Luminosity measurement by ZEUS @ HERA-II

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~~12.01.10~~ 15.02.19

Outline

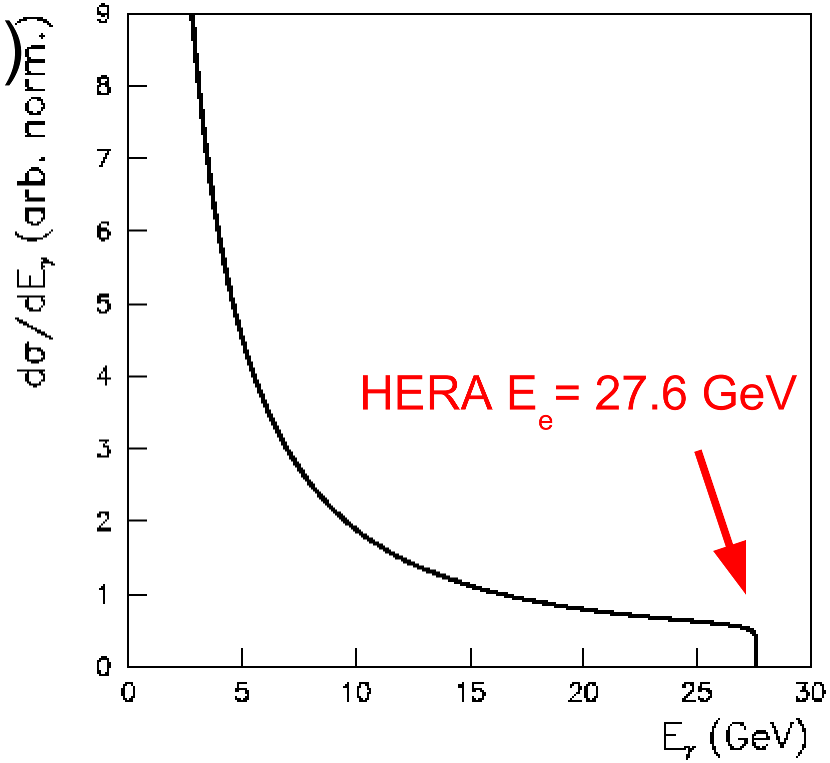
- The process: $ep \rightarrow ep\gamma$ & measurement requirements
- ZEUS LUMI system components & layout
- Photon calorimeter: 'classic' direct γ measurement
- LUMI pair spectrometer: novel features
- Results, systematic uncertainties
- Lessons

Nucl.Instrum.Meth. A744 (2014) 80-90

Process: BH *ep*→*ep*γ

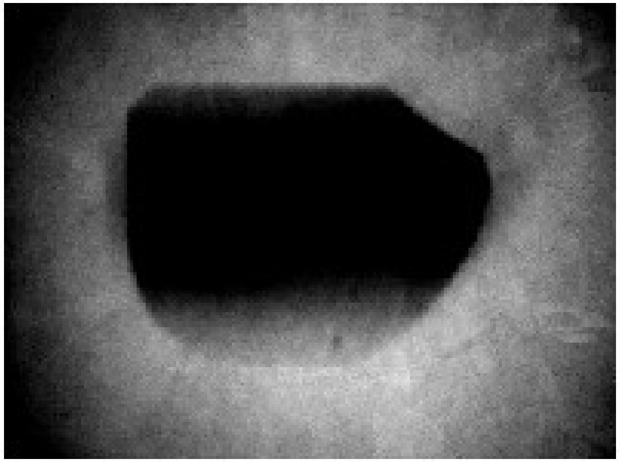
<u>*ep* bremsstrahlung</u> (Bethe, Heitler 1934)

- High rate, σ_{BH} known to <0.5%
- Steeply falling w/ E_γ (IR divergent)
- Drops to zero @ endpoint $E_\gamma = E_e$
- Sharply forward-peaked
  @ HERA θ_γ dominated by
  e-beam p_T spread



<u>Photon measurement requirements</u>

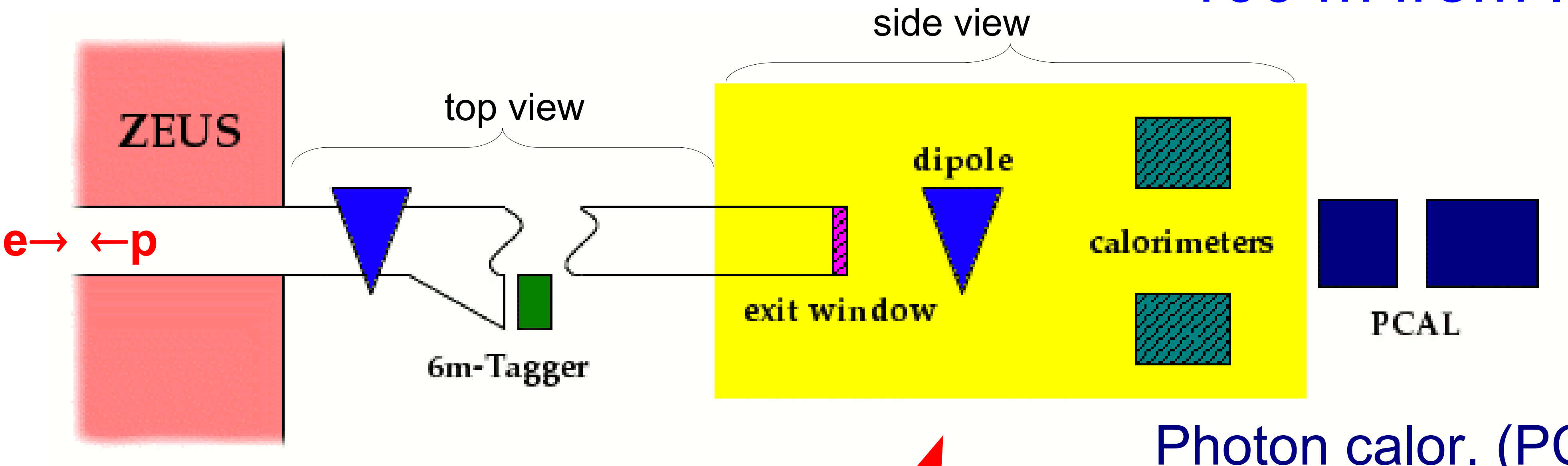
- E_γ in range few GeV → ~25 GeV
- @ high L_{inst}, low E_γ >1 γ per HERA bunch
- Measure θ_γ, correct for aperture loss



aperture as measured by
foil exposed to sync. rad.

ZEUS LUMI system: 2 γ detectors

~100 m from I.P.



Photon calor. (PCAL)

- Direct measure γ

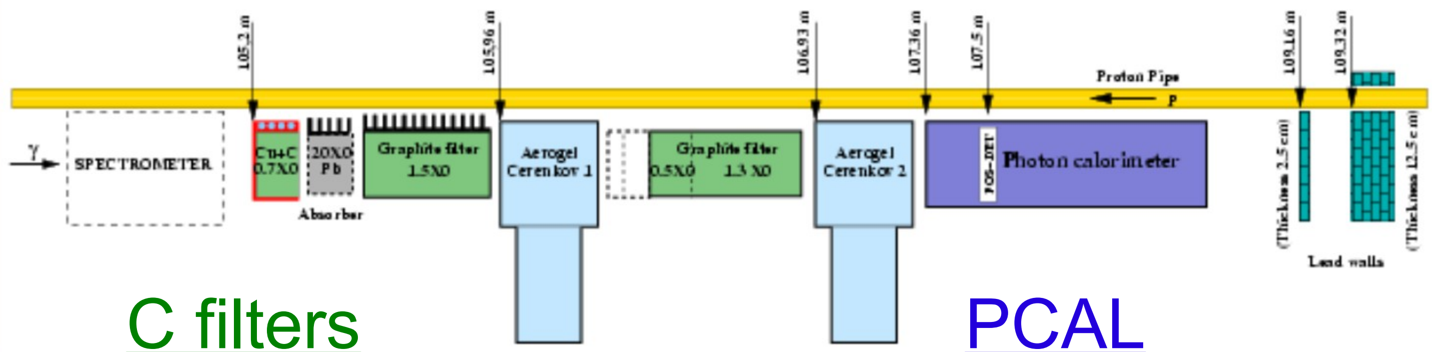
Pair spectrometer

- Measure pairs from $\gamma \rightarrow e^+e^-$ in exit window

e **tagger @ 6m from I.P.**

- Measure scattered *e*
- W-scint. spaghetti calor.
- Check photon accept. (work in progress...)
- Also for physics: tag high W photoprod.
- Not discussed more here...

PCAL: direct γ measurement



<u>C filters</u>

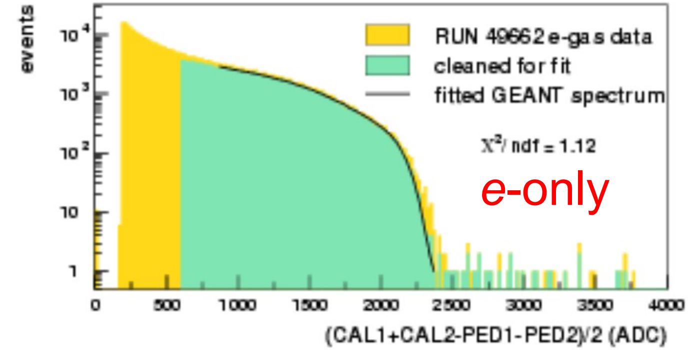
- ~3-4 X_0
- w/ Aerogel Ckv. det. (not used for LUMI, used for physics)

<u>PCAL</u>

- Pb-scint. sandwich
- Scint. hodoscope for position recon.

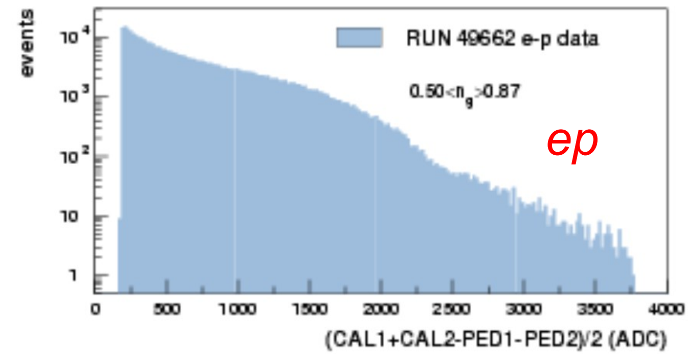
- PCAL sits in direct γ beam, also primary syc. rad. fan
- PCAL *must* be shielded: C/graphite filters
- Serious resolution degradation; must be MC modeled
- Does provide soft cutoff E_γ<few hundred MeV, protect against IR divergence in B-H spectrum

PCAL



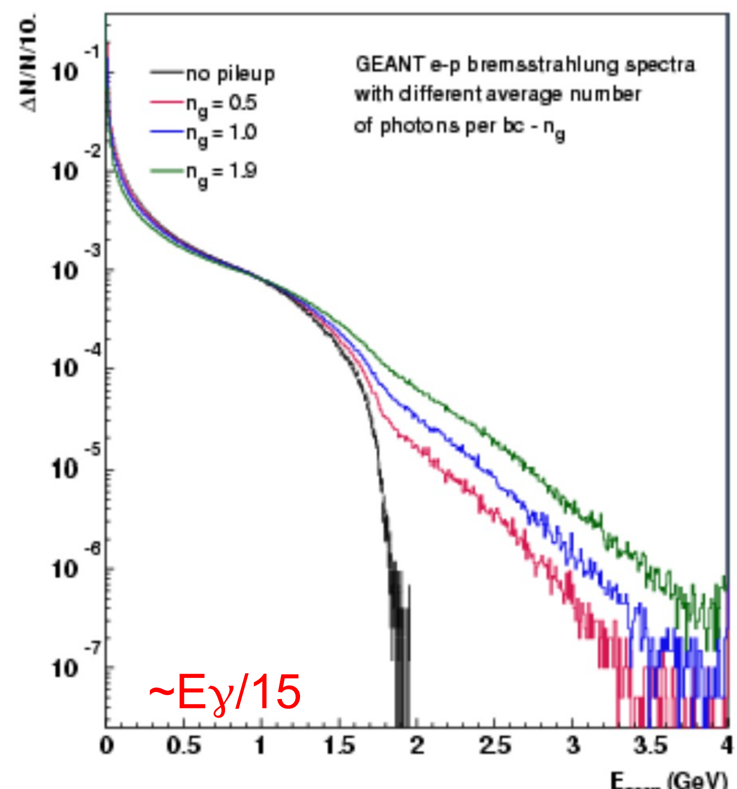
<u>Calibration: endpoint B-H spectrum</u>

- Colliding *ep* bunch endpoint smeared
- Use unpaired *e*-only HERA bunches
  - *e*-gas rate ~10^{-2} ep rate
  - *e*-gas spectrum ~B-H undistorted
  - MC fit to endpoint



<u>LUMI measurement</u>

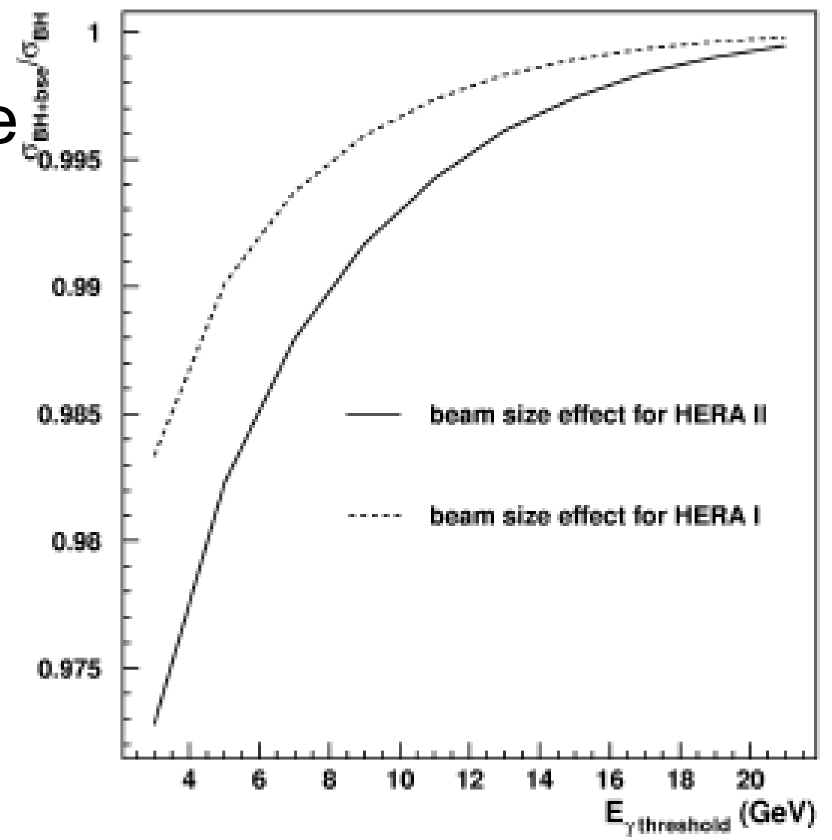
- Scalers count γs E_γ > threshold
- Spectrum distorted by multiple γ's / bunch ∉ing (pileup)
- Use several thresholds, compare to MC for various n_γ
  e.g.: E_γ>0.1GeV, n_γ=0,0.5,1,1.9
- Several % correction: requires precise PCAL MC model



PCAL

<u>Beam-size effect</u>

- Impact parameter limited by transverse beam size: low E_γ suppressed
- Observed e.g. VEPP e^+e^-, HERA-I *ep*
- HERA-II smaller beam size, stronger effect >2%



<u>Other effects, corrections:</u>

- Electronics pileup (pulse overlaps)
- Pedestal shift from sync. rad.

<u>PCAL summary:</u>

- Concept & detector simple
- Complications: shielding, high rates, low E_γ
- Large (several %) corrections require accurate MC modeling

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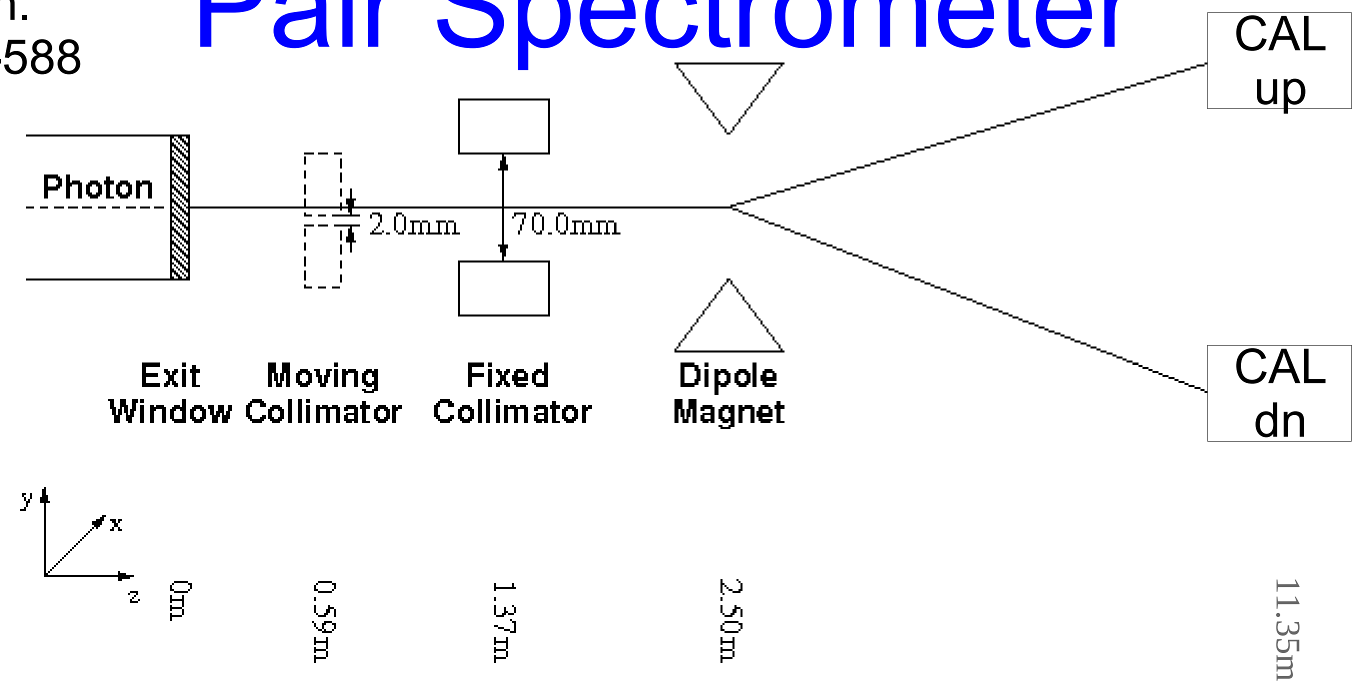
A565 (2006) 572-588

Pair Spectrometer



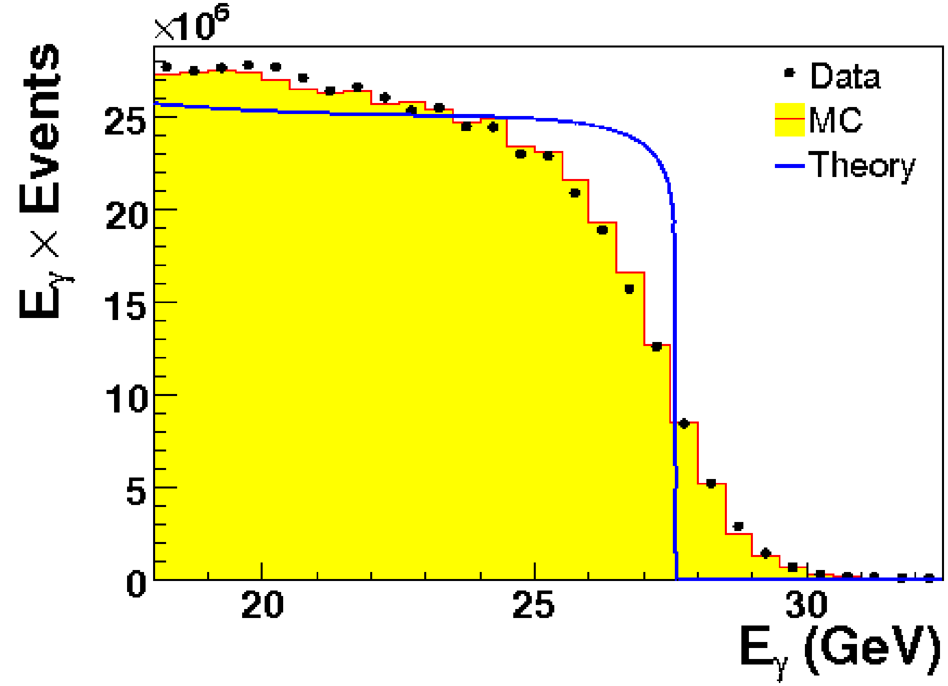
- In exit window ~9% $\gamma \rightarrow e^+e^-$ conversions $\Rightarrow$ **>10 rate reduction**
- Pair separated vertically by dipole $\int Bdl \approx 0.3$ T-m ≈ 0.1 GeV p_T
- e^+,e^- detected in W-scint. sandwich calorimeters
  horiz., vert. segmented for position recon. $\Rightarrow$ **out of primary sync. rad. fan**

Calibration:

- Insert 'moving collimator', defines narrow vert. pair position
- Now a 'true spectrometer':
  - From $\int Bdl$ & distance to calorimeters, vertical position in calorimeter determines energies e^+,e^-
  - known energy, calibrate calorim. showers

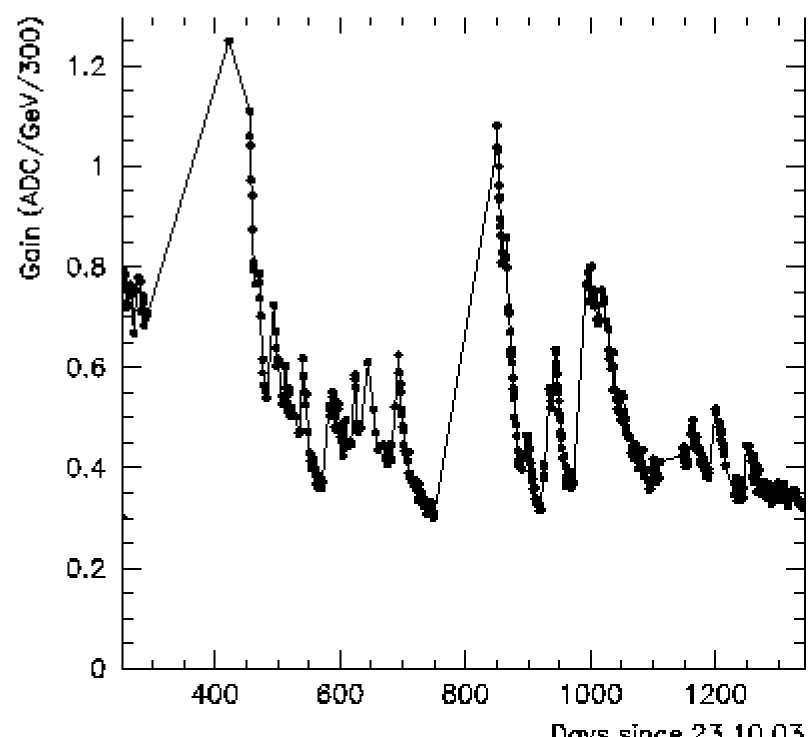
Spectrometer: calibration

- Check endpoint of B-H spectrum (special run w/ higher dipole field):
- E-scale agrees ~1%



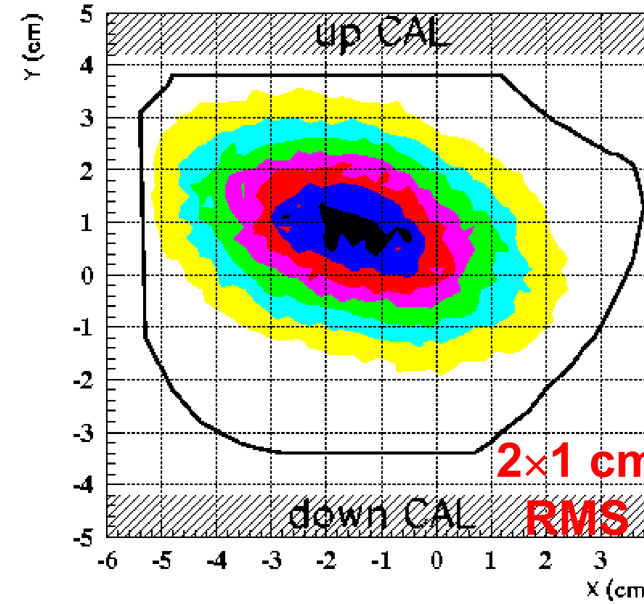
However:

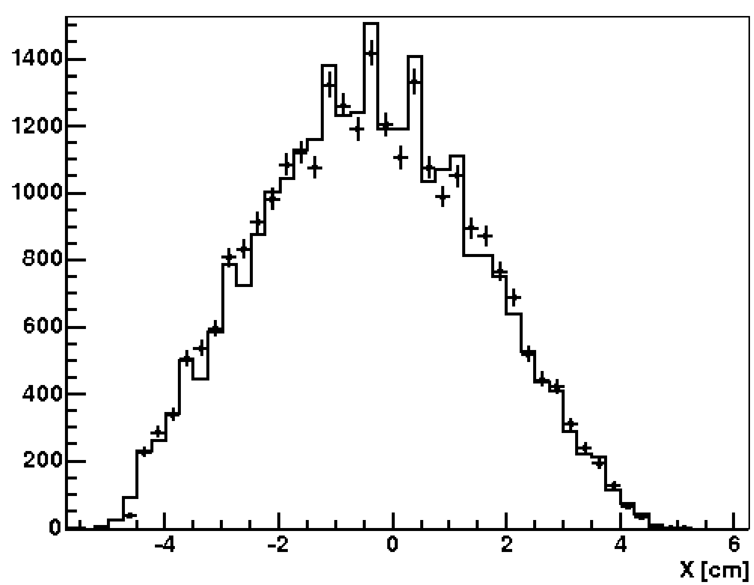
- Calorimeters were not well shielded from secondary synchrotron radiation
- Gains varied considerably; here worst channel last ~3 years HERA operation:
- Gain dropped in HERA operation; recovered HERA shutdowns (it was wavelength shifters)
- A calorimetry based E_γ LUMI measurement problematic
- Solution in a few slides...

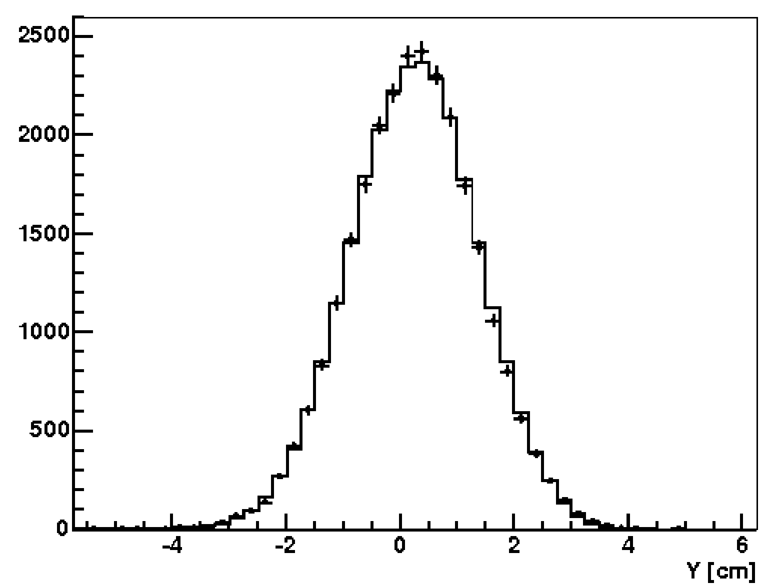


Spectrometer: LUMI measurement

- Count up, down calor. <u>coincidences</u> for ~16 sec. (ZEUS $\int$ time)
- Accumulate E_γ, X_γ, Y_γ, histograms
- Account for ellipse tilt:
- Fit MC for photon beam (X0, Y0)
  and gaussian spread major-/minor axes
  □ accept. corr. for aperture, spec. geom.
- Fits made to X_γ, Y_γ distributions, good:

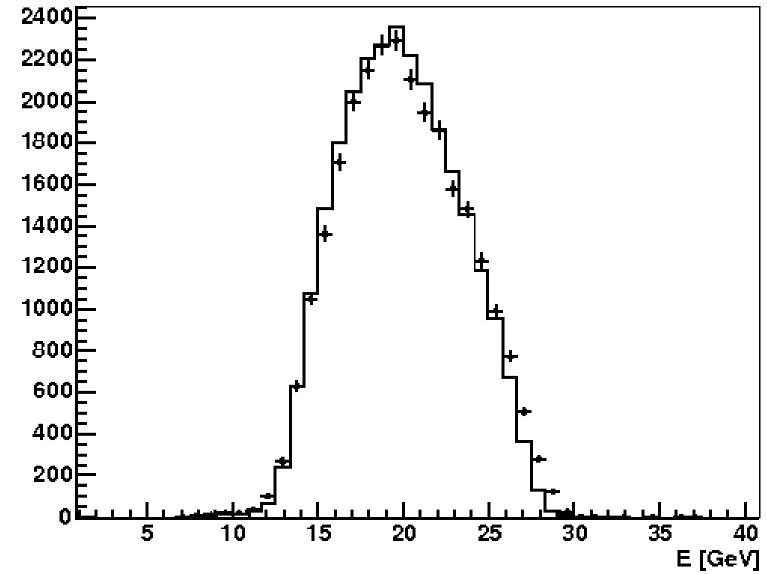




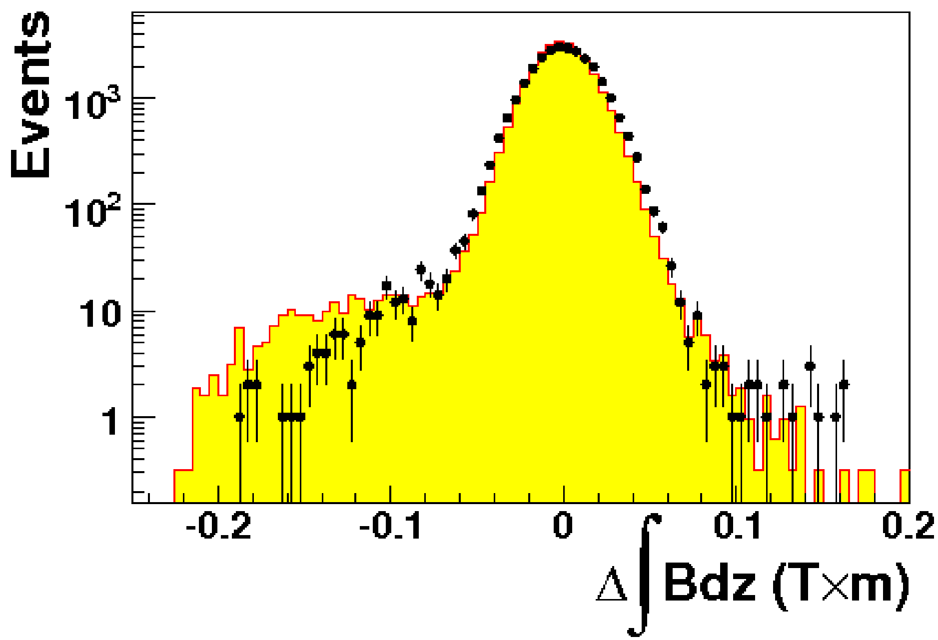


Spectrometer: LUMI measurement

- Fit not made to E_γ spectrum, but resulting MC prediction from fit to X_γ, Y_γ agrees well:



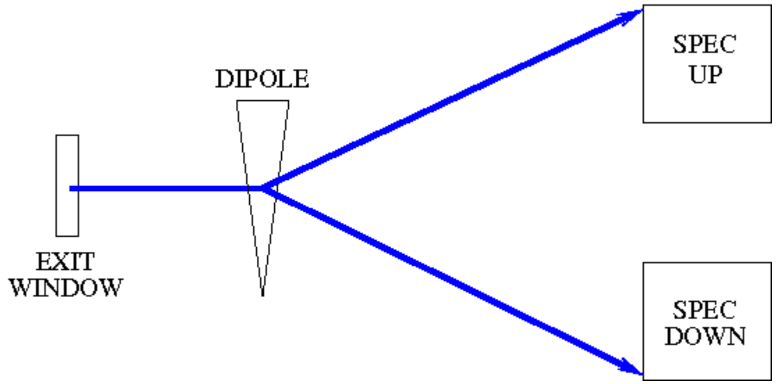
- Can also reconstruct $\int Bdl$ each event
- Compare difference from nominal $\int Bdl$ to MC prediction:
- Tail @ low $\Delta\int Bdl$ due to $\gamma \to e^+e^-$ in *air inside dipole gap*
- Good agreement data↔MC



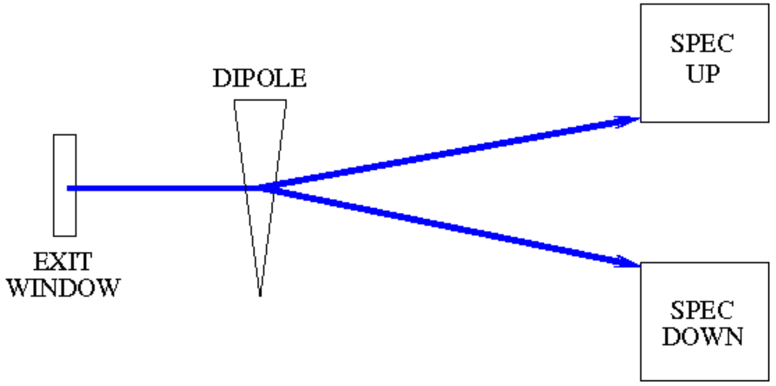
<u>MC verified by independent checks, accurate acceptance</u>

Spectrometer: E_γ range

- Consider pair midway between calorimeters, with equal shared energy e^+,e^-
- There is a minimum E_γ which will produce a coincidence; lower E_γ either e^+or e^- will miss outside calorimeters:

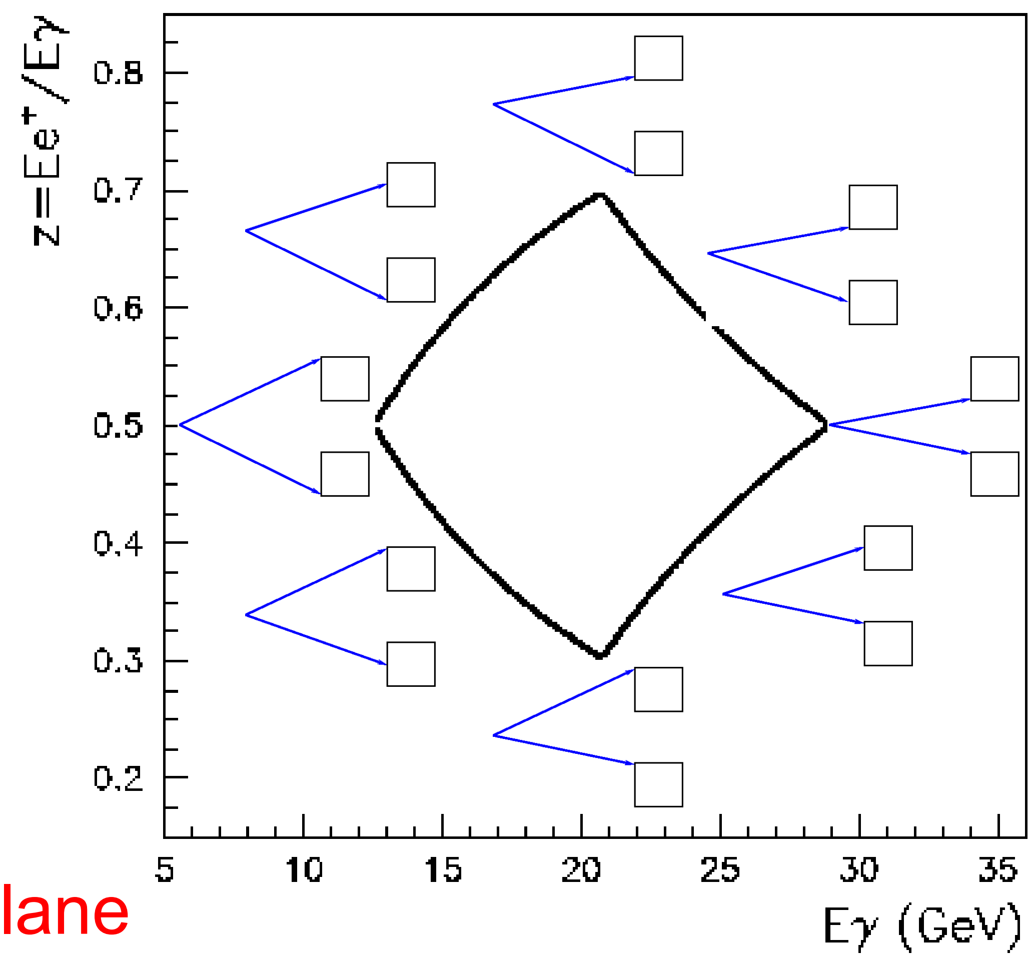


- Similarly there is a maximum E_γ which will produce a coincidence; higher E_γ either e^+or e^- will miss inside calorimeters:



Spectrometer: E_γ range

- Define the energy sharing $z=E_{e+}/E_\gamma$, $0 \leq z \leq 1$
- Then can plot SPEC acceptance in the (E_γ,z) plane, inside kite-shaped region:
- Insets show the pair configurations at edges, corners of acceptance: one or both $e^\pm$ at edge of calorimeter

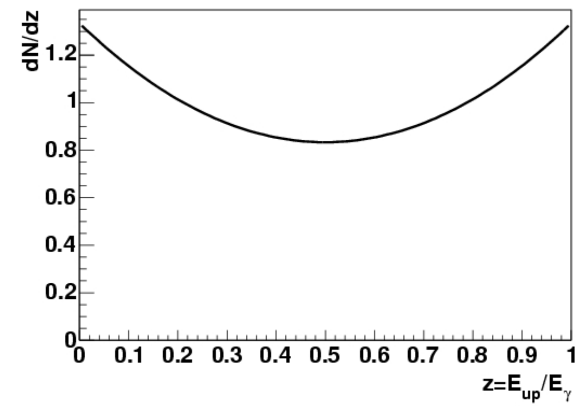


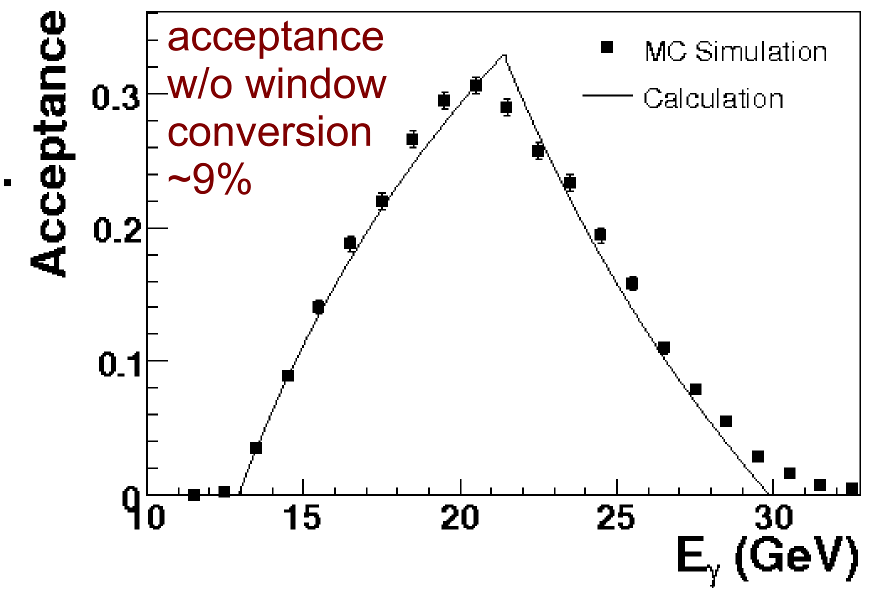
- Pair spectrometer geometry defines an inherent region of acceptance in the (E_γ,z) plane

Spectrometer: E_γ range

- The energy sharing distribution symmetric, slightly peaked @ z=0,1:
- Integrate over acceptance region to get acceptance vs. E_γ
- Simple calculation describes features of full MC simulation including beam spread, resolutions, …
- SPEC cross section:

$$\sigma_{SPEC} = \int dE_\gamma \cdot \sigma_{BH}(E_\gamma) \cdot acc(E_\gamma)$$



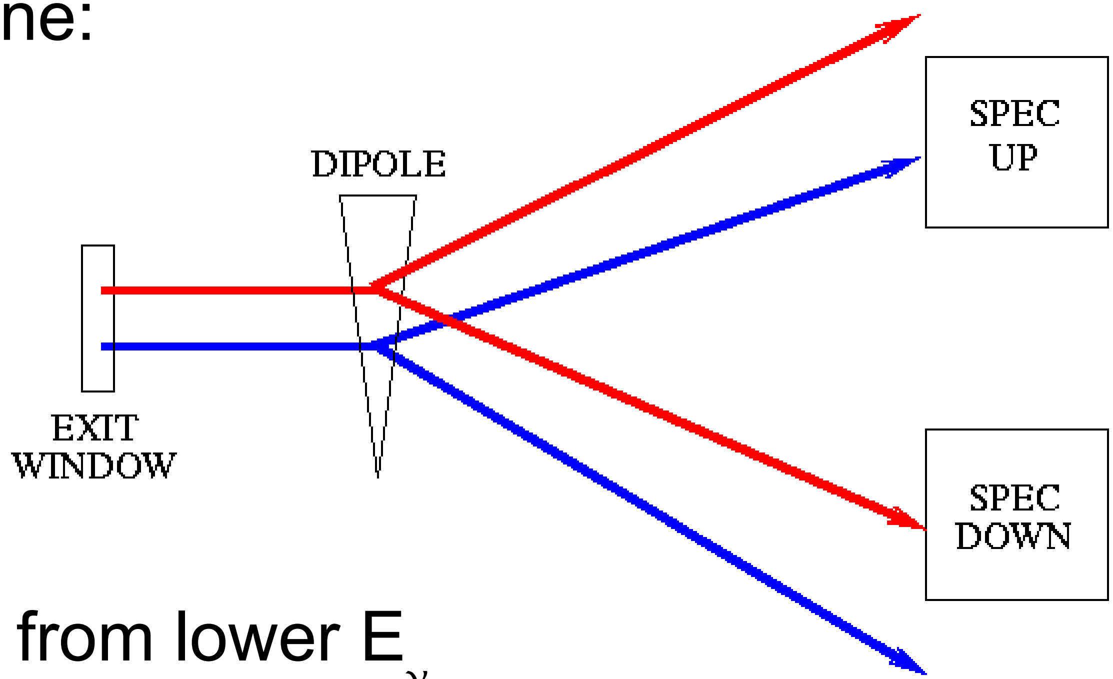


Pair spectrometer geometry defines an inherent E_γ range:

- Low E_γ cutoff, protect against IR divergence of B-H spectrum, low E_γ beam-size effects
- Fiducial regions of detectors: shower max. not edge channel weak dependence on calibration, protect against gain variations

Spectrometer: pileup

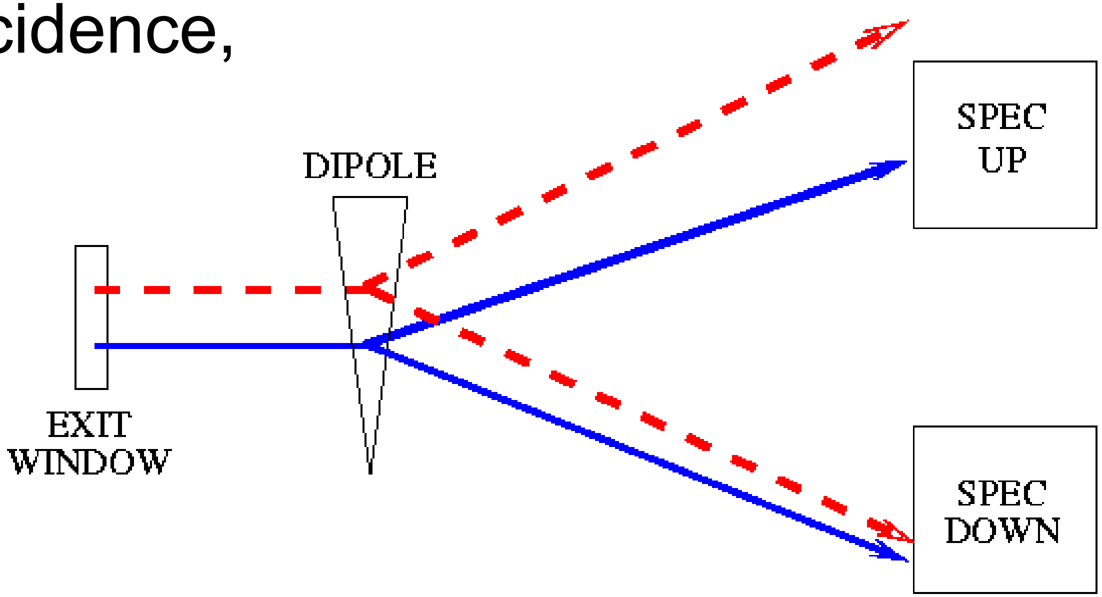
- Can have >1 γ conversion in 1 HERA bunch ∉ing
- 2 pairs that would not each make a coincidence could make one:



- Such single hits can come from lower E_γ than possible for true coincidences ⇒ potentially high rate
- This leads to *overcounting* of coincidences at high L_{inst}

Spectrometer: pileup

- The spectrometer DAQ did baseline (pedestal) subtraction by subtracting channel energies from previous HERA bunch
- A single from a previous bunch conversion (- - - -) could overlap a valid coincidence, stealing its energy and failing threshold cuts

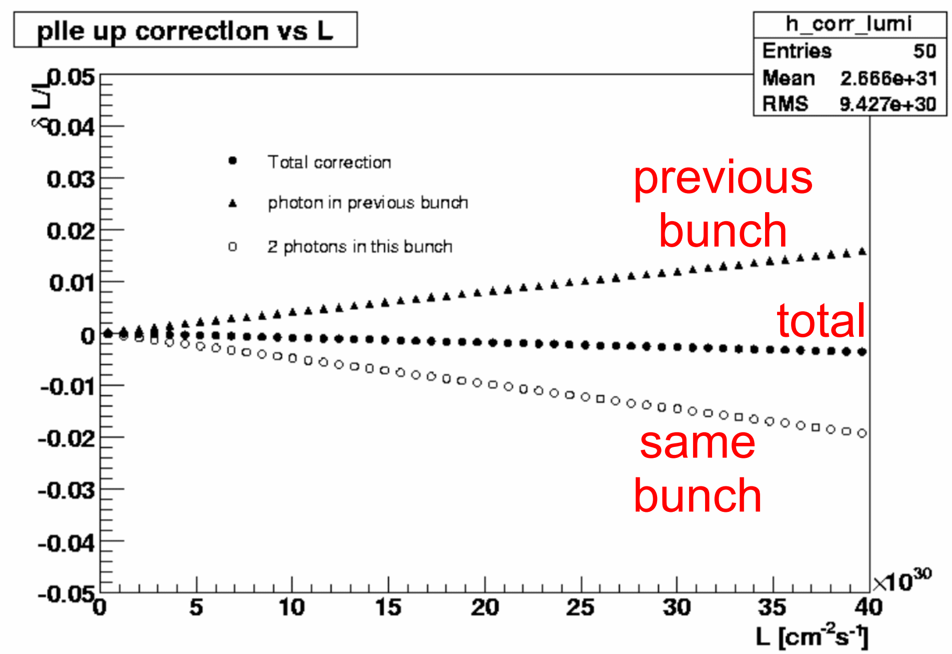


- Such single hits can come from lower E_{γ}
- than possible for true coincidences $\Rightarrow$ potentially high rate

- This leads to *undercounting* of coincidences at high L_{inst}

Spectrometer: pileup

- Model in MC: overlap conversions, add/subtract channel energies:
- As expected 2 effects opposite sign, **and nearly cancel**
- Total pileup correction <0.5% @ highest HERA L_{inst}



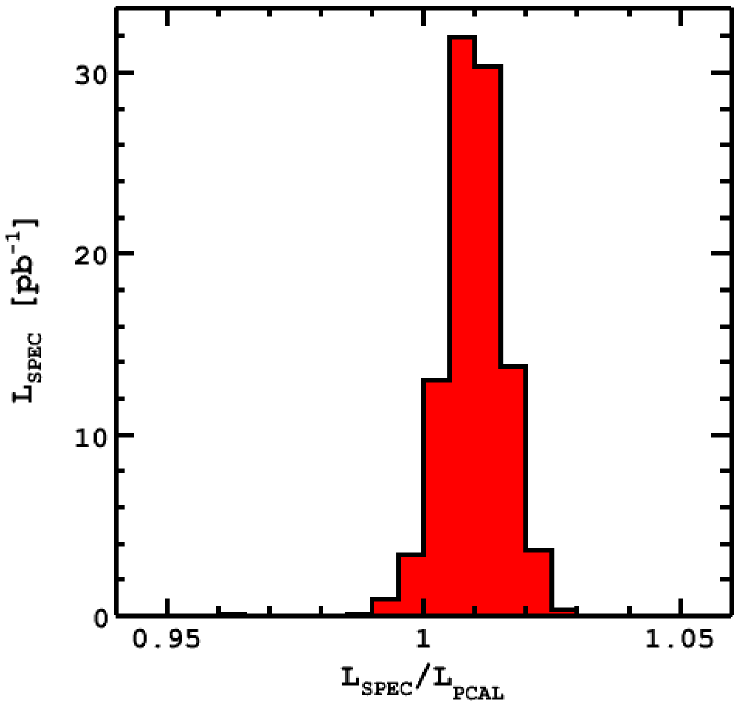
Spectrometer: summary

- Concept & detector more complex than PCAL, <u>but:</u>
- Straightforward calibration, E-scale ~1%
- Natural E_γ range: no low E_γ complications, weak dependence on calorimeter calibration
- Negligible pileup correction

Results

PCAL & SPEC comparison:

- PCAL & SPEC operated and analyzed by two independent groups
- They agree within 1%
- Plotted here L weighted ratio per physics run:



Status Jan. 2010, final next slide ↘

Systematic uncertainties:

- Both PCAL & SPEC have sys. uncert. **±2.5%**
- PCAL uncert. comes equally from the several corrections, probably irreducible
- SPEC uncert. dominated by window conversion prob.: **±2%** already improvement found; window being remeasured...
- Hope to improve further with *e*-tagger studies...

Systematic uncertainties

Common to PCAL & SPEC

Nucl.Instrum.Meth. A744 (2014) 80-90

- Theory: negligible T. Haas and V. Makarenko, Eur. Phys. J. C 71 (2011) 1574
- Aperture & alignment: 1% measured to ~1mm
- Geometric acceptance correction: 1.1-1.2% compared DIS NC event rate
- LUMI rate: 0.-0.6% compared DIS NC event rate
- Total common: 1.6%

PCAL specific

- Pedestal/calibration shifts: 1.5%
- Pileup: 0.5% compared different E thresholds
- Total common⊕PCAL: 2.2%

SPEC specific

- Photon conversion probability: 0.7% compared NIST/GEANT4 cross section
- Event selection: 0.5% effect of bad shower RMS cut
- **Total common⊕SPEC: 1.8%**
- Much of uncertainty is scale;
  run-to-run uncert. ~1.1-1.2% geom. acc. & rate corrections

Lessons

PCAL & SPEC both useful for future installation:

- Complement each other well:
  - PCAL simple concept, detector; tricky LUMI analysis
  - SPEC complex idea hardware; novel features aid LUMI meas.
- Also: backup, redundancy, cross checks...
  - SPEC (recycled hardware, HV) failed several periods
- PCAL also useful for initial state radiation tagging
- SPEC has several parameters that can be tuned:
  - window thickness (conversion probability)
  - dipole field
  - detector geometry, fiducial volume

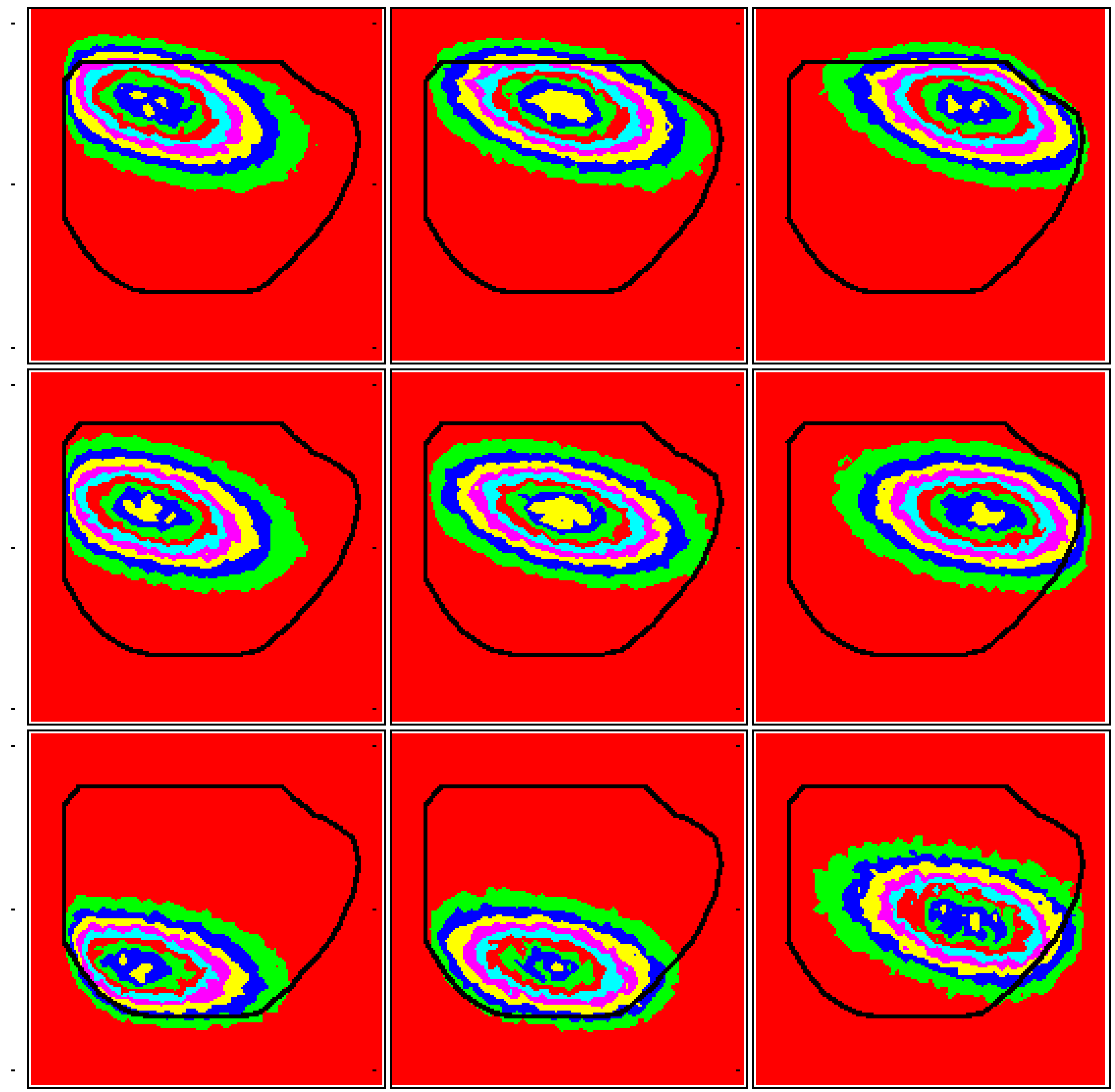
Not discussed in detail here, but
electron tagging very useful:

- Measure LUMI acceptances, other checks...
- Low angle *e* tagging already EIC priority

EXTRAS

HERA tilt scans

- HERA made extreme tilts of *e* beam to probe aperture edges:



(E_γ,z) plane acceptance

- Acceptance region in (E_γ,z) plane
  varies with γ vertical position
- Shown here for 0,1,2 cm above
  SPEC midpoint