Struttura del nucleone: fattori di forma - SBS e HCAL per la Hall A

E. Cisbani

INFN Rome – Sanità Group

and

Italian National Institute of Health

- **Overview of Form Factors**
- **JLab, Hall A, SBS and FF experiments**
- **Front Tracker: GEM and μSiD**
- **HCAL-J**

People		
E. Basile	Affiliation	Analysis of lab test
V. Bellini	CT	Coordination GEM and HCAL
E. Cisbani	ISS	Montecarlo, analysis, daq, test, Coordination GEM
M. Capogni	ENEA/ISS	Digitization, montecarlo, test
S. Colilli	ISS	GEM assembling and test
F. De Persio	RM	SiD Detector
V. De Smet	CT	Gas simulation, assembling procedure, test
R. Fratoni	ISS	GEM assembling
F. Giuliani	ISS	GEM Assembling, electronics
M. Gricia	ISS	GEM assembling
A. Grimaldi	CT	GEM assembling
L. Lagamba	BA	Gas system, beam test
F. Librizzi	CT	GEM assembling, coordination
M. Lucentini	ISS	Slow control for test
F. Mammoliti	CT	Analysis
F. Meddi	RM	SiD Detector
S. Minutoli	GE	Electronics
P. Musico	GE	Electronics, daq, test
F. Noto	CT	Mechanics design and simulation (GEM and HCAL)
R. Perrino	BA/LE	Gas system, test
G. Ruscica	CT	Analysis
F. Santavenere	ISS	GEM assembling, mechanics
D. Sciliberto	CT	GEM assembling
C. Sutera	CT	GEM Assembling, test, HCAL
G. M. Urciuoli	RM	Sid Detector

+ International collaborators

Definition of EM elastic nucleon Form Factors

The hadronic current:

$$\mathcal{J}^{\mu}_{\mathrm{hadronic}} = e\overline{N}(p')\left[\gamma^{\mu}\underbrace{F_1(Q^2)}_{\text{Dirac FF}} + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}\underbrace{F_2(Q^2)}_{\text{Pauli FF}}\right]N(p)$$

The Sachs FFs:

$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2$$

where

$$\tau = \mathrm{Q}^2/4\mathrm{M}^2_{\mathrm{nucleon}}$$

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Mott}} \frac{E'}{E}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right]$$

GE contribution suppressed at high Q^2

$F2 = 0$ or $G_E = G_M$ for pointlike particle

$G^n_{E,M} = \sum_q e_q G^{nq}_{E,M}$ flavour decomposition

The "ultimate" **description** of the nucleon

Wigner Mother Functions
$W^u_{\Gamma,p}(x, \vec{k}_T, \vec{r})$

$\int d^3\vec{r}$

$\int d^2\vec{k}_T$ (FT)

TMD PDFs
$f^u_p(x, \vec{k}_T)\ldots$

GPDs
$H^u_p(x, \xi, t)\ldots$

(SI)DIS

$\int d^2\vec{k}_T$

$\xi = 0$
$t = 0$

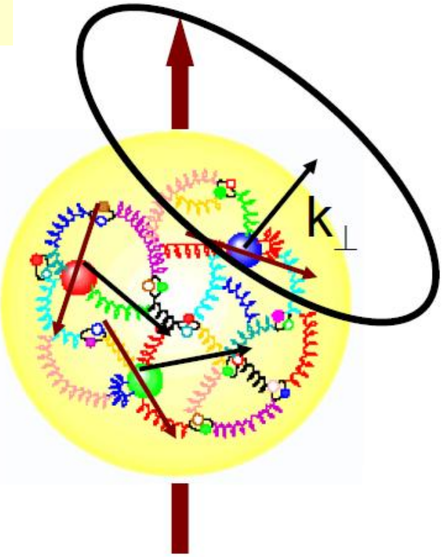
$\int dx$

Exclusive Reactions

PDFs
$f^u_{1p}(x), g^u_{1p}, h^u_{1p}$

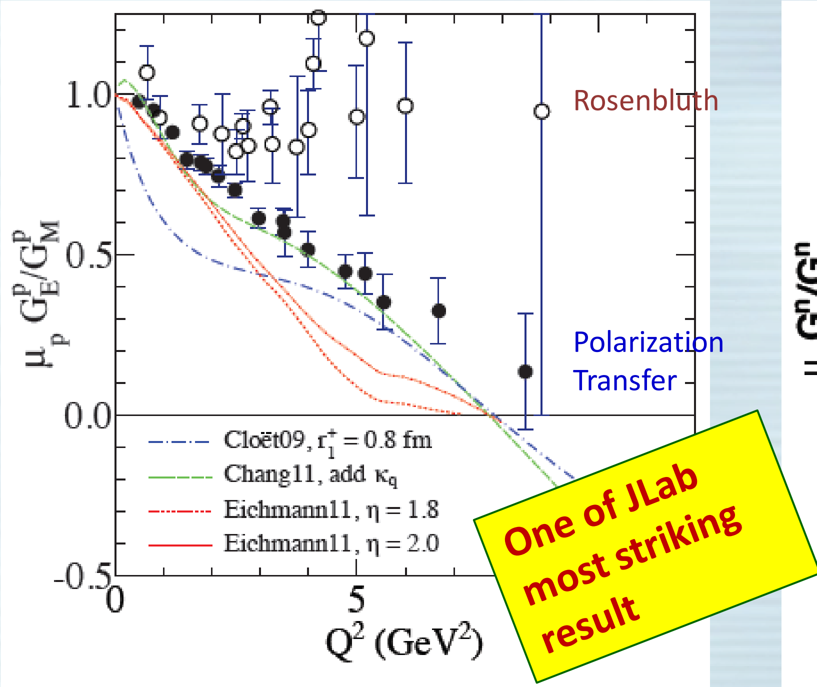
Form Factors
$F^u_{1p}(t), F^u_{2p}(t)\ldots$

*Probability ($h \rightarrow 0$) to find a quark **u** in a nucleon **P** with a given polarization in a position **r** and momentum x,$\mathbf{k_T}$*

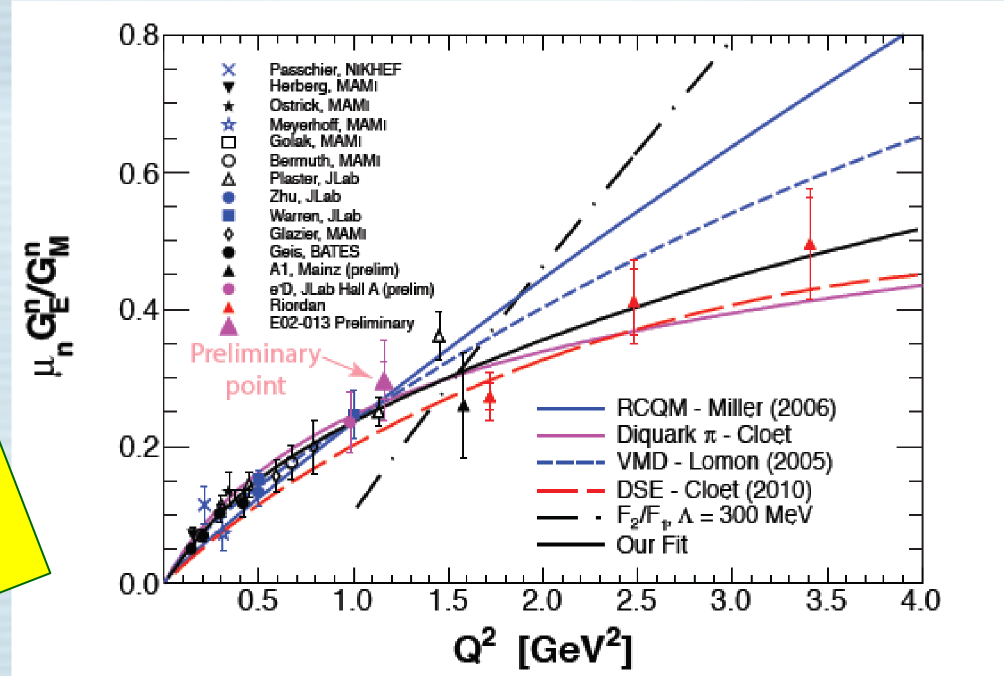


Proton and Neutron G_E/G_M

Proton



Neutron



$$\frac{d\sigma}{d\Omega} \propto G_{Ep}^2 + \frac{\tau}{\varepsilon} G_{Mp}^2$$

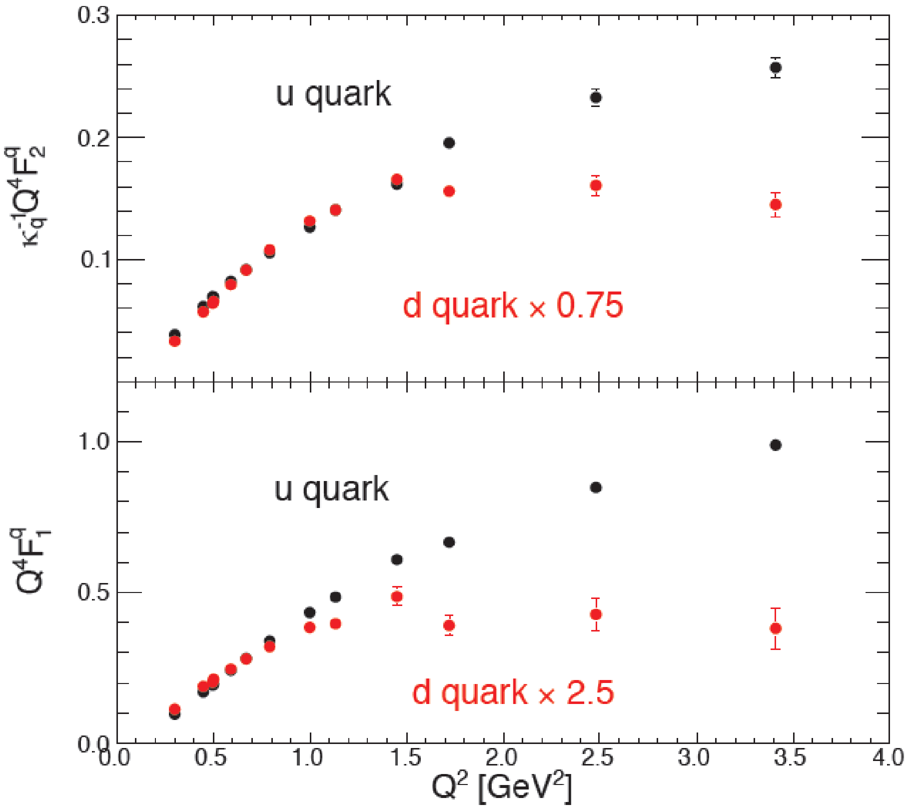
Rosenbluth, one photon exchange approximation

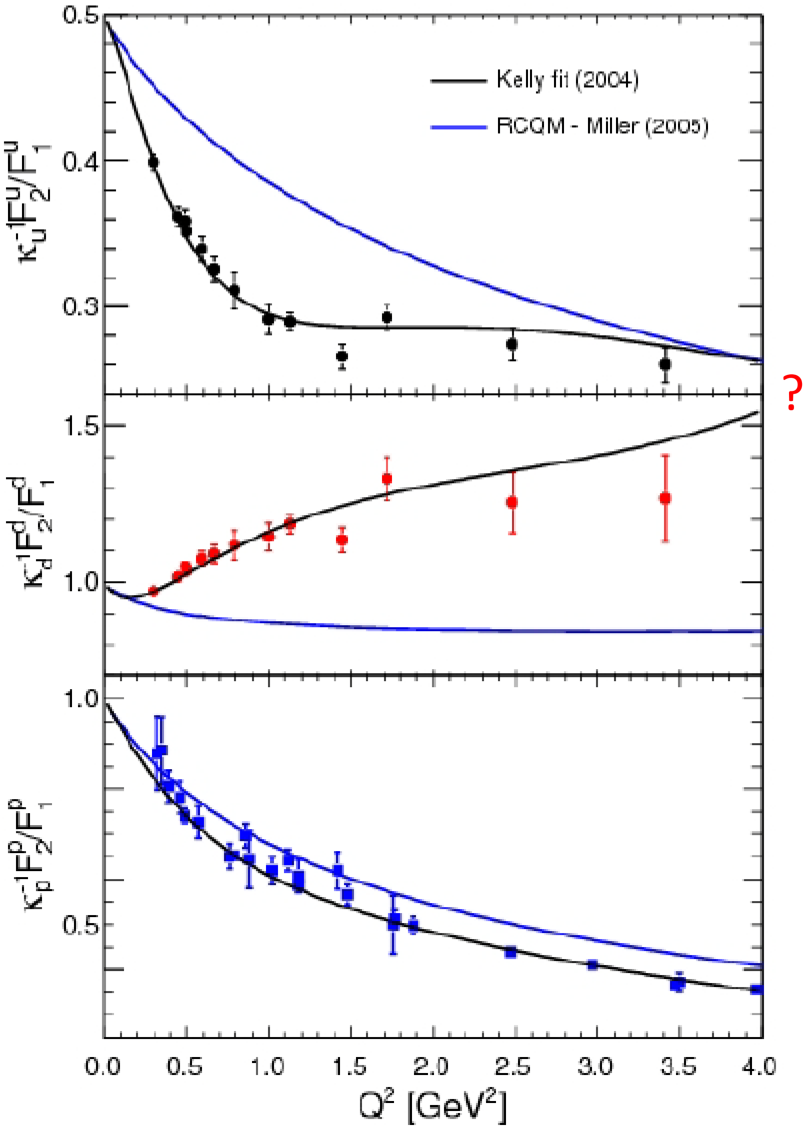
$$\mu \frac{G_{Ep}}{G_{Mp}} = -\mu \frac{P_t}{P_l} \frac{(E_{beam} + E_e)}{2M_p} \tan\frac{\vartheta_e}{2}$$

Longitudinal P_l and transverse P_t **polarizations** of the scattered proton

- Proton measurements incompatible No data at high Q^2
  - models diverge
  - perturbative QCD applicable
  - proton behaviour: $G_E/G_M \rightarrow$ constant ? (not yet)
- Limited statistics

(Recent) FF Flavour decomposition





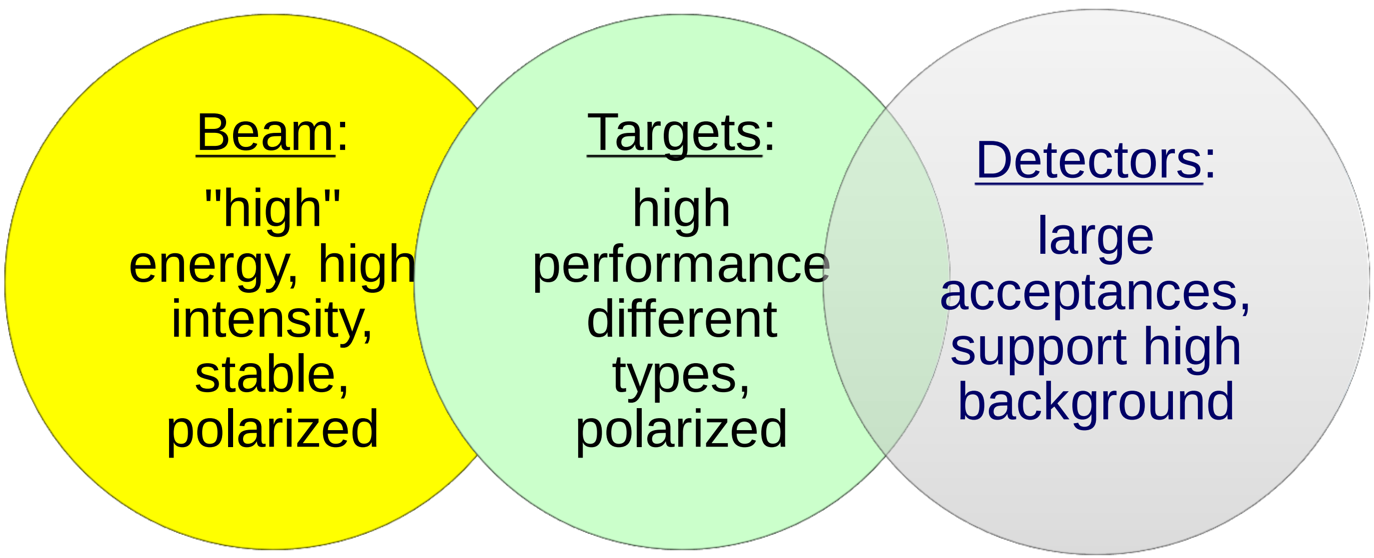
$$F_d \sim 1/Q^4$$
$$F_u \sim 1/Q^2$$

Different high Q^2 behaviour
Evidence of diquark in nucleon ?

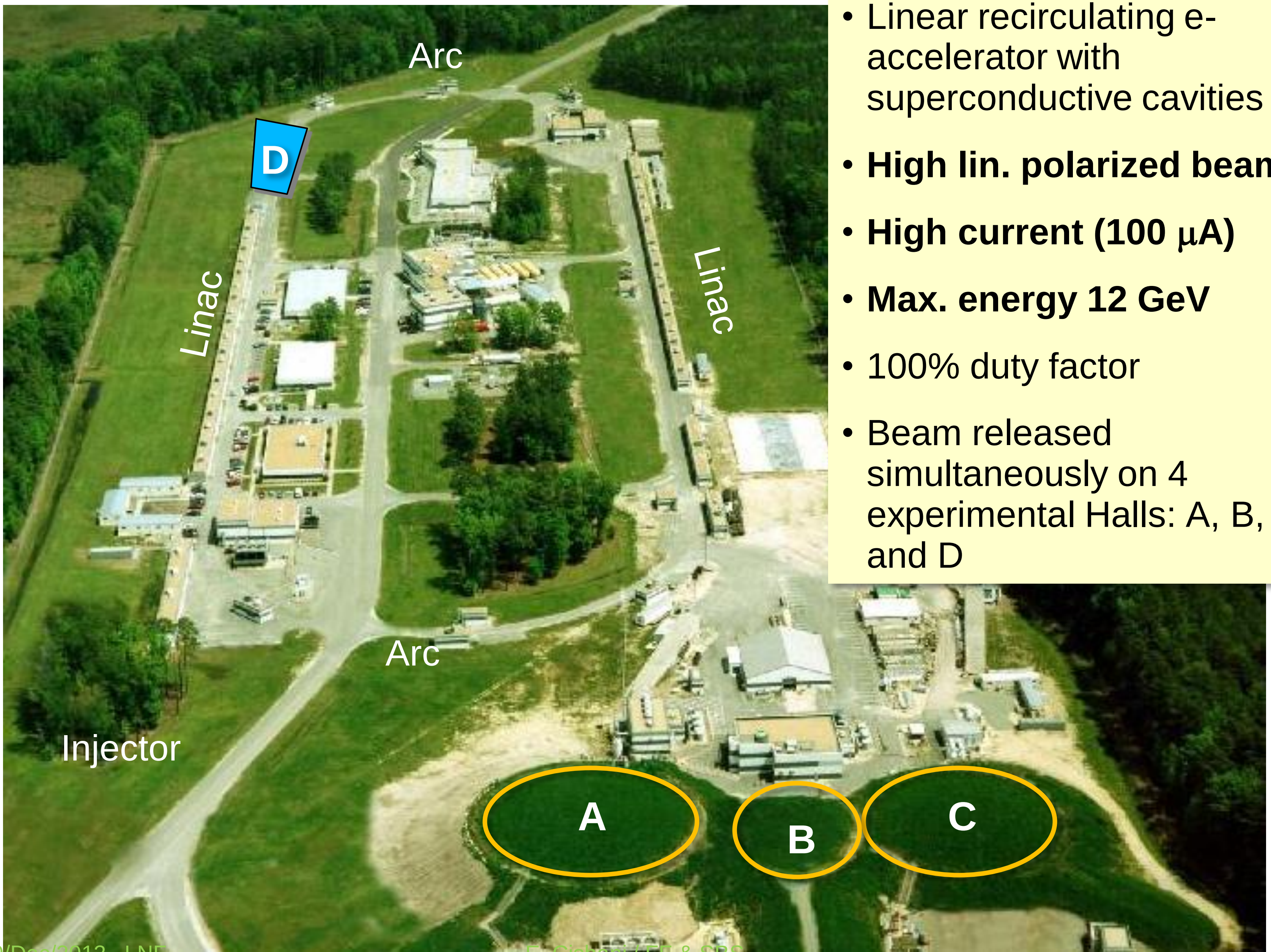
Cates et al. PRL (2010) 106

Physics goals and experimental challenges

- Determination electrical form factors at high Q^2 in the regime of valence quark dominance.
- Perform **precision measurements** of the magnetic form factors
- Uncover the origin of the GEp/GMp fall in the Q^2-dependence
- Provide flavor decomposition of the nucleon form factors at small impact parameter (constraint GPDs)

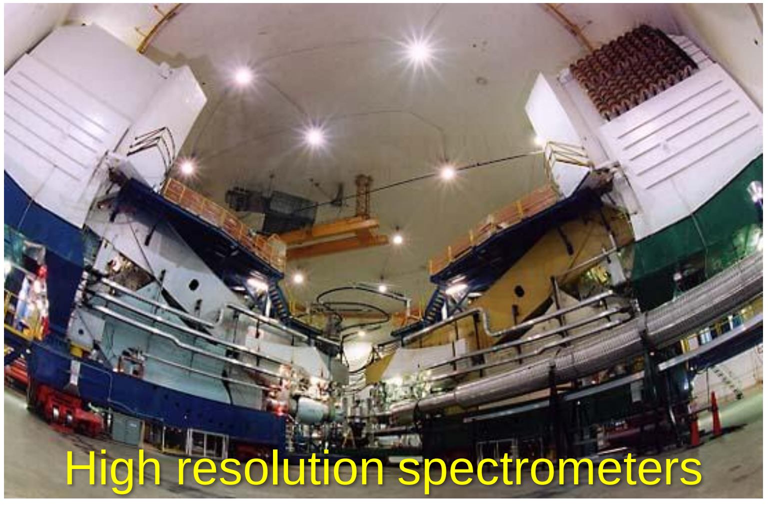


CEBAF in 2014

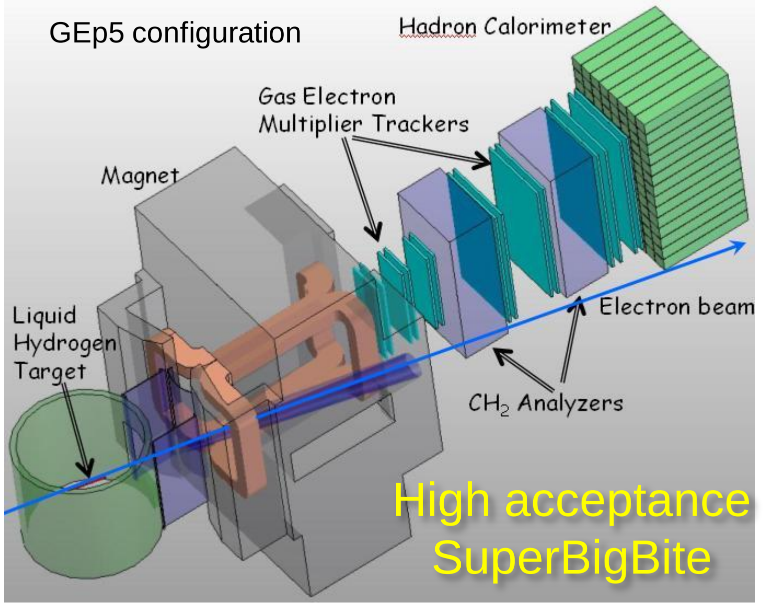


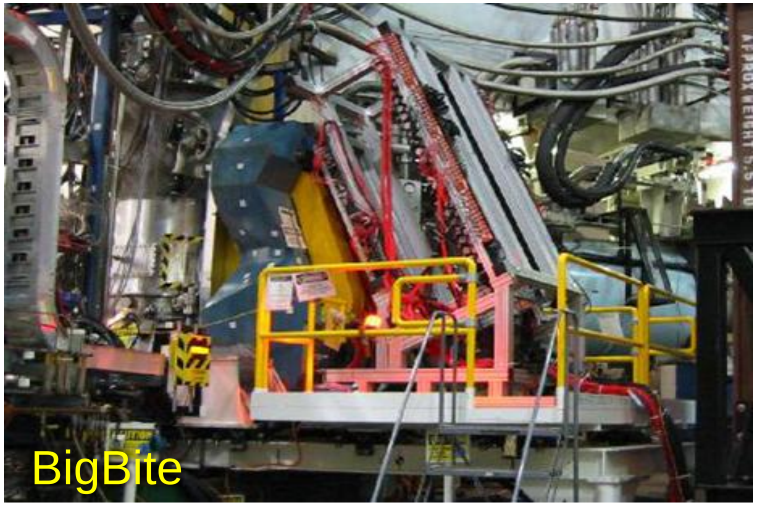
- Linear recirculating e- accelerator with superconductive cavities
- **High lin. polarized beam**
- **High current (100 μA)**
- **Max. energy 12 GeV**
- 100% duty factor
- Beam released simultaneously on 4 experimental Halls: A, B, C and D

JLab/Hall A

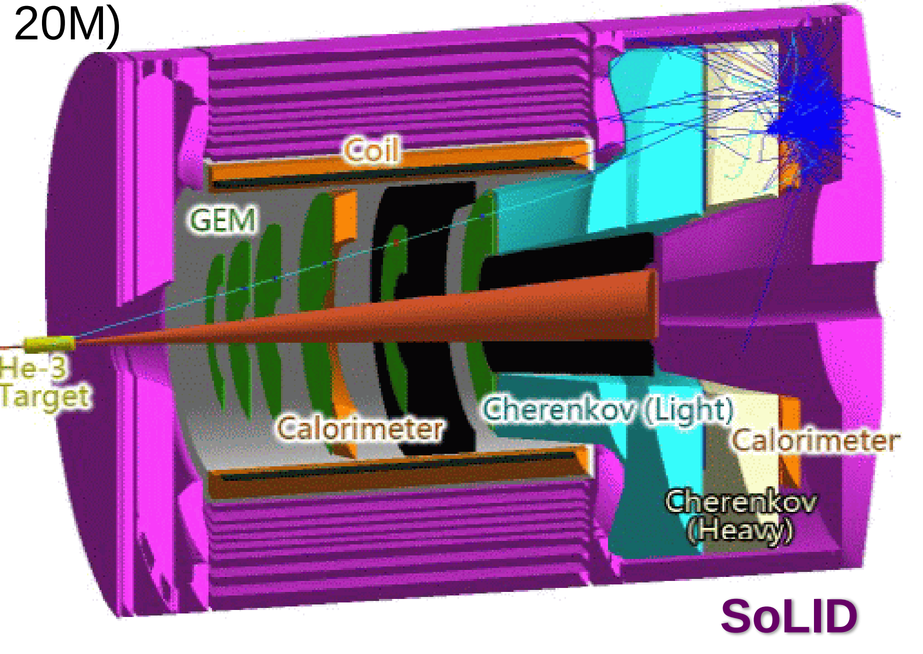


2015
($ 5M)



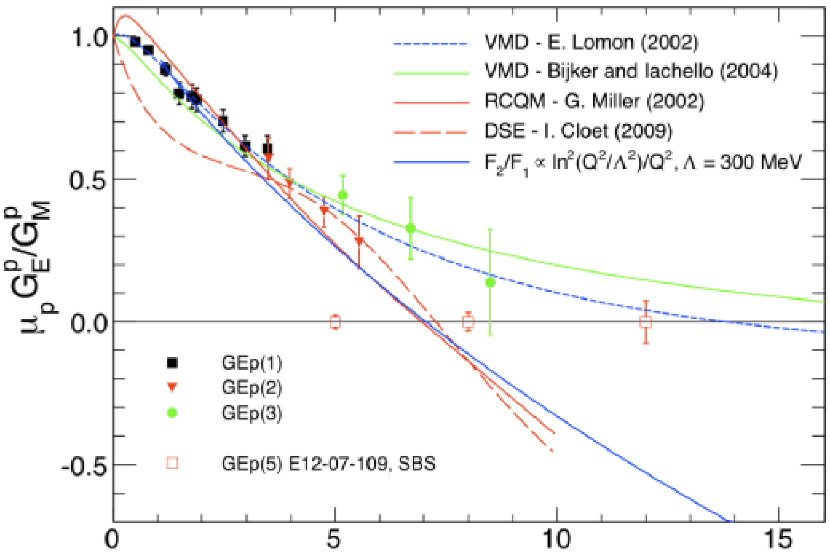


2018
($ 20M)



+ other dedicated detectors and large selection of targets

FF Proposed Measurements at high Q^2



[Pol. Transfer (H)]

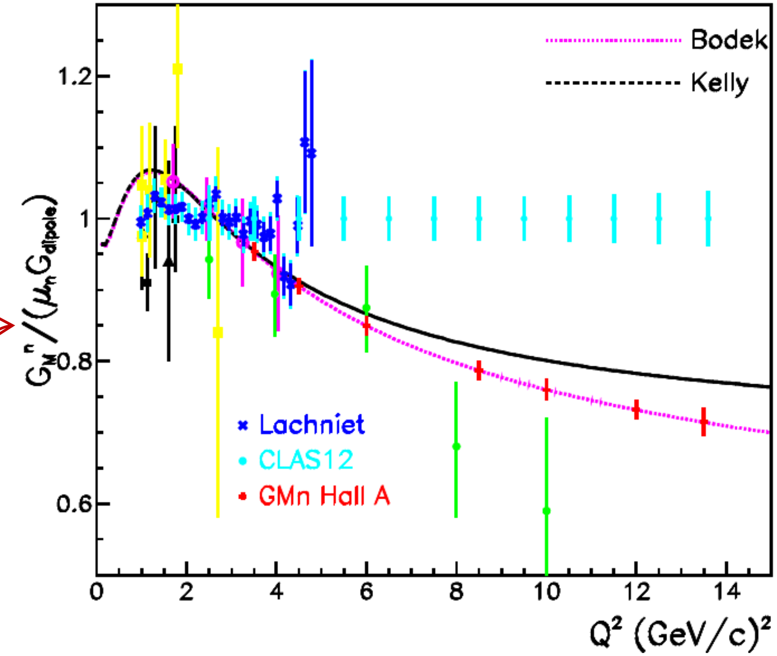
$$\mu\frac{G_{Ep}}{G_{Mp}} = -\mu\frac{P_t}{P_l}\frac{(E_{beam}+E_e)}{2M_p}\tan\frac{\vartheta_e}{2}$$

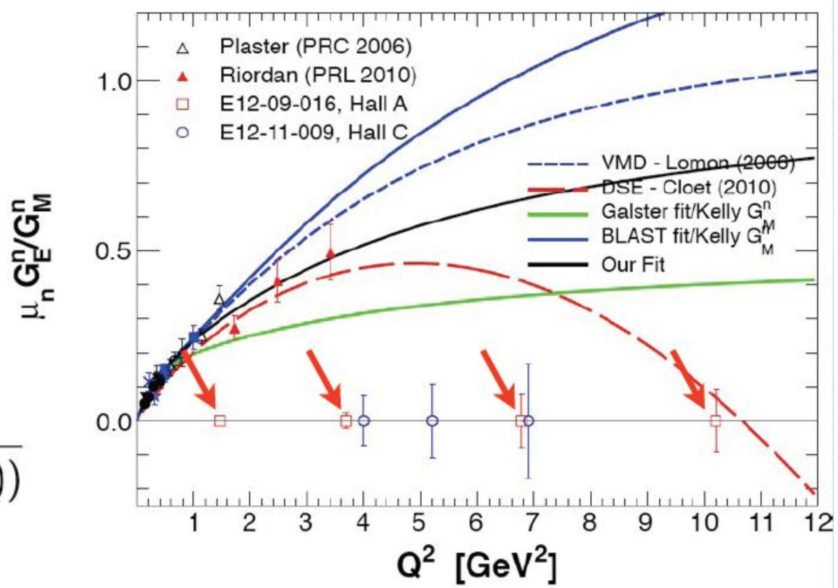
[xSection Ratio (D)]

$$R'' = \frac{\frac{d\sigma}{d\Omega}d(e,e'n)}{\frac{d\sigma}{d\Omega}d(e,e'p)} \to \frac{\eta\frac{\sigma_{Mott}}{1+\tau}\left((G_E^n)^2+\frac{\tau}{\epsilon}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}p(e,e')}$$

[Double Asym. (^{3}He)]

$$\frac{\sigma_+-\sigma_-}{\sigma_++\sigma_-}\approx A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)G_E/G_M}{(G_E/G_M)^2+(\tau+2\tau(1+\tau)\tan^2(\theta/2))}$$





G_E^p/G_M^p Experiment's Figure of Merit

For polarization transfer experiment with recoil polarization measurement:

$$FOM \propto \sigma \cdot \epsilon^{pp} \cdot (P_e \cdot A_y/k)^2 \cdot \Omega \cdot L$$

$$\sigma \propto E^2/Q^4 \cdot 1/Q^8 \quad ; \quad \frac{A_y}{k} \propto \frac{1}{Q^2} \cdot \frac{2M}{E+E'} \tan^{-1}\frac{\theta}{2}$$

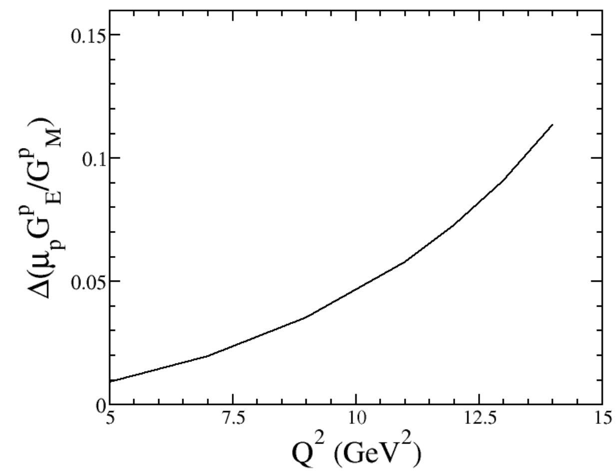
ε^{pp} = Proton polarimeter efficiency

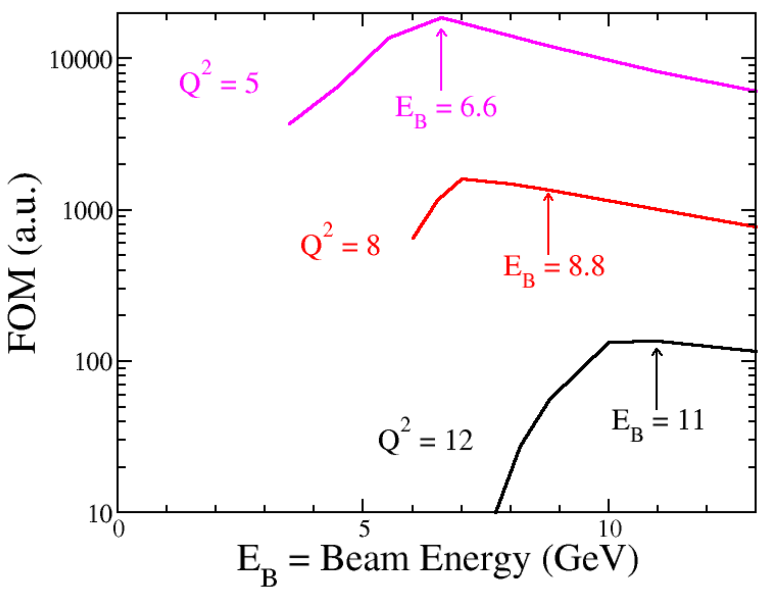
P_e = Beam polarization

$$\boxed{FOM \propto \frac{\epsilon^{pp} \cdot P_e^2 \cdot \Omega \cdot L}{Q^{16}} \cdot \frac{E^2 \tan^{-2}\frac{\theta}{2}}{(E+E')^2}}$$

Using **$\Delta Q^2/Q^2$=10%** as baseline

(due to fast fall of statistics with Q^2)





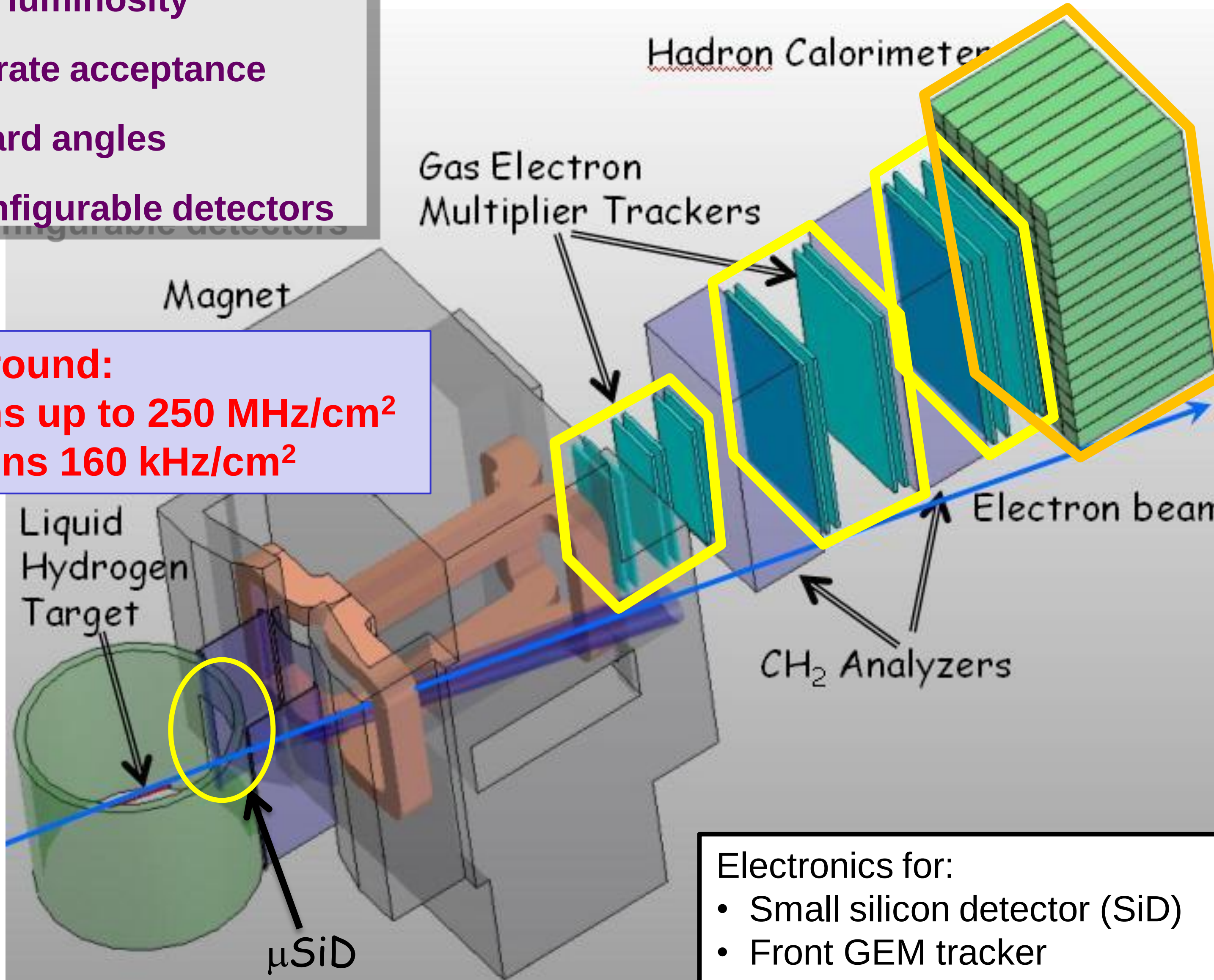
Maximize Luminosity (L) and polarimeter efficiency (ε^{pp})

Match electron and hadron acceptances

SuperBigbite Spectrometer in Hall A

- Large luminosity
- Moderate acceptance
- Forward angles
- Reconfigurable detectors

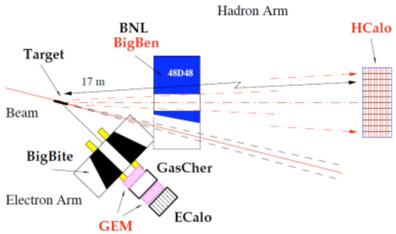
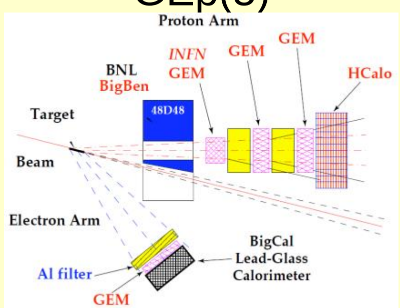
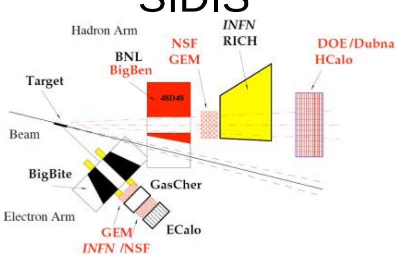
Background:
Photons up to 250 MHz/cm^2
Electrons 160 kHz/cm^2



Electronics for:
- Small silicon detector (SiD)
- Front GEM tracker
- Large backward GEM trackers

⇨ **>100k channels**

Some challenging experiments in Hall A

Experiment	Luminosity $(s\cdot cm^2)^{-1}$	Tracking Area (cm^2)	Resolution		
			Angular (mrad)	Vertex (mm)	Momentum (%)
GMn - GEn 	up to $7\cdot10^{37}$	40x150 and 50x200	< 1	<2	0.5%
GEp(5) 	**up to $8\cdot10^{38}$**	40x120, 50x200 and 80x300	<0.7 ~1.5	~ 1	0.5%
SIDIS 	up to $2\cdot10^{37}$	40x120, 40x150 and 50x200	~ 0.5	~1	<1%

Most demanding

High Rates

Large Area

Down to ~ 70 μm spatial resolution

Maximum reusability: same detectors in different experimental configuration

Choice of the technology

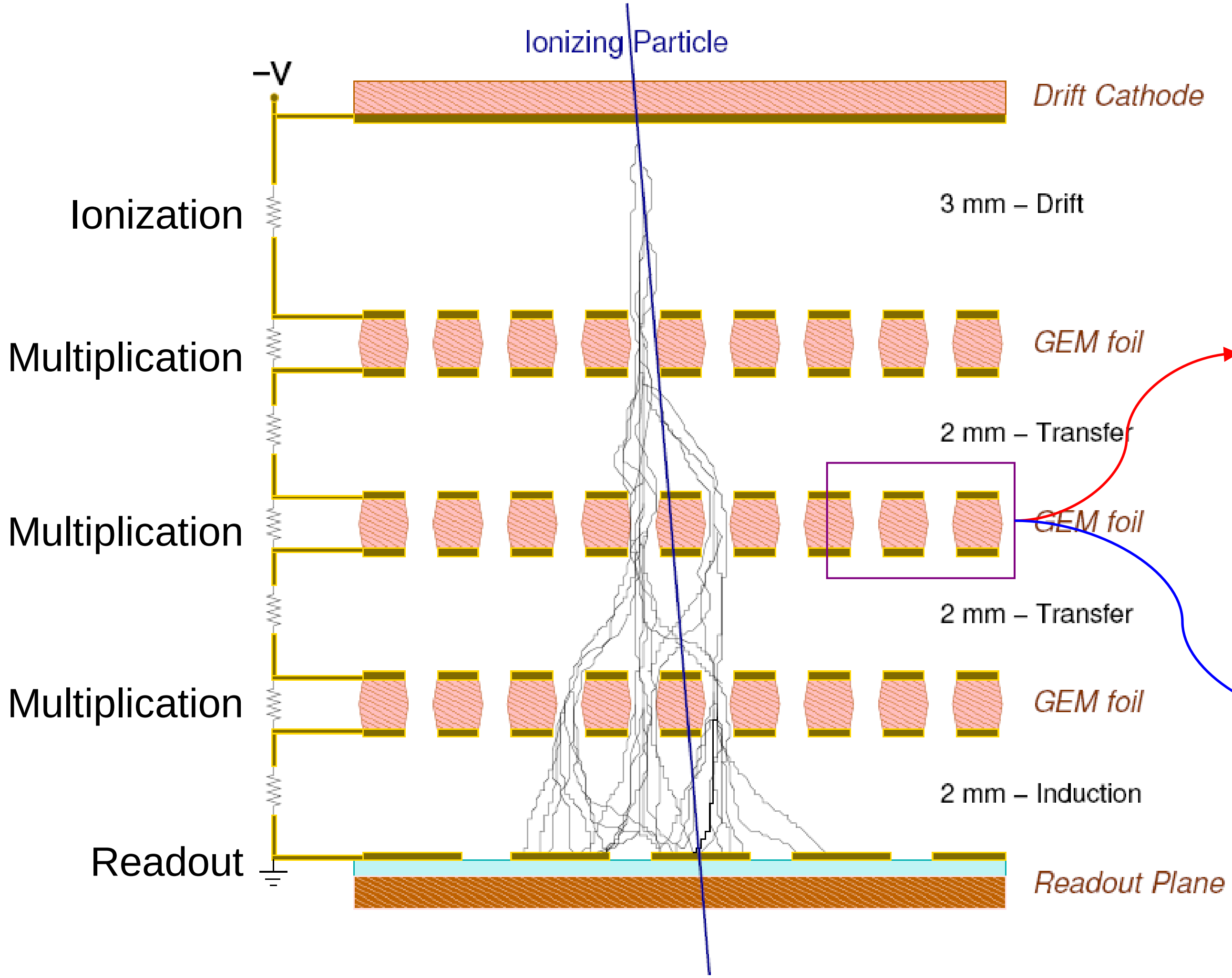
System Requirements	Tracking Technology: Drift	Tracking Technology: **MPGD**	Tracking Technology: Silicon
High Background Hit Rate: (low energy γ and e) **1 MHz/cm^2**	NO	**MHz/mm^2**	**MHz/mm^2**
High Resolution (down to): **70 μm**	Achievable	**50 μm**	30 μm
Large Area: from 40×150 to 80×300 cm^2	YES	**Doable**	Very Expensive

… and modular: reuse in different geometrical configurations

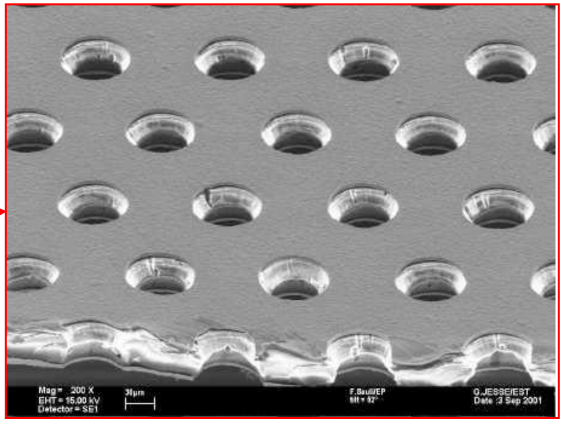
GEM **μMs**

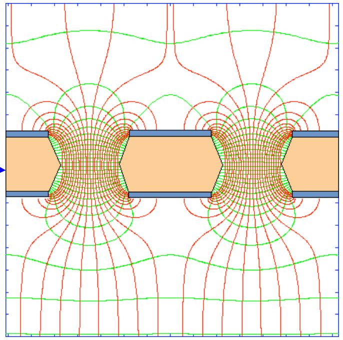
Flexibility in readout geometry and lower spark rate *(true in 2010)*

GEM working principle



GEM foil: 50 μm Kapton + few μm copper on both sides with 70 μm holes, 140 μm pitch



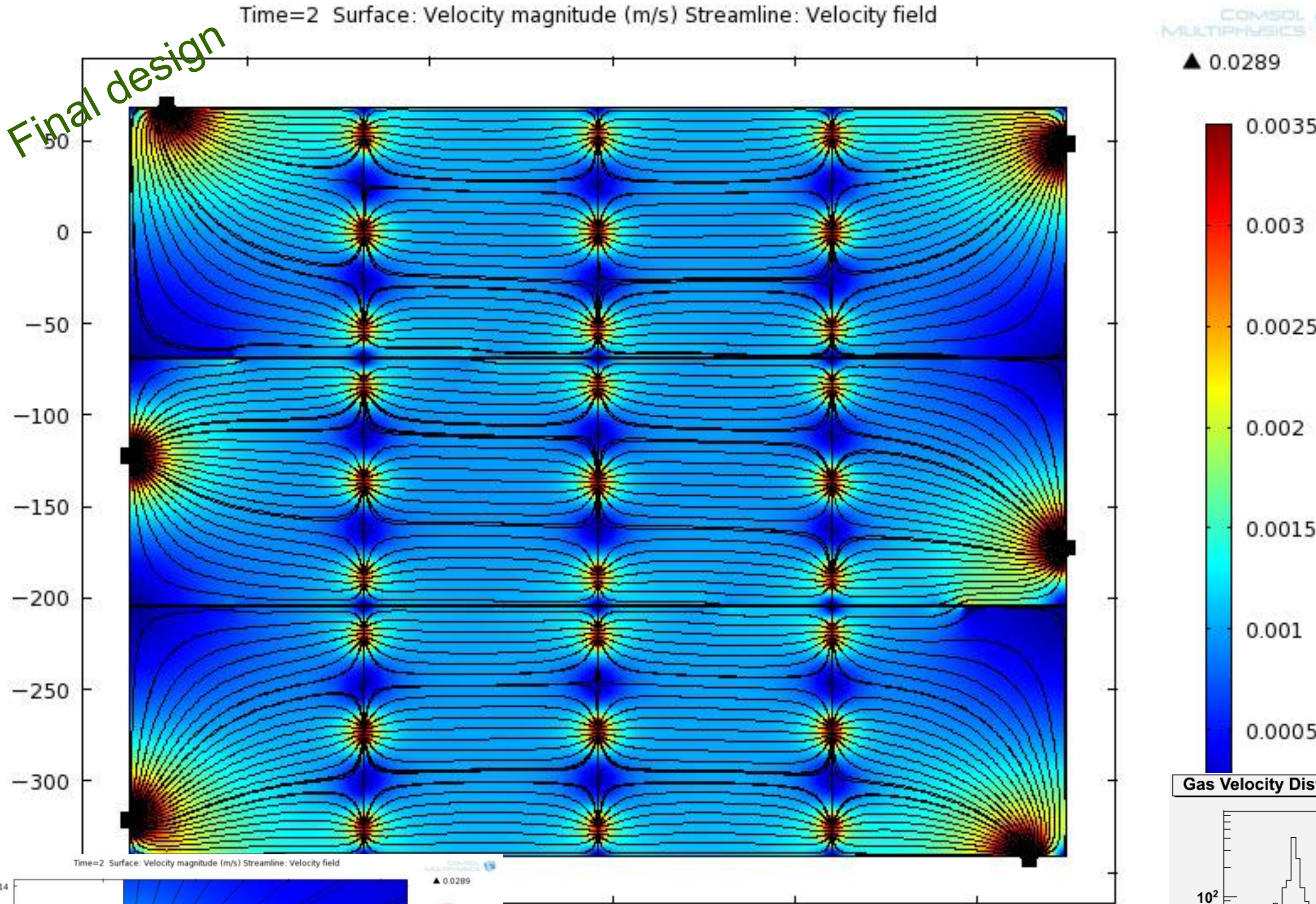


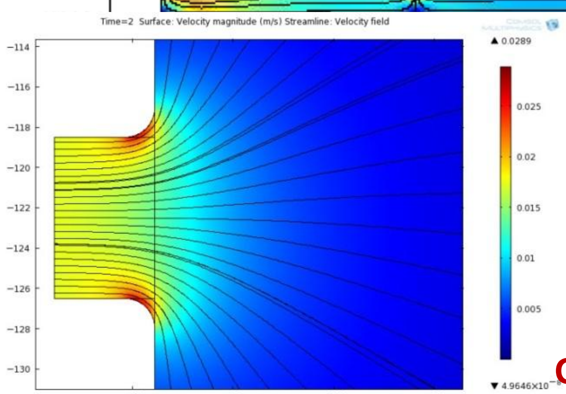
Strong electrostatic field in the GEM holes

Recent technology: F. Sauli, Nucl. Instrum. Methods A386(1997)531

Readout independent from ionization and multiplication stages

Gas Flow / COMSOL MultiPhysics Simulation





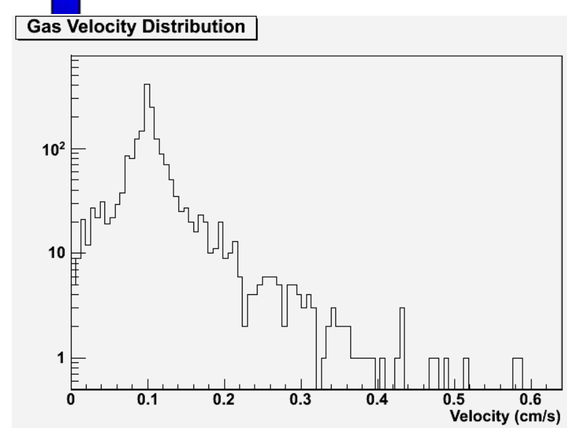
Flow:

60 cm^3/m = 2 Vol/h

Pressure drop (Pa):

Inlet:	0.0590
Spacers:	0.0015
Module:	0.0462
Outlet:	0.0575
Total:	0.1642

(underestimated)



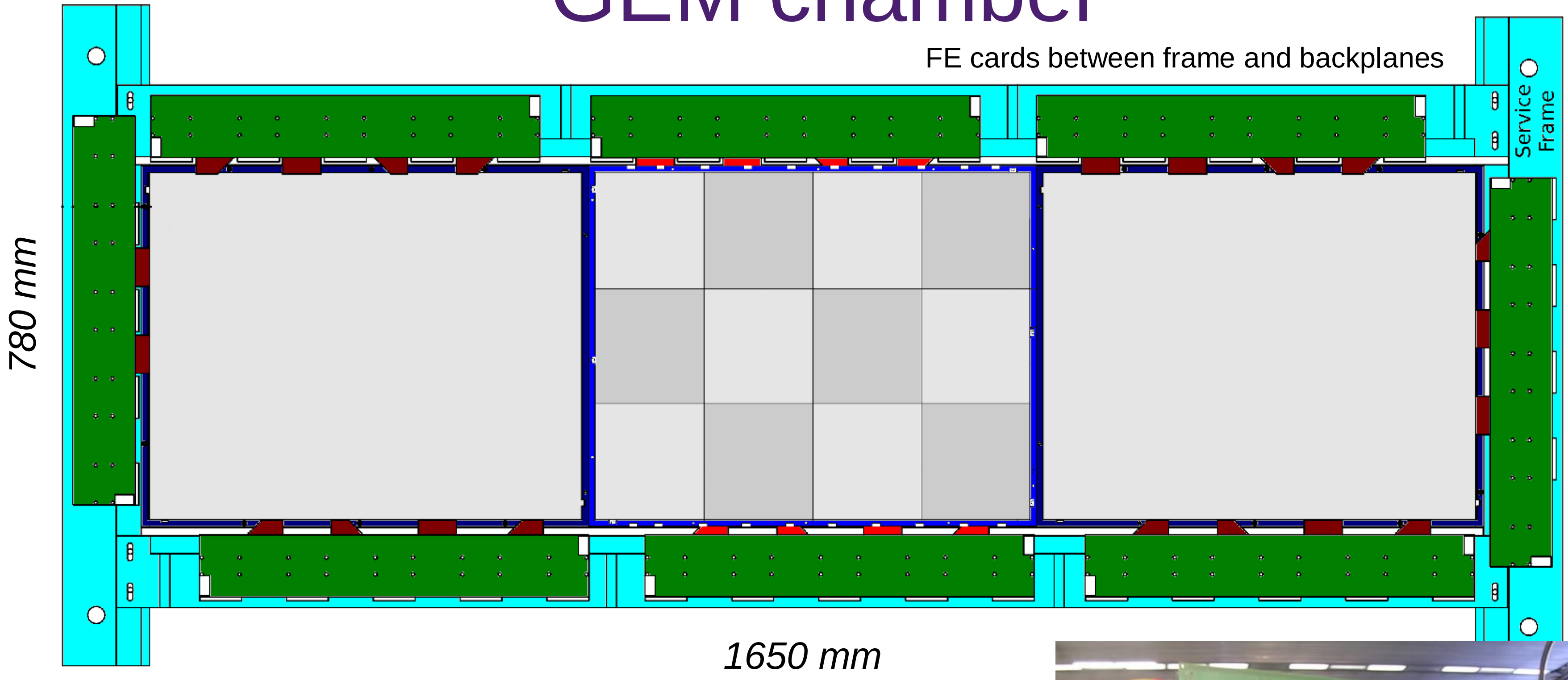
COMSOL/Thin-Film Flow Model

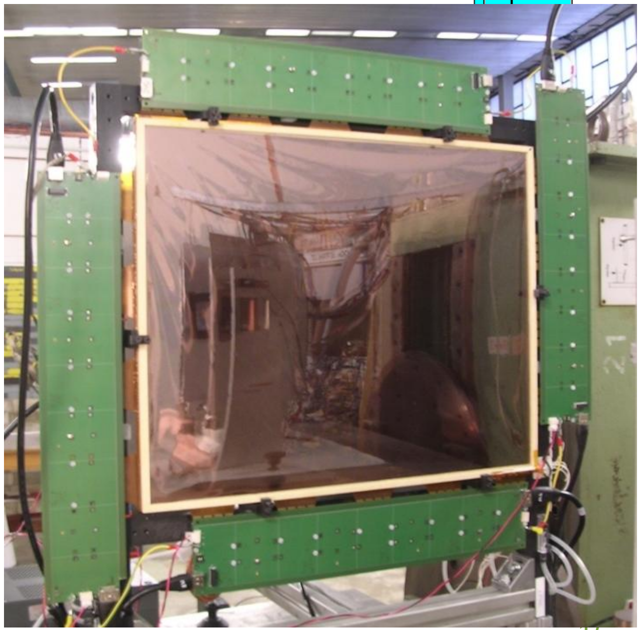
Maximize uniformity and steady flux

Minimize spacer apertures

Good gas flow important for minimizing aging effects in strong irradiation

GEM chamber





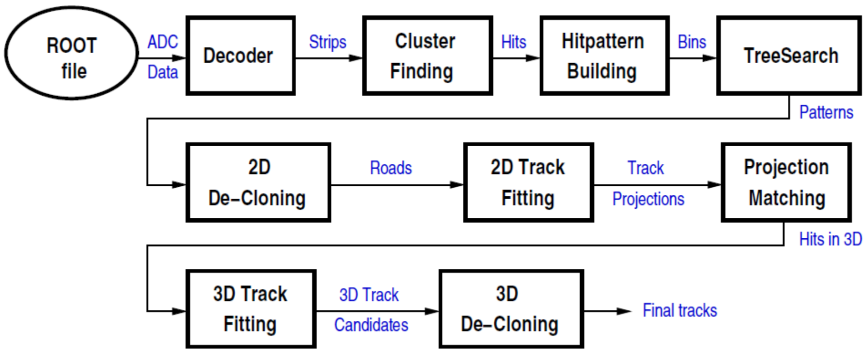
Use the same basic 40x50 cm2 3GEM module for all tracker

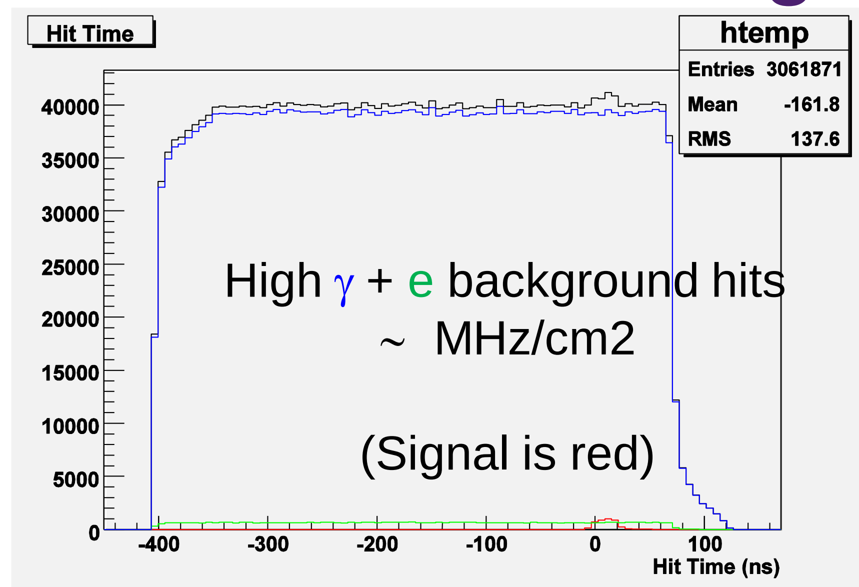
Size defined by technological limits (2010), maximum expected occupancy, capacitive noise of the strips

6 large chambers as combination of GEM modules with small dead area

x/y readout on the same module (a la COMPASS)

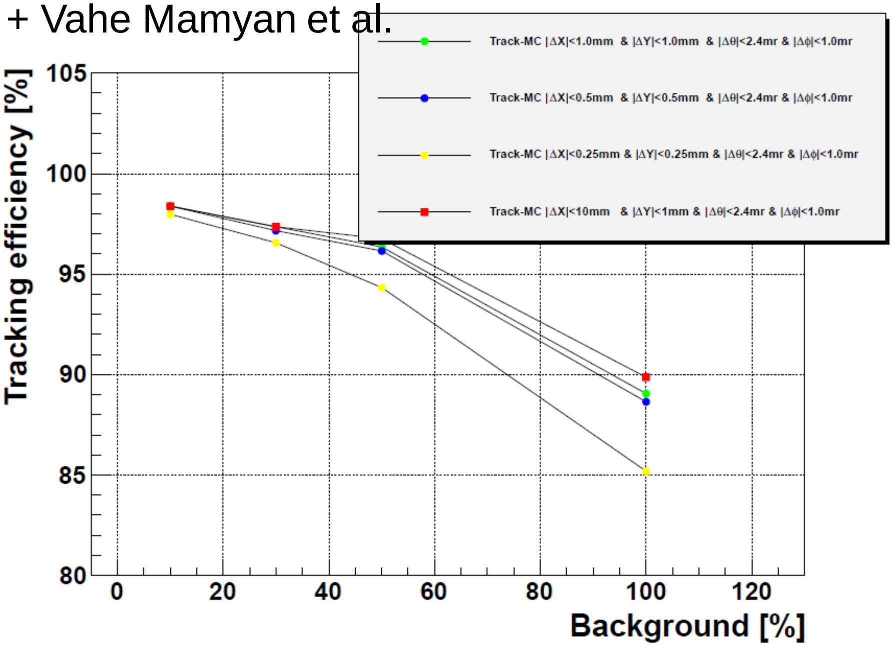
MonteCarlo + Digitazation + Tracking

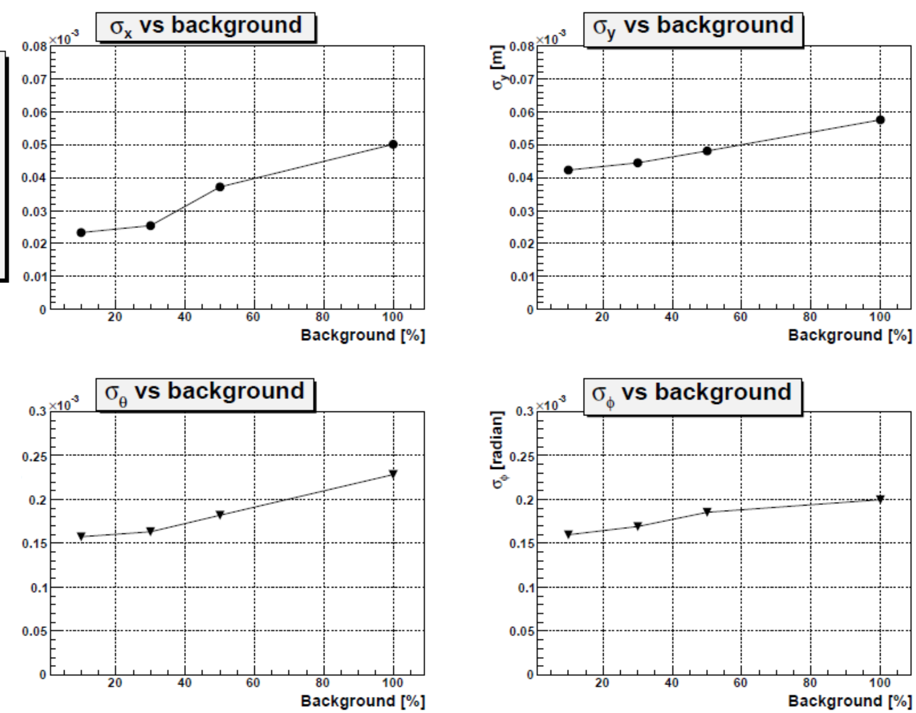




6 GEM chambers with x/y readout
Use multisamples (signal shape)
for background filtering

Bogdan Wojtsekhowski + Ole Hansen
+ Vahe Mamyan et al.

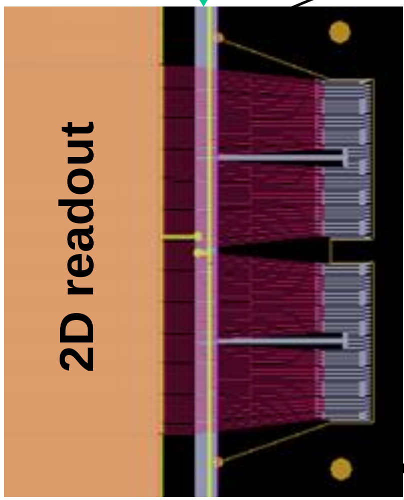


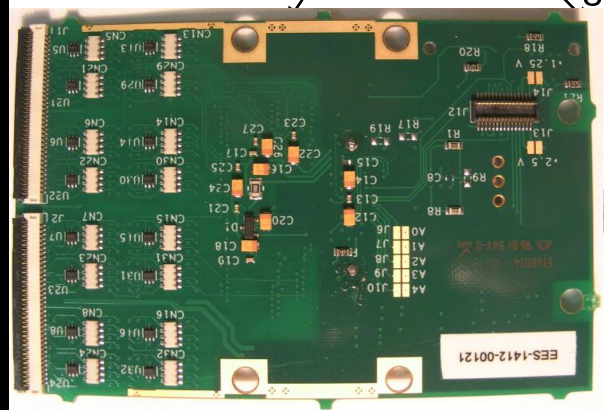


Electronics Components

GEM ⇒ FEC 4.0 ⇒ MPD ⇒ DAQ

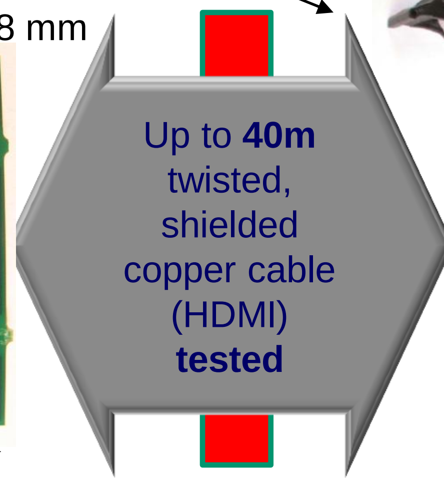
GND ring



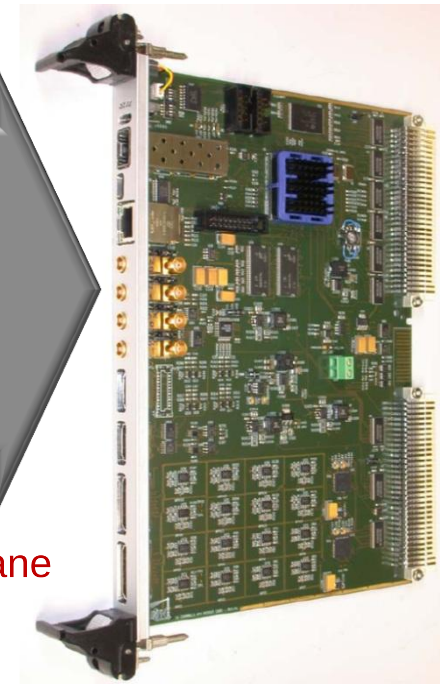


8 mm

75 mm



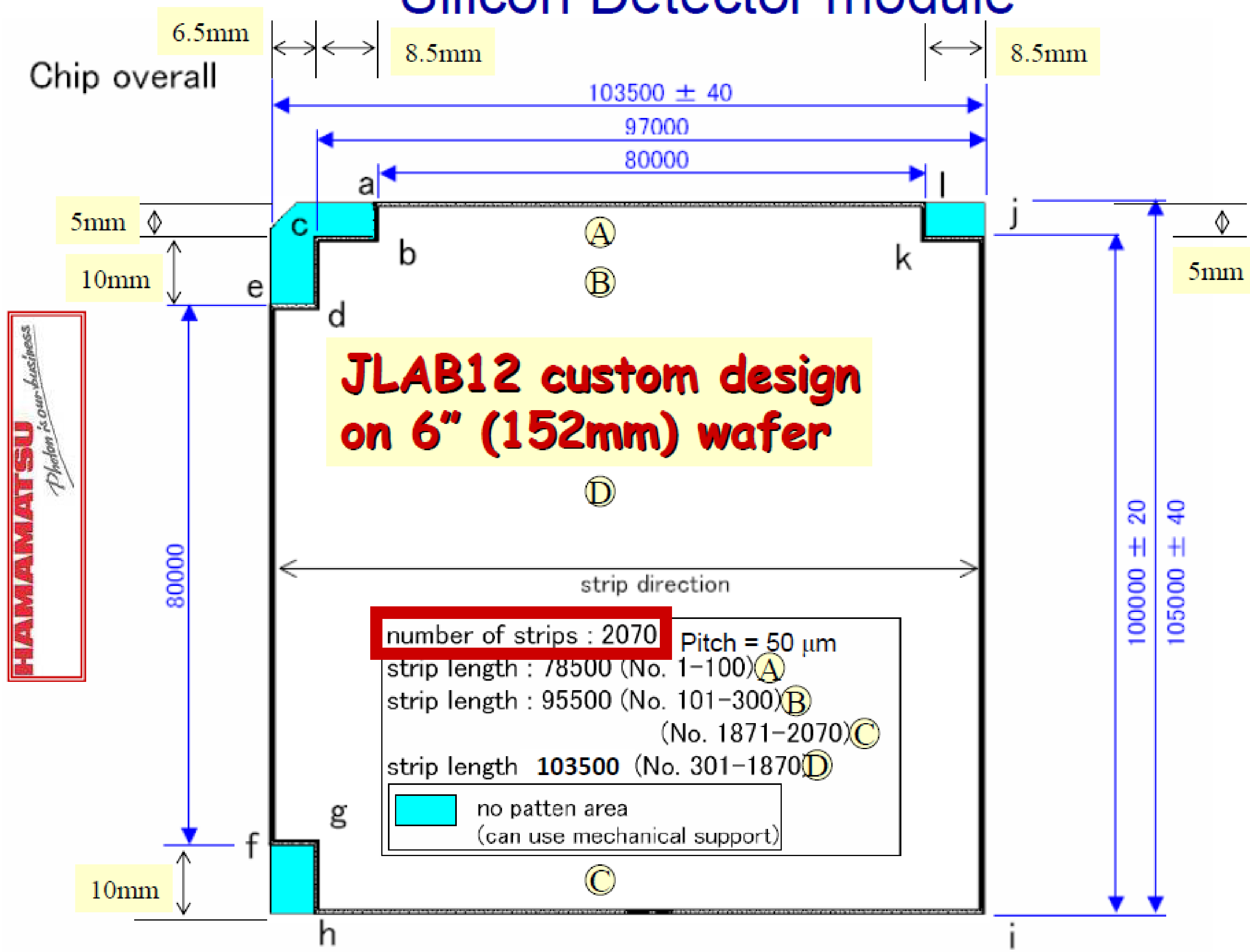
Passive backplane (optional)



Main features:

- Use analog readout APV25 chips
- 2 “active” components: Front-End card and VME64x custom module
- Copper cables between front-end and VME
- Optional backplane (user designed) acting as signal bus, electrical shielding, GND distributor and mechanical support
- Flex adapters available for “standard” PANASONIC GEM connectors.

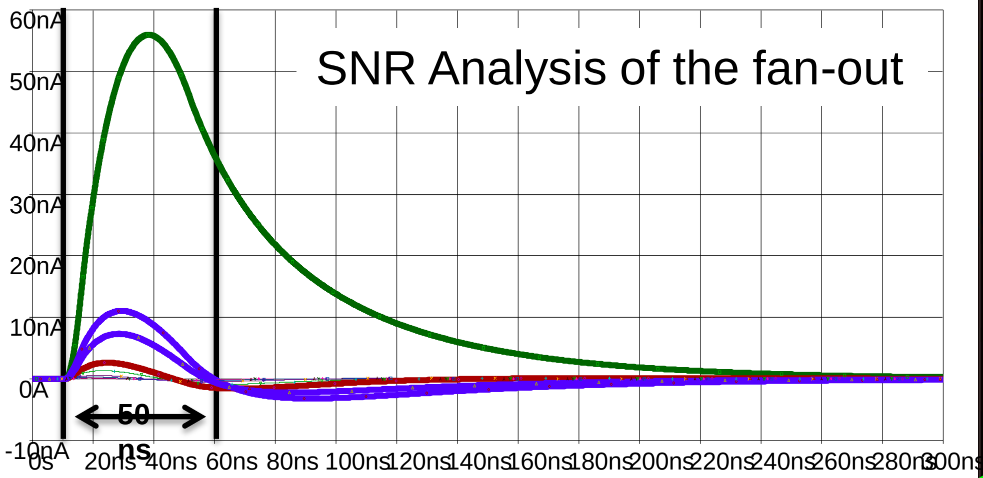
Silicon Detector module

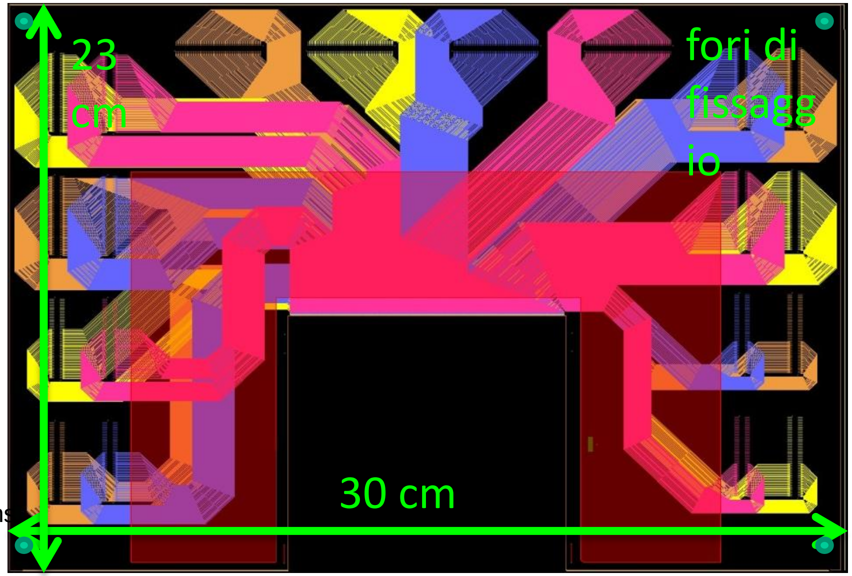


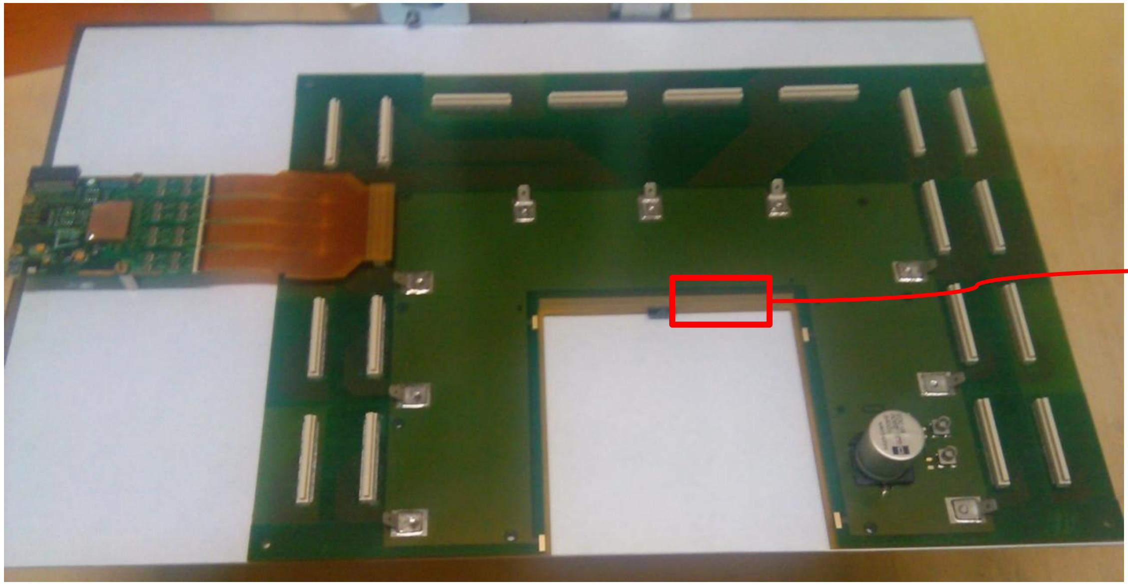
μSiD composed by 2 planes (x/y) each made of 2 of the above modules

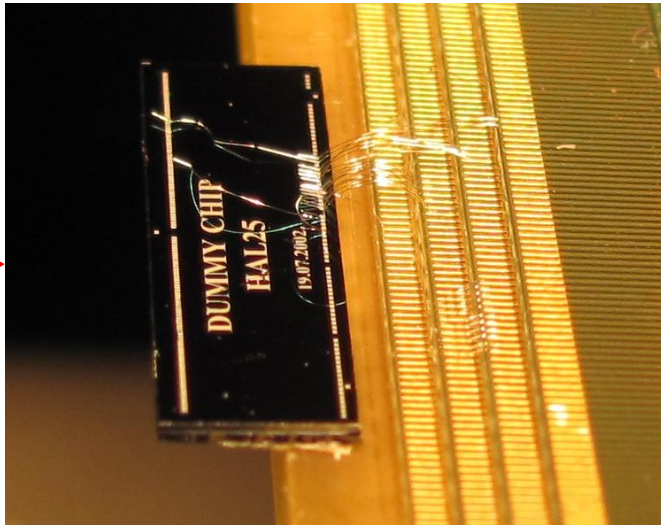
Maximize area, large segmentation, keep cost reasonable

Disegno finale del PCB X rigido con il piano di massa sagomato





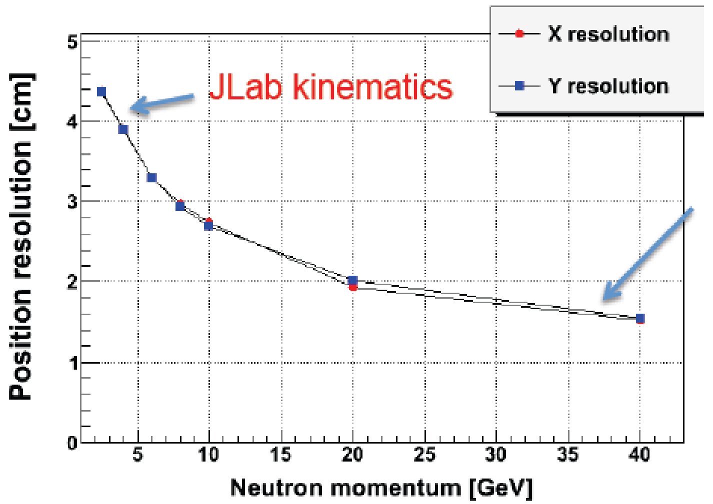


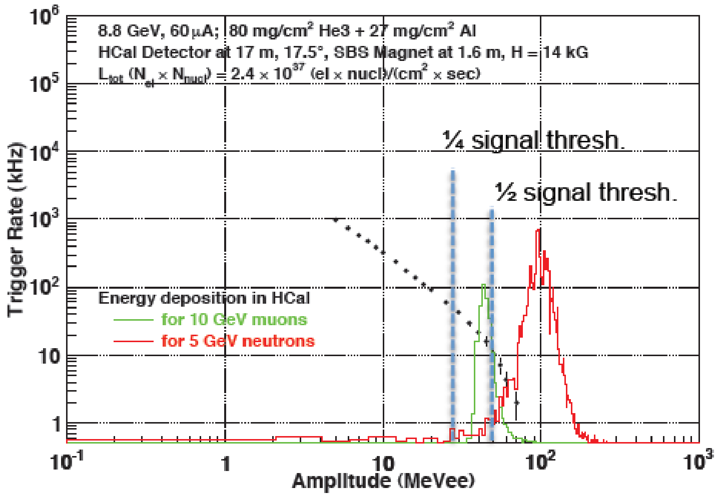


Multilayer bonding pads

HCAL-J

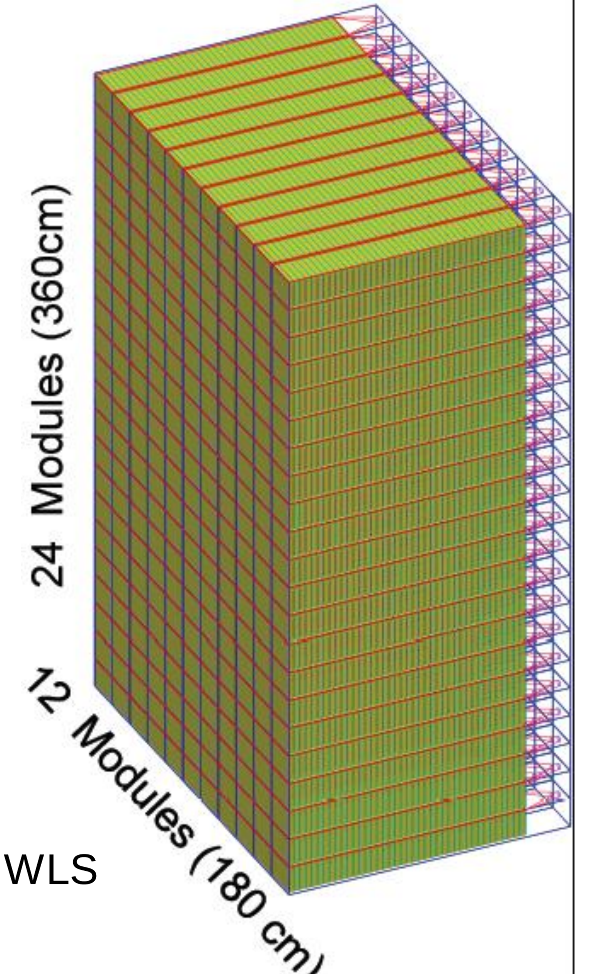
Used for: **trigger, PID and neutron «tracker»**





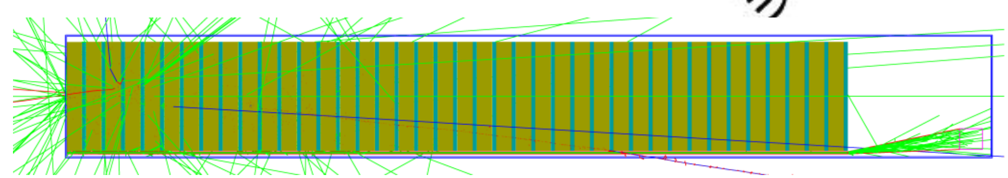
GEANT4 tuned by COMPASS data

- Match acceptance of SBS magnet/polarimeter
- Run with high threshold while maintaining high trigger efficiency



Design derived from COMPASS HCAL1

Iron plates + Scintillators + WLS + Light Guide



- Linear energy response
- 5 mrad angular resolution
- **0.5 ns time resolution**

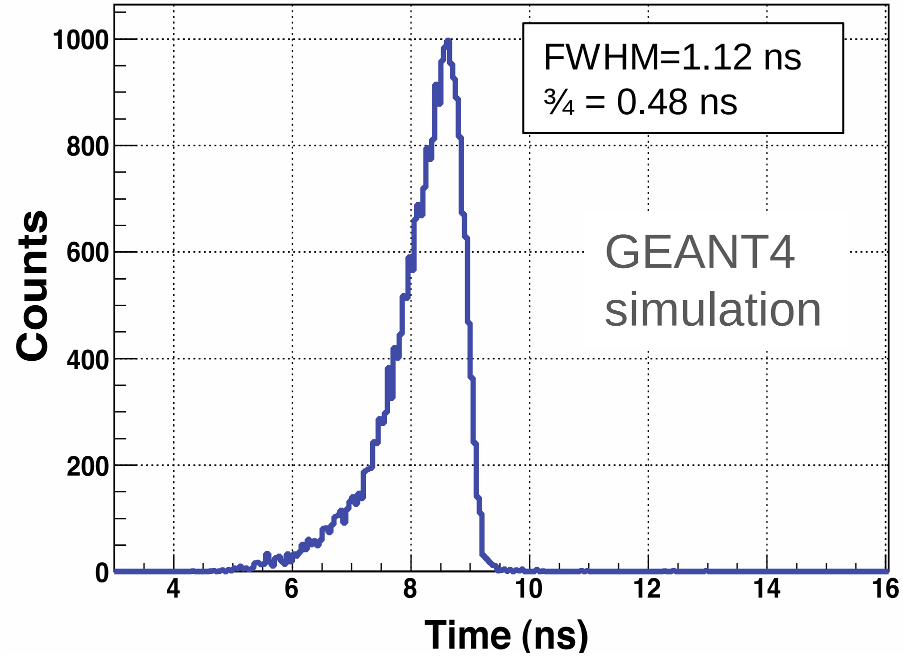
Time resolution

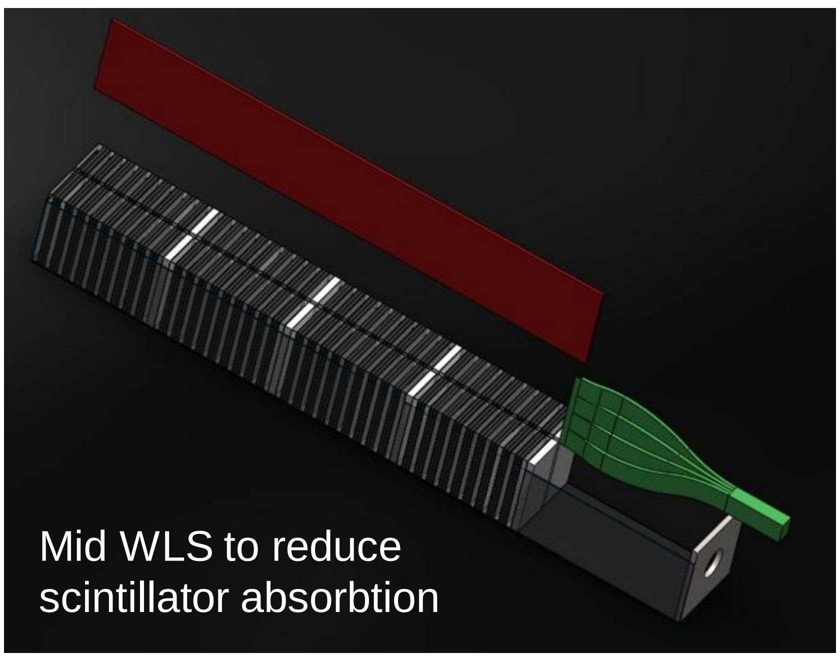
Simulation using faster waveshifter dye and PMTs
→ meets SBS requirements

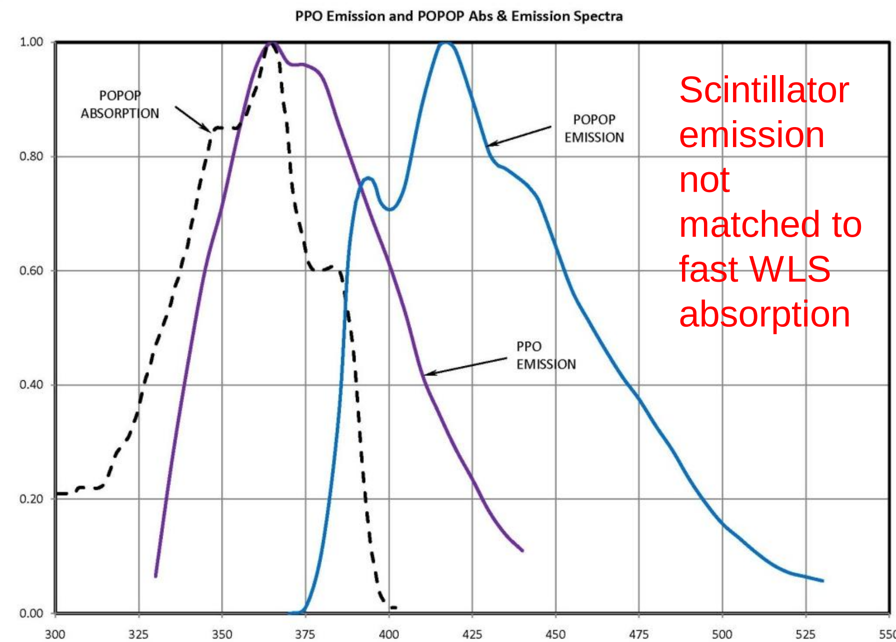
To be confirmed/ with prototype HCAL module

INFN-CT Task

Need optimization of design and coupling of scintillator-WLS-Light Guide – min cost







Conclusion

SBS expected to be in place in 2015

Front tracker essential to operate SBS in high luminosity (likely to be used in A1n DIS experiment before SBS experimes)
Pre-production started

HCAL-J fundamental in all SBS experiments for proton and neutron detection – need optimization of time resolution.
Finalize prototyping in 2013

Bright future for the nucleon structure investigation by EM form factors

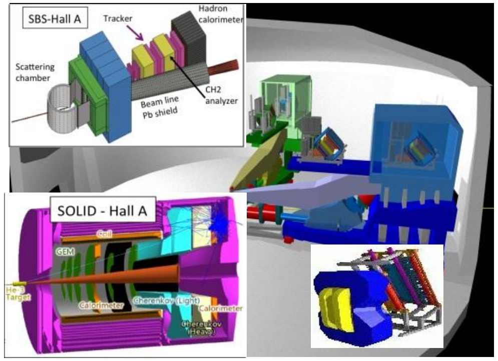
1815	Prout: all atoms composed of H atoms (protyles)	
1897	**Thomson: discover the «corpuscles» (electrons) ⇨ atoms are not the smallest possible division of matter**	
1909	Geiger/Marsden/Rutherford: classic model of the atom	Discovery of the nucleus
1913	Bohr: new model fo the atom	
1917		Rutherford/Moseley discover the proton and first hypothesis of the neutron
1928		Chadwick discover the neutron
1933		**Stern: measure the proton magnetic moment ⇨ first evidence on internal structure of the nucleon**
1935		Yukawa: meson theory
1947	**Lamb and Retherford measure the Lamb shift ⇨ modern QED**	Powell et al.: discover the pion
1954		Hofstadter: First measurements of the elastic scattering, Form Factors, measure of proton radius
1960-70		DIS, scaling and parton model
1980-		*Spin crisis, nucleon transverse momentum (spin) structure*
2000		*New measurmenets of the proton form factors*

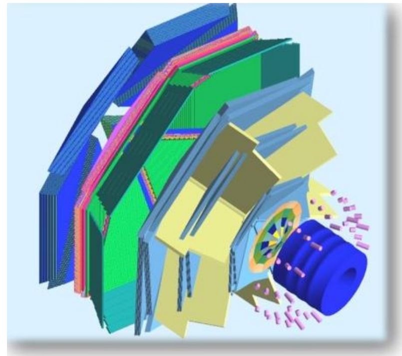
50 years to undestand the atom structure

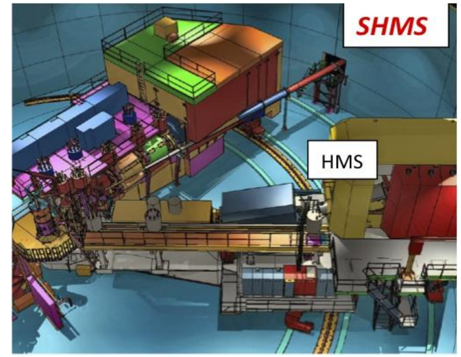
80 years passed from the first evidence of the structure of the nucleon

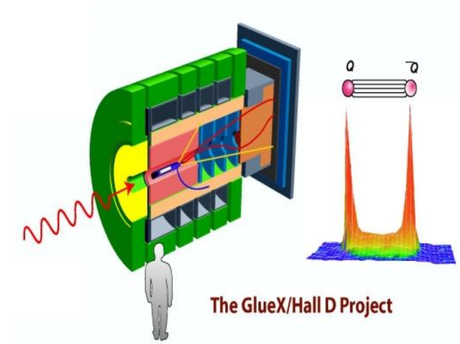
Support slides

Experimental Halls after 2014







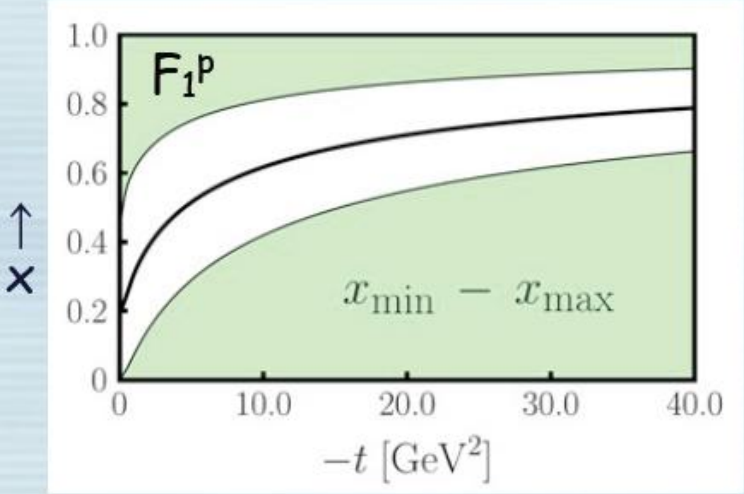


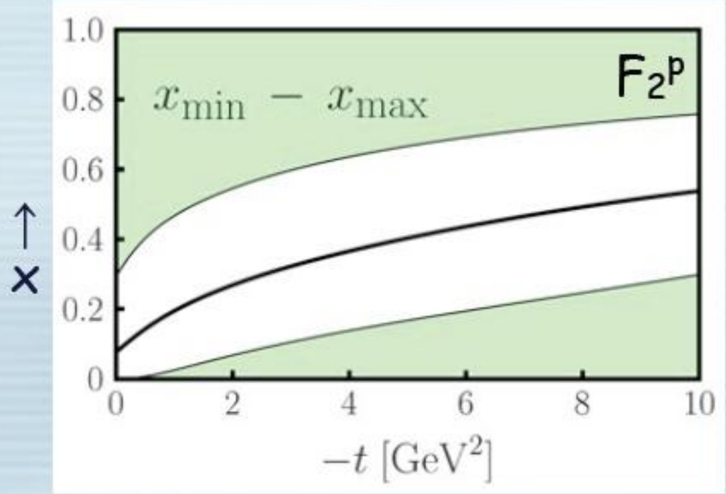
Hall A	Hall B/CLAS12	Hall C	Hall D/GLUEX
High res. Mom. spect. Large angular and momentum, high lumi spect. with hadron ID Neutron detector 'Solid' detector 'Möller' detector New beam line	New ~4π toroid detector with extended hadron ID	2 Asymmetric spectrometers, Super high momentum spectrometer Dedicated equipment	Excellent hermetic coverage, Solenoid field High multiplicity reconstruction
100 μA beam Lumi: 10^{38} cm^{-2} s^{-1}	Forward tagger for quasi-real photons	100 μA beam Lumi: 10^{38} cm^{-2} s^{-1}	10^8 linearly polarized <12 GeV real γ/s
3He T/L , H to Pb unpol	NH3/ND3 long/trans H/D target (?)	NH_3/ND_3 Polarized long. target, H to Pb unpol	
hallaweb.jlab.org	www.jlab.org/Hall-B	www.jlab.org/Hall-C	www.jlab.org/Hall-D www.gluex.org

<u>High Q^2 is required</u> to constrain GPDs at short distance scales

The integral of H^q and E^q over x is given by F_1 and F_2

$$\int_{-1}^{+1} dx H^q(x,\xi,Q^2) = F_1^q(Q^2) \quad \text{and} \quad \int_{-1}^{+1} dx E^q(x,\xi,Q^2) = F_2^q(Q^2)$$





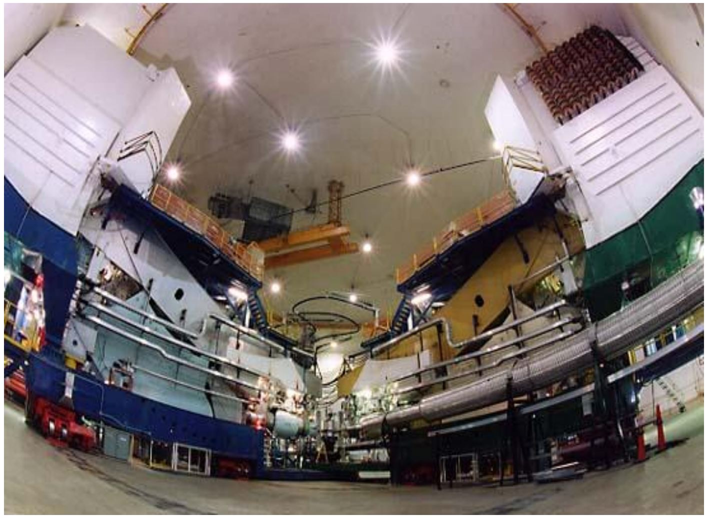
Shown above with the white bands are the regions of x that contribute 90% of the integral's strength (in this case for the proton.)

From G. Cates JLab/2012

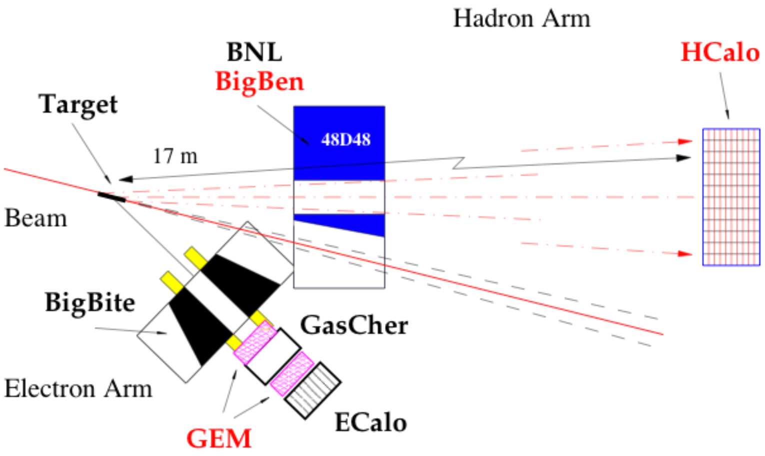
To constraint the GPDs at high x, where valence quarks dominate, we need to to know the form factors at high Q^2

Plans for Nucleon Form Factors in Hall A

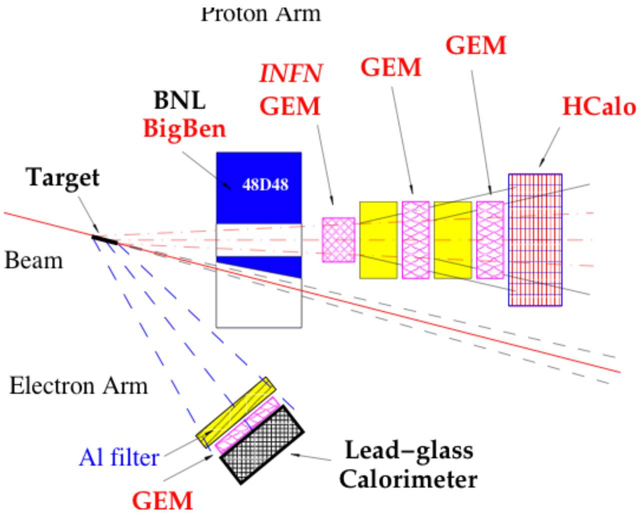
Proton magnetic form factor, GMp: E12-07-108



Neutron/proton form factors ratio, GMn/GMp: E12-09-019



Proton form factors ratio, GEp/GMp: E12-07-109



Neutron form factors ratio, GEn/GMn: E12-09-016