RHIC spin and Belle

Tomography workshop, July 31,
Kyoto

Ralf Seidl
(RIKEN)

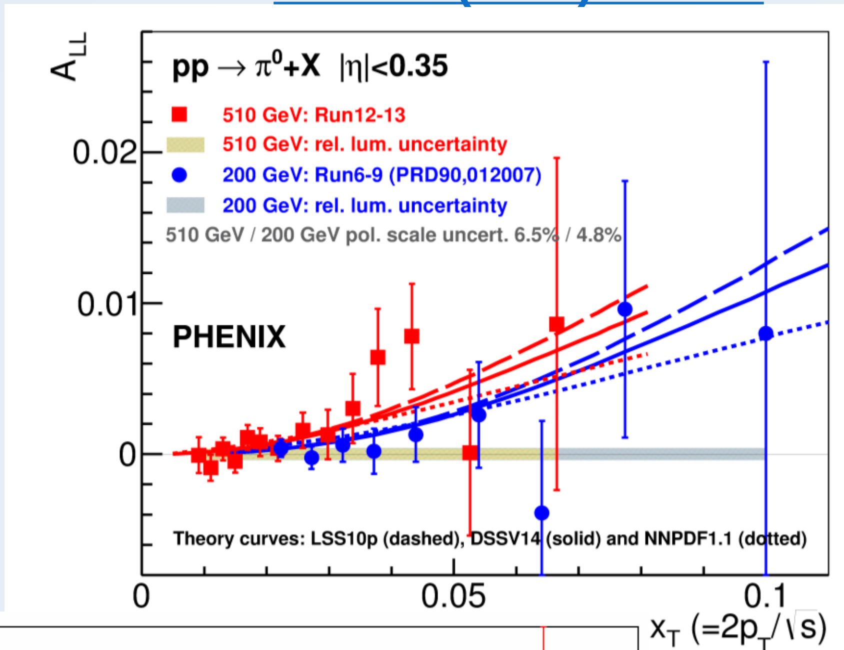
Outline

- Recent RHIC spin highlights
- RHIC spin and tomography
- Belle FF
- Belle and tomography

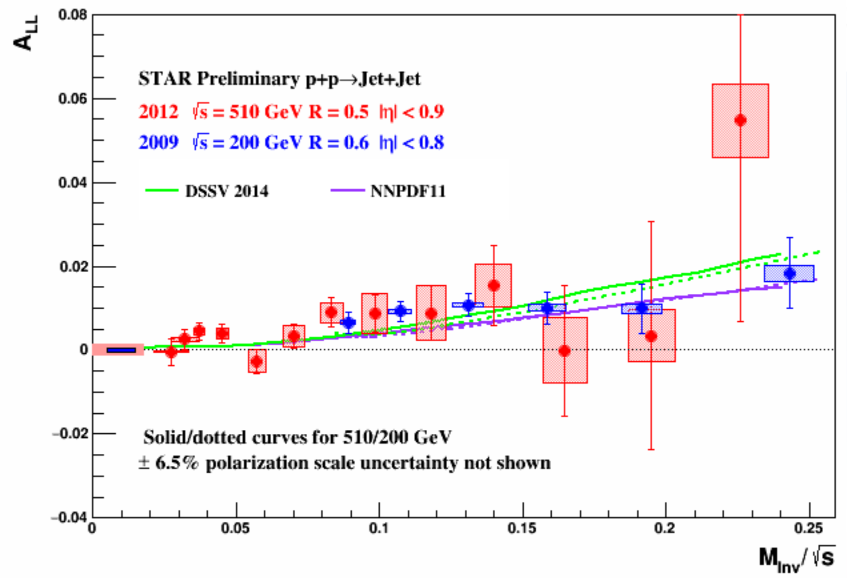
$\Delta g(x)$

Gluon spin: To higher energies

PHENIX PRD 93 (2016) 011501

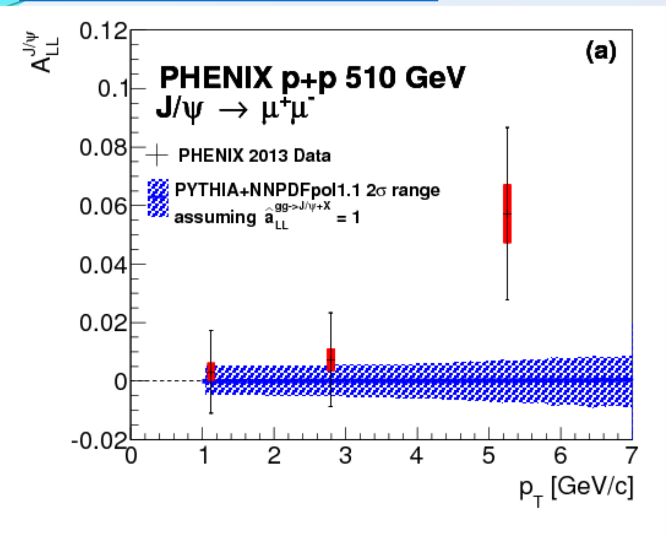


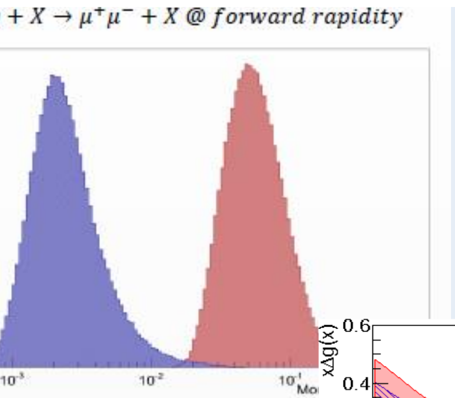
- Nonzero gluon polarization established with RHIC √s = 200 GeV data
- RHIC 510 GeV data (>2011) now confirms it in workhorse (jet, pion) measurements
- Extend access to lower x by higher energy (now~ 10^{-2})



…and lower x

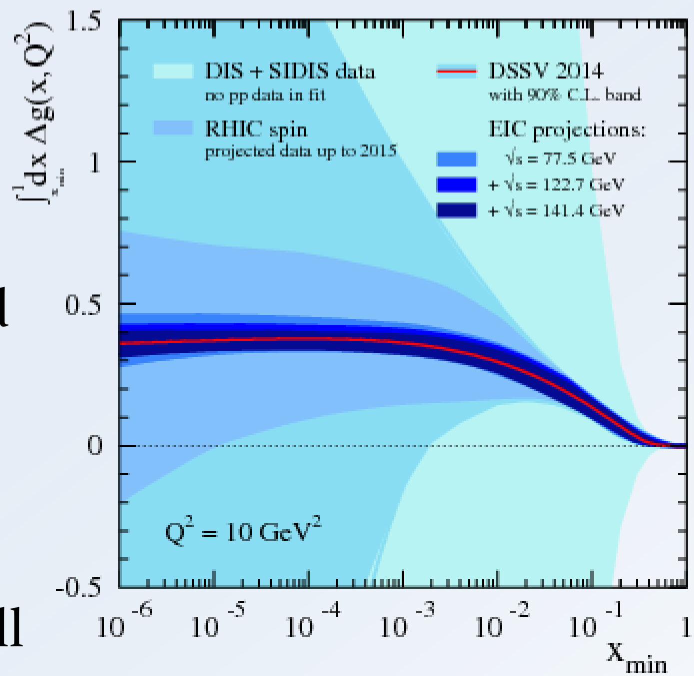
arXiv:1606.01815

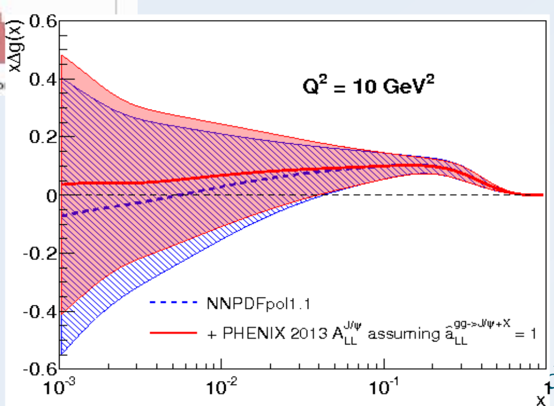




- PHENIX forward J/ψ measurements reach close to x~10⁻³
- Including feed-down almost entirely produced from gg
- Due lack of knowing production mechanism interpretation still difficult

RPD 92 (2015) 094030





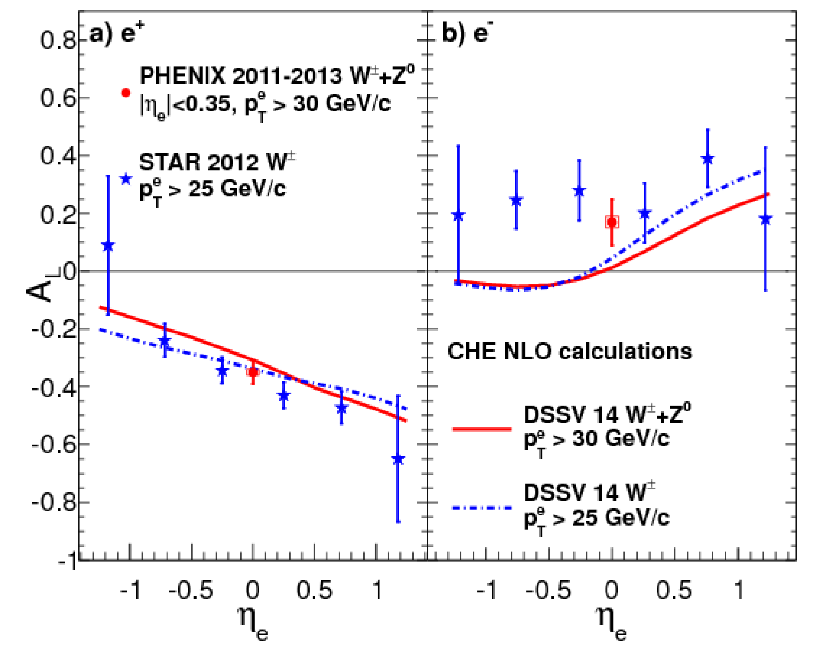
- Other forward π^0 measurements ongoing to get better precision down to $x\sim10^{-3}$
- Eventually EIC to pin down integrals, strangeness and need for OAM

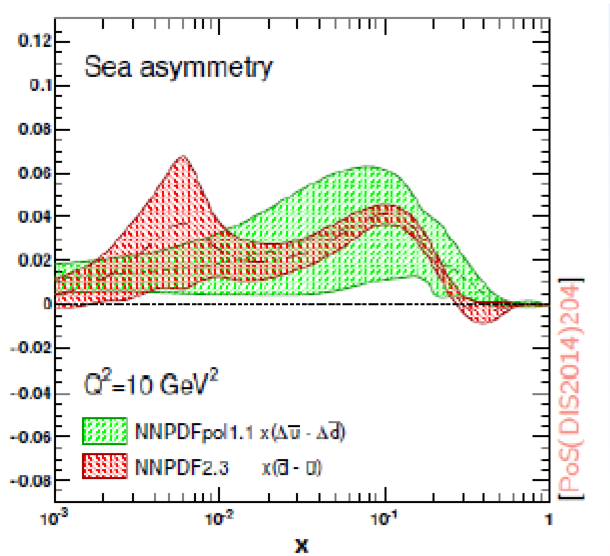
$\Delta q(x)$ $\Delta\bar{q}(x)$

Sea quark helicites

STAR: PRL 113 (2014) 072301
PHENIX: PRD 93 (2016) 051103

- STAR 2012 data at boundary of DSSV uncertainty bands
- Reweighted NNPDFpol1.1 shows substantial polarized light sea asymmetry
- opposite sign to most cloud models
- All central PHENIX data published,
- 2013 STAR data and forward PHENIX data pending





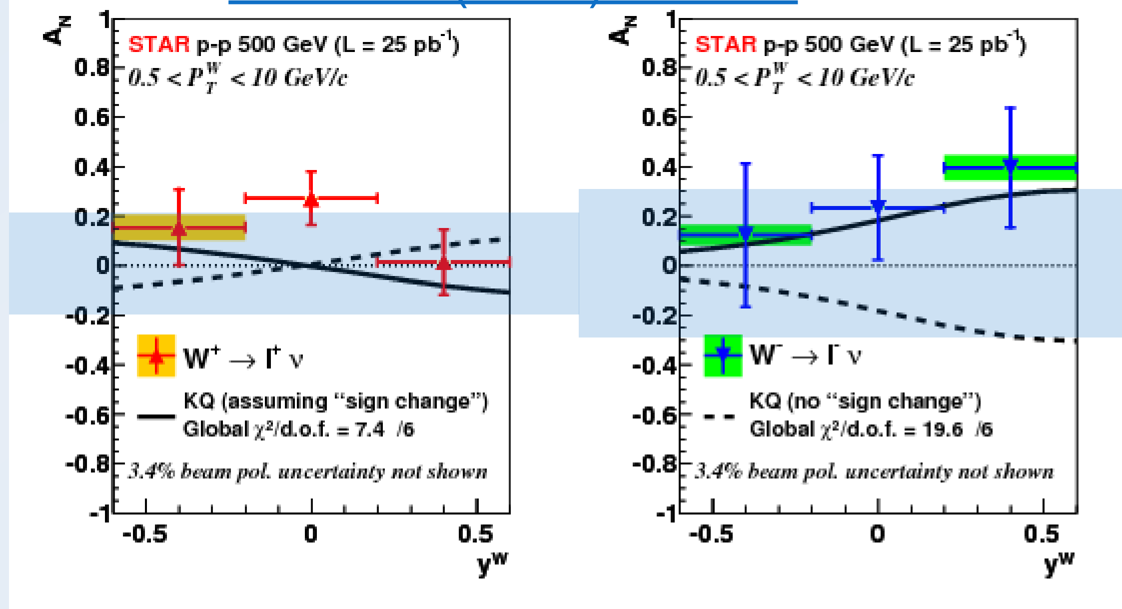
$f_{1T,q}^{\perp}(x, k_T)$

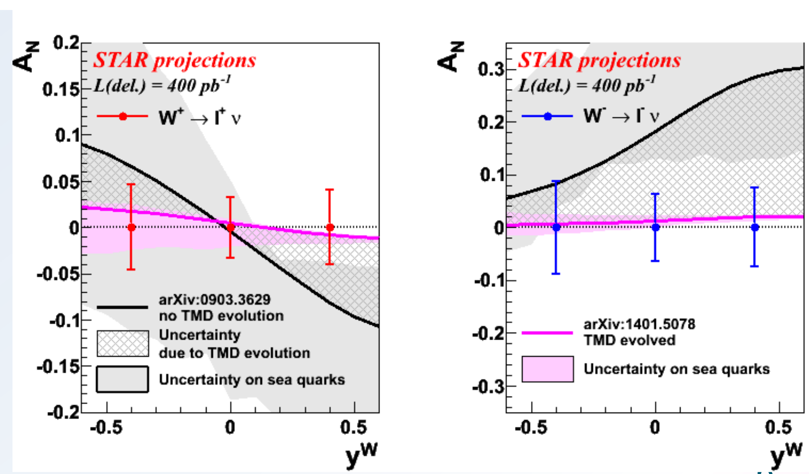
Towards the sign change

- Using recoil method reconstruct W transverse momentum and azimuthal asymmetry
- First indication of expected sign change!
- Evolution effects could reduce size of asymmetries
- 2017 data taking will substantially improve statistics; also DY and Z asymmetries

STAR: PRL 116 (2016) 132301

→Fazio

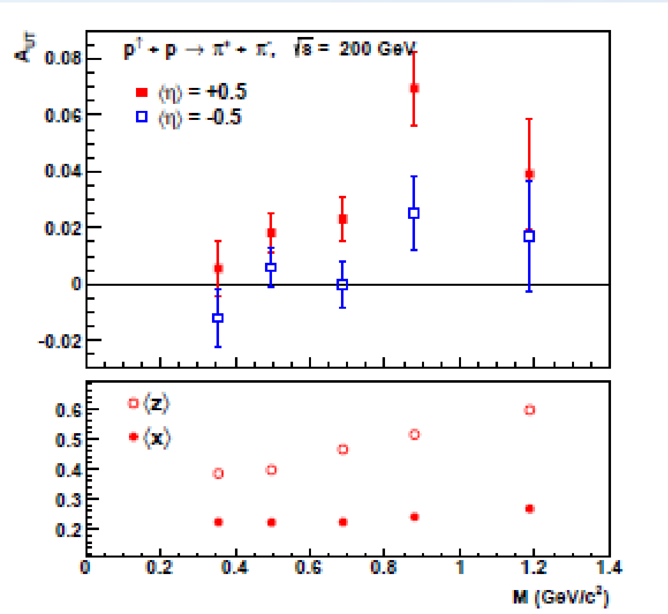




$h_{1,q}(x)\ H_{1,q}^{\perp,h}(z,k_T)\ H_{1,q}^{h_1h_2}(z,M_{hh})$

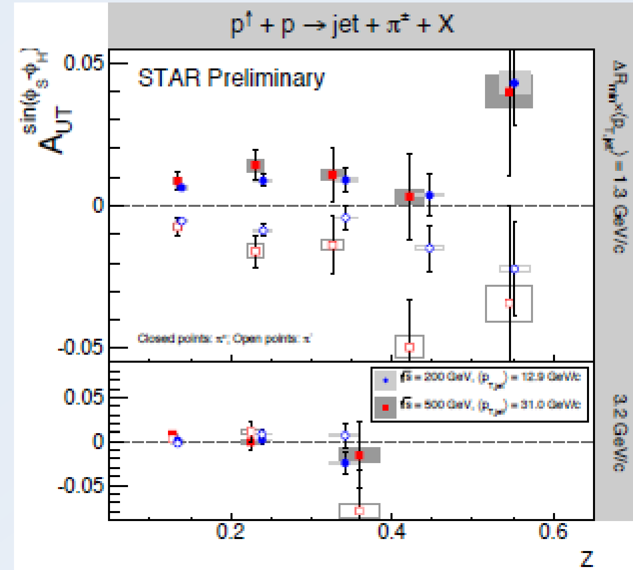
Transversity in proton collisions

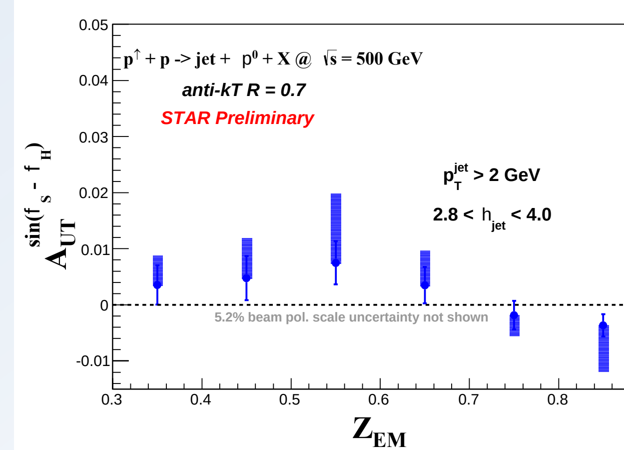
STAR: PRL 115 (2015) 242501



- Published Interference FF asymmetries from STAR + preliminary 500GeV data
- Pavia group with first global fits to SIDIS+RHIC+Belle data

- Nonzero Collins asymmetries (hadron in jets) at central rapidities
- Substantial theoretical progress for hadron in jet measurements
  - unpolarized: Kaufmann et al.
  - polarized Kang et al.
- For roughly same x and kt similar size → evolution effects moderate?
- Using forward EmCal first hint of nonzero Collins asymmetries for π^0 in EM jets



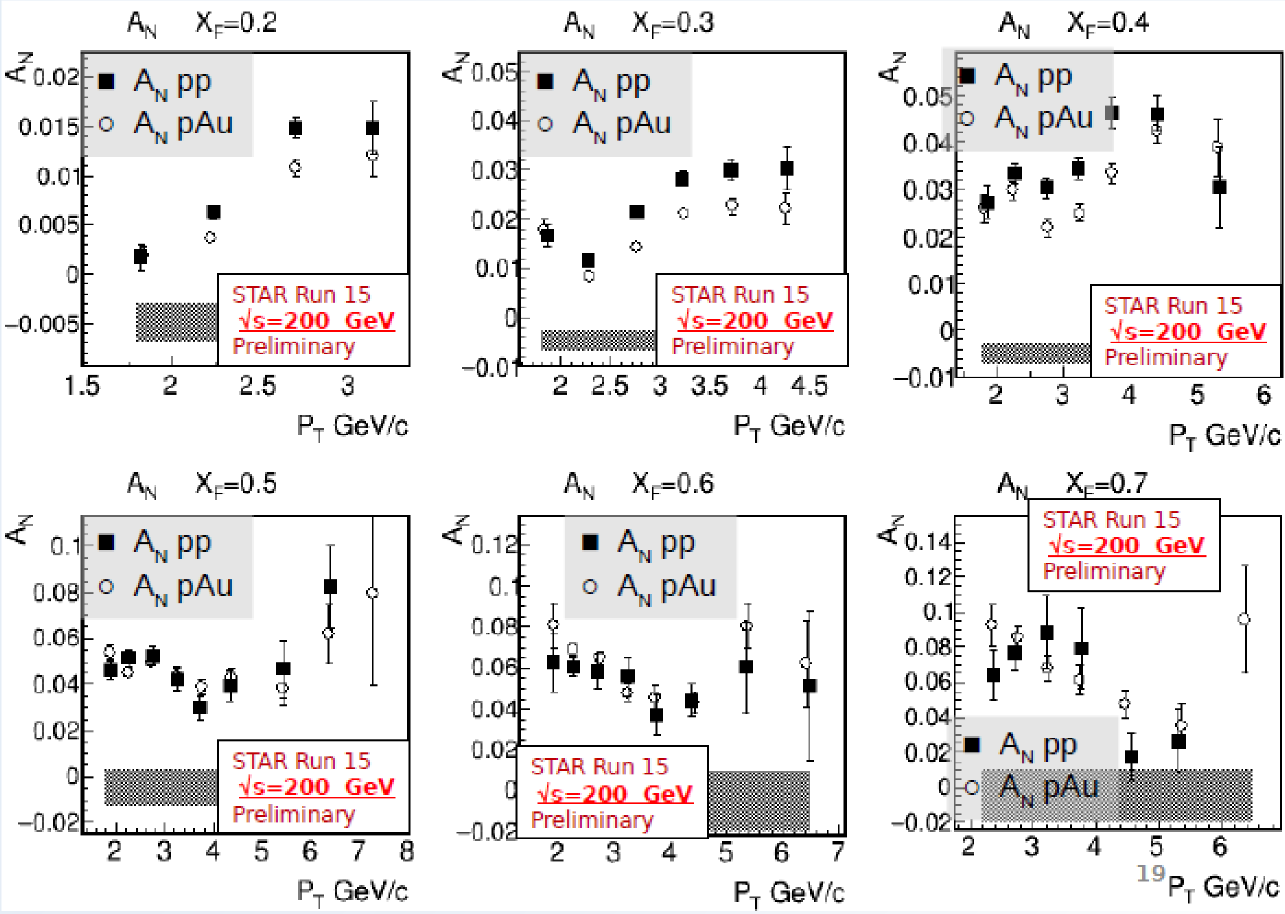


Qiu-Sterman, Koike, Metz-Pitonyak, Diffractive?

Transverse spin asymmetries in pA

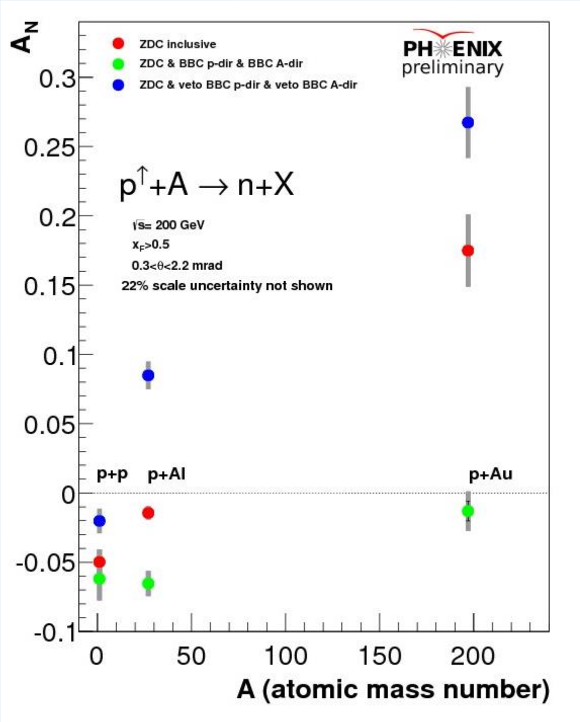
2015: $p^{\uparrow}$+A collision at $\sqrt{s_{NN}} = 200$ GeV

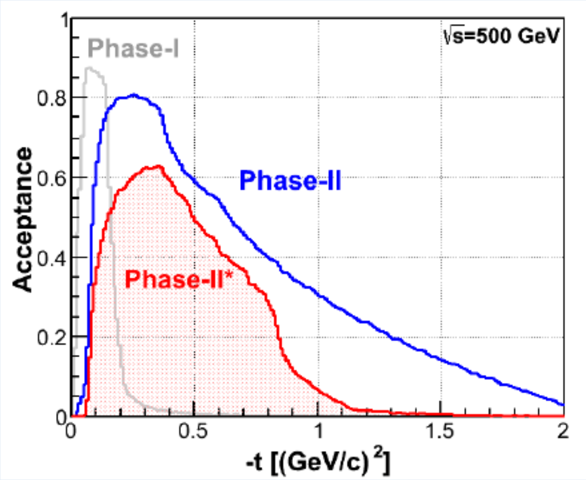
- Several theory predictions of diminished pA asymmetries due to nonlinear low-x behavior (either final or initial state effects)
- No substantial reduction seen in 2015 STAR data
- However, origin of A_N asymmetries still unclear



...and other surprises

- Some indications of forward pion asymmetries in pp not due to initial state (higher twist related to Sivers) or final state (related to Collins or other FF) hard effects but diffractive
- 2015 STAR data included roman pots to answer this question



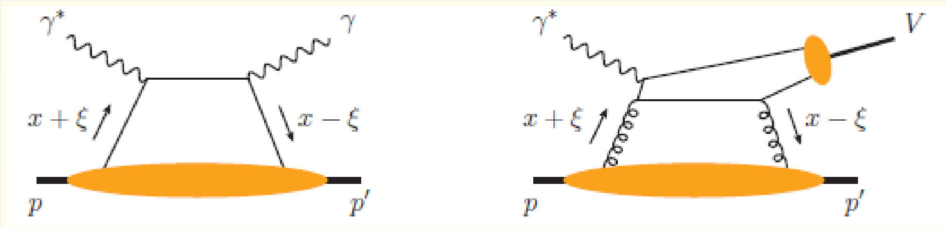


- Unexpected forward neutron asymmetry A behavior
- Potentially different contributions from Ultraperiphal collisions (EM) and hadronic (Reggeon) interactions
- More studies ongoing, including P_t dependence

Orbital angular momentum (OAM)

- Some indications for its existence from magnetic moments of p and n, nonzeroness of Sivers function
- Ji sum rule allows access to J_q via exclusive reactions:

$$J^q = \frac{1}{2}\int dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$



pdfs and form factors:

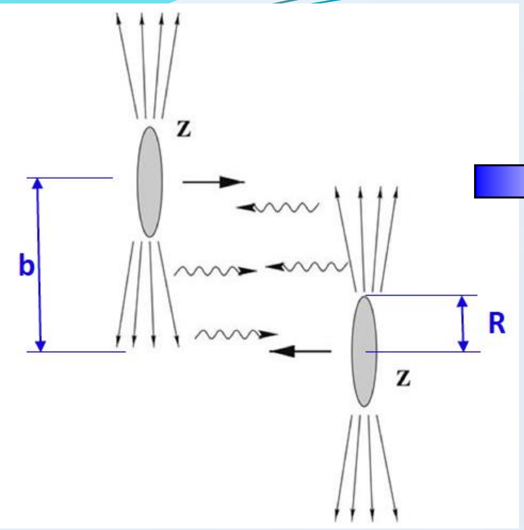
$H \rightarrow$ q, $\widetilde{H} \rightarrow \Delta$q for $\xi \rightarrow 0$

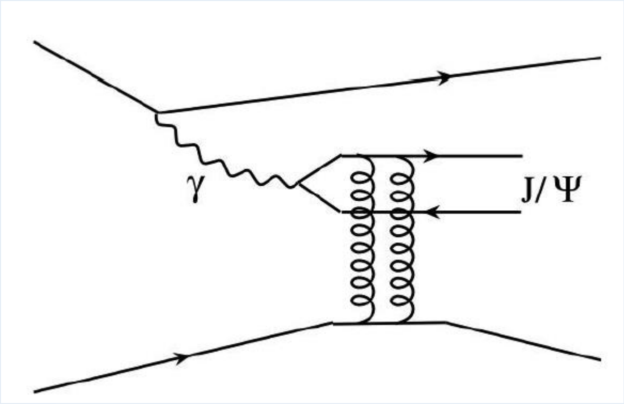
$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1^p(t)\,, \qquad \sum_q e_q \int dx\, E^q(x,\xi,t) = F_2^p(t)$$

- Any access to gluon OAM only via Twist 3

$t = (p' - p)^2$ → FT of impact parameter → spatial structure

RHIC as γA collider: UPC





Ultra-peripheral (UPC) collisions: b > 2R

→ hadronic interactions strongly suppressed

High photon flux ~ Z^2

→ well described in Weizsäcker-Williams approximation

→ high σ for ・ -induced reactions

e.g. exclusive vector meson production

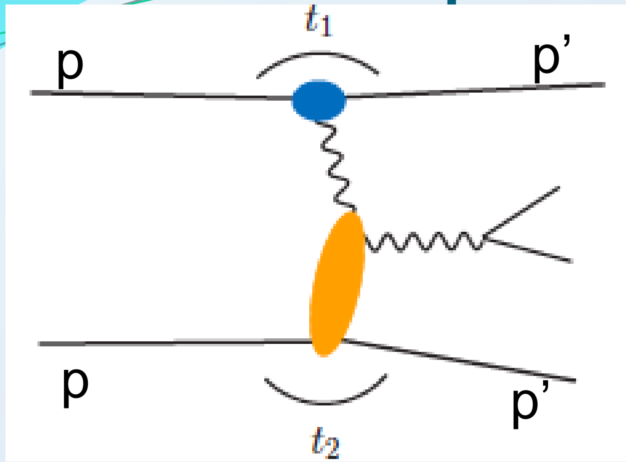
Coherent vector meson production:

- photon couples coherently to all nucleons
- $p_T \sim 1/R_A \sim 60$ MeV/c
- no neutron emission in ~80% of cases

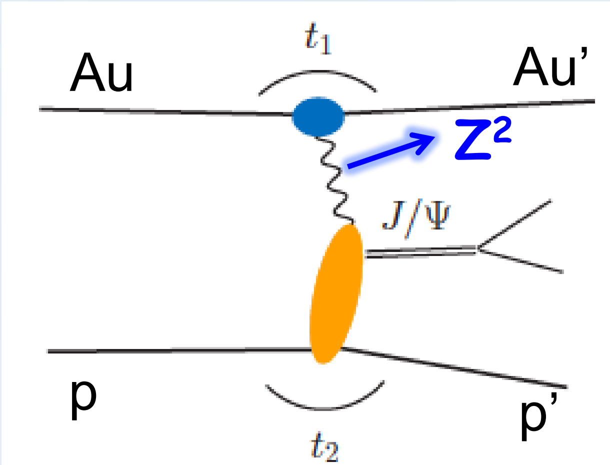
Incoherent vector meson production:

- photon couples to a single nucleon
- $p_T \sim 1/R_p \sim 450$ MeV/c
- target nucleus normally breaks up

UPC in polarized pp↑ or Ap↑ → GPD E_g



- Get quasi-real photon from one proton
- Ensure dominance of g from one identified proton by selecting very small t_1, while t_2 of "typical hadronic size"
- small t_1 ←→ large impact parameter b (UPC)
- Two possibilities:
  - Final state lepton pair ←→ timelike compton scattering
  - timelike Compton scattering: detailed access to GPDs
- including $E^{q/g}$ if have transv. target pol.
- Challenging to suppress all backgrounds



- Final state lepton pair not from g* but from J/ψ
  - Done already in AuAu
  - Estimates for J/ψ (hep-ph/0310223)
- transverse target spin asymmetry
- → calculable with GPDs

$$A_{UT}(t,t) \sim \frac{\sqrt{t_0 - t}}{m_p} \frac{\mathrm{Im}(E^* H)}{|H|} \qquad t = \frac{M^2_{J/Y}}{s}$$

- information on helicity-flip distribution E for gluons
- golden measurement for eRHIC

polarized p↑ A: gain in statistics ~ Z^2

Why UPC?

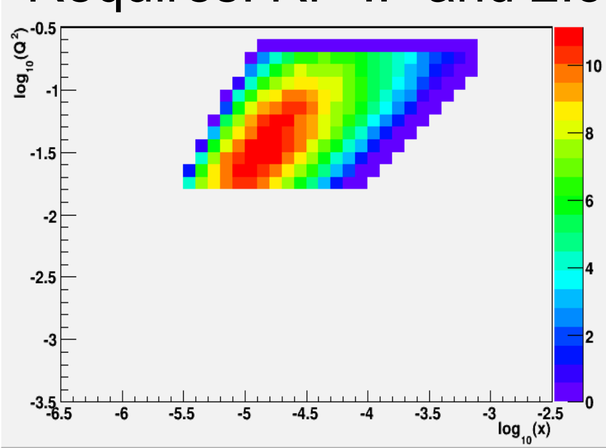
- Quarkonia photoproduction allows to study the gluon density $G(x,Q^2)$ in A
- as well as $G(x,Q^2, b_T)$
- LO pQCD: forward coherent photoproduction cross section is proportional to the squared gluon density
- Quarkonium photoproduction in UPC is a direct tool to measure nuclear gluon shadowing

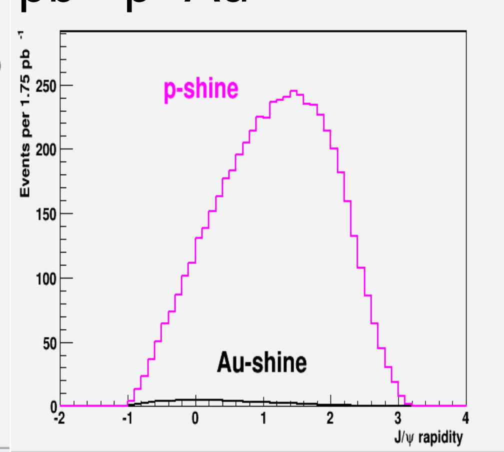
$$\frac{d\sigma_{\gamma A\to J/\psi A}(t=0)}{dt} = \frac{16\Gamma_{ee}\pi^3}{3\alpha_{em}M^5_{J/\psi}}\left[\alpha_s(Q^2)xG_A(x,Q^2)\right]^2 \qquad Q^2 \sim \frac{M^2_{J/\psi}}{4} \sim 2.5\,GeV^2$$

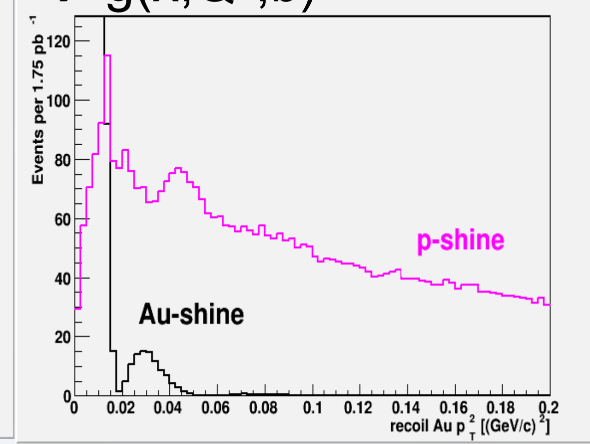
2020+ UPC: “proton-shine”-case:

Requires: RP-II* and 2.5 pb^{-1} p+Au

Fourier transform of σ vs. t → $g(x,Q^2,b)$



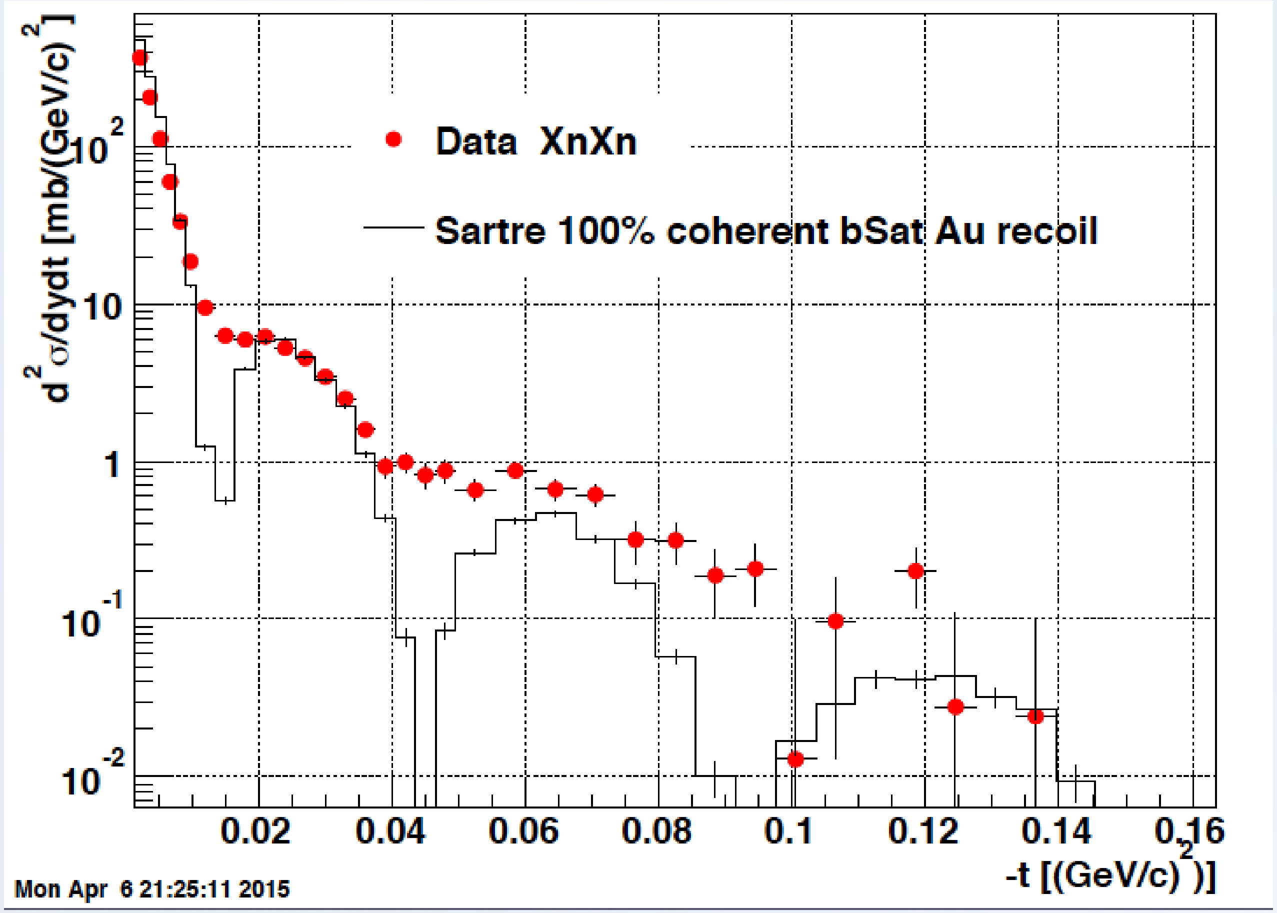




UPC at STAR

R. Debbe

- 2 tracks in STAR and one neutron in each ZDC Au+Au → n+n+e+e-



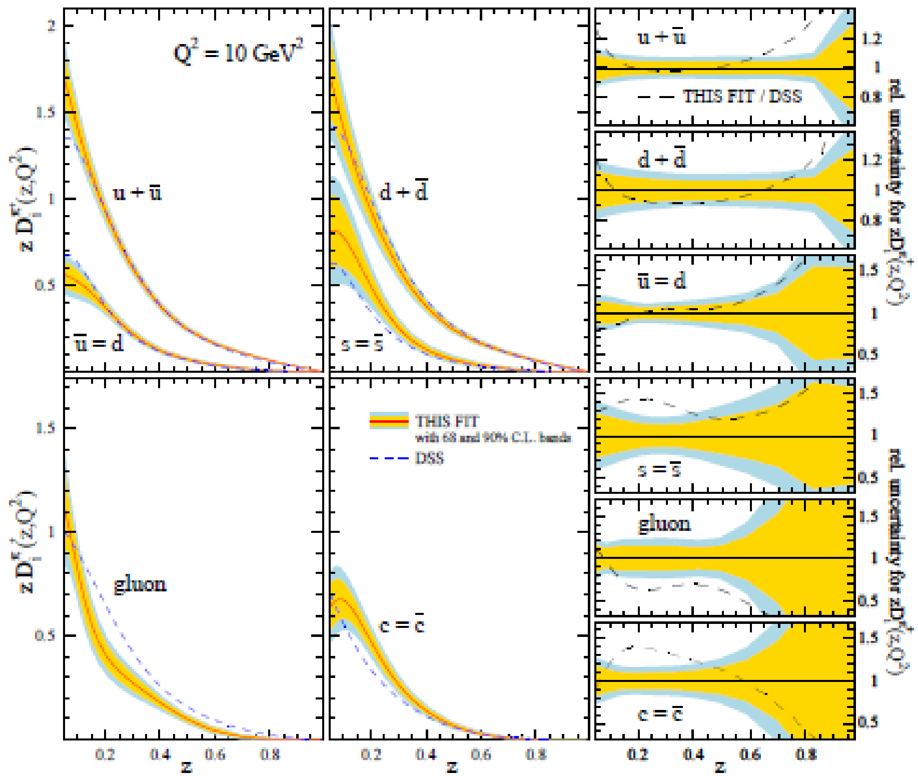
no attempt for a Fourier transform of σ vs. t has been made
→ g(x,Q^2,b)

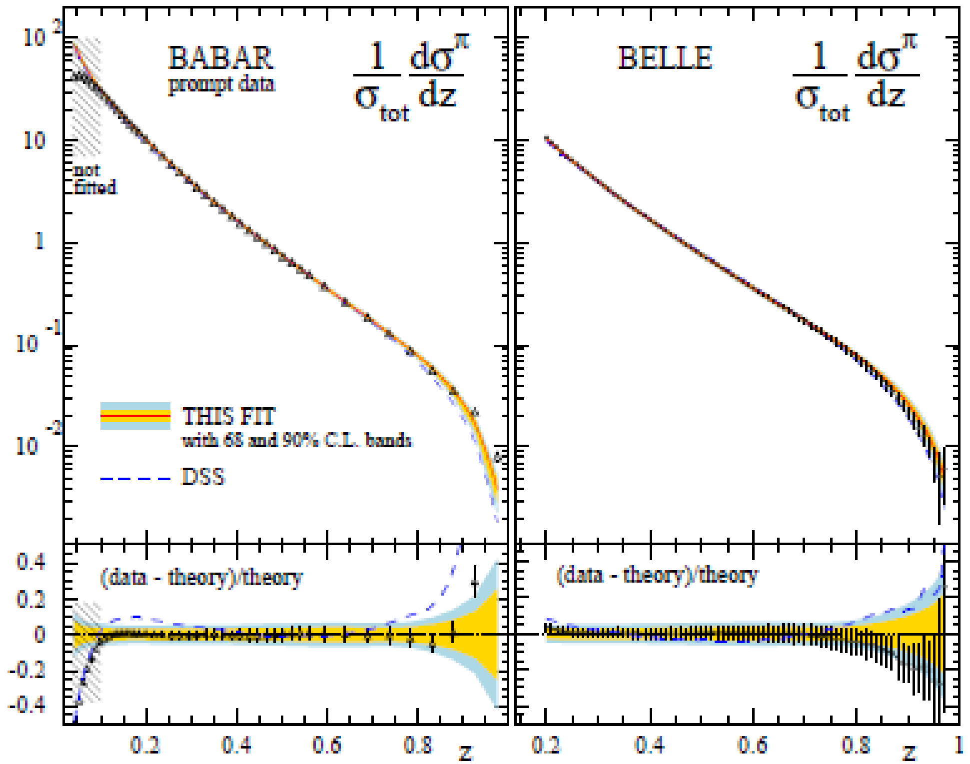
Fragmentation

$D_{1,q}^{h}(z)$

B factory data used in global FF fits

Phys.Rev. D91 (2015) 1, 014035

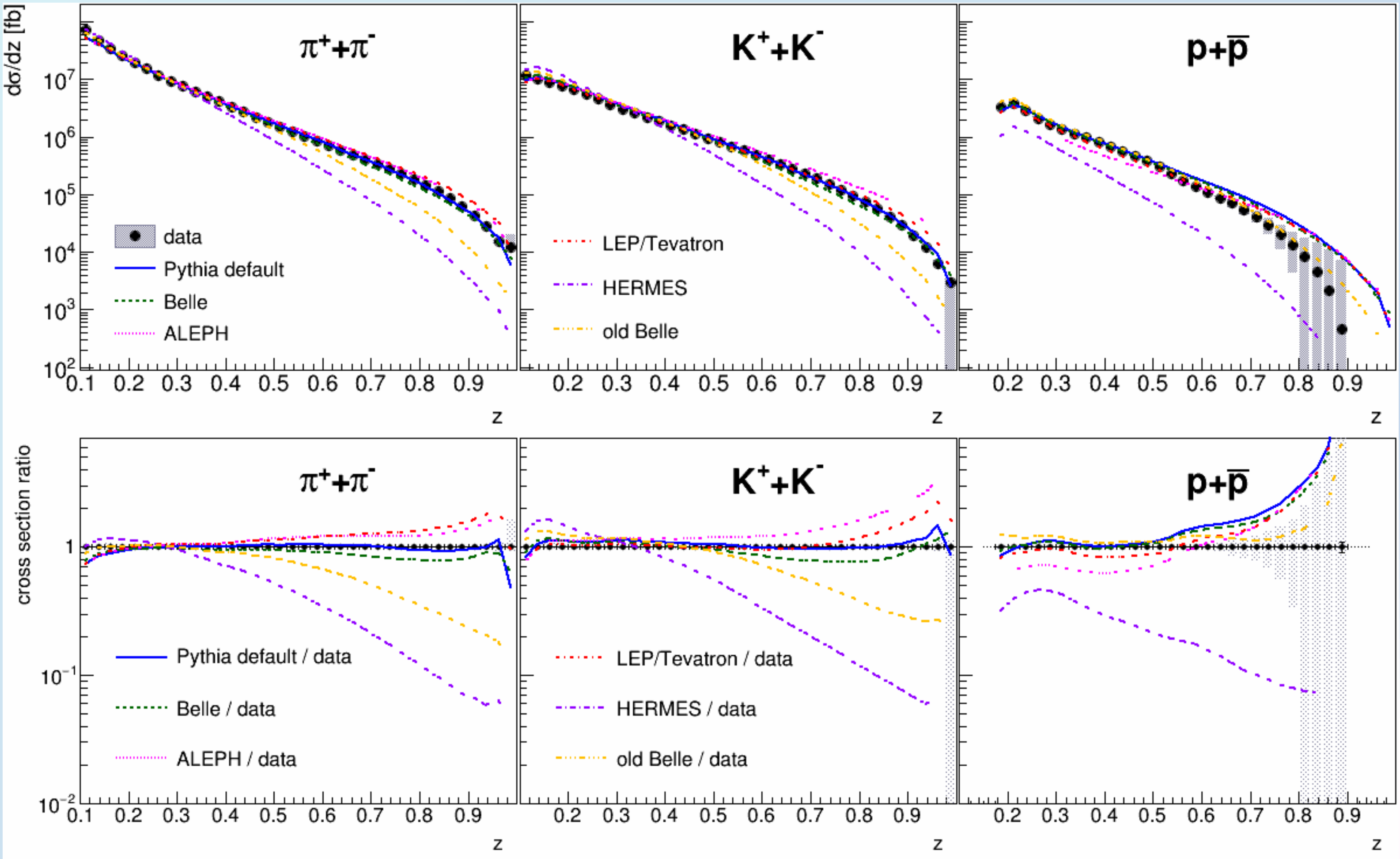




- Good description of B-factory data
- Together with other new data substantial improvement in uncertainties
- Shift in central values→relevant for RHIC gluon polarization measurements

New addition: single protons $D_{1,q}^h(z)$

PRD92 (2015) 092007



- Default Pythia and current Belle in good agreement with pions and kaons
- Protons not well described by any tune

Di-hadrons

$D^h_{1,q}(z_1) D^h_{1,\bar{q}}(z_2)$

In e^+e^- annihilation:

$$Q = \sqrt{s}$$
$$z = \frac{2E_h}{Q} \approx \frac{E_h}{E_q}$$

- Single inclusive hadron multiplicities (e+e-→hX) sum over all available flavors and quarks and antiquarks:

$$d\sigma(e^+e^- \rightarrow hX)/dz \propto \sum_q e_q^2 (D^h_{1,q}(z,Q^2) + D^h_{1,\bar{q}}(z,Q^2))$$

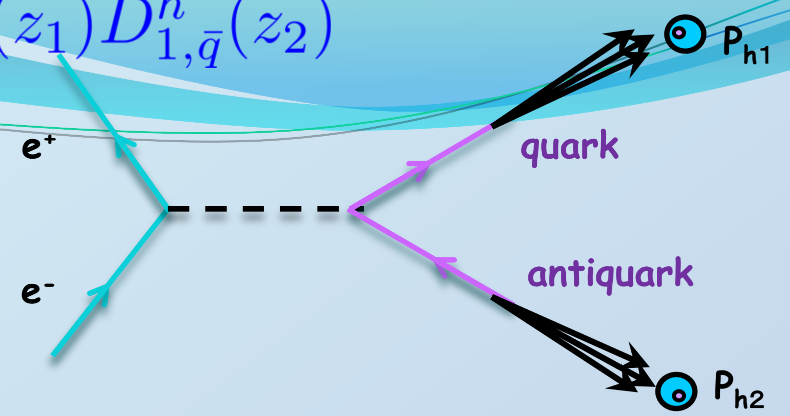
- Especially distinction between favored (ie u→π⁺) and disfavored (ū →π⁺) fragmentation would be important
- Idea: Use di-hadron fragmentation, preferably from opposite hemispheres and access favored and disfavored combinations:

$$u\bar{u} \rightarrow \pi^+\pi^- X \quad \propto \quad D^{\pi^+}_{u,fav}(z_1,Q^2) \cdot D^{\pi^-}_{\bar{u},fav}(z_2,Q^2) + D^{\pi^+}_{\bar{u},dis}(z_1,Q^2) \cdot D^{\pi^-}_{u,dis}(z_2,Q^2)$$
$$u\bar{u} \rightarrow \pi^+\pi^+ X \quad \propto \quad D^{\pi^+}_{u,fav}(z_1,Q^2) \cdot D^{\pi^+}_{\bar{u},dis}(z_2,Q^2) + D^{\pi^+}_{\bar{u},dis}(z_1,Q^2) \cdot D^{\pi^+}_{u,fav}(z_2,Q^2)$$

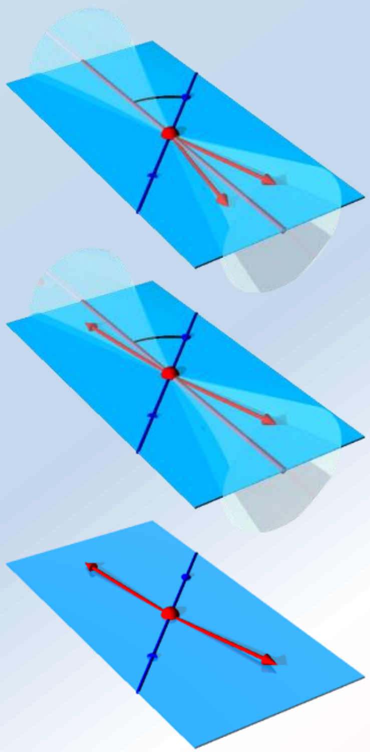
- Also: unpol baseline for interference fragmentation

Setup

$$D^h_{1,q}(z_1)D^h_{1,\bar{q}}(z_2)$$



- Generally look at 4 x 4 hadron combinations (π, K, +,-)
  - Keep separate until end: only 6 independent yields
- 3 hemisphere combinations:
  - same hemisphere (thrust >0.8)
  - opposite hemisphere (thrust >0.8)
  - any combination (no thrust selection)
- 16 x 16 z_1 z_2 binning between 0.2 - 1



$D^h_{1,q}(z_1) D^h_{1,\bar{q}}(z_2)$

Full results for pion pairs

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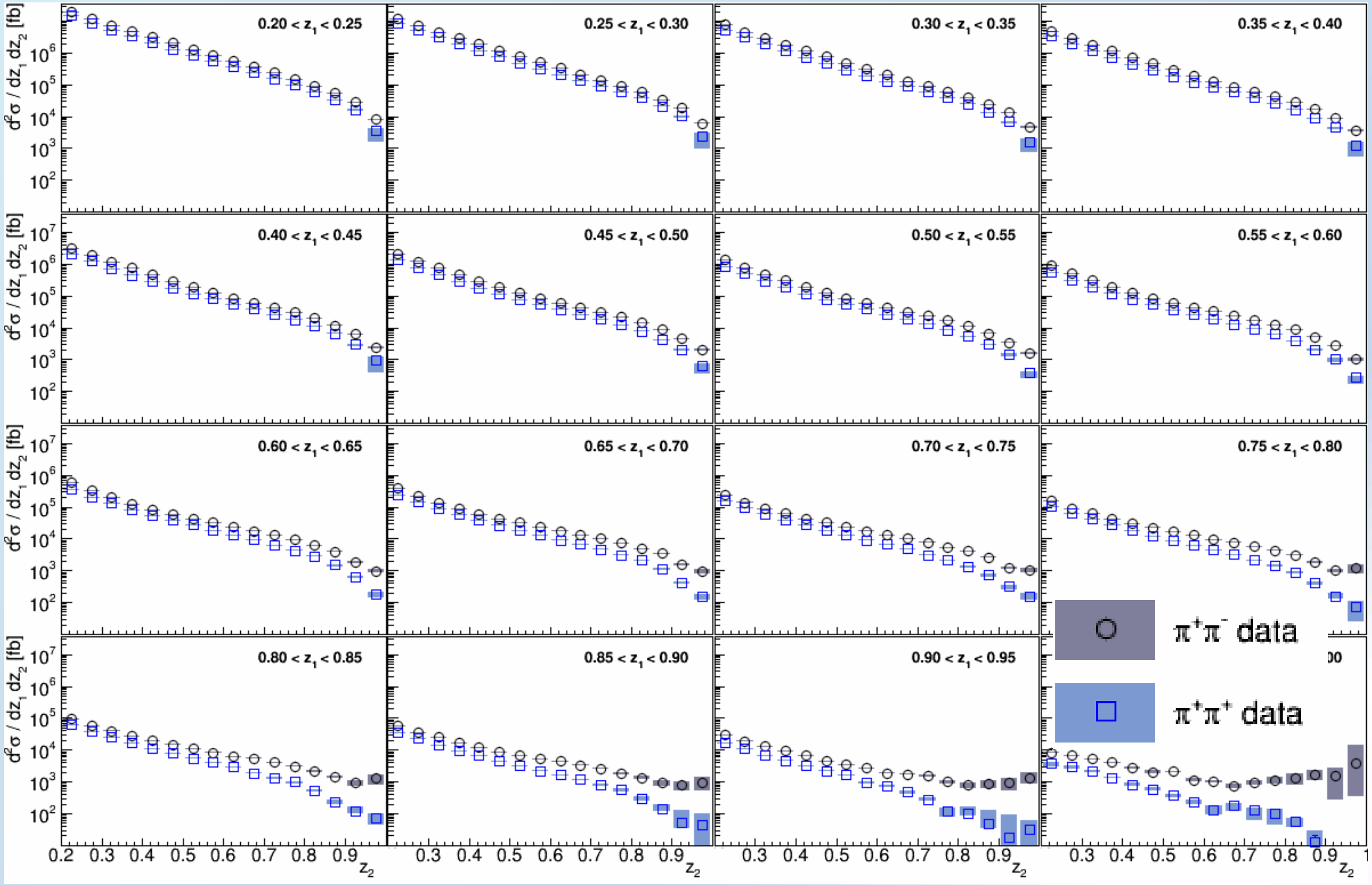
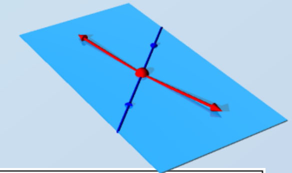


$D^h_{1,q}(z_1)D^h_{1,\bar{q}}(z_2)$

Results for diagonal $z_1\, z_2$ bins



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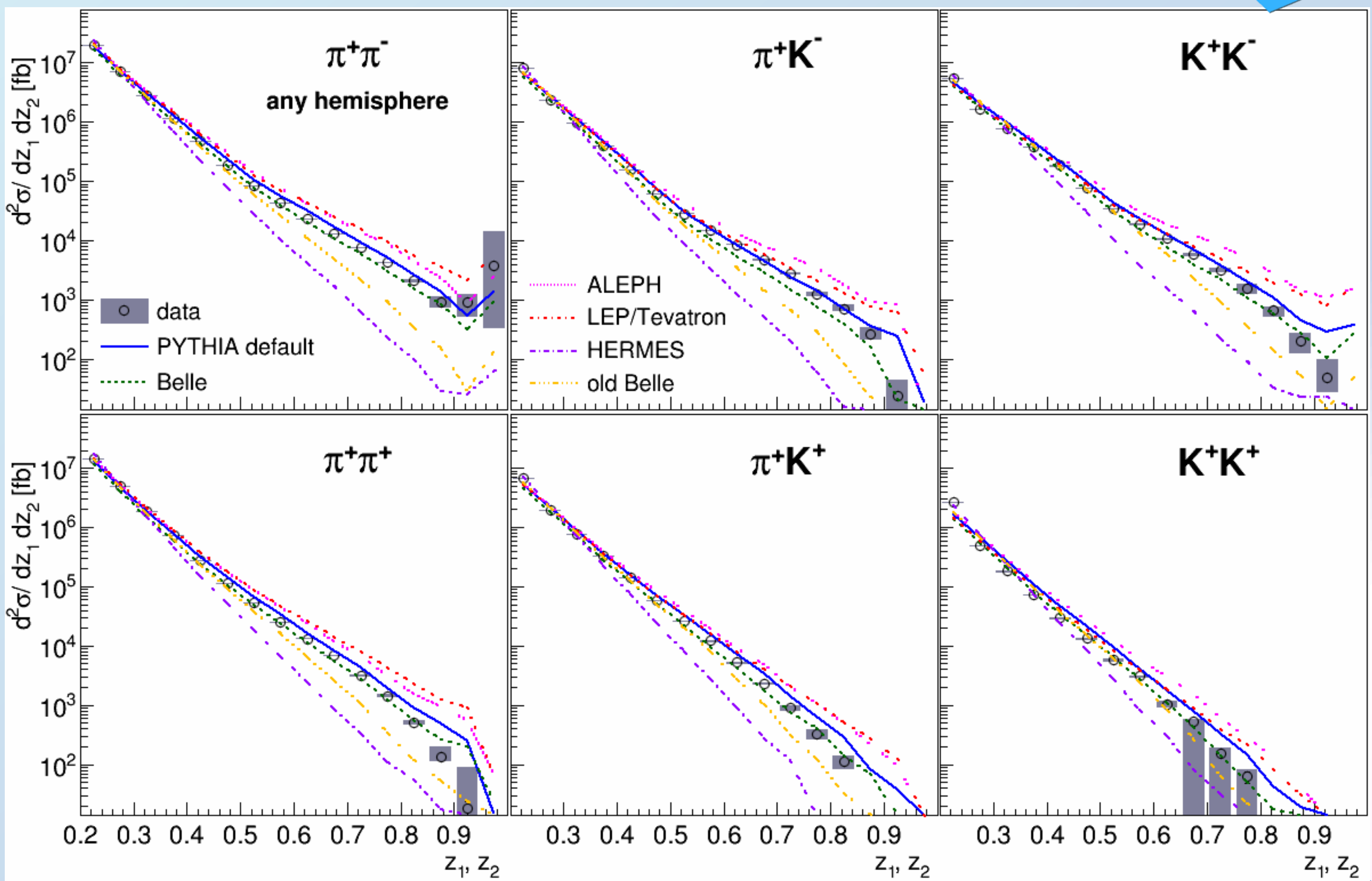
Low z dominates integral:
→Well defined, all tunes agree

High z not well measured, especially at Belle energies:
→large spread in tunes

Default Pythia settings and current Belle setting with good agreement

Diagonal z_1,z_2 bins

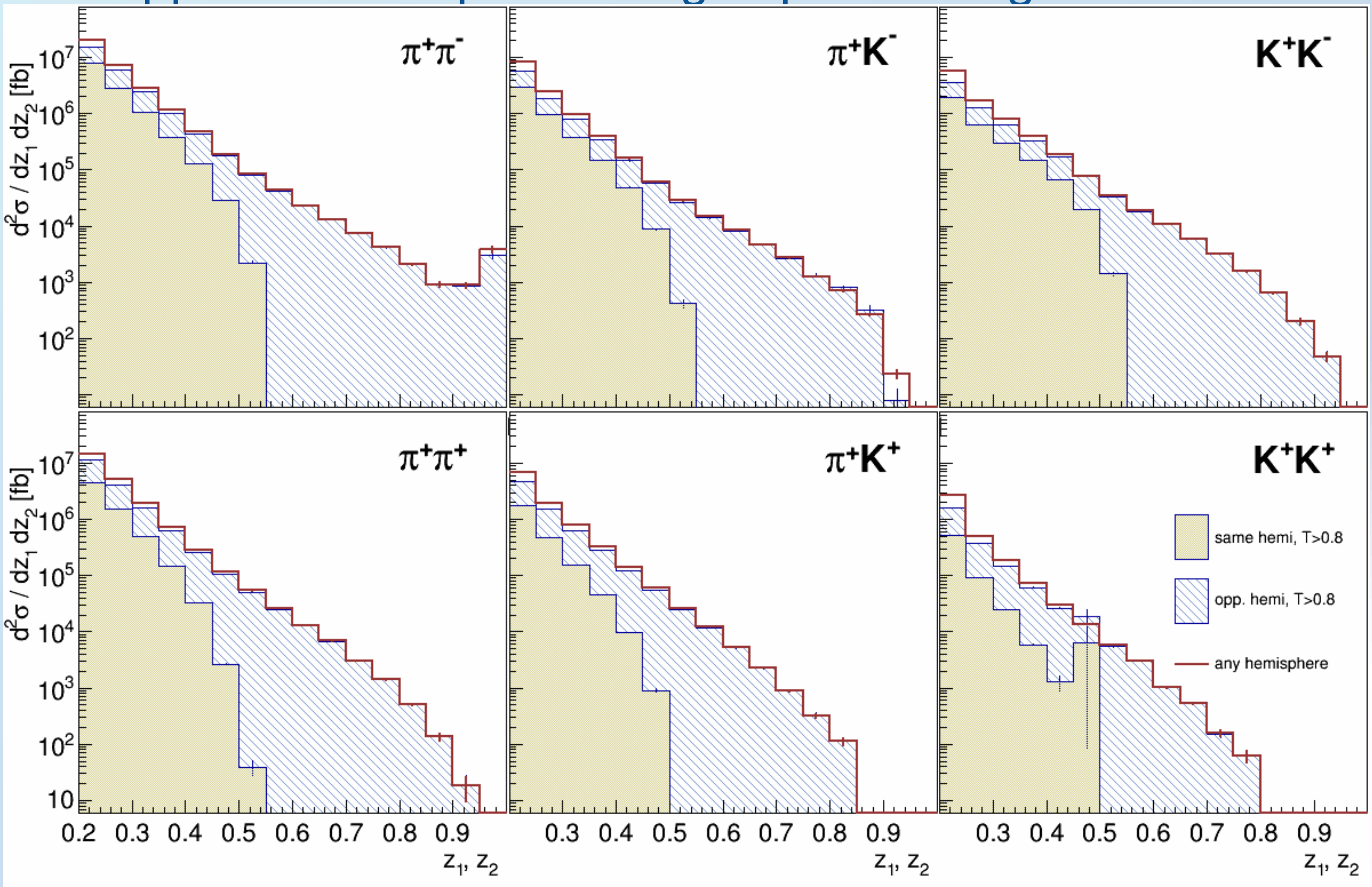


Hemisphere composition

$D^{h}_{1,q}(z_1) D^{h}_{1,\bar{q}}(z_2)$

Same hemisphere contribution drops rapidly
Consistent with LO assumption of
Same hemisphere: single quark → di-hadron FF: (z_1+z_2 <1)
Opposite hemisphere: single quark→single hadron FF

Diagonal z_1,z_2 bins

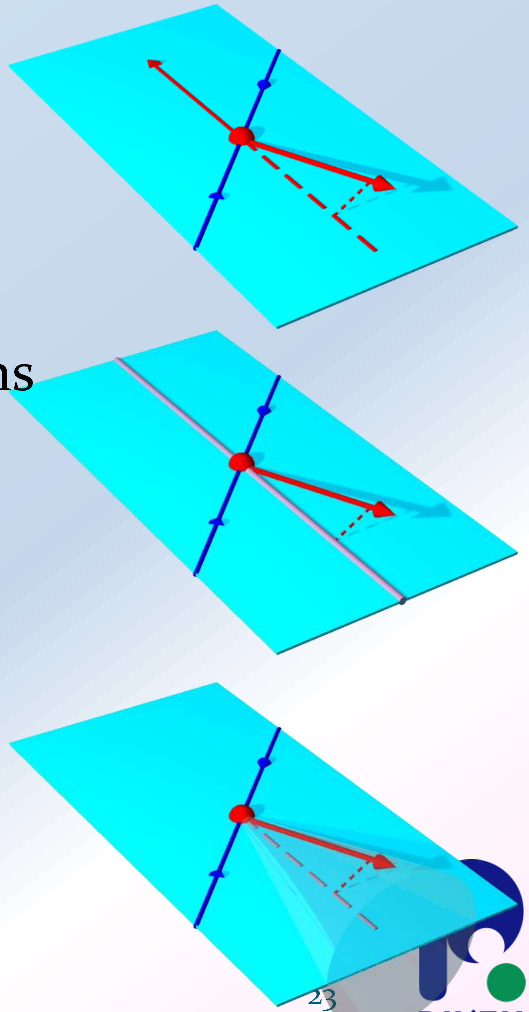


Systematic uncertainties not displayed

K_T Dependence of FFs

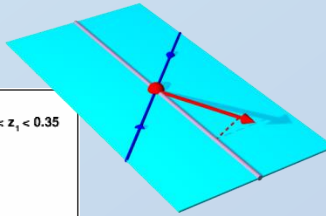
$D^h_{1,q}(z, k_T)$

- Gain also sensitivity into transverse momentum generated in fragmentation
- Two ways to obtain transverse momentum dependence
  - Traditional 2-hadron FF
    - → use transverse momentum between two hadrons (in opposite hemispheres)
    - → Usual convolution of two transverse momenta
  - Single-hadron FF wrt to Thrust or jet axis
    - → No convolution
    - → Need correction for $q\bar{q}$ axis

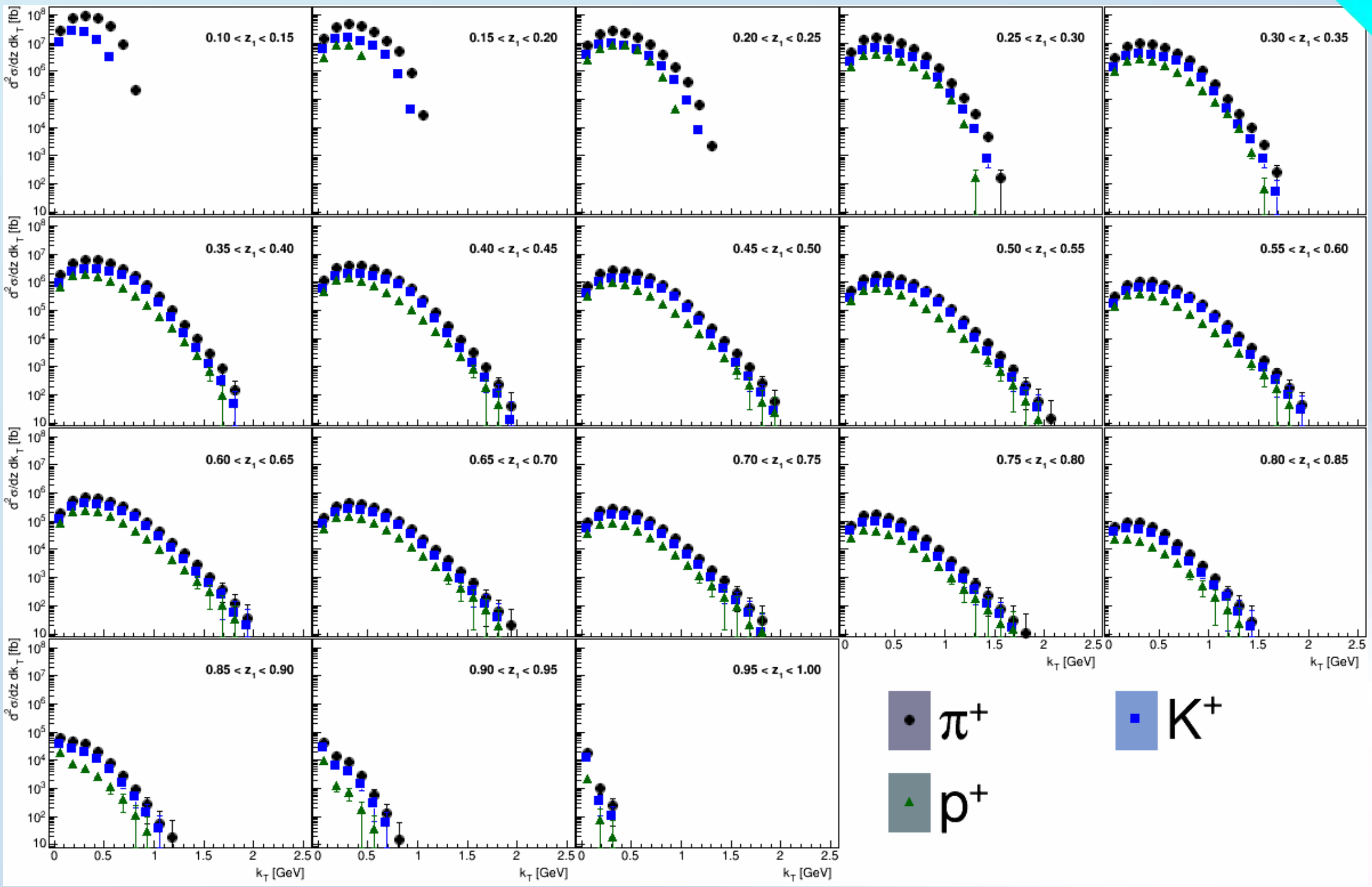


$D^h_{1,q}(z, k_T)$

MC sample for various hadrons



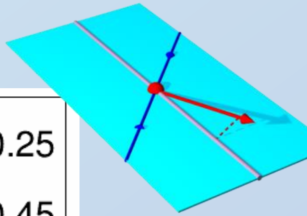
MC simulation

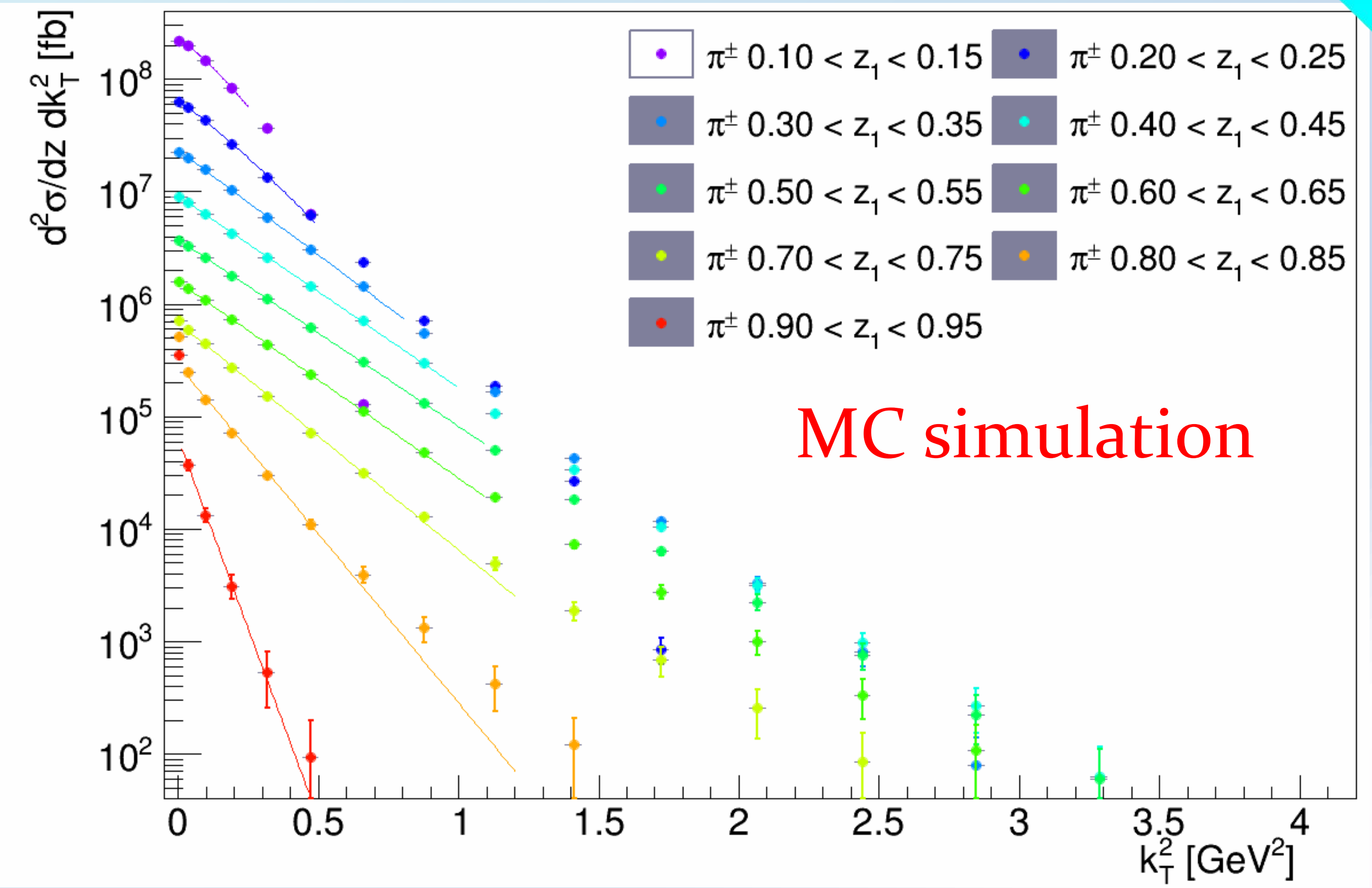


$D^{h}_{1,q}(z, k_T)$

MC examples vs k_T^2

Fit exponential to smaller transverse momenta for Gaussian k_T dependence





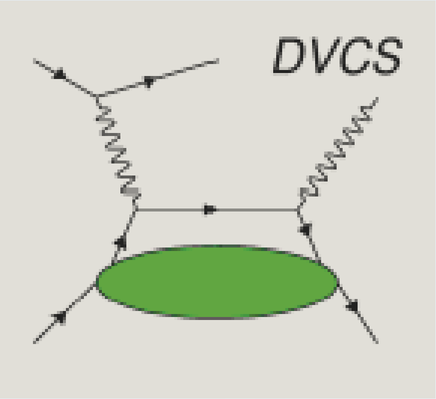
More to come soon from Belle:

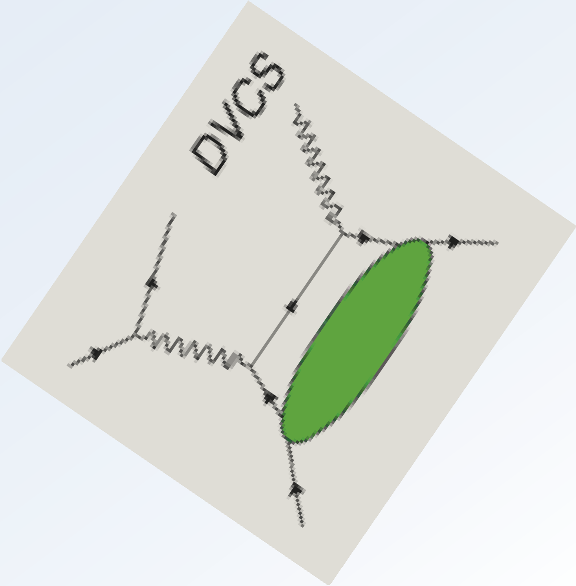
- Lambda transverse polarization $D_{1,q}^{\perp,h}(z,k_T)$
- Di-hadron FFs (same hemisphere, mass x z dependence) $D_{1,q}^{h_1 h_2}(z,M_{hh})$
- Kt dependence either in di-hadrons or single hadron vs thrust axis $D_{1,q}^{h}(z,k_T)$
- Neutral pion and eta Collins $H_{1,q}^{\perp,h}(z,k_T)$
- Finalization of kaon related Collins asymmetries

ca. 2006

DVCS at BELLE??

- Had several discussions with Markus Diehl ca. 2006
- A somewhat rotated DVCS amplitude should be possible: $e^+e^- \rightarrow p\ \bar{p}\ \gamma$
- Only difficulty: "timelike" t will always be > $2m_p$
- Belle Tau preselection data does contain this channel (ie 2 charged tracks, 1 Photon, visible Energy large)

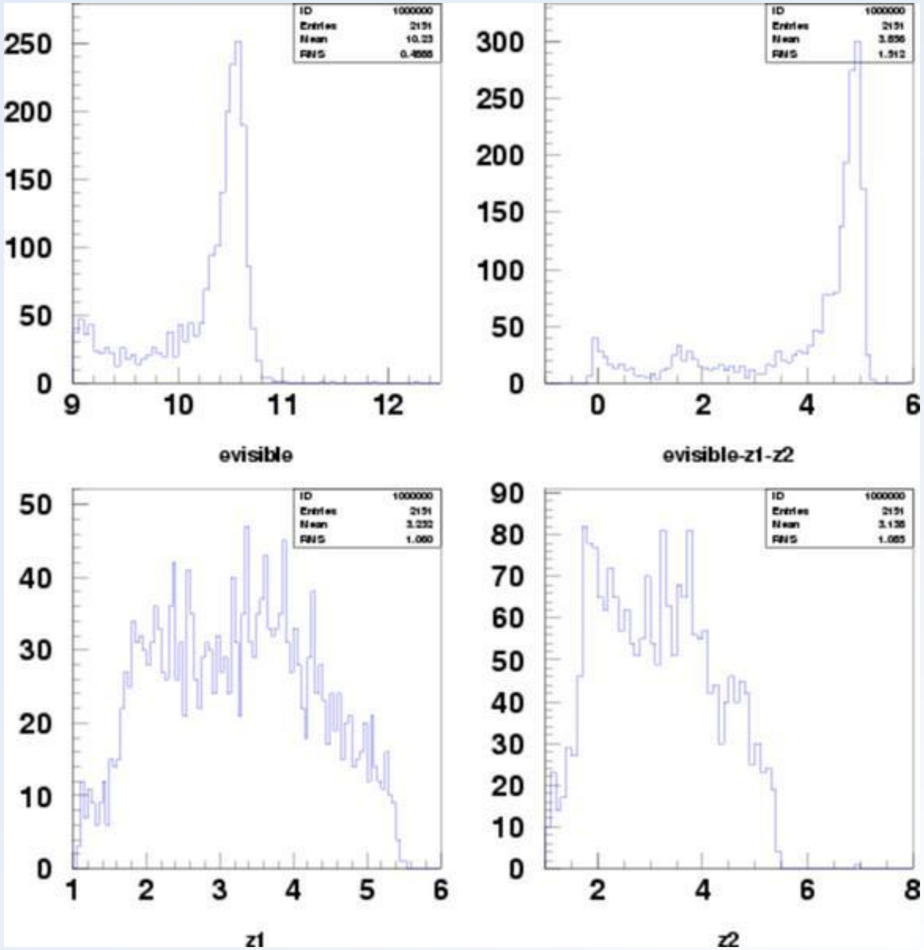




ca. 2006

First glimpse at "DVCS"

- About 18fb^{-1} data sample
- About 2k DVCS "signal"
- What kind of Background do we have? ISR (had one discussion with one BaBar ISR expert who saw unexplained behavior at pp threshold in ISR x sec)
- How do the DIS type DVCS variables translate in e^+e^- case?
- What do theorists think about it?



Summary

- Gluon spin contribution confirmed at higher collision energies, started accessing lower x
- Polarized light sea seems to be asymmetric and disfavors pion cloud models
- First indication of Sivers sign change, expect answer with STAR run17 results + Compass
- Transversity now also accessible at RHIC
- New information towards understanding transverse asymmetries in hadron collisions, but also new puzzles (such as A dependence)
- Diffractive measurements at RHIC ongoing , first access to GPD E possible in J/Psi production
- Various single and di-hadron fragmentation functions published
- Kt dependent cross sections expected soon
- More fragmentation measurements possible
- Timelike DVCS also possible at Belle?

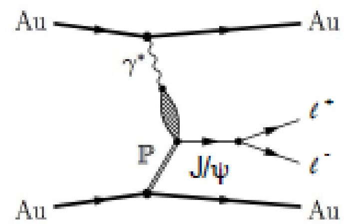
- More to come in the future:
  - RHIC (CNM 2017-23 plan)

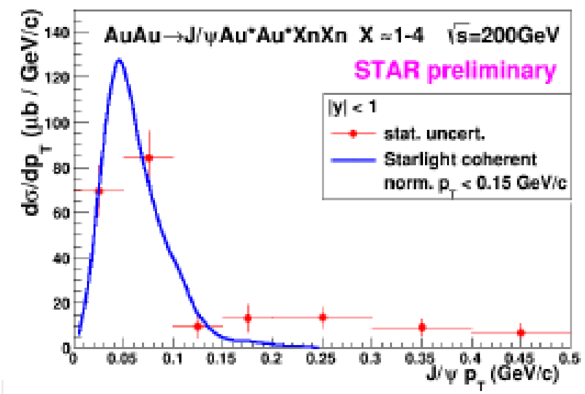
STAR

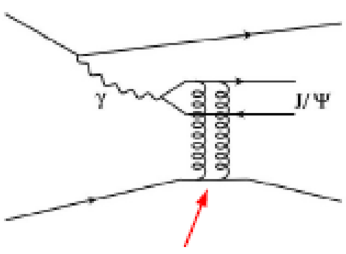
Ultra-Peripheral Collisions Highlight: J/ψ

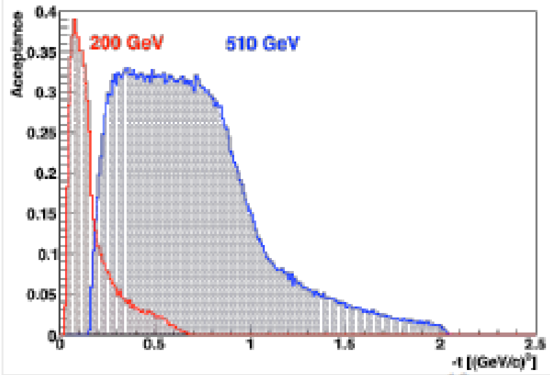
DIS 2016

- VM production from UPC photoproduction on other nucleus
- J/ψ production sensitive to Au gluon content
  - clear signal in Run 10/11
  - run14: large sample with new EM trigger
- GPDs in polarized p
  - run15: RPs tag/measure scattered p
  - phase-II*: RPs closer than Run9
  - larger |t| range, increased acc.









BNL -- 6/16/16

2016 PAC Meeting :: Run 14/15

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