CHARMED BARYON MEASUREMENTS IN PROTON-PROTON COLLISIONS AT $\sqrt{s} = 13.6$ TeV WITH THE ALICE EXPERIMENT IN RUN 3

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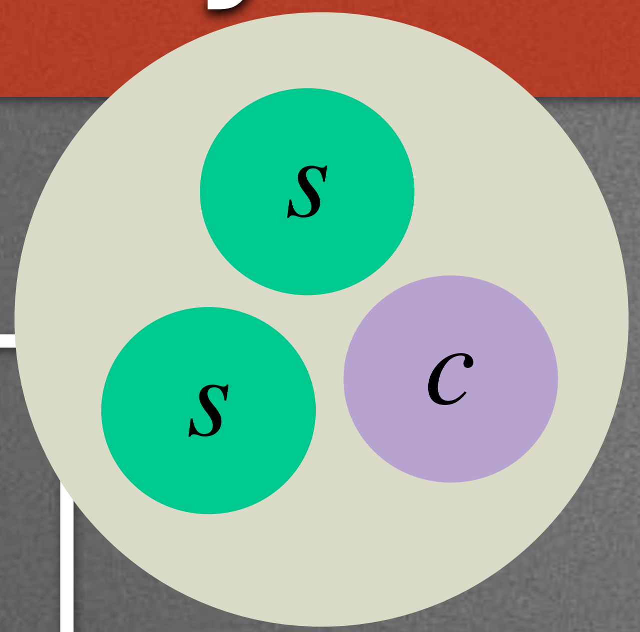
Ruprecht-Karls-Universität Heidelberg

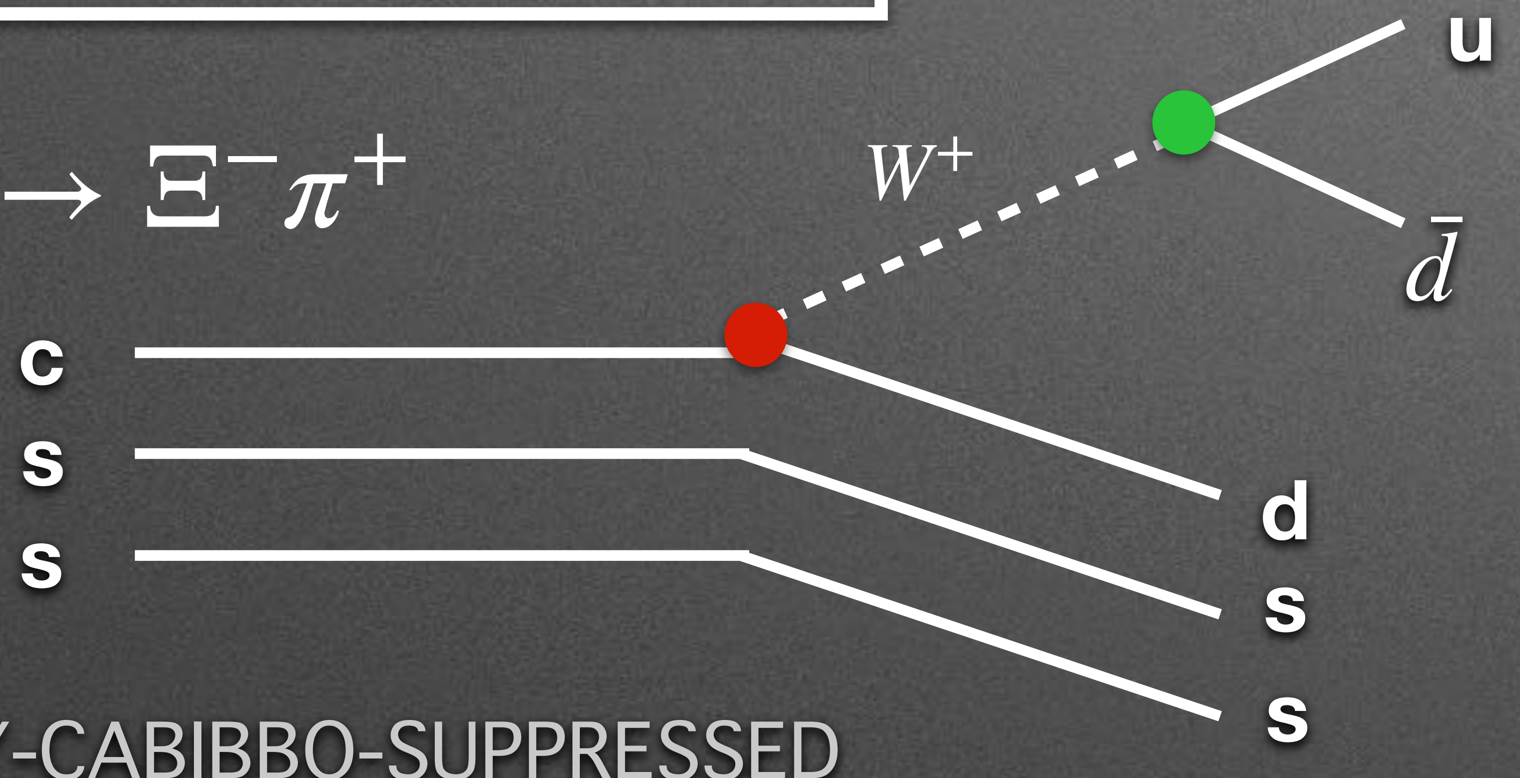
Erice International School of Subnuclear Physics, 18th June 2024

Strange charmed baryons decaying to $\Xi^{\pm}\pi^{\mp}$



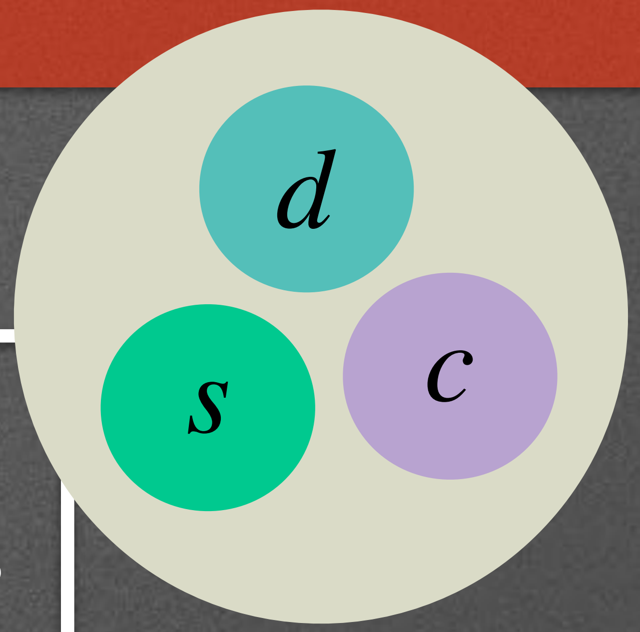
$m_{\Omega_c^0} = (2695.2 \pm 1.7)$ MeV
$\tau_{\Omega_c^0} = (2.68 \pm 0.26) \cdot 10^{-13}$ s

$\Omega_c^0 \rightarrow \Xi^-\pi^+$



SINGLY-CABIBBO-SUPPRESSED

$\Omega_c^0 \rightarrow \pi^+\Xi^- \rightarrow \pi^+(\pi^-\Lambda) \rightarrow \pi^+(\pi^-(p\pi^-))$



$m_{\Xi_c^0} = (2470.44 \pm 0.28)$ MeV
$\tau_{\Xi_c^0} = (1.519 \pm 0.024) \cdot 10^{-13}$ s

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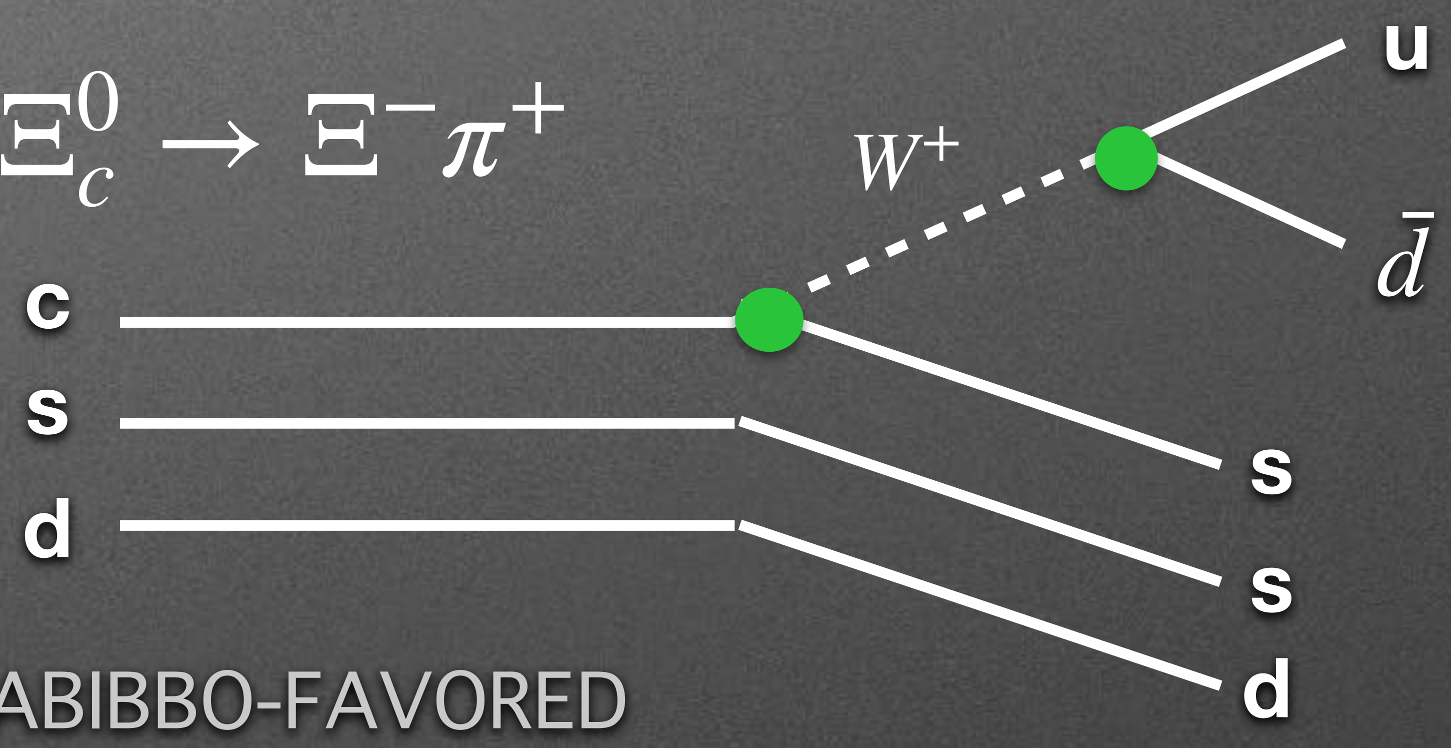

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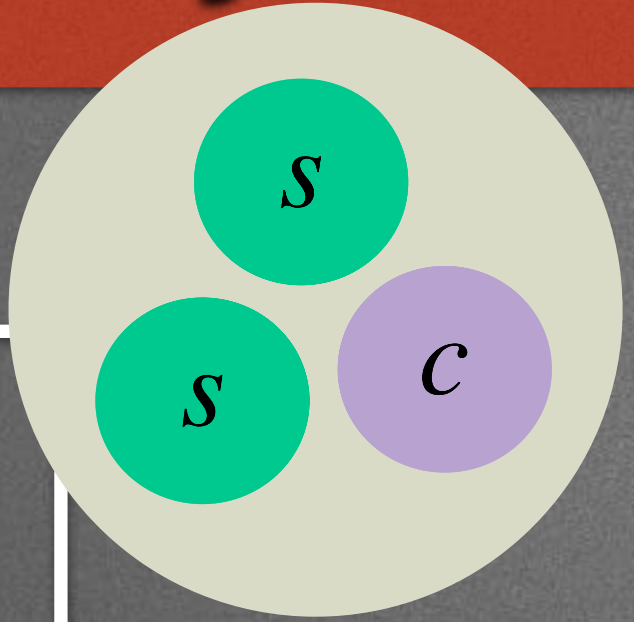

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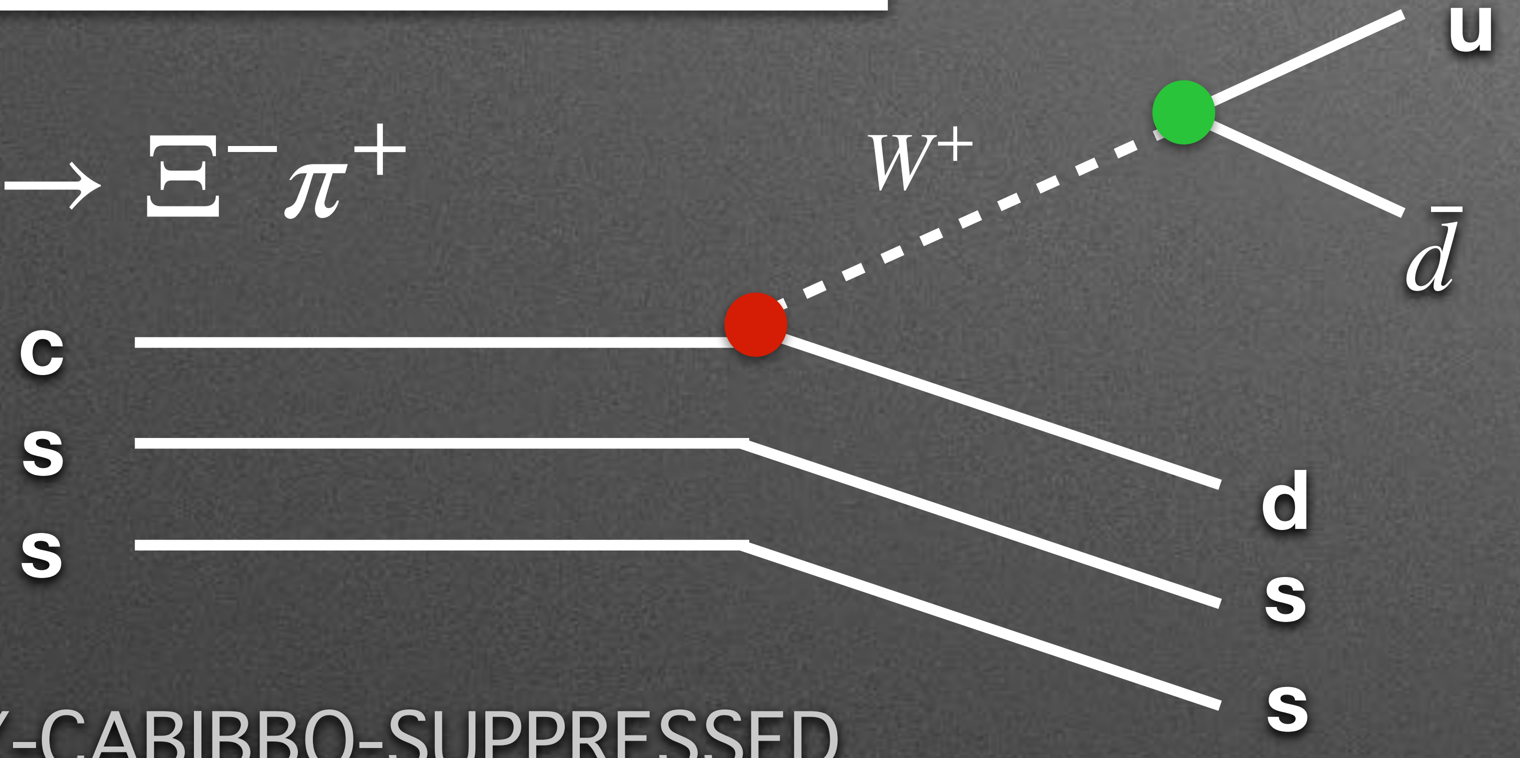

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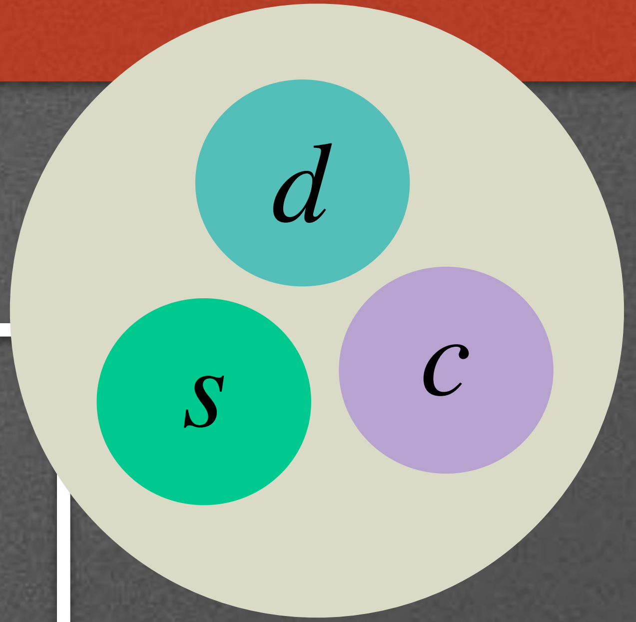

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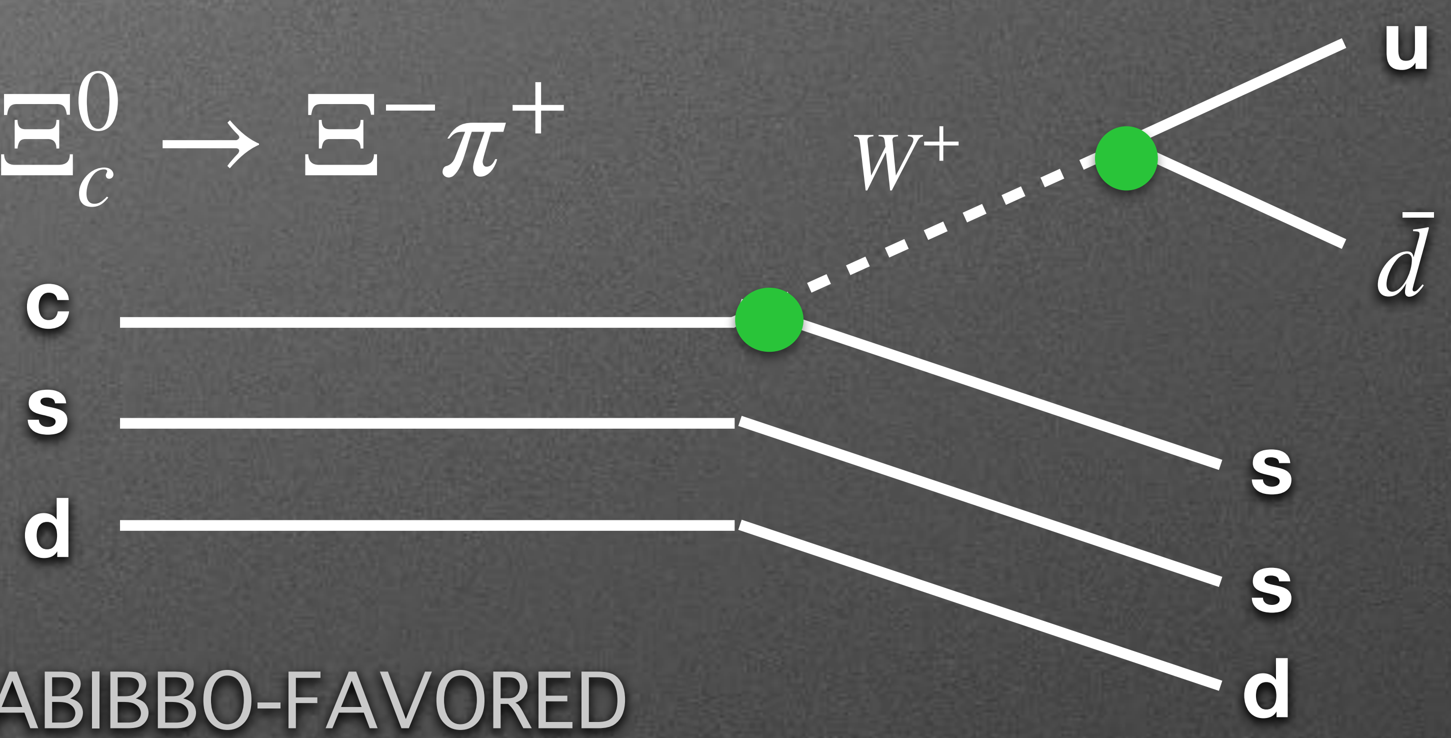

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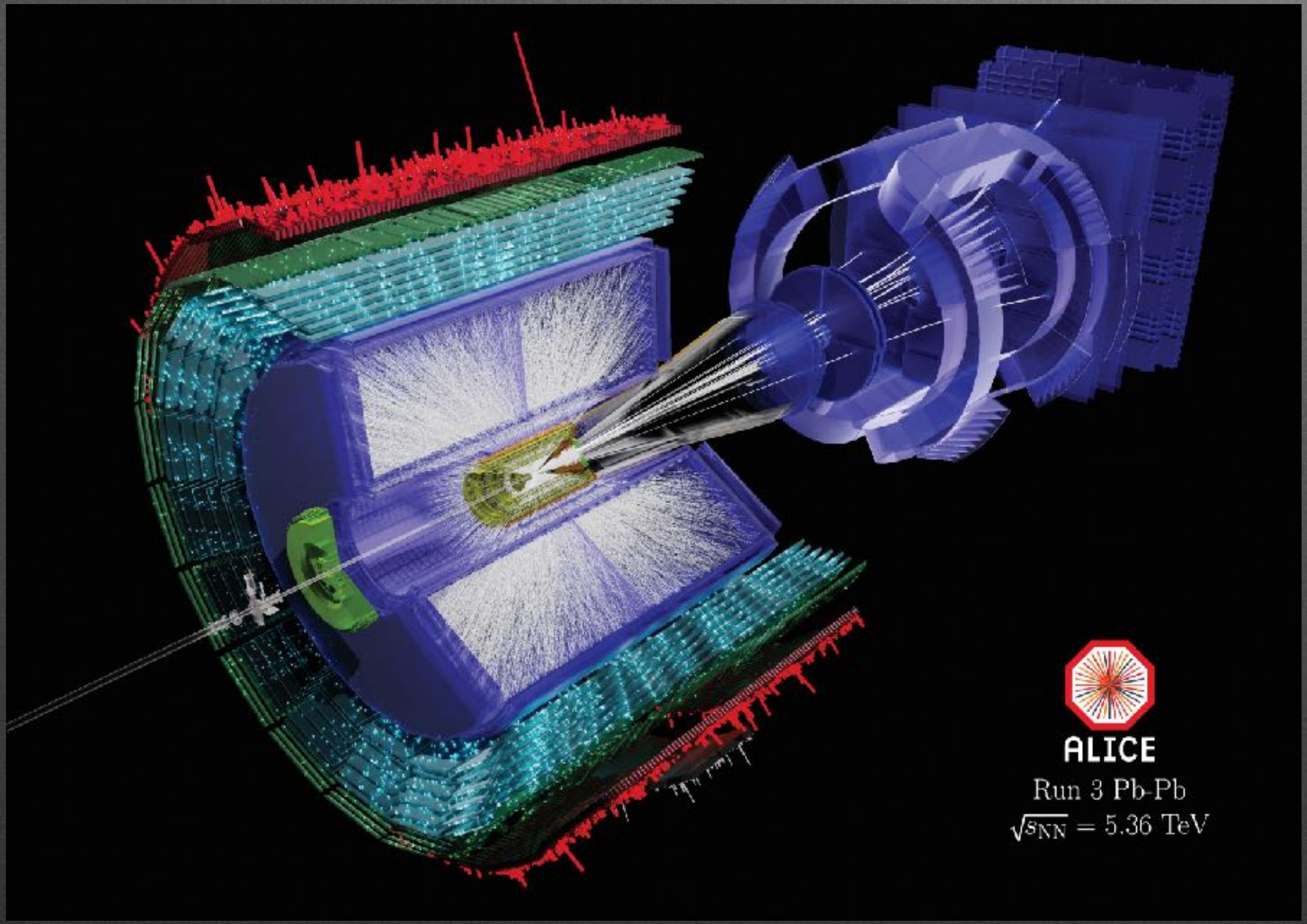
$$\Xi_c^0 \to \pi^+\Xi^- \to \pi^+(\pi^-\Lambda) \to \pi^+(\pi^-(p\pi^-))$$

MOTIVATIONS

- Establish measurements of all charmed baryons ground states with ALICE
- Hadronization mechanisms are still poorly understood and the hypothesis of fragmentation function universality has been disproved → measurements of charmed hadron-to-hadron production ratios are an effective tool to study hadronization
- Predicting BR is very challenging because of the presence of the surrounding nuclear environment → provide measurements of Cabibbo suppressed decay channels and corresponding Ω_c^0 BR fractions to validate theoretical models
- Available measurements of Ω_c^0 BR fraction for $\Xi\,\pi$ decay channel by BELLE and LHCb are not in agreement → provide an extra independent measurement

ALICE Run 3



- ALICE underwent major upgrades during long shutdown 2 that allow for continuous readout operations
- Enormous stream of data from detectors to the online system, of the order of few TB/s
- Run 3 dates is already orders of magnitude larger than the whole Run 2 sample
- Innovative software framework, data model and analysis submission system, new data taking strategy, different Monte Carlo simulation methods

Analysis framework: O2Physics

- based on arrow tables → columnar memory format for flat and hierarchical data
- optimised for bulk operations
- supporting highly modular and extensible data representation
- allowing for vectorized optimisation of analytical data processing

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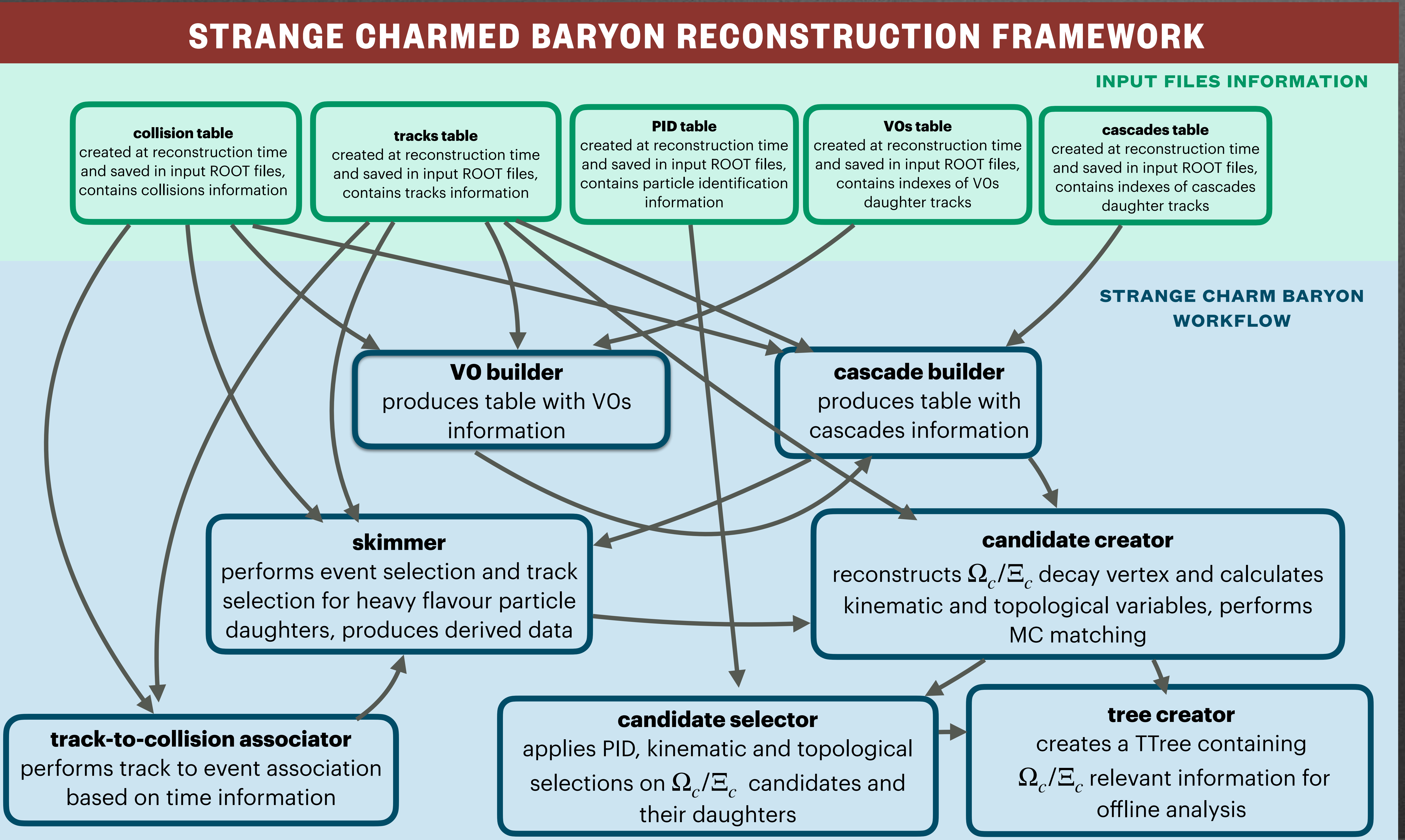

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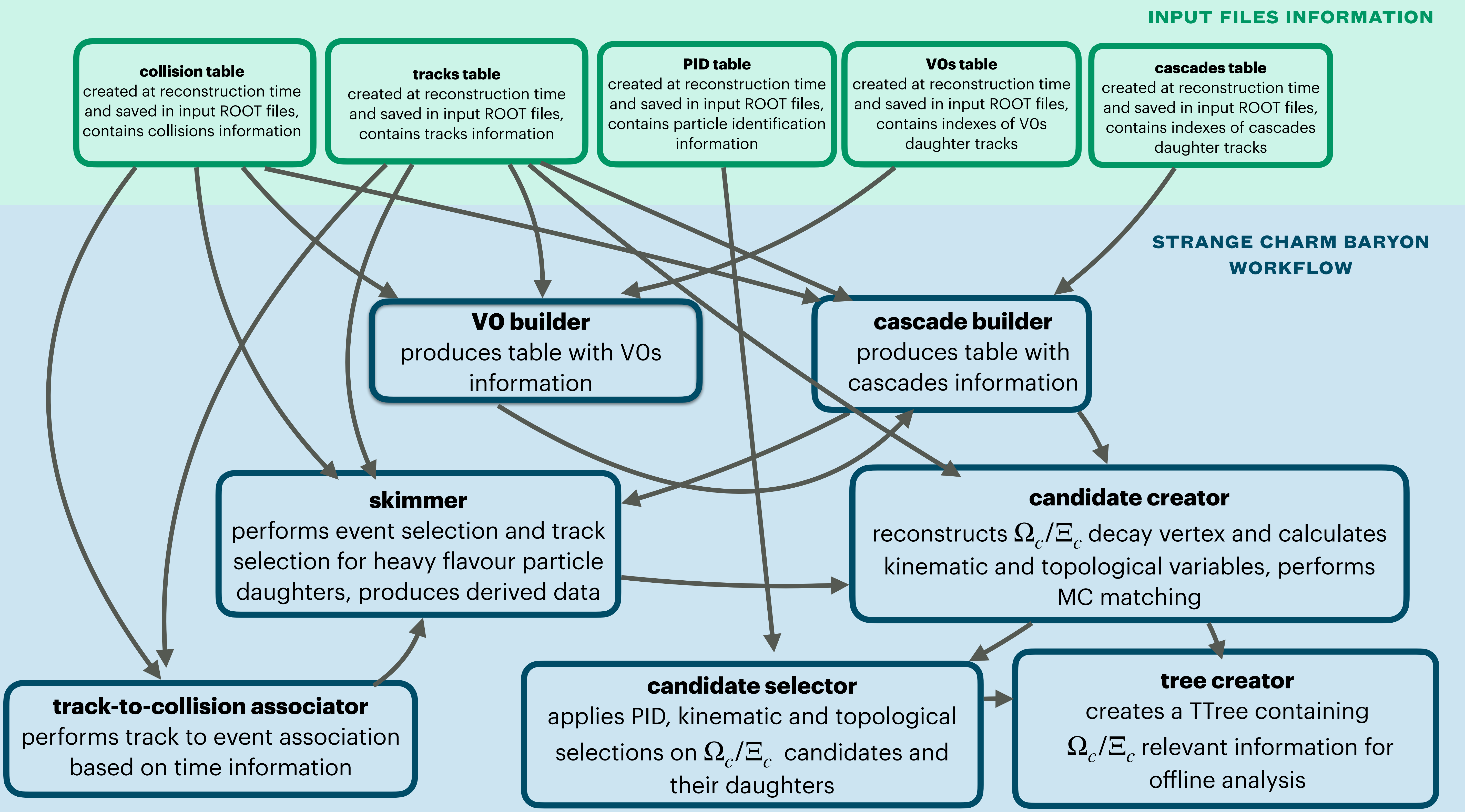
STRANGE CHARMED BARYON RECONSTRUCTION FRAMEWORK



DERIVED DATA

- Need to process enormous datasets, much larger than the whole Run 2 statistics
- The analysis submission system imposes limits on single analysis computing resources

↓

Factorize part of the analysis workflow producing an intermediate-step dataset profitable for multiple analyses and providing access to parent input file information only for selected table elements

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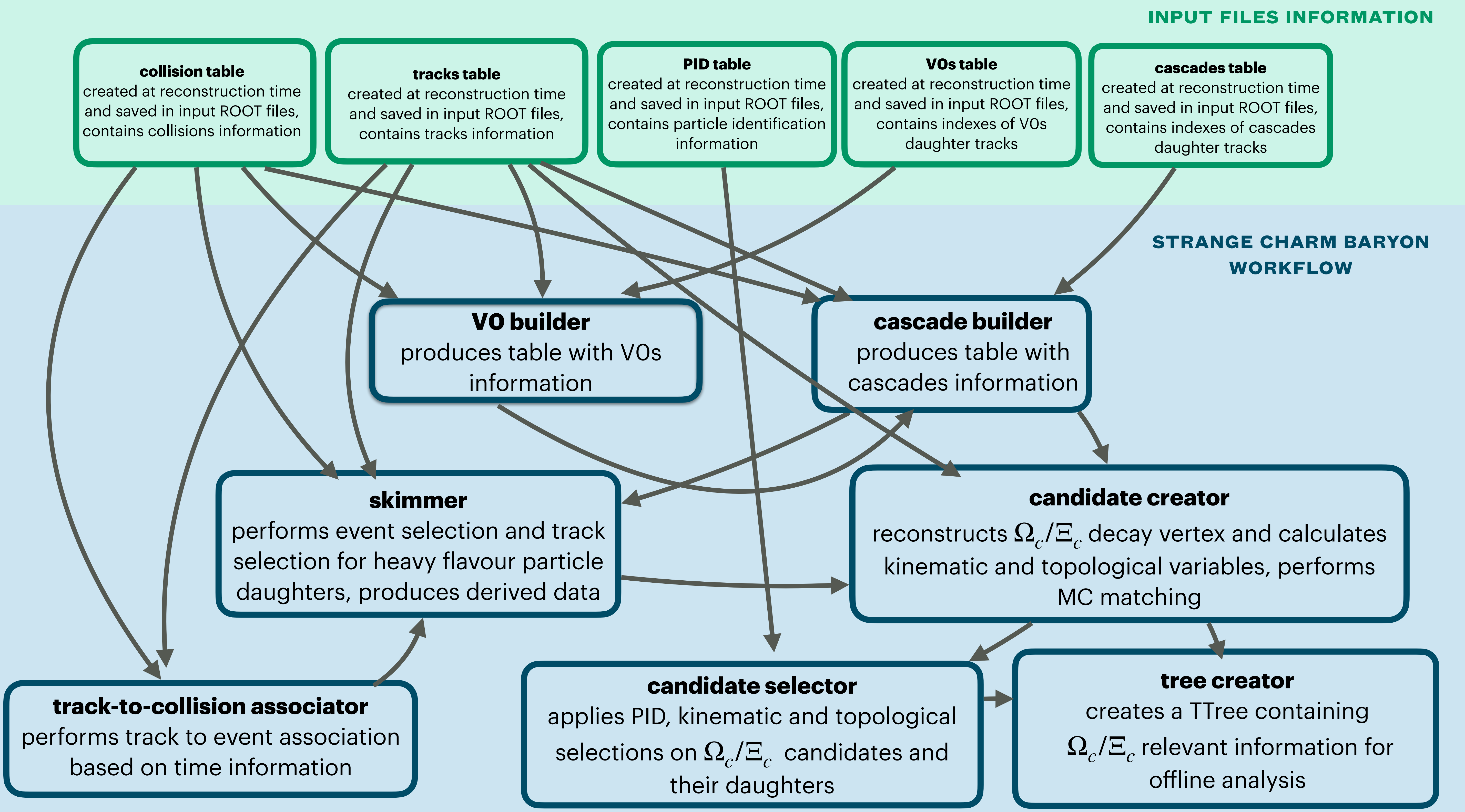

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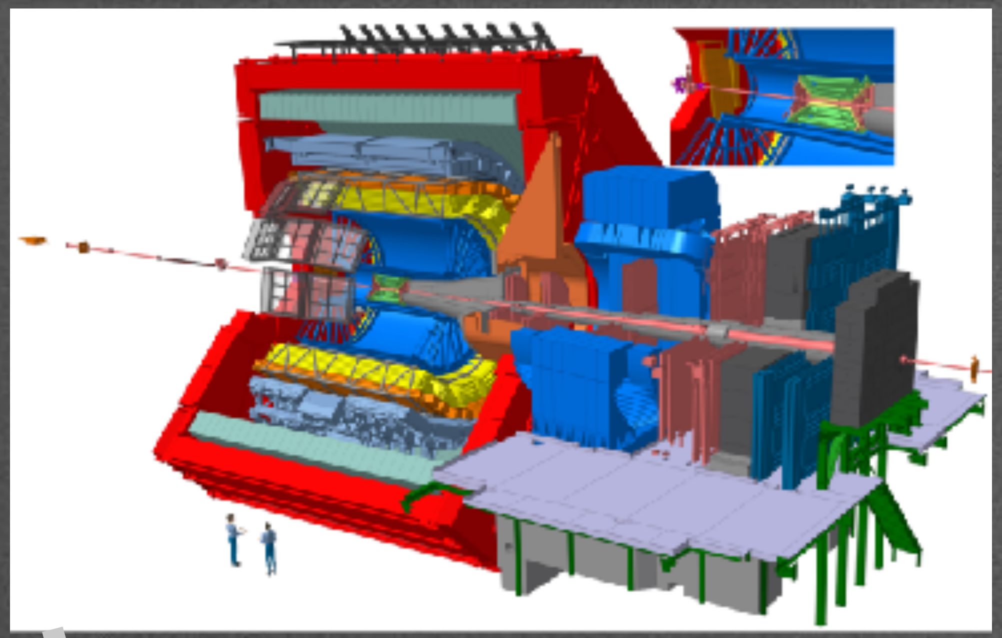
RESOURCES NEEDED FOR DIFFERENT CONFIGURATIONS OF THE $\Xi_c^0 \to \Xi\,\pi$ ANALYSIS

Reduction factor:	980	*Derived data production*
Wall time:	1y 34d	*Full workflow*
Throughput:	482.4 KB/s/core	
Wall time:	111d 13h	*Analysis on derived data*
Throughput:	1.7 MB/s/core	

Remarkable speed up the execution of the analysis!

Dedicated offline triggers in pp collisions and data skimming



~ 3 TB/s

(with 3 PB ~ 1 pb^{-1})

Online system

~ 90 GB/s

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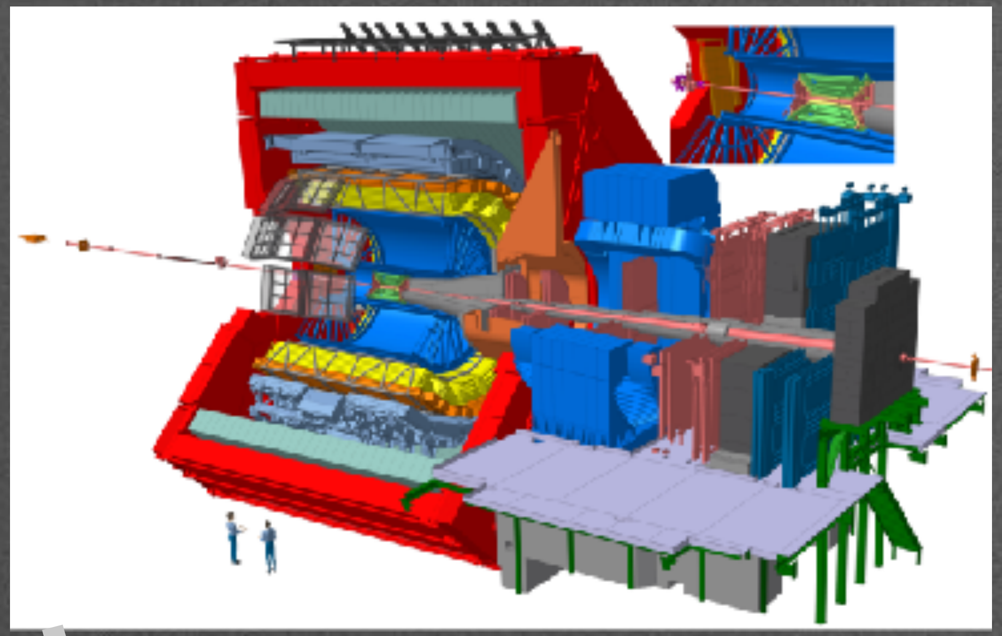

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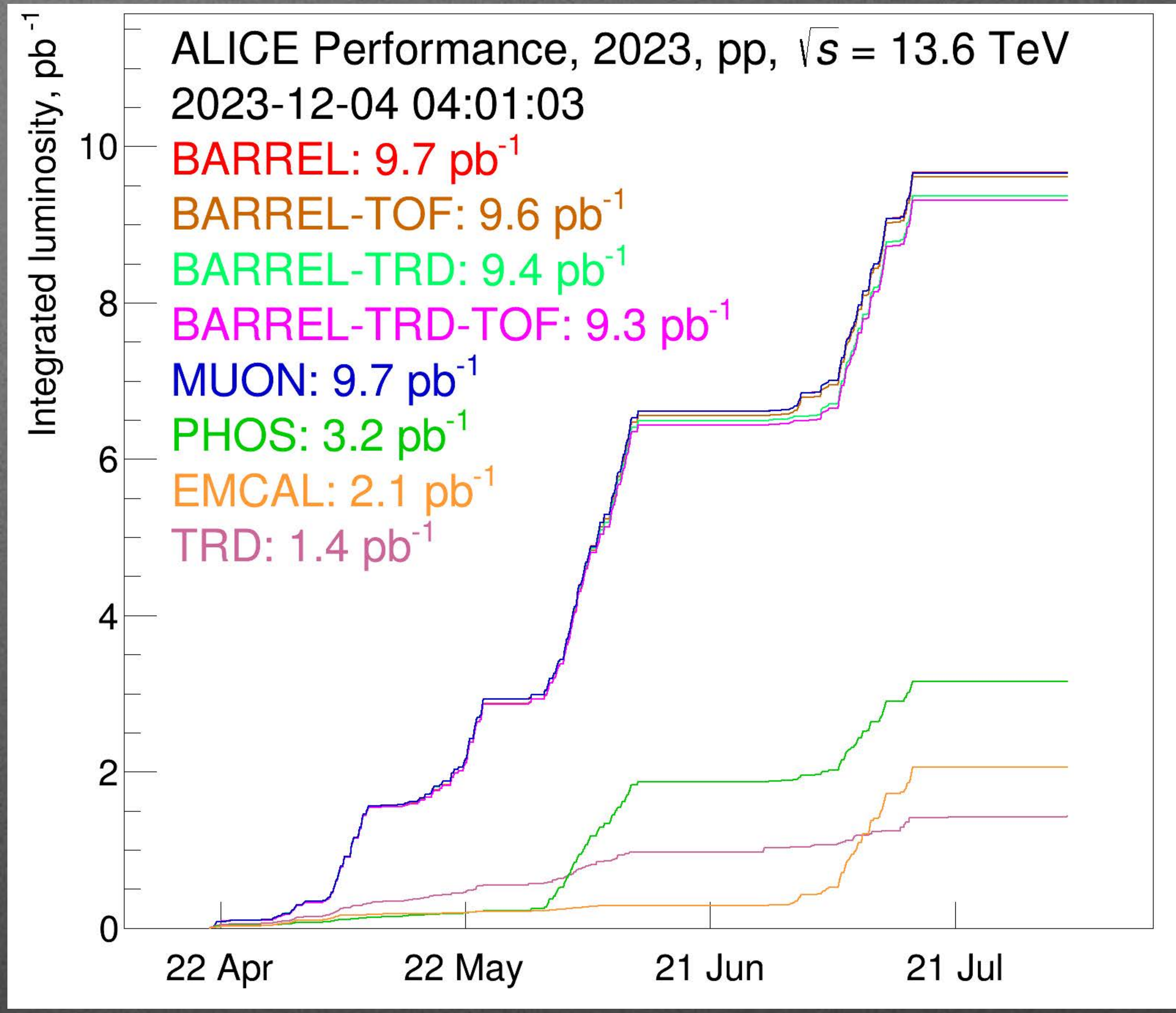

2023 pp data sample

$\mathscr{L}_{int} \sim 9.7\ \mathrm{pb}^{-1}$

Run2 MB statistics:
32 nb^{-1}

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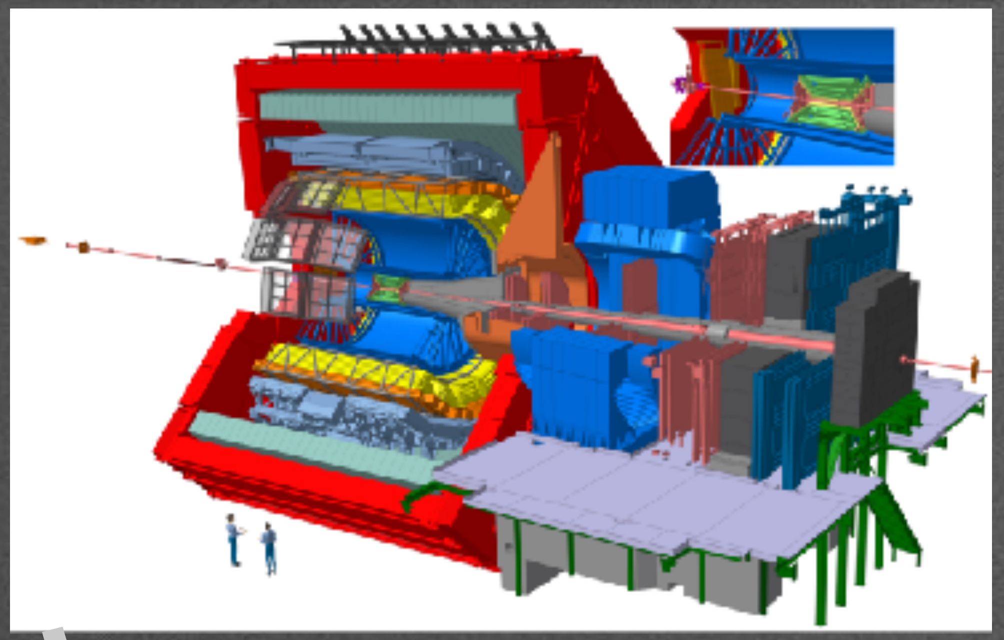

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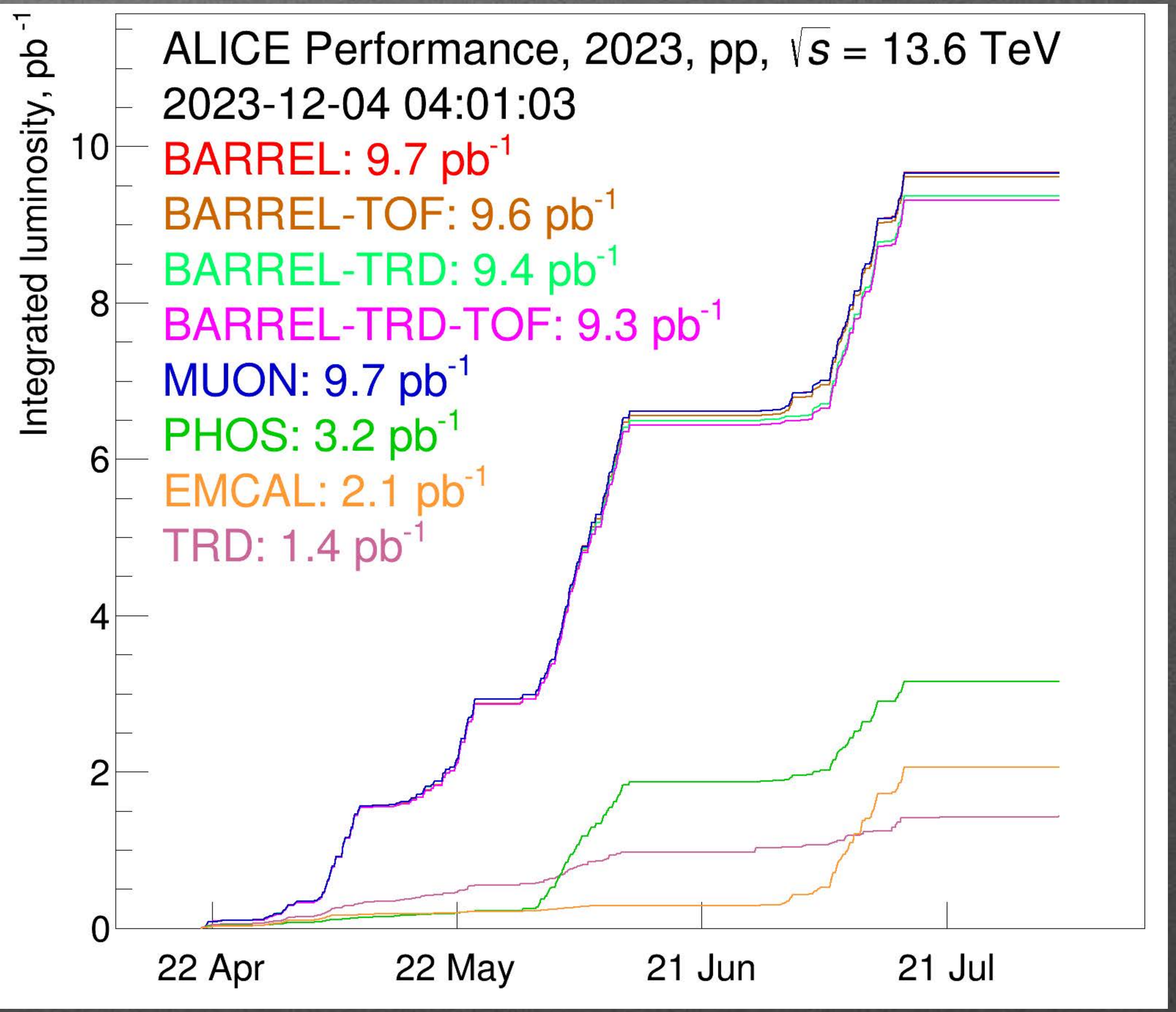

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Asynchronous reconstruction pass over the full data → Event tagging according to software triggers → CTF skimming → Asynchronous reconstruction of the skimmed CTFs

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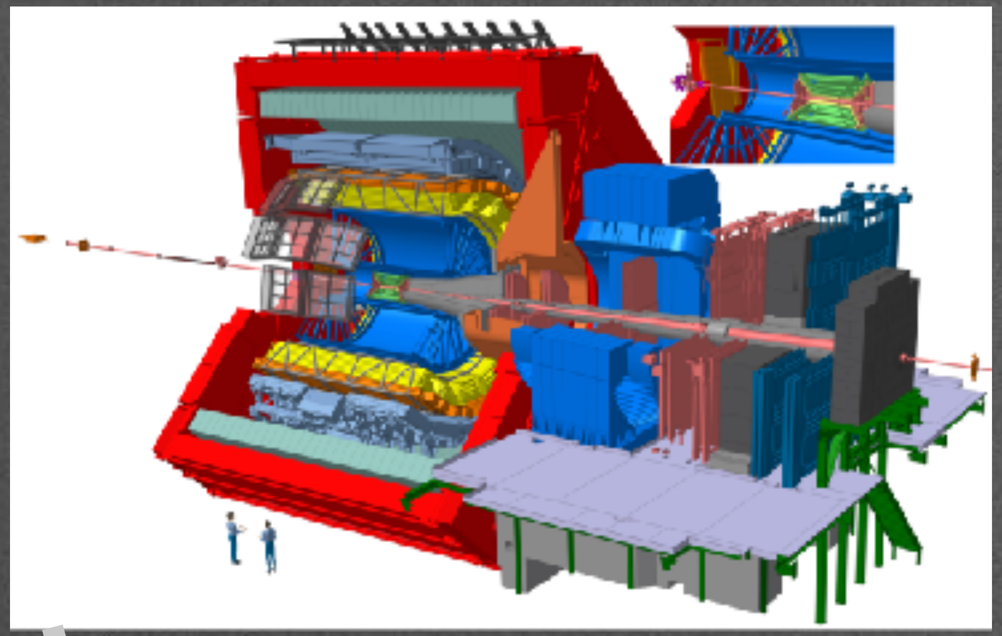

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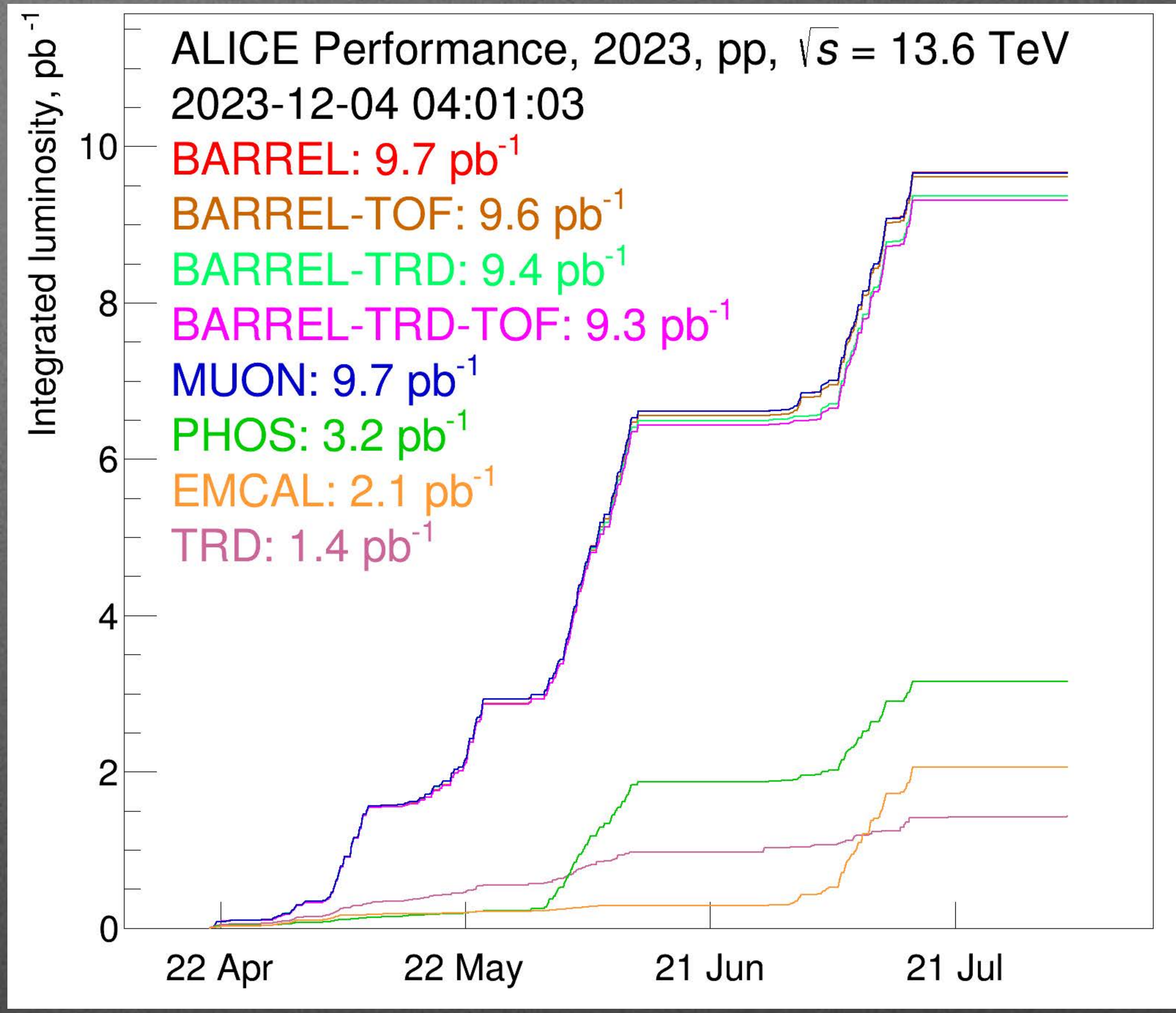

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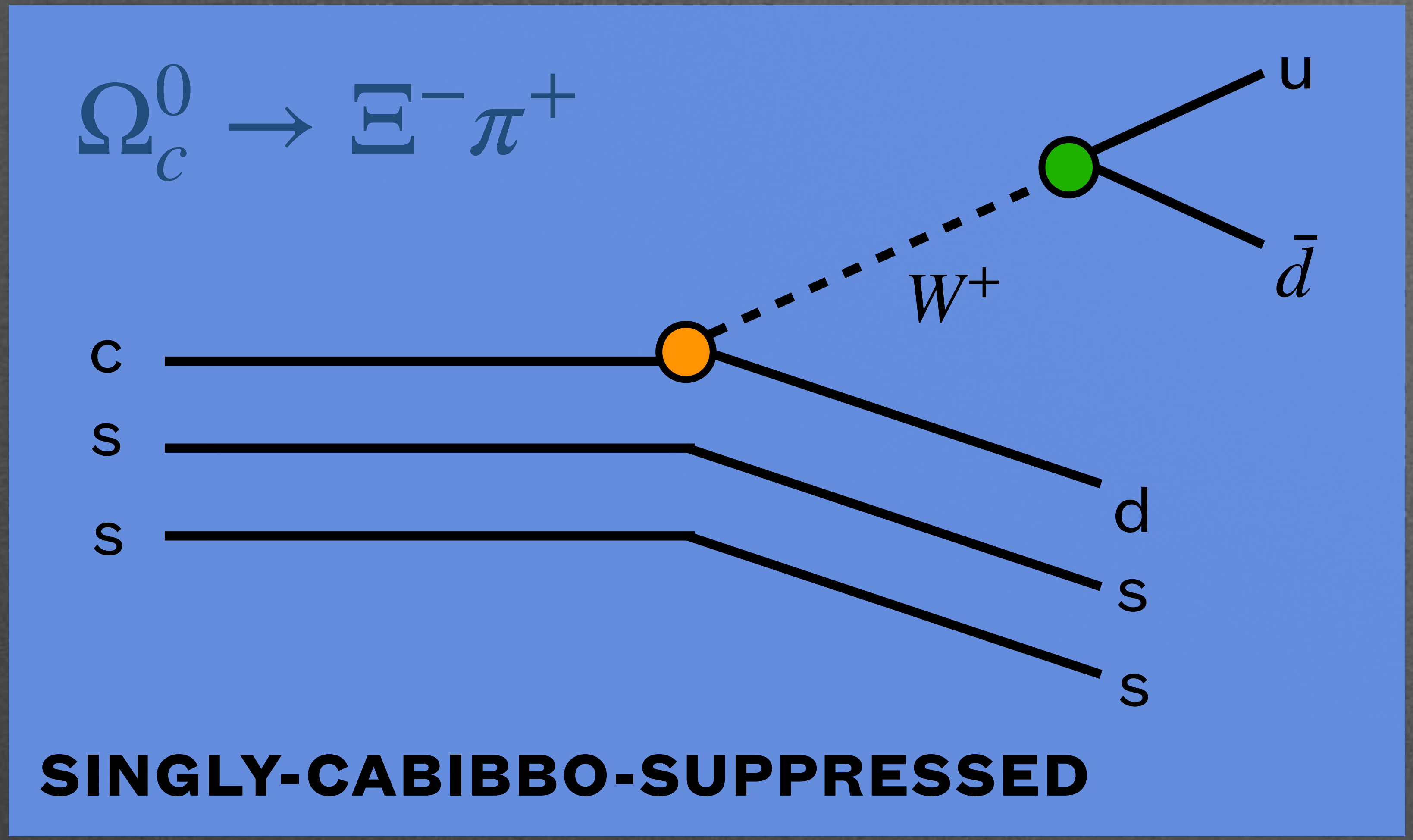
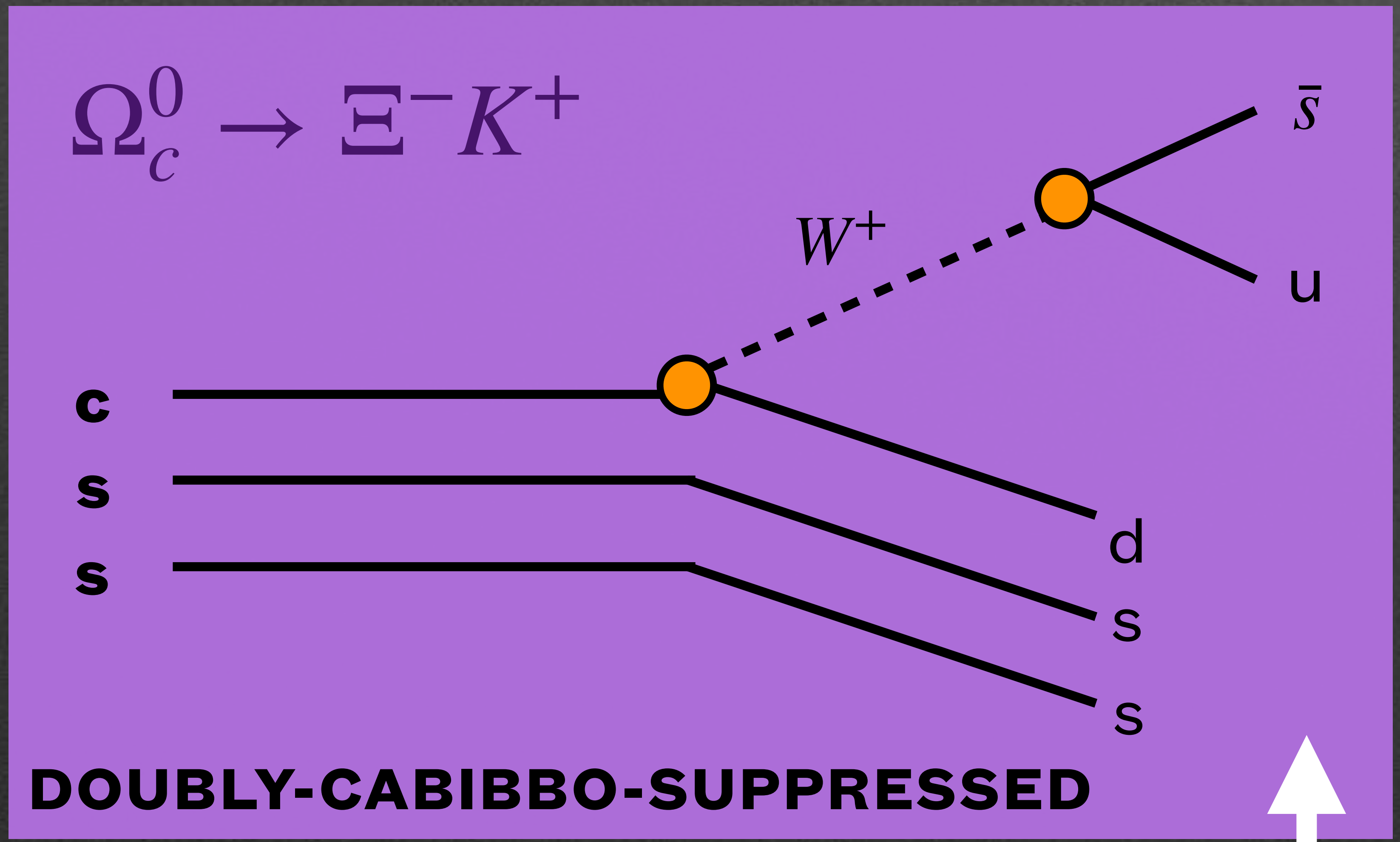
PWG 2023 rejection factor budget: $5.5 \cdot 10^{-5}$

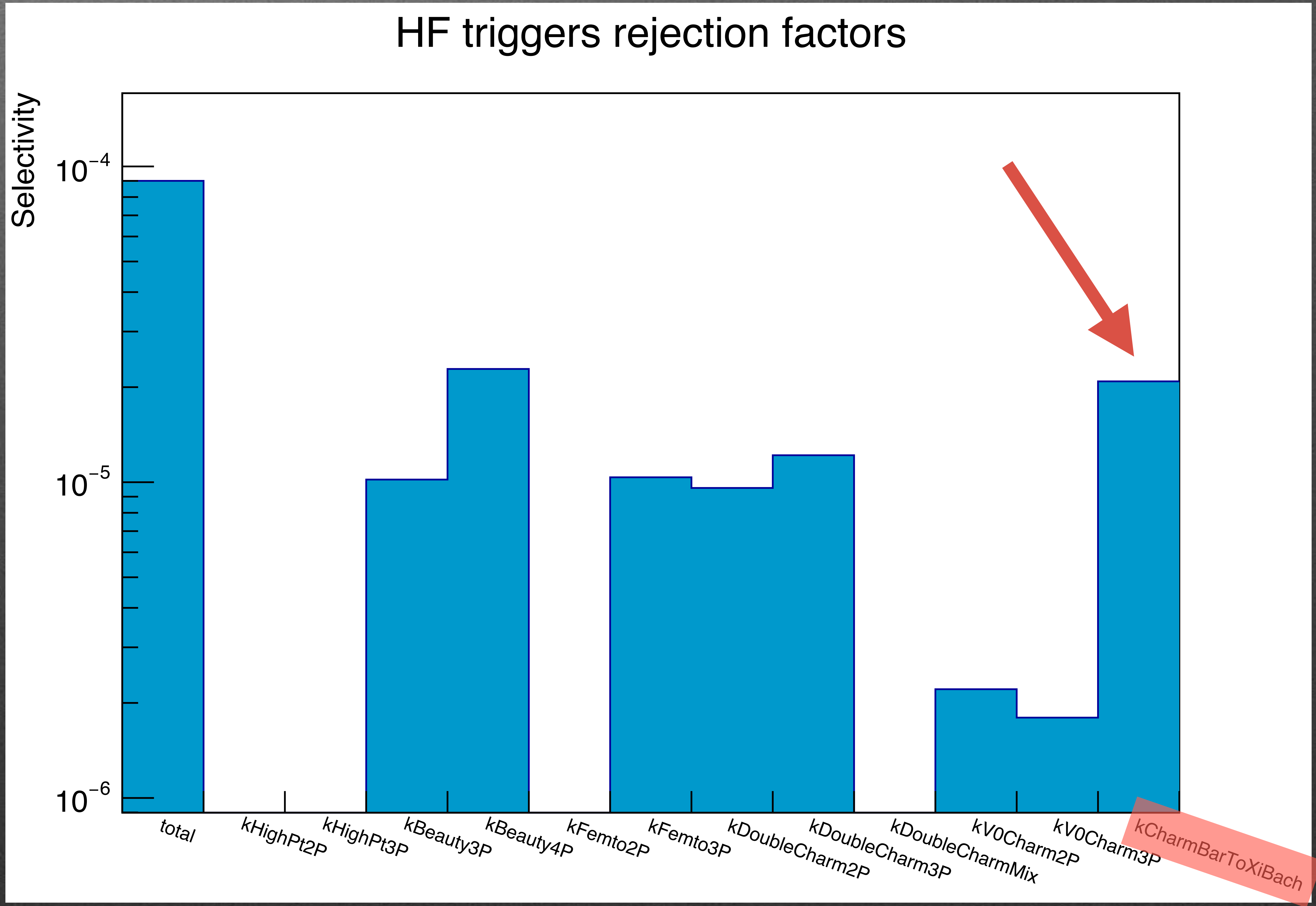
Ω_c^0 dedicated offline software trigger





NEW MEASUREMENT!

The algorithm loops over the cascades produced in each collisions combining them with tracks and tags pairs fulfilling a set of kinematic and topological selections with suitable invariant mass



HF filters selectivity on 2023 data (downscale factors not shown)

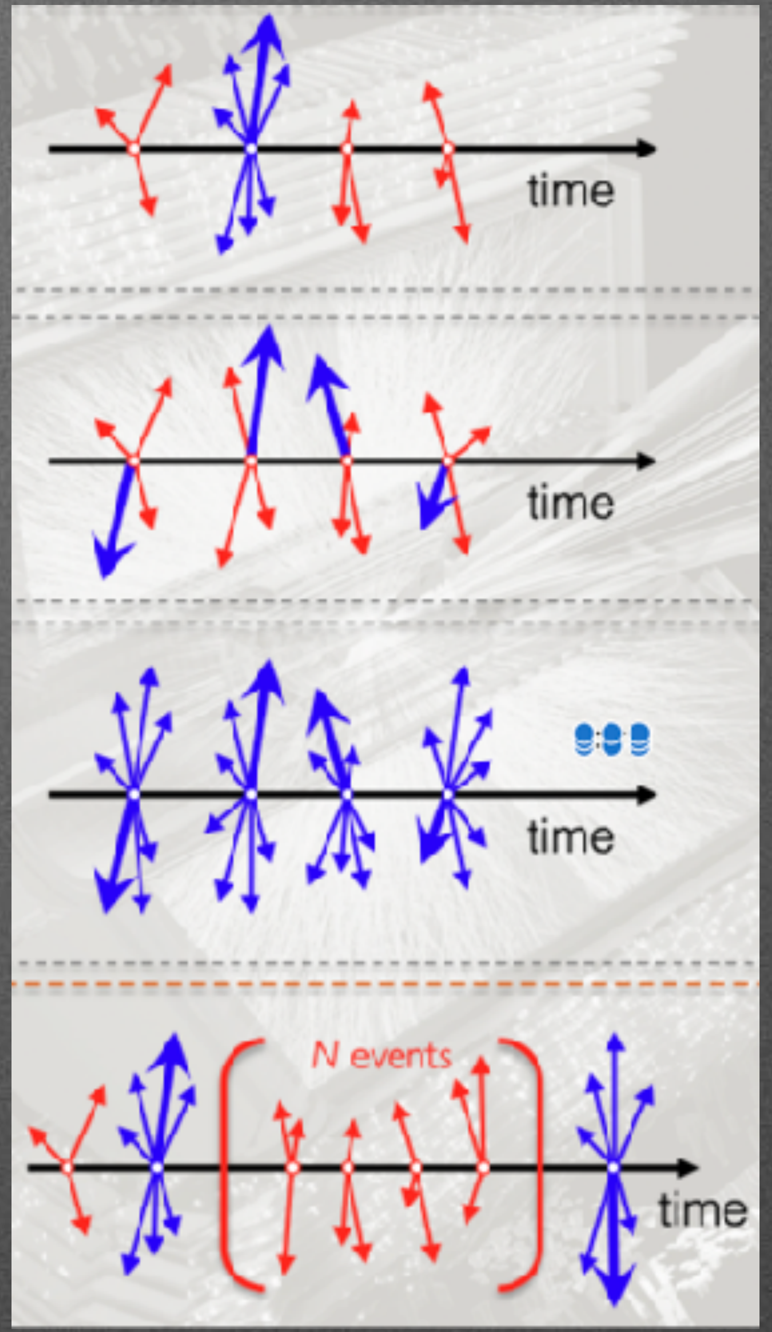
Monte Carlo studies for charm enriched productions

In Run 3, ALICE takes data in continuous mode

↓

we need a MC simulation that realistically describes the data taking conditions

- Different types of MC available: injected, triggered, gap triggered
- Gap triggered MC is the most realistic version
- The gap is needed because the presence of charm affects (worsens) the event reconstruction → increasing the number of MB events mitigates the this problem, helping to recover heavy flavour particles ϵ_{RECO} and improving PV reconstruction



Example: MB event, Ξ

Standard (general purpose MC)

Injected

Triggered

Gap-triggered

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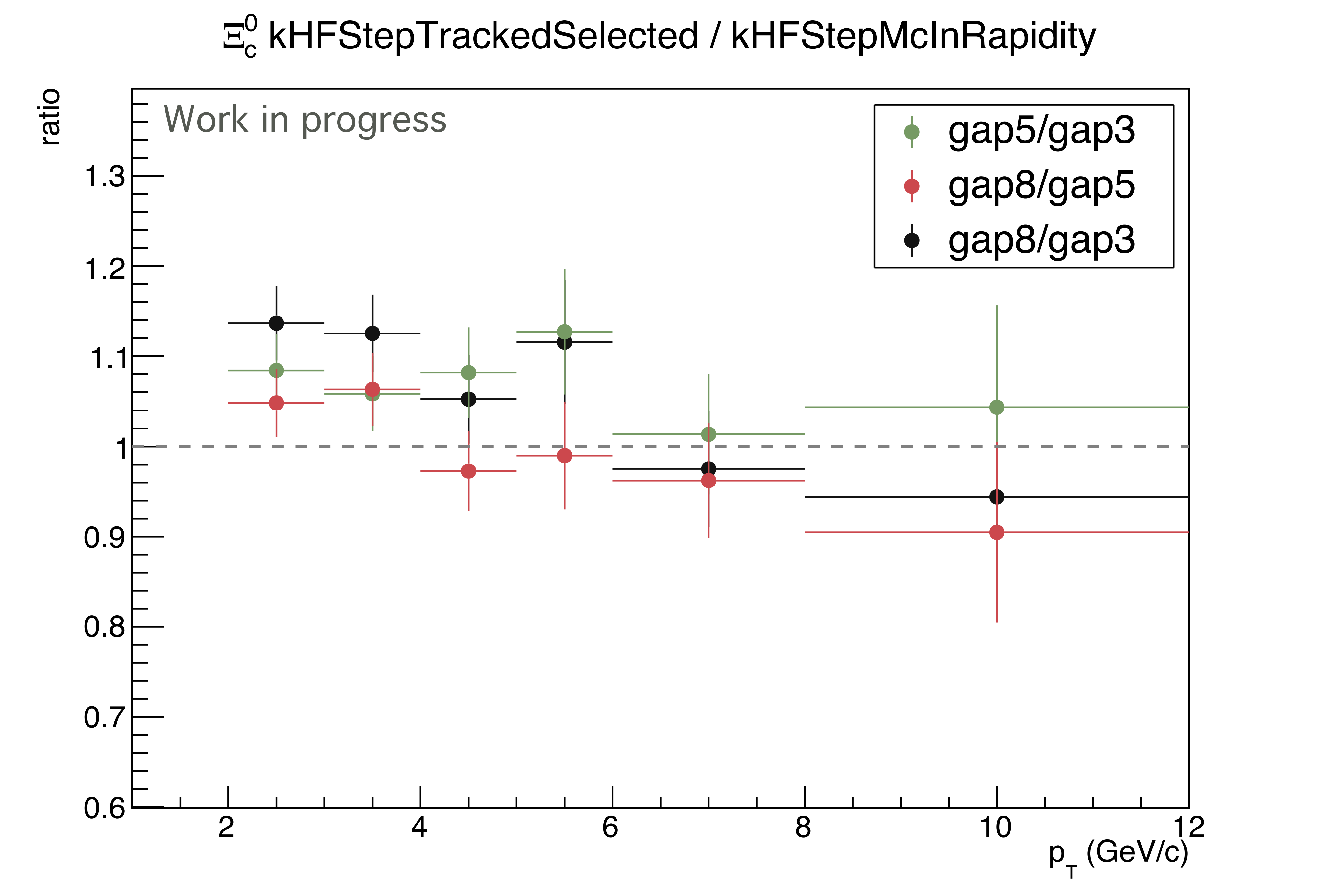

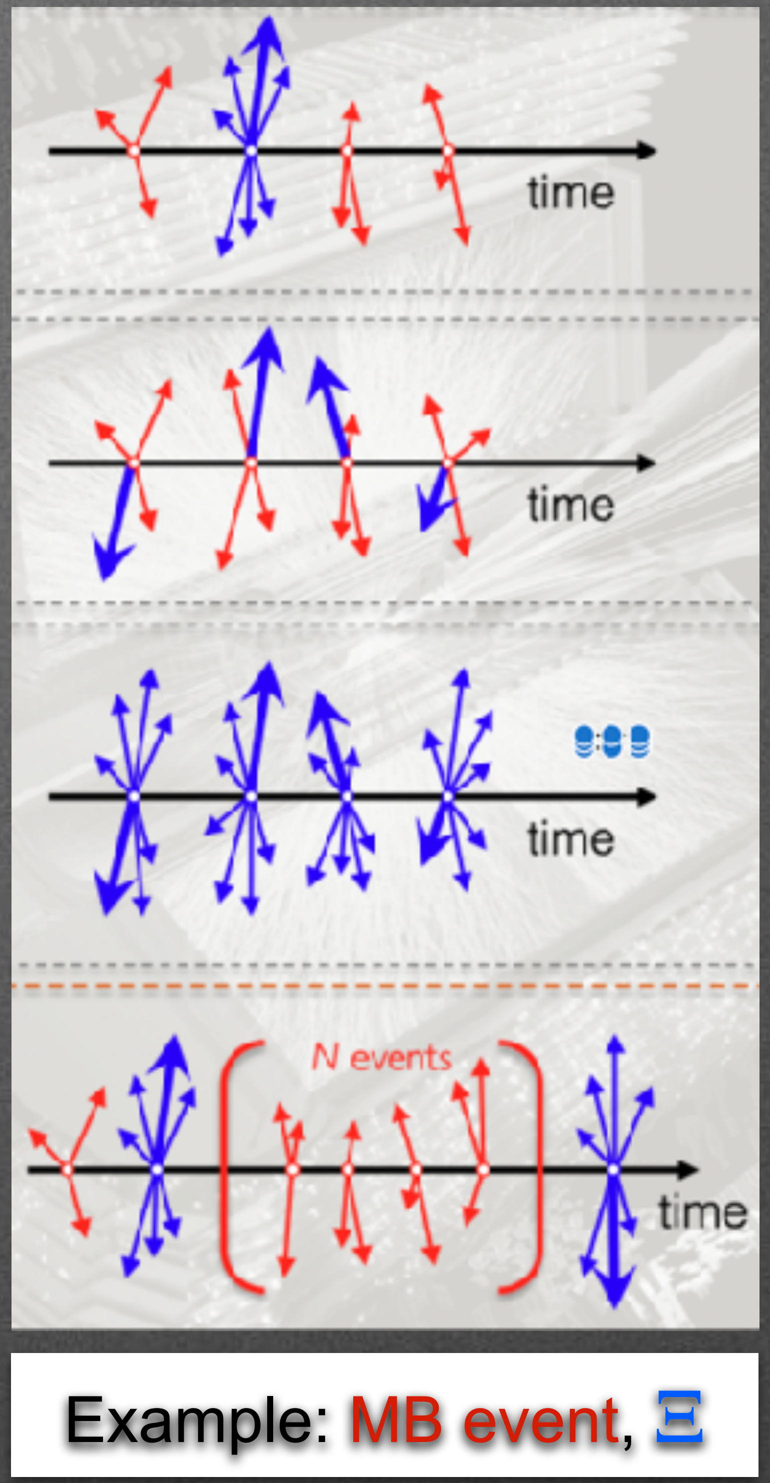

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Triggered

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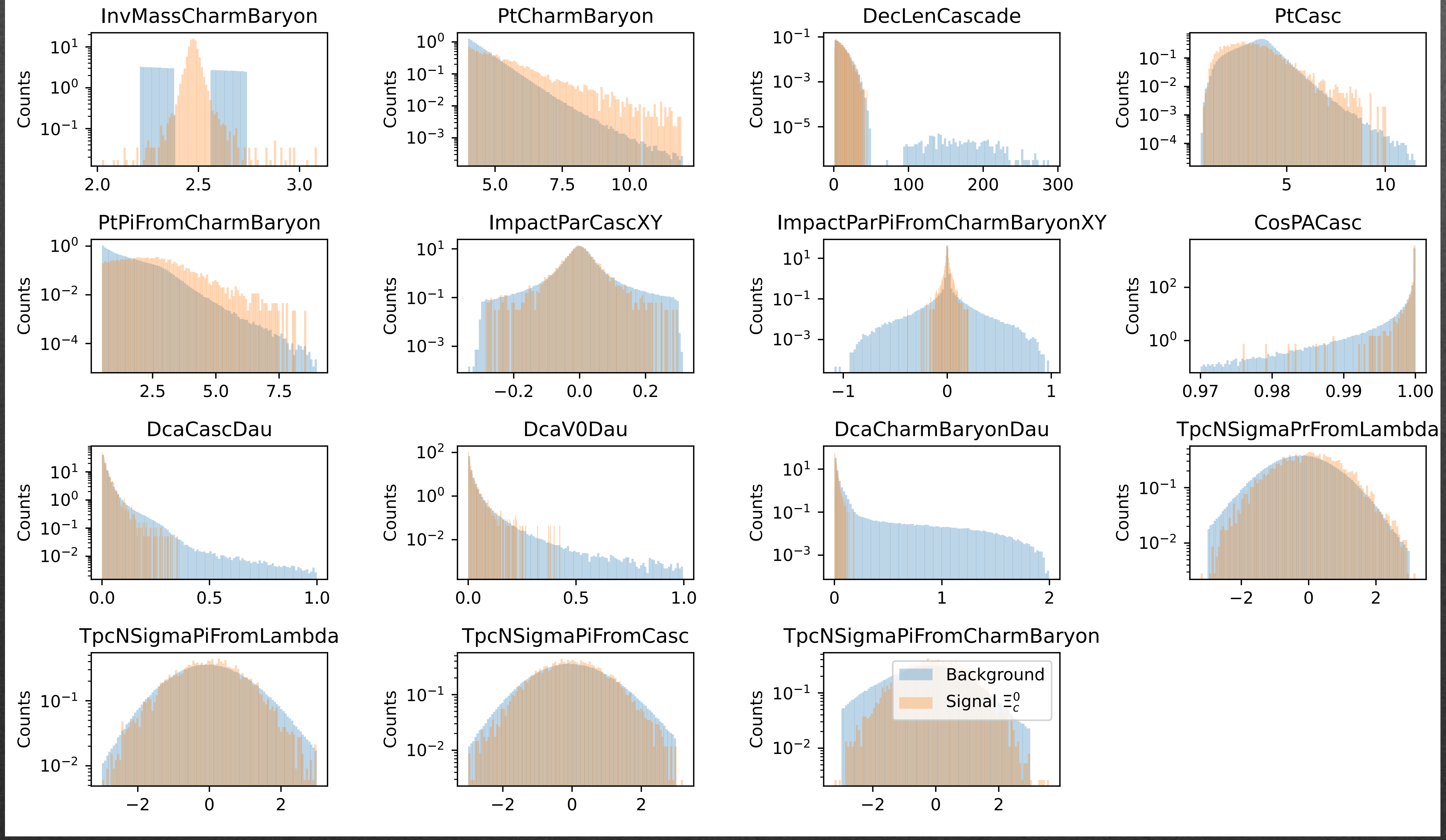
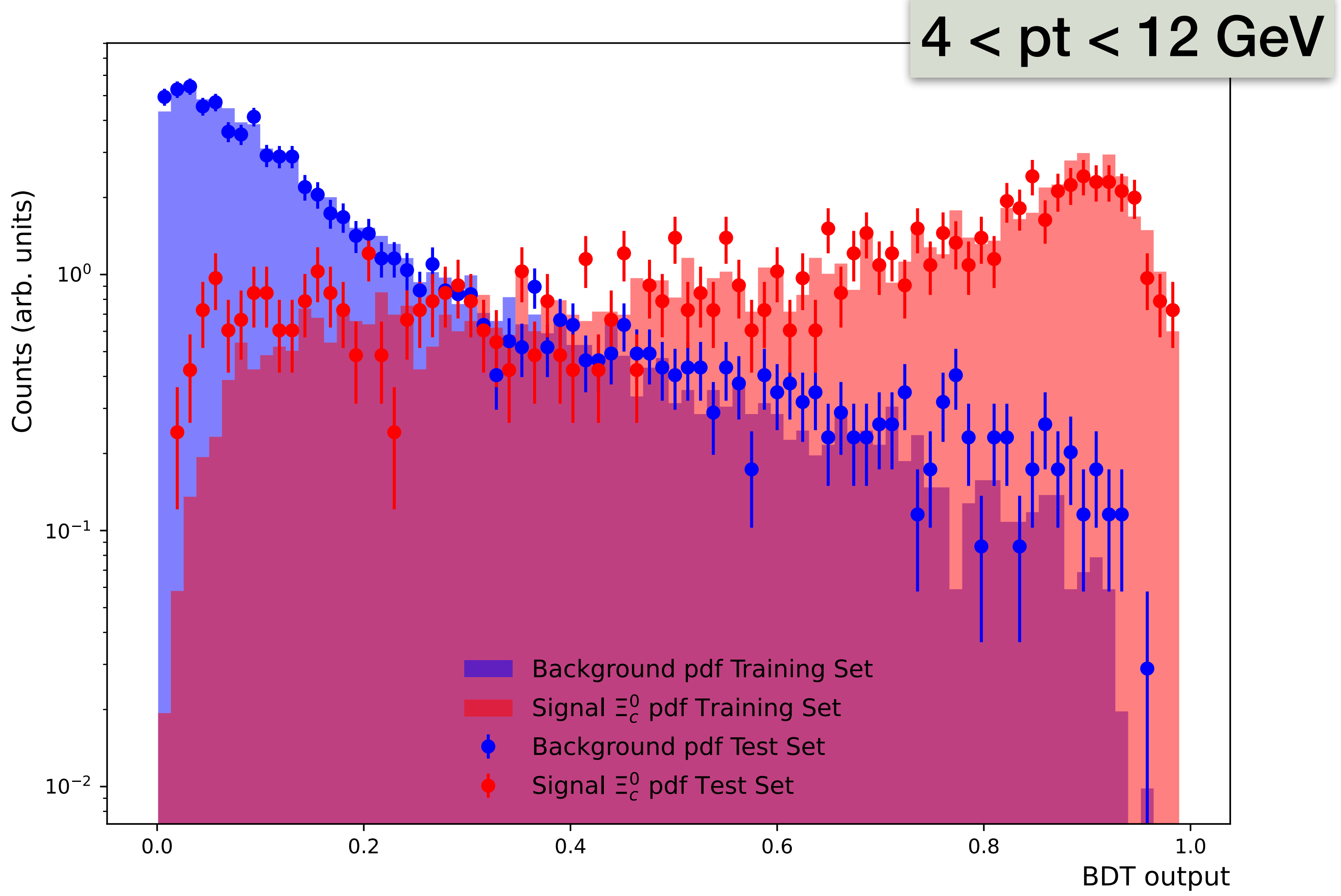
Make efficient and reasonable use of resources minimising the loss in ϵ_{RECO} → gap 5 configuration

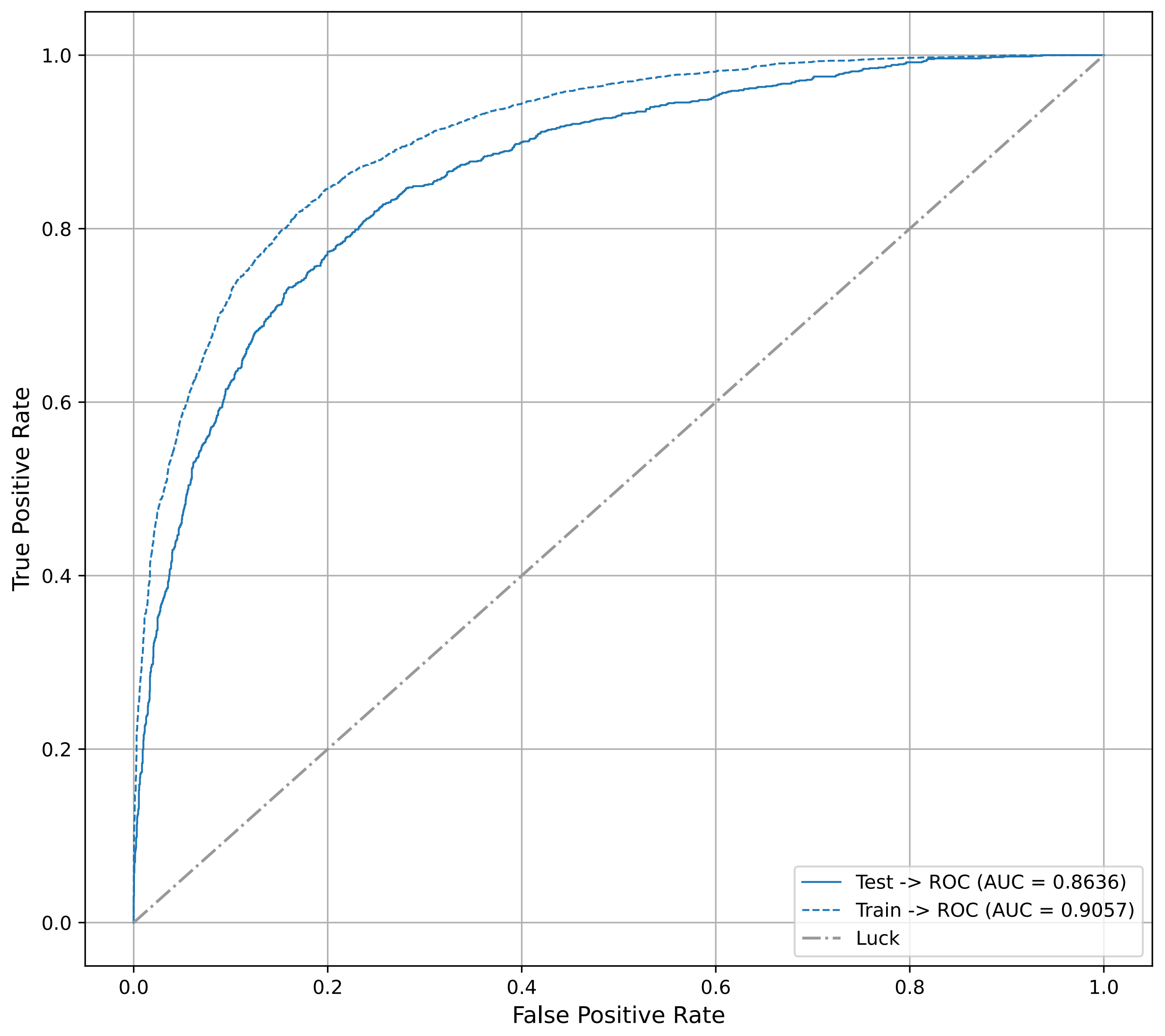
First results - Ξ_c^0 signal extraction and machine learning

- Boosted Decision Trees are applied to improve the signal extraction for rare charm baryons
- The ML algorithm applies a set of consecutive rectangular cuts exploiting correlations in training features space to optimise the separation between signal and background
- Hyperparameters are optimised with Bayesian iterations
- For training purposes, signal candidates are taken from MC and background candidates from data



Work in progress





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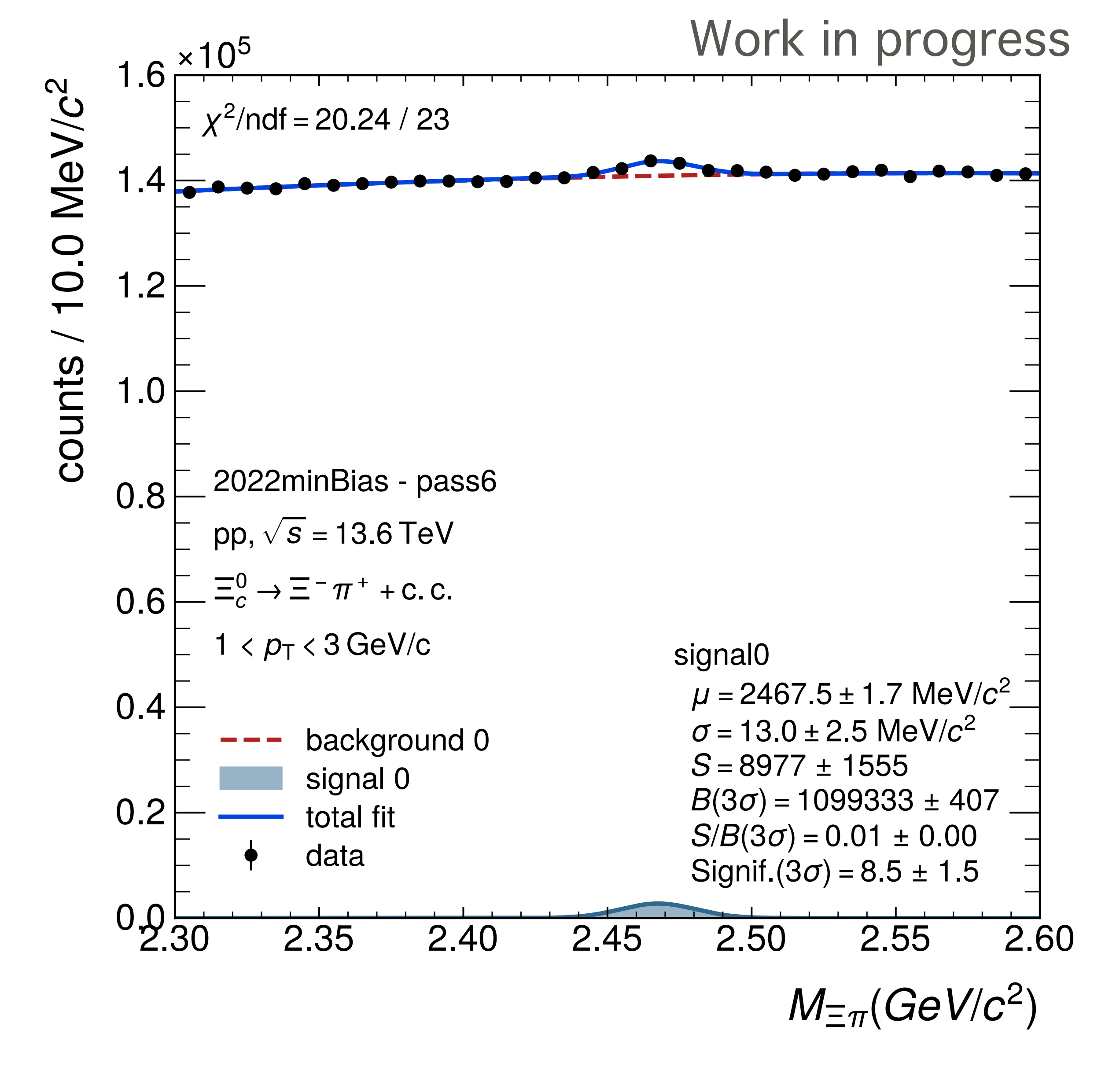
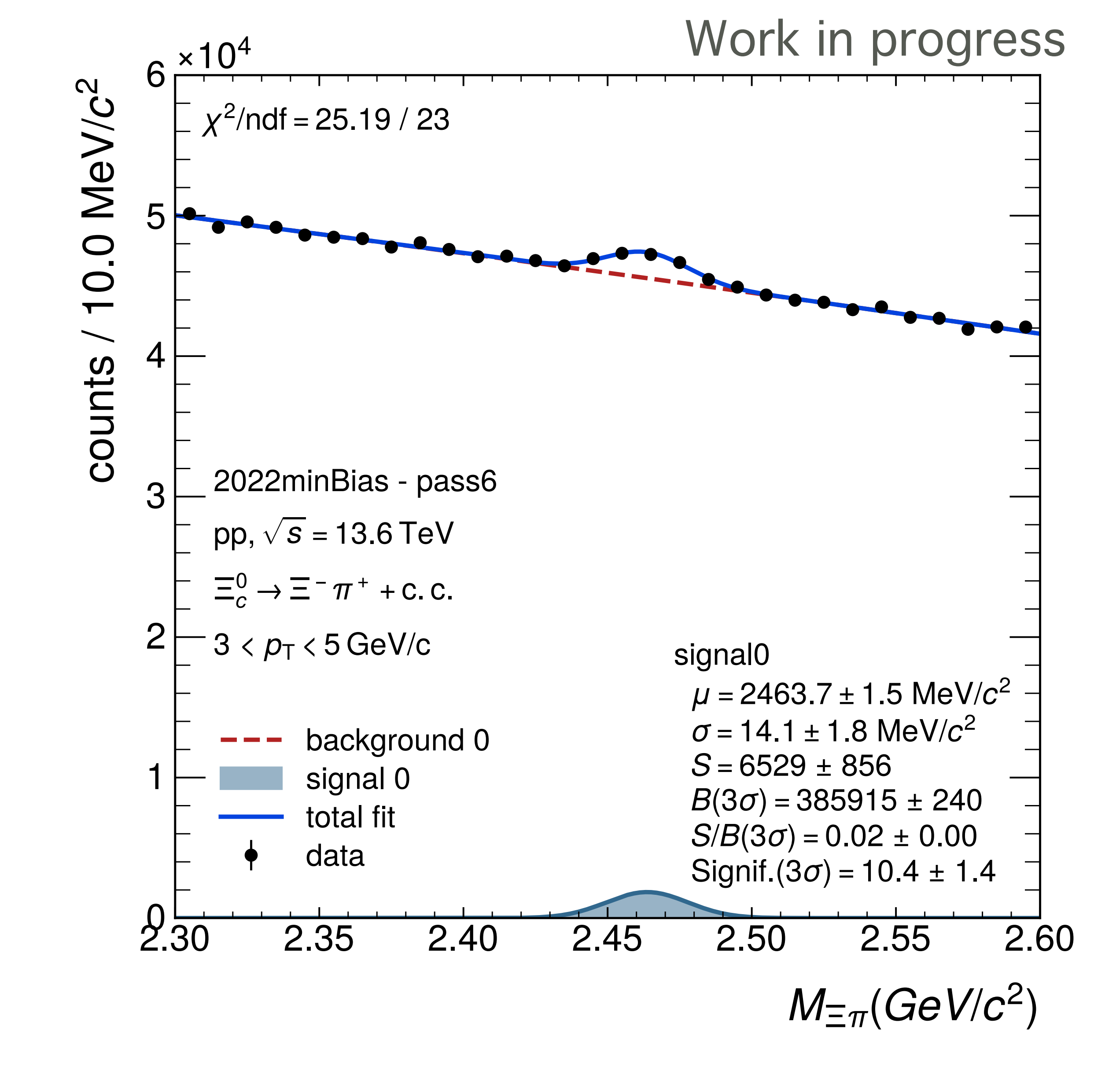
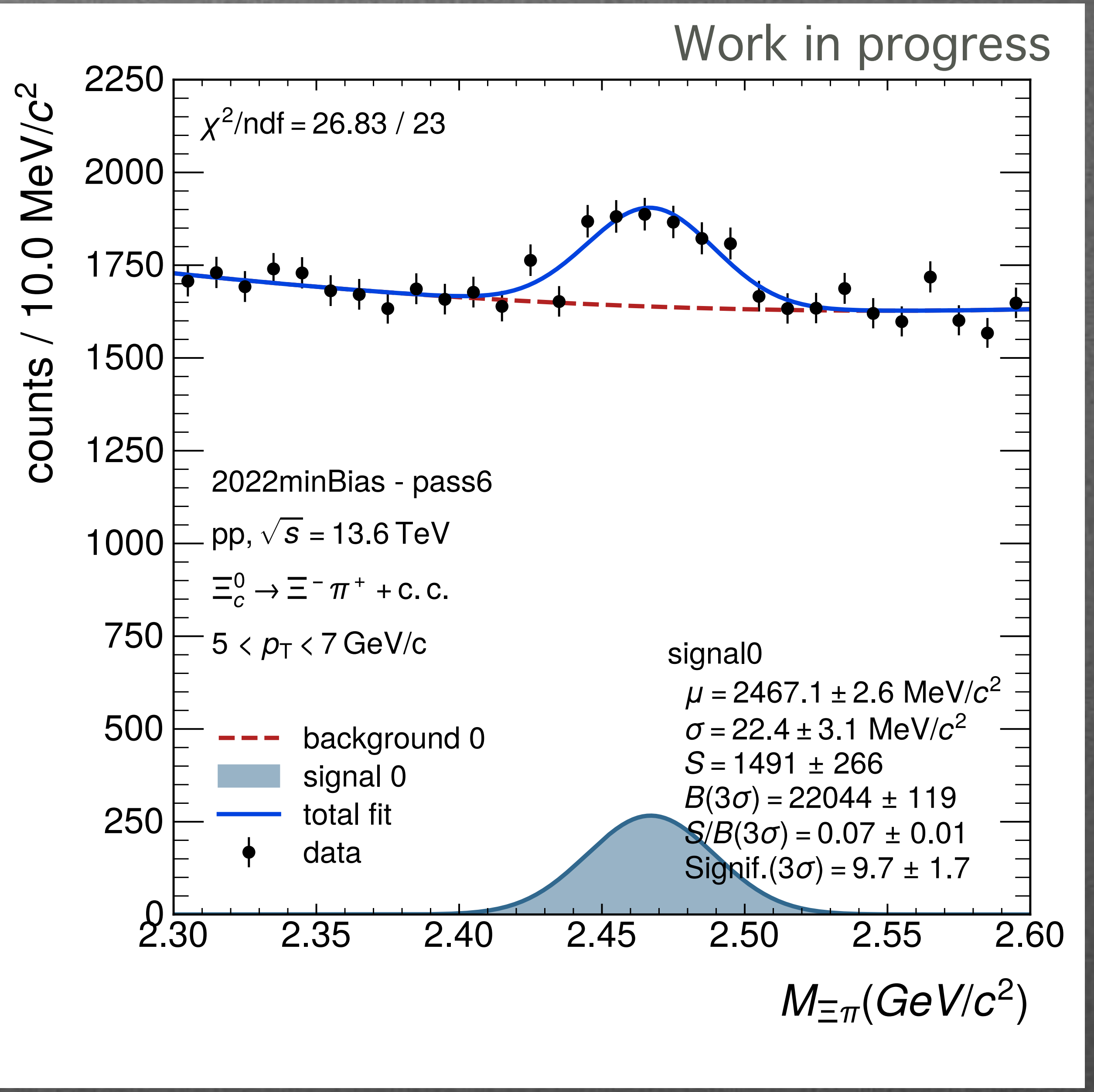
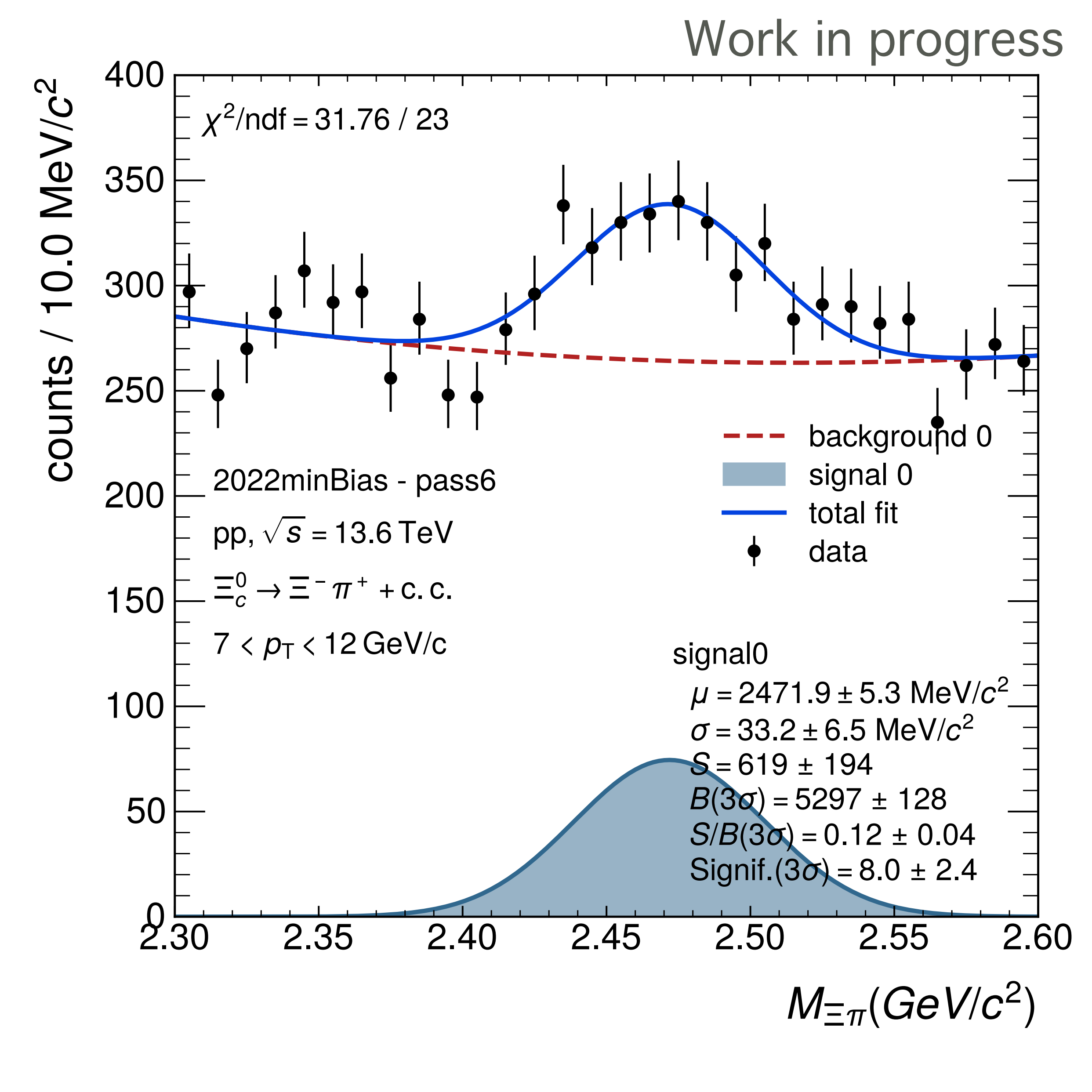








- Derived dataset for 2022 minimum bias sample
- ~60B events processed ($\sim 1\, pb^{-1}$)
- More than $1.7 \cdot 10^4$ Ξ_c^0 extracted
- Run 2 performance not yet reached

Conclusions

- With an upgraded detector system and software framework, ALICE is collecting and processing an enormous amount of data in Run 3
- Rare strange charm baryon analyses strongly benefit from the availability of such large statistics
- Ω_c^0 dedicated software trigger is applied for event skimming
- New MC simulation strategies for charm enriched productions have been tested
- First results for Ξ_c^0 signal extraction with BDT application

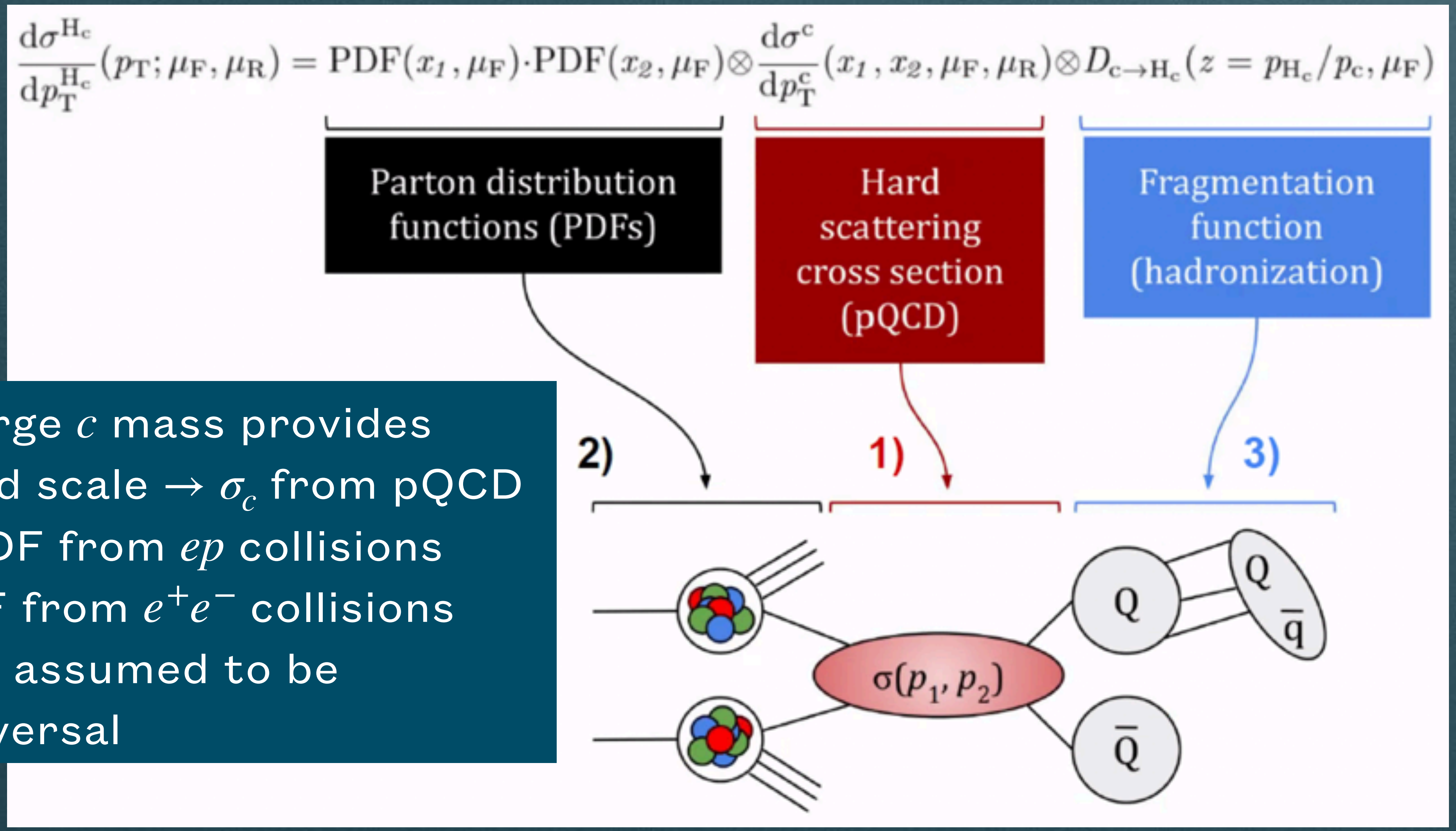
... NEXT

- Analyse larger dataset (2023 p-p sample, $\sim 10\ pb^{-1}$)
- Refine Ξ_c^0 p_{T} spectrum measurement in the $\Xi\,\pi$ decay channel
- Extract Ω_c^0 signal in the $\Xi\,\pi$ decay channel to provide the hadron-to-hadron production ratio wrt Ξ_c^0 and the BR fraction measurement wrt the Cabibbo-favored decay channel

BACKUP

Heavy flavour measurements

HADRONIZATION



- large c mass provides hard scale → σ_c from pQCD
- PDF from ep collisions
- FF from e^+e^- collisions and assumed to be universal

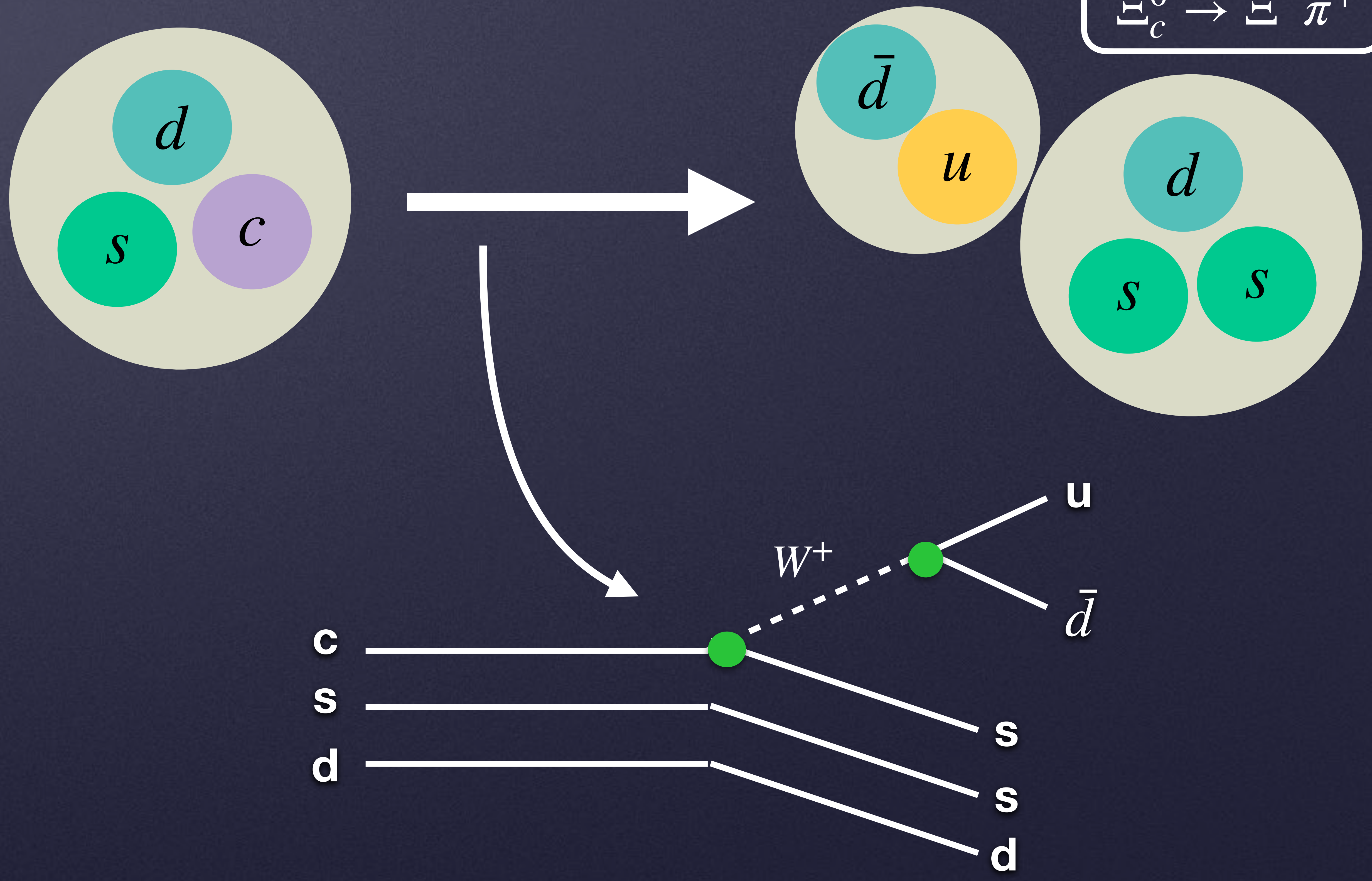
Hadronization mechanisms are still poorly understood and the hypothesis of universality of fragmentation functions has been disproved

↓

Measurements of charm hadron-to-hadron production ratios are an effective tool to study hadronization as al the other contributions cancel out

BRANCHING RATIOS

$\Xi_c^0 \to \Xi^- \pi^+$



The presence of the surrounding nuclear environment makes it challenging to compute branching ratios, especially for decays with spin rearrangement processes

↓

New measurements will help to validate the models

Belle and LHCb Ω_c^0 BR measurements

BELLE

- BELLE measurement from 2023 (paper)
- $\mathscr{L}_{int} \sim 980\ \mathrm{fb}^{-1}$ in e^+e^- collisions
- Results:
  - Evidence for Ω_c^0 signal in $\Omega_c^0 \to \Xi^-\pi^+$ mode with significance 4.5σ
  - No significant signals of $\Omega_c^0 \to \Xi^-K^+$ and $\Omega_c^0 \to \Omega^-K^+$ found
  - $BR(\Omega_c^0 \to \Xi^-\pi^+)/BR(\Omega_c^0 \to \Omega^-\pi^+) = 0.253 \pm 0.052\ (\mathrm{stat.}) \pm 0.030\ (\mathrm{syst.})$
  - $BR(\Omega_c^0 \to \Xi^-K^+)/BR(\Omega_c^0 \to \Omega^-\pi^+) < 0.070$
  - $BR(\Omega_c^0 \to \Omega^-K^+)/BR(\Omega_c^0 \to \Omega^-\pi^+) < 0.29$

- Measured yield:
  - $\Omega_c^0 \to \Xi^-\pi^+ \ \to\ 208 \pm 41\ (\mathrm{stat.})$ with $\epsilon_{reco_{\Xi\pi}} = 10.7\ \%$
    $\to$ corrected yield $N_{\Omega_c^0 \to \Xi\pi} \sim 2200$
  - $\Omega_c^0 \to \Xi^-K^+ \ \to\ -47 \pm 23\ (\mathrm{stat.})$
  - $\Omega_c^0 \to \Omega^-K^+ \ \to\ 41 \pm 17\ (\mathrm{stat.})$
  - $\Omega_c^0 \to \Omega^-\pi^+ \ \to\ 606 \pm 29\ (\mathrm{stat.})$

LHCb

- LHCB measurement from 2023 (paper)
- $\mathscr{L}_{int} \sim 5.4\ \mathrm{fb}^{-1}$ in pp collisions
- Results:

$$\frac{BR(\Omega_c^0 \to \Omega^-K^+)}{BR(\Omega_c^0 \to \Omega^-\pi^+)} = 0.0608 \pm 0.0051\ (\mathrm{stat}) \pm 0.0040\ (\mathrm{syst})$$

$$\frac{BR(\Omega_c^0 \to \Xi^-\pi^+)}{BR(\Omega_c^0 \to \Omega^-\pi^+)} = 0.1581 \pm 0.0087\ (\mathrm{stat}) \pm 0.0043\ (\mathrm{syst}) \pm 0.0015\ (\mathrm{ext})$$

- Measured yield:
  - $\Omega_c^0 \to \Omega^-\pi^+ \ \to\ 9330 \pm 110$
  - $\Omega_c^0 \to \Xi^-\pi^+ \ \to\ 2780 \pm 150$
  - $\Omega_c^0 \to \Omega^-K^+ \ \to\ 425 \pm 35$

$M(\Omega_c^0) = 2695.28 \pm 0.07\ (\mathrm{stat}) \pm 0.27\ (\mathrm{syst}) \pm 0.30\ (\mathrm{ext})\ \mathrm{MeV}/c^2$ using the Cabibbo-favored $\Omega_c^0 \to \Omega\pi$ decay channel

Derived data

	AliEn	O2
CPU time:	80d 10h	75d 18h
Wall time:	1y 34d	1y 32d
Throughput:	482.4 KB/s/core	484.6 KB/s/core
CPU efficiency:	20%	19%
Grid overhead:	Startup: 0.1%	Saving: 0.4%
CPU cores:	2	
Output size:	8.9 GB	
Output size (AO2D only):	8.3 GB	
Reduction factor:	1910	

Analysis on parent input file

	AliEn	O2
CPU time:	77d 8h	76d 5h
Wall time:	108d 14h	107d 14h
Throughput:	1.7 MB/s/core	1.7 MB/s/core
CPU efficiency:	71%	71%
Grid overhead:	Startup: 0.1%	Saving: 0.6%
CPU cores:	2	
Output size:	16.4 GB	
Output size (AO2D only):	16.2 GB	
Reduction factor:	980	

Derived data production

	AliEn	O2
CPU time:	90d 4h	88d 14h
Wall time:	111d 13h	111d 5h
Throughput:	1.7 MB/s/core	1.7 MB/s/core
CPU efficiency:	81%	80%
Grid overhead:	Startup: 0%	Saving: 0.2%
CPU cores:	2	
Output size:	8.1 GB	
Output size (AO2D only):	8.0 GB	
Reduction factor:	2	

Analysis on derived data

Resources needed for different configurations of the $\Xi_c^0 \rightarrow \Xi\,\pi$ analysis

- Size of the input file to be directly processed by the analysers consistently reduced
- Derived data is common for all the strange charm baryon analyses
- Increased throughput
- Total processing time reduced

↓

speed up the execution of the analysis

Ω_c^0 dedicated offline software trigger - tuning the selections

The algorithm loops over the cascades produced in each collisions combining them with a tracks and tags pairs fulfilling a set of selections and with suitable invariant mass

Cascade selections

Minimum cascade transverse decay radius	0.6 cm
Minimum V0 transverse decay radius	1.2 cm
Minimum cascade cosPA	0.99
Minimum V0 cosPA	0.99
Maximum DCA cascade daughters	1 cm
Maximum DCA V0 daughters	1 cm
Cascade and V0 daughters $\|\eta\|_{MAX}$	1
Minimum $p_{T\ \pi\leftarrow\Xi}$	0.2 GeV/c
Mass tolerance V0 and cascade	0.01 GeV/c^2
PID nSigma cut V0 and cascade daughters (TPC | TOF)	3σ
Tracks minimum number of TPC clusters	70
Tracks minimum number of TPC crossed rows	70
Tracks minimumTPC crossed rows over findable clusters	0.8
Maximum transverse cascade DCA	0.3 cm
Minimum cascade p_T	2 GeV/c

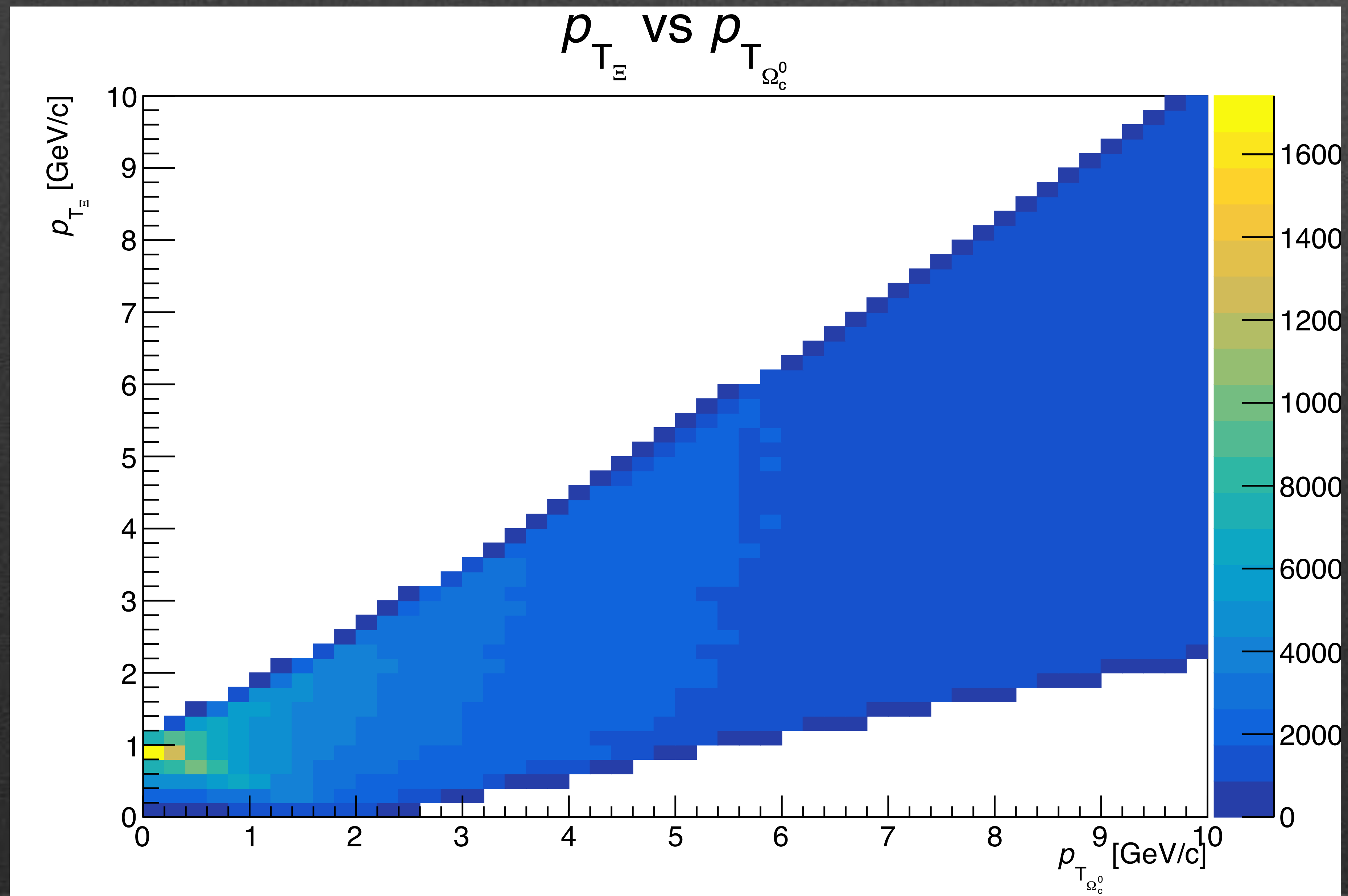
Charm bachelor selections

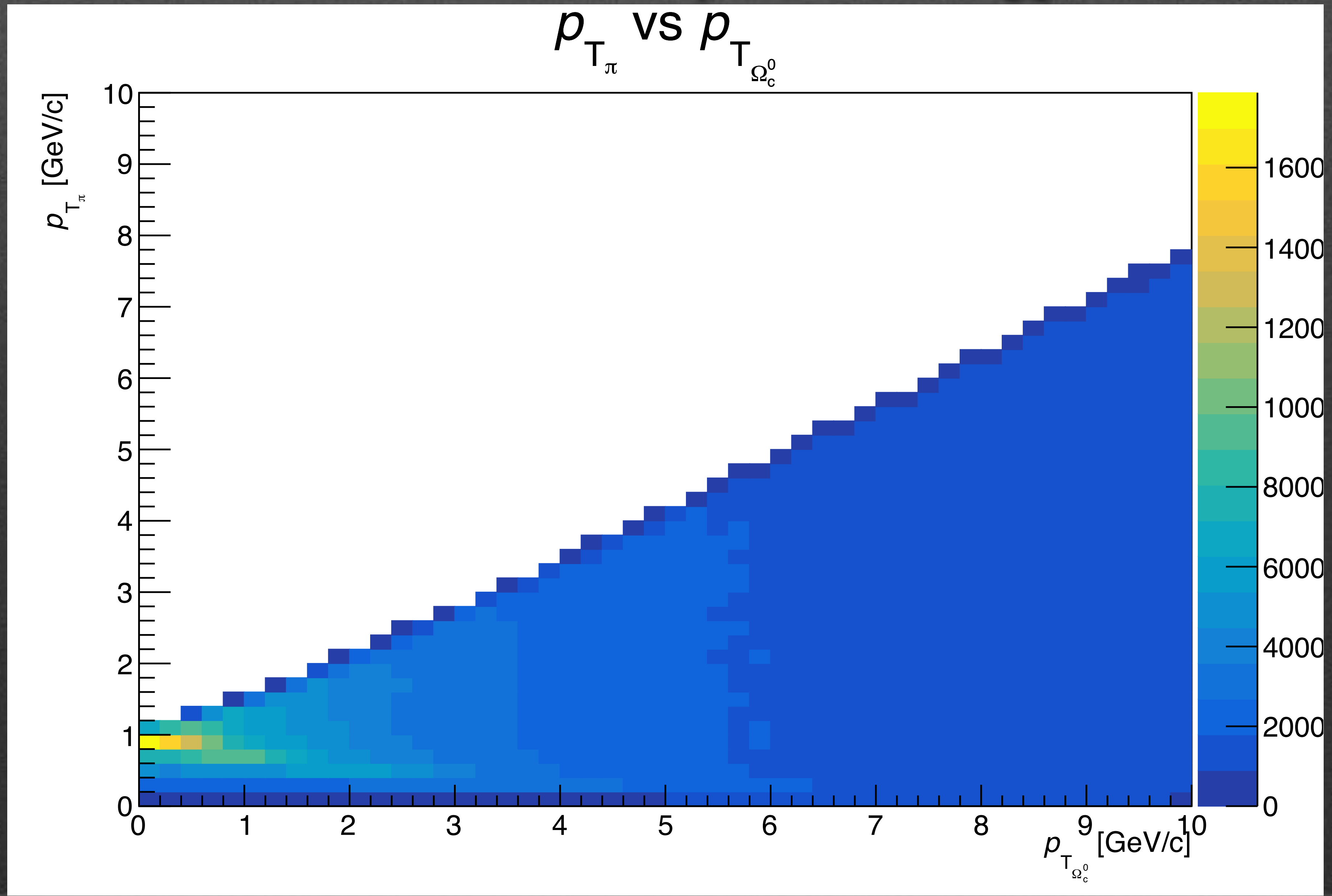
$\|\eta\|_{MAX}$	0.8
$p_{T\ MIN}$	1.2 GeV/c
isGlobalTracksWoDCA	true
PID nSigma cut V0 (TPC | TOF)	3σ
Maximum transverse DCA to PV for $p_T < 2$ GeV/c	0.2 cm
Maximum transverse DCA to PV for $p_T > 2$ GeV/c	10 cm
Tracks minimum number of TPC clusters	70
Tracks minimum number of TPC crossed rows	70
Tracks minimumTPC crossed rows over findable clusters	0.8
Minimum number of ITS clusters	3
Minimum number of ITS inner barrel clusters	1

Event selection

Trigger sel8	True
$\|z_{PV}\|_{MAX}$	11 cm

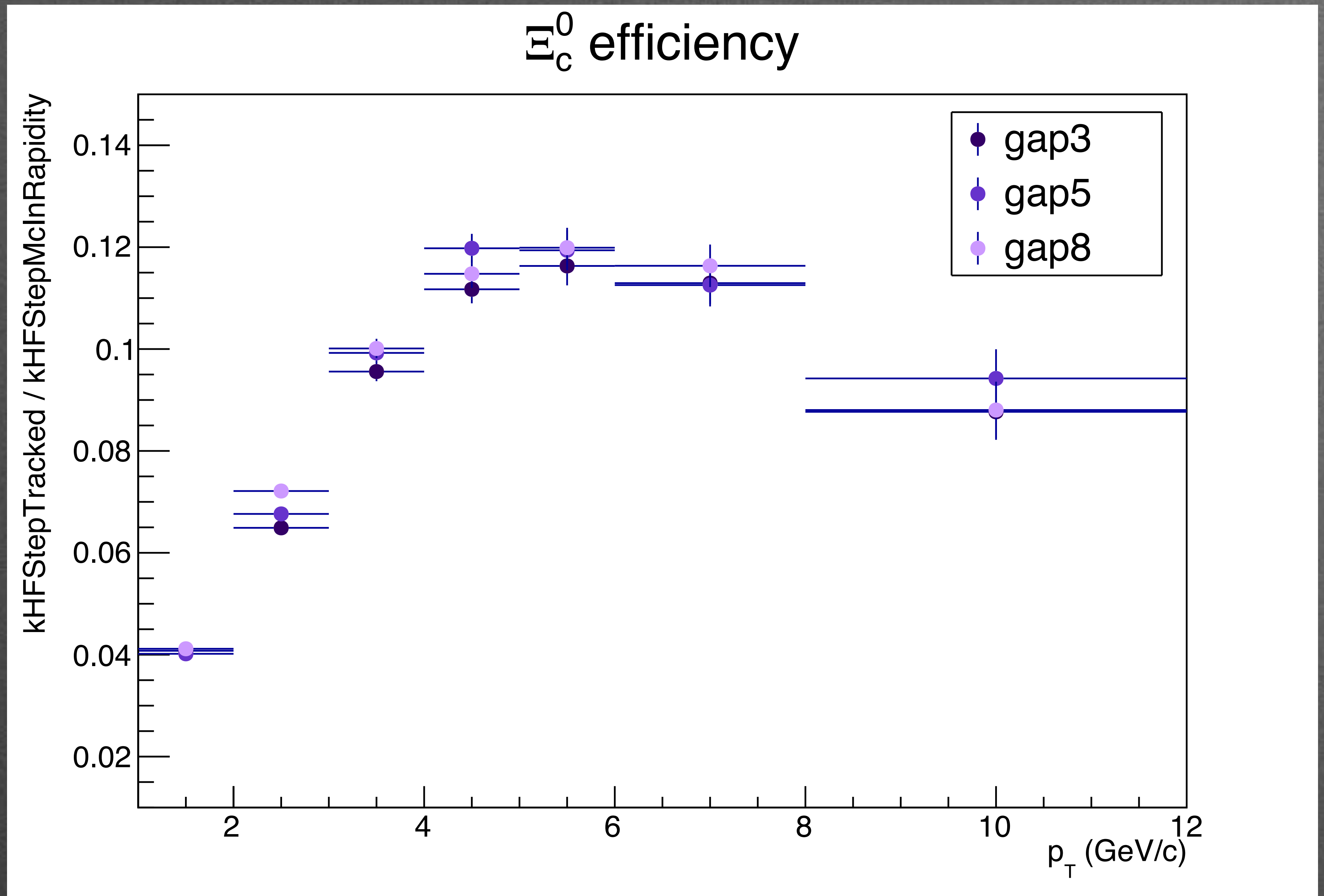
Ω_c^0 dedicated trigger selections for $p_T > 5$ GeV/c - downscale factor 2

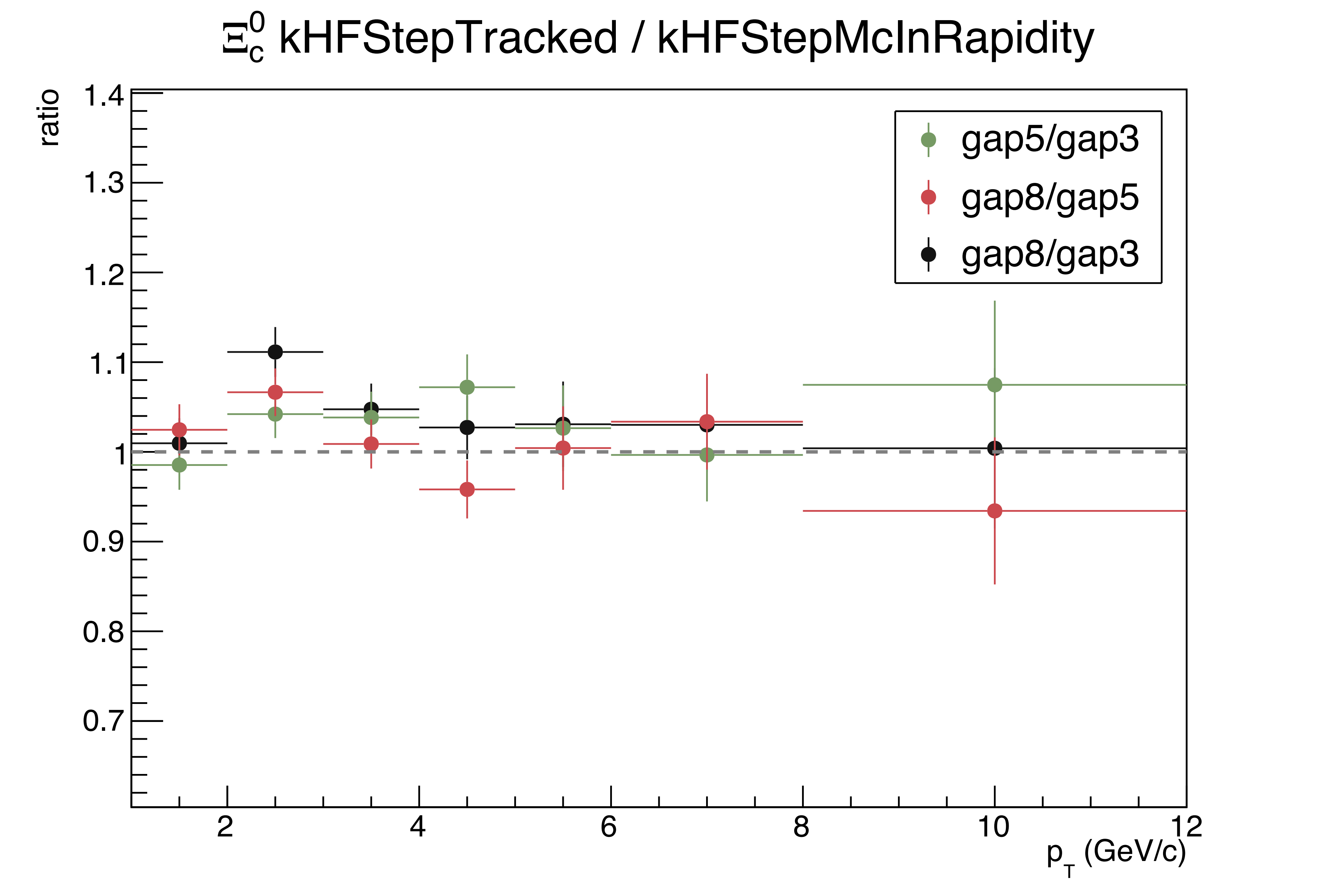


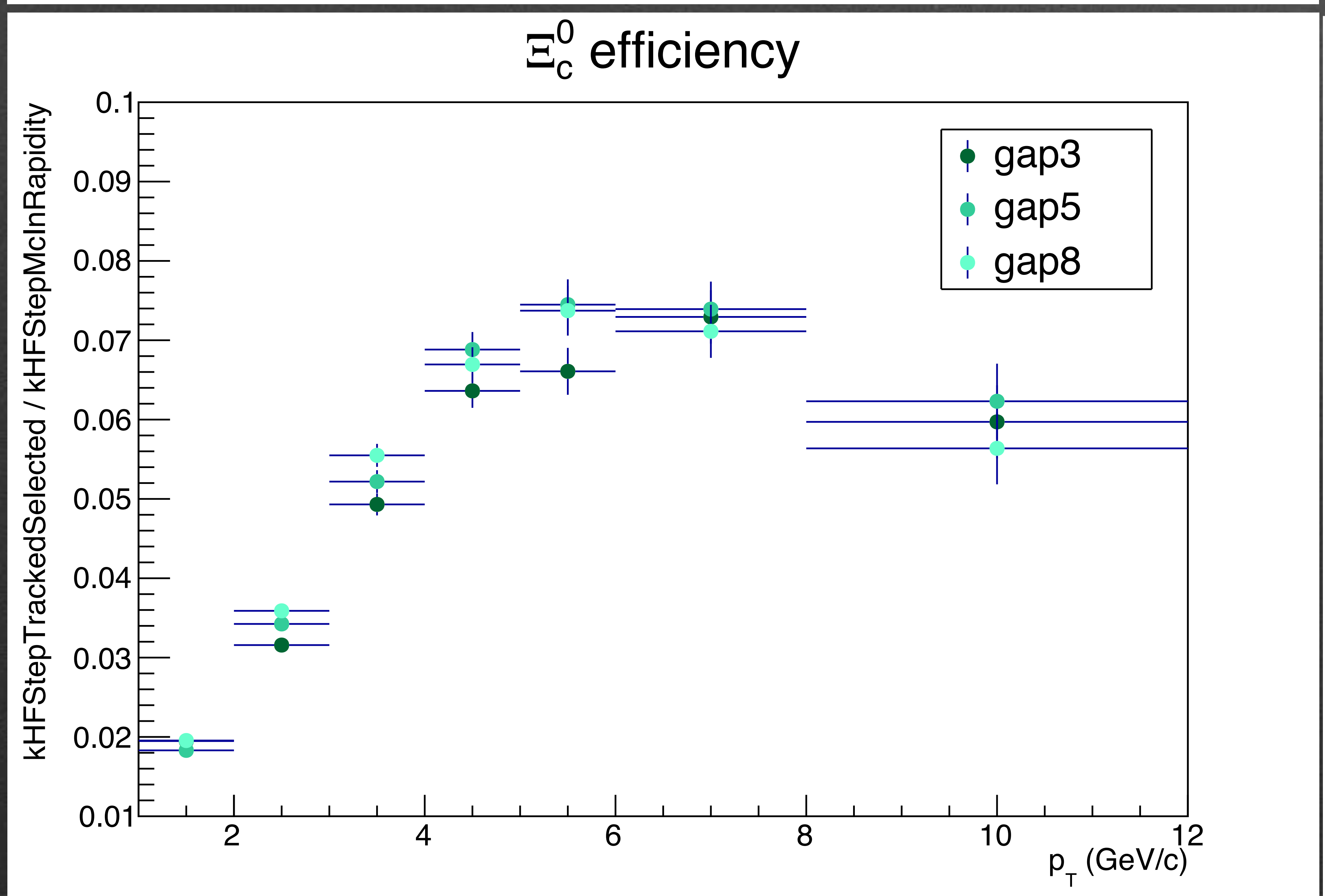


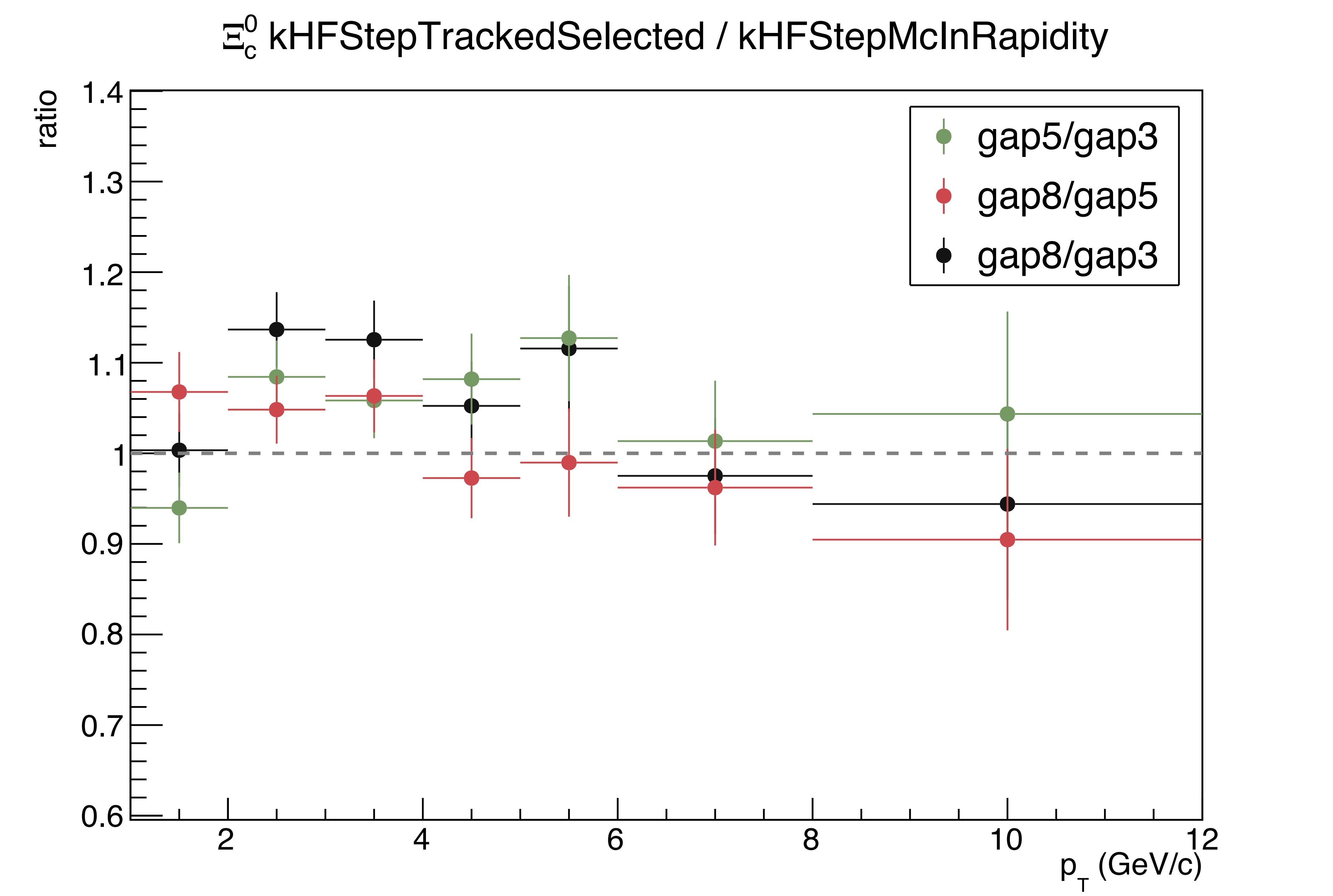
p_T cuts are tuned using a Pythia toy simulation of 10^7 Ω_c^0 decays

Monte Carlo studies for charm baryon enriched productions





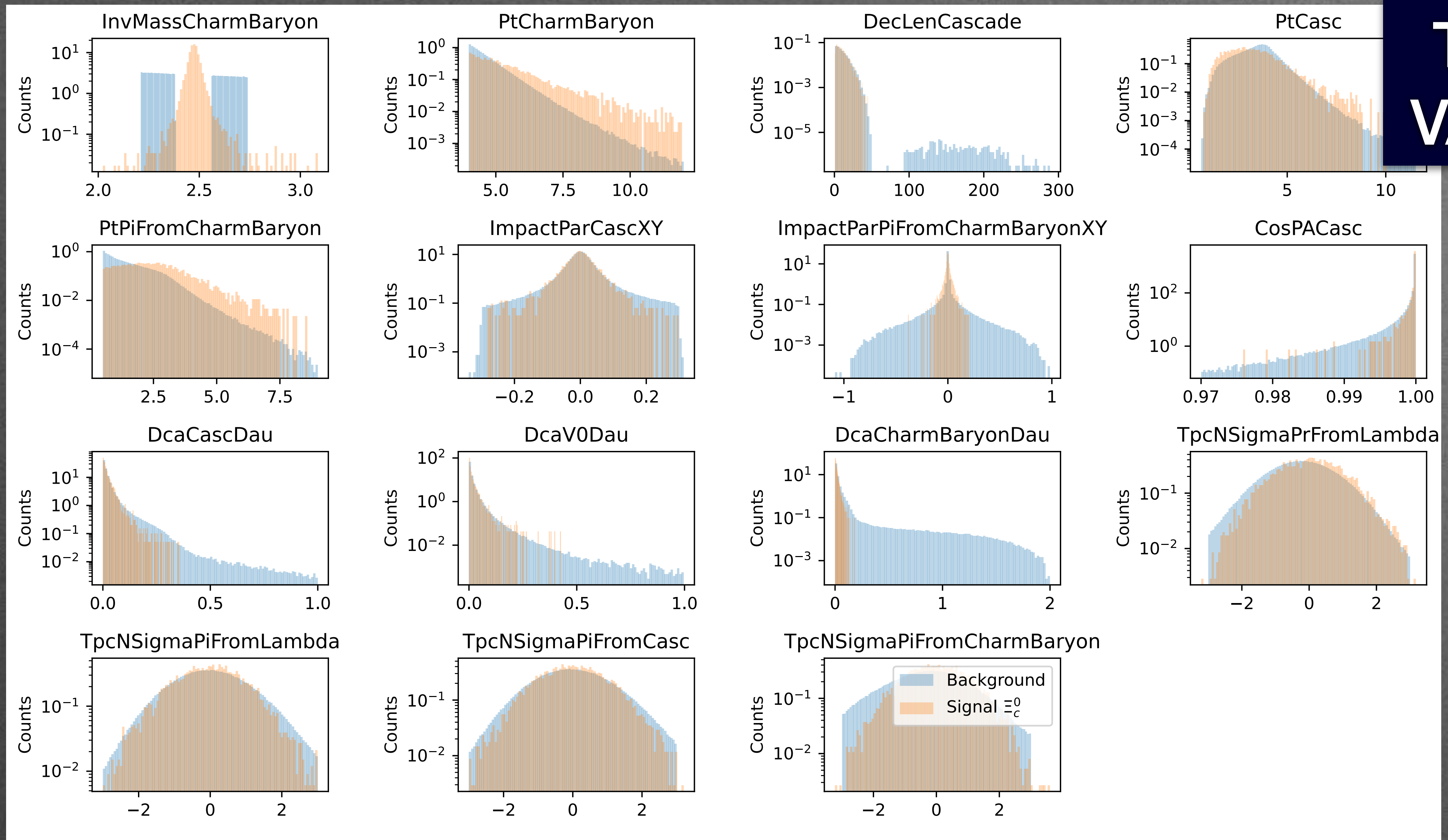


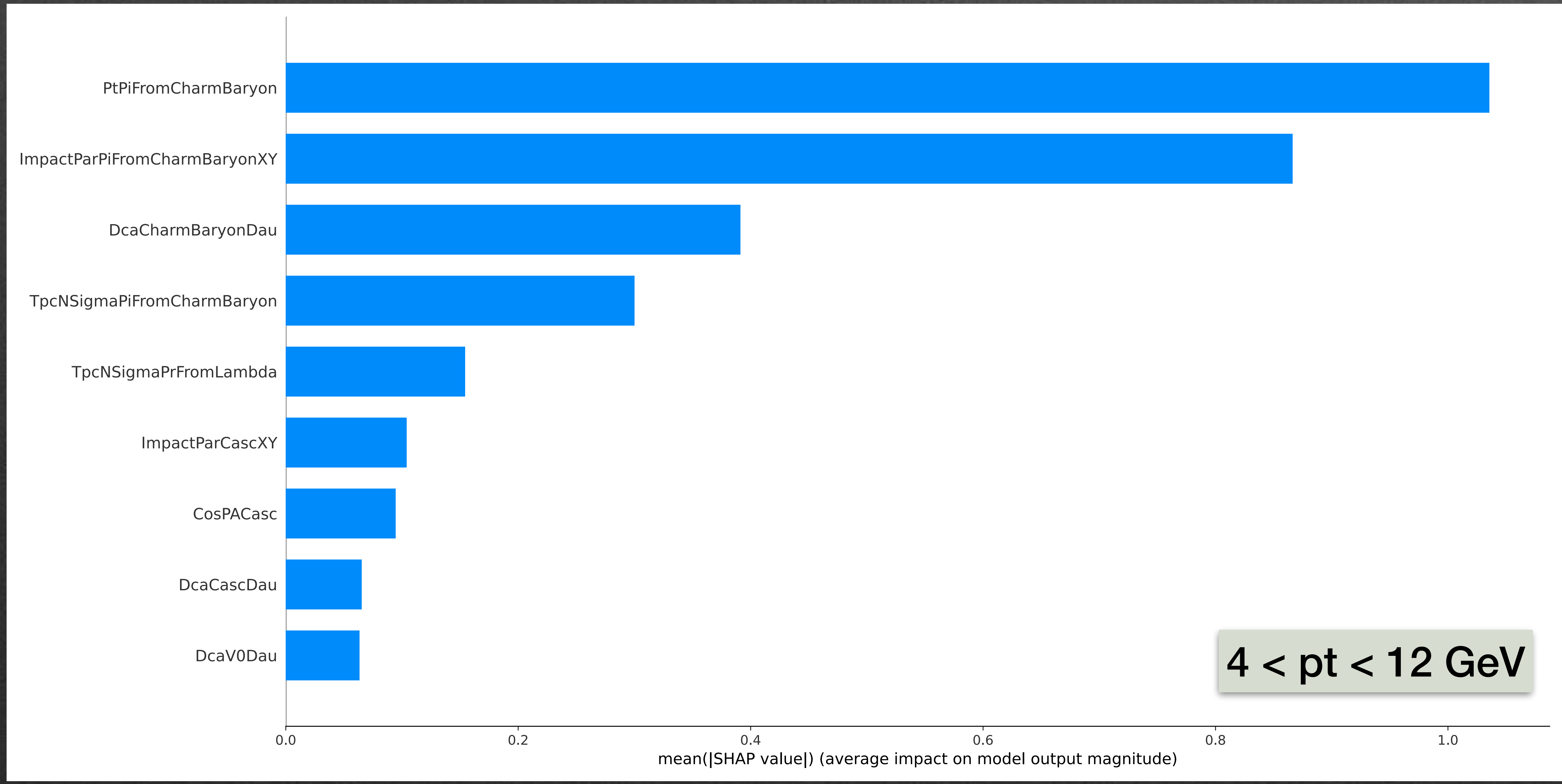


- Studies performed for gap 3 (1 triggered event - 2 MB events - 1 triggered event) 5 and 8 using centralized anchored MC productions
- Gap 5 is the configuration chosen for charm baryon enriched MC

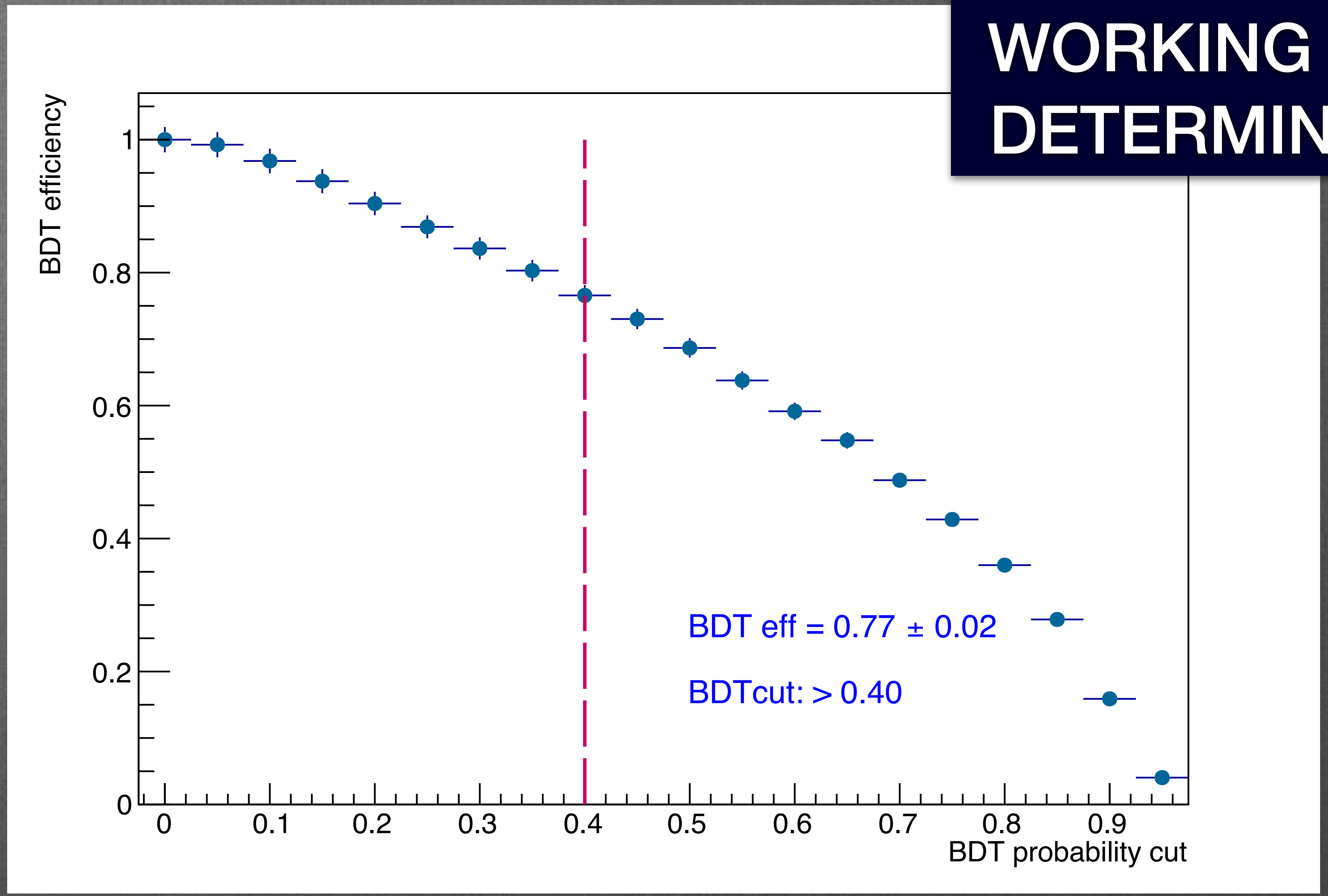
First results - Ξ_c^0 signal extraction and machine learning

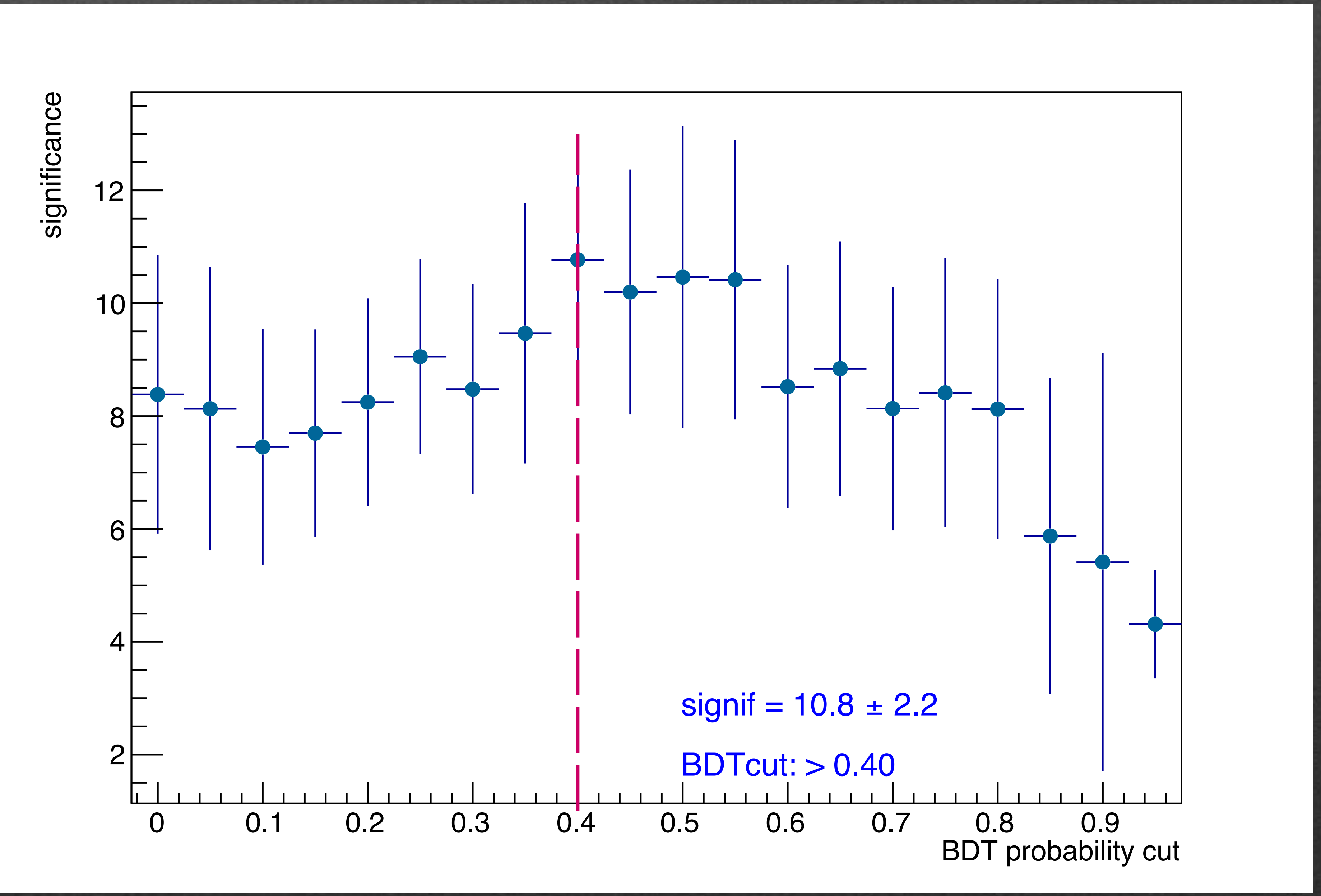
TRAINING VARIABLES



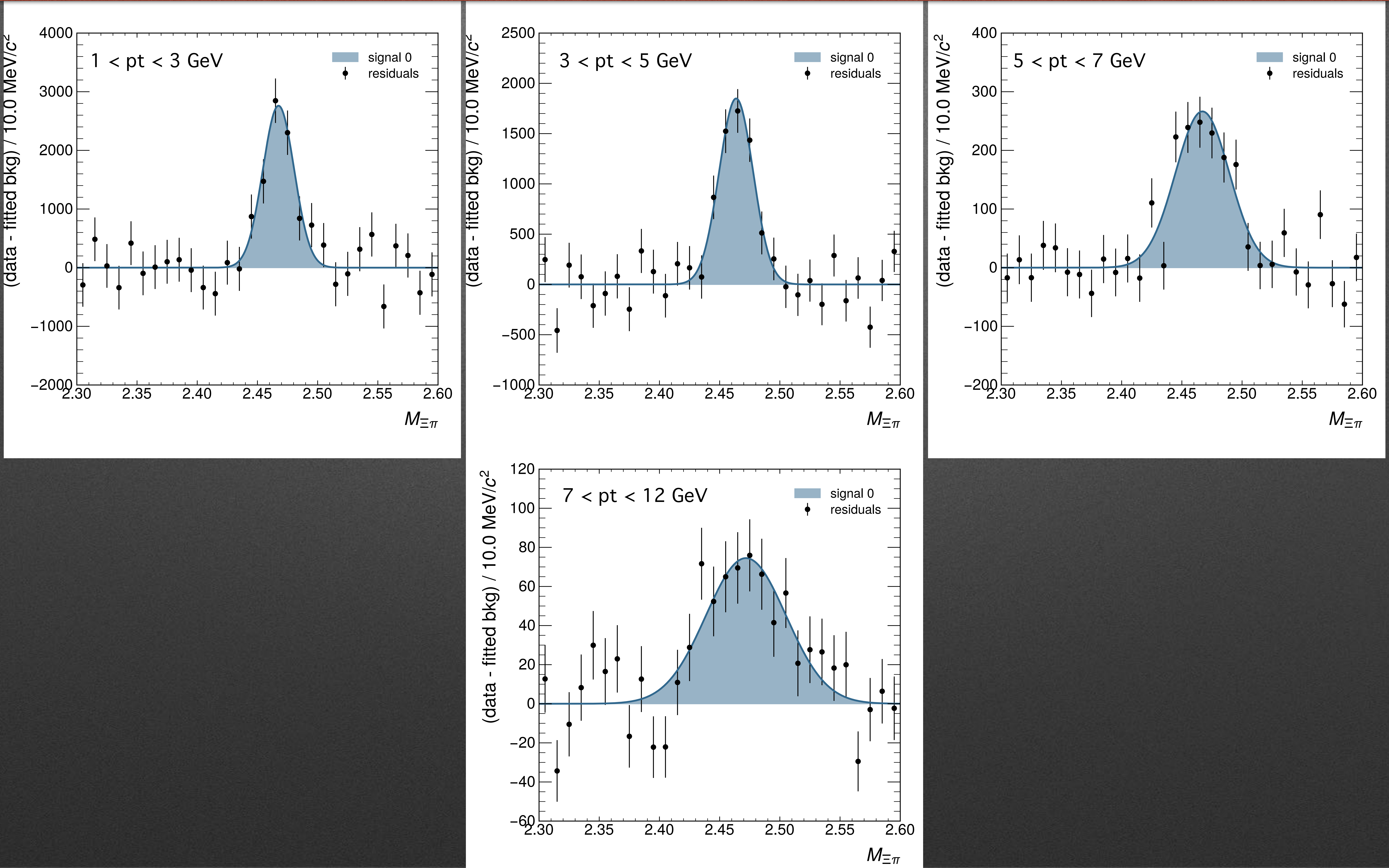


WORKING POINT DETERMINATION





p_{T} differential Ξ_c^0 signal - residuals



p_{T} differential Ξ_c^0 signal - selections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$\lvert z_{\mathrm{PV}} \rvert$	< 10 cm
sel8	true
TF and ITSROF border cut	true
globalTrackWoDca	true
$\lvert \eta \rvert_{\pi \leftarrow \Xi_c^0}$	< 0.8
$p_{\mathrm{T}\ \pi \leftarrow \Xi_c^0}$	> 0.5 GeV
$\lvert \mathrm{DCAxyToPV}_{\ \Xi} \rvert$	< 2.0 cm
$\lvert \mathrm{DCAxyToPV}_{\ \pi \leftarrow \Xi_c^0} \rvert$	> 0.002 cm
$\lvert n\sigma \rvert$ TPC	< 3
K0s rejection	10 MeV

p_{T} differential Ξ_c^0 signal - selections

Table 2: Selections applied to K_S^0, Λ and $\bar{\Lambda}$ candidates.

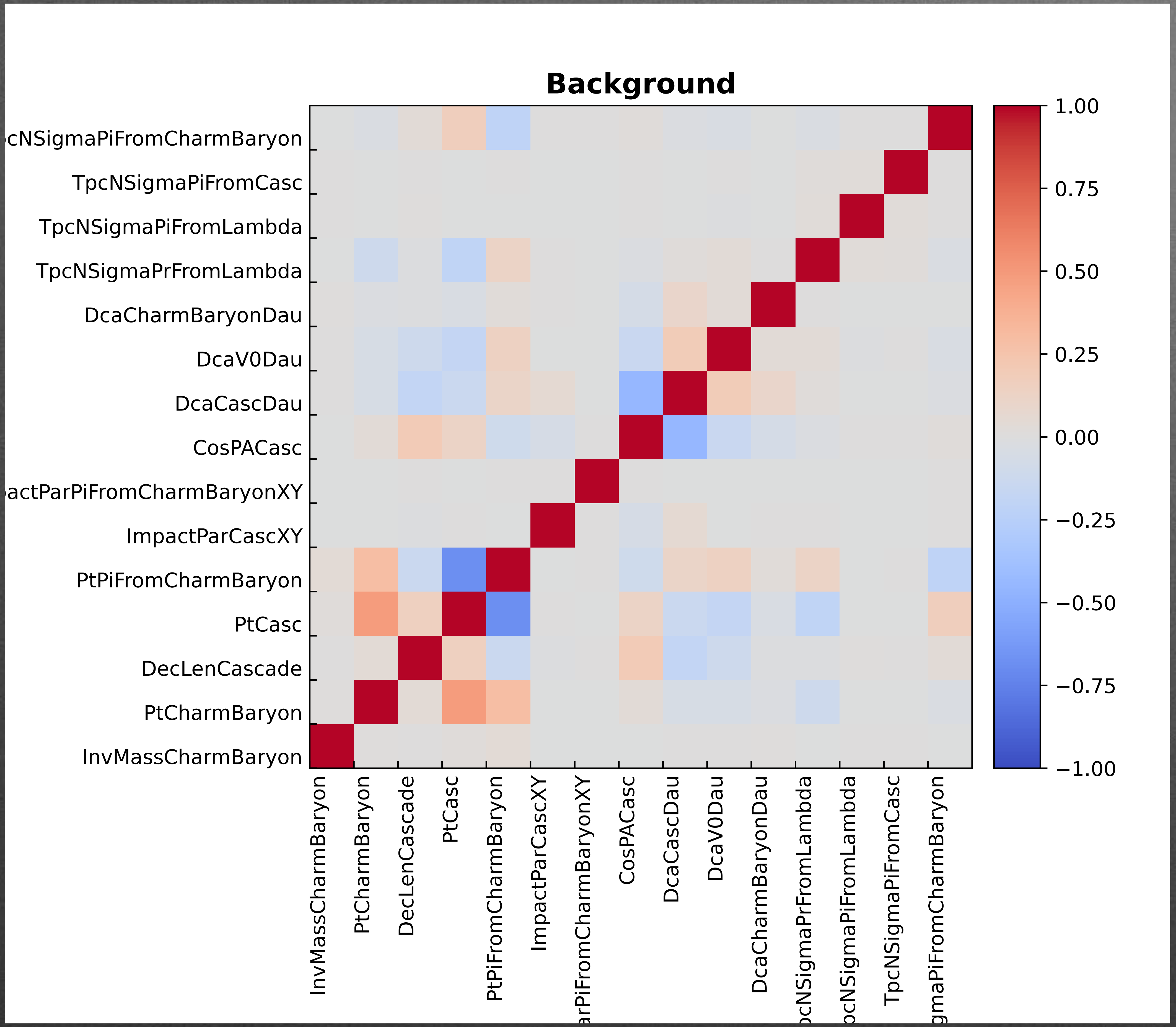
Toplogical Variable	**K_S^0 (Λ and $\bar{\Lambda}$) Cut**
V0 transv. decay radius	> 0.50 cm
DCA Negative Track to PV	> 0.06cm
DCA Positive Track to PV	> 0.06cm
V0 Cosine of Pointing Angle	> 0.97 (0.995)
DCA V0 Daughters	$< 1.0\ \sigma$
Selection	**K_S^0 (Λ and $\bar{\Lambda}$) Cut**
V0 Vertex Type	Generated with Offline Vertexer
Rapidity Interval	$\|y\| < 0.5$ (MC value used for MC analysis)
Proper Lifetime (mL/p)	< 20 cm (30 cm)
Competing V0 Rejection	5 MeV/c^2 (10 MeV/c^2)
TPC dE/dx Selection (Real data only)	$< 5\sigma$
Primary Selection (MC Only)	AliStack::IsPhysicalPrimary()
MC Association (MC Only)	PDG code association for V0 and for daughter tracks
Tracking flags for daughters	kTPCrefit
Daughter Track Pseudorapidity Interval	$\|\eta\| < 0.8$
Daughter Track $N_{crossedrows}$	≥ 70
Daughter Track $N_{crossed}/N_{findable}$	≥ 0.8

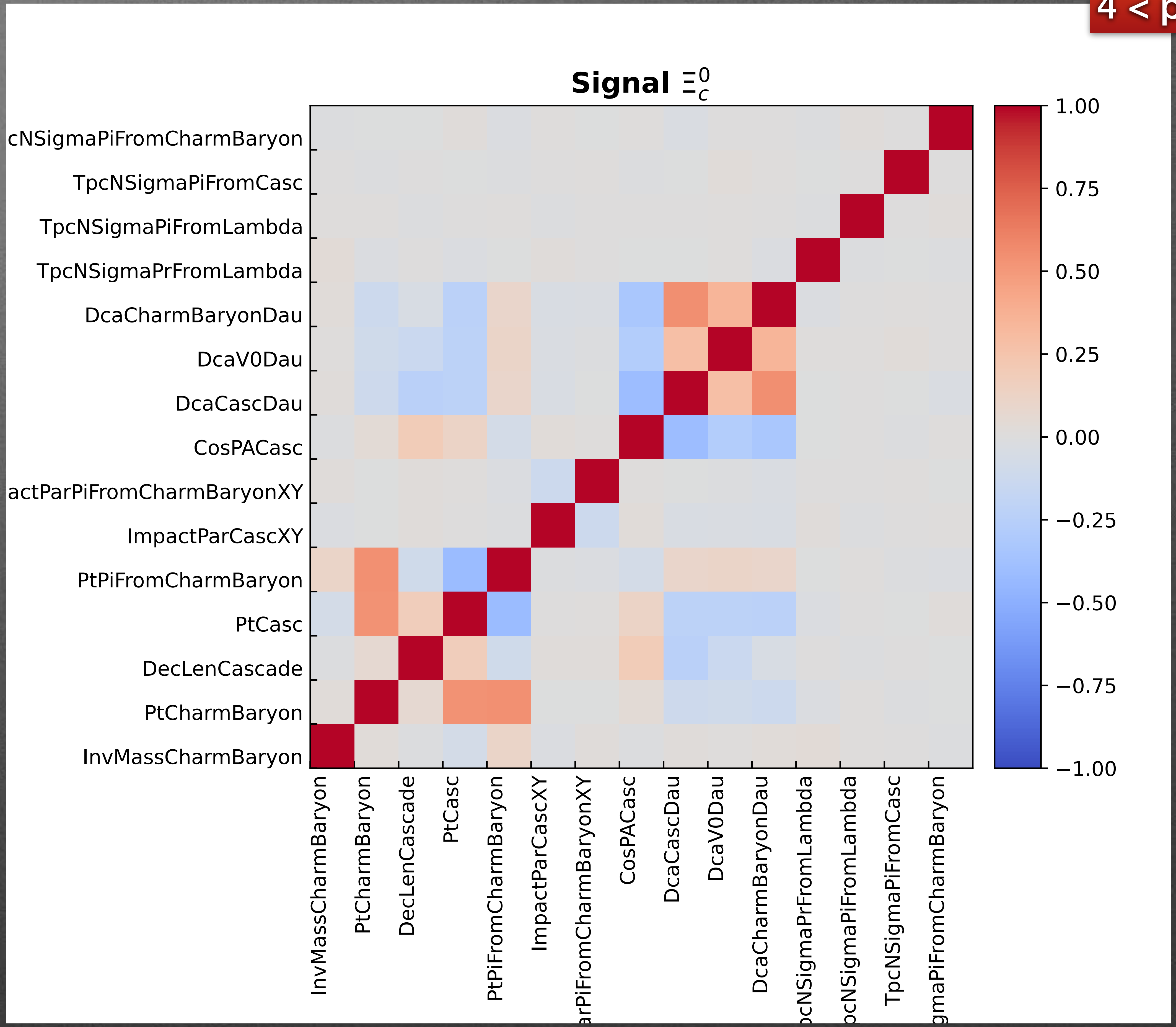
Table 3: Selections applied to charged Ξ and Ω candidates.

Topological Variable	**Ξ (Ω) Cut**
Cascade transv. decay radius R_{2D}	> 0.6 (0.5) cm
V0 transv. decay radius	> 1.2 (1.1) cm
DCA (bach - PV)	> 0.04 cm
DCA (V0 - PV)	> 0.06 cm
DCA (meson V0 track - PV)	> 0.04 cm
DCA (baryon V0 track - PV)	> 0.03 cm
DCA (V0 tracks)	$< 1.5\ \sigma$
DCA (bach - V0)	< 1.3 cm
cascade cos(PA)	> 0.97
V0 cos(PA)	> 0.97
V0 invariant mass window	$\pm 0.008\ GeV/c^2$
Selection	**Ξ (Ω) Cut**
Rapidity Interval	$\|y\| < 0.5$ (MC value used for MC analysis)
TPC dE/dx Selection (Real data only)	$< 4\sigma$
Proper Lifetime (mL/p)	$< 3 \times c\tau$
Competing Cascade Rejection (only Ω)	$\|M(\Xi) - 1.321\| > 8\ MeV/c^2$
Daughter Track Pseudorapidity Interval	$\|\eta\| < 0.8$
Tracking flags for daughters	kTPCrefit
Daughter Track $N_{TPCclusters}$	≥ 70

p_T differential Ξ_c^0 signal - BDT training

4 < pt < 12 GeV





pT bin	1 < pT < 4 GeV	4 < pT < 12 GeV
Signal candidates	15 508	5 519
Bkg candidates	15 508	11 038

Ω_c^0 expected statistics

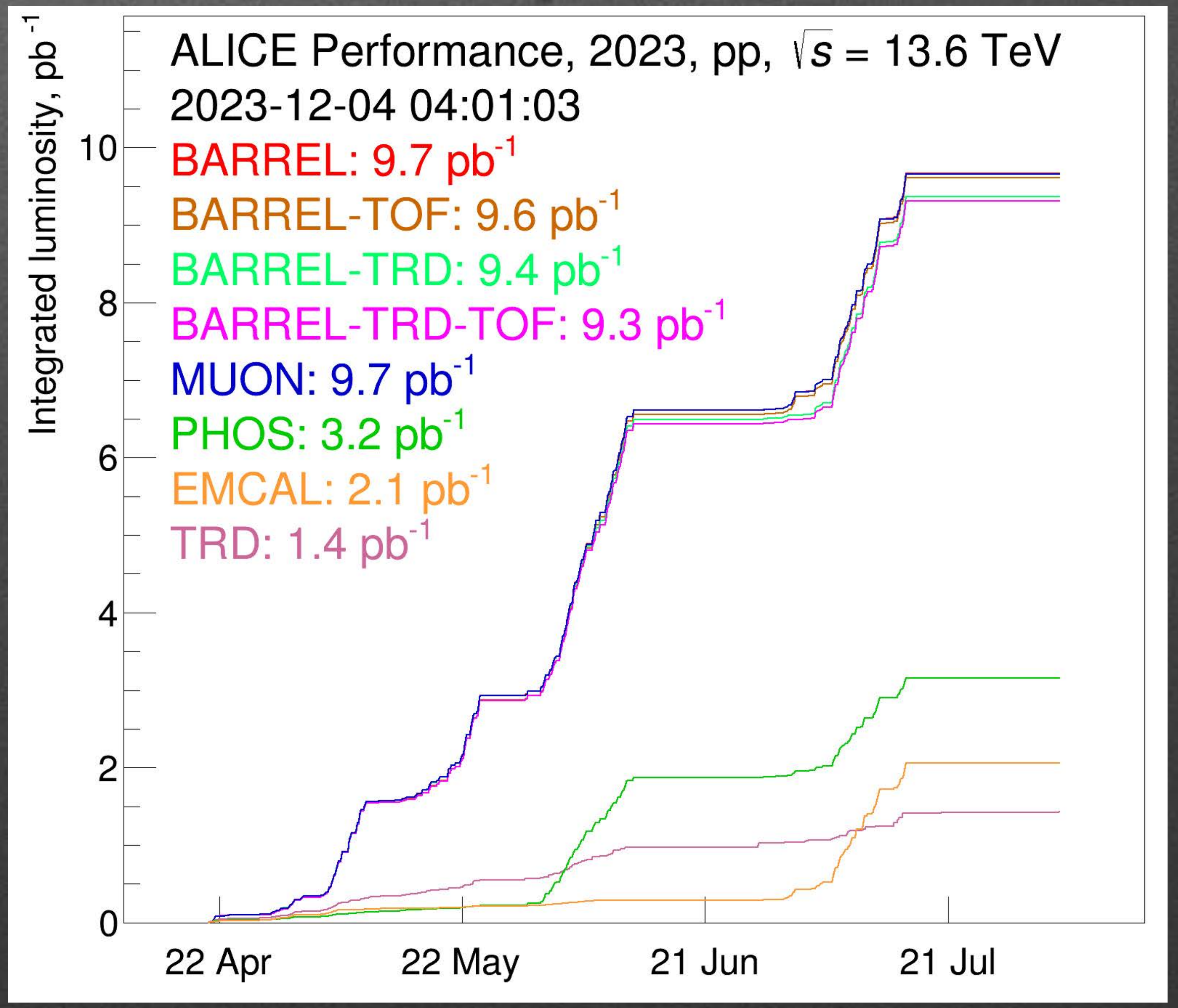
- Branching ratio from LHCb measurement: $BR(\Omega_c^0 \to \Xi^-\pi^+)/BR(\Omega_c^0 \to \Omega^-\pi^+) = 0.1581 \pm 0.0087\,(\text{stat}) \pm 0.0043\,(\text{syst}) \pm 0.0015\,(\text{ext})$
- $BR(\Omega^- \to \Lambda K^-) \sim 0.678 \;\to\; BR(\Xi^- \to \Lambda\pi^-) \sim 0.999 \to \sim 47$%
- $Q-value:\; 0.884 \to 1.235\; GeV$ $\to$ increase in available phase-space and increase in p_π $\to$ increase in $A \cdot \epsilon$
- Strange baryons reconstruction performance (Run2) $\to \sim 2$
- Increase in $\mathscr{L}_{int}$ (Run2 $\sim 30\; nb^{-1}$)

Run2 yield* $\Omega_c^0 \to \Omega\pi$	$2.6 \cdot 10^2$
Branching ratio Ω_c^0	16%
Branching ratio cascade	3/2
Cascade reconstruction	2
Luminosity (2022 data sample)	$\sim 5.9 \cdot 10^2$
Luminosity (2023 data sample)	$\sim 3 \cdot 10^2$

* raw yield after BDT for $2 < p_T < 12\; GeV/c$

The order of magnitude of the Ω_c^0 yield in the $\to \Xi\,\pi$ decay channel is comparable to the one in the $\to \Omega\,\pi$ decay channel

2023 data sample to be skimmed

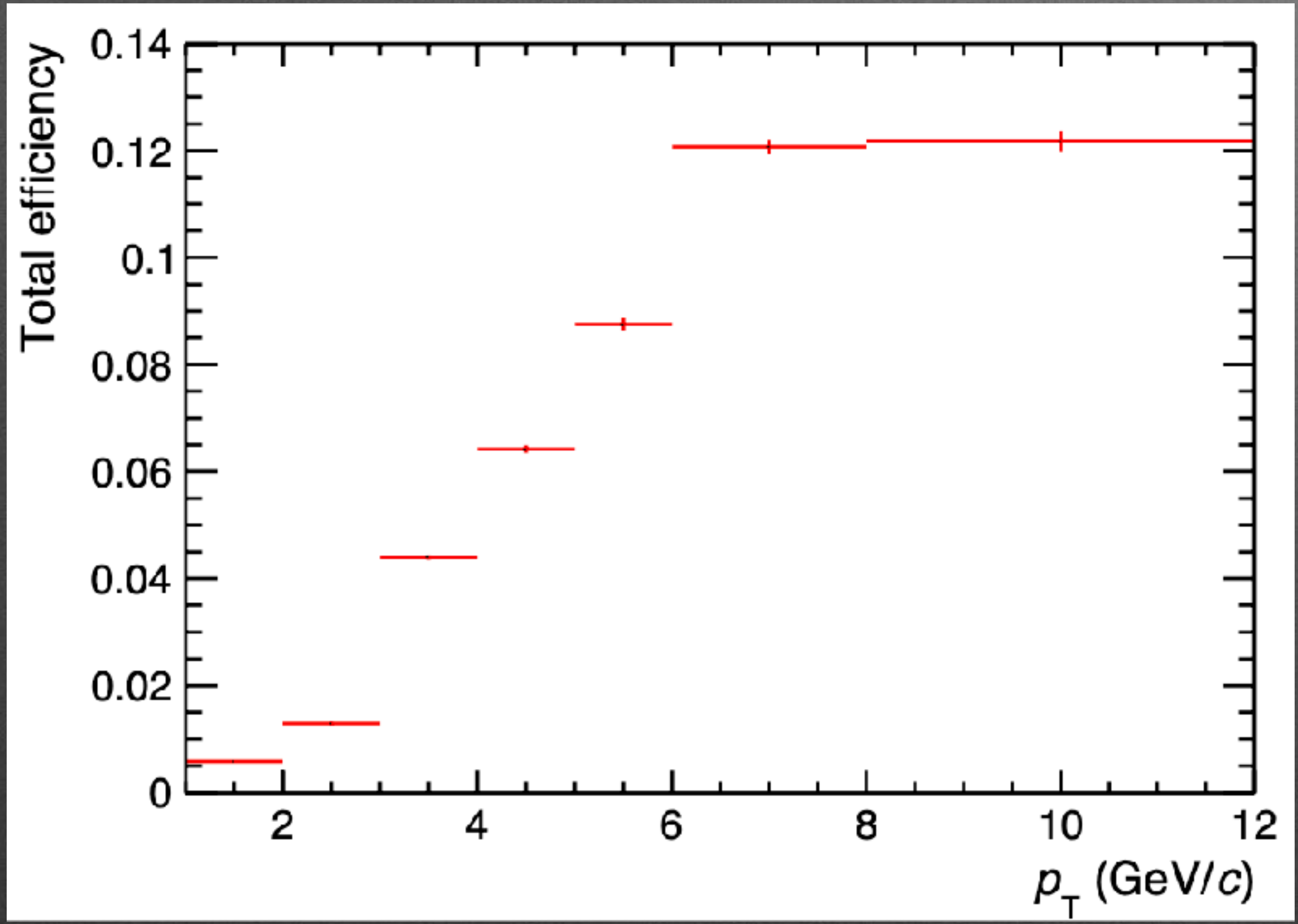


$\mathscr{L}_{int} \sim 9.6\; pb^{-1}$

$3.7 \cdot 10^4 \quad \Omega_c^0 + \overline{\Omega}_c^0$

prediction based on Run2 performance

Ξ_c^0 efficiency in Run2



From analysis notes of $\Xi_c^0 \rightarrow \Xi\pi$

STATISTICS

30 nb^{-1} $\rightarrow \sim 2\mathrm{B}$ events

~3800 Ξ_c^0 (after BDT, before $A \cdot \epsilon$ correction)