Gauge-boson Physics with ATLAS at the LHC

with an emphasis on:
Triple Gauge-boson Couplings and
Monte Carlo Techniques for QCD Corrections

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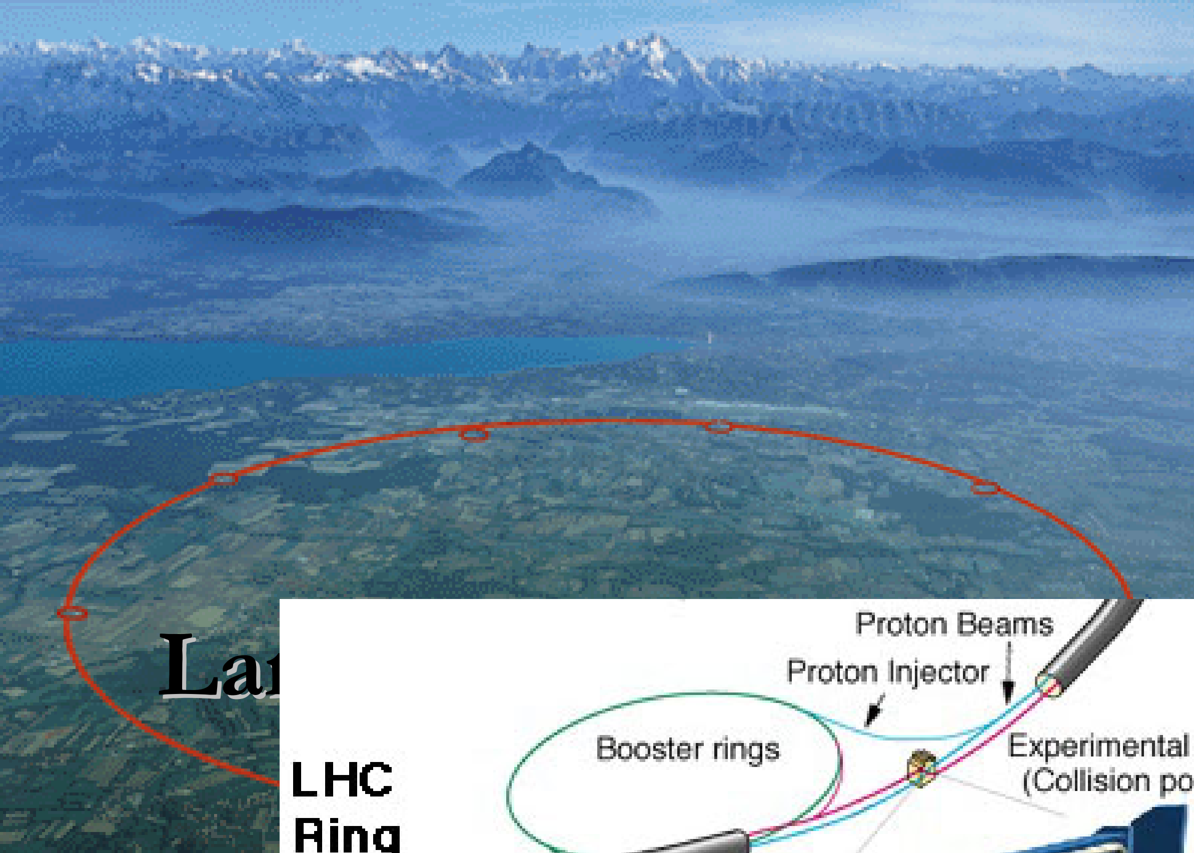
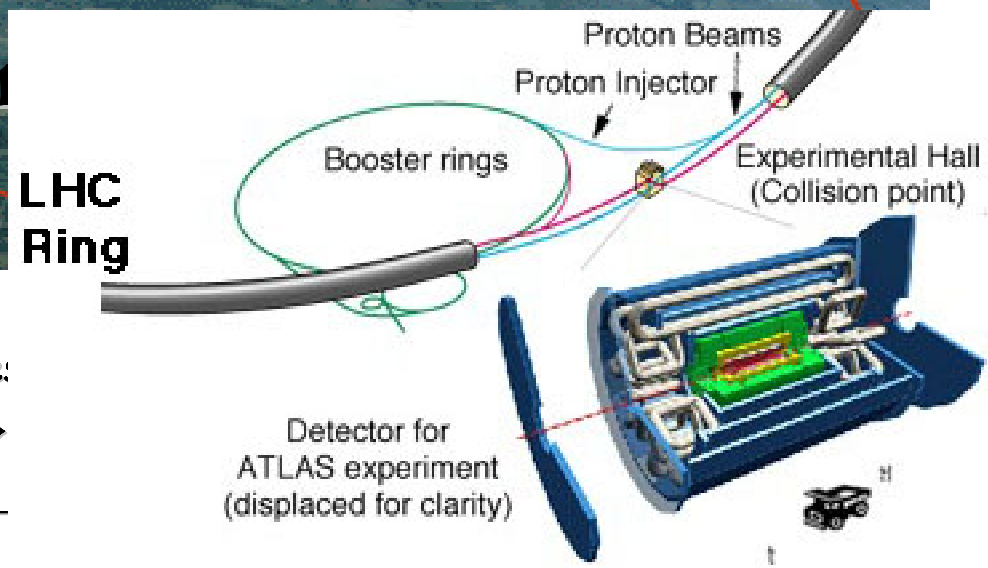
Outline

- LHC & the ATLAS Detector
  - Performance example: Hadronic Endcap Calorimeter
- Gauge-boson Physics
  - Measuring A_{FB} and $\sin^2\theta_W$
- (Modeling our Predictions:
  - New Monte Carlo Techniques for combining NLO(α_S) matrix elements with the parton shower
  - sketch of problem to be solved, results & implications (but no details)

)
- Testing the SM with Triple Gauge-boson Couplings



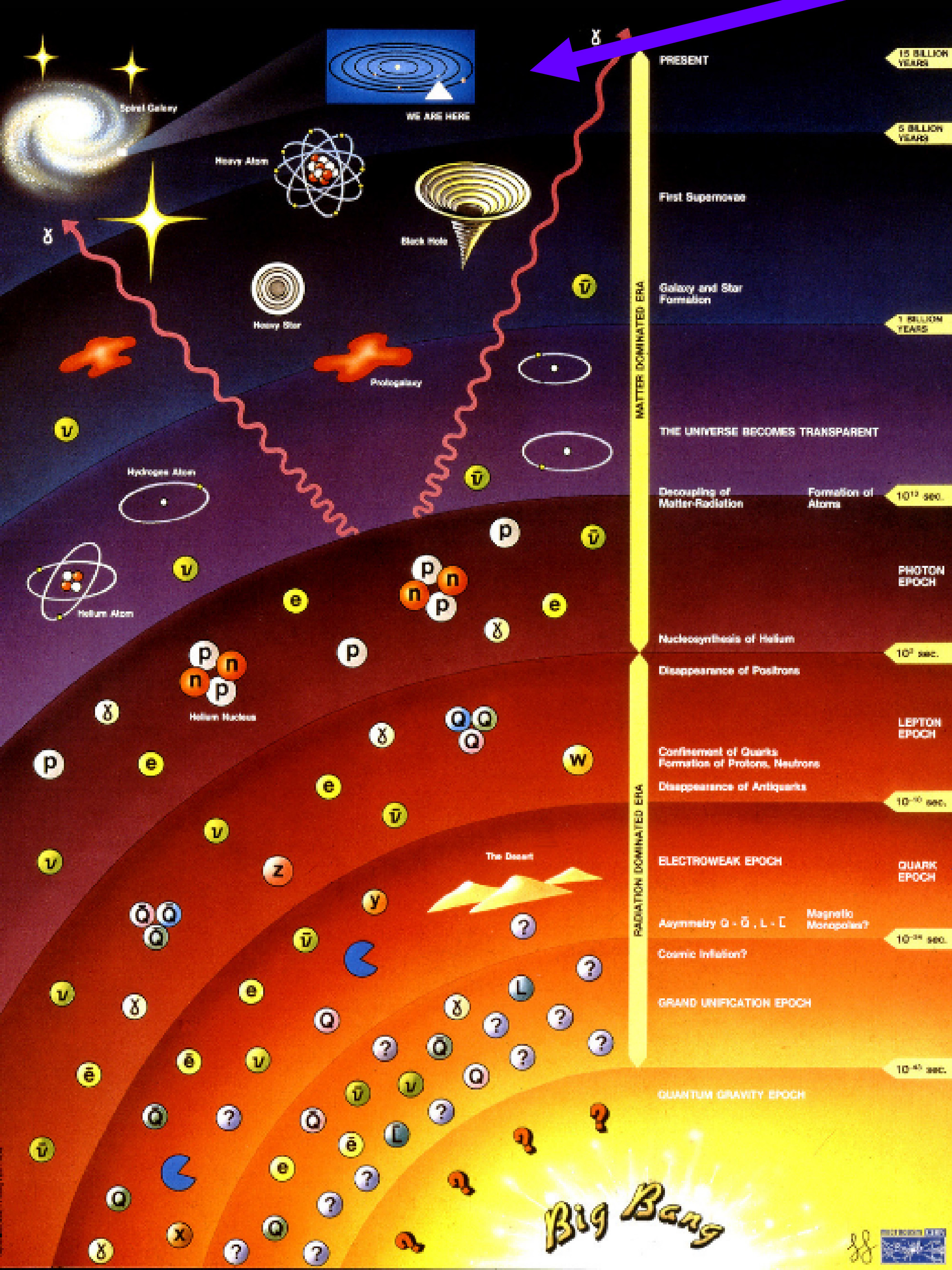
La…



- 14 TeV … *q & g collider*,
  - scale…
- Low L → …
- High L – … b^{-1} in $\leq$ 10 years
  - 25 interactions per bunch crossing
  - 40 MHz crossing rate at high L (25ns bunch spacing)

History of the universe

You are here



←NOW (15 Billion years)

←Stars form (1 Billion years)

Cosmic Microwave Background

←Atoms Form (300 000 years)

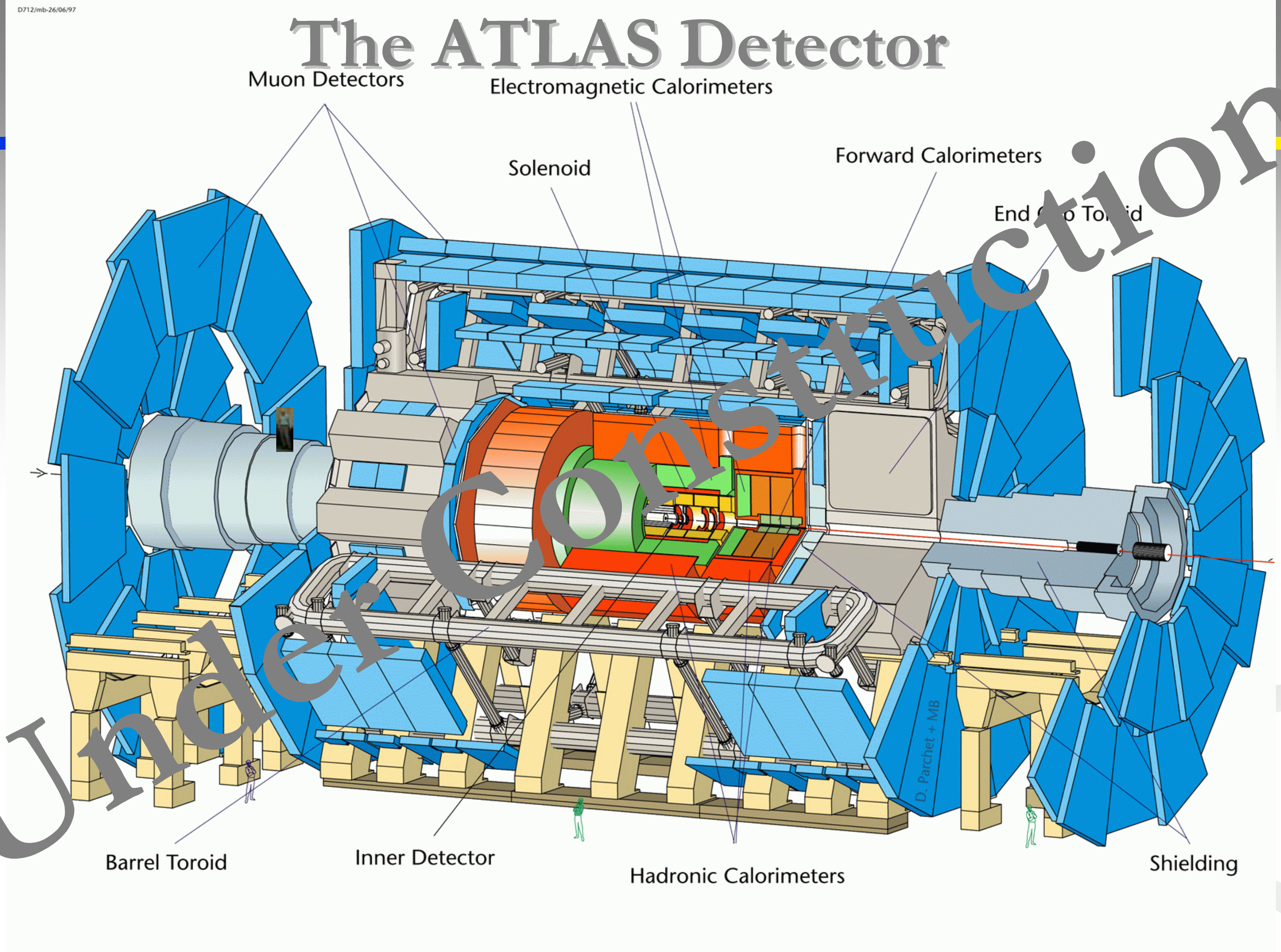
←Nuclei Form (180 seconds)

←Protons and Neutrons Form (10^{-10} sec)

←Quarks Differentiate (10^{-34} sec ?)

LHC probes physics relevant to the universe at age 10^{-14} sec.

The ATLAS Detector



- Multi-purpose detector for LHC
- 22 m diameter, 7000 tons

- ~1850 People
- 149 Institutions, 34 Countries
- 37 Funding Agencies

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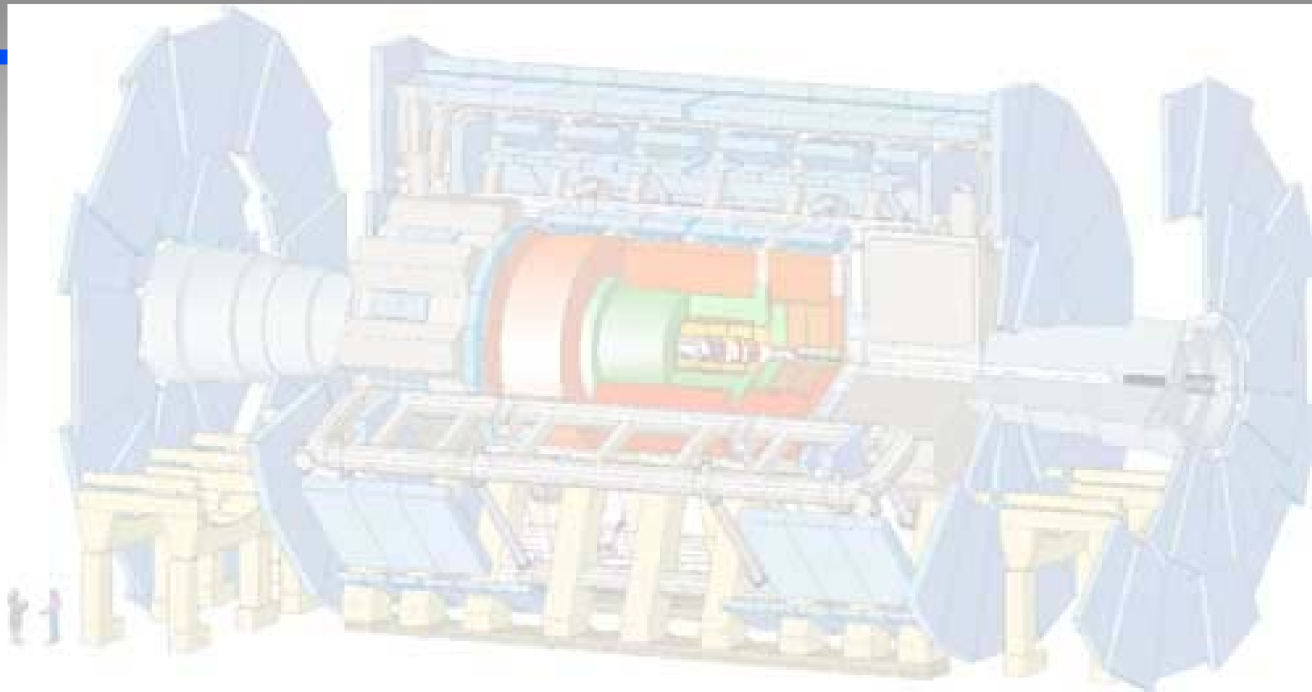
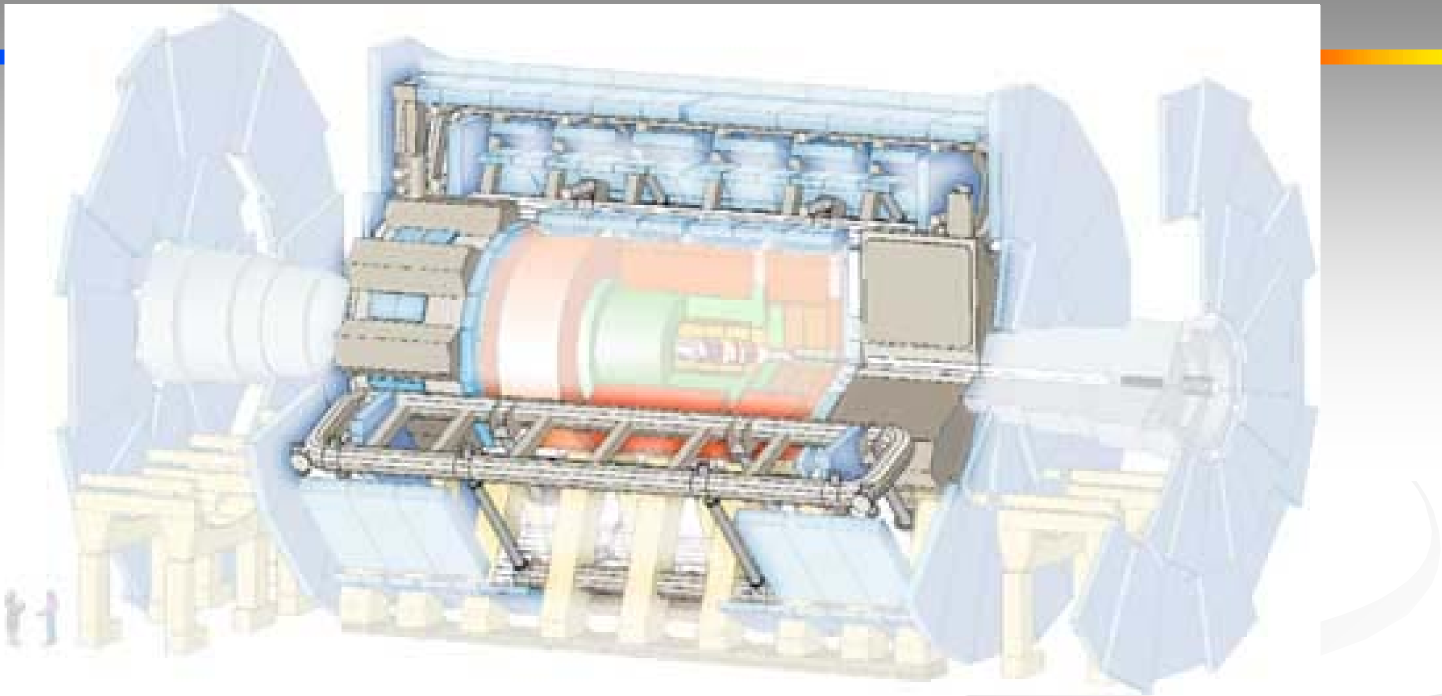
The ATLAS Detector



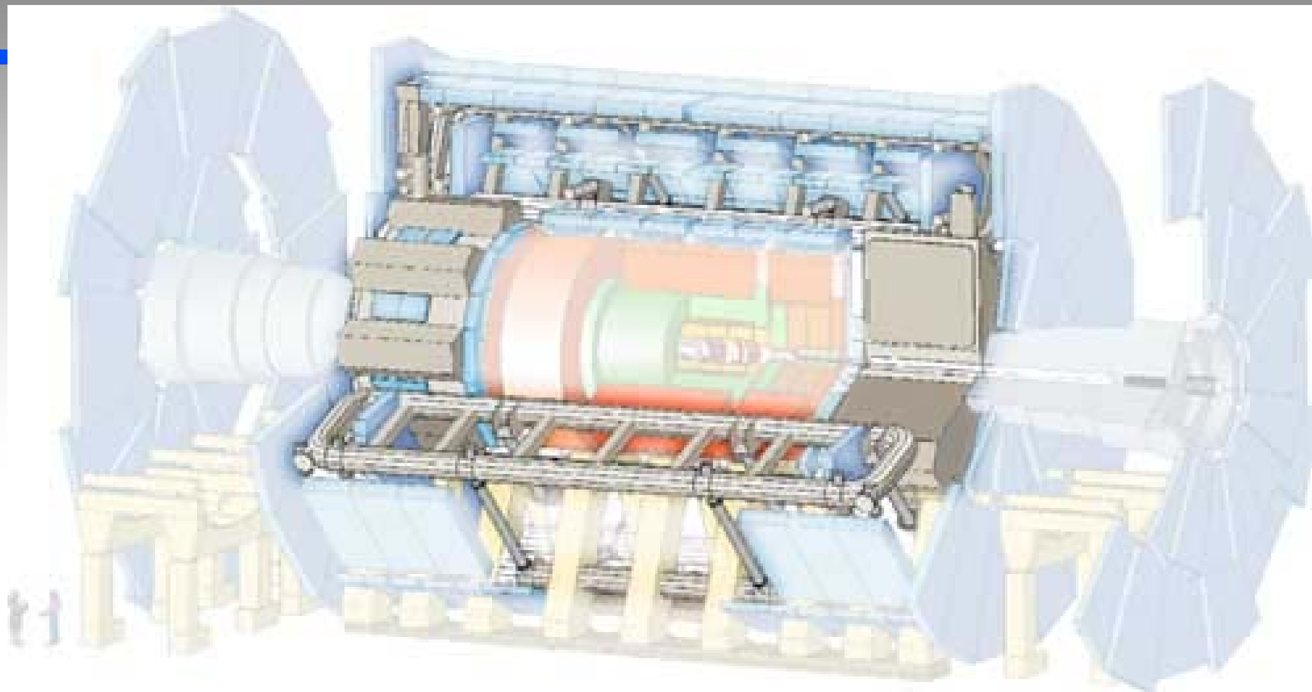
The ATLAS Detector



Magnet System

- 2T Solenoid surrounds inner detector (no field at calorimeters)
- 3.9 - 4T air core toroids for muon system

The ATLAS Detector

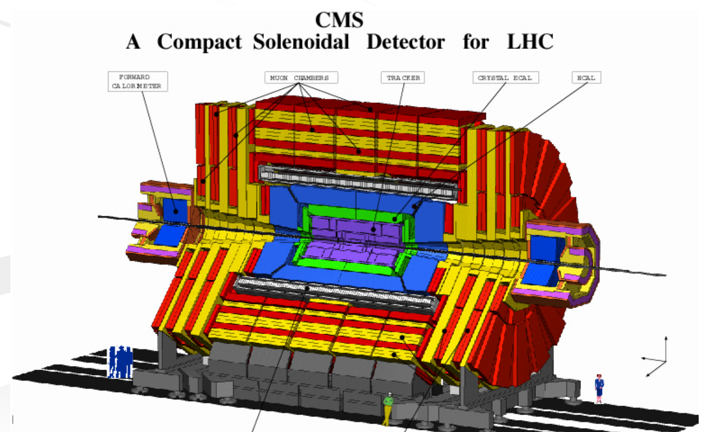


Magnet System

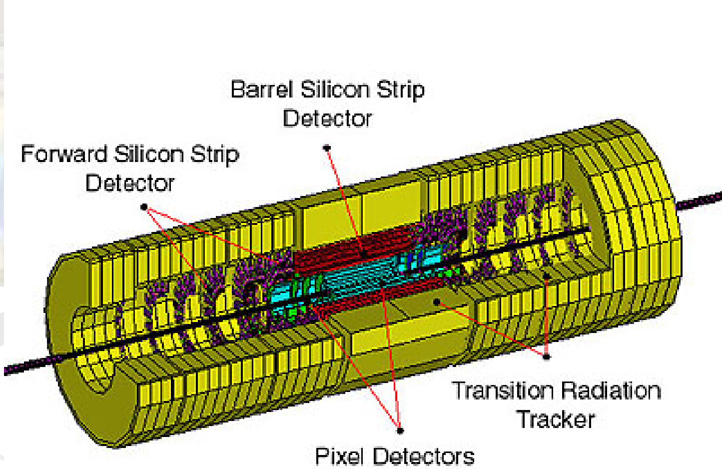
... provides names for the LHC expts

A Toroidal **L**HC **A**pparatu**S**

vs. Compact **M**uon **S**olenoid



The ATLAS Detector



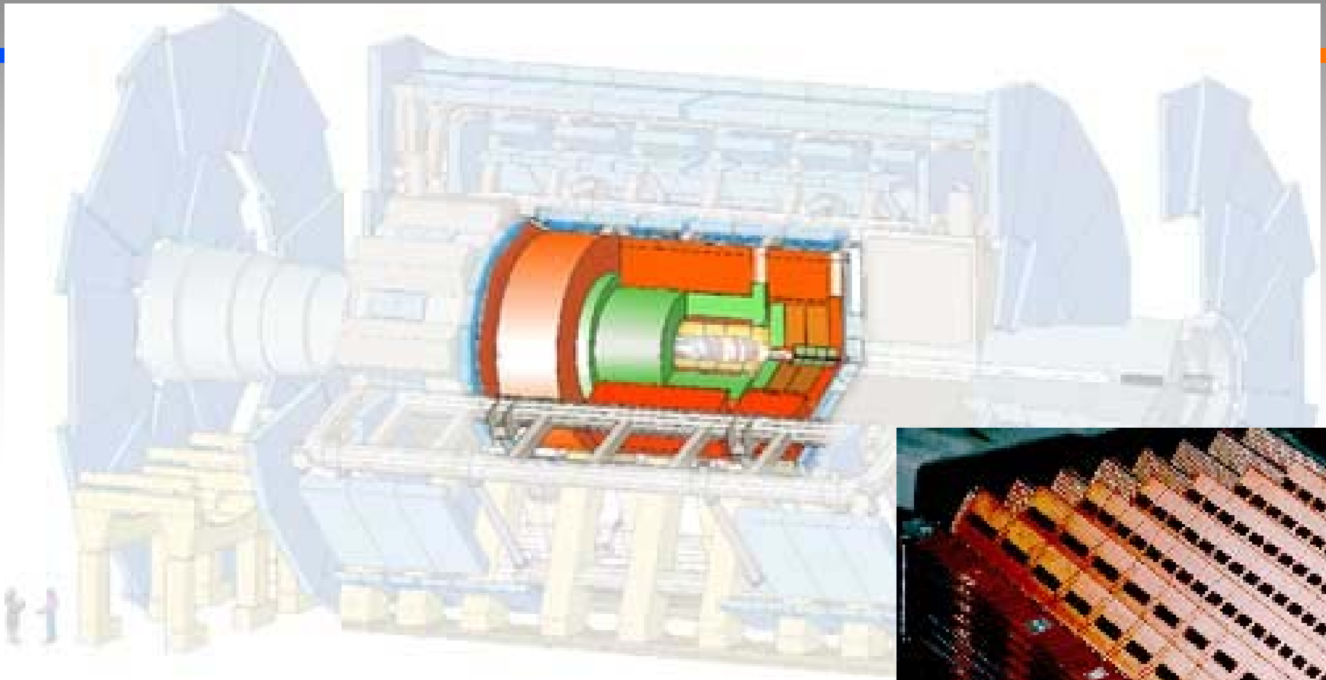
Inner Tracker

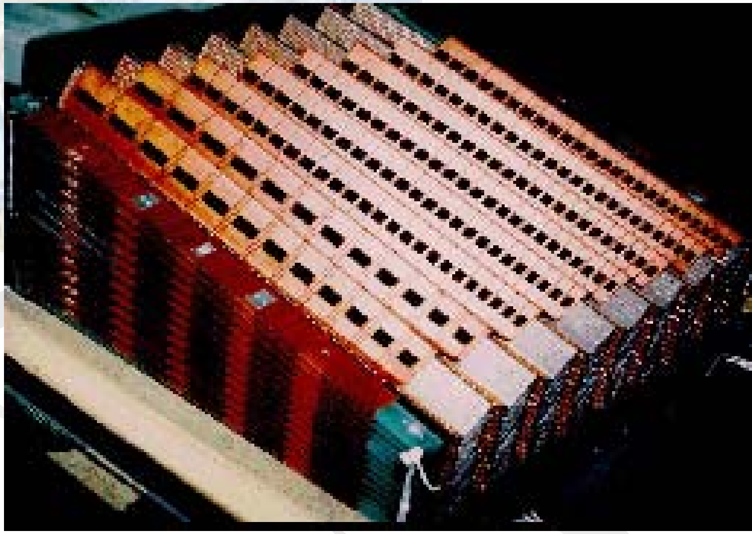
$$\frac{\sigma}{P_T} = \frac{P_T(GeV)}{2000} \oplus 0.01$$

Inner Detector

- Silicon pixels and strips
- transition radiation tracker with e/π separation capabilities

The ATLAS Detector





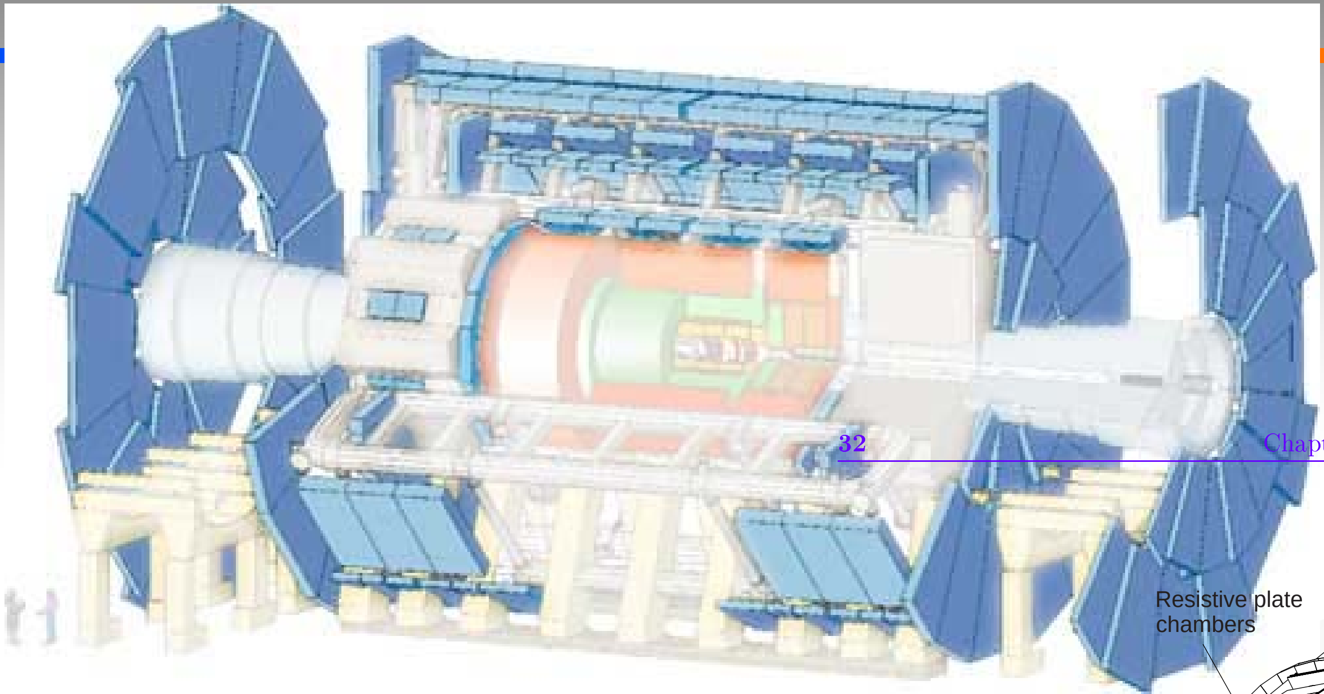
- EM Calorimeters — Pb / LAr

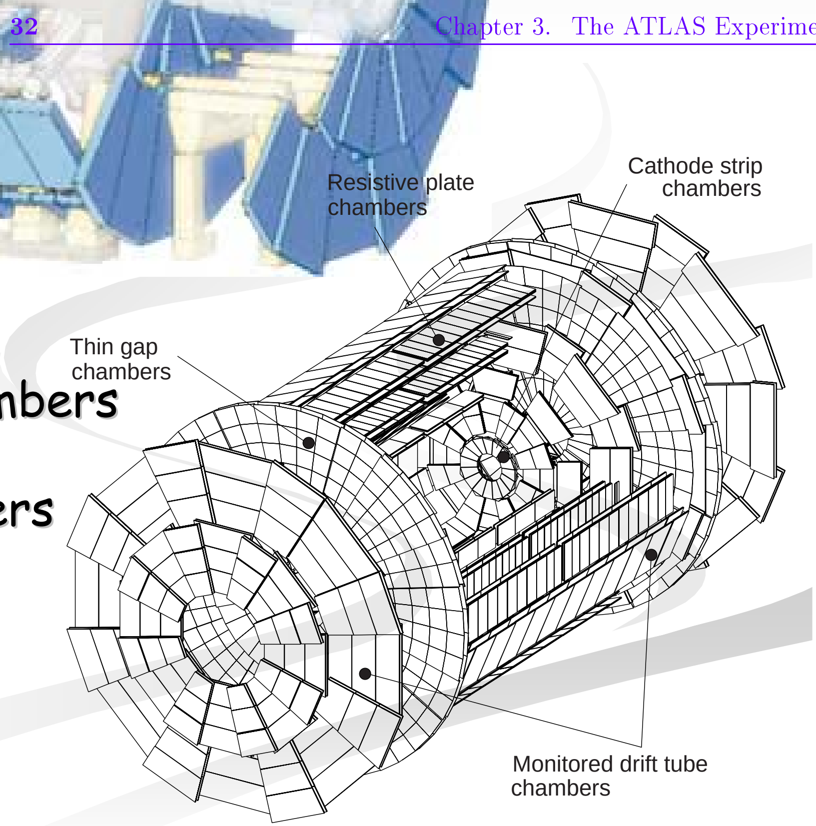
$$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E(GeV)}}$$

- Hadron Calorimeters — Barrel: Fe / Scintillating Tiles; Endcaps: Cu & W / LAr

$$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E(GeV)}} \oplus 0.03$$

The ATLAS Detector



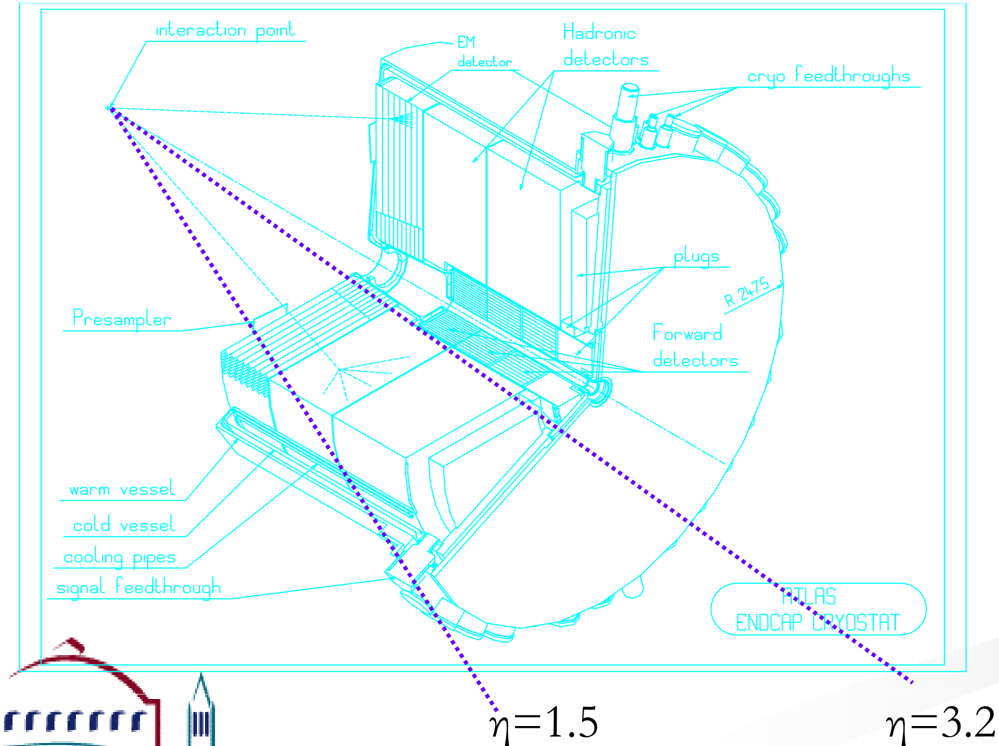


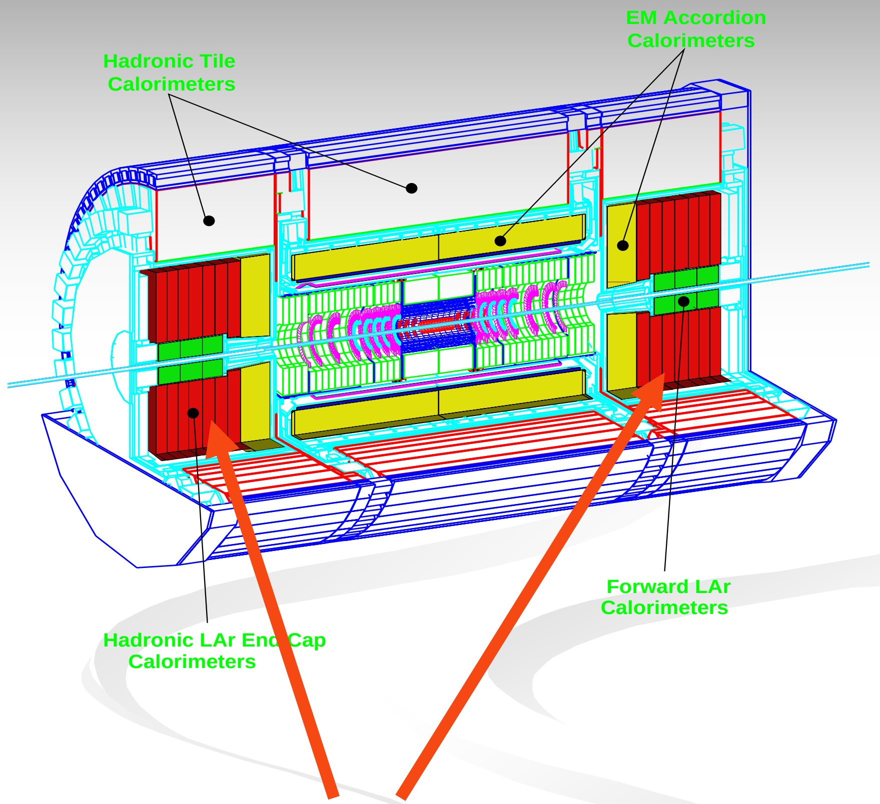
(Air Core) Muon Spectrometer

- monitored drift tubes and cathode strip chambers (precision tracking)
- resistive plate chambers and thin gap chambers (fast triggering)
- Good standalone performance

$$\frac{\sigma}{P_T} \cong 2-3\% \text{ for } P_T < 1\,\text{TeV}$$

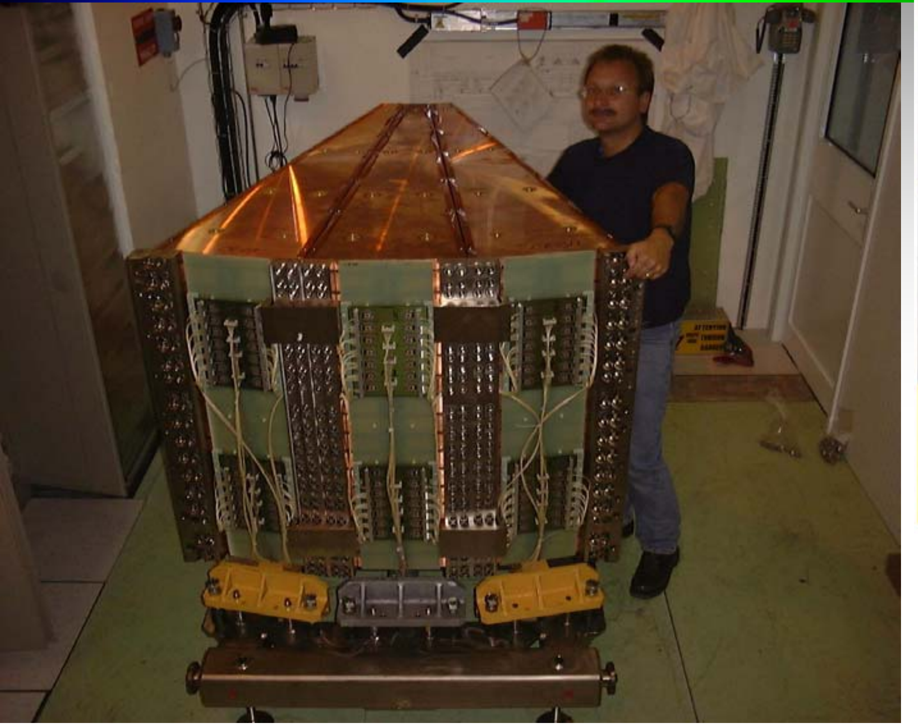
- Subdetector collaborations are busy calibrating, evaluating and understanding their detectors in beam tests.

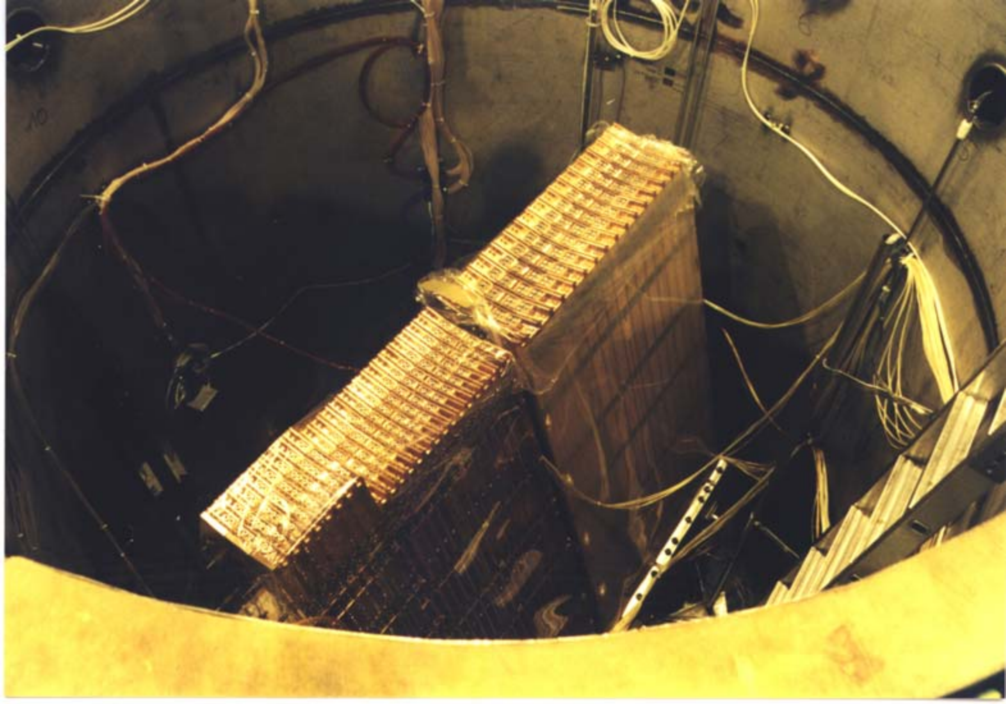




Example: Hadronic Endcap Calorimeter

HEC Beam Test



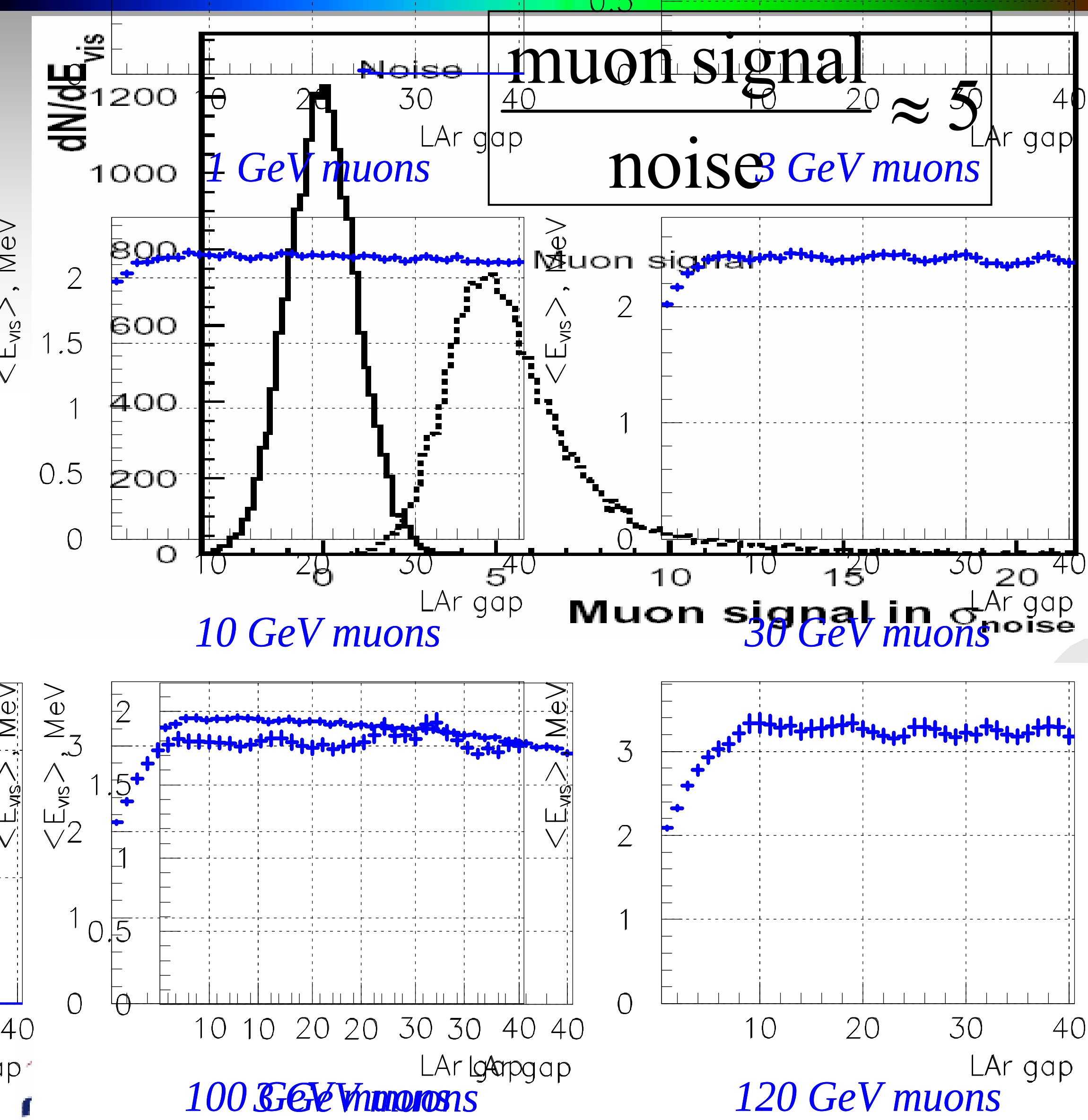


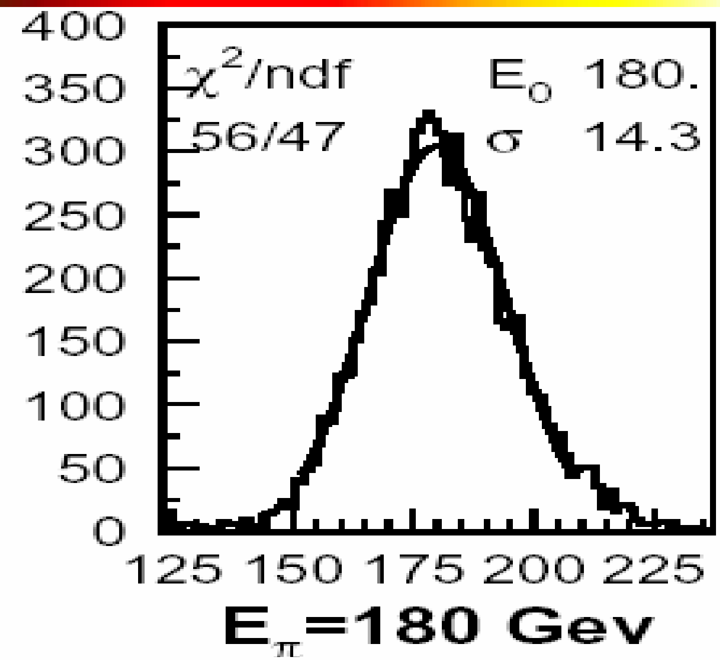
1 wheel constructed and assembled
at Triumf, Vancouver

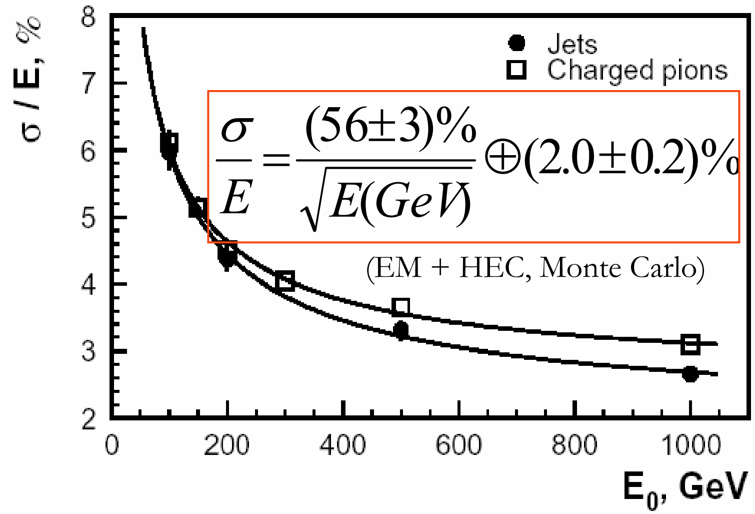
1 wheel constructed at Dubna (Russia)
and assembled at MPI, Munich

Tested in CERN SPS e/μ/π beams, 1998-2001

Dynamic range from MIP to few TeV

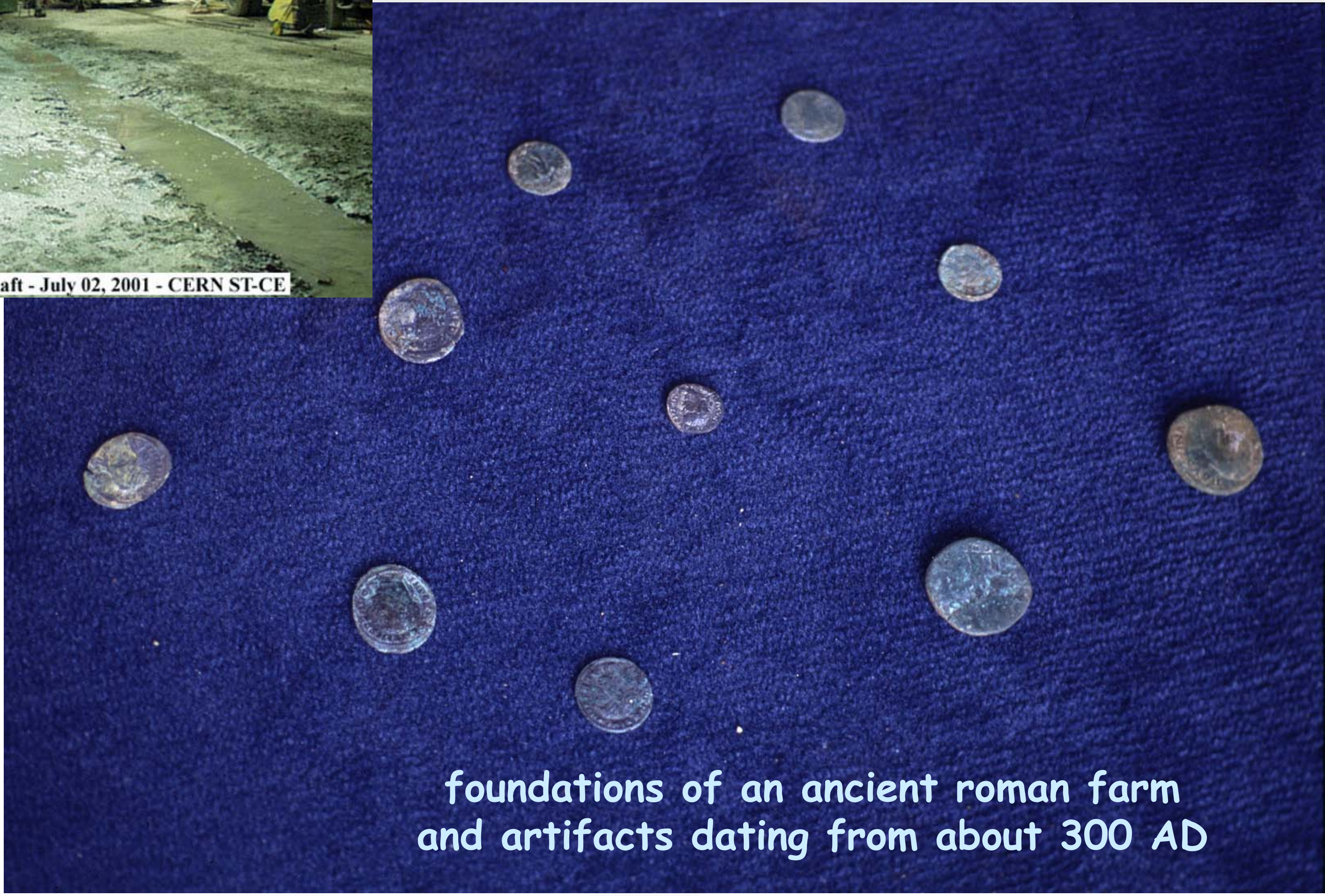






announcing the first LHC discovery

Point 1 - UX15 cavern vault; intersection with PX14 shaft - July 02, 2001 - CERN ST-CE



Gauge-boson Physics

- Drell-Yan lepton pair production

  (2 Nobel prizes… so far, 30 years of Drell Yan measurements)

  └→ channel for large extra Dimensions, Z'

  - probe proton structure: parton density functions at small *x*
  - Calibrate the detector
    - EM energy & momentum scale from pp ➔ Z° ➔ $l^{+}l^{-}$
    - jet energy scale from pp ➔ Z° + jet ➔ $l^{+}l^{-}$ + jet
    - luminosity from pp ➔ Z°,$W^{\pm}$ event rate

    ➔ **Important!, our knowledge of this process feeds into the systematic errors for all physics measurements and searches**

- Key Precision Measurements of fundamental SM parameters

  $\sin^2\theta_W$, Mass(W)

  → **let's explore the $\sin^2\theta_W$ example…**

Measuring $\sin^2\theta_W$ with A_{FB}

- $pp \rightarrow l^+l^-$ di-lepton signature is (almost) background free
- asymmetry arises from interference between neutral currents

$$\frac{d\sigma}{d\Omega} \propto \left| \gamma^* + Z^o + (\text{New Physics!?}) \right|^2$$

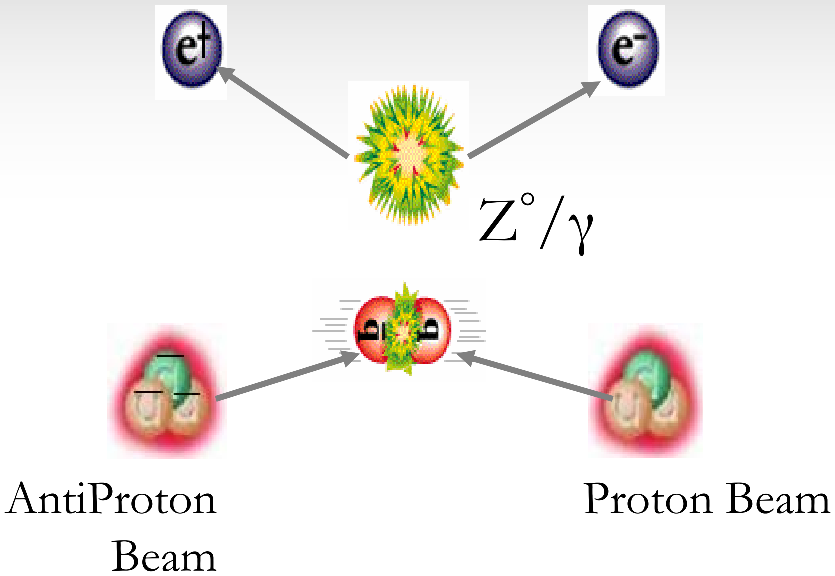
- constrains M_{HIGGS} and checks model consistency

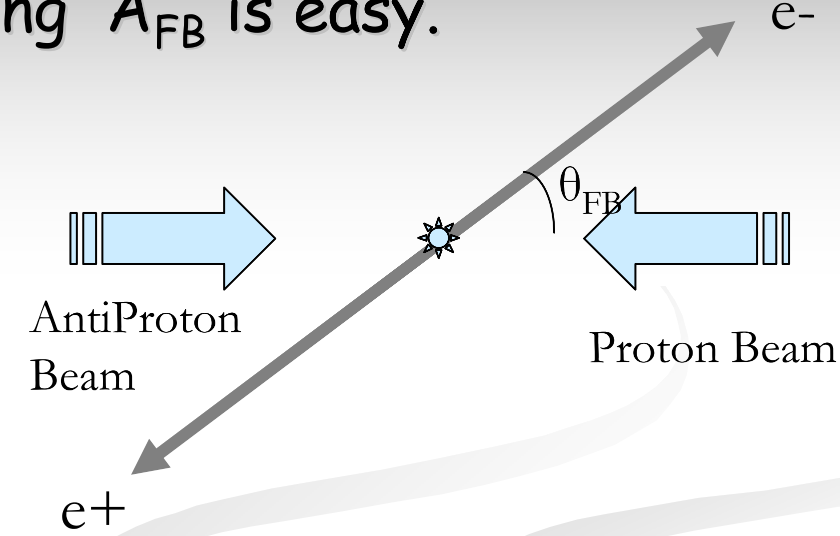
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = b\left(a - \sin^2\theta_{eff}^{lept}(M_Z)\right)$$

known to NLO in EW, QCD
(effects can be as large as 30%)

Measuring $\sin^2\theta_W$ with A_{FB}

- At the $\bar{p}p$ Tevatron, defining A_{FB} is easy.

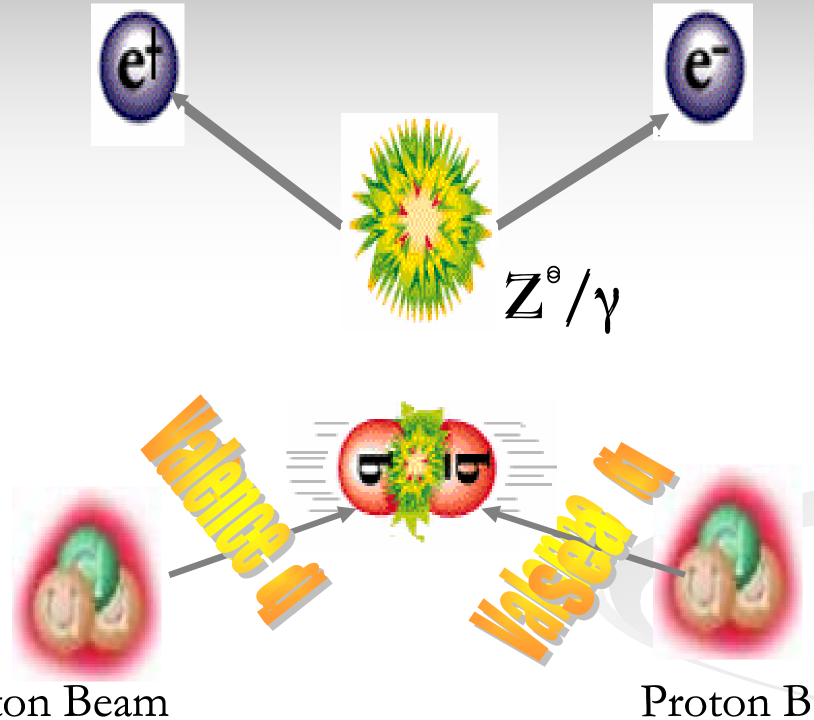




- but for symmetric proton-proton beams (LHC), there is no asymmetry WRT the beams.

Measuring $\sin^2\theta_W$ with A_{FB}

- instead, we "sign" the forward direction by the l^+l^- boost.



- measure asymmetry in charged lepton direction WRT CMS boost direction
- Asymmetry increases at high $Y(l^+l^-)$

Measuring $\sin^2\theta_W$ with A_{FB}

- **Statistical precision using 100 fb^{-1}, near Z-pole (±6GeV)**

Cuts	A_{FB} (%)	ΔA_{FB} (%)	$\Delta \sin^2\theta_{eff}(M_Z)$
Both e±, |η|<2.5	0.774	0.020	0.00066
One e±, |η|<2.5 other e±,|η|<4.9	1.98	0.018	0.00014

ATL-PHYS-2000-018
Sliwa, Riley, Baur

for comparison, $\Delta \sin^2\theta_{eff}$=0.00053 combining 4 LEP expts and e,μ,τ channels [CERN-EP/2001-098]

- Performance issue: **increasing forward lepton tagging acceptance greatly improves measurement**
- systematic PDF uncertainty is most challenging.

Modeling our Predictions: New Monte Carlo Techniques for QCD corrections

the real challenge for M.C. authors is modeling subtle Standard Model effects… new physics is (usually) easy!

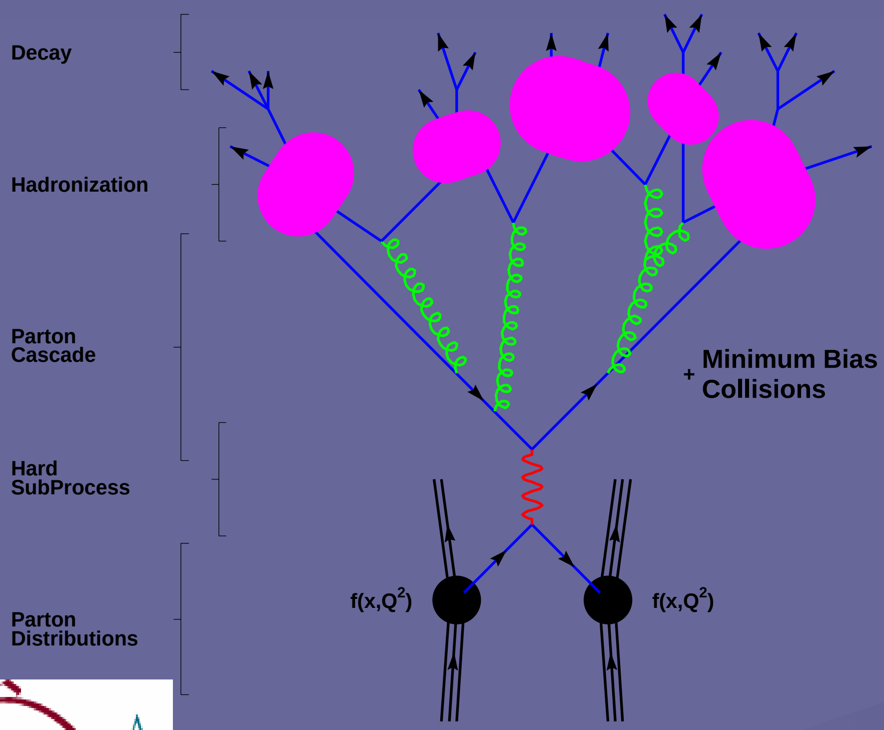
Physics Division
Berkeley Lab

Simulating QCD Corrections

2 common approaches

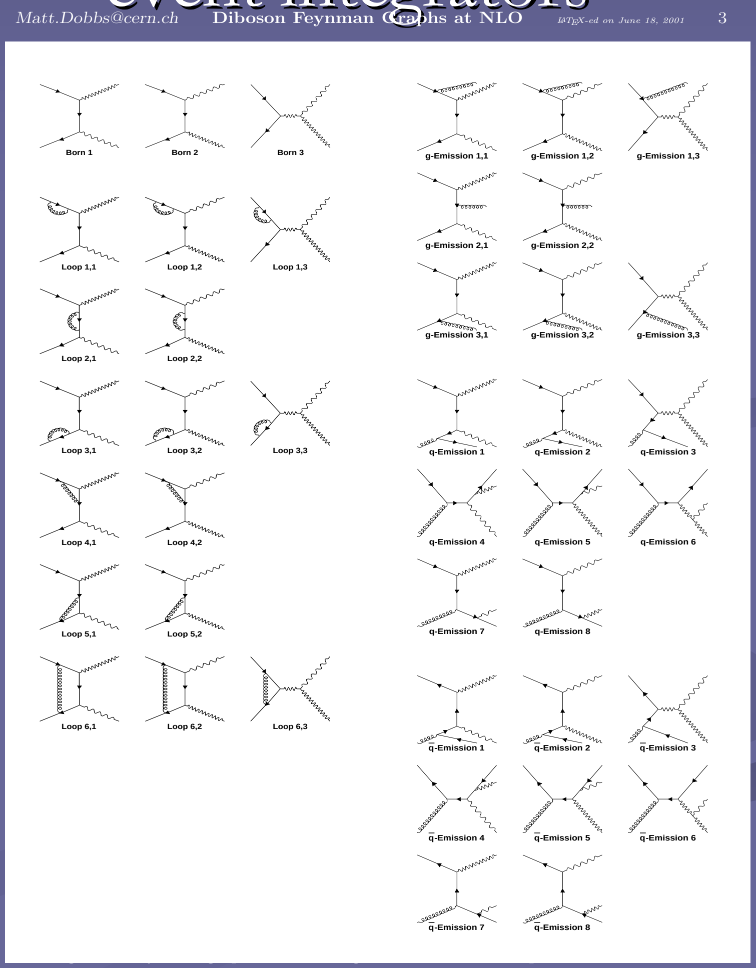
Showering event Generators

(Pythia, Herwig, Isajet)

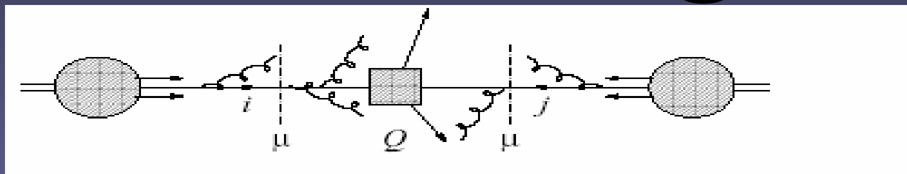


Next-to-leading order

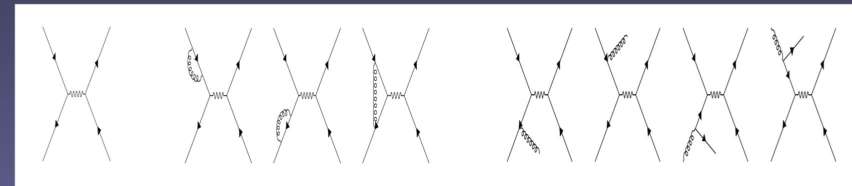
"event integrators"



Simulating QCD Corrections



(this figure from B.Webber, QCD Academic Training 1999)



Showering Event Generators

- ☺ Event generation is probabilistic… freq predicted by theory.
- ☺ exclusive prediction
  - → you get the whole event record
- ☺ all orders approximation of multiple emissions
- ☺ valid in soft/collinear emission regions
- ☹ not valid for hard, well separated partons
- ☹ Normalization is LO

NLO Matrix Elements

- ☺ good prediction of hard central emissions
- ☺ best prediction of total σ
- ☹ one order in α_S
  - →at most one "jet"
- ☹ fixed order perturbation is not valid for small P_T(jet)
- ☹ event weights are negative (unphysical) in some phase space regions

→ Complementary Approaches ←

Phase Space Veto Method

Implemented as an event generator for

$$p\bar{p} \rightarrow Z^0 + X \rightarrow l^+ l^- + X$$

but everything ***applies in general to any colour singlet production*** process at hadron colliders

(Matt: Click here if you are short on time!)

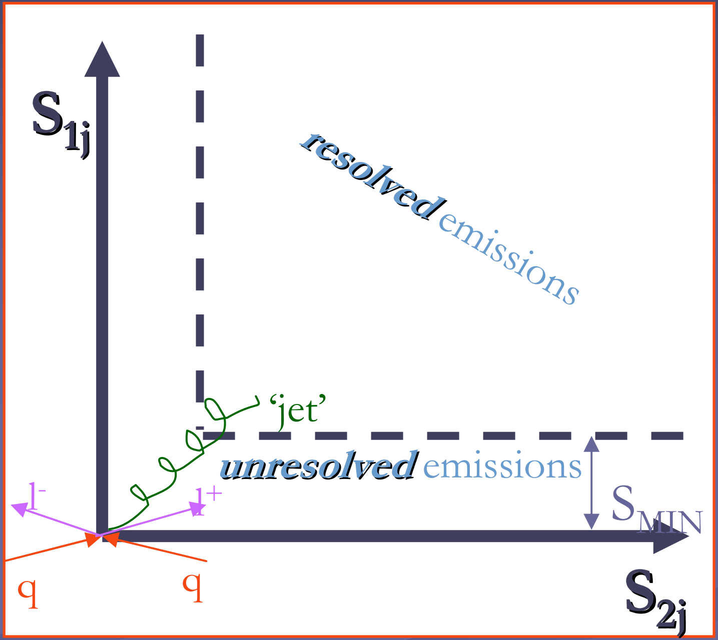
NLO 'event integrators' pp→Z+X→ l^+l^-+X

Regularization scheme example:

Phase Space Slicing

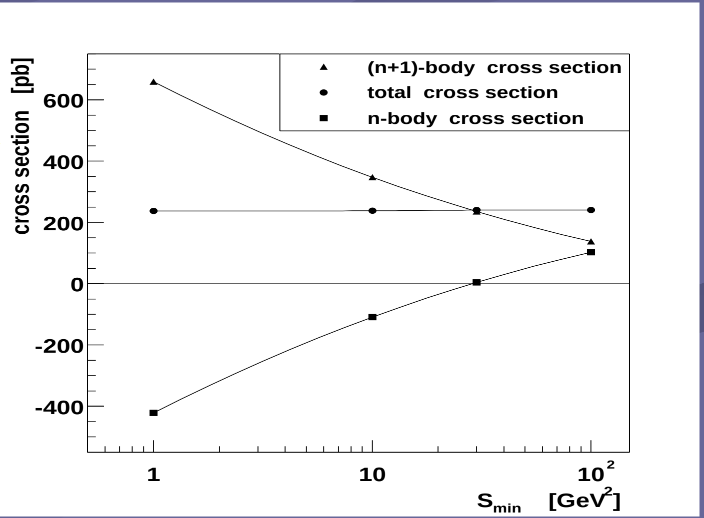
("S_{MIN} slicing")

- partition phase space:
  - **resolved** region: integrated numerically
  - **unresolved** region: integrated analytically
- programmed as two separate generators



- cross section is independent of our S_{MIN} choice

$$\sigma^n(S_{MIN}) + \int_{s_{ik}>S_{MIN}} \sigma^{n+1}(\Phi_{+1})\, d\Phi_{+1} = \text{Const}$$



→ **can choose** (almost) **any S_{MIN} we like**.

Phase Space Veto Method

Dobbs, Phys.Rev.D64,034016 (2001), Phys Rev D65,094011 (2002)

Pötter, Phys.Rev.D 63,114017 (2001) [DIS]

Recall: → can choose (almost) any S_{MIN} we like

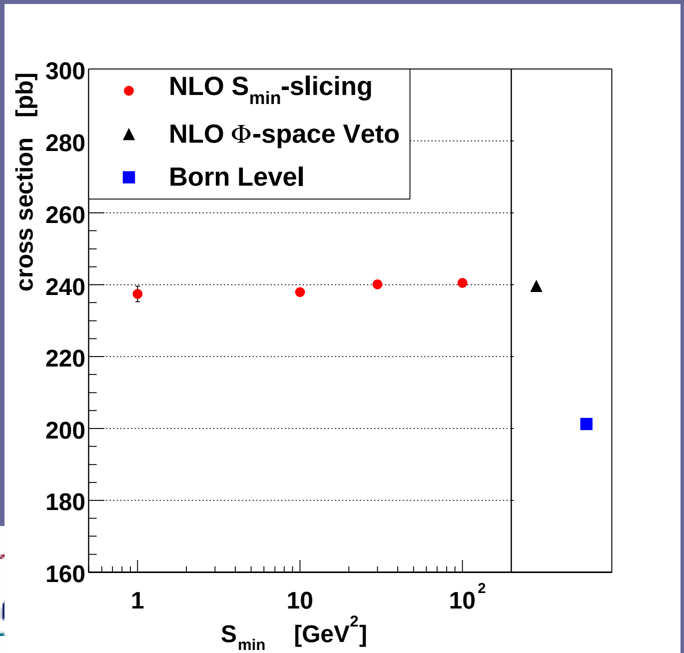
$$\sigma^{n}(S_{MIN}) + \int_{s_{ik} > S_{MIN}} \sigma^{n+1}(\Phi_{+1})\, d\Phi_{+1} = \text{Const}$$

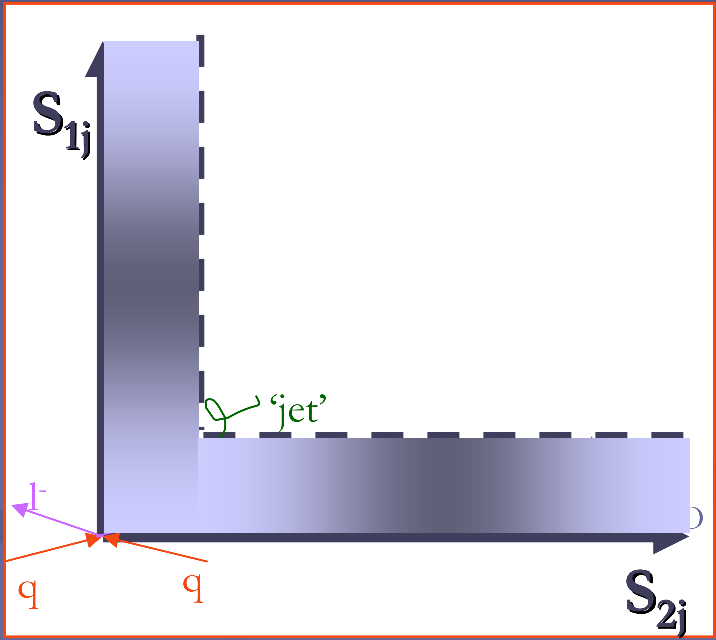
S_{ZERO}

choose S_{ZERO}

i.e. unresolved contribution, $\sigma^n(S_{ZERO})=0$

on an *event-by-event basis.*

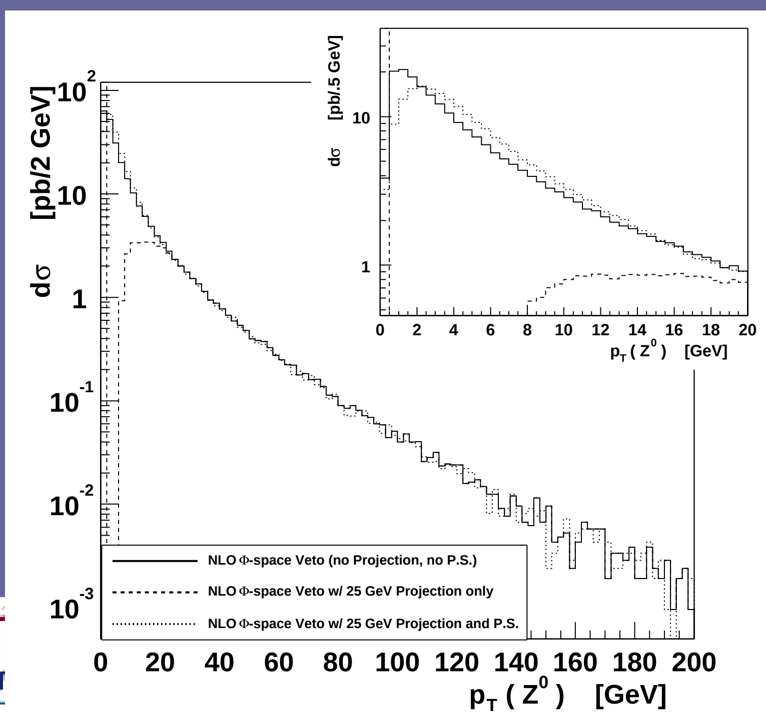


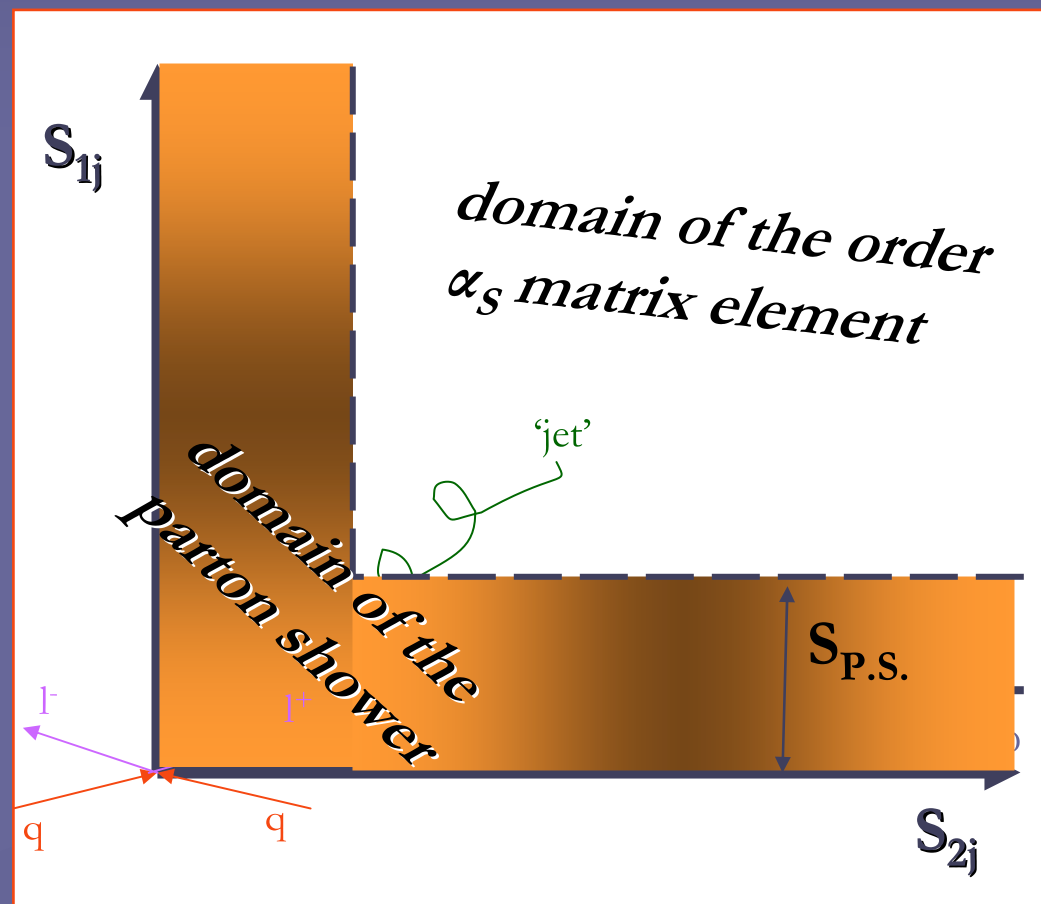


Addresses the first issue, because it carves out the region of negative weights → i.e. it allows us to re-formulate the NLO calculation into a ***true (probabilistic) event generator.***
→ while maintaining the **reduced scale dependence** provided by the NLO calculation.

Phase Space Veto Method: shower evolution

- our description of the hard central region is dominated by the NLO matrix elements
- ideally, we want the small P_T region to be the domain of the Parton Shower



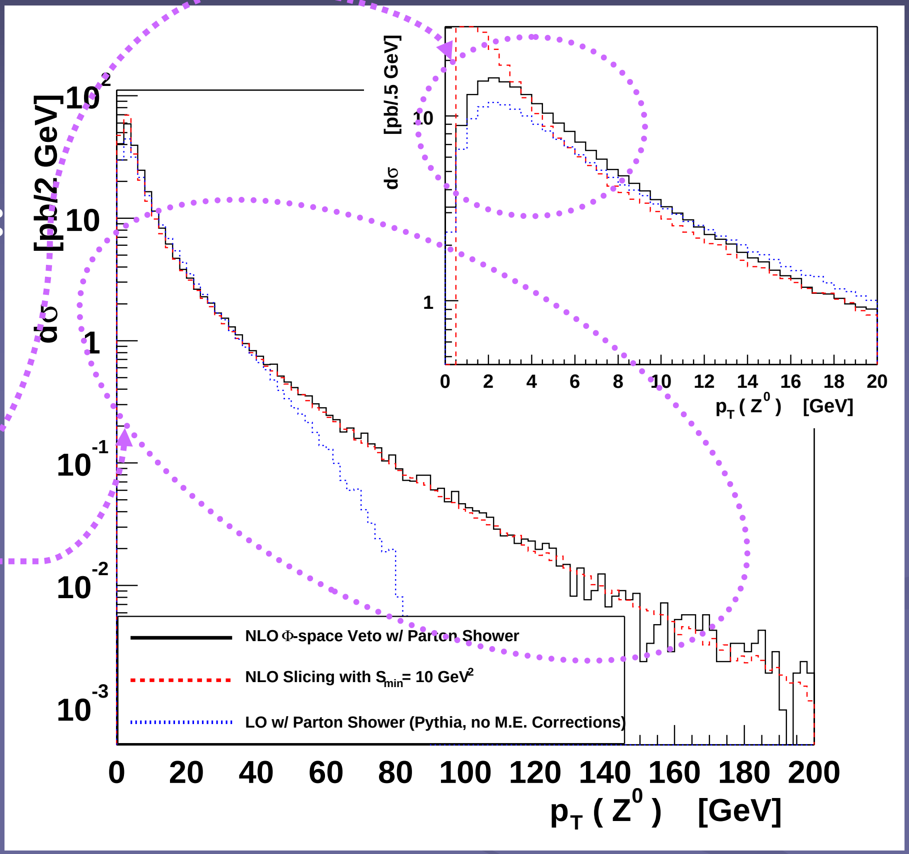


Phase Space Veto Method

- **event generator in the true sense**

→ you get unweighted events

→ **well suited for expt. applications:**
  - **detector simulation,**
  - **hadronization, etc.**
- dominated by **parton shower in the soft/collinear regions**
- dominated by **$O(\alpha_S)$ matrix element in hard/central regions**
- **normalization is NLO**, maintains **reduced scale dependence.**



Phase Space Veto Method

- attacks a phenomenological issue from an experimental viewpoint
- implemented as a new $p\overset{(-)}{p} \rightarrow Z^0/\gamma^* + X \rightarrow l^+ l^- + X$ event generator
  - see Dobbs, Phys Rev D65,094011 (2002)
  - (uses LUND parton shower)
  - efficiency and event generation time competes with L.O. generators
  - another step towards modularized event generators (HepMC, HepUP)
  - written in Object Oriented C++
- preliminary results indicate there will be further benefits for more complicated processes like diboson production.

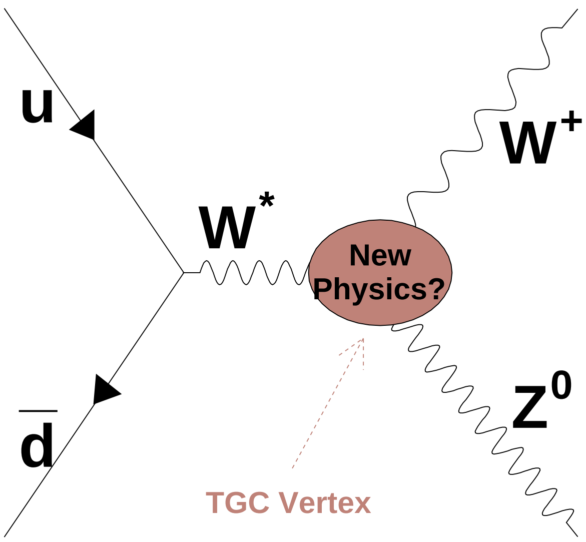
  [see Dobbs, Phys Rev D64,034016 (2001)]
- The phenomenology community is listening!
  - `competing' version from Herwig announced February 2002: S.Frixione/B.Webber (hadronic diboson production at NLO)
  - Minami-Tateya (KEK) group (GRACE), Yoshimasa Kurihara, $pp \rightarrow Z+X$
  - Lund has new effort underway: S. Burby/T. Sjöstrand

    (ME corrections to Wγ WW WZ)

… Modeling our Predictions New Monte Carlo Techniques for QCD corrections

J

Probing the Triple Gauge-boson Couplings



- non-abelian $SU(2)_L \times U(1)_Y$ gauge group **(foundation of SM!)**

  → $WW\gamma$ WWZ couplings

- most-general C & P conserving WWZ,WWγ vertices are specified by just **5 parameters**:

$$\underbrace{\Delta g_Z^1, \Delta\kappa_Z, \Delta\kappa_\gamma}_{\text{grow like } \sqrt{\hat{s}}} \quad \underbrace{\lambda_Z, \lambda_\gamma}_{\text{grow like } \hat{s}} \quad \equiv \text{ZERO in the S.M.}$$

big advantage for LHC

➔ model independent parameterization

- **Probe tool:** sensitive to low energy remnants of new physics operating at a higher scale
- ***complement*** to direct searches

Probing the Triple Gauge-boson Couplings

- theoretical expectation for new physics at 1 TeV

anomalous TGC's at most
for new physics at 1 TeV
[hep-ph/9503425 DPF]

$$\mathcal{O}\left(\frac{M_W^2}{\Lambda_{N.P.}^2}\right) \approx \mathcal{O}(0.01)$$

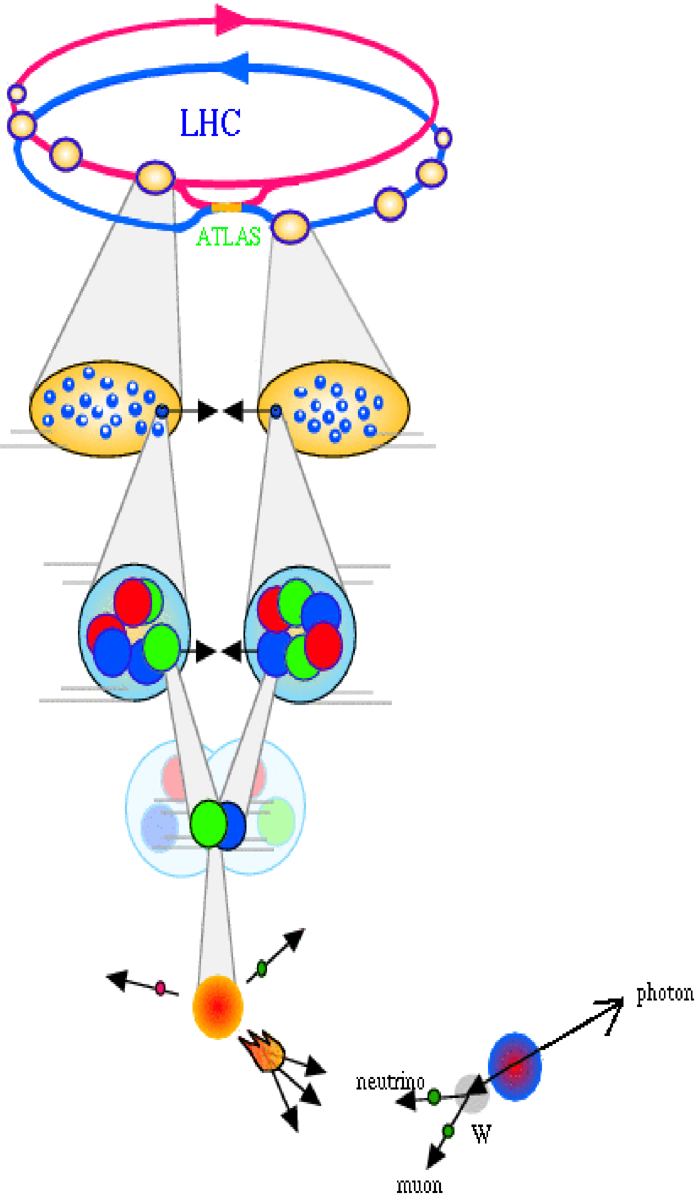
- **LEP**$^{\text{Combined,ICHEP2000}}$ & **Tevatron**$^{\text{Expected, RunII}}$

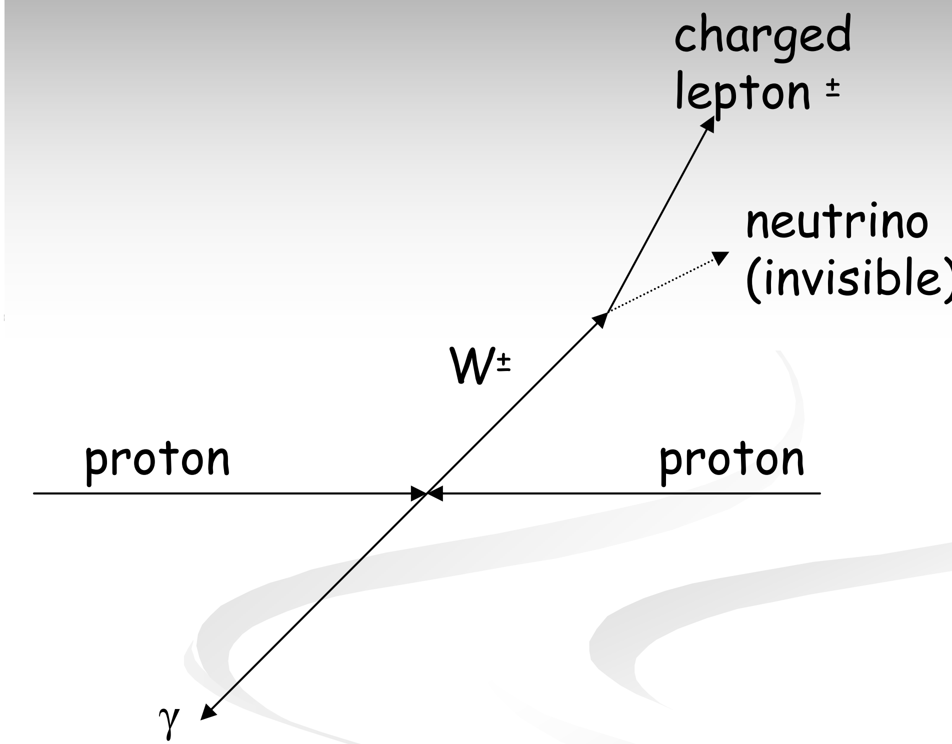
$$\mathcal{O}(.10\text{-}.20)$$

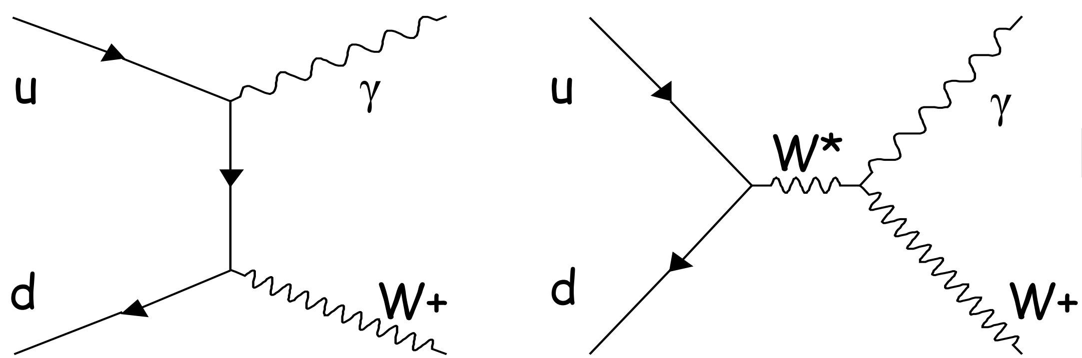
95% Confidence Limits

- probe the WWZ,WWγ vertices with ***leptonic decay channels*** of WZ and Wγ production

$pp \rightarrow W^{\pm}\gamma \rightarrow l^{\pm}\nu\gamma$







Wγ production at LHC

Consider leptonic decay channels only: $e^{\pm}\nu\gamma$, $\mu^{\pm}\nu\gamma$

Number of Events for 30 fb^{-1}

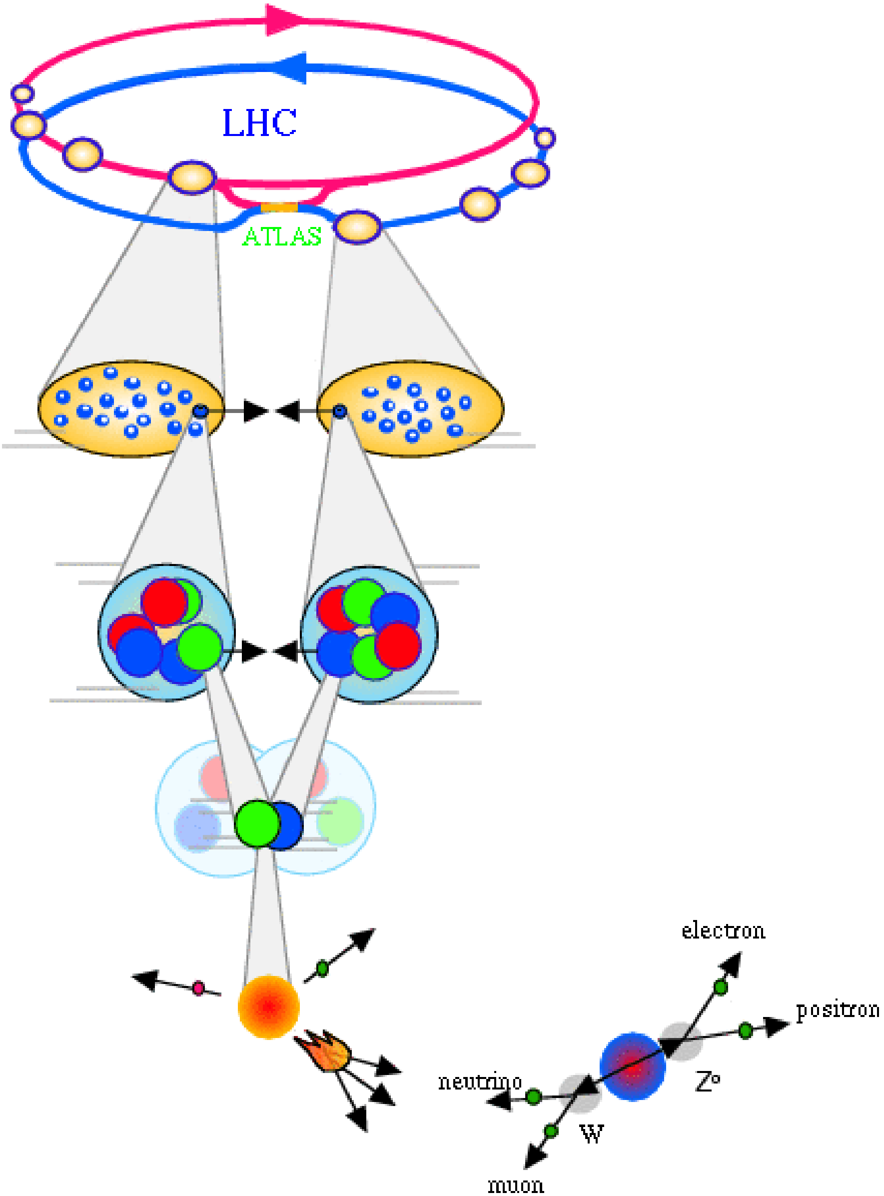
	$Z\gamma$	W+jet	Z+jet	$t\bar{t}(\gamma)$	$b\bar{b}(\gamma)$	γ+jet	$W\to l\nu\gamma$	$W\gamma\to\tau\nu\gamma$	All Backgrounds	$W\gamma$ Signal	$\frac{S}{B}$
preselection	2436	4367	7398	1561	253	956	20	710	17701	17717	1.0
$P_\gamma^T > 100$ GeV	1277	2097	2101	945	160	894	14	665	8153	10638	1.30
$P_{l^\pm}^T > 25$ GeV	1196	1938	1800	837	64	664	13	586	7098	10066	1.42
$P_{\rm miss}^T > 25$ GeV	377	1557	215	689	43	44	12	574	3511	7311	2.08
$\Delta R(\gamma, l^\pm) <1$	376	1543	183	611	42	44	12	574	3385	6791	2.01
$\Sigma_{\rm jets} P_{{\rm jet}_i}^{\vec{T}} < 100$ GeV	341	1280	133	286	26	11	12	534	2623	4262	1.62

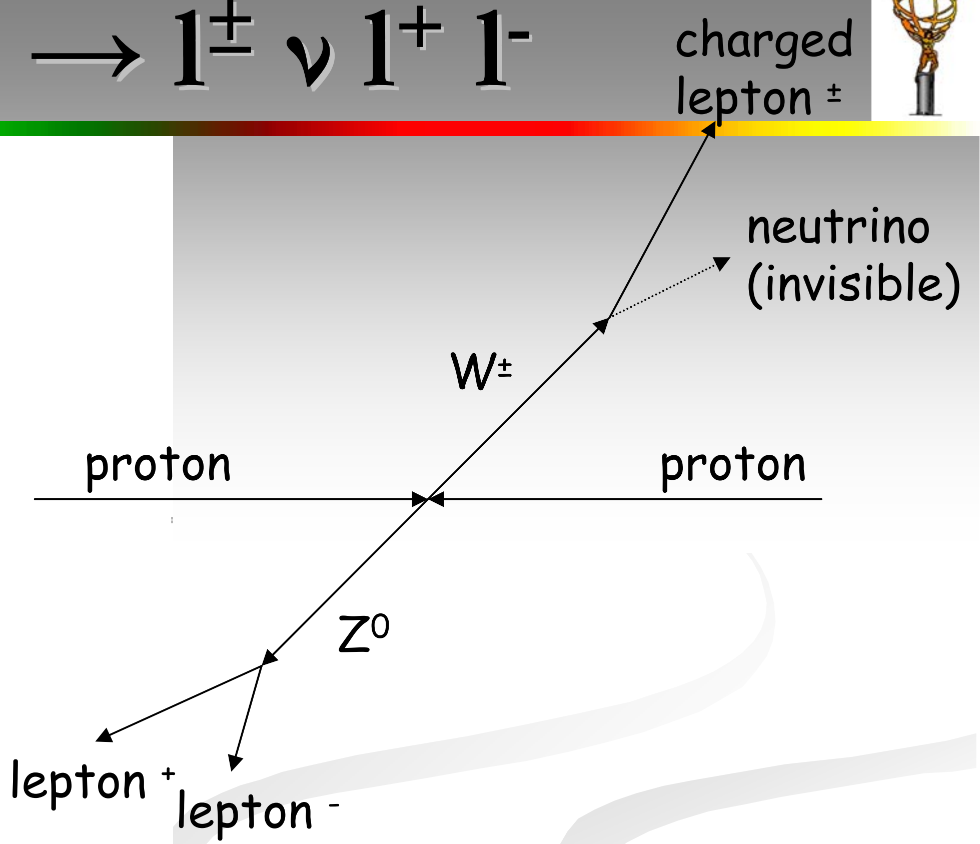
jets faking photons is largest background
→ highlights particle ID performance

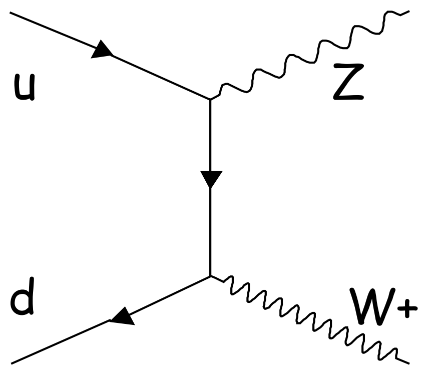
unlike the Tevatron,
W→τ ν is significant
background for LHC

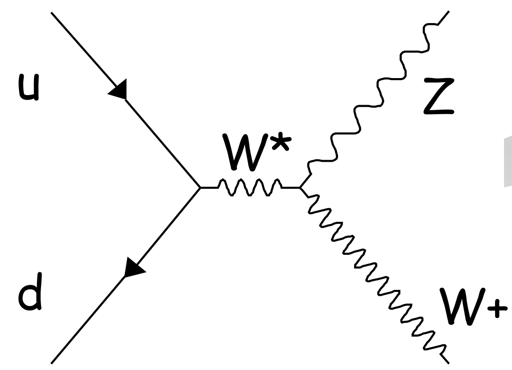
- Backgrounds: LO × (k=1.5)
- Signal: NLO(α_S)
  - cuts designed for purity are optimized at LO
  - cuts which isolate the phase space where TGC diagrams dominate (i.e. address $\mathcal{O}(\alpha_S)$) effects) are chosen so as to optimize the confidence limits.

$pp \rightarrow W^{\pm}Z^{o} \rightarrow l^{\pm}\,\nu\,l^{+}\,l^{-}$









Backgrounds to WZ production

Number of Events for 30 fb^{-1}

	# events						Spread in Stat. 95% C.L.		
	Backgrounds			All	WZ				
	Z+jet	ZZ	$t\bar{t}$	Backgrounds	Signal	$\frac{S}{B}$	λ_Z	$\Delta\kappa_Z$	Δg_Z^1
preselection	631	576	745	1952	3663	1.88	0.014	0.29	0.020
3 leptons, $P_{l\pm}^T > 25$ GeV	398	500	461	1359	3285	2.42	0.014	0.29	0.020
$P_{miss}^T > 25$ GeV	3.2	90	357	450	2453	5.44	0.014	0.28	0.019
$\lvert M_{l^+l^-} - M_Z \rvert < 10$ GeV	2.8	76	65	144	2331	16.2	0.014	0.29	0.020
$\Sigma_{jets}\, \vec{P}_{jet_i}^T < 100$ GeV	2.5	72	44	119	1987	16.7	0.013	0.23	0.016

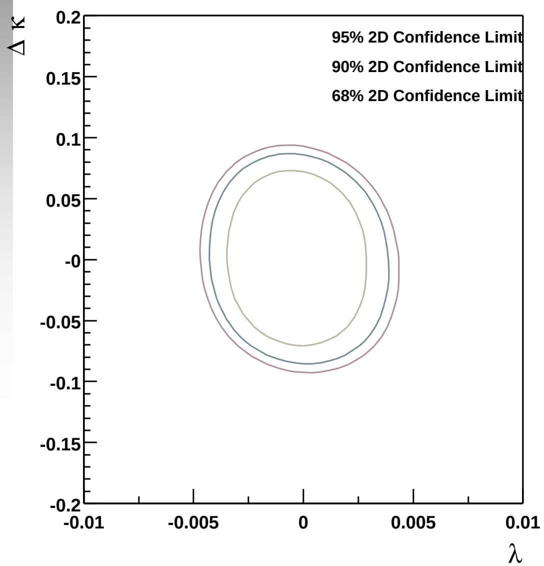
almost background free

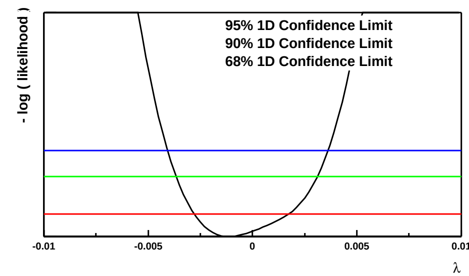
statistical limits depend very weakly on obtaining good purity.

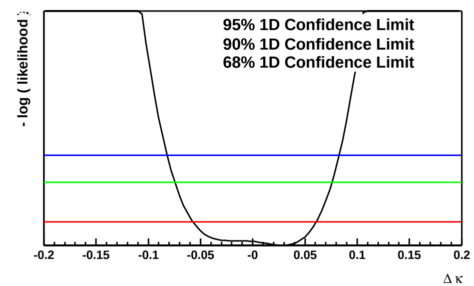
- Backgrounds: LO × (k=1.5)
- Signal: NLO(α_s)
  - bb and Zγ backgrounds are negligible

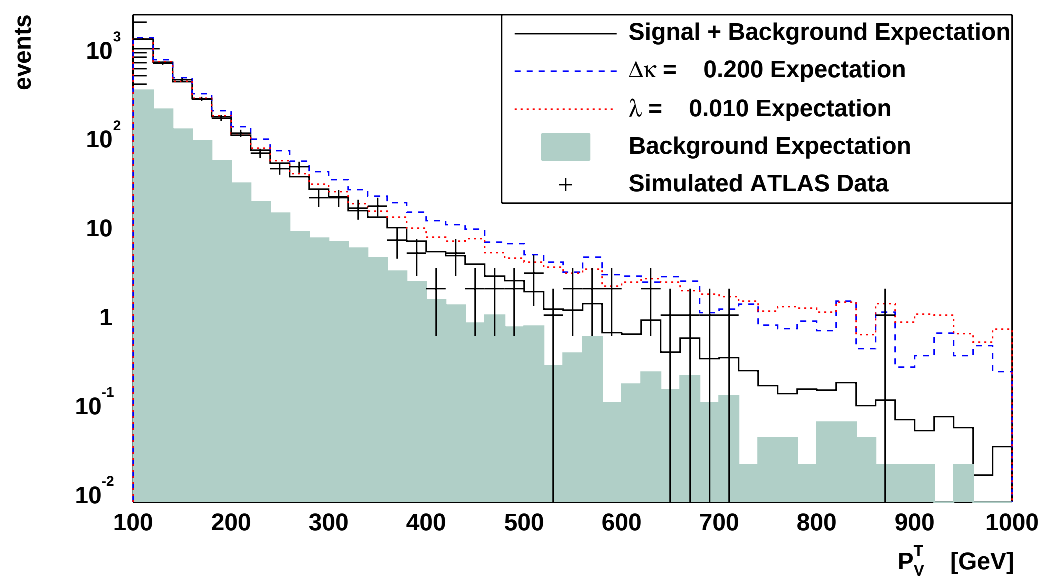
Extracting the confidence intervals

- binned max. likelihood fit to $P_T(V)$ distribution
  - robust → no need to reconstruct CMS vectors
  - directly measured
- investigated :
  - optimal observables
  - multi-variant fits $[P_T(V) \times P_T(\not{E}_W)]$ is best]
  - other 1-D distributions
- luminosity systematic avoided by considering distribution shapes only

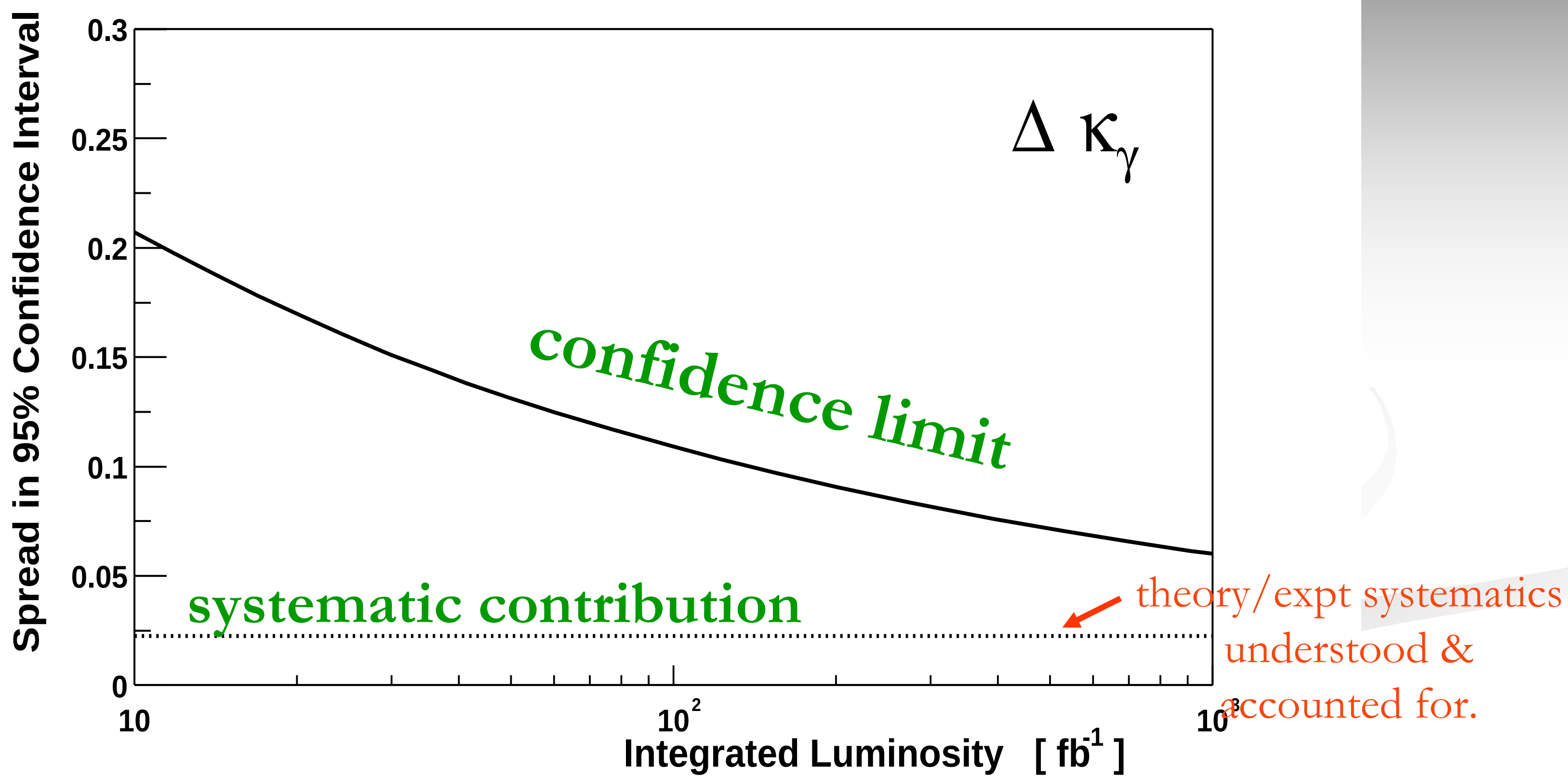








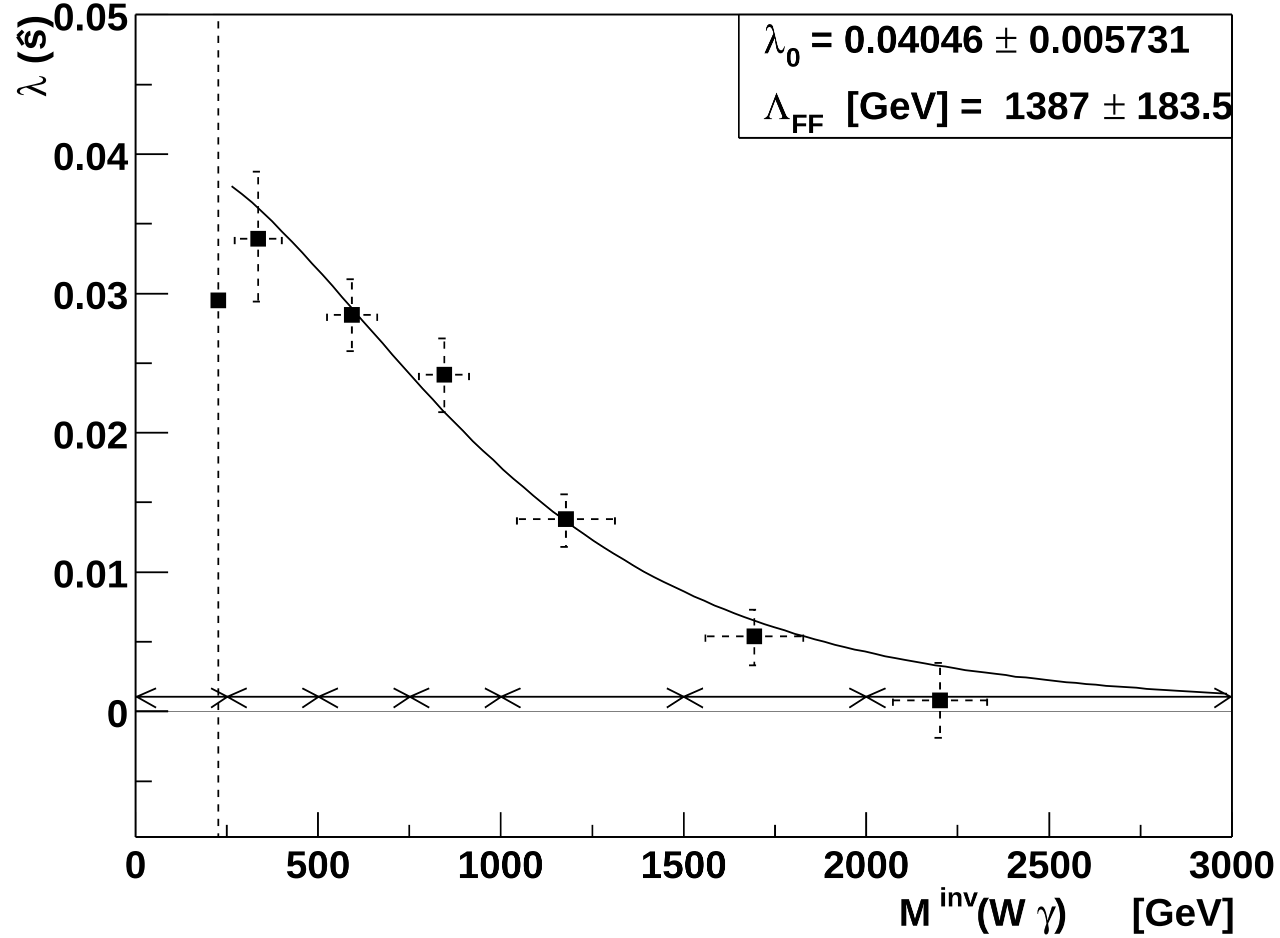
Limits vs. Integrated Luminosity



- Statistics will dominate LHC measurements (except for $\Delta\ g^1$)
  - →sensitivity derived from a few events in the high $P_T(V)$ tail
- Dominant systematics are theoretical:
  - →neglected higher orders and pdf's
- Systematics reported here are worst case scenario,
  - → assumes we are unable to correct for the mis-modeling.

What can we do if we observe anomalous couplings??

➔LHC will have sufficient statistics to measure the form factor behavior (energy dependence) of anomalous couplings.

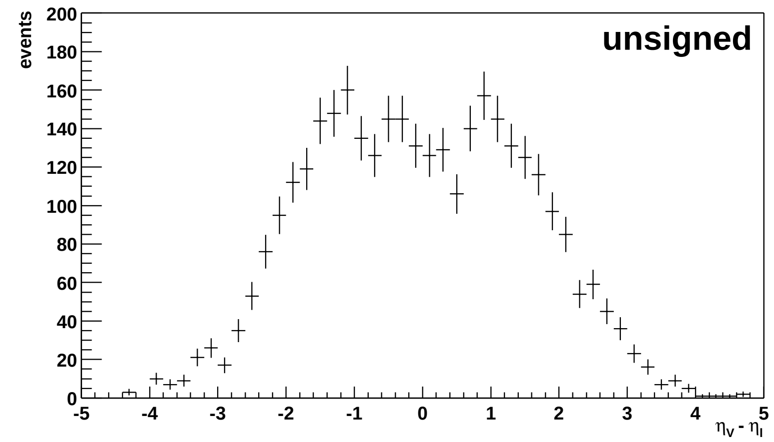


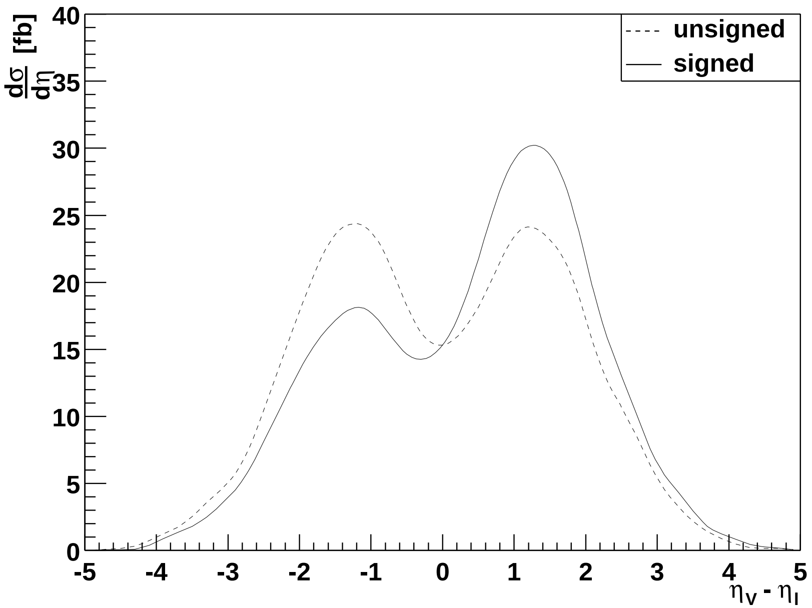
Physics Division
Berkeley Lab

Radiation Zero

- specific production angle of the photon is forbidden by subtle gauge cancellations
- one of very few remaining electroweak discoveries
- normal statement "Tevatron has a distinct advantage because of the asymmetric beams."

➔ borrow the (Drell-Yan) idea of signing forward direction by the system boost.





Triple Gauge-boson Couplings:

RESULTS & Summary

- 95% Confidence Intervals are:
  - limits derived by averaging over 5000 "mock" ATLAS expts.
  - **typically order of magnitude improvement over LEP / Tevatron**

$-0.0035 < \lambda_\gamma < +0.0035$

$-0.0073 < \lambda_Z < +0.0073$

$-0.075 < \Delta\kappa_\gamma < +0.076$

$-0.11 < \Delta\kappa_Z < +0.12$

$-0.0086 < \Delta g^1_Z < 0.011$

For 30 fb^{-1}, systematics included.

- statistically limited measurement (!)
  - **sensitivity from a few events in high P_T tail**

  (except Δg^1_Z, for which systematics & statistics are comparable)
- theoretical errors dominate the systematics
  - "tools" for controlling these systematics have been developed, not discussed here.
- new means of ensuring unitarity developed (not discussed here)
- measurements of anomalous couplings as a function of energy will be possible.

Conclusions

- ATLAS is under construction.
  - performance requirements are being met in beam tests.
  - physics studies drive the performance goals.
- ATLAS physics potential includes ***competitive precision*** electroweak measurements: $\sin^2\theta_W$, mass(W), TGCs,…
- new Monte Carlo techniques for combining NLO(α_S) matrix elements with the parton shower approach have been developed ➔ excellent **tool for** (by!) **experimentalists**.
- Triple Gauge-boson couplings probe the very foundation of the Standard Model.
  - measurements will be statistically limited, even at LHC
  - order of magnitude improvement in confidence limits over previous expts.
  - new means of ensuring unitarity (form factors) has been introduced (not discussed in this talk, ask if you're interested)