First results of $W^{\pm}$ boson production in high-energy polarized p+p collisions at RHIC at BNL

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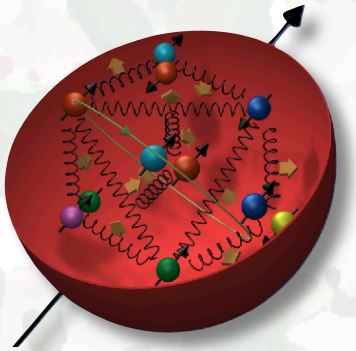
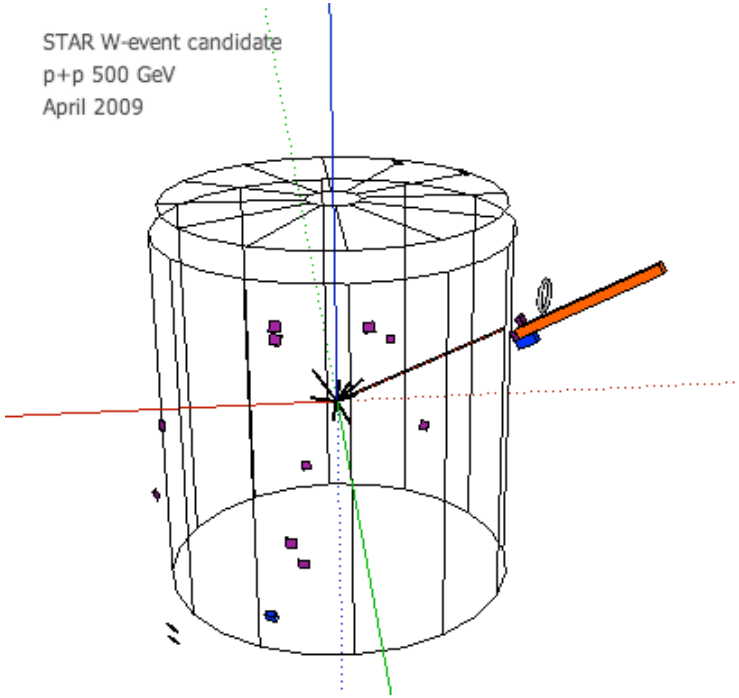
Massachusetts Institute of Technology



Outline

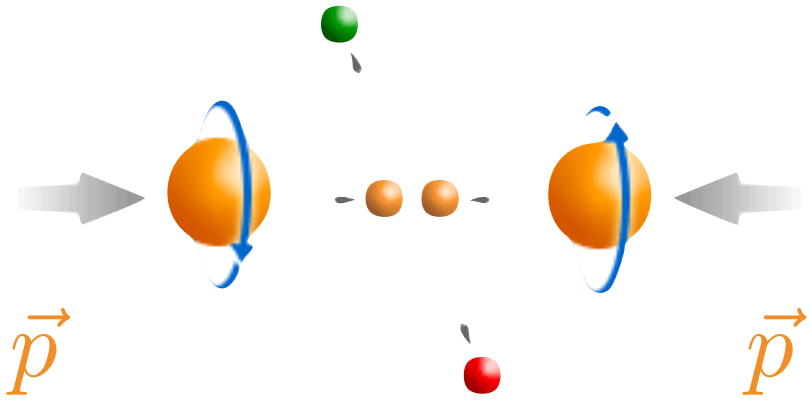


- W production - Recent Results

  First W^+/W^- Cross-section and A_L Measurement at STAR

- Experimental aspects: RHIC / STAR

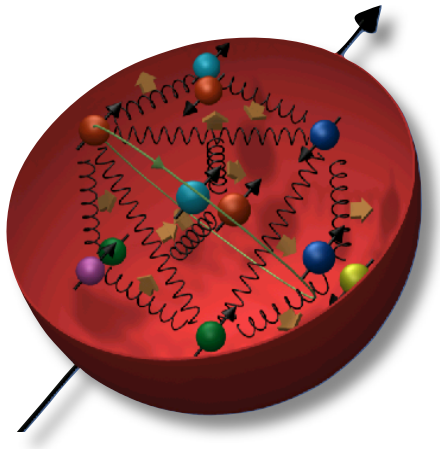
- Introduction

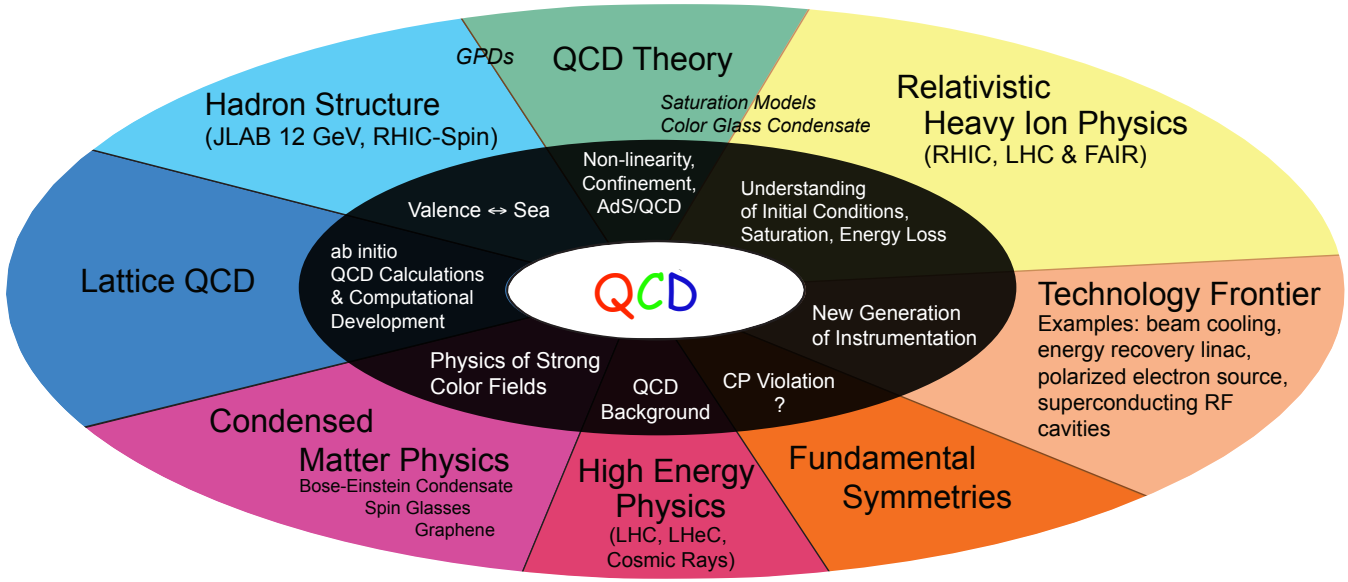


- Summary and Outlook

Introduction

- Exploring the proton spin structure and dynamics





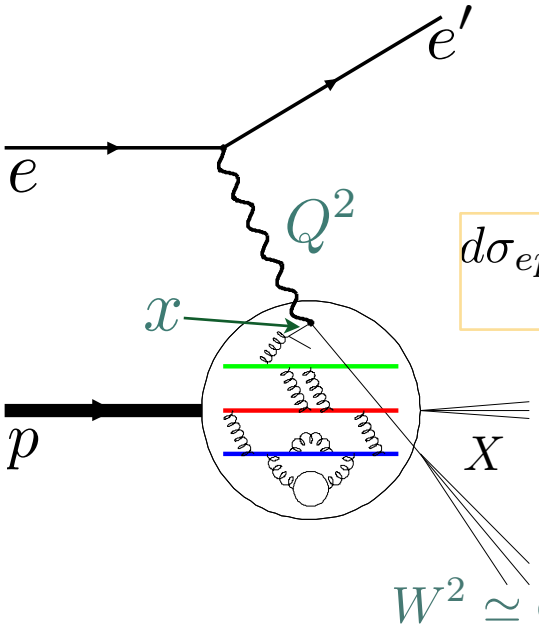
Structure and dynamics of proton (**mass**) (→ visible universe) originates from QCD-interactions!

What about **spin** as another fundamental quantum number?

Synergy of experimental progress and theory (Lattice QCD / Phenomenology incl. phenomenological fits / Modeling) critical!

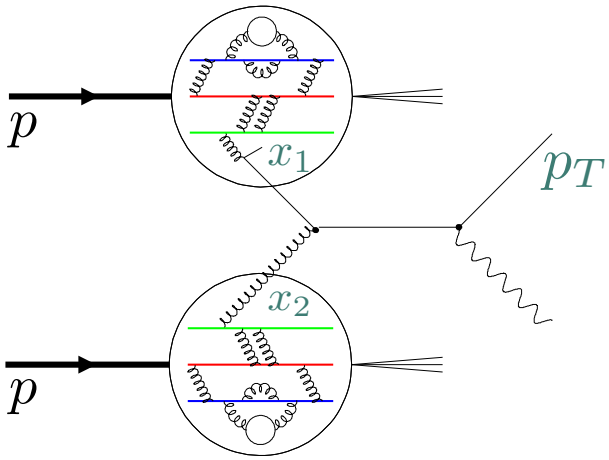
Introduction

- How do we probe the structure and dynamics of matter in ep / pp scattering?



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

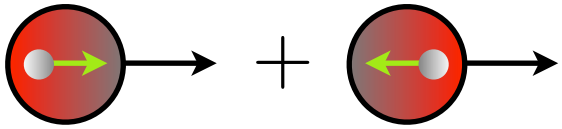
Universality



$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$ Factorization

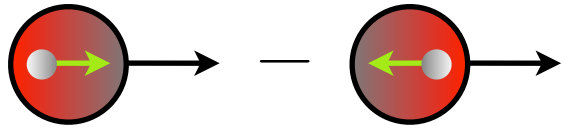
Momentum contribution

$$f(x) =$$



$$f^+(x) + f^-(x)$$

$$\Delta f(x) =$$



$$f^+(x) - f^-(x)$$

Spin contribution

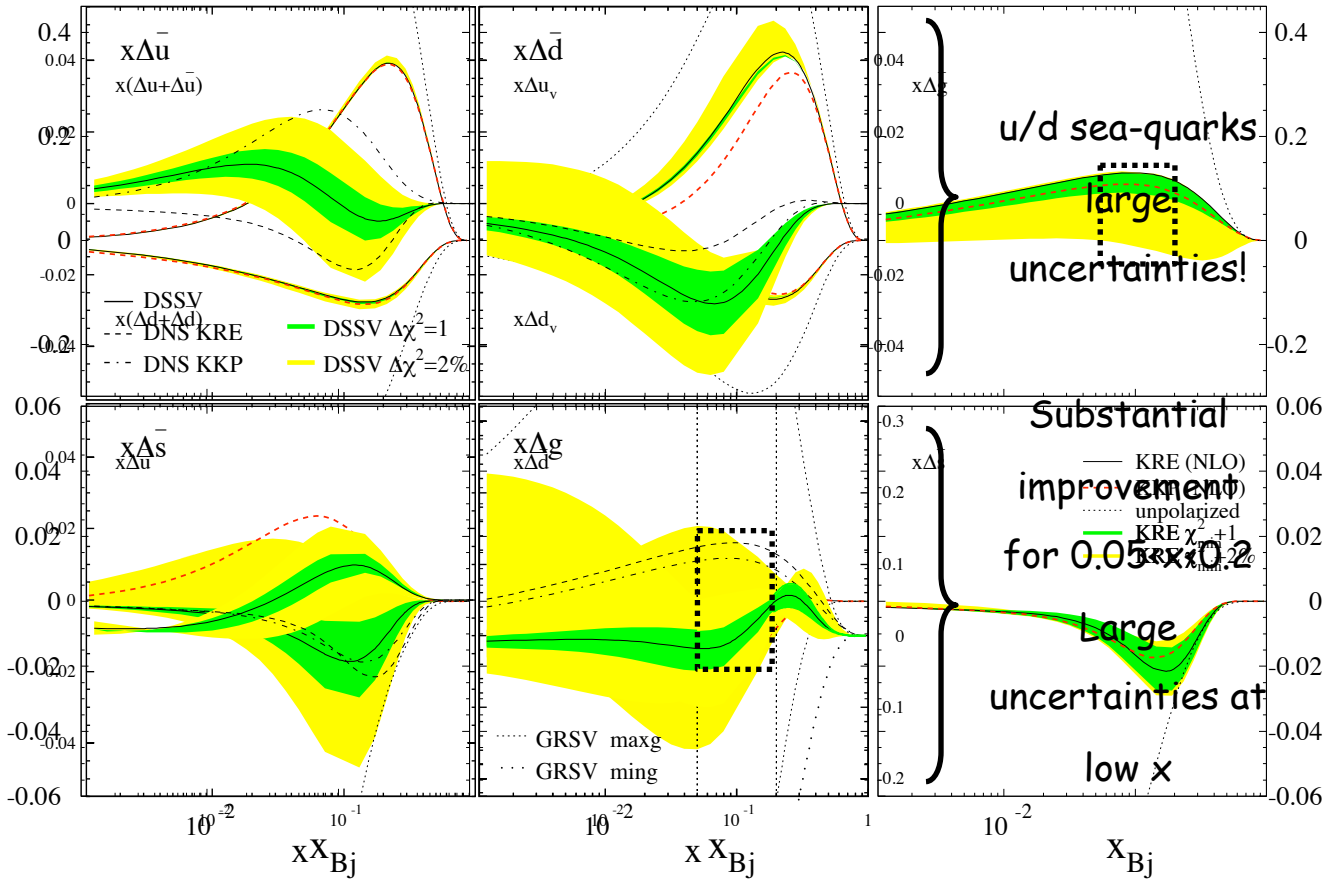
Introduction

- What do we know about the polarized quark and gluon distributions?
  - Spin carried by quarks is very small ($\Delta\Sigma \sim 0.3$)!

$$\underbrace{\frac{1}{2}\Delta\Sigma}$$

$$\frac{1}{2} = \langle S_q \rangle + \underbrace{\langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle}_{\Delta G}$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$



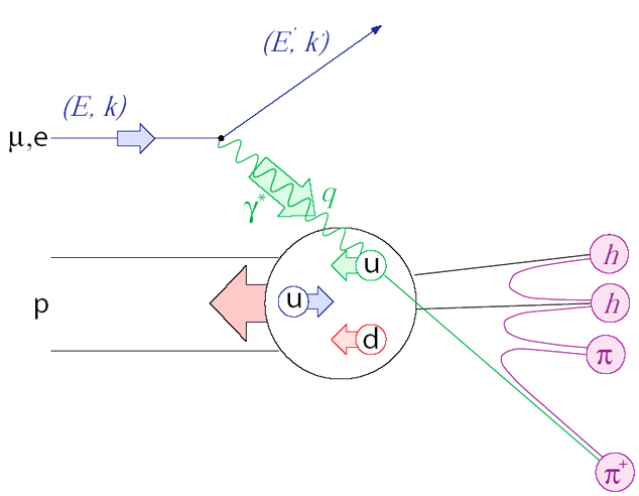
D. de Florian et al., Phys. Rev. D71, 094018 (2005), 2001

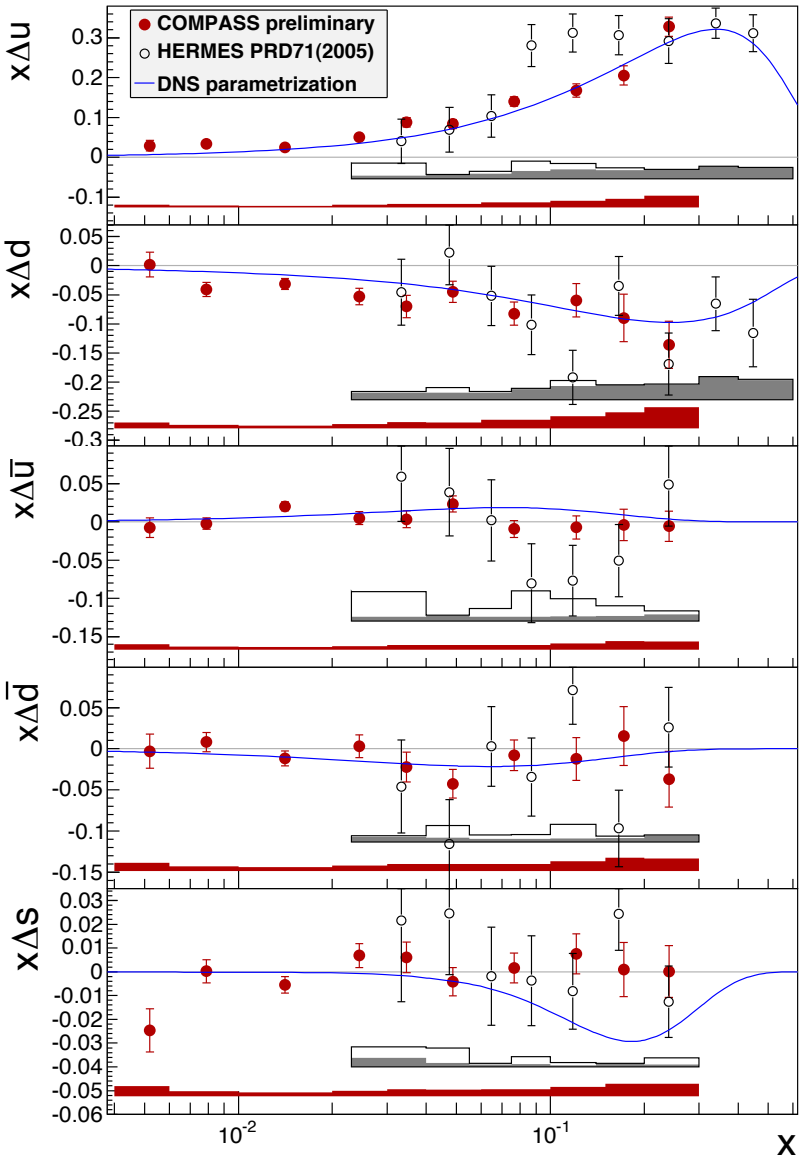
$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2)dx$$

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)dx$$

Introduction

- Polarized semi-inclusive DIS results: HERMES / COMPASS



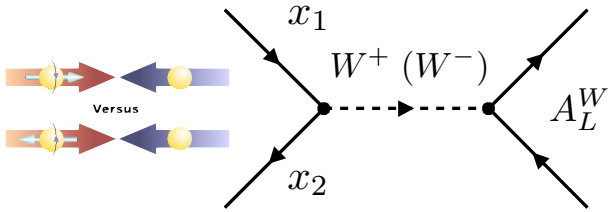


- Semi-inclusive DIS: Correlation of flavor content of hadron with flavor of quark / antiquark probed
- Good agreement of COMPASS and HERMES LO analysis
- Good agreement with global fit analysis / Sea quark distributions compatible with zero
- Great value of independent probe at large momentum scales (sub-leading twist effects unimportant) without hadronic fragmentation

Introduction

- STAR W program in e-decay mode at mid-rapidity and forward/backward rapidity

$u\,/\Delta u\;(d\,/\Delta d)$



$\Delta\bar{d}\,/\bar{d}\;(\Delta\bar{u}\,/\bar{u})$

$\nu_e\;(\bar{\nu}_e)$

$e^+\;(e^-)$

$$A_L^W = \frac{1}{P}\frac{N^+(W) - N^-(W)}{N^+(W) + N^-(W)}$$

$$y_l = y_W + \underbrace{\frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*}}_{y_l^*}$$

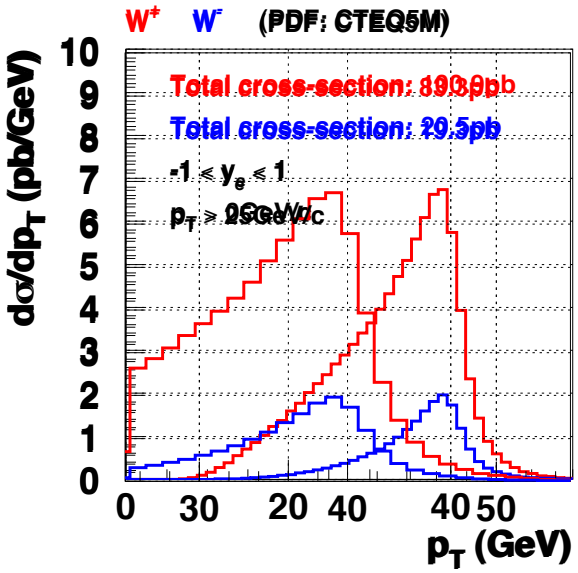
$$p_T = p_T^* = \frac{M_W}{2}\sin\theta^*$$

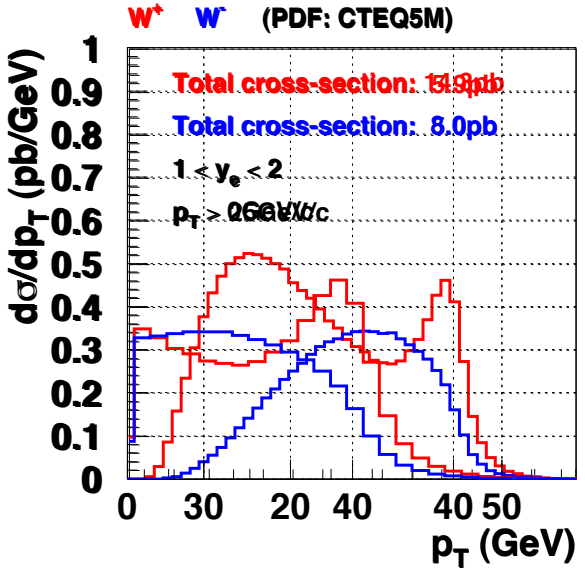
$$x_1 = \frac{M_W}{\sqrt{s}}e^{y_W}$$

$$x_2 = \frac{M_W}{\sqrt{s}}e^{-y_W}$$

$$\frac{M_W}{\sqrt{s}} = 0.16$$

- Key signature: High p_T lepton (e^-/e^+)(Max. $M_W/2$) - Selection of W^+/W^- : Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination



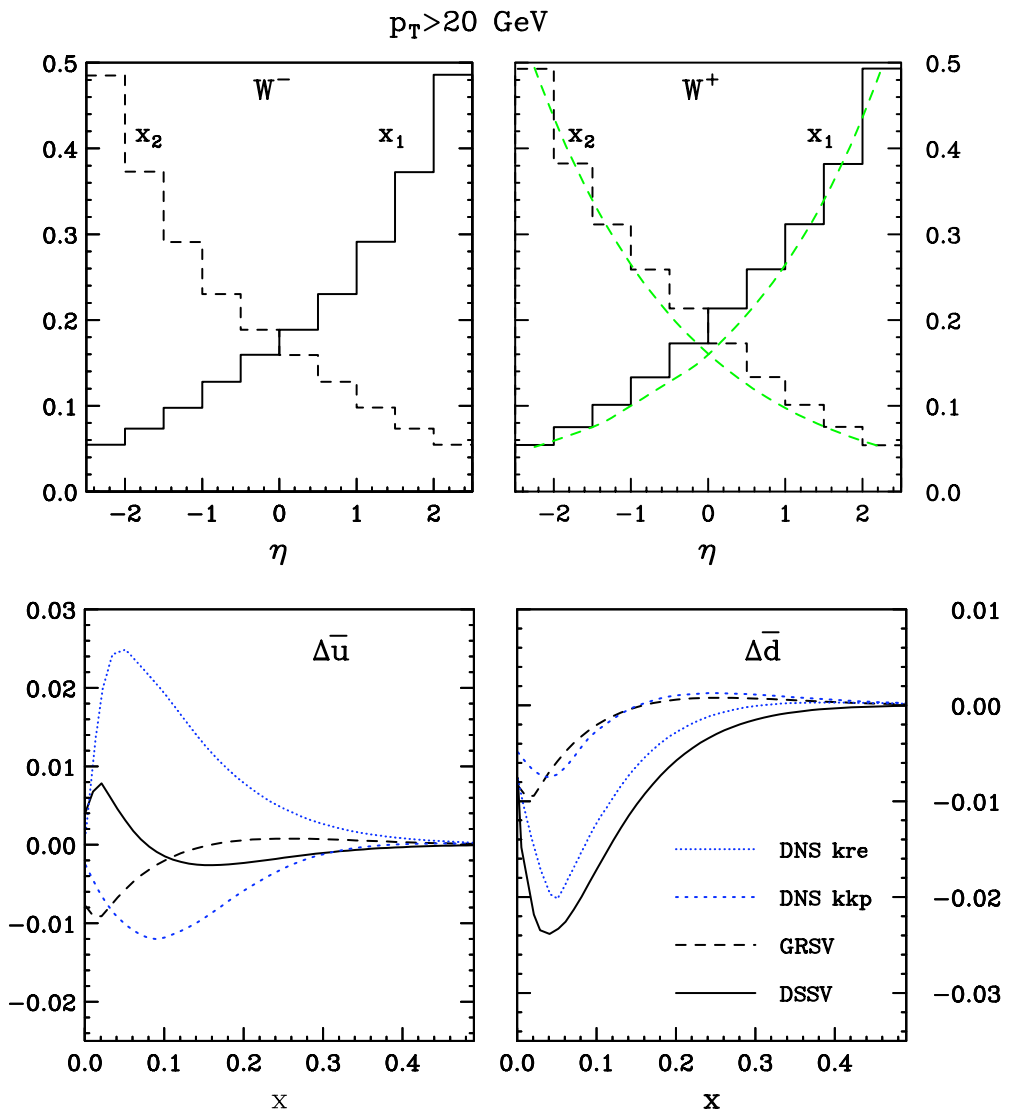


Total (√s=500GeV) σ(W⁺)=135pb and σ(W⁻)=42pb

Introduction

- W boson kinematics relevant for STAR rapidity acceptance
  - Leptonic rapidity inherits relation to mean x
  - Forward rapidity:
    - $\eta > 0$
    - $\langle x_1 \rangle$ larger than $\langle x_2 \rangle$
  - Backward rapidity:
    - $\eta < 0$
    - $\langle x_1 \rangle$ less than $\langle x_2 \rangle$
  - Mid-rapidity:
    - $\eta \sim 0$
    - $\langle x_1 \rangle$ similar to $\langle x_2 \rangle$

$< X >$



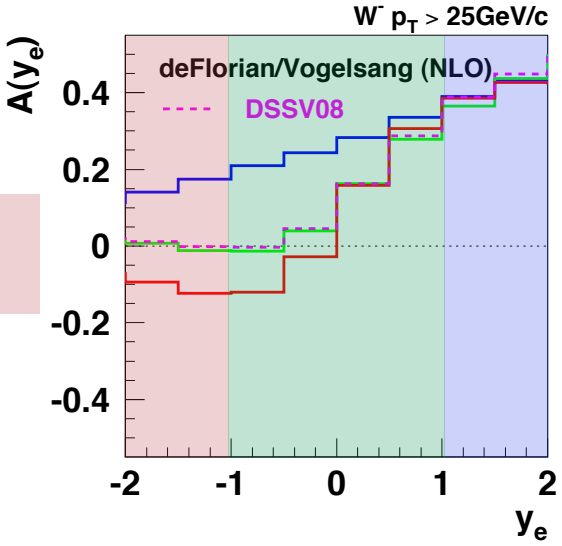
$$< X_{1,2} > \simeq \frac{M_W}{\sqrt{S}} e^{[\pm\eta/2]}$$

D. deFlorian and W. Vogelsang, hep-ph/1003.4533

Introduction

- A_L behavior for STAR mid-rapidity and forward/backward rapidity region

$$A_L^{W^-} = \frac{\Delta\bar{u}}{\bar{u}} \qquad x_1 \ll x_2$$



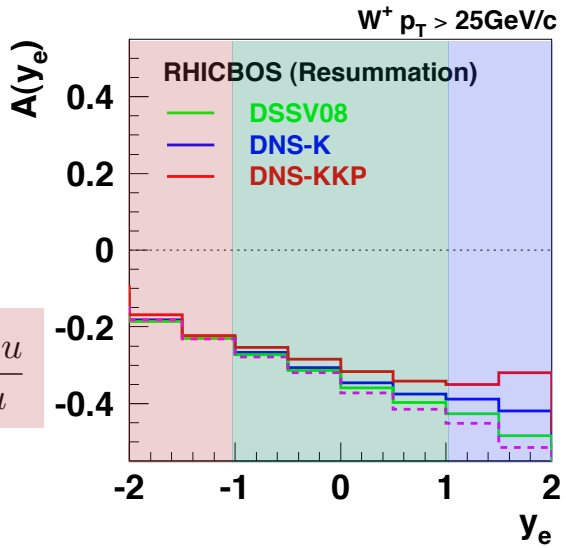
$$A_L^{W^-} = -\frac{\Delta d}{d} \qquad x_1 \gg x_2$$

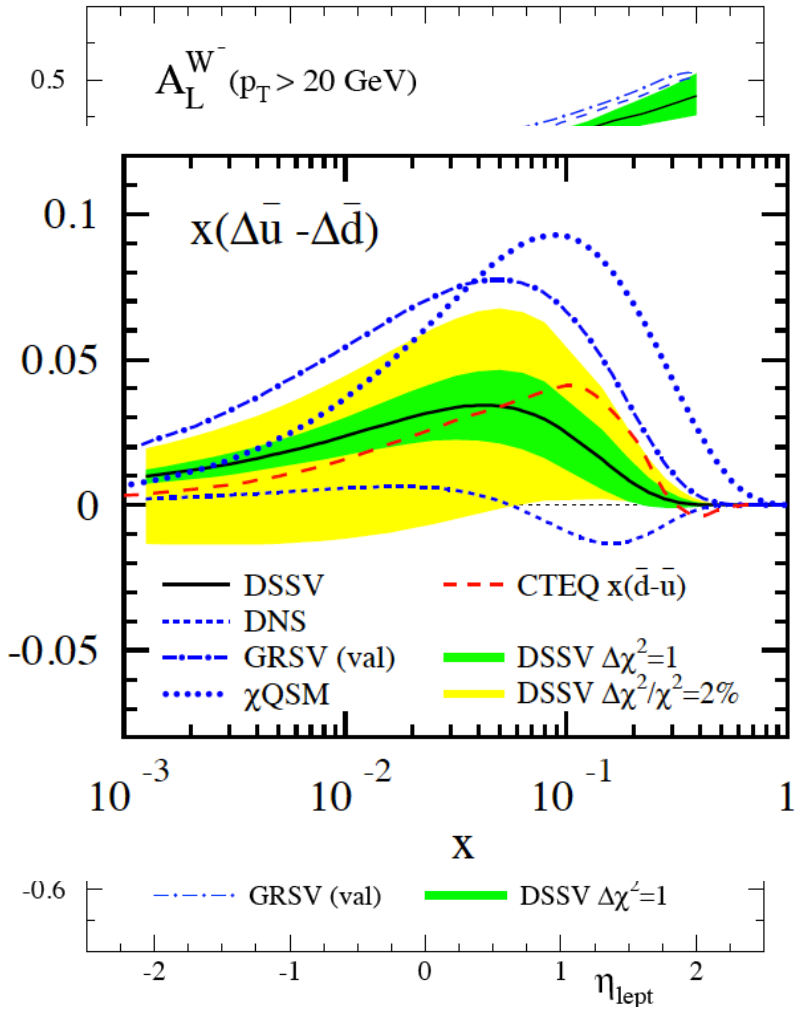
$$A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta\bar{u}}{\bar{u}} - \frac{\Delta d}{d}\right) \qquad x_1 = x_2$$

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u}\right)$$

$$A_L^{W^+} = \frac{\Delta\bar{d}}{\bar{d}} \qquad x_1 \gg x_2$$

$$A_L^{W^+} = -\frac{\Delta u}{u} \qquad x_1 \ll x_2$$





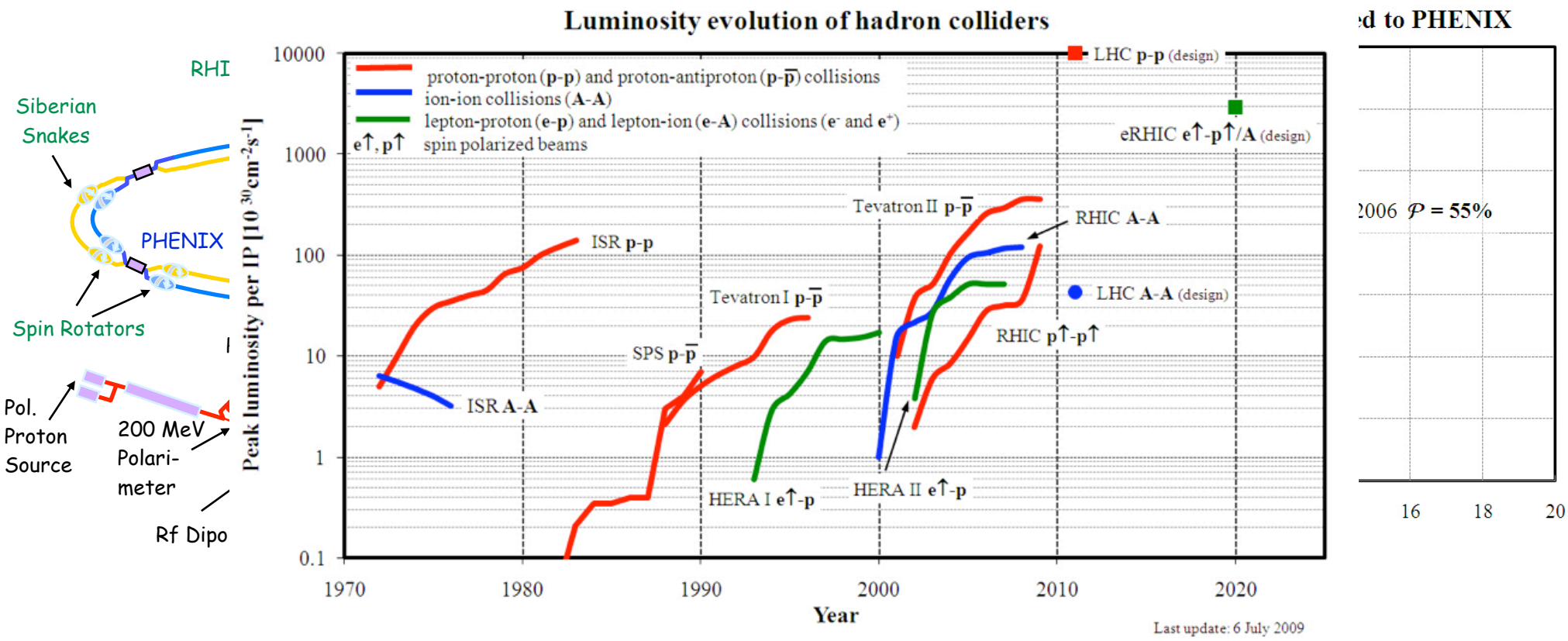
Calculations:

1) RHICBOS: P.M. Nadolsky and C.-P. Yuan, Nucl. Phys. B666 (2003) 31.

2) deFlorian / Vogelsang: D. deFlorian, private communications.

Collider: The First polarized p+p collider at BNL

- RHIC Performance - Overview



- Long 200GeV production runs at $\sqrt{s}$=200GeV (long. polarization): Run 5 / Run 6 / Run 9
- First collisions of polarized proton beams at $\sqrt{s}$=500GeV (long. polarization): Run 9

Collider: The First polarized p+p collider at BNL

- RHIC polarized p+p running

RHIC RUN	s [GeV]	$L_{recorded}$ [pb^{-1}] (trans.)	$L_{recorded}$ [pb^{-1}] (long.)	Polarization [%]
RUN 2	200	0.15	0.3	15
RUN 3	200	0.25	0.3	30
RUN 4	200	0	0.4	40-45
RUN 5	200	0.4	3.1	45-50
RUN 6	200	3.4/6.8	8.5	60
RUN 8	200	7.8	-	45
RUN 9	200 / 500	-	25 / 14	55 / 40

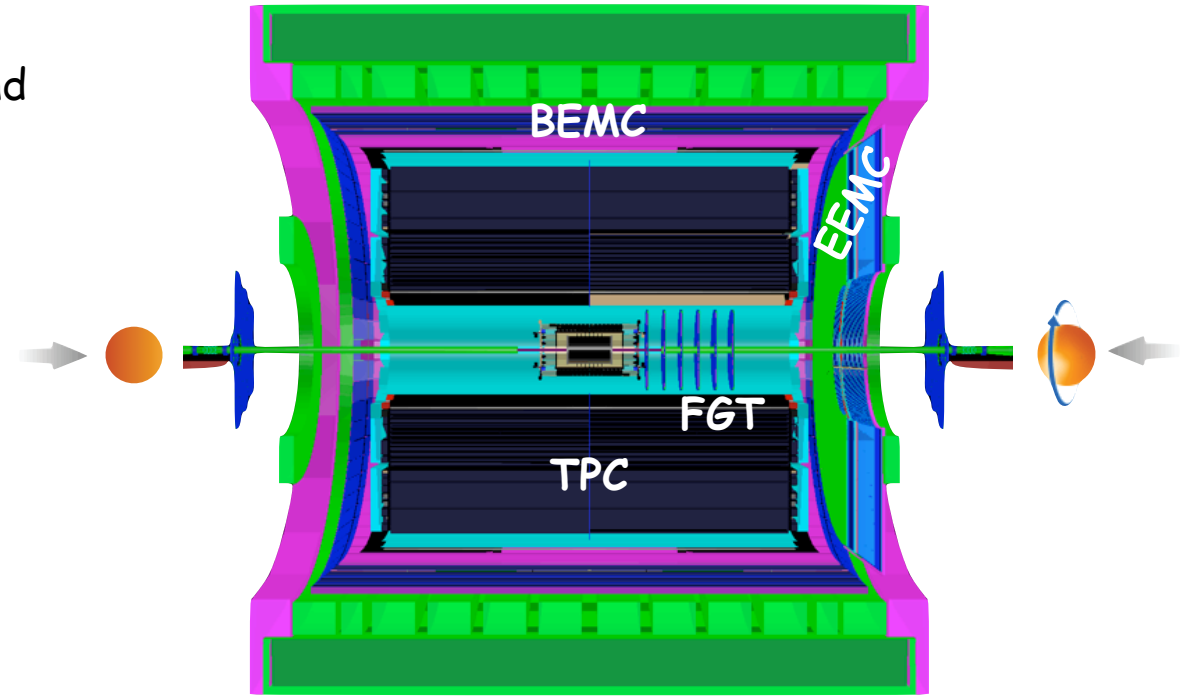
- Transverse program: A_N measurement of forward π^0 and η production (Run 2 / Run 6 / Run 8)
- Gluon polarization program: Inclusive jet and hadron production (Run 3/4, Run 5, Run 6 and Run 9)
- W program: First A_L measurement W^+ and W^- boson production from Run 9

The STAR Experiment at RHIC

- Overview

First collisions of polarized proton beams at STAR at $\sqrt{s}$ = 500GeV: Run 9 (P~40% / L~14pb^{-1})

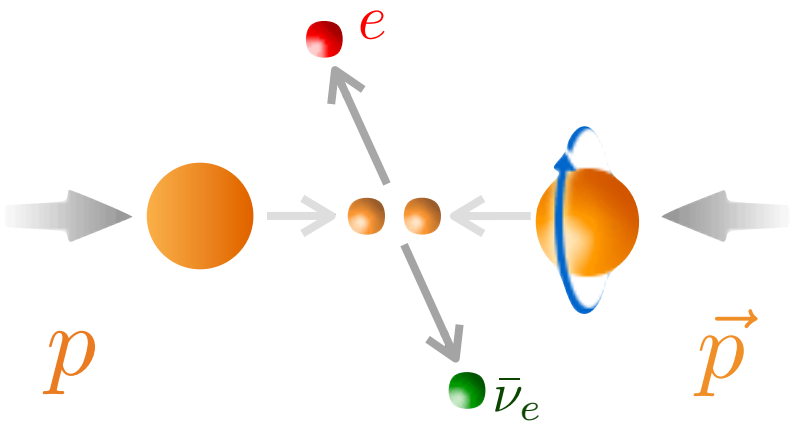
- Calorimetry system with 2π coverage: BEMC ($-1 < \eta < 1$) and EEMC ($1 < \eta < 2$)
- TPC: Tracking and particle ID
- ZDC: Relative luminosity and local polarimetry
- BBC: Relative luminosity and Minimum bias trigger



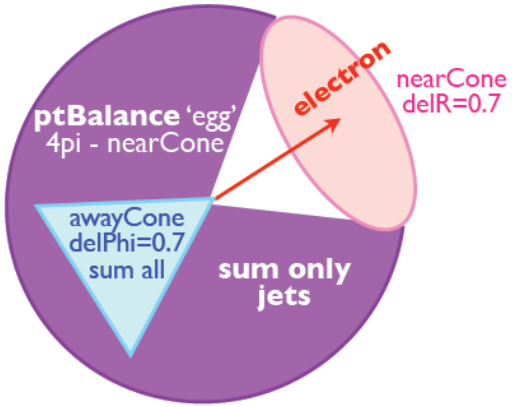
- STAR Mid-rapidity W program ($-1 < \eta < 1$): BEMC and TPC
- STAR Forward/Backward W program ($1 < \eta < 2$): EEMC and TPC / FGT (Installation in summer 2011)

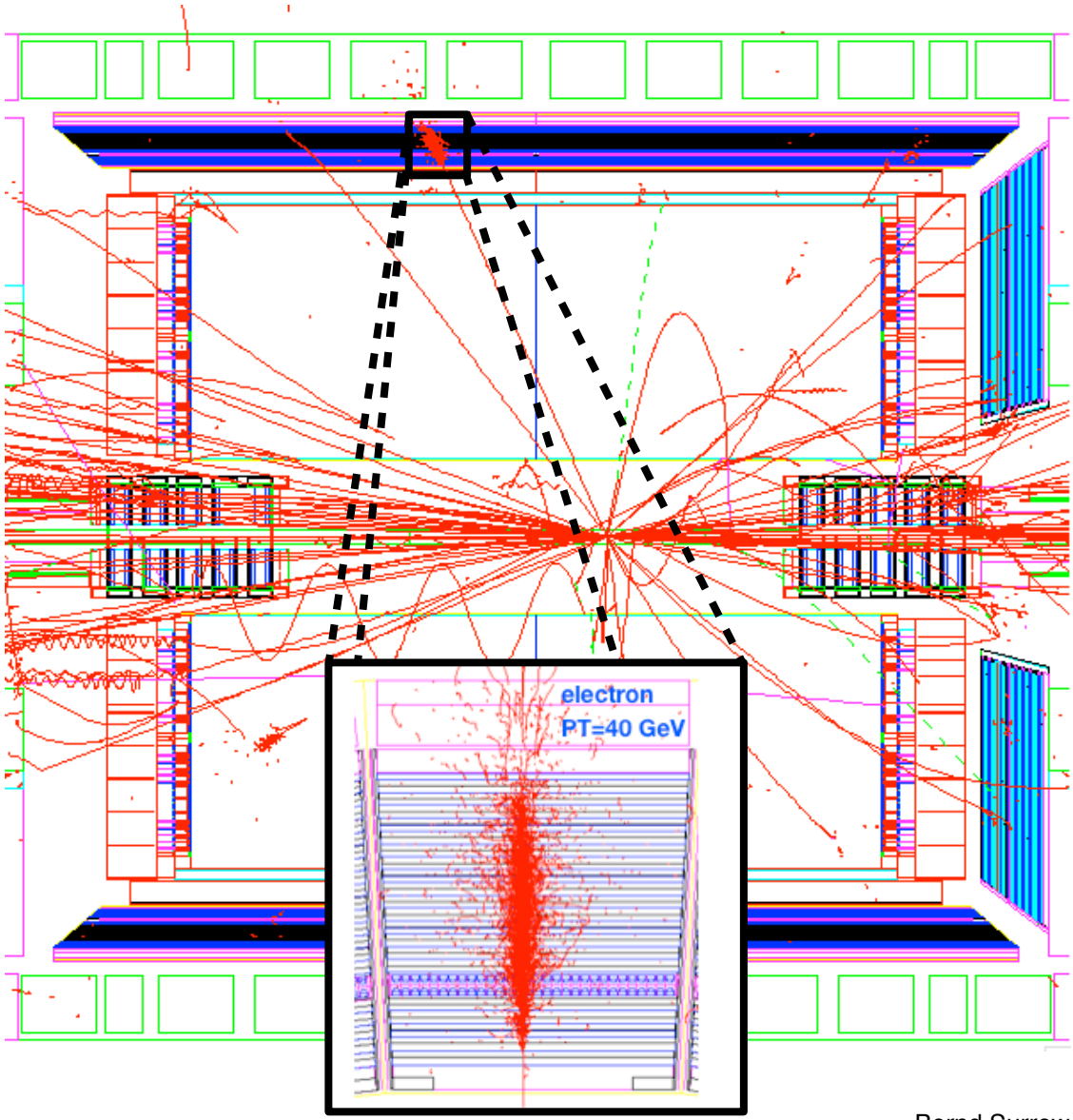
W production results: Algorithm

- W reconstruction - Algorithm : Idea



Transverse plane view

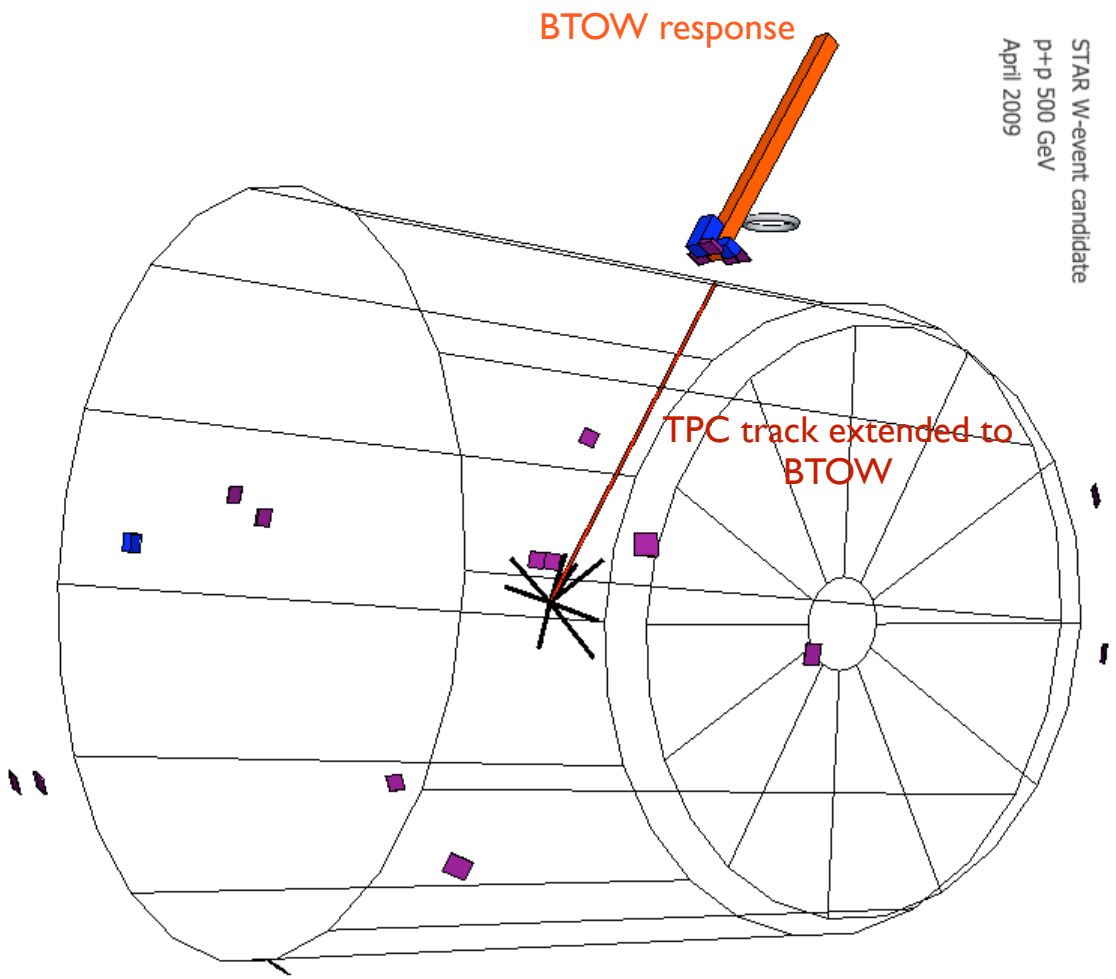




W production results: W event

- Event display (W event candidate) and detector signature

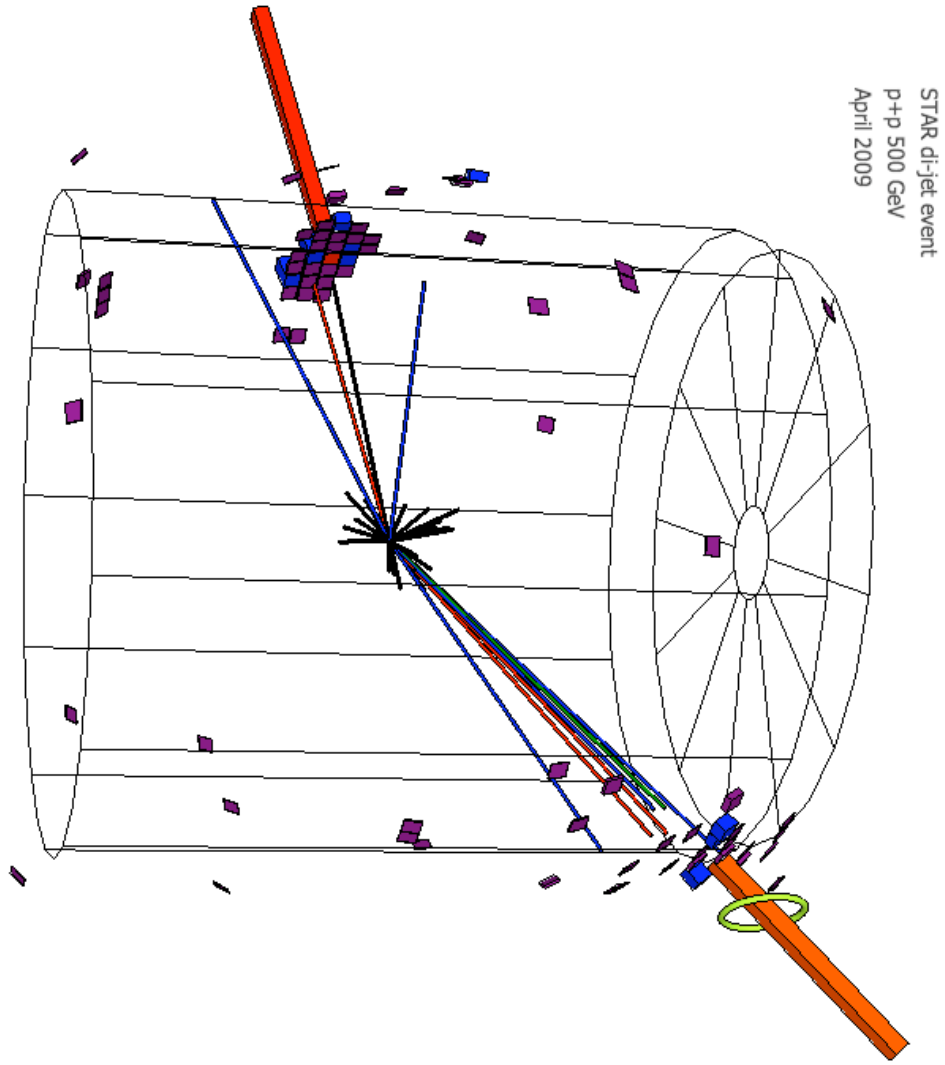
We found ~600 of those kinds of events!



W production results: QCD Background event

- Event display (Di-Jet event candidate) and detector signature

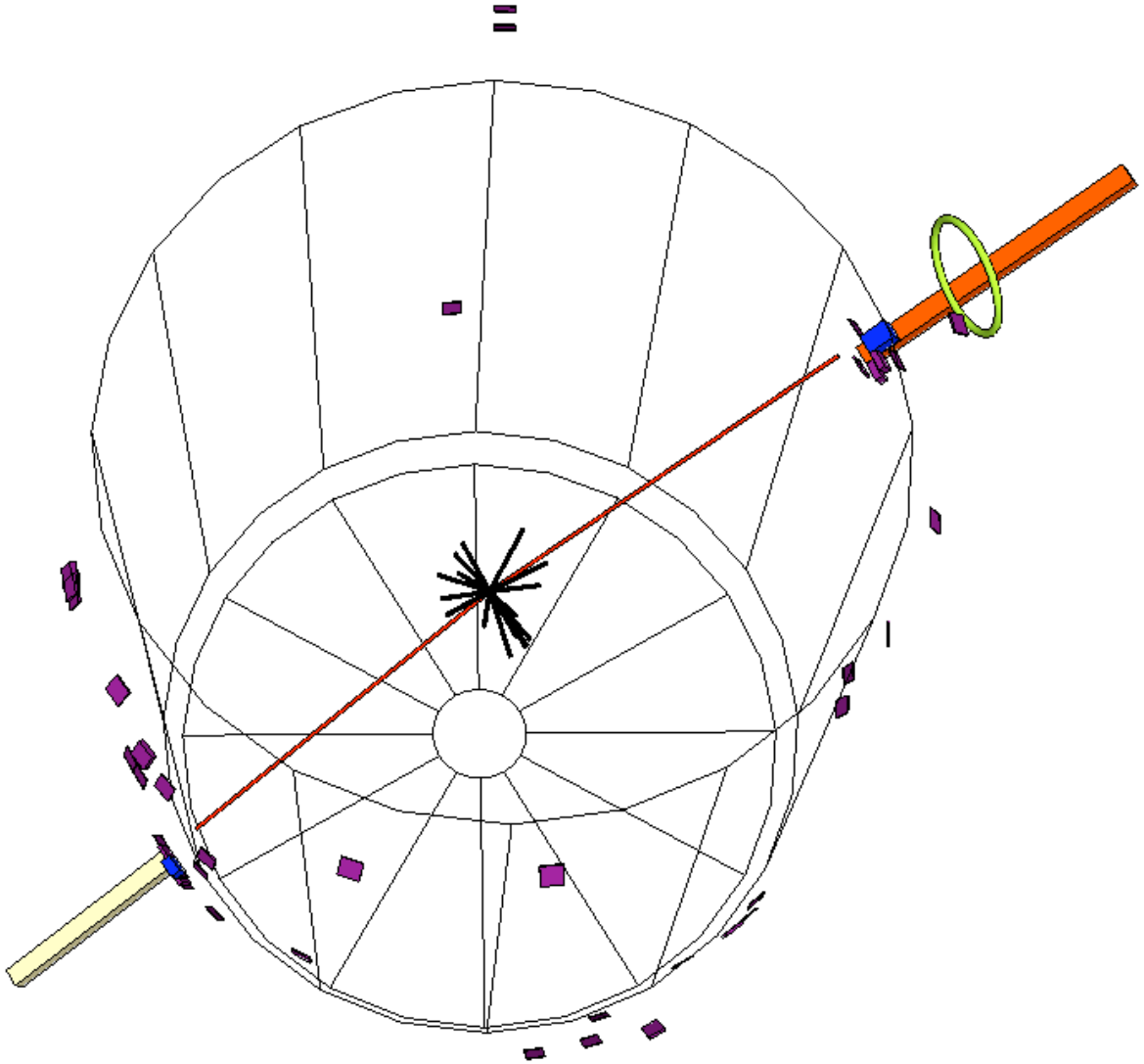
We recorded and rejected ~1.5M of those kinds of events!



W production results: Z^0 event

- Event display (Z event candidate) and detector signature

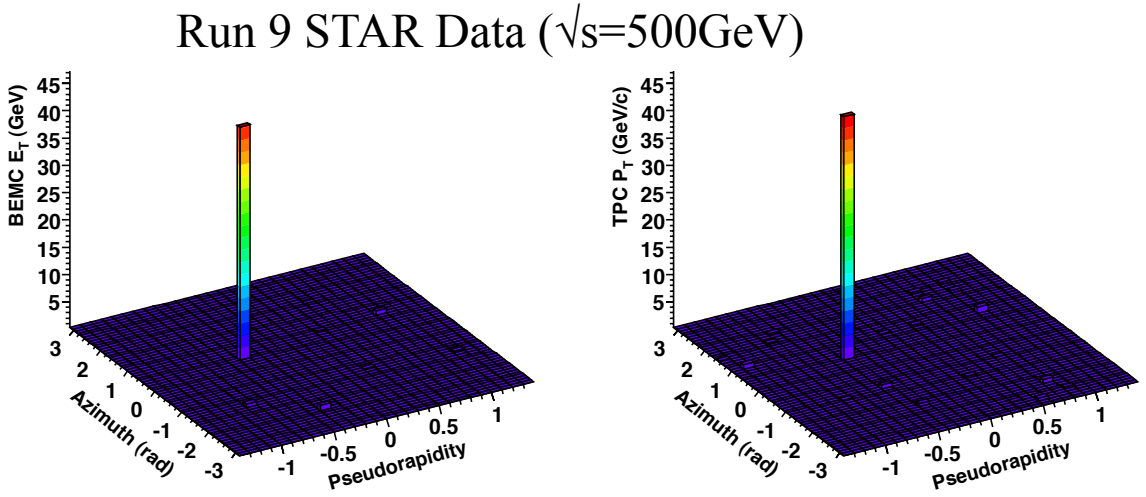
We found a handful of those kinds of events!



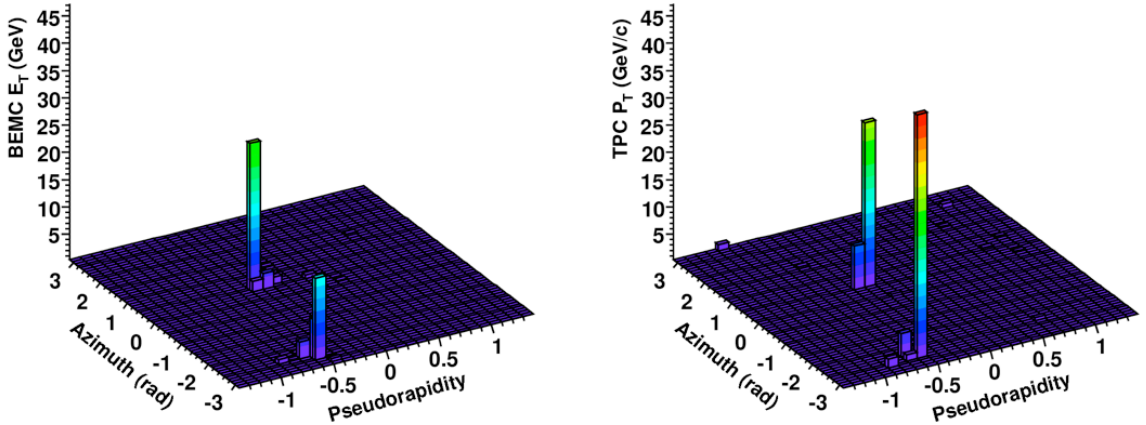
W production results: Lego plots

- Lego plots - STAR BEMC/TPC

W event



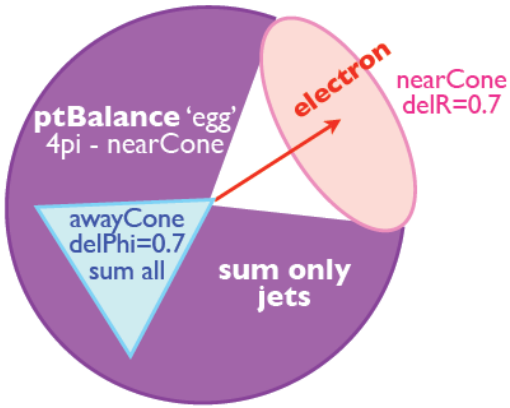
Di-Jet event

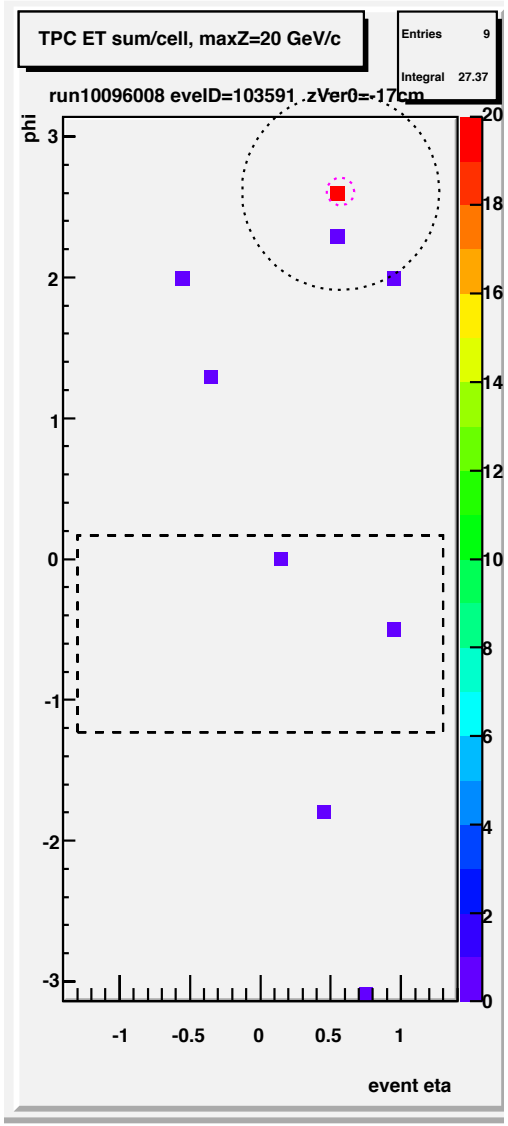


W production results: Algorithm Details

W reconstruction - Algorithm : Details (1)

Transverse plane view





General:

- Select L2W-E_T triggered events
- Select vertices with |Z|<100 cm

Electron isolation cuts:

- Electron candidate is any primary TPC track with global P_T >10 GeV/c
- Extrapolate TPC track to BTOW tower
- Compute 2x2 tower cluster E_T, require E_T sum > 15 GeV
- Require the excess E_T in 4x4 tower patch over 2x2 patch to be below 5%
- Require distance of 2x2 cluster vs. TPC track below 7 cm

Near-cone veto:

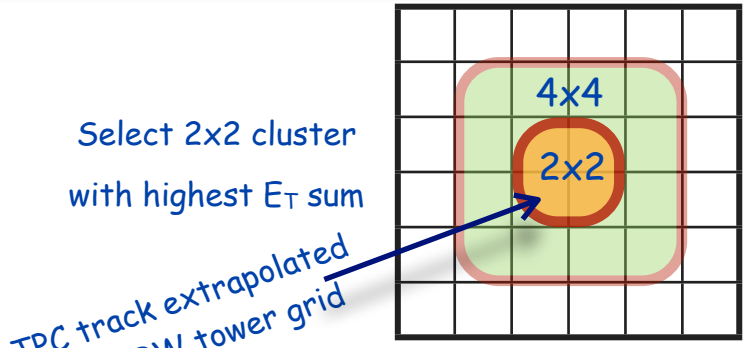
- Compute near-cone E_T sum of BEMC+TPC over $\Delta R=0.7$ in eta-phi space
- Require near-cone excess E_T below 12%

Away-'cone' cuts: p_T balance requirement

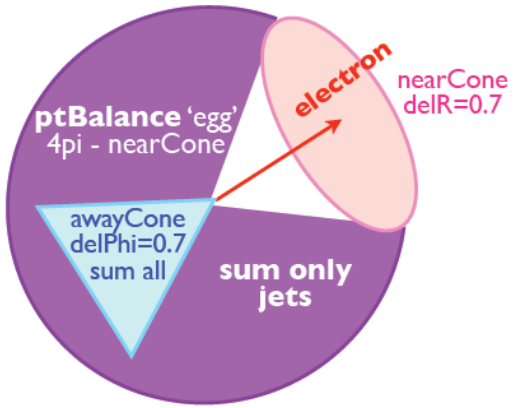
- Vector sum > 15GeV/c of: 2X2 tower cluster p_T and p_T of any number of jets outside near-cone
- E_T of jet > 3.5GeV

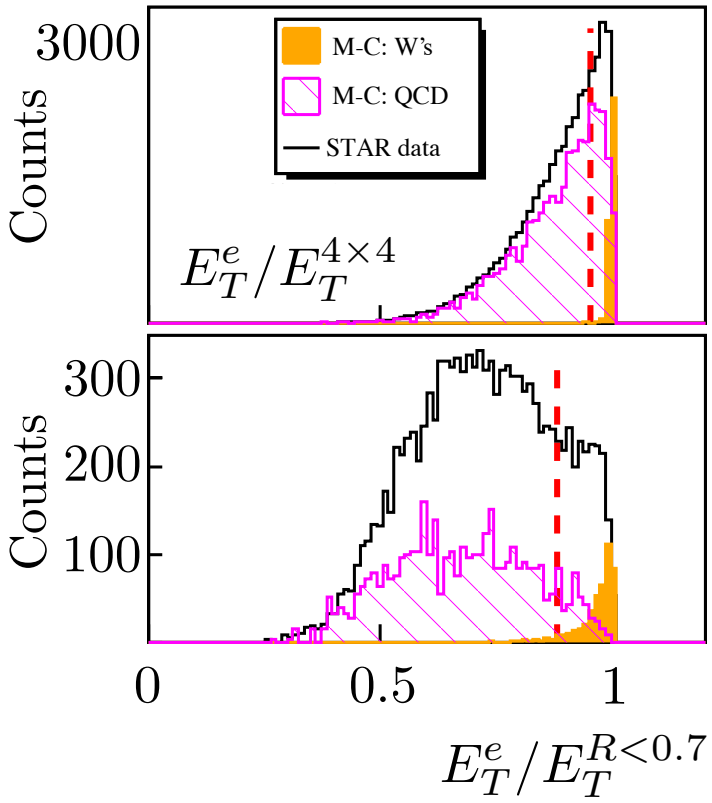
W production results: Algorithm Details

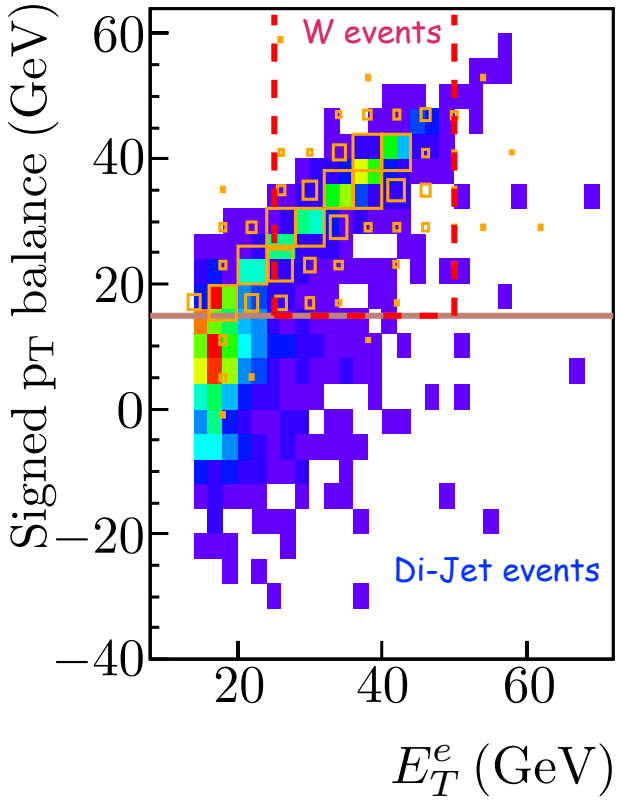
- W reconstruction - Algorithm : Details (2)
  - Lepton meas. in TPC (direction) and in BEMC (energy)
    - TPC & BEMC matching
  - Suppress background
    - BEMC cluster isolation
    - Near-side veto
    - Away-side veto



Transverse plane view

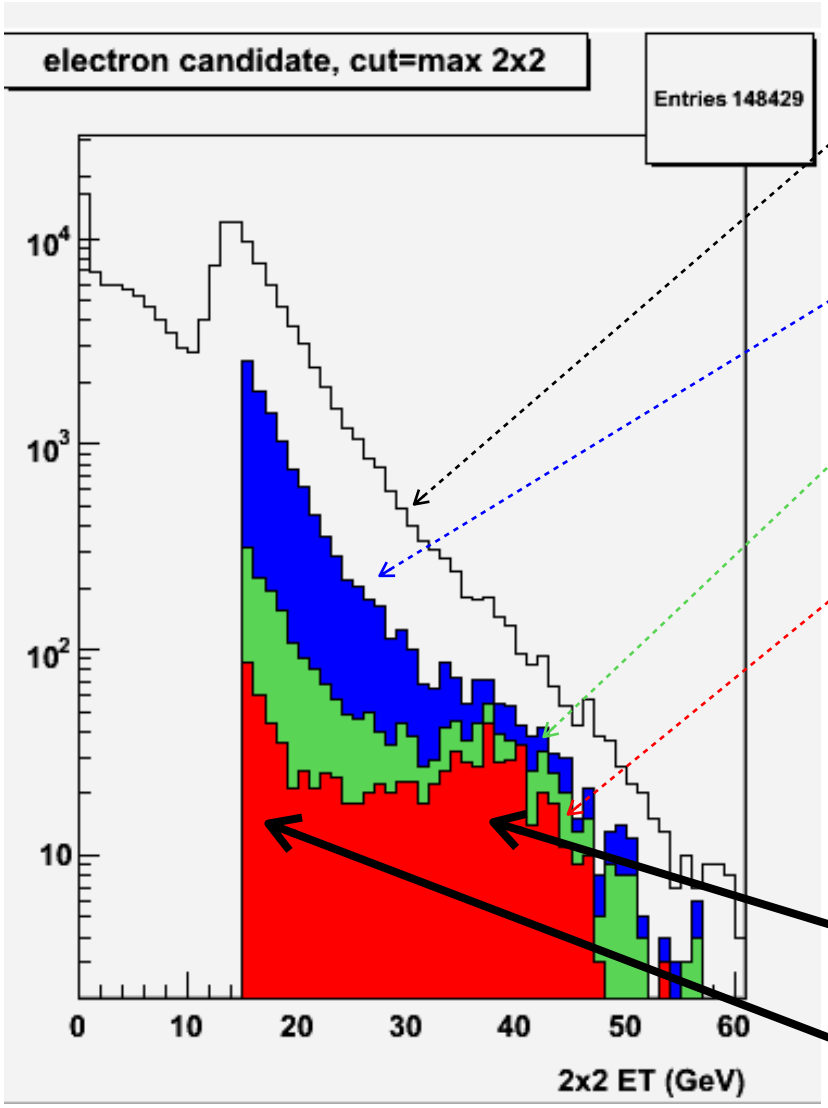






W production results: Algorithm Details

- Evolution of E_T distribution vs. cut ID



Starting raw distribution

Track-cluster match

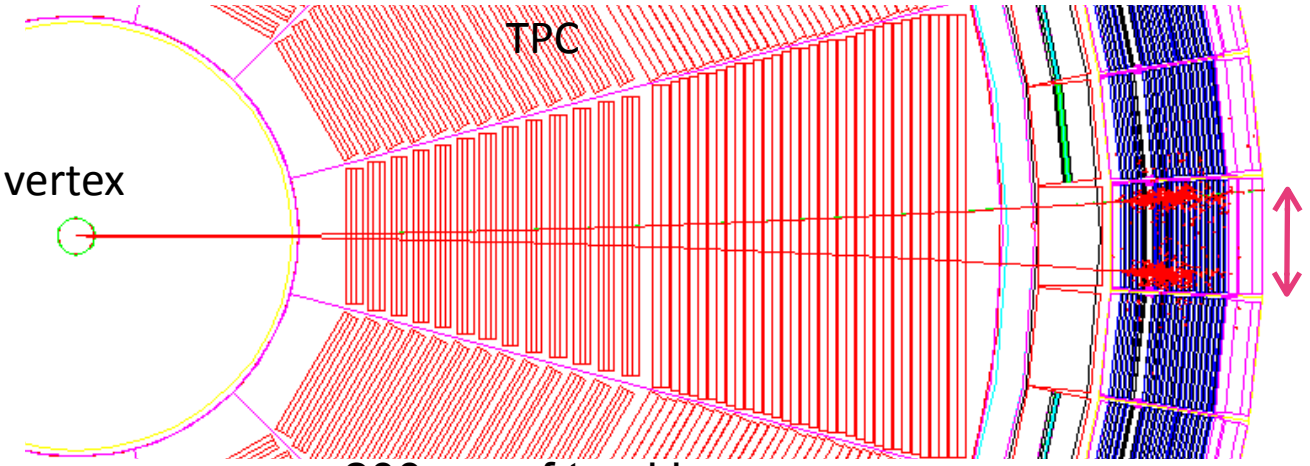
No near cone E_T

No away cone E_T

Using the algorithm a clear Jacobian peak can be seen characteristic for W production in contrast to QCD background!

W production results: Charge separation

- Mid-rapidity high p_T $e^{\pm}$ charge separation



positron p_T = 5 GeV/c

electron p_T = 5 GeV/c

+/- distance D: ~1/P_T

p_T = 5 GeV/c : D ~15 cm

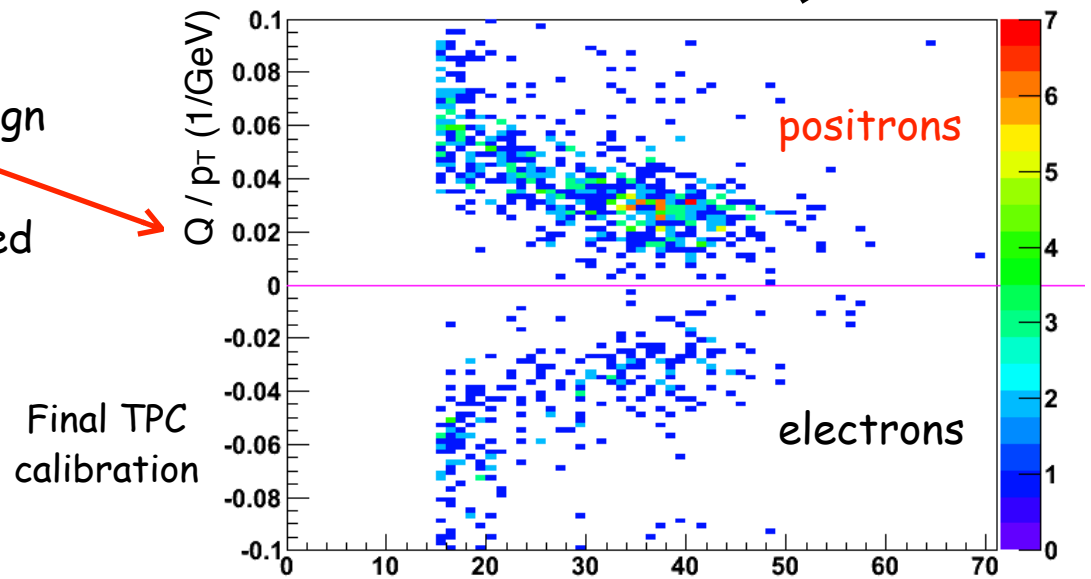
p_T = 40 GeV/c : D ~2 cm

Assign:

Q/p_T > 0 positrons

Q/p_T < 0 to be electrons

Q: Charge-sign of reconstructed track

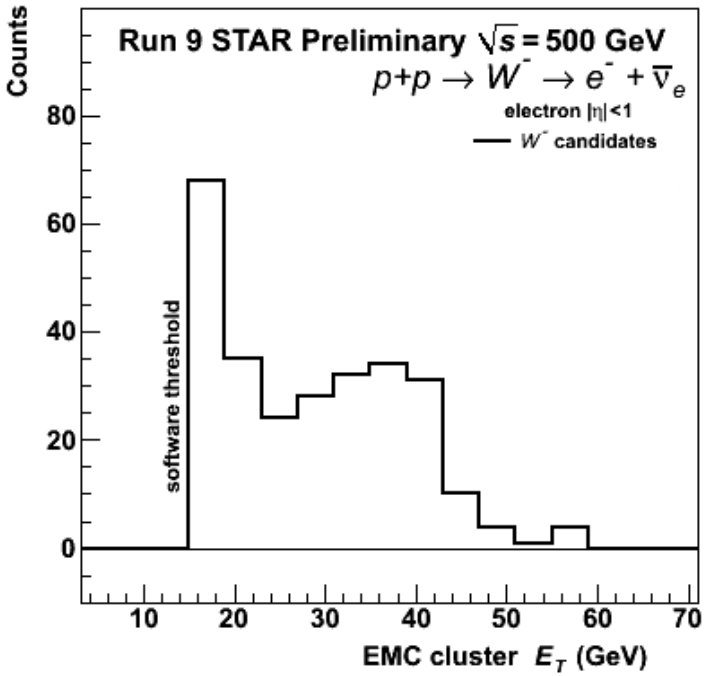


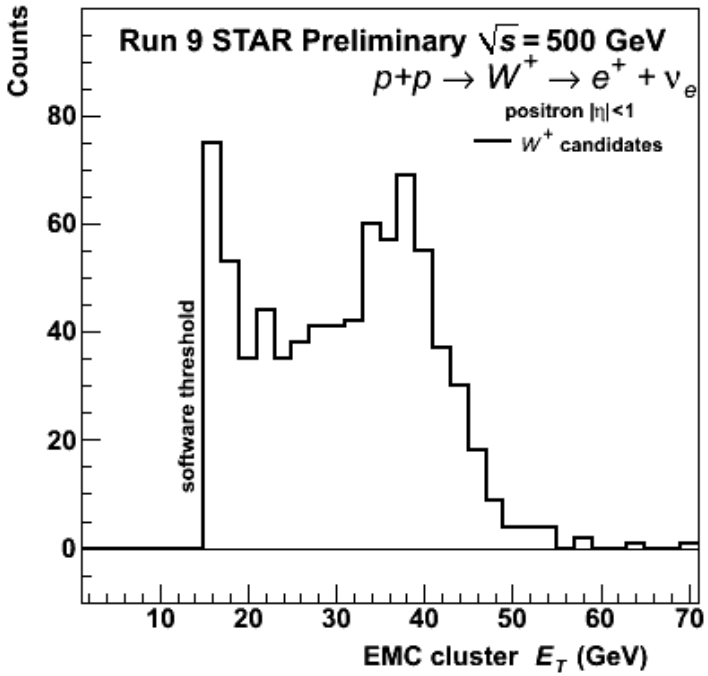
Final TPC calibration

Successful separation of different charge states!

W production results: Charged-separated Yields

- Charge separated raw Signal / Jacobian Peak Distributions





- Charged separated W^+/W^- candidate distributions of the BEMC cluster transverse energy E_T (GeV)
- Cuts: All previously discussed cuts!

W production results: Background

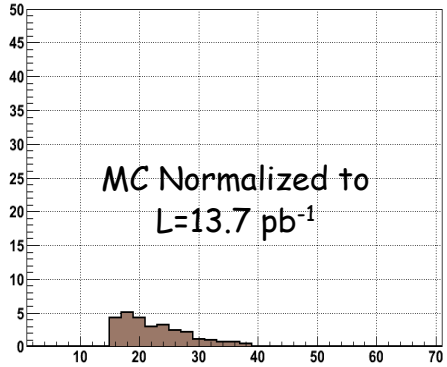
Background treatment

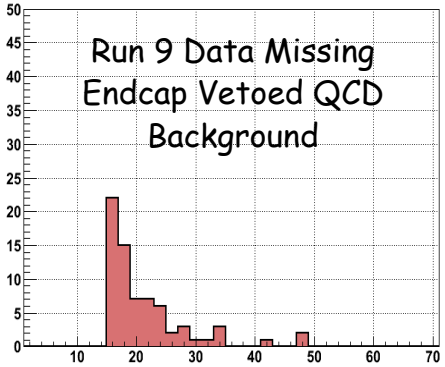
PYTHIA+GEANT MC →

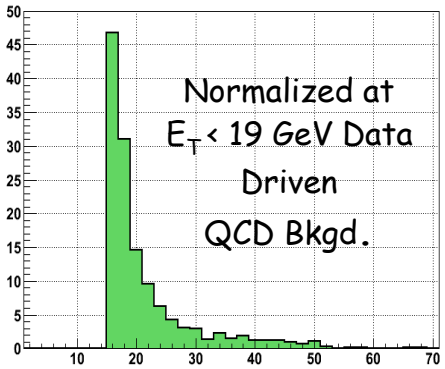
$W \rightarrow \tau + \nu_\tau$

$\tau \rightarrow e + \nu_e + \nu_\tau$

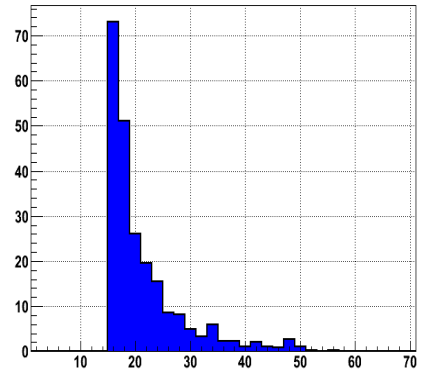
W^+ distributions





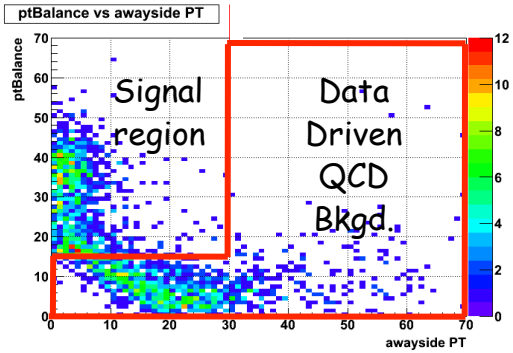


Total Background



EMC Cluster E_T (GeV)

1. Run analysis with EEMC in veto cuts
2. Run analysis without EEMC in veto cuts
3. Subtract two raw signals

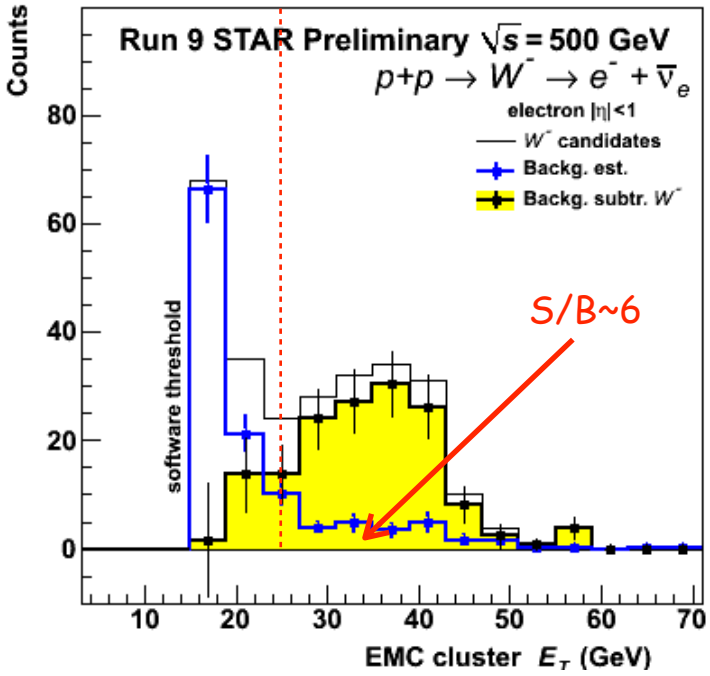


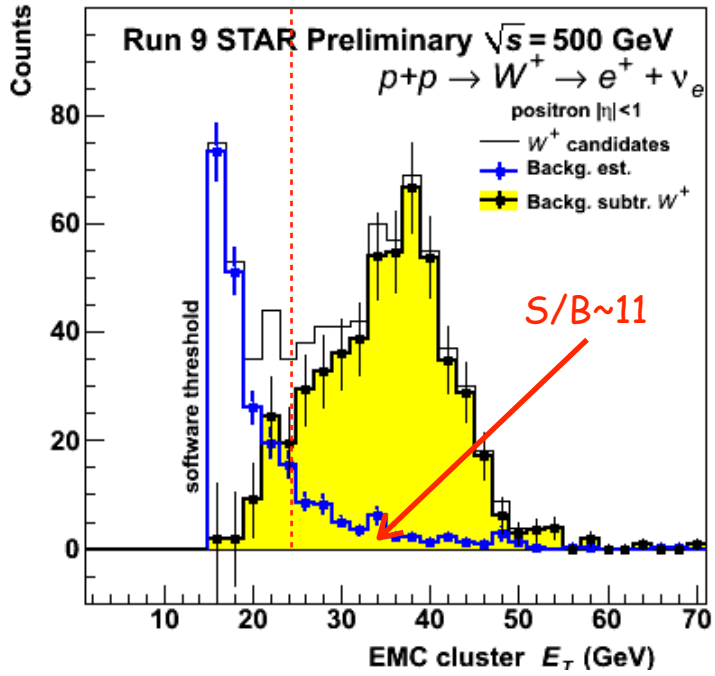
Background systematics:

- Calculate different data driven QCD background shapes by varying p_T balance and away-side p_T cuts
- Vary normalization region (E_T < 17 - 21 GeV)
- The largest deviation in each bin used for sys. error estimate

W production results: Background

- Background subtraction



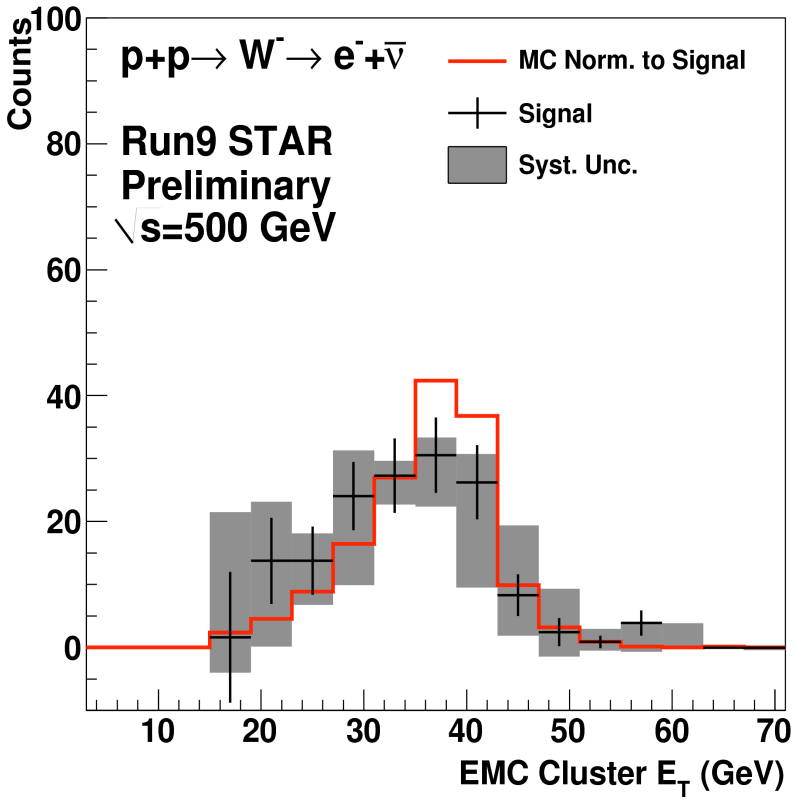


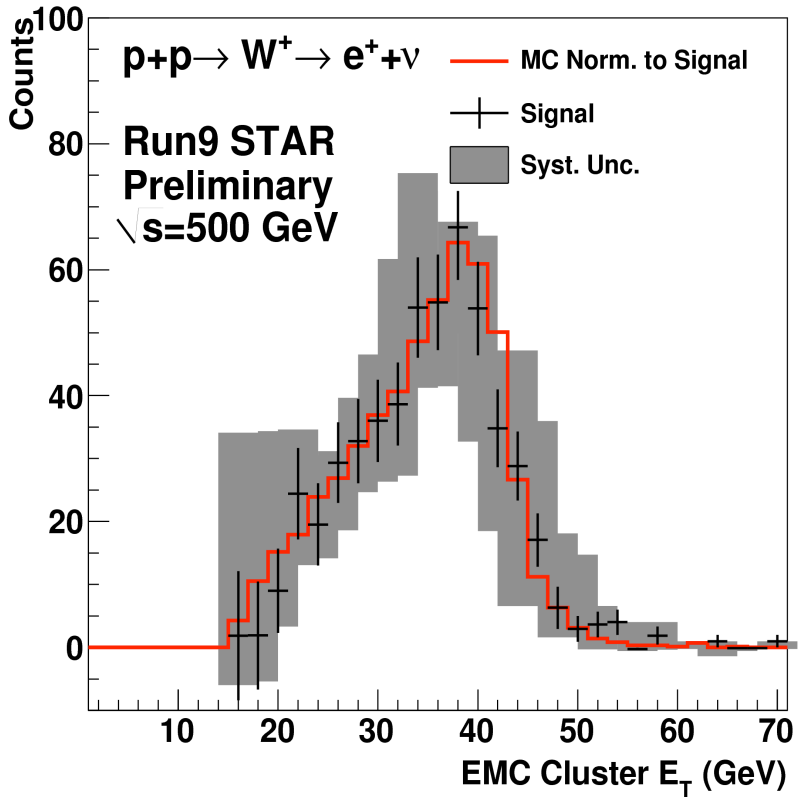
- Background distribution and background-subtracted signal distribution
- B/(S+B) (E_T > 25GeV) W^-: 16%
- B/(S+B) (E_T > 25GeV) W^+: 8%

Background Events ($E_T > 25$ GeV)	$W^- \rightarrow e^- + \bar{\nu}_e$	$W^+ \rightarrow e^+ + \nu_e$
$W \rightarrow \tau + \nu_\tau$	2.7 ± 0.7	8.4 ± 2.2
Missing Endcap	14 ± 4	13 ± 4
Normalized QCD	$8.0\ ^{+20}_{-4}$	$25\ ^{+36}_{-9}$
Total	$25\ ^{+21}_{-7}$	$46\ ^{+36}_{-11}$

W production results: Data/MC Comparison

- Data/MC Comparison of charge-separated Jacobian peak distributions

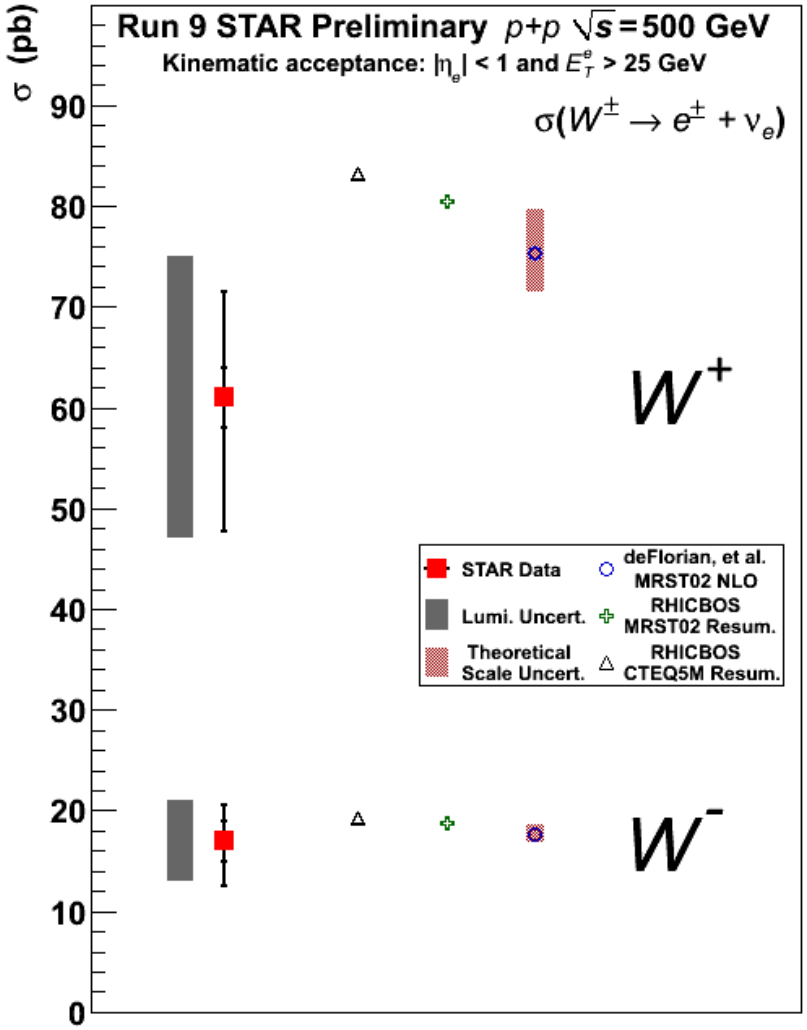




- Comparison of data and PYTHIA+GEANT simulations for W signal events at $\sqrt{s}$=500GeV
- Systematic uncertainties were estimated by varying cuts and normalization regions for QCD background and by varying BEMC energy scale uncertainty (±7.5%)

W production results: Cross-Section

- Total W^+/W^- Cross-section results



	$W^- \to e^- + \bar{\nu}_e$	$W^+ \to e^+ + \nu_e$
N_W^{obs}	156	513
N_{back}	$25\ ^{+21}_{-7}$	$46\ ^{+36}_{-11}$
ϵ_{total}	$0.56\ ^{+0.11}_{-0.09}$	$0.56\ ^{+0.12}_{-0.09}$
$\int Ldt\ (\mathrm{pb}^{-1})$	13.7 ± 3.2	13.7 ± 3.2

STAR Preliminary Run 9 (p+p $\sqrt{s}$=500 GeV)

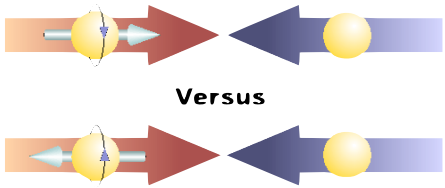
$$\sigma_{W^+ \to e^+ + \nu} = 61 \pm 3\ (\mathrm{stat.})\ ^{+10}_{-13}\ (\mathrm{syst.}) \pm 14\ (\mathrm{lumi.})\ \mathrm{pb}$$

$$\sigma_{W^- \to e^- + \bar{\nu}} = 17 \pm 2\ (\mathrm{stat.})\ ^{+3}_{-4}\ (\mathrm{syst.}) \pm 4\ (\mathrm{lumi.})\ \mathrm{pb}$$

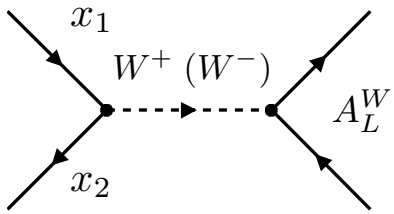
- Reasonable agreement between measured and theory evaluated cross-sections within uncertainties!

W production results: Asymmetry measurement

- A_L determination



$u\,/\Delta u\;(d\,/\Delta d)$

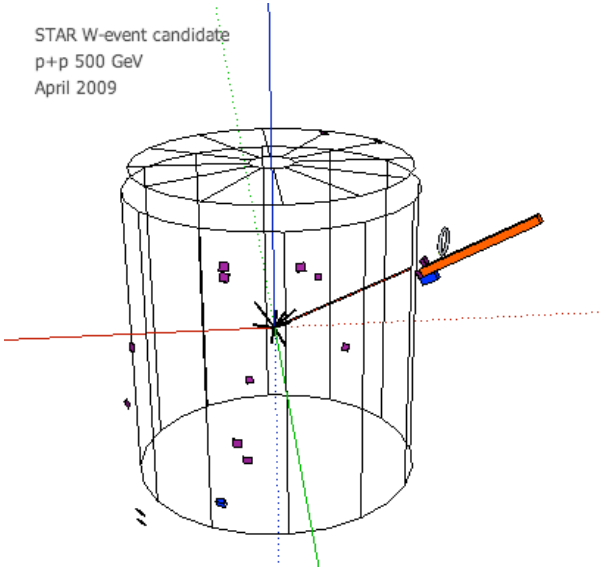


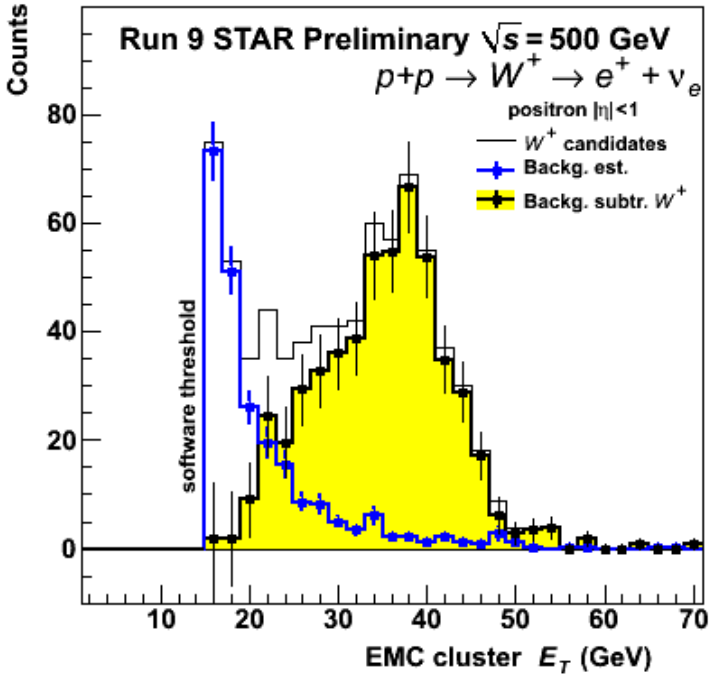
$\nu_e\;(\bar{\nu}_e)$

$$A_L^W = \frac{1}{P}\frac{N^+(W) - N^-(W)}{N^+(W) + N^-(W)}$$

$e^+\;(e^-)$

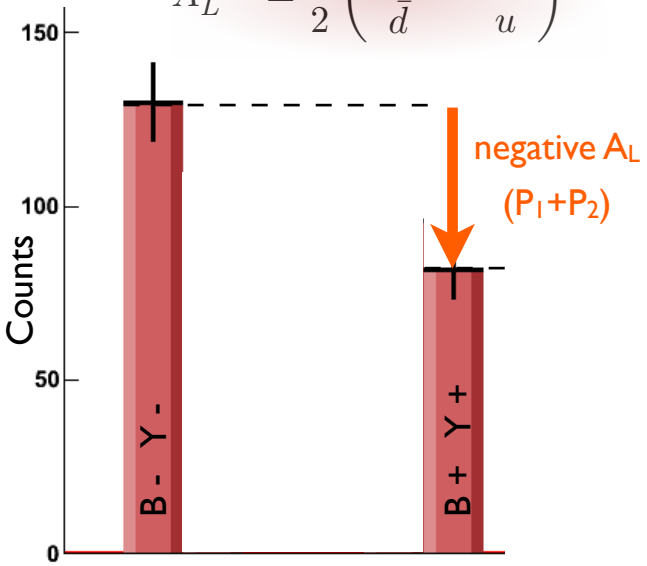
$\Delta\bar{d}\,/\bar{d}\;(\Delta\bar{u}\,/\bar{u})$





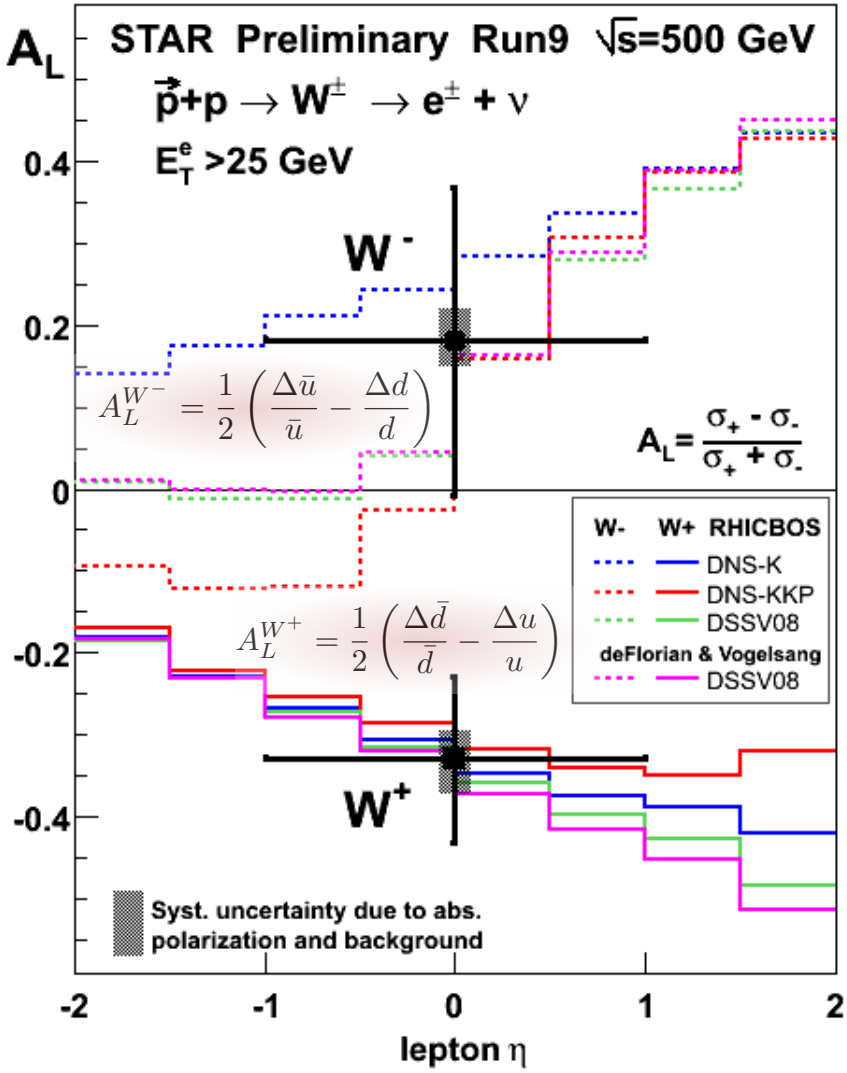
- First measurement of parity-violation in polarized proton-proton collisions at RHIC
- W^+: Observe directly u quark polarization!

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u}\right)$$



W production results: Asymmetry result

- Parity-violating single-spin asymmetry W^+/W^- A_L results



STAR Preliminary Run 9 (p+p $\sqrt{s}$=500 GeV)

$$A_L(W^+) = -0.33 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$

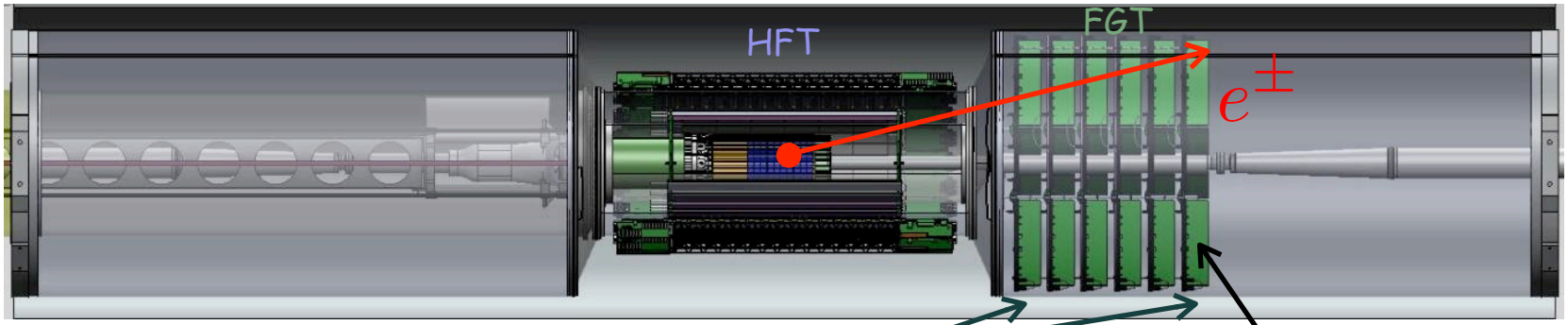
$$A_L(W^-) = 0.18 \pm 0.19(\text{stat.}) \; ^{+0.04}_{-0.03}(\text{syst.})$$

- $A_L(W^+)$ negative with a significance of 3.3 σ
- $A_L(W^-)$ central value positive
- Systematic errors of A_L under control
- TPC charge separation works up to p_T ~ 50GeV
- Measured asymmetries are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data

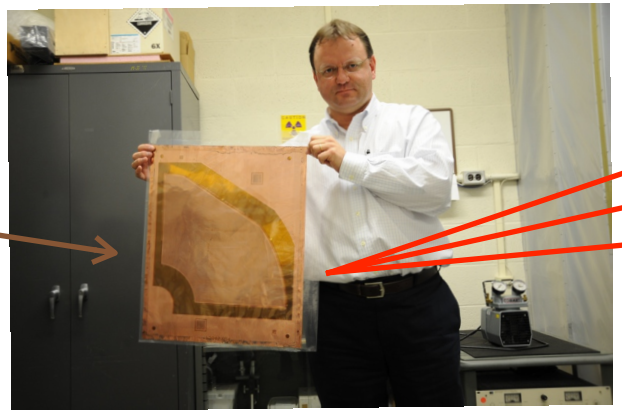
  ⇒ Universality of helicity distribution functions!

Future W program: Forward GEM Tracker

- FGT layout

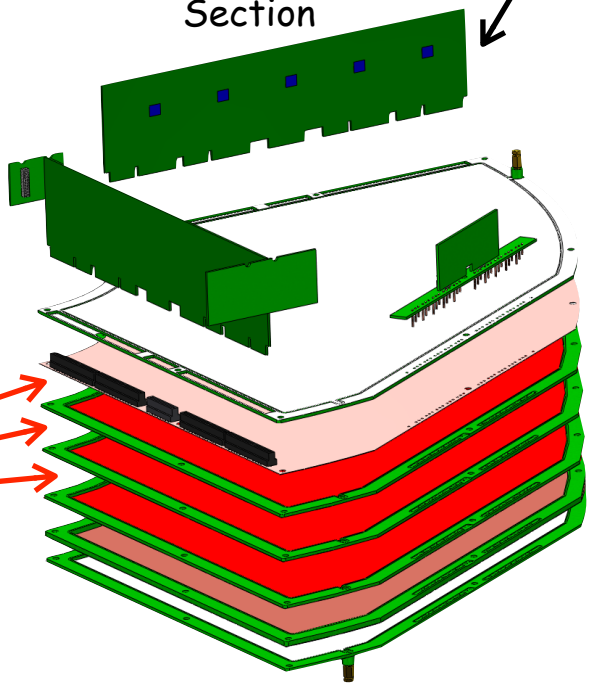


- FGT: 6 light-weight triple-GEM disks using industrially produced GEM foils (Tech-Etch Inc.)
- New mechanical support structure
- Expected installation: Summer 2011

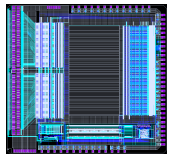


FGT GEM foil

FGT Quarter Section



APV module



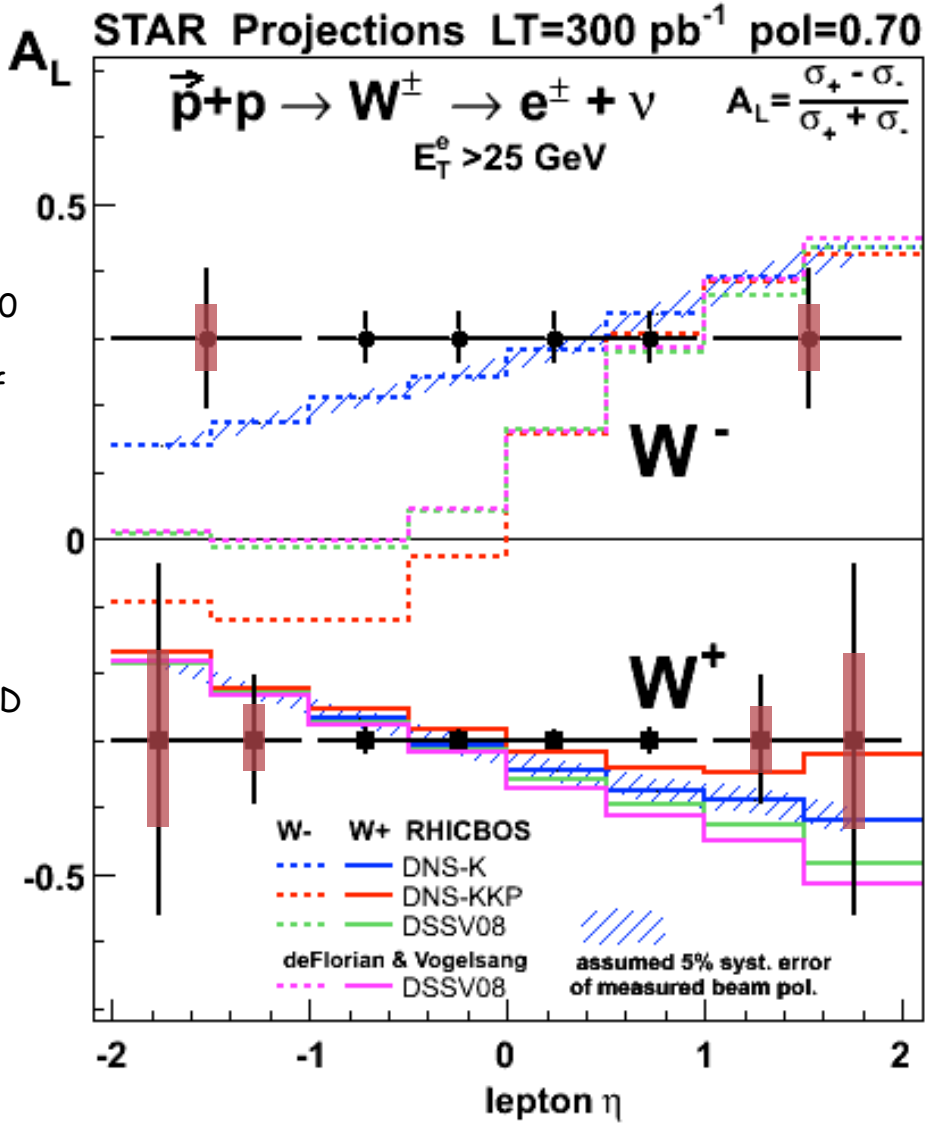
APV chip

Future W program: Projections

- A_L projections

lepton $|\eta|<1$: 2 beams, eff=0.65 w/ 9MHz RF, Run9 QCD bckg, rhicbos $\sigma W^{+},W^{-}$=82, 19 pb
lepton $|\eta|\in[1,2]$: 1 beam, eff=0.60 w/ 9MHz RF, M-C QCD bckg, rhicbos $\sigma W^{+},W^{-}$=5.3, 4.7 pb

- Assumptions:
  - Efficiency:
    - Mid-rapidity: 0.65
    - Forward rapidity: 0.60
    - Assume availability of 9MHz RF
  - Background:
    - Mid-rapidity: Run 9
    - Forward rapidity: QCD MC simulations
  - Full charge-sign discrimination at high-p_T

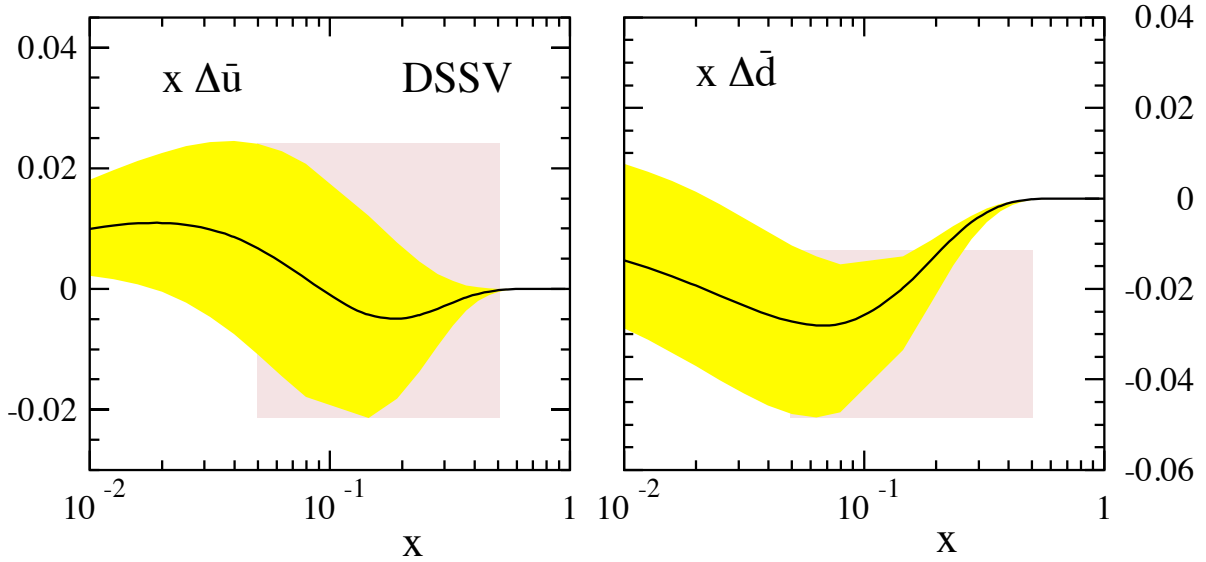


- Conclusions:
  - W Program at RHIC is a multi-year program - Initial sample of ~100pb^{-1} / ~50% is only a step along the way!
  - Critical:
    - Design polarization performance of 70% to collect at least 300pb^{-1}
    - Polarization uncertainty ~5%

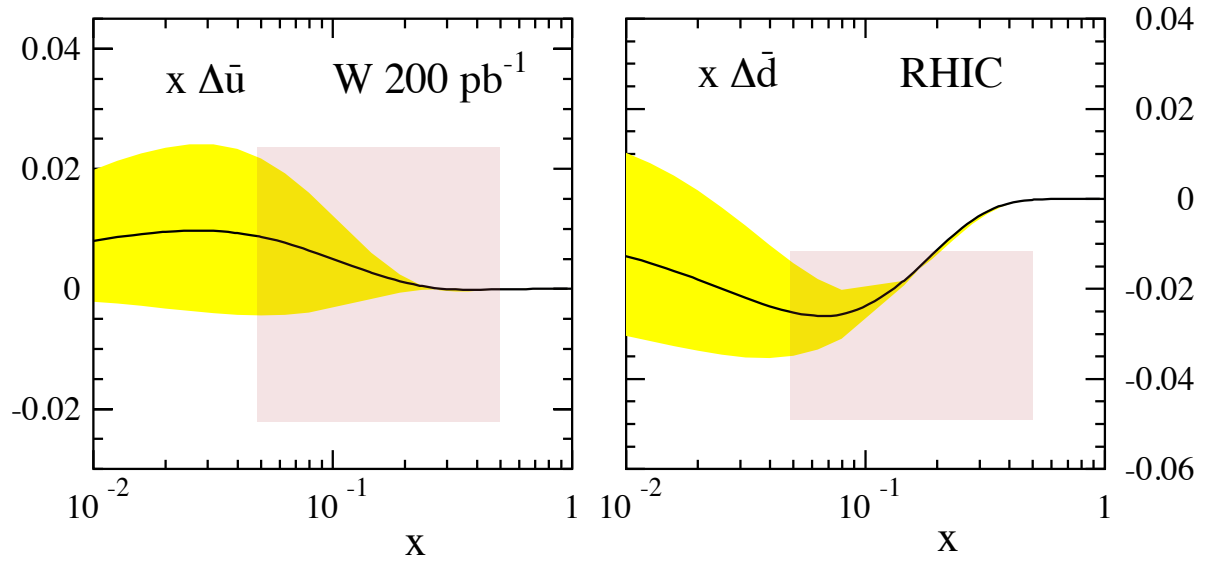
Future W program: Projections

- STAR W Impact on polarized QCD sea

D. deFlorian and W. Vogelsang, hep-ph/1003.4533



DSSV08 Fit



Include W results at RHIC

(PHENIX and STAR)

assuming $-2 < \eta < 2$

with 200pb-1

Strong constrain for x>0.05

Summary

- STAR High-energy polarized p-p program
  - pQCD: Critical role to interpret measured asymmetries
  - First global analysis incl. RHIC SPIN data ⇒ Evidence for small gluon polarization for 0.05<x<0.2
  - Correlation measurements (Di-Jets / γ -Jets) will allow to provide needed constrain on the partonic kinematics ⇒ First Di-Jet cross-section measurement at RHIC at $\sqrt{s}$=200GeV
  - Run 9 analysis of 200GeV in full swing - Strong focus on di-jet measurements!
  - First Run 9 STAR W result (Cross-section and A_L for W^+/W^- at mid-rapidity) important milestone!
  - Forward rapidity: Complete FGT construction in ~fall 2010 followed by full system test and subsequent full installation in ~summer 2011
    ⇒ Ready for anticipated long 500GeV polarized pp run in FY12 (Run 12)
  - Future measurements of A_L at STAR at mid-rapidity and forward rapidity (Wide rapidity coverage!) are expected to play an important role in our understanding of the polarized QCD sea!

Outlook

- Outlook - RHIC SPIN
  - Three key elements:
    - Gluon polarization
    - Quark / Anti-Quark Polarization
    - Transverse spin dynamics
  - Critical:
    - Beam polarization: 70% / Narrow vertex region / Spin flipper
    - Critical: Sufficient running time!

Recorded Luminosity	Main physics Objective	Remarks
~50pb^{-1}	Gluon polarization using di-jets and precision inclusive measurements	200 GeV
~100pb^{-1}	W production (Important consistency check to DIS results - Phase I) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~300pb^{-1}	W production (Constrain antiquark polarization - Phase II) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~30pb^{-1}	Transverse spin gamma-jet	200 GeV
~250pb^{-1}	Transverse spin Drell-Yan (Long term)	200 GeV