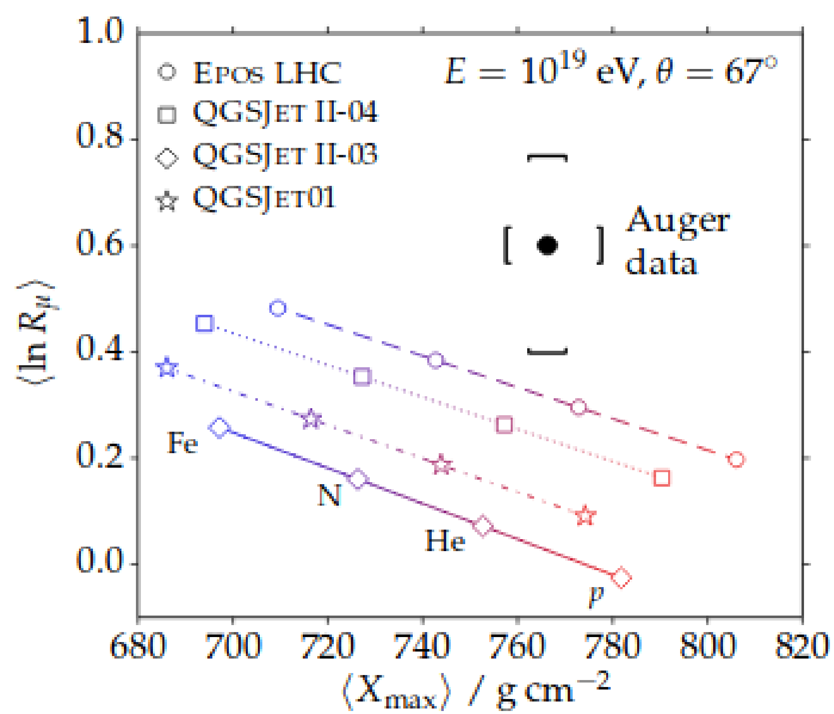


CR Mysteries

1 pc (≈3,1·10 [16] m) that distance, from where 1 AU (Astronomical Unit; i.e. SunEarth distance ≈150 · 10^6 km) can be seen in 1 arc second angle in case of transversal view

- OMG particle (Greisen-Zatsepin-Kuzmin limit: collision with background radiation → proton coming from afar than 50 Mpc: can have maximum ~8 J energy)
- Antiprotons have larger average energy than protons
- No antinuclei (AMS)
- Heavier elements at larger energies with higher probability
- Muonic component / shower not given back by simulations





Sources

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- https://physicsopenlab.org/2016/01/10/cosmic-muons-decay/
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