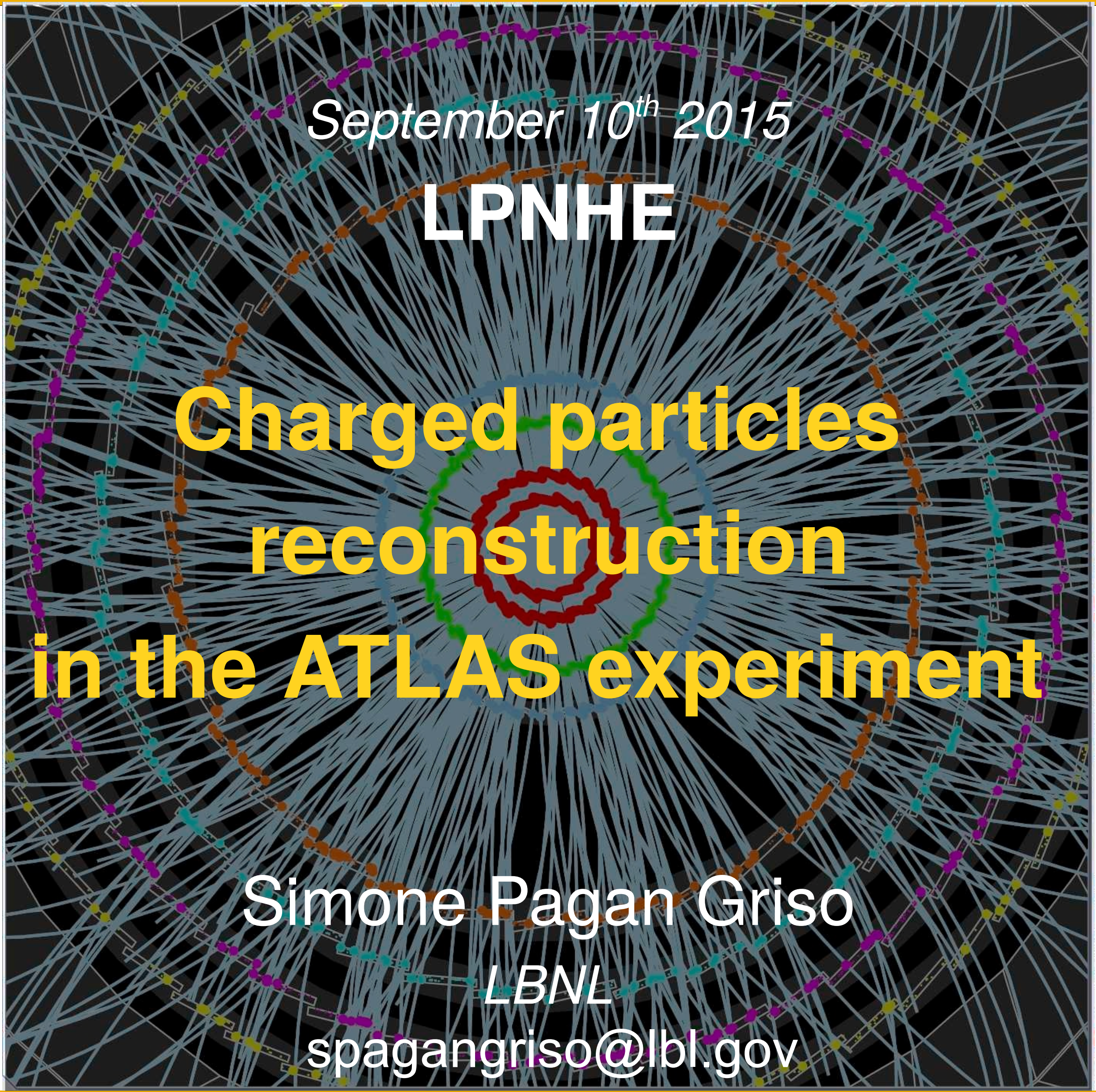

September 10th 2015

LPNHE

Charged particles reconstruction in the ATLAS experiment

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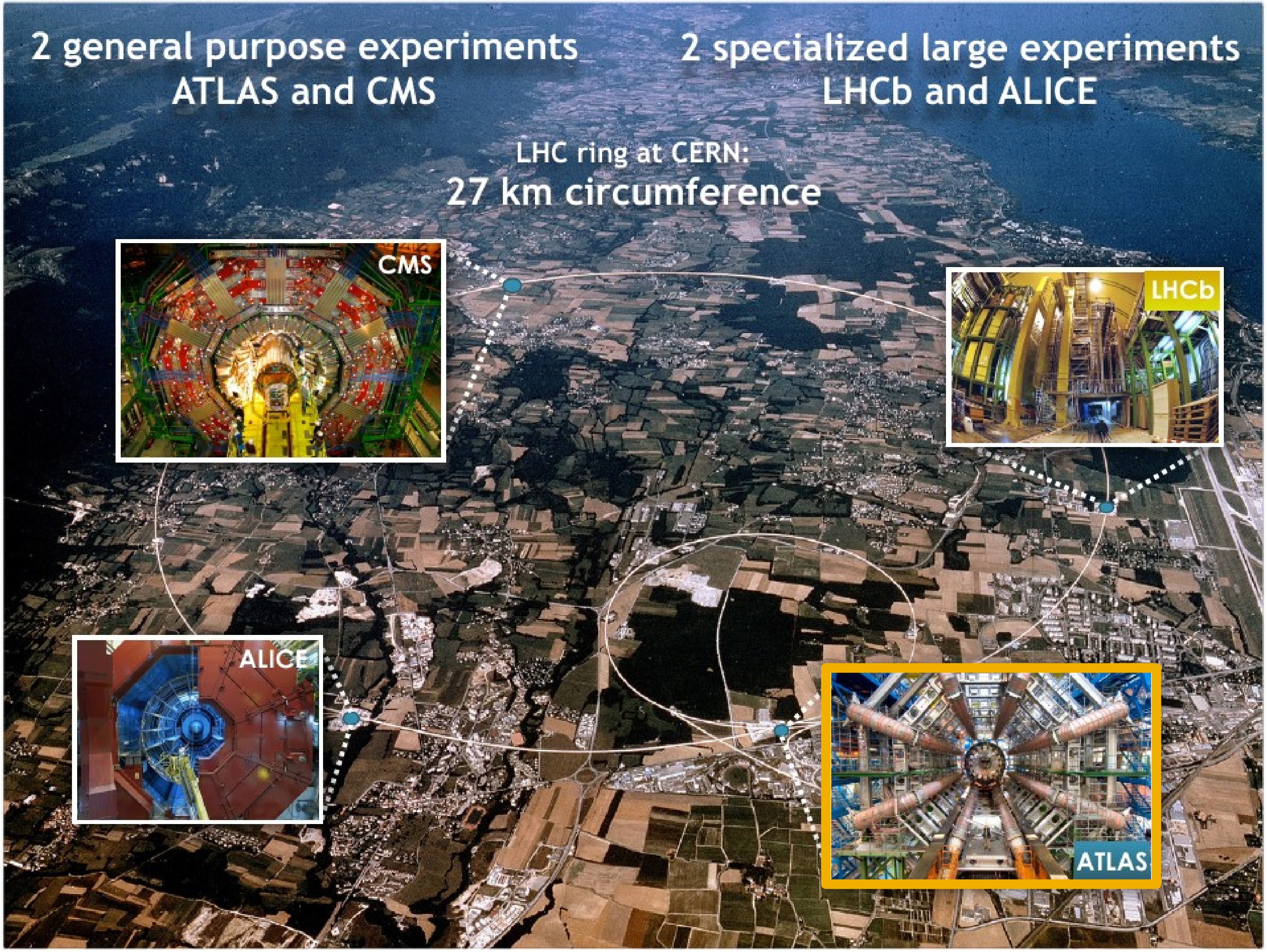
Outline

- Introduction
- Overview of ATLAS charged particles reconstruction
  - Quick tour of offline charged particles reconstruction
    - "real-time" (trigger-level) reconstruction deserves its own seminar
  - Basic performance in simulation and collisions data
  - Special setups
- Recent developments and challenges
- A look into the future: HL-LHC

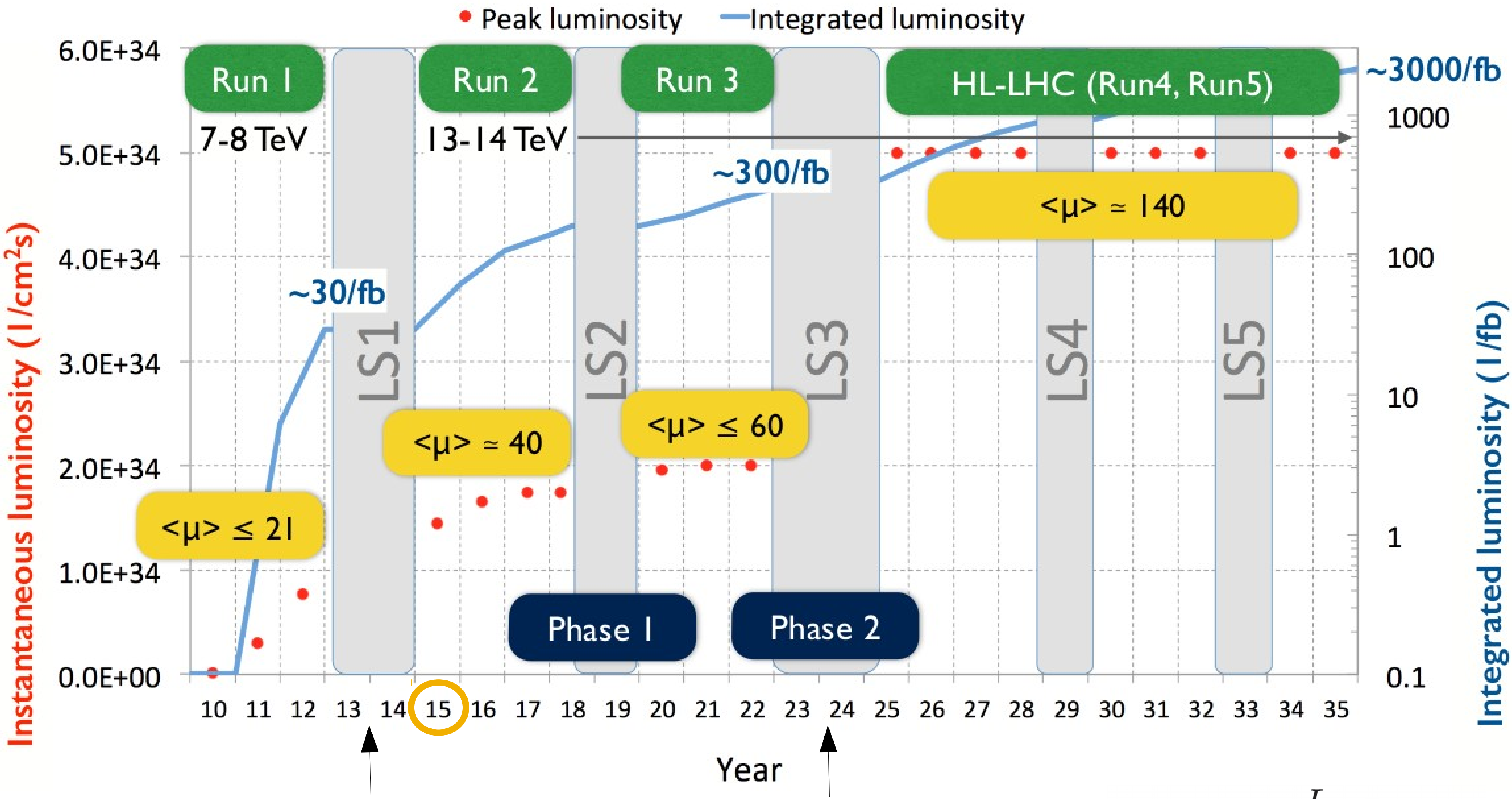
The Large Hadron Collider

- Last stage of accelerator complex at CERN (protons, Pb ions)
- Protons up to 7.5 TeV per beam:
  $\sqrt{s}$ = 13 TeV
- ~11kHz revolution frequency
- ~1300(2500) bunches separated by 50(25)ns

The Large Hadron Collider



LHC operations timeline

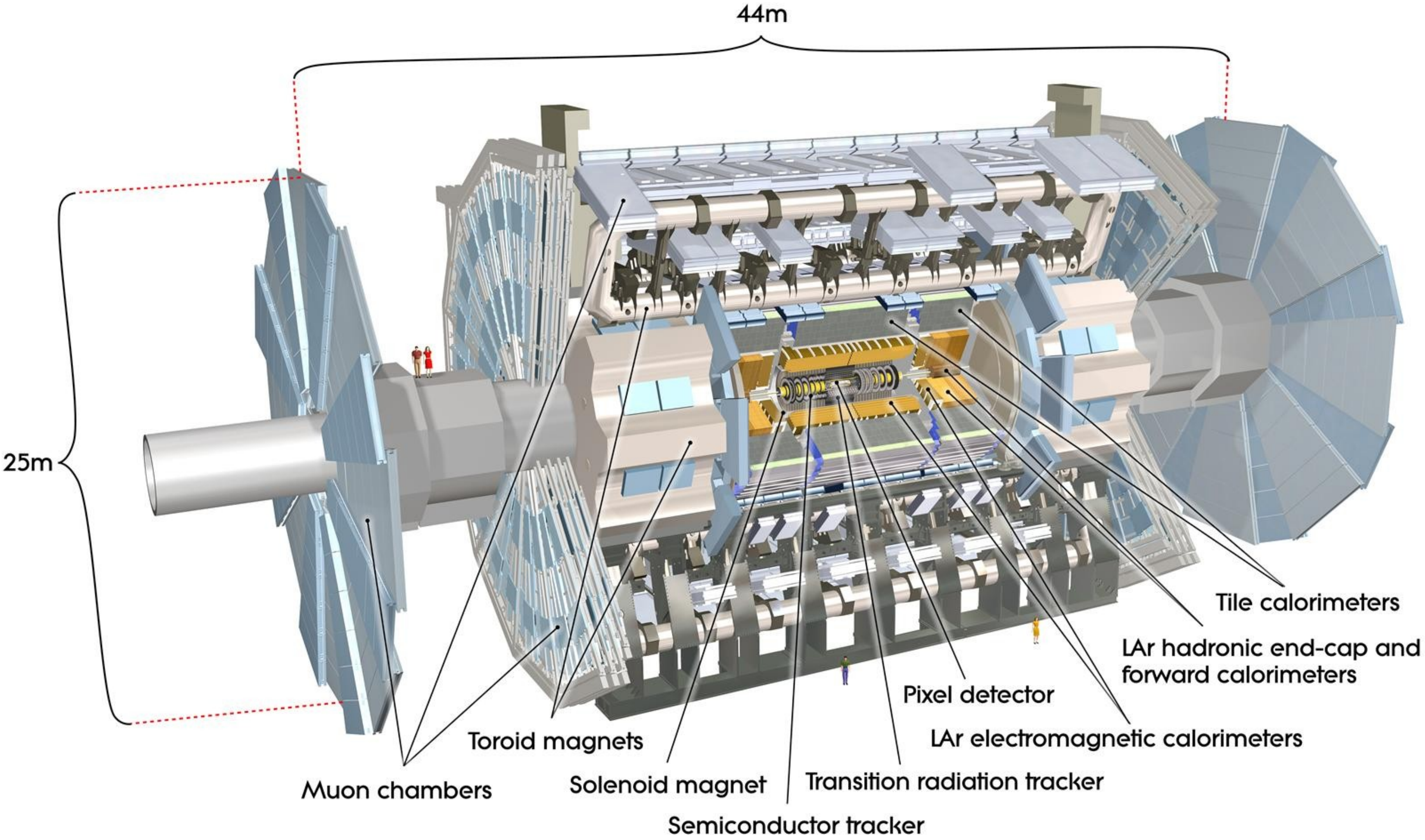


LHC Energy close to nominal
Some detector upgrade

Jump in LHC inst. luminosity
Detectors big upgrades

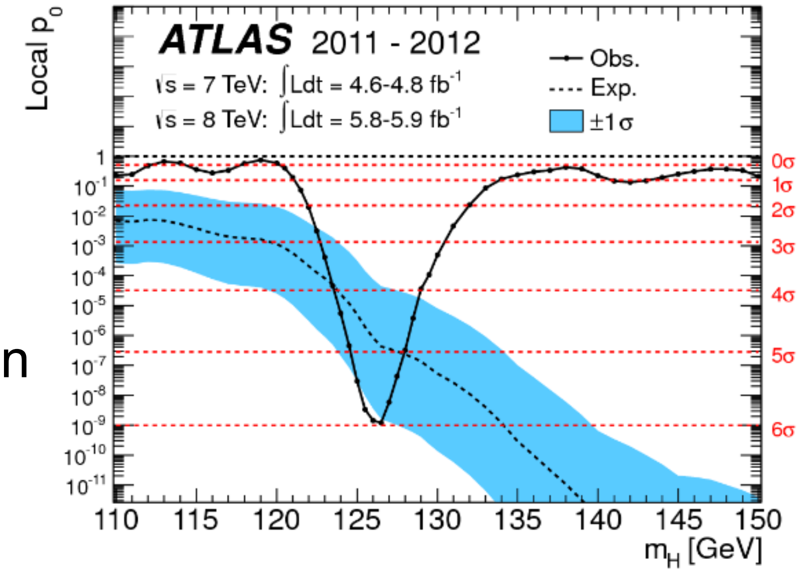
$$< \mu >= \frac{L \cdot \sigma_{\mathrm{inel.}}}{N_{\mathrm{bunch}} \cdot f_{\mathrm{LHC}}}$$

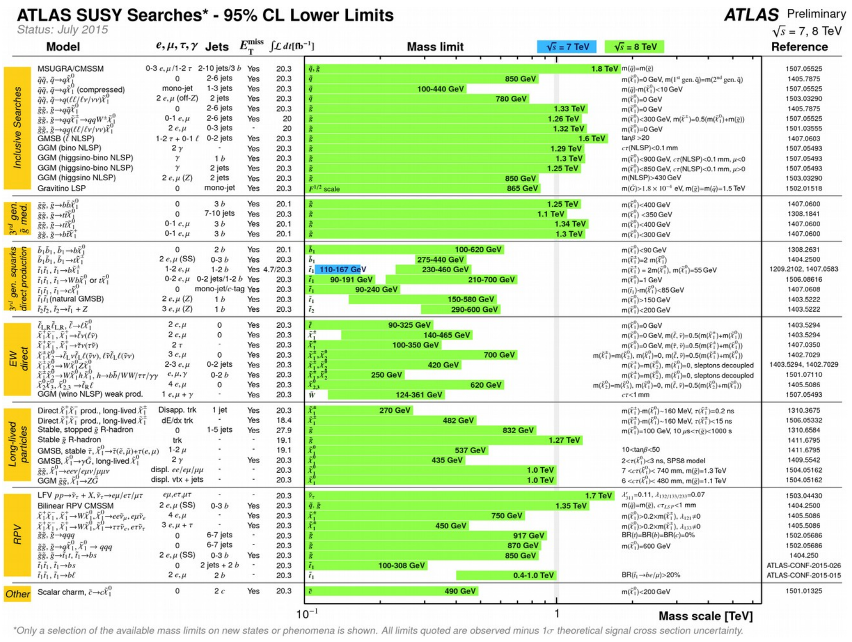
The ATLAS detector



Physics output

- More than 450 papers submitted up to date
    - About 200 measurements
        - Higgs boson observation
    - About 230 (null) searches
    - Papers documenting performance of detector, reconstruction, simulation





ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

$\sqrt{s}$ = 7 TeV 🟦 $\sqrt{s}$ = 8 TeV 🟩

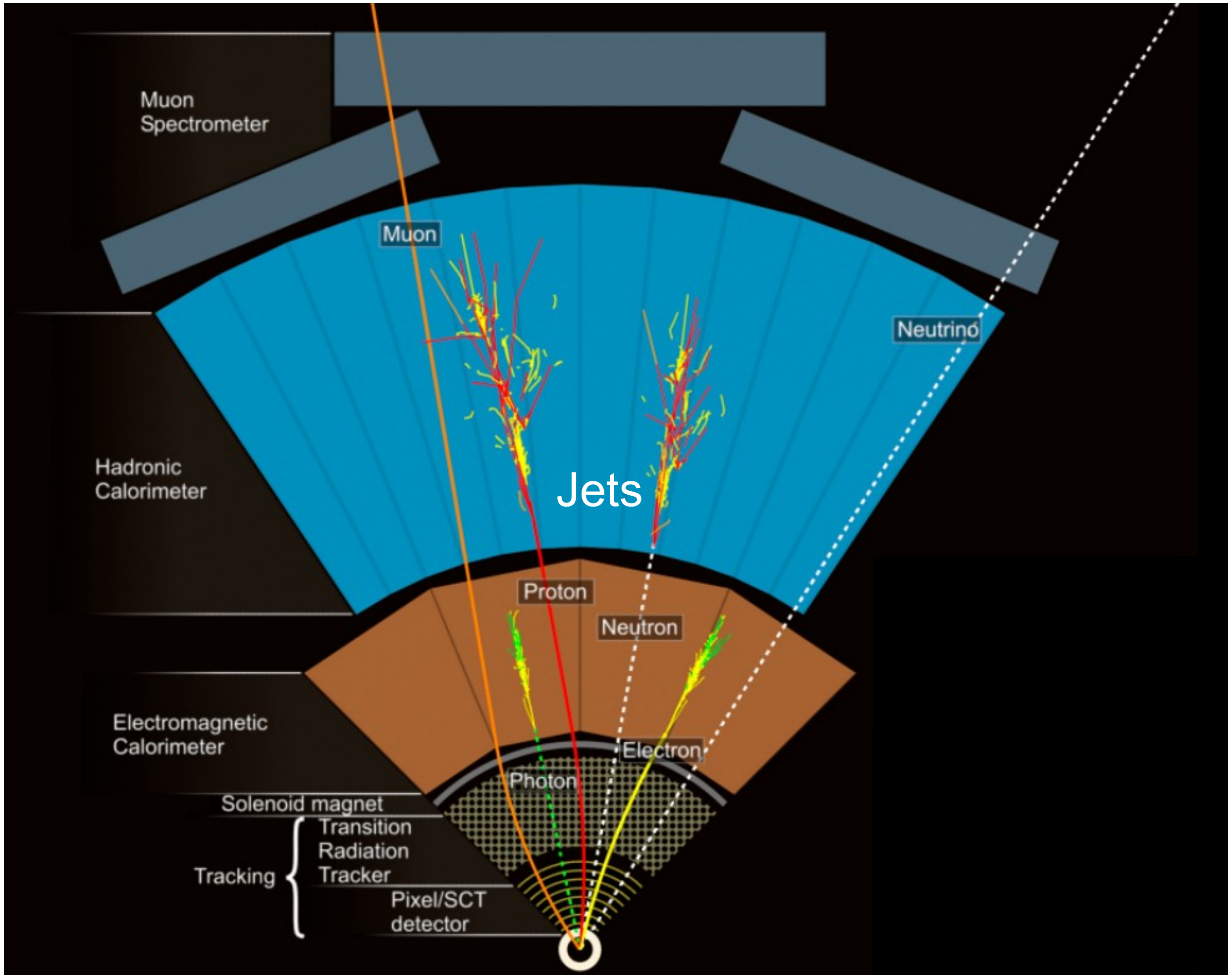
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$	100-440 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$	780 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$	1.26 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1507.05525
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	110-167 GeV 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	90-191 GeV 210-700 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	700 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	420 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	250 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$	124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	482 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$	1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to q\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	870 GeV	$m(\tilde{\chi}_1^0)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$	100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

- Broad physics program
- Look for / study rare processes
- Need efficient, accurate and fast collision event reconstruction

Event reconstruction

- Task of event reconstruction is to identify objects



Tracker to measure charged particles

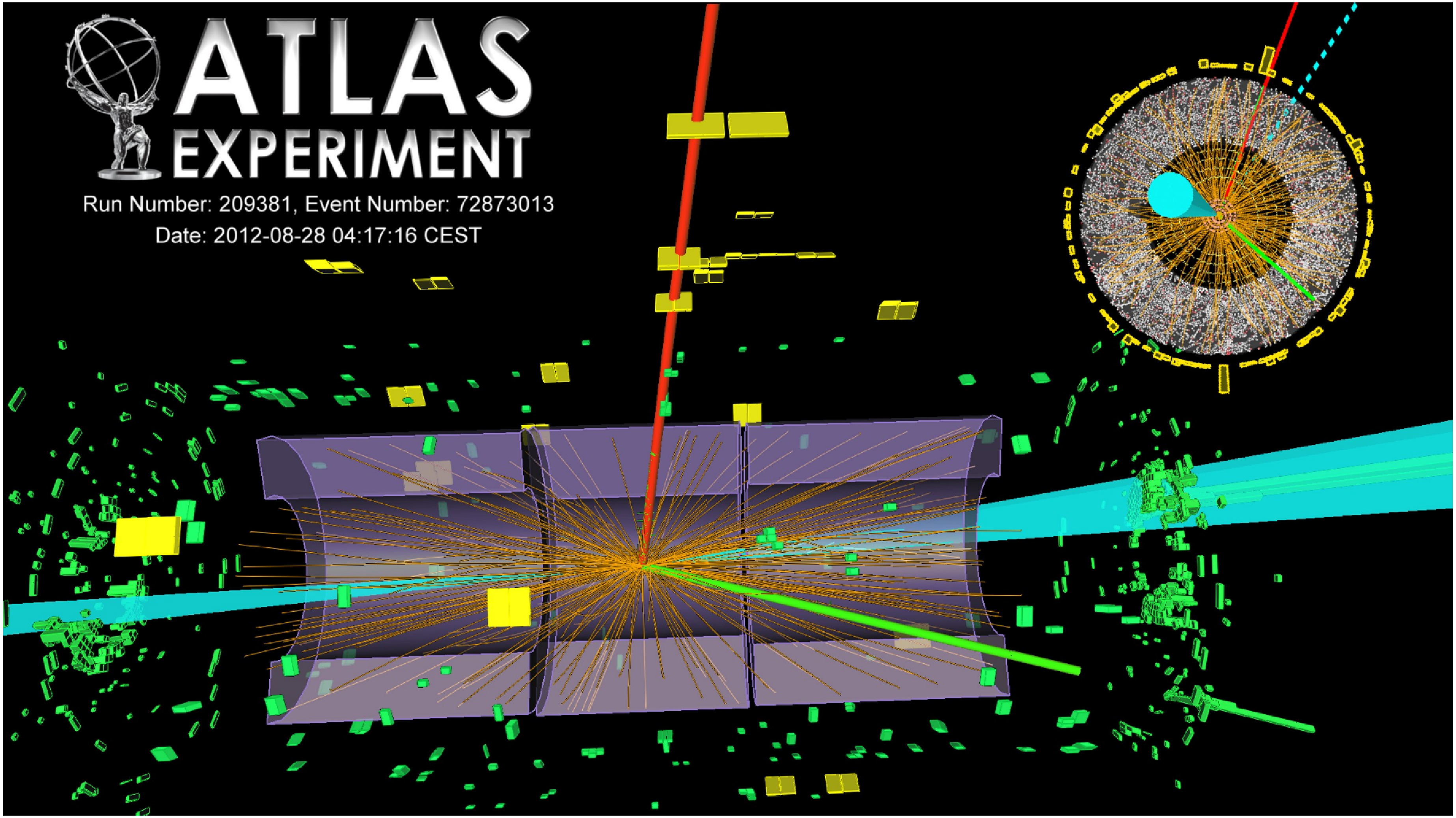
e.m. and hadronic calorimeters to measure energy of particles (jets)

Muon spectrometer to detect muons penetrating the rest of the detector

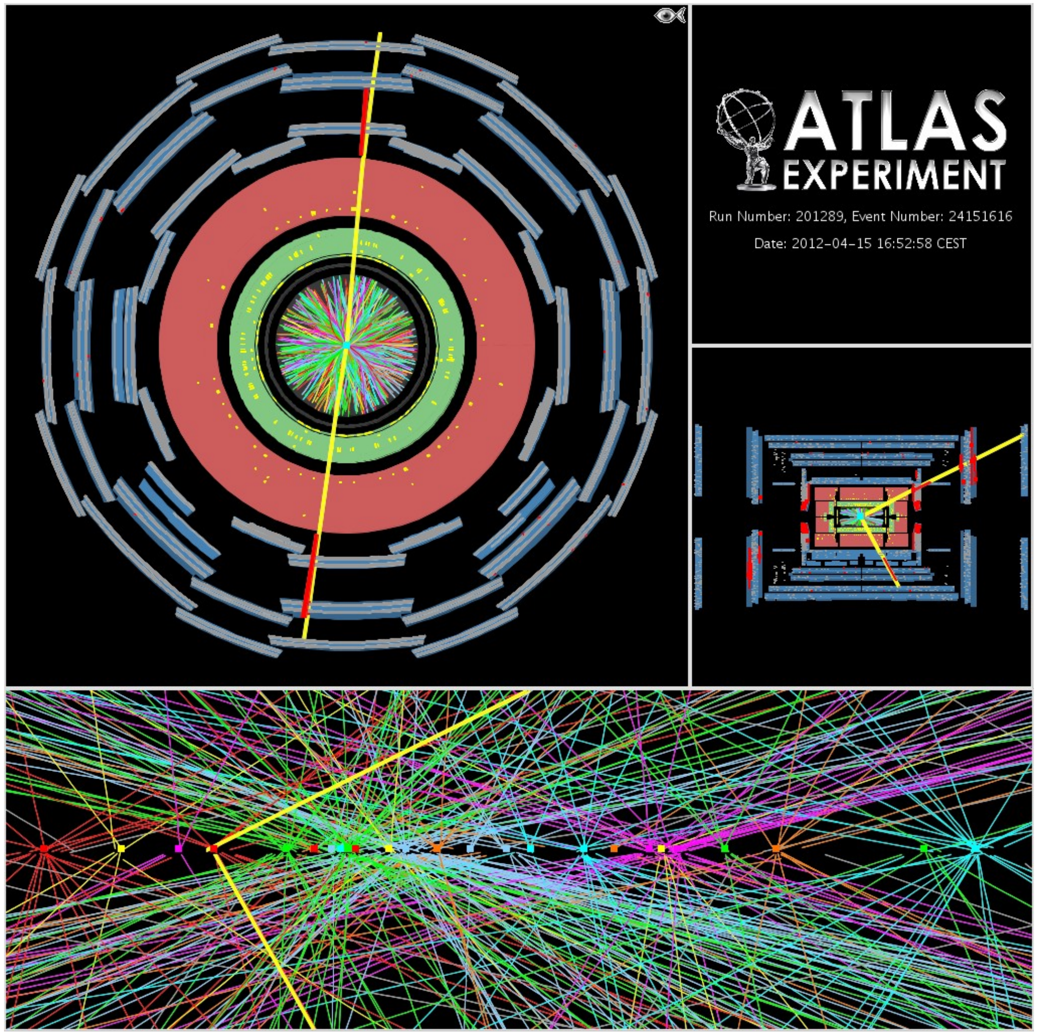
Missing transverse energy for weekly interacting particles (e.g. neutrinos)

- Tracking is a central aspect of the event reconstruction and analysis

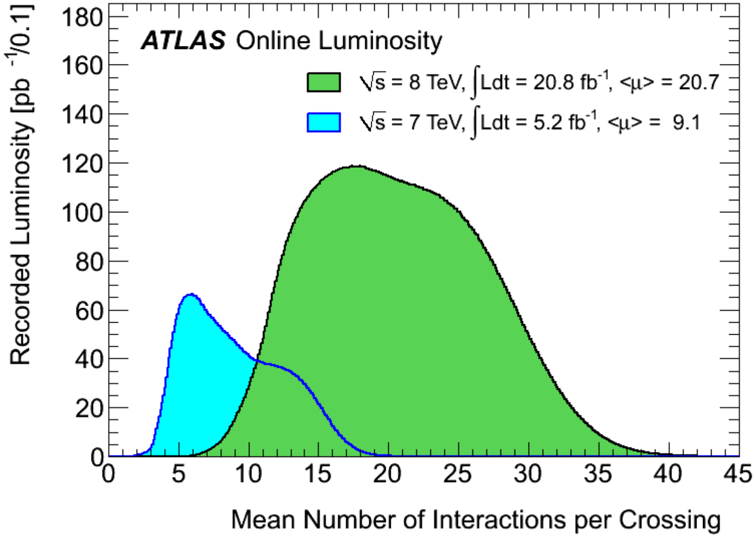
In reality ...


ATLAS EXPERIMENT
Run Number: 209381, Event Number: 72873013
Date: 2012-08-28 04:17:16 CEST

In reality …



Each event sees multiple pp collisions = pile-up



Interaction region (~Gaussian)

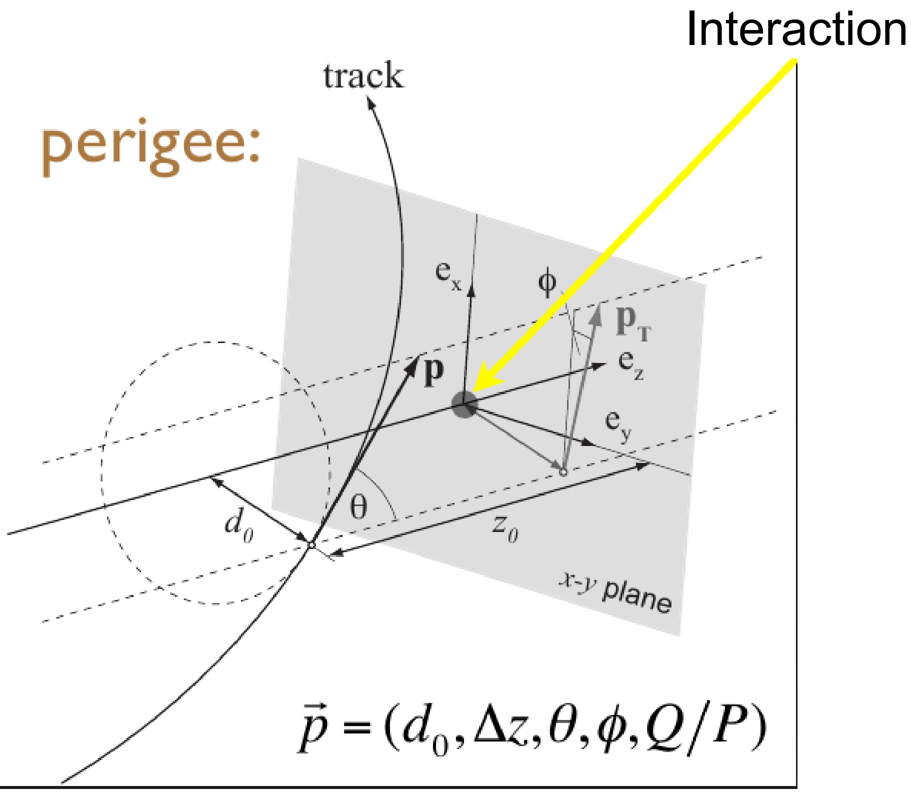
Transverse size (σ): 12-16 μm

Longitudinal size (σ): 45-50 mm

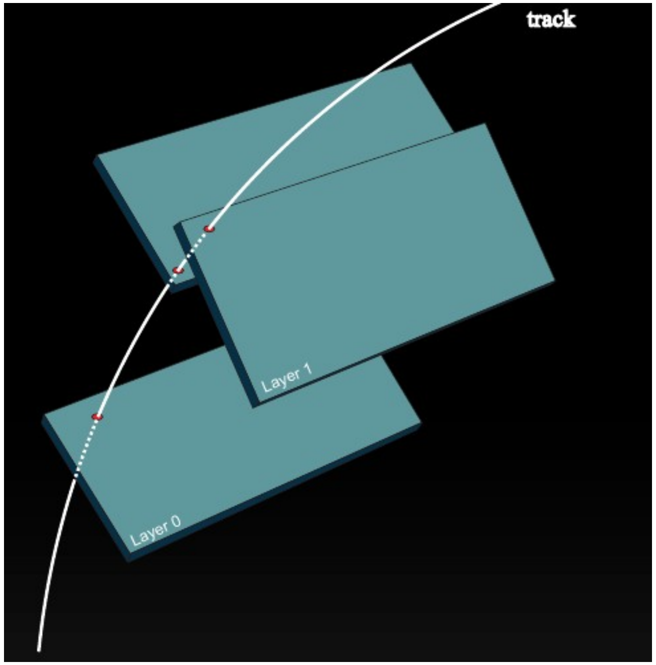
[average 2012 data]

Track reconstruction

- **Charged particle trajectories (tracks) traveling in magnetic field are helicoidal**



$$\vec{p} = (d_0, \Delta z, \theta, \phi, Q/P)$$



Trajectory defined with 5 parameters
ATLAS choice:

$$(\underbrace{d_0, z_0}_{\text{local}}, \underbrace{\theta, \phi, q/p}_{\text{global}})$$

$\downarrow$

Reference point:
interaction position

Track reconstruction

- Charged particle trajectories (tracks) traveling in magnetic field are helicoidal, **but**:

- **Non-uniform magnetic field**

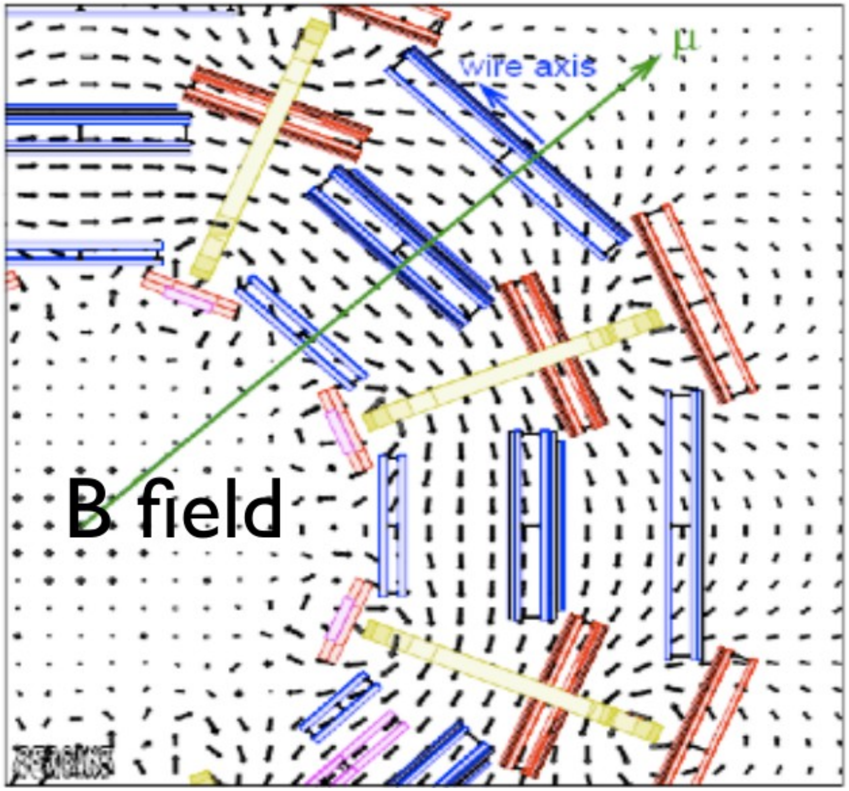
Equation of motion

$$\frac{d^2x}{dz^2} = \frac{q}{p} R \left[\frac{dx}{dz}\frac{dy}{dz} B_x - \left(1 + \left(\frac{dx}{dz}\right)^2\right) B_y + \frac{dy}{dz} B_z \right]$$

$$\frac{d^2y}{dz^2} = \frac{q}{p} R \left[\left(1 + \left(\frac{dy}{dz}\right)^2\right) B_x - \frac{dx}{dz}\frac{dy}{dz} B_y - \frac{dx}{dz} B_z \right]$$

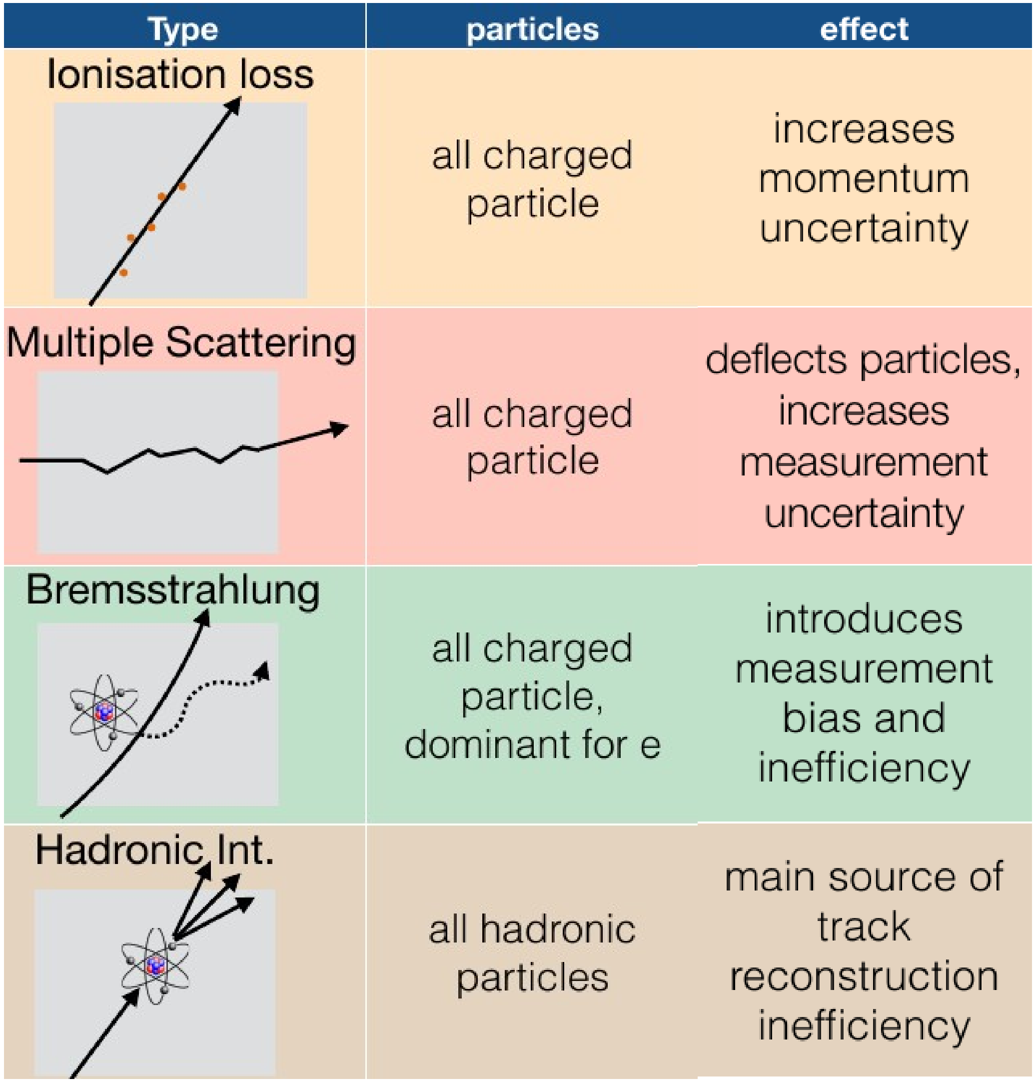
$$R = \frac{ds}{dz} = \sqrt{1 + \left(\frac{dx}{dz}\right)^2 + \left(\frac{dy}{dz}\right)^2}$$

Has to be solved numerically for non-uniform magnetic field



Track reconstruction

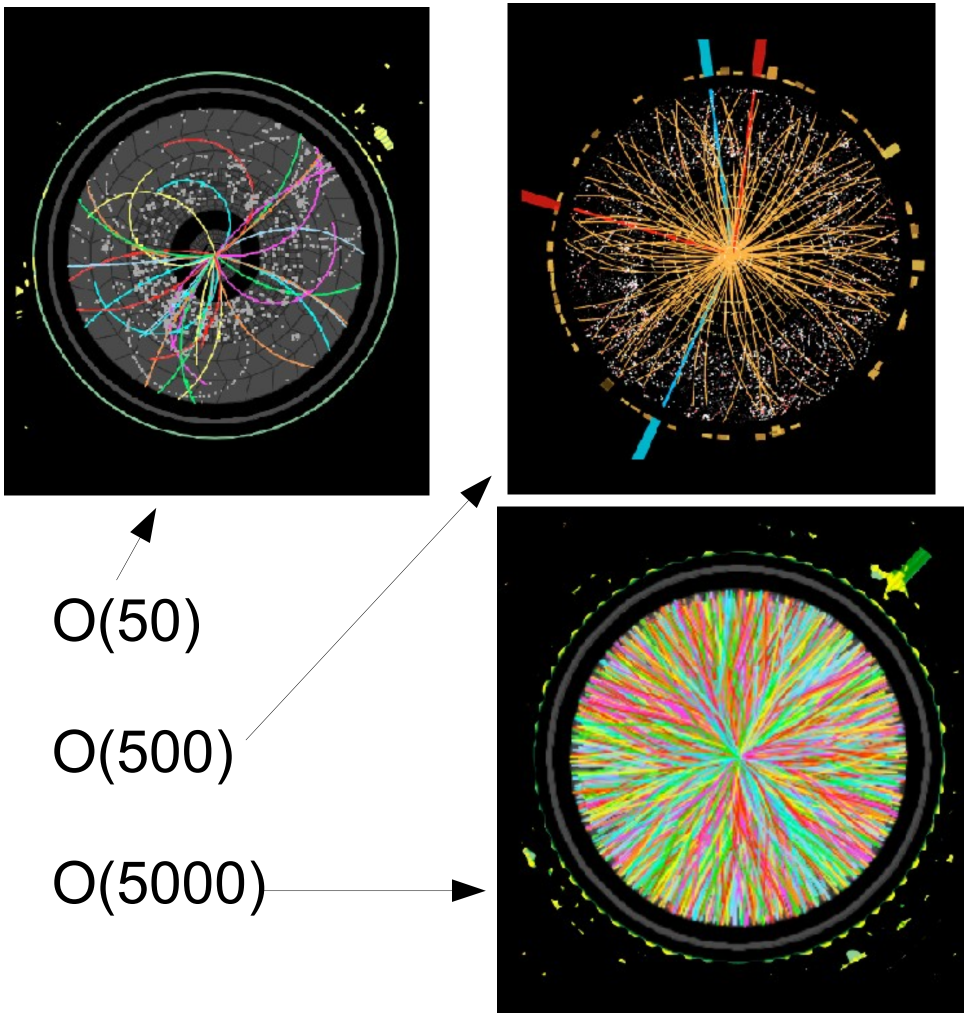
- Charged particle trajectories (tracks) traveling in magnetic field are helicoidal, but:
- Non-uniform magnetic field
- **To measure it, you need to interact with it!**
- **Active + Passive material from detectors**



Type	particles	effect
Ionisation loss	all charged particle	increases momentum uncertainty
Multiple Scattering	all charged particle	deflects particles, increases measurement uncertainty
Bremsstrahlung	all charged particle, dominant for e	introduces measurement bias and inefficiency
Hadronic Int.	all hadronic particles	main source of track reconstruction inefficiency

Track reconstruction

- Charged particle trajectories (tracks) traveling in magnetic field are helicoidal, but:
- Non-uniform magnetic field
- To measure it, you need to interact with it!
- Active + Passive material from detectors
- **Hundreds to Thousands particles per event**



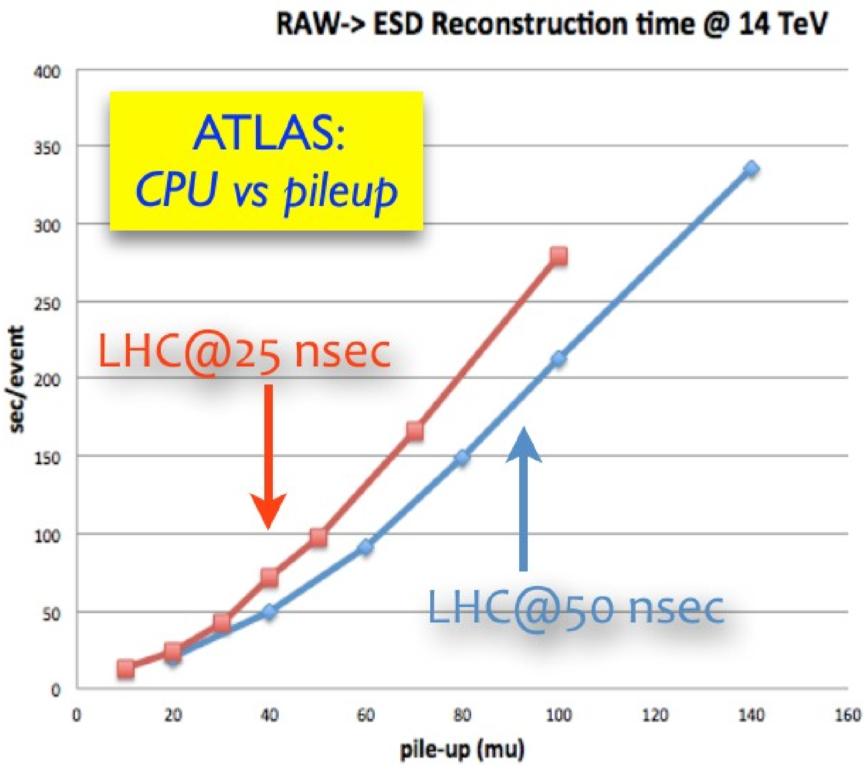
O(50)

O(500)

O(5000)

Track reconstruction

- Charged particle trajectories (tracks) traveling in magnetic field are helicoidal, but:
- Non-uniform magnetic field
- To measure it, you need to interact with it!
- Active + Passive material from detectors
- Hundreds to Thousands particles per event
- **Tight CPU timing constraints (~1kHz of event rate to disk!)**



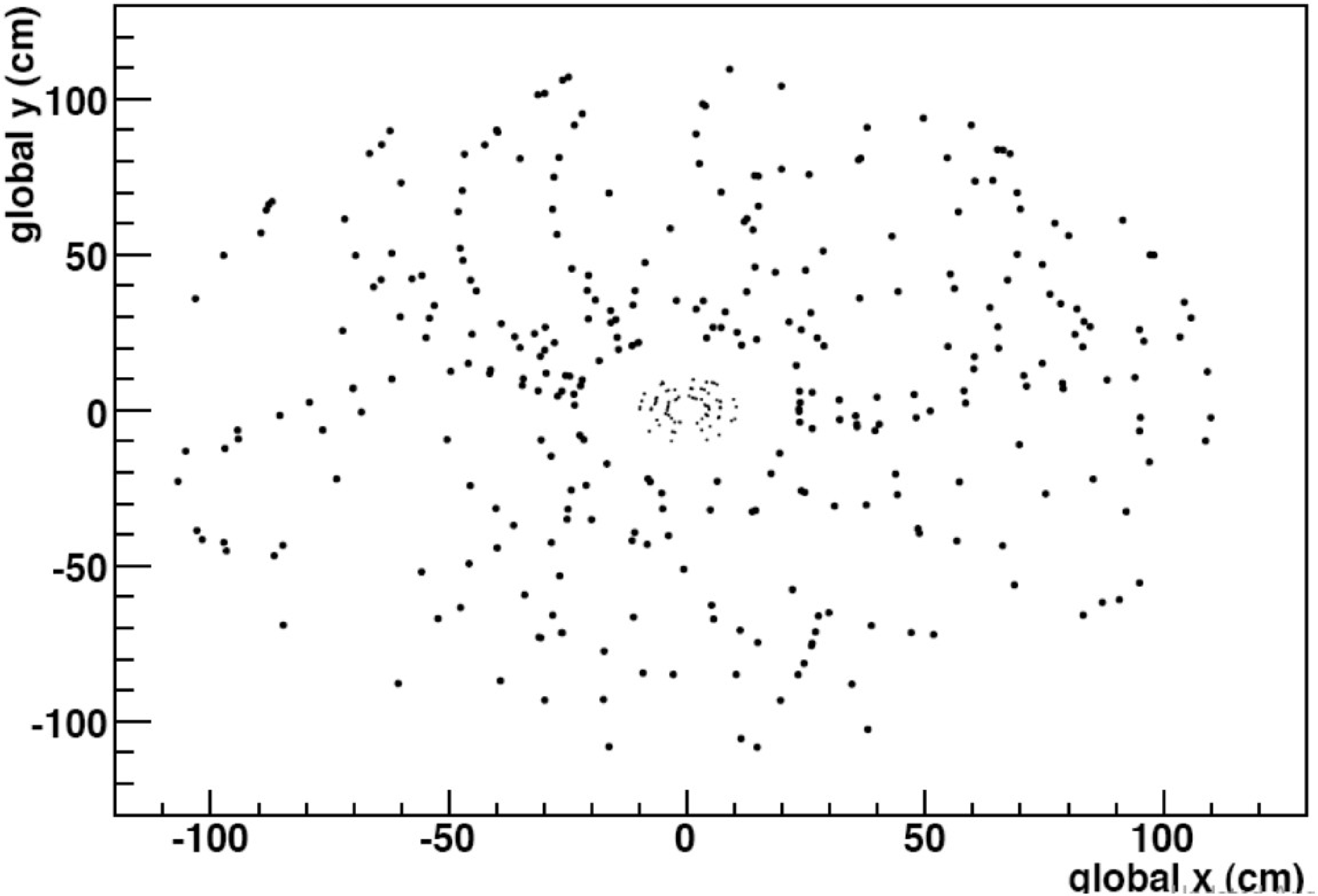
Track reconstruction

- Charged particle trajectories (tracks) traveling in magnetic field are helicoidal, but:
- Non-uniform
- To measure i to interact wi
- Active + Pas from detectors
- Hundreds to Thousands particles per event
- Tight CPU timing constraints (~1kHz of event rate to disk!)

The solution of the track reconstruction problem is challenging!

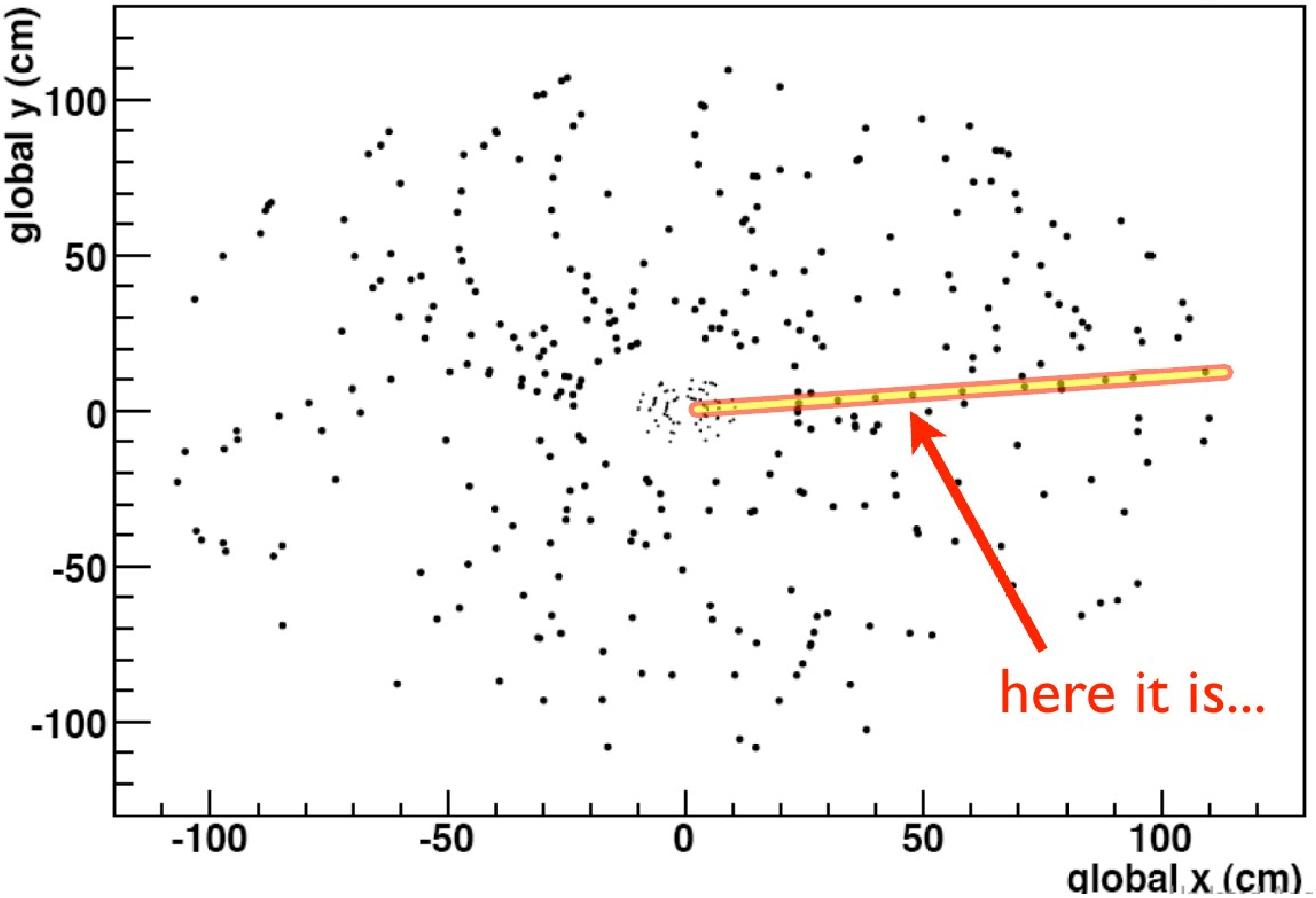
Can you find the 50 GeV track?

cf Aaron Dominguez



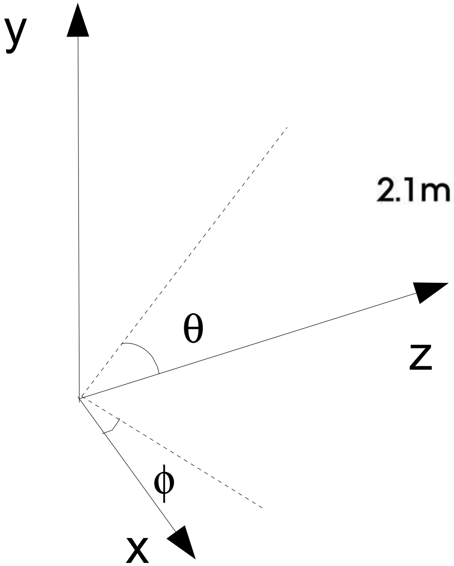
Can you find the 50 GeV track?

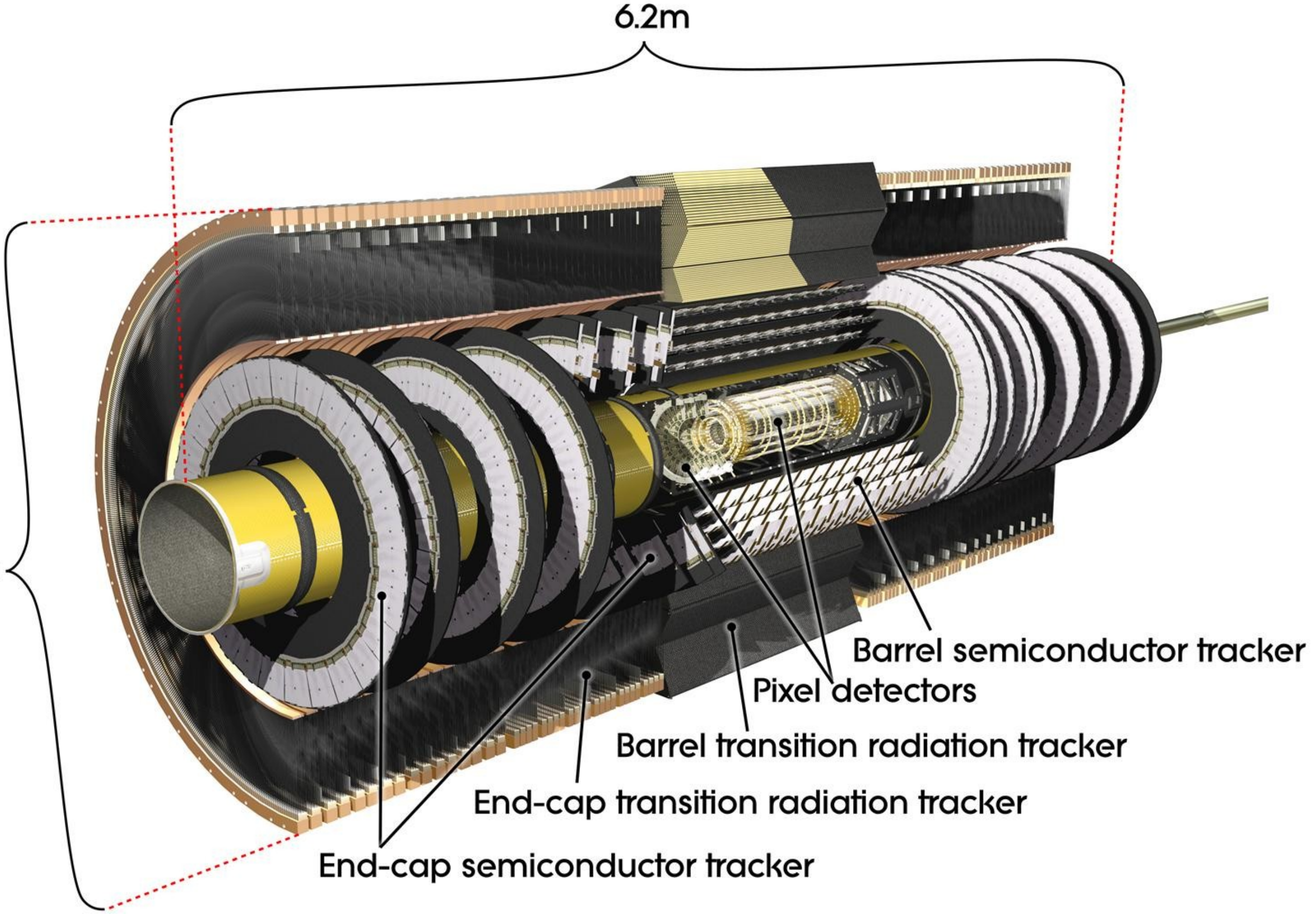
cf Aaron Dominguez



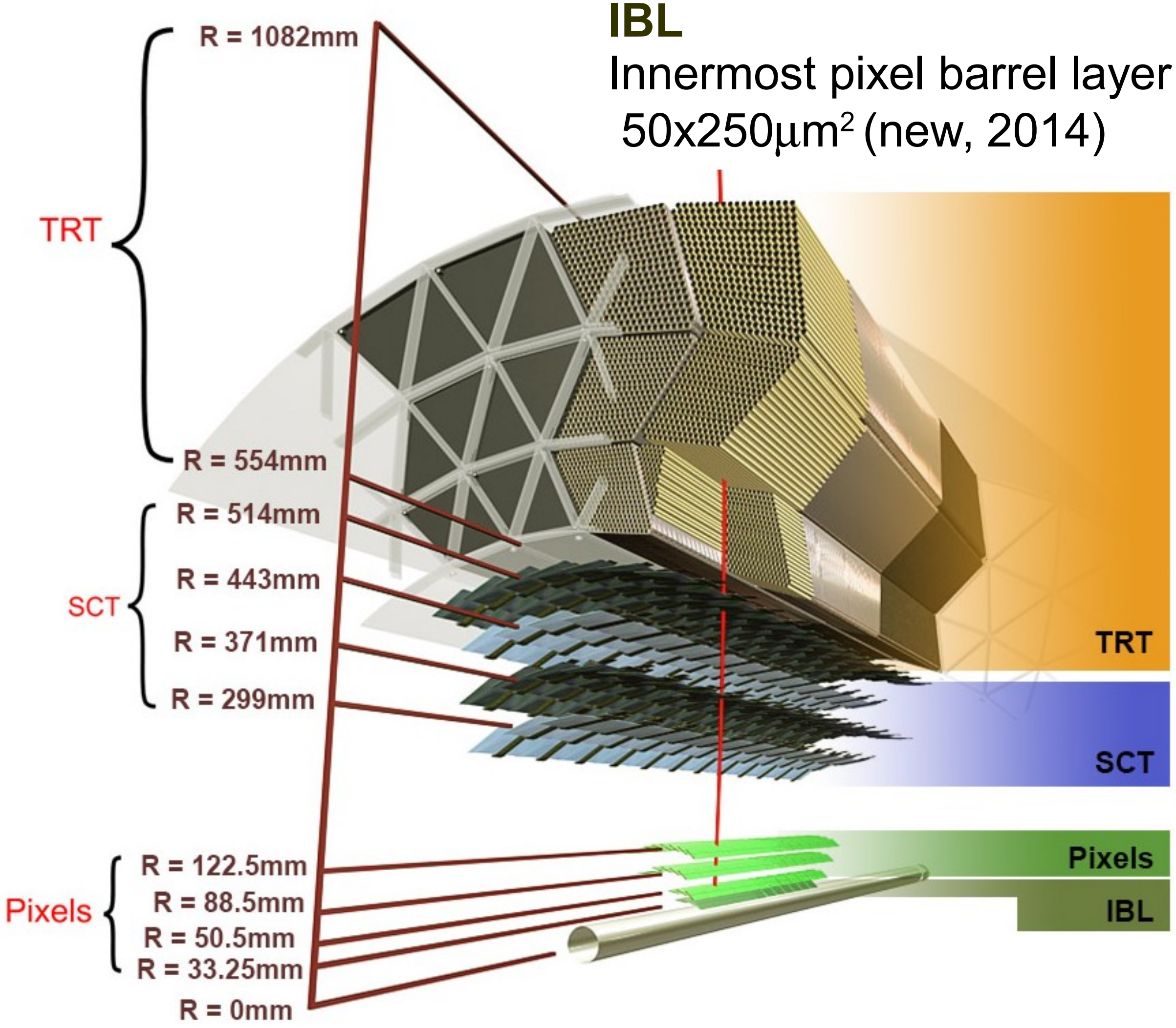
Inner Tracking Detector (ID)

- Reconstruct charged particles trajectories before calorimeter
- Coverage $|\eta| < 2.5$ ($|\theta| > 0.16 = 9.4°$)





Inner Tracking Detector (ID)



IBL

Innermost pixel barrel layer
50x250μm^2 (new, 2014)

Pixel detector

80M silicon pixels,
50x400μm^2 (90%)
3 barrels and 2x3 end-caps
Charge measurement
Pix+IBL: <hits/track> ~ 4

Semiconductor Tracker

6.3M silicon strips, 80μm pitch
4 barrels and 2x9 end-caps
Axial/Stereo layers
~binary read-out (hit/no-hit)
<hits/track> ~ 8 (4 3D points)

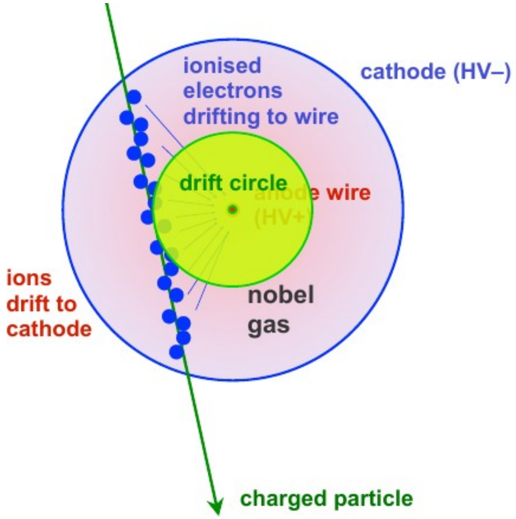
Transition radiation tracker

350K straws, 4mm. 73 barrel and 160 end-cap planes
Provides 2D measurements
<hits/track>~30
Particle ID w/ transition radiation

ATLAS Track reconstruction

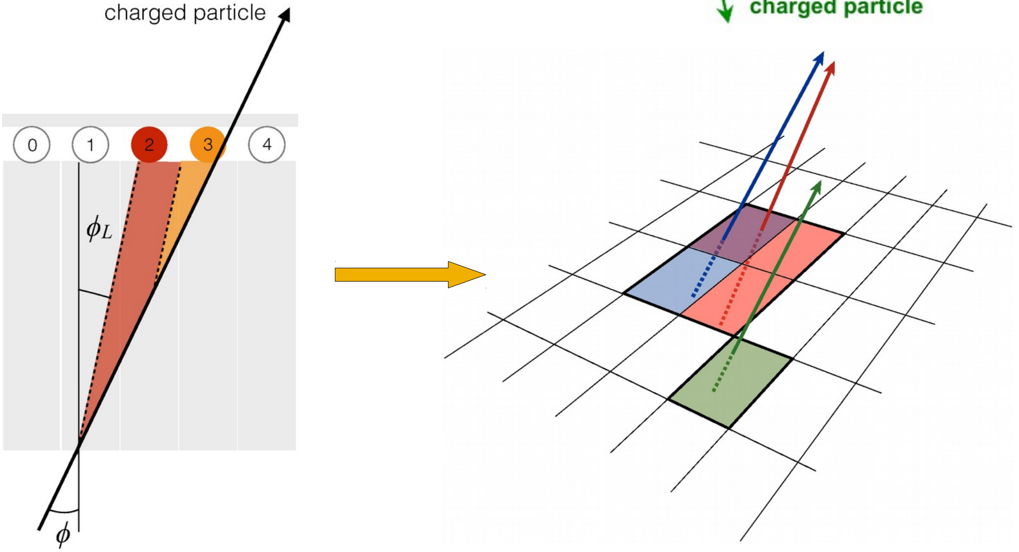
Pre-processing:
- Pixel/SCT Clusters
- TRT Drift Circles
- Space-point formation

TRT system



- Use detector information to create space-points
- 3D information when available:
  - Pixel system
  - Strip system, associating axial and stereo information

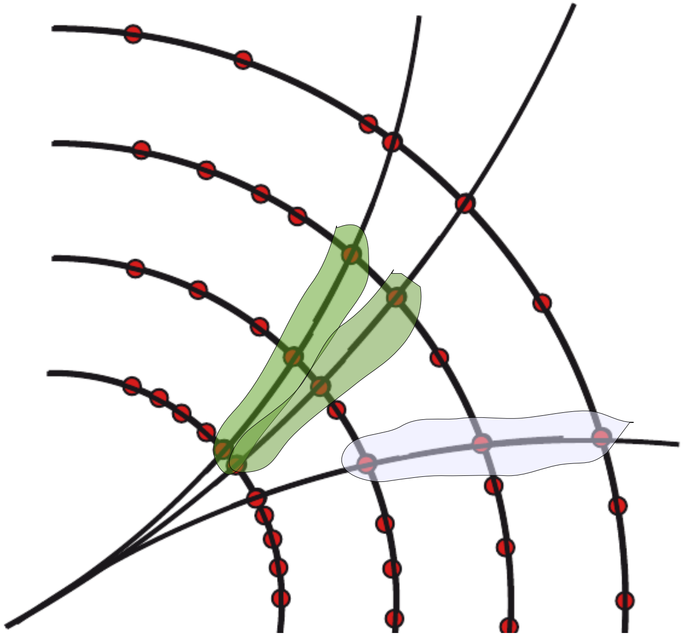
Pixel system



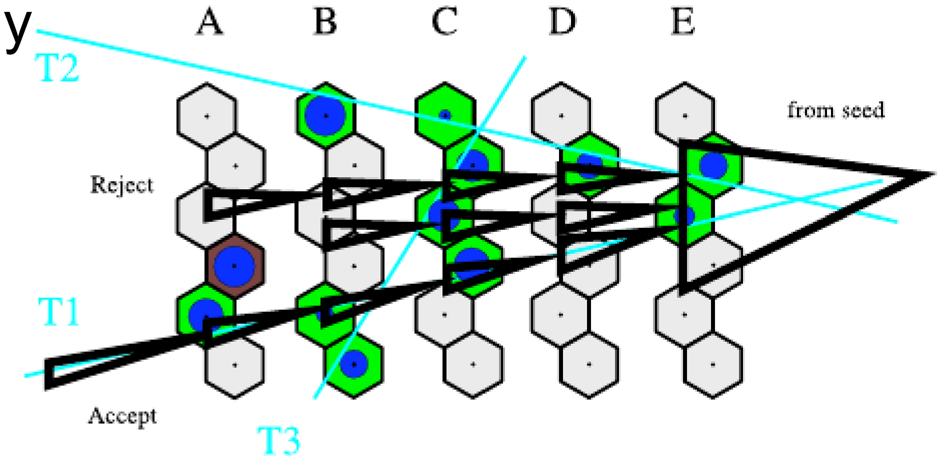
ATLAS Track reconstruction

Pre-processing:
- Space-point formation

Combinatorial track-finder in Silicon detectors
- Iterative procedure
- Create 3-points seeds
- Combinatorial Kalman filter→track candidates



- Extend seed following most likely paths → early rejection of unlikely track candidates
  - Multiple paths if plausible, very efficient for nearby particles
- Typically 20k seeds → 2k Track candidates → 1k Tracks



ATLAS Track reconstruction

Pre-processing:
- Space-point formation

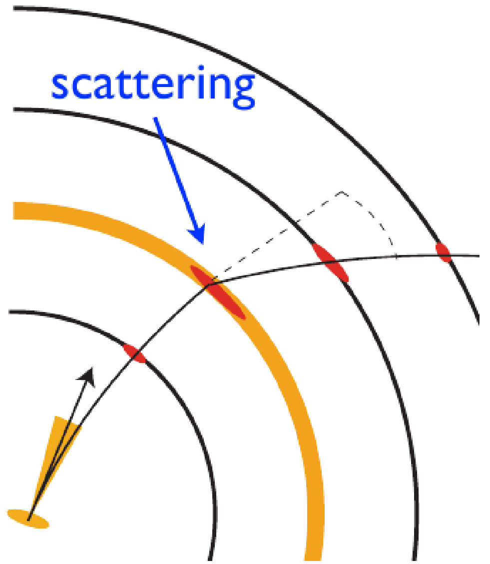
Combinatorial track-finder in Silicon detectors

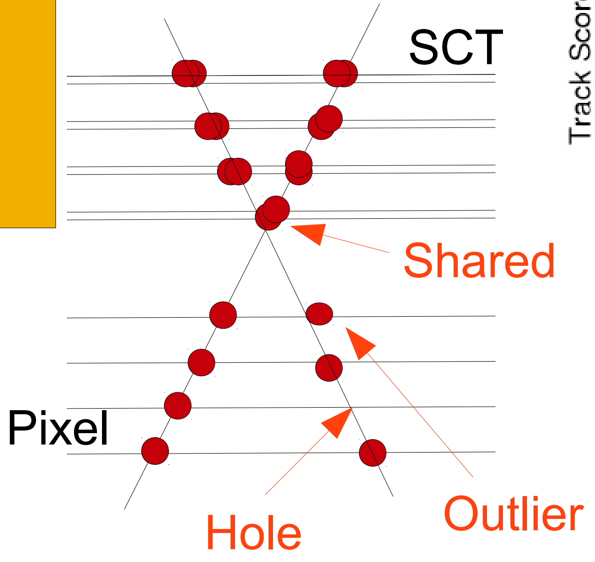
Ambiguity solver:
- Precise least-square fit
- Selection of best silicon-only tracks:
  - hit content, holes
  - shared hits
  - fit quality, ...

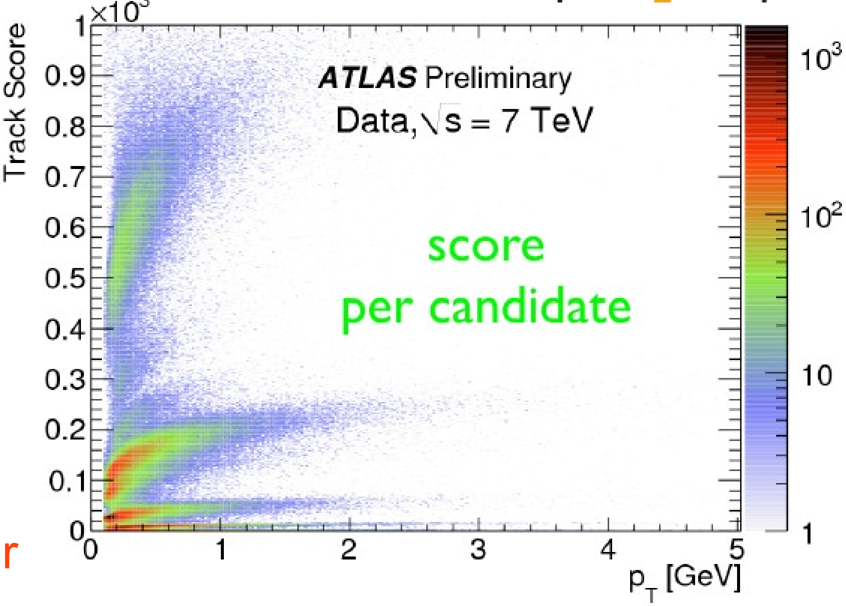
- Track least-square fit taking into account material effects: allows scattering angles in the fit

$$\chi^2 = \sum_k \Delta m_k^T G_K^{-1} \Delta m_k + \sum_i \delta\theta_i^T Q_i^{-1} \delta\theta_i$$

with: $\Delta m_k = m_k - d_k\left(p, \delta\theta_i\right)$







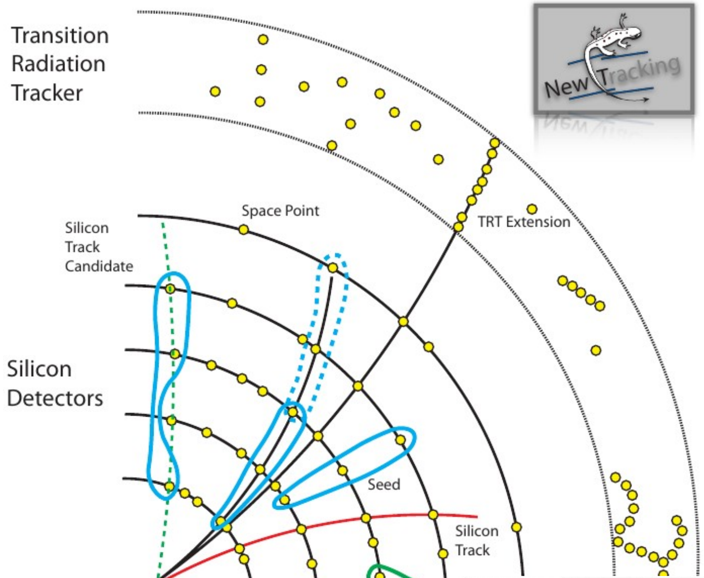
ATLAS Track reconstruction

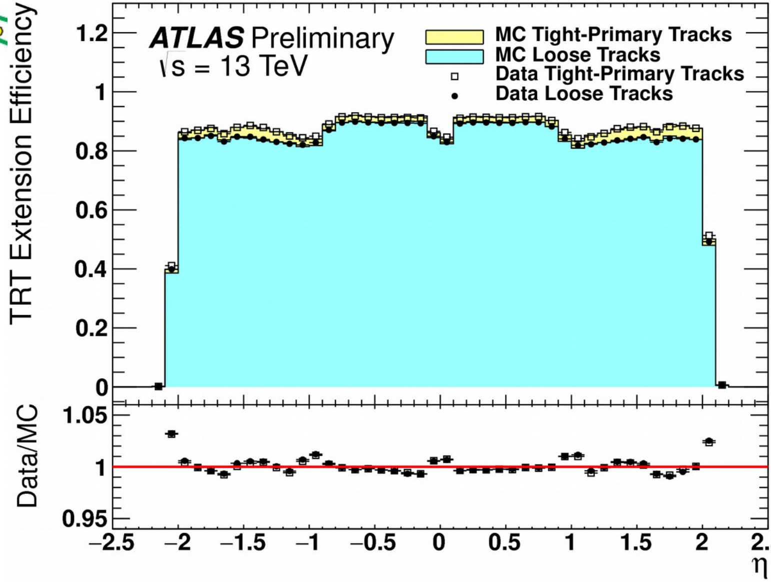
Pre-processing:
- Space-point formation

Combinatorial track-finder in Silicon detectors

Ambiguity solver

Extension to TRT:
- Progressive finder
- Refit of track and selection





ATLAS Track reconstruction

Pre-processing:
- Space-point formation

Combinatorial track-finder in Silicon detectors

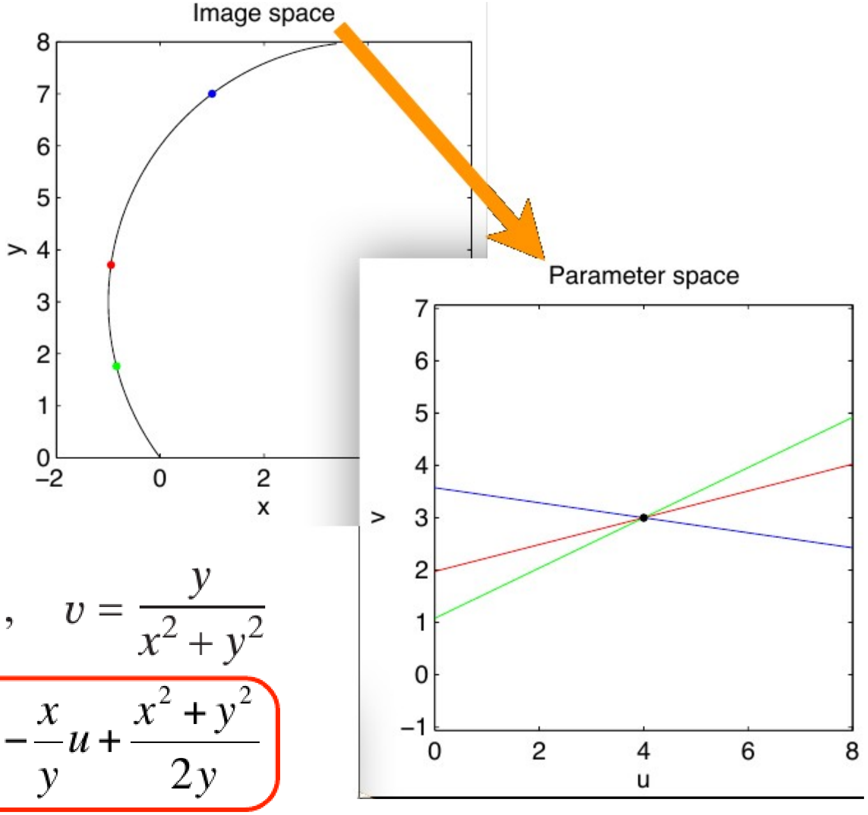
Ambiguity solver

Extension to TRT

- Search for maxima in parameter space
- Run ony in region of interest in Run-2

TRT Segment finder
- On remaining drift circles

- Conformal mapping with Hough transform



$$u = \frac{x}{x^2+y^2}, \quad v = \frac{y}{x^2+y^2}$$

$$\Rightarrow \boxed{v = -\frac{x}{y}u + \frac{x^2+y^2}{2y}}$$

ATLAS Track reconstruction

Pre-processing:
- Space-point formation

Combinatorial track-finder in Silicon detectors

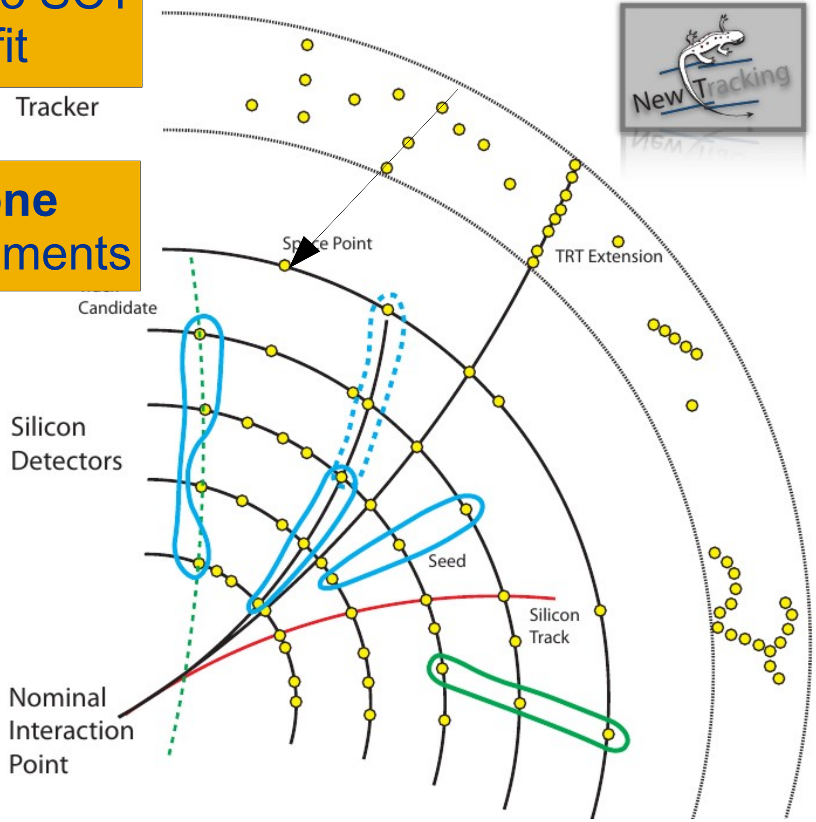
Ambiguity solver

Extension to TRT

TRT Segment finder

TRT-seeded finder + ambiguity solver
- From TRT back to SCT
- Precise track re-fit

TRT standalone
- Unused TRT segments



ATLAS Track reconstruction

Pre-processing:
- Space-point formation

Combinatorial track-finder in Silicon detectors

Ambiguity solver

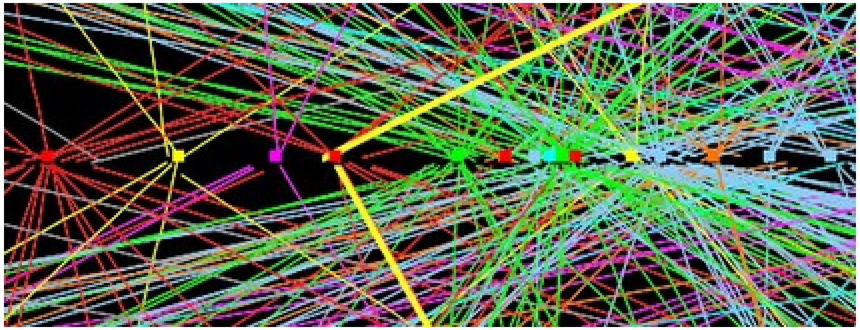
Extension to TRT

TRT Segment finder

TRT-seeded finder + ambiguity solver
- From TRT back to SCT
- Precise track re-fit

TRT standalone
- Unused TRT segments

Post-processing:
- Vertex finding
- Conversions
- ...



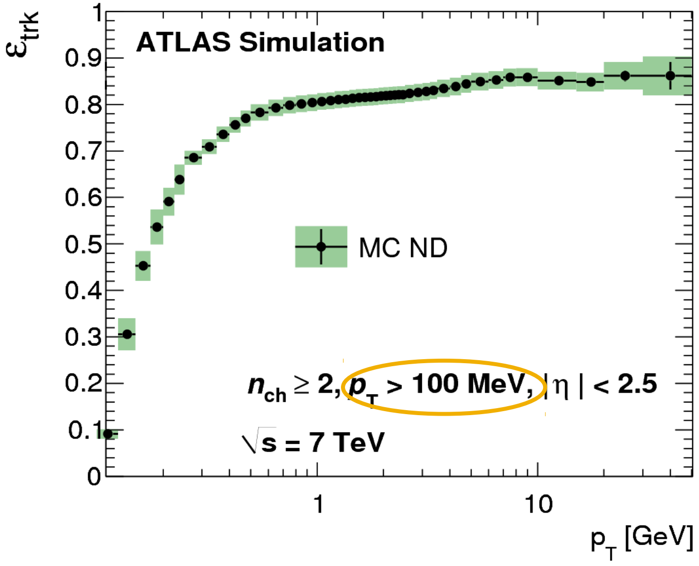
ATLAS Tracking setup

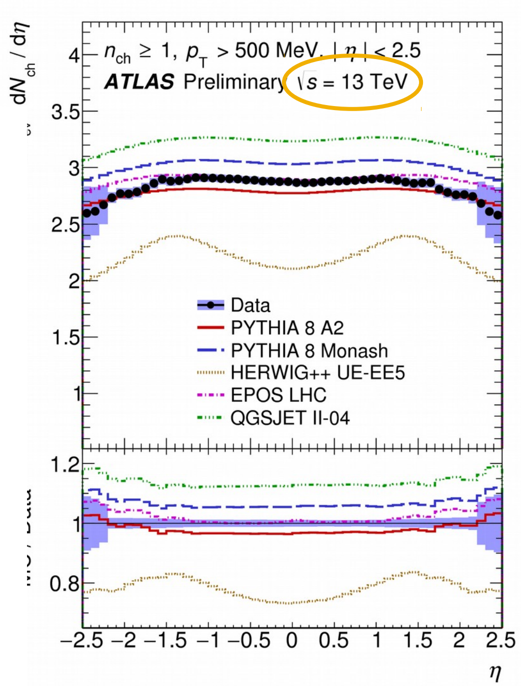
- Setup very modular and adapted to running conditions
- Reconstruct tracks with p_T > 400 MeV, $|d_0|$ < ~20mm (CPU req.)
- Significant updates during last years (Long Shutdown 1)
  - incorporate new IBL
  - re-optimize for expected pile-up conditions
  - Capitalize on Run-1 experience
  - Reduce CPU timing

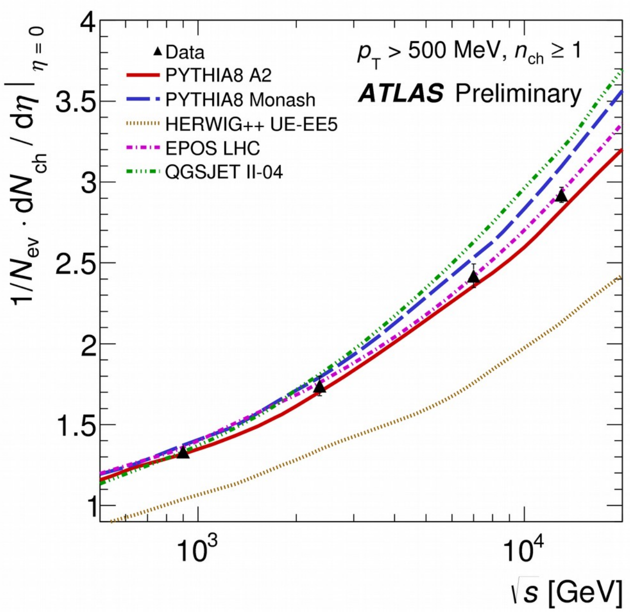
- Start-up in 2015 (Run-2): validate on data!

Minimum-bias analysis

- Unfold charged particle distributions, rely on tracking efficiency (and its uncertainties) as main ingredient to the analysis
  - Mostly pions produced from pp collisions (then Kaons, …)
- “Special” tracking setup → p_T > 100 MeV
- First results at 13 TeV already (among first results for Run-2!)

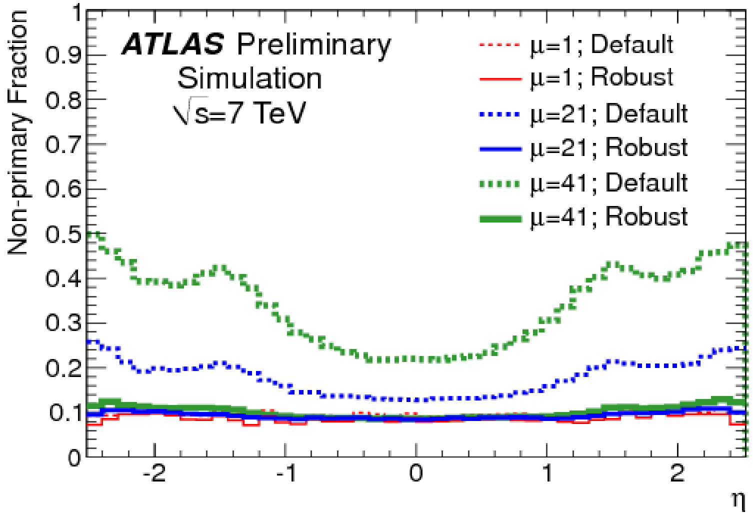


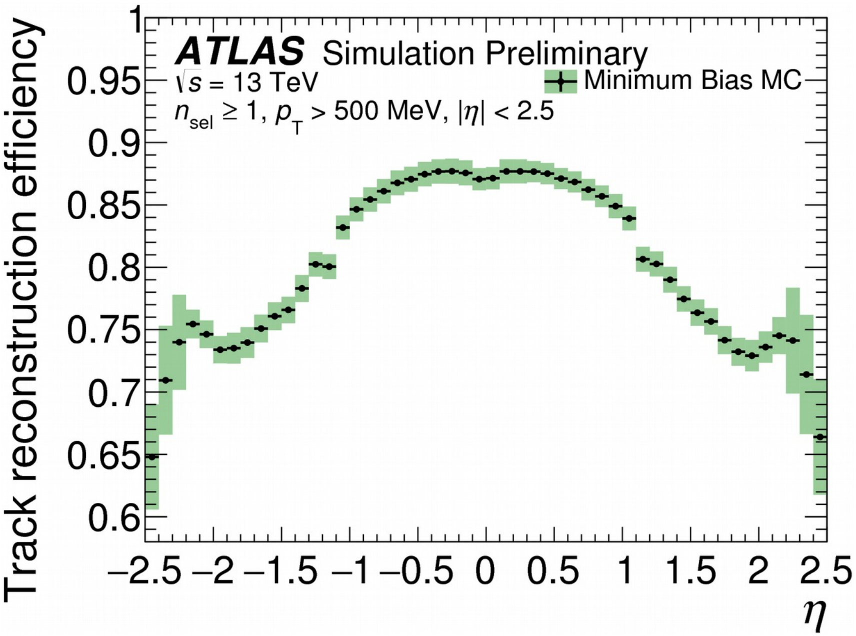


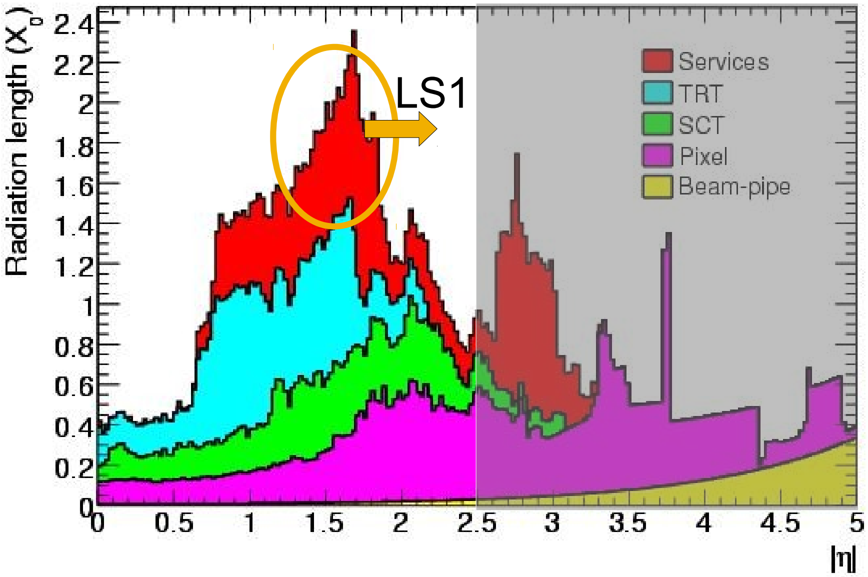


Tracking efficiency

- Reconstruction efficiency and rate of duplicate/fake tracks estimated from MC
  - Hadronic interactions: main cause of tracking inefficiency
    - For muons: efficiency ~99.5%
  - Precise knowledge of active/passive material crucial!

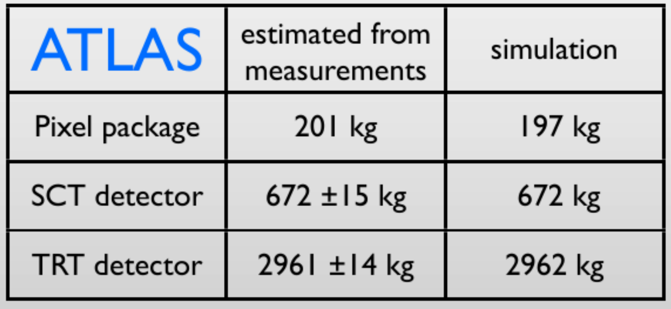




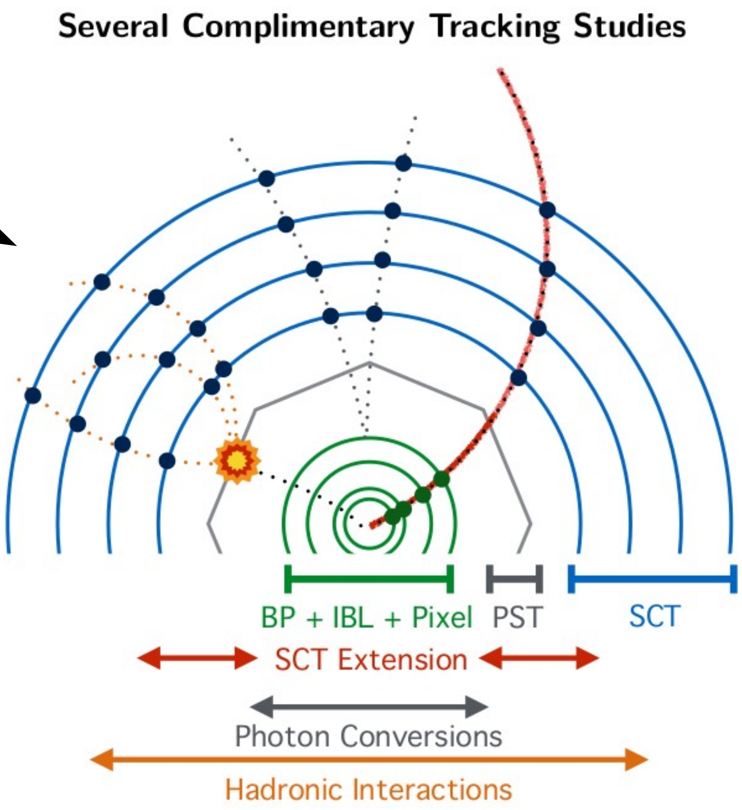


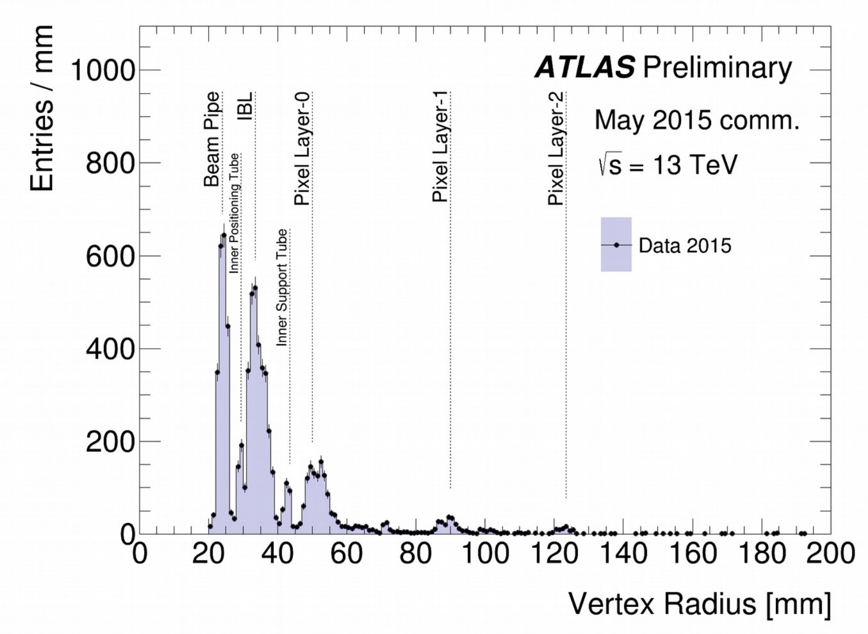
ID Material

- We've built the detector, therefore we know what it is made of….
- Kind of.. check with data itself!
- Radiography of Inner Detector using various techniques

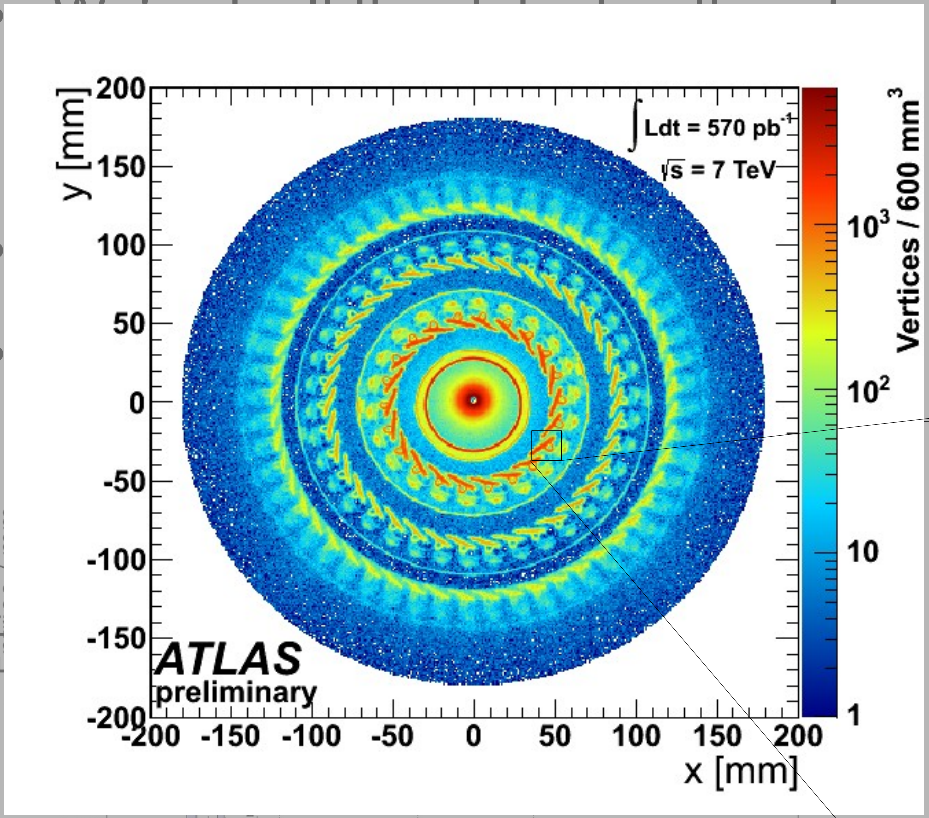


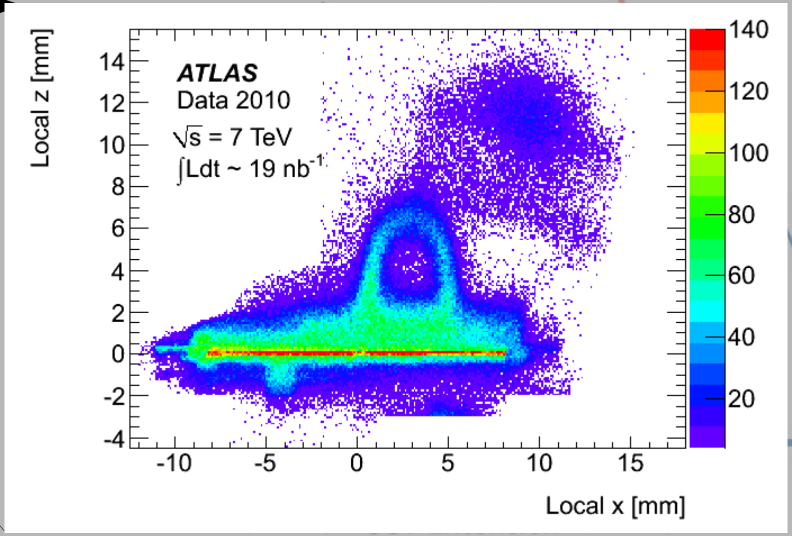
ATLAS	estimated from measurements	simulation
Pixel package	201 kg	197 kg
SCT detector	672 ±15 kg	672 kg
TRT detector	2961 ±14 kg	2962 kg





ID Material



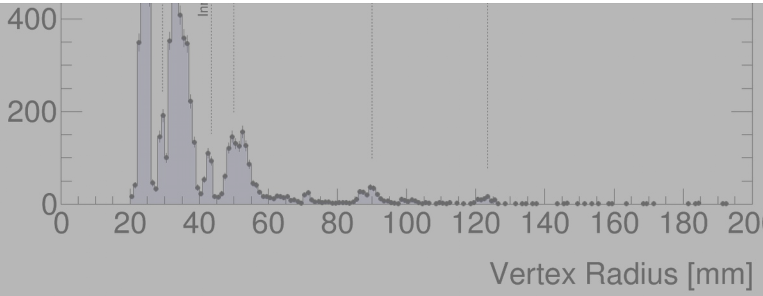


ATLAS	estimated from measurements	simulation
Pixel package	201 kg	197 kg
SCT detector	672 ±15 kg	672 kg
TRT detector	2961 ±14 kg	2962 kg

Several Complimentary Tracking Studies

Photon Conversions

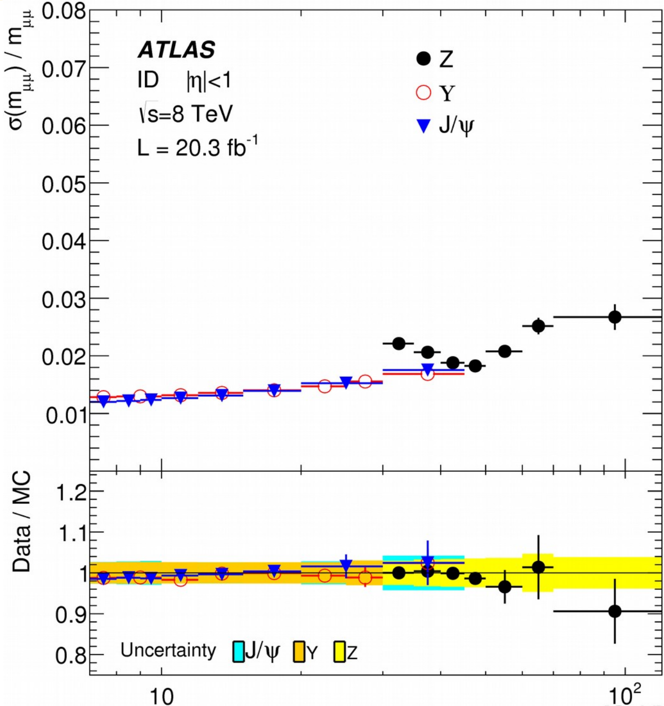
Hadronic Interactions

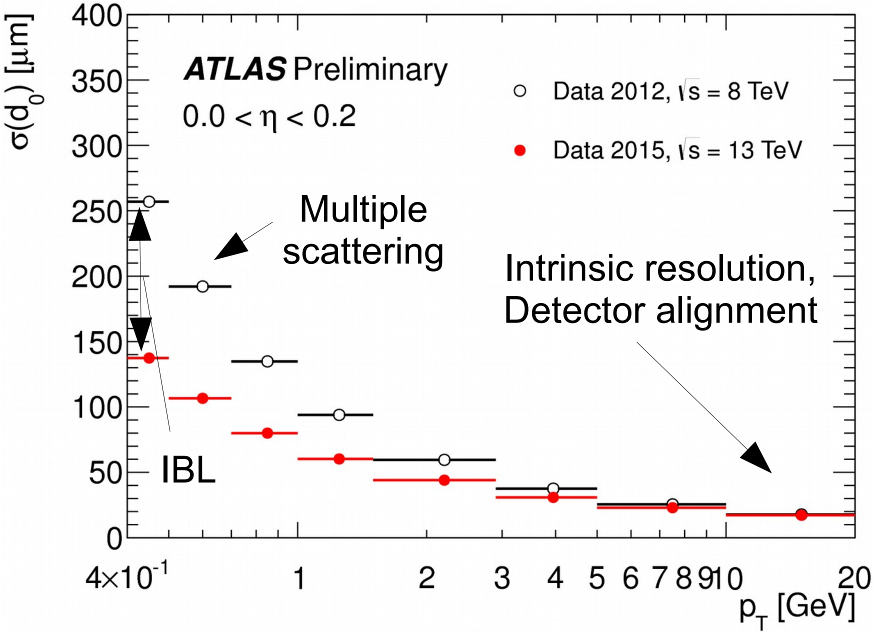


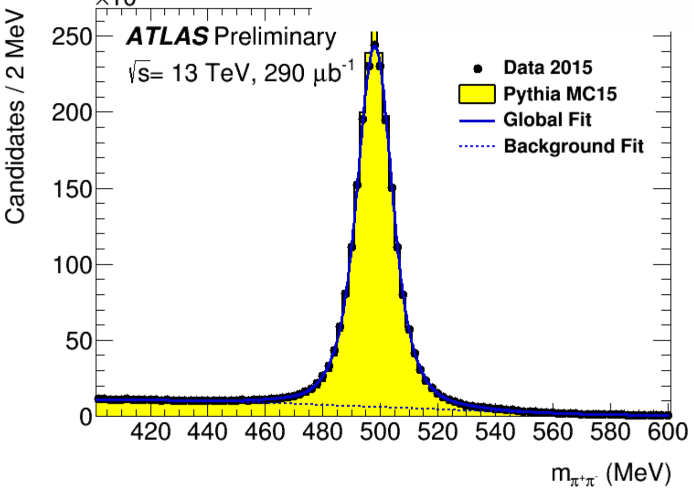
Track parameters resolution

$(d_0, z_0, \theta, \phi, q/p)$

- Momentum resolution from known resonances ($K_S \to \pi\pi$, J/Ψ or Y or $Z \to \mu\mu$)
- Impact parameter resolution from prompt tracks originating from the same interaction







ID Alignment

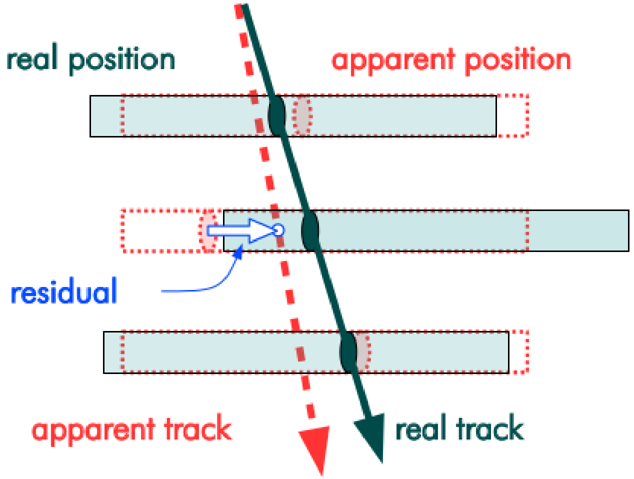
- Ultimate alignment is track-based
- χ^2 minimization of measurements-track residuals

$$\chi^2 = \sum_{hits} \left(\frac{m_i - h_i(\vec{\alpha})}{\sigma_i} \right)^2$$

Measurement

Expectiation

Expected uncertainty
(intrinsic resolution)

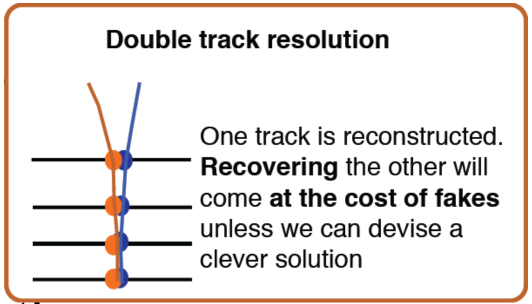


- Iterative procedure starting from rigid-bodies down to module-level

Alignable Structures				
	IBL	Pixel	SCT	TRT
L11	1	1	3	3
L2(27)	1(14)	9	22	96
L3	280	1744	4088	~350k

Tracking in dense environments

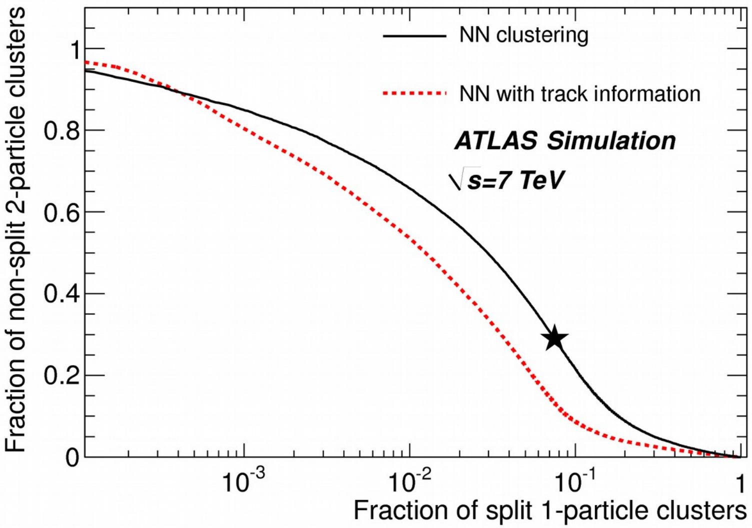
- Loss of tracking efficiency near core of high-p_T jets or taus
- Artificial NN to identify pixel measurements compatible with more than one particle
  - Based on charge, shape (>1 pixel hit)

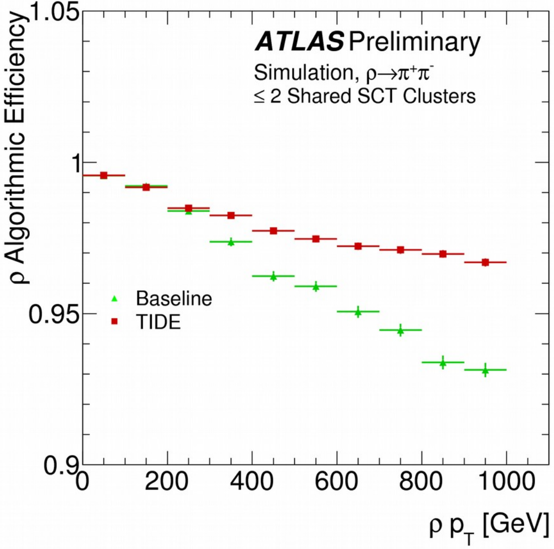


Double track resolution

One track is reconstructed. **Recovering** the other will come **at the cost of fakes** unless we can devise a clever solution

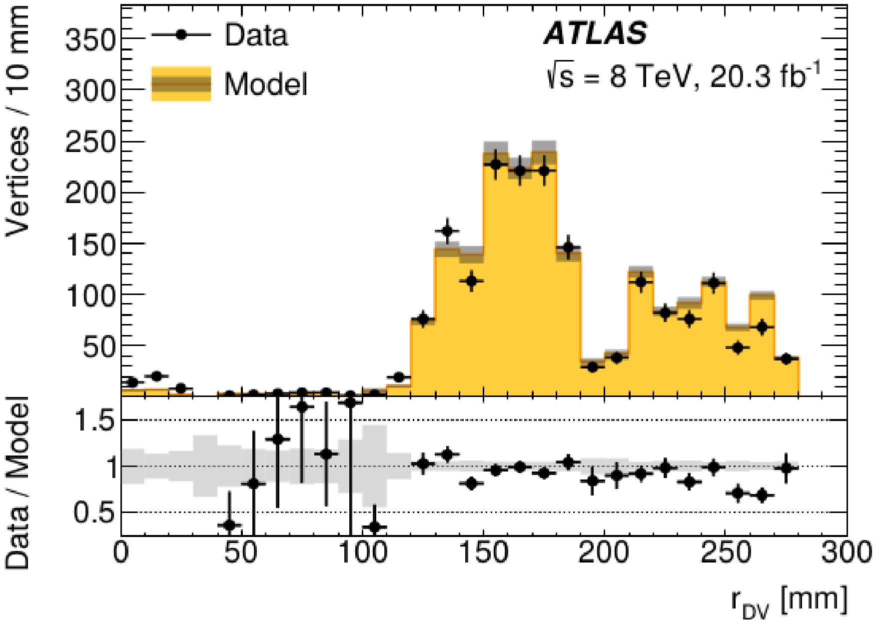
- Recently improved using track candidate information
  - Use "global" information to discriminate good/fake nearby tracks
  - Interestingly, now efficiency limited by shared measurements in SCT!

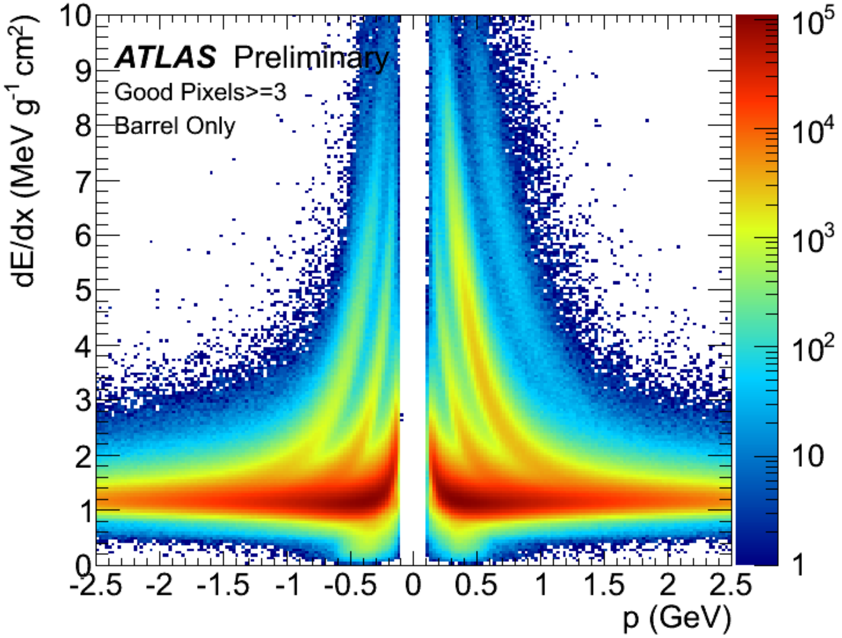




Special setups

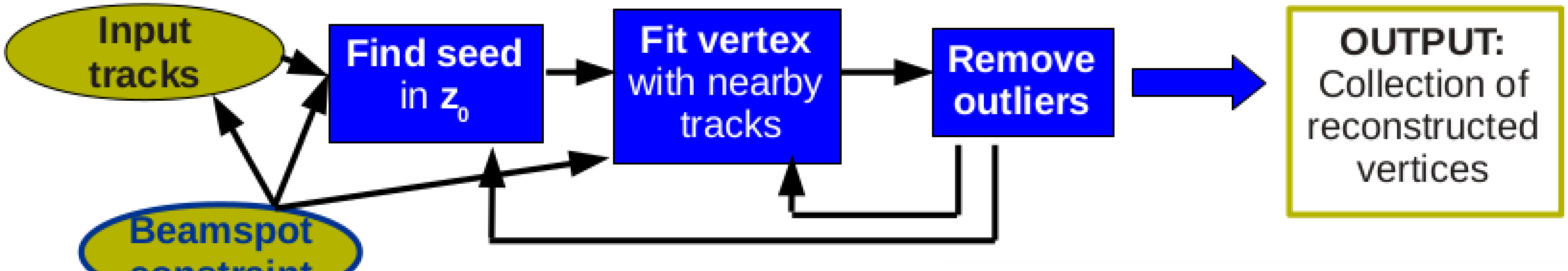
- Some Exotic/SUSY searches use special setups to find non-standard signatures, for instance:
  - Displaced Vertices from long-lived particles decaying far from interaction region: recover large d_0 tracks, reconstruct vertices
  - Heavily ionizing particles → large dE/dx as measured in Pixel system





Primary Vertex reconstruction

- Find the **number** and **position** of primary p-p collisions
  - Determine position of interaction region
  - Use as reference point for life-time of non-prompt particles (b,τ,K_S,..)



Input tracks

Find seed in z_0

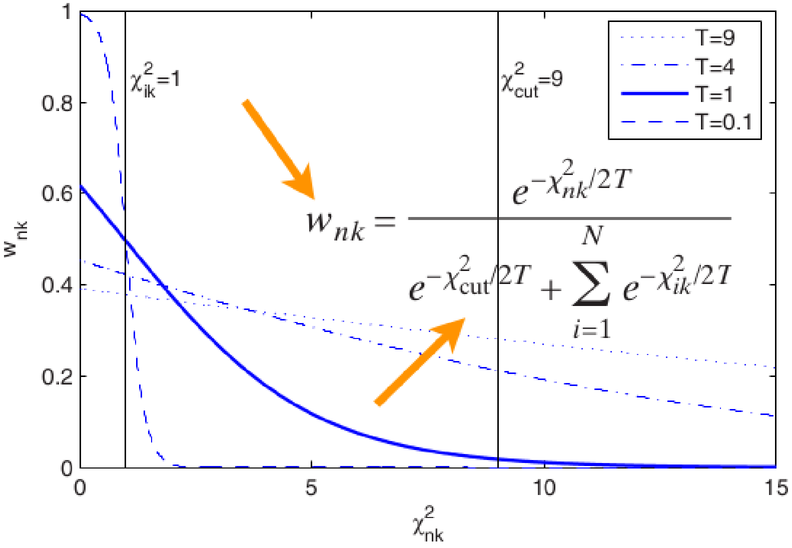
Fit vertex with nearby tracks

Remove outliers

OUTPUT: Collection of reconstructed vertices

Beamspot constraint

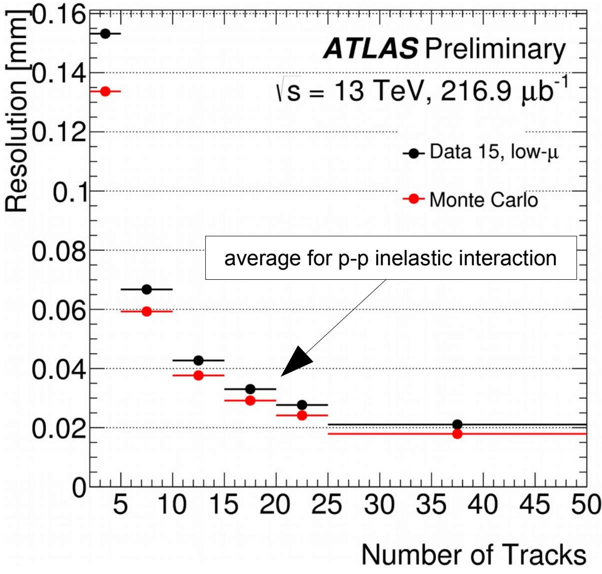
- Output vertices by at least two tracks
- "Hard-scattering" vertex: highest Σp_T^2
- Vertex fit: Adaptive Kalman fit
  - Outlier track contributions down-weighted → robust

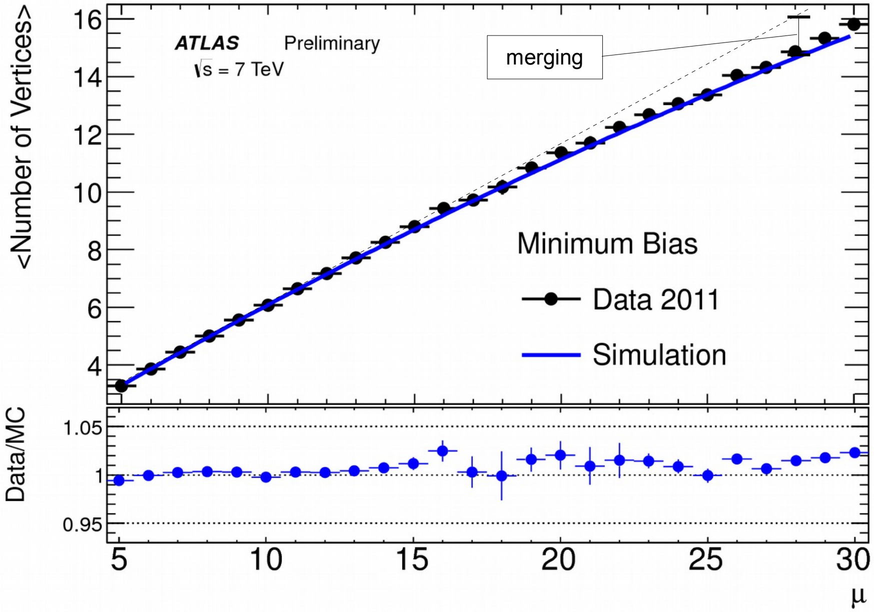


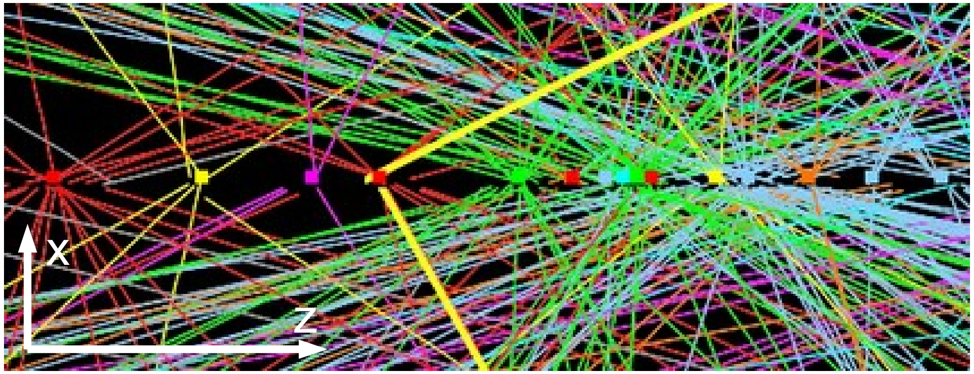
$$w_{nk} = \frac{e^{-\chi^2_{nk}/2T}}{e^{-\chi^2_{cut}/2T} + \sum_{i=1}^{N} e^{-\chi^2_{ik}/2T}}$$

Vertex reconstruction performance

- Typical resolution: 10-40μm (x), 30-50μm (z)
- Reconstruction efficiency of generic p-p collision ~ 70%
    - > 99% if two tracks within acceptance
- Merging of nearby interactions limits efficiency at large number of interactions







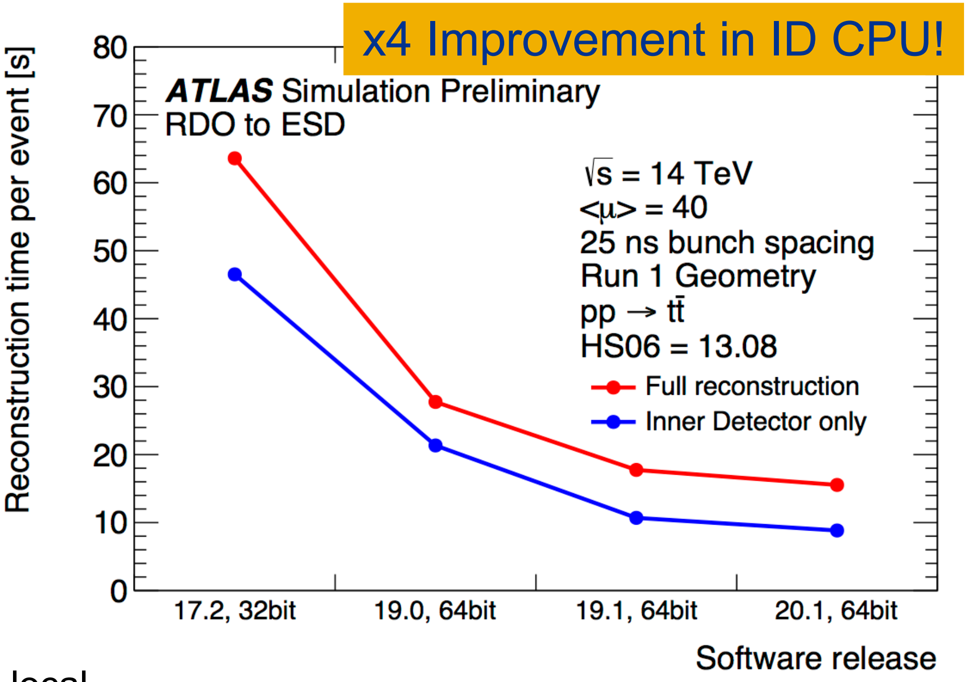
Interaction region (~Gaussian):

Transverse size (σ_x): 12-16μm, 8-15μm, Run2

Longitudinal size (σ_z): 45-50 mm

CPU Timing

- Tracking is a combinatorial problem → large increase of CPU timing with increase of the number of particles (interactions)
- Large effort during past three years to improve performance
  - Driven by increased output trigger rate ~300-400Hz → 1kHz, expected increase of pile-up and available processing power
- Improve software technology
- Seeding strategy tuning
  - Purity of seed changes with pile-up conditions
  - Guarantees flat efficiency, no fake increase and improves cpu
  - Promote seeds with 4th-point


x4 Improvement in ID CPU!

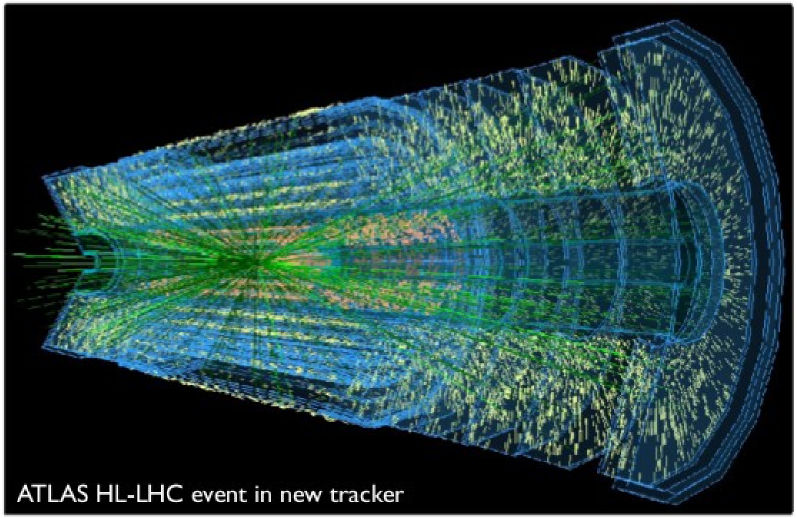
seeding	efficiency	CPU*
"Run-I"	94.0%	9.5 sec
"Run-2"	94.2%	4.7 sec

* = on local machine

A look into the future

- High-Luminosity LHC (> 2023) will see
  - Even more extreme conditions: L~5x10^{34}, μ~140
  - New Inner Detector, all silicon-based (pixels + strips)
- How to reconstruct HL-LHC events?
- Processor technologies are changing
  - Beyond event-level parallelism
  - Current tracking heavily sequential, Need to exploit new ideas!

$$\mathrm{Time}_{||} = \mathrm{Para} / N + \mathrm{Seq}$$


ATLAS HL-LHC event in new tracker


Titan: World's Fastest Supercomputer 2012

18,688 Tesla K20X GPUs

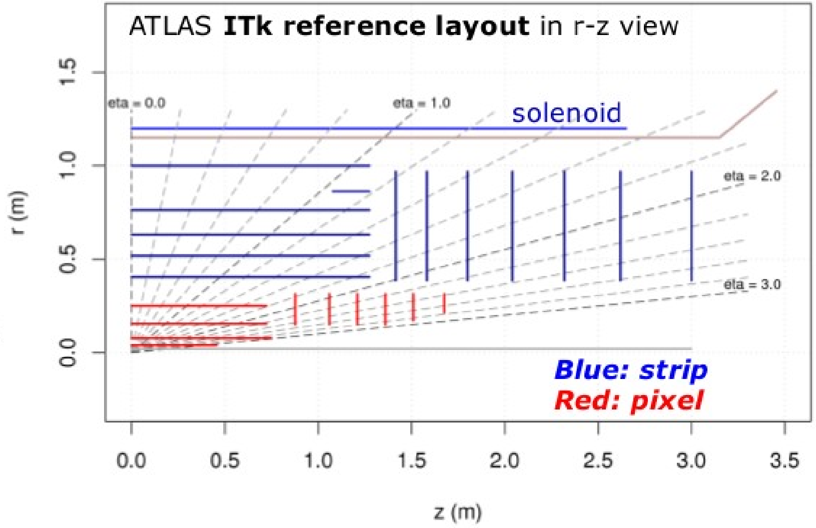
27 Petaflops Peak: 90% of Performance from GPUs

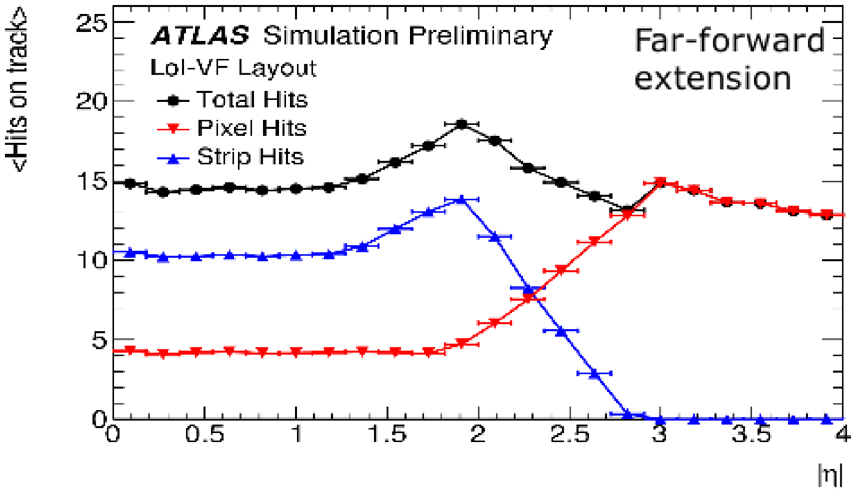
17.59 Petaflops Sustained Performance on Linpack

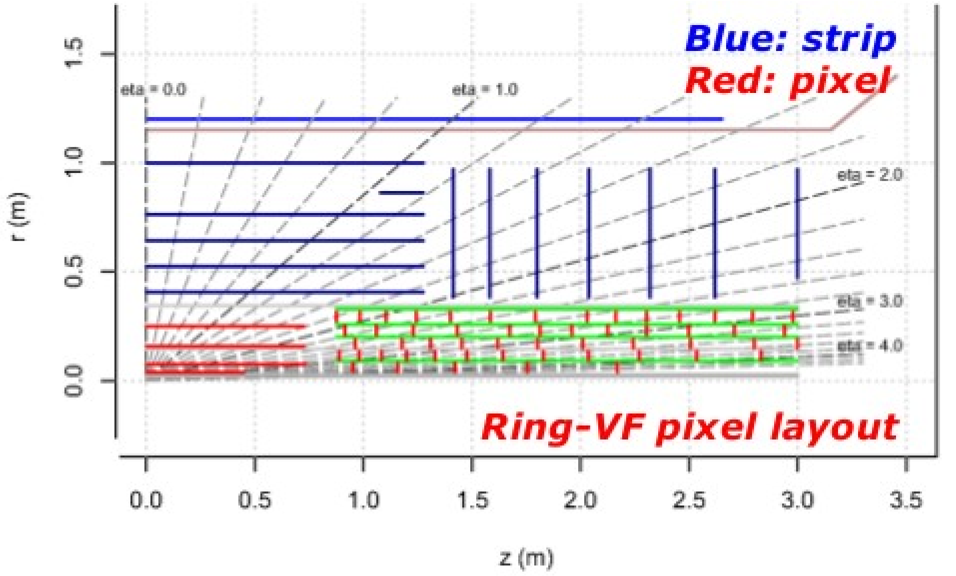
#3 on the Green 500 list

Layout studies

- Baseline layout for initial studies
- Alternative layouts being developed
  - Extension of tracking beyond current coverage, up to |η| < 4?
- Current tracking algorithms work reasonably, but need re-design for achieving best performance

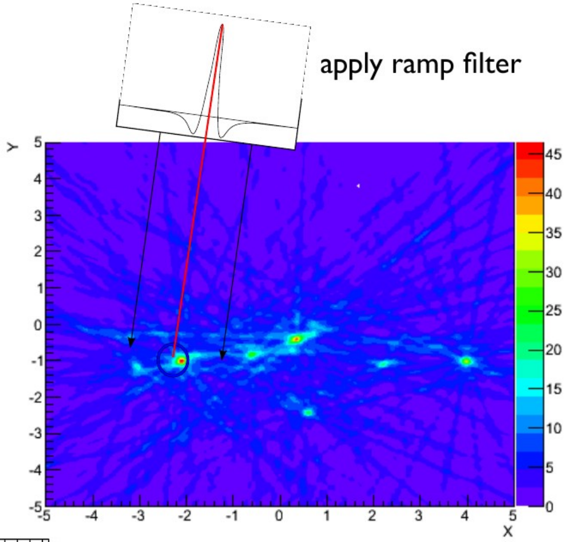


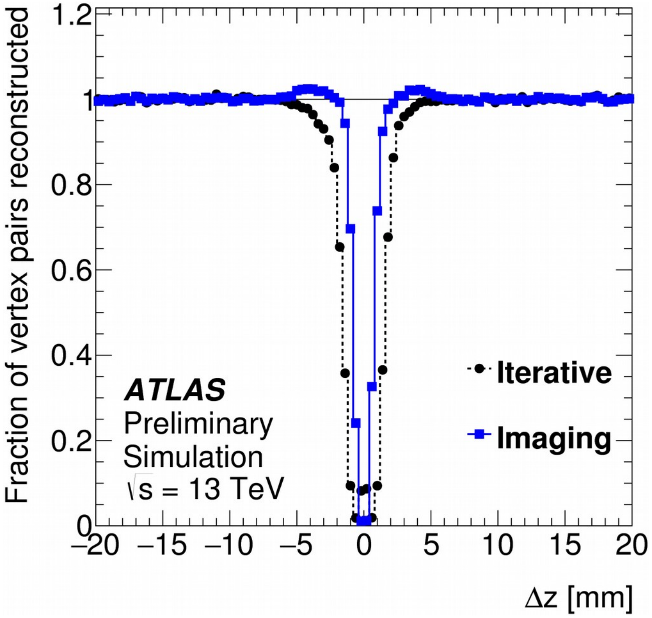


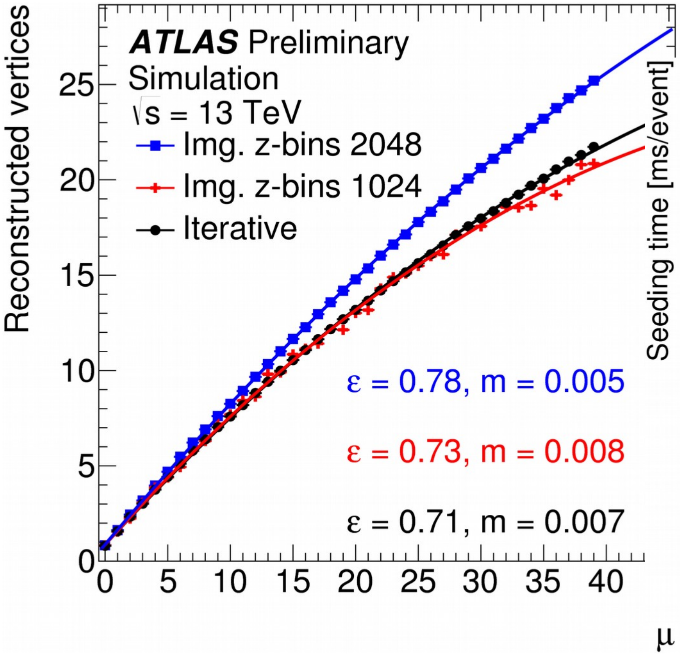


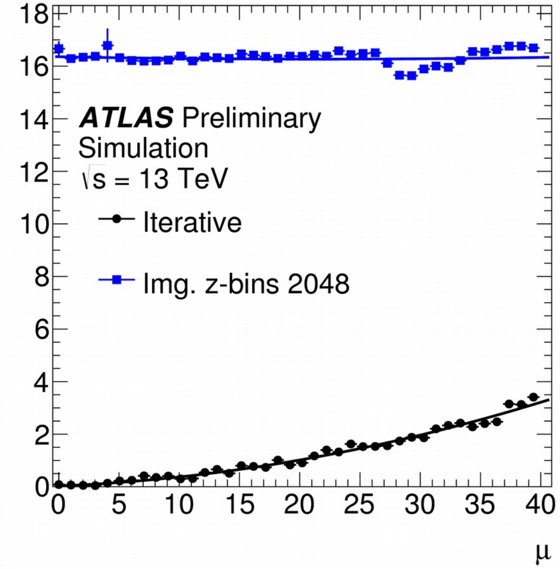
Vertexing at HL-LHC

- Bottleneck for distinguishing high density of pile-up interactions is seeding stage
- Medical-imaging inspired seeding
  - Based on inverse Radon transform
  - Apply filter, project back in position space









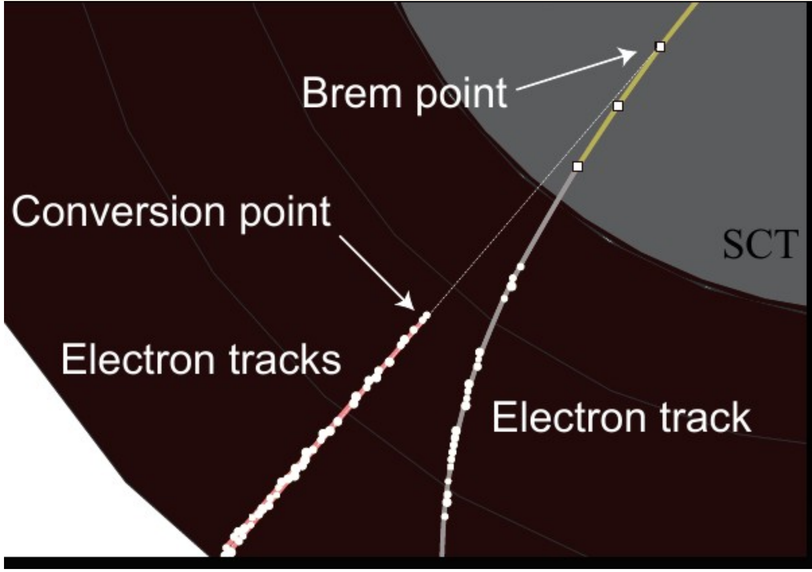
Conclusions

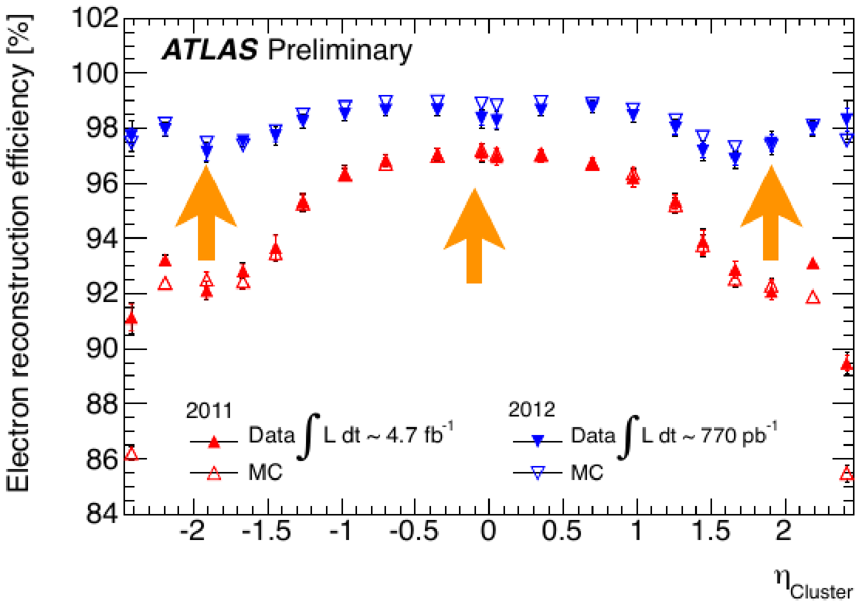
- Track reconstruction in hadron colliders is a challenging problem
- ATLAS has developed a very modular setup to cope with very different conditions
- We never stop learning.. developments are still ongoing and new ideas will be essential for addressing at the best future challenges!

BACKUP

Electron reconstruction: a special case

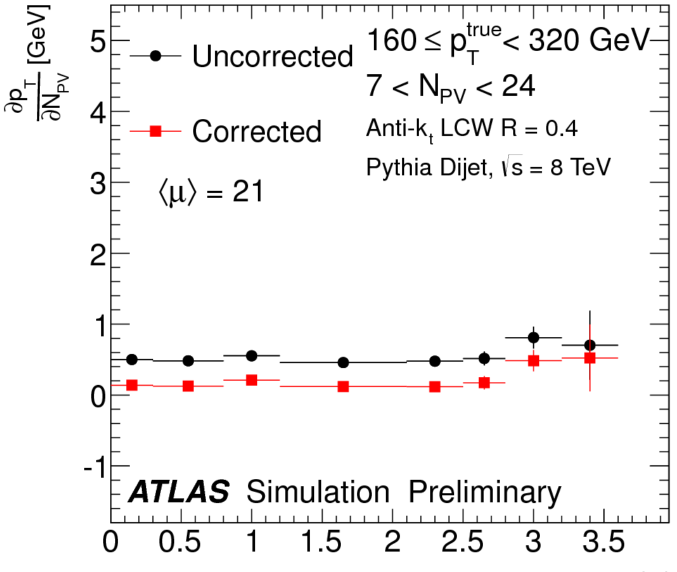
- Electrons require special handling
- Bremsstrahlung significantly alters their trajectory
  - Pion-hypothesis fit fails
  - Momentum estimation biased
- Dedicated treatment
  - seeded by EM clusters
  - allow up to 30% energy loss at each material surface
  - energy loss parametrize as multiple Gaussians component

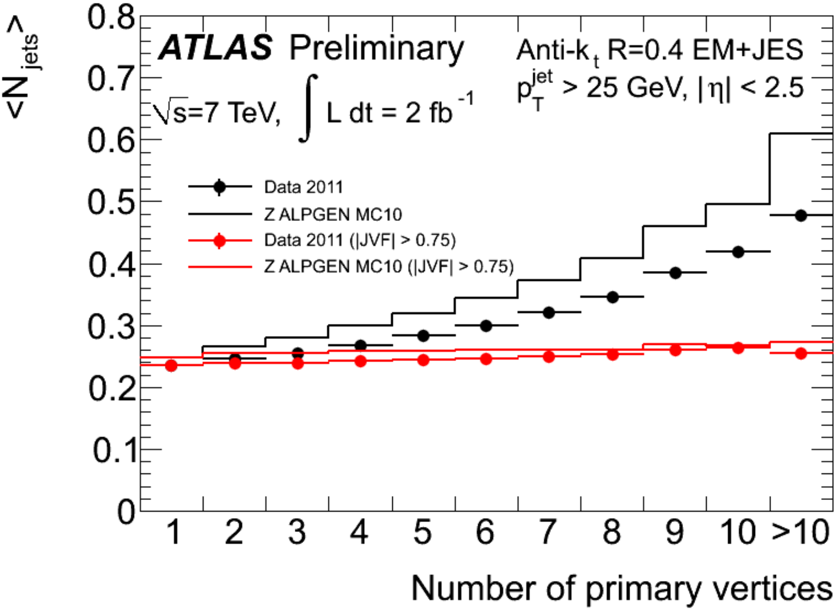


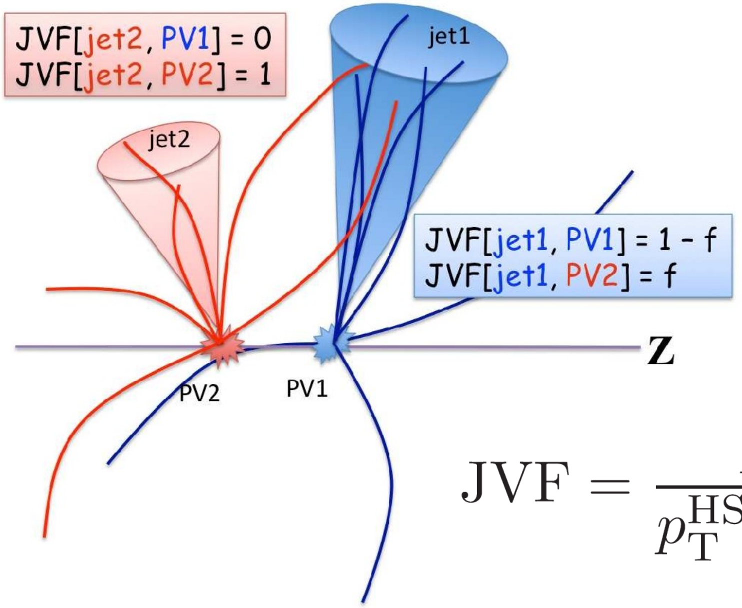


Pile-up mitigation (e.g. in jets)

- Contributes to energy of reconstructed jets (~0.5 GeV / vertex)
- Jets from pile-up interactions
  - Use reconstructed tracks to match jets to the hard-scattering primary vertex

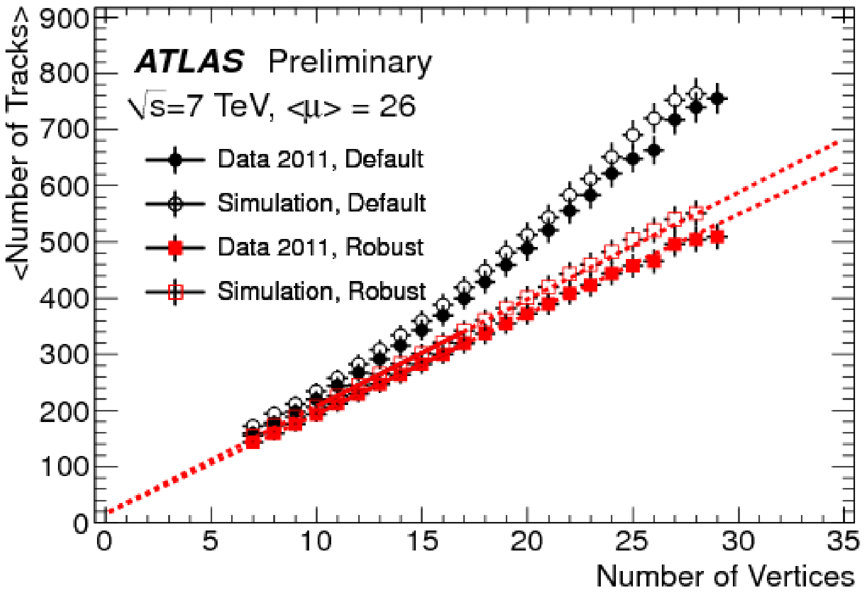


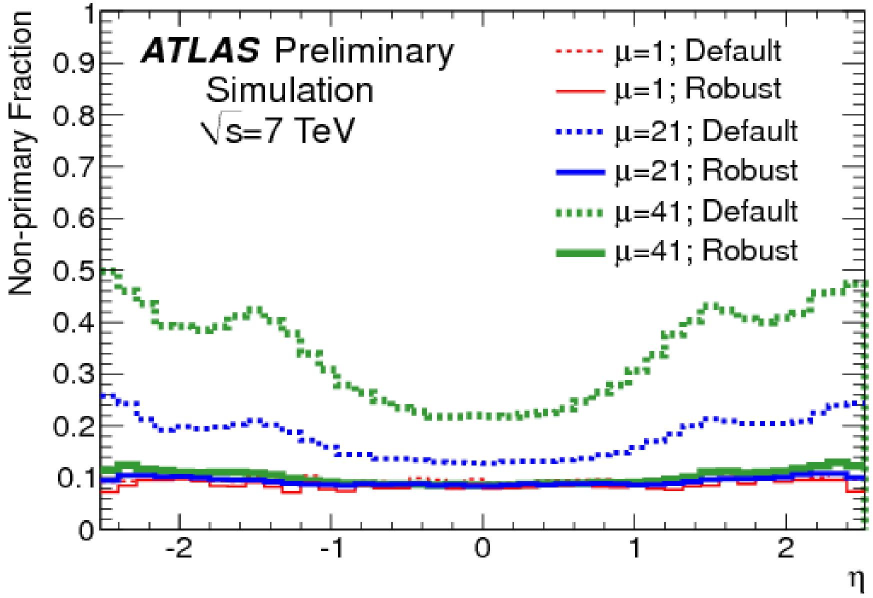




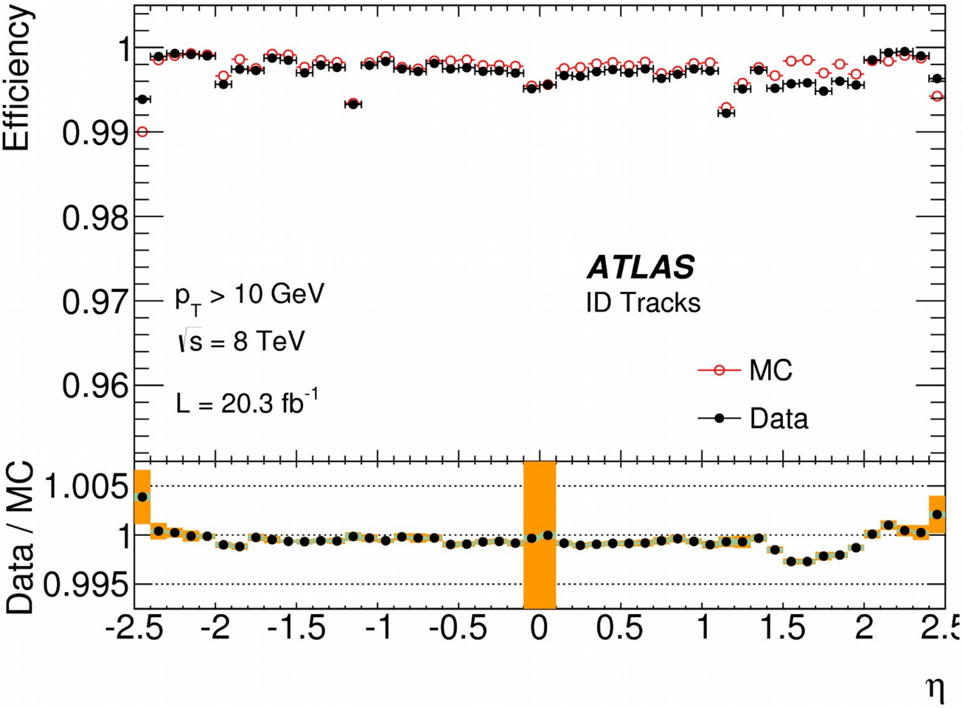
$$\mathrm{JVF} = \frac{p_{\mathrm{T}}^{\mathrm{HS}}}{p_{\mathrm{T}}^{\mathrm{HS}} + p_{\mathrm{T}}^{\mathrm{PU}}}$$

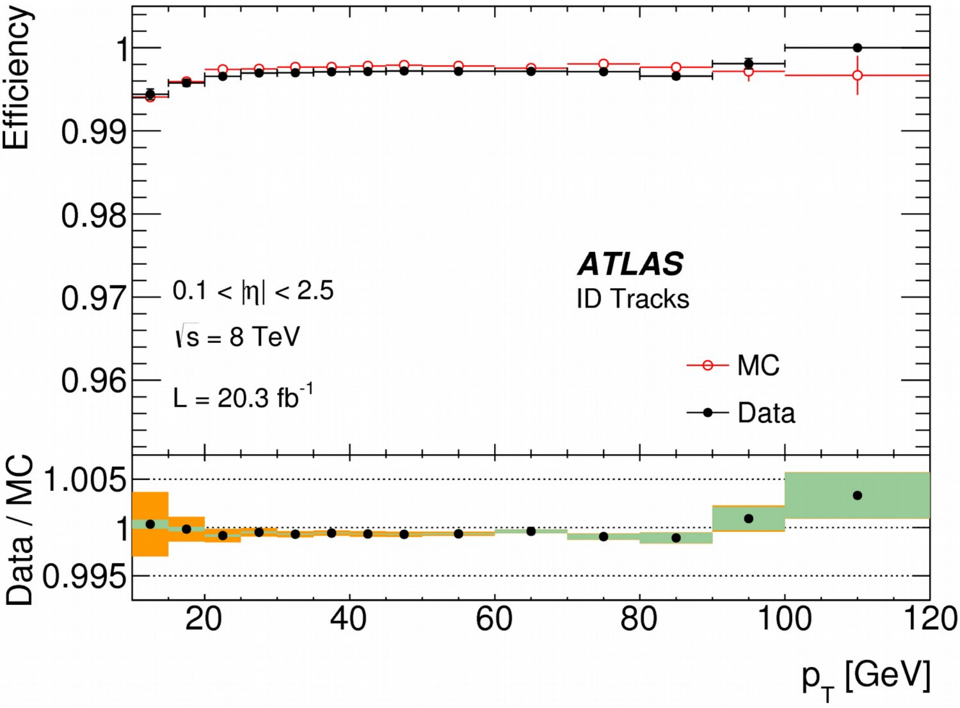
Tracking “fake” rate



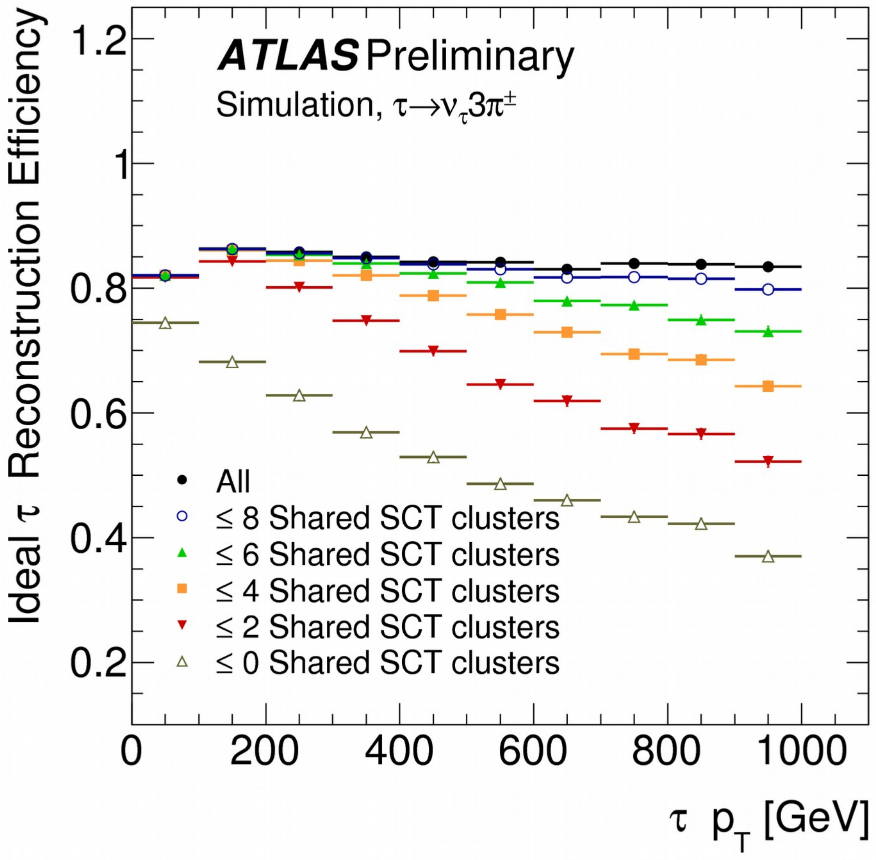


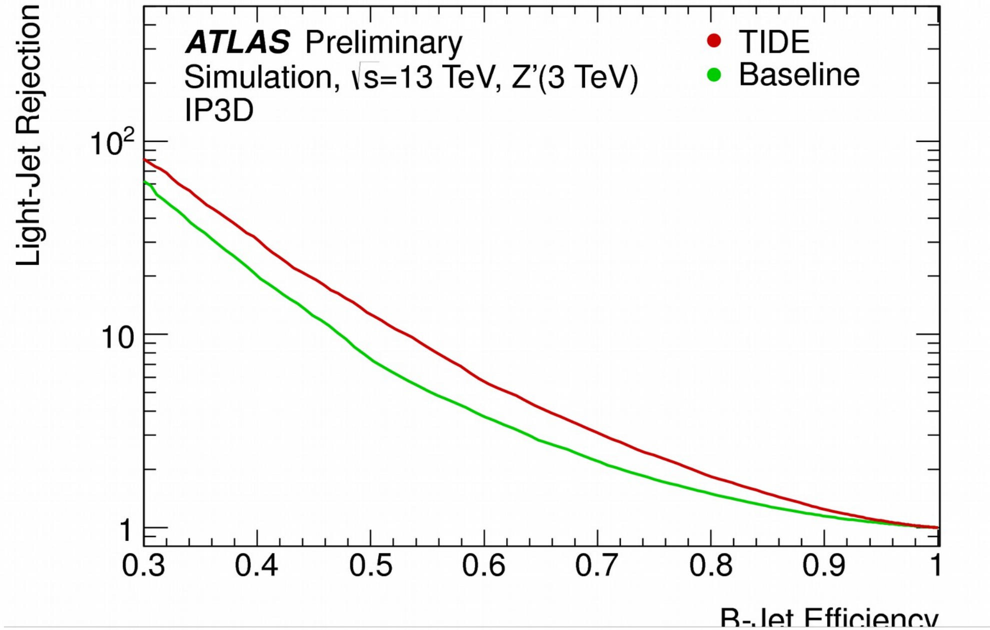
Muon reconstruction efficiency





TIDE


ATLAS Preliminary
Simulation, τ→ν_τ3π±
Ideal τ Reconstruction Efficiency
τ p_T [GeV]
0
200
400
600
800
1000
0.2
0.4
0.6
0.8
1
1.2
All
≤ 8 Shared SCT clusters
≤ 6 Shared SCT clusters
≤ 4 Shared SCT clusters
≤ 2 Shared SCT clusters
≤ 0 Shared SCT clusters


ATLAS Preliminary
Simulation, √s=13 TeV, Z'(3 TeV)
IP3D
TIDE
Baseline
Light-Jet Rejection
1
10
10^2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
B-Jet Efficiency