MESON PDFs – status at COMPASS and future options

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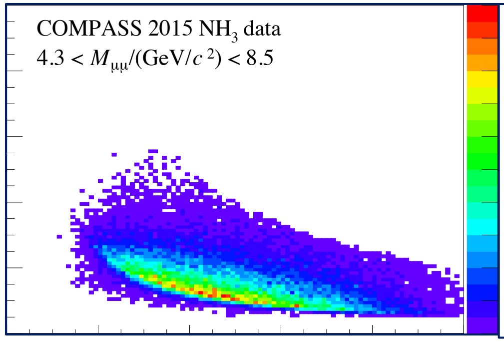
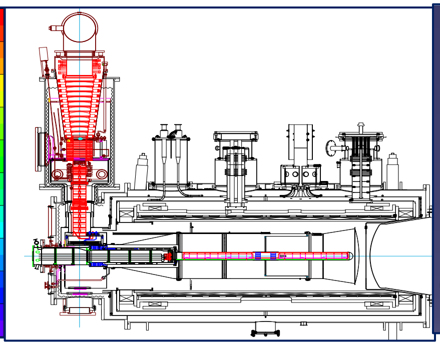
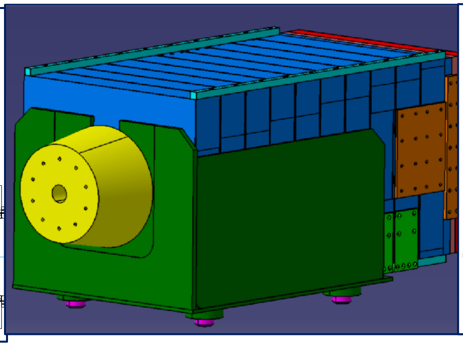
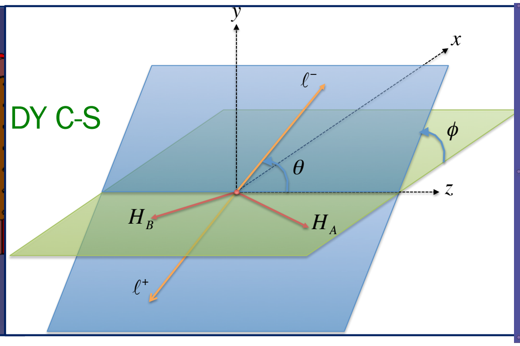
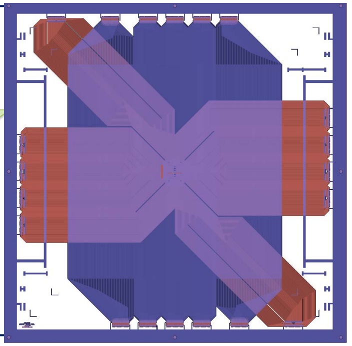




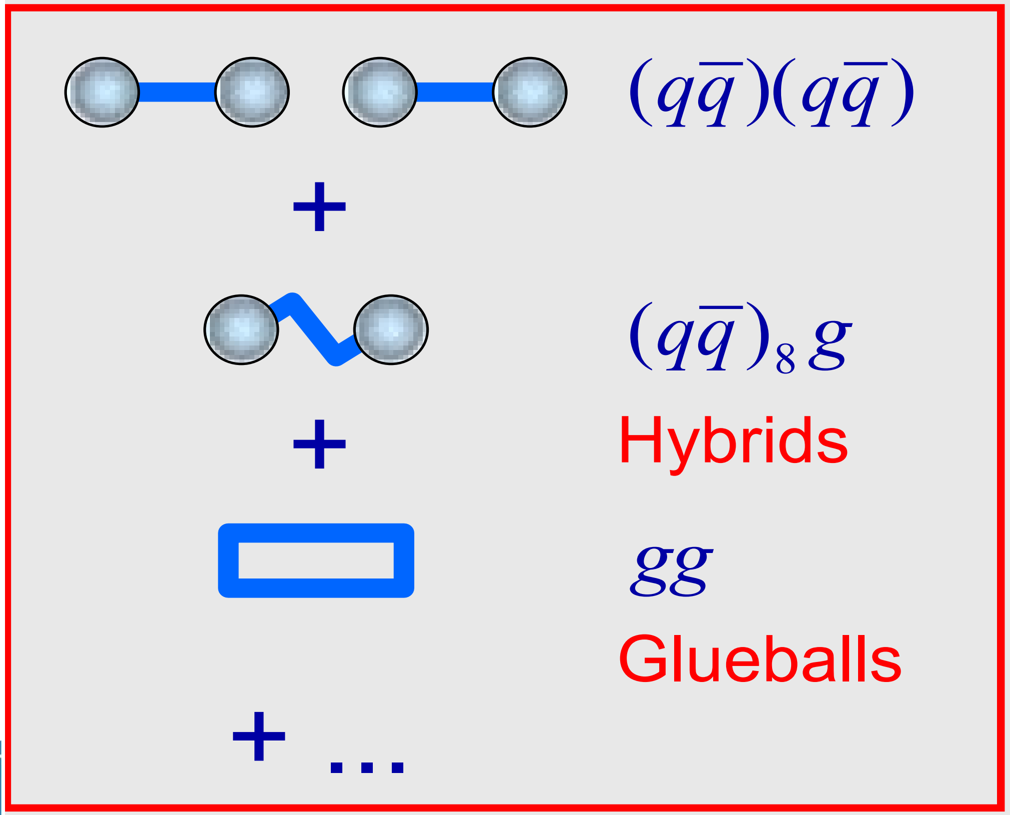




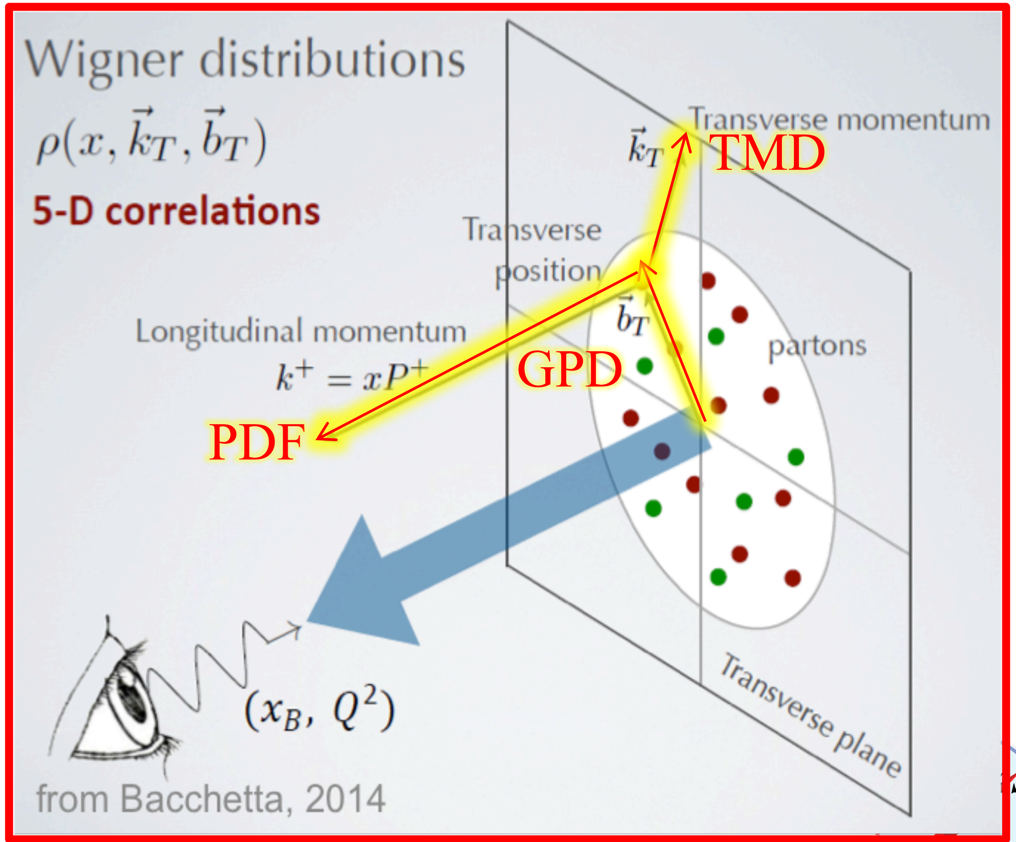


COMPASS@CERN : FACILITY FOR QCD STUDIES

- Hadron spectroscopy, chiral dynamics
  - Mainly light mesons domain
    - With hadron (and muon) beams



- Hadron Structure
  - 5-dim. structure of the hadron(s)
    - With muon and hadron beams

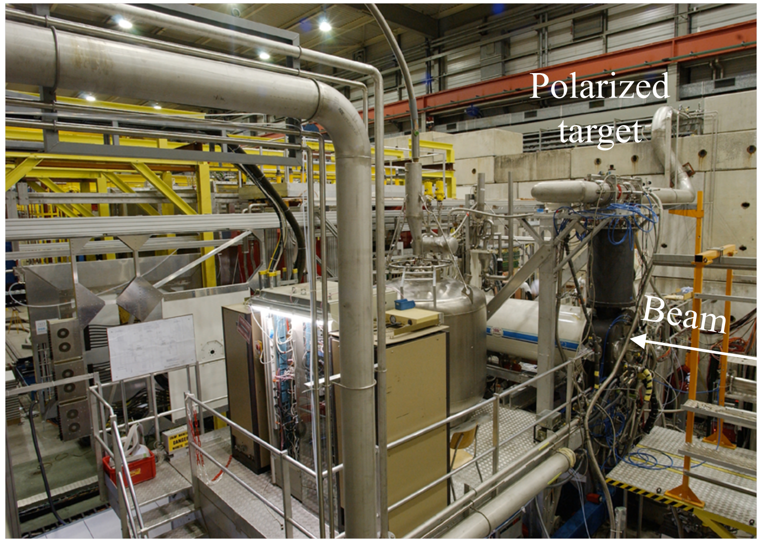


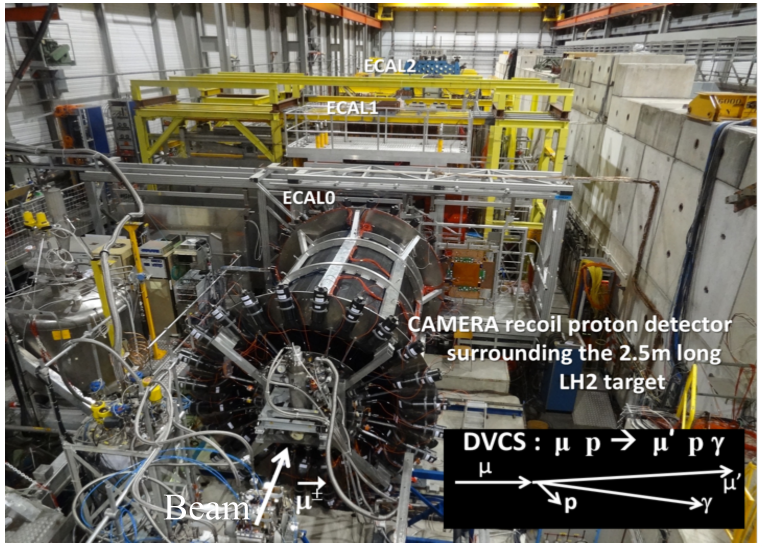
COMPASS is an old experiment - already two “phases”

- COMPASS I : 2002 – 2011
  - Longitudinally polarized DIS and SIDIS
  - Transversely polarized SIDIS
  - Hadron spectroscopy and chiral dynamics
- COMPASS II : 2012 – 2018
  - Primakoff studies (2012)
  - DVCS and Meson-production (2016, 2017)
  - Polarized Drell-Yan process (2015, 2018)

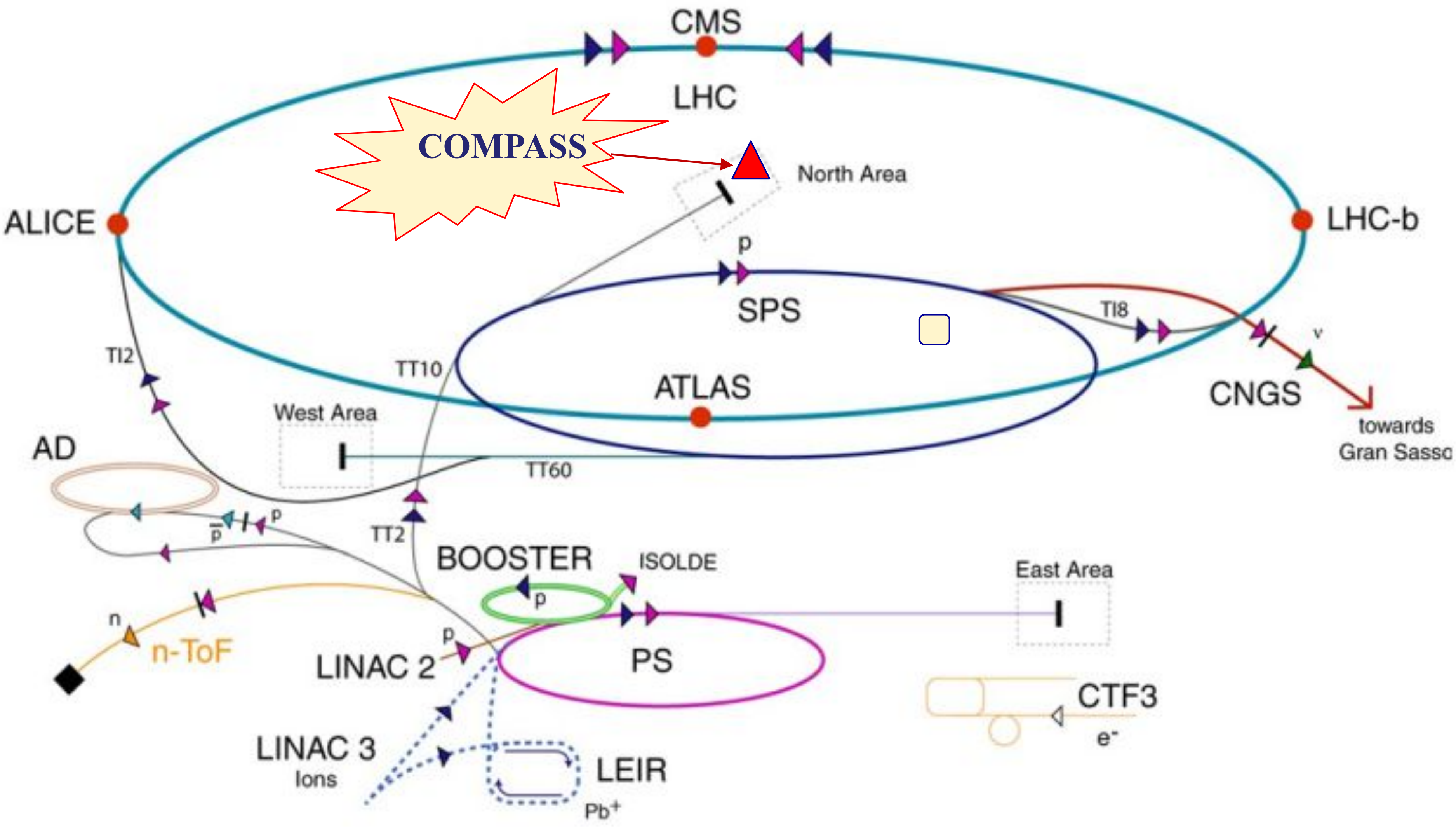
<u>Beam</u>

	Beam
Longitudinally polarized DIS and SIDIS; Transversely polarized SIDIS	Muons
Hadron spectroscopy and chiral dynamics	Hadrons
Primakoff studies (2012)	Hadrons
DVCS and Meson-production (2016, 2017)	Muons
Polarized Drell-Yan process (2015, 2018)	Hadrons





CERN accelerator complex

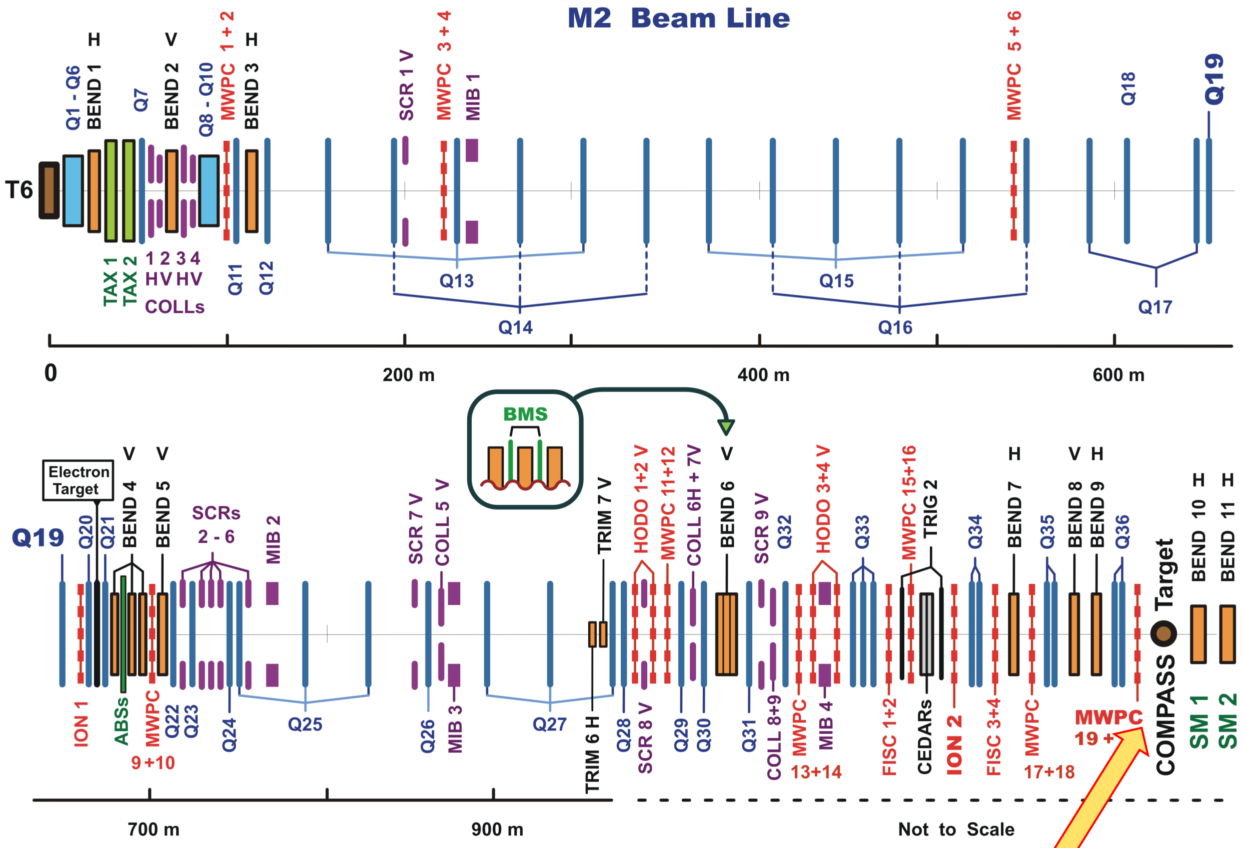


CERN M2 beam line

Abbon et al., NIM A779 (2015) 69-115

- Beams at COMPASS:
  - muons: μ^+, μ^-,
  - hadrons: $h^+(p, \pi^+, K^+)$, $h^-(\pi^-, K^- \bar{p})$
  - electrons: e^-
  - 1 or 2 spills of 5 s every 33-48 sec

SPS protons

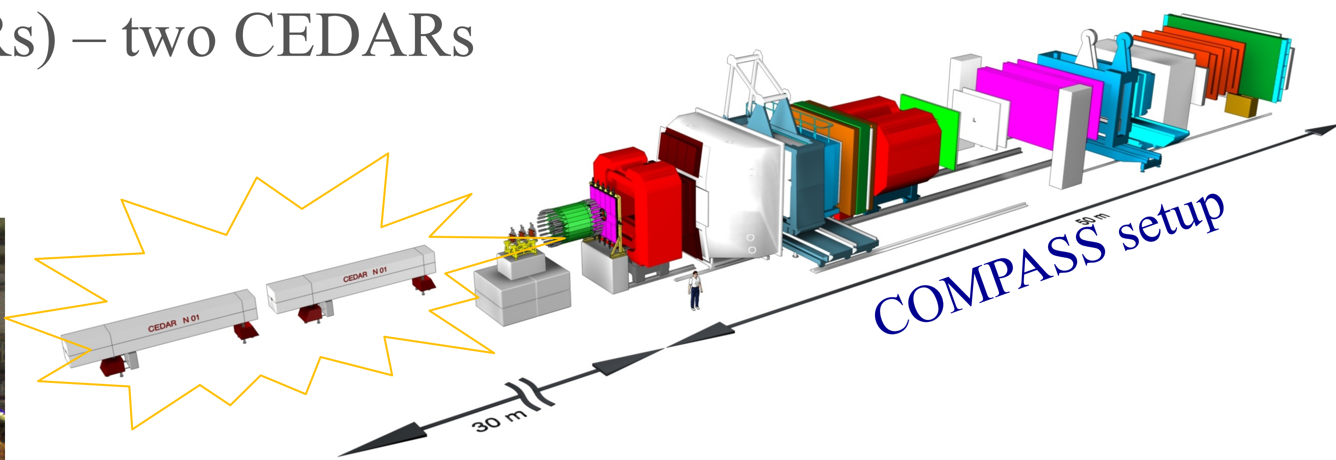


Unique combination of positive and negative beams of different species

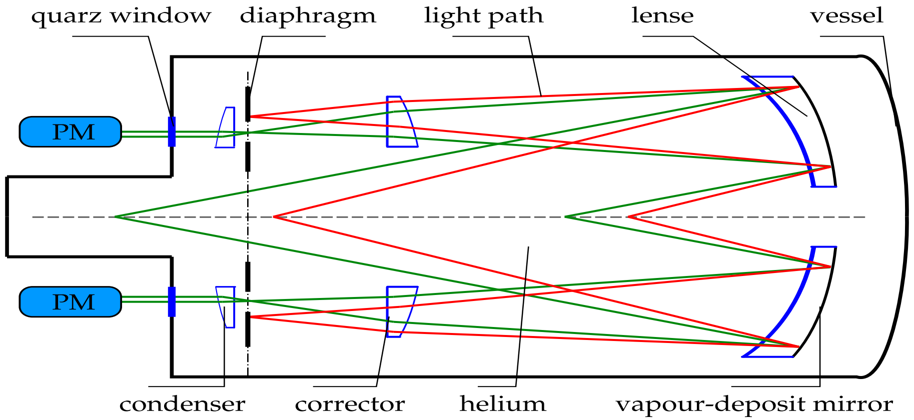
COMPASS Target

Beam particle identification

- Differential Cerenkov counters (CEDARs) – two CEDARs



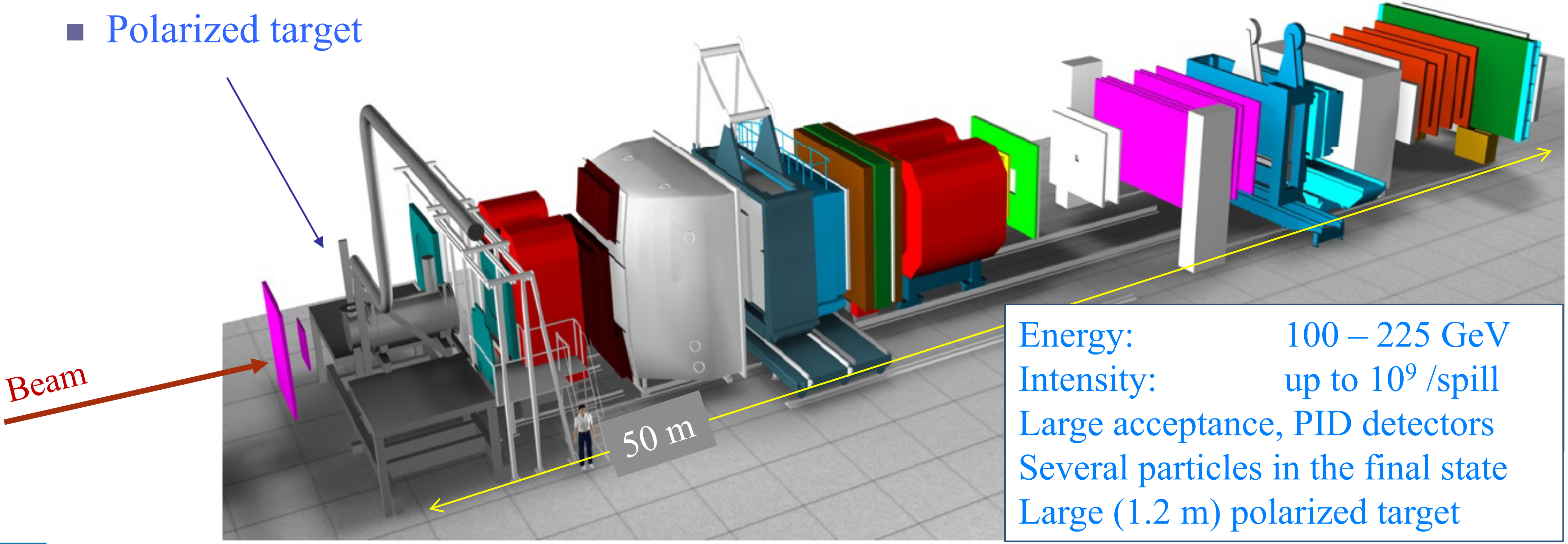
CEDAR principle



The two CEDARs are located upstream of the COMPASS experimental hall

COMPASS : a large, fixed-target, versatile setup

- COMPASS apparatus
  - Built for detecting several particles in the final state
  - Two spectrometers: Small-angle and Large-angle – large and flat acceptance
  - Polarized target

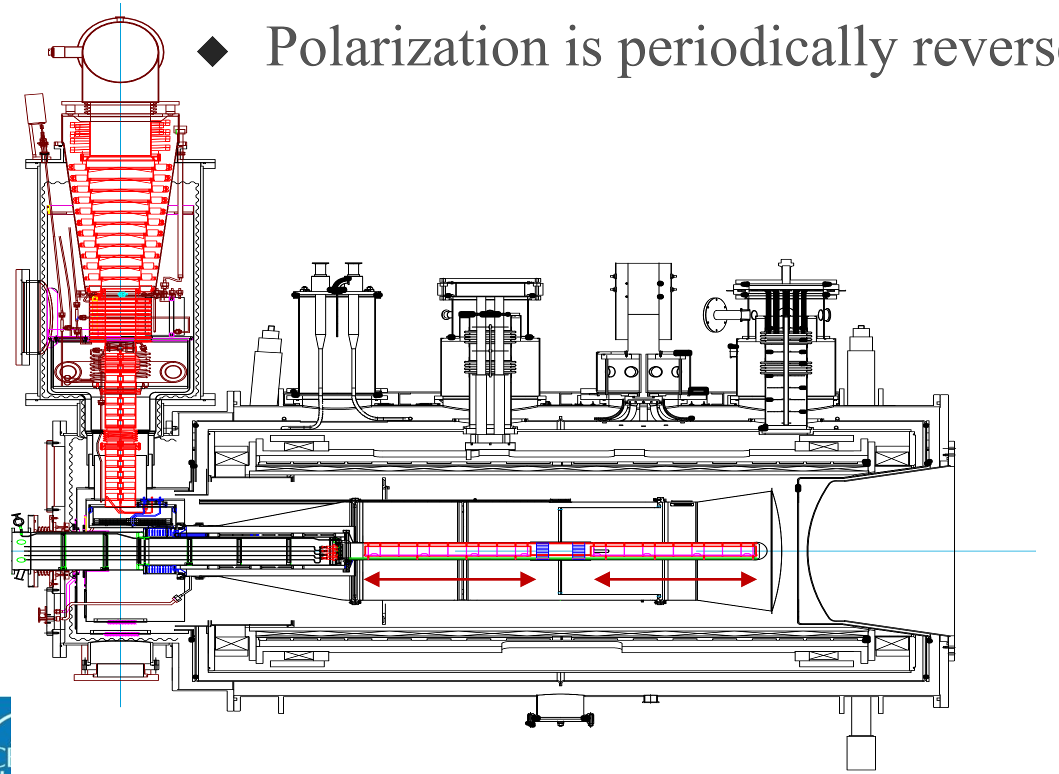


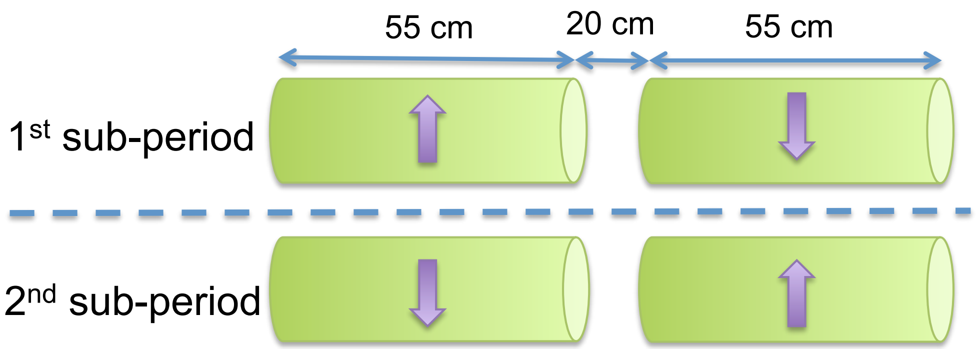
Energy:	100 – 225 GeV
Intensity:	up to 10^9 /spill
Large acceptance, PID detectors	
Several particles in the final state	
Large (1.2 m) polarized target	

"Minor" changes to the setup – switch between various physics programs

COMPASS polarized target

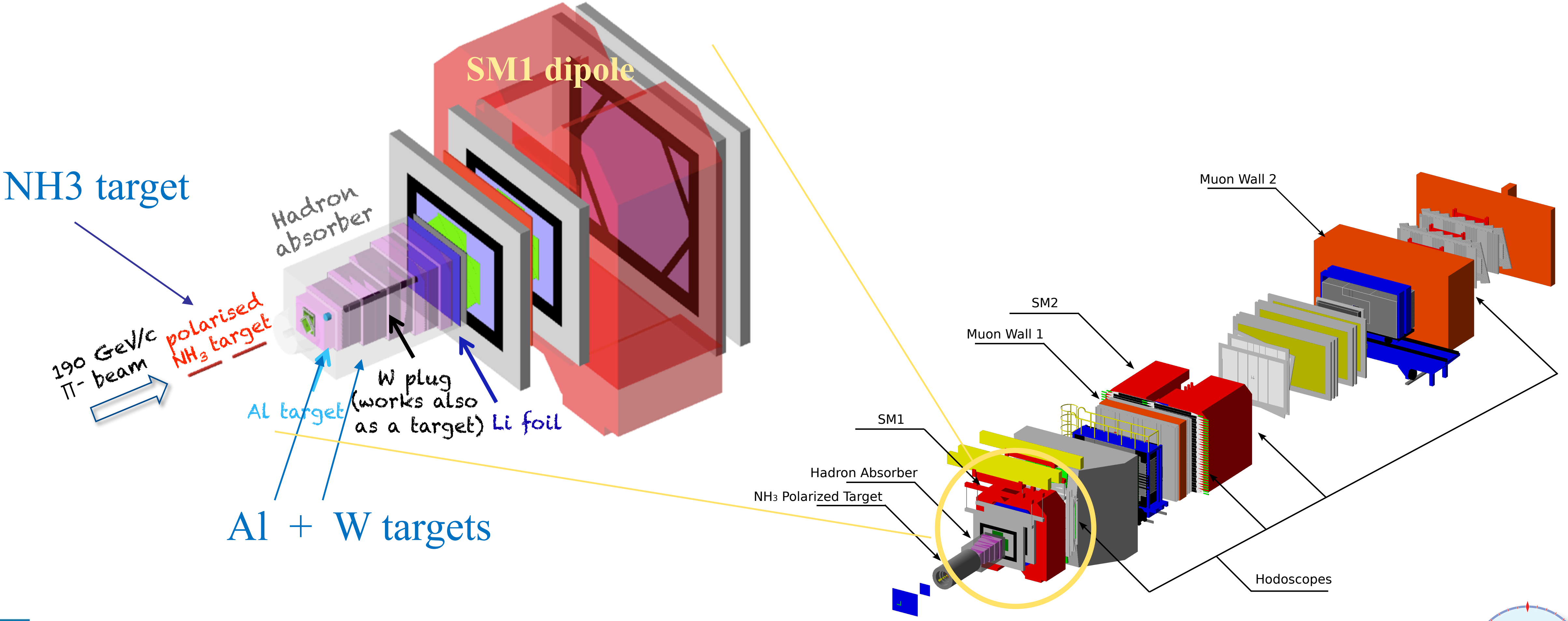
- Polarized target with two 55 cm long cells (for DY); three cells for SIDIS
- Superconducting magnets: solenoid + dipole
- Target filled with ammonia (NH_3) solid beads; also available: ^{6}LiD
- Polarization in longitudinal mode, data is taken in transverse mode
- Polarization is periodically reversed





COMPASS – Drell-Yan setup

- Large hadron absorber, with a central Tungsten plug



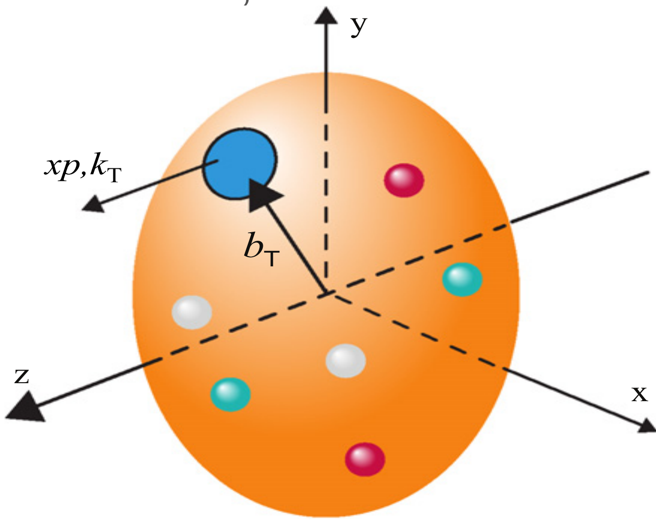
Drell-Yan data taking: 2015 and 2018

Drell-Yan – interlude

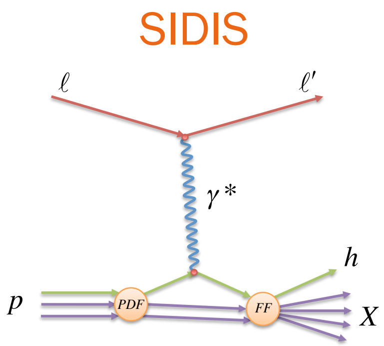
the COMPASS most recent result

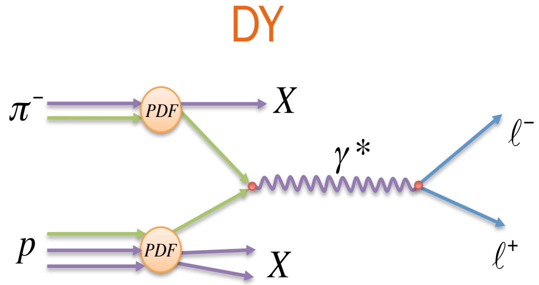
Polarized Drell-Yan – a tool to access TMD PDFs

- Goal of nucleon structure studies: distributions of partons inside the nucleon; understand their internal dynamics
  - Study PDF as a function of both x and $b_\perp$ (GPDs) or x and k_T (TMDs)



- TMDs: can be accessed both in SIDIS and Drell-Yan:





- Collinear factorization: short distance cross-section $\otimes$ the universal long-distance PDFs
  - TMD factorization: generalization for partons with transverse momentum components

Collins, Soper, Sterman, Adv. Ser. High En Phys. 5, 1988 + arXiv:hep-ph/0409313v1

Transverse Momentum Dependent PDFs

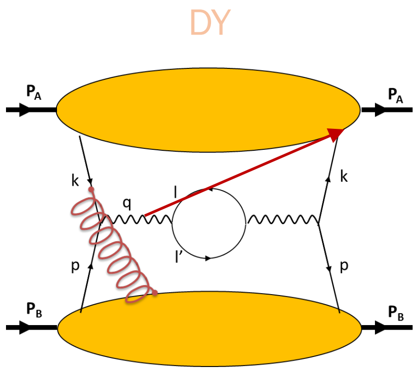
- 8 TMDs at leading twist

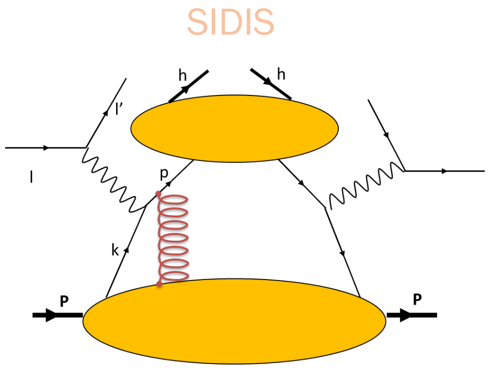
"TMDs"

nucleon polarization (columns) / **quark** polarization (rows)

	U	L	T
U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*
L		g_1 *helicity* Δq	g_{1T}
T	$h_1^{\perp}$ *Boer-Mulders*	$h_{1L}^{\perp}$	h_1 *transversity* $h_{1T}^{\perp}$ *pretzelosity*

- Sign change for Sivers and BM TMDs





Sivers $\quad f_{1T}^{\perp}\,(\text{SIDIS}) = -f_{1T}^{\perp}\,(\text{DY})$

Boer-Mulders $\quad h_1^{\perp}\,(\text{SIDIS}) = -h_1^{\perp}\,(\text{DY})$

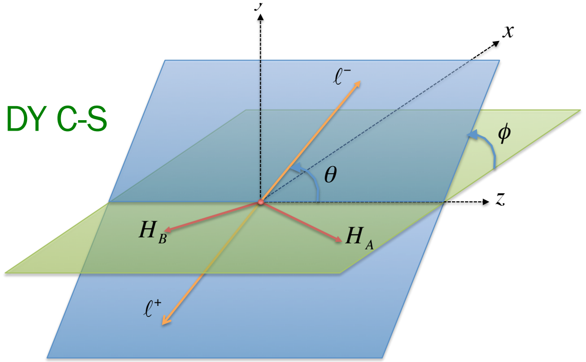
Sivers and BM TMDs are process-dependent (modified universality)

If the QCD factorization is correct, the sign of Sivers and BM TMDs should change

Leading twist asymmetries in transversely polarized DY/SIDIS

Simultaneous measurement of all asymmetries

- ✦ Drell-Yan

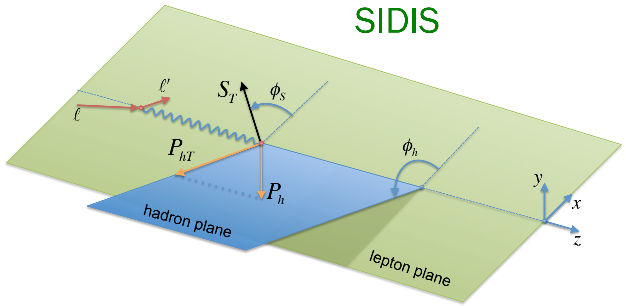


pion PDFs:

PDF: $h_{1,\pi}^{\perp q}$

BM: $f_{1,\pi}^{q}$

- ✦ SIDIS



Fragmentation functions:

Collins: $H_{1,q}^{\perp h}$

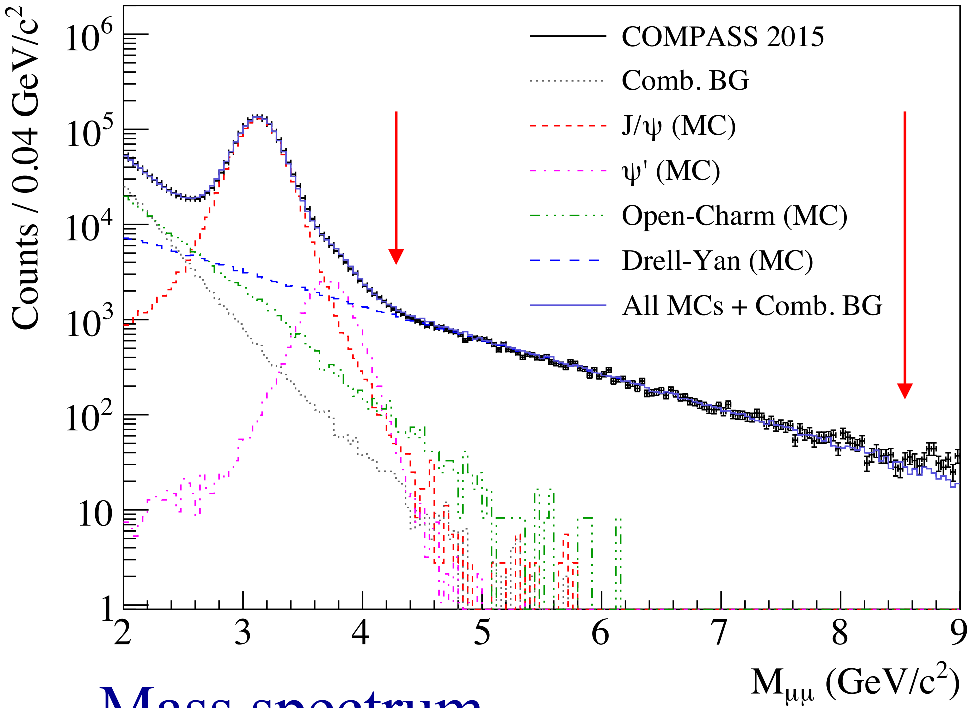
Unpol: $D_{1,q}^{h}$

	Drell-Yan		SIDIS
unpolarized	$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	**Boer-Mulders**	$A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$
	$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	**Sivers**	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$
	$A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$	**transversity**	$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$
	$A_{UT}^{\sin(2\phi+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$	**pretzelosity**	$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$

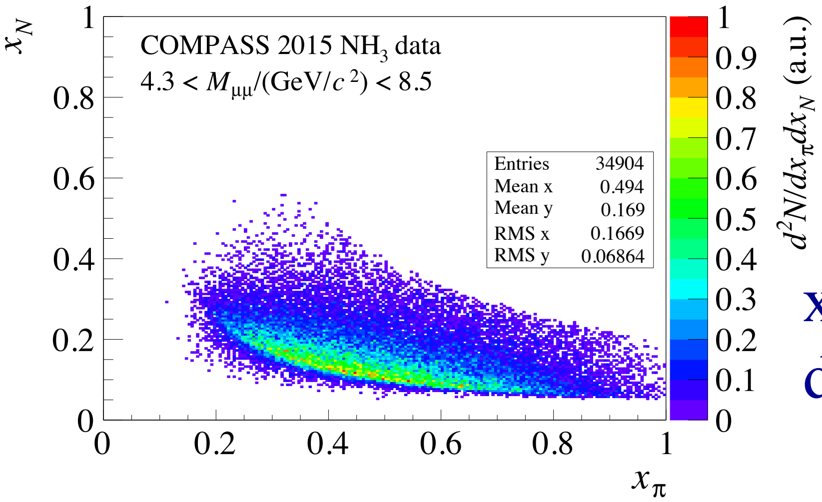
The four asymmetries are simultaneously extracted from either SIDIS or DY data

Di-muon sample – some results from 2015

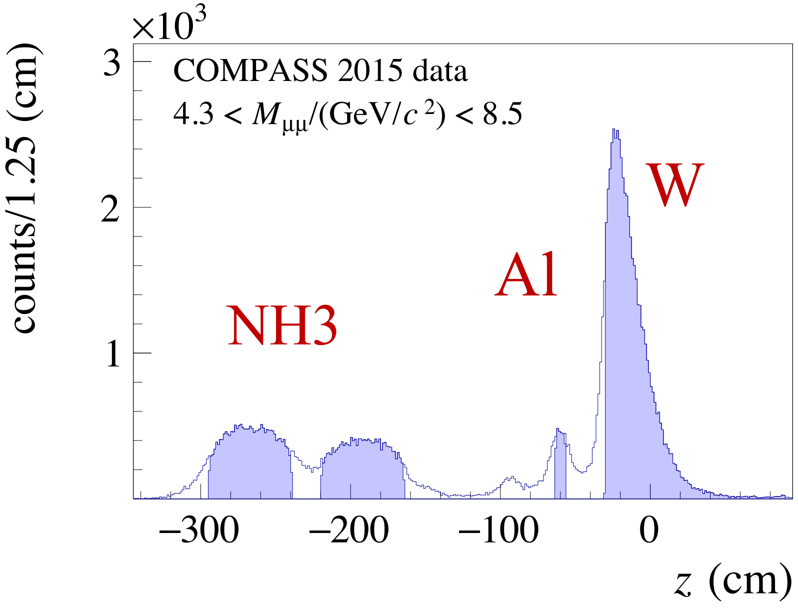
- Drell-Yan data from 2015: 4.3 – 8.5 GeV/c^2



Mass spectrum



x_N vs x_π distribution

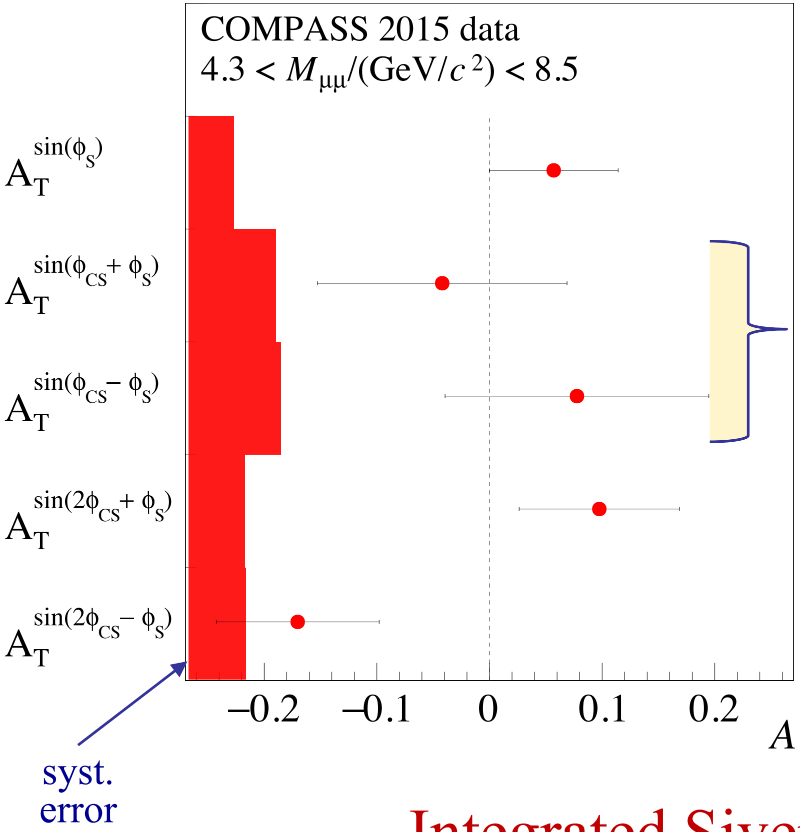


Vertex distribution

First Transverse Spin Asymmetries (TSA) results

- Averaged TSAs for 2015 data

Preprint CERN-EP-2017-059, arXiv: 1704.00488, subm. PRL



Density PDF (π) ⊗ Sivers (p)

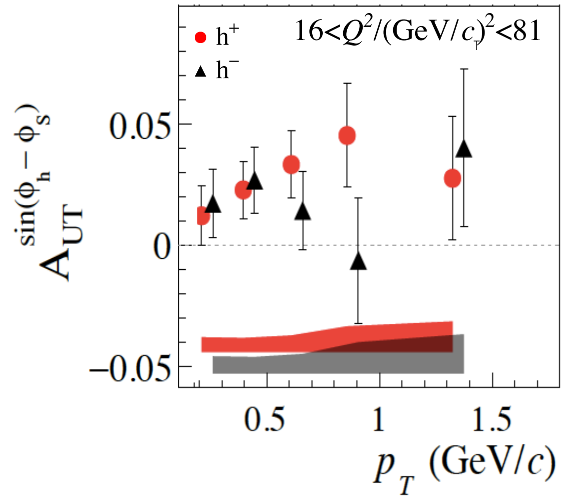
Higher twist asymmetries

BM PDF (π) ⊗ Pretzelosity (p)

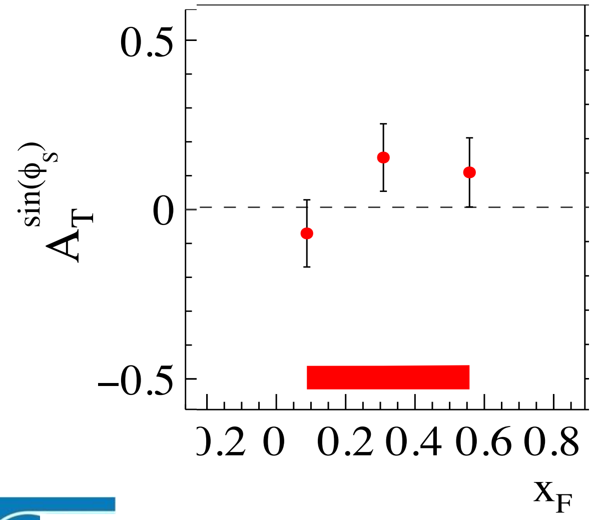
BM PDF (π) ⊗ Transversity (p)

Integrated Sivers asymmetry is positive (within one sigma)
Transversity is negative (two sigma), Pretzelosity positive (one sigma)

Final Sivers asymmetry

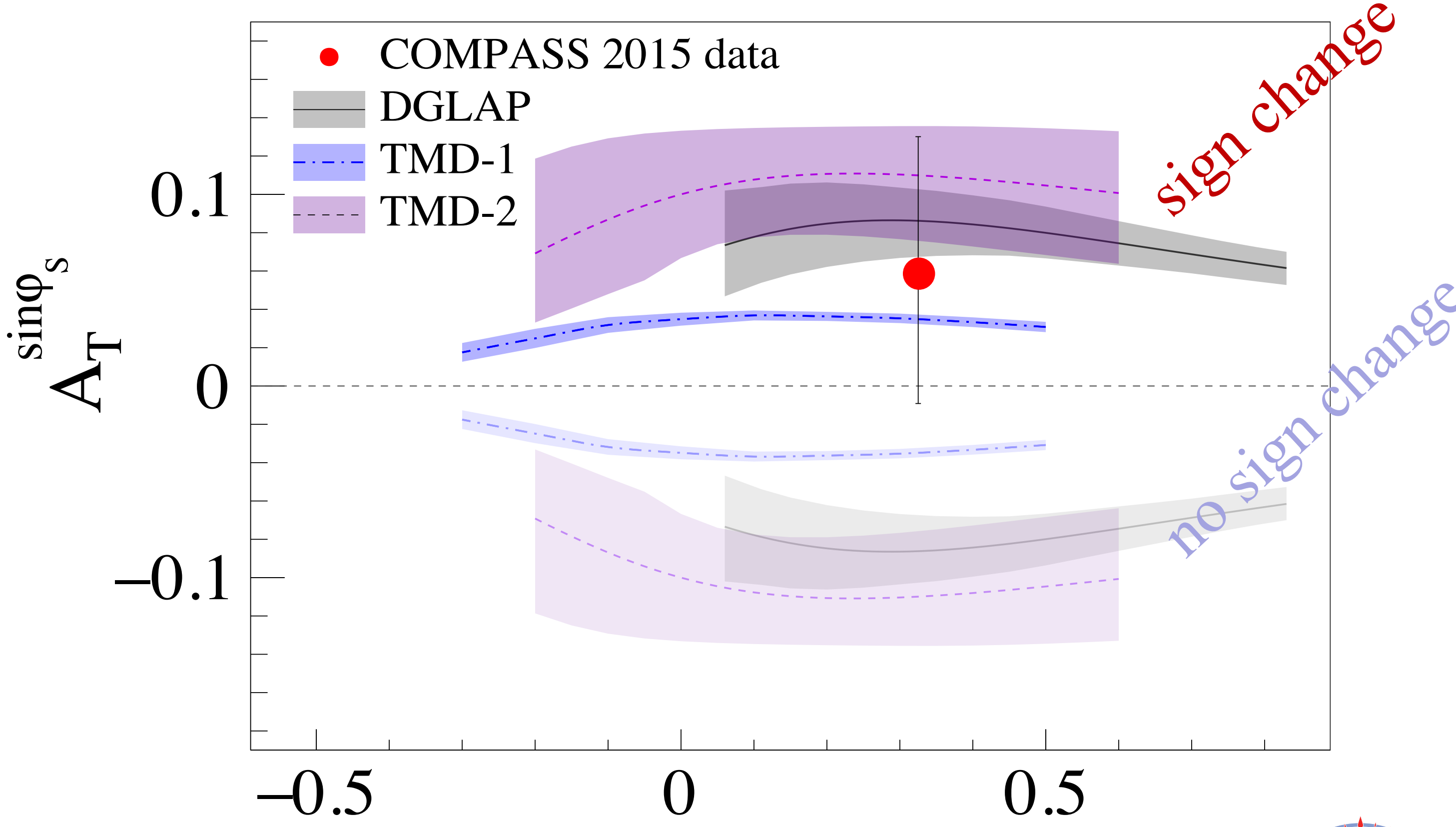


SIDIS data / Compass, same Q^2 range as in DY



DY data Compass

DGLAP: Anselmino et al. arXiv:1612.06413
TMD1: Echevarria et al. Phys Rev D89, 074013 (2014)
TMD2: Sun and Yuan, Phys Rev D88, 114012 (2013)



The measurement of the Sivers asymmetry is consistent with the sign-change prediction

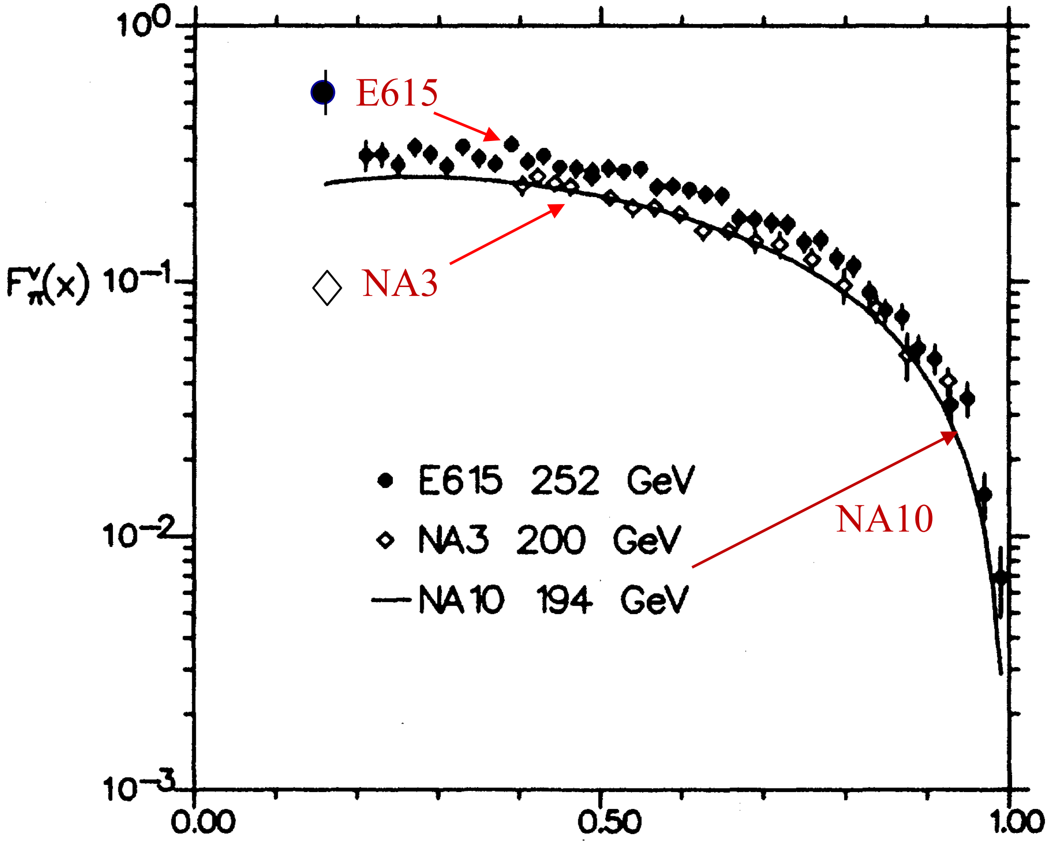
Meson PDFs – status and further options

In collaboration with Wen-Chen Chang, Jen-Chieh Peng and Takahiro Sawada

Pion valence PDF – Available data

- Pion PDF data (see also Jen-Chieh's talk)
  - NA3 : 150, 200, 280 GeV, Pt target
  - NA10 : 194 GeV, W target
  - E615 : 252 GeV, W target
- Analysis
  - Val. PDF: $Ax^{\alpha}(1-x)^{\beta}$
  - Sea quarks subtraction: use NA3 data
  - Correct for A-dependence
  - Analysis at LO only
- Result
  - Pseudo-data PDF points from R615 (LO)

Conway et al., PRD 39, 92 (1989).



Note: up to 20% difference between NA3/NA10 and E615
Three "global fit" parametrizations:1989

Pion global fit – SMRS (1992)

- SMRS : fit at NLO
  - valence quarks: data from NA3, NA10, E615
  - sea: vary from 5% to 20% of the total pion momentum
  - gluons: use $\pi p \to \gamma X$ data from WA70 (1989)

  - Parametrize PDFs:

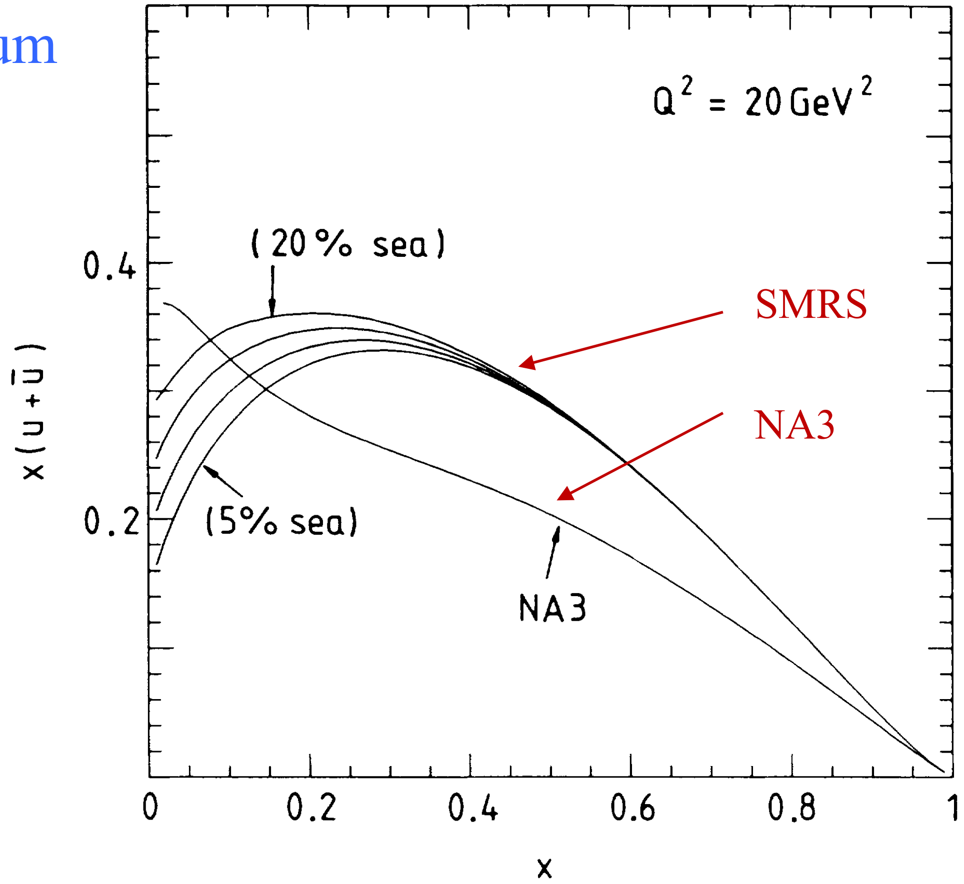
$$xV_\pi = A_V x^\alpha (1-x)^\beta ,$$

$$xS_\pi \equiv 2x(u+\bar{d}+\bar{s}) = A_s(1-x)^{\eta_s} ,$$

$$xg = A_g(1-x)^{\eta_g} ,$$

  - First moments @4 GeV^2
    - valence: 0.47
    - sea: 0.10 – 0.20
    - gluons: 0.43 – 0.33

Sutton, Martin, Roberts and Strirling, PRD 45, 2349 (1992).



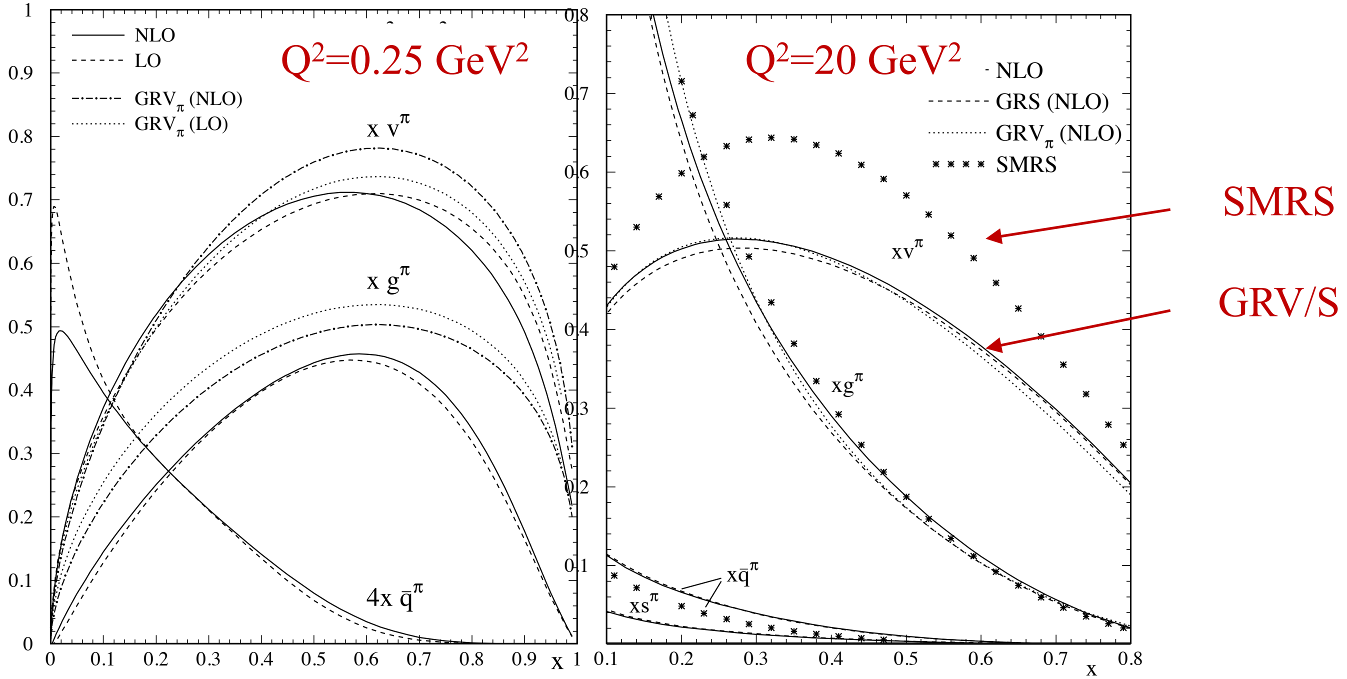
SMRS: “tension” with NA3 data

Pion global fits – GRV/S: 1992, 1998, 1999

- GRV inputs (NLO):
  - 1992: π-induced DY from NA3, NA10, E615
  - 1999: Constituent Quark Model constraints
  - Gluons: π-induced prompt photon data

GRV: Z Phys C53, 651 (1992).

GRS: Eur Phys J C10, 313 (1999).

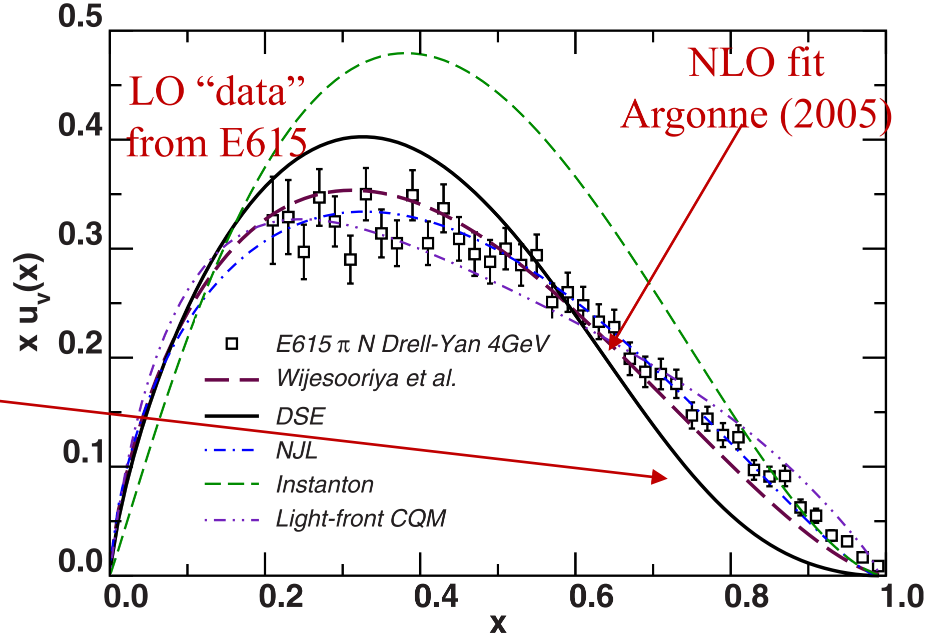


The two global fits are non-consistent

Pion PDF: agreement with theory?

- Pion PDF : parametrized as: $\sim Ax^{\alpha}(1-x)^{\beta}$
  - Large x: the fall-off is described by the slope parameter β.
    - NA3: $\beta = 1.17$
    - E615: $\beta = 1.26$
    - SMRS: $\beta = 1.08$
    - GRS: $\beta = 1.05$
    - Const Quark Mod: $\beta < 2.0$
  - However: pQCD (Brodsky), DSE: $\beta \gtrsim 2.0$
  - DSE (C. Roberts et al.,) $\beta = 3.0$

Holt and Roberts, Rev. Mod. Phys. 82, 2991 (2010).



Slope can be re-measured

Medium x: data accuracy is not good enough

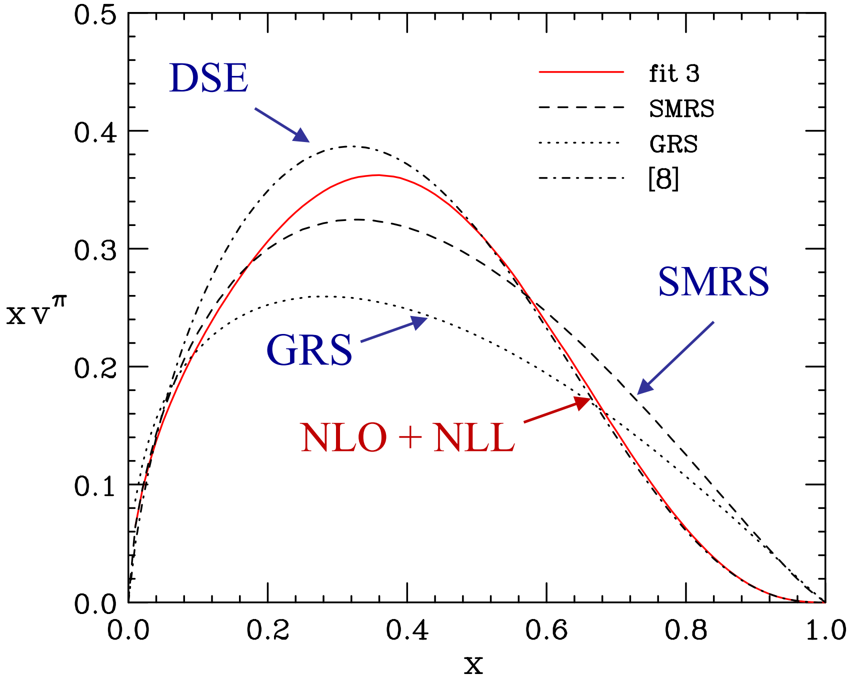
Pion (valence) PDF – reanalysis with NLL resummation (2010)

- New analysis of E615 data
  - NLO, NLL
  - sea + gluons: from GRSh – 1999 ☹
  - take into account nuclear effects
  - Valence PDF:

$$xv^{\pi}(x) = Nvx^{\alpha}(1-x)^{\beta}(1+\gamma x^{\delta})$$

Falloff at Q = 4 GeV: $\beta = 2.34$
~ agreement with pQCD, DSE

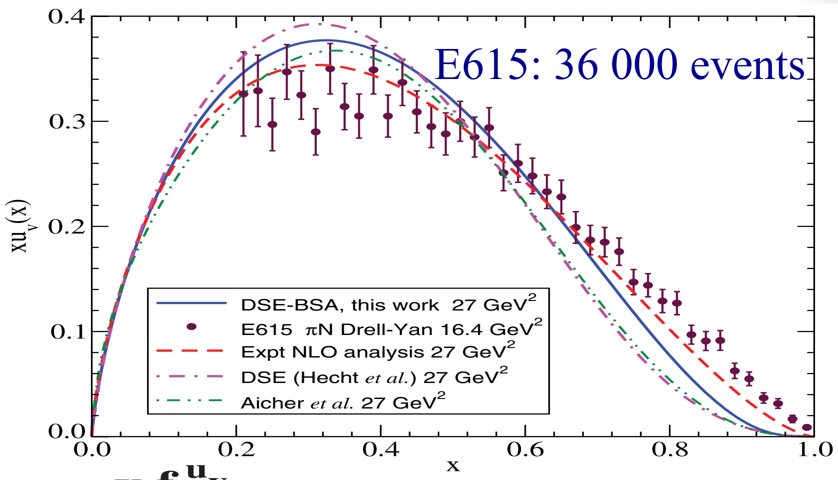
Aicher, Schäfer and Vogelsang, PRL 105, 252003 (2010).

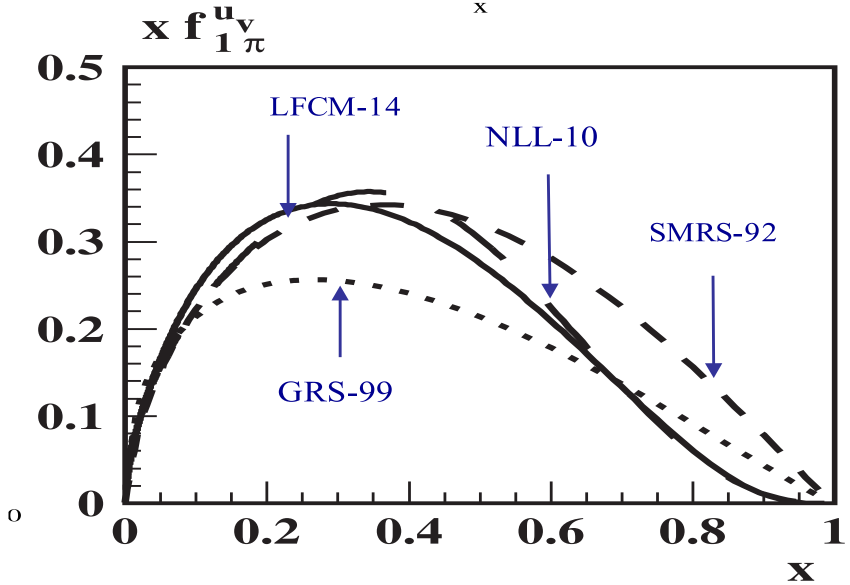


NLL: makes the valence distribution softer at high x

Data and (some of the) present calculations of the pion PDF

- Data (see also Jen-Chieh's talk)
  - E615 – only pseudo data (LO) available, 1989
  - NA3,1983 and NA10, 1985
- Global fits
  - SMRS, 1992
  - GRV/GRS, 1992 – 1999
- Re-analysis
  - NLO : Wijesoorija, Reimer, Holt, 2005
  - NLO/NLL : Aicher, Shaffer, Voglesang, 2010
- Model calculations
  - DSE : Nguyen et al., 2011, Chen et al., 2016
  - LFCM : Pasquini et al., 2014
  - NLChQM: Nam, 2012



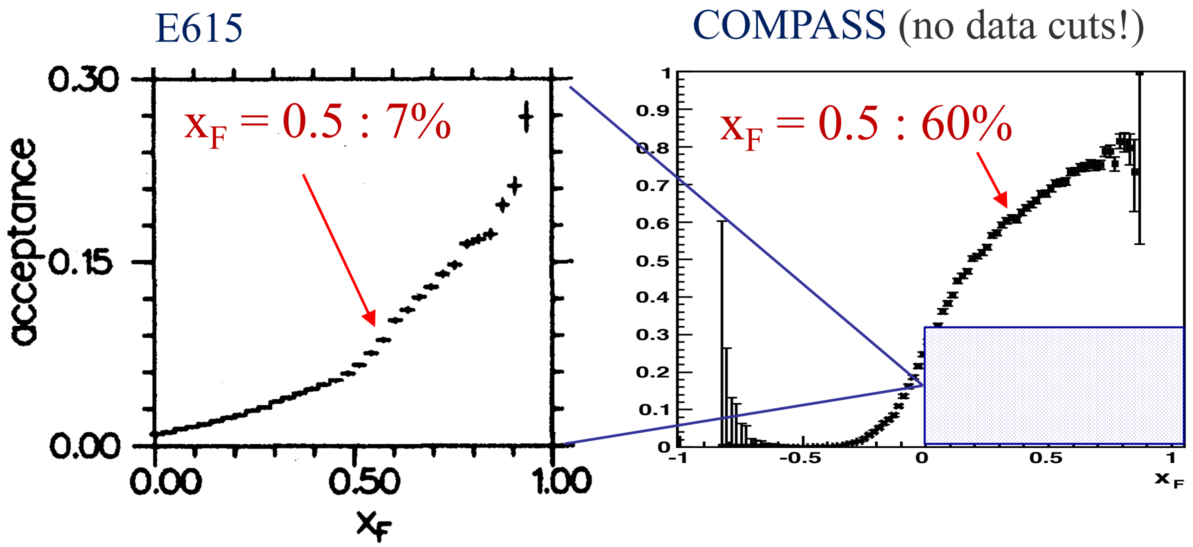


(c)

Continuous interest, no no new data since 1989

New data from COMPASS to come

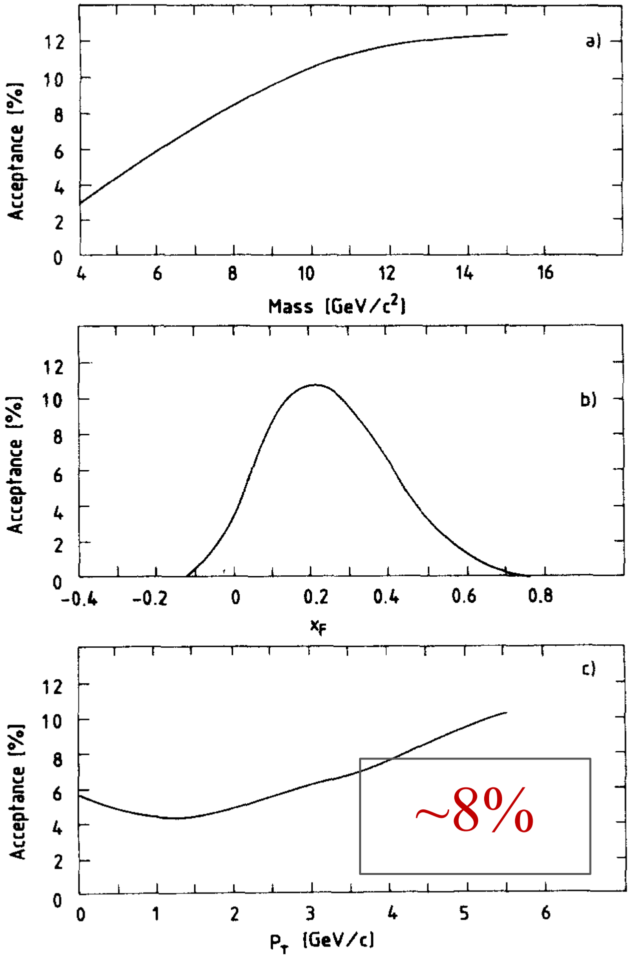
- COMPASS features
  - Better statistics on NH_3, and also W:
    - E615: 36 000; Compass 2015+2018: up to ~150 000 (x4); and about ~300 000 events on W.
  - Very good x_F resolution (~0.01)
  - Better acceptance ; large x_F coverage



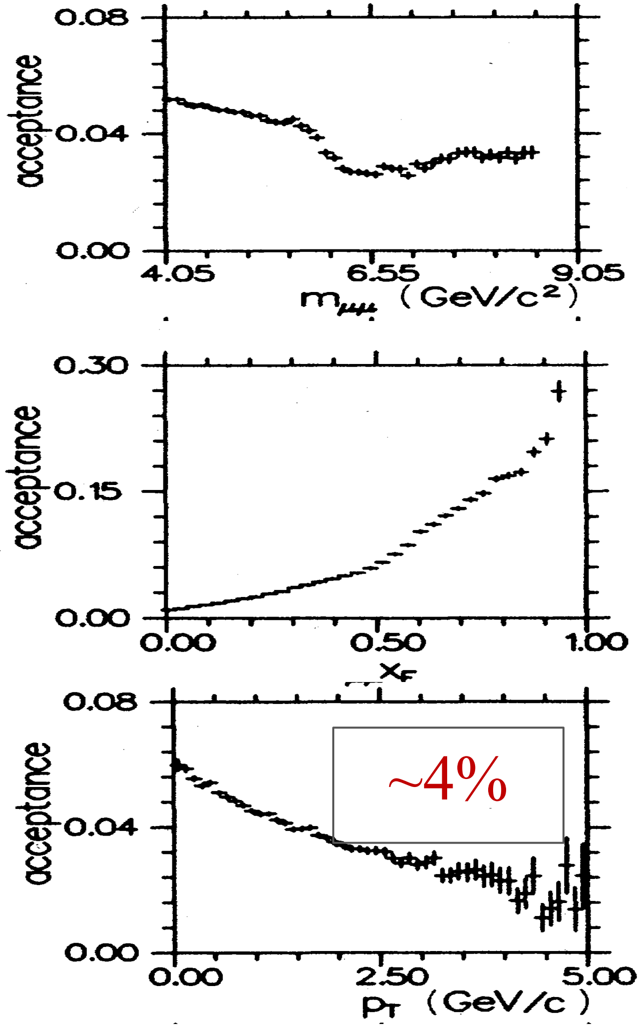
Needed is also : state-of-the-art analysis (NNLO / NLL)

Acceptances : COMPASS vs NA10 vs E615

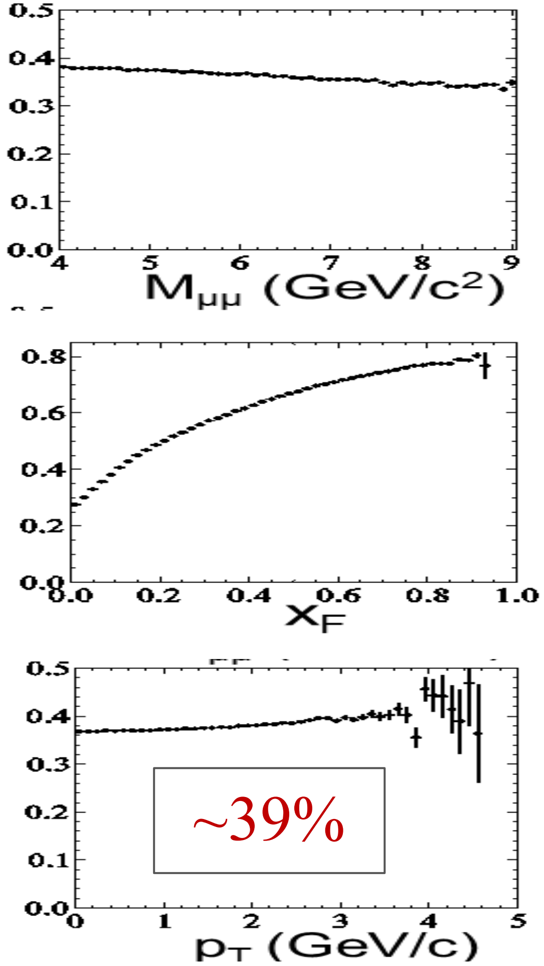
NA10



E615



COMPASS



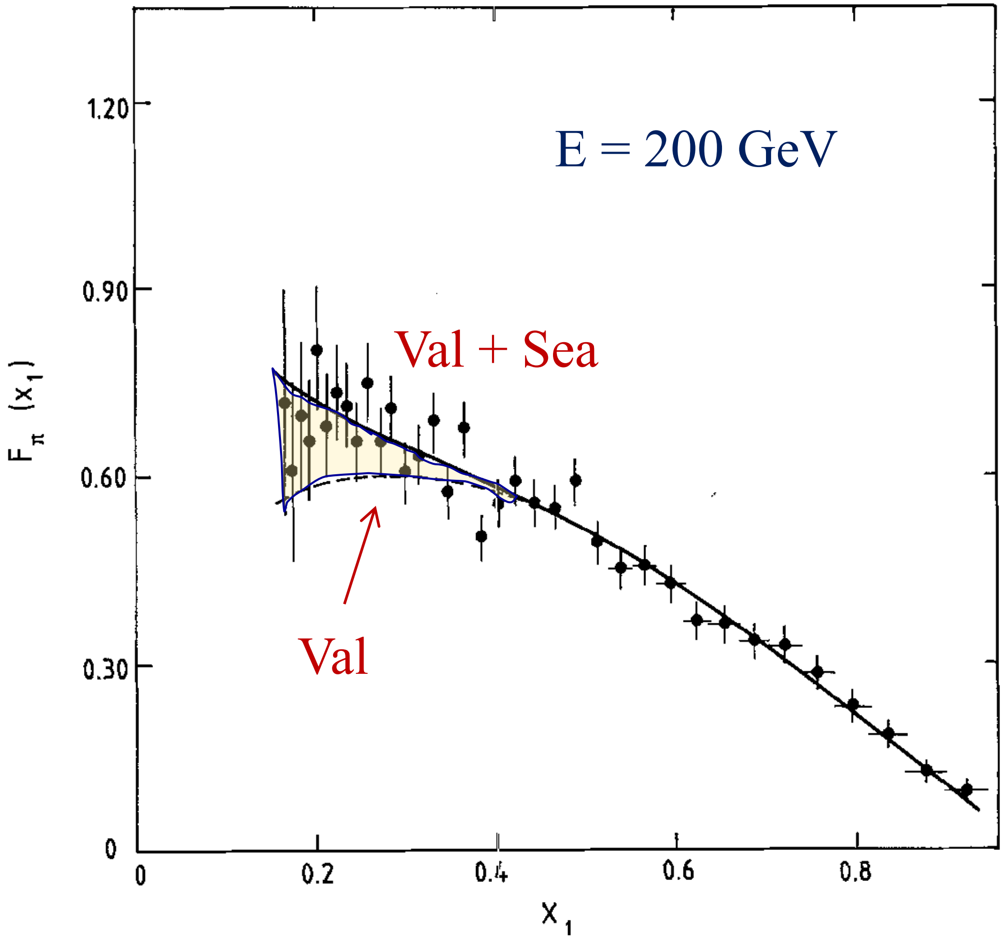
COMPASS acceptance is relatively flat and a factor of 5 -10 better

Can we measure the pion sea?

Pion sea determination – NA3 results (1983)

- First measurement: NA3
  - Target: ^{195}Pt
  - Beam : π− (4.7k) and π+ (1.7k) at 200 GeV
- Analysis (LO)
  - Assume SU(2) and SU(3) symmetry
  - Nucleon PDF: from CDHS (1979)
  - Determine valence pion: $Ax^{\alpha}(1-x)^{\beta}$
  - Determine sea pion $B(1-x)^{\gamma}$
- Drawbacks
  - Statistics: only 1700 events
  - Analysis: old nucleon PDFs, only LO

Badier et al., Z.Phys. C18, 281 (1983).



There is much room for an improvement

Valence sea separation in the pion

- Use positive and negative pion beams : possible only at CERN
- Drell-Yan cross sections for each polarity:

$$\sigma(\pi^+ p) \propto \frac{4}{9}\left[u_v^\pi(x)\cdot\bar{u}_s^p(x)\right] + \frac{4}{9}\left[\bar{u}_s^\pi(x)\cdot u_v^p(x)\right] + \frac{1}{9}\left[\bar{d}_v^\pi(x)\cdot d_v^p(x)\right] + \frac{1}{9}\left[d_s^\pi(x)\cdot\bar{d}_s^p(x)\right]$$

$$\sigma(\pi^- p) \propto \frac{4}{9}\left[\bar{u}_v^\pi(x)\cdot u_v^p(x)\right] + \frac{4}{9}\left[u_s^\pi(x)\cdot\bar{u}_s^p(x)\right] + \frac{1}{9}\left[\bar{d}_s^\pi(x)\cdot d_v^p(x)\right] + \frac{1}{9}\left[d_v^\pi(x)\cdot\bar{d}_s^p(x)\right]$$

val-val sea-sea sea-val val-sea

  - assume SU(2) and charge invariance

- Two linear combinations :
  - Sea : $\Sigma_{sea}^{\pi D} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}$ no valence-valence terms
  - Valence: $\Sigma_{val}^{\pi D} = -\sigma^{\pi^+ D} + \sigma^{\pi^- D}$ only valence-valence terms

Londergan, Liu and Thomas, PL B361, 110 (1995).

Appropriate combinations select valence or sea terms

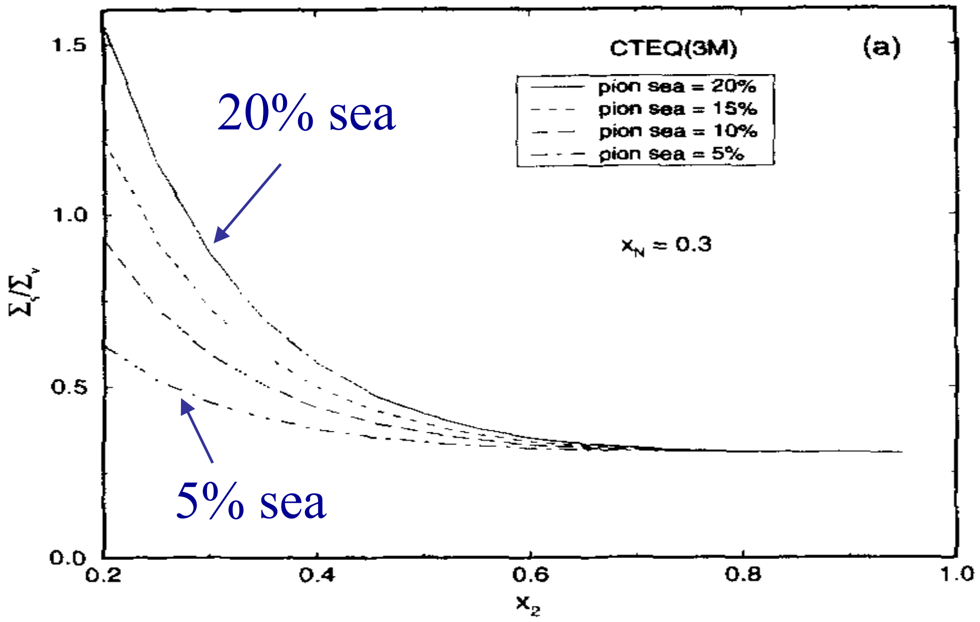
Valence-sea separation in the pion

Londergan, Liu and Thomas, PL B361, 110 (1995).

- Assumptions
  - Sea contribution not known: assume from 5% to 20% (as in SMRS)

- Requirements :
  - Need π^- and π^+ beams
  - Need an isoscalar target (D)
  - Need a good σ normalization
  - Knowledge of the nucleon PDFs

- Form the ratio: $R_{S/V} = \frac{\Sigma_{sea}^{\pi D}}{\Sigma_{val}^{\pi D}}$,



Single out the sea with π^+/π^- beams ?

- Possible new experiment
  - Hadron intensity: $8x10^7\ s^{-1}$ (as present)
  - Target: C or ^{2}D, same Luminosity as in 2015
  - Large and flat acceptance down
- BUT: ☹
  - π^+ cross section smaller than π^- (x ~1/2)
  - pion fraction in the beam smaller

Momentum (GeV/c)	Positive beams			Negative beams		
	π^+	K^+	p	π^-	K^-	$\overline{p}$
100	0.618	0.015	0.367	0.958	0.018	0.024
160	0.360	0.017	0.623	0.966	0.023	0.011
190	0.240	0.014	0.746	0.968	0.024	0.008
200	0.205	0.012	0.783	0.969	0.024	0.007

Badier et al., PL B89, 145 (1979).

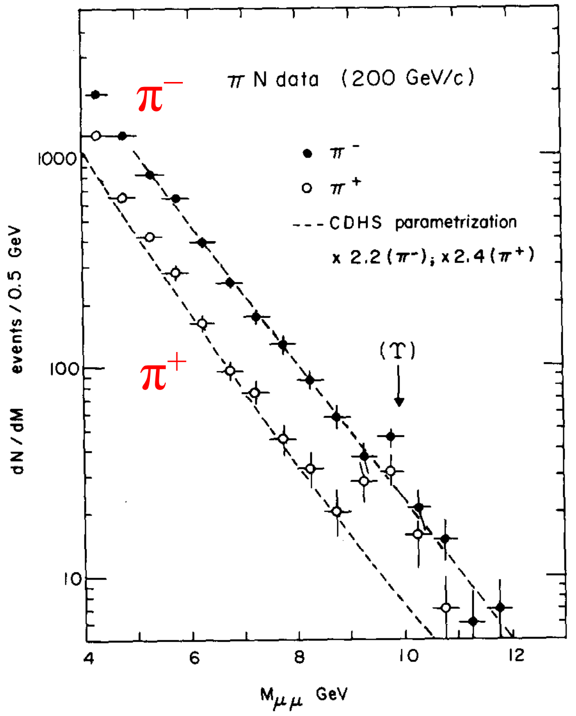


Fig. 4. Dimuon mass spectrum in the reactions $\pi^{\pm}$N at 200 GeV/c; the data are compared to predictions with the CDHS nucleon parameters as input.

Compromise between higher energy (low x_1) and π+ fraction in the beam
In one "year" (5 months), an order of magnitude better statistics can be collected

What about kaon PDFs?

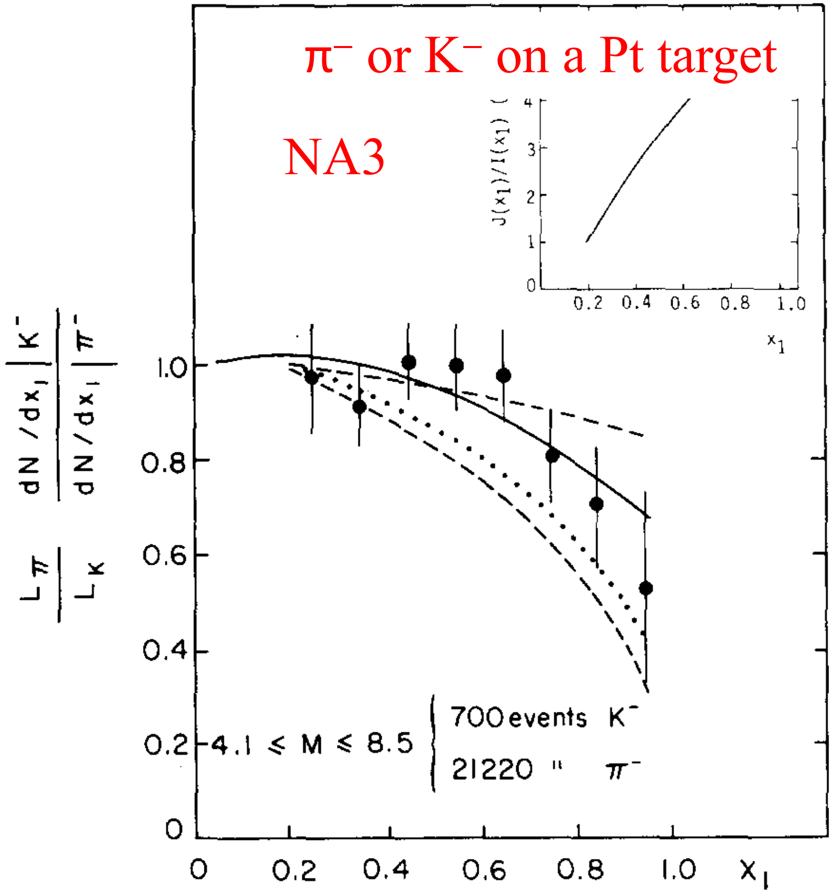
A single measurement (NA3) from 1983

- Results
  - The cross section ratio for K^- and π^- beams is proportional to:

$$\bar{u}^{K^-}(x)/\bar{u}^{\pi^-}(x)$$

  - At large x, the kaon $\bar{u}(x)$ is smaller than the pion $\bar{u}(x)$
  - The heavier s quark carries a larger fraction of the kaon momentum

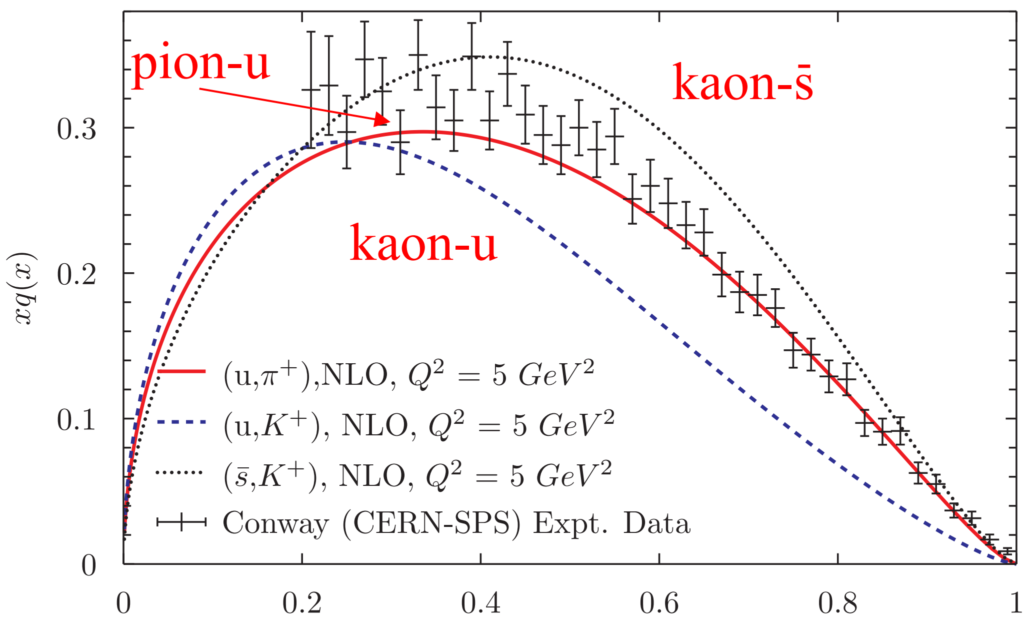
Badier et al, PL 93B, 355 1980.



Theoretical predictions (NJL, 2016)

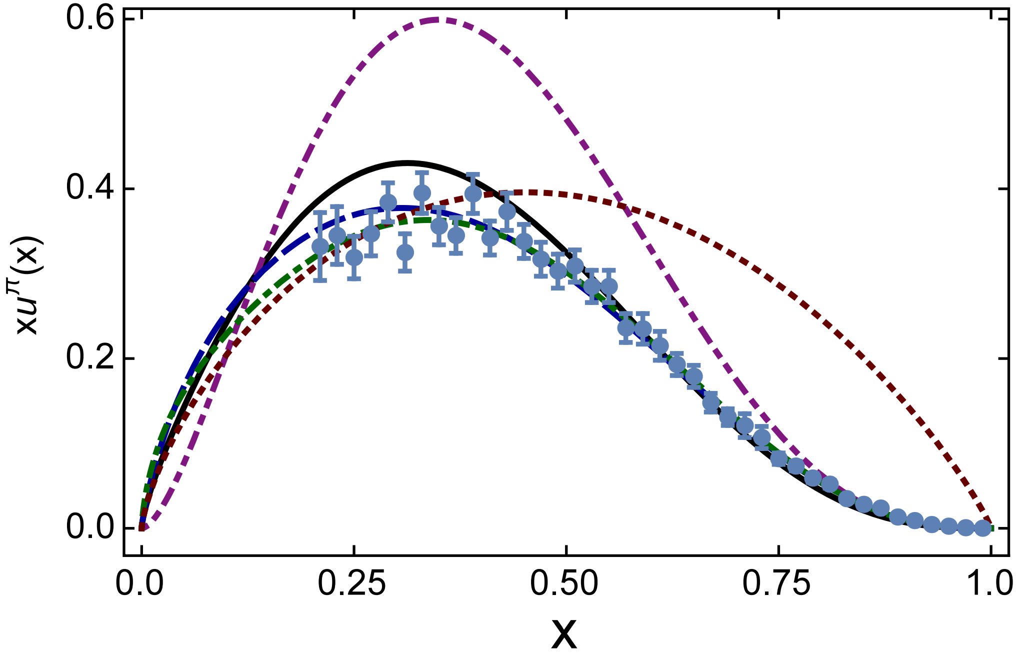
- ## Nambu-Jona-Lasinio model

Hauturuk, Cloët and Thomas, Phys. Rev. C 94, 035201 (2016).



- ## Dyson-Schwinger Equation

Chen chen et al., Phys. Rev. D 93, 074021 (2016).

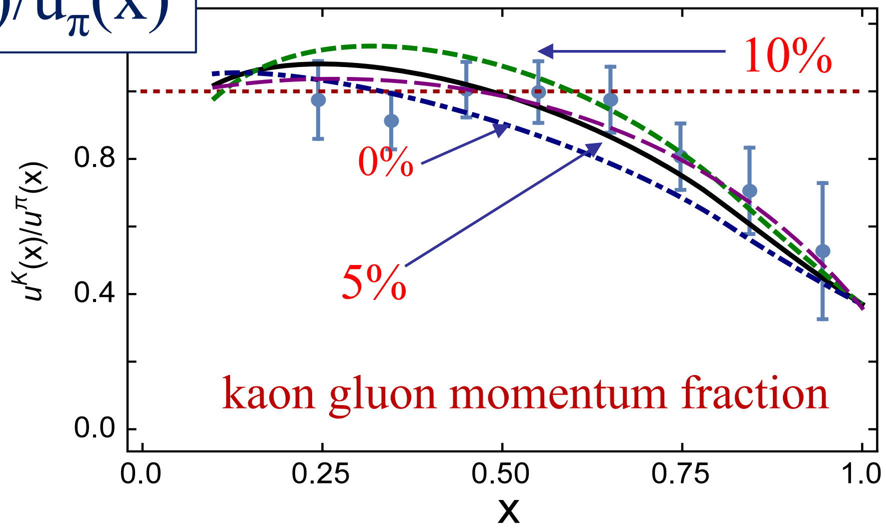


Gluon PDF for kaons (see Craig's talk) ?

- From Chen Chen et al., 2016 (BS + DSE)
  - Derive valence distributions
  - Incorporate sea and gluons.
  - Evolve.
  - Fit u(K)/u(π) ratio and adjust the gluon PDF.

$u_k(x)/u_\pi(x)$

PHYSICAL REVIEW D **93,** 074021 (2016)



- Chen et al. conclusion:
  - At the hadronic scale gluons carry only 5% of the momentum of the kaon
  - At the hadronic scale gluons carry only 35% of the momentum of the pion

=> Another good reason for a measurement of the kaon PDFs using a RF-separated beam

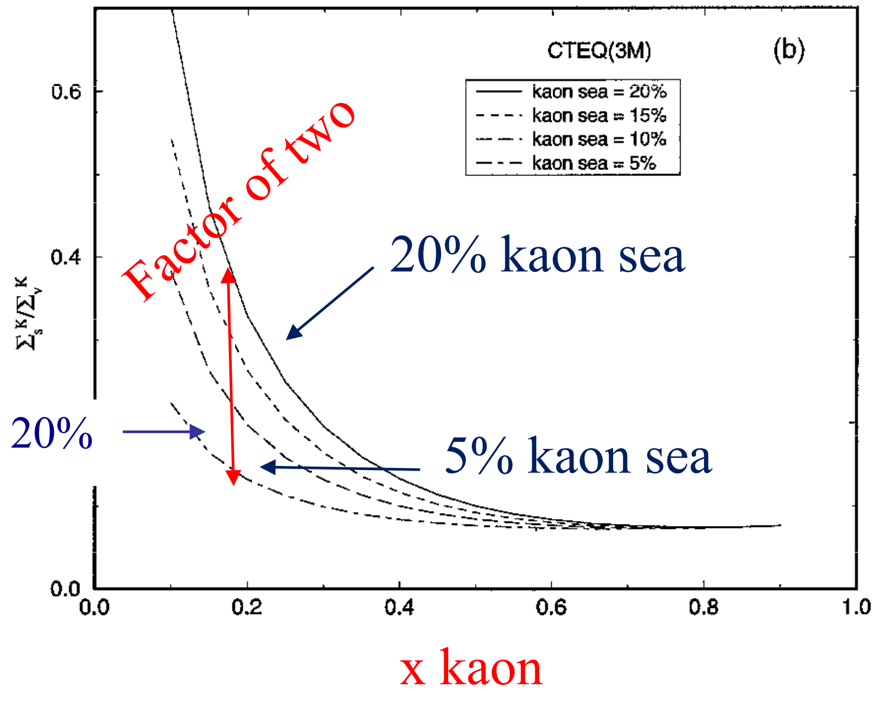
Valence sea/separation in the kaon

- Use intense K^+ and K^- beams
- Deuteron target
- Form the combinations

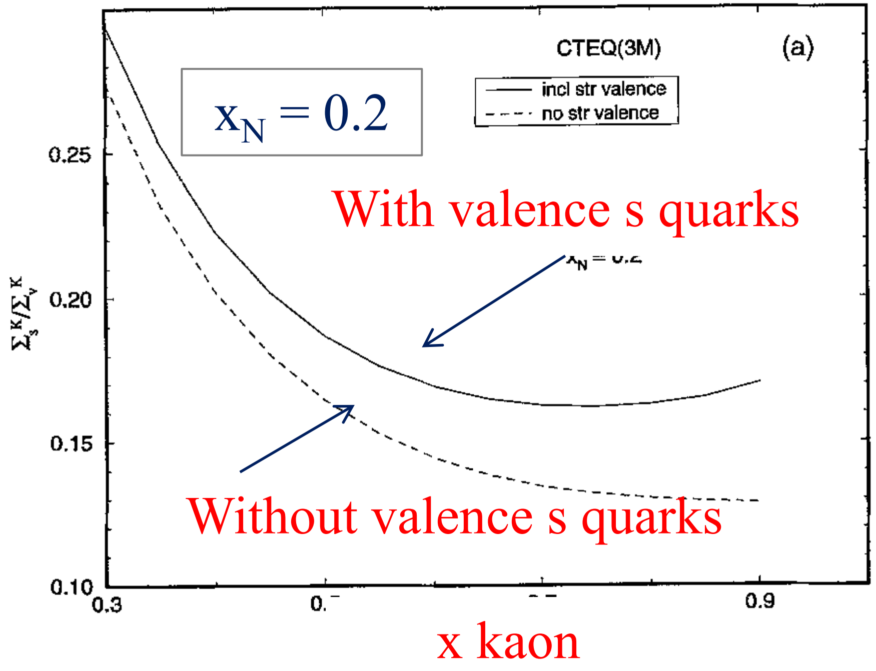
Londergan, Liu and Thomas, PL B380, 393 (1996).

$$\Sigma_{val}^{KD} = -\sigma^{K^+D} + \sigma^{K^-D}$$
$$R_{s/v}^{KD} = \sigma^{K^+D} / \Sigma_{val}^{KD}$$

Sea/valence ratio $R_{S/V}$ for x_N=0.3



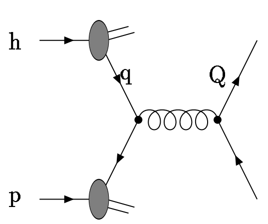
Sensitivity to s quarks for x_N=0.2

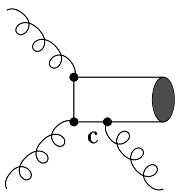


How to measure g(x) directly?

Gluon PDFs – method-1 : J/psi production

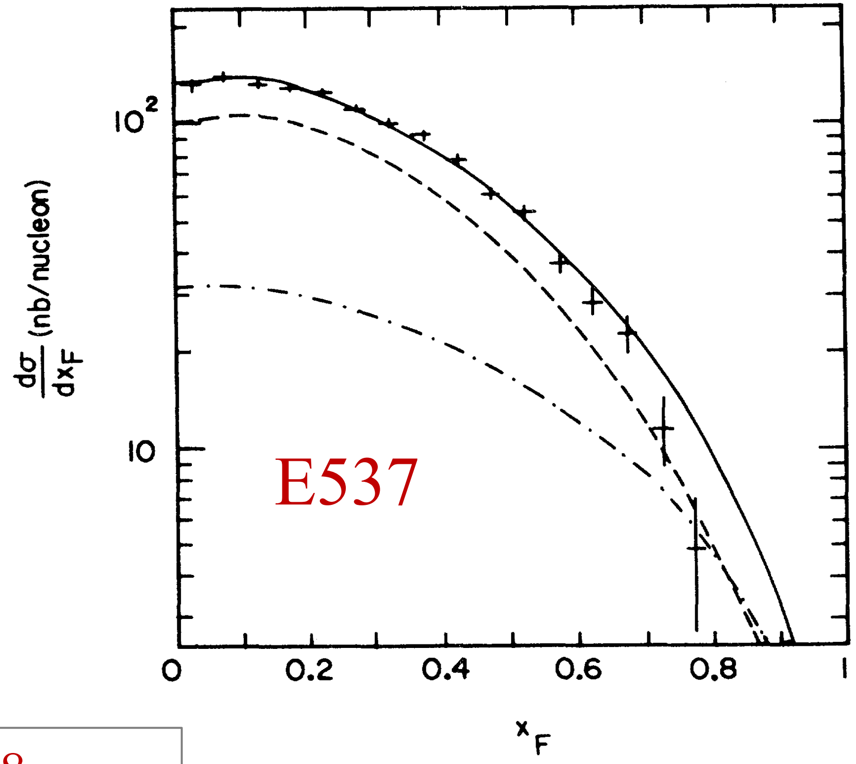
- J/psi are produced through two processes: $q\bar{q}$ and gg (+g)





- π − induced J/psi production
  - => gluon PDF: $xG(x) = A(1\text{-}x)^{\beta}$
  - NA3 (150, 200 GeV)
  - E537 (125 GeV),
  - WA11 (McEwen, 1983, 190 GeV),
  - NA10 (ϒ prod)

Akerlof et al., PRD48, 5067 (1993)



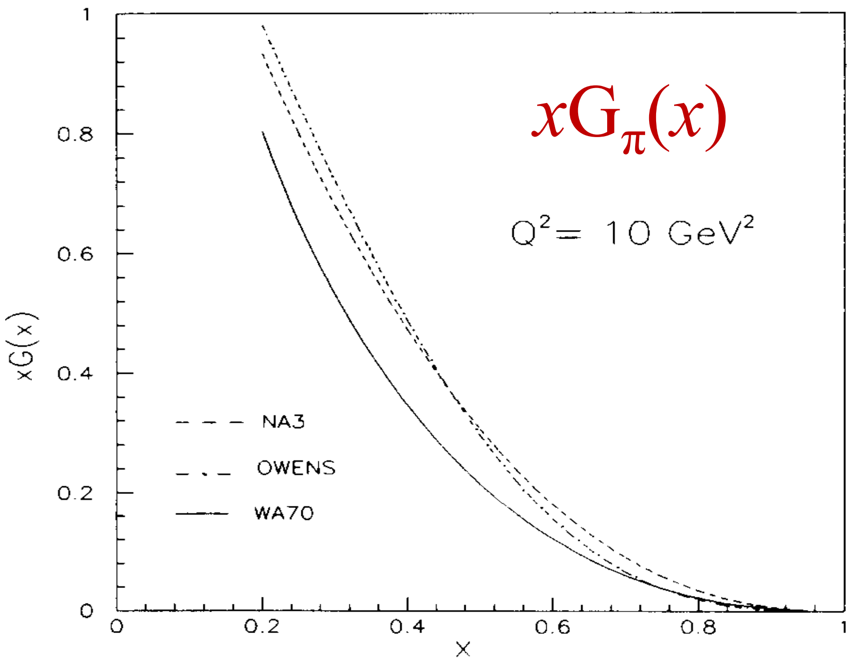
ß parameter: varies from 1.20 to 2.38

Large statistics, but difficult interpretation

Gluon PDFs – method-2 : direct photon production

- High-pt prompt photons in $\pi + p \rightarrow \gamma + X$ (π^+ and π^- beams)
  - two processes: qg -> γq and qq -> γq
  - Data from WA70 (CERN) at 280 GeV (1989)
    - Intensity : ~2x10^7 pions/spill
    - 1 m long H target
    - $4.0 < p_T < 7.0$ GeV
  - Cross section ratio dominated by: qg -> γq
  - Analysis by Aurenche et al., 1989
  - Used in SMRS -1992

Bonesini et al., Z.Phys. C37, 535 (1988)
Aurenche et al, PLB233,v517 (1989)



Results for xG(x) depend on the assumptions about valence and sea

π^+/π^- and K^+/K^- beams are available only at CERN !

RF-separated beams

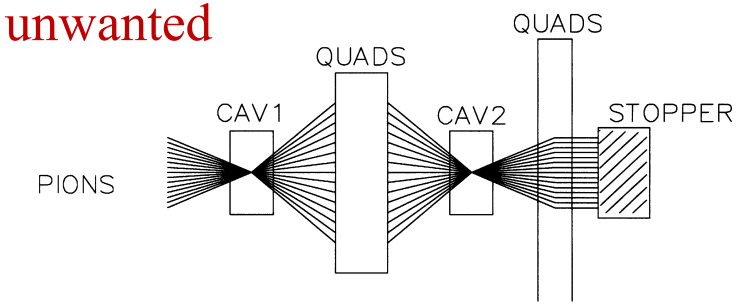
- Idea: Panofsky and Wenzel, 1956
- Studies for Triumph (~1998) and at CERN (~2005) for rare kaon decay experiments
- Method:
  - particles with same momenta have different velocities – small TOF differences
  - produce a time-dependent transverse kick with RF cavities
  - select particles by the phase space difference:

$$\Delta\Phi = 2\pi(Lf/c)(\beta_1^{-1} - \beta_2^{-1})$$

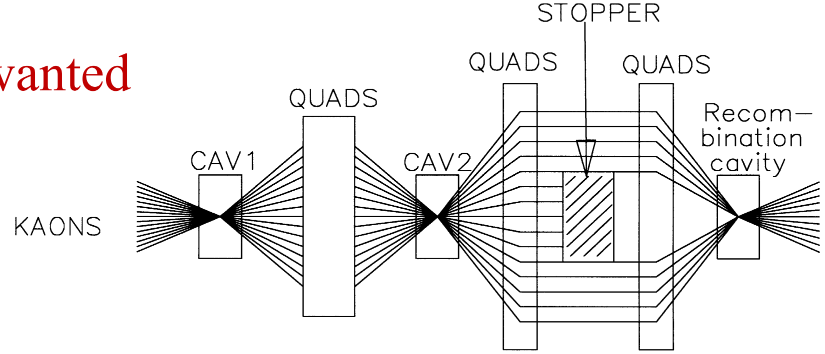
  - available length at CERN: up to 900 meters
  - working frequency: 3.9 GHz

J. Doornbos, NIM A455, 253 (2000)

unwanted



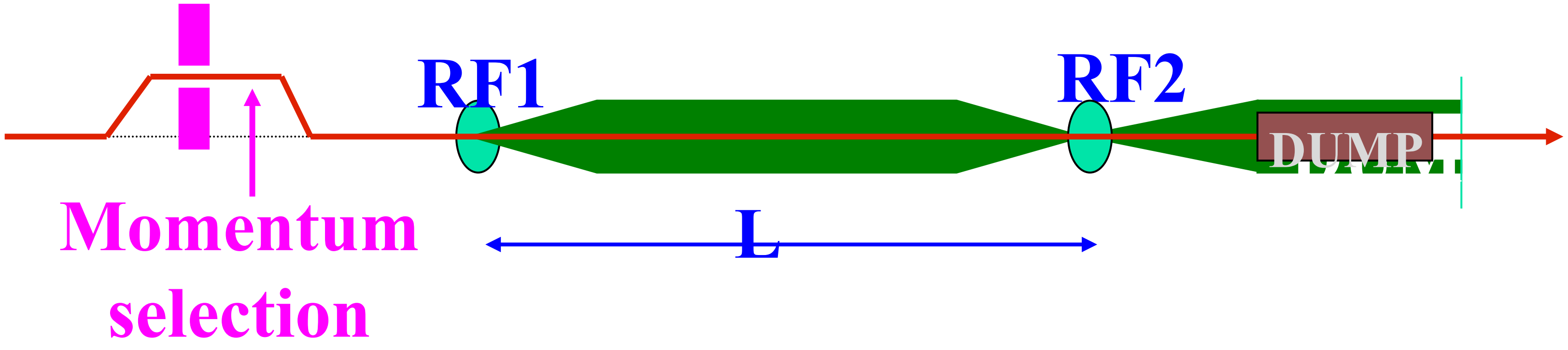
wanted



Example: preliminary estimates for antiprotons and kaons

J. Bernhard, IWHSS Cortona, 2-5 April 2017

- Studies underway at CERN
- Some assumptions:
  - L = 450 m, f = 3.9 GHz, beam spot within 1.5 mm
  - Reasonable primary target efficiency, 80% wanted particles pass dump
  - Number of primary protons: 100 - 400x10^{11} ppp on the production target



  - Energy limitation : 120 GeV

Large improvement in flux with purity of the order of 50%

CERN strategy : support physics other than LHC

- "Physics Beyond Colliders" initiative – meetings Sept. 6/7, 2016; March 1st 2017
  - Initiated by CERN' DG as part of the CERN's future
  - Exploit the full potential of CERN's accelerator complex; complement the LHC programme
  - Set working groups with deliverables for each project that include:
    - evaluation of the physics case
    - detector building and optimizations
    - CERN's uniqueness
  - Physics QCD subgroup (among others) :
    - COMPASS++, LHC Fixed-target, other experiments....
  - Conventional beams subgroup
    - comprises studies for RF-separated beams fro COMPASS

Info at: http://pbc.web.cern.ch//

Deliverables due end 2018

In time for the European Strategy for Particle Physics update in 2019/2020

Timelines (meson PDFs only)

- Present: (2015 and 2018) data – improved knowledge:
  - Pion valence PDF
  - Kaon/Pion u(x) ratio measurement: with an upgraded beam identification (CEDAR) in 2018

Compass

----------- Future options ------------

- Near future (No RF needed): 1 year $\pi+/\pi-$ run immediately after LS2
  - valence – sea separation of the pion PDFs
  - direct photon production : measurement of $g_\pi(x)$

New experiment

- RF separation: dedicated runs with an intense kaon beam
  - Kaon valence PDF
  - Kaon sea and/or valence strange distribution
  - Direct photon production : measurement of $g_K(x)$

New experiment

Letter of Intent writing has started. Ideas and contributions from people outside COMPASS more than appreciated