Planned Measurements of the Underlying Event

For:

London Workshop on Standard Model Discoveries with Early LHC Data

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Outline

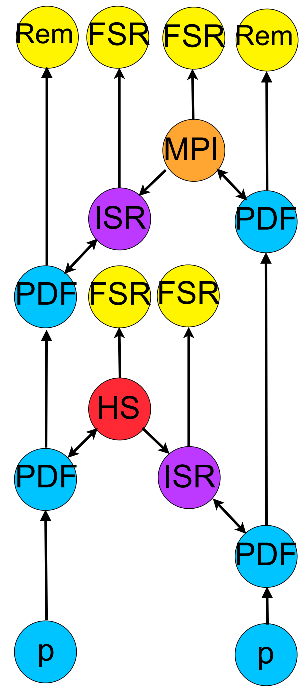
- A brief summary of three monte carlo generator models for the underlying event.
  - Herwig + Jimmy
  - Pythia 6.4
  - PhoJet
- The underlying event measurements, in the context of these models.
  - Particle Number
  - Particle Summed Pt
  - KNO Shape
- The properties of the ATLAS and CMS tracking & triggers, relevant to these measurements.

Herwig + Jimmy (roughly)

- Multiple interactions, including the primary Hard Scatter are introduced by Jimmy.
  - Assumes a Poisson distribution of parton interactions.
  - The hard scatters are identified as a subset of the general parton interactions.
- HS incoming partons high Pt are back-evolved to lower Pt by including:
  - Initial State Radiation (ISR) using Sudakov method weighted by PDFs.
  - Angular ordering is applied between the proton on the radiated partons.
- Final State Radiation (FSR) from the hard scatter is forward evolved by a parton shower.
  - Primary ordering is by angle. This limits the solid angle that is populated by the shower.
- The final collection of partons is made by splitting gluons to consist only of quarks (or diquarks), which are paired to form color-singlet clusters. These are then fragmented to on-shell hadrons.
- Minimum Bias events are generated using a negative binomial distribution for the particles in the event. (More on this later...)

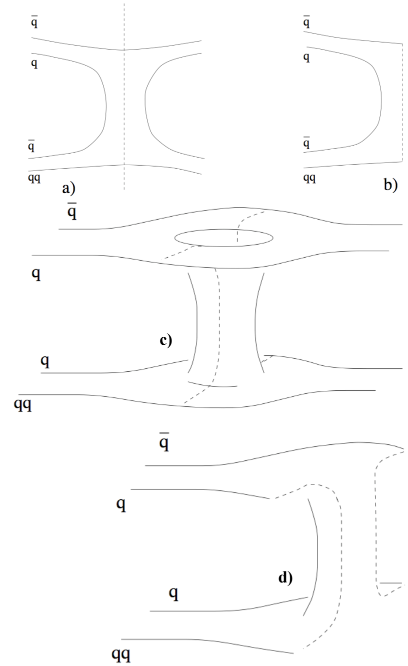
Pythia 6.4 model (roughly)

- The incoming partons to the hard scatter are back-evolved to lower Pt by including:
  - (ISR) Initial State Radiation using Pt shower weighted by back-evolved PDFs.
  - (MPI) Multiple Parton Interactions that amend the PDFs in question.
- The full event (ISR and MPI included) is forward evolved (FSR) to lower Pt by a Sudakov shower.
  - Primary ordering is by Pt.
- The final collection of partons and remnants are assigned to strings and fragmented using the Lund model.
- Minimum bias cross-sections are calculated using a pomeron and reggeon exchange model.
  - MPI are rescaled to match pomeron & reggeon predictions.



PhoJet 1.12 model (roughly)

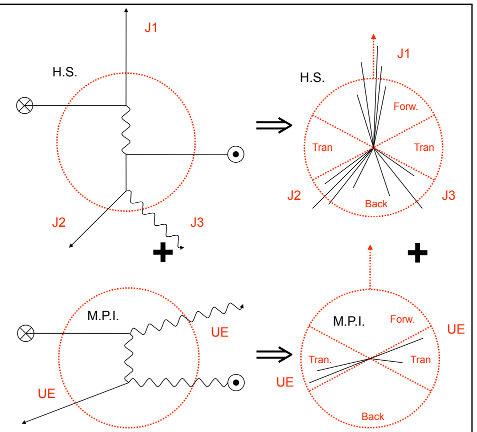
- Cut Reggeon & Pomeron exchanges are calculated.
  - Elastic scattering occurs via Pomeron exchange (c), and in resonances by Reggeon exchange (a).
  - Inelastic scattering includes string pairs from cut Pomerons (d) and from cut Reggeons (b) that account for MPI.
- The hard scatter (2→2) matrix element is calculated.
  - Parton exchange, rather than Reggeon or Pomeron.
- The ISR & FSR for partons from the hard scatter is calculated.
- The FSR partons and proton remnants are assigned to strings. These strings and the strings from cuts are then fragmented using the Lund model.

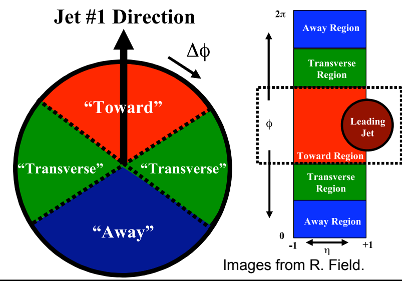


Figures from PhoJet Manual

UE Characterization

- Hard Scatter yields* 2 or 3 hard jets.
  *Given sufficient qualifying statements...
- Two equally hard jets will be roughly back-to-back.
- Additional interactions yield softer particles whose directions are not correlated to the hard scatter axis.
- Fragmentation, especially due to connections to remnants, can yield additional particles.
- Three equally hard jets are roughly at $2\pi/3$ intervals.
- $\pi/3 < |\Delta\varphi| < 2\pi/3$ and $|\eta| < 1$ defines the transverse region.
- For the third hardest jet to be in the transverse region it must be softened.

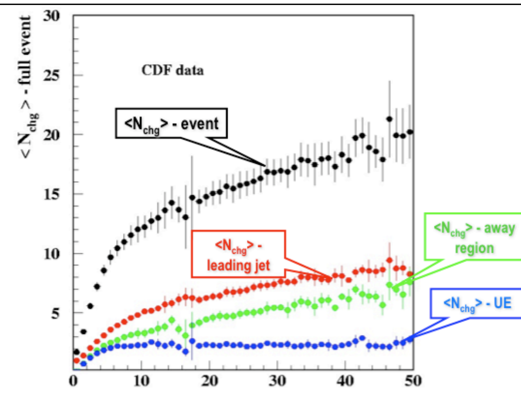




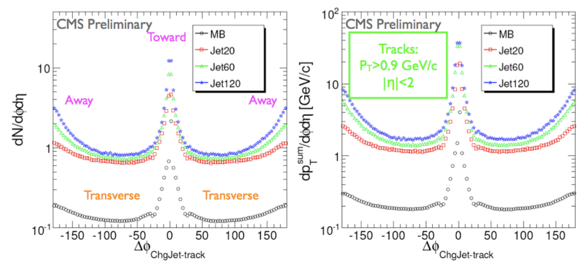
Images from R. Field.

UE Characterization

- The number of tracks in the transverse region is less correlated to the lead jet energy.
- Sources of transverse tracks:
  - MPI
  - Fragmentation of string connections to remnants.
- <u>Track Jets</u> are used, so that low energy calorimeter response is not involved.
  - Also simplifies comparison to models.
- <u>Drell-Yan</u>: Look for $\mu^+\mu^-$ there is no FSR associated with their production.
  - The entire φ range characterizes the UE.



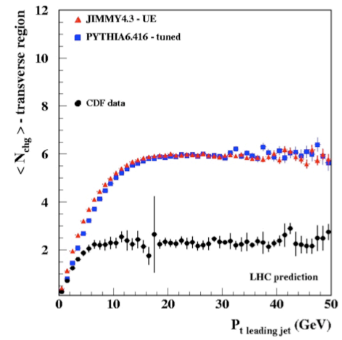
Above: Plot by Affolder at al.

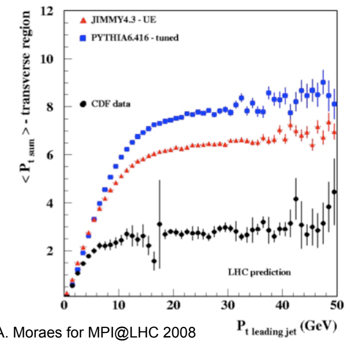


Above: Plots from F. Ambroglini

UE in Jet Events

- Above: track number in transverse region.
- Below: track summed Pt in transverse region.
  - Tracks must have:
    - Pt > 0.5 GeV (ATLAS predictions shown here)
  - Changes in the mean charged particle Pt also alters the track count.
- Each generator was tuned to CDF (black data) then extrapolated to LHC@14TeV
- Pythia yields a spectrum with a higher mean track Pt, but matched multiplicity of tracks with Pt > 0.5 GeV.
- Used to tune the Pt cutoff for MPI & ISR
  - Lower cutoff (~ gluon screening) yields more partons.
- Sensitive to Pythia's string connection scheme.
  - Length minimization yields fewer, higher Pt particles.

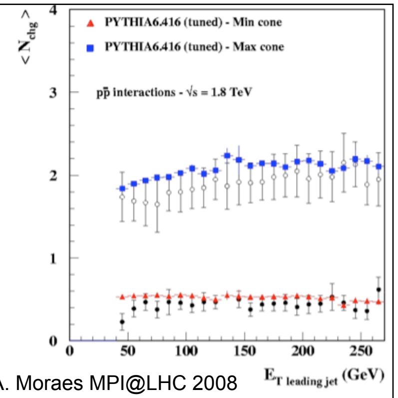




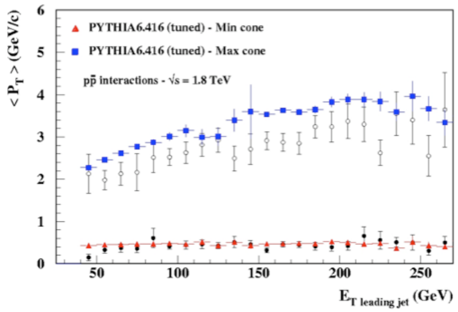
Plots by A. Moraes for MPI@LHC 2008

UE in Jet Events

- Transverse min and max regions are defined by cones of radius 0.7, perpendicular to lead jet, and with equal η.
- Above: track number in transverse min and max regions.
- Below: track summed Pt in transverse min and max regions.
- Pythia tuned to CDF@1.8TeV
  - B&W points are CDF data
  - R&B points are Pythia 6.4 estimates
- In di-jet events the smaller ϕ between the highest (J1) and second highest (J2) Et jets generally contains more tracks.
- The particles in the Min cone region are supposed to principally come from the fragmentation of strings connected to remnants.

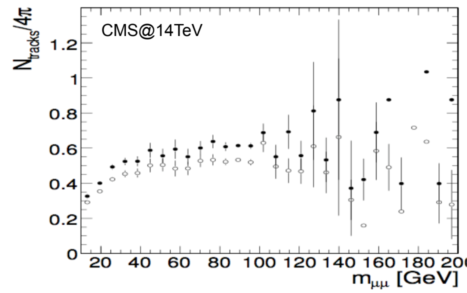


A. Moraes MPI@LHC 2008

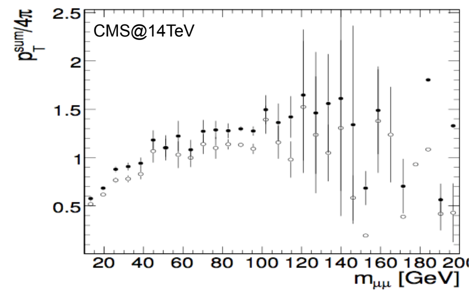


UE in Drell-Yan Events

- Drell-Yan: qq-bar → $\mu^+ \mu^-$
  - Via t-channel γ^* so few statistics above Z mass.
  - General lepton triggers are available.
- Characterization for tracks with $|\eta| < 1$, any ϕ.
  - Pt > 0.5 GeV at ATLAS & CMS
- Event selection requires isolated μ.
  - No tracks with Pt > 15 GeV within $\Delta R < 0.3$
- Naïve expectations assume the similarity of the generator's ISR & MPI in these events and di-jet.
  - Parton shower and string connections do not involve the hard scatter products
  - Asymmetric remnants.

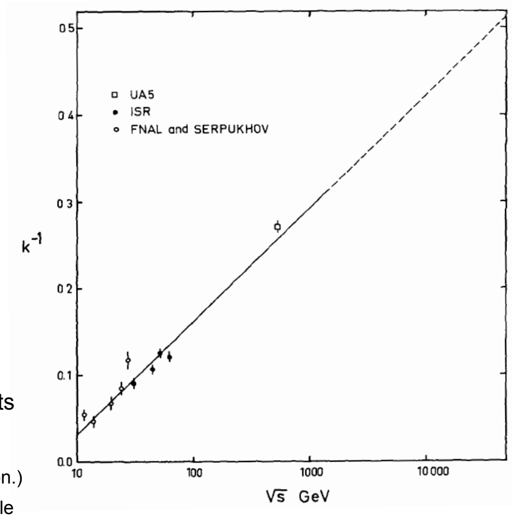


Plots from CMS TDR volume 2 using Pythia 6.2
Black Circles: Generator Distributions
White Circles: Reconstructed Distributions



KNO Scaling

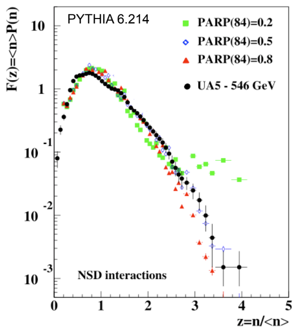
- KNO Hypothesis: Moments $\langle n^m \rangle$ of the multiplicity distribution depend on the event energy scale only through the change of <n>.
- KNO variables characterize the reduced moments in particle production.
  - z=n/<n> yields reduced m^{th} moment of the multiplicity distribution as $\langle n^m \rangle / \langle n \rangle^m = \langle z^m \rangle$.
  - F=<n>*P(n) yields the mean multiplicity as $\langle n \rangle = \Sigma_n P(n)*n \approx \int_z F(z)*z$.
- Amended: The reduced factorial moments $\langle n!/m! \rangle / \langle n \rangle^m$ are invariant in general.
  - Consistent with a Negative Binomial (NB) Distribution. (General memory-less distribution.)
  - Poisson at low energies ~ independent particle production.
  - Exponential at high energies ~ sequential (parton shower) particle production.



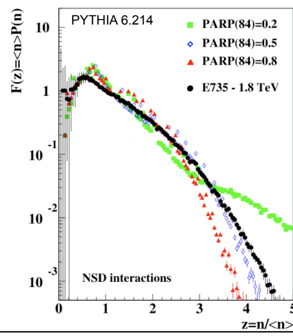
$$P_n = \binom{n+k-1}{n} \left(\frac{\bar{n}/k}{1+\bar{n}/k} \right)^n \frac{1}{(1+\bar{n}/k)^k}$$

MPI Tuning

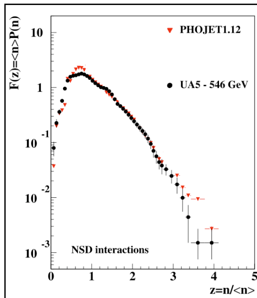
- Above: All tracks with |eta| < 1 at UA5
- Below: All tracks with |eta| < 1 at E735
- Including MPI alters the particle number distribution
  - A smaller impact parameter increases the probability of MPI.
  - This increase is ~ independent of the Hard Scatter √s.
- Consider counting tracks in a sequence of detector regions...
  - If you find a high-than-mean (z > 1) number of tracks in the first few regions it is likely that the impact parameter was smaller than average.
  - Consequently, it is more likely to find a higher-than-mean number of tracks in the remaining regions
  - So, the distribution is not memory-less, meaning it is not Negative Binomial.
- Pythia distribution shoulder is due to double Gaussian core shape.
  - The spatial distribution of partons within the proton is described by a the sum of gaussian of width equal to the proton's radius, plus a narrower core.
  - When z > 2.5 it is likely the the impact parameter is within the core radius, so MPI are significantly increased.
  - PARP(82) defines the ratio of the core radius to proton radius.

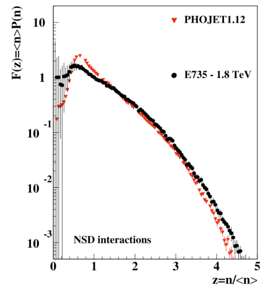


Plots by A. Moraes et al
Eur. Phys. J. C 50, 435-466 (2007)



MPI Tuning





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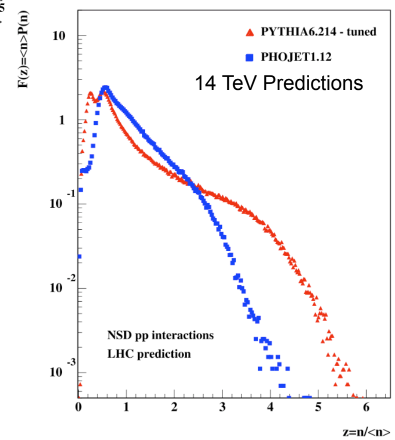
Pythia 6.214 tuned is compared to PhoJet 1.12

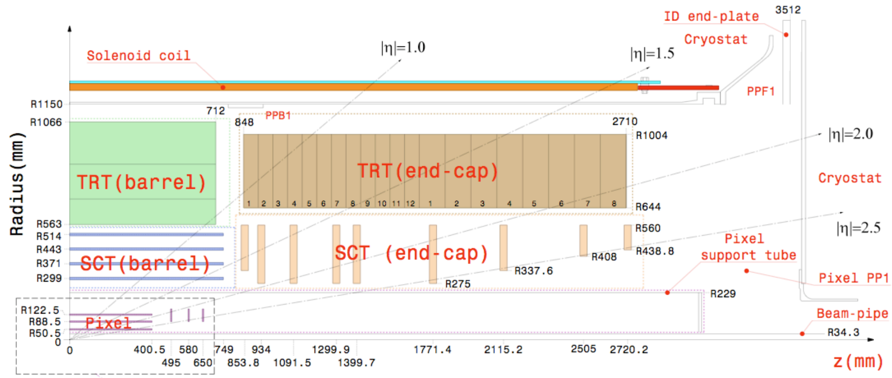
- Above: PhoJet comparison to data from UA5 & E735
- Fragmented strings from multiple Pomeron & Reggeon cuts also raise distribution tail (z > 1) above the NB distribution prediction.
- Right: PhoJet & Pythia predictions after tuning for pp 14 TeV collisions.
- Pythia double peak at low z is a pp collision specific prediction.
  - In a pp collision string connections can be from a valance quark to a diquark or sea anti-quark, yielding two peaks.
  - In a pp-bar collision the valence to valence conntion dominates.
  - PhoJet uses pomeron exchange in lieu of MPI, and consequently predicts no difference between pp and pp-bar collision features.

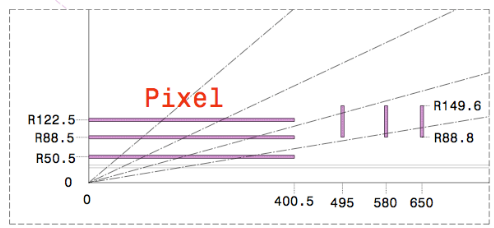


Backgrounds

- Pile-Up (Adjacent Vertex) contribution
  - Beginning at a luminosity $L = 10^{32}$ and $\sqrt{s} = 10$ TeV one expects on average ~ 0.1 - 0.3 additional minimum bias collisions.
  - Use vertex finding to flag these events & then discard them.
    - Diffractive collisions yield minimal central contributions, making this difficult.
  - At a luminosity of 10^{34} & $\sqrt{s}$ of 14 TeV one expects on average ~ 35 additional minimum bias collisions!
    - The current start-up plan is very helpful for UE measurements.
- Displaced Vertex contributions
  - Neutral decays: $\rho^0 \to \pi^+ \pi^-$ (for example)
    - So long as a consistent choice is made a direct comparison to generator results should be safe.
    - Requires verification of production rates.
  - Pair production: $\pi^0 \to \gamma\,\gamma$ & $\gamma\, p \to p\, e^+ e^-$ (principally)
    - Requires verification of material interactions.
  - Beam gas & halo, cavern background...
  - Primary vertex cut is very effective for all of these backgrounds.

ATLAS Inner Detector (R, Z, Eta)





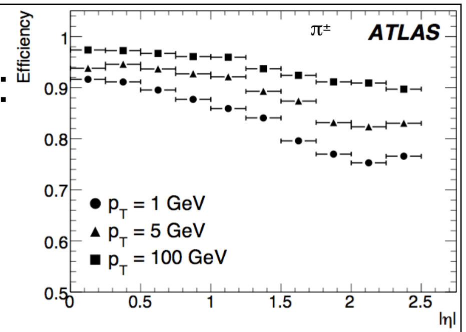
Envelopes

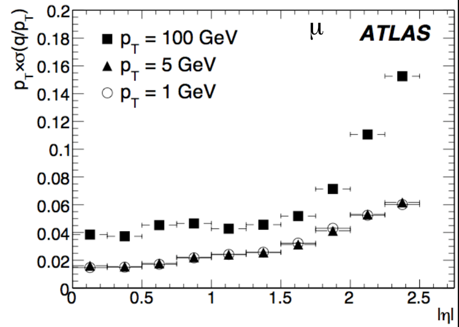
Pixel		45.5<R<242mm |Z|<3092mm
SCT barrel		255<R<549mm |Z|<805mm
SCT end-cap		251<R<610mm 810<|Z|<2797mm
TRT barrel		554<R<1082mm |Z|<780mm
TRT end-cap		617<R<1106mm 827<|Z|<2744mm

ATLAS Inner Detector: Tracking

- 2 T Solenoid
  - Inner Bore Radius = 1.23 m
  - Pt > 500 MeV required for standard track reconstruction.
- Tracking scheme:
  - Use pixel hit pairs for seeds.
  - Extrapolate out via Kalman filter.
  - Backtracking recovers conversions.
- Pion Resolution
  - Barrel, no gap: $0.25 < |\eta| < 0.5$

    $\sigma(q/Pt) = a * (1 \oplus (b / Pt))$
    - 0.34 = a: TeV^{-1} high Pt intrinsic resolution limit.
    - 44 GeV = b: equality of intrinsic and low Pt multiple scattering

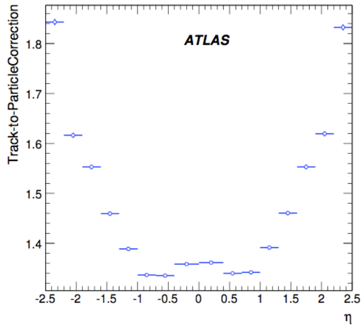


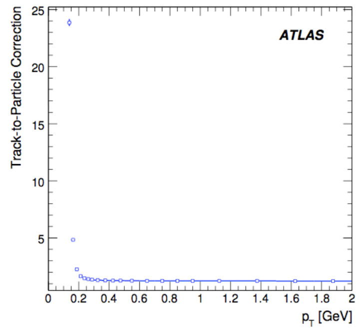


ATLAS Tracking CSC Note

ATLAS Inner Detector: Tracking

- Track counting requires corrections for estimated track finding efficiency.
- Very low Pt tracks do not reach all layers of the tracker.
  - Extended hit searches
  - Consideration of cluster characteristics
- Presently, low Pt tracking algorithms are used to extend the ATLAS tracking algorithm to Pt > 0.15 GeV.

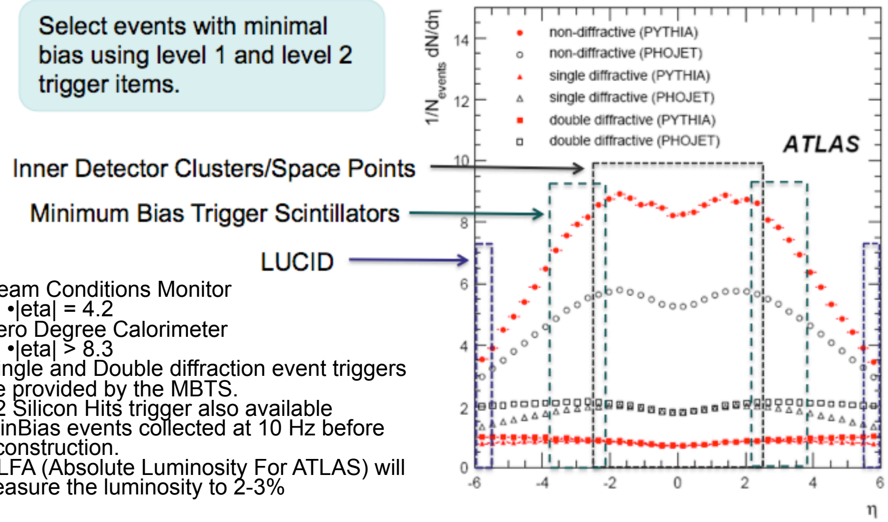




Plots from ATLAS MinBias CSC Note

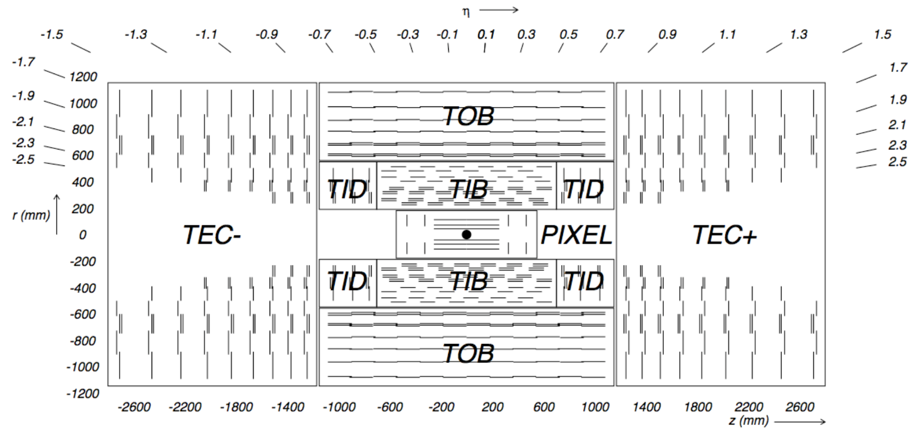
ATLAS Minimum Bias Triggers

Select events with minimal bias using level 1 and level 2 trigger items.



- •Beam Conditions Monitor
  - •|eta| = 4.2
- •Zero Degree Calorimeter
  - •|eta| > 8.3
- •Single and Double diffraction event triggers are provided by the MBTS.
- •L2 Silicon Hits trigger also available
- •MinBias events collected at 10 Hz before reconstruction.
- •ALFA (Absolute Luminosity For ATLAS) will measure the luminosity to 2-3%

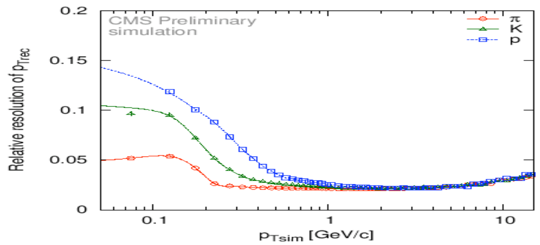
CMS Inner Detector (R, Z, Eta)

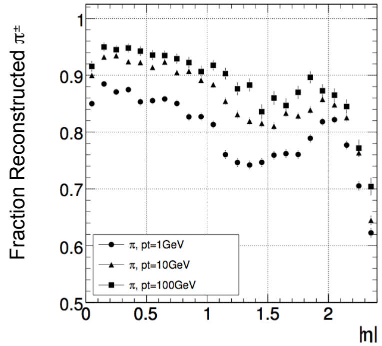


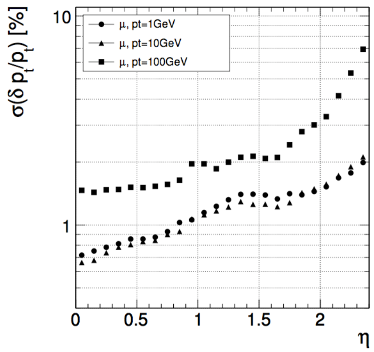
Strip Detectors:
TIB: Tracker Inner Barrel
TID: Tracker Inner Disk

TOB: Tracker Outer Barrel
TEC: Tracker End Cap

CMS Inner Detector: Tracking



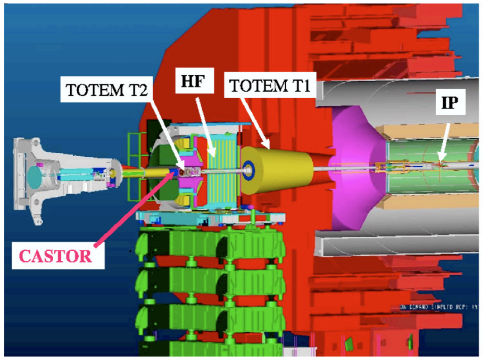


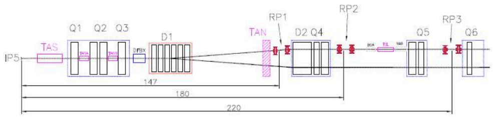


- 4 T Solenoid
  - Inner Bore Radius = 2.9 m
  - Pt > 0.9 GeV required for standard track reconstruction.
  - CMS UE group has modified the standard tracking acceptance to Pt > 0.5 GeV.
- Tracking scheme:
  - Uses pixel hit pairs for track seeds
  - Extrapolate outward via Kalman filter.
  - Track recovery using Alignment Position Error algorithm considers a larger search window.
  - Tracklets: Using on pixel hit triplets the tracking can be extended to Pt > 75 MeV

CMS Minimum Bias Trigger

- Hadronic Forward (HF) calorimeter will provide Minimum Bias triggering.
  - Threshold exceeding 2.3 σ applies to the outer-most layer.
  - Threshold exceeding 10.4 σ applies to the inner-most layer.
  - Goal is to have a rate of 10Hz before reconstruction.
- TOTEM can provide L1 trigger input
  - Provides tracking coverage up to $|\eta| < 6.5$
- Castor: EM Forward Calorimeter L1 $5.1 < |\eta| < 6.5$
- Zero Degree Calorimeter located 140m from the Interaction Point (IP5)
  - EM & Hadronic calorimetry.
  - Luminosity measurements.
  - Diffractive event triggers.





Measurement Steps

- Tracker alignment
  - At the moment the ATLAS tracker is aligned as well as muon data permits...
  - APE algorithm for CMS will enable immediate high efficiency tracking.
- MinBias & Jet slice triggers
  - Sample sizes are limited by prescale choices.
  - Aim is for 100 Hz contribution to events for full reconstruction for each jet slice.
  - Expect several million reconstructed MinBias events by end of first run. (Depends on prescale decisions.)
- Drell Yan muon triggered events
  - Expect ~ thousand lepton pair drell-yan events.
- Verify & Correct Tracking Efficiencies
- Verify & Remove Background Contributions

Next Steps

- Look for process dependence in UE.
  - Characterize difference in MB & UE track Pt distributions.
- Include very low Pt tracking.
  - CMS has already made substantial progress on this.
- Measurement specific application of jet algorithms.
  - Kt with large R may be best suited for lower $\sqrt{s}$ events
  - Anti-Kt with smaller R may be appropriate for multi-jet high $\sqrt{s}$ events.
- Try alternative UE characterizations suitable for events with many hard jets.
- Incorporate calorimeter information
  - Try using calorimeter jets.
  - Try using energy flow algorithms.

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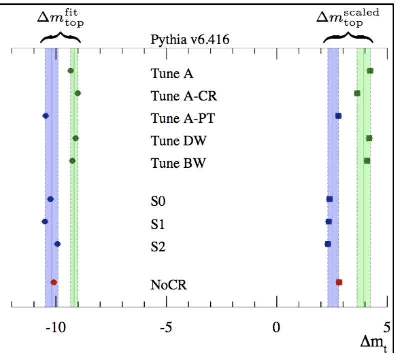
- CMS Collaboration; Measurement of the Underlying Event in Jet Topologies using Charged Particle and Momentum Densities; CMS PAS QCD_07_003
- CMS Collaboration; Measurement of the Charged Hadron Spectra in proton-proton collisions at Sqrt(s) = 14 TeV; CMS PAS QCD_07_001
- W. Bell; http://indico.cern.ch/conferenceDisplay.py?confId=46407

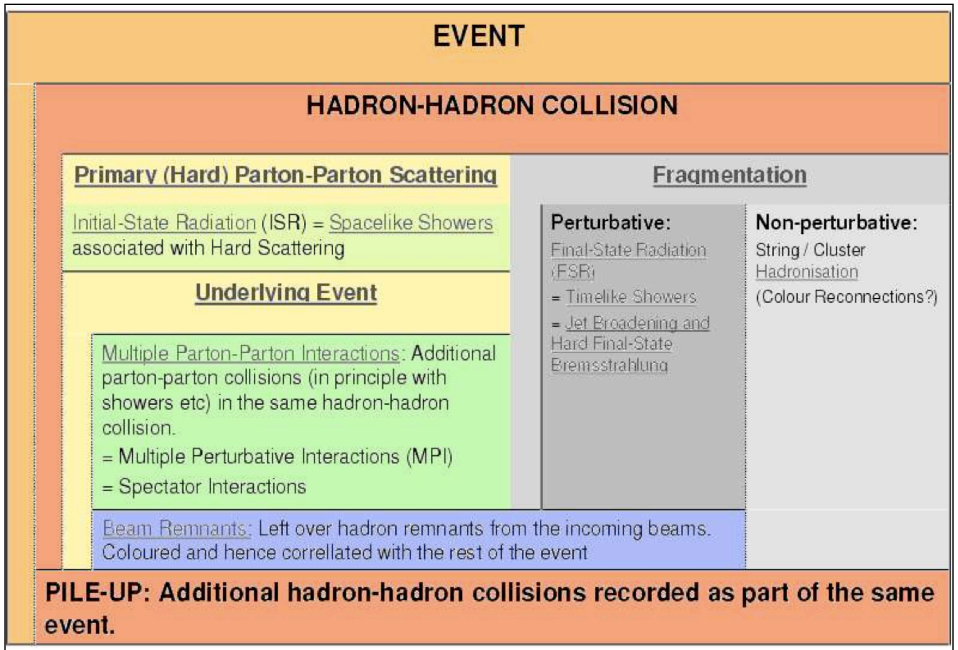
Extras...

An Example: Top Mass

- Tunes A, DW, BW for CDF data
  - No Pt ordering & no Color Reconnection
- Tunes S0 S1 S2 for CDF Data
  - Uses Pt ordering.
- NoCR Tune
  - No Color Reconnection



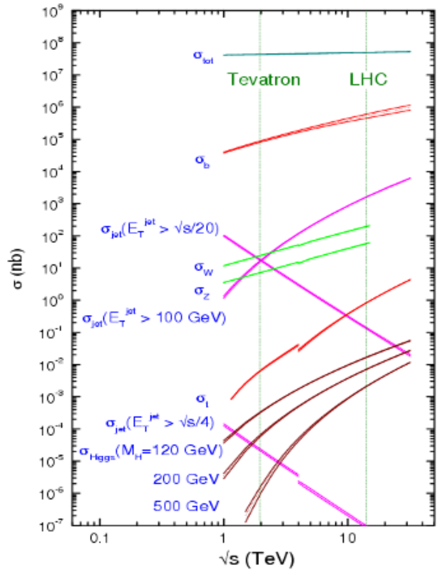
- Top quark mass measurement relies on particles gathering particles from top shower into the jet, and characterizing the extra particles.
- Generator based Jet Mass corrections are estimated, analogous to the standard Jet Energy Scale (JES) corrections.
  - Further refined by using the jet masses in W reconstruction.
- Need to have a good understanding of jet systematic uncertainties:
  - Fragmentation tuning can increase soft particle fraction, which can yield energy outside of the jet cone.
  - MPI & ISR tuning increases soft background of particles.
- Pythia can include color reconnection via annealing.
  - Introduces tunable probability for strings to participate in length minimizing reconnection.



Visual dictionary by Rick Field

LHC Luminosity & Energy

- Planned start-up in October 2009.
- Plan to run from November 2009 through September 2010.
- Planned running √s is 10TeV.
- Planned running luminosity of $5*10^{32}$ $cm^{-1}s^{-1}$.
  - ★Expect roughly 200pb^{-1} by end of first run.
  - ★At least $5*10^6$ MinimumBias events
  - ★At least 10^3 Drell-Yan lepton pairs.

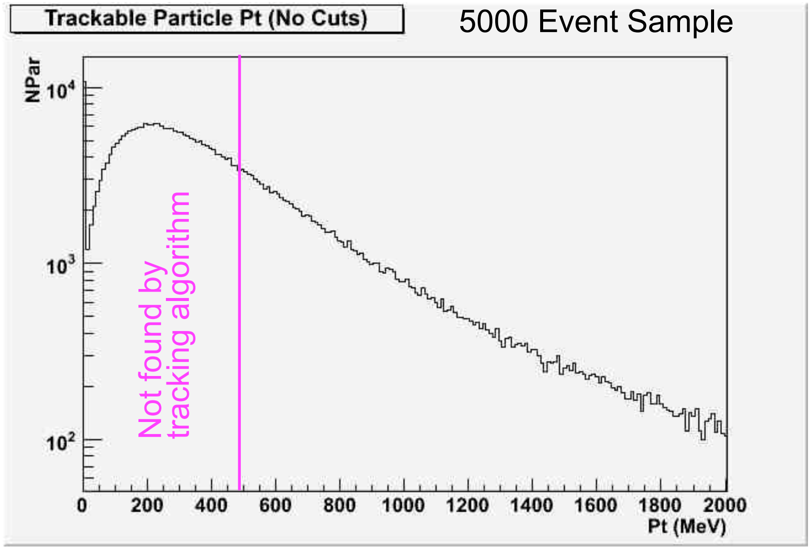


A. Tricoli, MPI@LHC 2008

ATLAS Jet X-Sec. Triggers

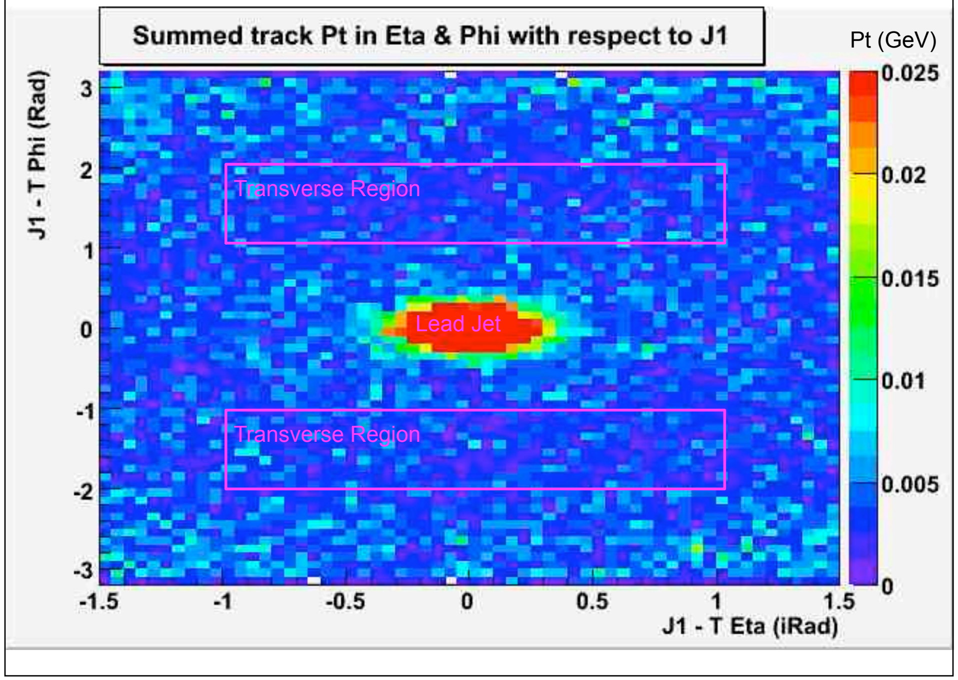
- Level 1: Total energy in towers from EM & Hadronic calorimeter are grouped & compared to an energy threshold.
  - Towers are ~ 0.1x0.1 in $\eta x \phi$
  - Groups are 4x4 towers by default.
  - Accepted groups yield a Region of Interest (RoI) on which a partial reconstruction will be performed.
- Level 2: A cone jet is searched for within the RoI, using constituent calorimeter cells.
- Aim is for highest energy jet events to have ~100Hz rate before reconstruction.

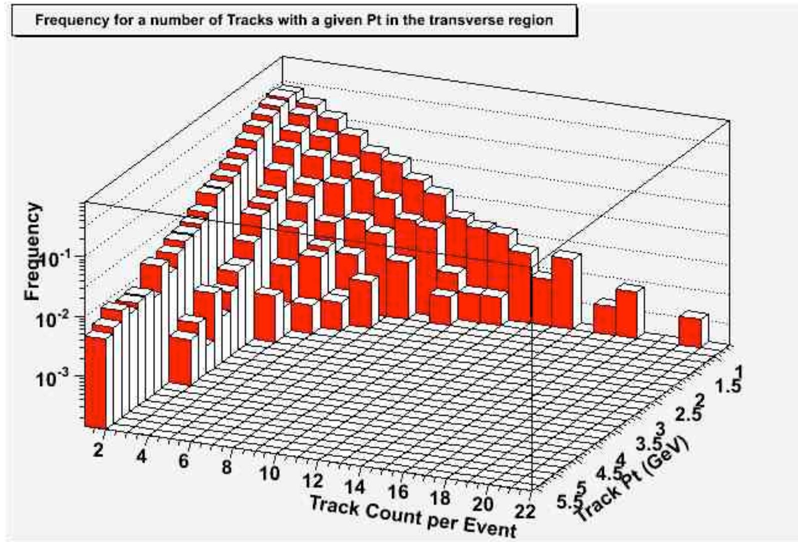
Sketch Plots...



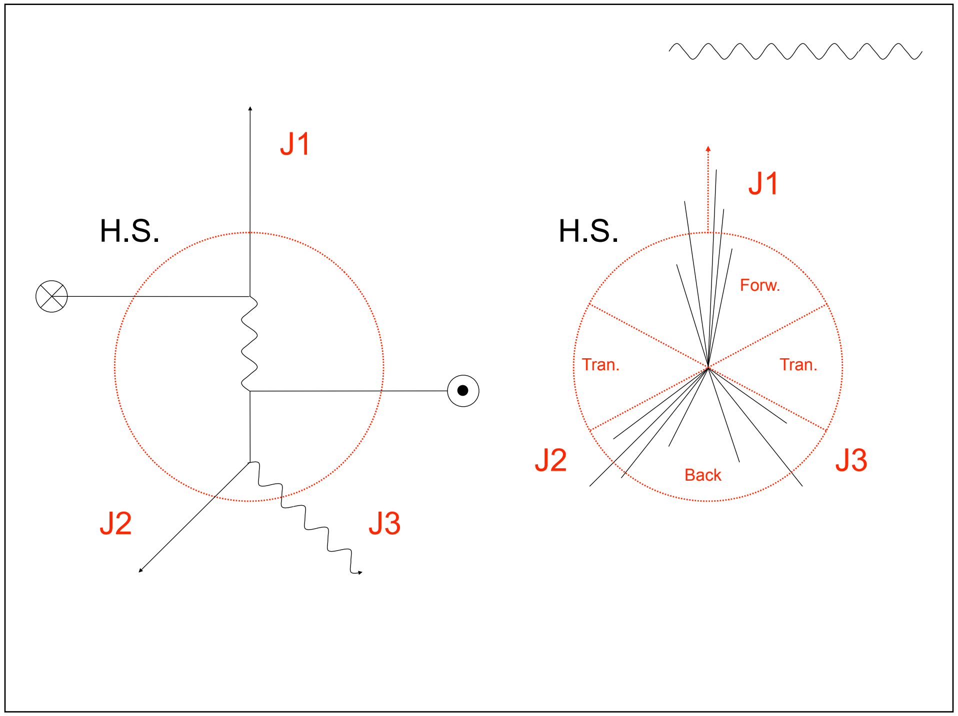
- Neither Track Number, Summed Track Pt, or Mean Track Pt are stable with respect to changes in this threshold.

REDO: Save as PDF or PS

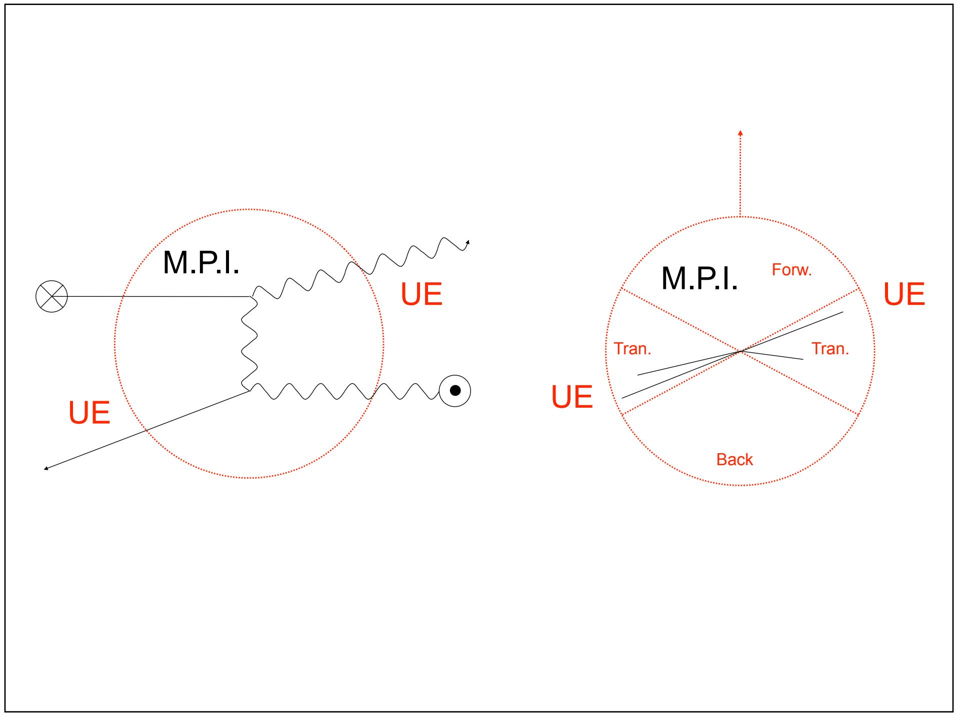


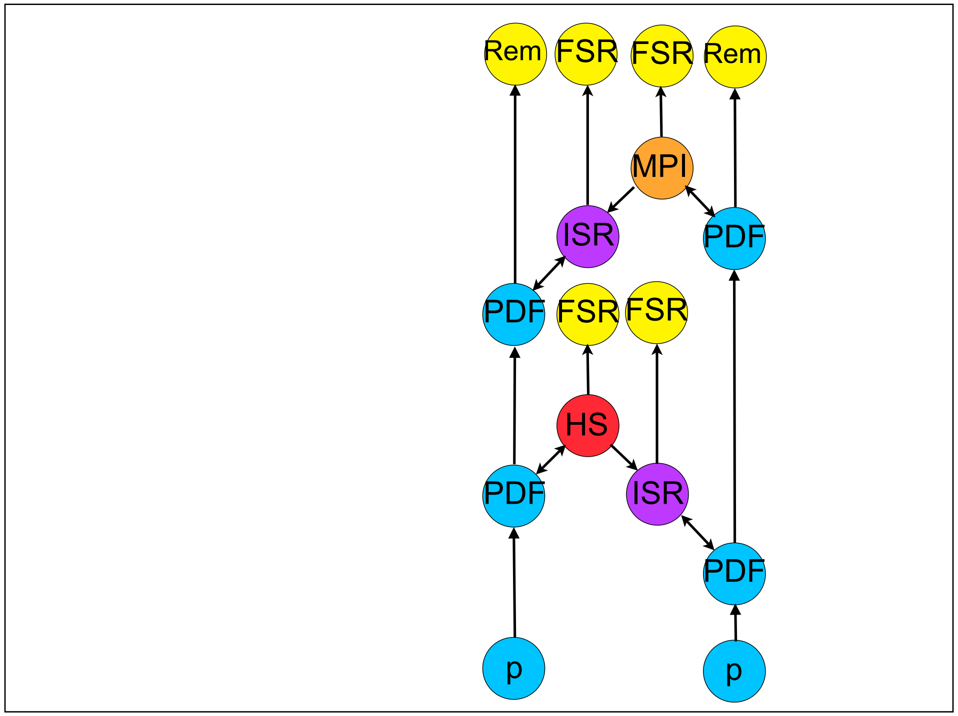


- The number of tracks in a given Pt range has an exponential distribution.
- The decay rate depends on the Pt range.



J1
H.S.
J2
J3
J1
H.S.
Forw.
Tran.
Tran.
J2
Back
J3


M.P.I.
UE
UE
M.P.I.
Forw.
UE
Tran.
Tran.
UE
Back


Rem
FSR
FSR
Rem
MPI
ISR
PDF
PDF
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HS
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p