Towards the measurement of charged hadron spectra in CMS

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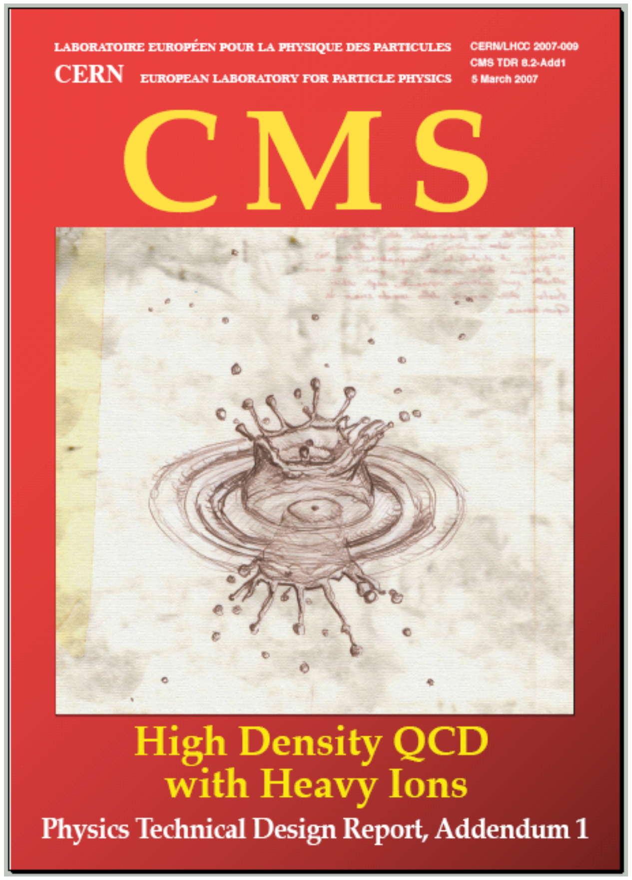
The CMS experiment

- Soft physics
  - The detector
  - Level-1 trigger
  - Centrality selection
  - Charged hadron rapidity density
  - Charged hadron spectra
  - Particle identification capabilities
    - ∗ charged hadrons via energy loss (dE/dx)
    - ∗ neutral hadrons via decay topology (V0)
  - Azimuthal asymmetry, flow



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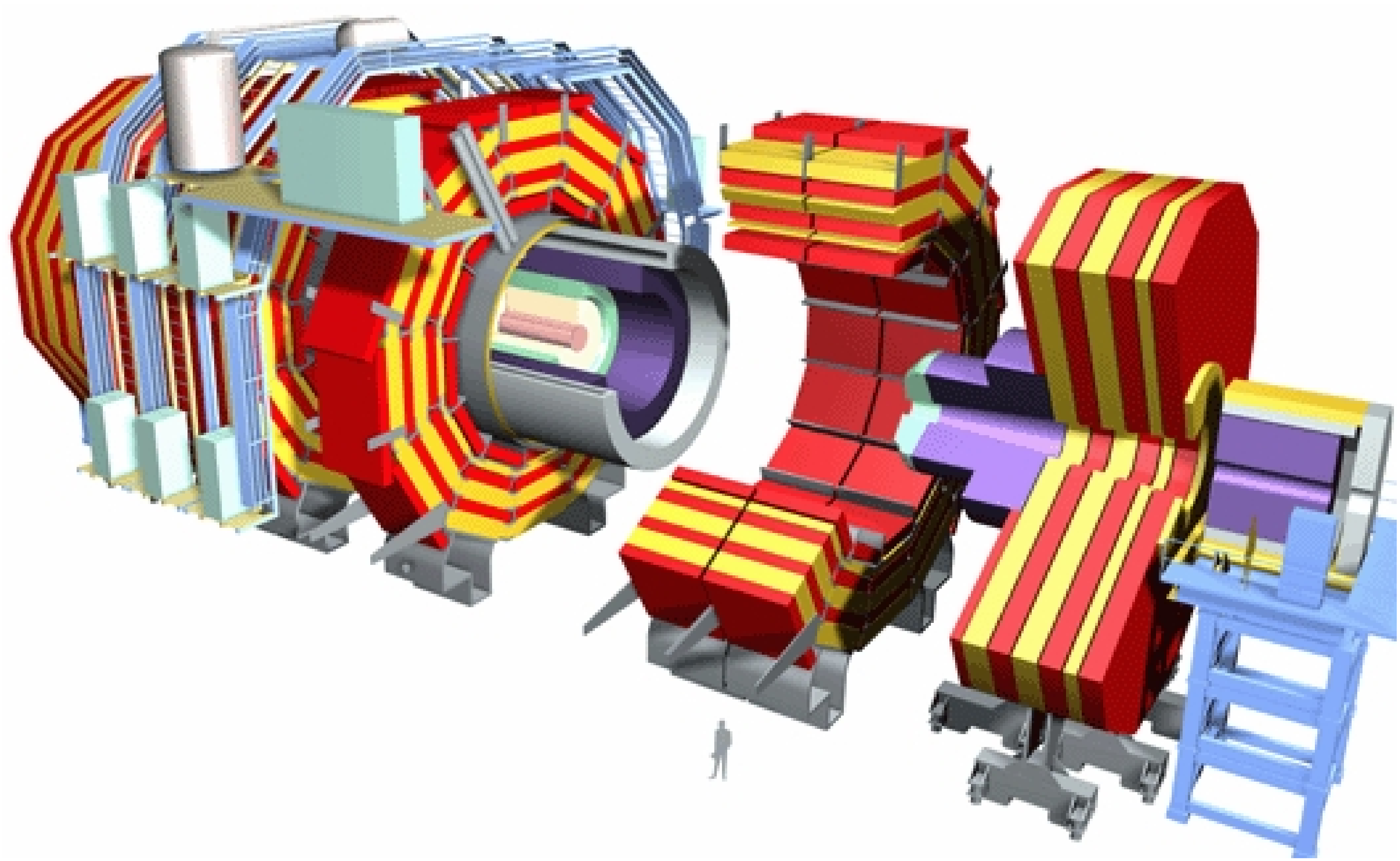
Proton-proton program: analysis exercise, first measurements
Heavy-ion program: study of QCD matter under extreme conditions

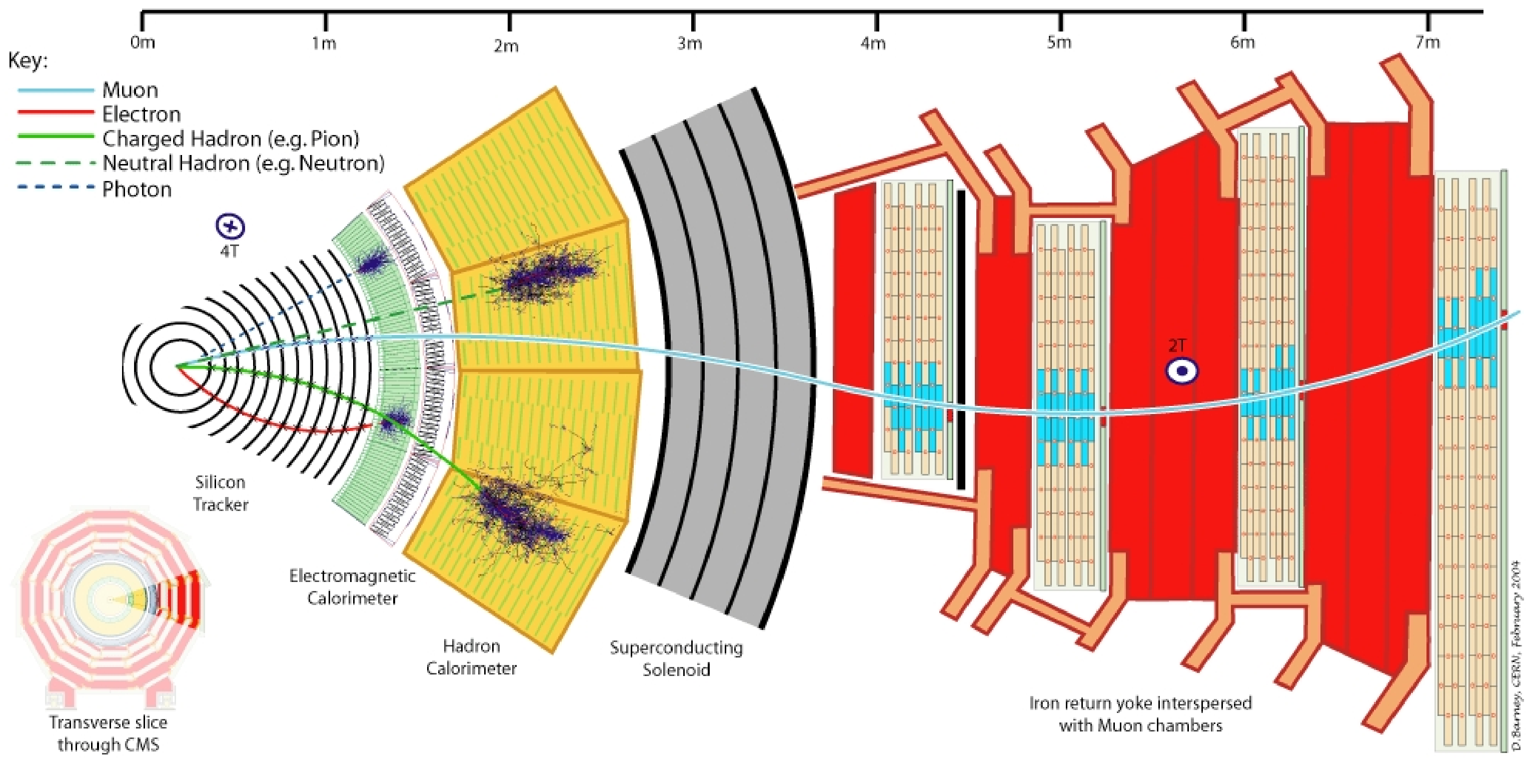
The CMS detector



Compact Muon Solenoid

One single detector combines global characterization and specific probes

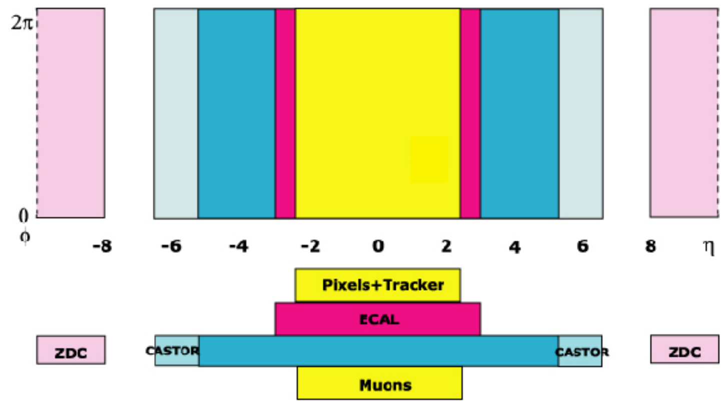
The CMS detector – slice



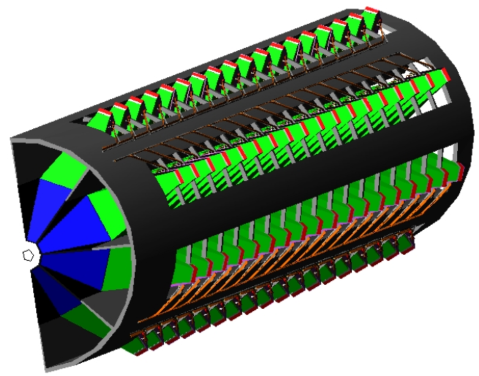
- Detectors
  - Silicon tracker: pixels and strips ($|\eta| < 2.4$)
  - Electromagnetic ($|\eta| < 3$) and hadronic ($|\eta| < 5$) calorimeters
  - Muon chambers ($|\eta| < 2.4$)
  - Extension with forward detectors (next slide)

Can measure leptons (e, μ), hadrons (π, K, p), charged and neutrals (n, γ)

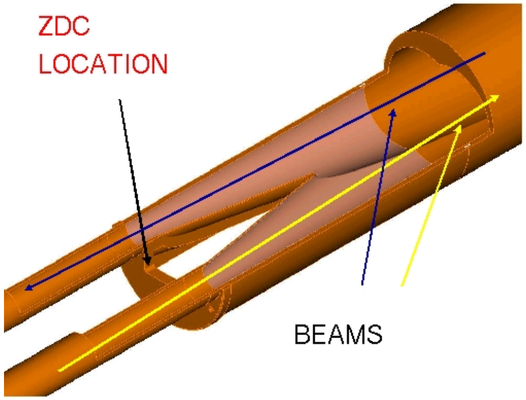
The CMS detector – forward



CASTOR



ZDC



- CASTOR
  - tungsten and quartz plates ($5.3 < |\eta| < 6.6$)
  - covers region where baryon density is expected to be maximal in Pb-Pb

- ZDC
  - quartz fibers in a tungsten matrix, 140 m away from the IP ($|\eta| > 8.3$)
  - measures spectator neutrons and forward photons

Very wide acceptance

Charged hadron spectra in p-p at $\sqrt{s} = 14$ TeV

One of the first physics results from the LHC will be the measurement of charged hadron spectra in proton-proton collisions

Will constrain QCD models of hadron production at the highest energies ever reached at the lab ($\sqrt{s} = 14$ TeV).

Important in terms of physics (QCD UE/MB/MPI), Monte Carlo tuning, backgrounds/pile-up, characterization, etc.

The measurement of these basic observables will also serve as an important tool for the calibration and understanding of the CMS detector and will help establishing a solid basis for exclusive physics.

- Infos
  - CSA07MinBias dataset, Pythia generator, 2 M events
  - Corresponds to about 1 month running with 1 Hz, 70% machine efficiency

Analysis exercise

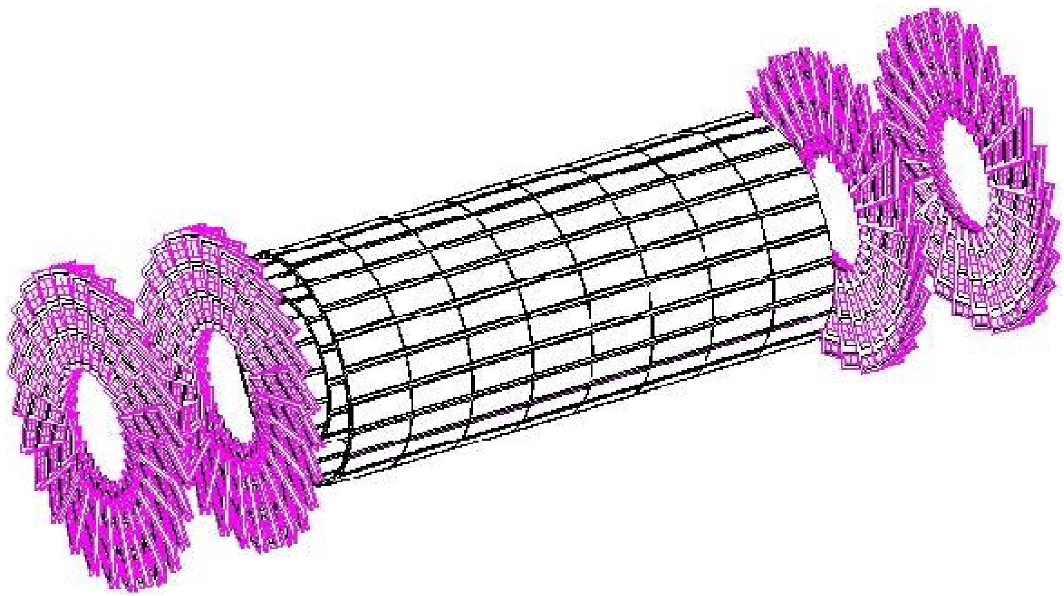
Trigger concepts

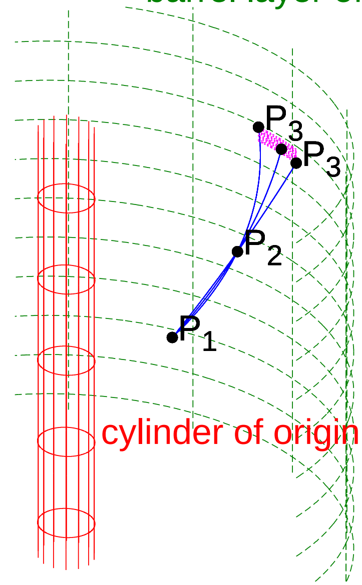
- Inelastic processes
  - Single diffractive
  - Double diffractive
  - Non-diffractive
- Triggers
  - Minimum bias with forward hadronic calorimeter
  - Zero-bias trigger (random, clock) with off-line track or vertex trigger

Pythia	Process	Fraction of inelastic [%]	
11	$f + f'' \to f + f''$ (QCD)	15.65 ± 0.13	ND 69.2
28	$f + g \to f + g$	13.92 ± 0.12	
53	$g + g \to f + f$	0.92 ± 0.03	
68	$g + g \to g + g$	38.69 ± 0.20	
92	Single diffractive (XB)	8.86 ± 0.09	SD 17.9
93	Single diffractive (AX)	9.00 ± 0.09	
94	Double diffractive	12.94 ± 0.11	DD 12.9

Usability of different triggers is a function of luminosity

Charged particle tracking



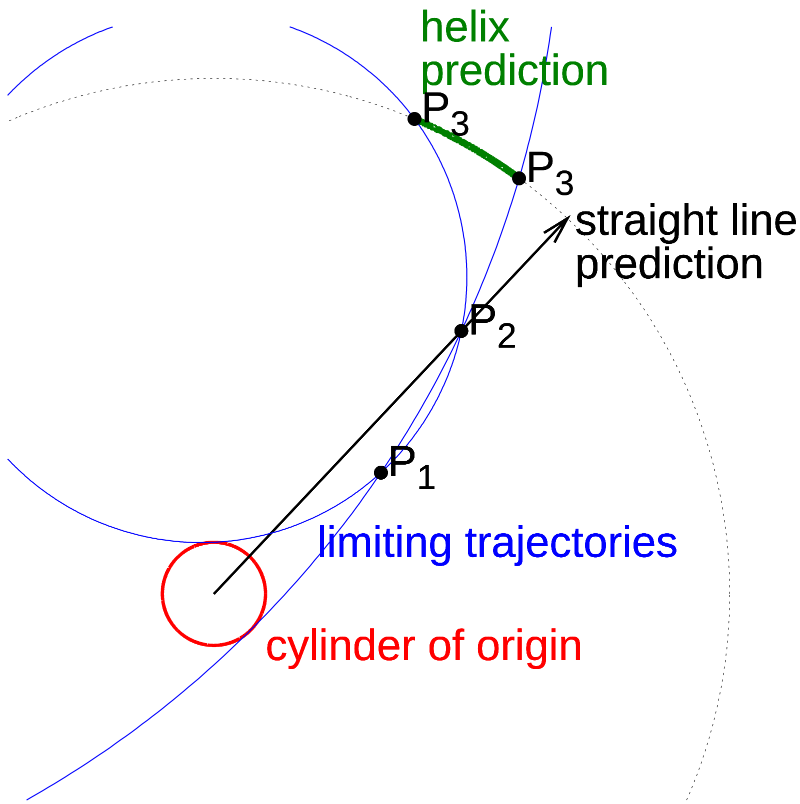


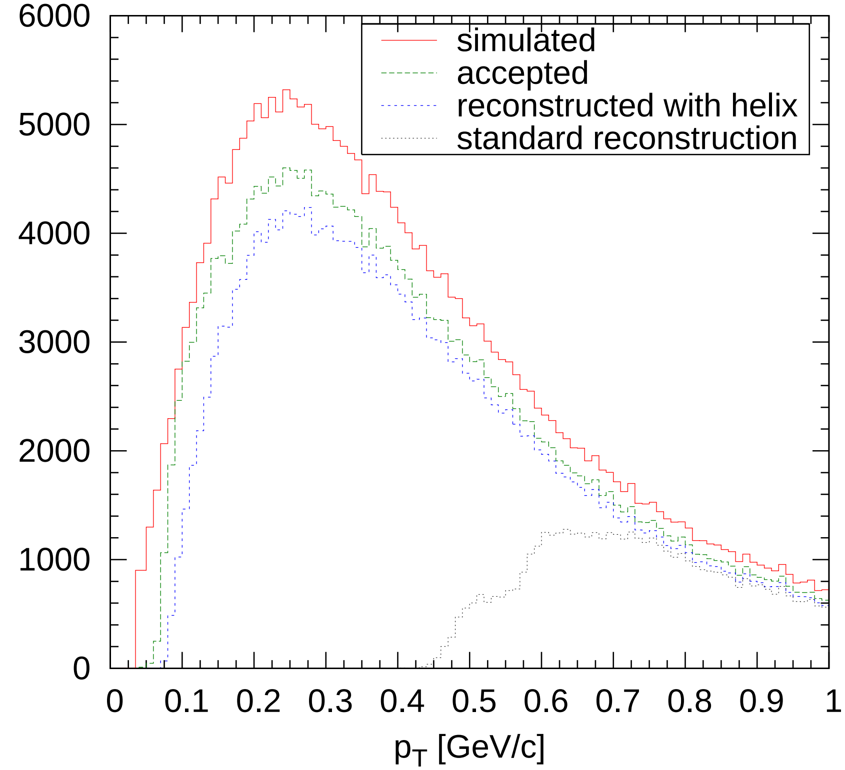
- Pixel detector
  - 3 barrel layers (4, 7 and 10 cm radii) and 2 endcaps on each side
  - $100 \times 150\ \mu\text{m}^2$ pixels, 2% occupancy even at $dN/d\eta_{ch} = 5000$

- Hit triplets
  - Use pixel hit triplets instead of pairs, loss of acceptance but lower fake rate
  - Modified triplet finding, reconstructing down to $p_T = 0.075$ GeV/c

Tracking optimized for the p-p analysis exercise, 2M events

Modified hit triplet finding

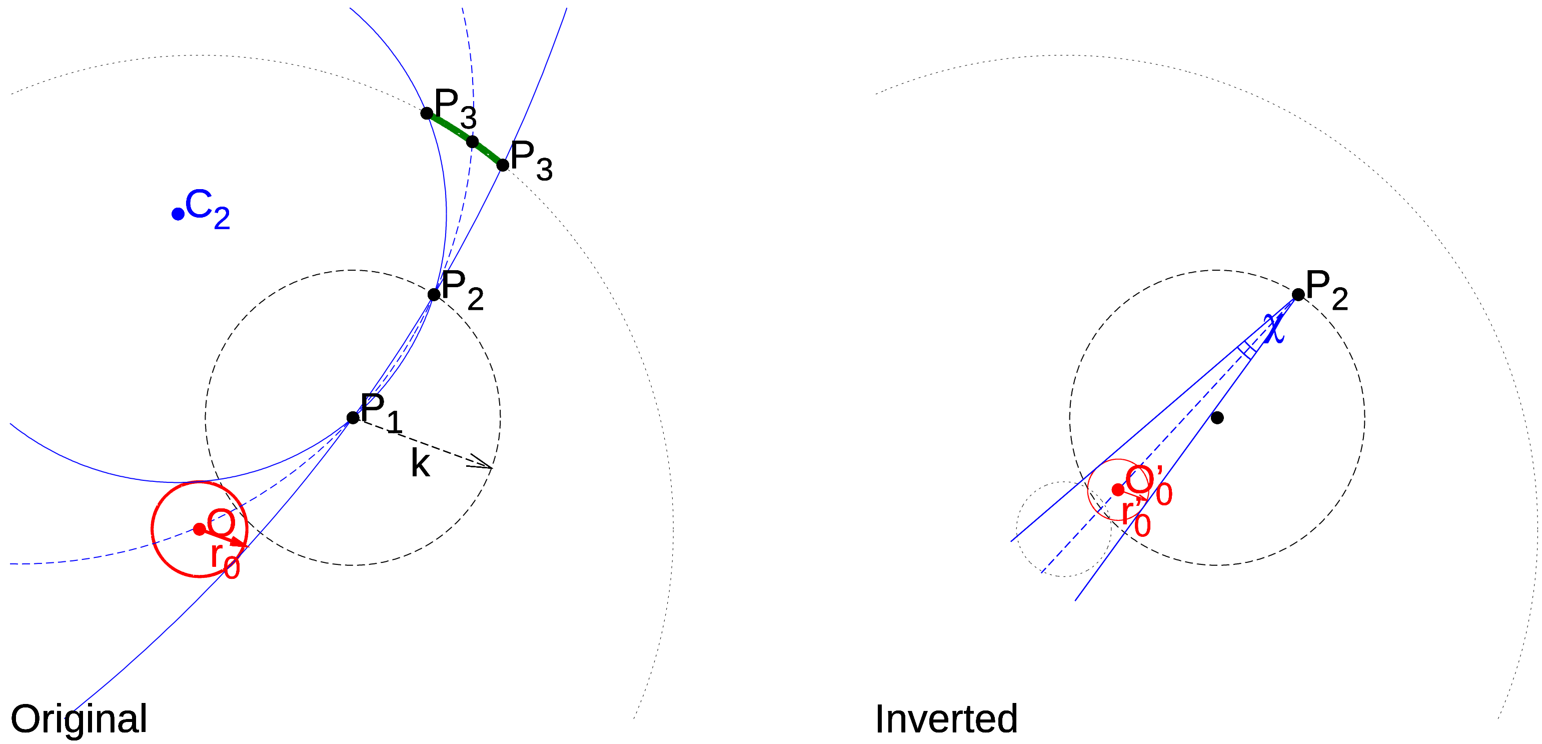




- Modified method
  - Hit pair finding, then prediction for the third hit: same logic
  - "origin": the track must come from the cylinder of origin
  - "minimum": the p_T of the track must be above the minimal value
  - "third": the track must be able to reach the third layer (barrel or endcap)

How? Limiting circles in planar projection

Limiting circles – some geometry – "origin"



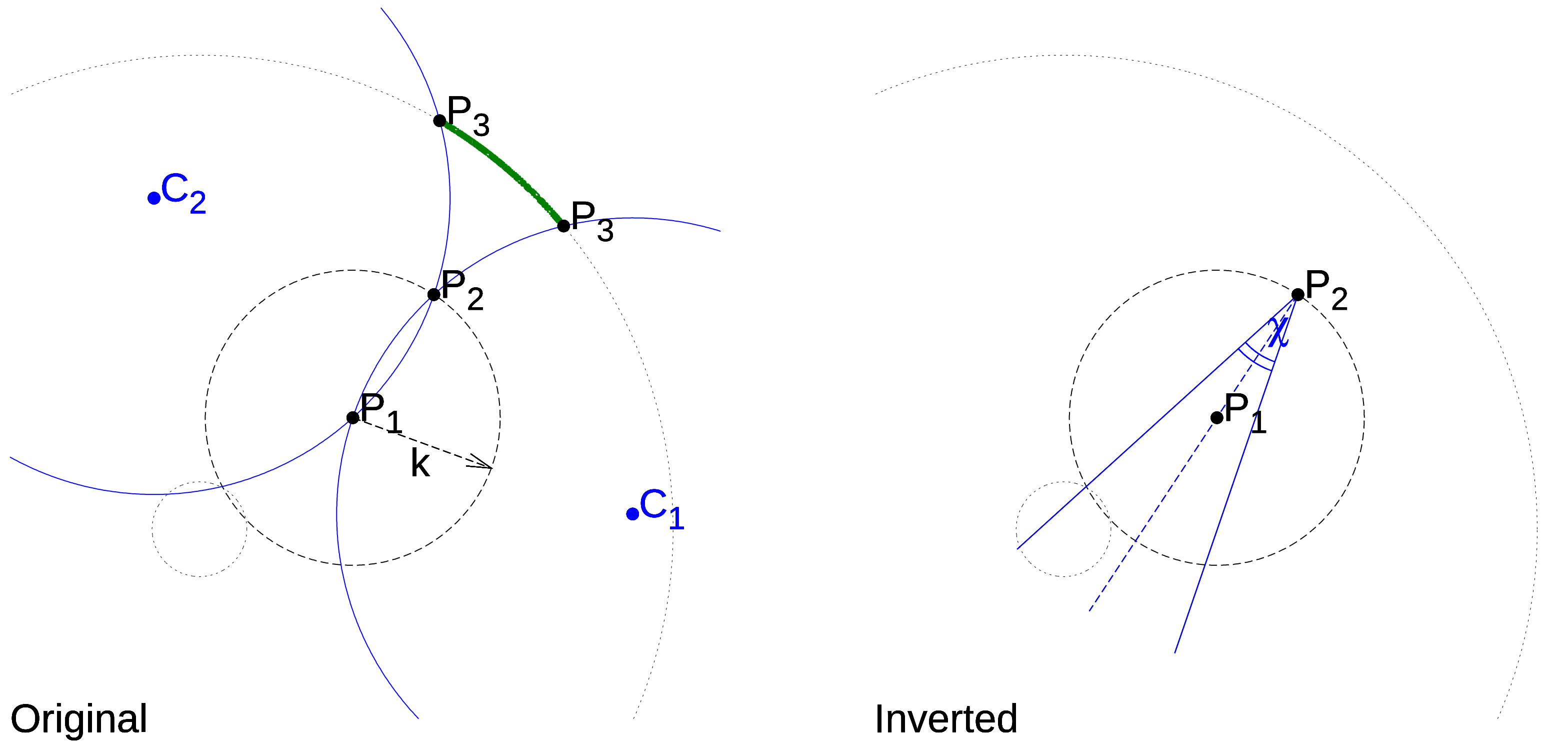
Points of the pair: P_1 and P_2

Two limiting circles: touch origin and pass though P_1 and P_2

Construction with help of inversion with center P_1 and radius $k = P_1P_2$

Limiting circles cut out an arc $P_3 - P_3$ from the circle of third barrel

Limiting circles – some geometry – ”minimal”

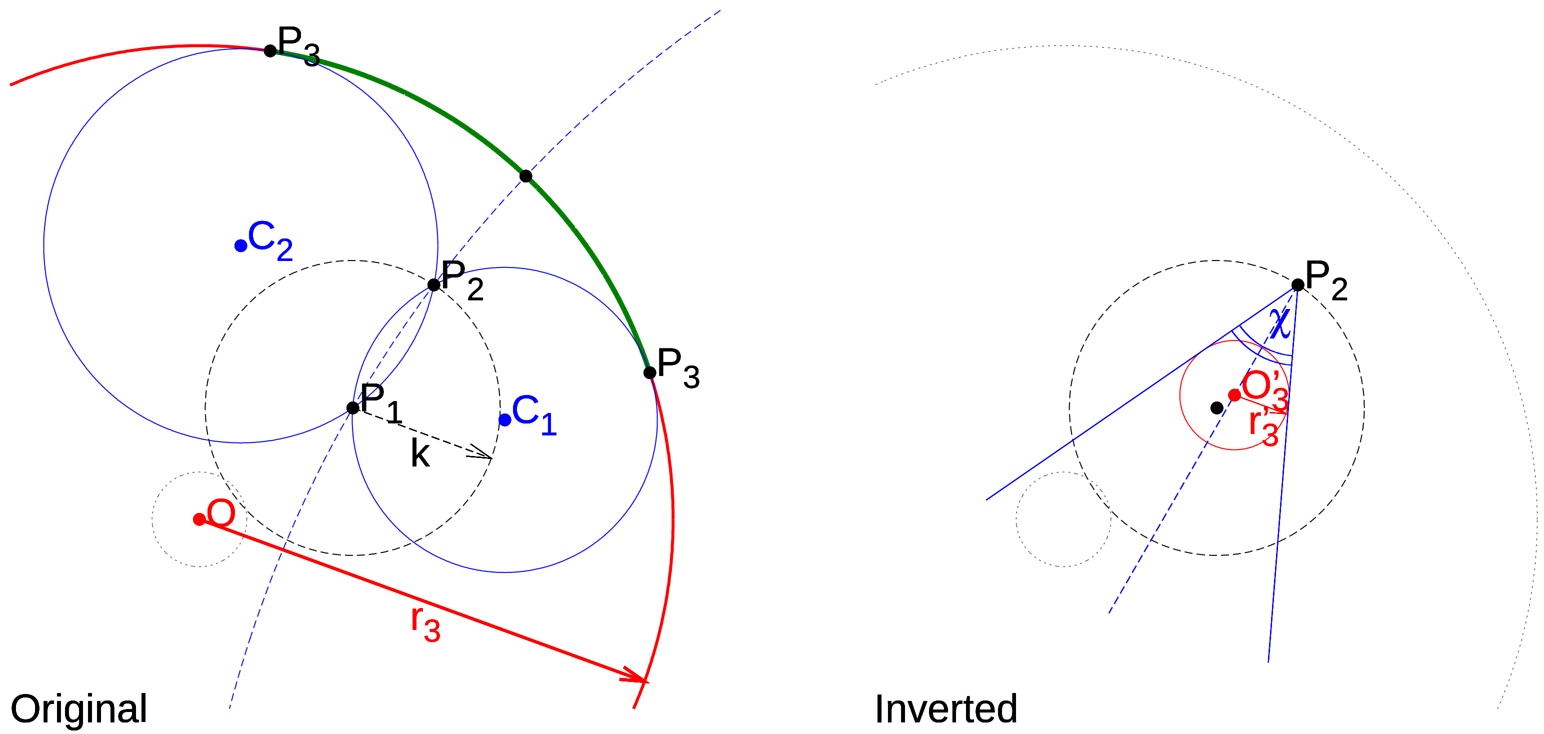


Radii according to minimal p_T

Limiting circles cut out an arc $P_3 - P_3$ from the circle of third barrel

Project circles back to 3D using the z coordinates of the pairs
The resulting region is enclosed by limiting helices

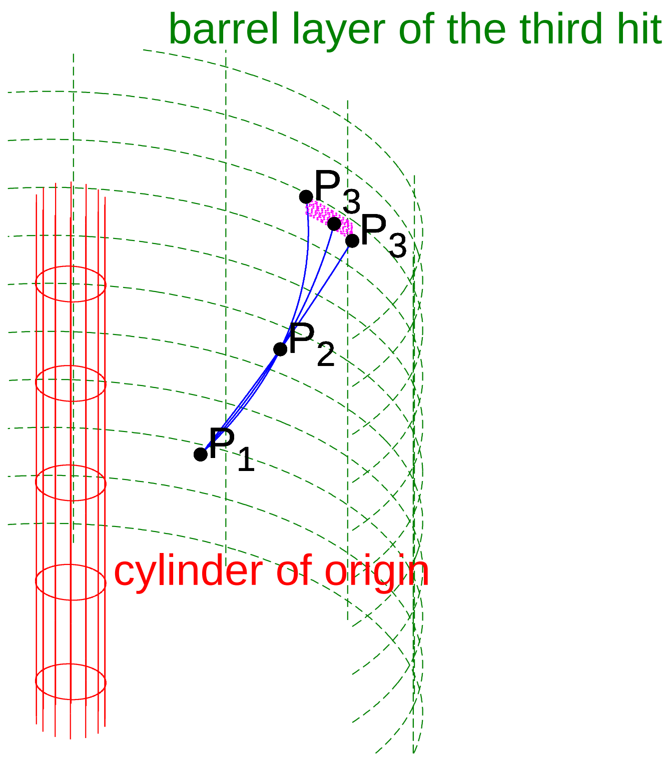
Limiting circles – some geometry – "third" on barrel

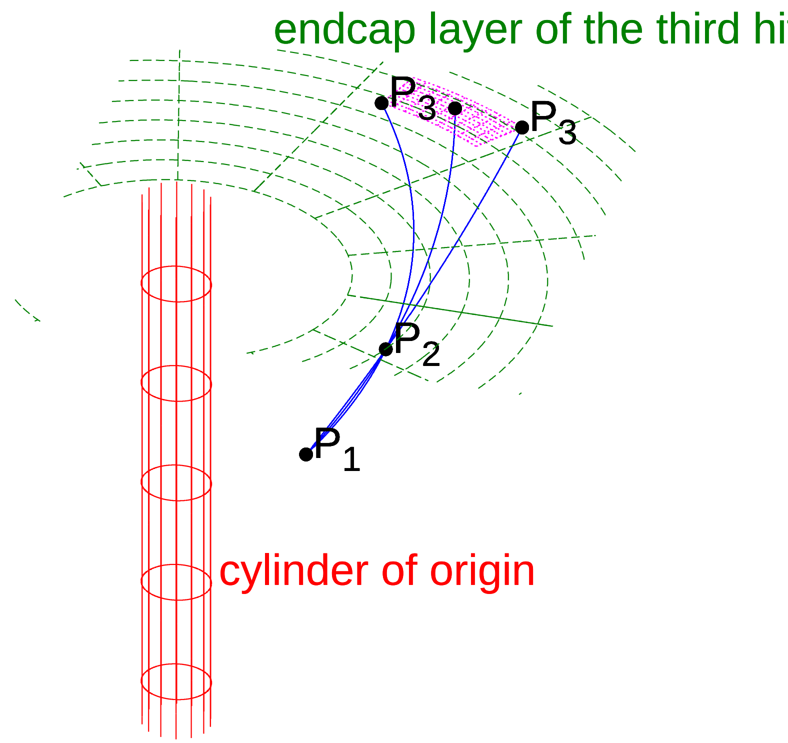


Allowed tracks are in the intersection of the two (three) regions

Project circles back to 3D using the z coordinates of the pairs
The resulting region is enclosed by limiting helices

Charged particle tracking – allowed ranges





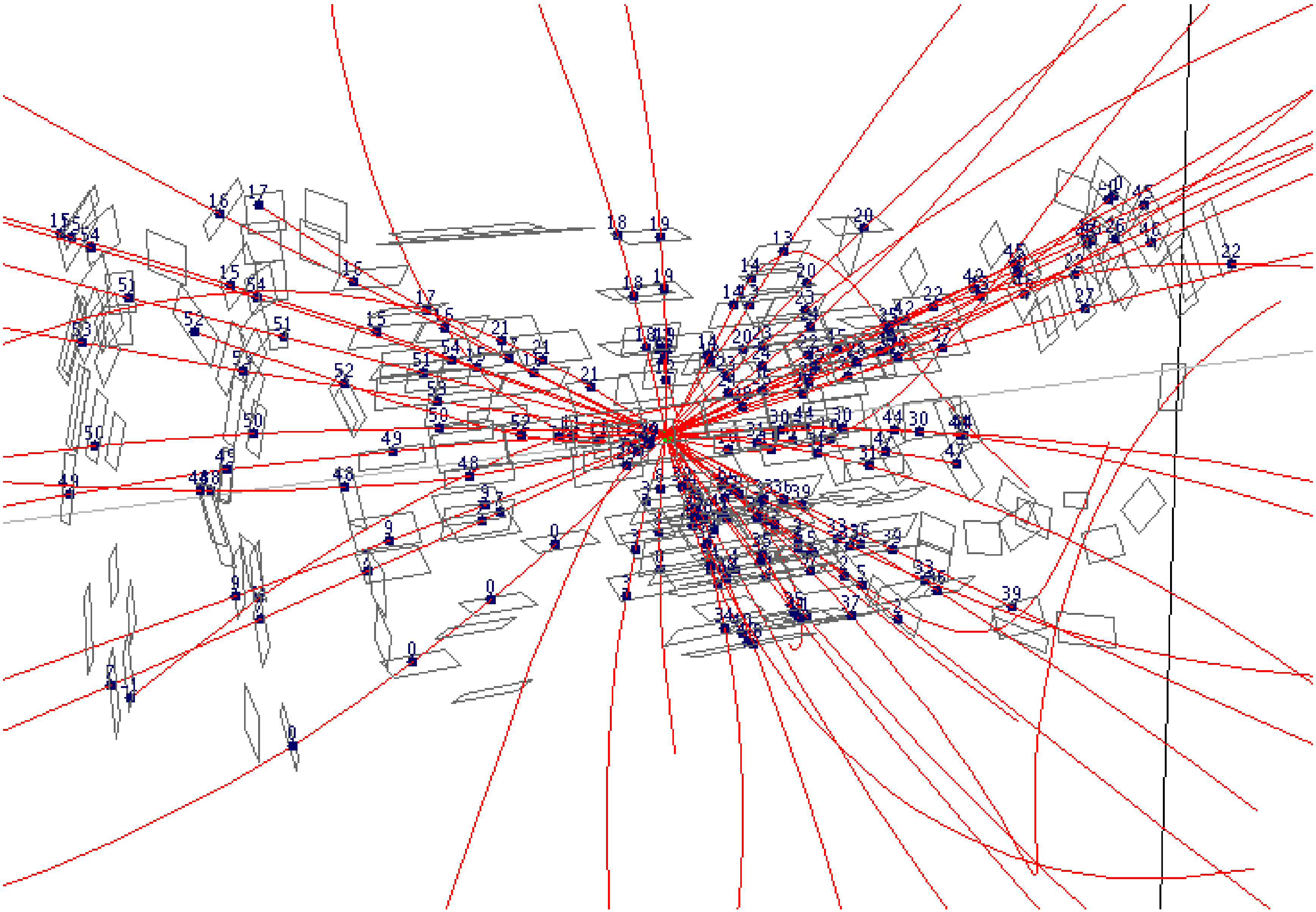
Intercepts of three special trajectories on the layer form a curve

Three points ⇒ parabola ⇒ rectangular envelope

How to select third hits?

Check if position is compatible with multiple scattering

Charged particle tracking – pixel tracks

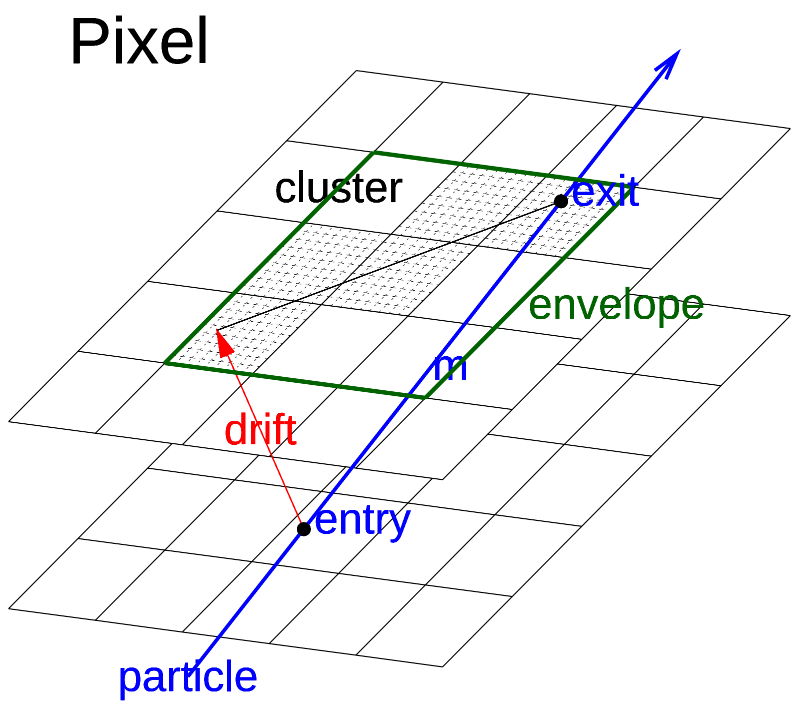


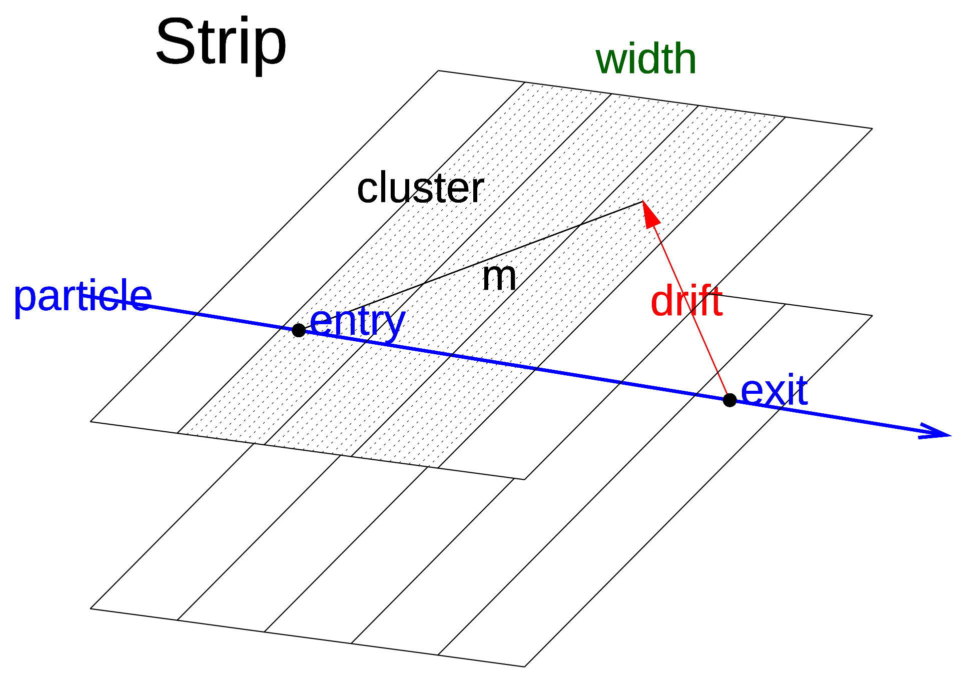
Charged particle tracking – strategy, steps

- Seed generation
  - Use pixel hit triplets instead of pairs, loss of acceptance but lower fake rate
  - Modified triplet finding, reconstructing down to $p_T = 0.075$ GeV/c
  - Pixel cluster shape filter
  - Pixel track cleaning and merging, pixel tracks with 3–8 hits
- Determination of primary vertex (or vertices)
  - Optimized, dedicated study
  - Best parameters: NTrkMin = 3, ZSeparation = 0.3 cm, PtMin = 0.15 GeV/c
- Seed re-generation
  - Constrain triplets with previously found primary vertex
- Trajectory building, fit
  - Filtering: strip cluster width filter
  - Smoothing: retry failed fits with last points successively removed
  - Cleaning: clean seeds, expect to produce only a single global track

Use pixel and strip silicon detectors for tracking: global tracks
Many improvements and additions to standard p-p reconstruction chain

Track and trajectory filters – cluster shape

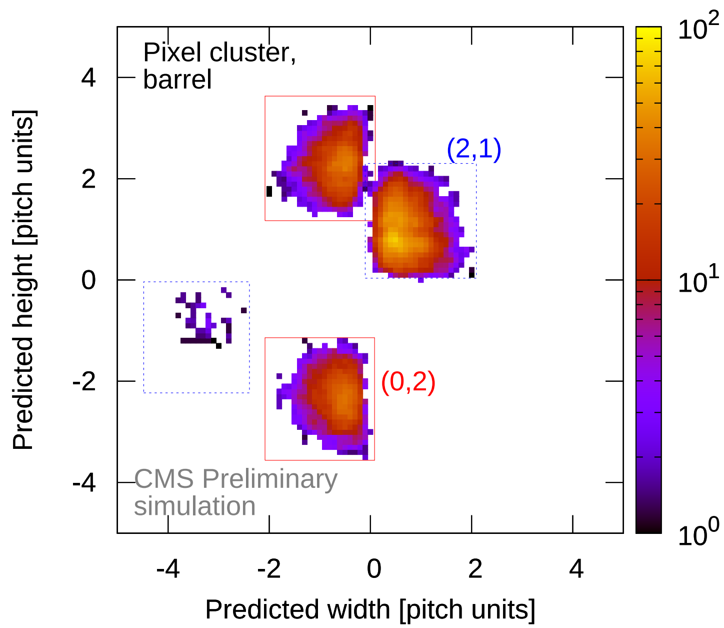




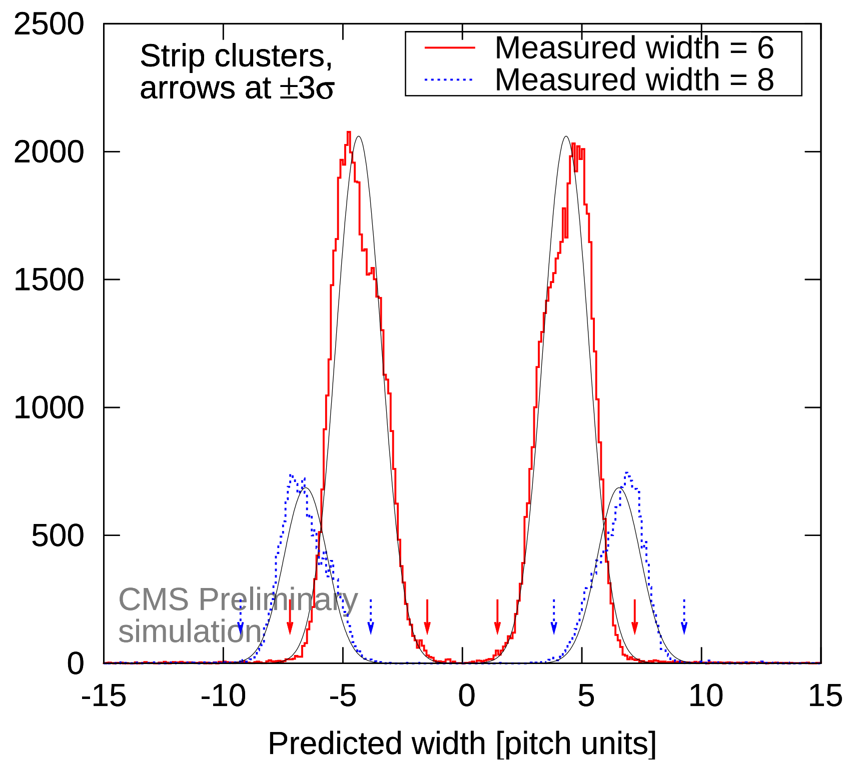
Cluster shape must match trajectory direction

Track and trajectory filters – cluster shape

Pixel

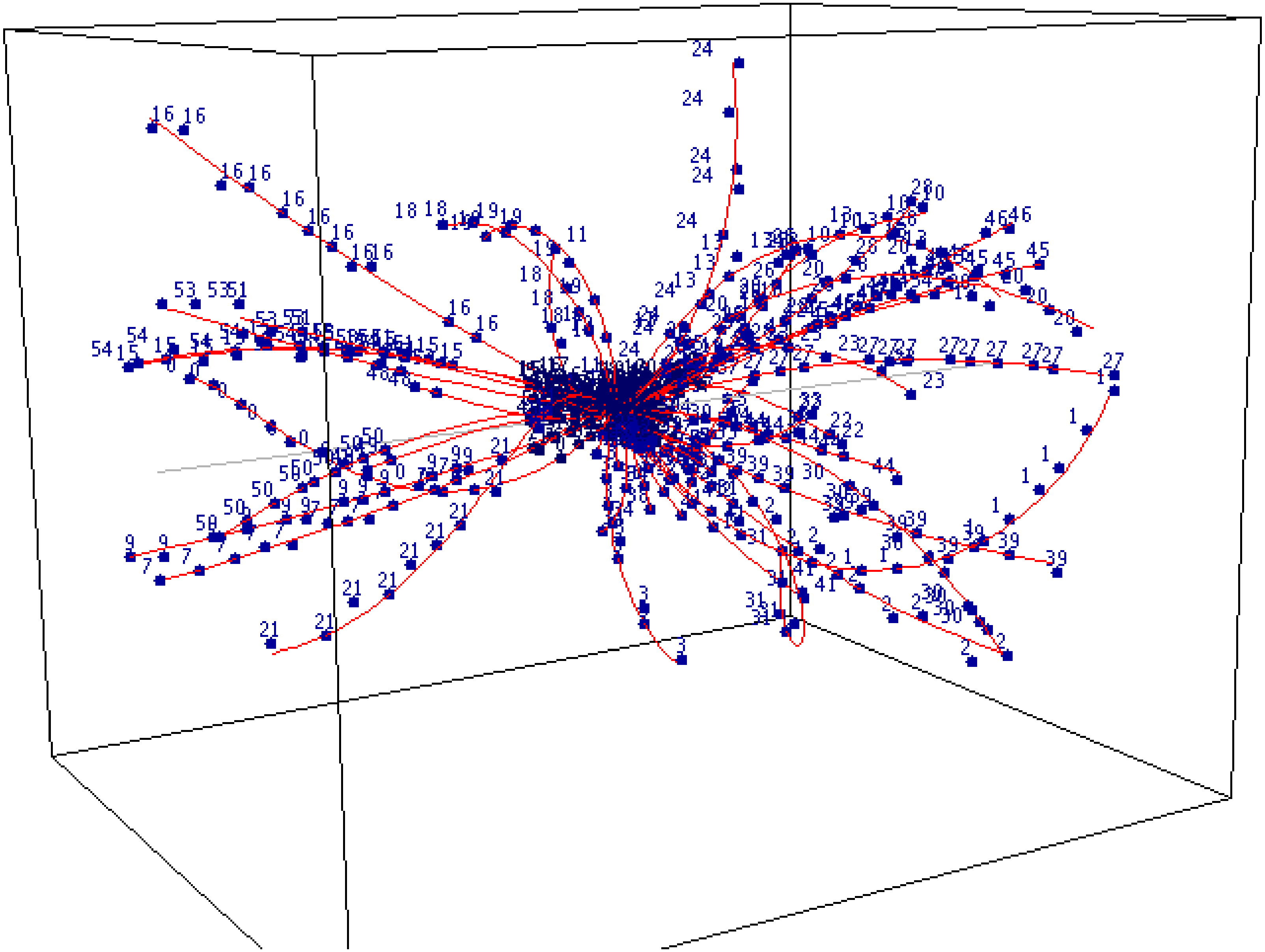


Strip

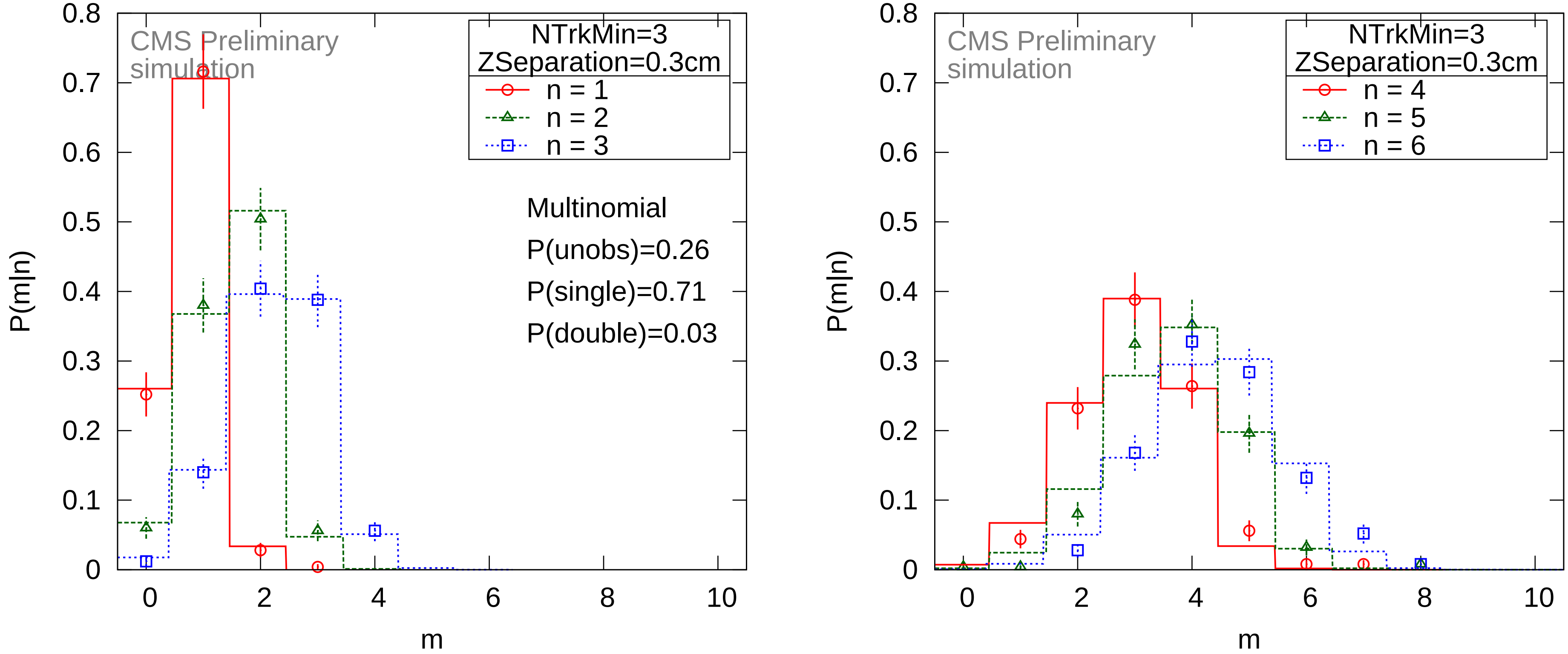


Essential for reducing the fake track rate

Charged particle tracking – global tracks



Optimization of vertexing

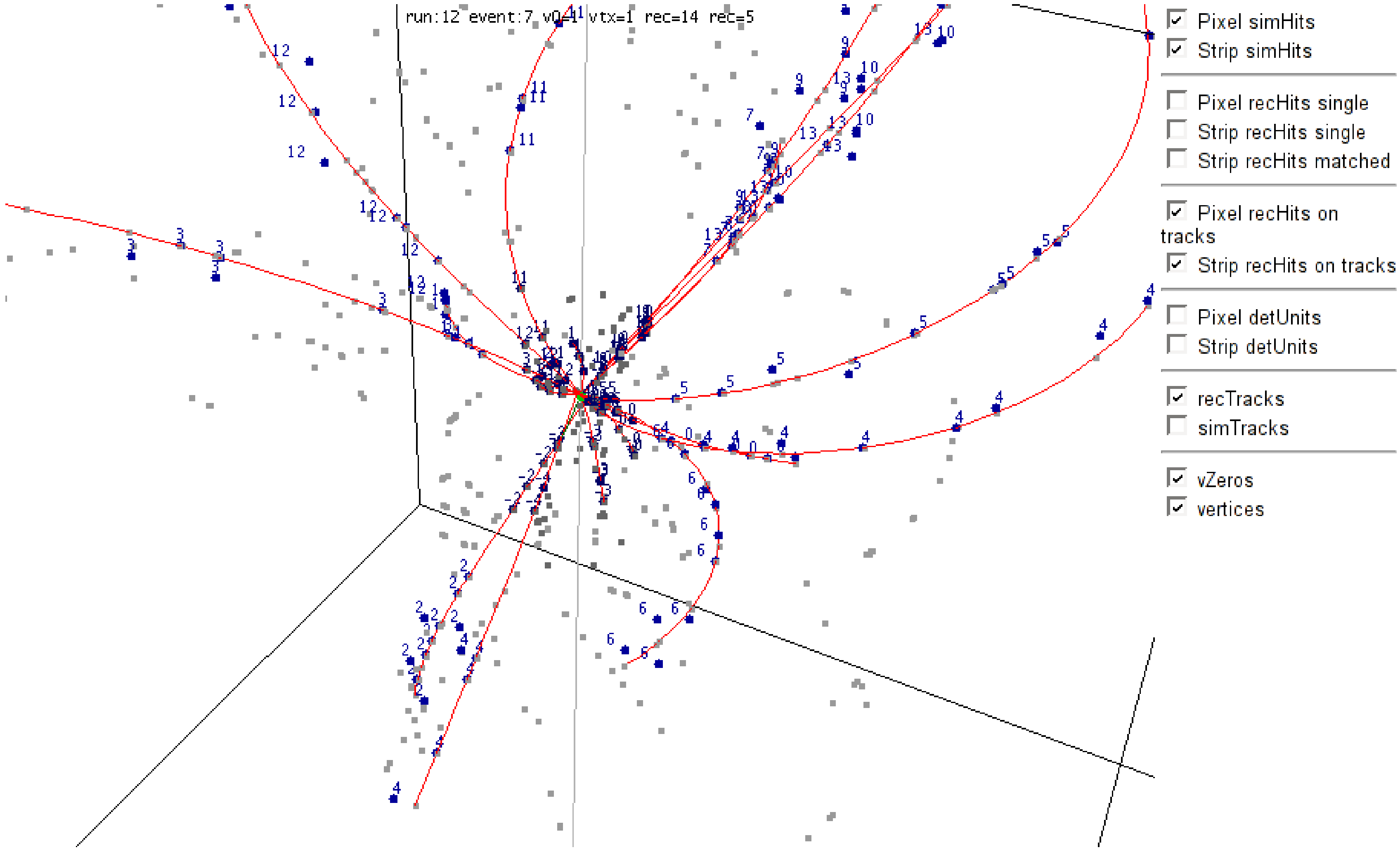


If there are n interactions, how many vertices (m) can we detect?

Multinomial distribution, 75% of the inelastic events get a vertex

Vertex finding is an independent process ⇒ can treat pile-up

Charged particle tracking – interactive events



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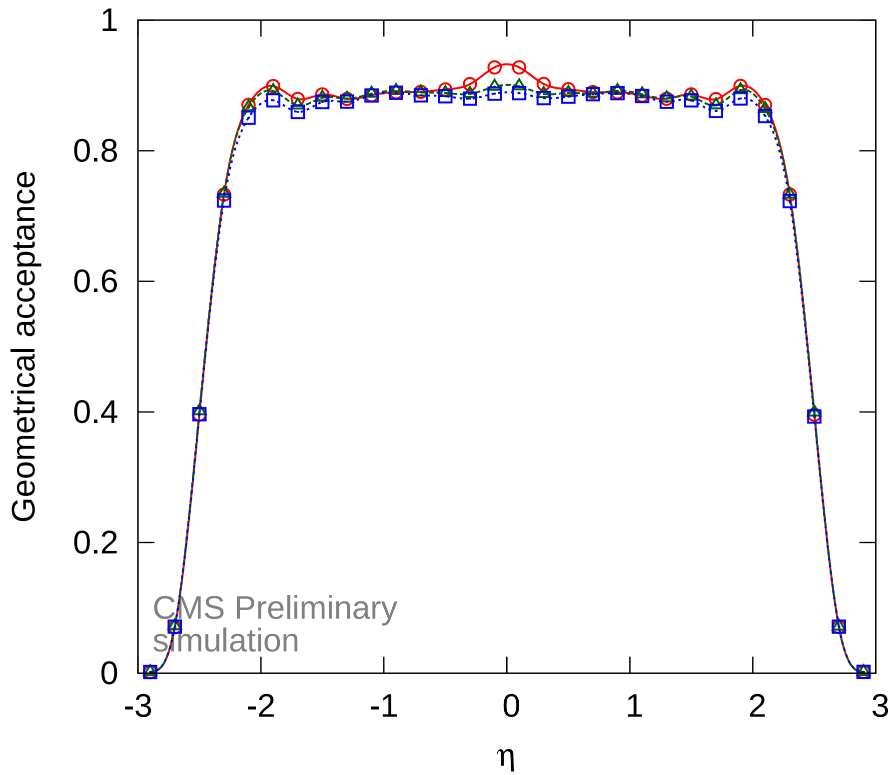
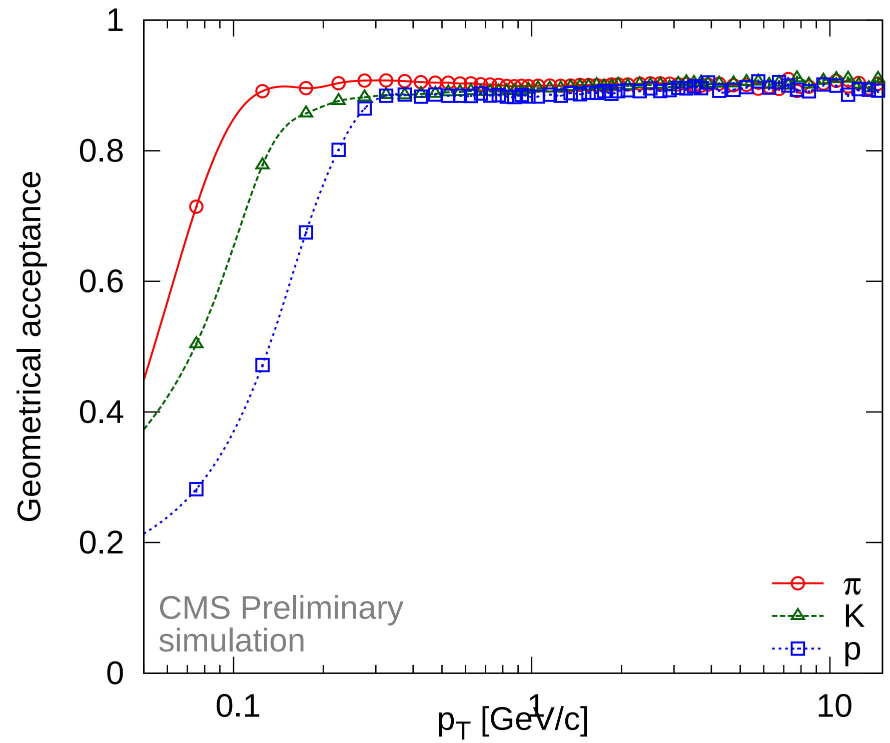
mouse drag: rotate | mouse release: spin | Shift + mouse vert: zoom | Shift + mouse horiz: rotate perp | 's': stereo | 'Home'

Example event, gallery at SoftPhysicsGallery

Charged particle tracking – acceptance



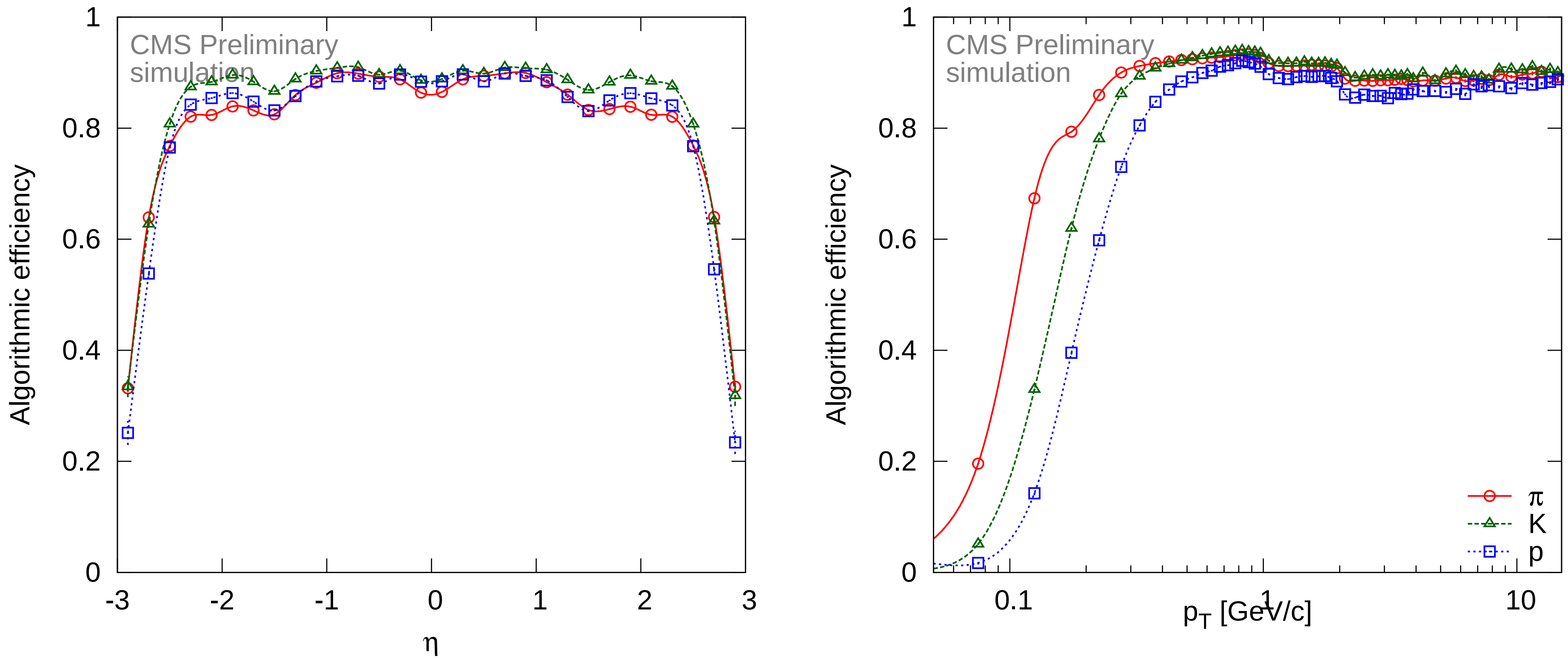


Fraction of simulated particles which are reconstructible
(it has at least three hits in different pixel layers)

At low p_T the effect of the mass is visible
Flat and smooth in central region

p_T [GeV/c]	0–1	1–2	2–4	4–8	8–16
Δp_T [GeV/c]	0.05	0.1	0.2	0.5	1

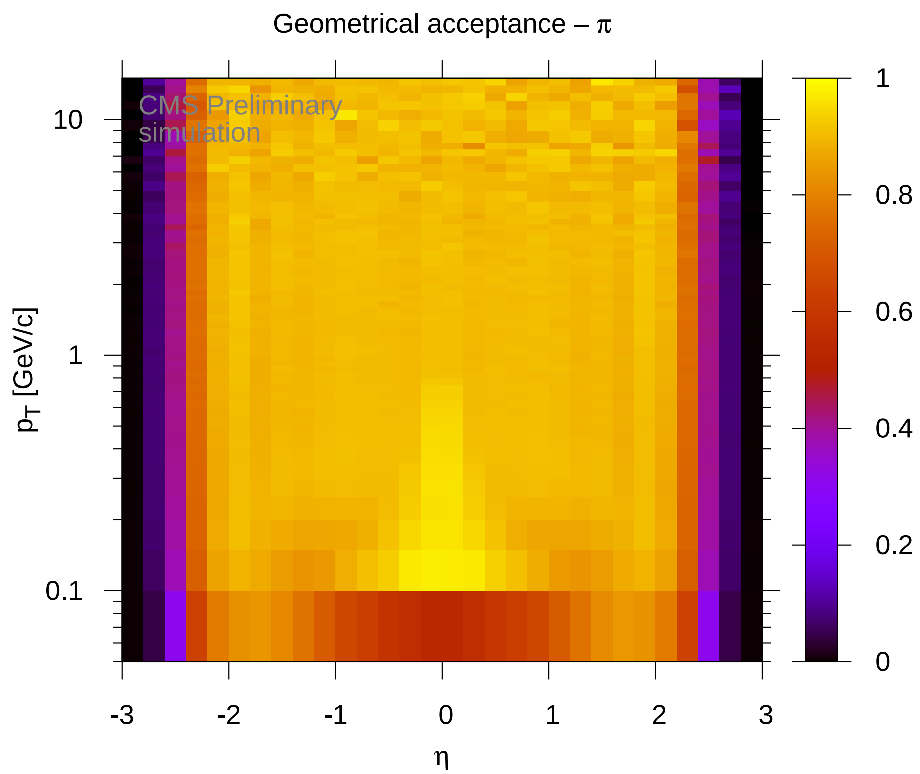
Charged particle tracking – efficiency

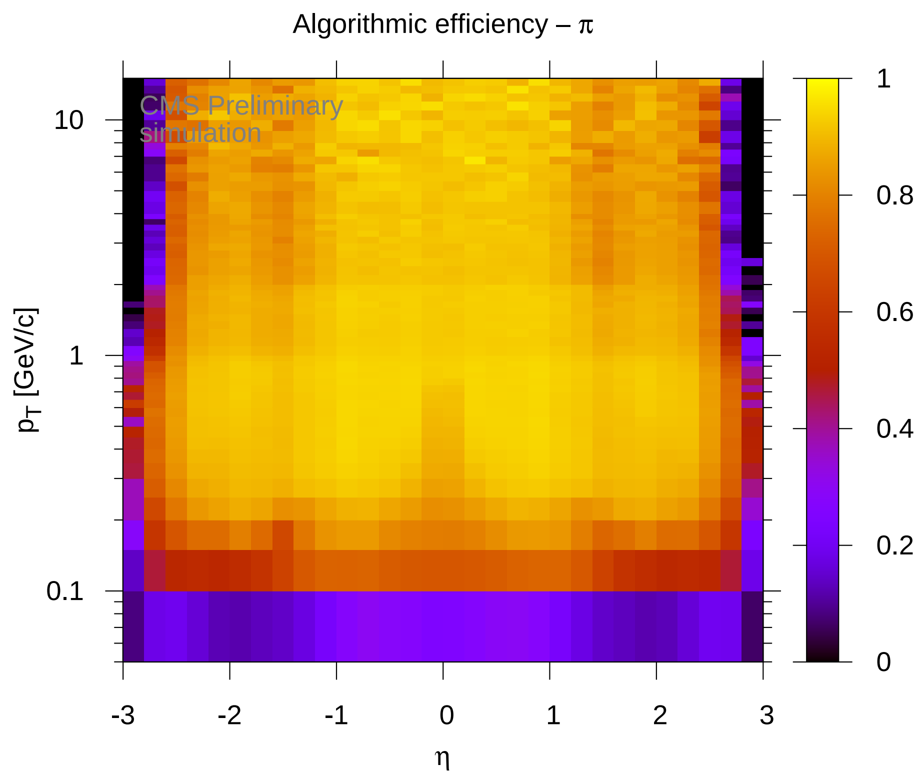


Fraction of reconstructible particles which are at least once reconstructed
(a reconstructed track is associated to a simulated particle if more than half of its hits, but at least three, are shared)

For low p_T different for particles with different mass
Steps at 1 and 2 GeV/c are due to stricter requirements (points on track)
Close to flat and smooth in central region

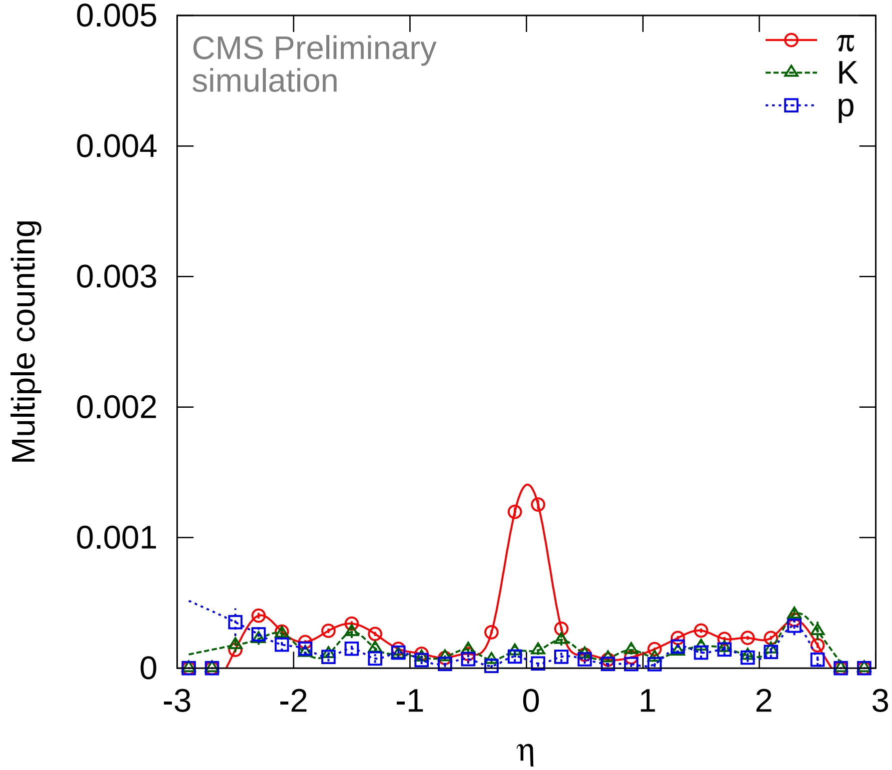
Charged particle tracking – correction tables

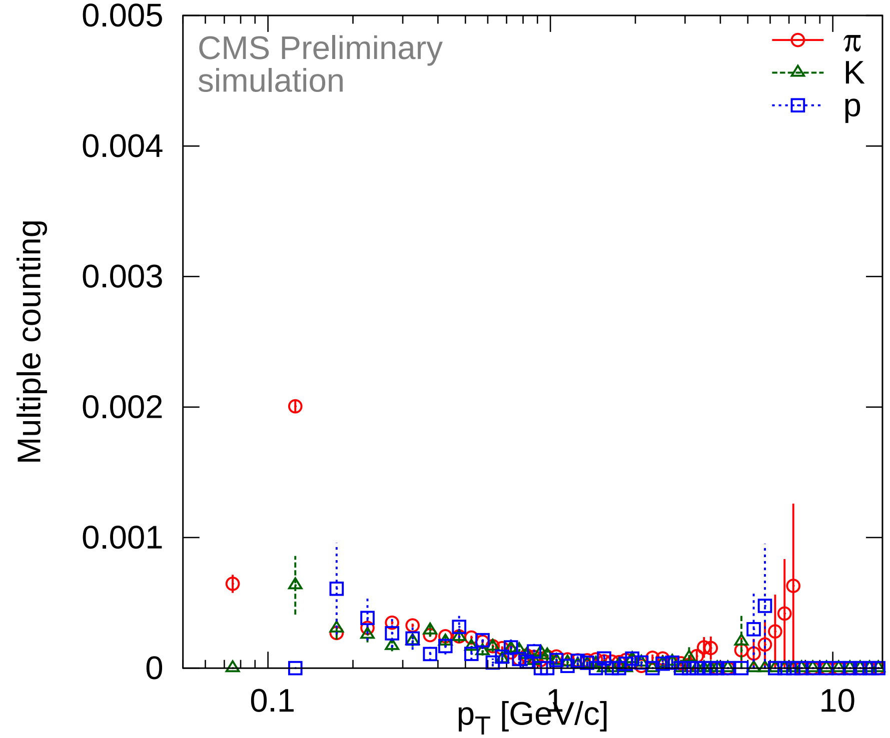




Two dimensional tables, they are used for correction

Charged particle tracking – multiple counting



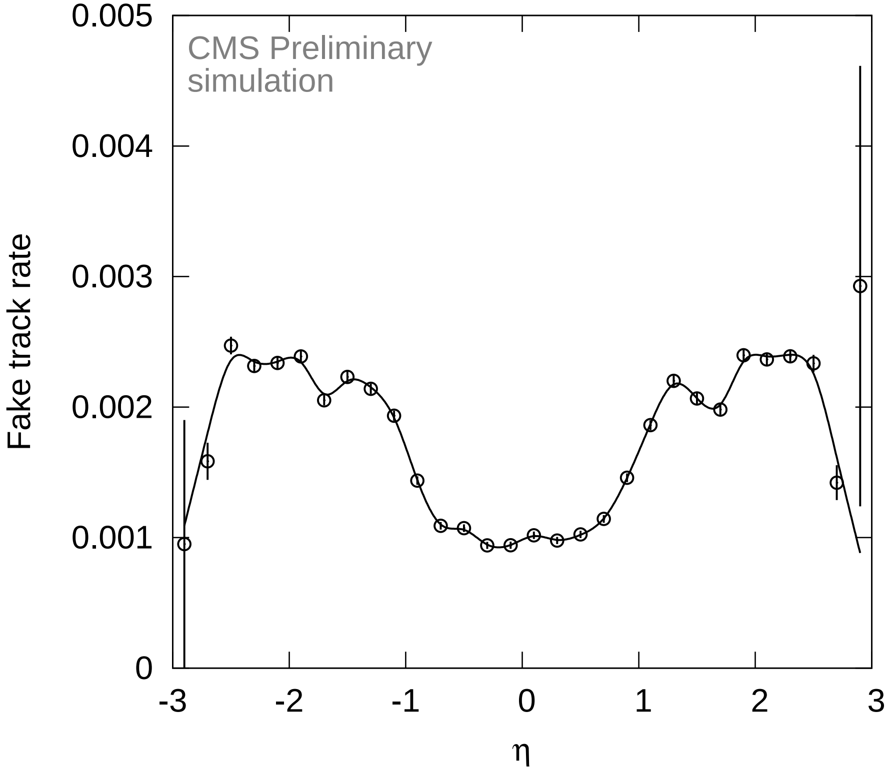


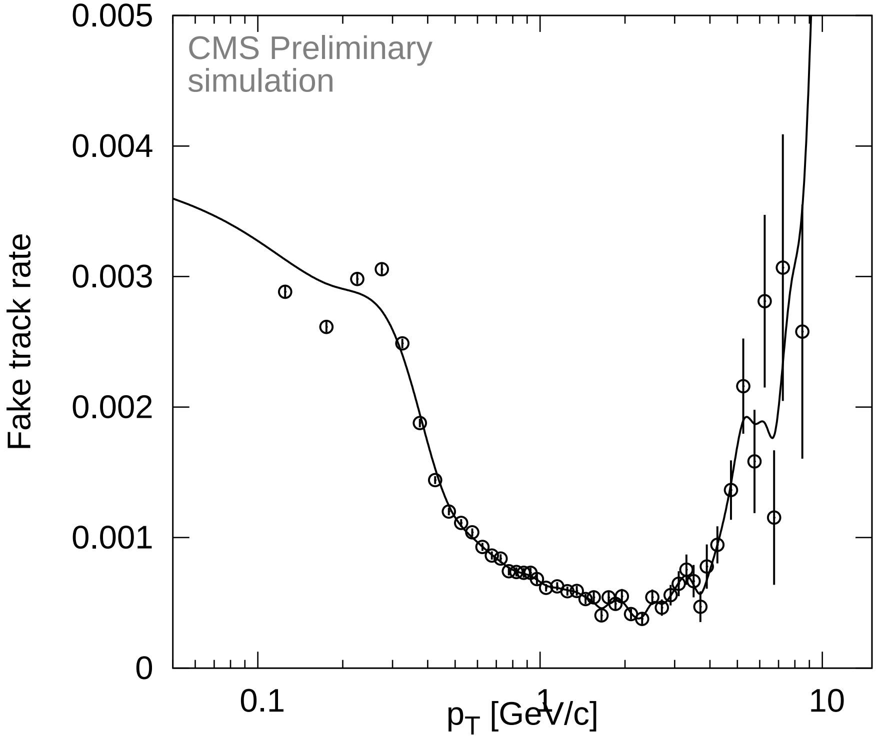
Fraction of reconstructible particles which are more than once reconstructed

Note the looping pions at $\eta \approx 0$

Very small, below per mille level

Charged particle tracking – fake track rate

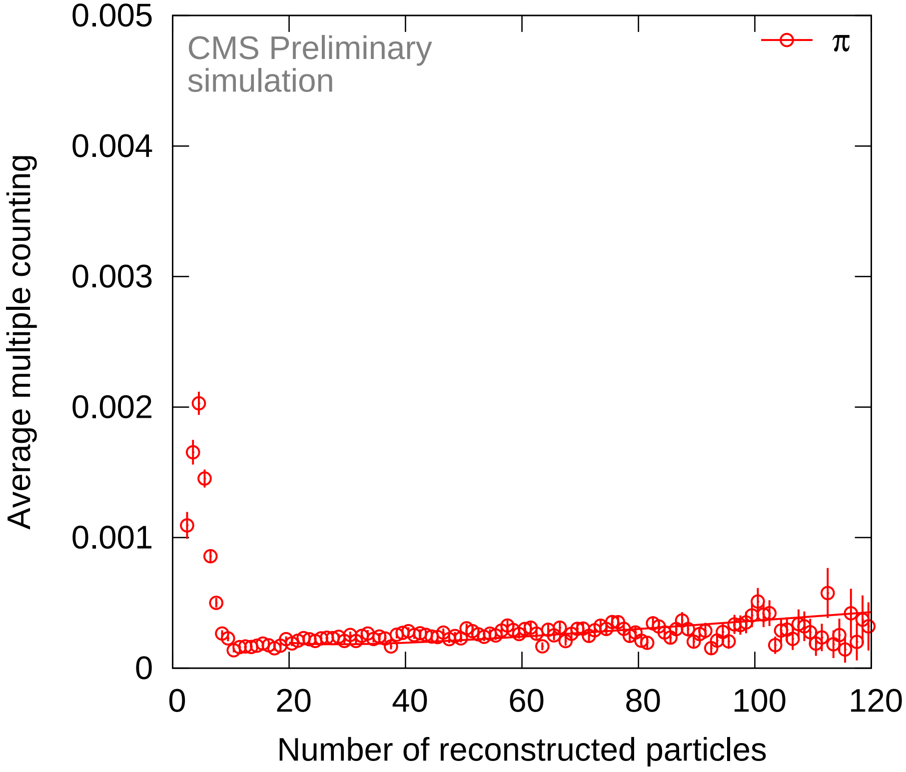


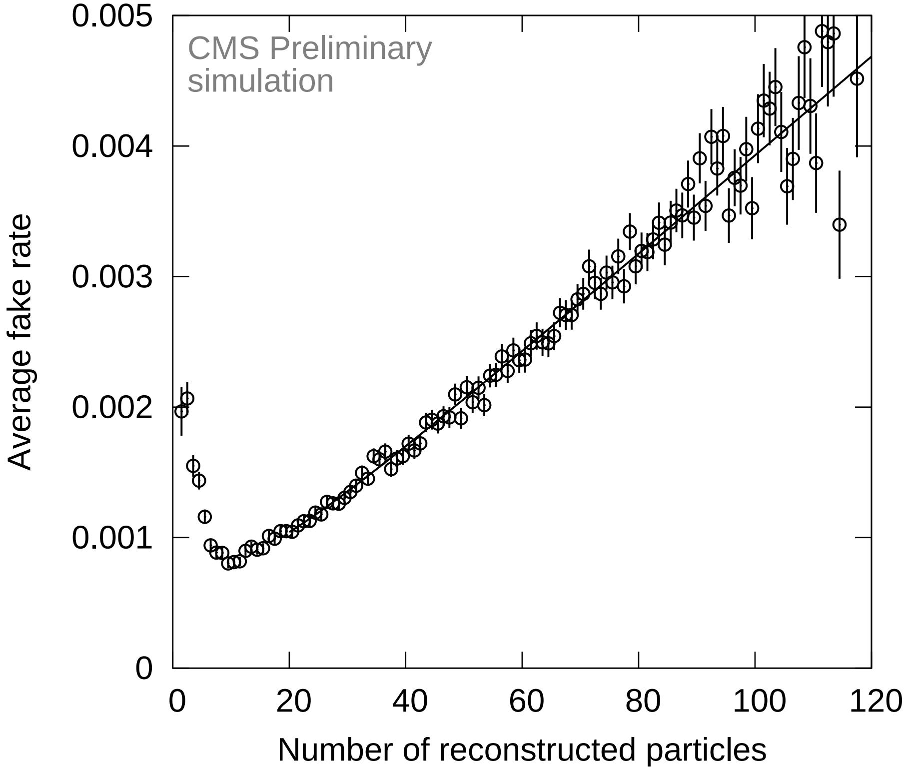


Fraction of reconstructed tracks which are fake
(a reconstructed track is fake if it has no associated particles)

Very small, around per mille level
Note: tracker is seeded with triplets + found event vertex

Multiplicity dependence





In case of no vertex (low multiplicity) averages go up

Linear dependence on multiplicity also in pile-up

Multiplicity dependent correction

Corrections

Dependence of several corrections on parameters, such as kinematical variables, particle type and event multiplicity (also on number of pile-up collisions). The magnitude of the correction and the estimated contribution to the overall systematic error is shown as well.

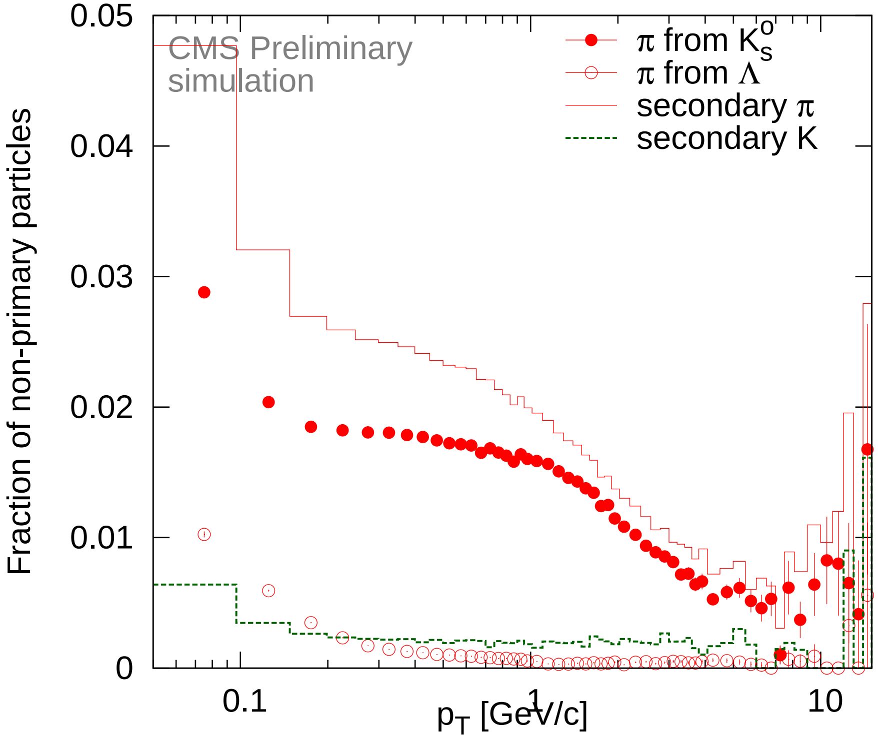
Correction	Dependence on			Corr.	Syst.
	kine	part	mult	[%]	
Trigger	no	no	yes	15	5
Geometrical acceptance	yes	yes	no	10-20	2
Algorithmic efficiency	yes	yes	no	10-20	2
Multiple track counting	yes	no	no	small	small
Fake track rate	yes	no	yes	small	small
Feed-down	yes	yes	no	2-15	1-2
η, p_T resolution	no	no	no	1-5	1-5
Total	yes	yes	yes		7-9

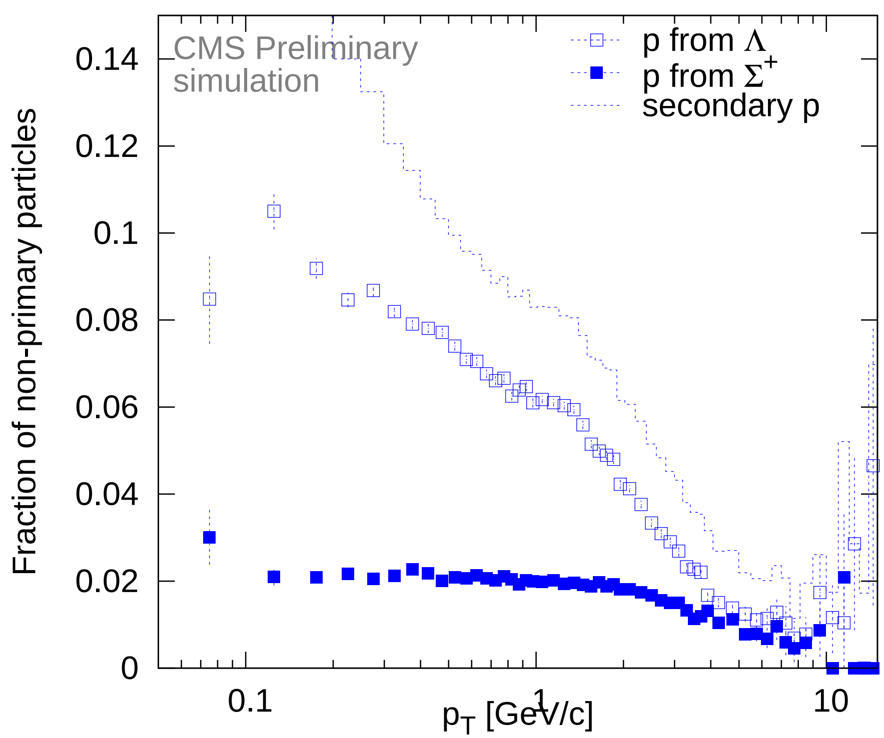
$$\Delta N_{\mathrm{corrected}} = \frac{(1-\mathrm{fakeRate})\cdot(1-\mathrm{feedDown})}{\mathrm{geomAccep}\cdot\mathrm{algoEffic}\cdot(1-\mathrm{multiCount})}\cdot\Delta N_{\mathrm{measured}} \qquad (1)$$

Corrections are dominated by trigger definition

Summary table

Corrections – feed-down



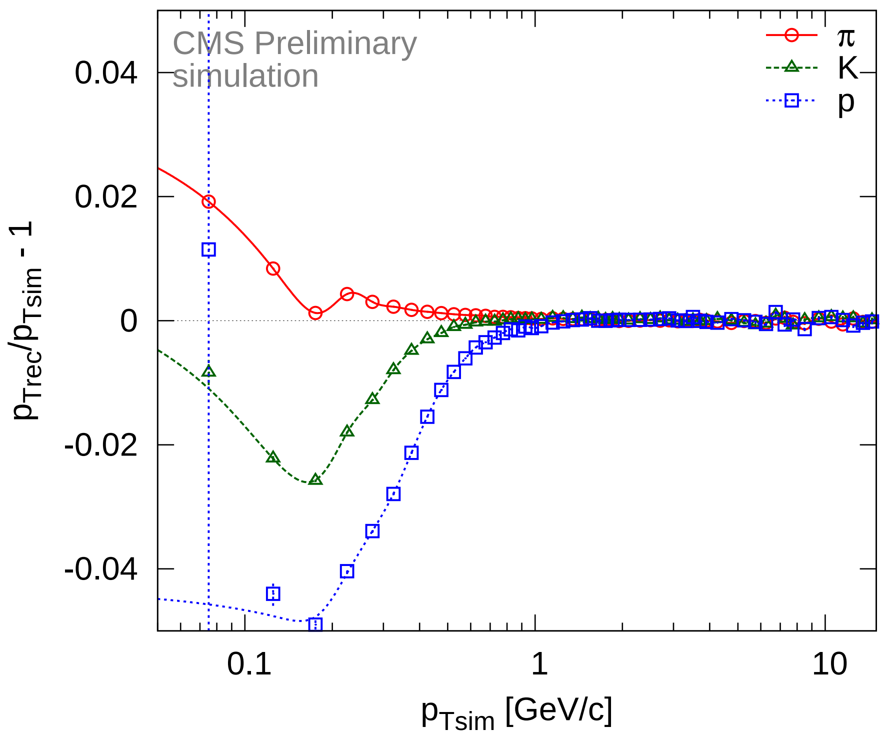


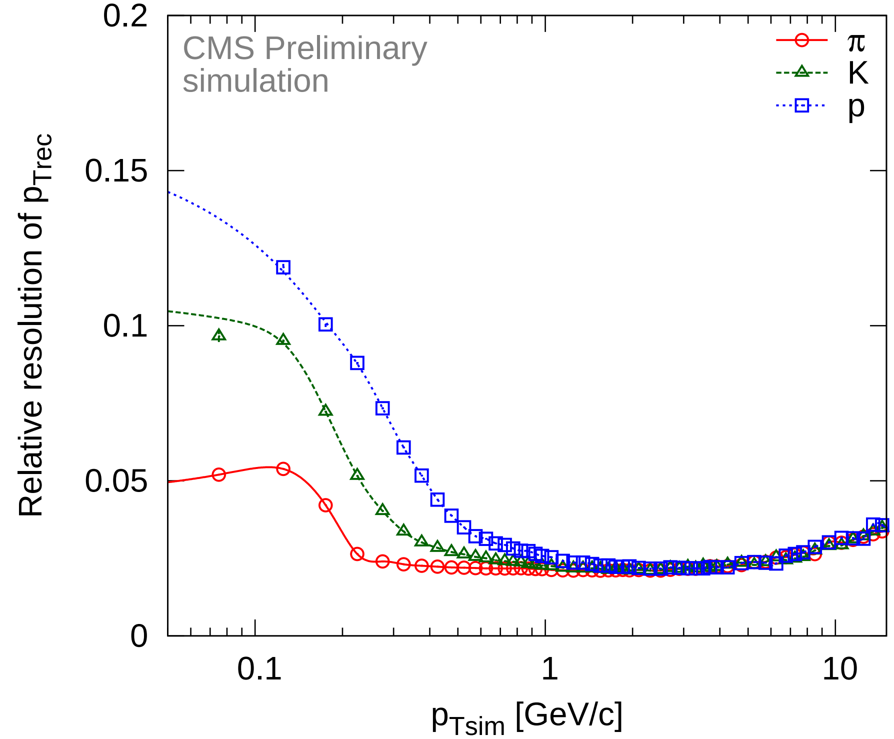
Resonance	Decay	Branching	$c\tau$ [cm]
K_S^0	$\pi^+\pi^-$	69.2%	2.68
$\Lambda/\overline{\Lambda}$	p π^- / $\overline{\mathrm{p}}$ π^+	63.9%	7.89
$\Sigma^+/\overline{\Sigma}^-$	p π^0 / $\overline{\mathrm{p}}$ π^0	51.6%	2.40

Sizeable correction for protons from Λ decays

Later: get the correction from direct measurement of K_S^0, Λ,$\overline{\Lambda}$, even Σ^+ and $\overline{\Sigma}^-$

Corrections – p_T bias and resolution



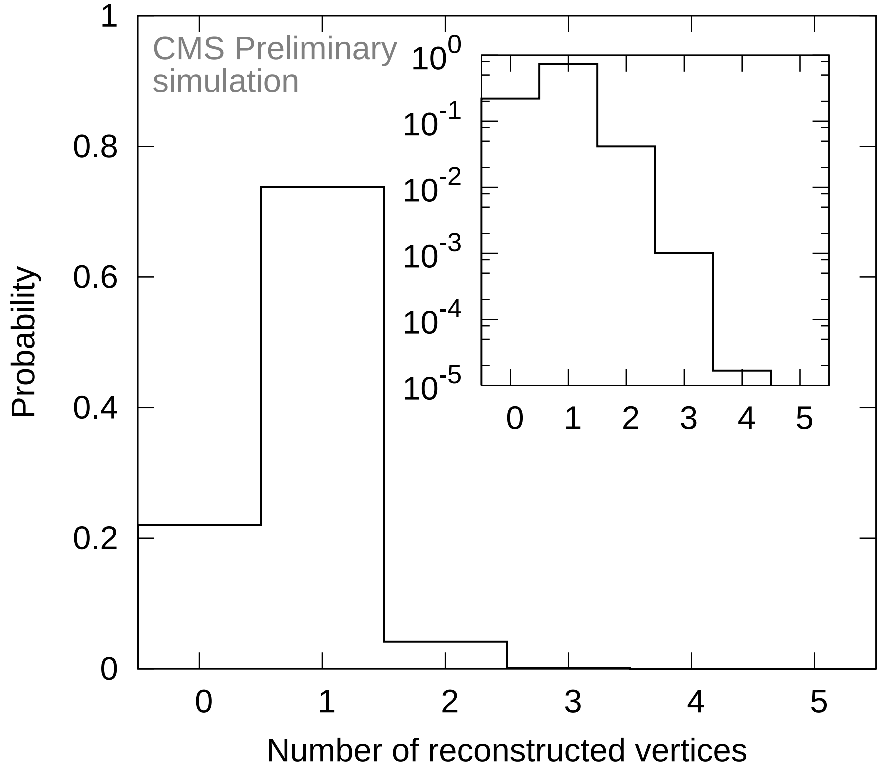


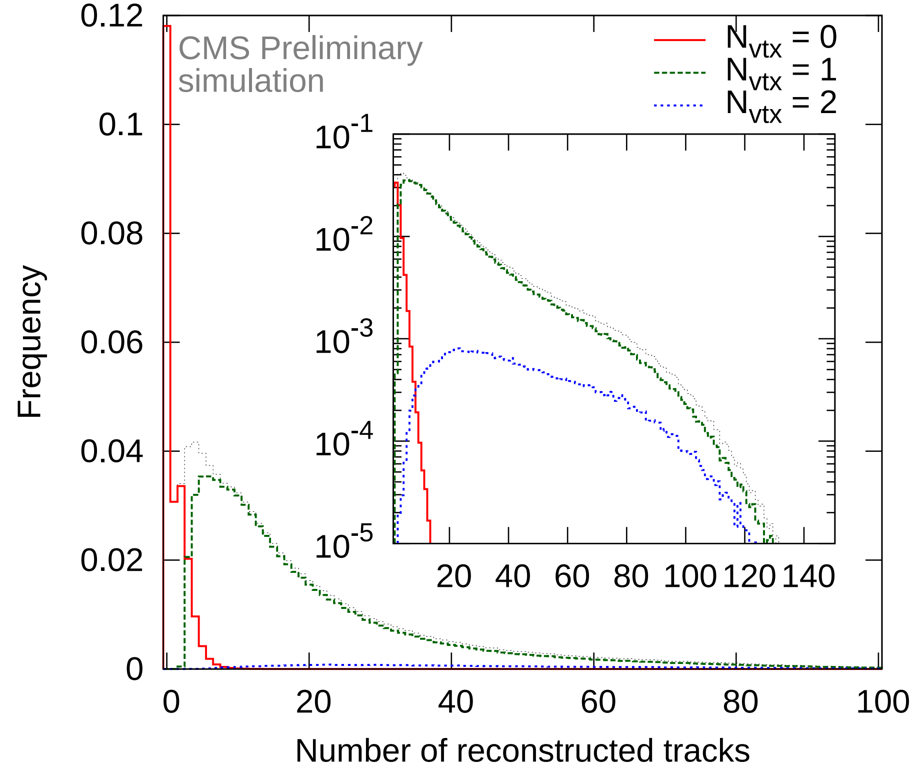
Very small bias

Particles are fitted with pion mass assumption

p_T resolution is (η,p_T) dependent, η resolution is neglected

Corrections – triggers, vertexing

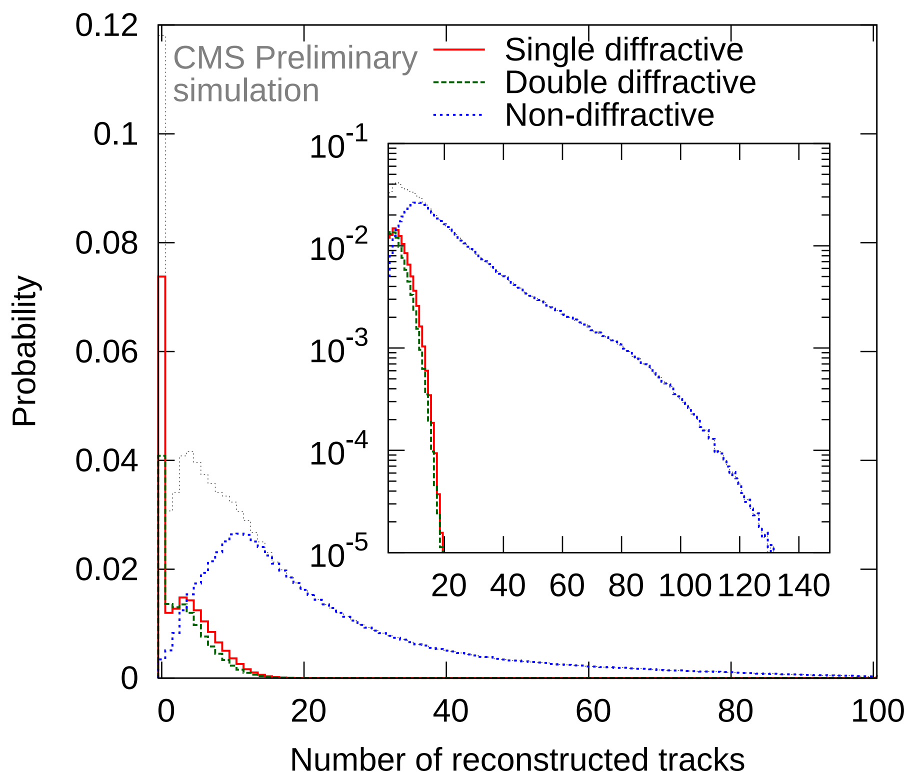




- Zero-bias off-line triggers
  - Track trigger : the event has at least one reconstructed track
  - Vertex trigger: the event has at least one reconstructed primary vertex

Probability to reconstruct 0, 1 or 2 interaction vertices are 22.0%, 73.7% and 4.2%

Corrections – multiplicity distribution

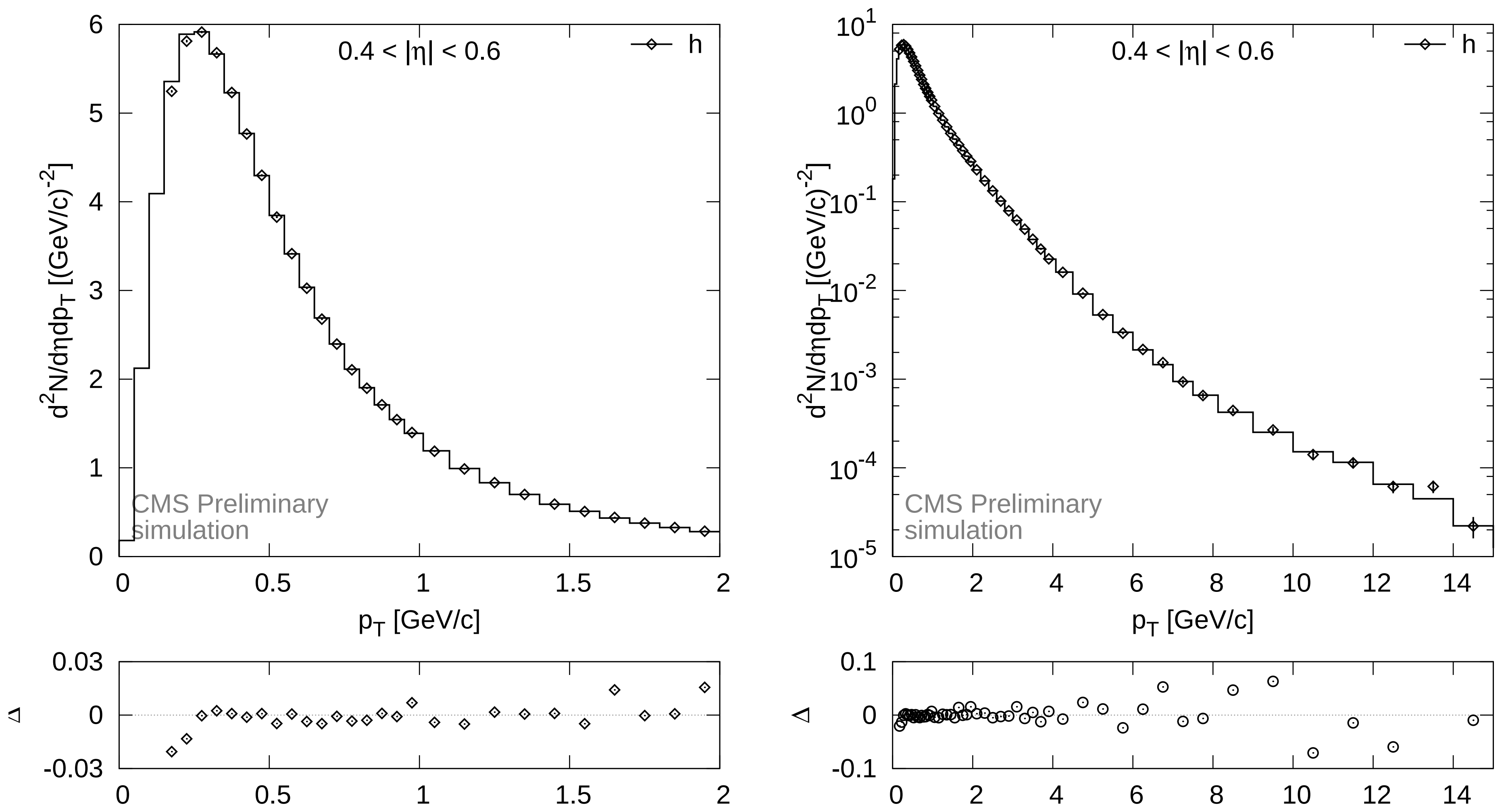


	Trigger efficiency			
	SD	DD	ND	Inelastic
Track trigger	59.2%	68.6%	99.5%	88.2%
Vertex trigger	38.5%	39.7%	95.6%	77.9%

Peak due to diffractive events is visible

Can measure multiplicity distributions

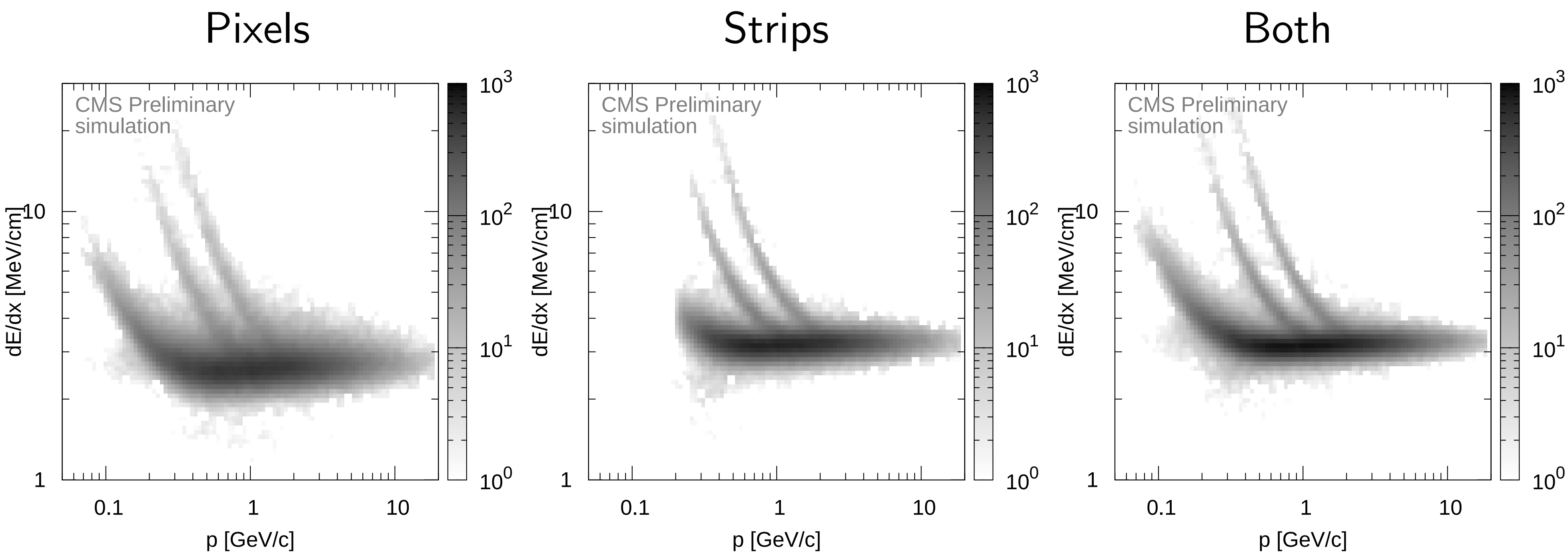
Results – charged spectra, comparisons



Comparison of simulated (histogram) and reconstructed (symbols), $0.4 < |\eta| < 0.6$

Can one identify these particles? $\Rightarrow$ dE/dx

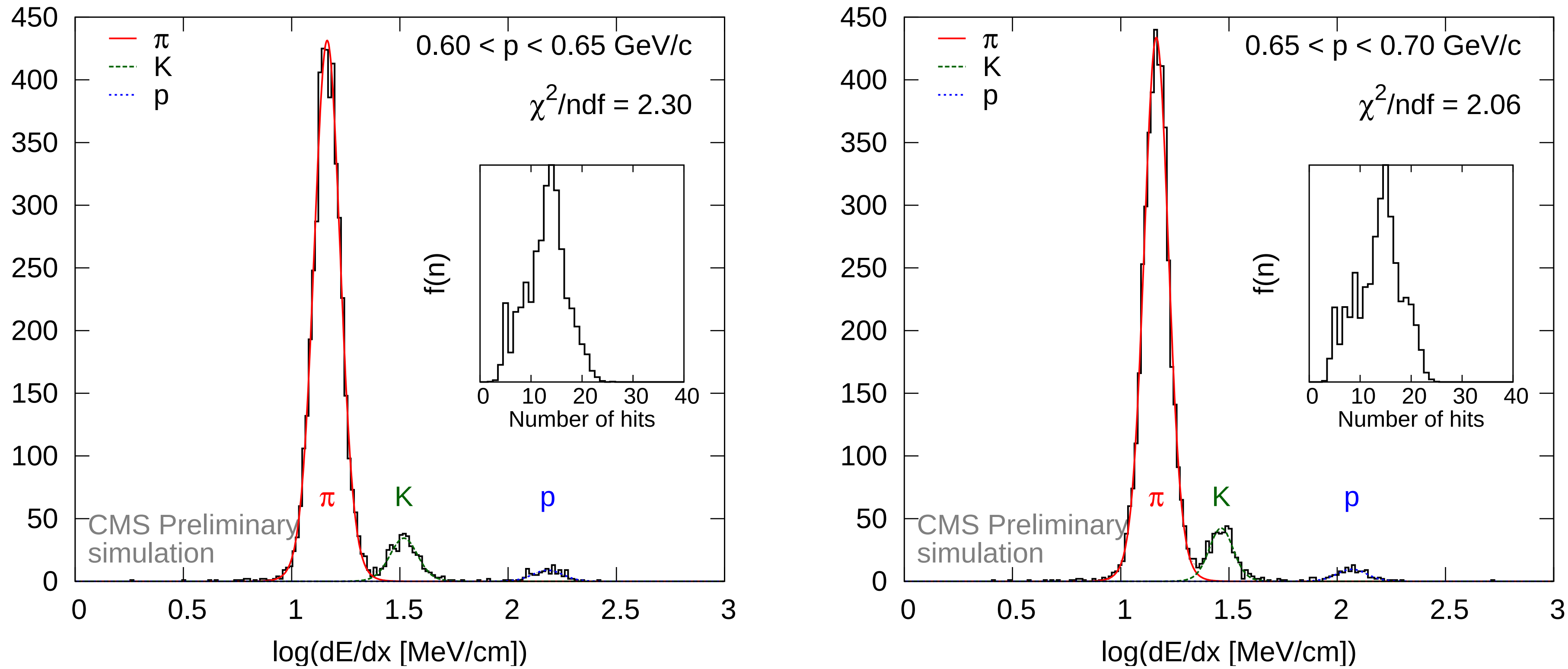
Energy loss analysis – estimator



Truncated mean dE/dx (average of lowest half) using both pixel and strip hits

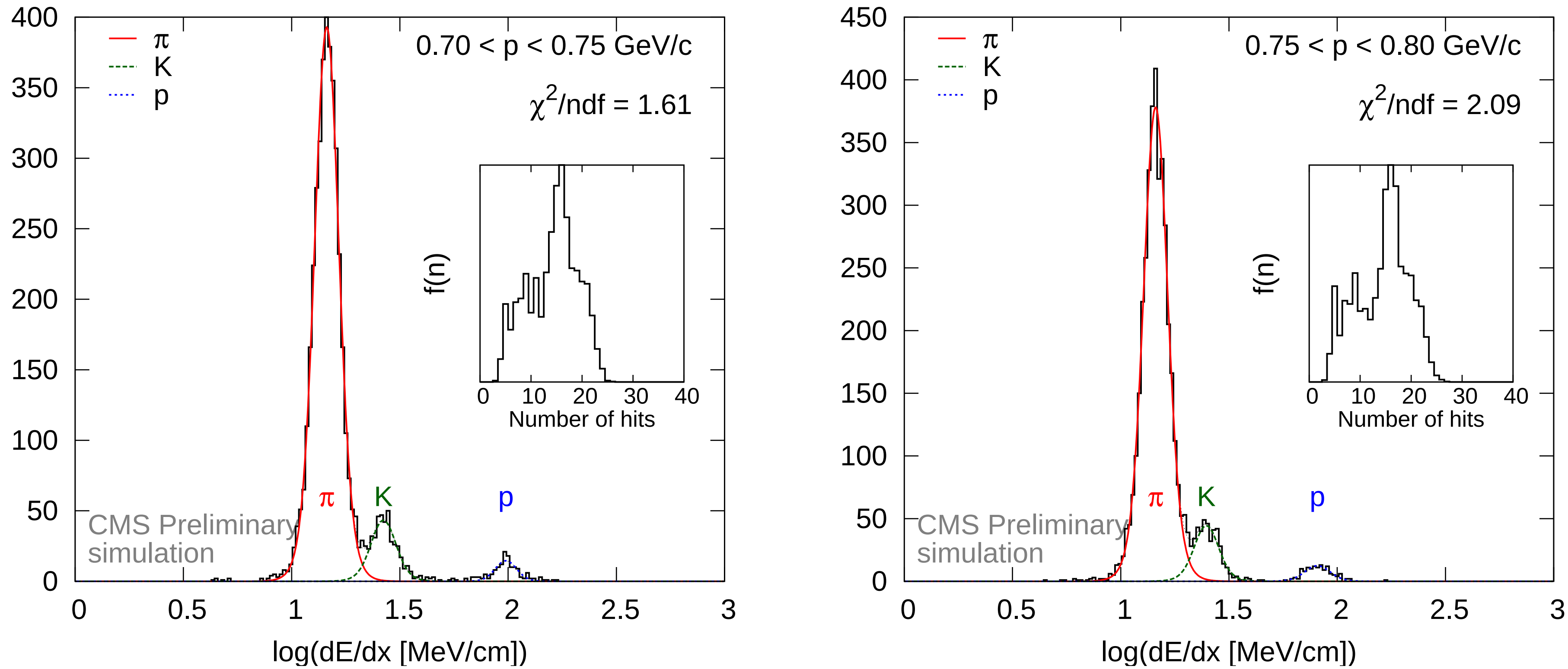
Proper treatment for overflows

Energy loss analysis – fits (1)



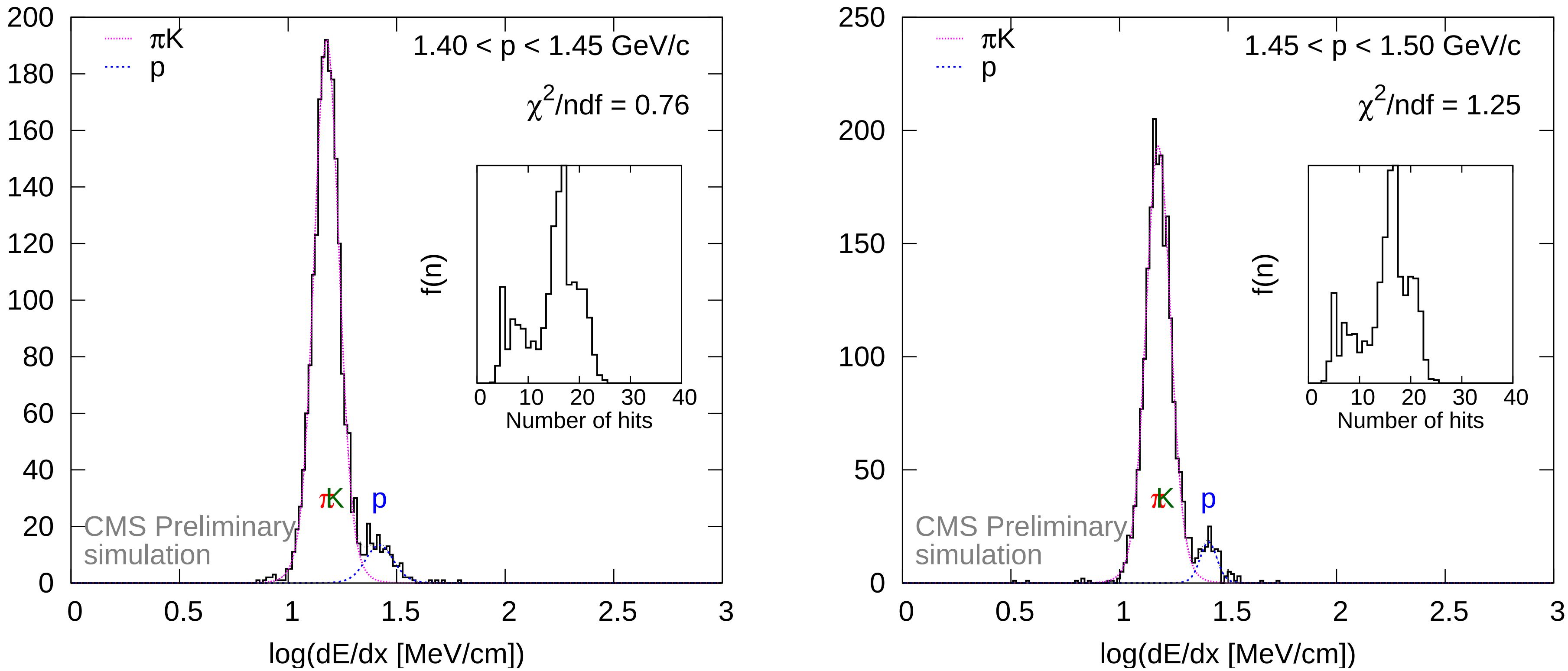
Combined fit using sum of many gaussians, where $\sigma \propto 1/\sqrt{n_{hits}}$

Energy loss analysis – fits (2)



Relative yields can be extracted via fitting and integration
(identification in the statistical sense)

Energy loss analysis – fits (3)

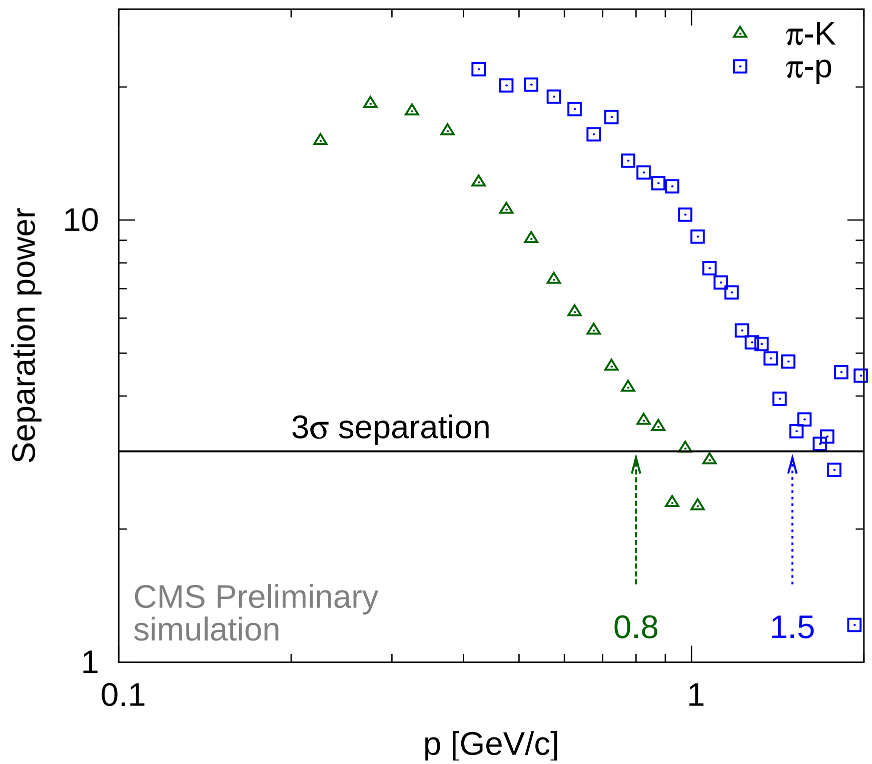


About 5-7% expected resolution

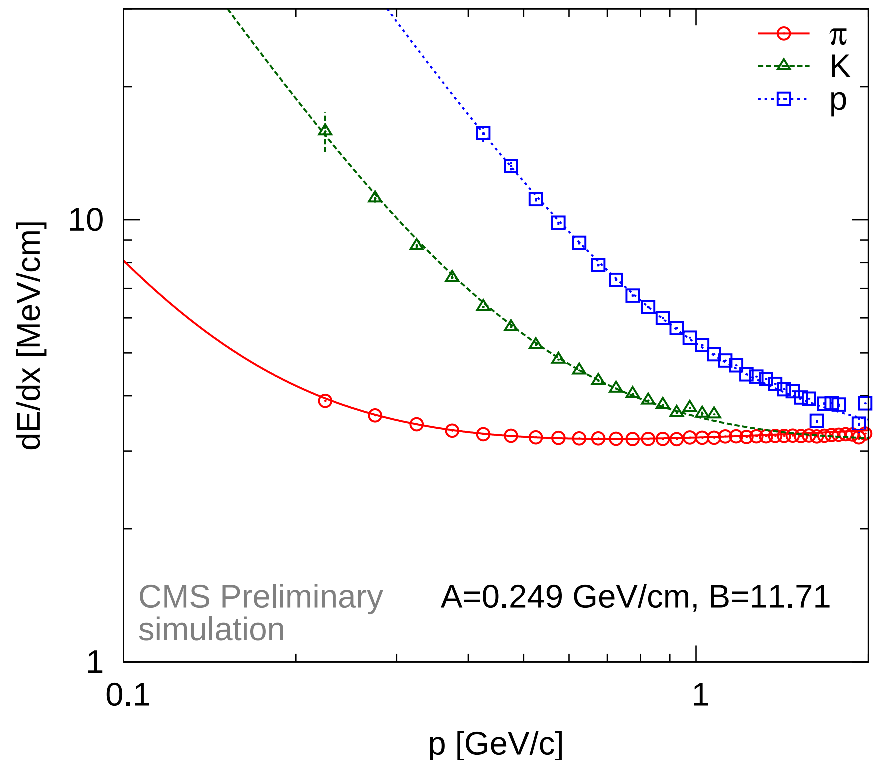
Depends on final channel-to-channel calibration

Energy loss analysis

Separation power



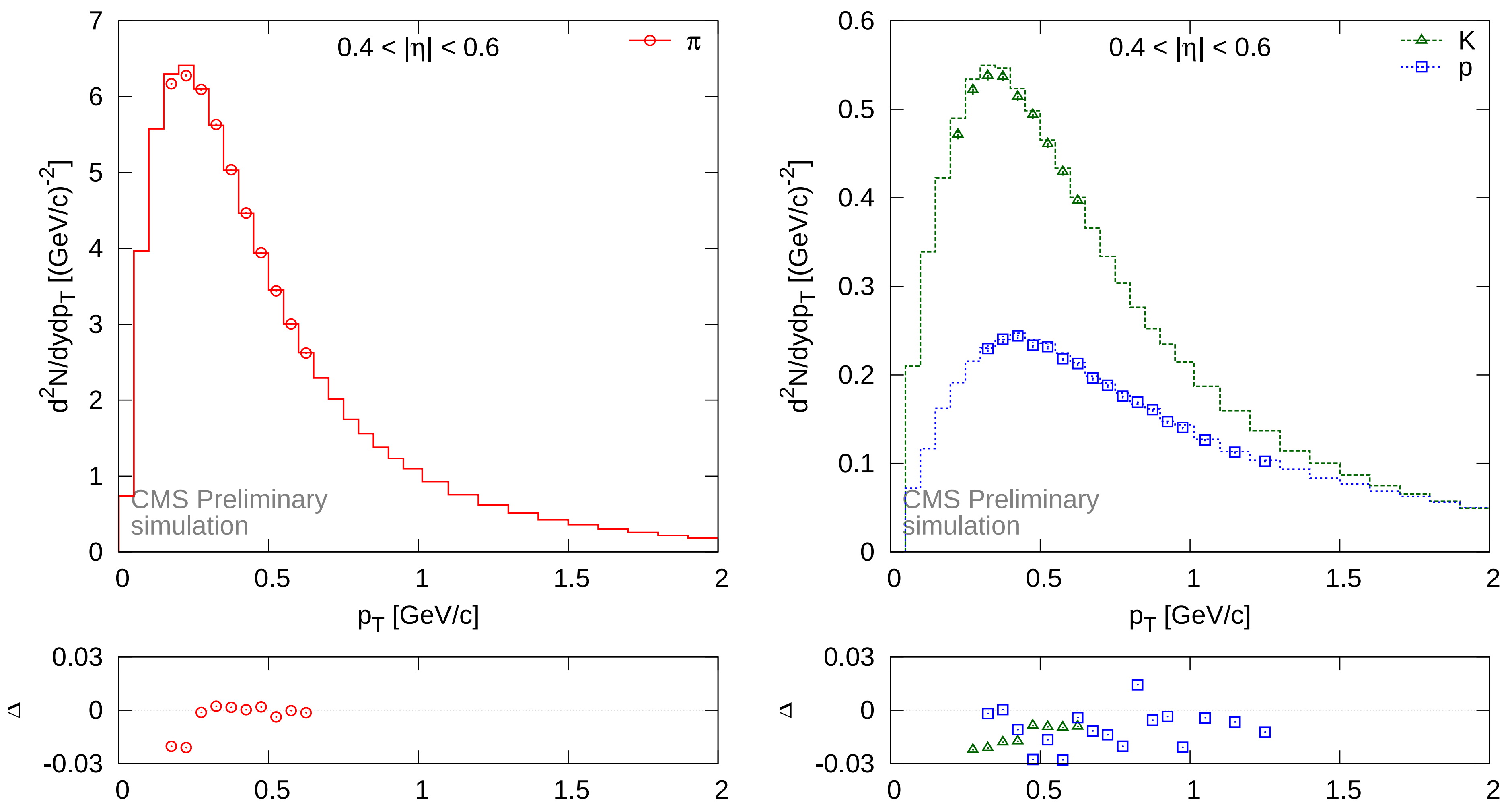
Bethe-Bloch



Momentum limit of yield extraction is set to 3σ separation

Could use $\beta\gamma$ scaling to fix parameters and push up limit

Results – particle spectra, comparisons



PID expected for pions and kaons ($p < 0.8$ GeV/c) and protons ($p < 1.5$ GeV/c)

Comparison of simulated (histogram) and reconstructed (symbols), $0.4 < |y| < 0.6$

Results – variables, fit functions

Invariant yields

$$E\frac{d^3N}{dp^3} = \frac{d^3N}{d\phi\, dy\, p_T\, dp_T} = \frac{1}{2\pi p_T}\frac{d^2N}{dy\, dp_T} \tag{2}$$

Interpolation to y

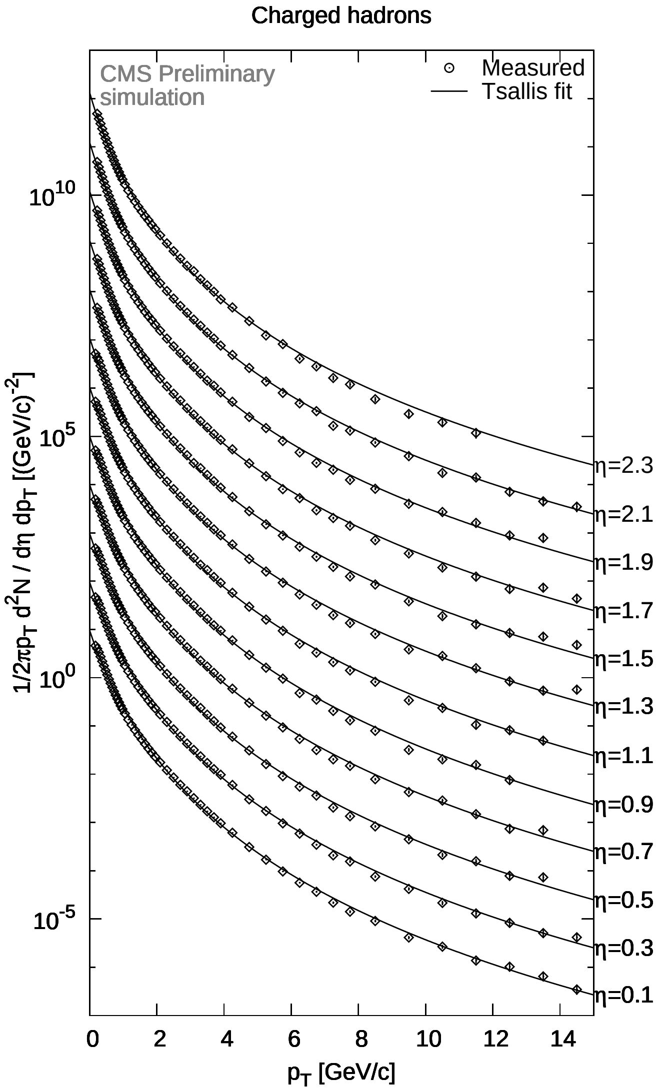
$$\frac{d^2N}{dy\, dp_T} = \frac{E}{p}\,\frac{d^2N}{d\eta\, dp_T} \tag{3}$$

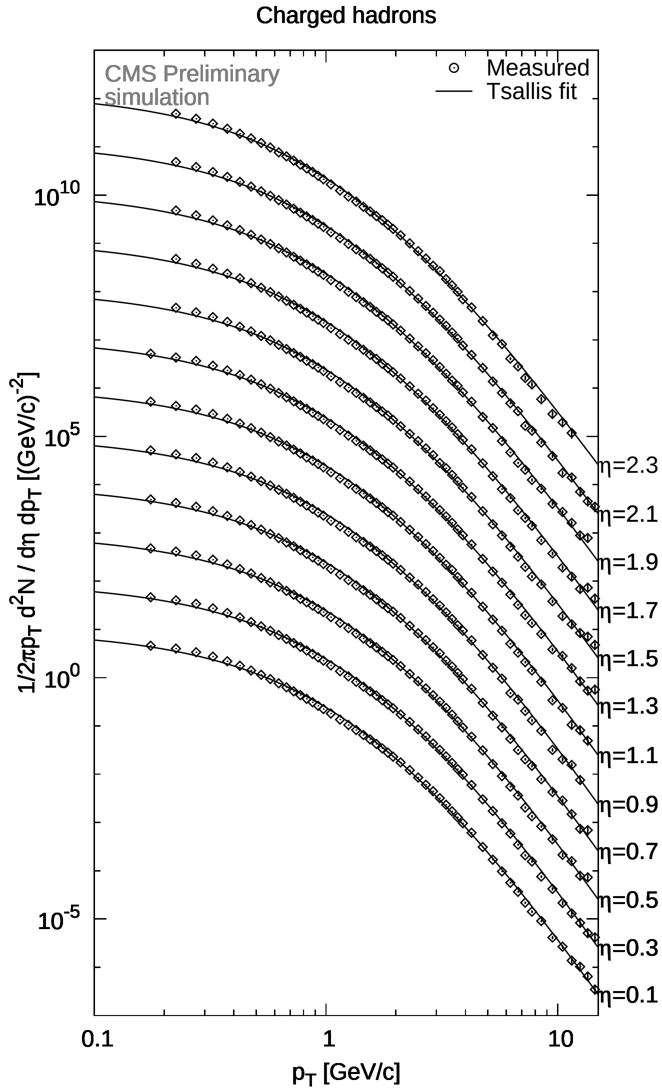
Empirical fit function (Tsallis or Levy) from UA1, Tevatron, RHIC

$$E\frac{d^3N}{dp^3} = \frac{dN}{dy}\,\frac{(n-1)(n-2)}{2\pi\, nT\,[nT+(n-2)m]}\,\left[1+\frac{E_T(p_T)}{nT}\right]^{-n} \tag{4}$$

Thermal and power-law function in low and high p_T limits
Good description of data

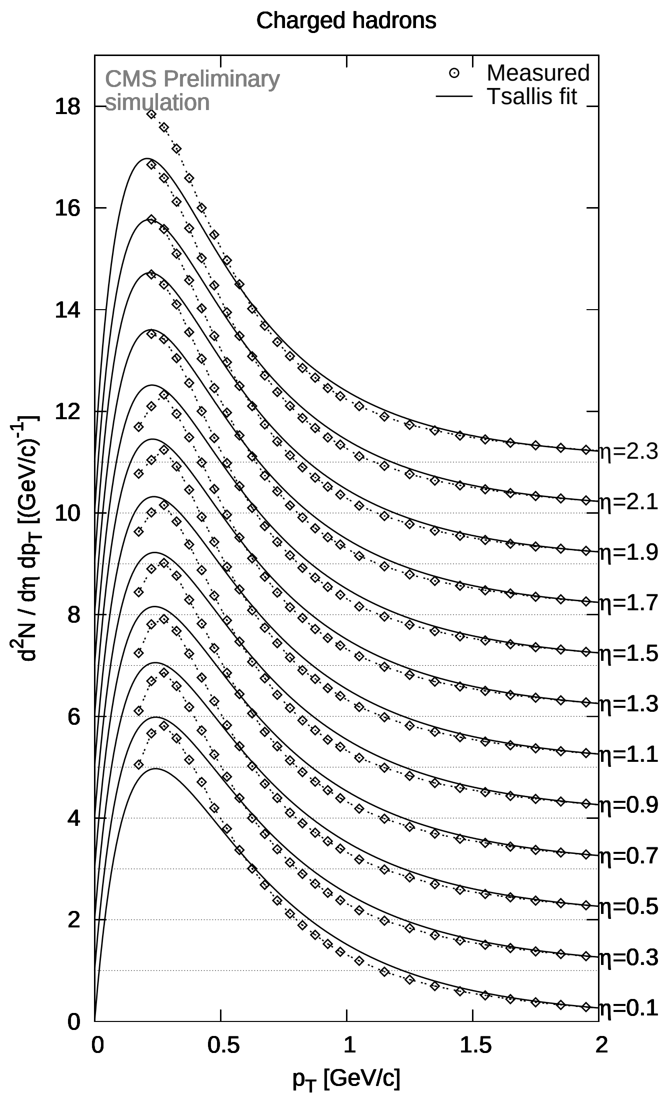
Detailed results – charged hadrons

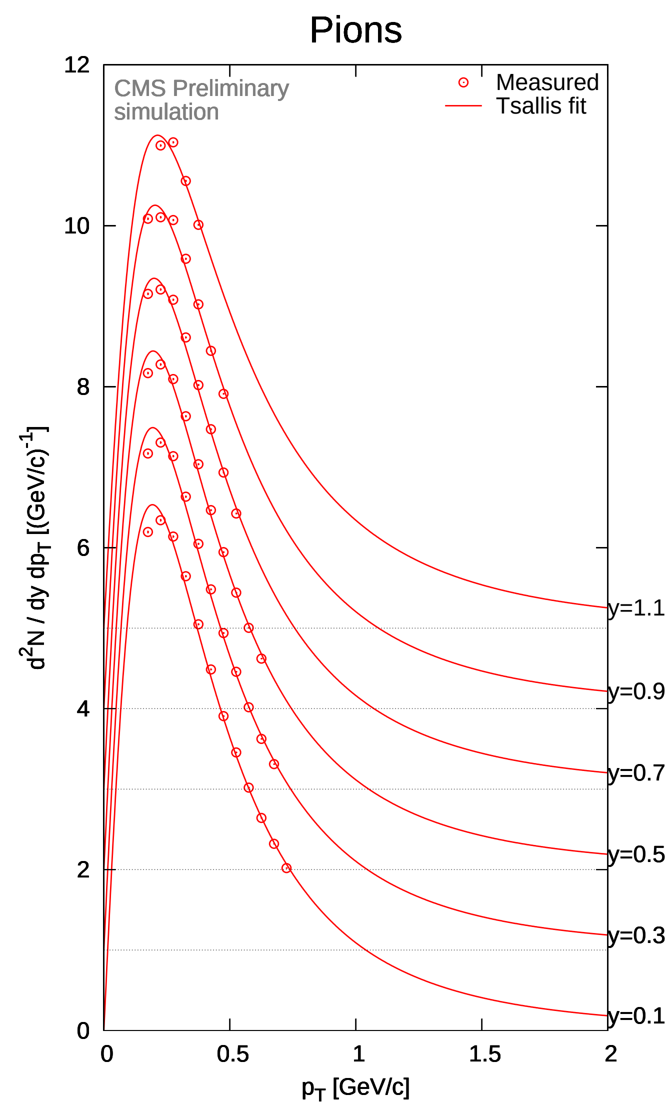




Good fit, only slight changes with η

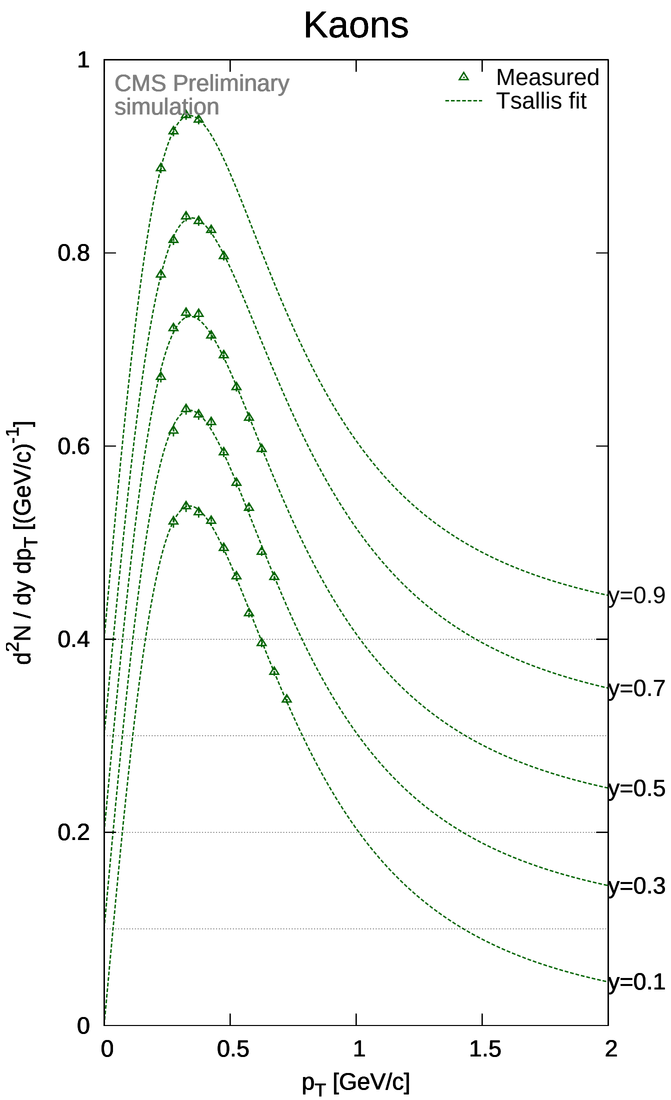
Detailed results – hadrons, pions

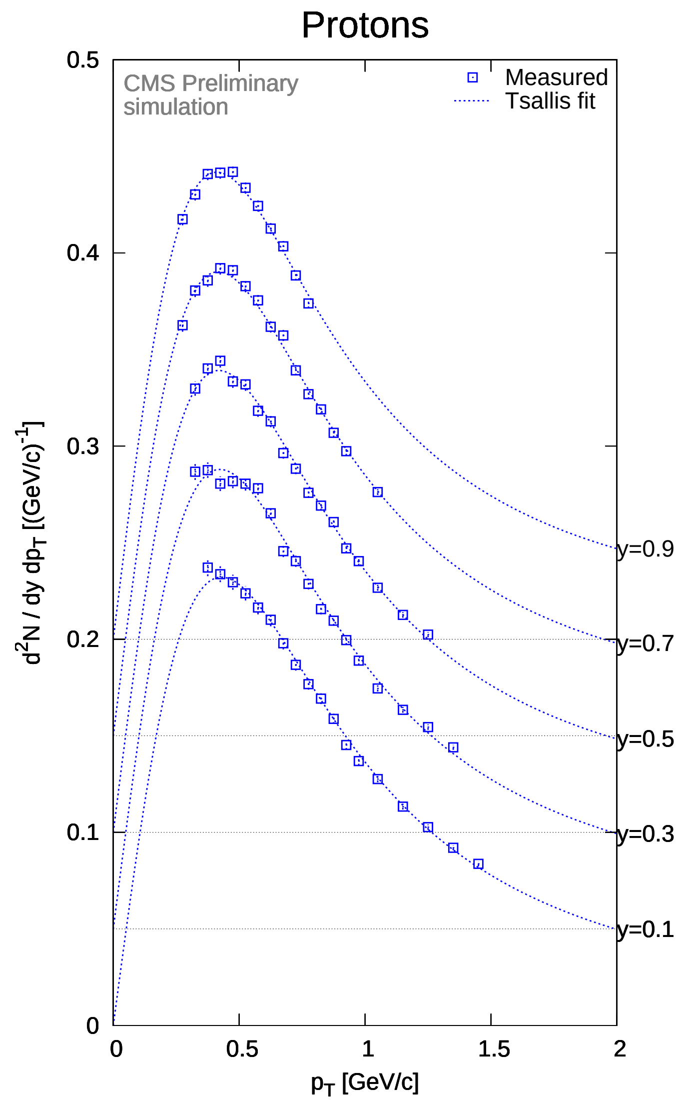




Good fit but departures for low p_T

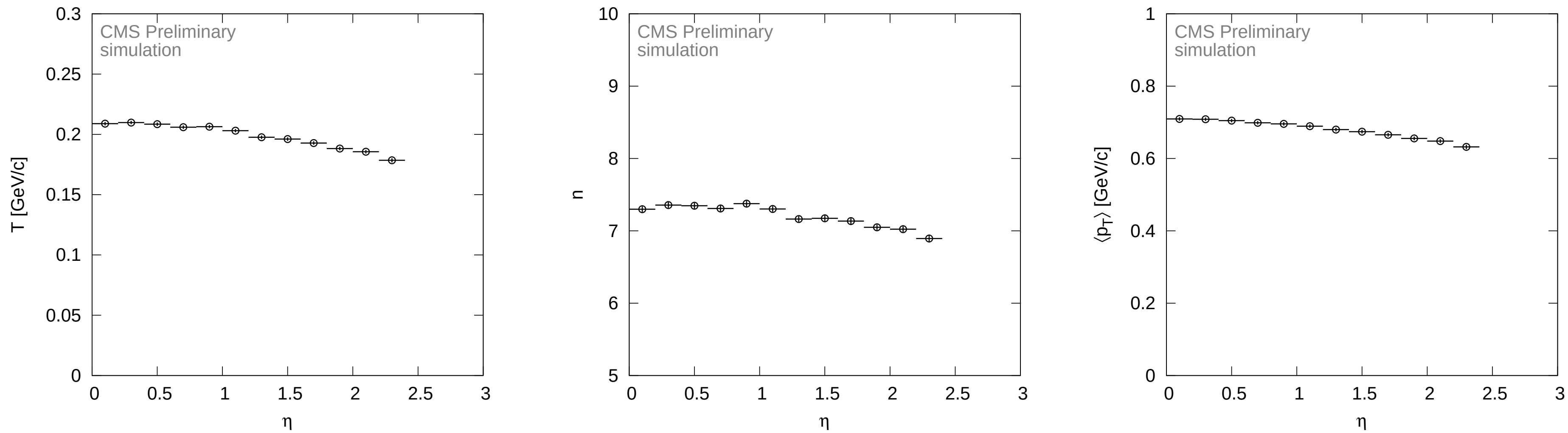
Detailed results – kaons, protons





Exponent of the power-law is taken from unidentified spectra

Detailed results – charged hadron fit results

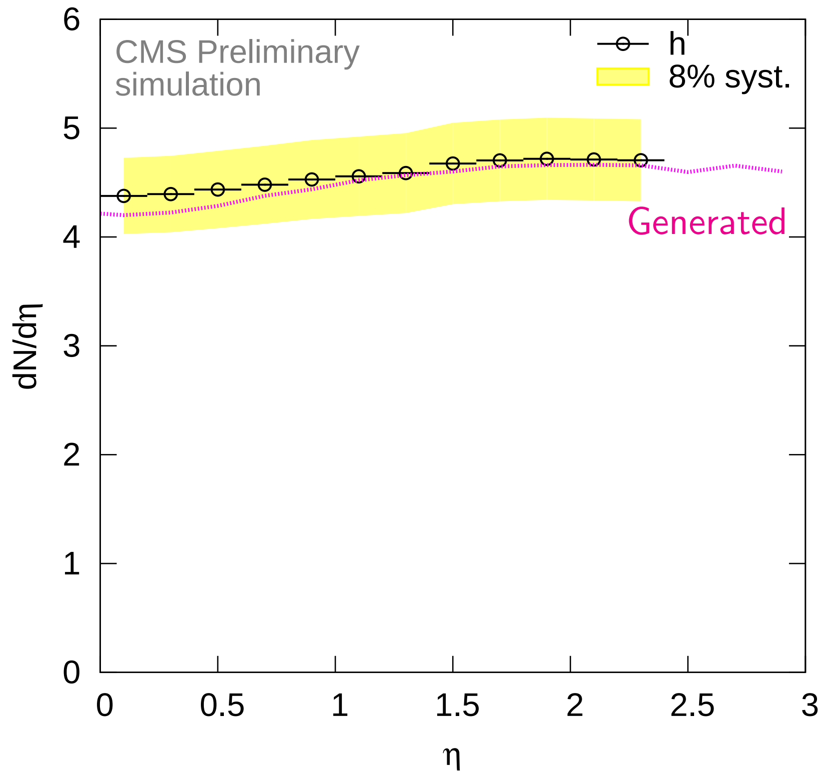


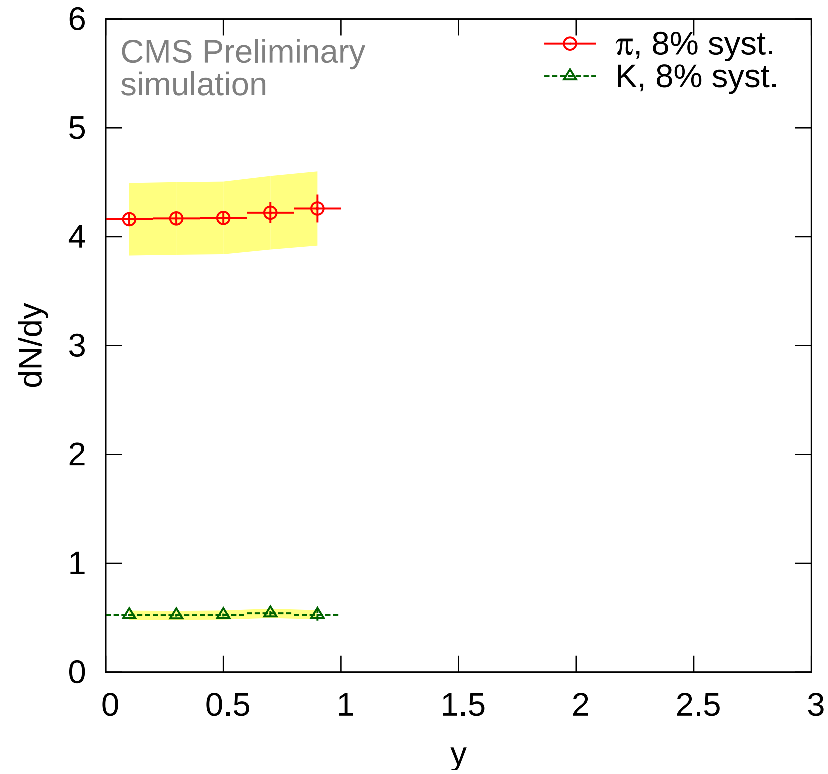
Fitted parameters of unidentified charged hadron spectra

- Parameters
  - Inverse slope $T \approx 0.2$ GeV/c
  - Exponent of the high p_T power-law tail is $n \approx 7.2$
  - Average transverse momentum is $\langle p_T \rangle \approx 0.7$ GeV/c

All parameters change only slightly with increasing η
Empirical parameterization, three parameters

Detailed results – rapidity density





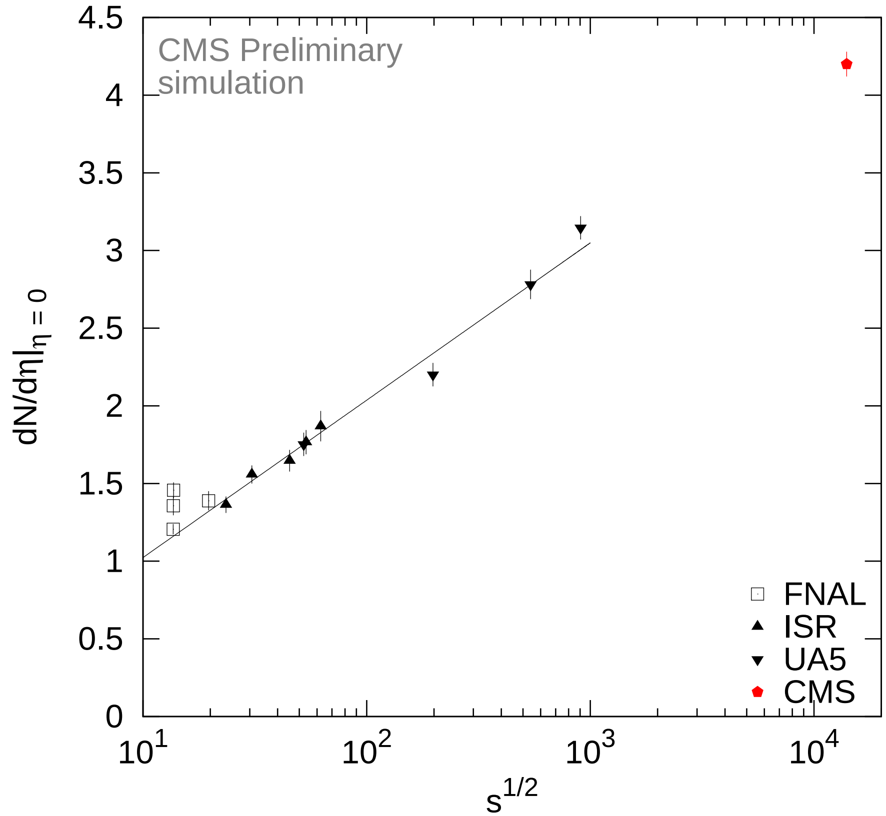
p_T spectrum is summed and integrated

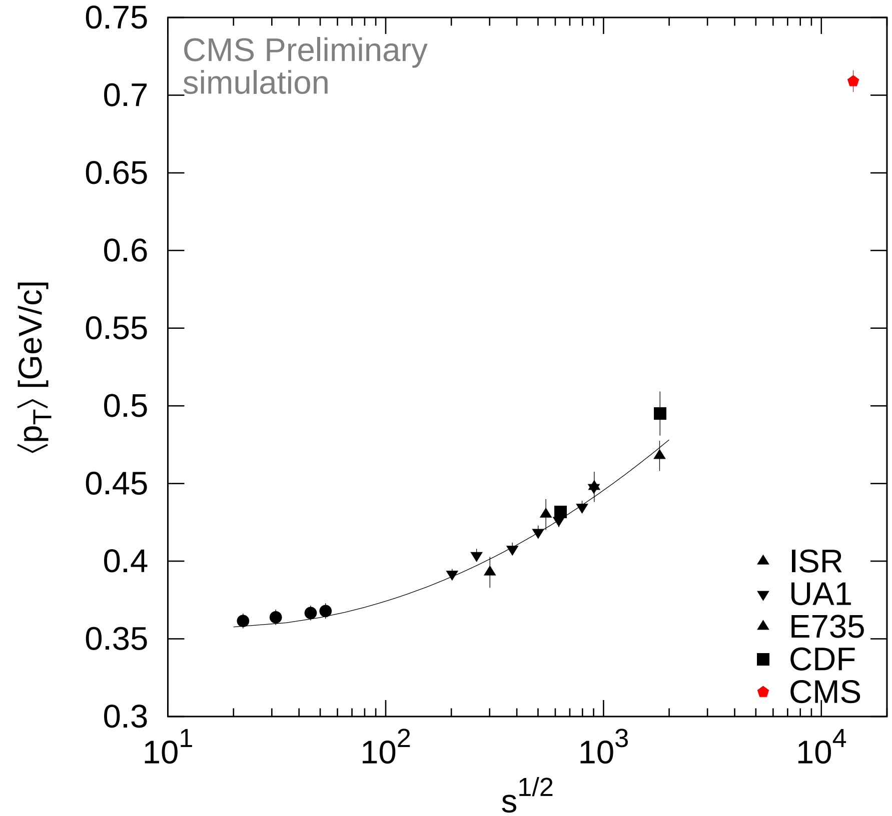
The acceptance of the tracker limits the accessible η/y range,
total number of produced charged particles cannot be measured

Total and differential cross-sections
can also be obtained using luminosity measurements

Detailed results – energy dependence

Pythia expectations



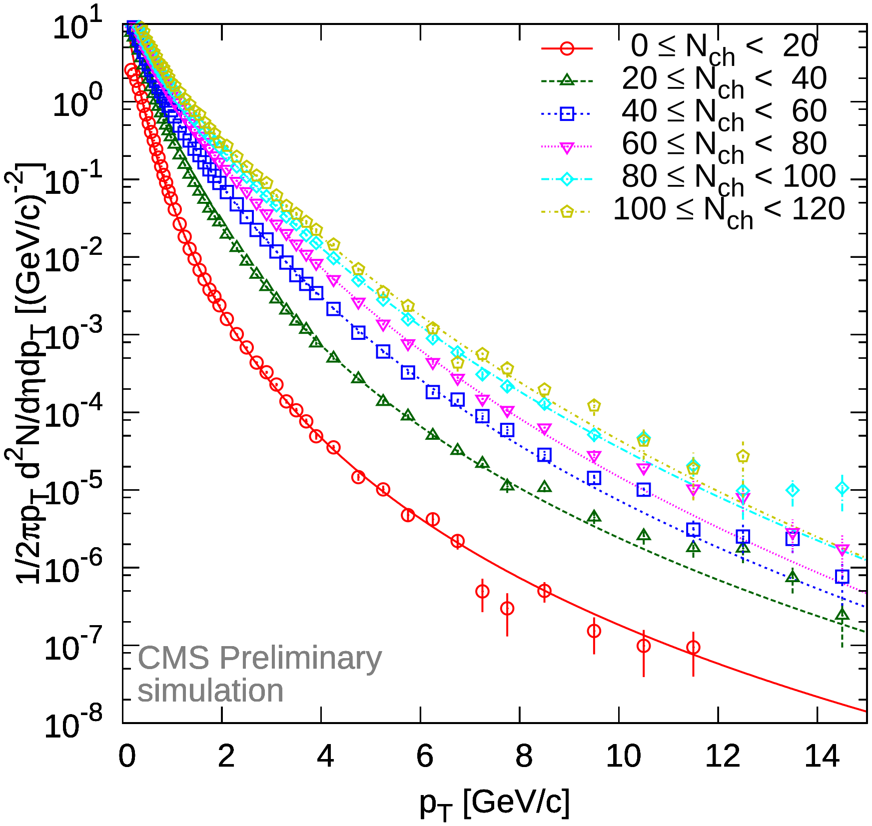


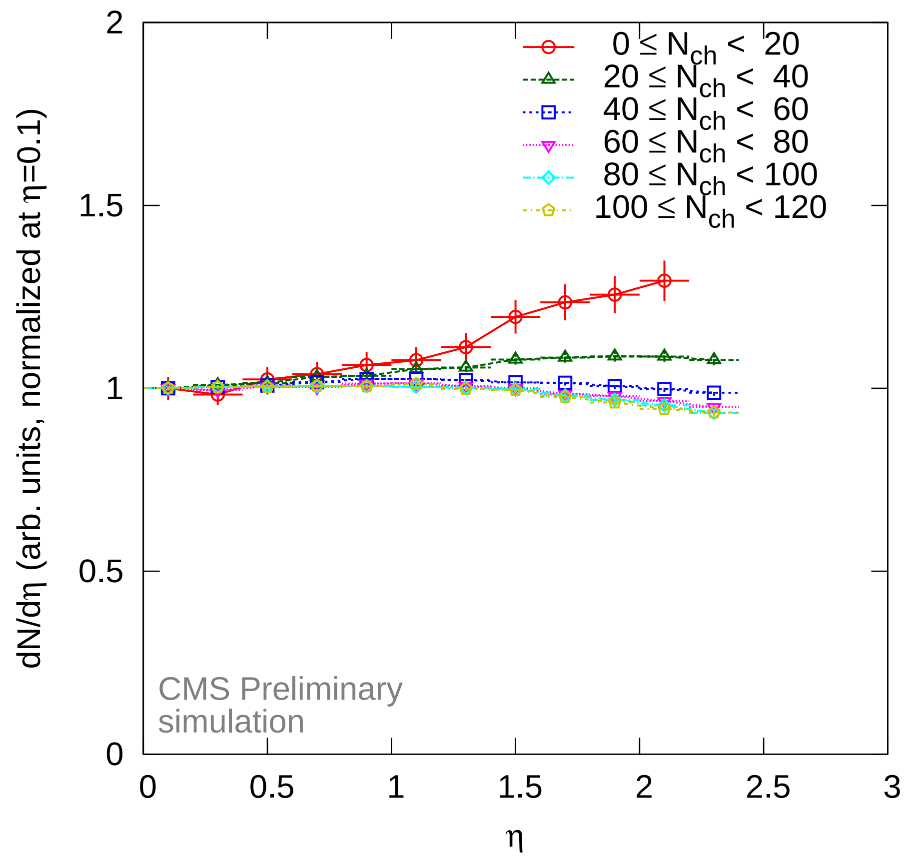
Comparison to lower energy measurements: FNAL, ISR, UA1, UA5, E735, CDF

$dN/d\eta|_{\eta=0}$ continues its linear increase in $\log \sqrt{s}$
Strong, non-linear increase of $\langle p_T \rangle$

Detailed results – multiplicity dependence

Pythia expectations



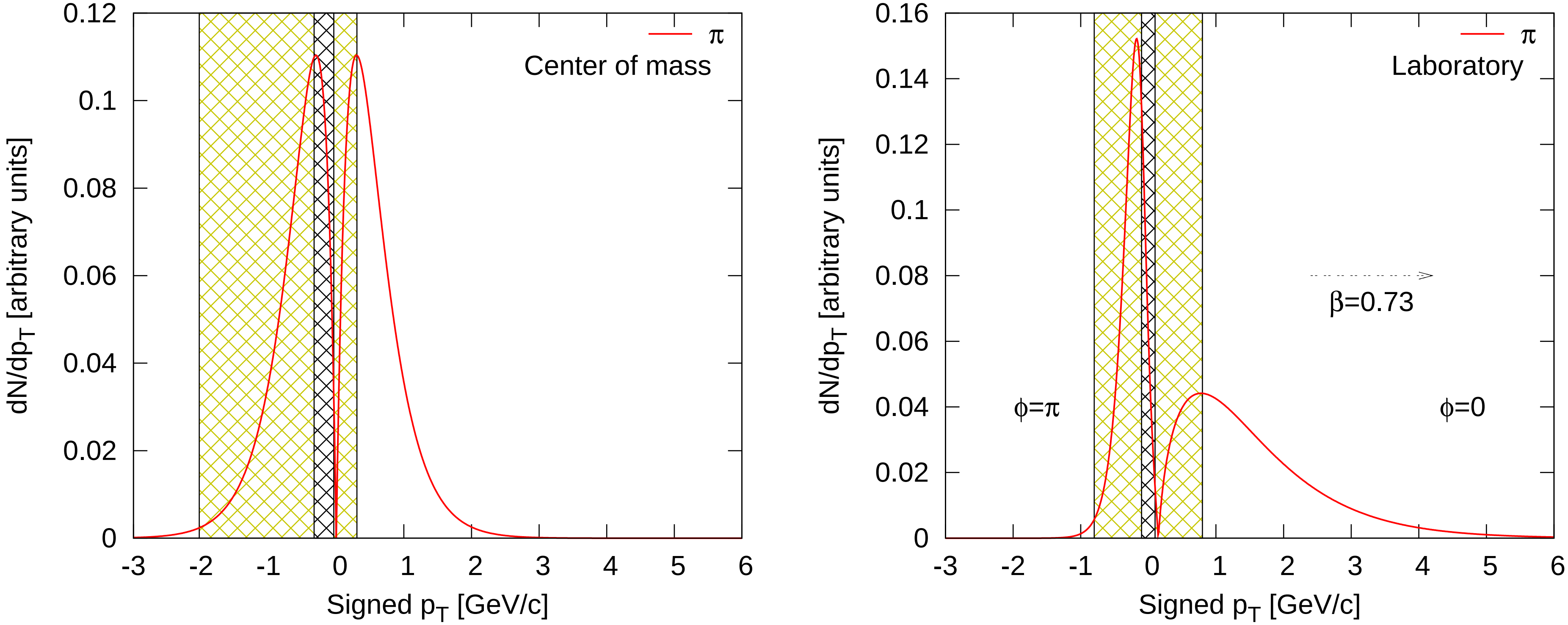


p_T distribution gets flatter with increasing N_{ch}

Shape of η distribution also varies

Interesting physics (multiparton interactions, underlying event, . . .)

Other considerations – beam crossing angle

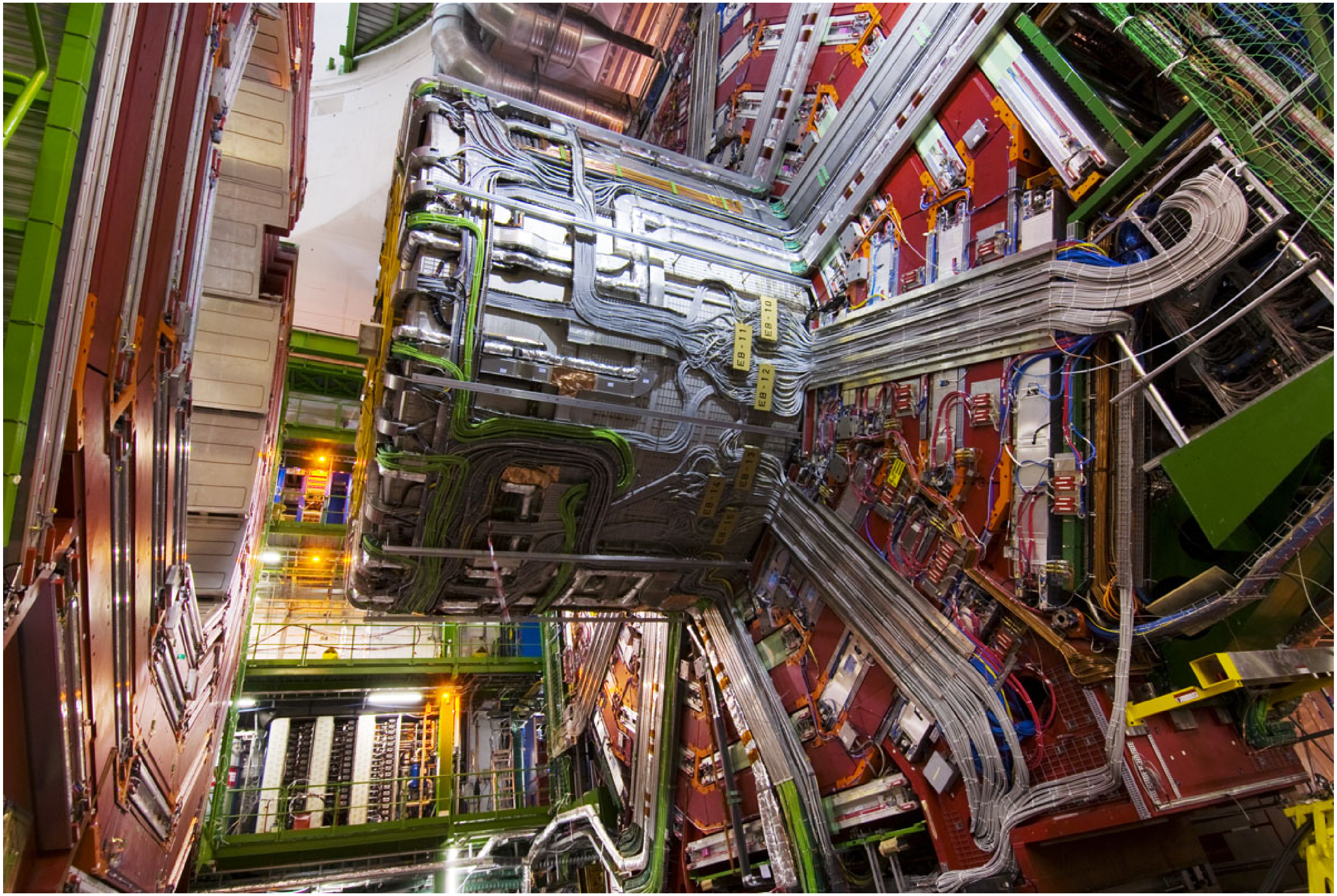


p_{beam}	450 GeV	7 TeV
beam crossing half-angle	142 μrad	
β	0.07	0.73
γ	1.00	1.46

Acceptance+efficiency window (black) shifted

Interesting possibilities if beam crossing angle is not zero

CMS now



Wiring up YB0 (barrel yoke)

Conclusions and outlook

- Inclusive hadron physics program
  - Charged hadrons ($h^{\pm}$)
  - Identified charged particles via dE/dx ($\pi^{\pm}$, $K^{\pm}$, $p/\overline{p}$)
  - Identified neutral particles via decay (K^0_S, Λ, also Ξ^-, Ω^- and antiparticles)
  - On-vertex resonances (ρ, K^*, ϕ)
  - Add calorimetry: extend η range, provide medium or high momentum PID